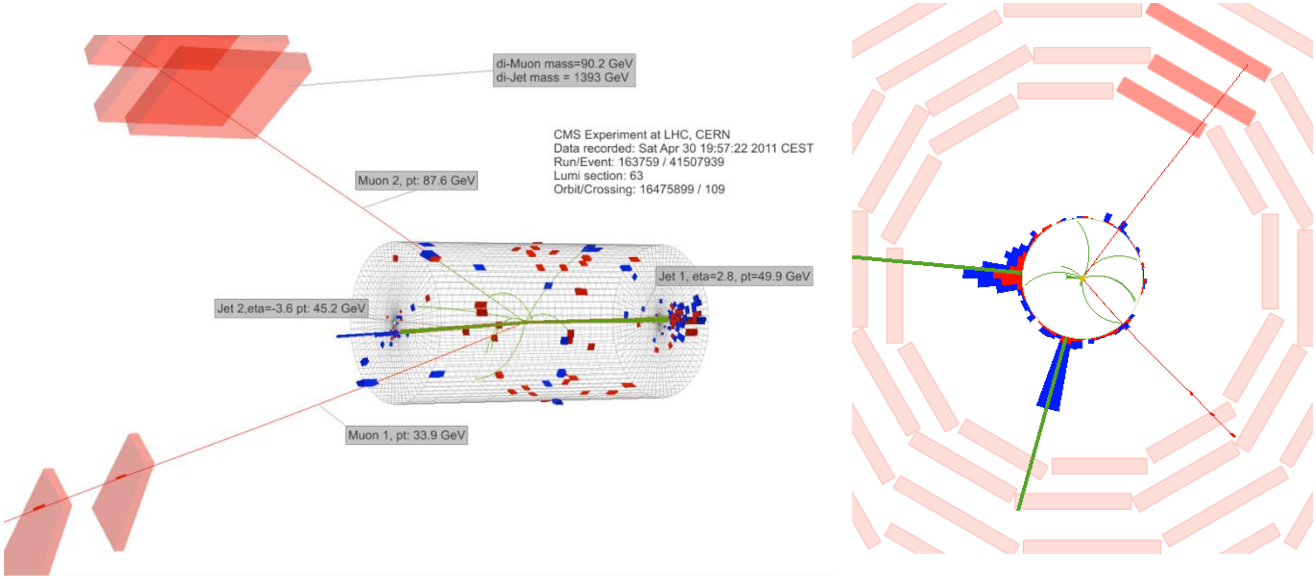
Production of Vector bosons in association with jets at CMS

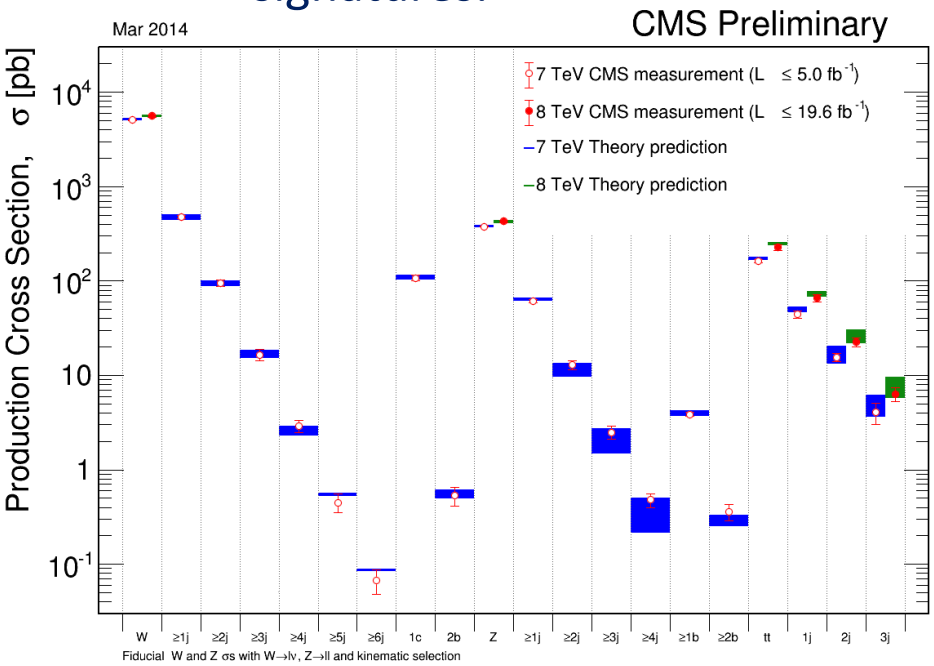
Emanuela Barberis
on behalf of the CMS collaboration
Northeastern University

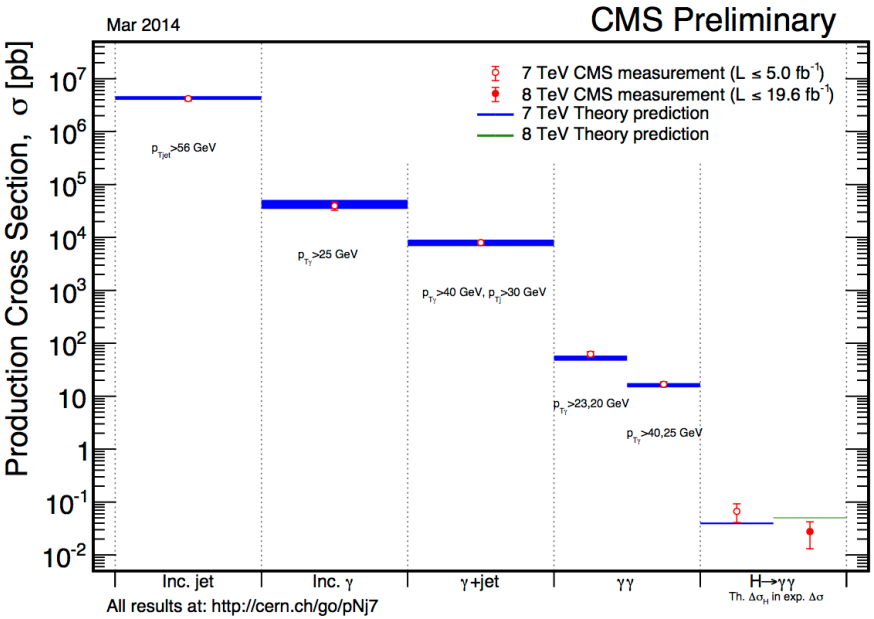


DPF2015. Ann Arbor, MI 4-8 August.

Overview

- Measurements of vector bosons + jets production rates and properties in proton-proton collisions at the LHC are important for:
  - ✓ testing pQCD predictions at the highest jet p_T and jet multiplicities.
  - ✓ tuning MC generators and theoretical calculations.
  - ✓ probing strange, heavy flavour, and gluon content in proton.
  - ✓ constraining parton distribution functions.
  - ✓ modeling backgrounds to rare SM (Higgs, single top) and beyond SM signatures.





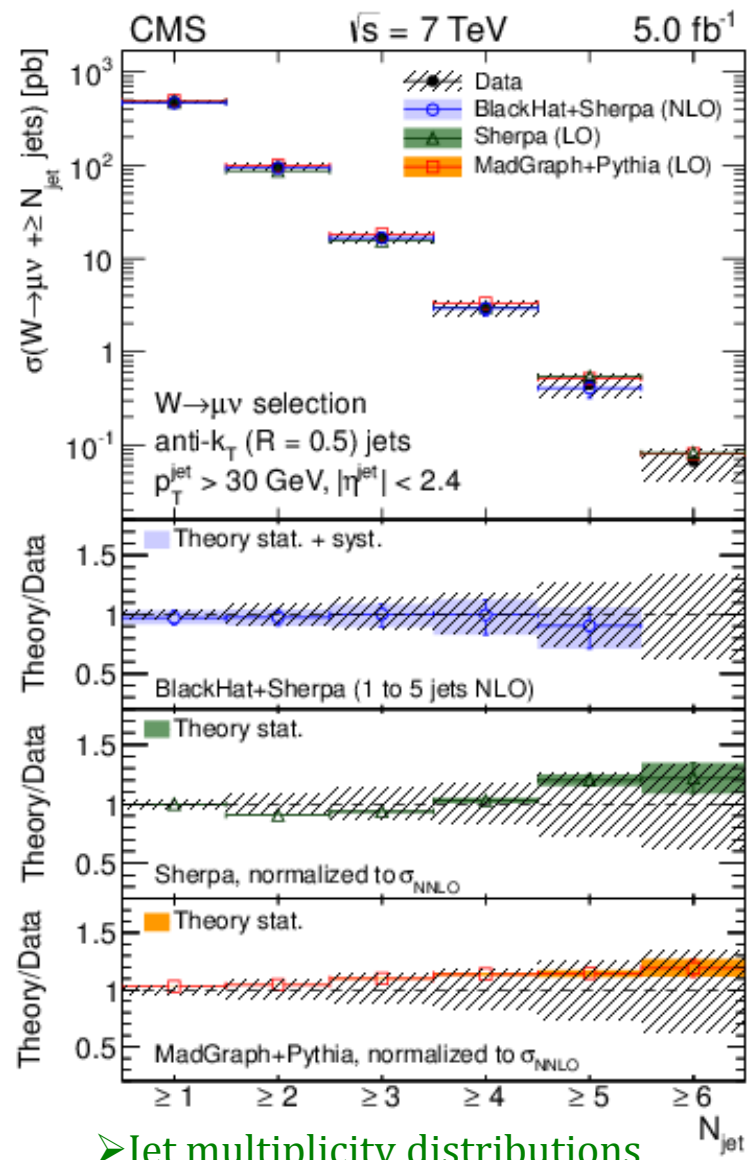
V+jets measurements at CMS

- CMS recent results covered in this talk:
  a mix of measurements at 7 TeV and at 8 TeV.

channel	measurement	documentation
W+jets	Differential cross section at 7 TeV	PLB 741 (2015) 12
Z+jets	Differential cross section at 8 TeV	CMS-PAS-SMP-13-007
Z+jets	Double differential cross section at 8 TeV	CMS-PAS-SMP-14-009
Z/γ + jets	Ratio of cross sections at 8 TeV	arXiv.1505.06250 submitted to JHEP
W+2 jets	EW production cross section at 8 TeV	CMS-PAS-SMP-13-012
$\gamma\gamma$ + jets	Differential cross section at 7 TeV	CMS-PAS-SMP-14-012
Z+b, bb	cross section at 7 TeV	JHEP06(2014)120, JHEP12(2013)39
W+bb	cross section at 7 TeV	PLB 735 (2014) 204
W+c	differential cross section at 7 TeV	JHEP 02 (2014) 013

Differential W+jets at 7 TeV

- Basic W+jets selection:
  - ✓ one muon with p_T>25 GeV and $|\eta|$<2.1
  - ✓ ≥ 1 jet (anti-k_T ΔR=0.5), p_T>30 GeV and $|\eta|$<2.4
  - ✓ transverse mass M_T (μ, E^{miss}_T) > 50 GeV
- Background estimates:
  - ✓ using NNLO theory σ's for MC Drell-Yan, NNLO+NNLL for ttbar, and NLO for VV
  - ✓ ttbar at high jet multiplicities reduced by b-tag veto. Normalization from two b-tag control region.
  - ✓ QCD background estimated with data in inverted isolation region.
- Data unfolded to correct for detector effects and compared with MC particle-level.
- Comparison with:
  - ✓BLACKHAT(NLO up to 5 jets)+ SHERPA (NP corrections from MADGRAPH)
  - ✓MADGRAPH(LO)+PYTHIA6
  - ✓SHERPA1.4

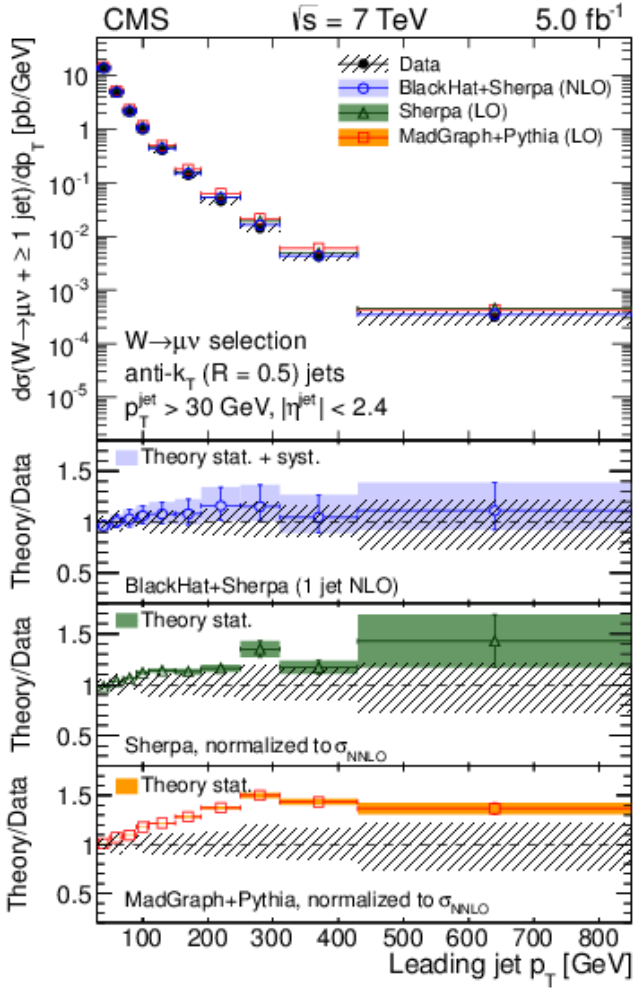


➢Jet multiplicity distributions well modeled.

PLB 741 (2015) 12

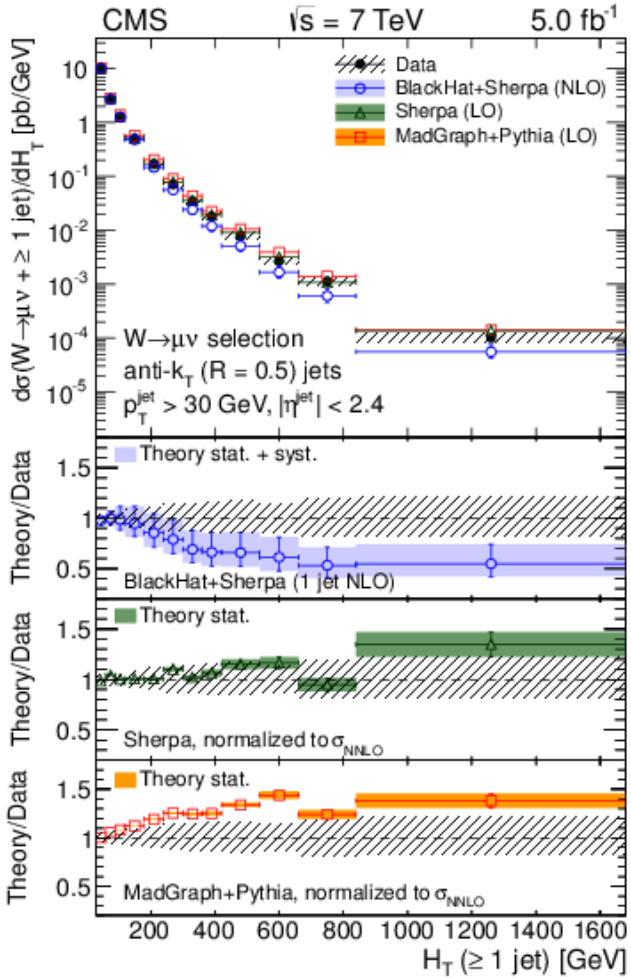
Differential W+jets at 7 TeV

Leading jet p_T ($N_{jets}\geq1$)



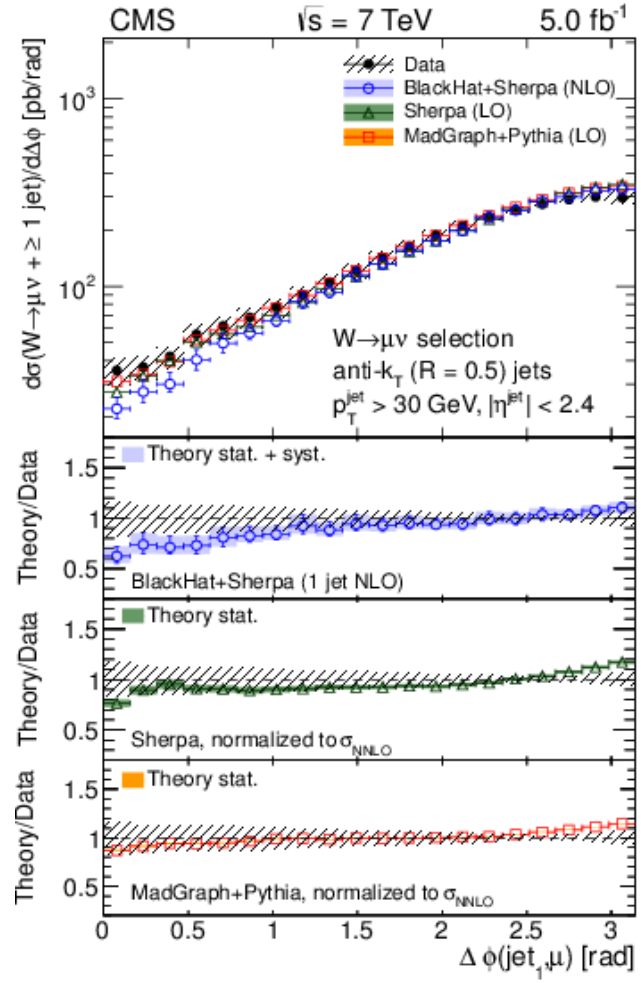
- Good agreement for NLO, some mismodeling in LO (ME+PS) predictions.

$H_T = \Sigma$jet p_T ($N_{jets}\geq1$)



- Some expected deficits in NLO due to lack of higher order contributions.

$\Delta\phi(\mu,\text{jet})$ ($N_{jets}\geq1$)

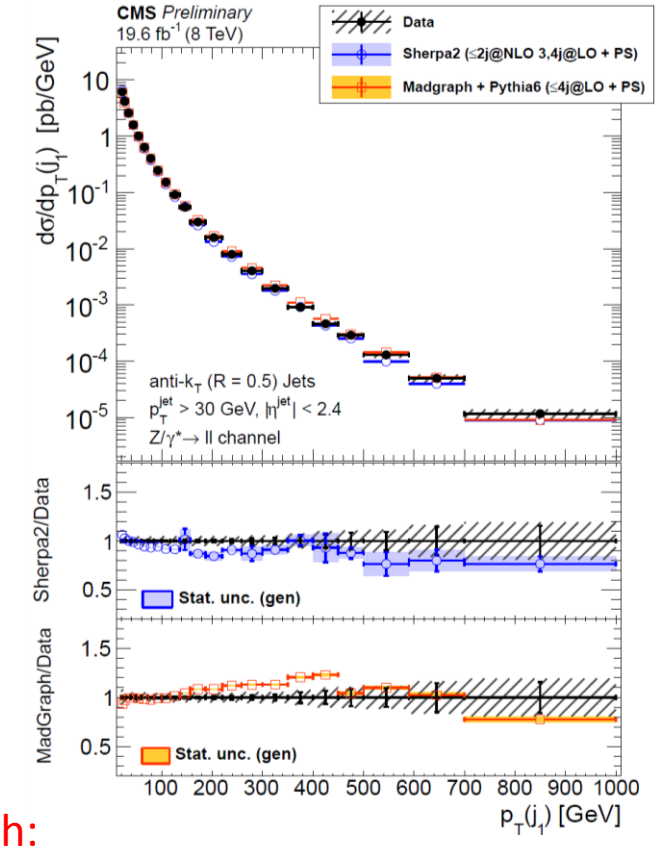


- Disagreement near zero for LO and NLO predictions.

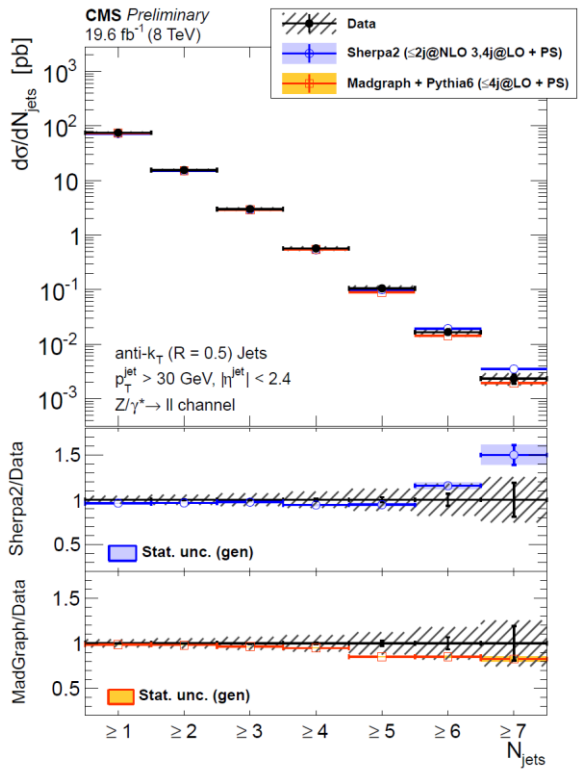
PLB 741 (2015) 12

Differential Z+jets at 8 TeV

- Basic Z+jets selection:
  - ✓ ee, μμ with p_T>20 GeV and |η|<2.4
  - ✓ ≥ 1 jet (anti-k_T ΔR=0.5), p_T>30 GeV and |η|<2.4
  - ✓ dilepton mass 71 < $M_{\ell\ell}$ < 111 GeV
- Background estimates:
  - ✓ NNLO+NNLL σ's for MC ttbar, NLO for VV
- Data unfolded and compared with MC particle-level.



CMS-PAS-SMP-13-007



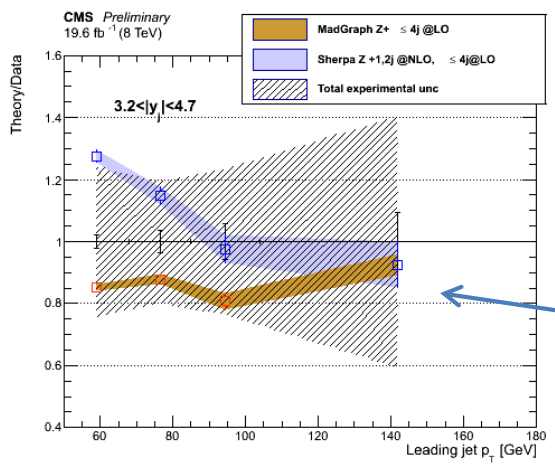
- Comparison with:
  - ✓MADGRAPH(LO)+PYTHIA6
  - ✓SHERPA2(uses BLACKHAT NLO ME ≤2 jets, LO ME ≤ 4 jets, MEPS@NLO for merging)

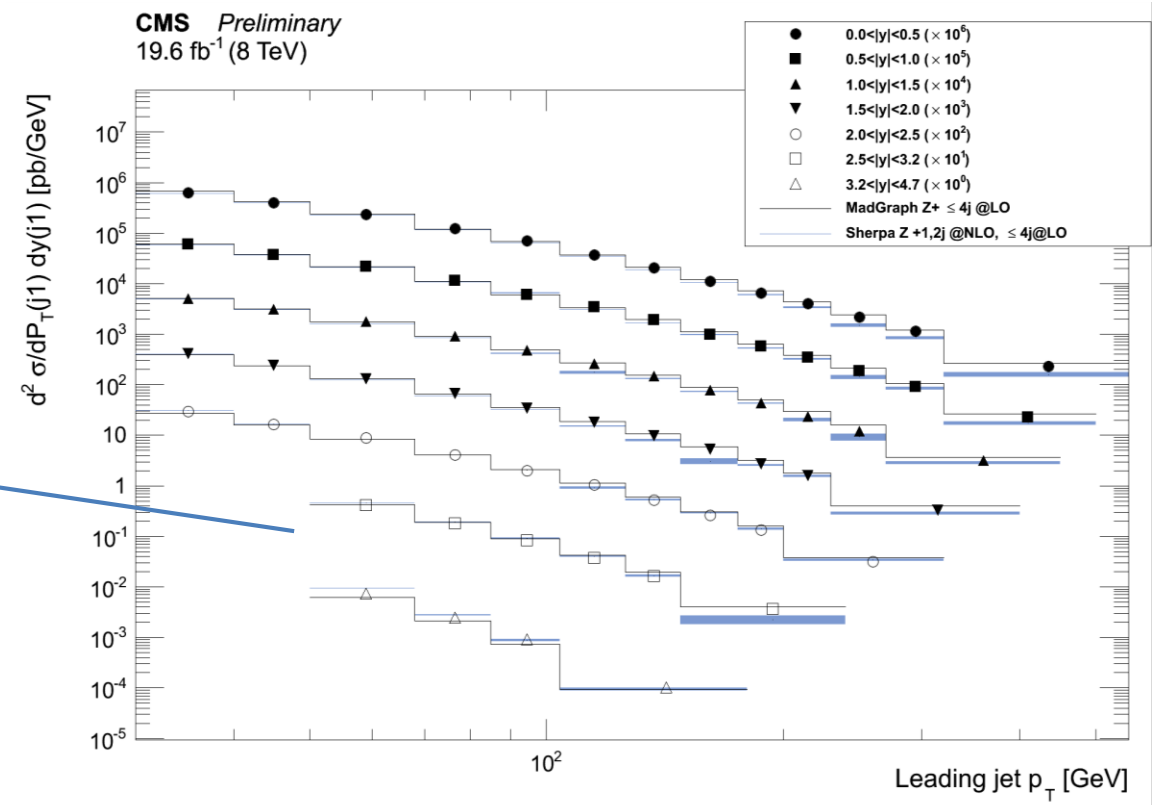
➢ Jet multiplicity distributions well modeled.

➢ LO overestimates leading jet p_T.

Double differential Z+jets at 8 TeV

- Selection and backgrounds similar to single differential measurements, but:
  - ✓ only muons considered.
  - ✓ extends jet rapidity coverage to $|\eta|<4.7$ ($p_T>30(50)$ GeV for $|\eta|<2.5(4.7)$).
  - ✓ double differential in leading jet p_T and rapidity.
- Comparison with: MADGRAPH(LO)+PYTHIA6 and SHERPA2

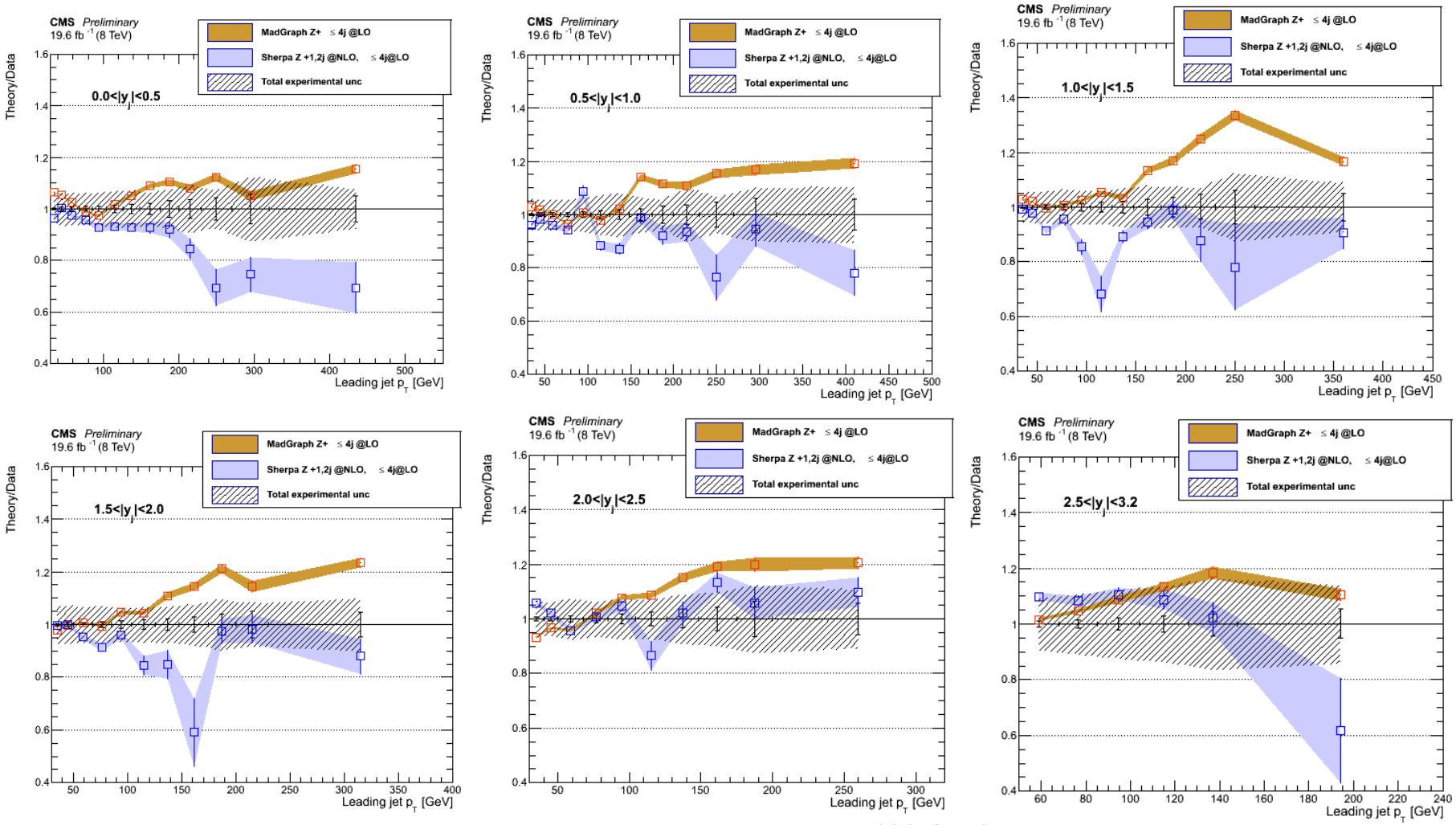




CMS-PAS-SMP-14-009

Double differential Z+jets at 8 TeV

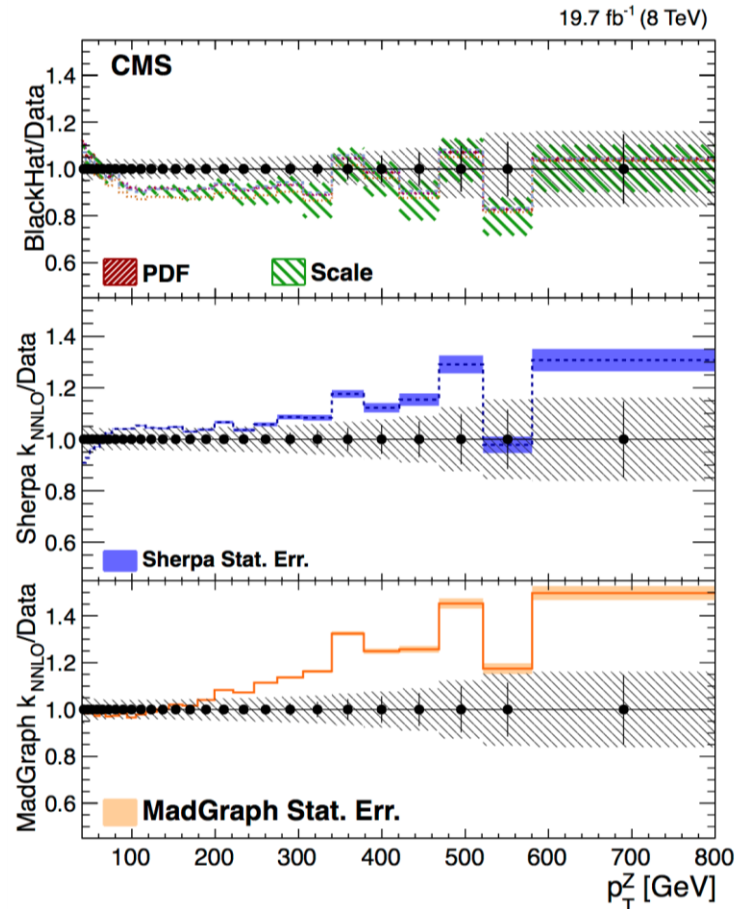
CMS-PAS-SMP-14-009

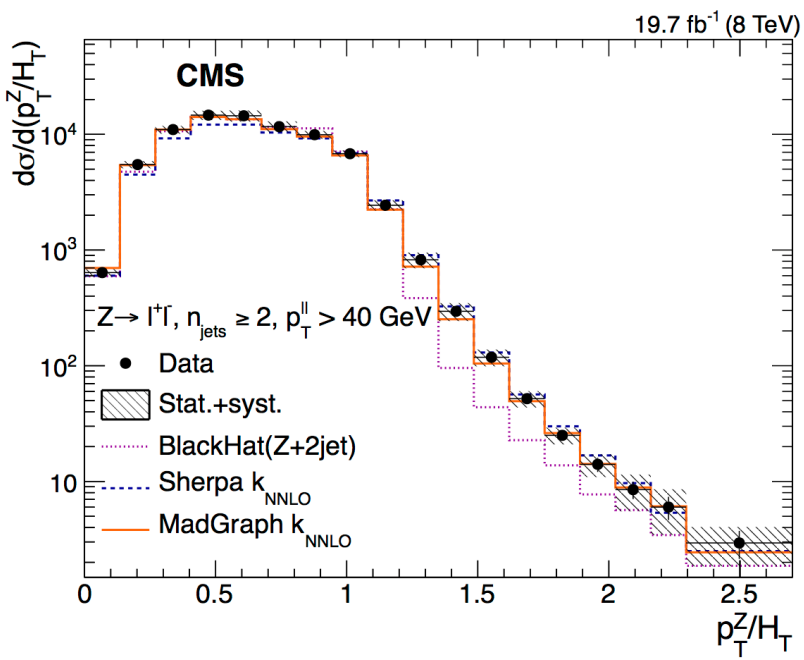


- MADGRAPH observed to overestimates at high (≥ 100 GeV) jet p_T in all rapidity bins up to 3.2

Ratio of differential Z+jets/γ+jets at 8 TeV

- Z+jets selection:
  - ✓ ee, μμ (OS) with p_T>20 GeV, |η|<2.4
  - ✓ ≥ 1 jet (anti-k_T ΔR=0.5) p_T>30 GeV, |η|<2.4
  - ✓ 71 < $M_{\ell\ell}$ < 121 GeV and $p_T^{\ell\ell}$ > 40 GeV
- γ+jets selection:
  - ✓ ≥ 1 photon with p_T>100 GeV, |η|<1.4
  - ✓ ≥ 1 jet (anti-k_T ΔR=0.5), p_T>30 GeV, |η|<2.4
- Comparison with: MADGRAPH(LO)+PYTHIA6, SHERPA1.4, BLACKHAT+SHERPA(NLO 1,2,3 jets),



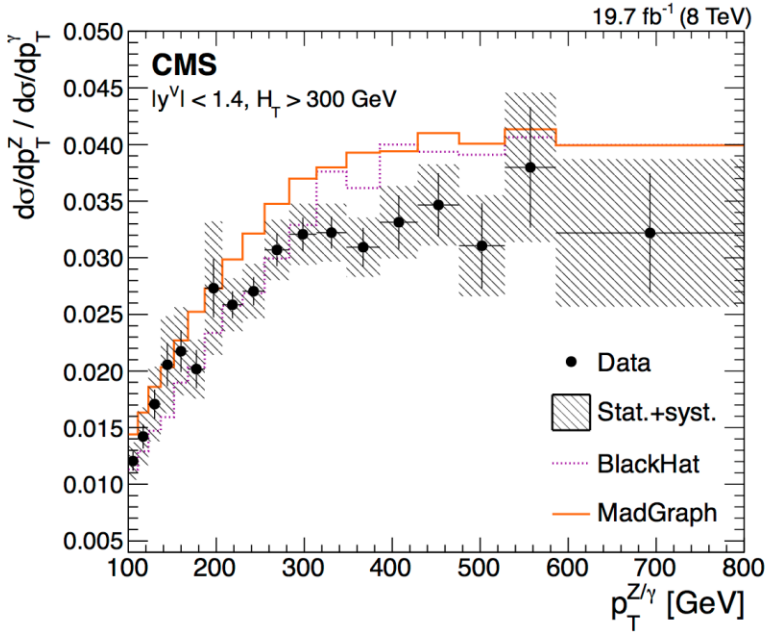


arXiv.1505.06250
Submitted to JHEP

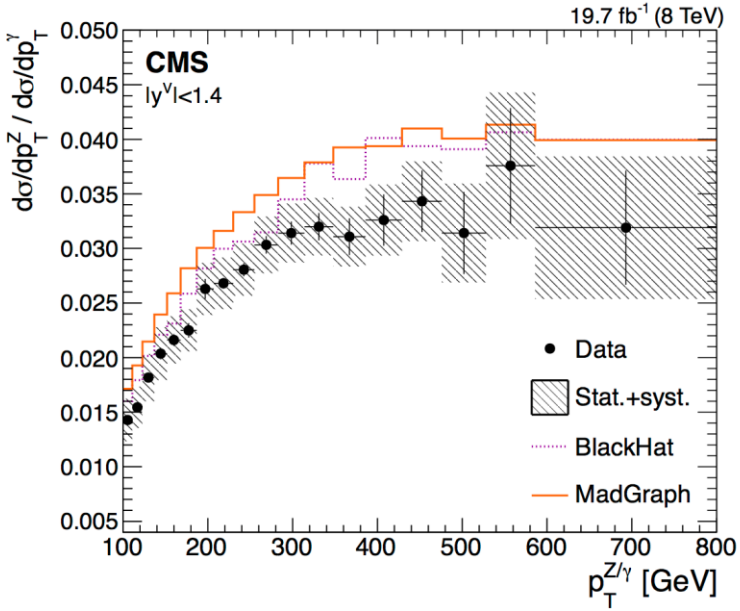
- ➢ Overestimate at high p^Z_T for LO MCs, NLO agrees better (~10% level for N_{jets}≥1).
- ➢ LO+PS(scaled to NNLO) in agreement for p^Z_T /H_T. NLO has limited application.

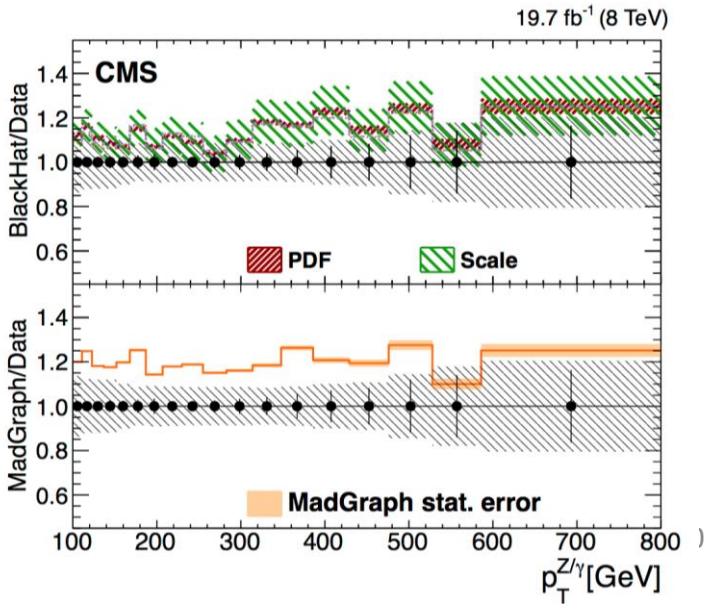
Ratio of differential Z+jets/γ+jets at 8 TeV

- Differential cross-section ratio (Z/γ) vs boson p_T for different kinematic selections: at LO and high p_T, the ratio is expected to reach a plateau.
  - Saturation of ratio observed, ~20% normalization differences with theory in all kinematic regions.



  - H_T>300 GeV, region of interest for multi-hadronic searches for new physics.

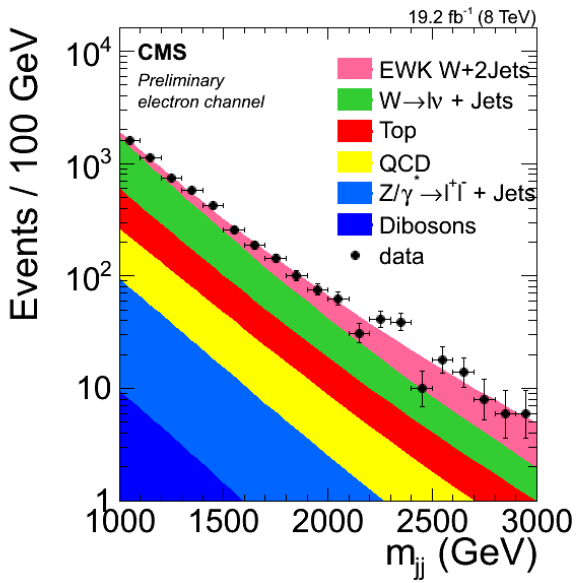


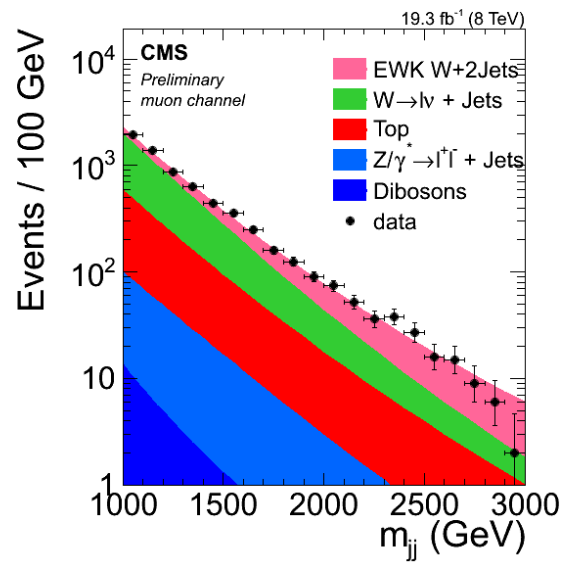


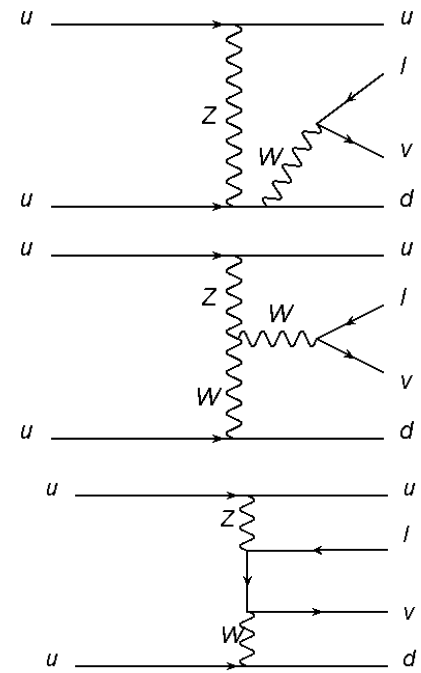
arXiv.1505.06250
Submitted to JHEP

EW production of W+2 jets at 8 TeV

- Probes Triple Gauge Couplings and background to VBF Higgs searches
- Forward-backward jets (plus W) topology:
  - ✓ $j_1(j_2)$ p_T > 60(50) GeV, $|\eta_j|$<4.7, $m(j_1j_2)$ > 1 TeV
  - ✓ $|y_W-(y_{jet1}+y_{jet2})/2.0|$ < 1.2 and M_T>30 GeV
  - ✓ $\mu(e)$ with p_T>25(30) GeV, $|\eta|$<2.1, E_T^{miss}>25(30)
- BDT used to separate signal and background (QCD W+jets)
  - ✓ Signal extracted via fits to: $m(j_1j_2)$







CMS-PAS-SMP-13-012

✓ Measured cross section in agreement with MADGRAPH+PYTHIA6 predictions

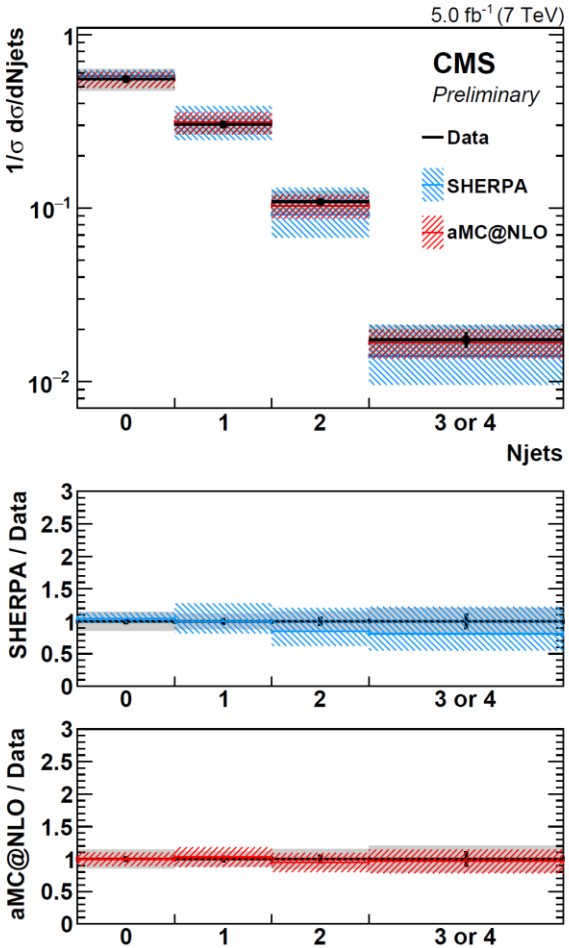
$\sigma(W\rightarrow l\nu + 2jets, l=e,\mu) = 0.42 \pm 0.04\ (stat.) \pm 0.09\ (syst.) \pm 0.01\ (lumi.)$ pb

Differential γγ + jets at 7 TeV

- First measurement of the γ γ + jets differential cross section at the LHC:
  - ✓ $p_T^{\gamma} > 40, 25$ GeV and $|\eta^{\gamma}|<1.44$ or $1.57<|\eta^{\gamma}|<2.5$
  - ✓ ≥ 1 jet with $p_T>30$ GeV and $|\eta|<4.7$
- Isolation and EM shower shape used to discriminate from energetic neutral mesons background: A data-driven method based on the photon component of the particle flow isolation used to extract the prompt diphoton yield.
- Data unfolded to particle-level after efficiency corrections.
- Comparison with the predictions of:

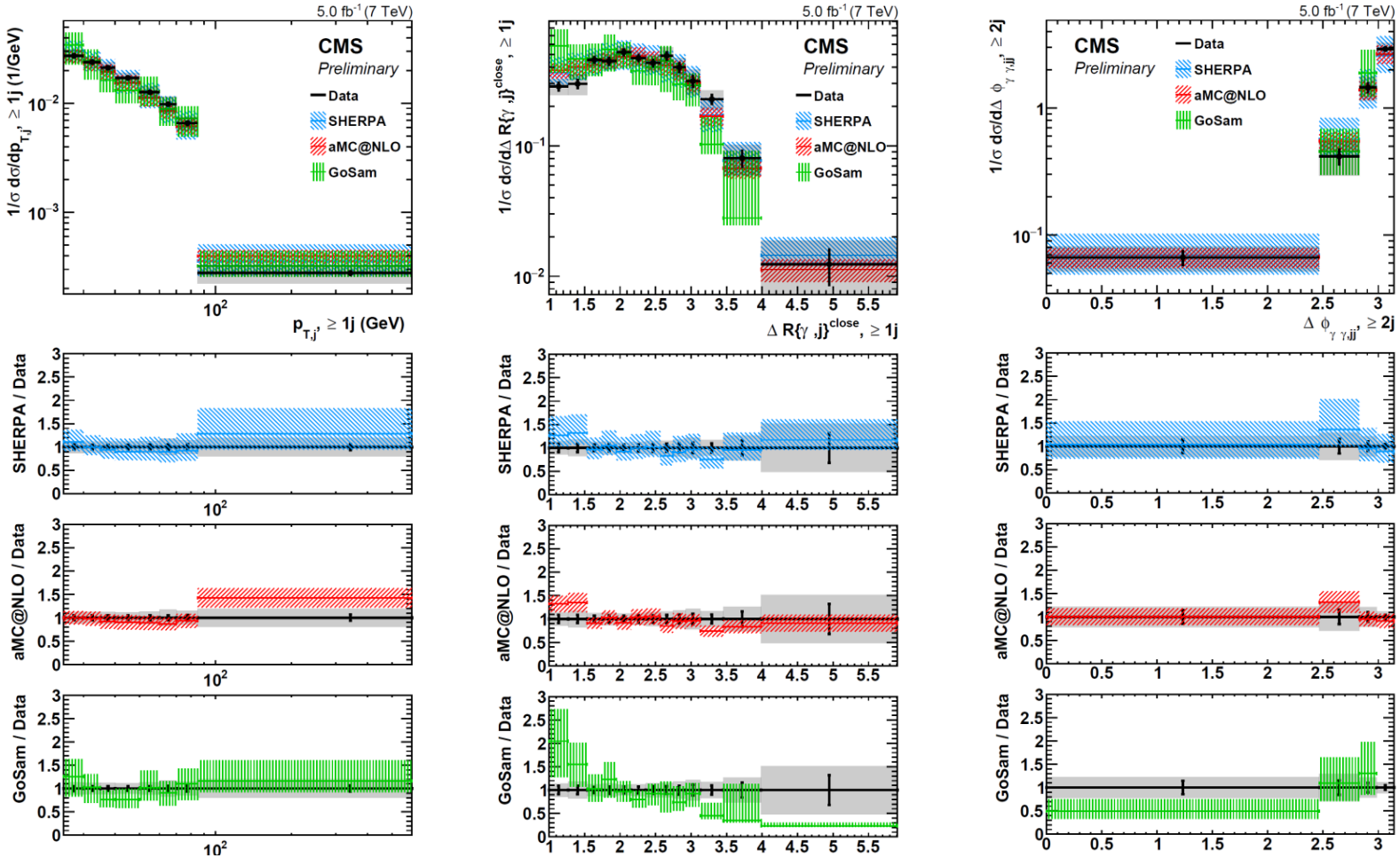
✓ SHERPA MC
✓ aMC@NLO (NLO up to 2 jets)
✓ GOSAM (parton-level, 1 or 2 jets at NLO, NP corrections from PYTHIA)

✓Good agreement in jet multiplicity distributions (excellent for aMC@NLO).



CMS-PAS-SMP-14-021

Differential γγ + jets at 7 TeV



CMS-PAS-SMP-14-021

✓SHERPA and aMC@NLO agree with data.

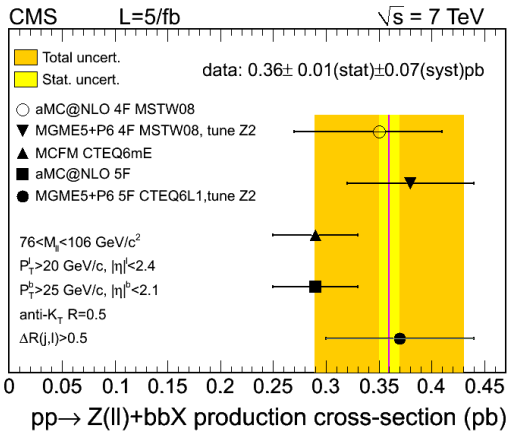
✓GOSAM disagrees on the angular observables (GOSAM is a fixed-order parton-level generator that does not account for additional jet emissions and hadronization).

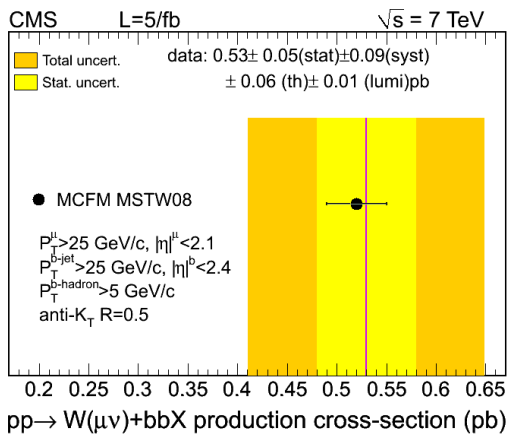
V(W,Z)+b(b) and W+c at 7 TeV

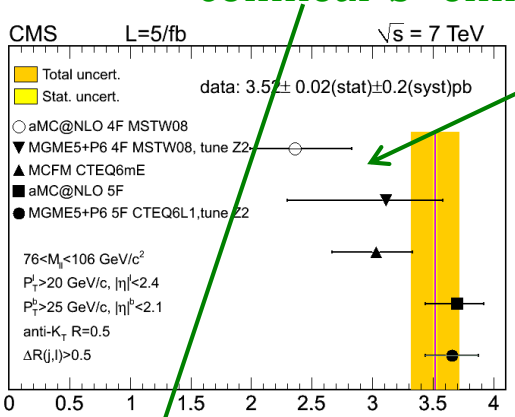
Z+b(b) and Wbb cross sections:
Z+bb sensitive to gluon splitting,
Z+b can probe b-quark PDF,
W+bb important background to
Higgs and BSM searches.

W+c cross-section: measurement sensitive to the strange quark content of the proton

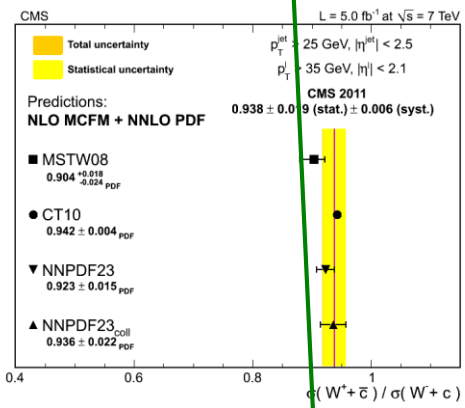
✓ 7 TeV results have points of disagreement, collinear b- emission, flavor scheme, PDFs

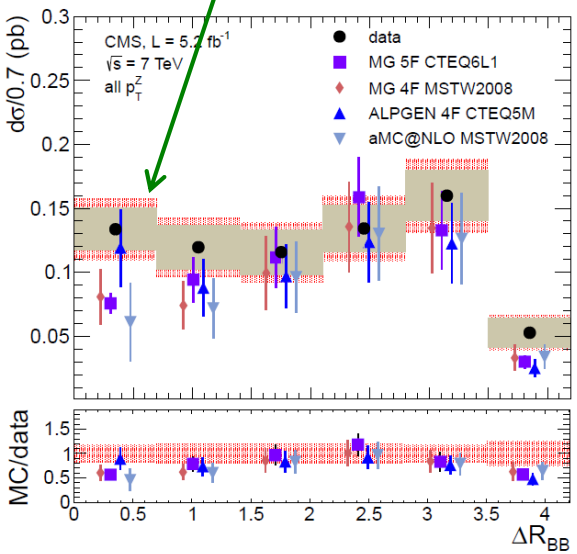




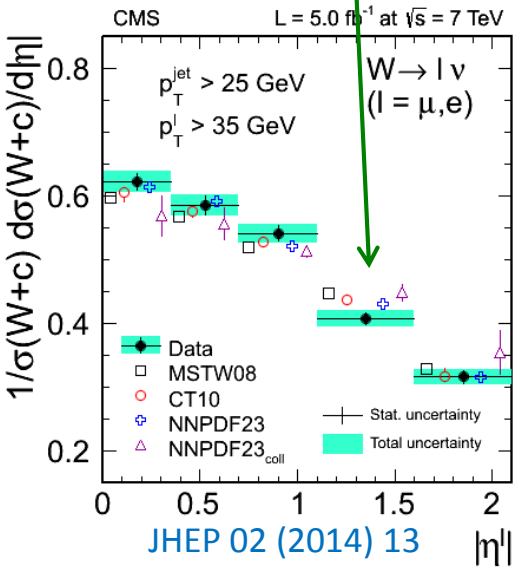


PLB 735 (2014) 204
JHEP 06 (2014) 120





JHEP 12 (2013) 39



JHEP 02 (2014) 13

Conclusions

- V+jets processes are essential to our understanding of LHC physics.
- Measurements at the LHC continue to extend the measured phase space and are able to constraint predictions with greater precision.
- Theory predictions are making great advances as well (NLO matrix elements to an increasing number of partons, matching to parton shower, non-perturbative and electroweak corrections, treatment of heavy flavors, beyond NLO, MC tunes, PDFs).
- Ready to test a new regime of QCD dynamics with 13 TeV.