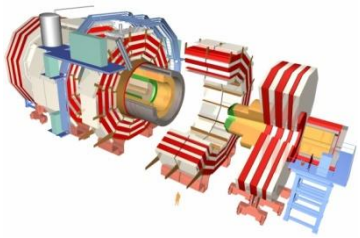


Associated production of vector bosons and jets in CMS

Fengwangdong Zhang

on behalf of CMS collaboration

Peking University & Université Libre de Bruxelles

QCD@LHC 2016

Zurich, Switzerland

2016/08/22 – 2016/08/26

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：

- 8TeV ($L \leq 19.8\ fb^{-1}$, BX = 50 ns):
  - 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

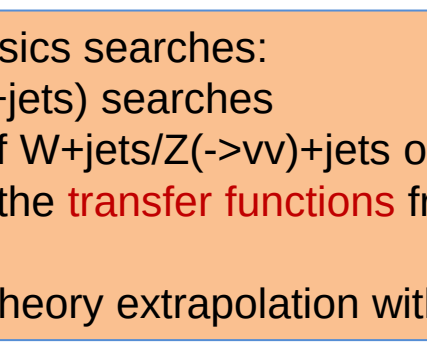
- 13 TeV ($L = 2.5\ fb^{-1}$, BX = 25 ns):
  - W boson + jets
  - Z boson + jets

◆Data taken during 2015

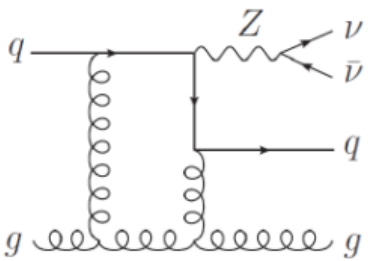
Motivations on V+jets physics

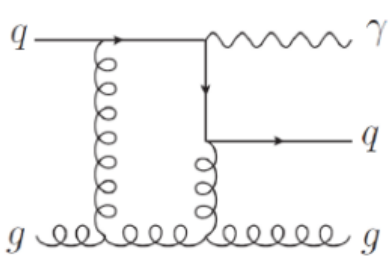
- One can probe different aspects of QCD calculations with V+jets processes
- Actual understanding and modeling of QCD interactions is crucial on the potentials for precision measurements
  - W/Z+jets is a dominant background for:
    - Top-quark measurements
    - Precision measurement of Higgs physics in VH(->bb) channel
  - It is significant for the modeling the production mechanism involved in new physics searches (e.g. Supersymmetry)

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



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





$$\sigma(pp \to Z(\to \nu\bar{\nu}) + \text{jets}) = \sigma(pp \to \gamma + \text{jets}) \times R_{Z/\gamma}$$

irreducible background — measure this — theory input

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 energy
- Jets are reconstructed using Particle Flow algorithm
  - Anti-Kt algorithm applied for jets with parameters R=0.5 (0.4) at 8 TeV (13 TeV)
  - Jets must be well isolated with the leptons from W/Z boson decays
  - Pileup subtraction is implemented in the isolation definition of the jets
  - Heavy flavor (c/b) jets are tagged for the dedicated analyses

- Restrict the phase space for an efficient selection and 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 modellings on the cross sections at particle level, including the differential cross section as a function of various observables
  - Compared theoretical predictions can be in different accuracy levels

Data statistics for W/Z +jets measurement (8 TeV)

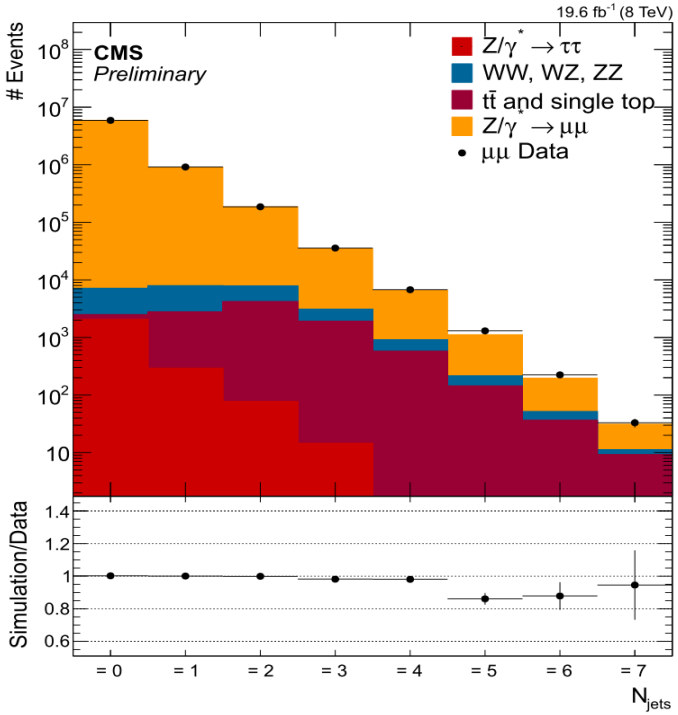
- **Measured differential cross section as a function of several observables**
- **The presence of data goes up to large jet multiplicity region for both W/Z + jets**

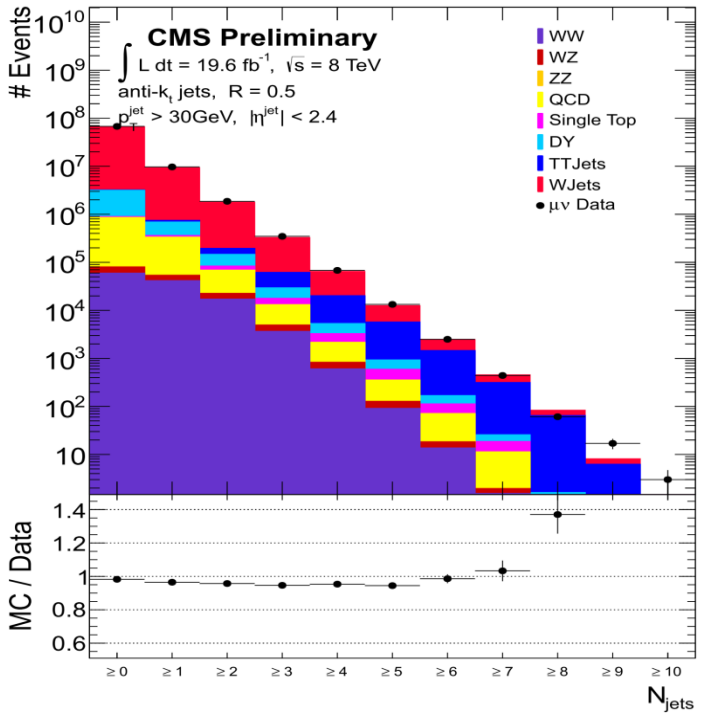
➢Phase space for Z+jets:

- **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:

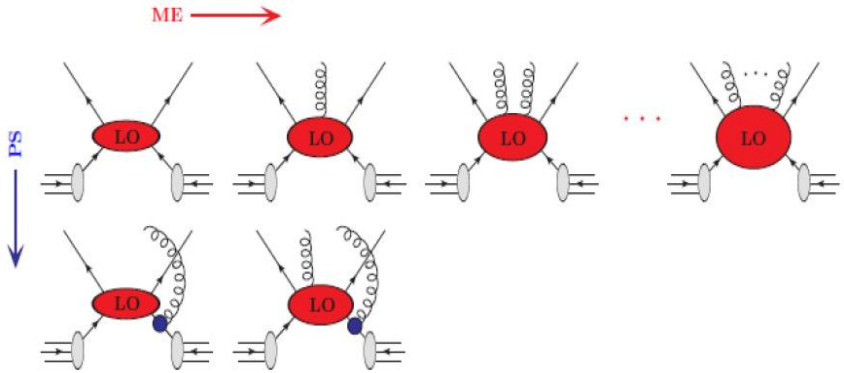
- **Lepton selection:**
  - p_T (l) > 25 GeV
  - |η (l)| < 2.1
  - M_T > 50 GeV
- **Jet selection:**
  - p_T (j) > 30 GeV
  - |η (j)| < 2.4



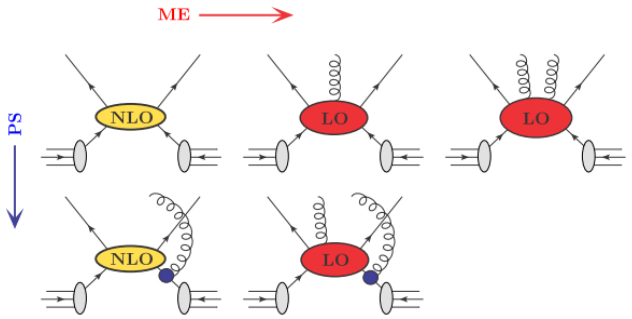


Theoretical predictions for Z + jets cross section comparison at 8 TeV

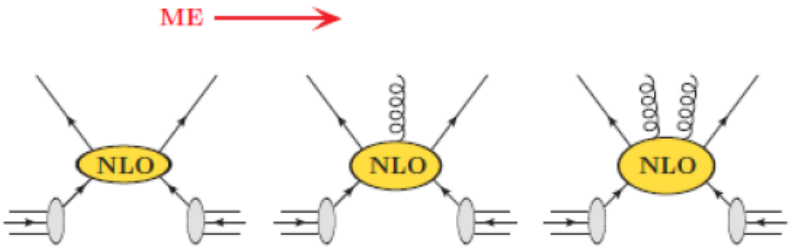
- **Multileg LO with 0~4 final partons in matrix element:**
  - MADGRAPH5 + PYTHIA6: kt-MLM merging, CTEQ6L1 PDF
  - SHERPA1.4: CKKW merging, CT10 PDF
  - Hadronization and mutiple parton interactions are implemented



- **Multileg with 0~2 partons at NLO, 3~4 partons at LO:**
  - SHERPA2 (+ BLACKHAT): MEPS@NLO merging, CT10 PDF
  - Hadronization and mutiple parton interactions are implemented



- **Fixed order Z + N jets (NLO):**
  - BLACKHAT (+SHERPA): MSTW2008 NLO PDF
  - Correction for hadronization and multiple parton interactions computed with MG5+PYTHIA6



Theoretical predictions for W + jets cross section comparison at 8 TeV

- MADGRAPH5 + PYTHIA6
  - Leading order multileg matrix element up to 4 partons in final state
  - kt-MLM merging, CTEQ6L1 PDF

- 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, NNPDF2.3 NLO PDF , CUETP8M1 PYTHIA8 tune

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

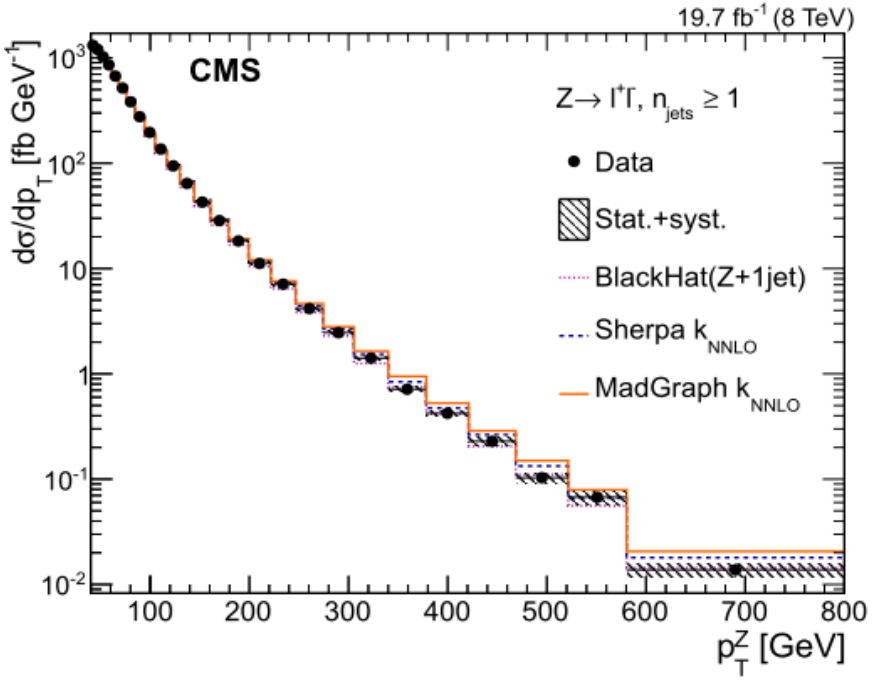
- BLACKHAT + SHERPA
  - NNLO W + njet with fixed order (n = 1~4)
  - CT10 PDF set
  - Correction for hadronization and multiple parton interactions computed with MG5+PYTHIA6

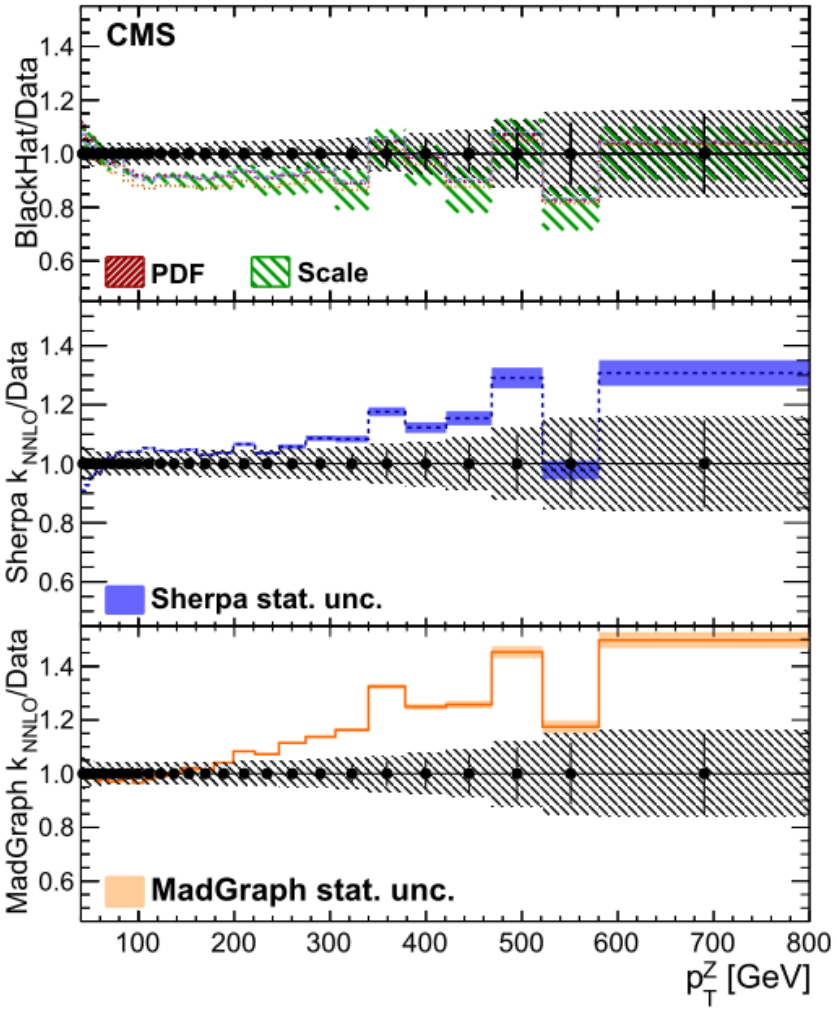
- NNLO (W+1jet fixed order)
  - Correction for hadronization and multiple parton interaction
  - CT14 PDF set
  - Reference: PRL.115.062002; arXiv:1602.08140; arXiv:1512.01291; arXiv:1602.06965

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

JHEP10(2015)128

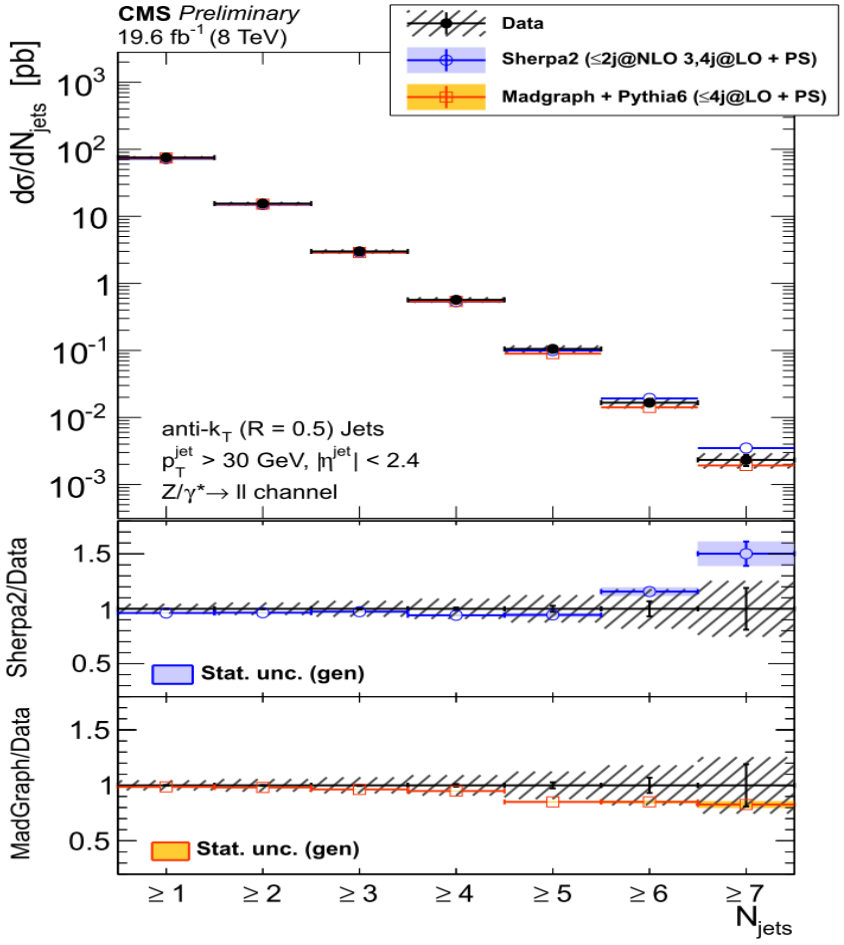
Published

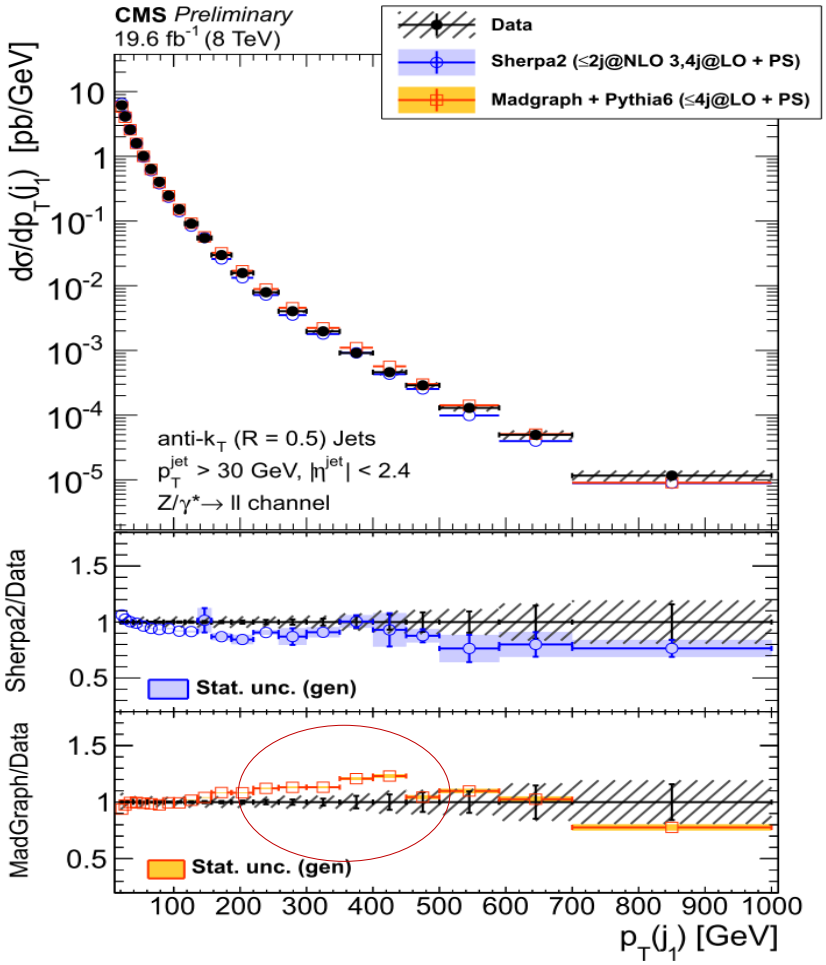




- K_{NNLO}: Z+>=0 jet cross section rescaled to NNLO value from FEWZ
- MG5+Pythia6 comparison is flat until around 200 GeV and up to about 30% discrepancy, which is same for Z+ ≥ 2 jets case
- BLACKHAT reproduces the shape of data in the same region

Z + jets differential cross section as function of jet observables



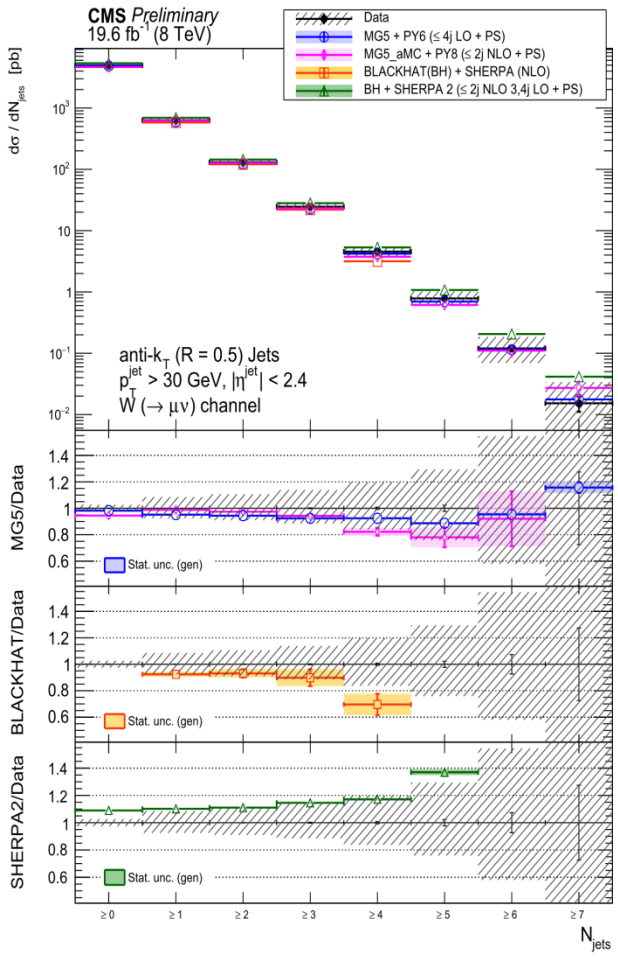


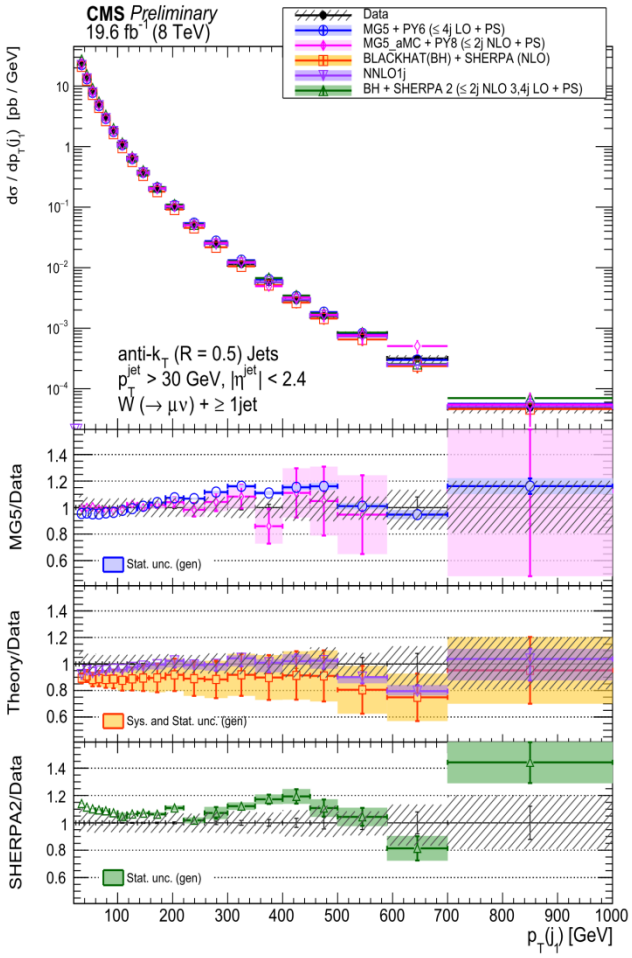
SMP-13-007

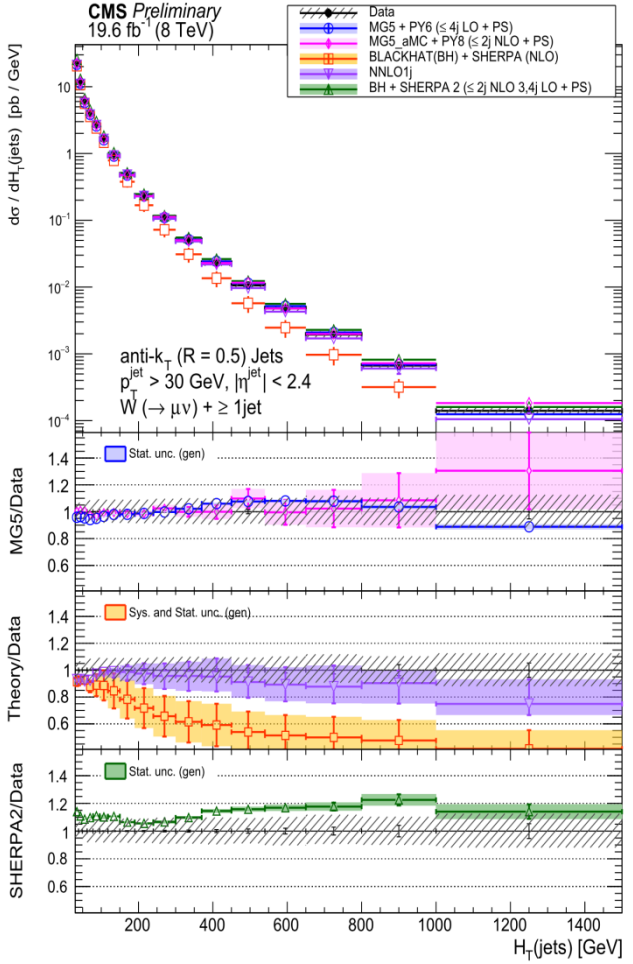
- Good agreement with SHERPA2 (NLO)
- Discrepancy with LO computation has disappeared with NLO accuracy

W + jets differential cross section as function of jet observables

SMP-14-023



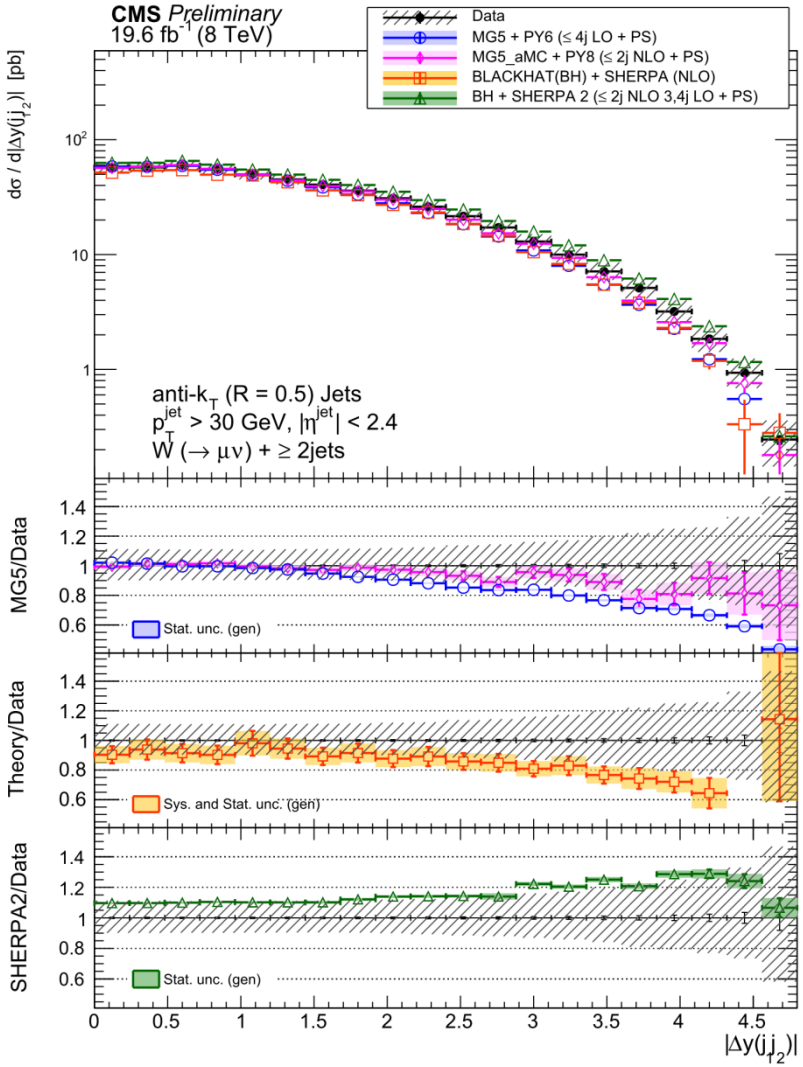


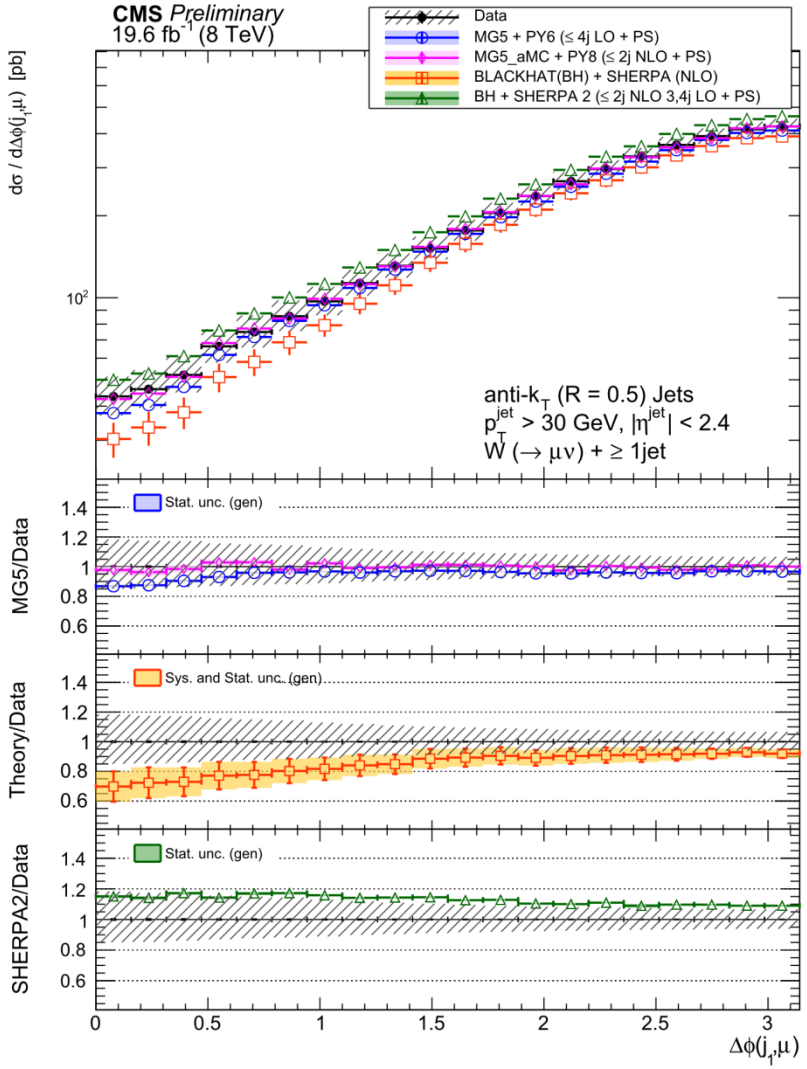


- Only the decay channel of W(->μν) + jets is measured
- Excellent agreement with AMC@NLO and NNLO W+1J predictions

Angular correlation measurement of W+jets

SMP-14-023





- Discrepancies in large rapidity difference between jets and in small azimuthal angle difference between muon and leading jet
- AMC@NLO describes the measured angular correlations best

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

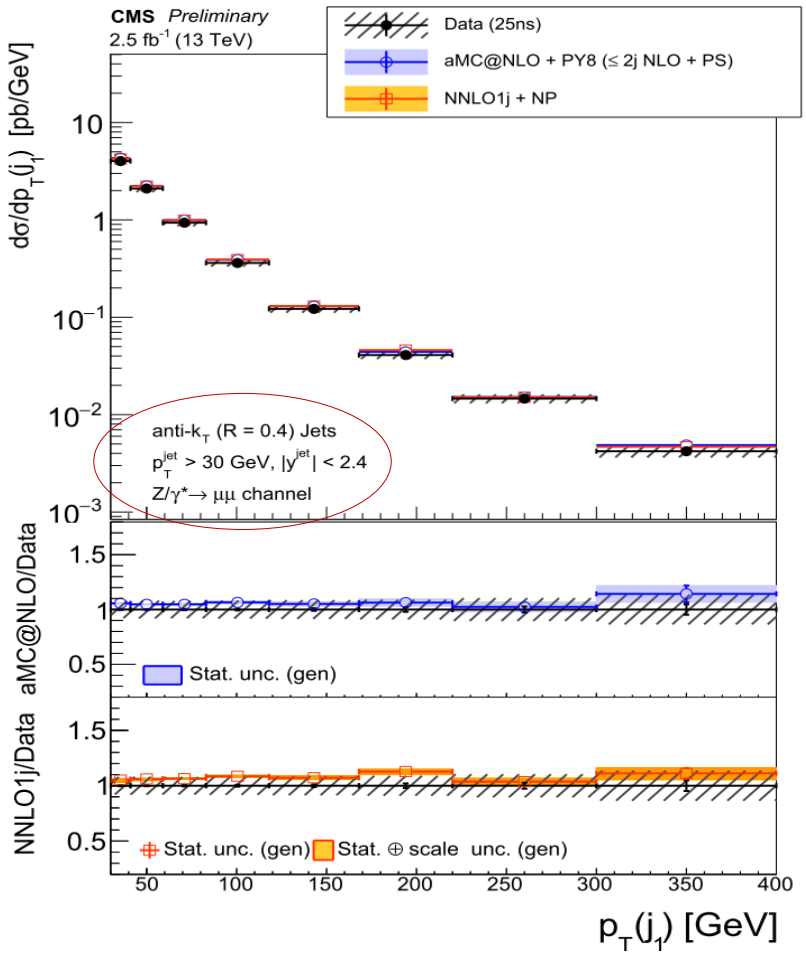
- MADGRAPH5_AMC@NLO + PYTHIA8
  - Next leading order multileg matrix element up to two partons in final state, LO accuracy for 3 partons
  - FxFx jet merging scheme
  - NNPDF3.0 NLO PDF set
  - CUETP8M1 PYTHIA8 tune

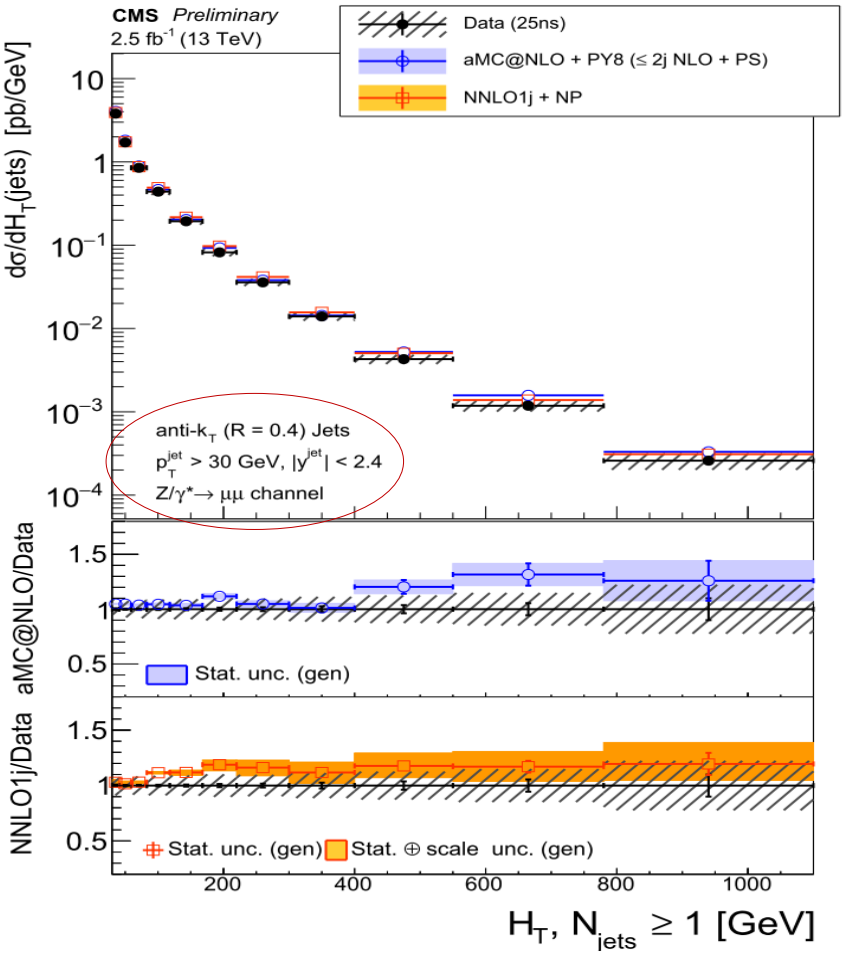
- NNLO
  - NNLO W/Z+1jet with fixed order
  - Correction for hadronization and multiple parton interaction computed with MADGRAPH5_AMC@NLO + PYTHIA8
  - CT14 PDF set
  - References:
    - arXiv:1602.08140
    - arXiv:1512.01291
    - arXiv:1602.06965
    - Phys. Rev. Lett. 115, no.6, 062002 (2015)

- 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

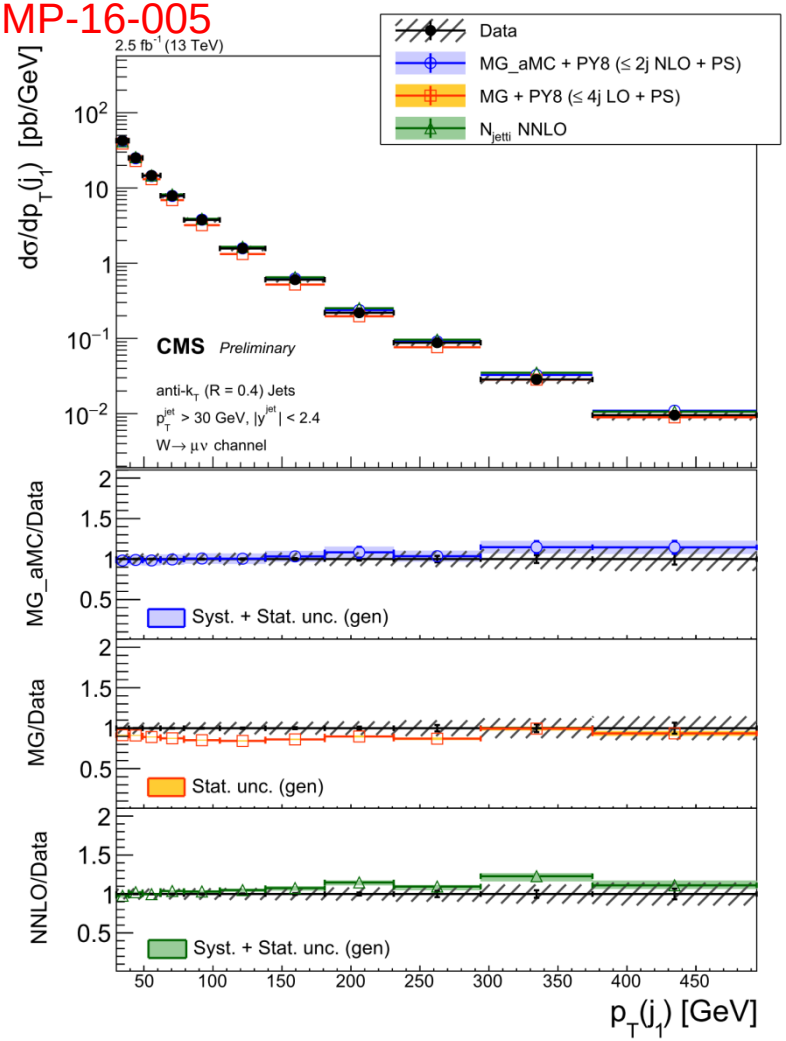


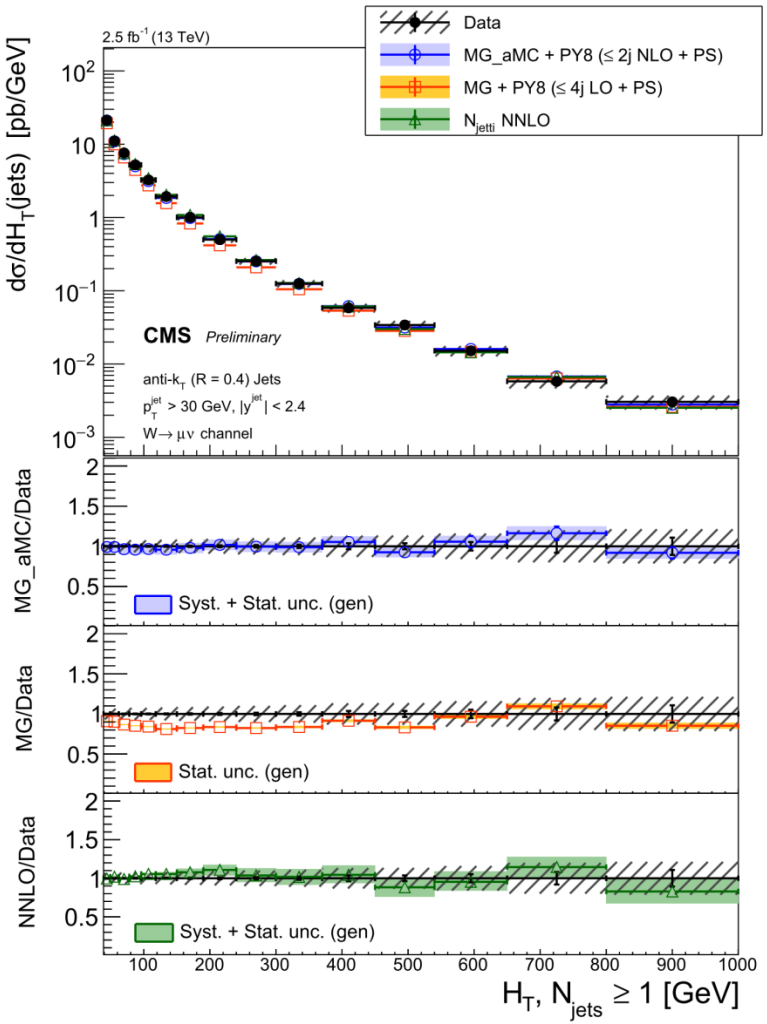


- Good agreement with multileg NLO and NNLO calculations
- The p_T , η, H_T of jet for inclusive jet multiplicities up to 3 jets have also been measured
  - H_T is the scalar sum of the p_T of jets

W + jets differential cross section at 13 TeV

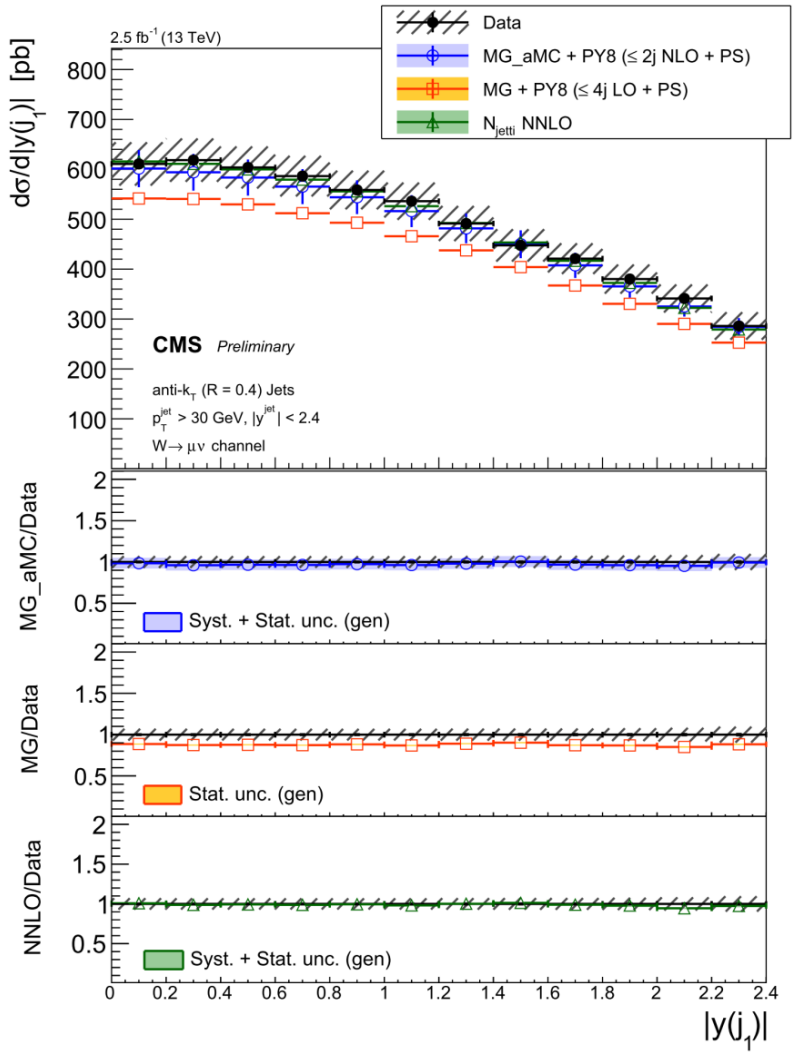
SMP-16-005

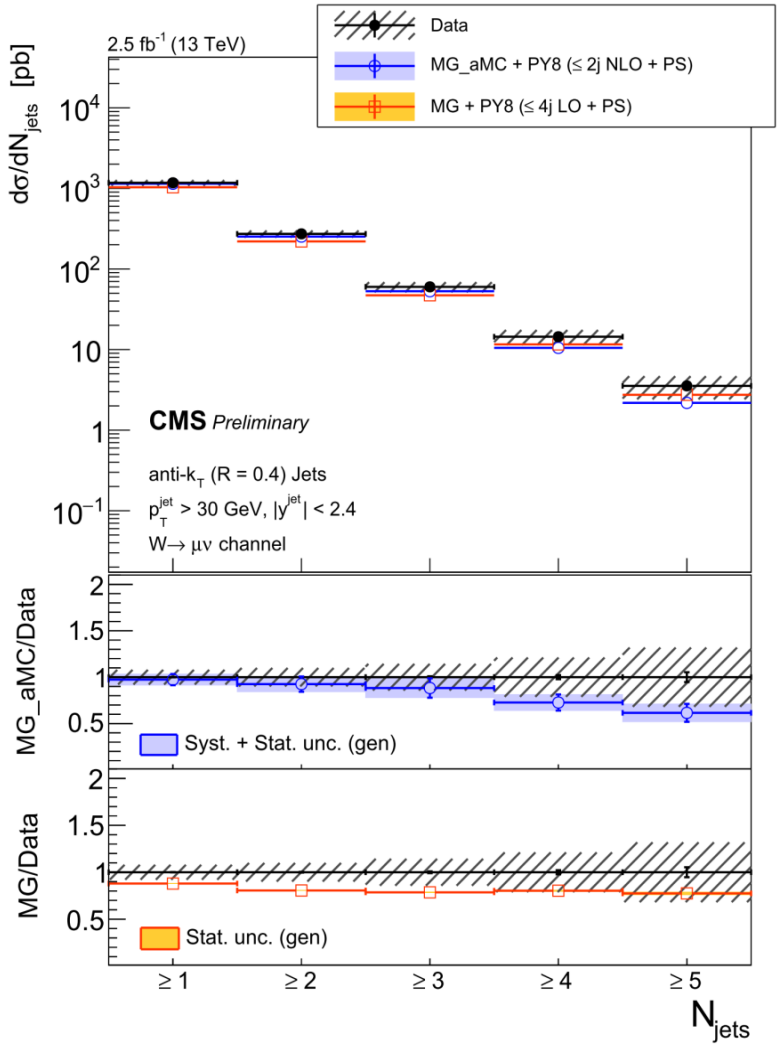




- Agreement is improved significantly with multileg NLO and NNLO calculations
- The p_T , η, H_T of jet for inclusive jet multiplicities up to 3 jets have also been measured
  - H_T is the scalar sum of the p_T of jets

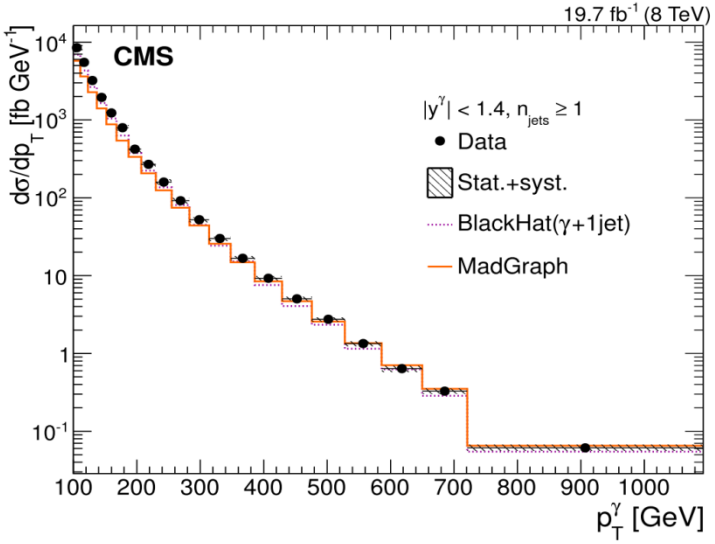
W + jets differential cross section at 13 TeV

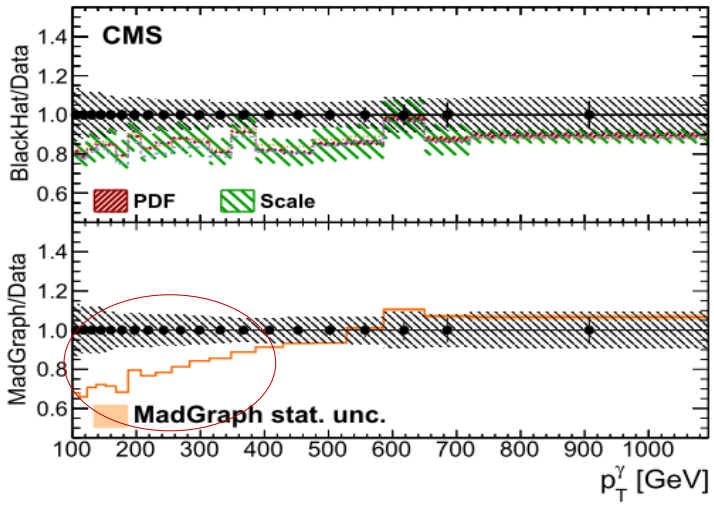




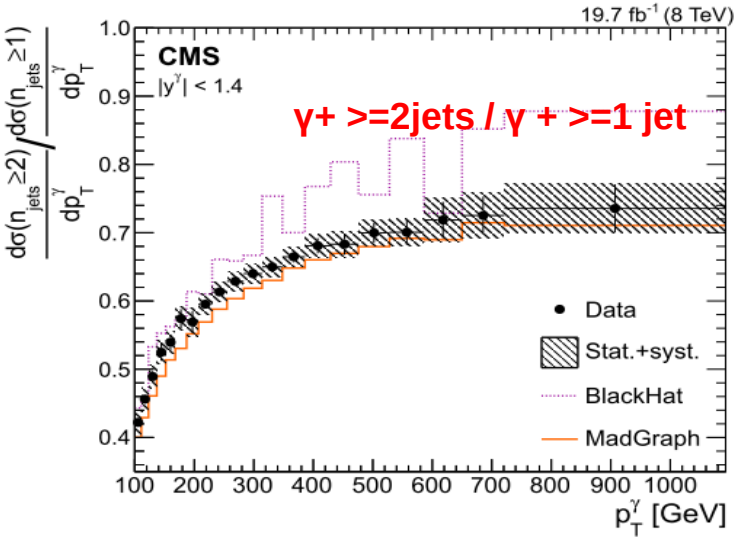
- Agreement is improved significantly with multileg NLO and NNLO calculations

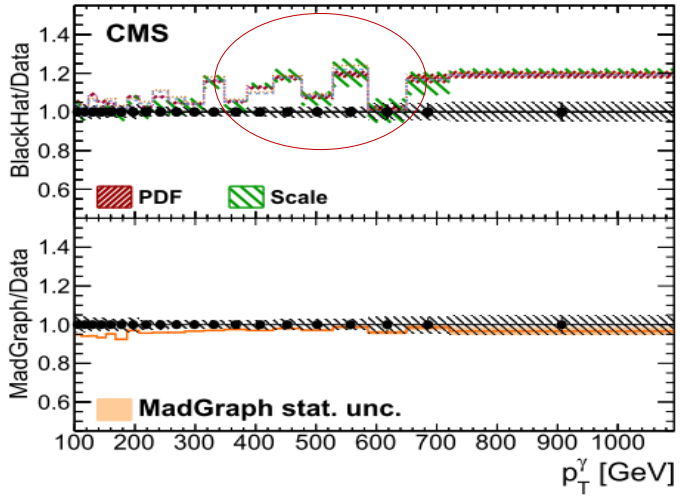
Photon (γ) + jets cross section at 8 TeV





- 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

- **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

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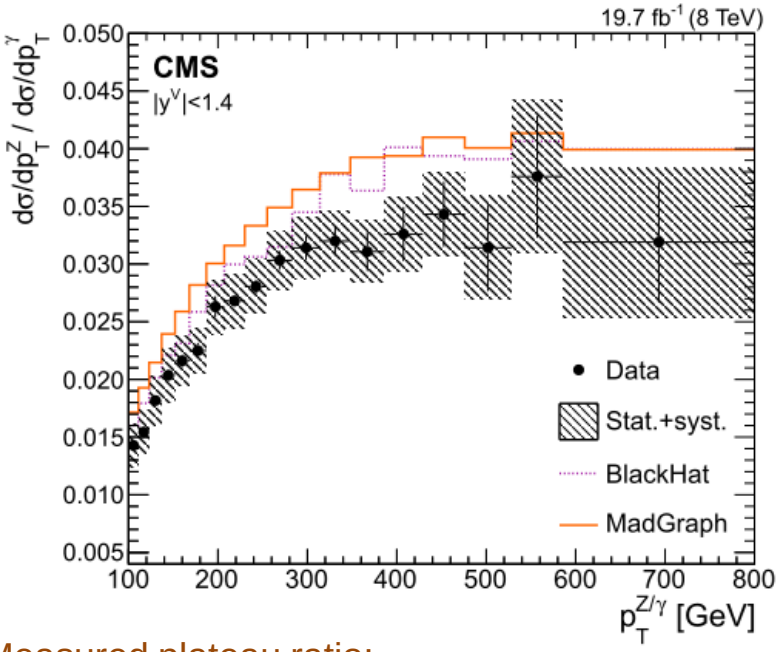
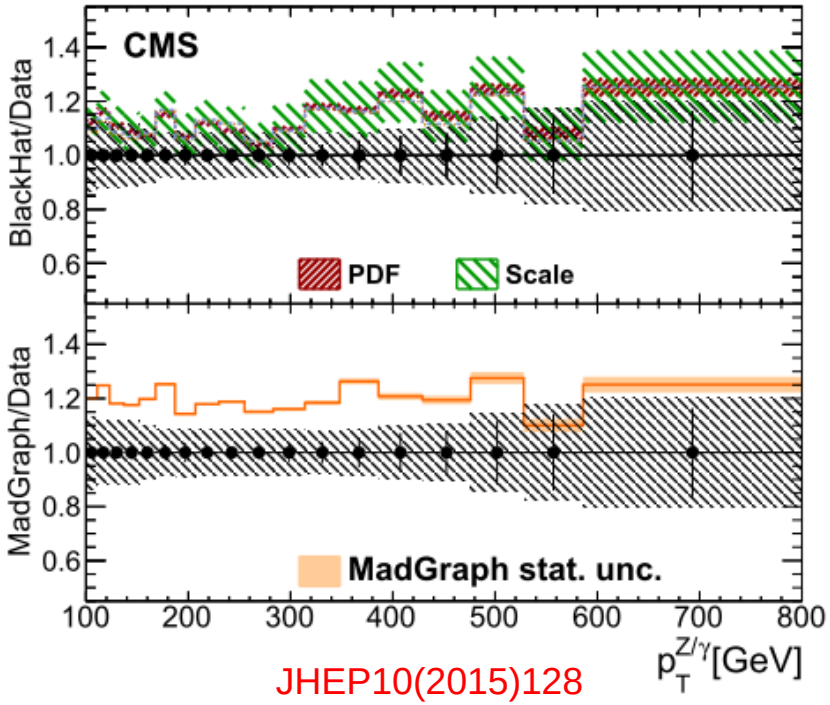
Z + jets & γ +jets cross section ratio at 8 TeV

- 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(->νν)+jets background estimation in SUSY searches





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- Measured plateau ratio:

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

- 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
- Madgraph (Tree level) has already reproduced the shape of data well

W/Z + heavy flavor jets ($b/\bar{b}$) 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 measurements
- 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 at 8 TeV

- Lepton selection:
  - P_T > 30 GeV
  - |η| < 2.1
- B-tagged jet selection:
  - P_T > 25 GeV
  - |η| < 2.4

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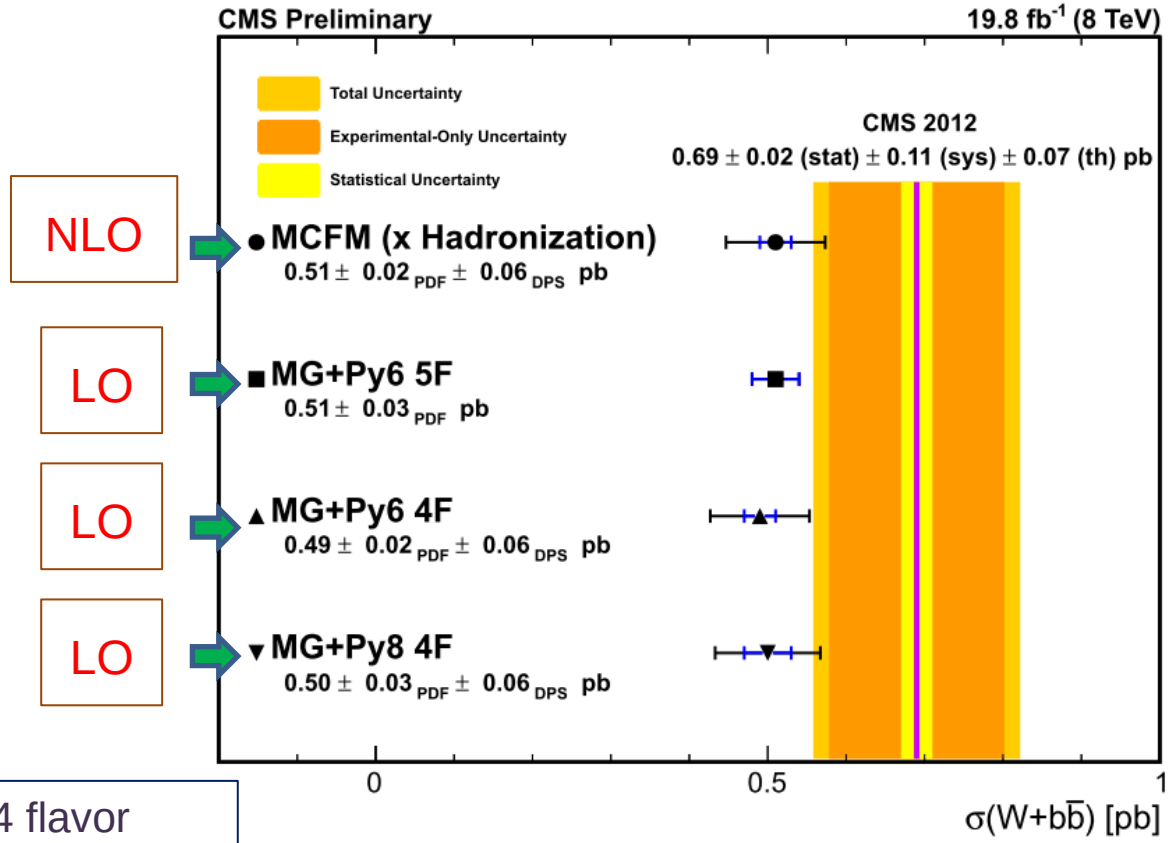

- The MCFM and MG+Py* with 4 flavor scheme do not account for the b$\bar{b}$ system coming from multiple parton interaction
- Hadronization correction is implemented for MCFM prediction which is at parton level

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

Z+b jets cross section at 8 TeV

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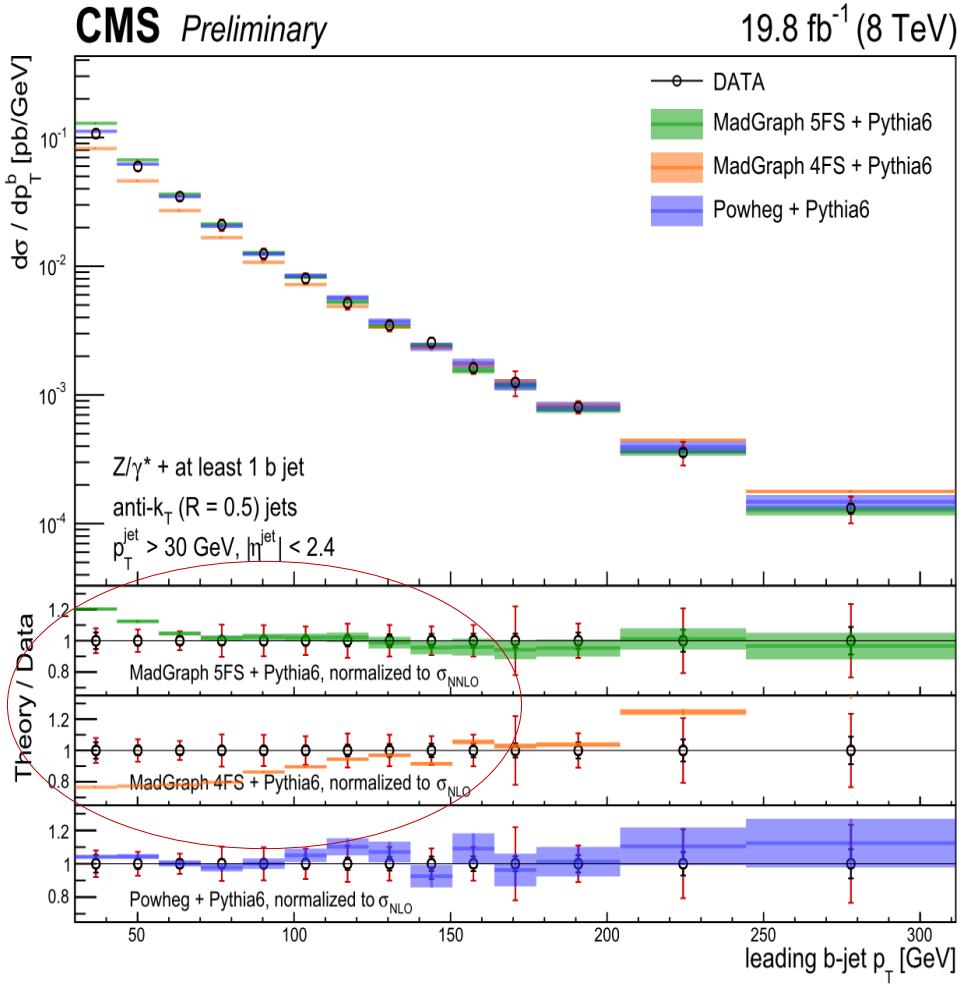
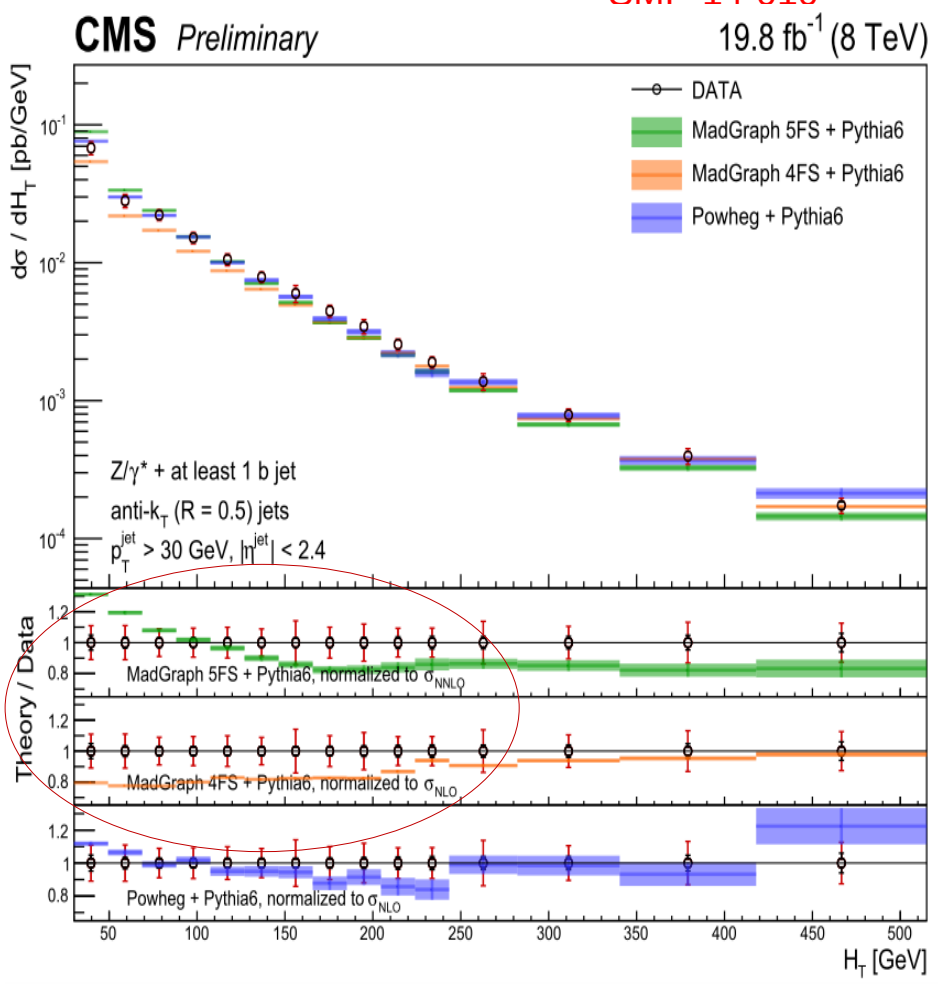




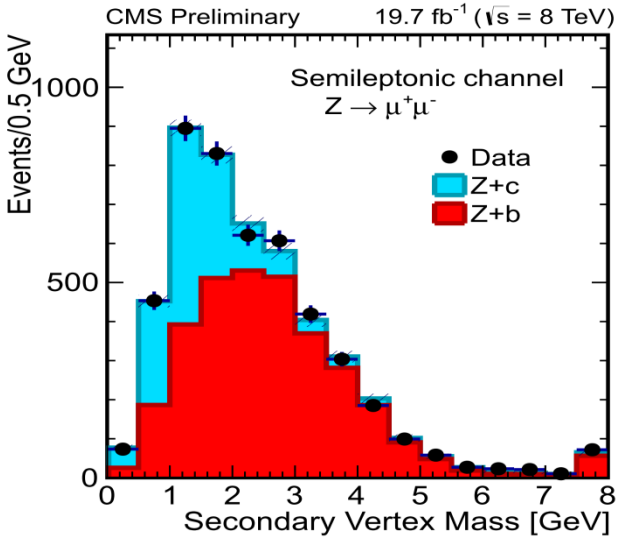
- **Discrepancy of about 20% observed for 4FNS-based LO prediction for Z + b jet case**
- **Overall agreement is observed between measurement and NLO prediction (Powheg), while the 5FNS-based prediction slightly overshoots the data at small transverse momentum of b jet (Z + b jet)**

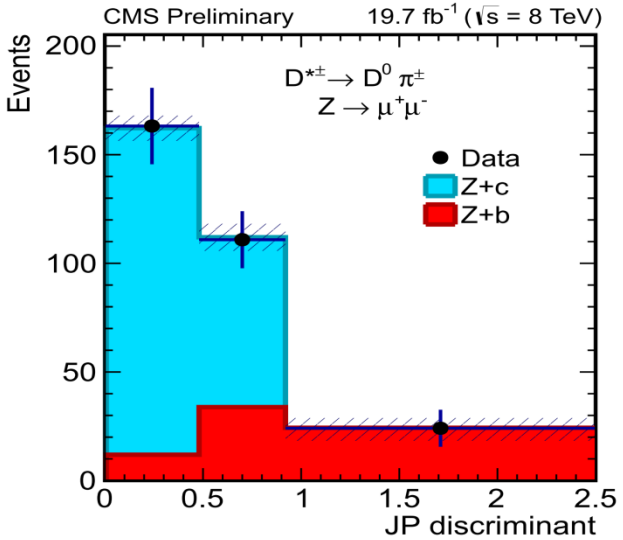
Z+c jets cross section at 8 TeV

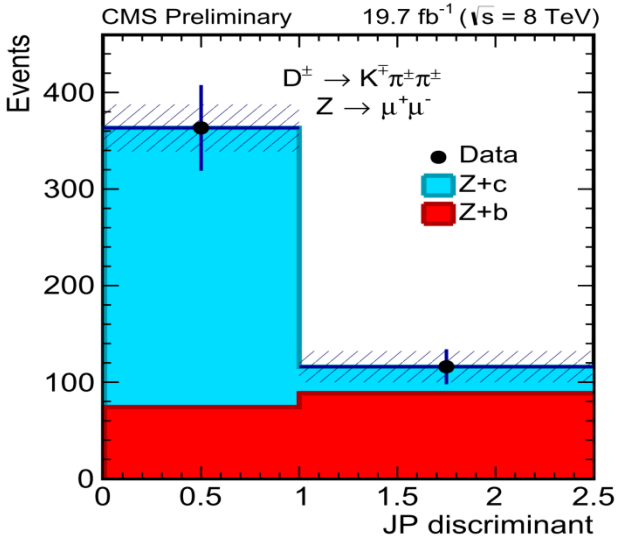
- Three modes for identifying a jet from heavy flavor quarks:
  - Semileptonic decay of a heavy flavor hadron:
    - A muon participating in a secondary vertex
  - $D^{\pm}$ mode: three tracks from a secondary vertex:
    - $D^{\pm}$ -> $K^{\mp}\pi^{\pm}\pi^{\pm}$
  - $D^{*\pm}$ mode: two tracks from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



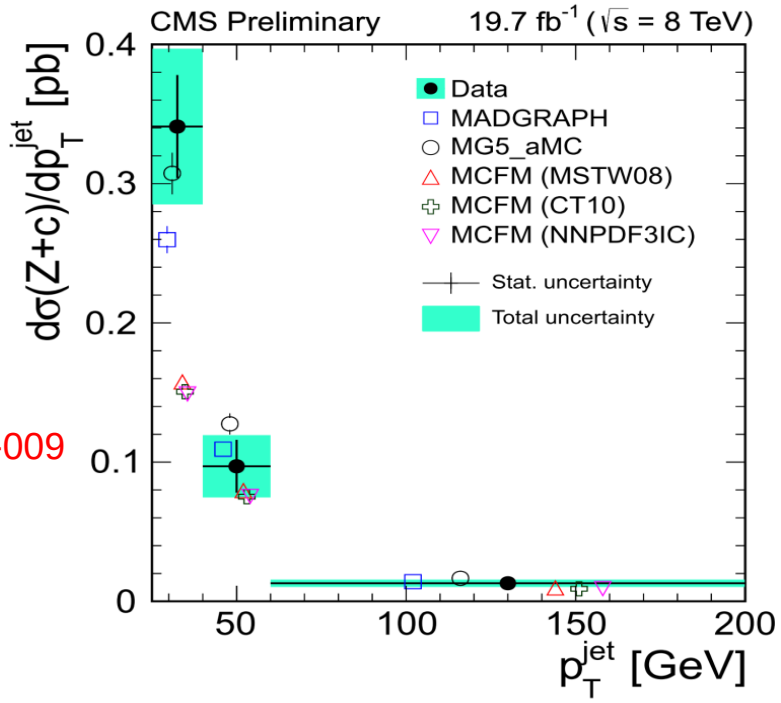


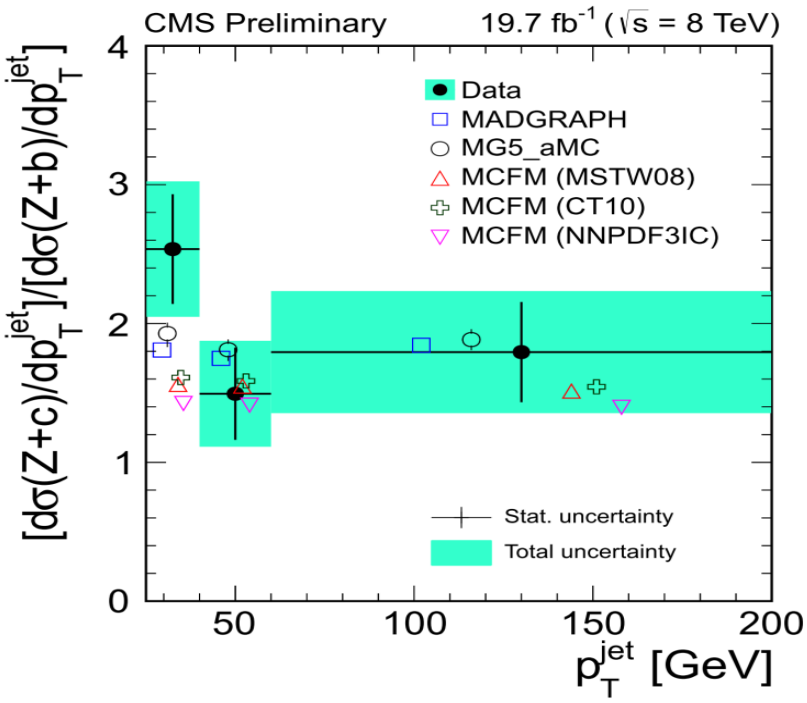


- A likelihood estimate of the probability that jet tracks comes from the primary vertex in the pure hadronic decay mode (JP discriminant)
- The invariant mass of all the charged particles (including a muon) constituting the secondary vertex in the semileptonic decay mode

Z+c jets cross section at 8 TeV

SMP-15-009





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

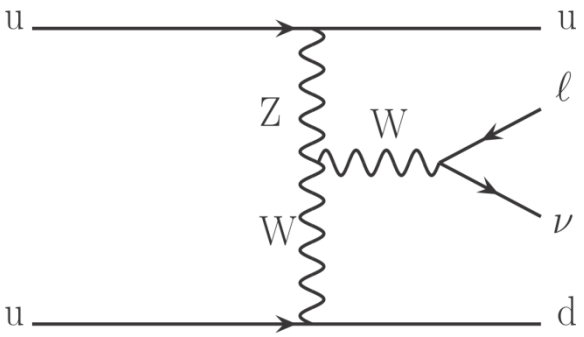
- **The measured Z + c-flavor-jet production cross section:**
  8.6 ± 0.5 (stat.) ± 0.7 (syst.) pb
- **The measured cross section ratio of Z+c to Z+b:**
  2.0 ± 0.2 (stat.) ± 0.2 (syst.) pb

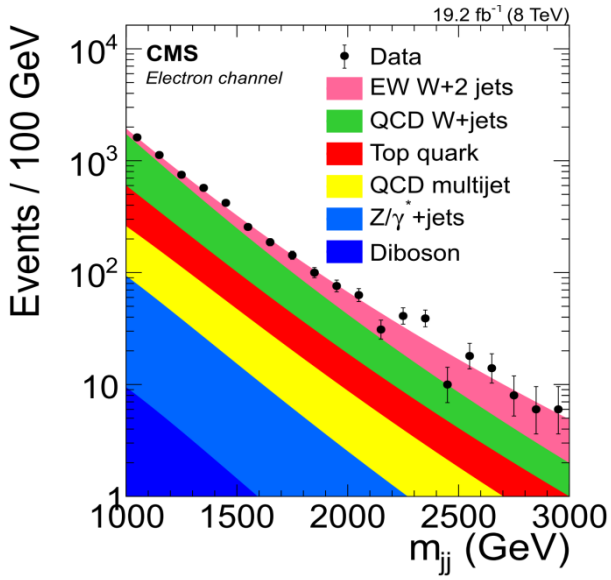
Electroweak W+2 jets cross section measurement at 8 TeV

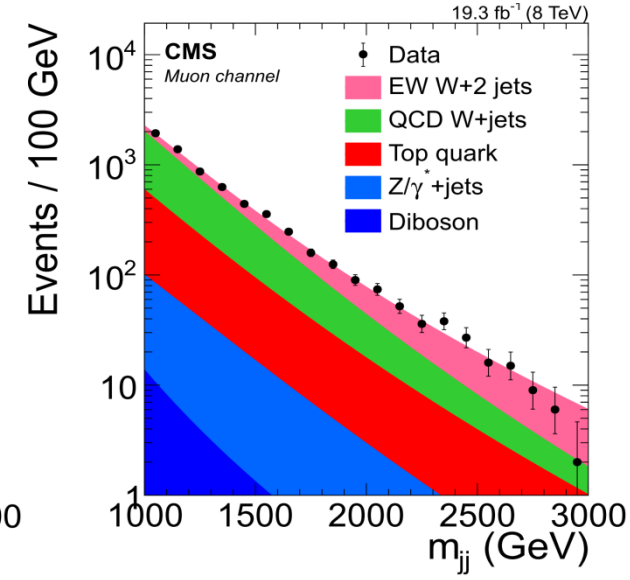
SMP-13-012 arXiv:1607.06975

Submitted to JHEP recently

- Lepton selection:
  - p_T (μ) > 25 GeV, p_T (e) > 30 GeV
  - |η (μ)| < 2.1, |η (e)| < 2.5
  - E_T > 25 (30) GeV
  - M_T (W) > 30 GeV
- Jet selection:
  - p_T (j1) > 60 GeV, p_T (j2) > 50 GeV
  - |η (j)| < 4.7
  - M(jj) > 1000 GeV
  - |y(W) – (y(j1) + y(j2))/2 | < 1.2







- **The signal process is predicted using MADGRAPH5 in LO accuracy (CTEQ6L1 PDF) and interfaced with PYTHIA6**
- **An unbinned maximum likelihood fit is used to extract the signal process yields**

- **The first time to measure the EW W+2jets (forward jets)**
- **It will benefit from more statistics at 13 TeV**

- **The measured EW W+2jets production cross section:**
  0.42 ± 0.04 (stat.) ± 0.09 (syst.) ± 0.01 (lumi.) pb
- **The LO prediction using MADGRAPH5:**
  0.50 ± 0.02 (scale) ± 0.02 (PDF) 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

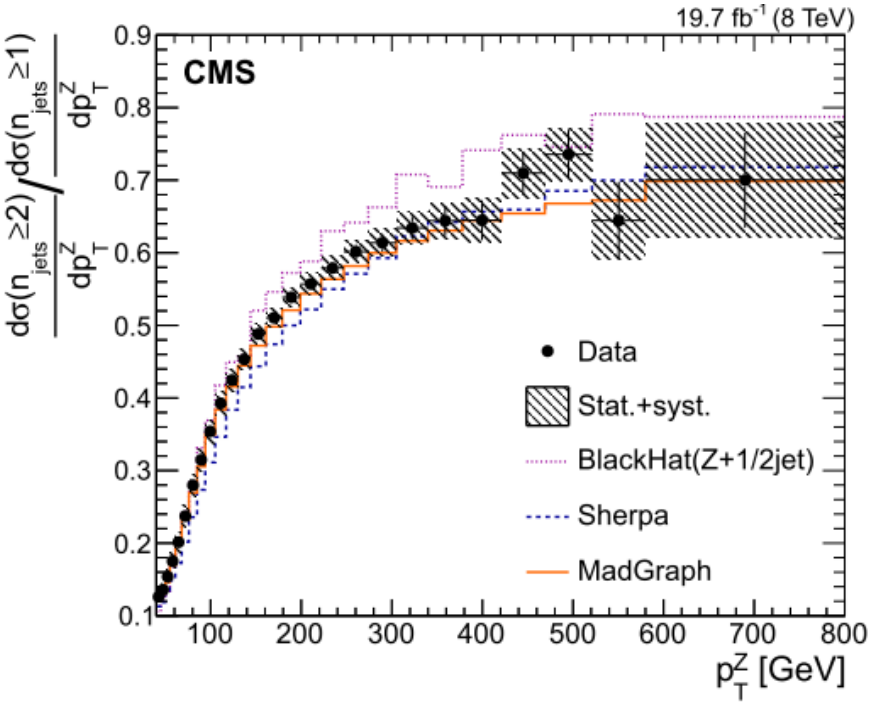
- More results at both 8TeV and 13TeV will come out soon!

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)

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



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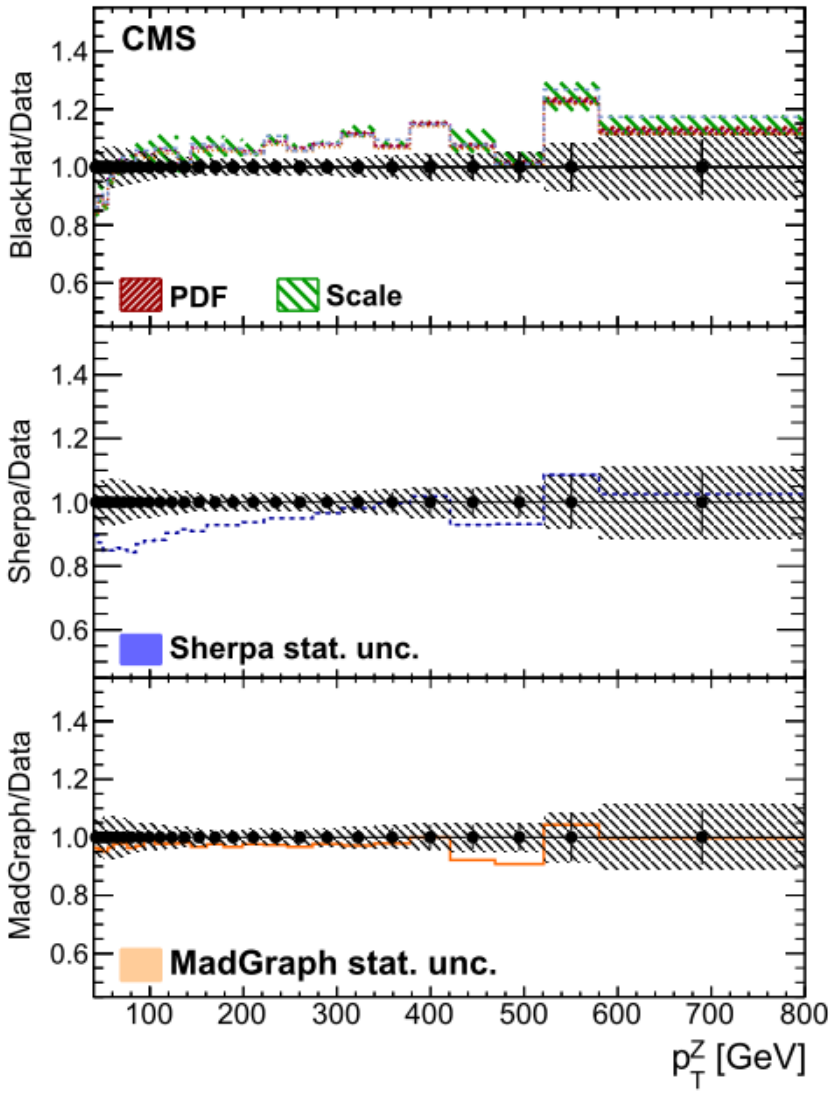

- The ratio increases until reaching around 350 GeV before a plateau
- SHERPA underestimates the relative rate of inclusive 2 jets case
- BLACKHAT overestimates the ratio after around 100 GeV

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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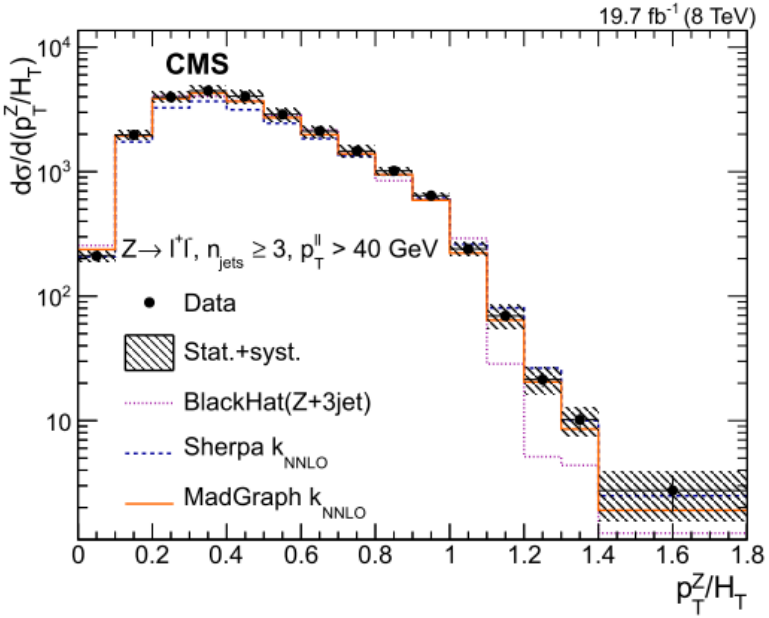
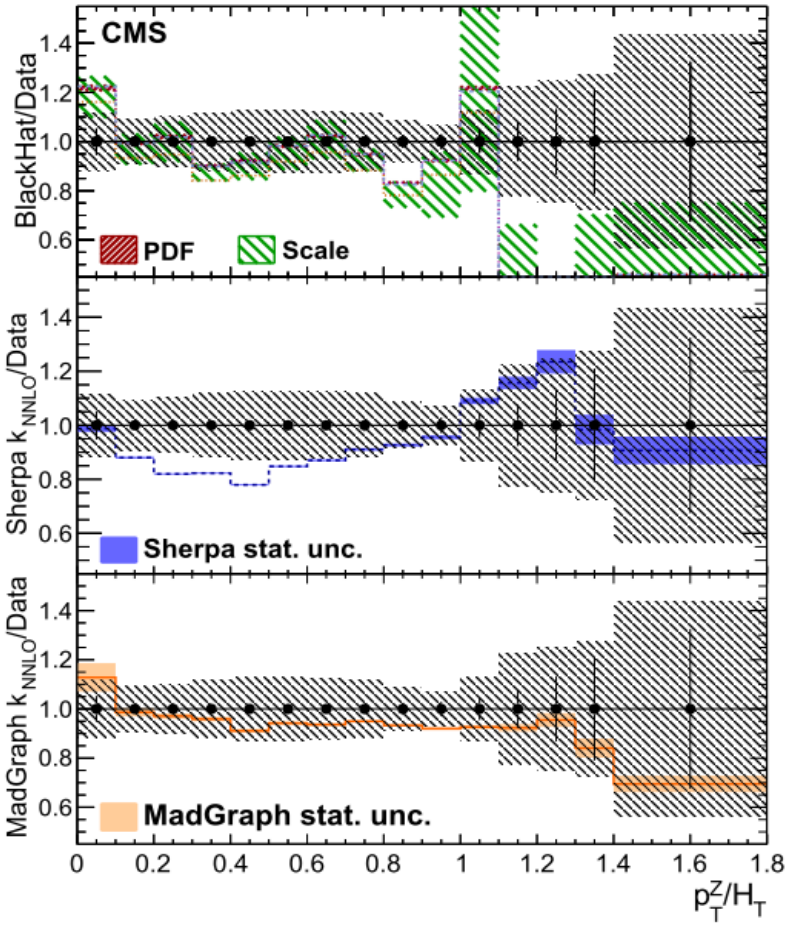




- MG5 generally predicts best on the shape
- SHERPA shows discrepancy on shape and rate
- BLACKHAT performs well on the bulk of distribution while failing to reproduce the tails

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

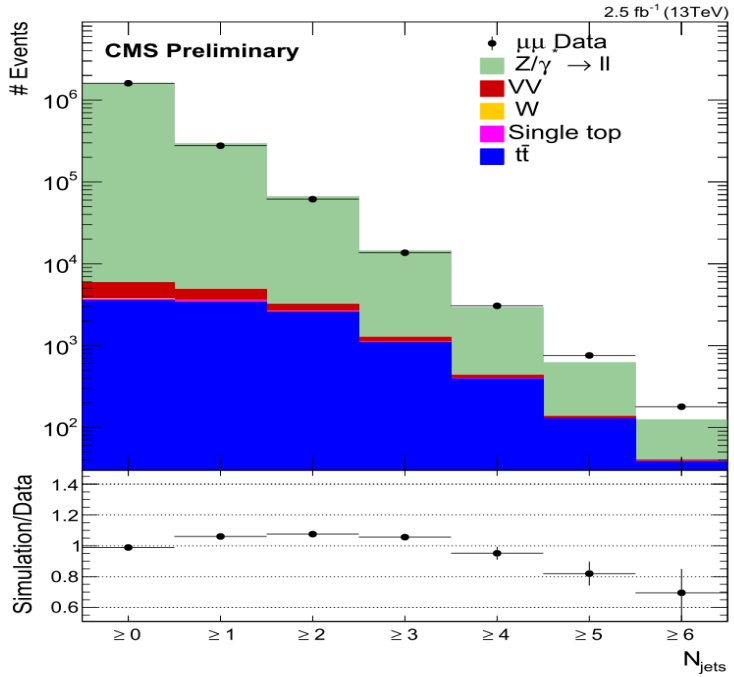
- **Data**
- **Measured differential cross section as a function of several observables**
- **The presence of data goes up to large jet multiplicity region for both W/Z + jets**

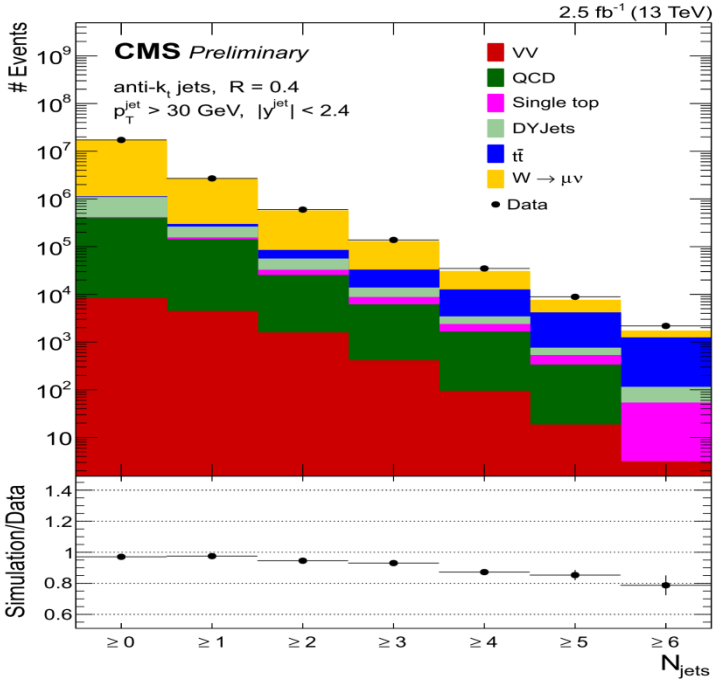
Phase space for Z+jets:

- **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

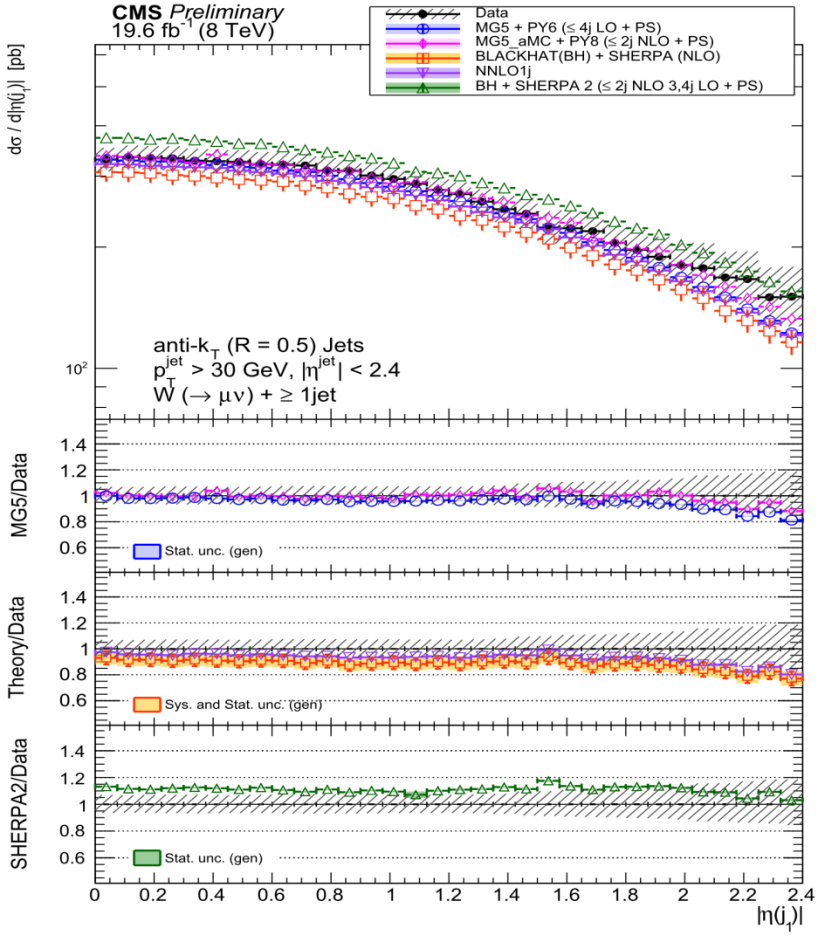
Phase space for W+jets:

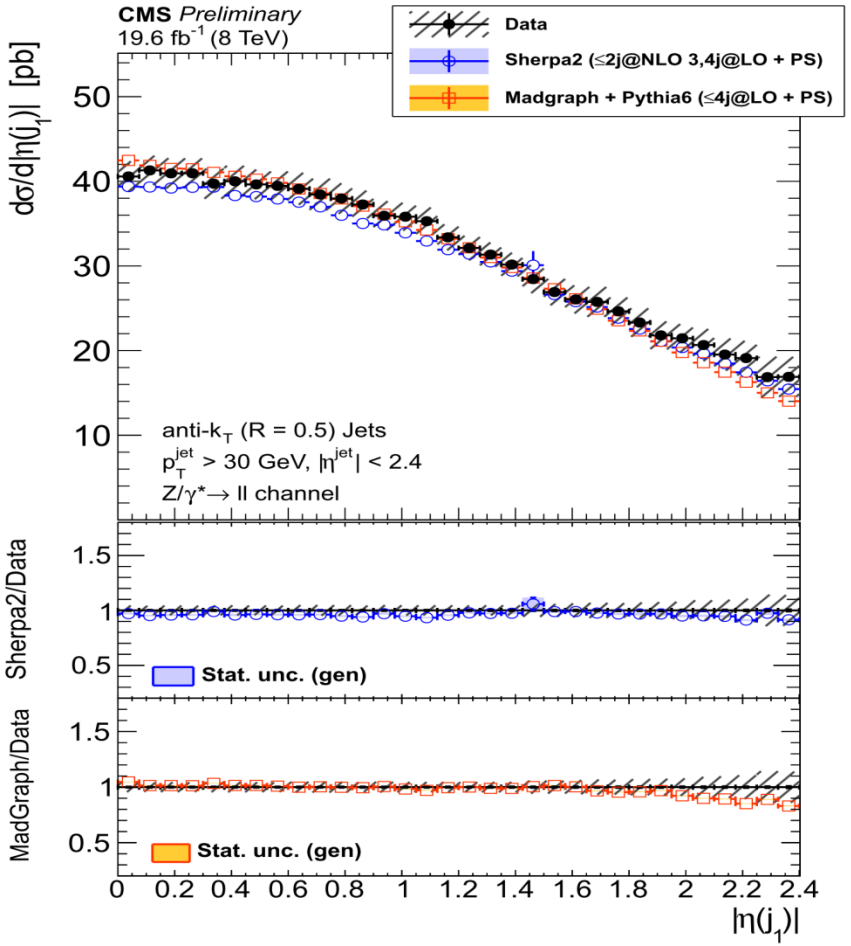
- **Lepton selection:**
  - p_T (l) > 25 GeV
  - |η (l)| < 2.1
  - M_T > 50 GeV
- **Jet selection:**
  - p_T (j) > 30 GeV
  - |y (j)| < 2.4





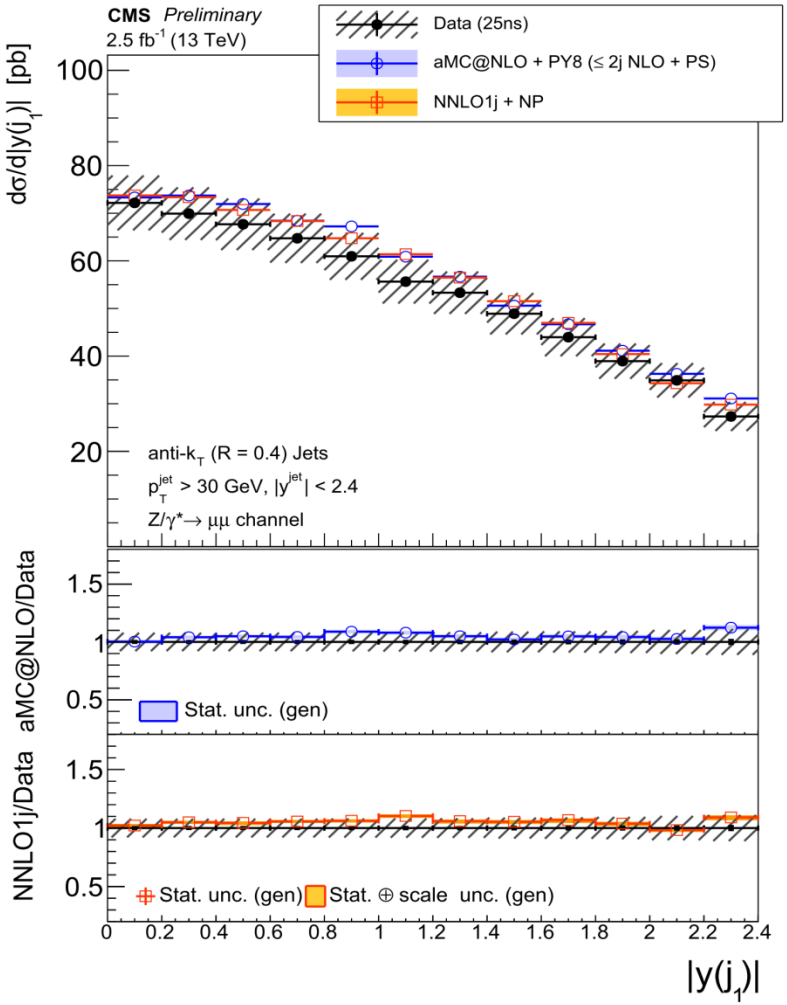
W/Z + jets differential cross section at 8 TeV

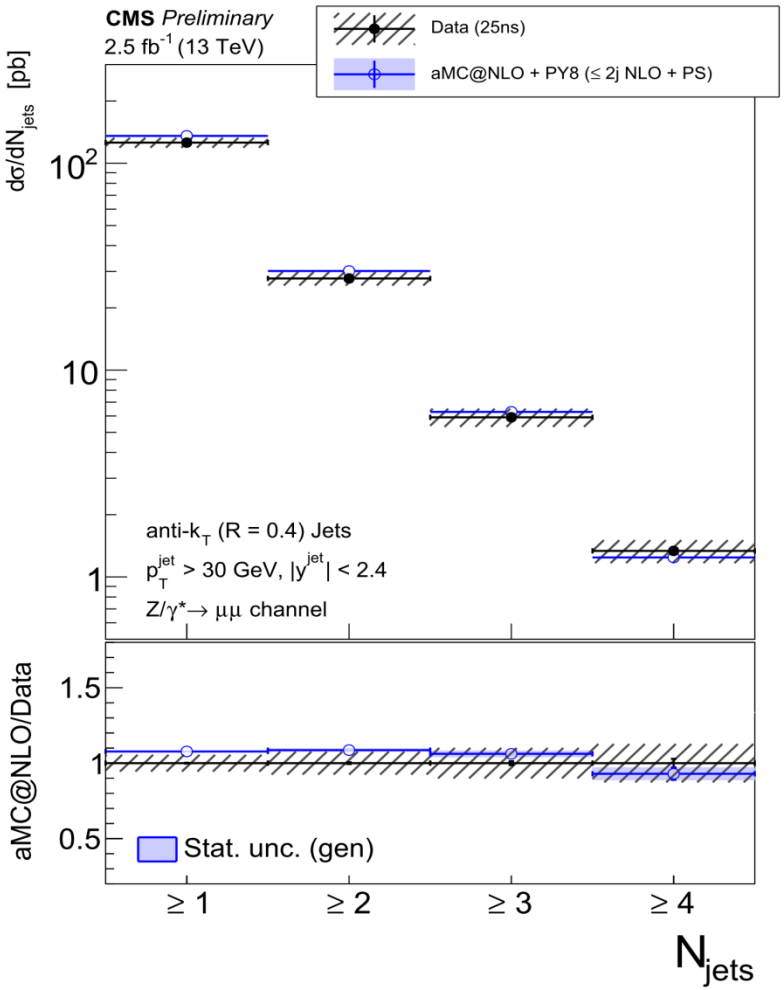




- Good agreement in general for all the predictions
- The p_T , η, H_T of jet for inclusive jet multiplicities up to 5 jets have also been measured
  - H_T is the scalar sum of the p_T of jets

Z + jets differential cross section at 13 TeV



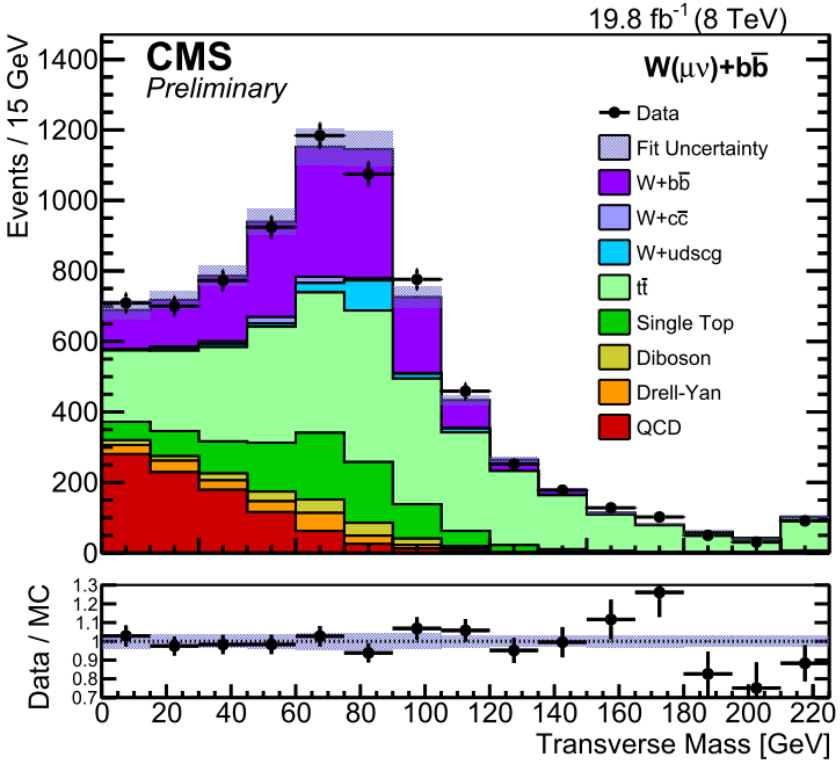


- Good agreement with both multileg NLO and NNLO calculations
- The p_T , η, H_T of jet for inclusive jet multiplicities up to 3 jets have also been measured
  - H_T is the scalar sum of the p_T of jets

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

PAS: SMP-14-020

- Lepton selection:
  - P_T > 30 GeV
  - |η| < 2.1
- B-tagged jet selection:
  - P_T > 25 GeV
  - |η| < 2.4

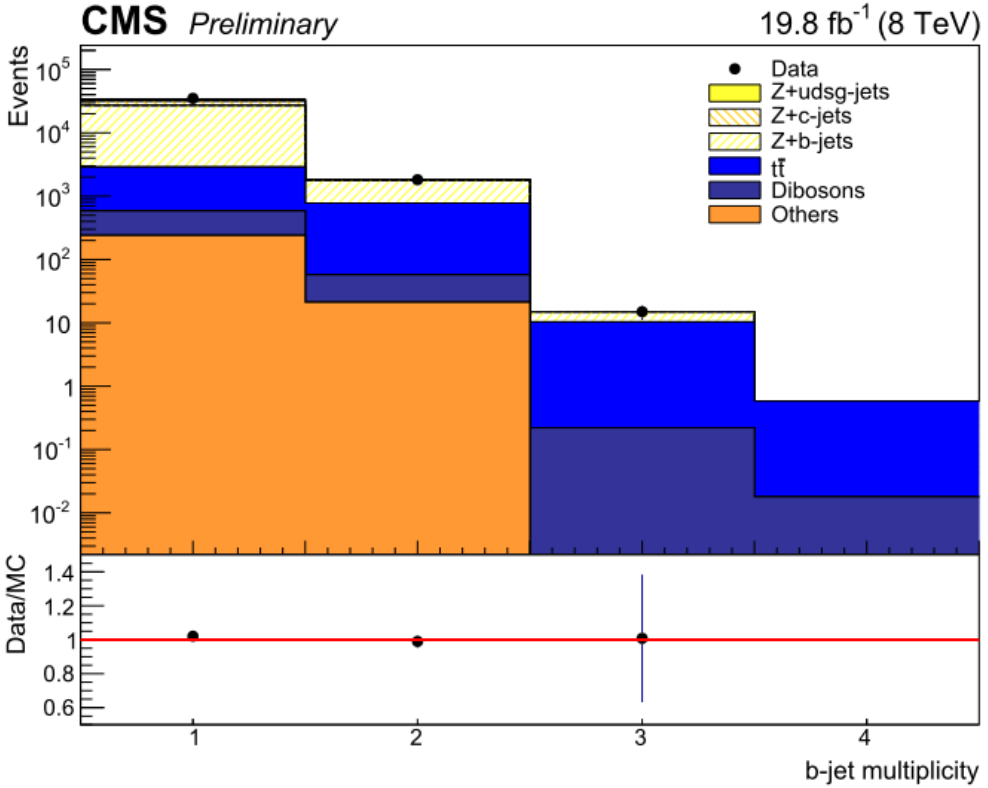


- The signal sample is generated at tree-level by MADGRAPH5 interfaced with PYTHIA6
- The t$\bar{t}$ is the dominant background, which is reweighted by data in the signal free region, in order to predict the transverse mass distribution in the signal region

Z+b jets measurement at 8 TeV

PAS: SMP-14-010

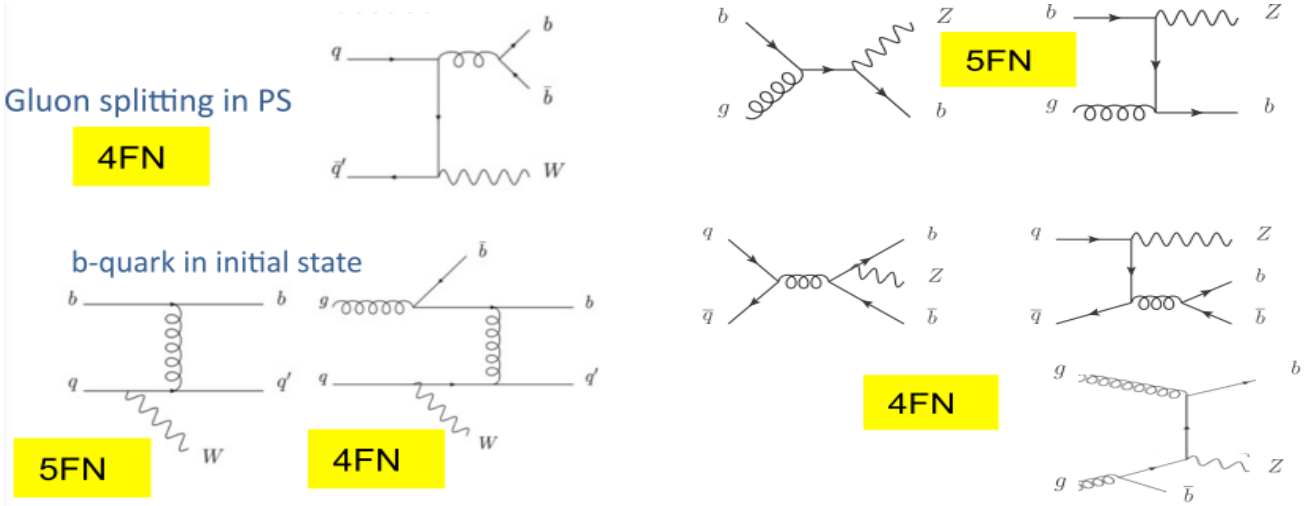
- Lepton selection:
  - P_T > 20 GeV
  - |η| < 2.4
  - 71 < Mll < 111 GeV
- B-tagged jet selection:
  - P_T > 30 GeV
  - |η| < 2.4



- 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

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

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^{signal}_{Z+c}	$\mathcal{C}_{Z+c}$ (%)	$\sigma(Z+c)$ (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^{signal}_{Z+b}	$\mathcal{C}_{Z+b}$ (%)	$\sigma(Z+c)/\sigma(Z+b)$
$Z \to e^+e^-$	2606 ± 114	2.90 ± 0.08	$1.9 \pm 0.2 \pm 0.2$
$Z \to \mu^+\mu^-$	3241 ± 147	3.93 ± 0.10	$2.2 \pm 0.3 \pm 0.2$

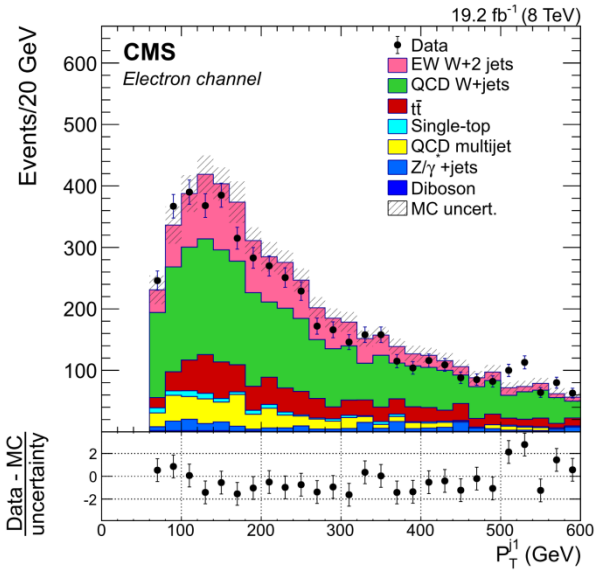
$D^{\pm}$ mode

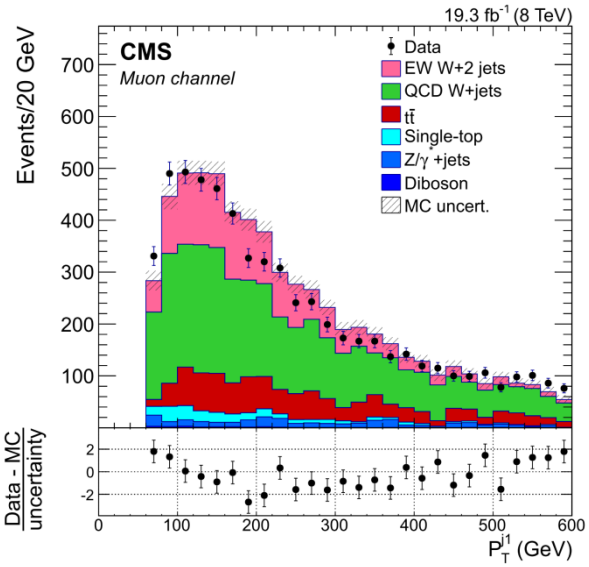
Channel	N^{signal}_{Z+c}	$\mathcal{C}_{Z+c}$ (%)	$\sigma(Z+c)$ (pb)
$Z \to e^+e^-$	275 ± 55	0.13 ± 0.02	$11.0 \pm 2.1 \pm 0.9$
$Z \to \mu^+\mu^-$	315 ± 75	0.18 ± 0.02	$9.0 \pm 2.1 \pm 0.8$

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

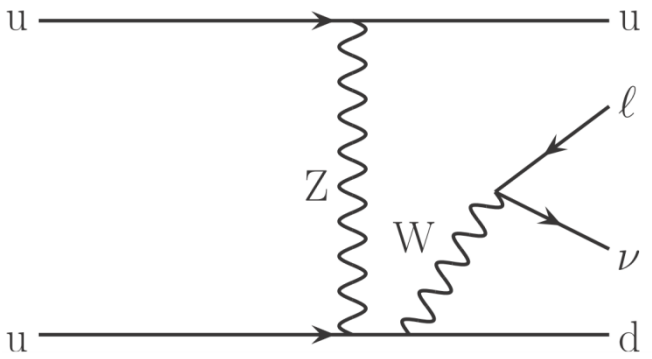
Channel	N^{signal}_{Z+c}	$\mathcal{C}_{Z+c}$ (%)	$\sigma(Z+c)$ (pb)
$Z \to e^+e^-$	151 ± 31	0.11 ± 0.01	$7.3 \pm 1.5 \pm 0.6$
$Z \to \mu^+\mu^-$	228 ± 30	0.14 ± 0.01	$8.6 \pm 1.1 \pm 0.6$

Electroweak W+2 jets cross section measurement at 8 TeV

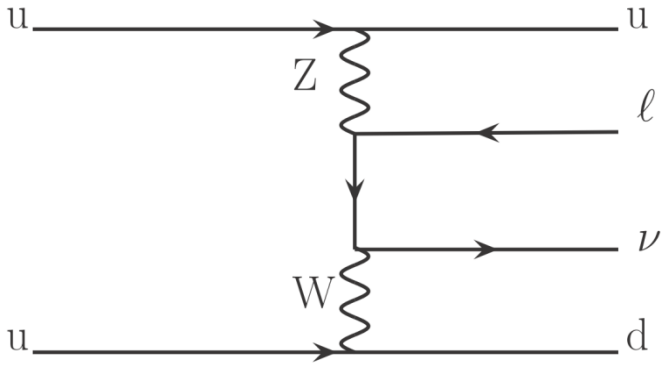




Bremsstrahlung



Multi-peripheral process

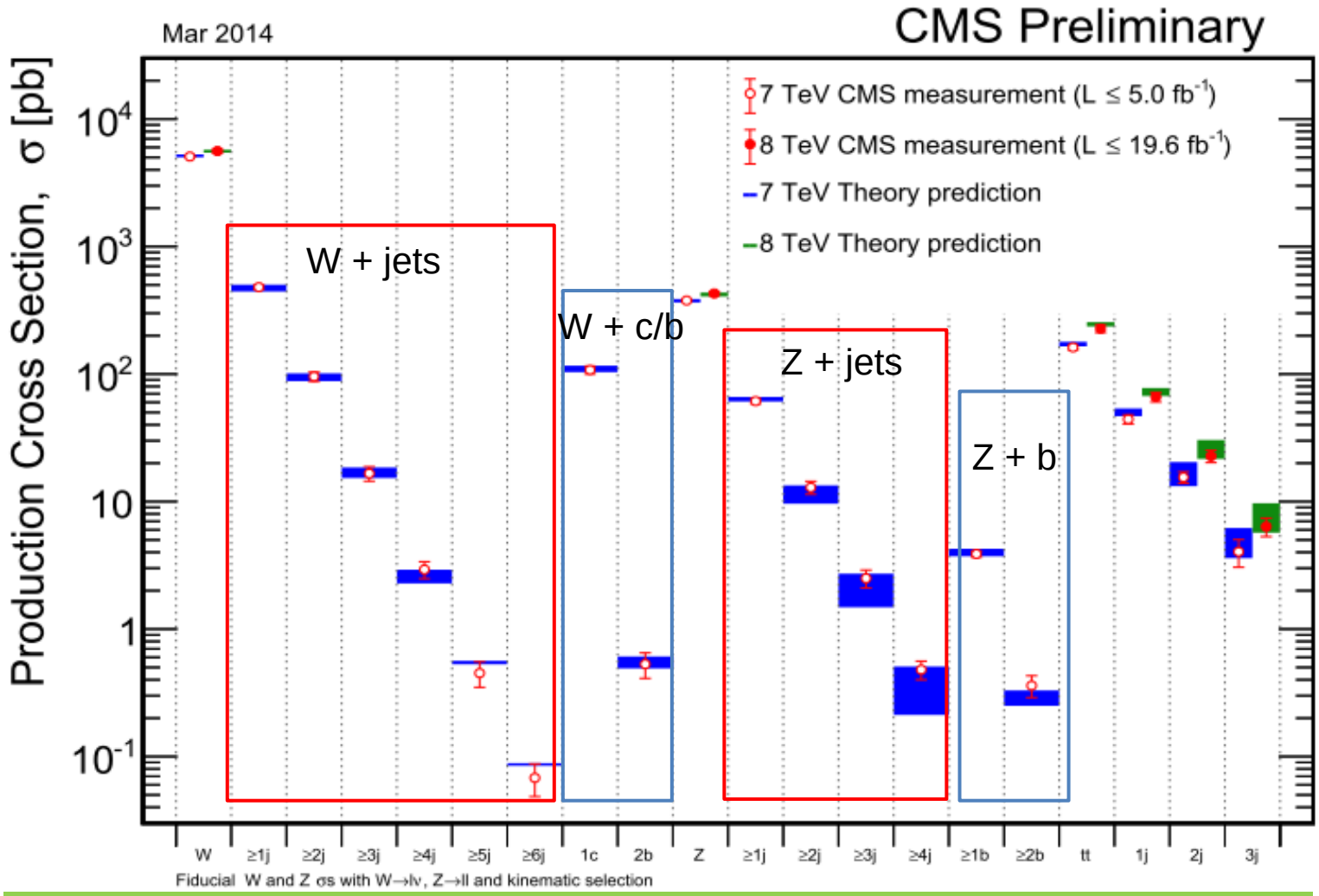


Process	Electrons		Muons	
Data	5481		6514	
	Pre-fit	Measured ratio	Pre-fit	Measured ratio
W+jets	3913	0.71 (fixed)	5084	0.70 (fixed)
Top quark	933	1.00 ± 0.07	1357	1.00 ± 0.07
QCD multijet	510	fixed to E_T^{miss} fit in data	—	—
DY+jets	236	1.00 (fixed)	256	1.00 (fixed)
Diboson	26	1.00 (fixed)	29	1.00 (fixed)
Total backgrounds	4488		5179	
Data − backgrounds	993		1335	
EW W+2-jets	1195	0.83 ± 0.08	1541	0.87 ± 0.08

Channel	Measured cross section
Electron	0.41 ± 0.04 (stat) ± 0.09 (syst) ± 0.01 (lumi) pb
Muon	0.43 ± 0.04 (stat) ± 0.10 (syst) ± 0.01 (lumi) pb
Combined	0.42 ± 0.04 (stat) ± 0.09 (syst) ± 0.01 (lumi) pb

- **Measured signal strength:**
  0.83 ± 0.08 (stat.) (electron channel)
  0.87 ± 0.08 (stat.) (muon channel)

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)