Vector Boson + Jets Production at CMS

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On behalf of CMS collaboration

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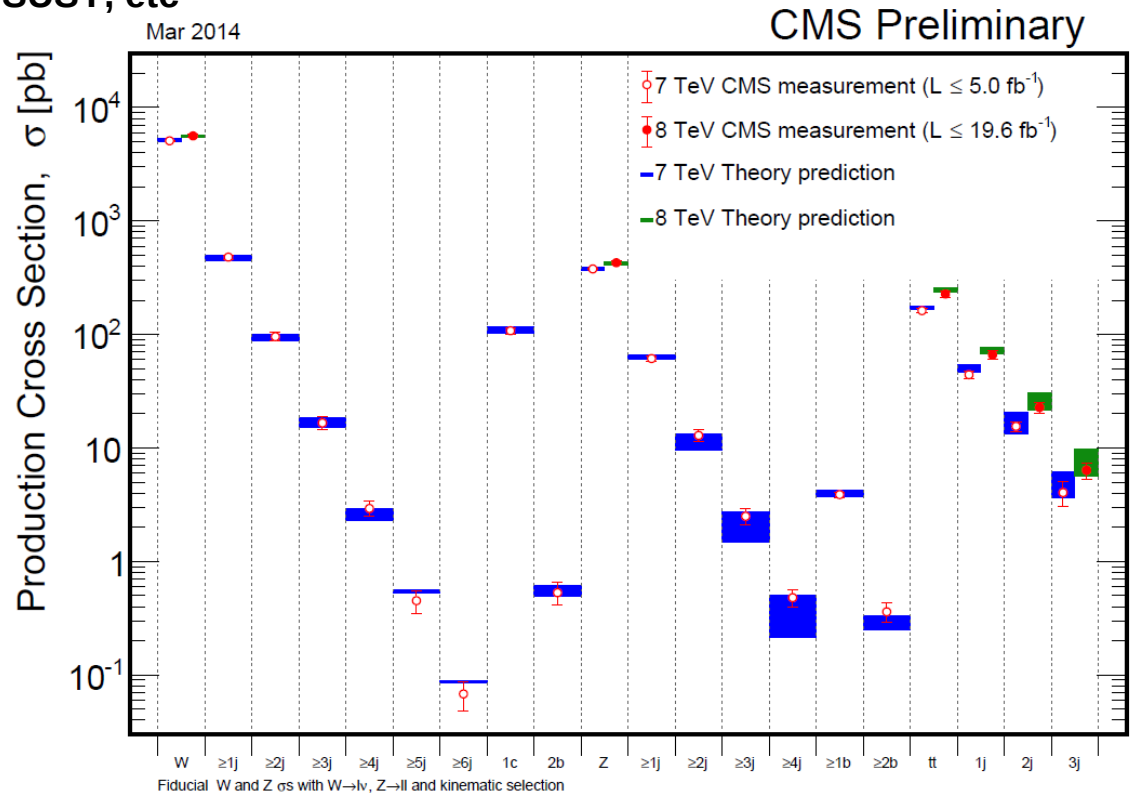
Motivation

- **Tests of perturbative QCD calculations**
- **Probes of parton distribution functions**
- **Irreducible backgrounds to SM measurements**
  - ttbar, single top, VBF, etc
- **Major backgrounds to many searches**
  - Higgs, SUSY, etc



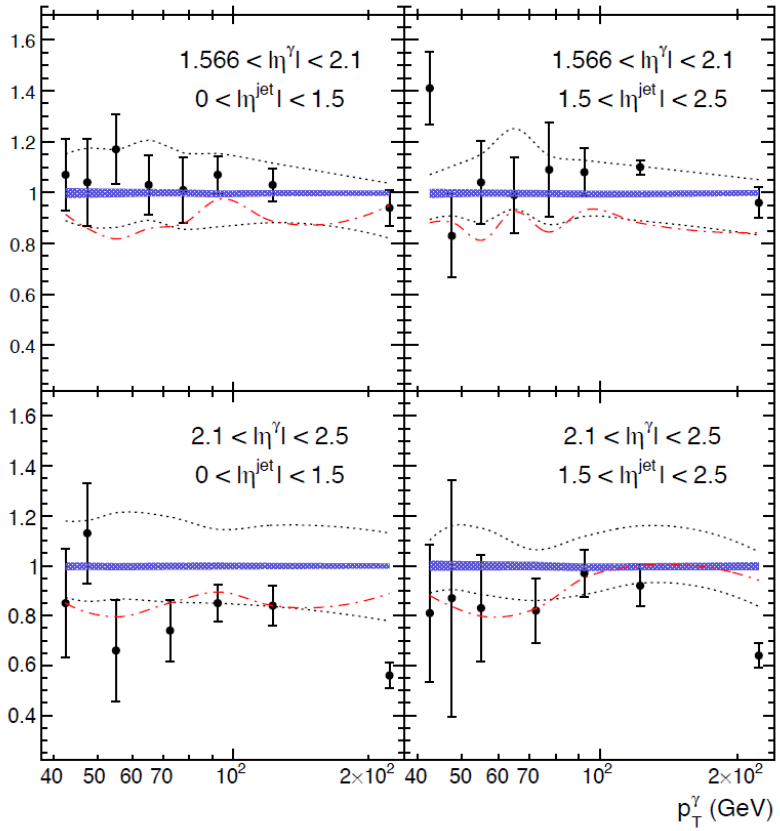
In this talk

- **Vector boson + jets**
  - γ + jets triple-differential cross section JHEP 06 (2014) 009
  - Z + jets differential cross section and jet multiplicity
    7 TeV arXiv:1408.3104 submitted to PRD
    8 TeV CMS-PAS-SMP-13-007, CMS-PAS-SMP-14-009
  - W + jets differential cross section arXiv:1406.7533 Submitted to PLB
  - Z + 1-jet, γ + 1 jet rapidity distributions Phys. Rev. D 88 (2013) 112009
  - Z/γ* + jets/ γ + jets cross section ratio CMS-PAS-SMP-14-005
- **Vector boson + heavy flavor**
  - Z + b and Z + bb cross sections JHEP 1406 (2014) 120
  - Z + bb jets, b hadron angular correlations J. High Energy Phys. 12 (2013) 39
  - W + bb cross section arXiv:1312.6608 accepted by PLB
  - W + c cross section JHEP 02 (2014) 013

γ + jets triple-differential cross section

JHEP 06 (2014) 009

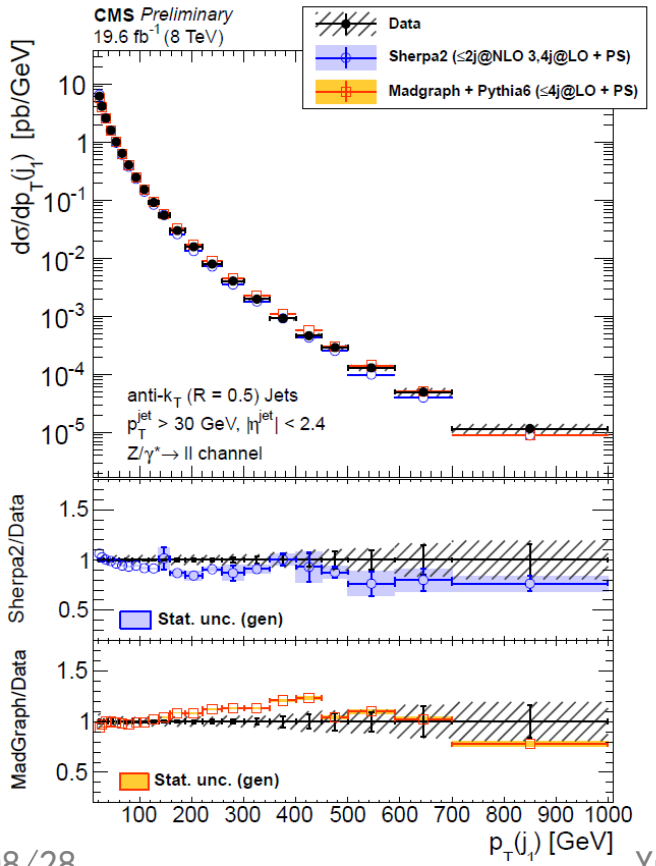
- **Observables**
  - Triple-differential cross section p_T^{γ} ,$|\eta_{\gamma}|$, $|\eta_{jet}|$
  - Ratio of cross section with different angular orientations
- **Fiducial cross section**
  - Leading photon 40 GeV< p_T^{γ} < 300 GeV
  - Leading jet p_T^{jet} > 30 GeV
  - 4 (2) regions in $|\eta_{\gamma}|$ ($|\eta_{jet}|$)
  - ΔR(γ, jet) > 0.5, isolation γ < 5 GeV
- **Results**
  - Theory agrees with data for ratio of cross section with different angular orientations
  - For cross section, theory agrees with data over most kinematic regions. In large η_{γ} and high P_T^{γ} region, theory prediction is higher than data

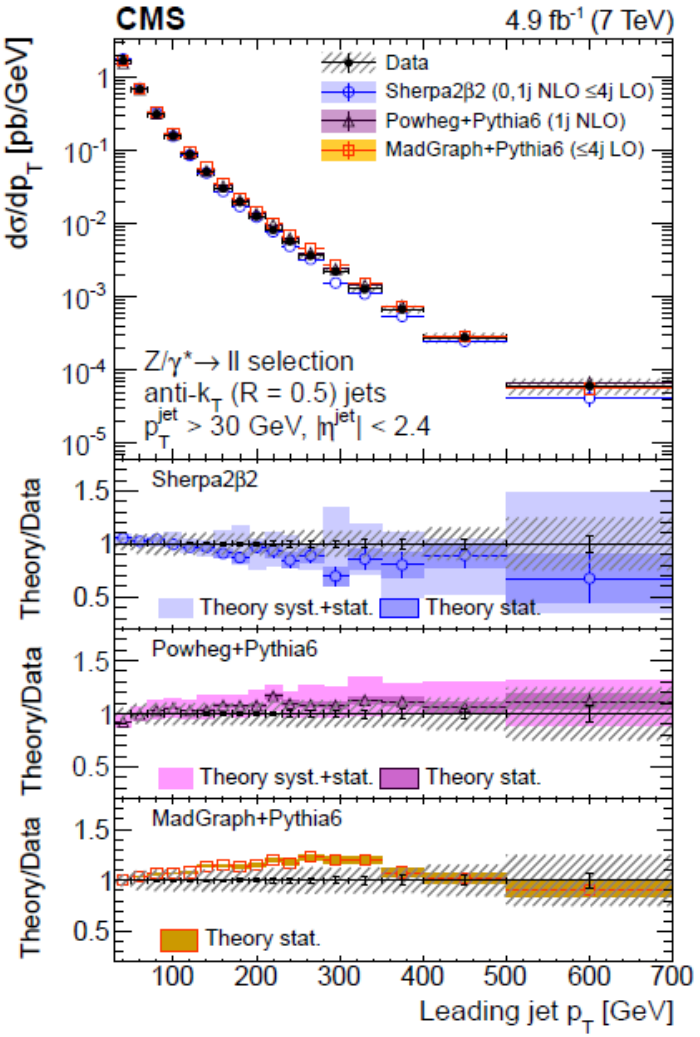


z + jets differential cross section

- 7 TeV 4.9 /fb and 8TeV 19.6/fb
- Differential cross section
  - p_T and $|\eta|$ of leading 4/5 jets ,
  - H_T scalar sum over p_T of jets

arXiv:1408.3104
CMS-PAS-SMP-13-007

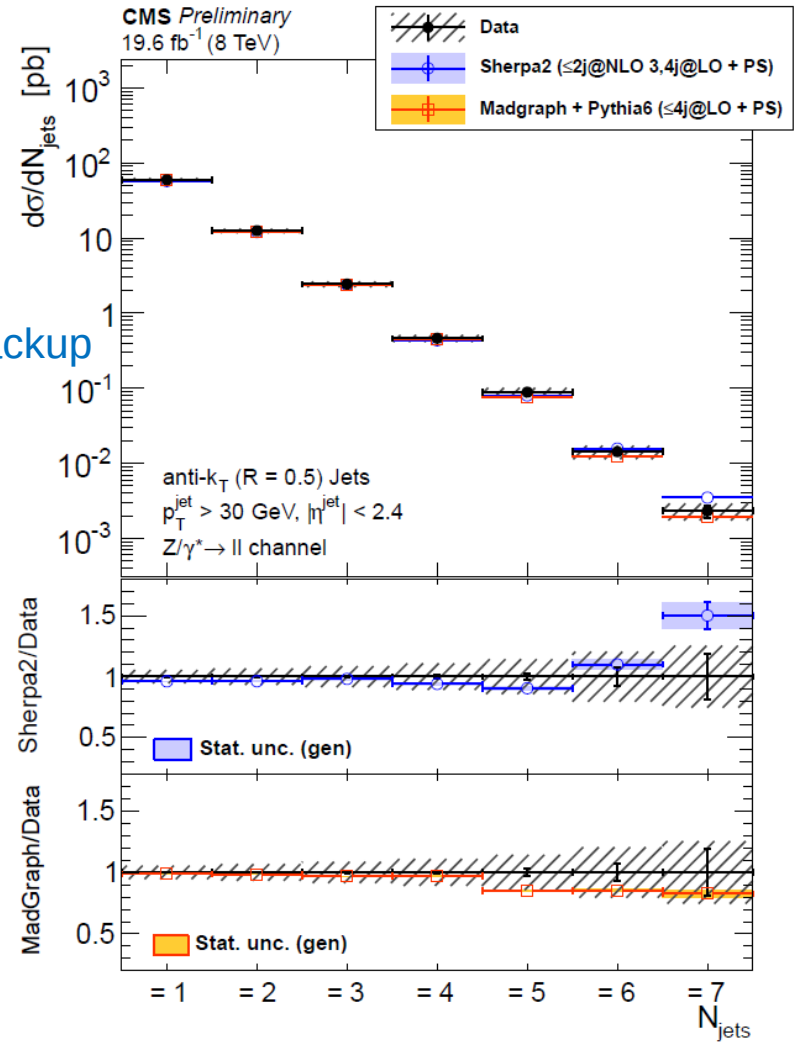


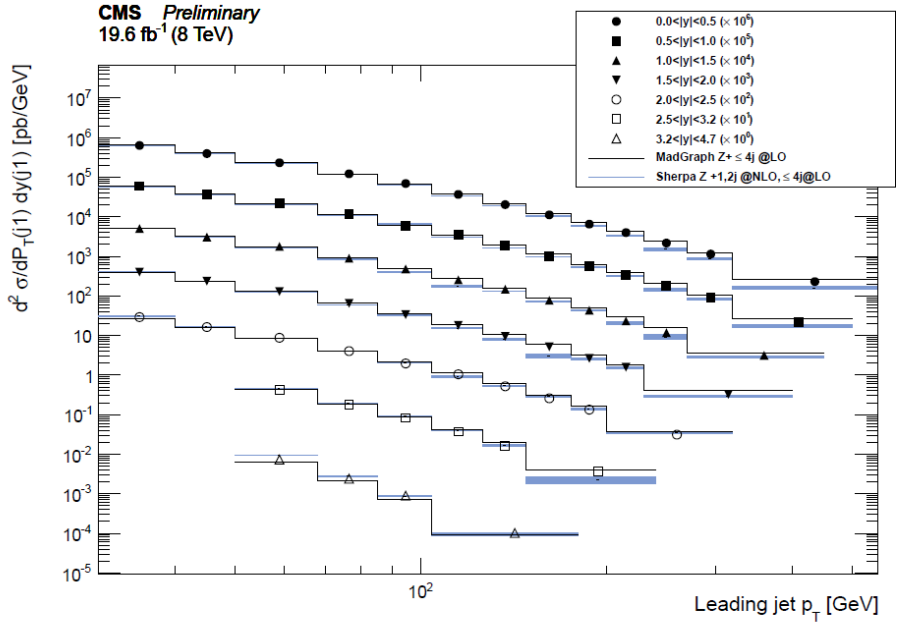


z + jets differential cross section

CMS-PAS-SMP-13-007
CMS-PAS-SMP-14-009

- Jet multiplicity up to 6/7 jets
  - Good agreement within number of final state partons included in the ME
- Double differential cross section
  - p_T and $|\eta|$ of the leading jet
  - Overall agreement : SHERPA2 and data
- Test effect s of PDFs using SHERPA See Backup
  - CT10, MSTW2008, and NNPDF2.1



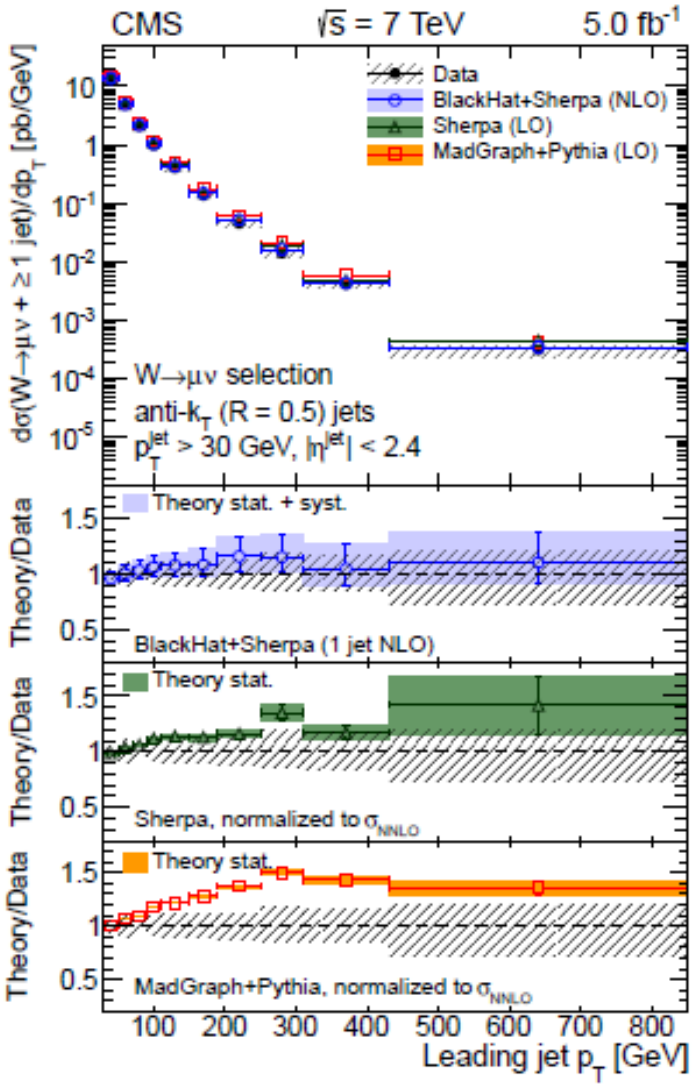


w + jets differential cross section

arXiv:1406.7533

- **Observables**
  - Jet multiplicity to six jets
  - Differential cross section
    - p_T and $|\eta|$ of leading 4 jets, H_T, $\Delta\Phi$(jet,μ)
- **Theoretical prediction**
  - LO+PS normalized to σ_{NNLO}
  - Effect of PDFs (BLACKHAT + SHERPA)
    - MSTW2008nlo68cl,NNPDF,CT10
- **Results**
  - Inclusive and exclusive jet multiplicity agrees with theoretical prediction within uncertainty
  - LO+PS overestimates p_T and H_T
  - BLACKHAT is a fixed order generator
  - For >=1 jet, underestimates $\Delta\Phi$(jet1,μ) and H_T in BLACKHAT + SHERPA

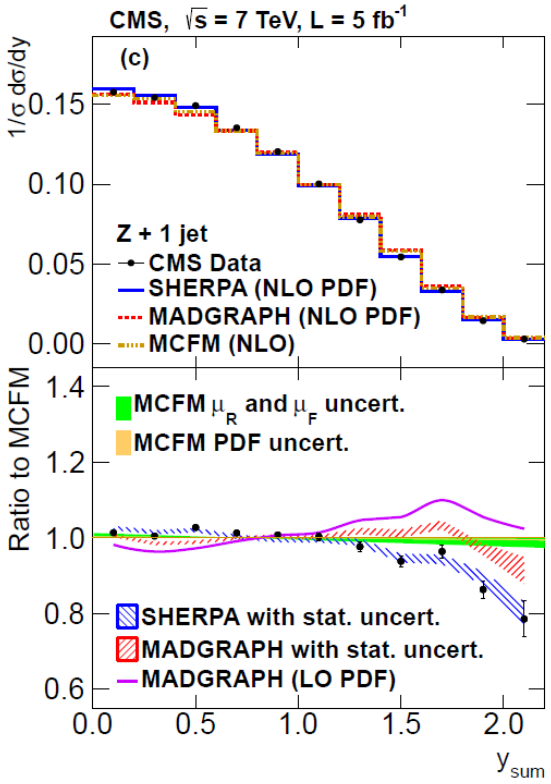
More in the backups

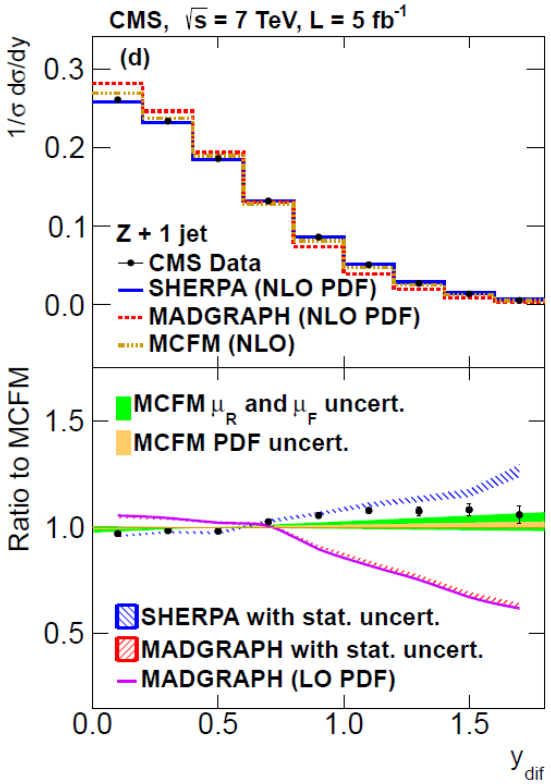


z +1 jet and γ + 1 jet rapidity distributions

- **Observables**
  - $|y_v|$, $|y_{jet}|$
  - $y_{diff} \equiv 0.5\ |y_v - -y_{jet}|$ (sensitive to LO partonic differential cross section)
  - $y_{sum} \equiv 0.5|y_v + y_{jet}|$ (sensitive to PDF)
- **Theoretical prediction**
  - Z+jet NLO: MCFM
  - γ+jet NLL: Owens
  - SHERPA 1.31
    - ➢ CKKW matching
  - MADGRAPH 5.1.1.0 + Pythia 6.4.24
    - ➢ KT-MLM matching
- **Results**
  - Theory agrees with data in γ + 1 jet
  - Difference is found in y_{diff} and y_{sum} in Z +1 jet

Phys. Rev. D 88 (2013) 112009



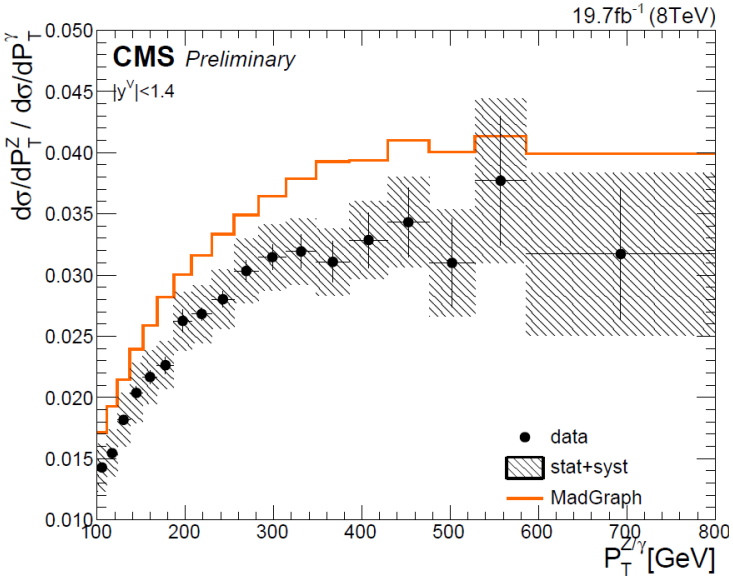


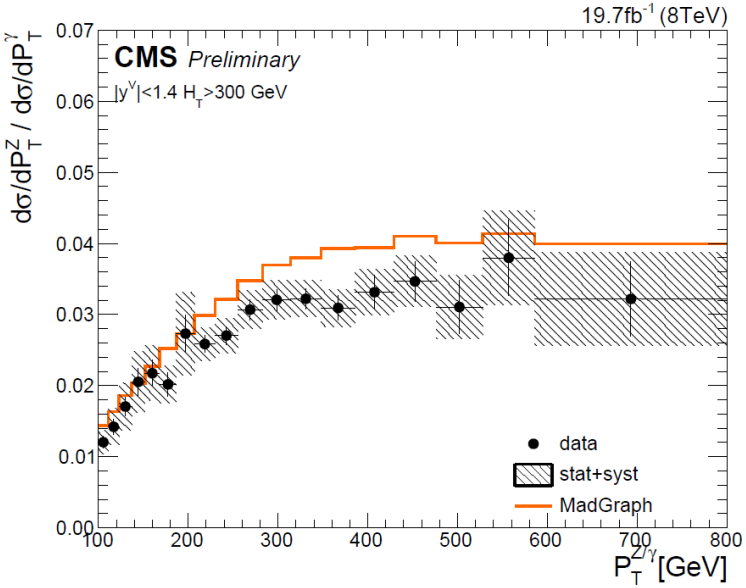
z/γ*+jets/γ+jets cross section ratio

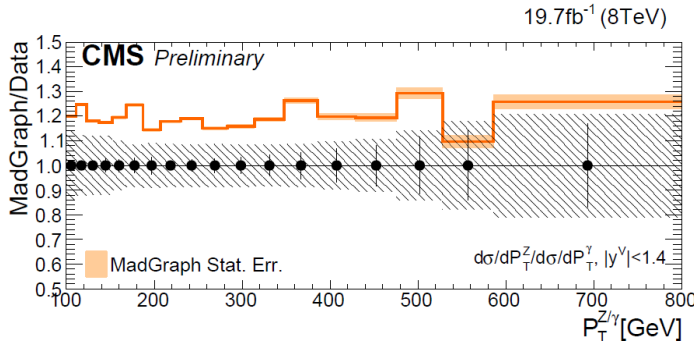
- Different kinematic regions

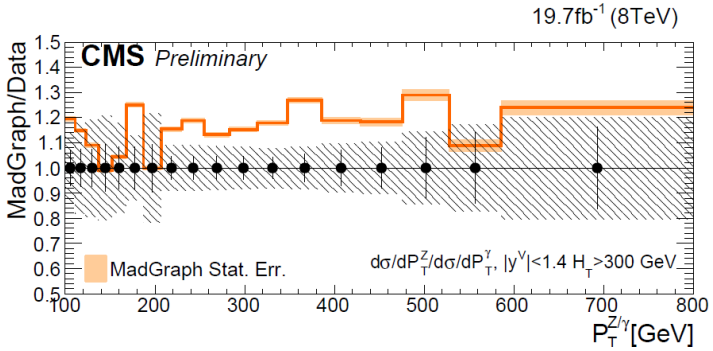
CMS-PAS-SMP-14-005

  - $p_T^{Z/\gamma}$>100GeV,njets>=1; $p_T^{Z/\gamma}$>100GeV, H_T>300GeV for p_T^{jets}> 30GeV
  - LO prediction agrees with data in shape, but overestimates the ratio









Vector Boson + Heavy flavor

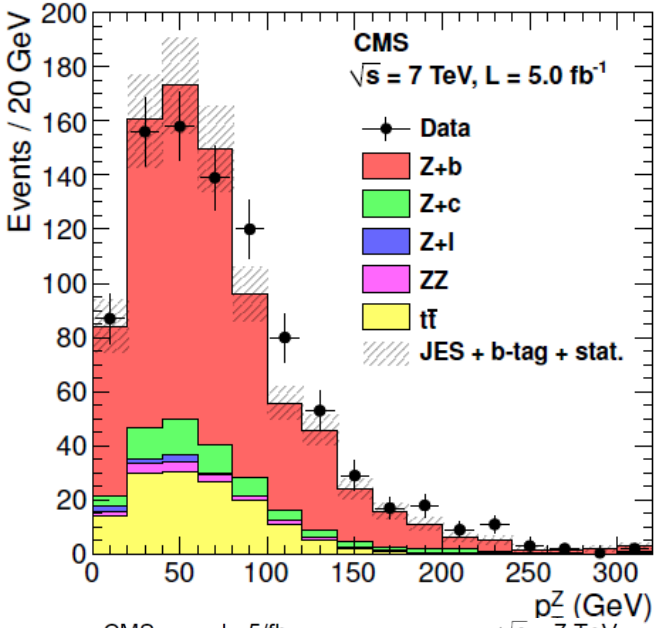
z + b and z + bb Cross Sections

- **Observables**

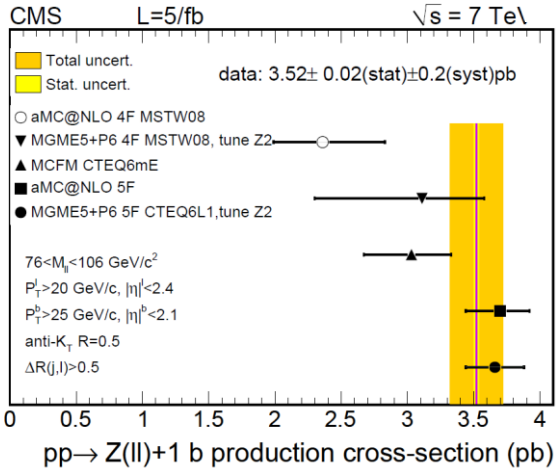
JHEP 1406 (2014) 120

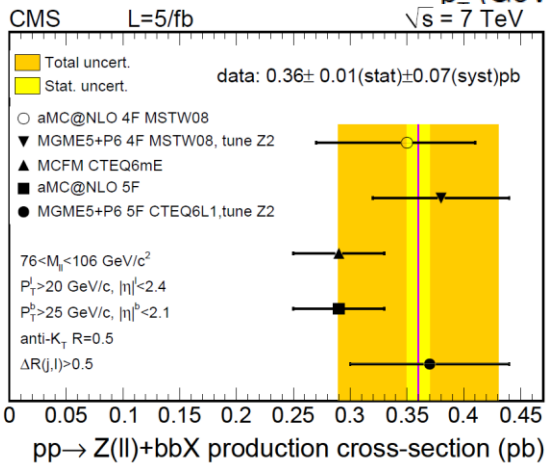
  - **Cross section**
    - z + >= 1 b jet, z + 1b jet, z + >= 2 b jet
  - **$\sigma_{Z+ >=1b\ jet} / \sigma_{Z+>=1jet}$**
  - **Z+ >= 2b jets final state**
    - M_{bb}, p^{bb}_T, p^z_T, $\Delta\Phi(Z,bb)$
      (comparing to MADGRAPH 5F scheme)

- **Results**
  - **P^Z_T : data has harder spectrum (same as JHEP 06 (2012) 126)**
  - **Measurement is in agreement with 5F scheme with massless b mass**



numbers for z +>= 1 b jet and ratio is in backup

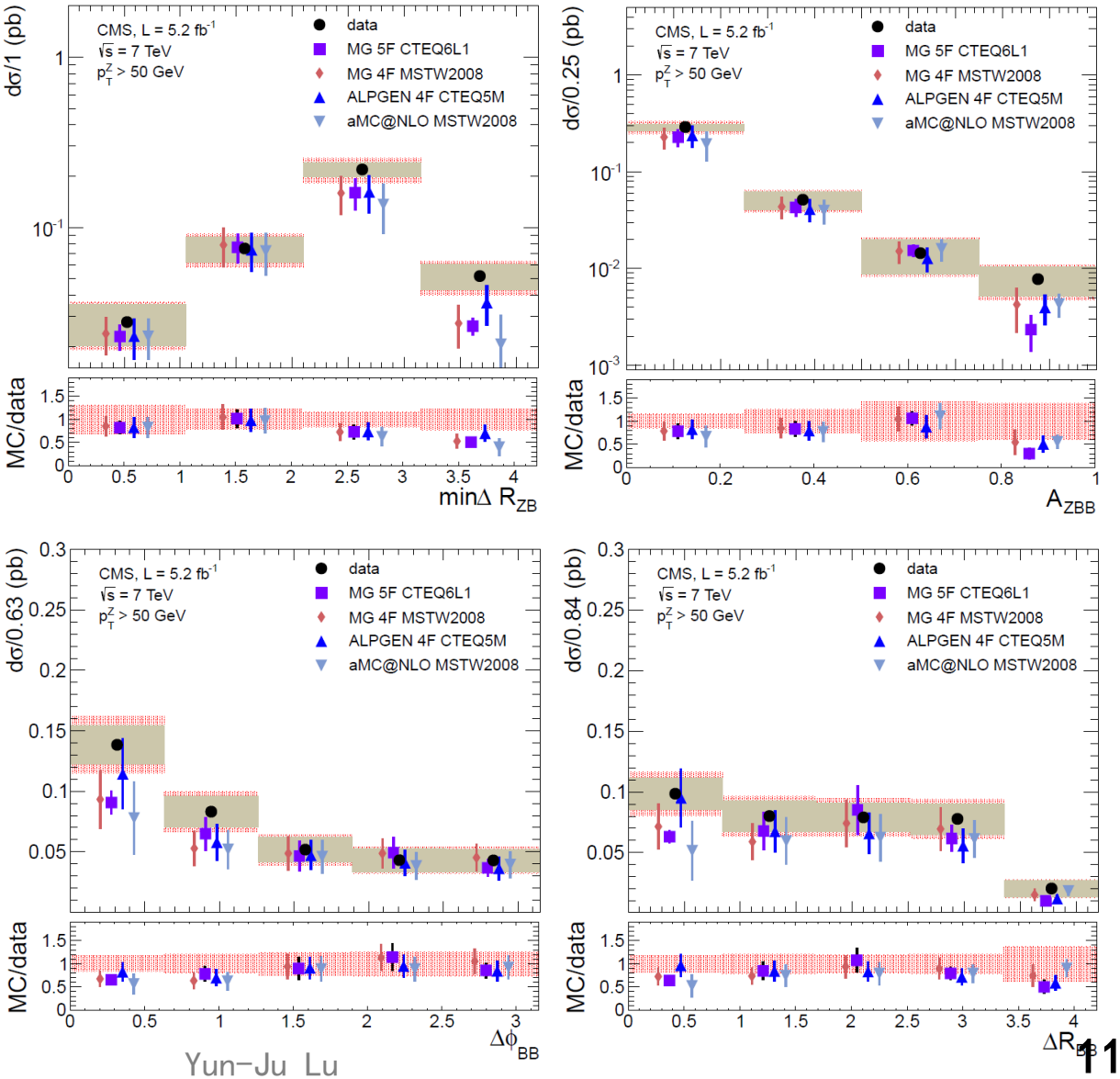




z+bb jets, b hadron angular correlations

J. High Energy Phys. 12 (2013) 39

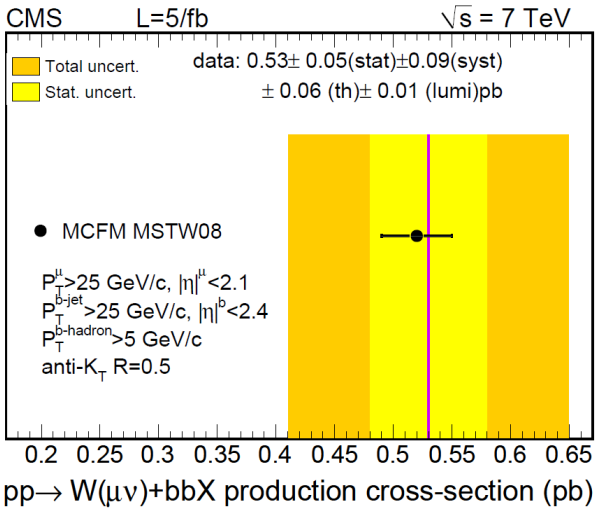
- **Overview**
  - Angular correlations of b hadrons
  - Tracker-only b tagging
  - Small opening angles
  - Fraction of quark- and gluon-initiated processes
- **Observables**
  - ΔR_{BB}
  - $\Delta\Phi_{BB}$
  - $\min\Delta R_{ZB}$
  - $A_{ZBB} = \frac{max\Delta R_{ZB} - min\Delta R_{ZB}}{max\Delta R_{ZB} + min\Delta R_{ZB}}$
- **Results**
  - Overall good description from ALPGEN 4F

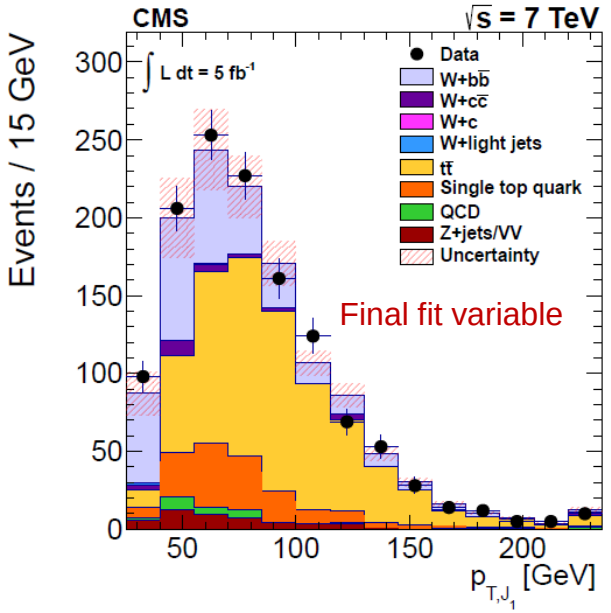


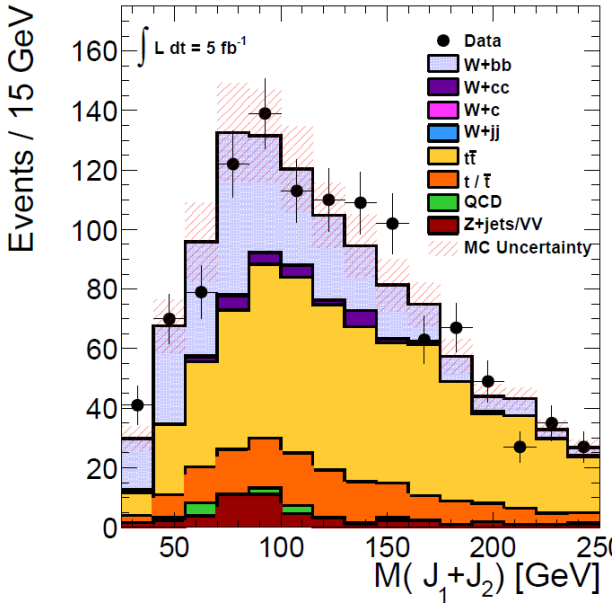
w + bb Cross Section

arXiv:1312.6608

- **Observables**
  - **Fiducial cross section**
    - Exactly 2 jets each contains ≥ 1 b-hadron with p_T b-hadron > 5 GeV
- **Theoretical prediction**
  - **MCFM NLO at parton level**
  - **MADGRAPH+ PYTHIA 5 flavor**
    - Hadronization correction
    - MPI contribution
- **σ (pp→W + bb) × B(W →μν)**



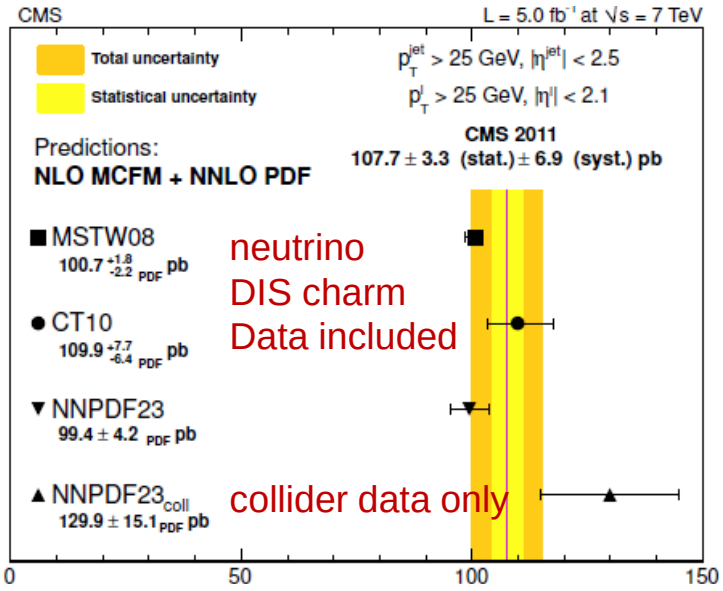


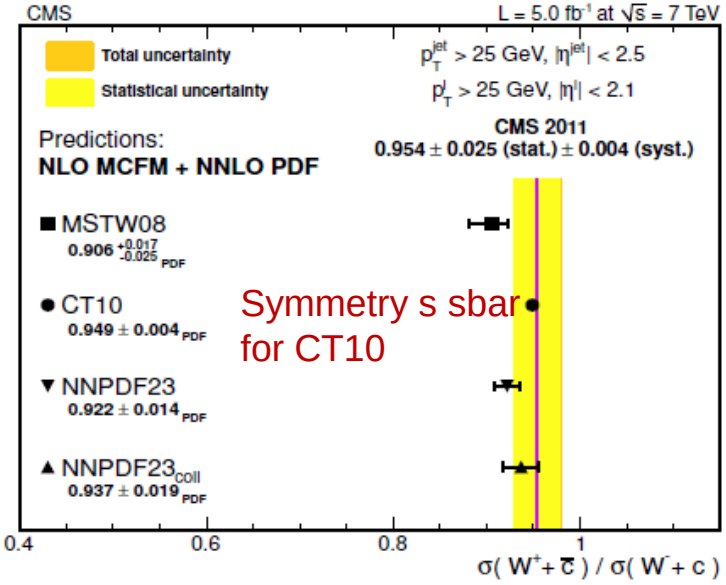


w + c Cross Section

JHEP 02 (2014) 013

- **Overview and observables**
  - **A test of s quark PDF**
  - **Fiducial cross section**
    - $M_T\mu(e) > 40\ (55)$ GeV
    - $p_T > 25$ GeV (μ), $p_T > 35$ GeV (e,μ)
  - **$\sigma(pp\to W^+ + \bar{c} + x)/\sigma(pp\to W^- + c + x)$**
    - Cross section ratio V.S. $|\eta_l|$
  - **Differential cross section of $|\eta_l|$**
- **Theoretical prediction**
  - **NLO MCFM with 4 NNLO PDF sets**
- **Results**
  - **General agreement is found in cross section and cross section ratio results**
  - **Different levels of agreement in differential cross section with 4 PDF sets**





Conclusion

- Presented the updated measurements of vector boson + jets in CMS
- In general, agreement is found between data and theory for most of observables in different regions
- Input to MC tools and background estimation of different standard model measurements and BSM searches.

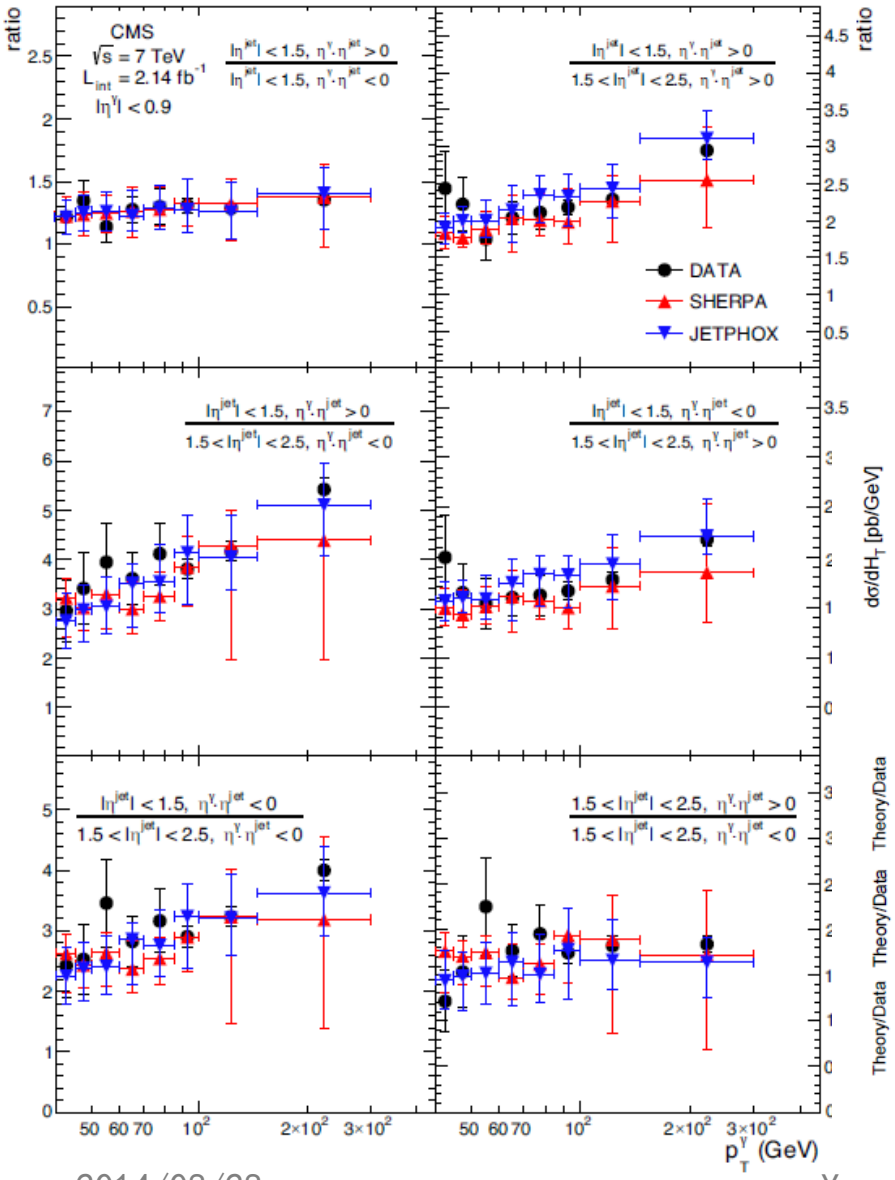
Thank you ！

CMS vector boson +jets page contains all these interesting results in detail !
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

Back up

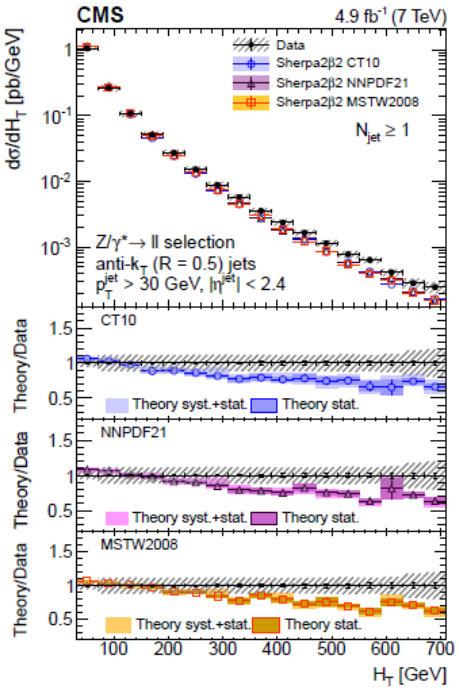
γ + jets and z + jets results

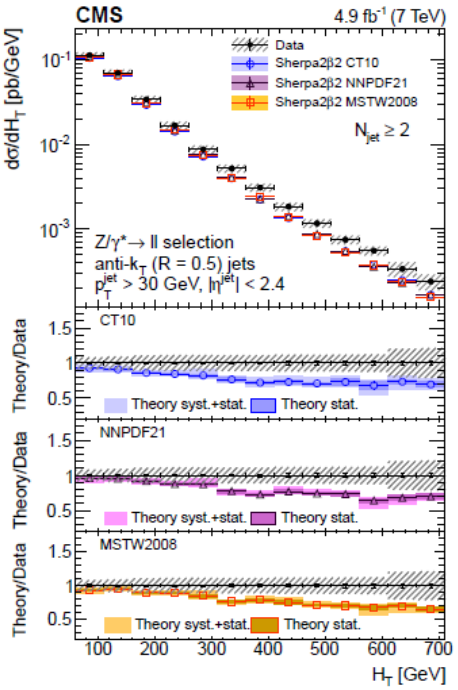
γ + jets cross section ratio



- z+jets
- Fiducial cross section
  - $p^{l}_{T} > 20$ GeV , $|\eta^{l}| < 2.4$, $71 < M_{ll} < 111$ GeV
  - $p_T^{jet} > 30$ GeV, $|\eta^{jet}| < 2.4$
  - $\Delta R(l, j) > 0.5$

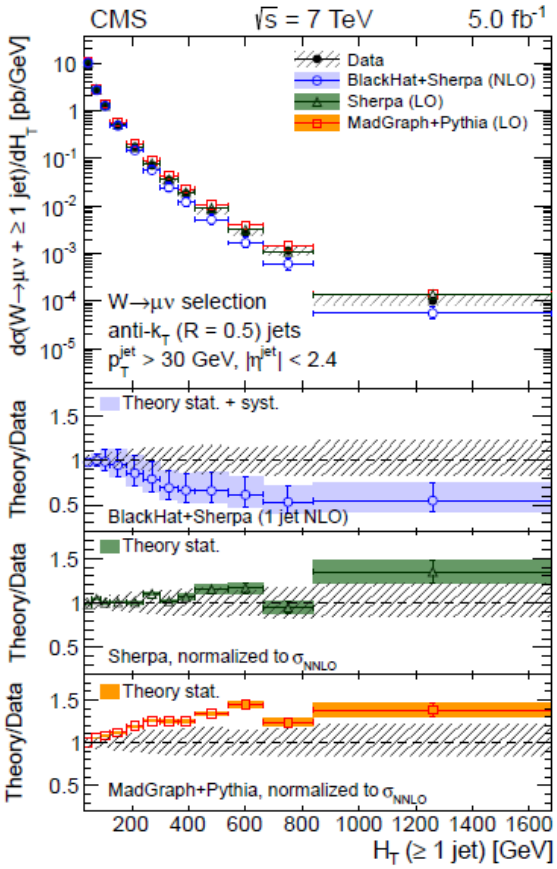
SHERPA for testing different PDF sets

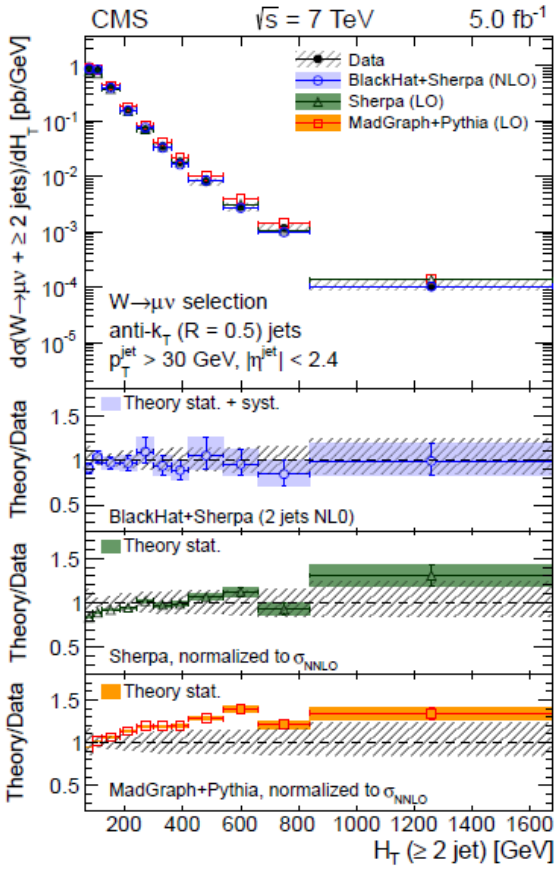




W + jets differential cross section

- **Fiducial cross section**
  - $p^{\mu}_{T} > 25$ GeV , $|\eta^{\mu}| < 2.1$
  - $p_{T}^{jet} > 30$ GeV, $|\eta^{jet}| < 2.4$
  - $\Delta R(l, j) > 0.5$
  - $M_T > 50$ GeV
- **H_T**

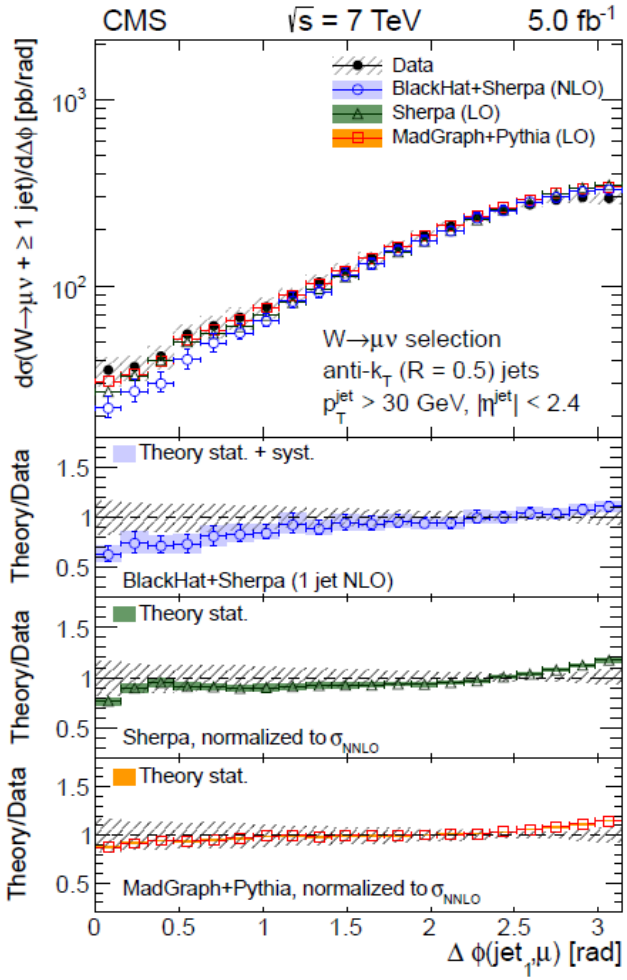


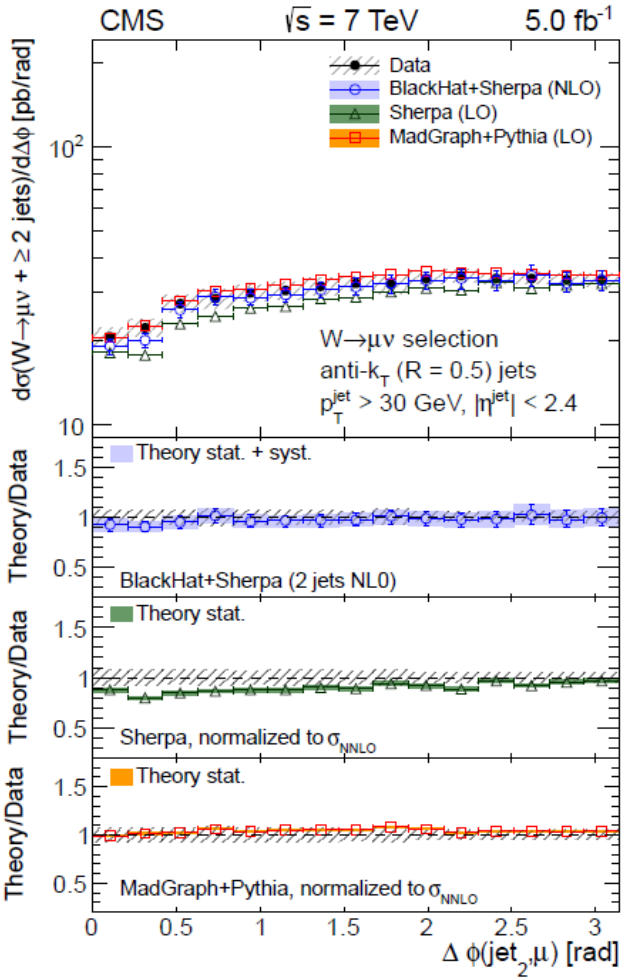


- **BLACKHAT+SHERPA underestimates in H_T for >=1 jet**

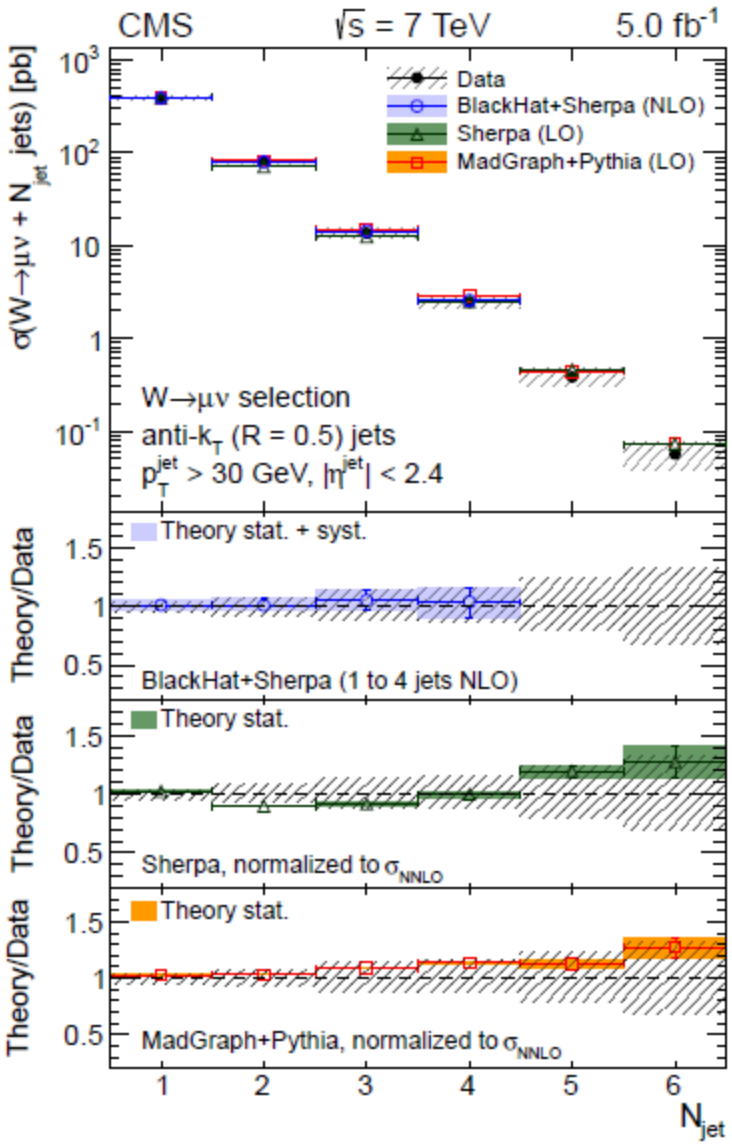
W + jets differential cross section

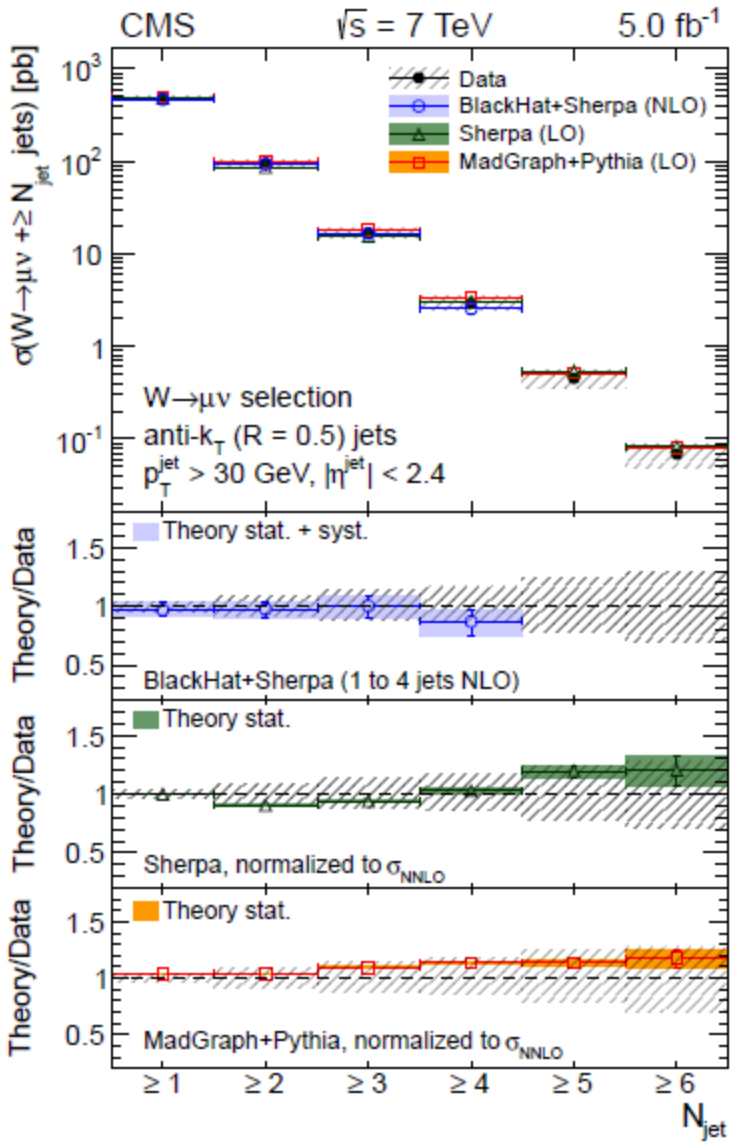
- **Contribution from W+>=3 jets is missing from NLO prediction of W+>=1 jet in BLACKHAT + SHERPA**





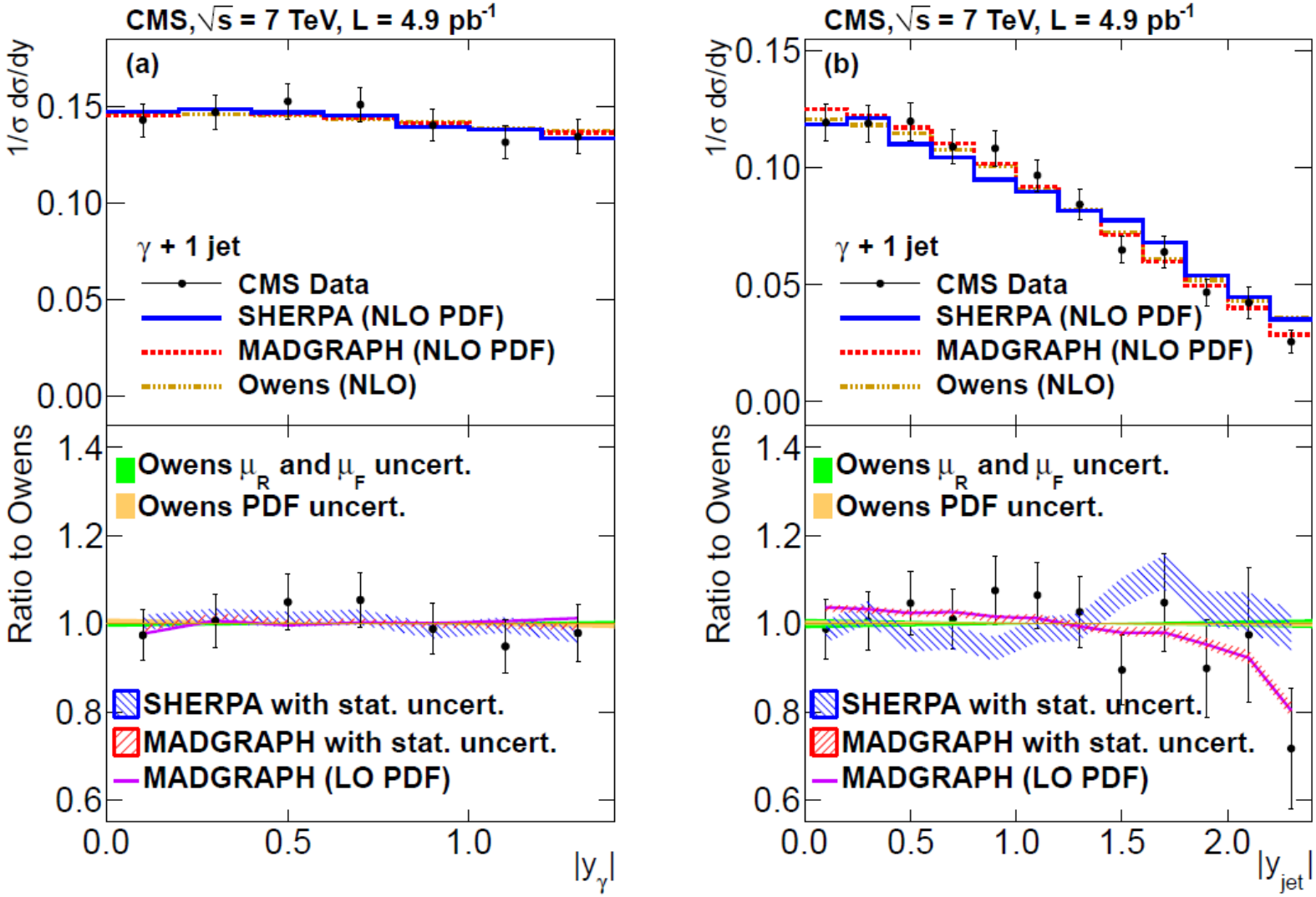
W + jets jet multiplicity





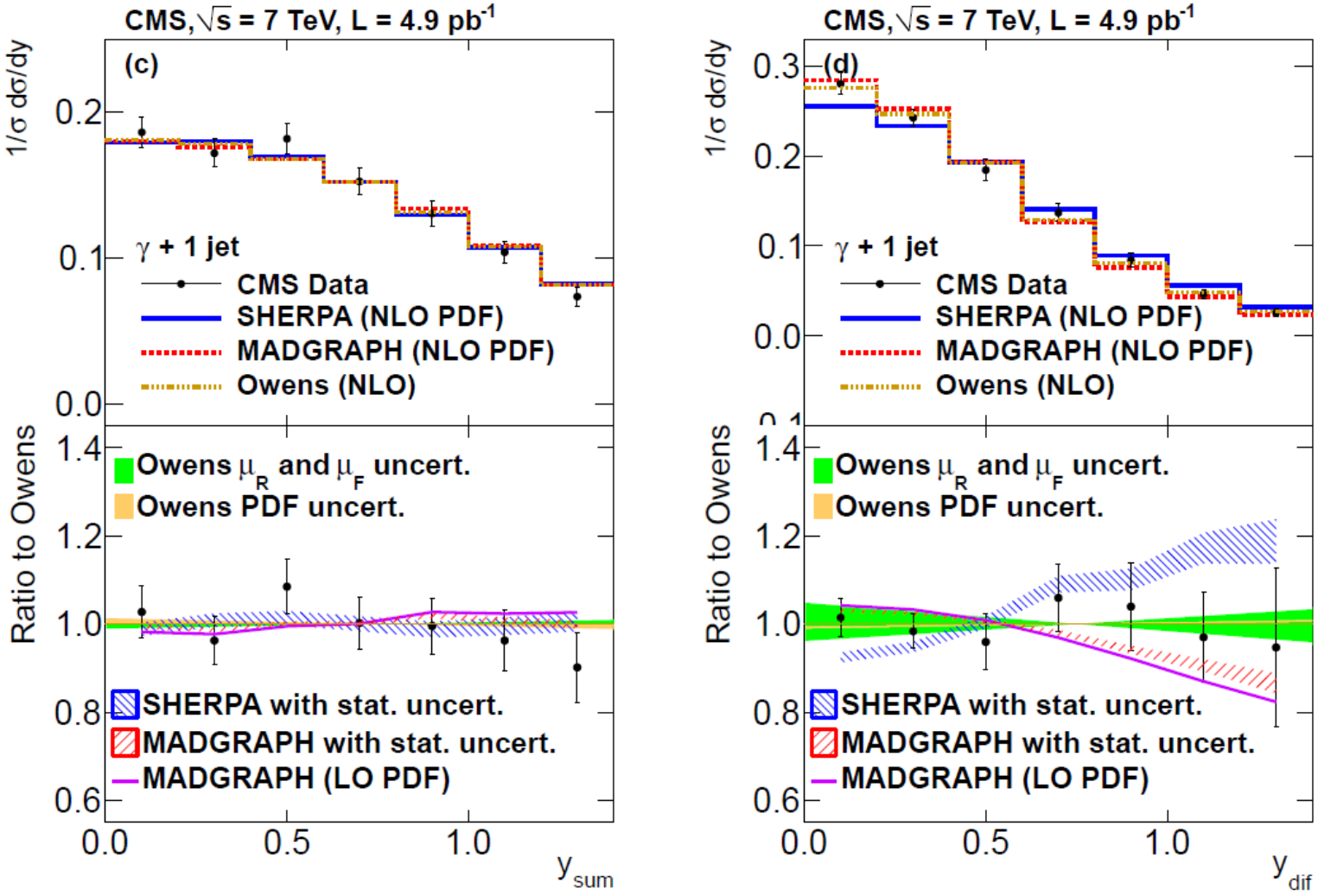
γ+jet results ($|y_\gamma|$,$|y_{jet}|$)

- Data are found to agree with theory predictions



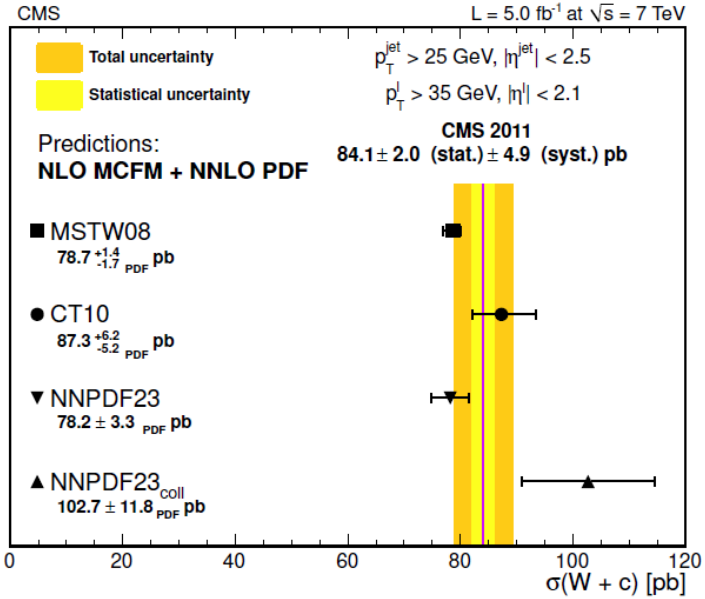
γ+jet results (y_{sum},y_{diff})

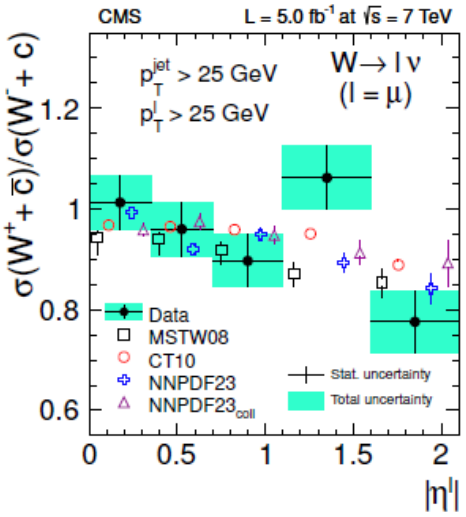
- Data are found to agree with predictions
- Same feature in SHERPA and MadGraph for Y_{diff} distribution

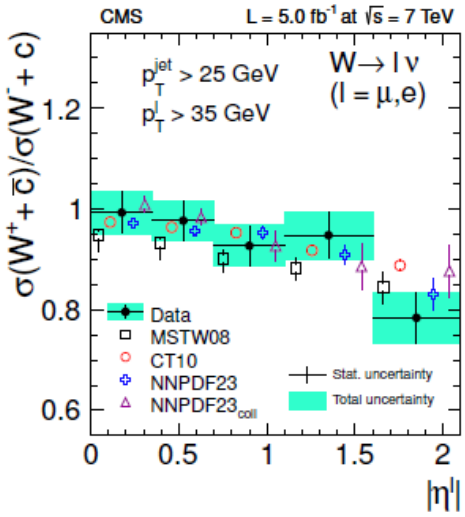


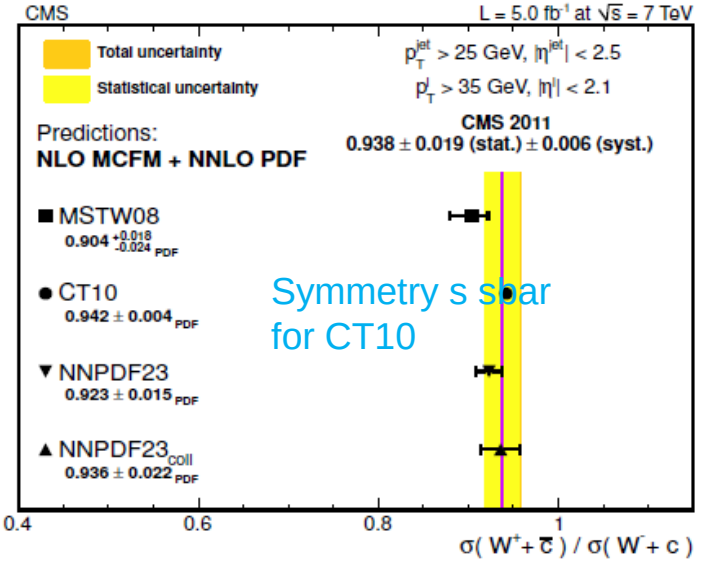
w + c Cross Section

- **3 charm decay modes**
- **Cross section ratio V.S. $|\eta_l|$**
  - Higher |ηl| is corresponding to the region where d dbar PDF has larger difference.
  - Theory is consistent with data
- **Total cross section ratio**
  - CT10,NNPDF23,NNPDF23$_{coll}$ consistent with data, MSTW08 < data ~ 1.5 sigma
  - Variations shown among different PDF sets









w + c Cross Section

- **Differential cross section**
  - **Shape of s quark PDF**
  - **Magnitude of s quark PDF**
  - **Different levels of agreement**