CMS: Vector-boson production plus N-jets

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Jet Vetoes and Multiplicity Observables

University of California, Los Angeles (UCLA)

Introduction

- Precise knowledge of W+jets and Z+jets is crucial as important backgrounds to BSM searches
- Both processes have large cross-sections, controllable background which enables precision measurement
  - Can confront predictions from theory in high end tails
- High statistics allows access to phase spaces not tested before

Overview:

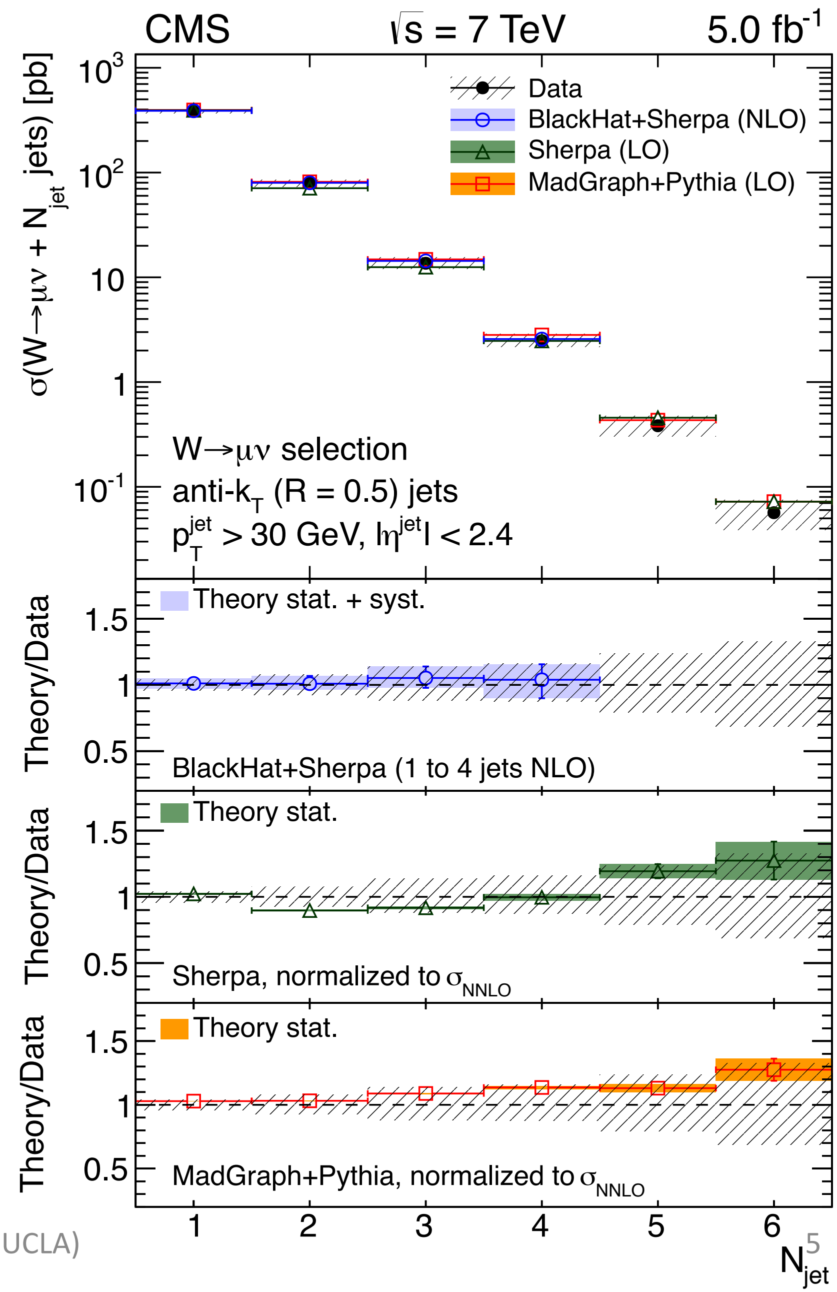
1. W + Jets
2. Z + Jets
3. γ + Jets
4. Z/γ Ratio

W+jets, $\sqrt{s}$=7 TeV

- $W \rightarrow \mu\nu$ decays
- Muon p_T>25GeV, $|\eta|$<2.1
- Jets are anti-k_T, ΔR=0.5, p_T>30GeV, $|\eta|$<2.4, $\Delta R(\mathrm{Jet},\mu)$>0.5

Jet multiplicity at 7 TeV

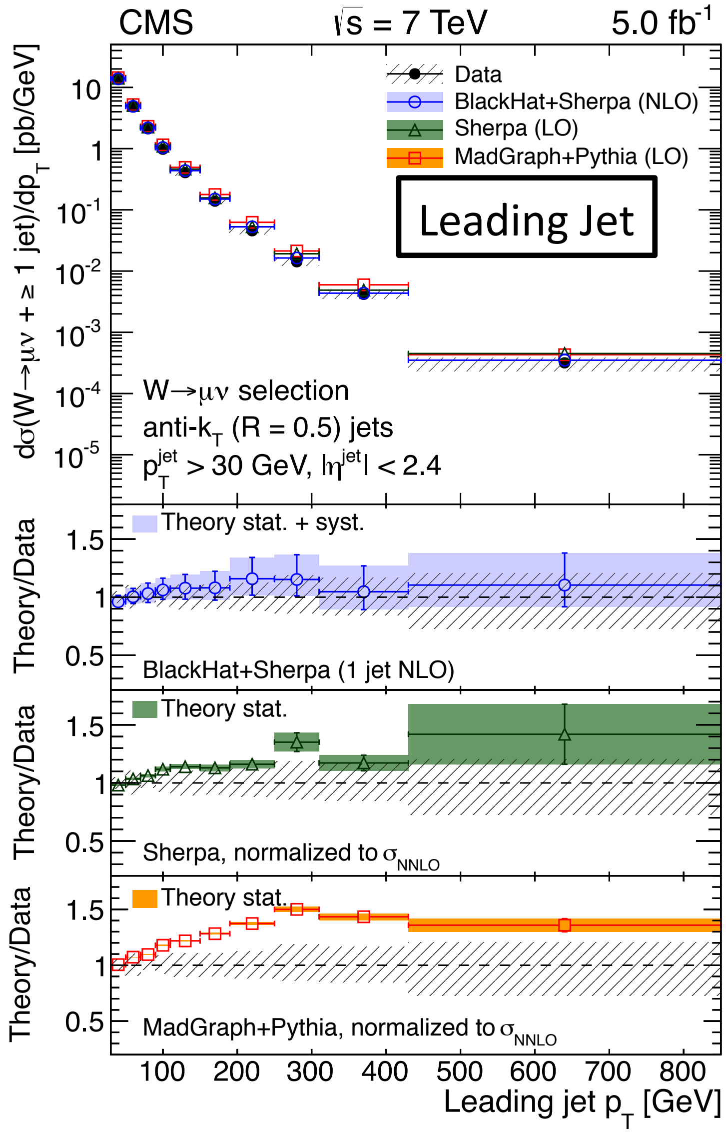
- Agreement up to 4 jets for BlackHat+Sherpa, 6 jets for Sherpa 1.4 and Madgraph
- Can test quantities with high accuracy up to 6 jets
  - Uncertainty at highest jet multiplicty is 30%, below 15% up to 4 jet multiplicity

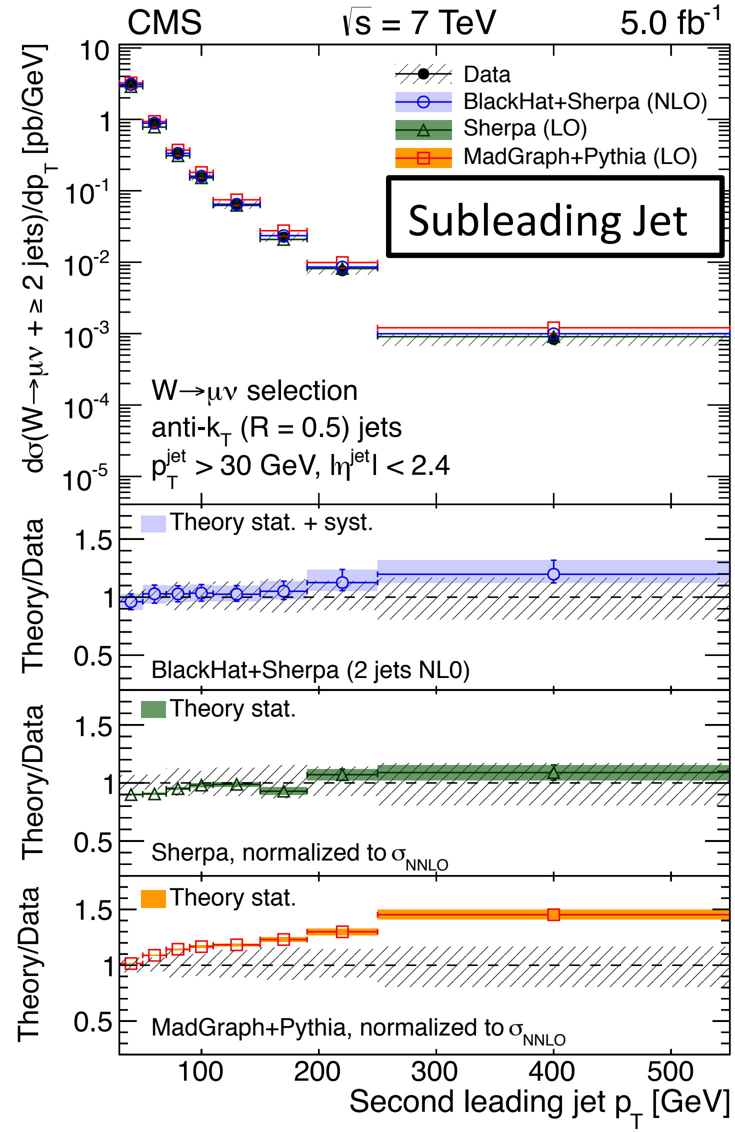


arXiv:1406.7533

Jet p_T at 7 TeV

- Upward trend in all cases
- BlackHat agrees through the entire p_T range
- MadGraph and Sherpa overestimate the rate in the leading jet
- MadGraph overestimates in second leading jet.



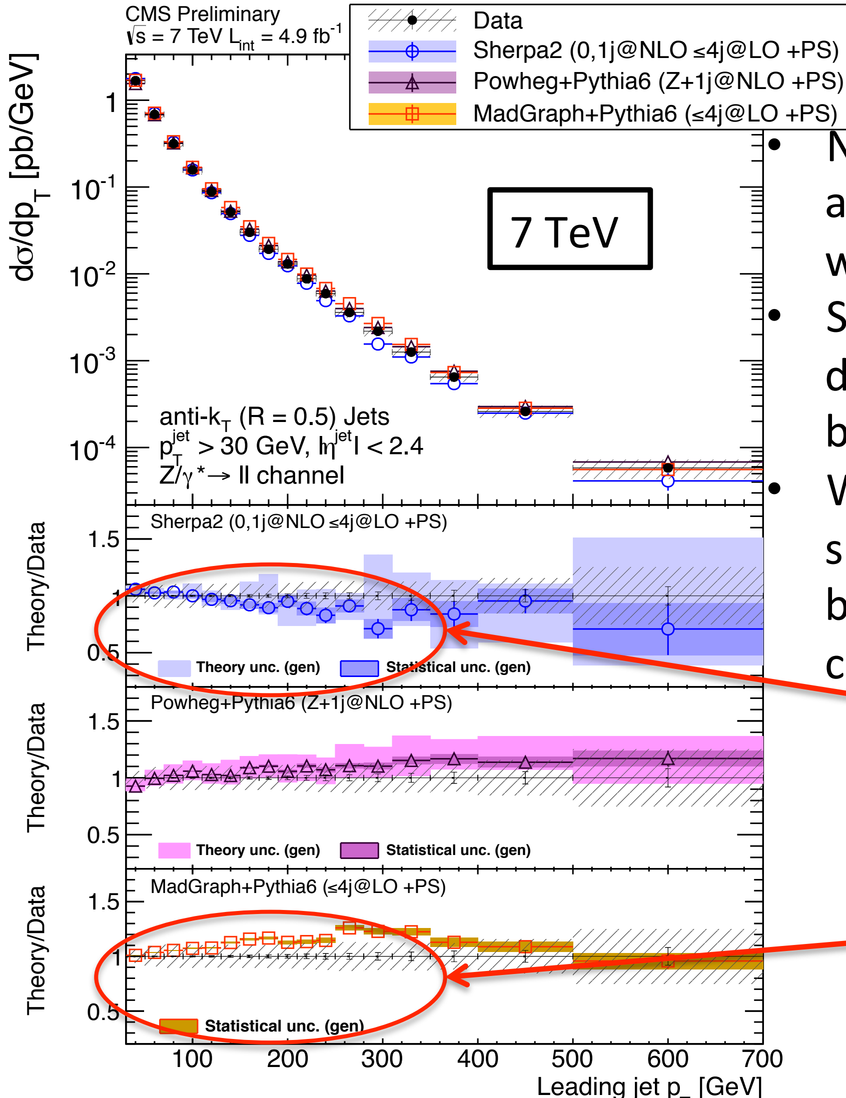


arXiv:1406.7533

Z+jets, √s=7 TeV and 8 TeV

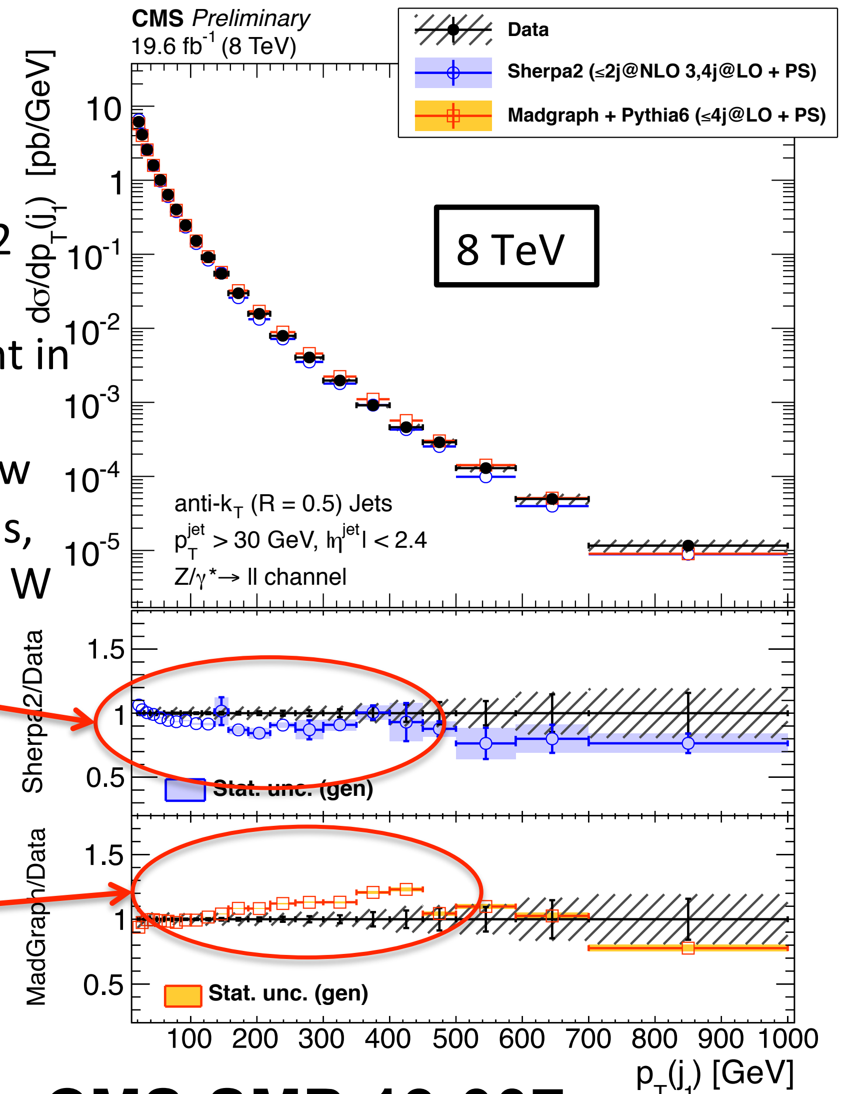
- Z→ll decays
- Leptons p_T>20GeV, $|\eta|$<2.4
- 71<M_{ll}<111GeV
- Jets are anti-k_T, ΔR=0.5, p_T>30GeV, $|\eta|$<2.4, ΔR(Jet,l)>0.5

Leading jet p_T



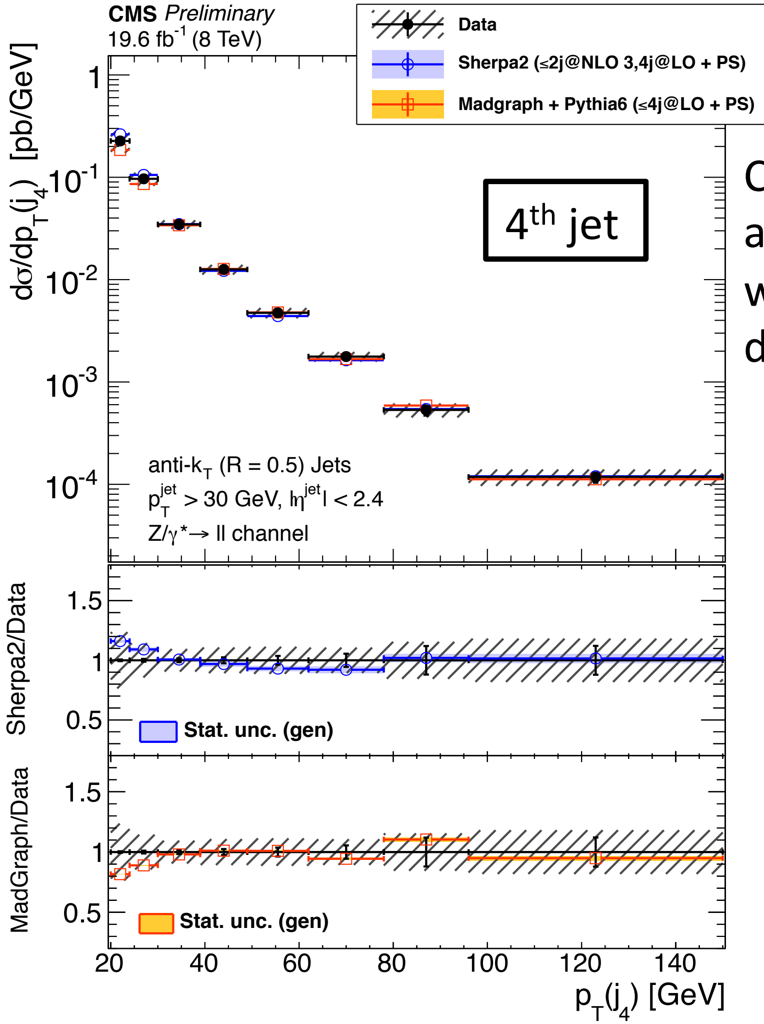
CMS-SMP-12-017

- N.B these analyses are with Sherpa2
- Same disagreement in both cases!
- W and Z show similar trends, but worse in W case

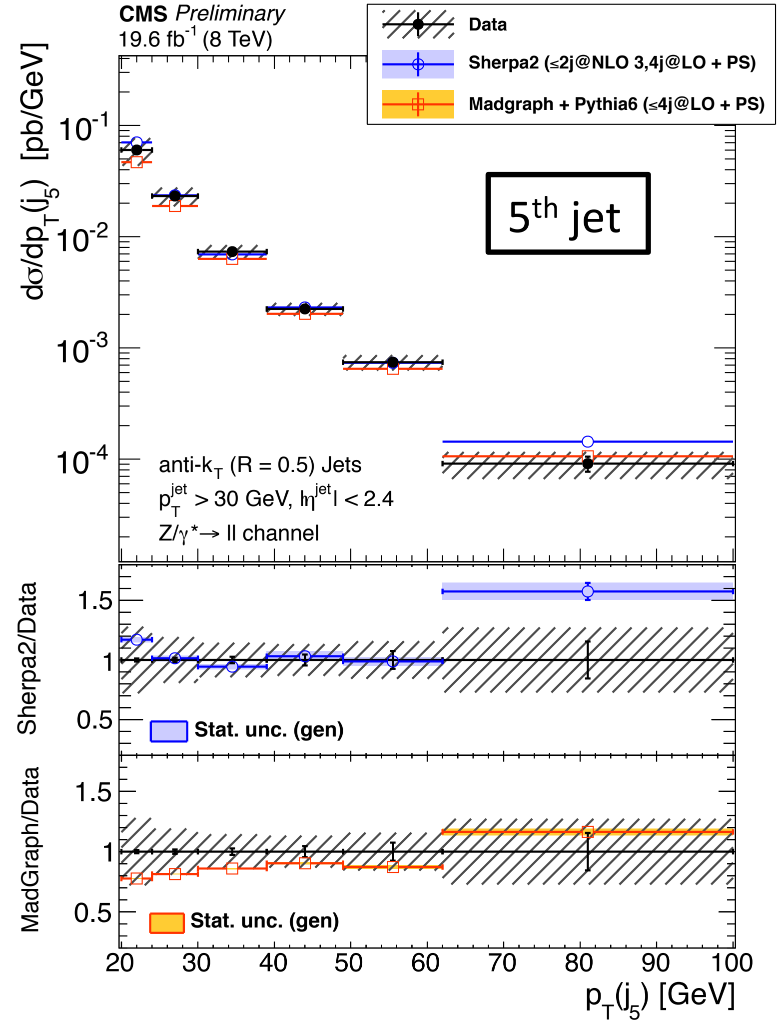


CMS-SMP-13-007

4th and 5th leading jet p_T at 8 TeV

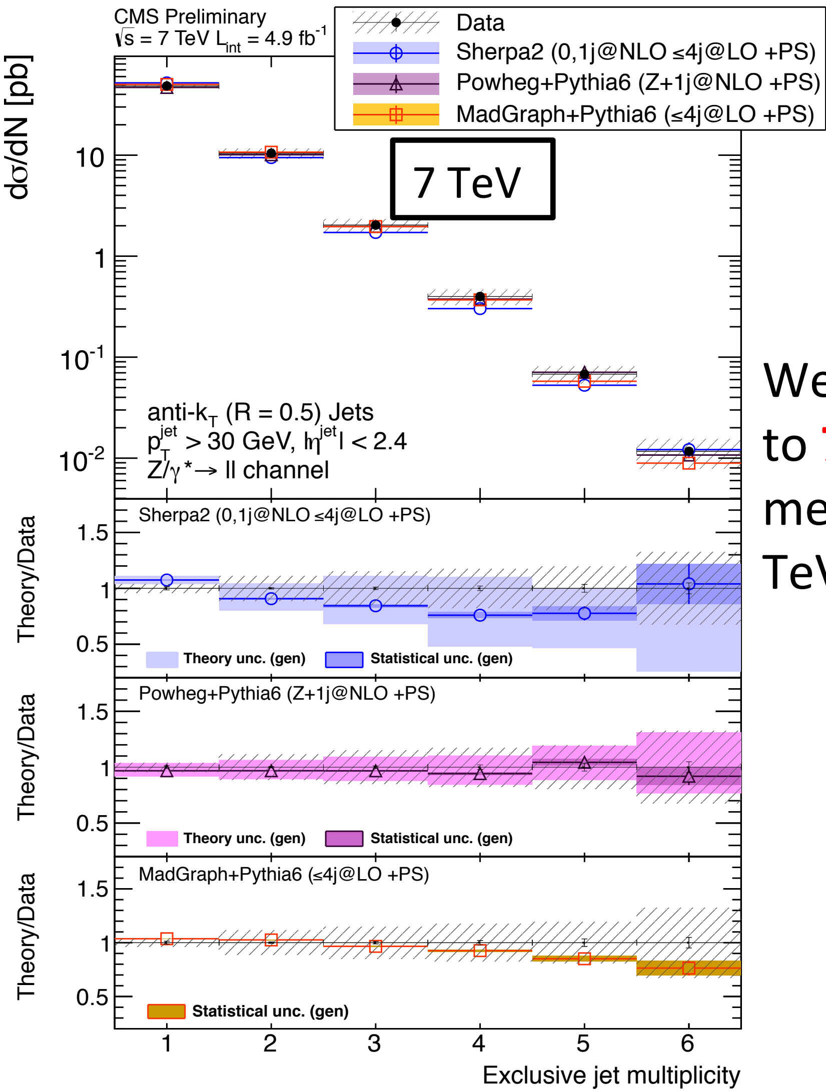


Can measure 4th and even 5th jet p_T with the available data



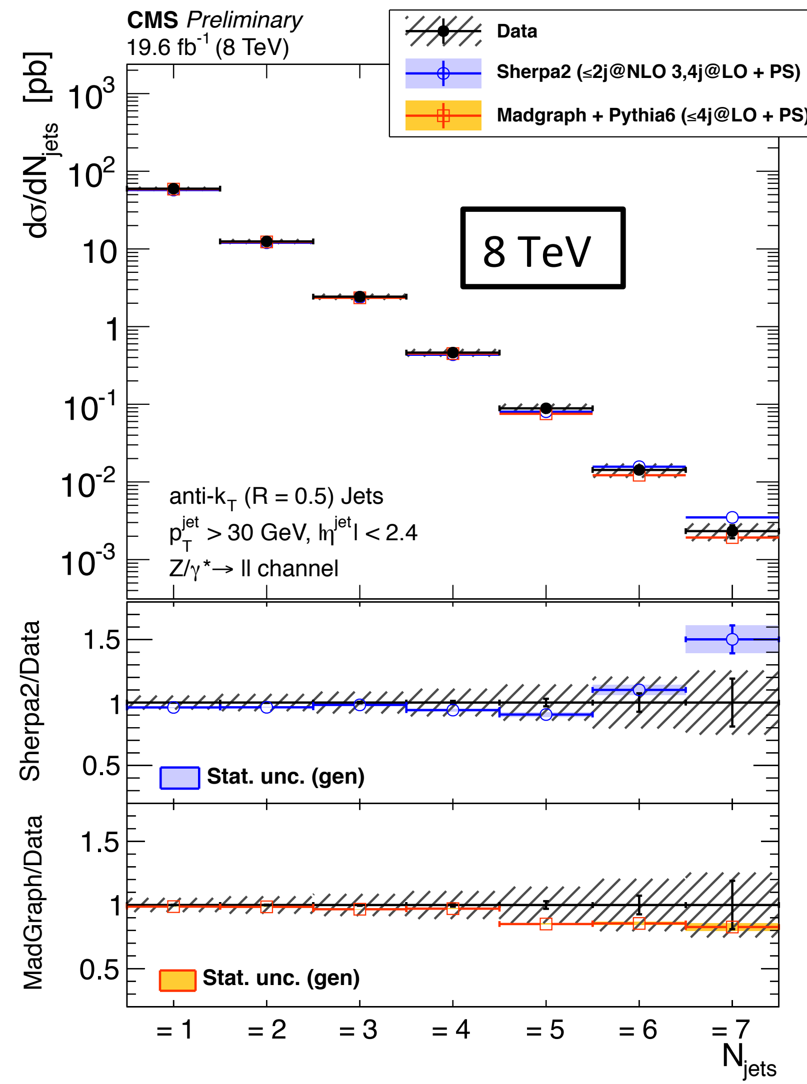
CMS-SMP-13-007

Exclusive jet multiplicity



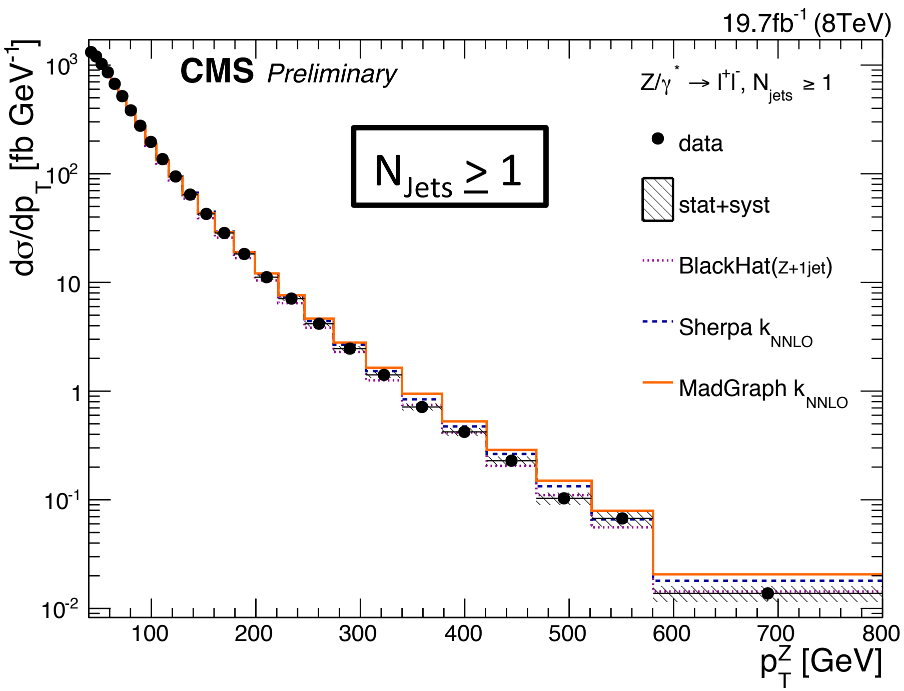
CMS-SMP-12-017

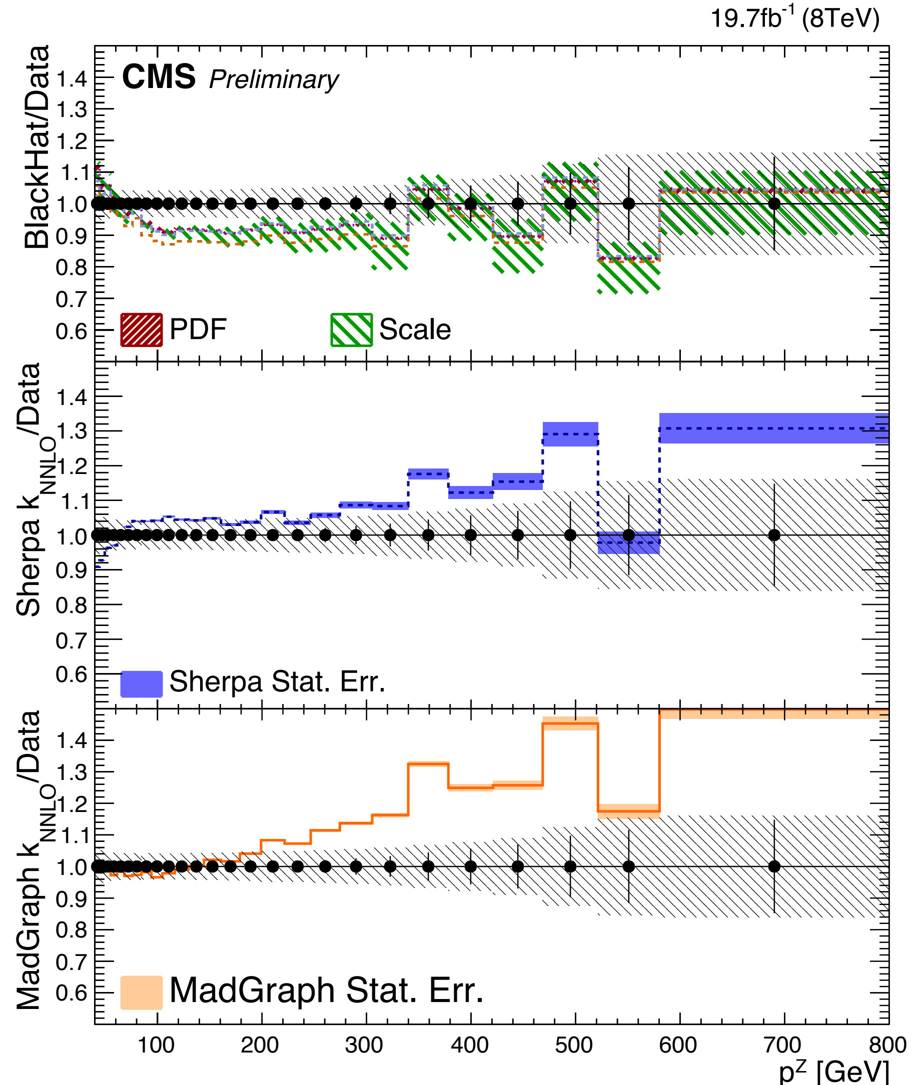
We have up to **7** jets measured at 8 TeV!



CMS-SMP-13-007

p_T^Z Spectrum, $N_{Jets} \geq 1$ at 8 TeV

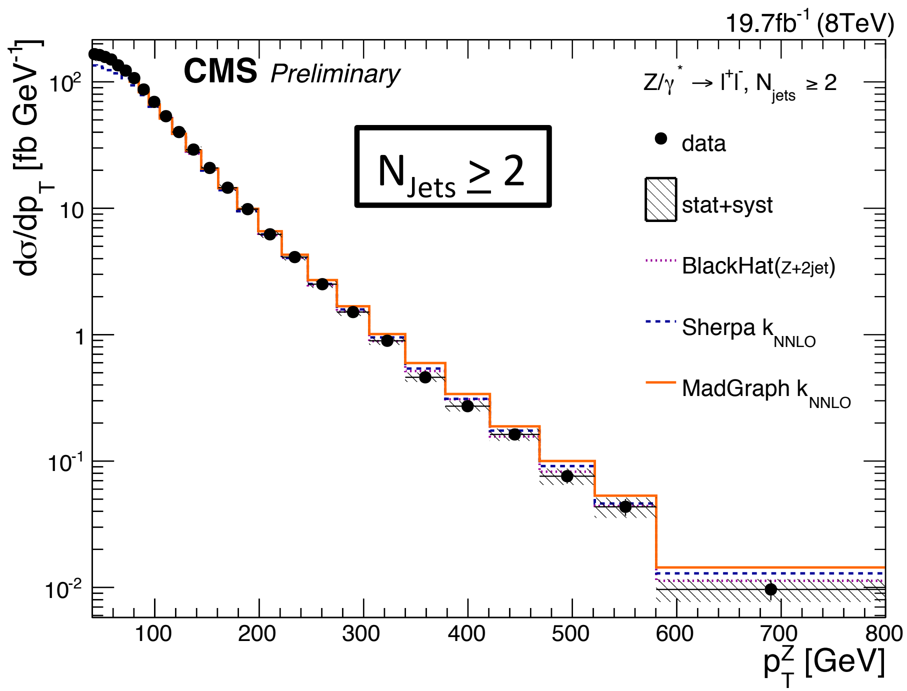




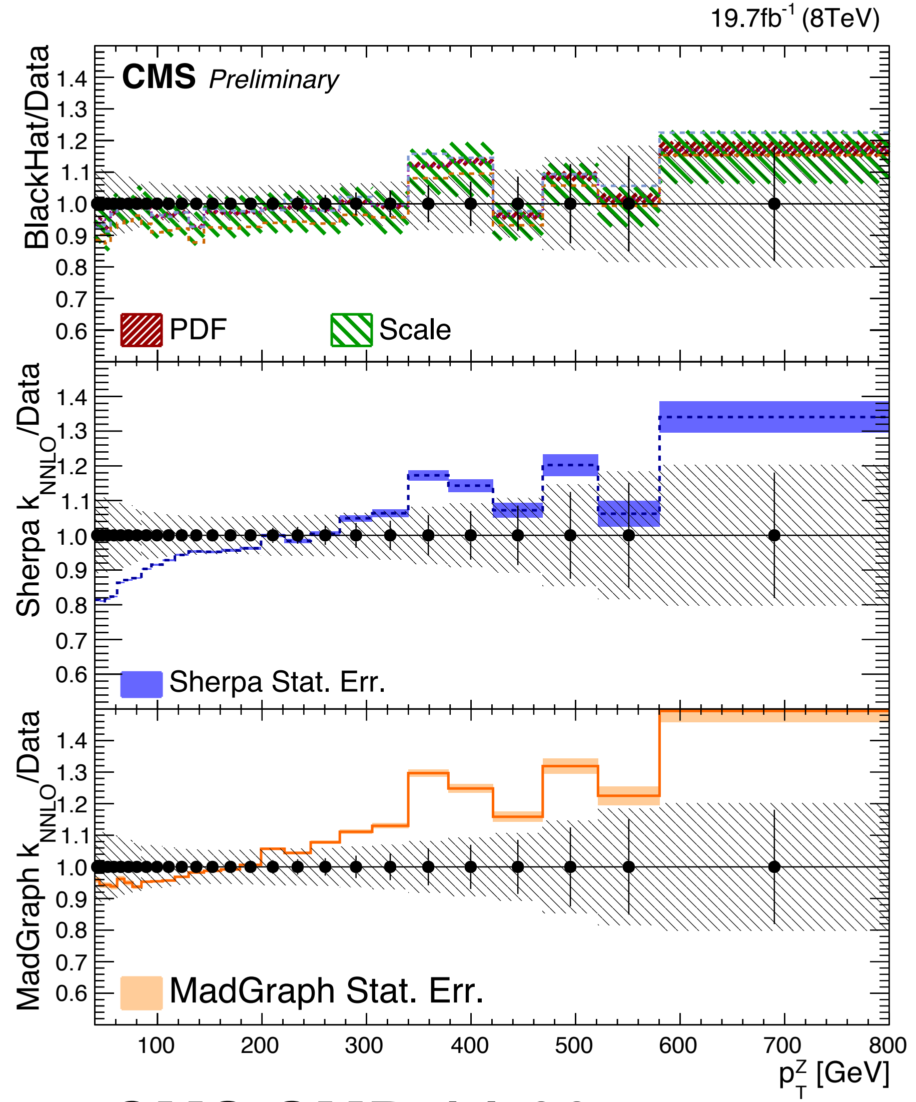
- Error band is statistics and systematics combined
- Black bar is statistics only
- MadGraph, Sherpa1.4 overestimate the high end tail by 15-30%
- Very good agreement between MadGraph and data in shape and rate at low end
- BlackHat+Sherpa is 10% lower in rate but flat in shape

CMS-SMP-14-005

p_T^Z Spectrum, $N_{Jets} \geq 2$ at 8 TeV

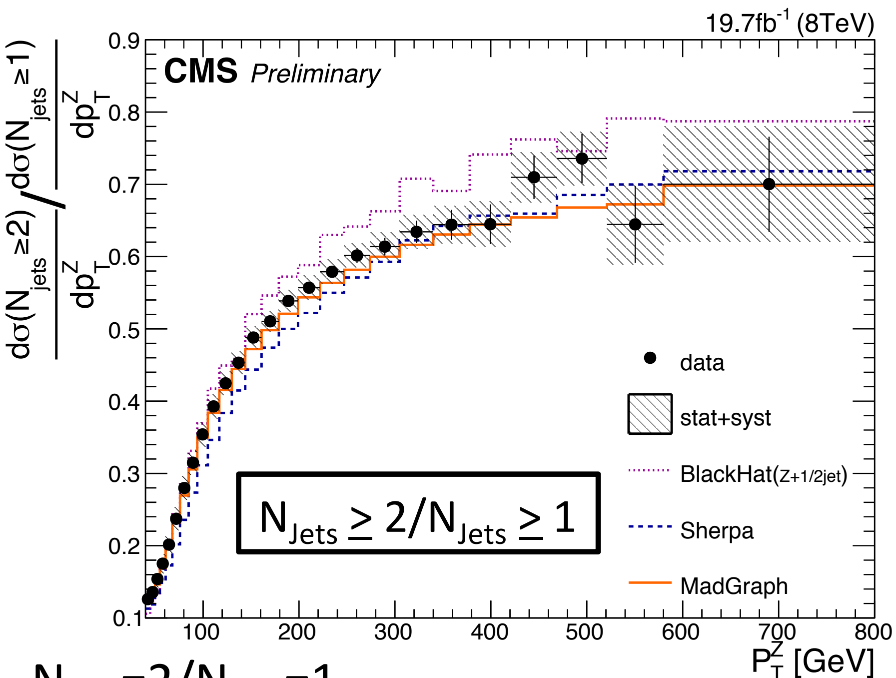


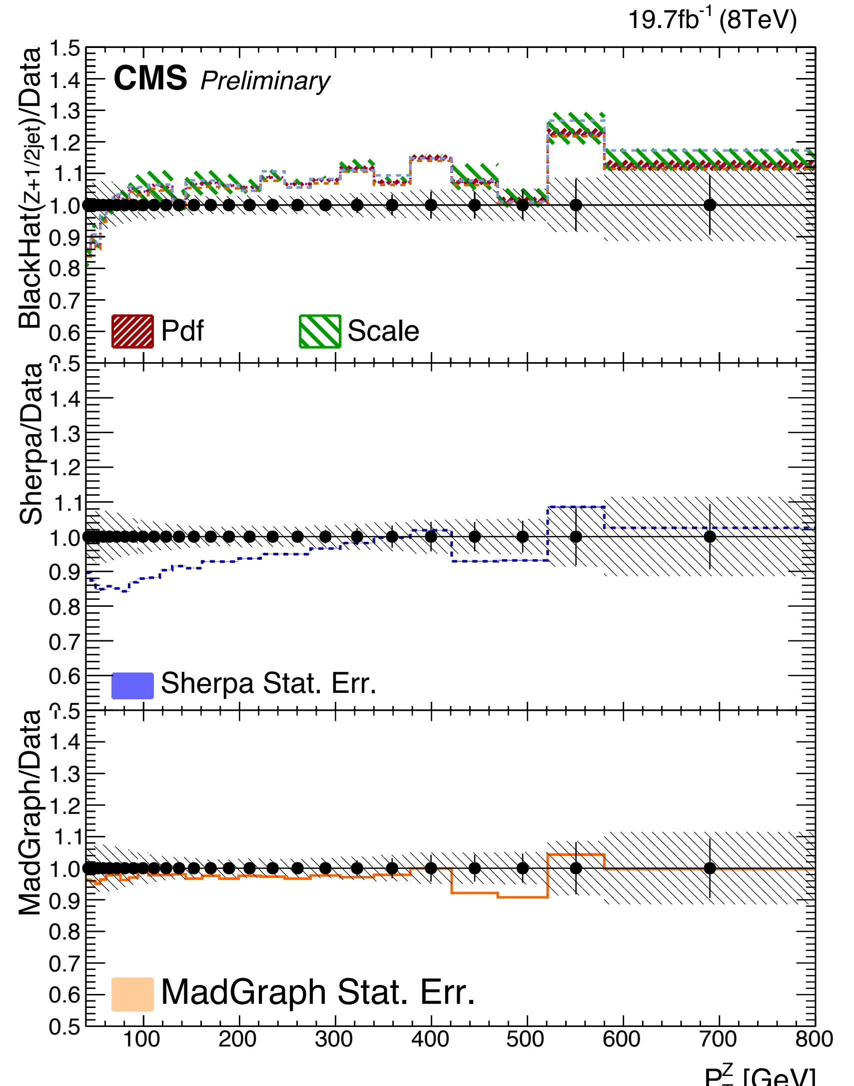
- MadGraph, Sherpa overestimate the high end tail by approx. 30%
- Sherpa1.4 underestimates the low end
- Very good agreement between MadGraph and data in shape and rate at low end
- BlackHat is flat in shape and rate
- Overall conclusions from before still hold



CMS-SMP-14-005

p_T^Z Cross Section Ratios at 8 TeV

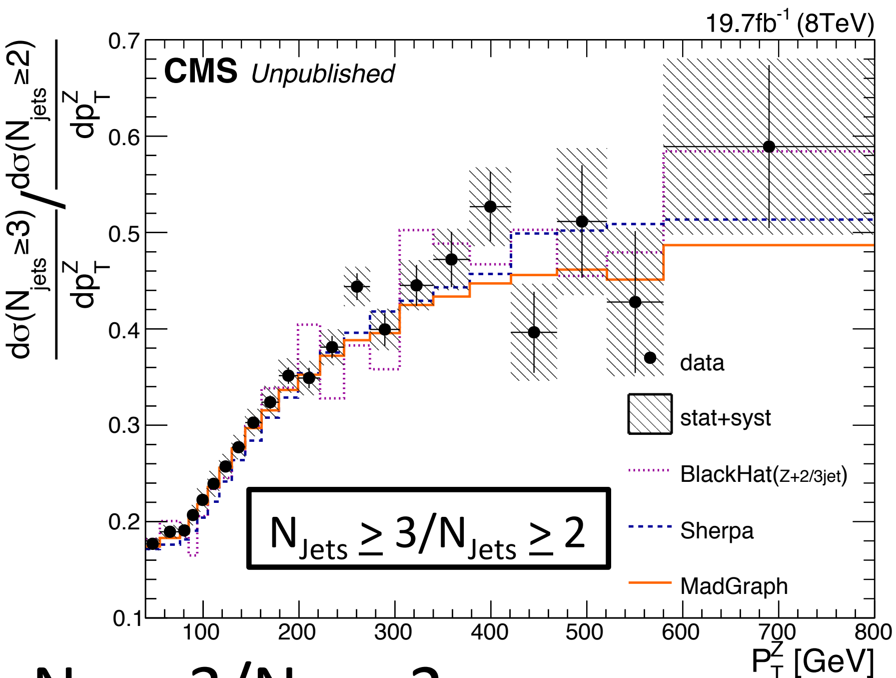




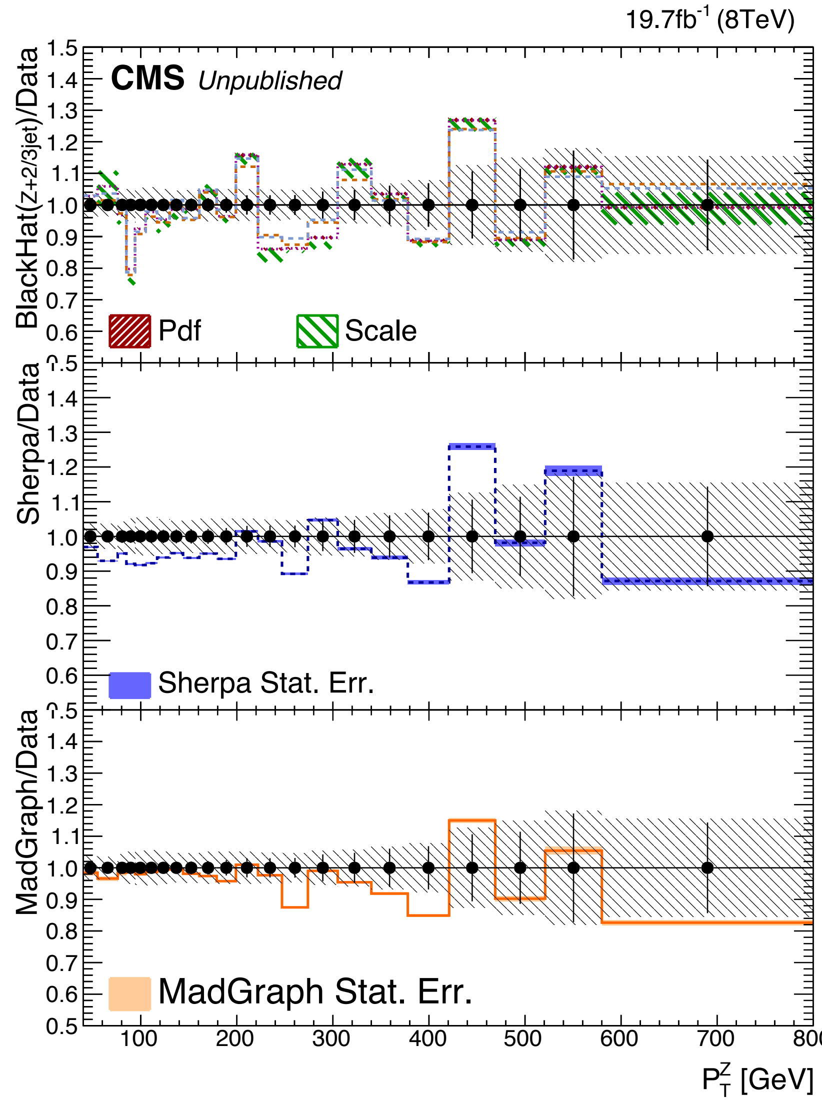
- $N_{Jets}=2/N_{Jets}=1$
  - Syst error are taken to be fully correlated (leads to cancellation, e.g. Jet and lepton scale and resolution uncertainties, etc.)
- BlackHat overestimates by approx. 10%
  - Recall: BlackHat underestimated rate in 1-jet case
- Sherpa1.4 underestimates in the low end
- MadGraph performs well through the entire range

CMS-SMP-14-005

p_T^Z Cross Section Ratios at 8 TeV

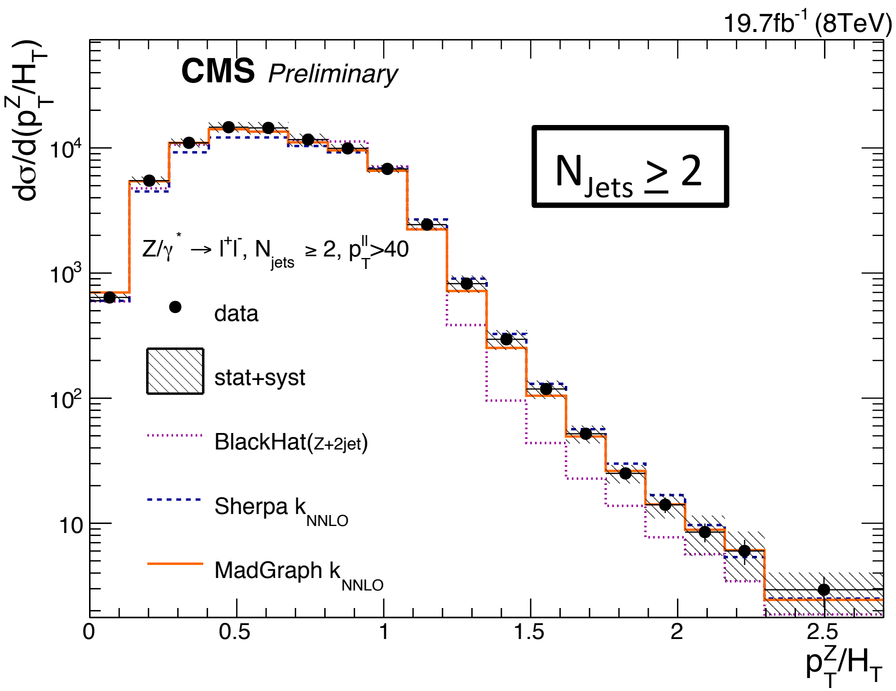


- $N_{Jets}=3/N_{Jets}=2$
- BlackHat is more accurate than before
- Sherpa1.4 underestimates in the low end as before
- MadGraph performs well

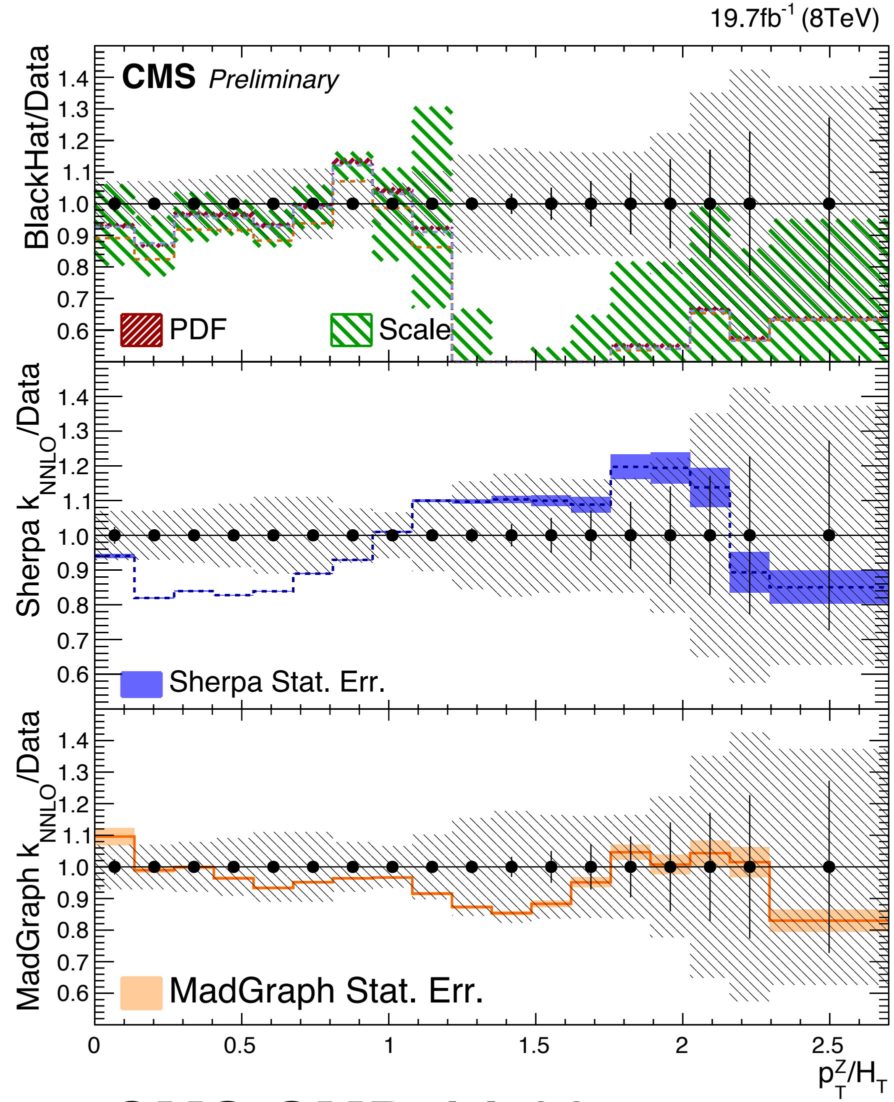


CMS-SMP-14-005

p_T^Z/H_T, $N_{Jets} \geq 2$ at 8 TeV

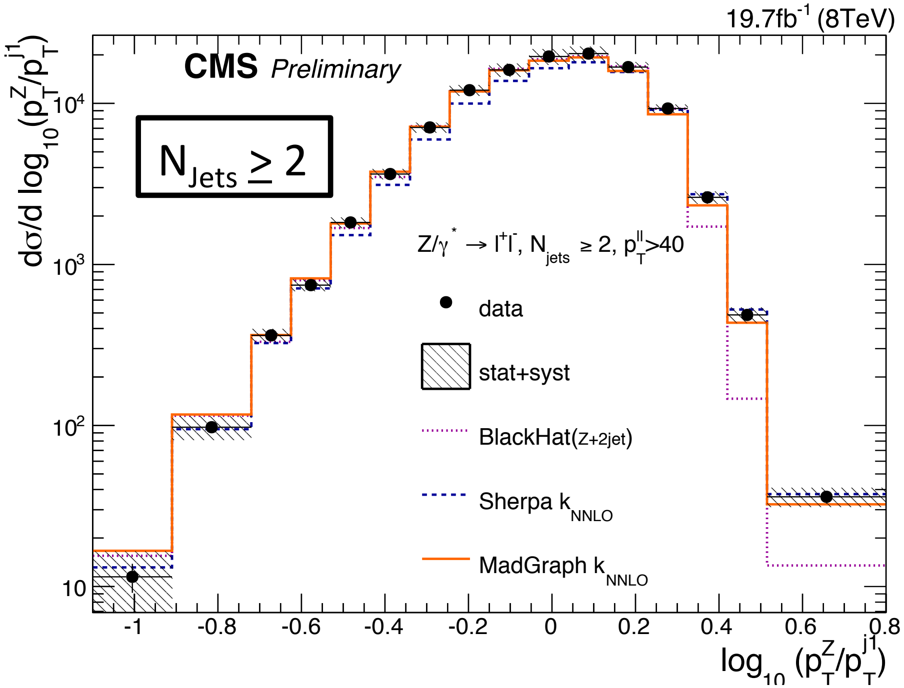


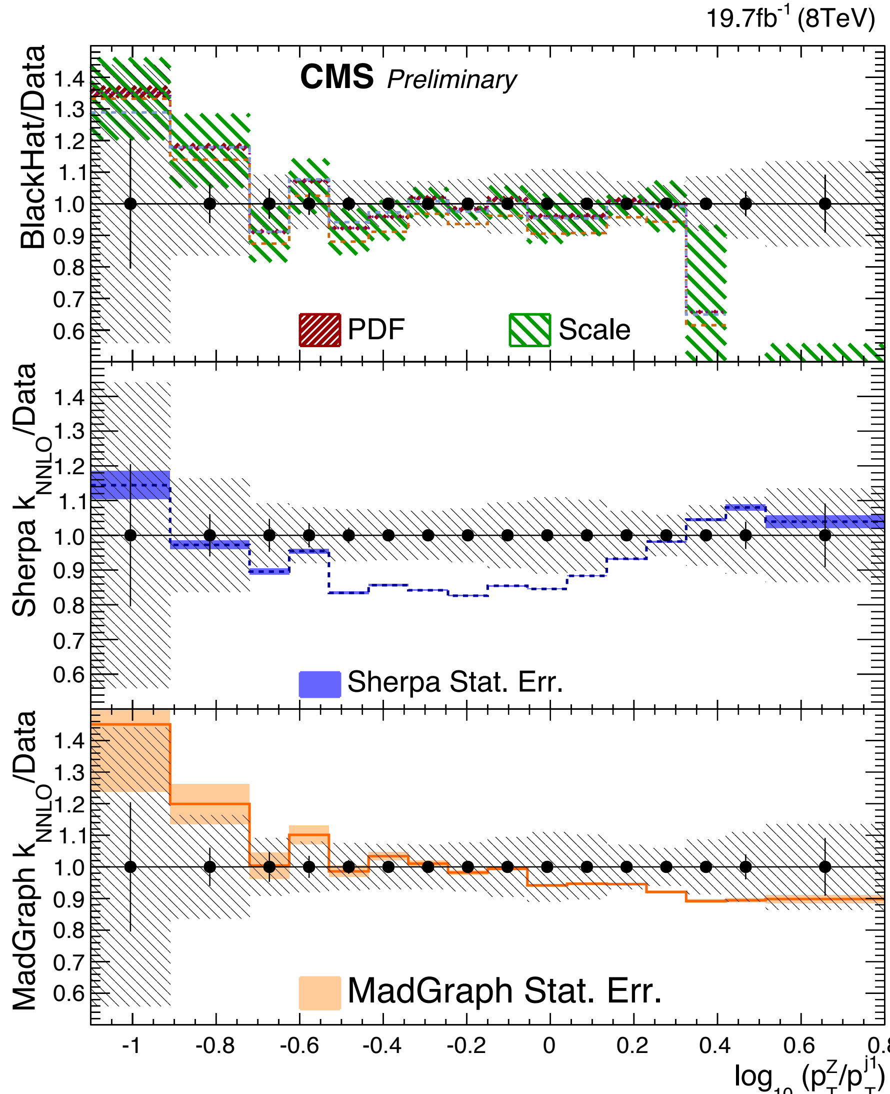
- Data well reproduced in MadGraph
- Sherpa1.4 underestimates in the low end
- BlackHat has a drop at 1.2 where BlackHat changes from NLO to LO



CMS-SMP-14-005

$\log_{10}(p_T^Z/p_T^1)$, $N_{Jets} \geq 2$ at 8 TeV





- Ratio works well in MadGraph
- Sherpa1.4 underestimates in the central area
- BlackHat has a drop at 0.3 where BlackHat changes from NLO to LO

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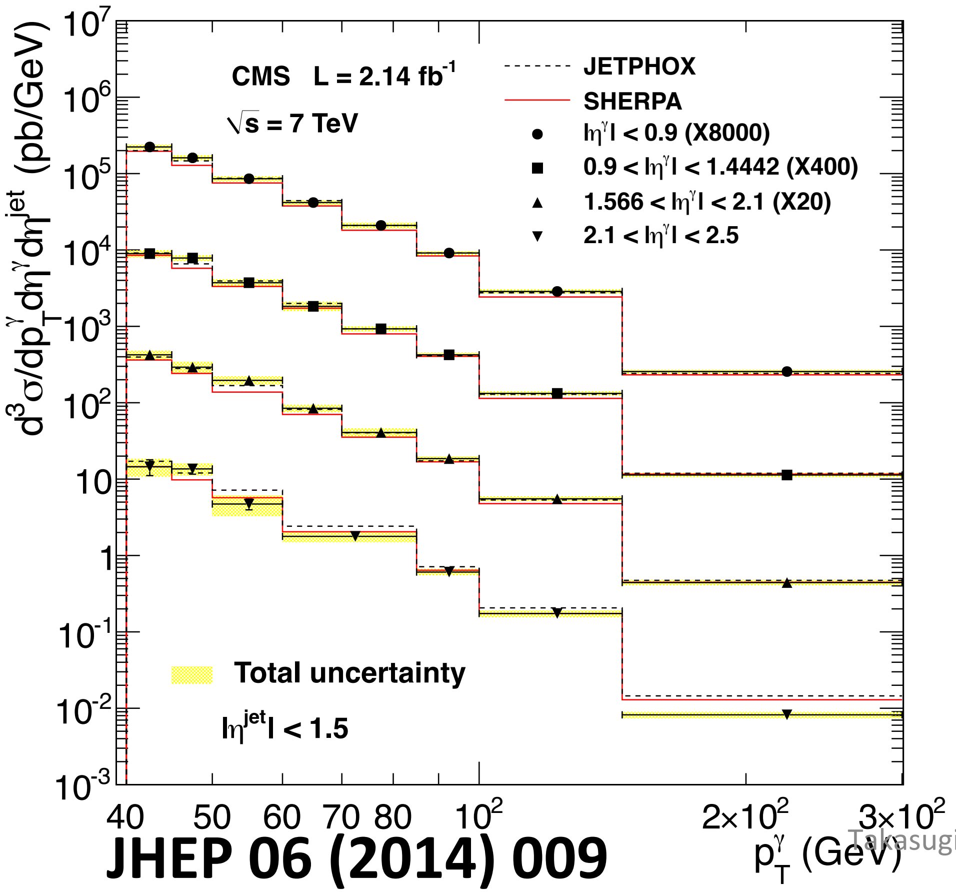
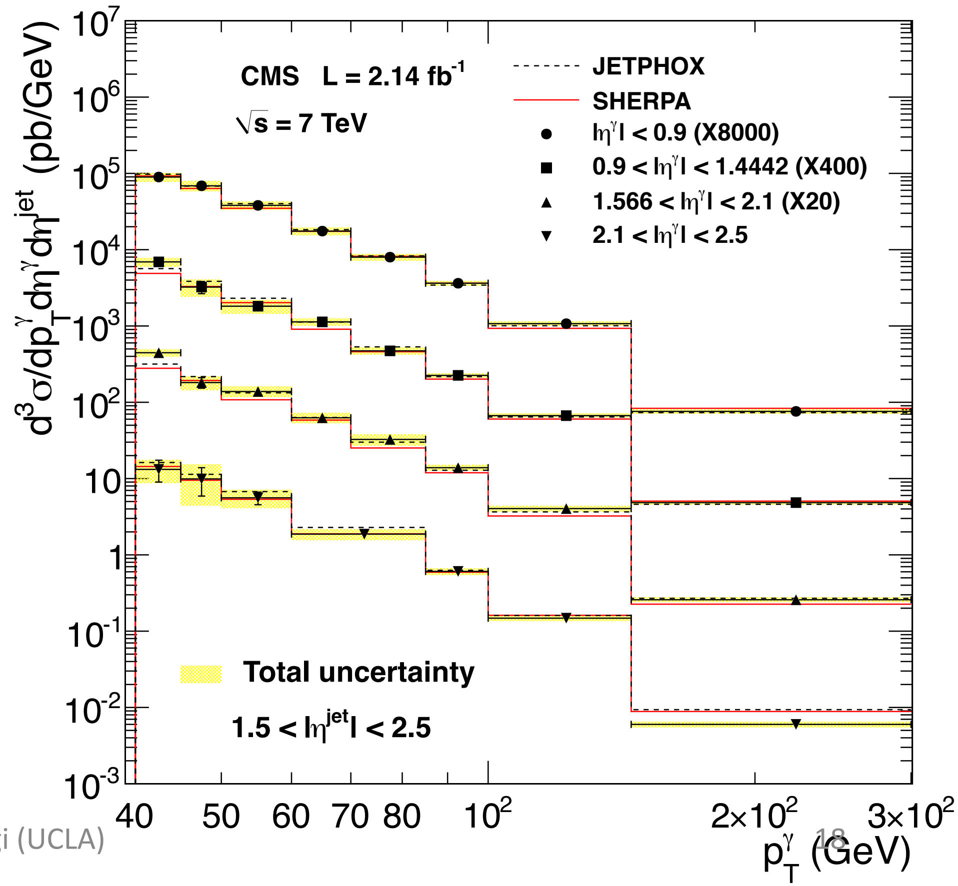
γ+jets, $\sqrt{s}$=7 TeV

- Photons $|\eta^{\gamma}| < 2.5$
- Jets are anti-k_T, ΔR=0.5, p_T>30GeV, $|\eta|$<2.5
- $\Delta R(\text{Jet},\gamma)$>0.4

p_T^γ Spectrum, 7 TeV

- The different canvases represent different jet eta selections
  - $|\eta^{jet}|<1.5$ on left, $1.5<|\eta^{jet}|<2.5$ on right
- The different distributions on each canvas represent different η^γ selections.
- Good agreement over several orders of magnitude!
  - Forward photons at high p_T are off by 10-20%





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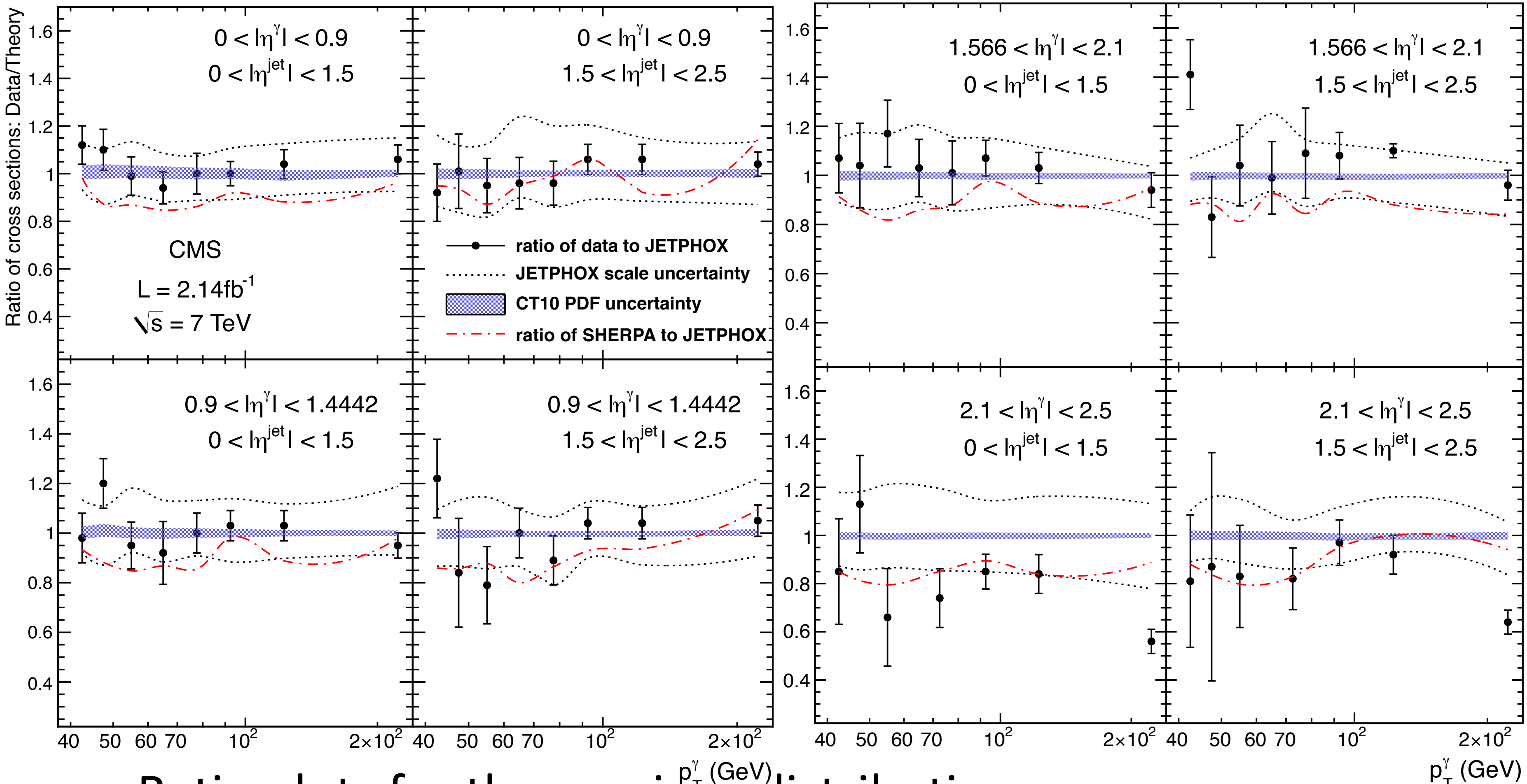
p_T^γ Spectrum, 7 TeV



- Ratio plots for the previous distributions
- We again see good agreement over orders of magnitude
  - Forward photons at high p_T are off by 10-20%

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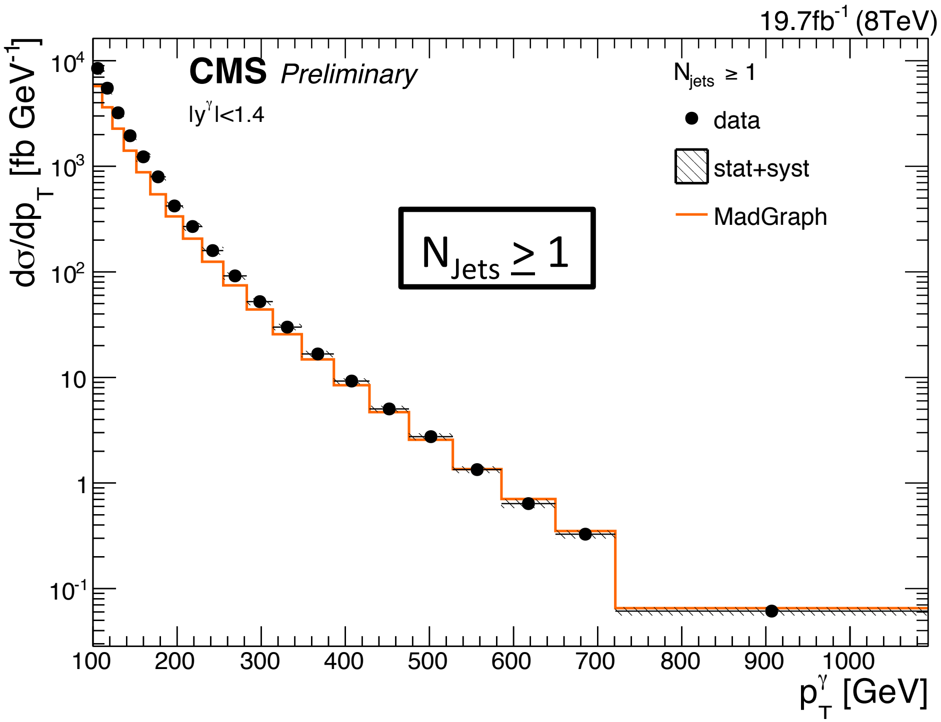
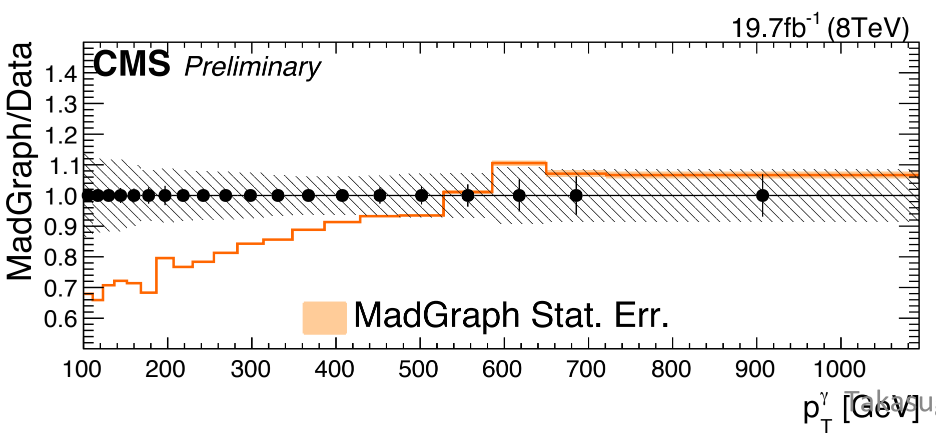
γ+jets, 8 TeV

- Photons $|\eta^{\gamma}| < 1.4$
- Jets are anti-k_T, $\Delta R=0.5$, $p_T>30$GeV, $|\eta|<2.4$
- $\Delta R(\mathrm{Jet},\gamma)>0.4$

p_T^γ Spectrum, $N_{Jets}\geq 1$ at 8 TeV





- No k-factor applied
- Qualitatively flat up to 200 GeV
  - Lower by approx. 20%
- Upward trend in ratio analogous to Z
- Largest uncertainty is template systematics (10%)

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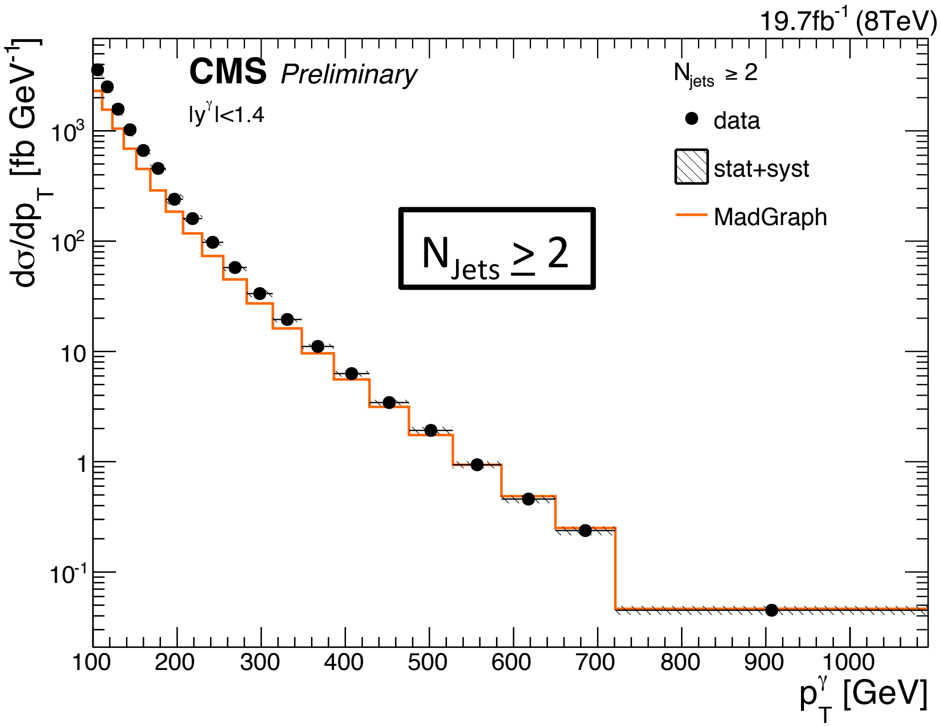
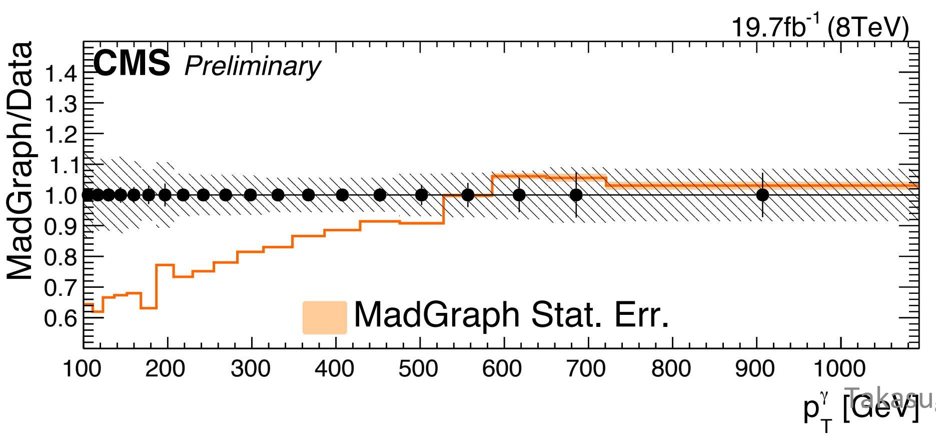
p_T^γ Spectrum, $N_{Jets} \geq 2$ at 8 TeV





- Similar trends as before
- MadGraph underestimates in the low end
- Similar trend to the Z case as well

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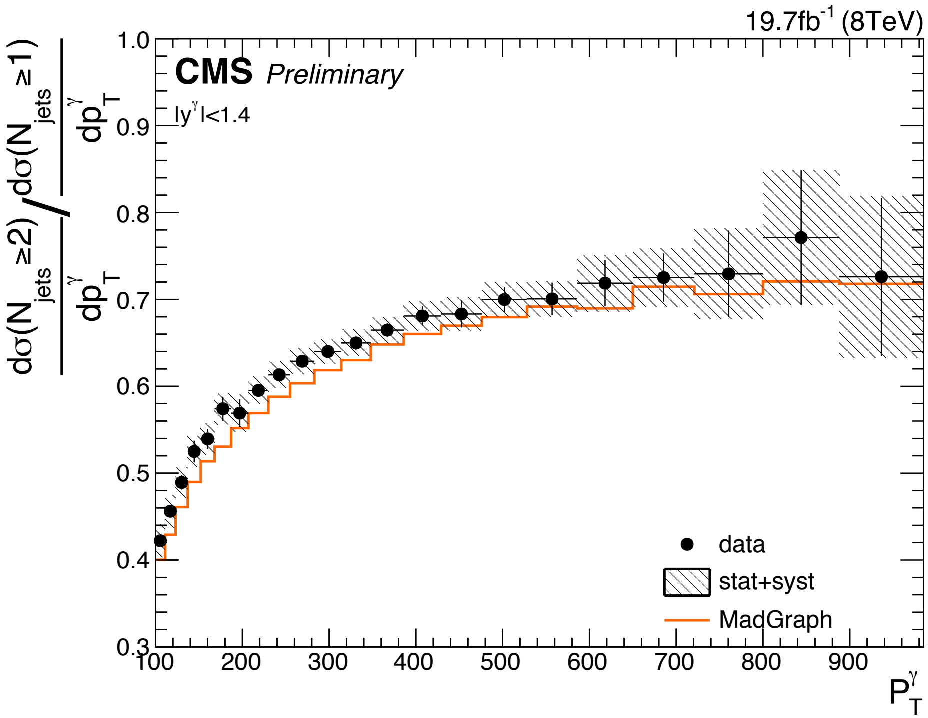
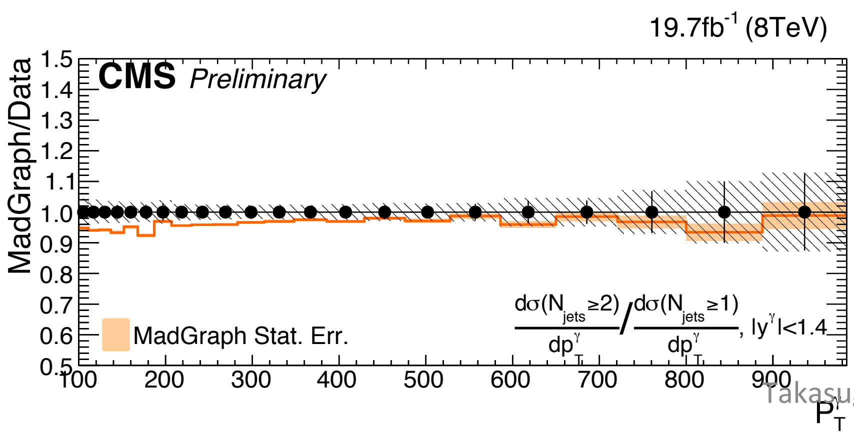
p_T^γ Spectrum Cross Section Ratios at 8 TeV

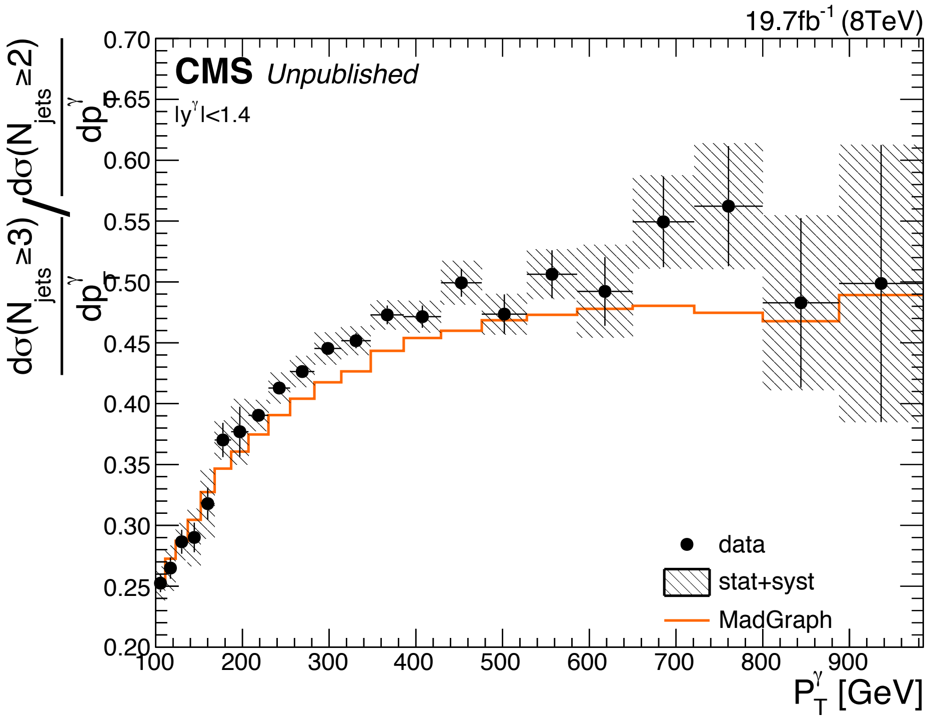


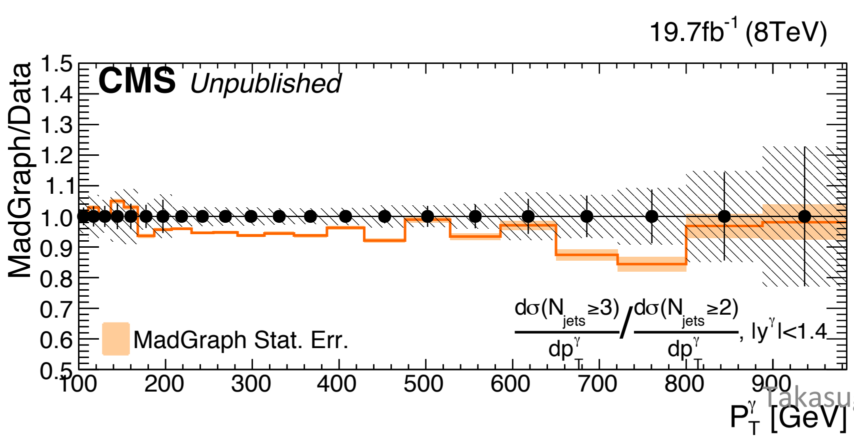


- $N_{Jets}=2/N_{Jets}=1$
  - Syst error are taken to be fully correlated (leads to cancellation, e.g. jet and photon scale and resolution uncertainties, etc.)
- MadGraph performs well through the entire range

CMS-SMP-14-005

p_T^γ Spectrum Cross Section Ratios at 8 TeV





- $N_{Jets}=3/N_{Jets}=2$
- MadGraph performs well through the entire range

CMS-SMP-14-005

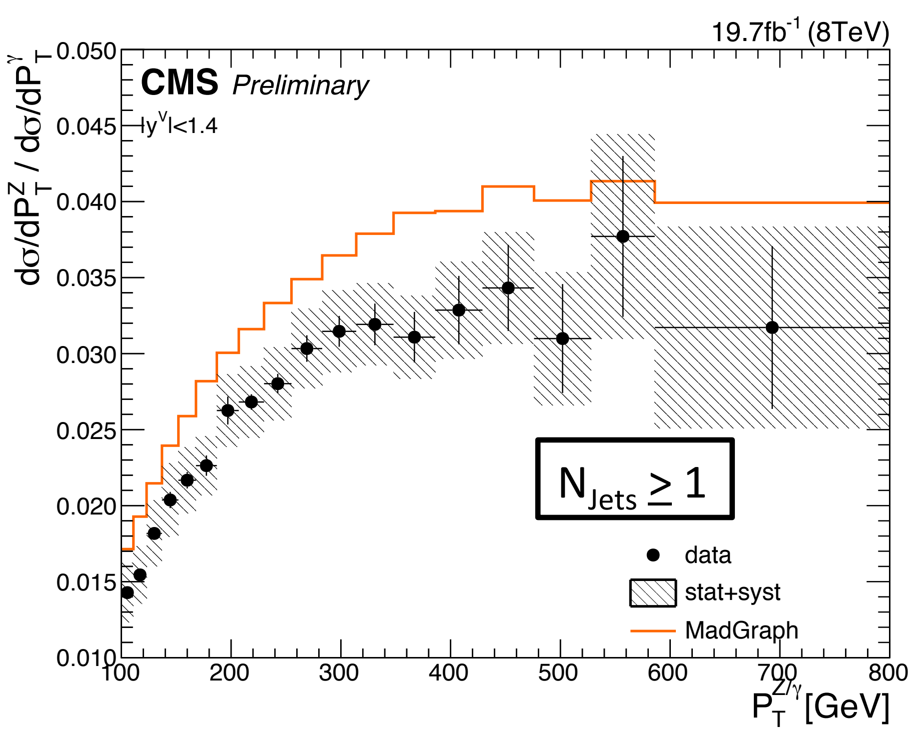
Z/γ RATIO

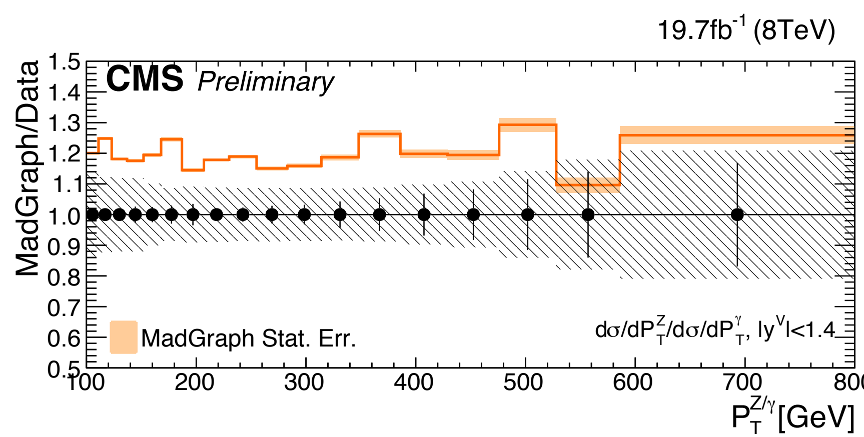
Systematics Correlation

- Systematics from the same source are treated as fully correlated as in previous cross section ratios
  - JES, JER and luminosity uncertainty are treated as fully correlated
- Systematics are added quadratically
- Statistics are propagated assuming gaussian-independent error propagation with the diagonal element of the covariance matrix
- We removed the NNLO k-factor on the Z distribution
  - we compare the LO cross section ratio for MC

Z/γ ratio: $N_{Jets} \geq 1$ at 8 TeV

- R is the ratio between the cross section of Z over gamma
- Measured for average dilepton, R_{lep}=0.0322±0.0007(stat)±0.0023(stat+sys)
- Rate overestimated by MadGraph by 20%, $R_{lep,MC}$ = 0.0370
- R_{lep}/(B.R. $Z \rightarrow l^+l^-$) =0.957±0.068
- Agreement in shape





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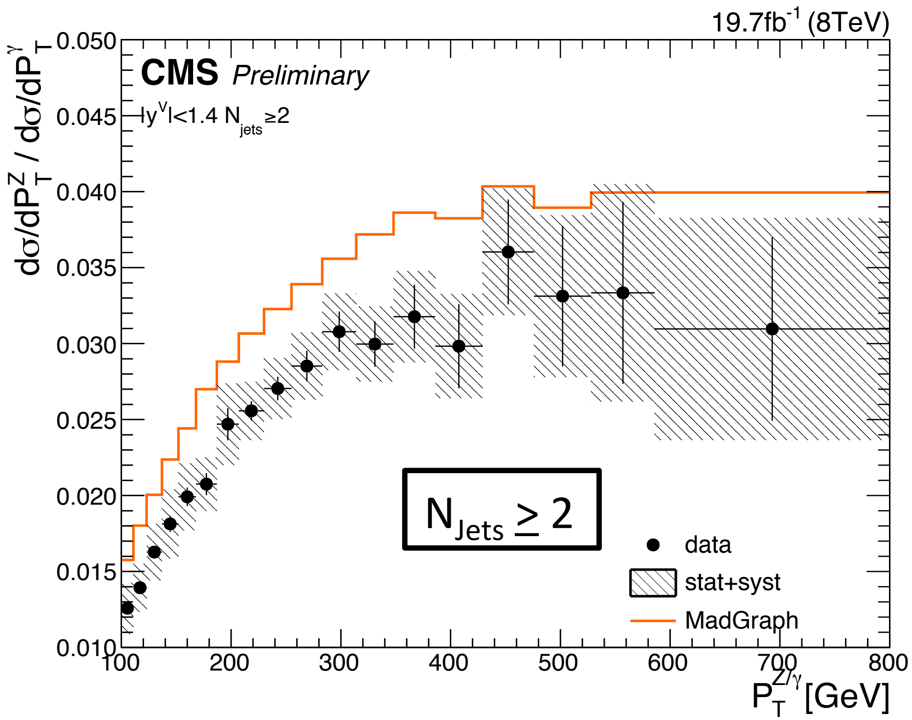
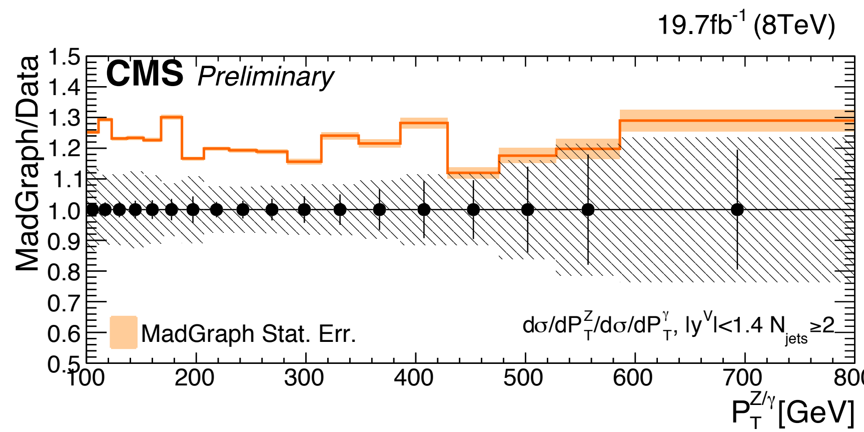
Z/γ ratio: $N_{Jets} \geq 2$ at 8 TeV

- Similar to $N_{Jets} \geq 1$





CMS-SMP-14-005

Conclusions

- Measured
  - Z and γ p_T spectra
  - Jet p_T spectra in W, Z and γ
  - Ratios in Z and γ p_T spectra
  - Jet multiplicities
- Observe similar trends in Z and γ p_T spectra
- Differential jet multiplicity ratios agree between data and MadGraph
- Plateau is observed in both Madgraph and data in ratio between Z and γ
  - Slight disagreement in scale but agreement in shape
- Dominated by statistical errors in tails
- Dominated by systematics at low p_T

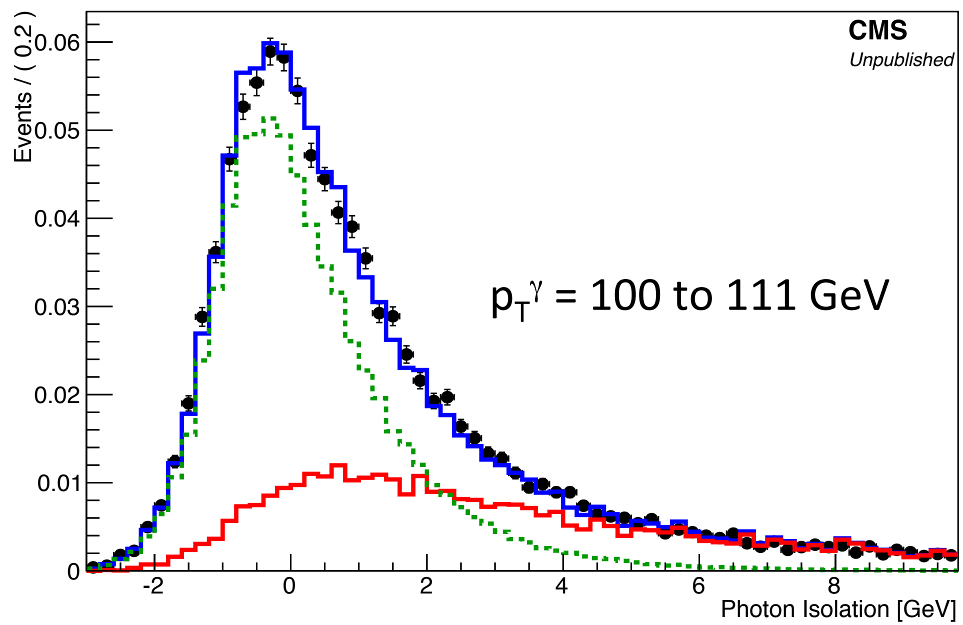
References

- W [7TeV]
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12023
  - http://cds.cern.ch/record/1712497
  - http://arxiv.org/abs/1406.7533
- Z [8TeV]
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP13007
  - http://cds.cern.ch/record/1728322
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP14005
  - http://cds.cern.ch/record/1740969?ln=en
- Z [7TeV]
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12017
  - http://cds.cern.ch/record/1667906?ln=en
- Photon [7TeV]
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsQCD11005
  - http://arxiv.org/abs/1311.6141
  - JHEP 06 (2014) 009
- Photon [8 TeV]
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP14005
  - http://cds.cern.ch/record/1740969?ln=en

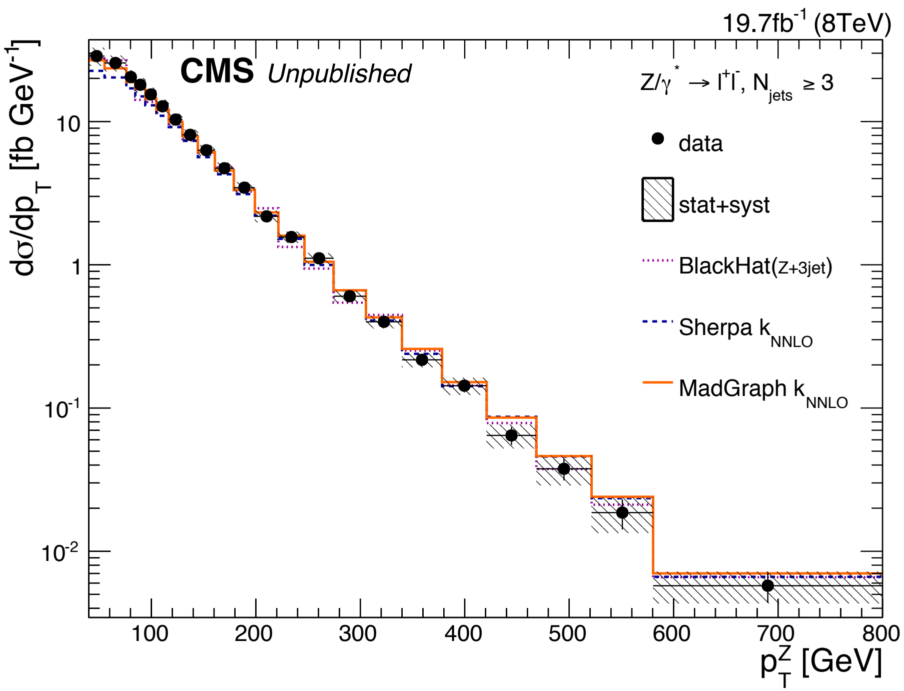
BACKUP

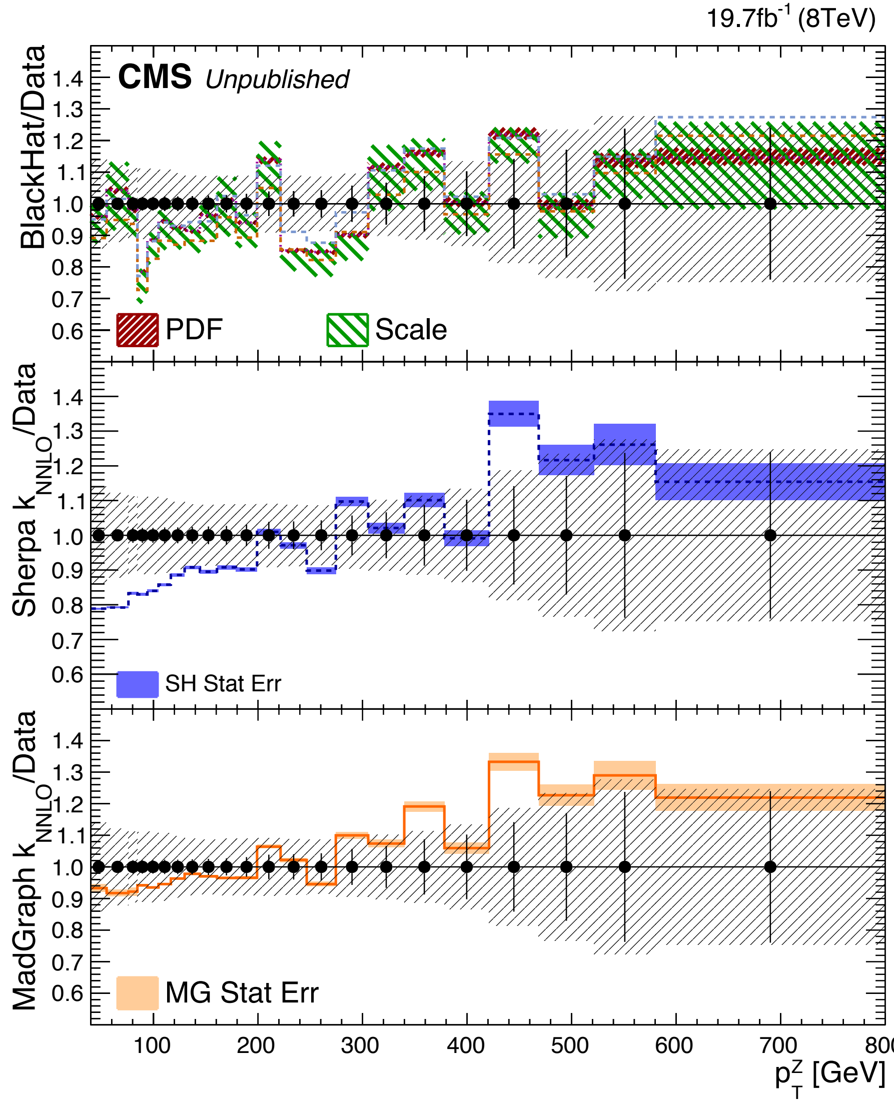
Templates and Purity

- Fit Variable: photon isolation with foot print removal
  - Rho corrections computed to minimize pileup dependencies
- Fit templates:
  - $\sigma_{i\eta i\eta} < 0.011$
- Background template:
  - $\sigma_{i\eta i\eta} \geq 0.011$
- Signal template is taken from RandomCone (RC) as in 7TeV PAS-SMP-13-001
- A purity fit is performed in each analysis bin
  - Signal and Background templates are taken with coarser bins
- Agreement in different order of magnitude



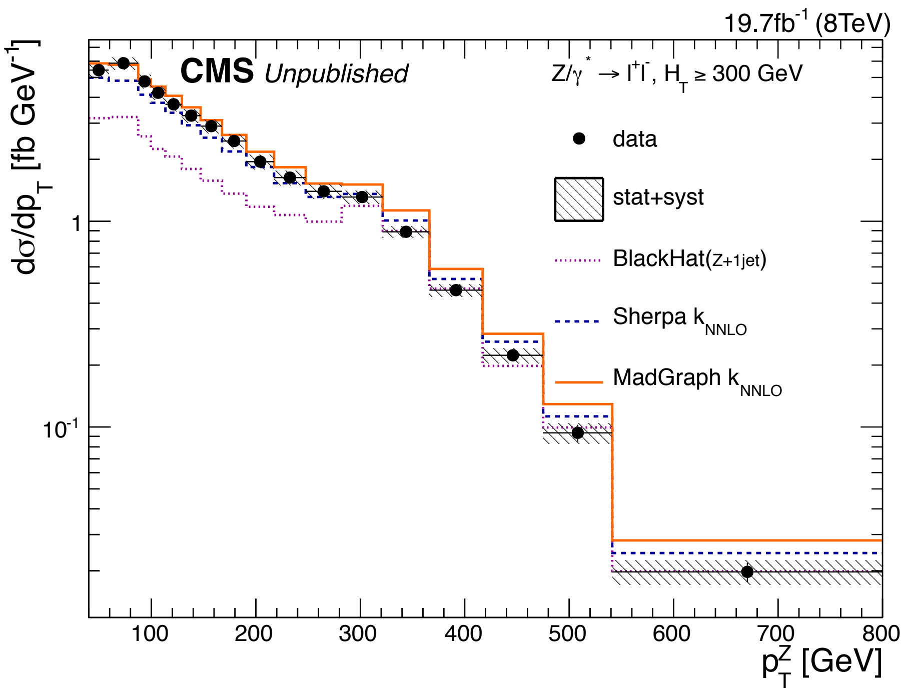
p_T^Z Spectrum, $N_{Jets} \geq 3$ at 8 TeV

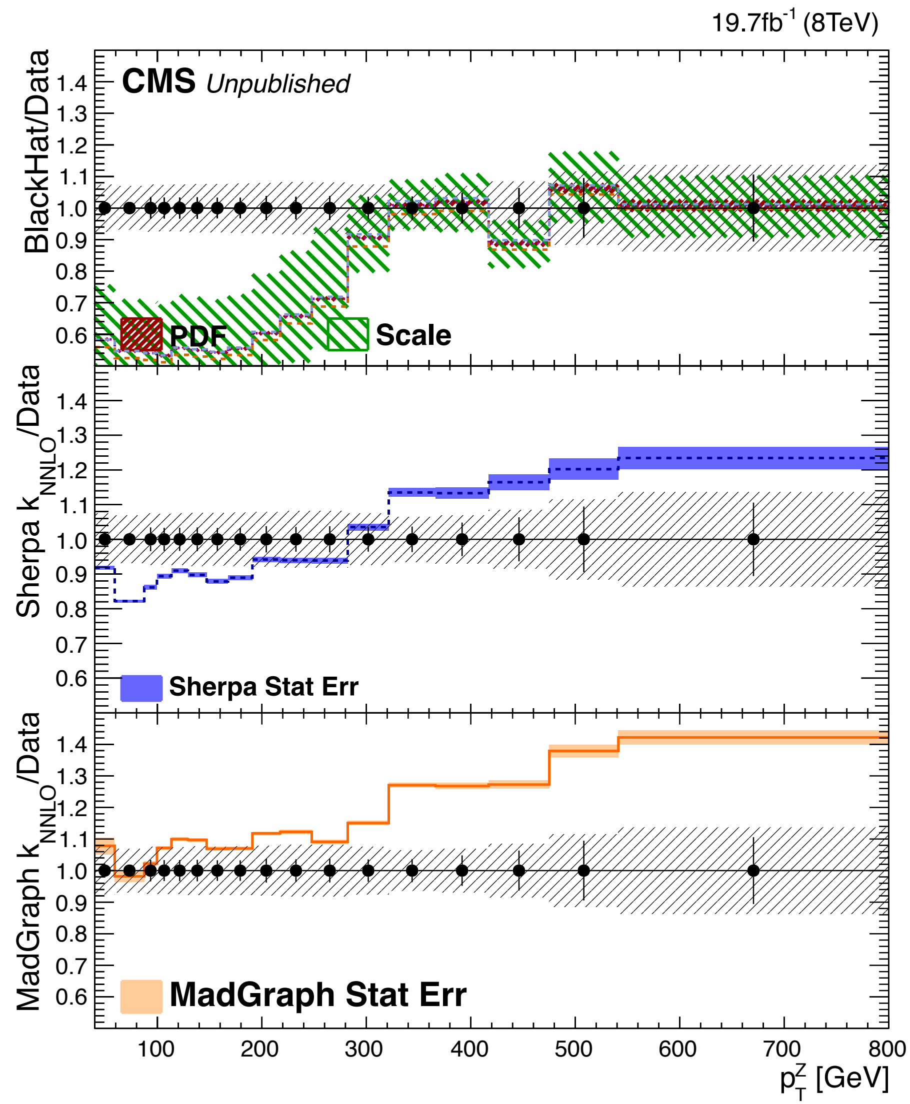




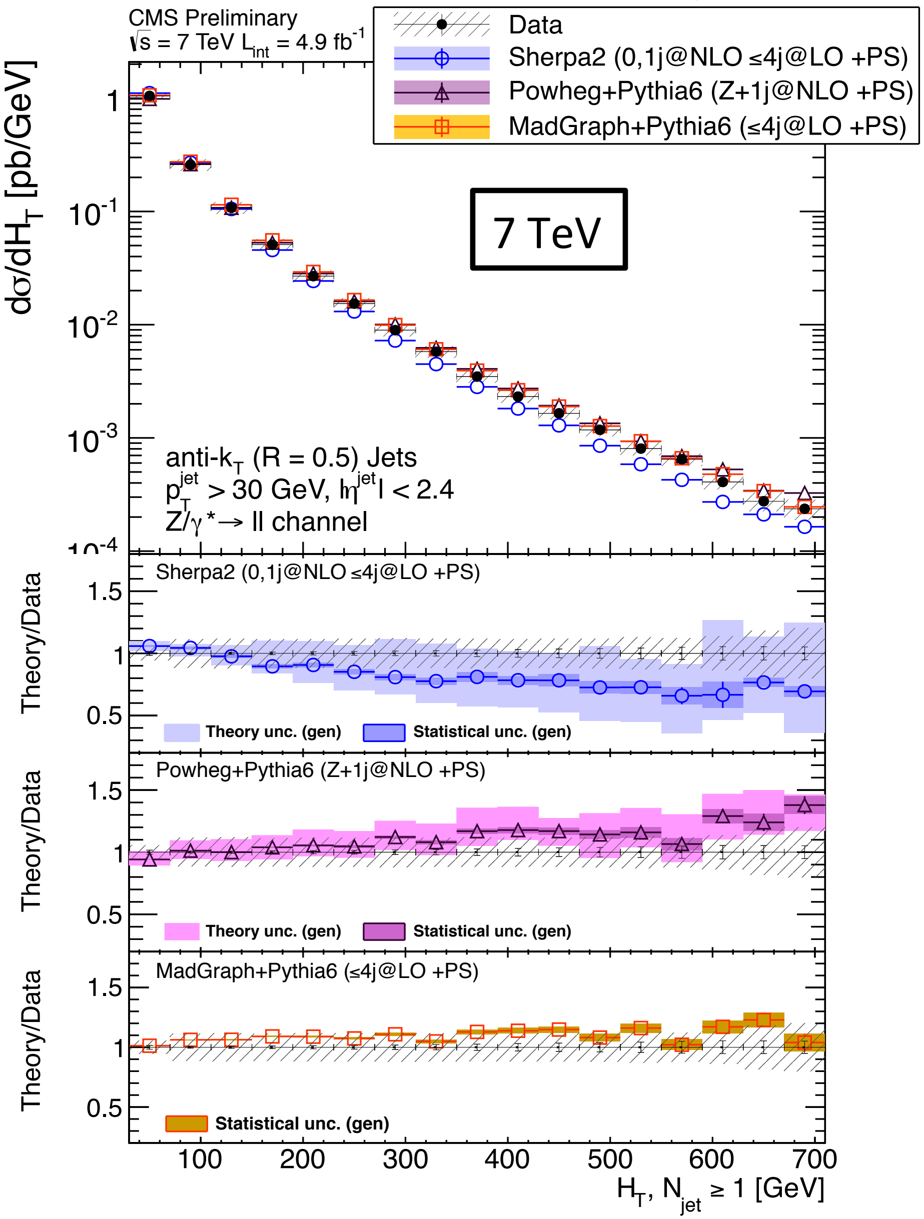
- MadGraph, Sherpa overestimate the high end tail by 10%
- Very good agreement between MadGraph and data in shape and rate at low end
- BlackHat accurate in rate and shape but suffers from statistics

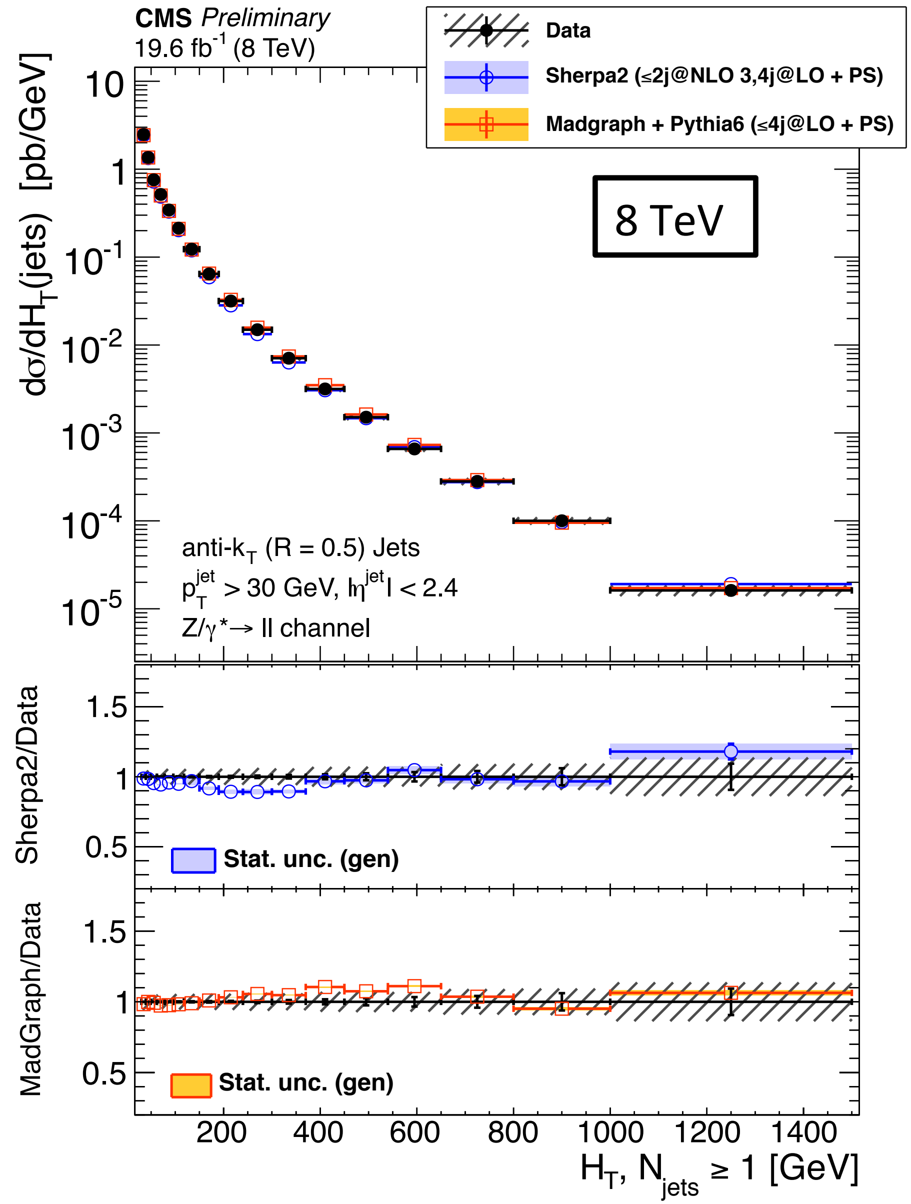
p_T^Z Spectrum, $H_T \geq 300$ at 8 TeV



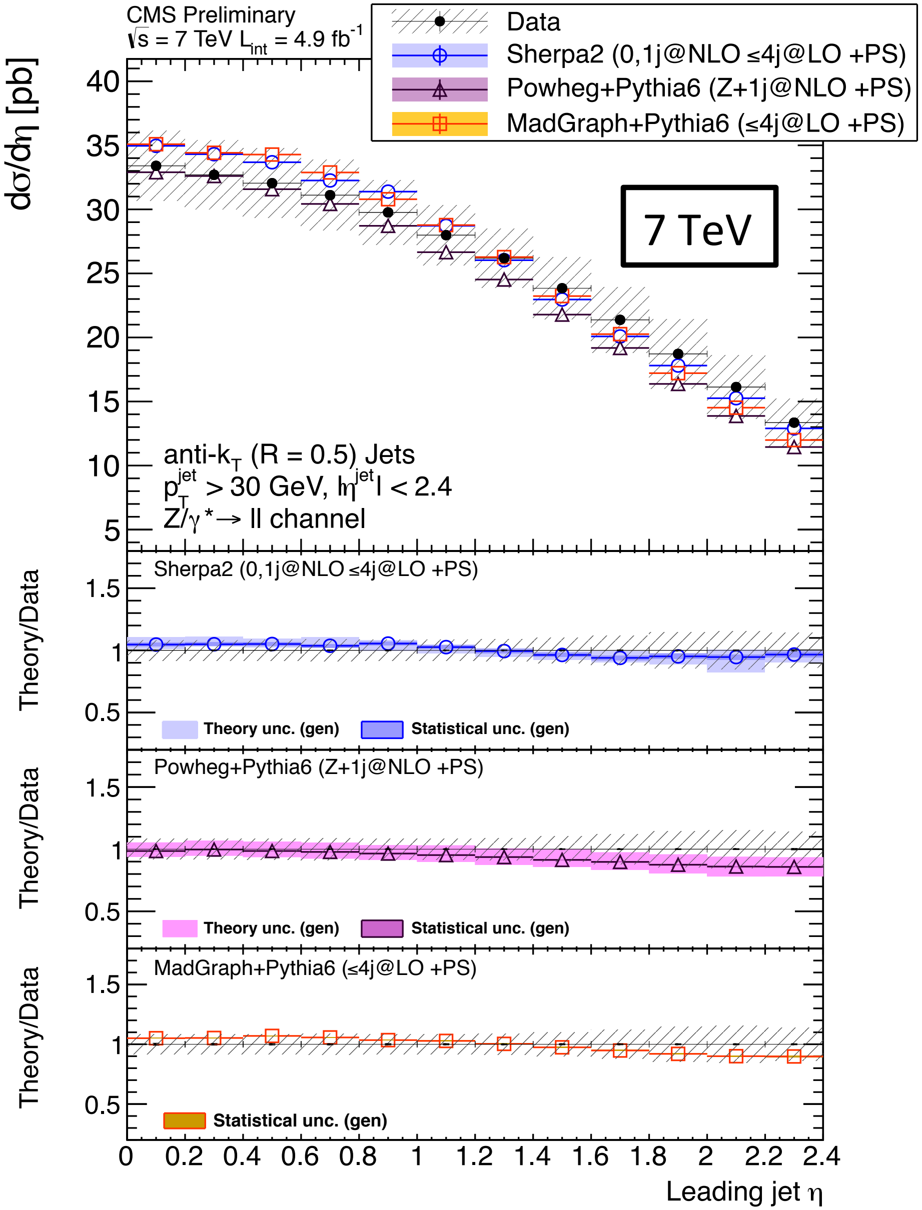


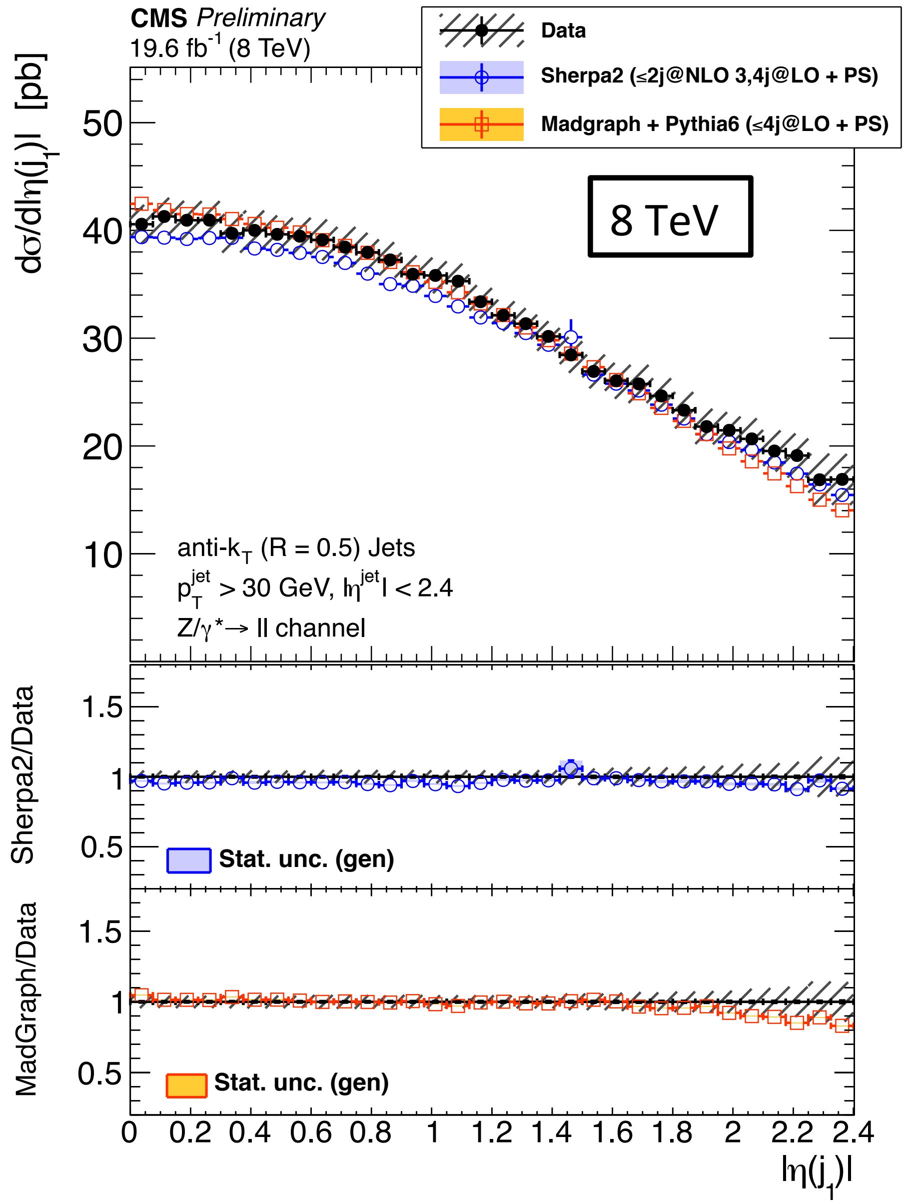
H_T for Z + Jets


CMS Preliminary
√s = 7 TeV L_int = 4.9 fb^-1
Data
Sherpa2 (0,1j@NLO ≤4j@LO +PS)
Powheg+Pythia6 (Z+1j@NLO +PS)
MadGraph+Pythia6 (≤4j@LO +PS)
7 TeV
dσ/dH_T [pb/GeV]
anti-k_T (R = 0.5) Jets
p_T^jet > 30 GeV, |η^jet| < 2.4
Z/γ*→ ll channel
Theory/Data
Theory unc. (gen)
Statistical unc. (gen)
H_T, N_jet ≥ 1 [GeV]

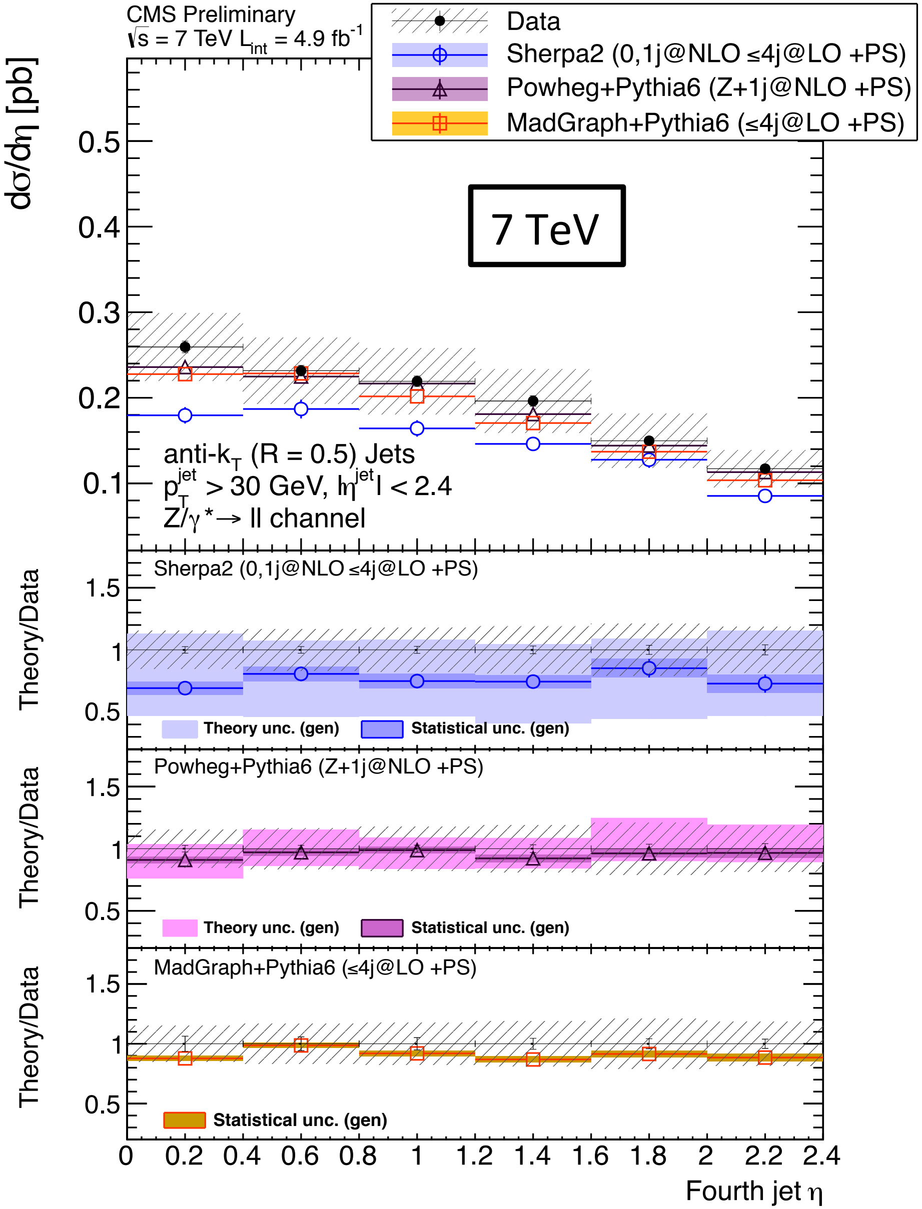

CMS Preliminary
19.6 fb^-1 (8 TeV)
Data
Sherpa2 (≤2j@NLO 3,4j@LO + PS)
Madgraph + Pythia6 (≤4j@LO + PS)
8 TeV
dσ/dH_T(jets) [pb/GeV]
anti-k_T (R = 0.5) Jets
p_T^jet > 30 GeV, |η^jet| < 2.4
Z/γ*→ ll channel
Sherpa2/Data
Stat. unc. (gen)
MadGraph/Data
H_T, N_jets ≥ 1 [GeV]

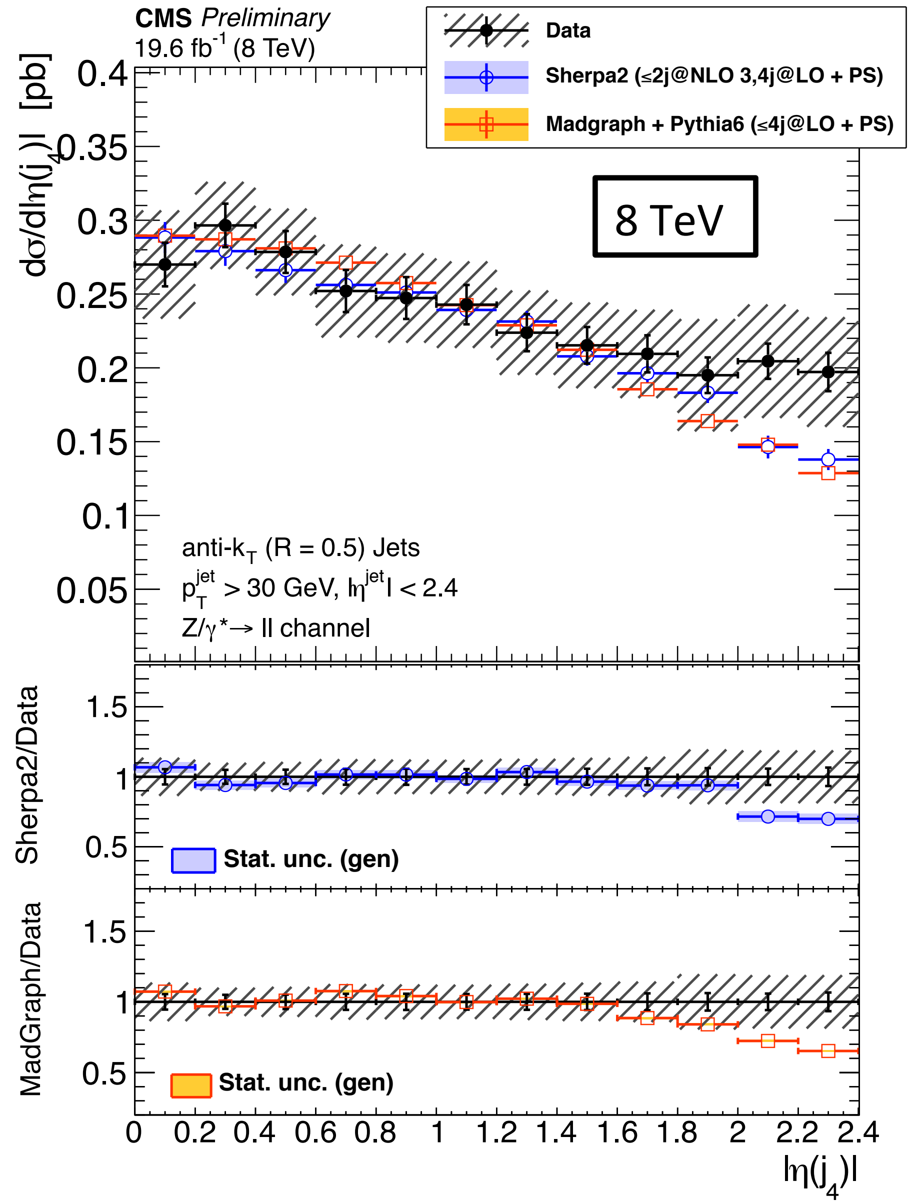
Leading Jet |η| for Z + Jets



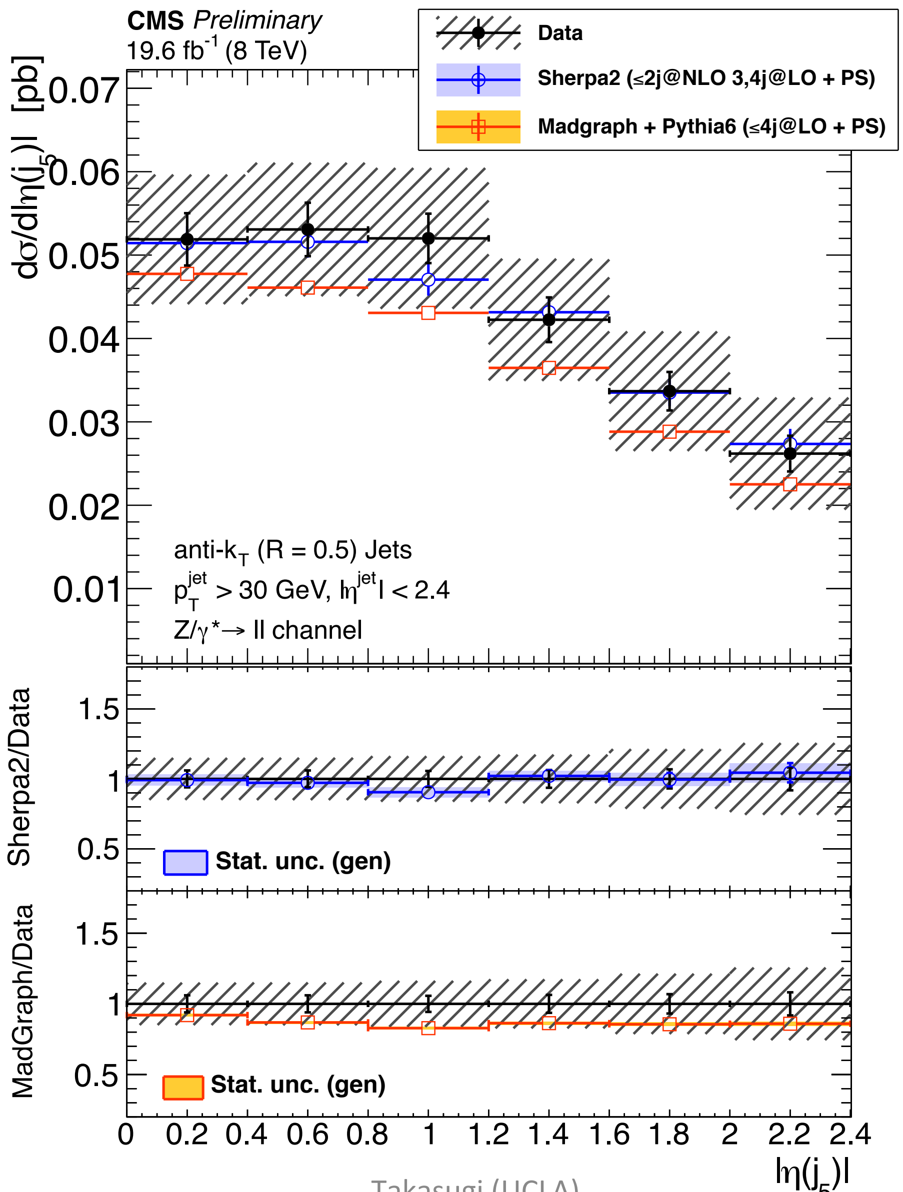


4^{th} Jet $|\eta|$ for Z + Jets

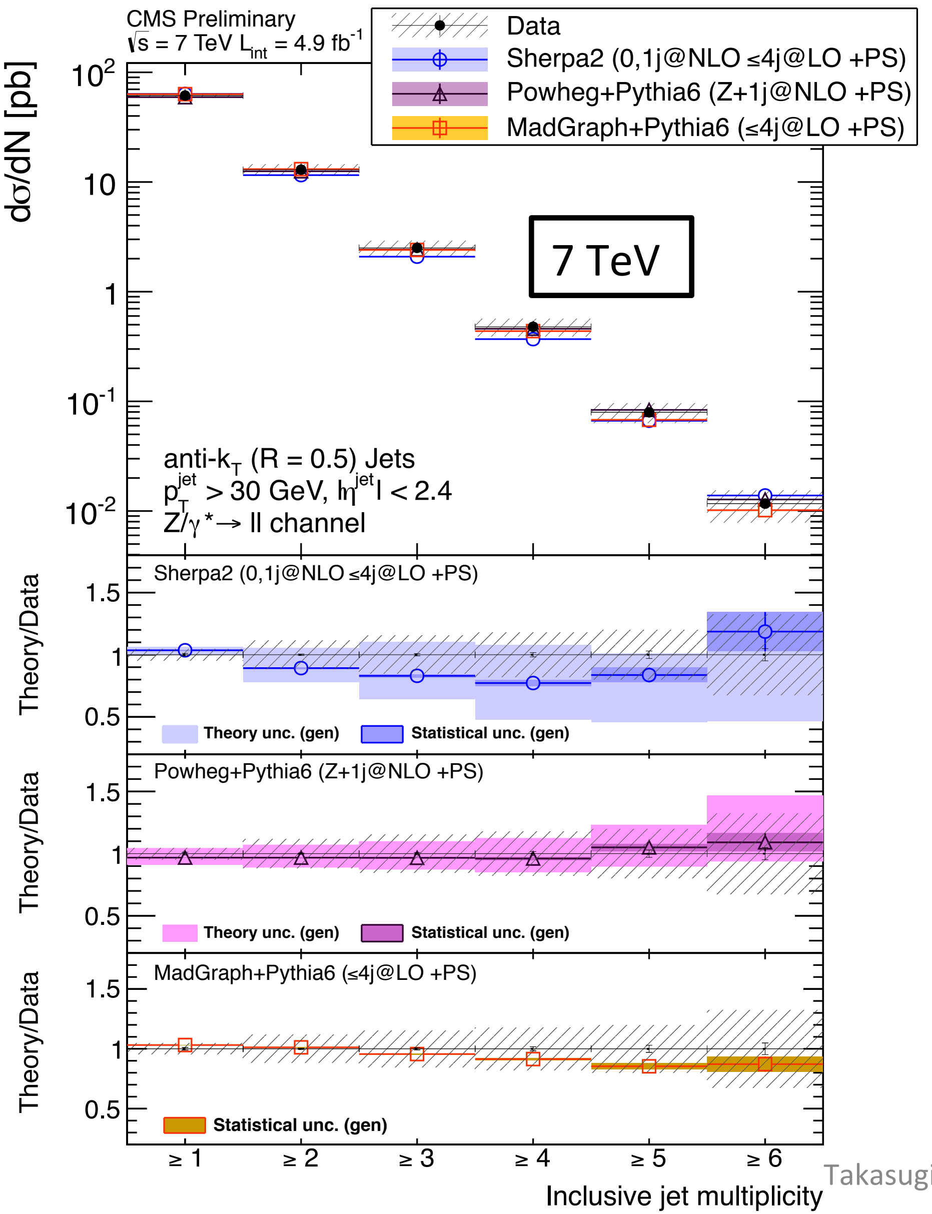


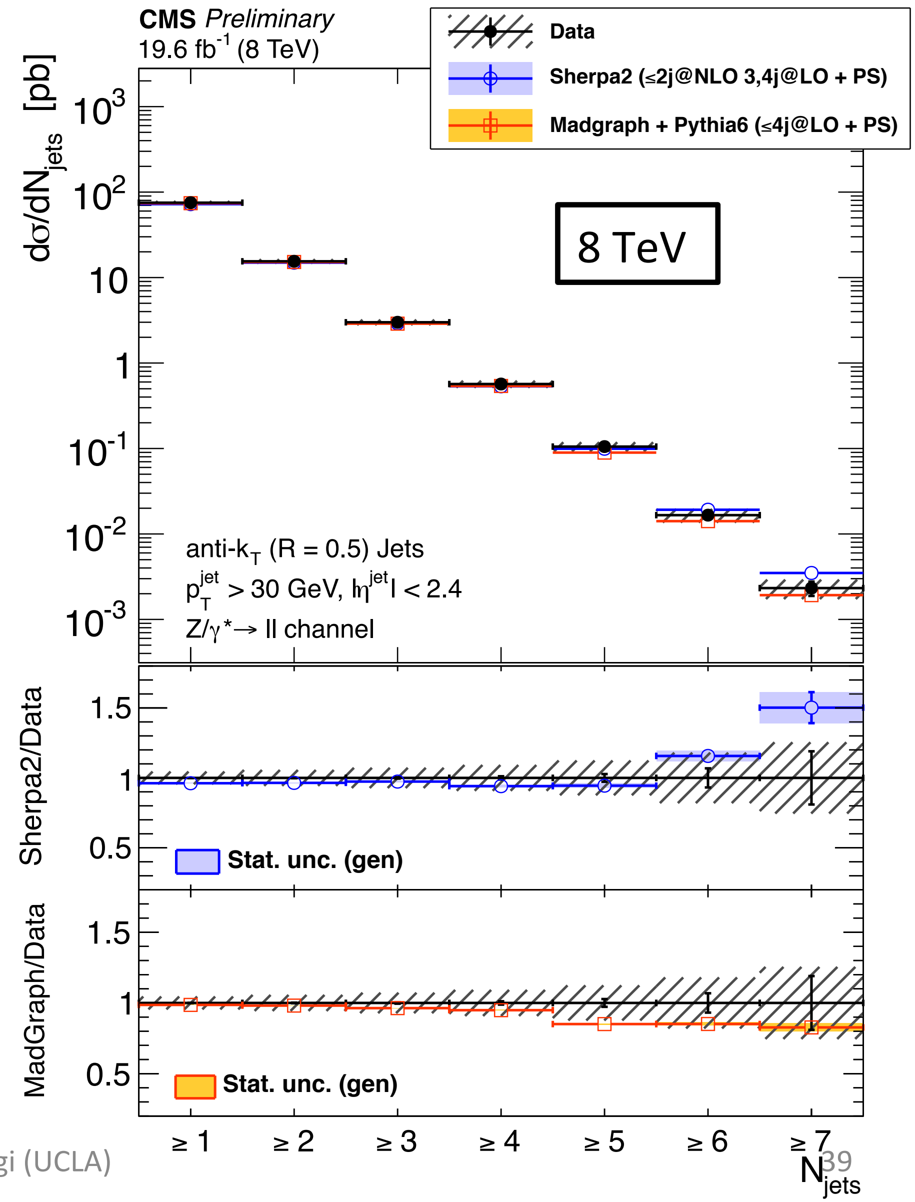


5th Jet |η| for Z + Jets at 8 TeV

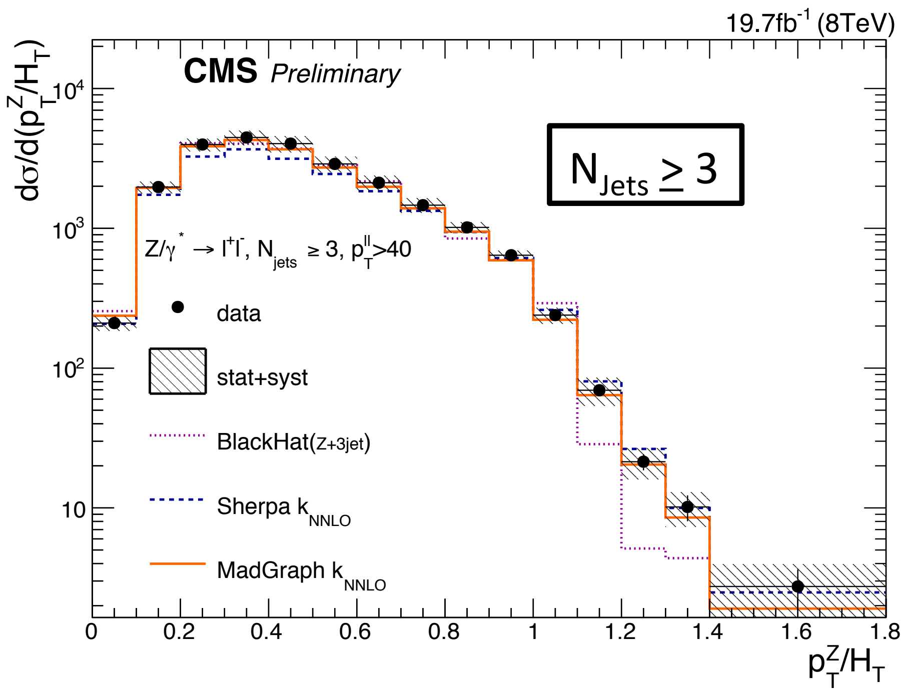


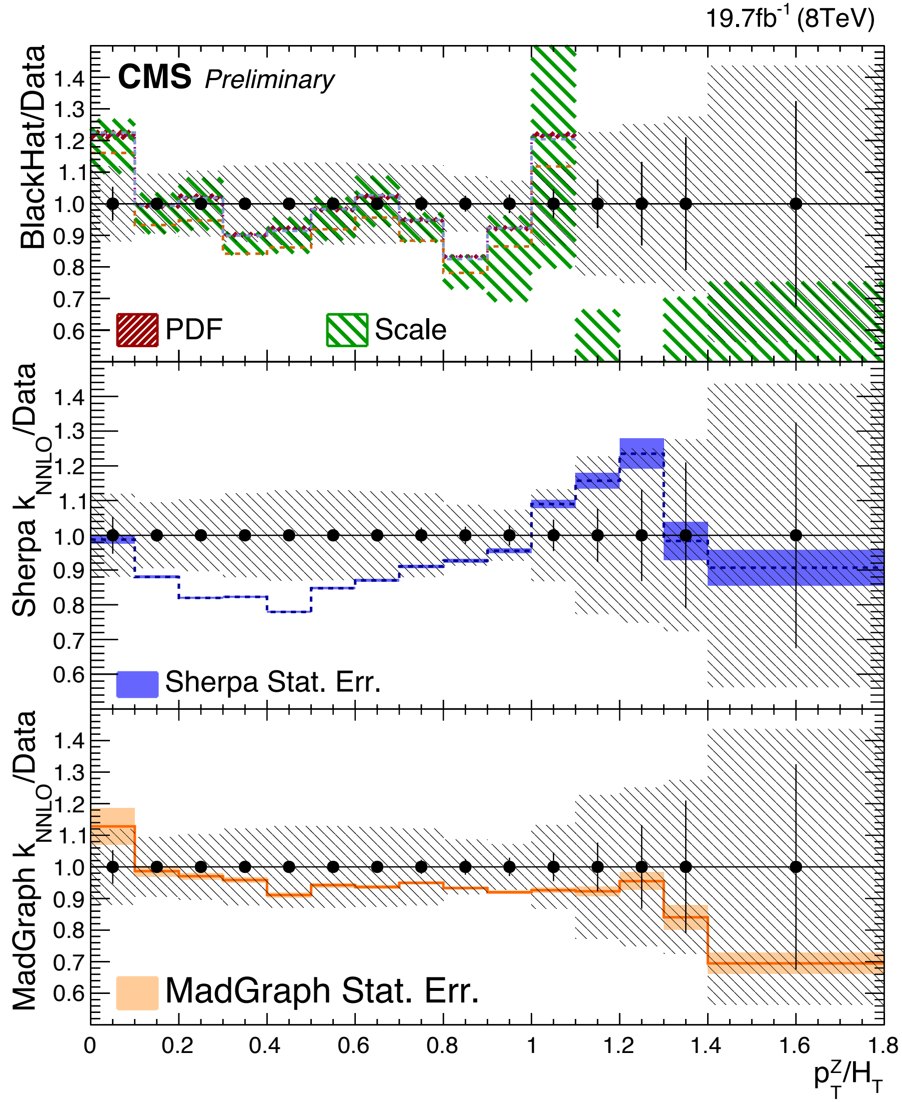
Inclusive jet multiplicity, Z + jets





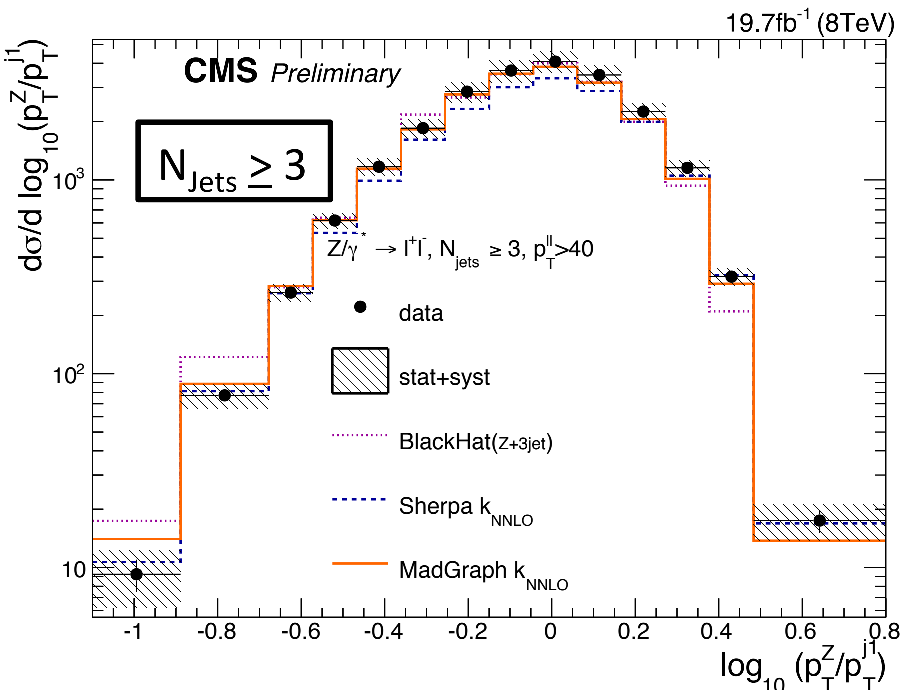
p_T^Z/H_T, $N_{Jets} \geq 3$ at 8 TeV

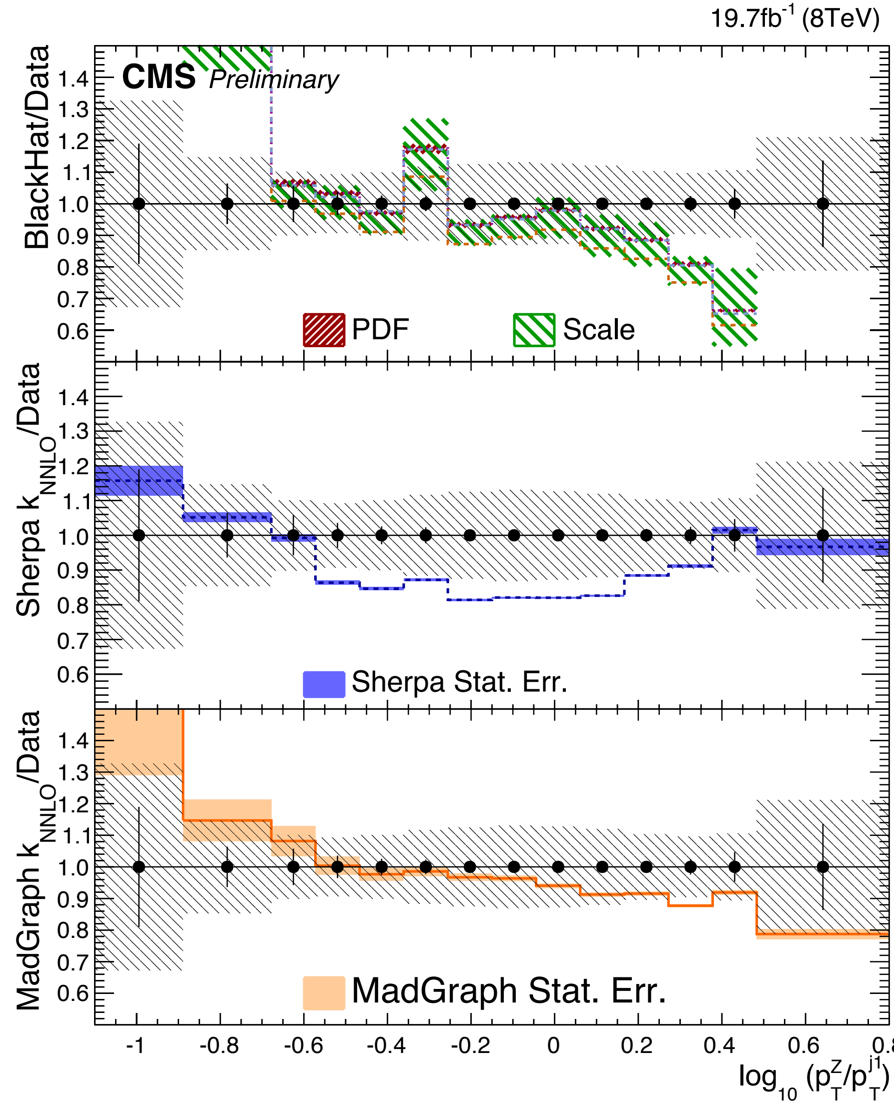




- As before:
  - Ratio works well in MadGraph
  - Sherpa underestimates in the lower end
  - BlackHat has a drop at 1.1 where BlackHat changes from NLO to LO

$\log_{10}(p_T^Z/p_T^1)$, $N_{Jets} \geq 3$ at 8 TeV

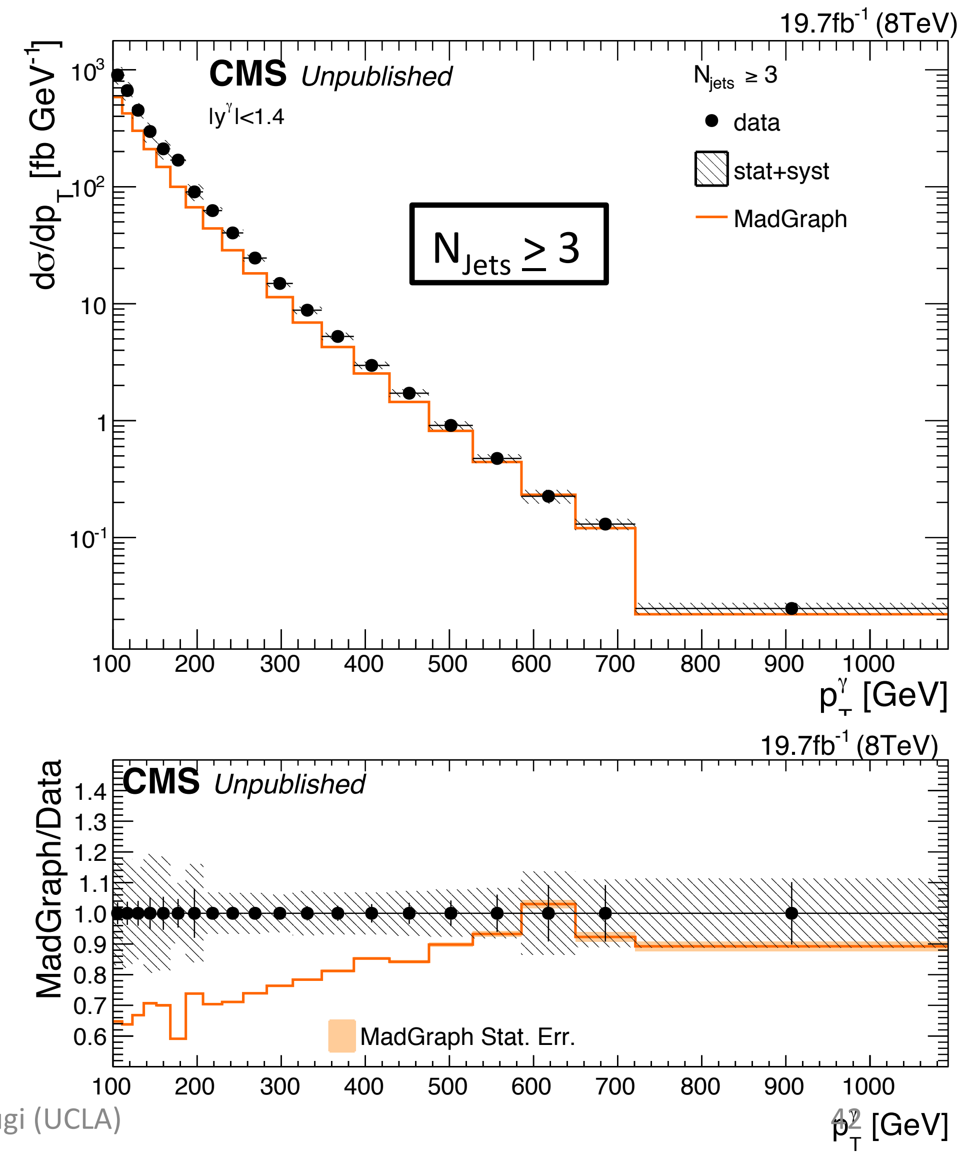




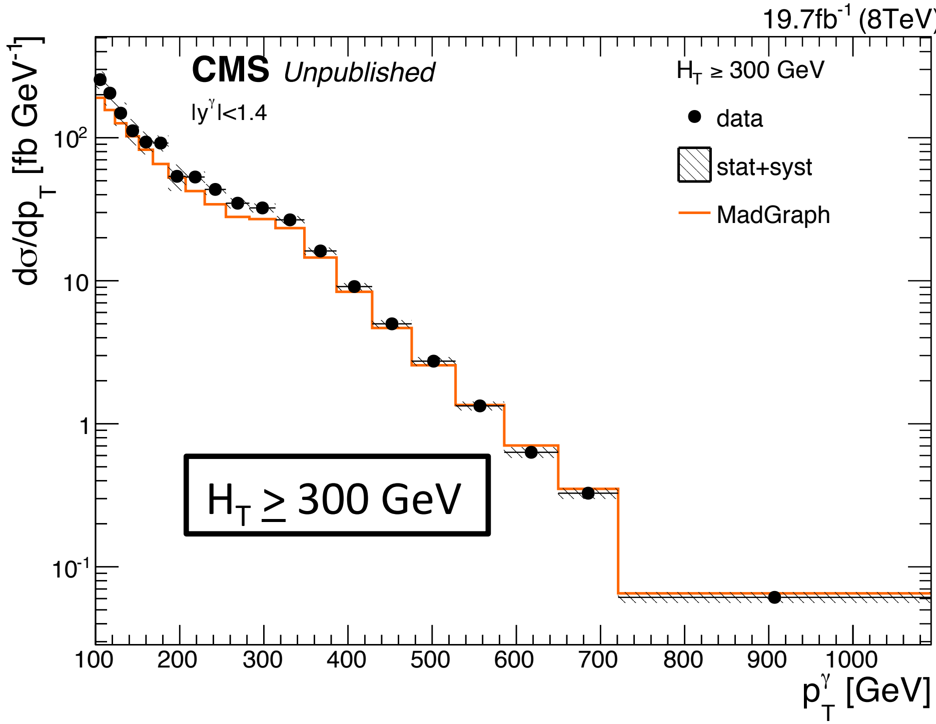
- Ratio works well in MadGraph
- Sherpa underestimates in the central area
- BlackHat has a drop at 0.3 where BlackHat changes from NLO to LO

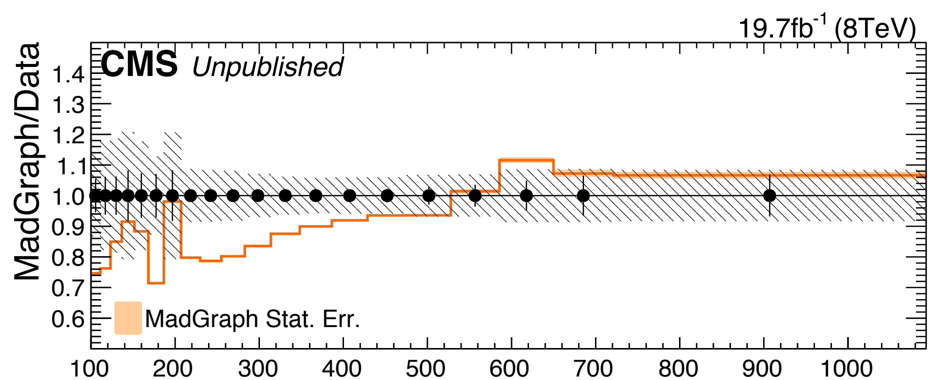
p_T^γ Spectrum, $N_{Jets} \geq 3$ at 8 TeV

- Similar to $N_{Jets} \geq 2$



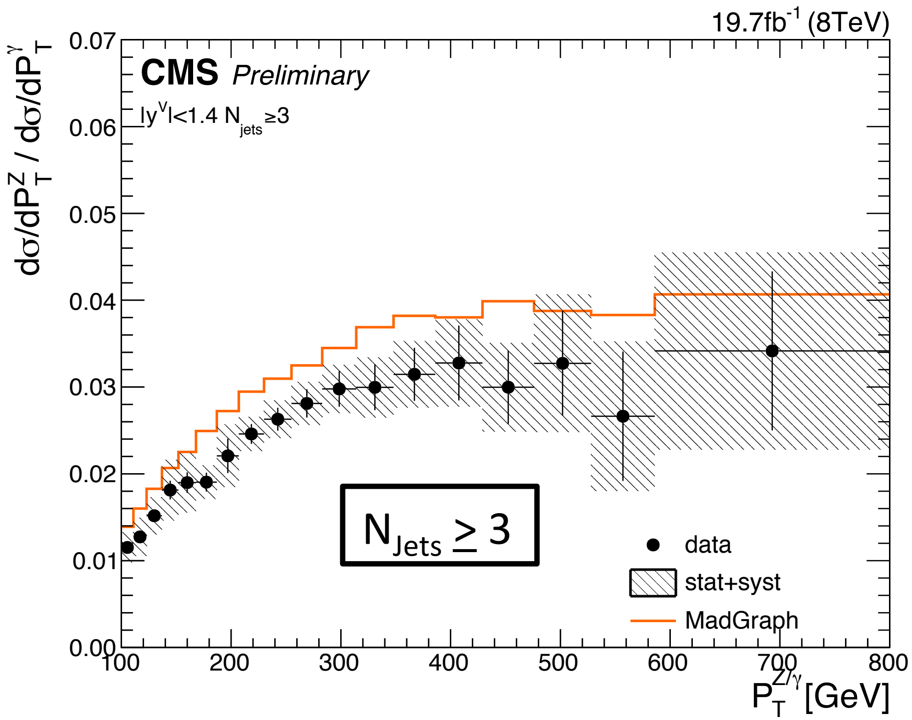
p_T^γ Spectrum, H_T > 300 GeV at 8 TeV

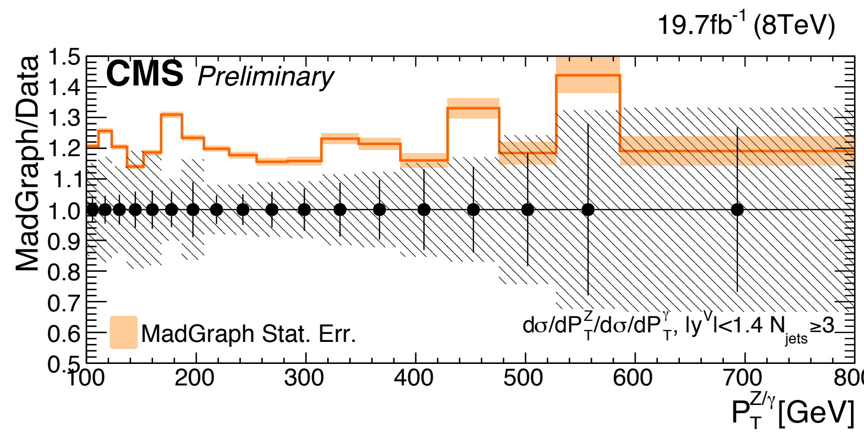




Z/γ ratio: $N_{Jets} \geq 3$ at 8 TeV

- Similar to $N_{Jets} \geq 1$ and $N_{Jets} \geq 2$





Z/γ ratio: H_T> 300 GeV at 8 TeV

- Due to a mixture of statistics and the high uncertainty on the photon purity measurement, shown for p_T>100 GeV