W and Z bosons + jets with CMS and ATLAS

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on behalf of the CMS and ATLAS Collaborations

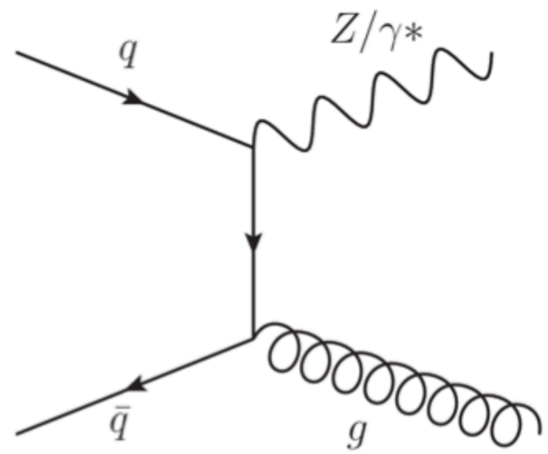
Related presentations (experimental)

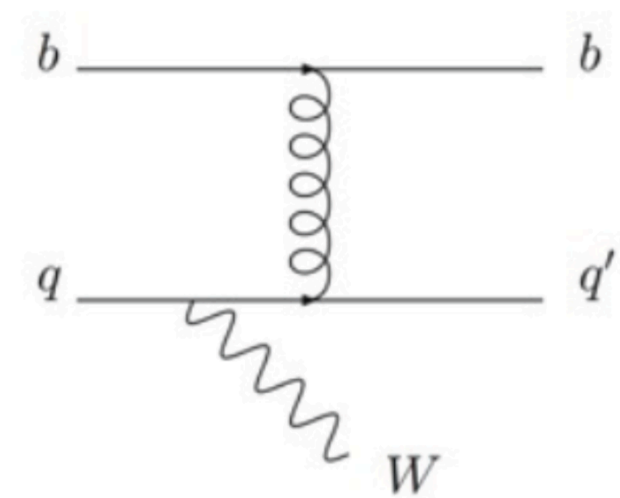
- Keynote talks, in particular
  - Kostas Kousouris: QCD from LHC experiments
- 12:00 Wed 4 Sep: Plenary
  - Anne-Marie Magnan: W/Z, heavy flavor, exp.(ATLAS+LHC)
    - W/Z+HF processes: W+c, W+b(b) and Z+b(b).
- 14:00 Tue 3 Sep: Hard QCD + PDF
  - François Corriveau: Jet cross sections (ATLAS)
  - Giannis Flouris: Jet cross section (CMS)
- 14:00 Wed 4 Sep: Hard QCD: NLO, NNLO, EW
  - Masaki Ishitsuka: Z,W+jets, ttbar+jets and W+heavy flavours (ATLAS)
- 14:25 Wed 4 Sep: Hard QCD: NLO, NNLO, EW
  - Matteo Marone: Z,W+jets, ttbar+jets and W+heavy flavours (CMS)

W/Z + jets: motivation

- Test pQCD calculations to high precision
  - study of topological properties
  - study of jet multiplicity and kinematic properties
  - LHC energies and large data sets open huge phase-space
- Study and constrain parton density functions
- Important for searches
  - many heavy exotic particles are expected to decay to W/Z
  - searches require the exploration of high p_T
- Important background for
  - Higgs studies
  - BSM searches
- High production rate
- Simple decay signature

$$Z \to \ell^+ \ell^-$$
$$W \to \ell \nu \qquad \ell = e,\ \mu$$



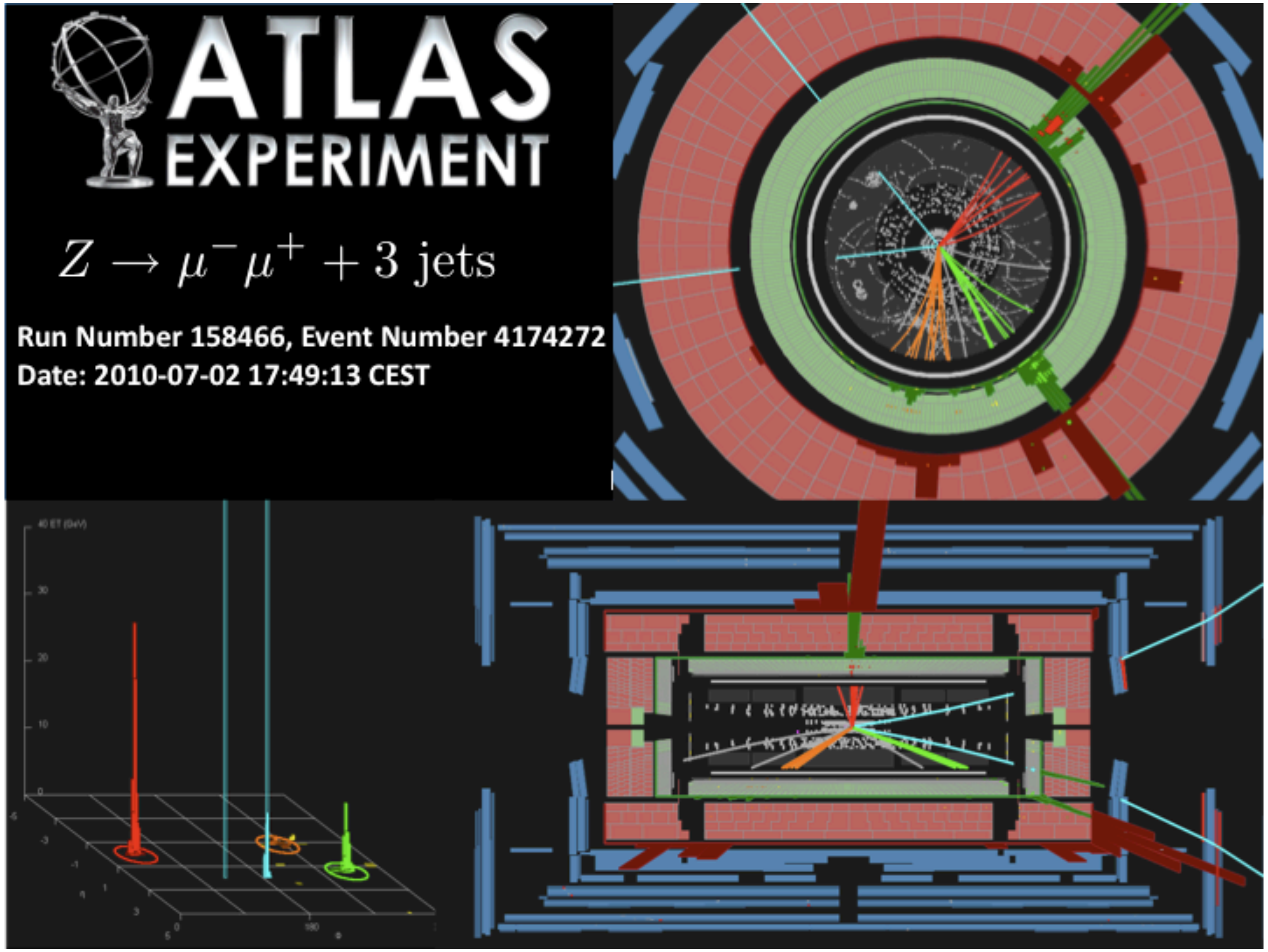


Outline

- W,Z analyses with jet reconstruction
  Probe high order pQCD
  Constrain parton densities
  - Z+jets
  - W+jets
  - (W+jets)/(Z+jets)
- Double parton interactions (DPI) in W + 2 jets
- Boosted W,Z analyses
  Test of high order pQCD
  Test of resummation techniques
  - Z p_T, W p_T, Z phi*

Z + jets

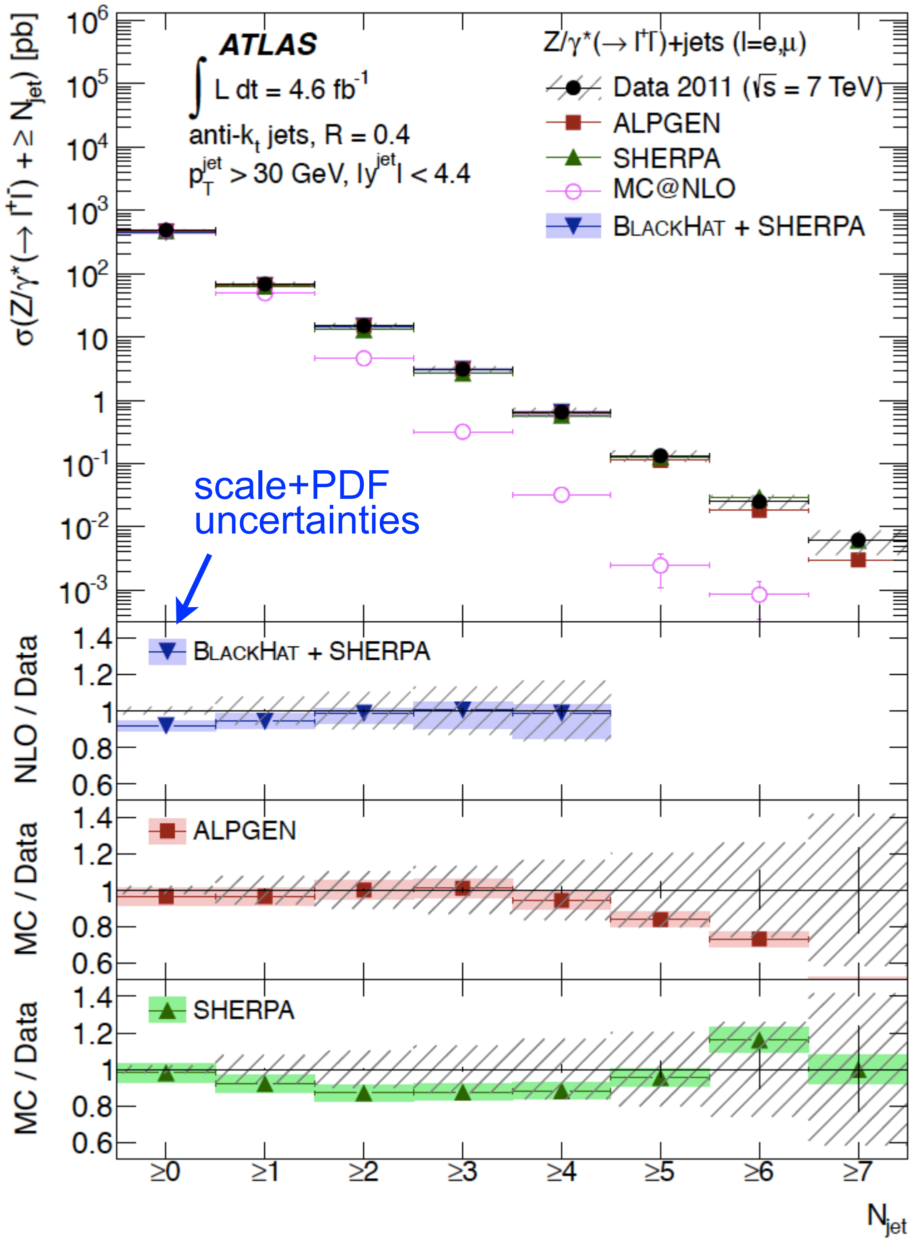
- LHC dataset allows measurement of
  - high jet multiplicities: up to 7 jets
  - up to high jet p_T: leading jet p_T up to 700 GeV at $\sqrt{s}$ 7 TeV

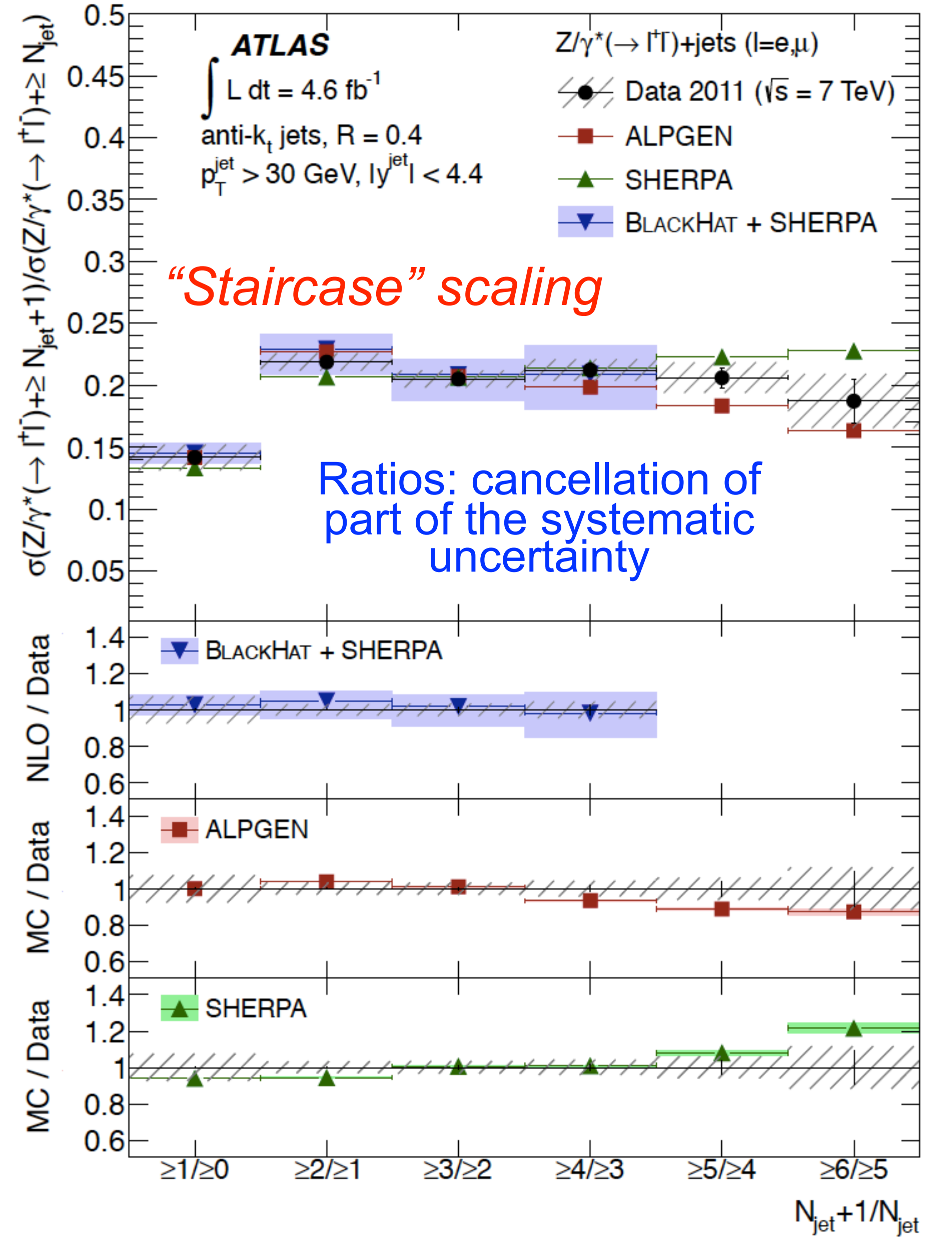


Z + jets - inclusive jet multiplicities

JHEP07(2013)032

- cross section for dressed electrons and particle jets in fiducial acceptance region
- normalized to inclusive cross section
  - cancel uncertainties on electron reco and integrated luminosity
- Jet energy scale is the dominant uncertainty
  - 20-30% effect in forward region





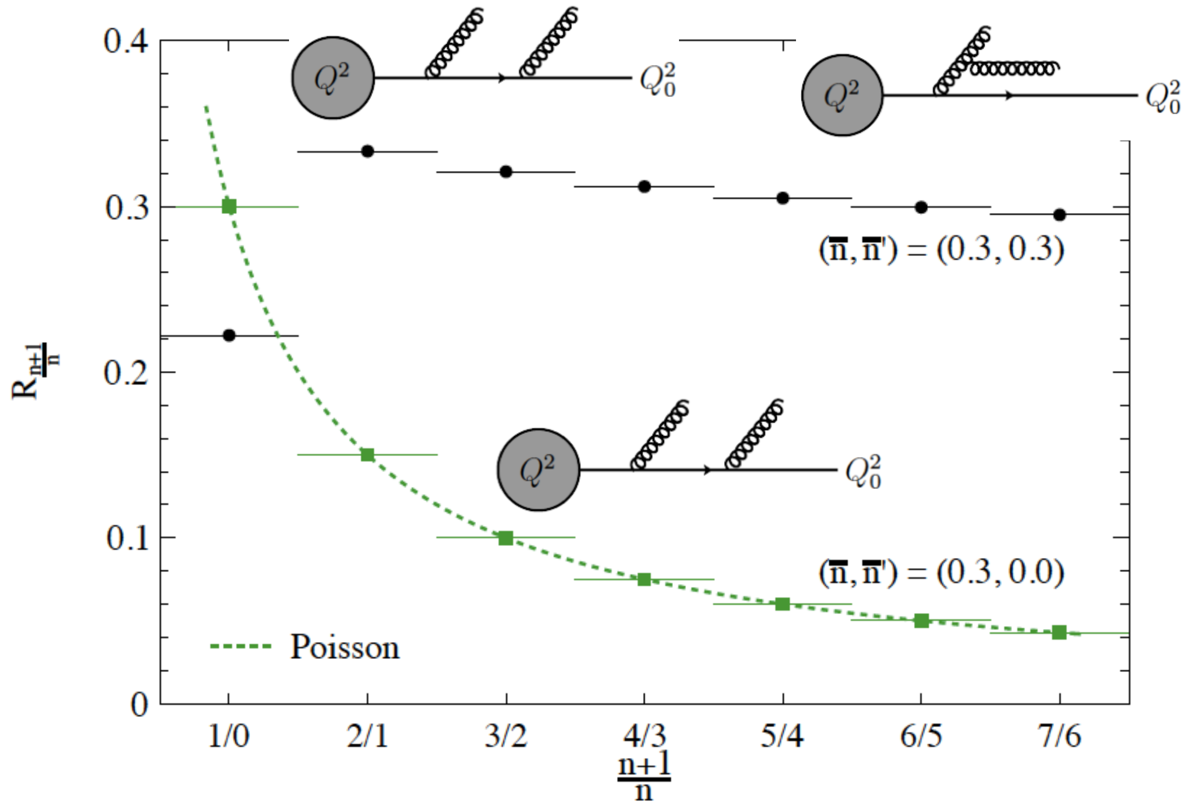
- BLACKHAT+SHERPA + CT10
- ALPGEN 2.13 + HERWIG +JIMMY + CTEQ6L1
- SHERPA 1.4.1 + MEnloPS + CT10

- Good description by fixed order NLO calculations and multi-leg MC + PS
  - MC@NLO agrees only for at most ≥ 1 jet (one parton from NLO real emission), otherwise HERWIG PS fails to model jet multiplicities

Z + jets - jet multiplicities ratio scaling

Gerwick et al., JHEP 1210 (2012) 162

- Jet multiplicity ratios are expected to follow one of two benchmark patterns
- Scaling can be used to extrapolate the jet rate to higher multiplicities
  - useful in analyses using jet vetoes to separate signal from W/Z+jets background



"Staircase" scaling

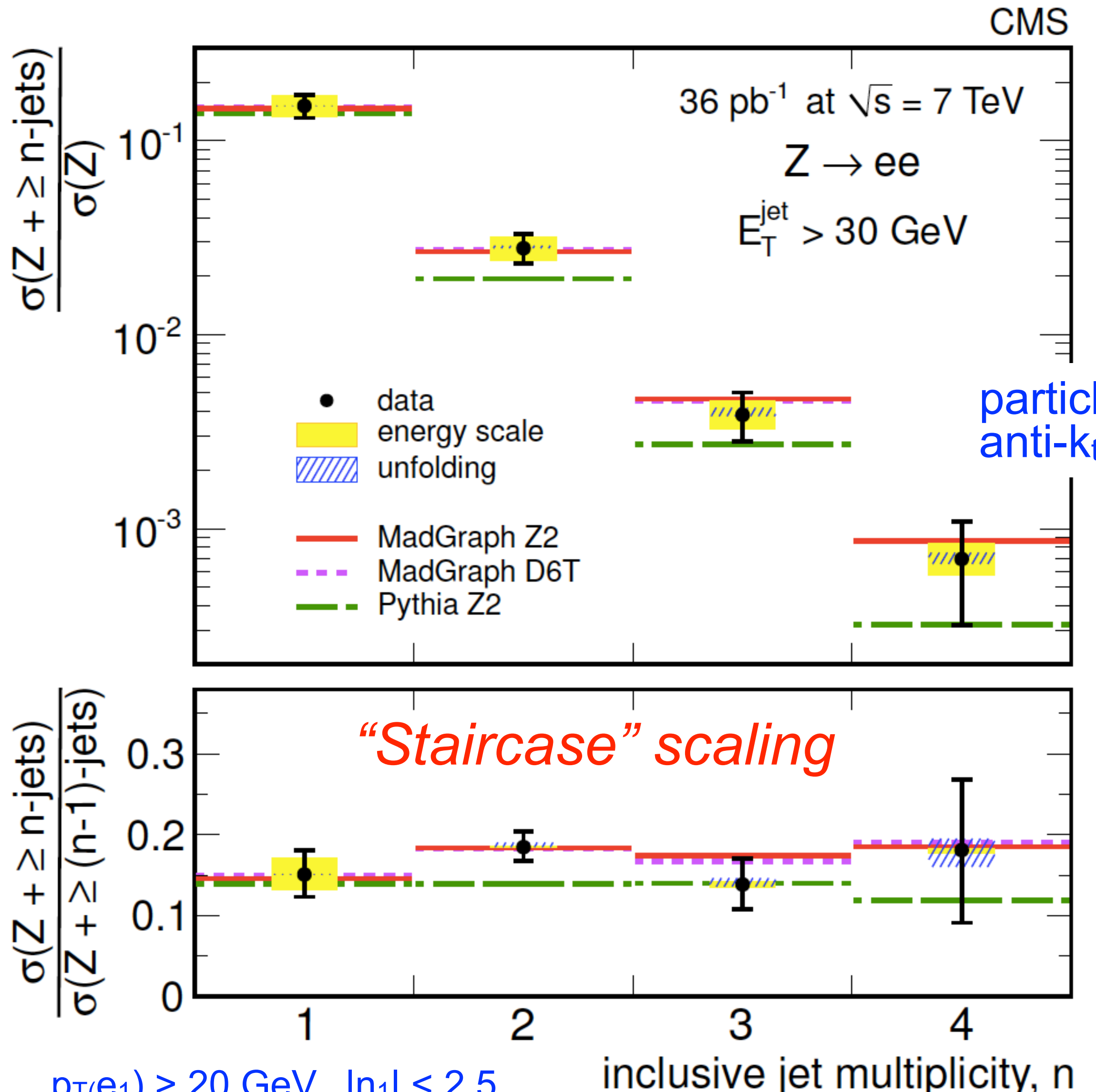
- Ratio $R_{(n+1)/n}$ constant
- Jet rate $\sigma_n \sim e^{-bn}$
- Inclusive and exclusive ratios scale the same way
- Expected in the absence of major kinematic cuts
  - low multiplicities: combined effect of Poisson-distributed multiplicity distributions and parton density suppression
    - emission of the first parton suppressed more strongly: $R_{1/0}$, by 60%
  - high multiplicities: effect of non-abelian nature of QCD FSR

"Poisson" scaling

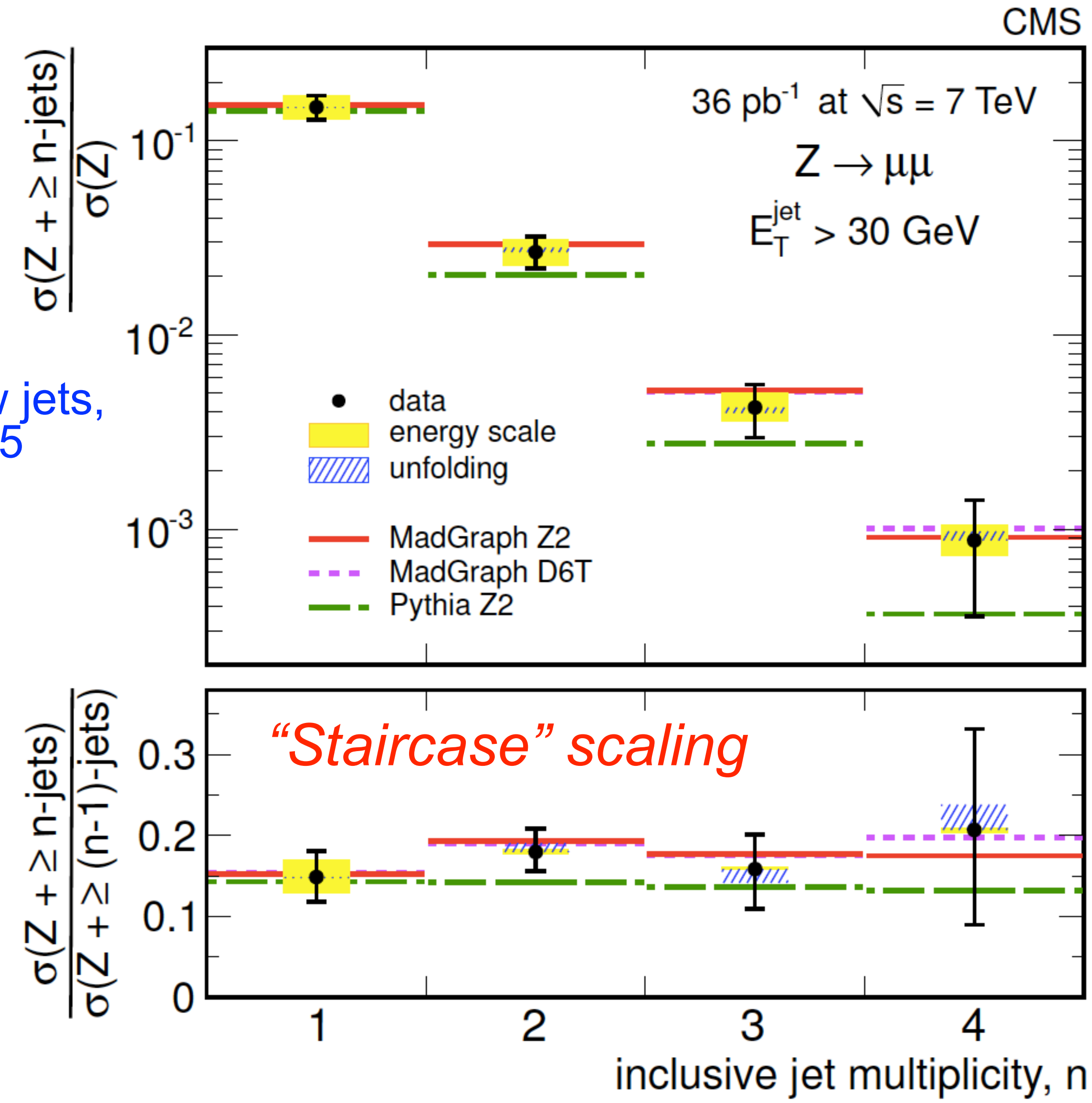
- Exclusive Ratio $R_{(n+1)/n} \sim \mu_n/(n+1)$
- Jet rate $\sigma_n \sim \text{Poisson}(n \mid \mu_n)$
- Emerges when large difference between Z+1jet and other jets energy scales
  - expected when jet acceptance cut much larger than hard process scale

Z + jets - inclusive jet multiplicities

JHEP01(2012)010



particle flow jets, anti-k_t R=0.5



$p_T(e_1)$ > 20 GeV, $|\eta_1|$ < 2.5
$p_T(e_2)$ > 10 GeV, $|\eta_2|$ < 2.5
e_1 and e_2 not in 1.44 < $|\eta|$ < 1.57, and isolated
60 < m_{ee} < 120 GeV

$p_T(\mu_1)$ > 20 GeV, $|\eta_1|$ < 2.1, isolated
$p_T(\mu_2)$ > 10 GeV, $|\eta_2|$ < 2.4, isolated
60 < $m_{\mu\mu}$ < 120 GeV

- For n > 1, scaling is compatible with a constant
- MadGraph (multi-leg MC) agrees well with data (both UE tunes Z2 and D6T)
  - PYTHIA parton shower fails to describe the data for $N_{jets} \geq 2$

Z + jets - exclusive jet multiplicities

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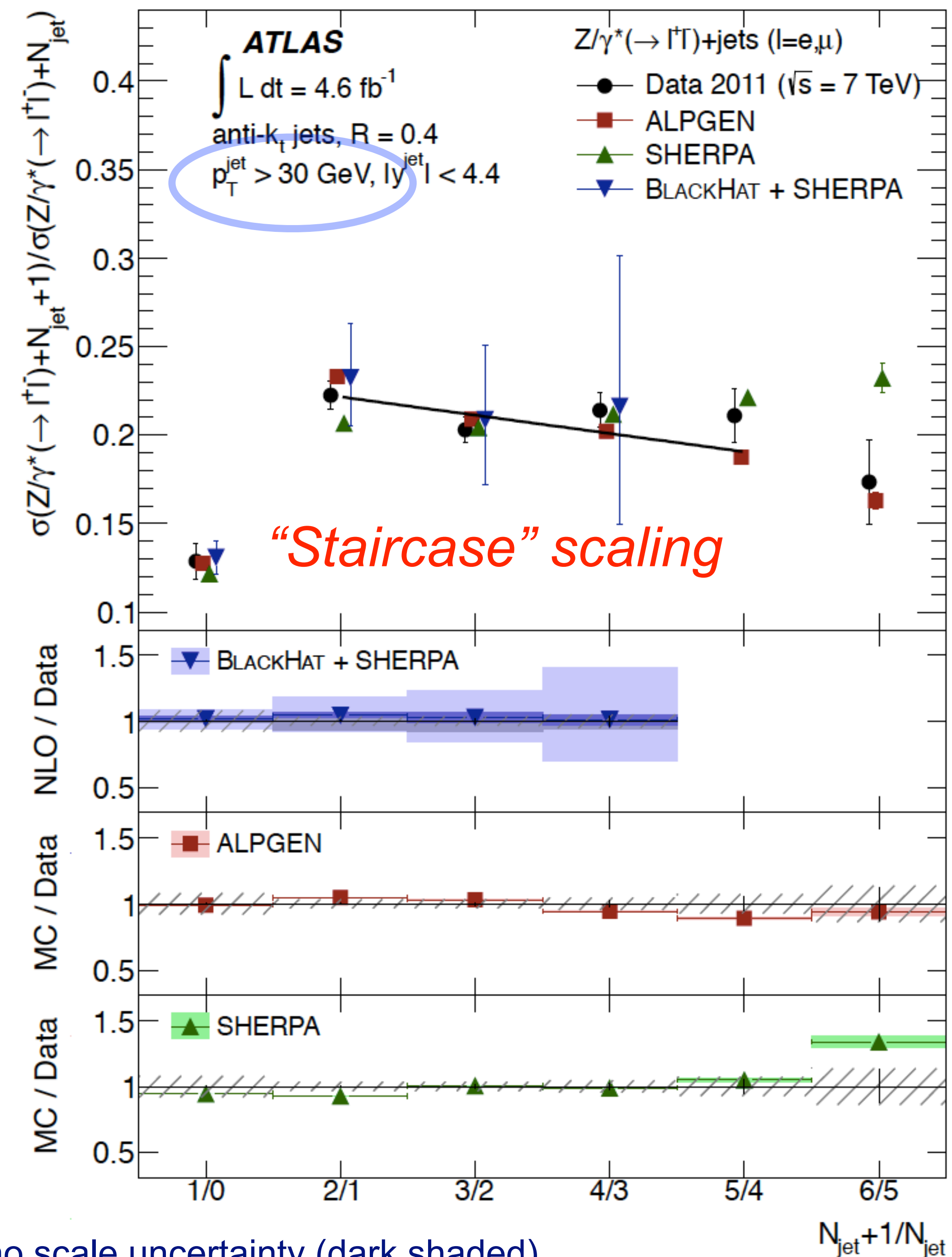
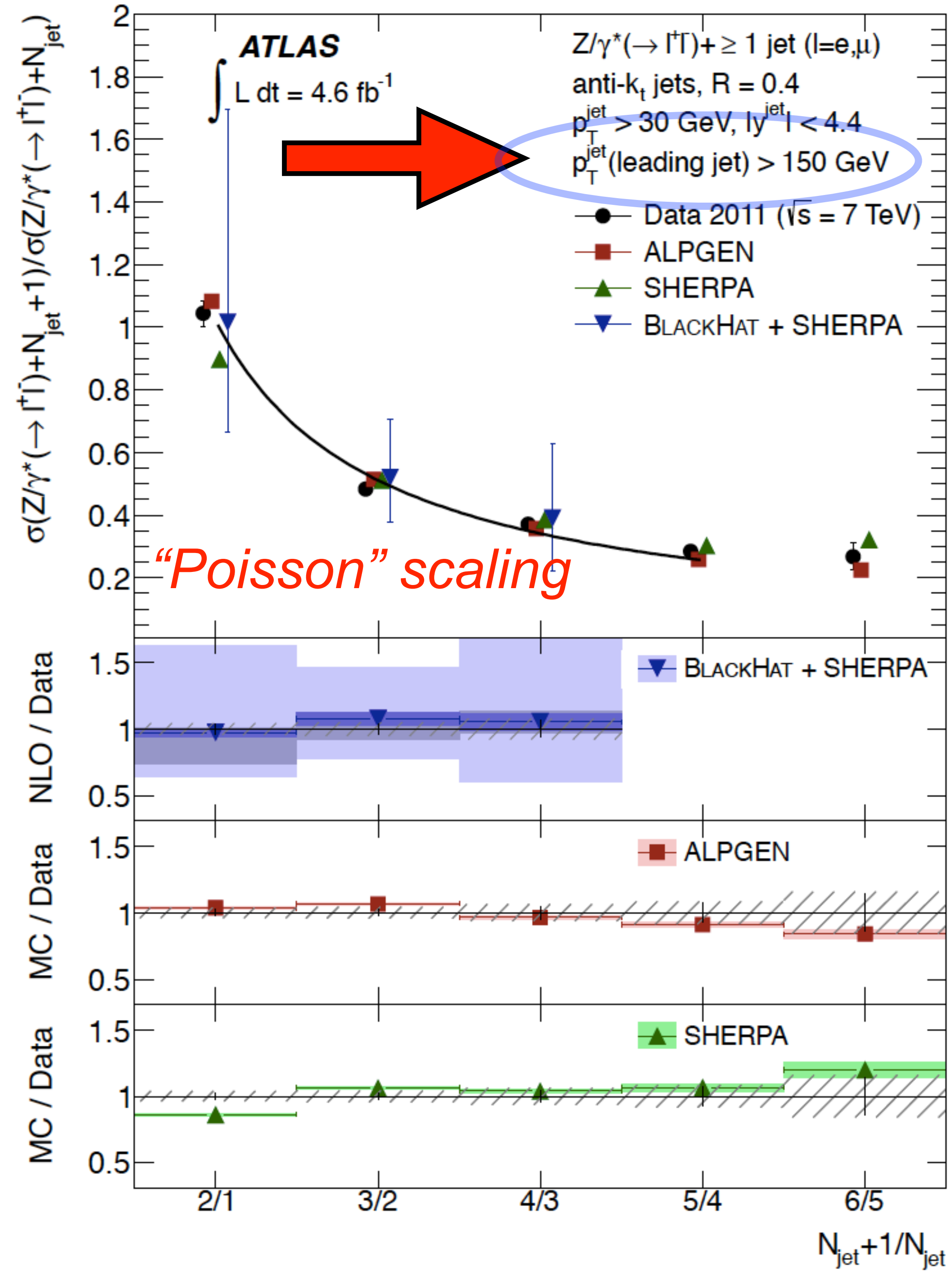




- no scale uncertainty (dark shaded)
- correlated between multiplicity bins (medium shaded)
- uncorrelated (light shaded), as prescribed in Phys.Rev.D85 (2012) 034011

- cross section well modeled by fixed order NLO pQCD
  - Transition between "Staircase" and "Poisson" scaling observed

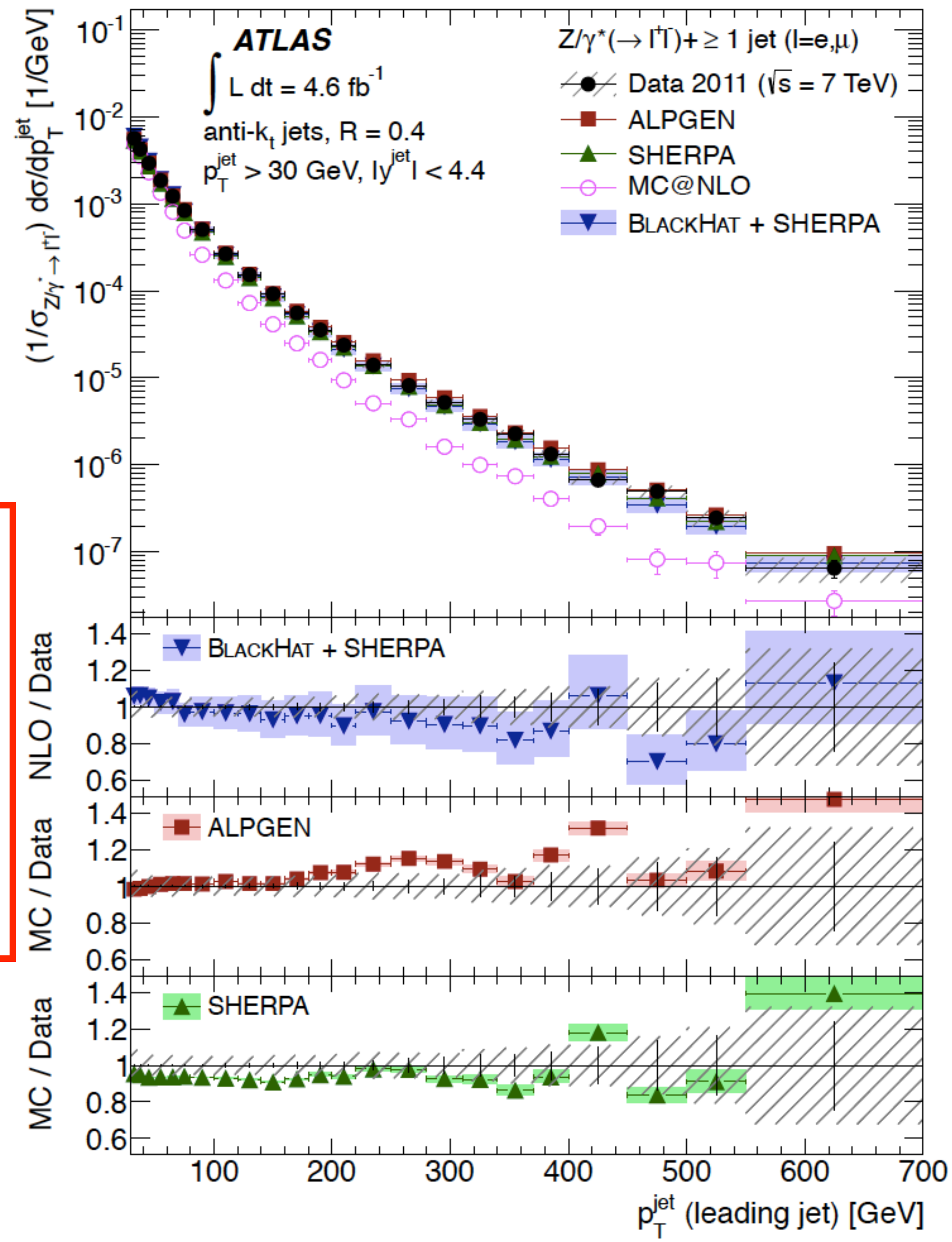
Z + jets - jet transverse momentum

JHEP07(2013)032

- Test of limitations of ME+PS generators and fixed order pQCD in regions where large logarithmic corrections and EW NLO corrections are expected to become important
  - p_T jets, jet p_T ratios, Z p_T
- For leading jet, experimental precision exceeds theory precision

normalized to inclusive cross section

leading jet



- Data consistent with fixed order NLO predictions of BLACKHAT+SHERPA
- ALPGEN predicts too hard a spectrum for large jet p_T
  - missing NLO EW+QCD corrections
- SHERPA prediction is 5-15% too low
- MC@NLO predicts too soft a spectrum
  - next to leading jets modeled via parton shower
  - since fraction of events with > 1 jet increases with leading jet p_T, soft p_T spectrum from parton shower leads to increase discrepancy with data

Z + jets - jet transverse momentum

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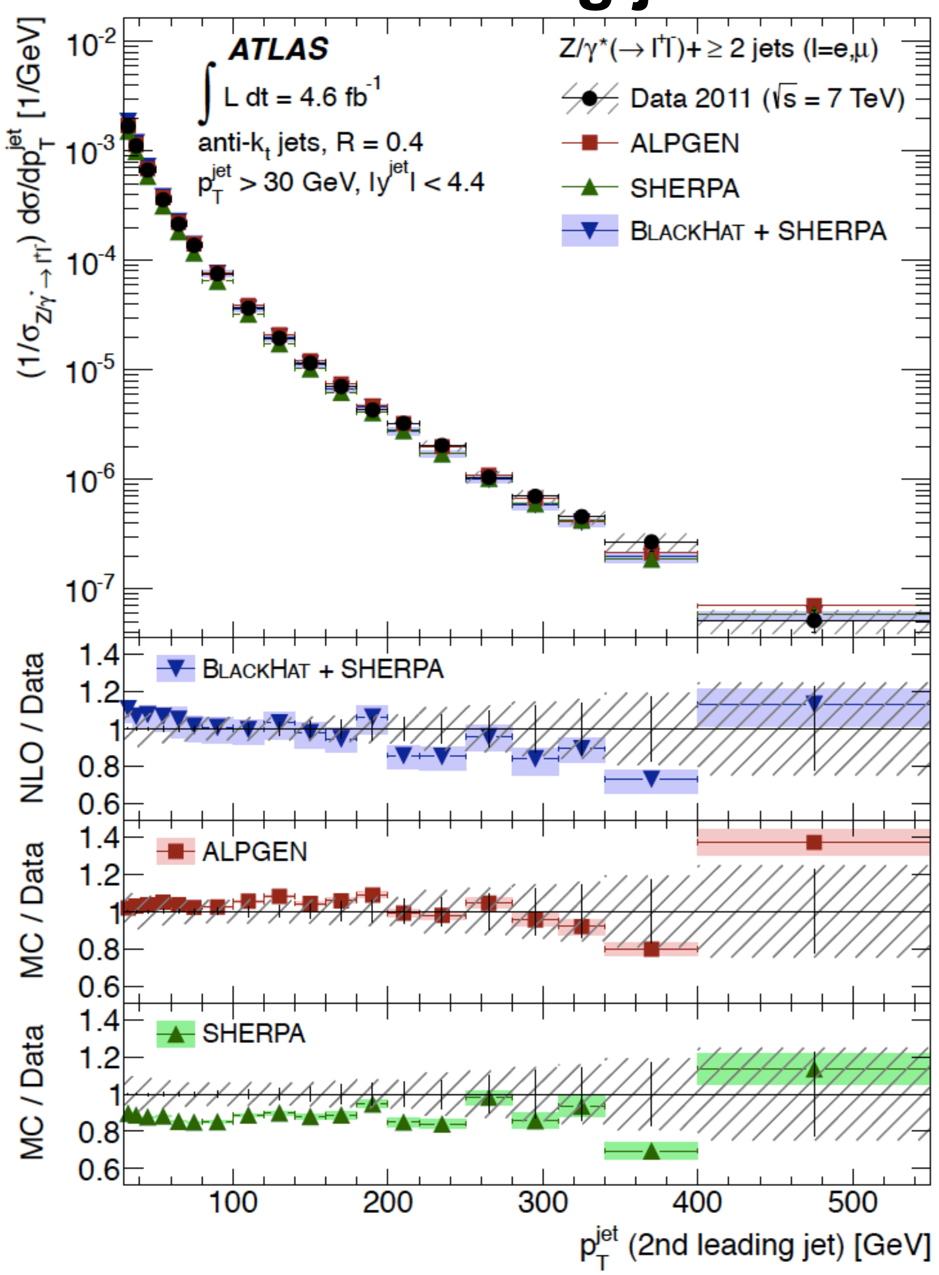
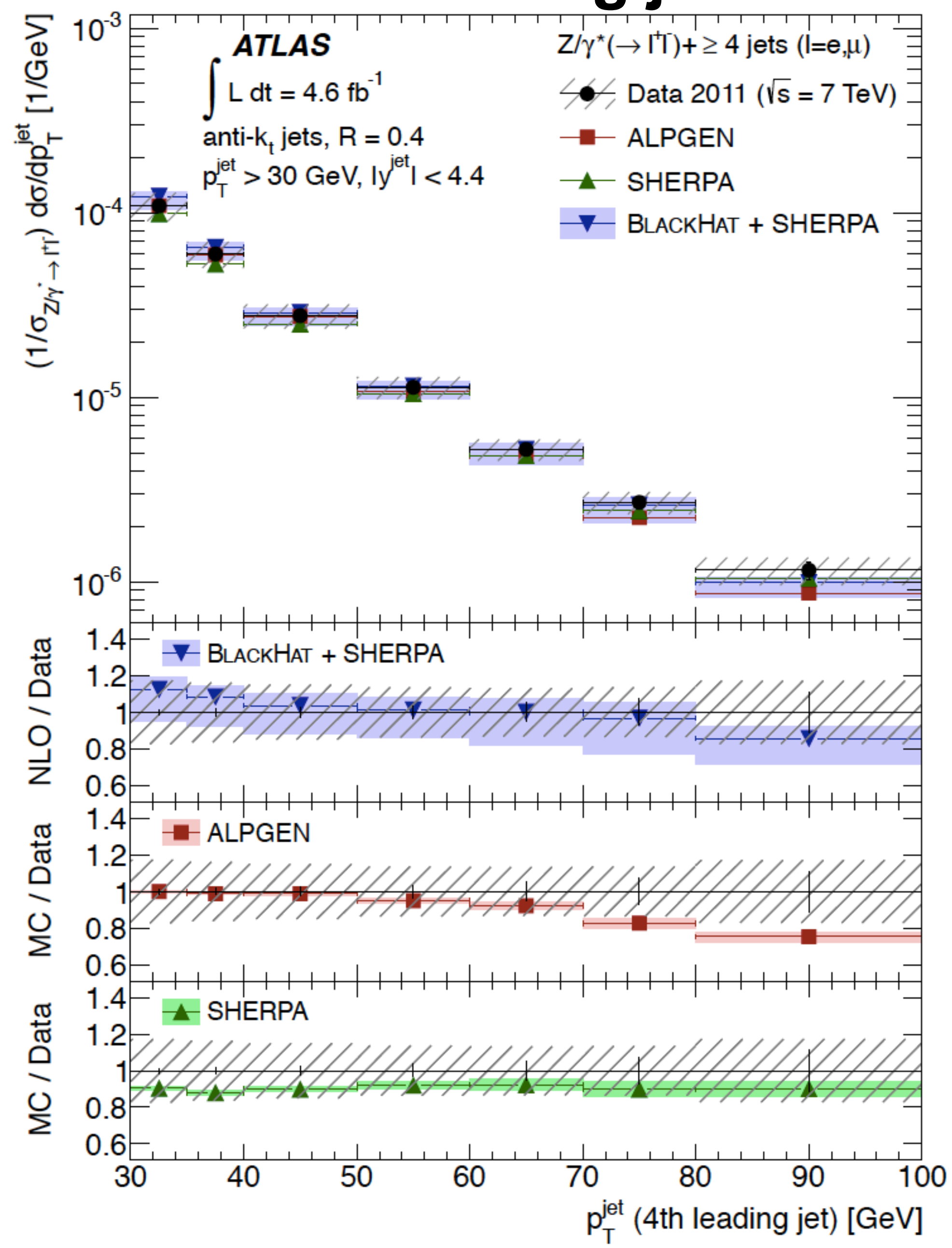
2nd leading jet



4th leading jet



- Data consistent with fixed order NLO predictions of BLACKHAT+SHERPA for all multiplicities
- ALPGEN predictions consistent with data
- SHERPA predictions are too low by 5-15%

Z + jets - jet transverse momentum

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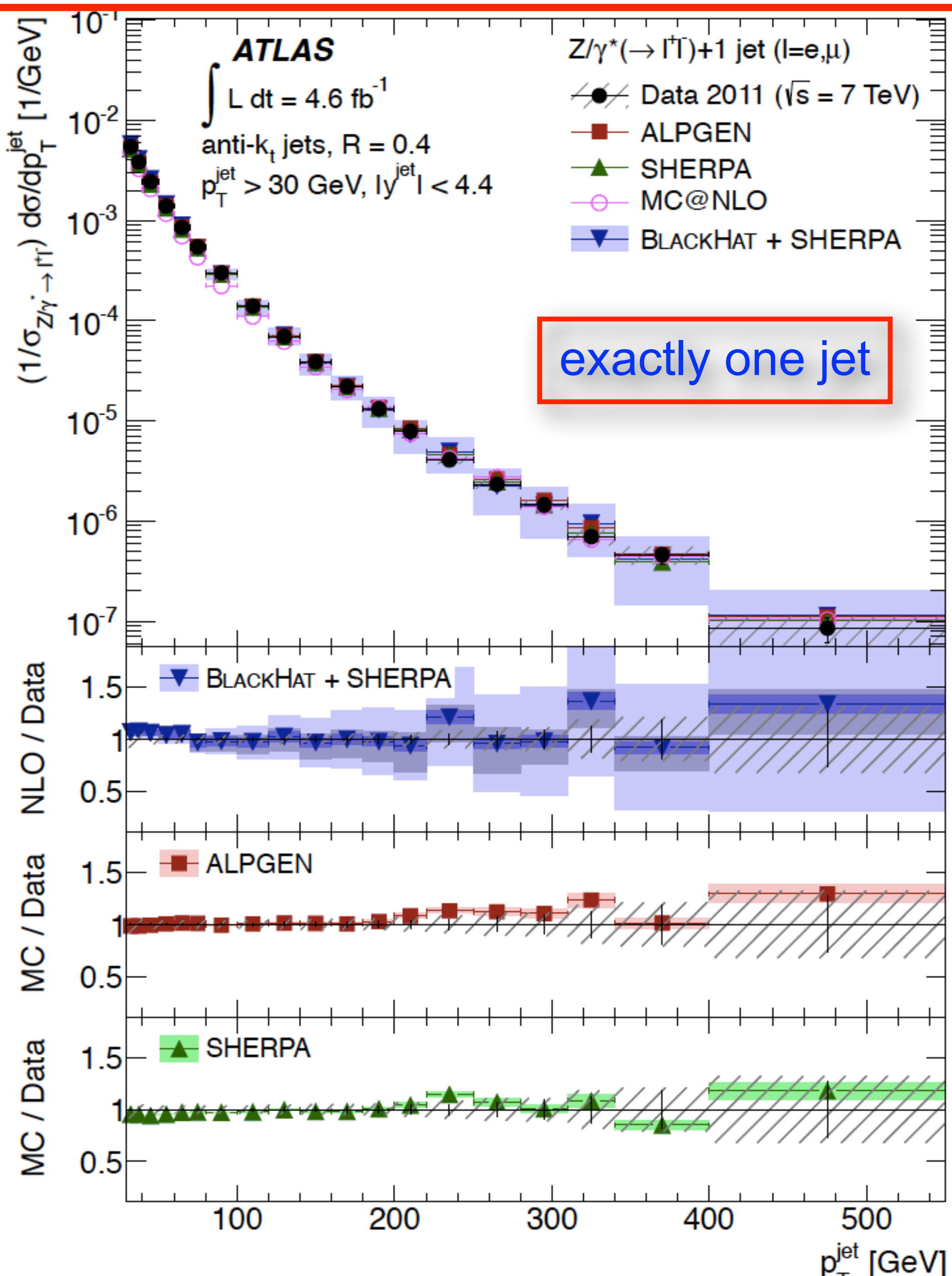
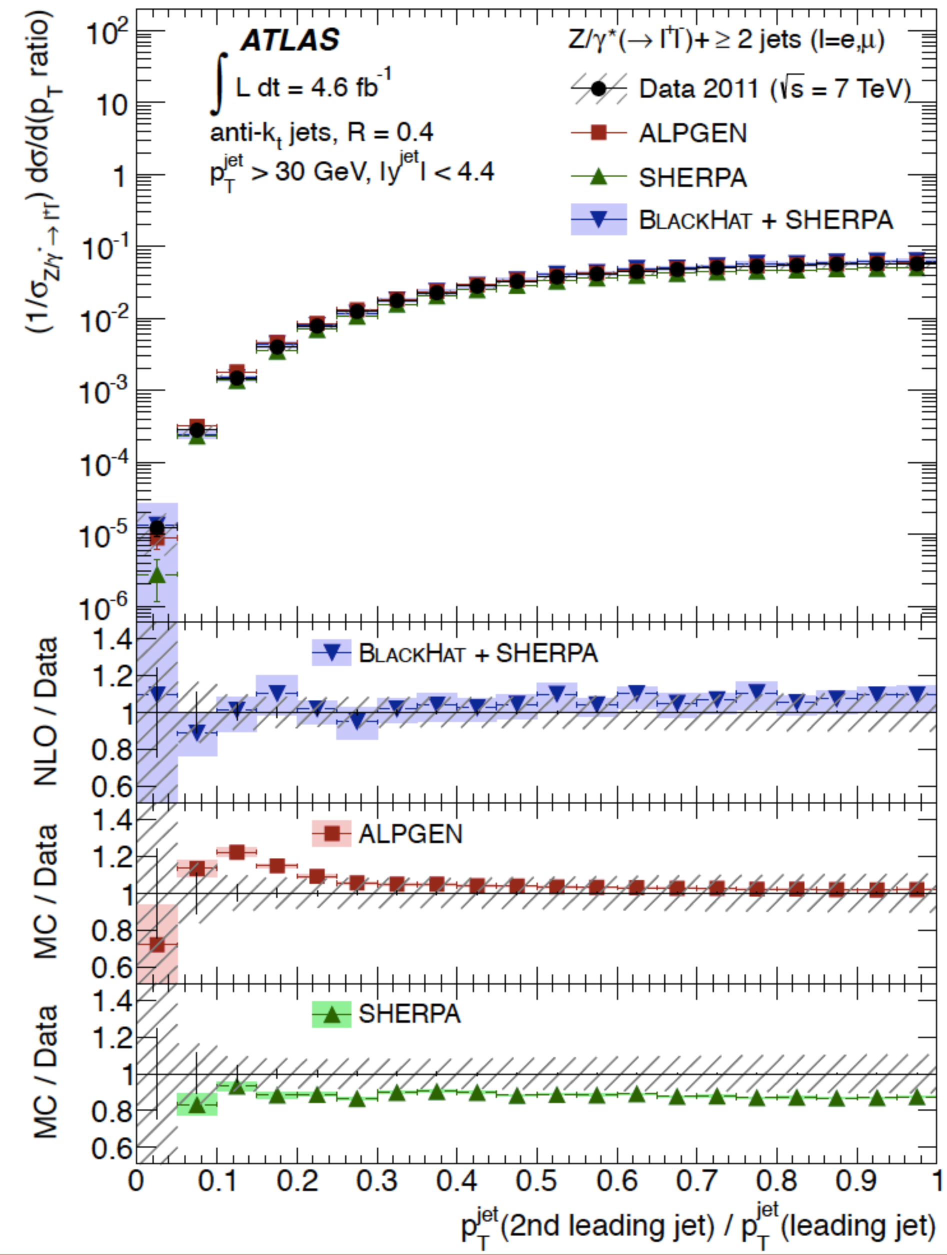
- Veto on second jet applied: better agreement



exactly one jet

normalized to inclusive cross section



- no scale uncertainty (dark shaded)
- correlated between multiplicity bins (medium shaded)
- uncorrelated (light shaded), as prescribed in Phys.Rev.D85 (2012) 034011

- p_T ratio of jet 1 and 2 for $N_{jets} > 1$
  - ALPGEN prediction overestimates the data in the region 0.1-0.2
  - SHERPA underestimates the cross section by ~15%

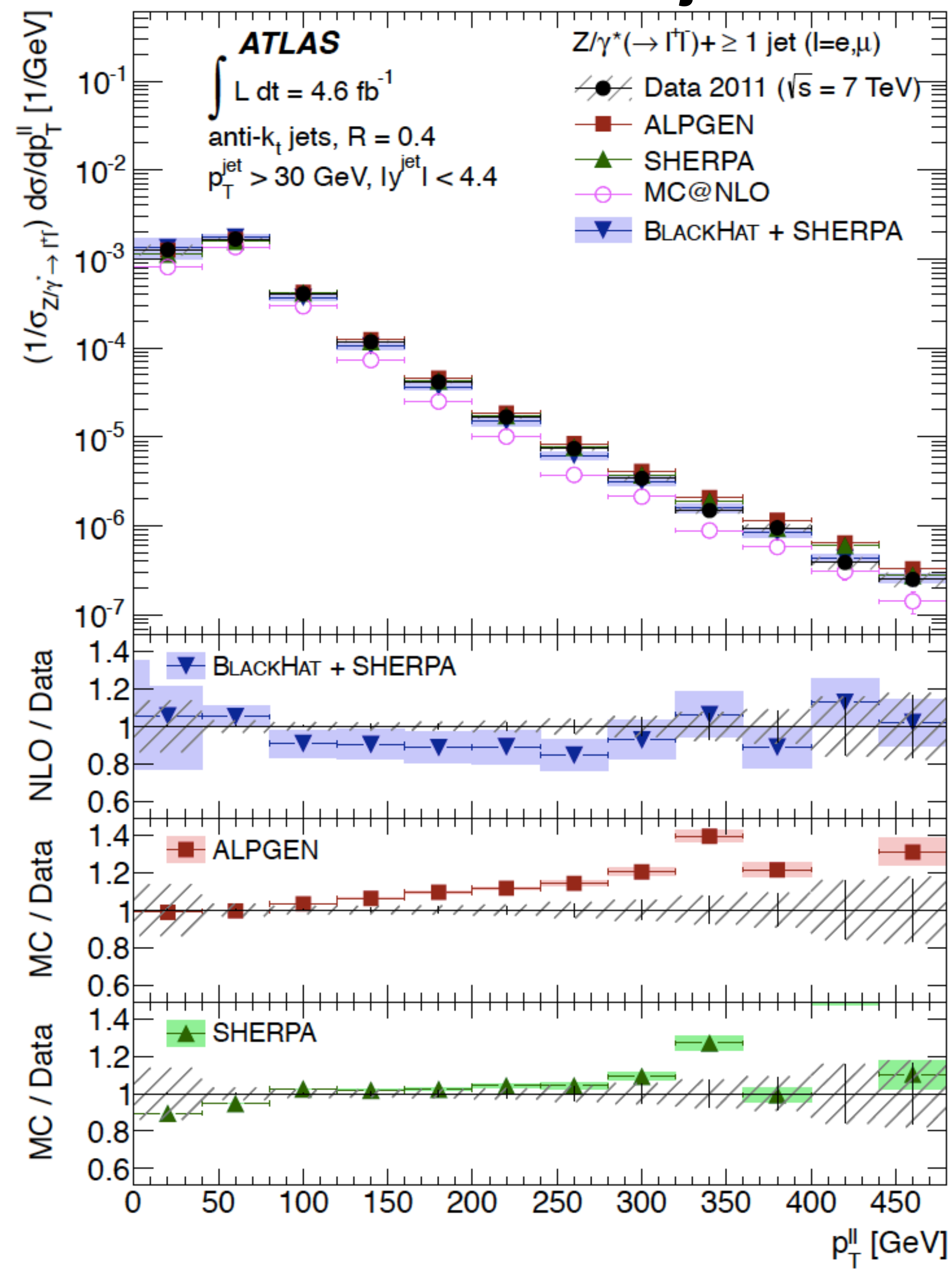
Z + jets - Z transverse momentum

JHEP07(2013)032

- Complementary approach to p_T differential cross section measurement
- Higher-order electroweak corrections expected to reduce the cross section by 5-20% for Z p_T > 100 GeV
- BLACKHAT+SHERPA fixed order calculation too soft for the inclusive ≥ 1 jet final state (but in agreement for the exclusive 1 jet final state)
  - attributed to missing higher-order jet multiplicities in the fixed-order calculation: use exclusive sums of NLO calculations to have better agreement
  - no indication for missing higher-order electroweak corrections in the large Z p_T region
  - BLACKHAT calculation corrected for non-perturbative effects
- Both ALPGEN and SHERPA predict too hard a spectrum
  - discrepancy comparable to the expected higher-order electroweak corrections, but higher-order QCD corrections are also a possible cause
- MC@NLO describes the exclusive 1 jet final state better than the inclusive ≥ 1 jet final state

normalized to inclusive cross section

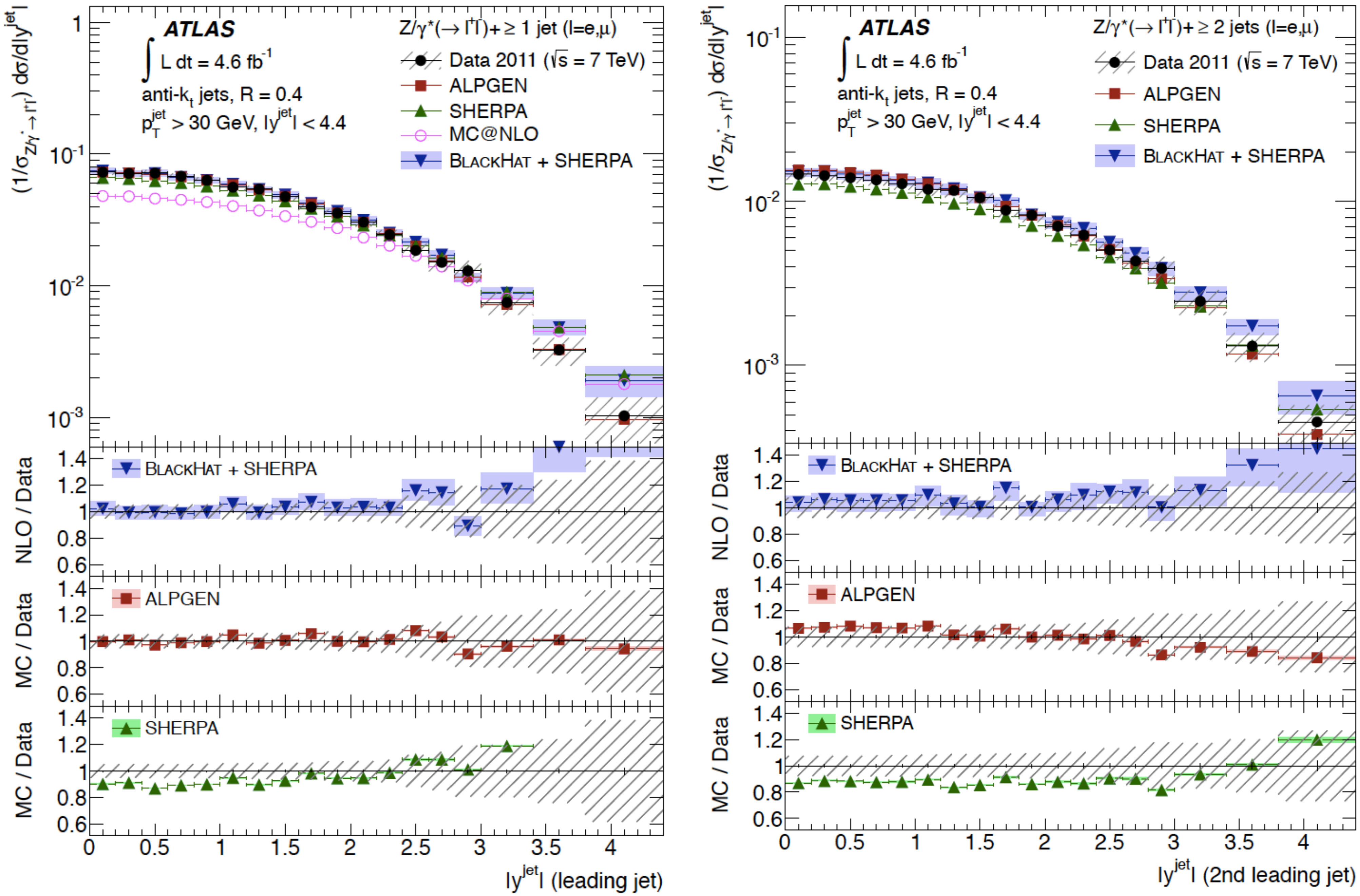
inclusive ≥ 1 jet



Z + jets - jet rapidities for $N_{jets} \geq 1$ and ≥ 2

JHEP07(2013)032

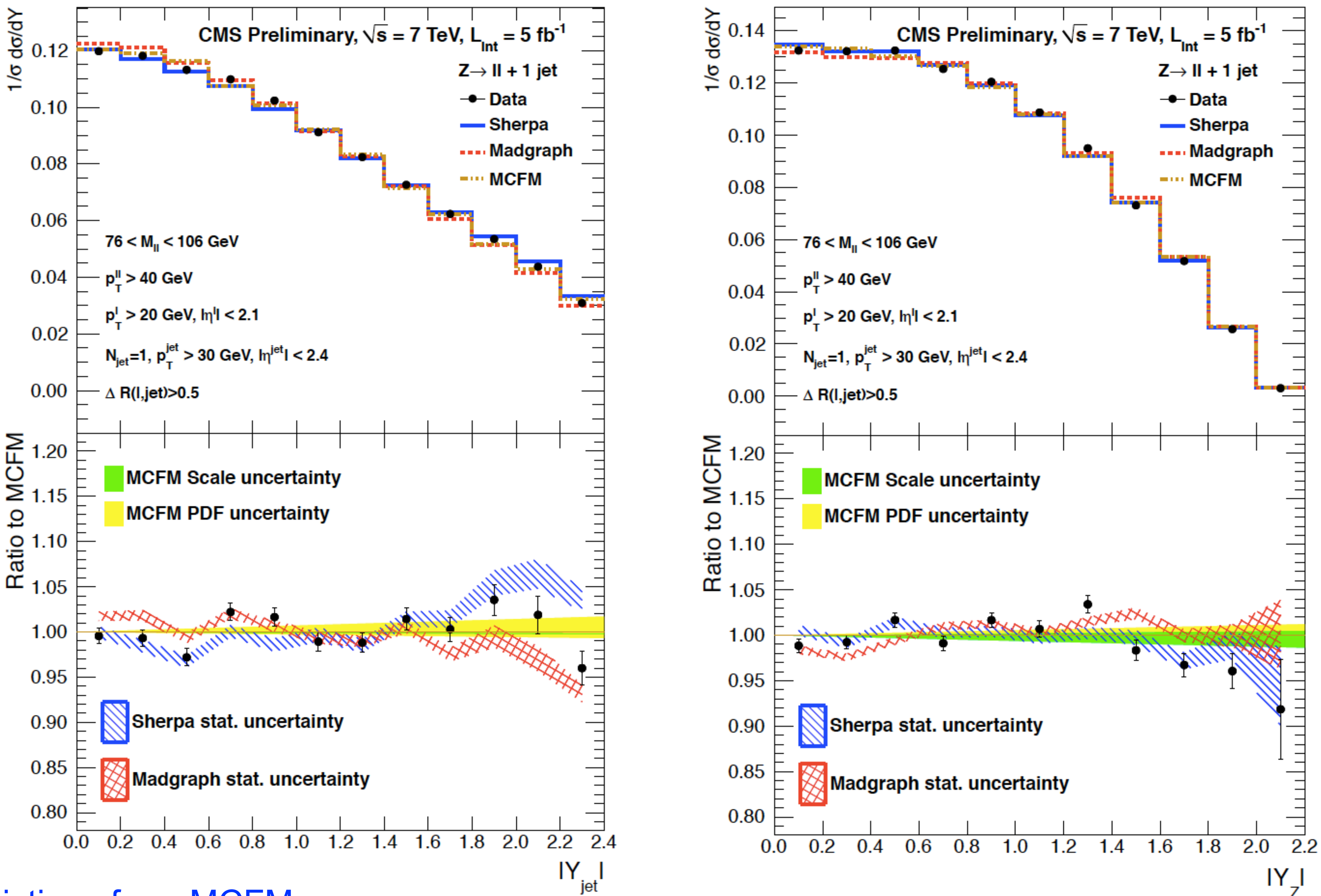
- Many physics signatures involved well separated forward jets
  - knowledge of angular distributions can be used to separated signal from background
- Experimental challenge: jet energy scale especially in the forward region



- NLO fixed order QCD and SHERPA overestimate cross section in the forward region
- ALPGEN predictions are in agreement with the data
- MC@NLO predicts too wide a rapidity distribution

Z + jets - jet and Z rapidities for N_{jet} = 1 (central)

CMS-PAS-SMP-12-004



- NLO predictions from MCFM
- MadGraph 5.1.1.0 + MLM scheme
- SHERPA 1.3.1 + CKKW scheme

■ All predictions agree with data within 5%

Z + jets - ~ uncorrelated rapidities for N_{jet} = 1

$$Y_{\rm dif} = |Y_Z - Y_j|/2$$

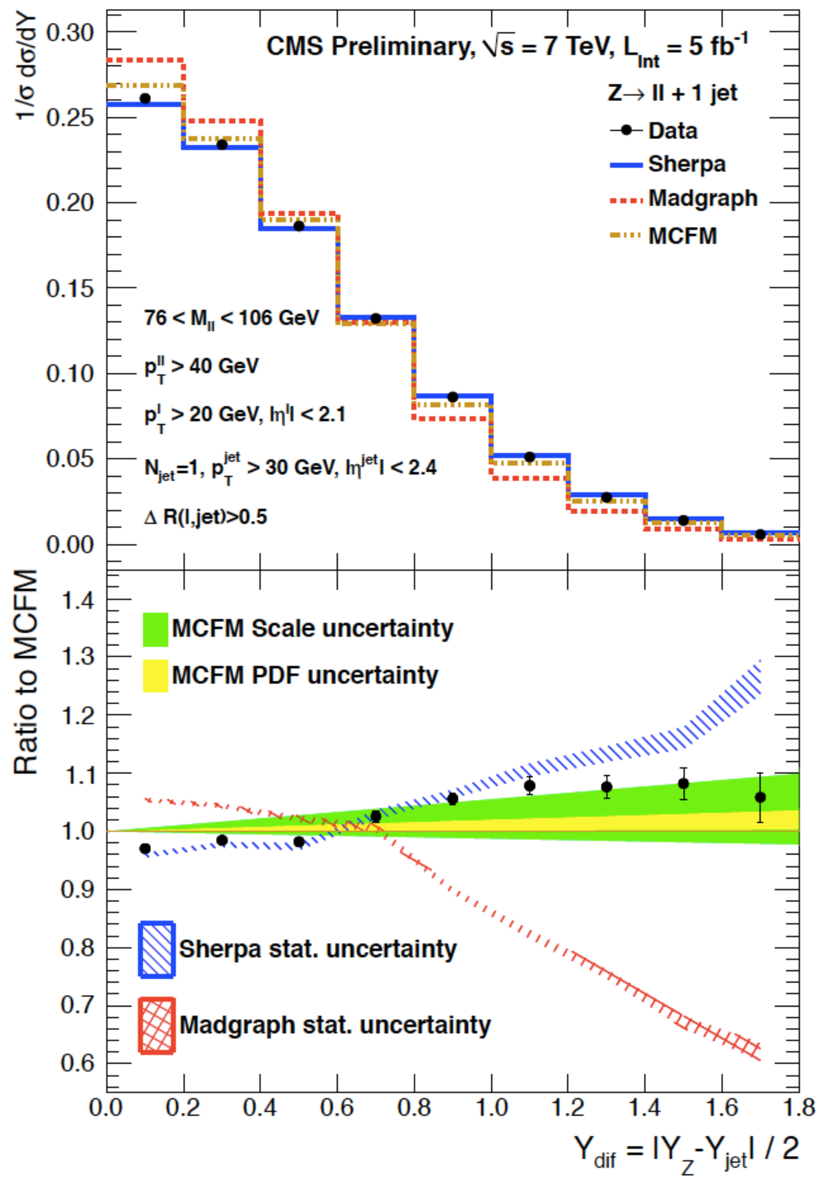
related to the polar scattering angle in the Z-j center of mass frame

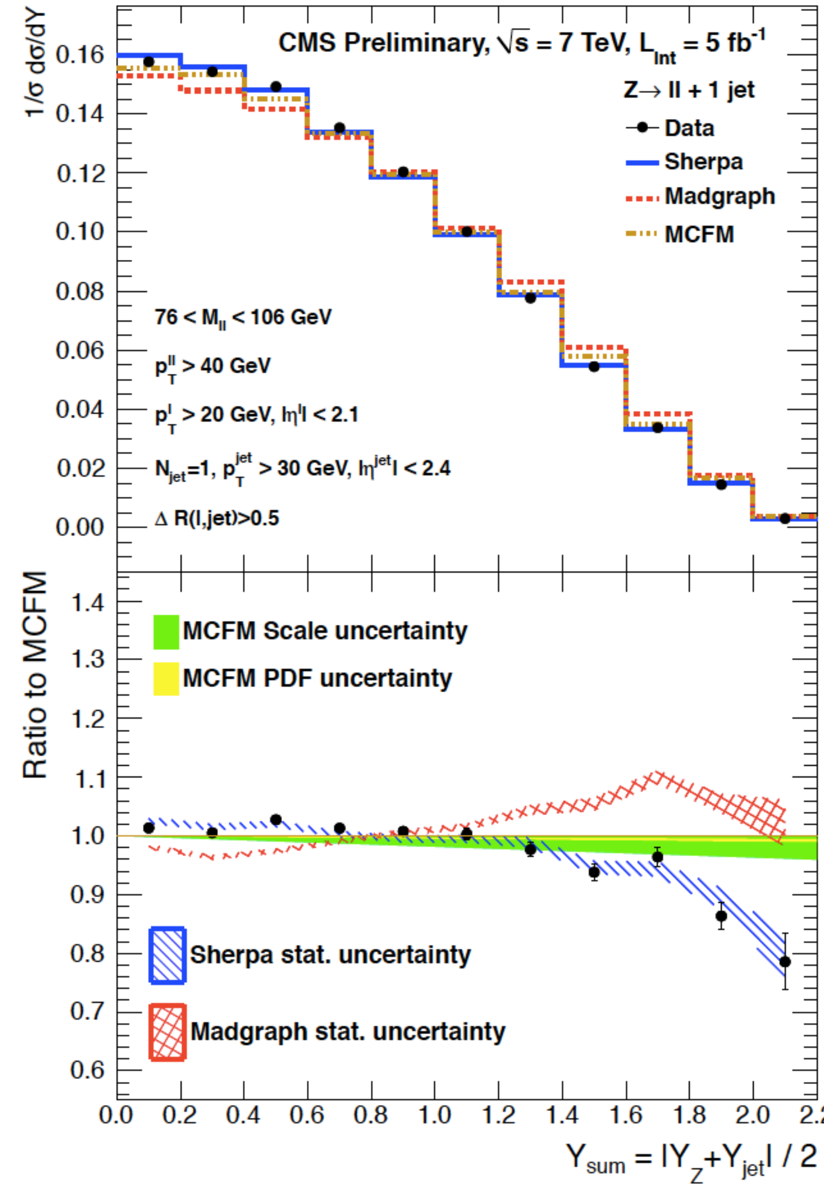
$$\cos\theta^* = \tanh(Y_{\rm dif})/\beta^*_Z$$

$$Y_{\rm sum} = |Y_Z + Y_j|/2$$

~rapidity boost from lab to COM frame

Y_j and Y_Z highly correlated because there is usually a relatively high momentum quark interacting with a low momentum gluon or anti-quark

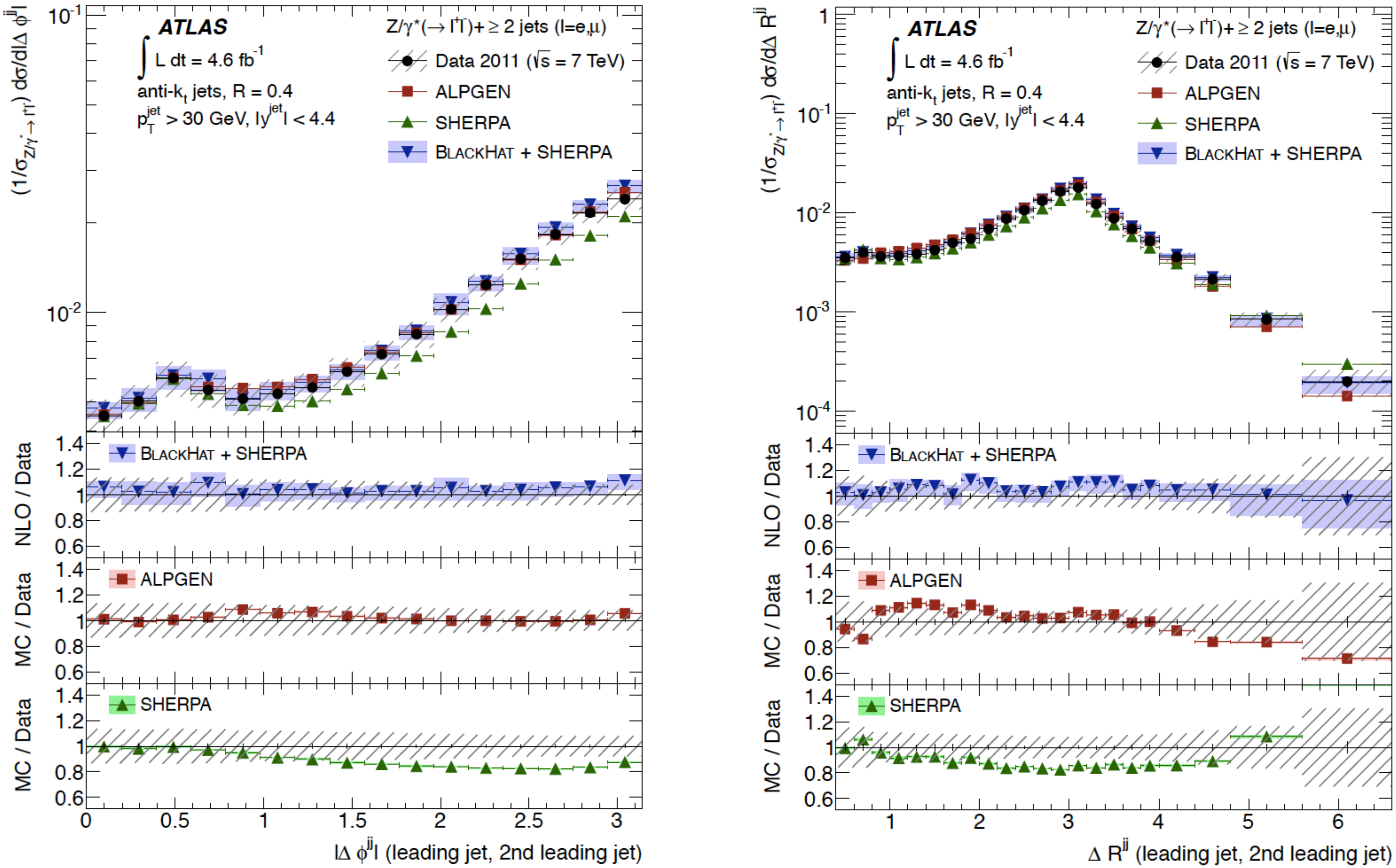




- Good agreement between data and NLO calculations from MCFM
- SHERPA reproduces data better than MadGraph
  - difference introduced in matching ME to PS
  - large difference for more forward distributions

JHEP07(2013)032

Z + jets - two leading jets ΔΦ and ΔR



- |ΔΦ| well modeled by BLACKHAT+SHERPA and ALPGEN
  - SHERPA predicts a spectrum that is less pronounced

Z + jets - H_T

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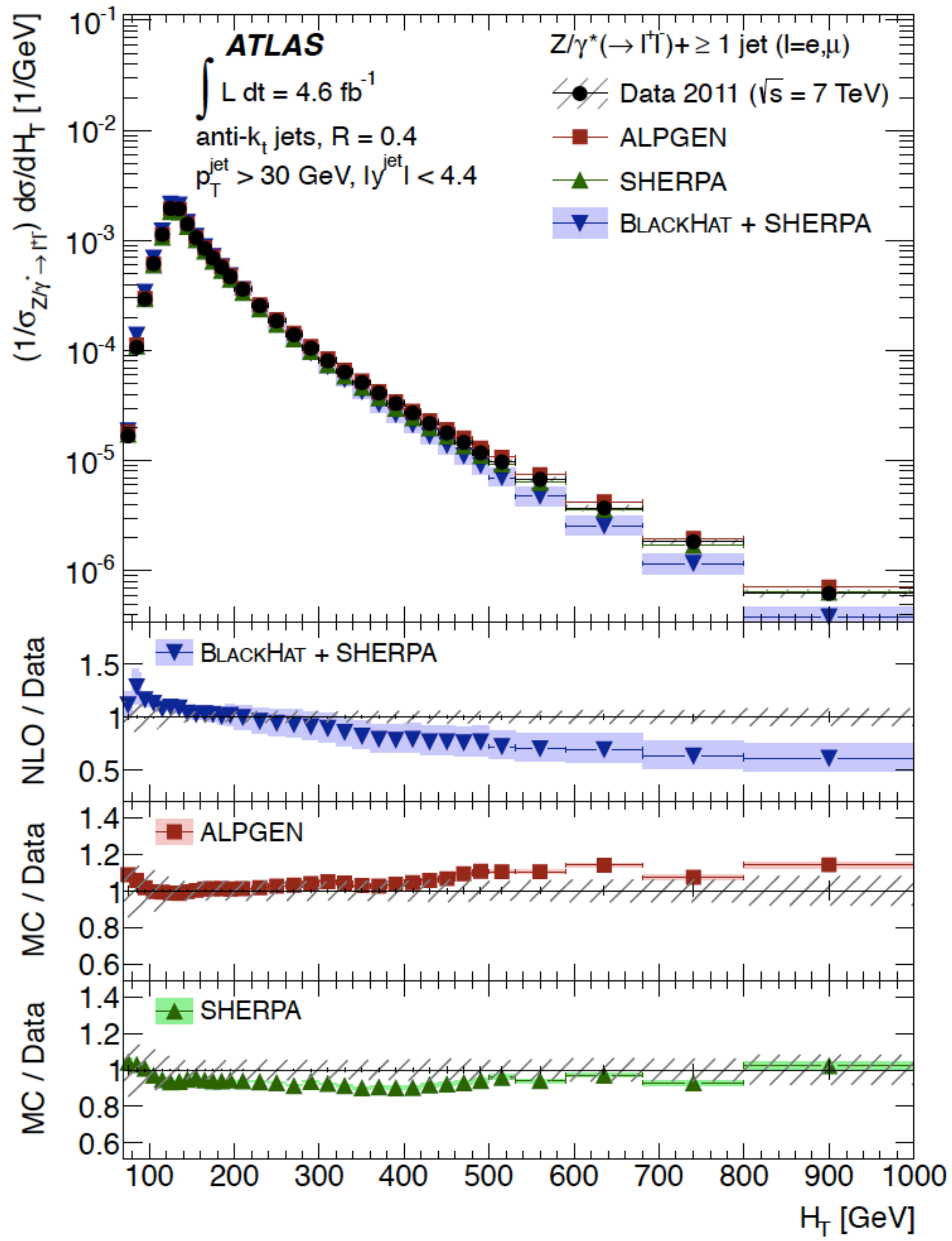
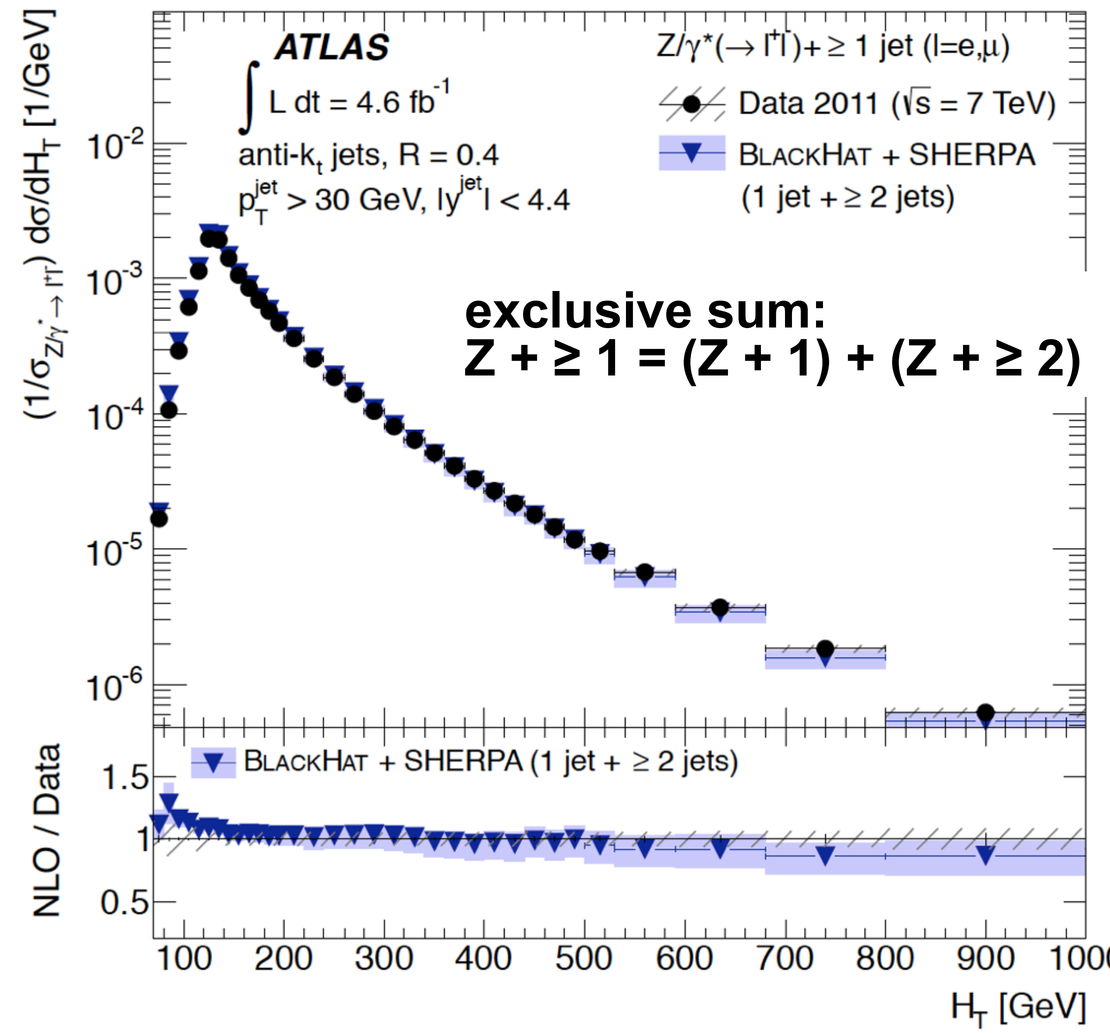
- H_T is the scalar sum of jets and leptons p_T



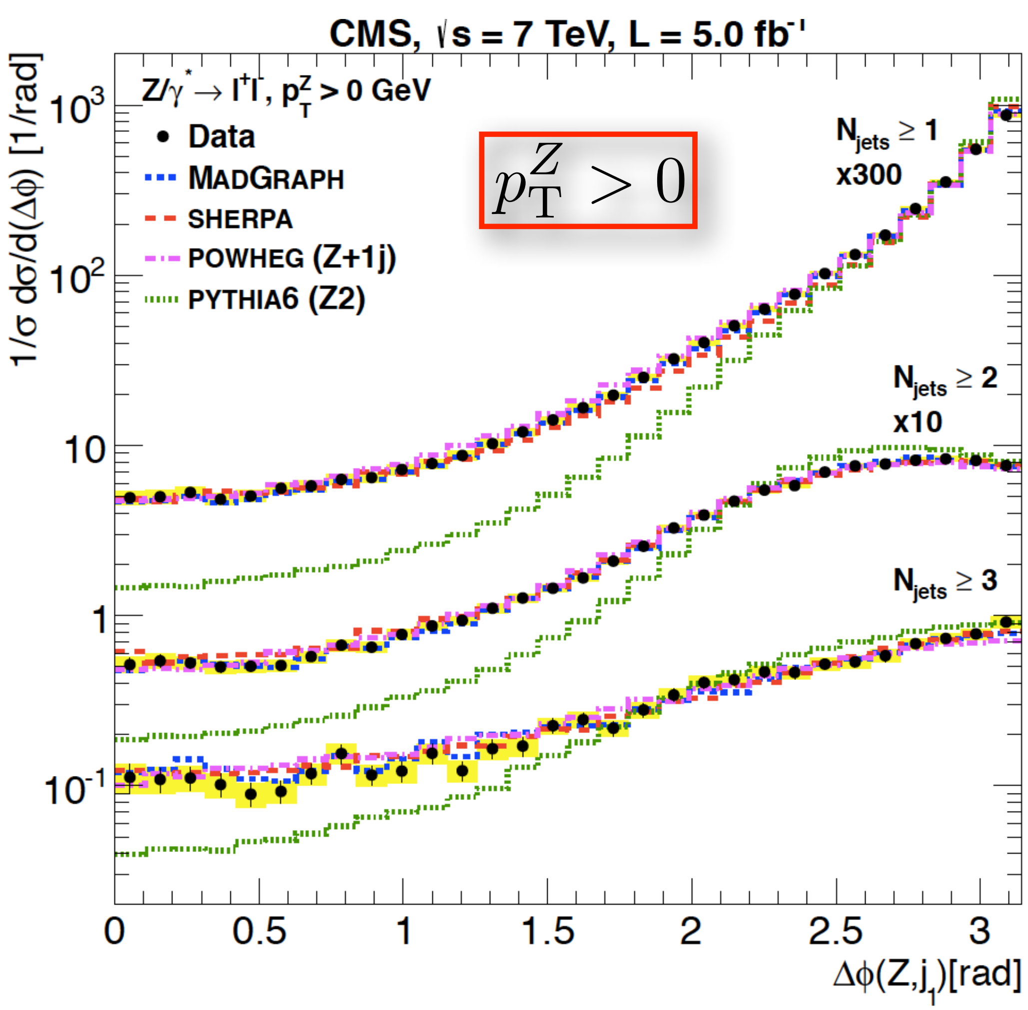


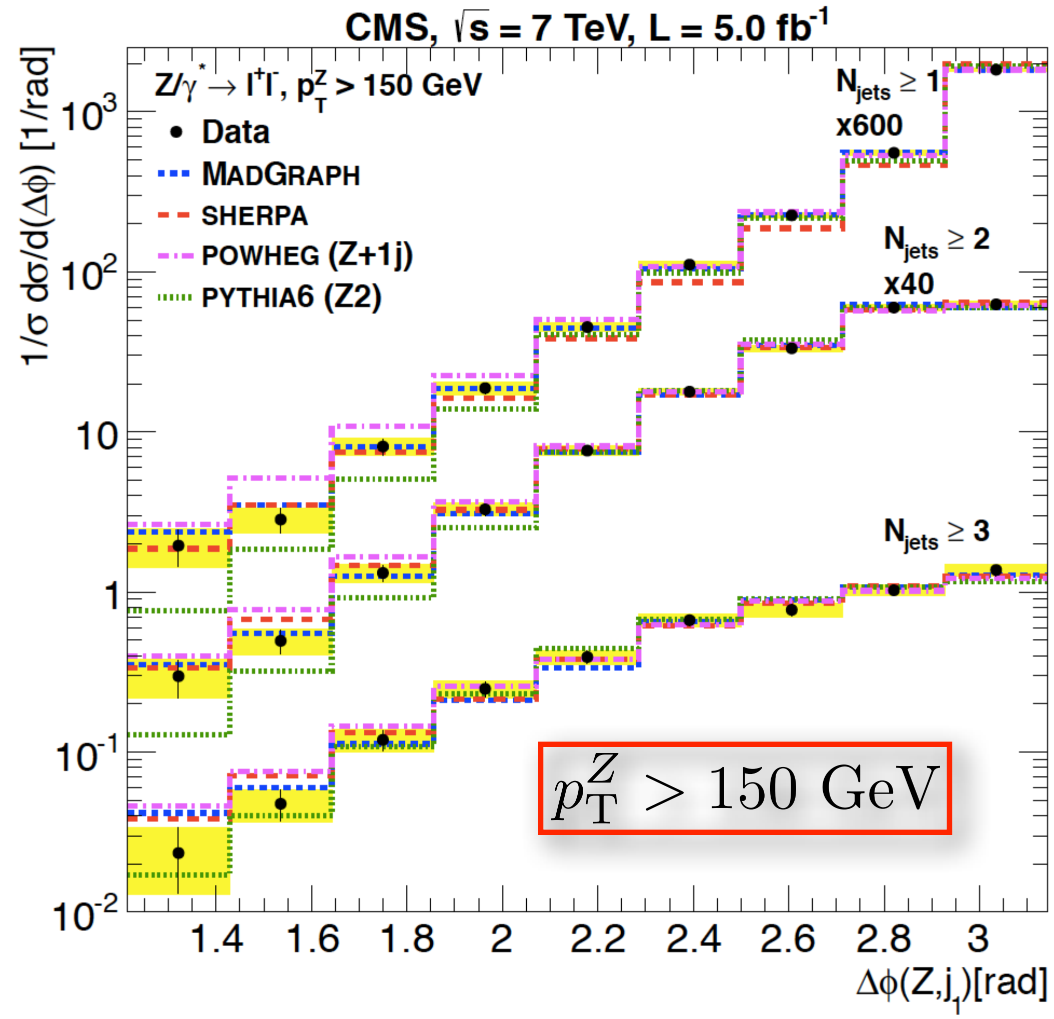
- NLO fixed order Z ≥ 1 jets deficit at large H_T
  - missing higher order QCD?
- ALPGEN, SHERPA agree with data

- Better agreement with data is reached for NLO calculations when using **exclusive sums**
  - H_T > ~300 GeV corresponds to an average jet multiplicity of more than 2 jets
  - same outcome for Z p_T

Phys. Lett. B722 (2013) 238

Z+jets - azimuthal correlations ΔΦ(Z, j₁)





- ΔΦ(Z, j₁): ΔΦ between the Z and the leading jet for the inclusive multiplicities
  - $N_{jets} \geq 1, \geq 2, \geq 3$
  - normalized to unity
- ΔΦ observable with largest systematics
  - 5-6% near 0, to 2% near π

- Agreement with POWHEG and SHERPA improve for larger multiplicities
- Multi-parton LO + PS do better than LO + PS !!
- PS important for NLO 1 jet in multijet environment

Z+jets - azimuthal correlations $\Delta\Phi(Z, j_i)$

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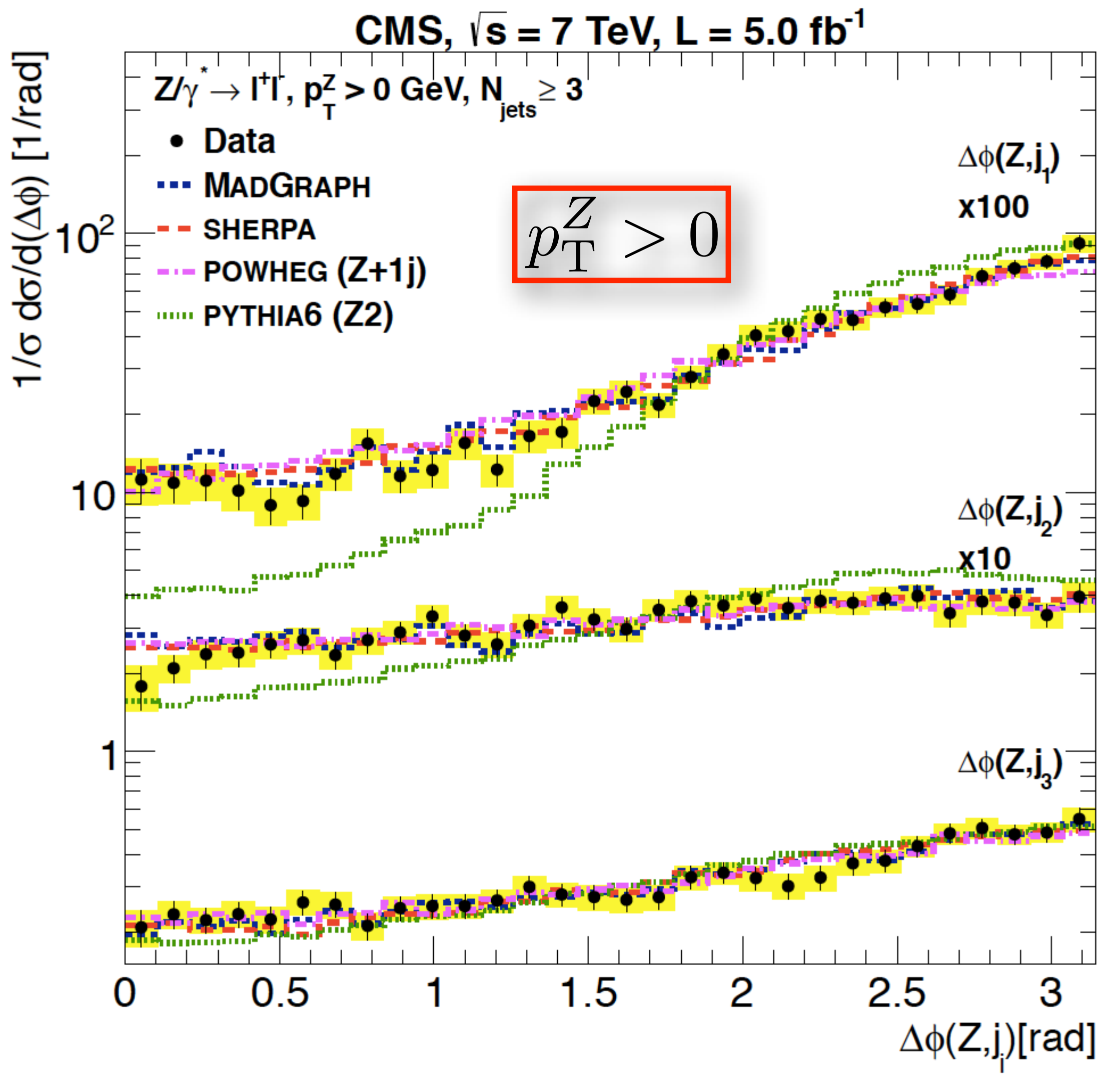
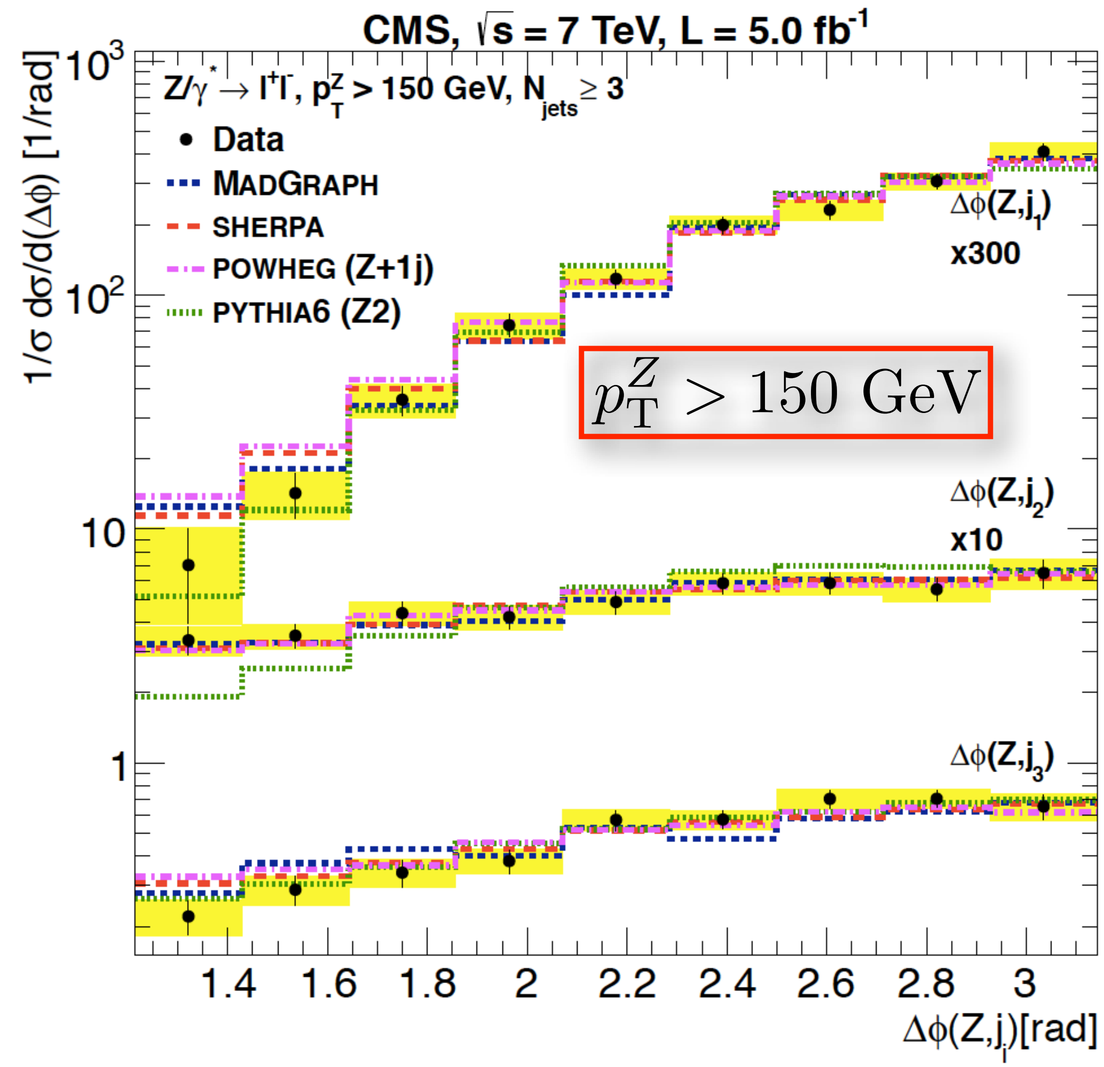


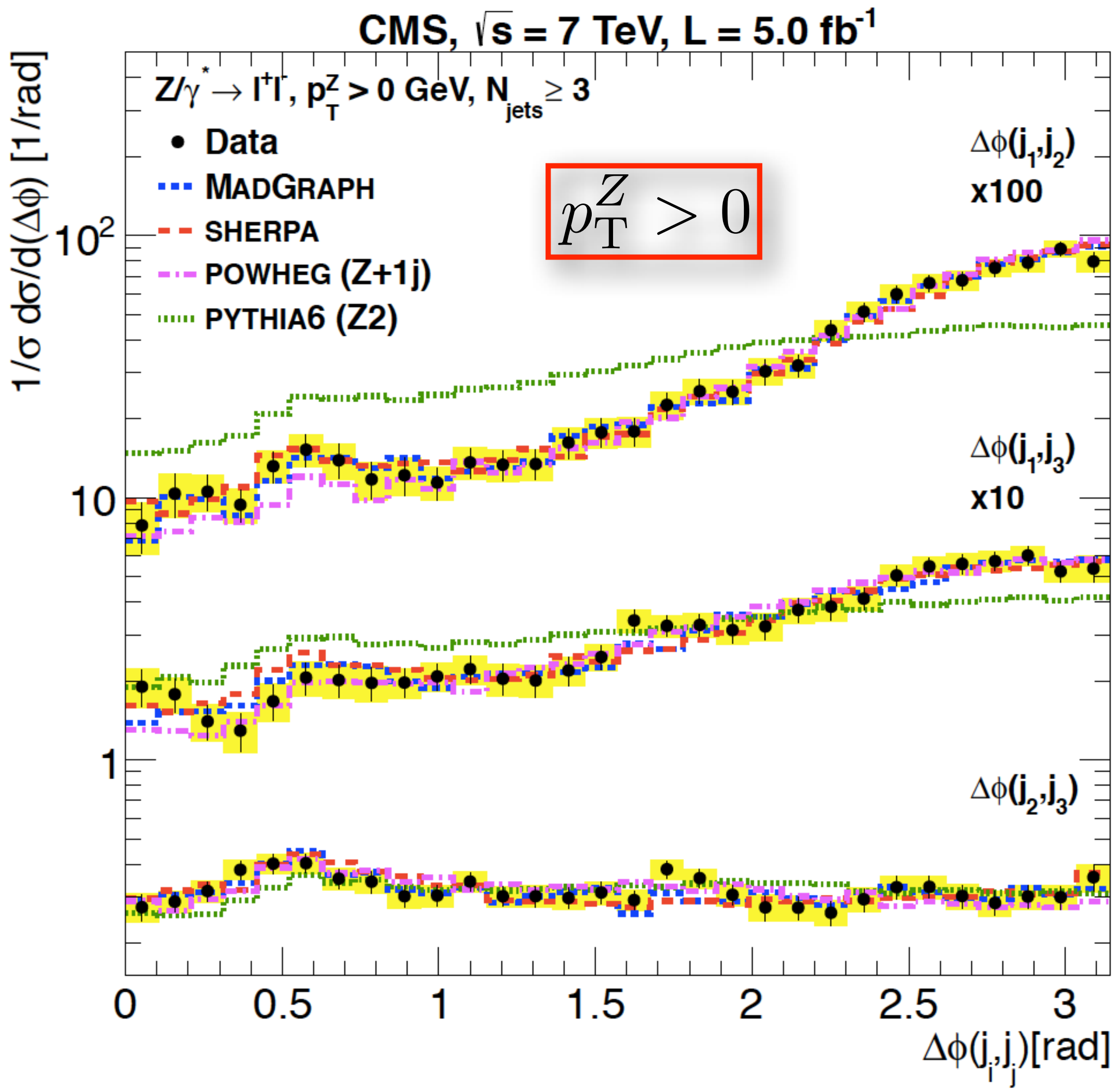


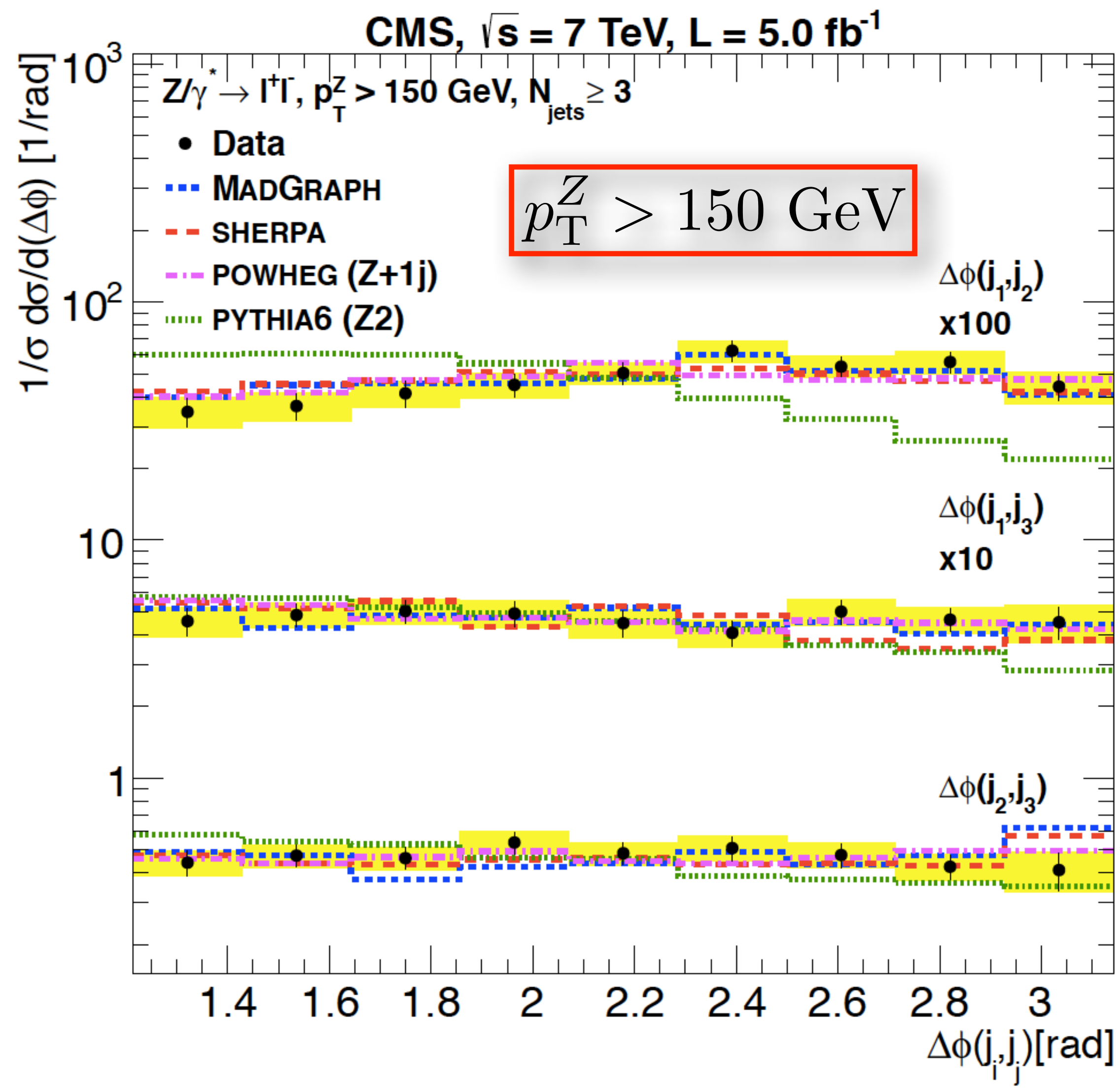
- $N_{jets} \geq 3$
  - $\Delta\Phi(Z, j_i)$
  - normalized to unity

- Good agreement with POWHEG, MadGraph and SHERPA
- For $\Delta\Phi(Z, j_3)$, PYTHIA LO + PS agrees with data
  - PS contribution

Phys. Lett. B722 (2013) 238

Z+jets - azimuthal correlations $\Delta\Phi(j_i, j_k)$





- $N_{jets} \geq 3$
  - $\Delta\Phi(j_1, j_2)$
  - $\Delta\Phi(j_1, j_3)$
  - $\Delta\Phi(j_2, j_3)$
  - normalized to unity

- Isotropic for $p_T^Z > 150$ GeV
  - improved agreement with PYTHIA consistent with increased phase space available for parton emission

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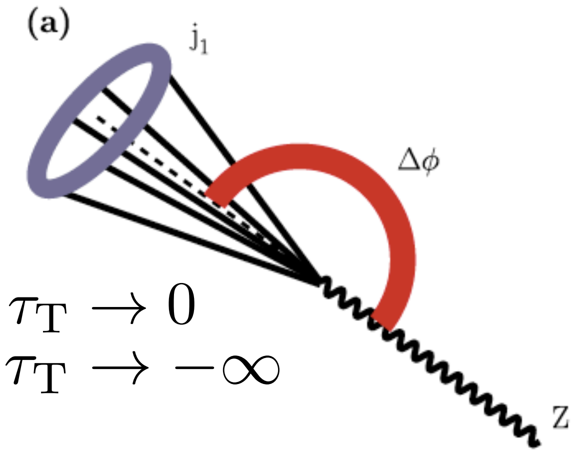
Z+jets - event shape: transverse thrust

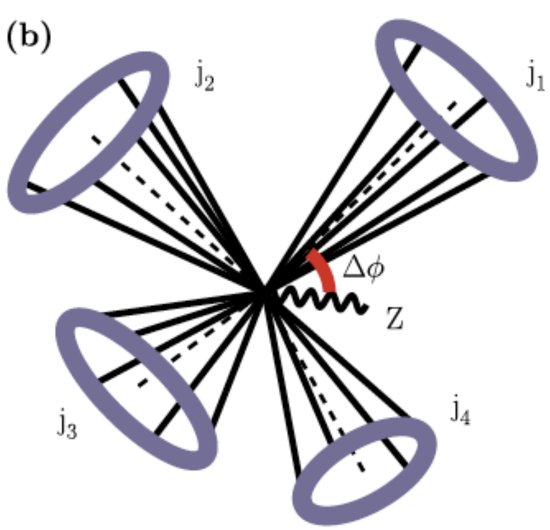
$$\tau_\mathrm{T} \equiv 1 - \max_{\vec{n}_\tau} \frac{\sum_i |\vec{p}_{\mathrm{T}i} \cdot \vec{n}_\tau|}{\sum_i p_{\mathrm{T}i}}$$

sum over Z and jets



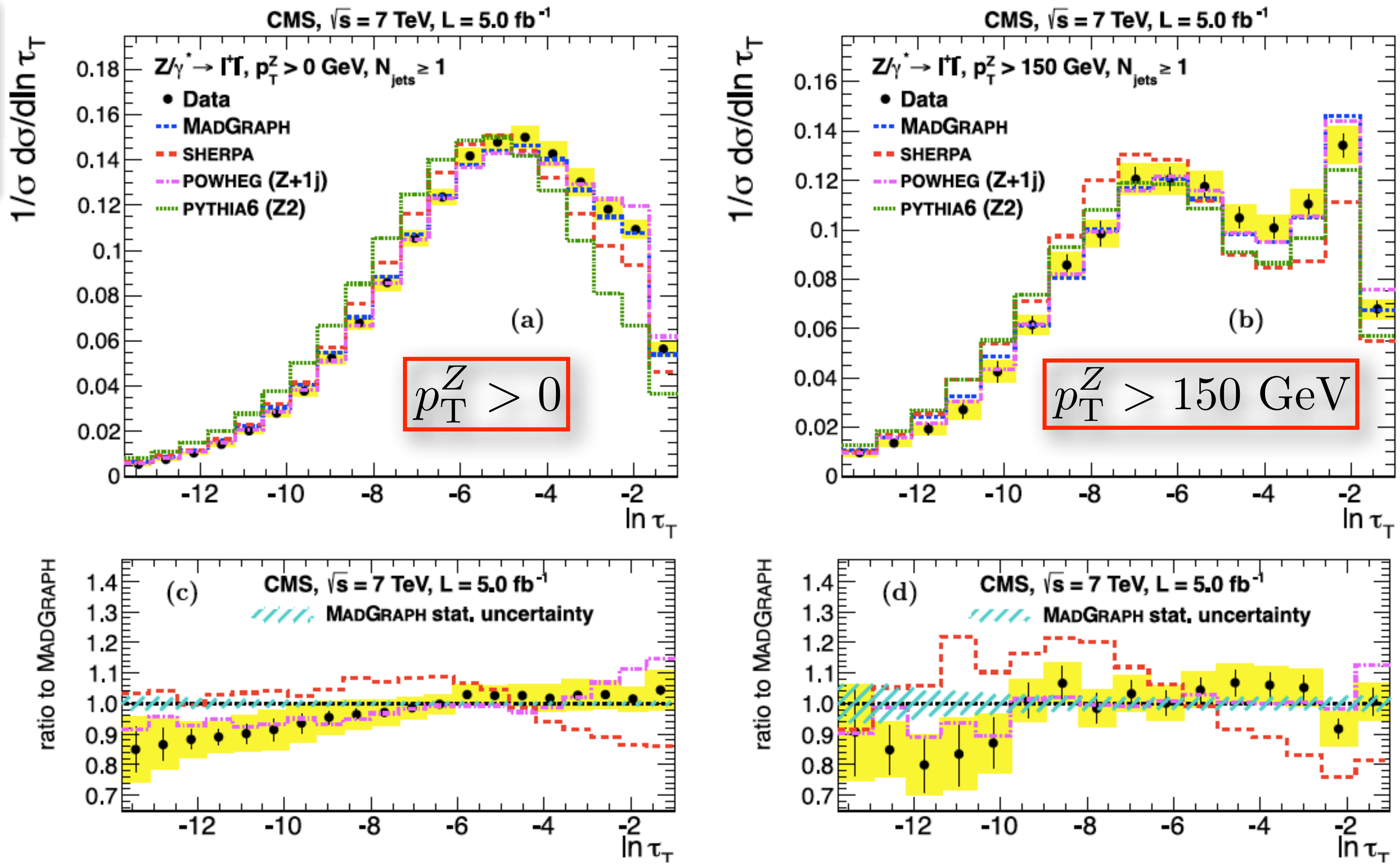
$\tau_\mathrm{T} \to 0$

$\ln \tau_\mathrm{T} \to -\infty$



$\tau_\mathrm{T} \to 1 - 2/\pi$

$\ln \tau_\mathrm{T} \to \approx -1$



- Transverse thrust, normalized to unity, ratio to MadGraph
  - dominant systematics from energy scale: 2%
  - at P_T^Z > 150 GeV, many events with spherical component

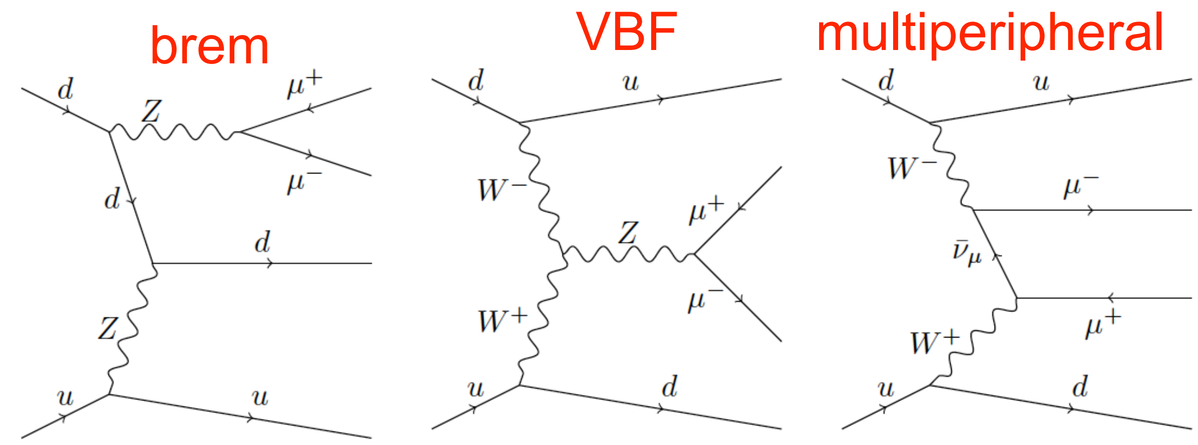
- POWHEG and MadGraph more consistent with data
- SHERPA and PYTHIA shifted to lower values (dijet-like)
- PYTHIA compares better for P_T^Z > 150 GeV

Z+jets - EW Z+2 forward jets

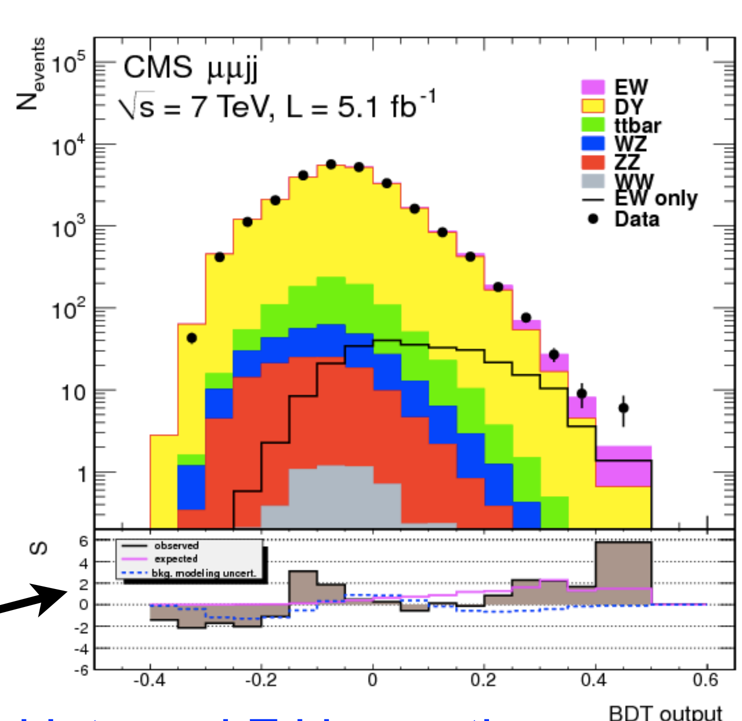
CMS-FSQ-12-019
arXiv:1305.7389

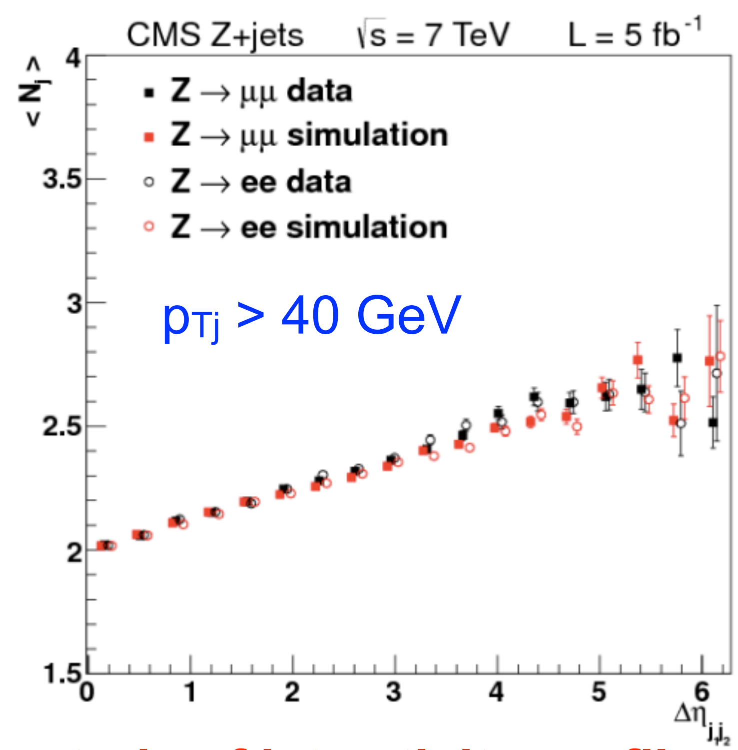
- Z production in association with two jets at order α^4_{EW}
  - includes TGC vertex (VBF), suppressed by a factor ~2.5 by interference terms
  - high p_T jets with large rapidity distance
- $\sigma(\mathrm{EW}\ \ell\ell jj)_{NLO}$ = 166 fb (DY ~ 29.3 pb!)
  - M_{jj} > 120 GeV, $M_{\ell\ell}$ > 50 GeV
  - p_{Tj} > 25 GeV, $|\eta_j|$ < 4
  - CT10 and $\mu_R = \mu_F$ = 90 GeV
- Optimized event selection (S/B ~ 11%)
  - leptons: $\ell\ell$ with $p_{T\ell}$ > 20 GeV, $|\eta_\ell|$ < 2.4
  - Z: $|M_{ee}-M_Z|$ < 20 GeV (15 GeV for $\mu\mu$)
  - two leading p_T jets in $|\eta|$ < 3.6
    - $p_T(1)$ > 65 GeV; $p_T(2)$ > 40 GeV
    - M_{jj} > 600 GeV
  - central Z in jj rest frame
    - $|y^*| = |y_Z - (y_{j1} - y_{j2})/2|$ < 1.2
- Signal extraction with MVA
  - Boosted decision tree, including tagged jets and Z kinematics

$$\sigma^{\mathrm{EWK}}_{\mathrm{meas},\ \mu\mu+\mathrm{ee}} = 154 \pm 24(\mathrm{stat}) \pm 46(\mathrm{exp.syst.}) \pm 27(\mathrm{th.syst}) \pm 3(\mathrm{lumi})\ \mathrm{fb}$$



- Important benchmark processes in search for VBF H!!



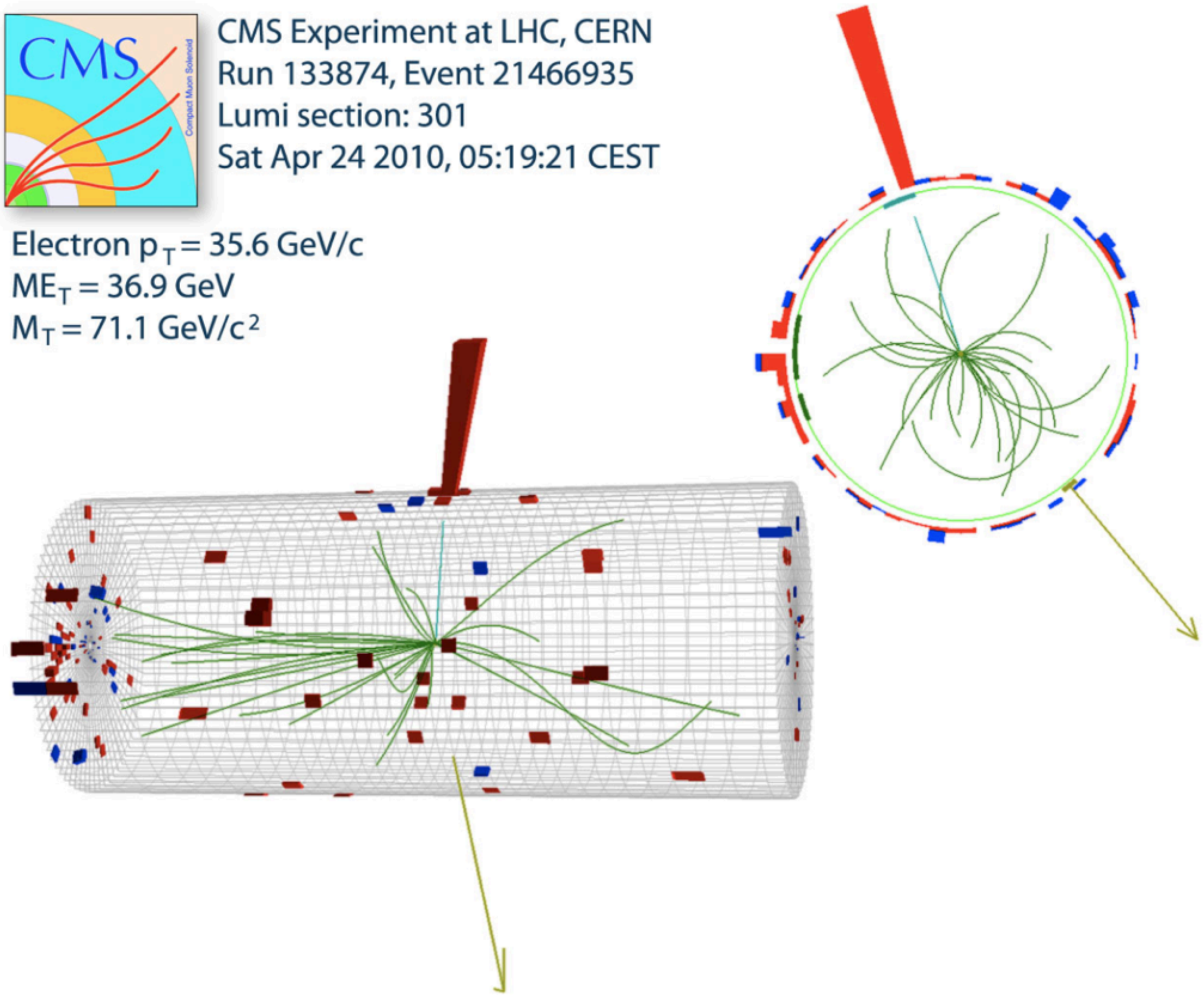


study of jet activity profiles: also for ΔΦ and H_T

- Jet activity profiles: MadGraph-based predictions in agreement with data (reco level)
- $\sigma(\mathrm{EW}\ \ell\ell jj)$ extracted (~2.6σ), compatible with prediction (NLO QCD corrections)

W + jets

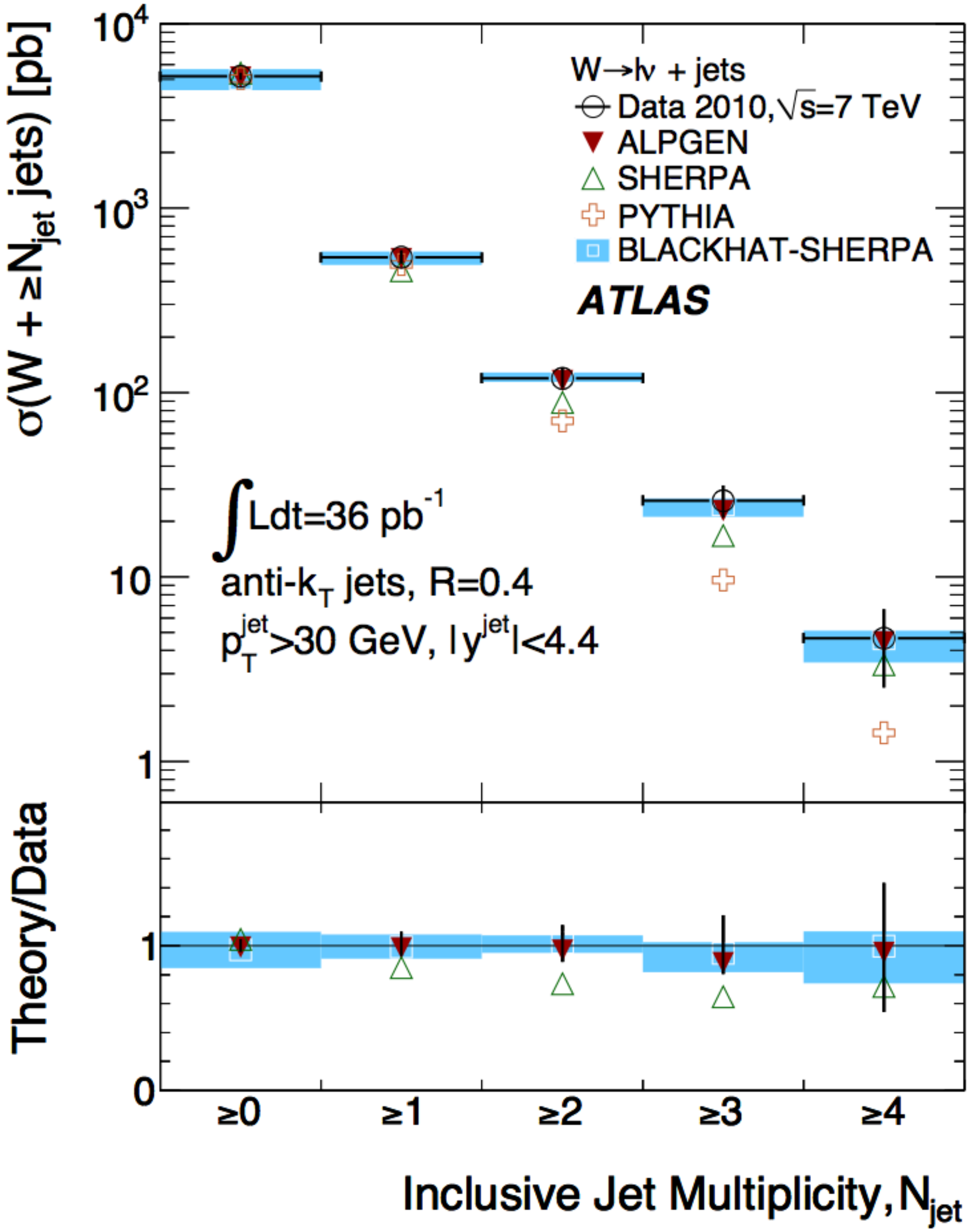
- W+jets complementary to Z+jets
  - larger statistics
  - larger systematics



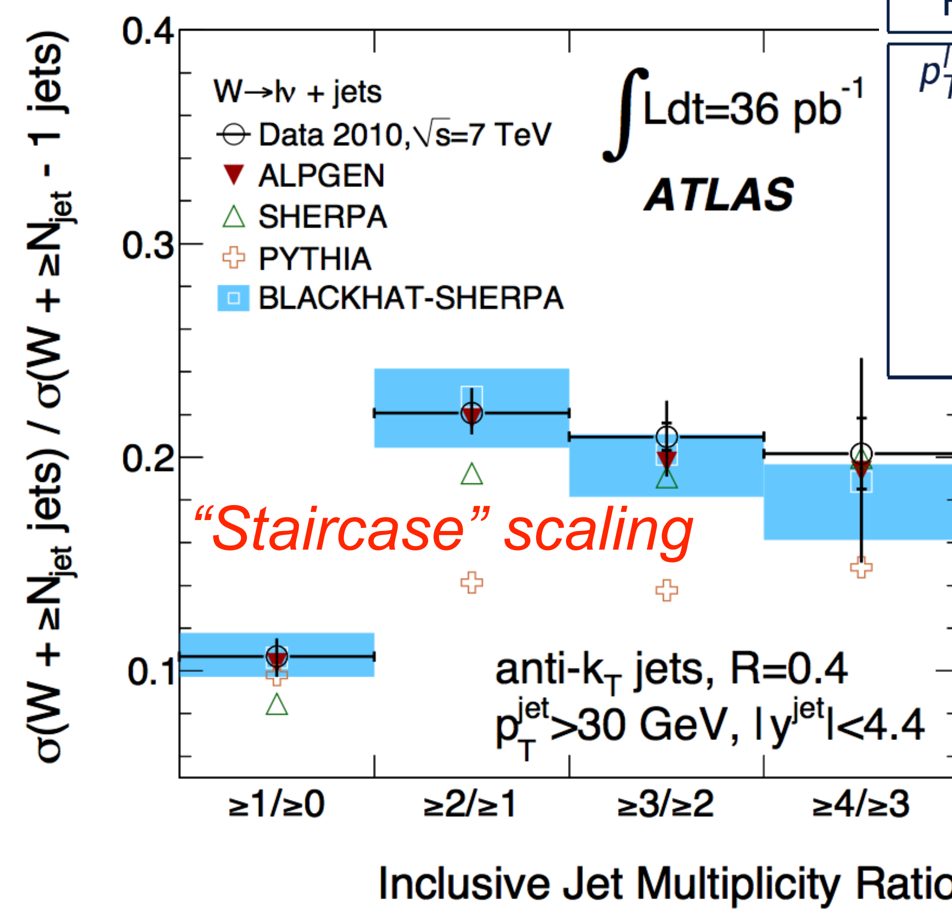
W + jets - jet multiplicities

Phys. Rev. D85 (2012) 092002

Br(W→ℓν) included in σ



- BLACKHAT+SHERPA + CTEQ6.6M + $\mu_{R/F}$ = $H_T/2$
- ALPGEN 2.13 + CTEQ6L1 + $\mu_{R/F}$ = $\sqrt{M_W^2 + \sum_j p_T^2}$ + MLM
- SHERPA 1.3.1 + CTEQ6.6M + default $\mu_{R/F}$ + CKKM
- PYTHIA 6.4.21



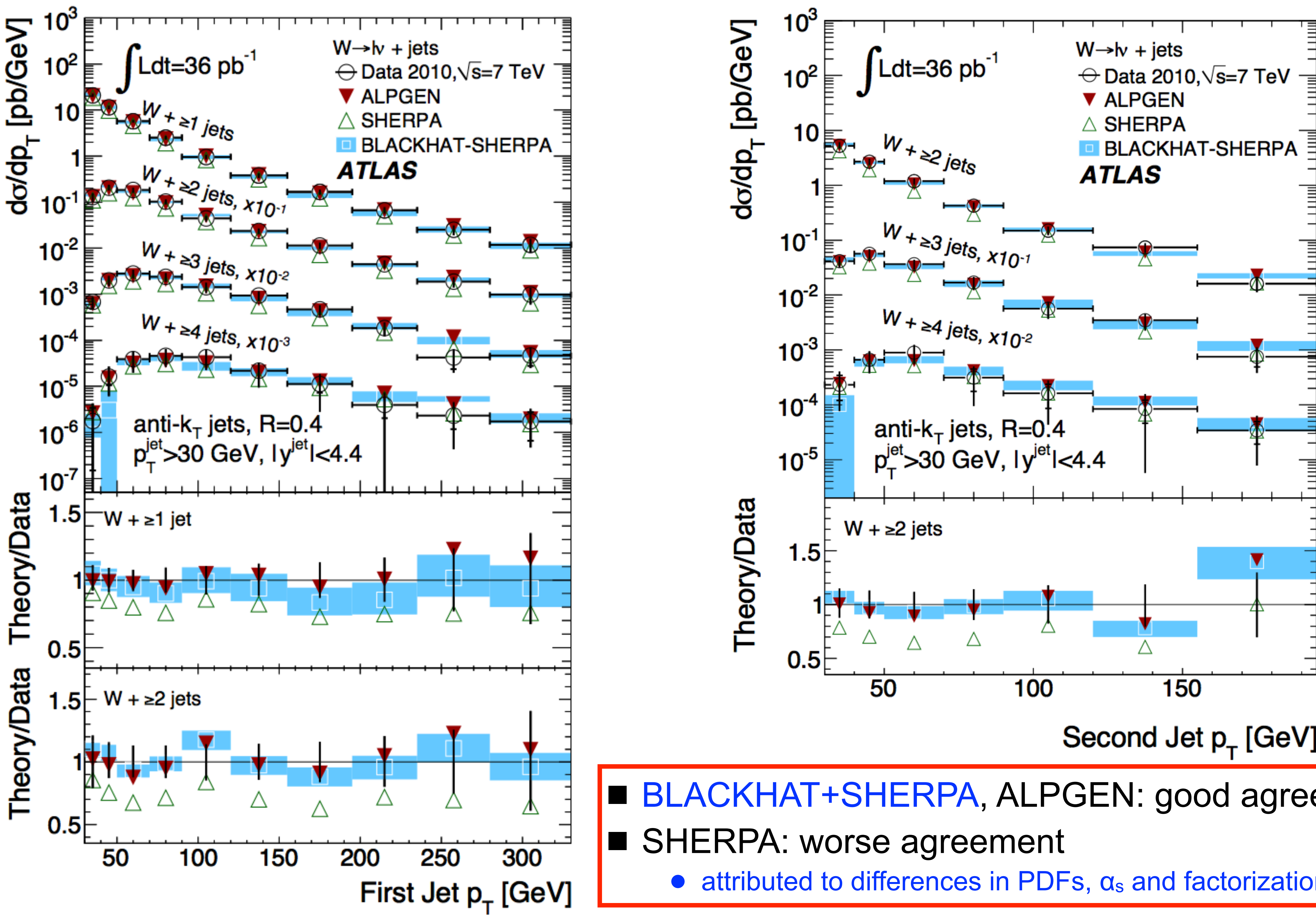
Fiducial Phase Space

$p_T^l > 20$ GeV, $|\eta| < 2.5$
$E_T^{miss} > 25$ GeV
$m_T(W) > 40$ GeV
$p_T^{jet} > 30$ GeV
$|y^{jet}| < 4.4$
$\Delta R^{lj} > 0.5$

- BLACKHAT+SHERPA: good agreement
- SHERPA: worse agreement
  - attributed to differences in PDFs, α_s and factorization/renormalization scales
- PYTHIA is LO ME up to 1 jet...

W + jets - first and second jet p_T

Phys. Rev. D85 (2012) 092002

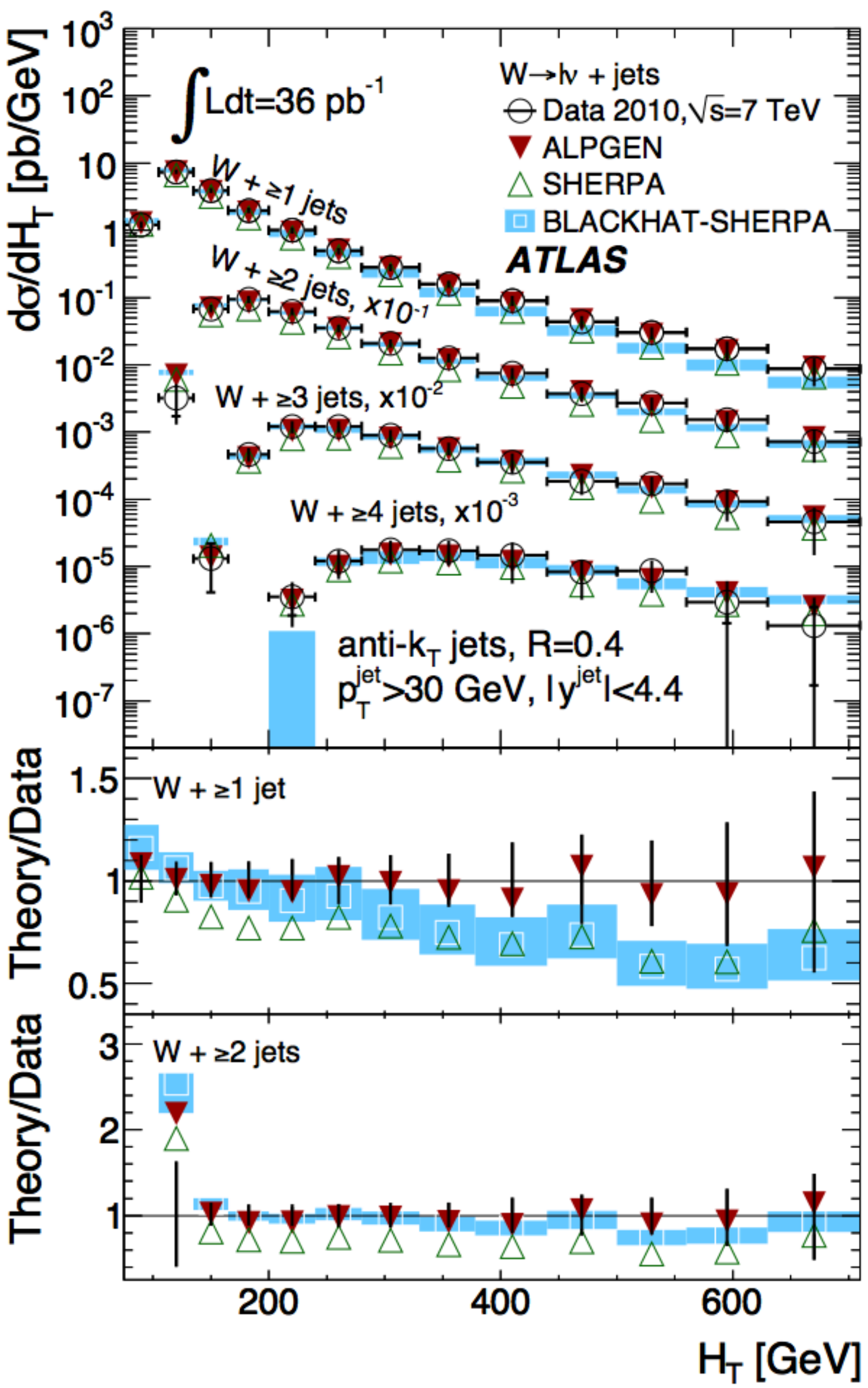


- BLACKHAT+SHERPA, ALPGEN: good agreement
- SHERPA: worse agreement
  - attributed to differences in PDFs, α_s and factorization scales

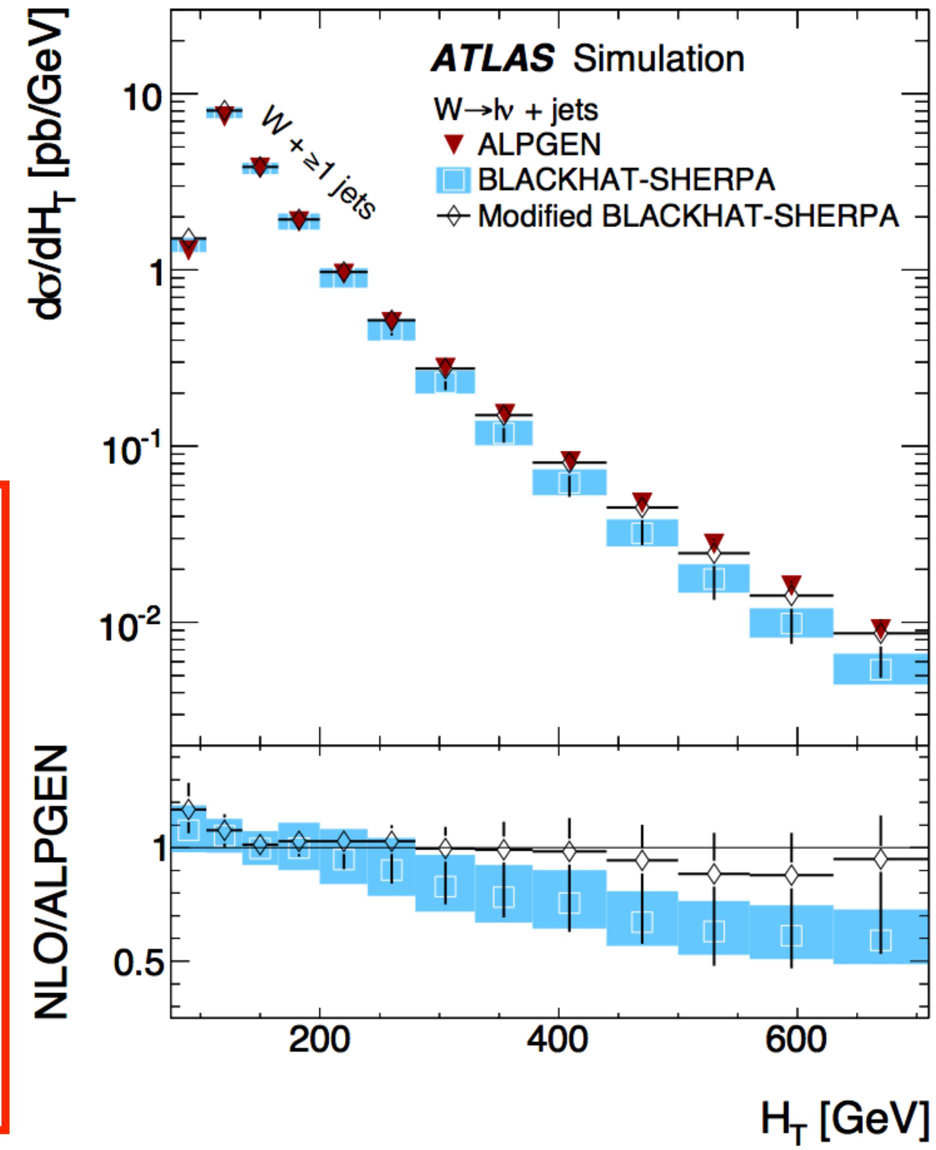
W + jets - H_T

Phys. Rev. D85 (2012) 092002

- H_T is the scalar sum over p_T of jets, the lepton, the neutrino (E_T^{miss})



- Probe NLO pQCD properties
- H_T often used for μ_R and μ_F



- ALPGEN (Multi-leg LO) agrees well with the data
- discrepancies in W + ≥ 1 jets with (limited order) NLO calculations for mean N_{jets} > 2 at large H_T

- Agreement improved on H_T with BLACKHAT by replacing NLO W + ≥1 jet with exclusive NLO sums (matched by counting parton jets with p_T > 30 GeV):
  - W + ≥ 1 = (W + 1) + (W + 2) + (W + 3) +(W + ≥ 4 jets)
  - confirmed in Z+jets

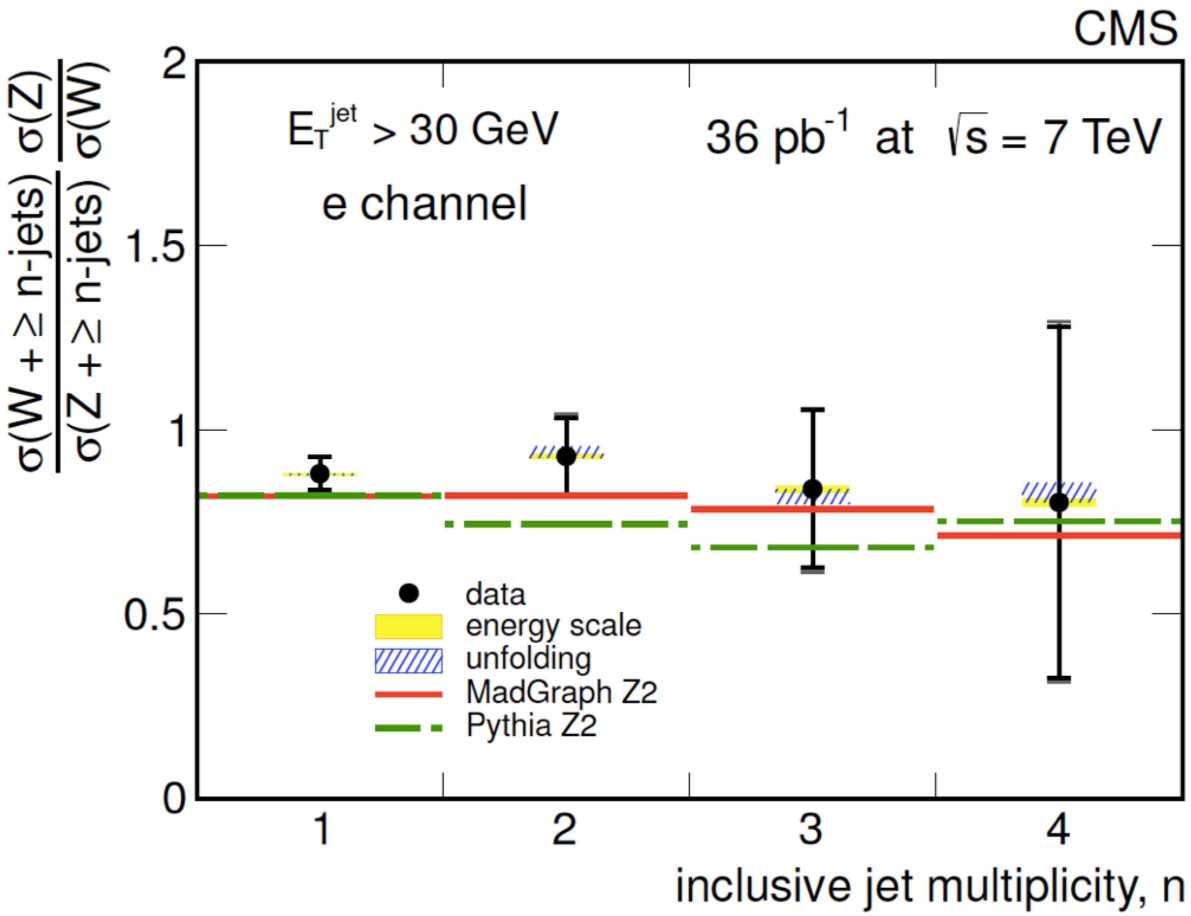
(W + jets)/(Z + jets)

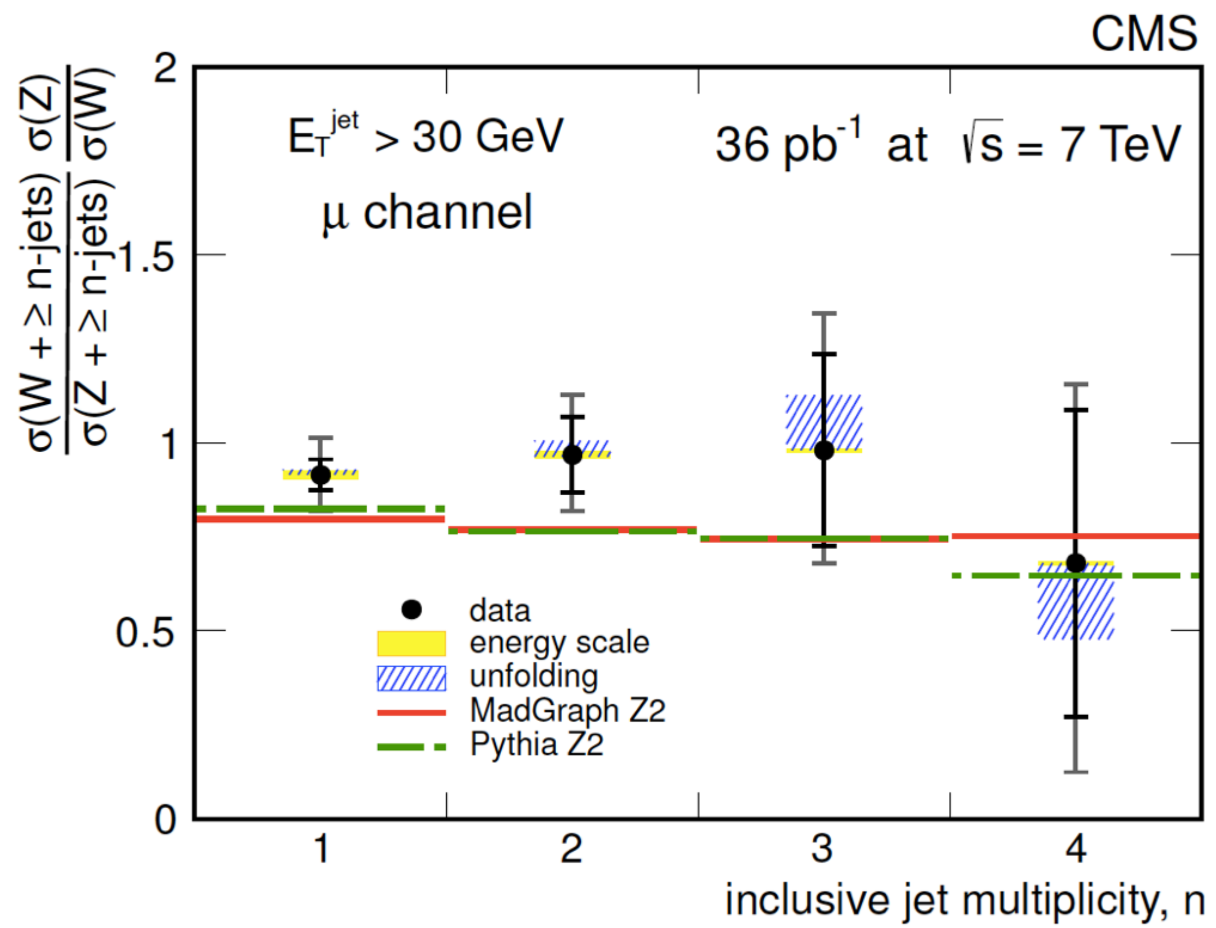
- Cancellation of many systematics
  - powerful test of pQCD

(W + ≥n jets)/(Z + ≥n jets)

JHEP01(2012)010

- Normalized to the inclusive cross section





- Many important systematic uncertainties cancel in the ratio
  - most important remaining from the selection efficiency (possible bin correlations due to M_T cut)
- difference in expected value in the e and μ channel due to larger electron acceptance in |η|

- Both MadGraph and PYTHIA agree with data within 1 σ_{exp}

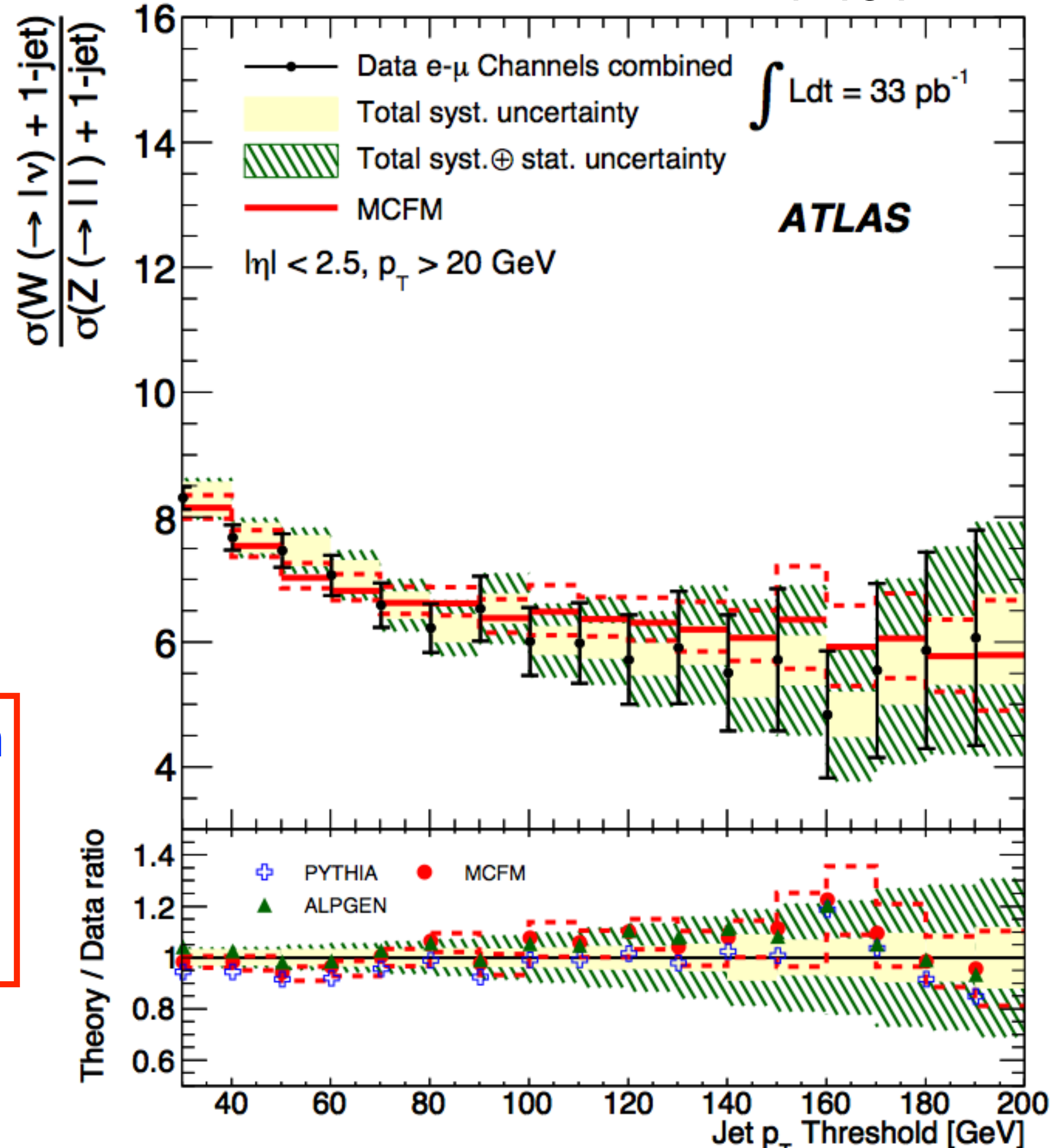
(W + 1 jet)/(Z + 1 jet)

Phys. Lett. B708 (2012) 221-240

- Ratio of production cross section of W and Z with exactly 1 jet as a function of the jet p_T threshold
  - $71 < m_{\ell\ell} < 111$ GeV and $|\eta_{jet}| < 2.8$
  - combination of the e and μ channels in the fiducial volume
- At p_T = 30 GeV
  - 8.29 ± 0.18(stat) ± 0.28(sys)
- W and Z production are similar: ratio less sensitive to systematics limitations of V + jets
  - remaining systematic dominated by the boson reconstruction
  - for jet p_T threshold > 50 GeV, the uncertainty is statistically dominated

- LO and NLO predictions agree with data
- Larger data samples (2011, 2012) will allow a very precise test of pQCD

7 TeV



MCFM with CTEQ6.6M, $\mu_R=\mu_F=H_T/2$

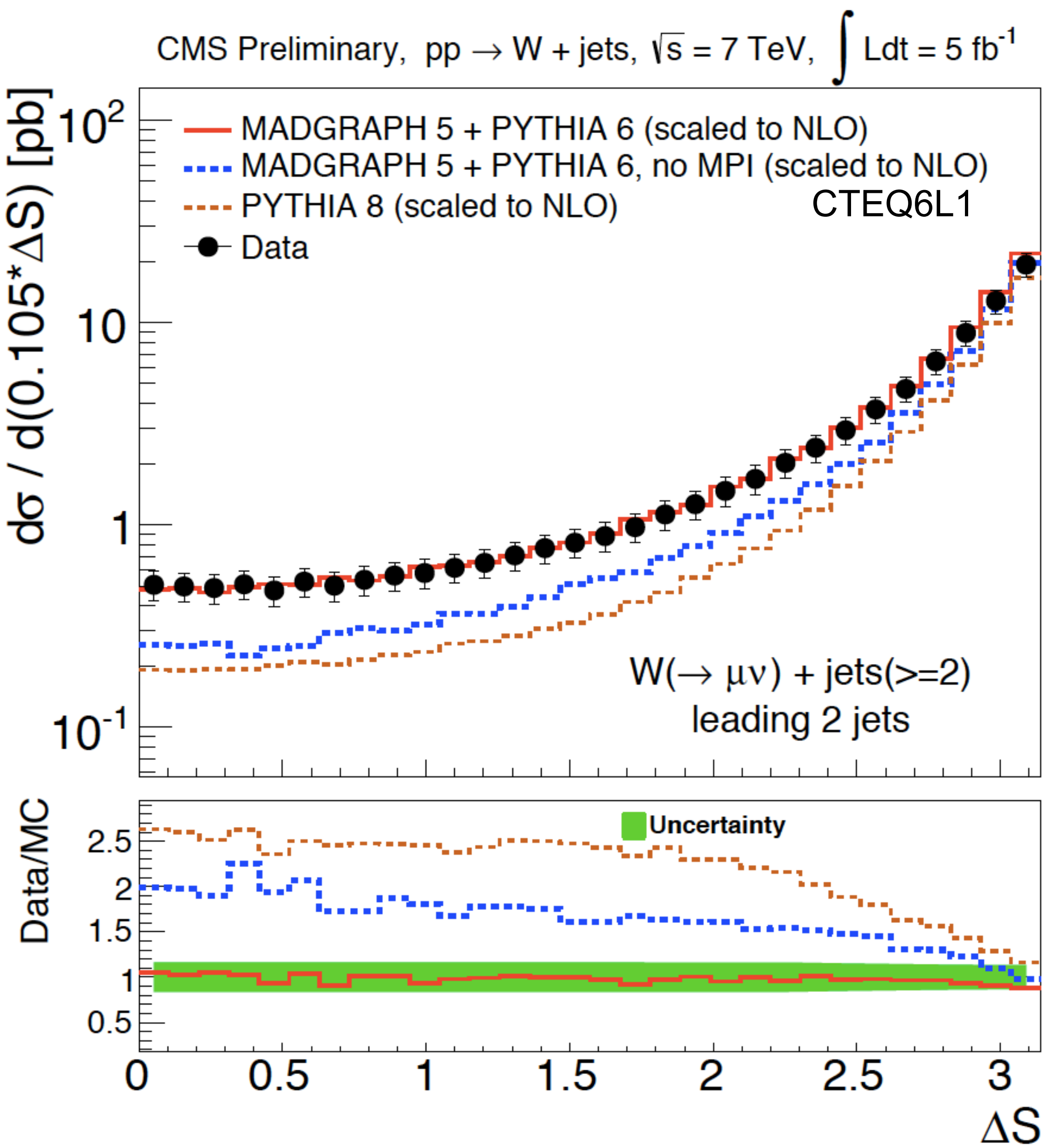
Double Parton Interaction

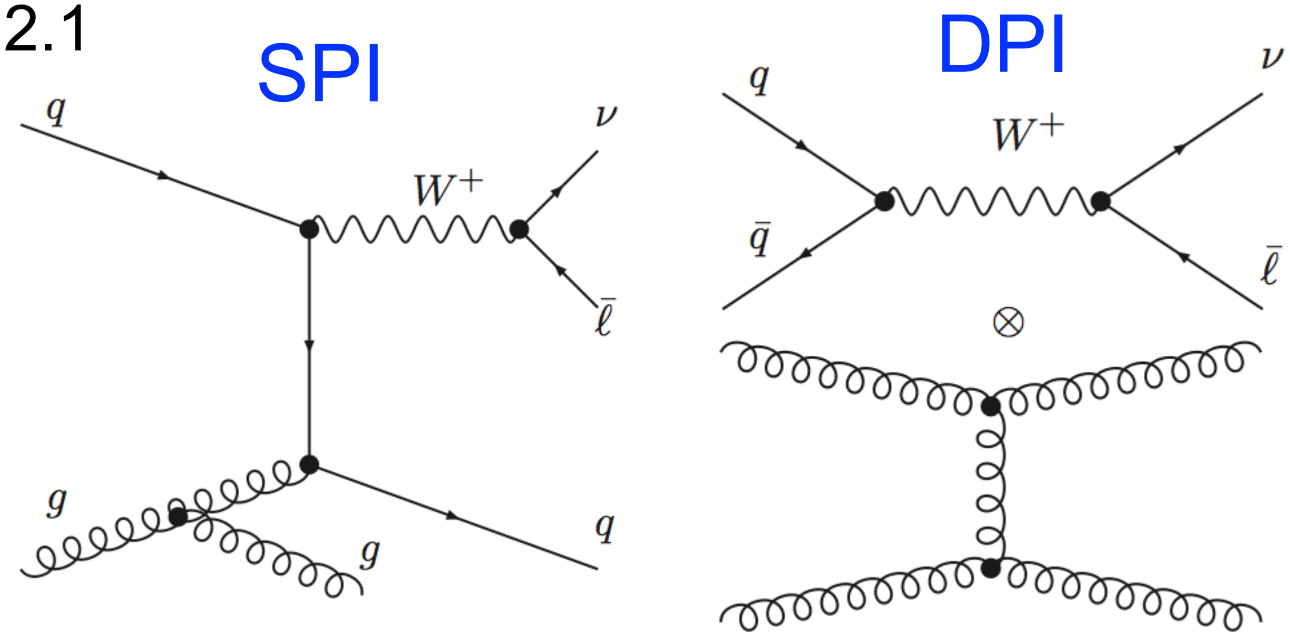
- Use W + 2 jets to probe DPI
  - Higher $\sqrt{s}$ and luminosity imply bigger impact of DPI, and at higher p_T
  - Relevant contribution for analyses such as
    - W+b cross section
    - W+j/ψ cross section
    - final states with same sign WW

W + 2 jets - double parton interaction

CMS-FSQ-12-028

- One muon with $p_{T\mu}$ > 35 GeV and |η| < 2.1
- E_T^{miss} > 30 GeV, M_T > 50 GeV
- Jets with p_T > 20 GeV and |η| < 2.0





- ΔS = ΔΦ between W and dijet system
  - ~random for DPI
  - ~back-to-back for SPI

- MadGraph+PYTHIA 6.4.25+Z2star tune
  - with multiple parton interaction: good description of the data
  - without multiple parton interaction: rate and shape not reproduced
- PYTHIA 8.165+4C tune
  - missing higher order diagram: predicts more back-to-back

W + 2 jets - double parton interaction

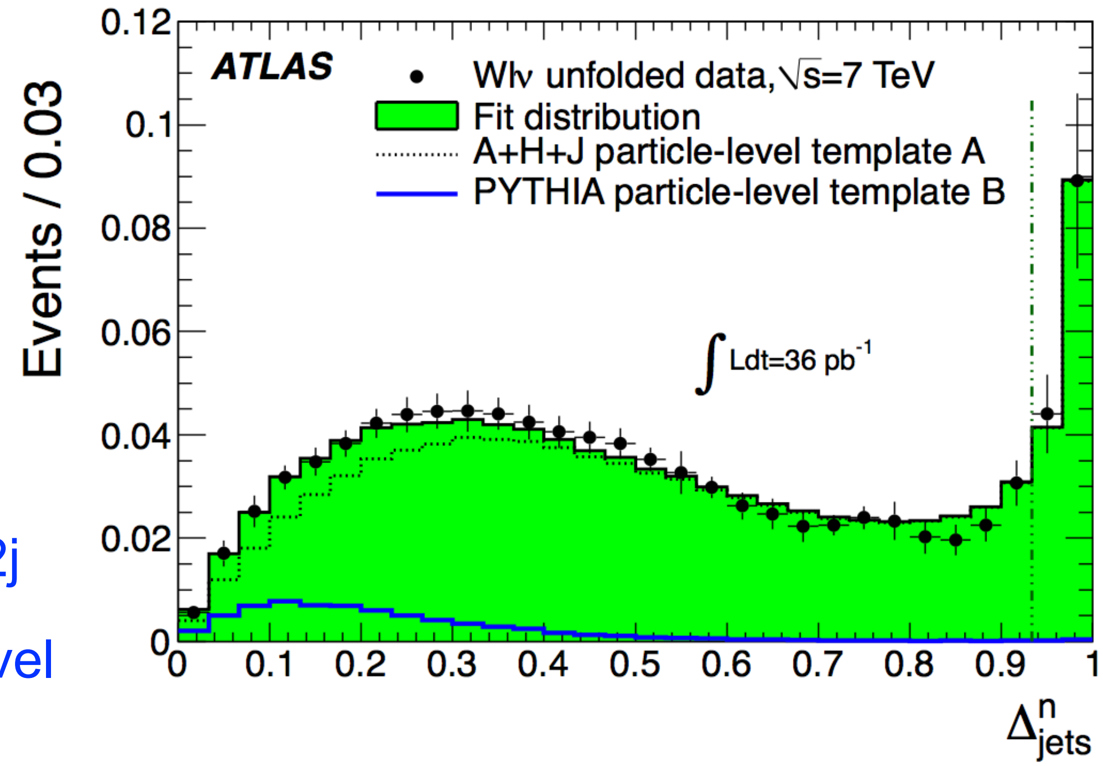
New J. Phys. 15 (2013) 033038

- DPI is characterized by the effective area parameter σ_{eff}
  - assumed to be independent of phase space an process. Naively expect ~ 50 mb

$$\hat{\sigma}^{(\mathrm{tot})}_{W+2\mathrm{j}}(s) = \hat{\sigma}^{(\mathrm{SPI})}_{W+2\mathrm{j}}(s) + \hat{\sigma}^{(\mathrm{DPI})}_{W+2\mathrm{j}}(s) = \hat{\sigma}^{(\mathrm{SPI})}_{W+2\mathrm{j}}(s) + \frac{\hat{\sigma}_{W0\mathrm{j}}(s)\cdot\hat{\sigma}_{2\mathrm{j}}(s)}{\sigma_{\mathrm{eff}}(s)} \qquad \sigma_{\mathrm{eff}}(s) = \frac{\hat{\sigma}_{W0\mathrm{j}}(s)\cdot\hat{\sigma}_{2\mathrm{j}}(s)}{f^{(\mathrm{D})}_{\mathrm{DP}}\,\hat{\sigma}^{(\mathrm{tot})}_{W+2\mathrm{j}}(s)}$$

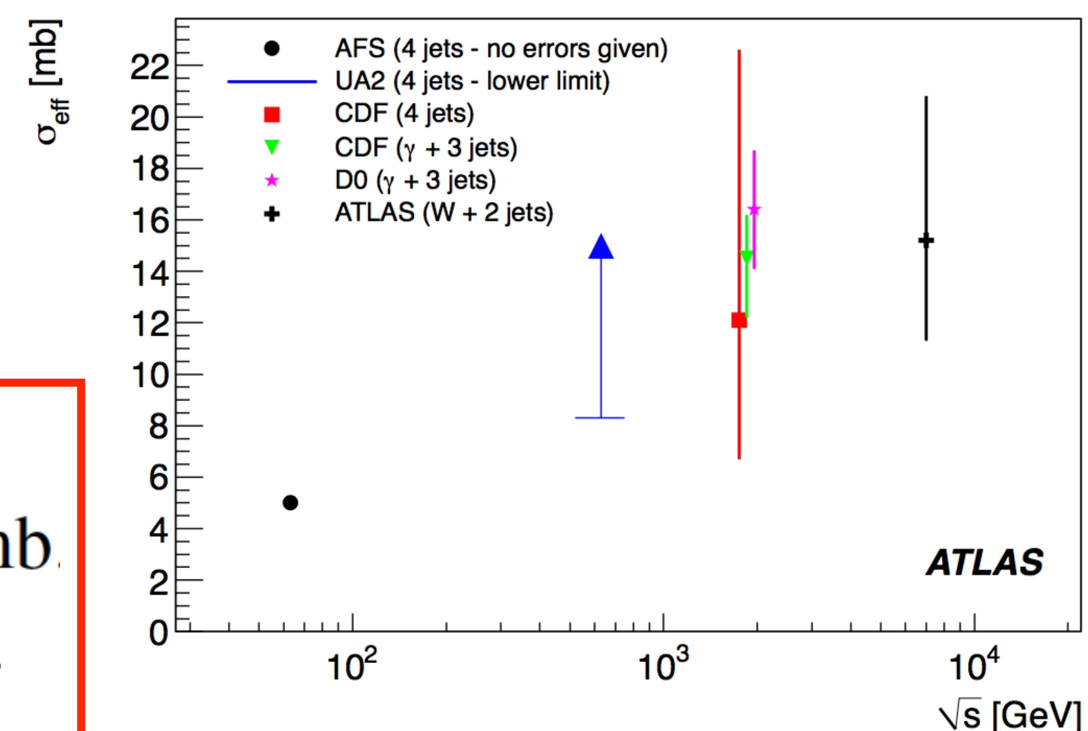
- Fraction of DPI events in W+2 jets data events extracted from template fit to the normalized distribution of transverse momentum balance

$f^{(\mathrm{D})}_{\mathrm{DP}}$ fraction of DPI in W+2j events at detector level



$$\Delta^{\mathrm{n}}_{\mathrm{jets}} = \frac{|\vec{p}^{\,J_1}_{\mathrm{T}} + \vec{p}^{\,J_2}_{\mathrm{T}}|}{|\vec{p}^{\,J_1}_{\mathrm{T}}| + |\vec{p}^{\,J_2}_{\mathrm{T}}|}$$ small for DPI

p_T > 20 GeV and |y| < 2.8



➡ $f^{(\mathrm{D})}_{\mathrm{DP}} = 0.08 \pm 0.01\,(\mathrm{stat.}) \pm 0.02\,(\mathrm{sys.})$

➡ $\sigma_{\mathrm{eff}}(7\ \mathrm{TeV}) = 15 \pm 3\,(\mathrm{stat.})\,^{+5}_{-3}\,(\mathrm{syst.})\ \mathrm{mb}$

- Result consistent with previous measurements at lower energies

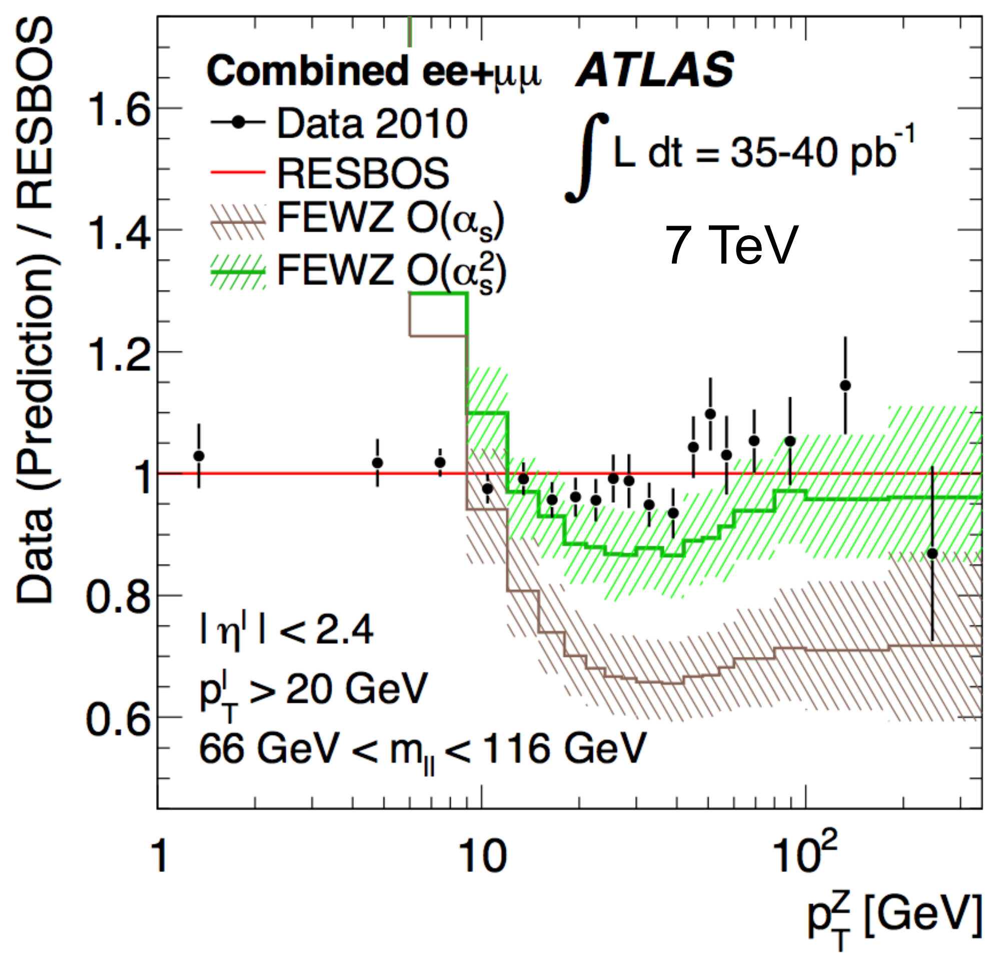
Inclusive Z and W p_T

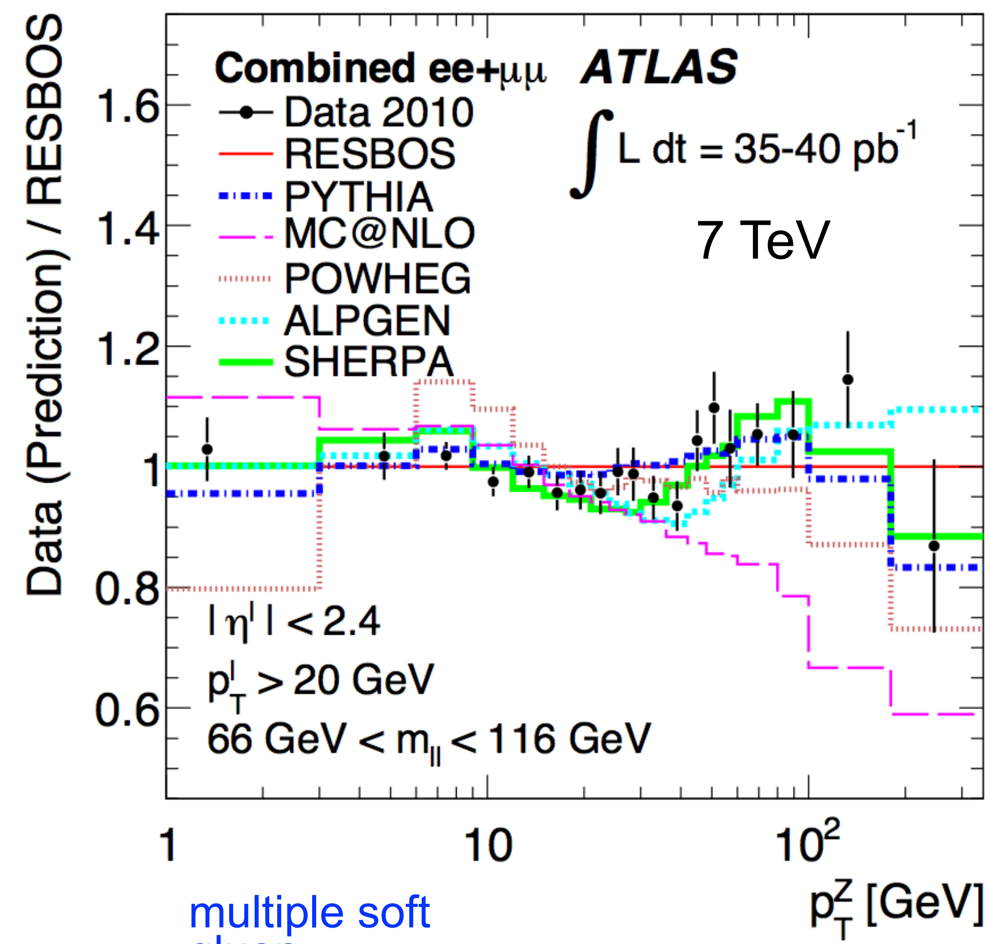
- Tests of high order pQCD and resummation techniques

Z p_T - at 7 TeV

Phys. Lett. B705 (2011) 415-434

- Total background: 0.4% (mu) 1.5% (e), up to 3.5% at high Z p_T
- Dominant exp uncertainties:
  - lepton ID and reconstruction: 1-3%
  - lepton energy scale and resolution: 0.7-4.4% (smaller for mu-channel)
  - unfolding (mainly Z p_T modeling used in efficiency correction): 1.3-4.7%





multiple soft gluon dominated

single or hard gluons dominated

FEWZ: O(α_s^2) pQCD:
in central region, underestimates data by about 10%

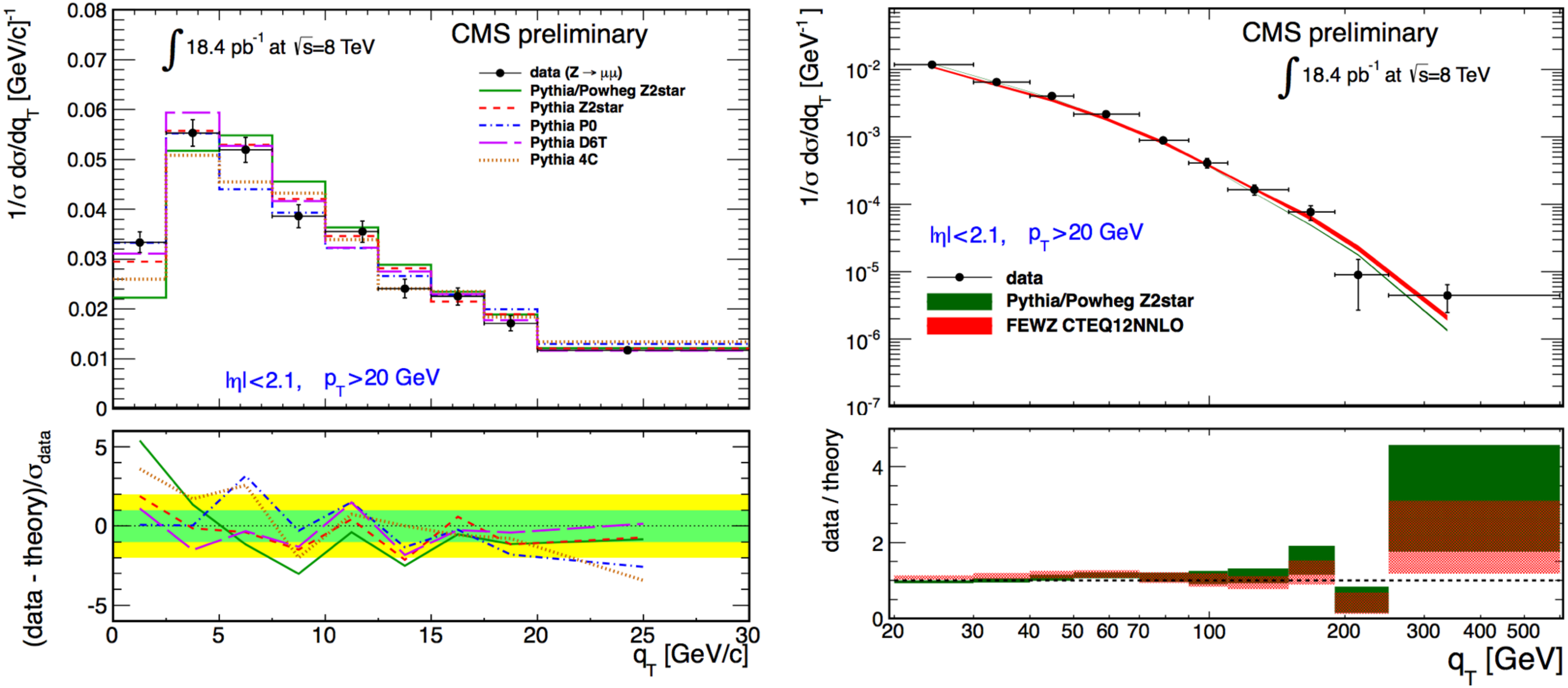
SHERPA, ALPGEN, PYTHIA
agree well with data

RESBOS: NNLL resummation + O(α_s) + O(α_s^2) pQCD:
describes the spectrum well over the entire range

Z p_T - at 8 TeV

CMS-PAS-SMP-12-025

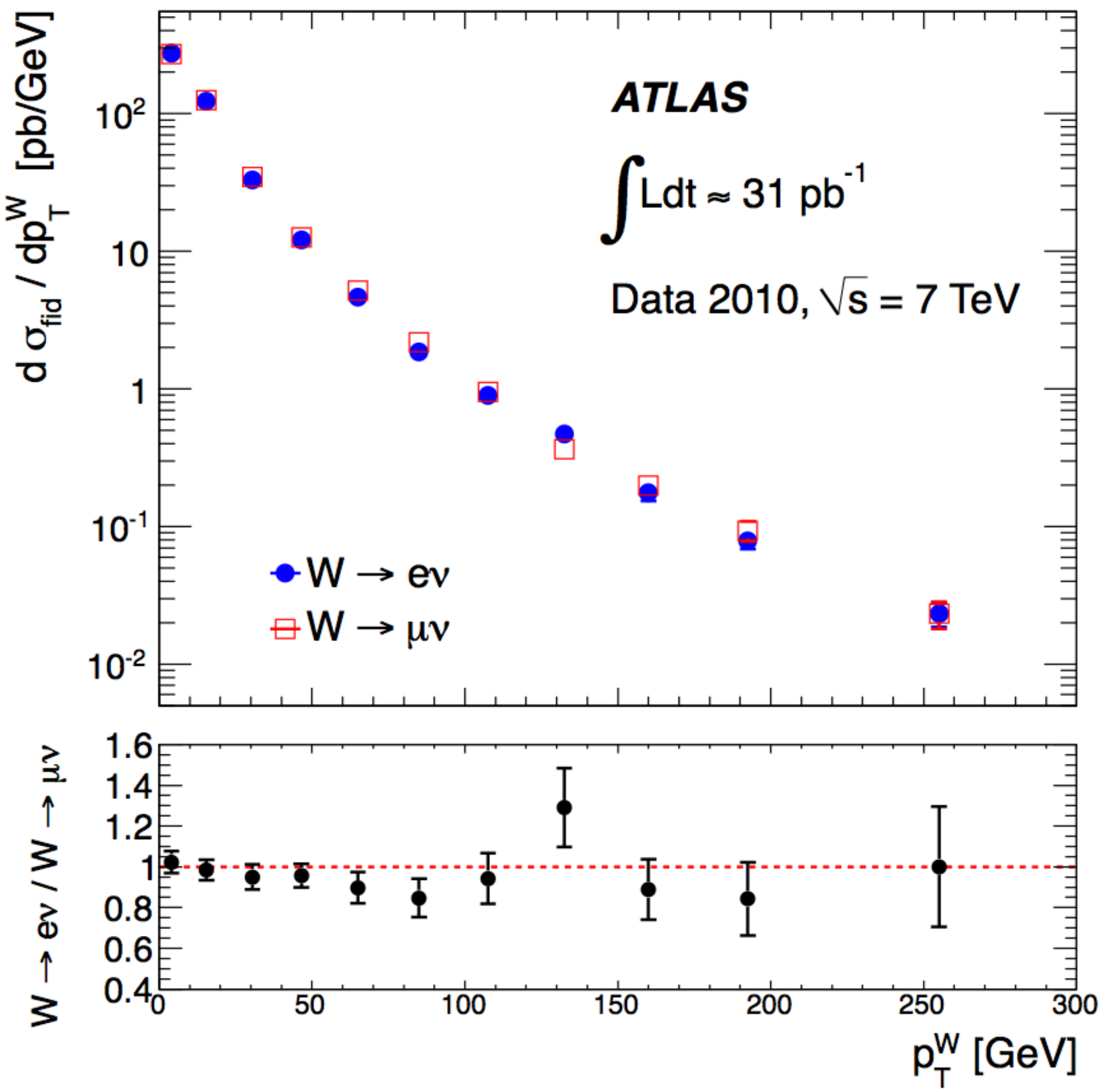
- Data from special 8 TeV LHC configuration with low pileup (average 5, ~ as for 7 TeV data)

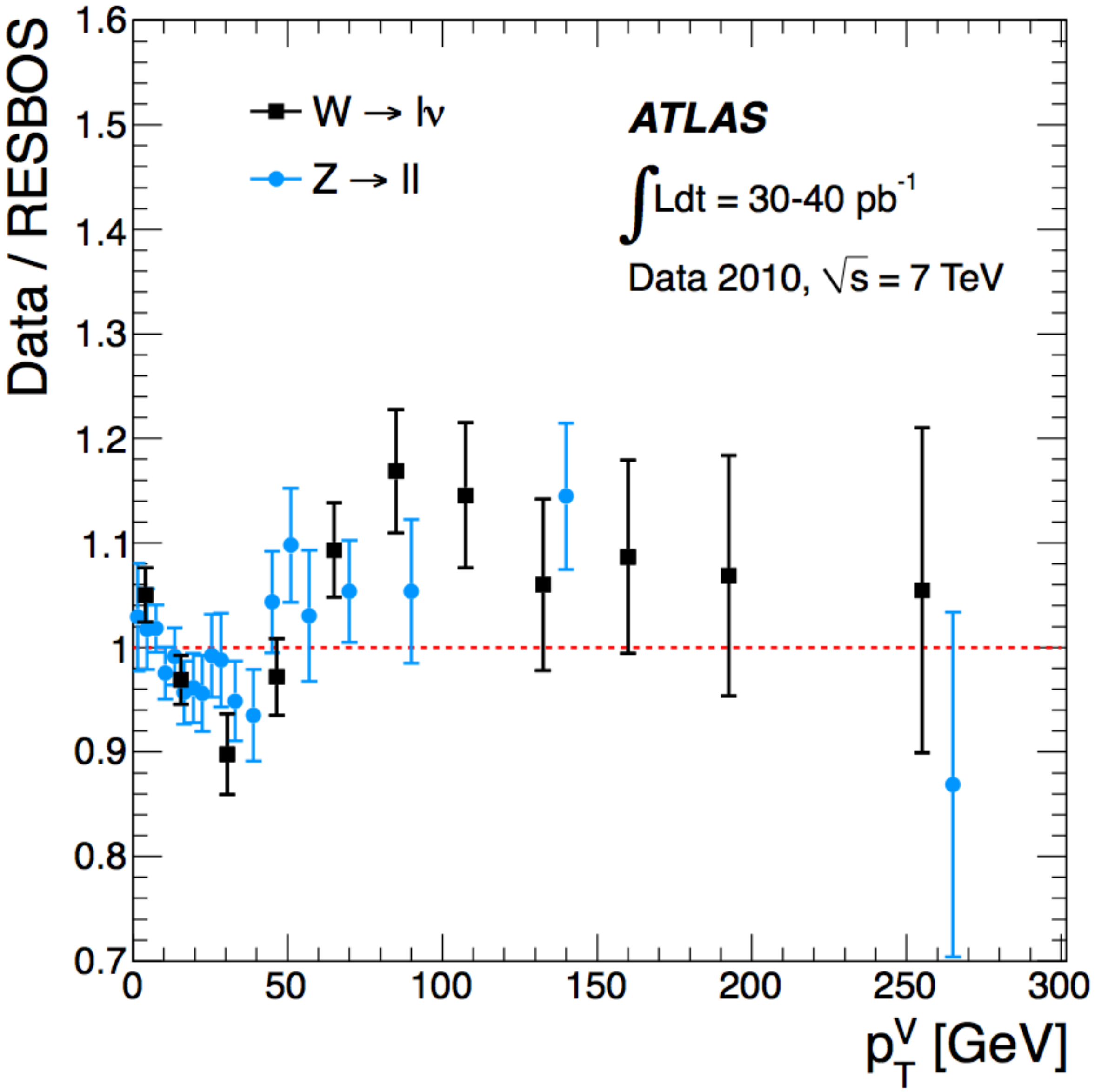


- Overall best agreement with MadGraph + PYTHIA + Z2star tune
- Low p_T region affected by underlying event
  - PYTHIA + Z2star tune gives best result
  - results validate POWHEG + PYTHIA + Z2star tune (obtained from low scales processes...)
- High p_T region good agreement with POWHEG + PYTHIA + Z2star tune, and with FEWZ 3.1
- Comparison with 7 TeV data as expected

W p_T and Z p_T

Phys. Rev. D85 (2012) 012005
Phys. Lett. B705 (2011) 415-434





- Resolution of hadronic recoil to obtain W p_T not as good as the resolution of the lepton momenta to obtain Z p_T, but there are ~10 times more W than Z!
- p_T^W unfolded to particle level
  - by default it is defined from the Born level W propagator

Z and W results display similar features

Supports the expected universality of QCD effects in W and Z production

Z Φ_η^* - definition

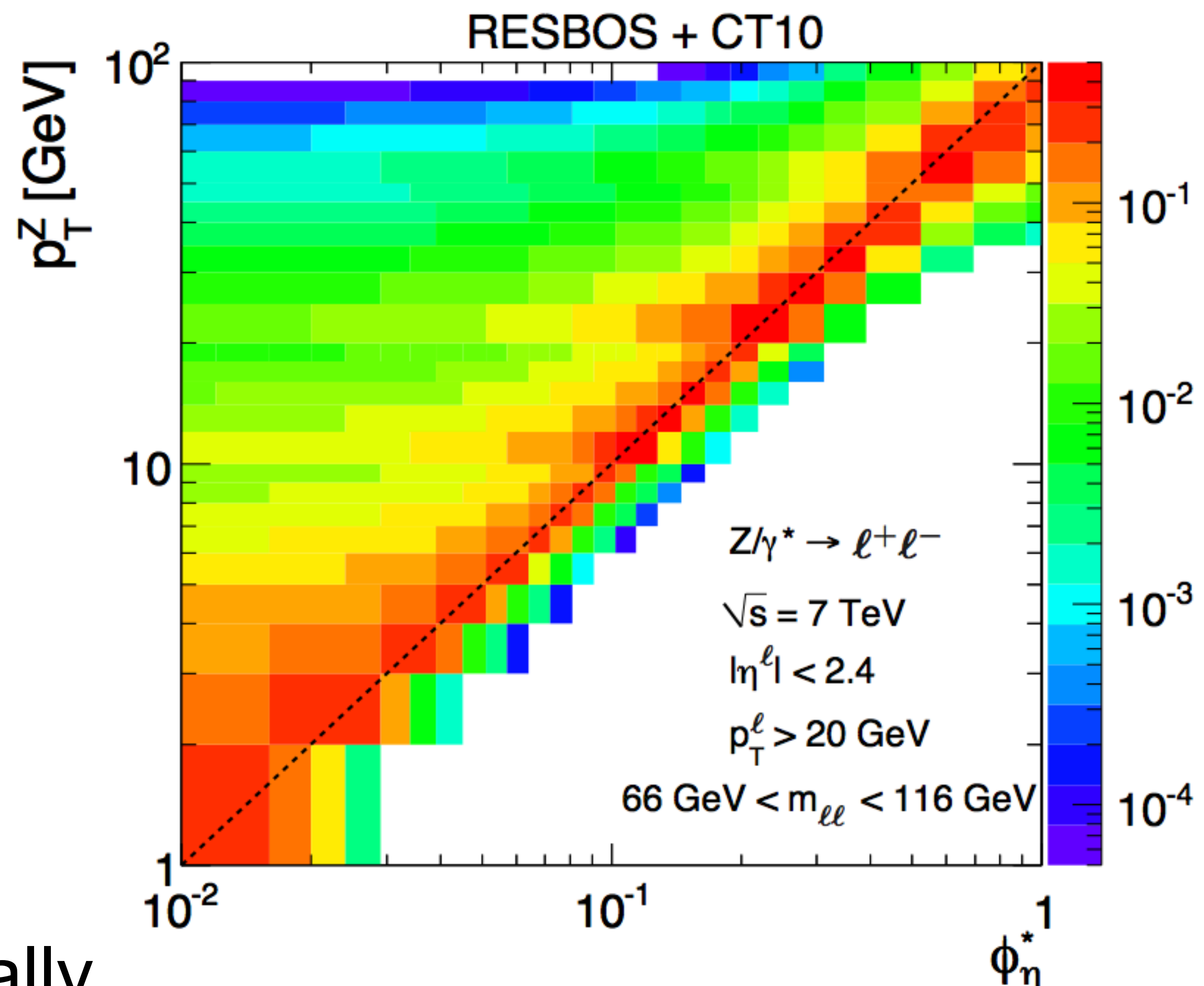
Phys. Lett. B720 (2013) 32-51

- Higher accuracy achieved by measuring cross section as a function of Φ_η^*
  - D0 PRL 106, 122001 (2011)

$$\phi_\eta^* \equiv \tan\left(\phi_{\mathrm{acop}}/2\right) \cdot \sin\left(\theta_\eta^*\right)$$

$$\phi_{\mathrm{acop}} \equiv \pi - \Delta\phi$$

$$\cos\left(\theta_\eta^*\right) \equiv \tanh\left[\left(\eta^- - \eta^+\right)/2\right]$$

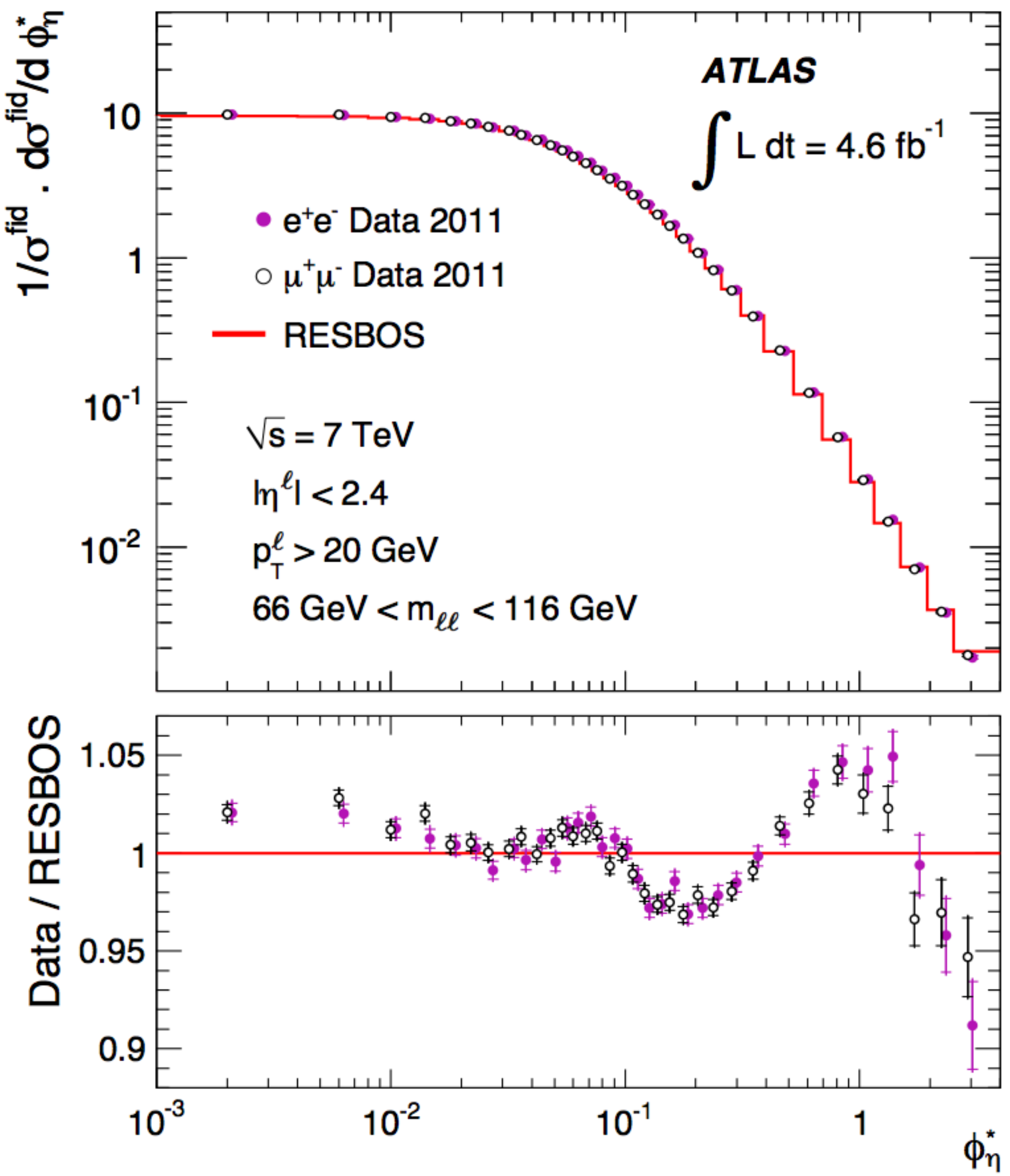


- This quantity only depends on direction of the leptons
- Extremely precise experimentally
- Correlates with Z p_T

$$\phi_\eta^* \approx \frac{p_T^Z}{M_{\ell\ell}}$$

Z Φ_η^* - distribution

Phys. Lett. B720 (2013) 32-51



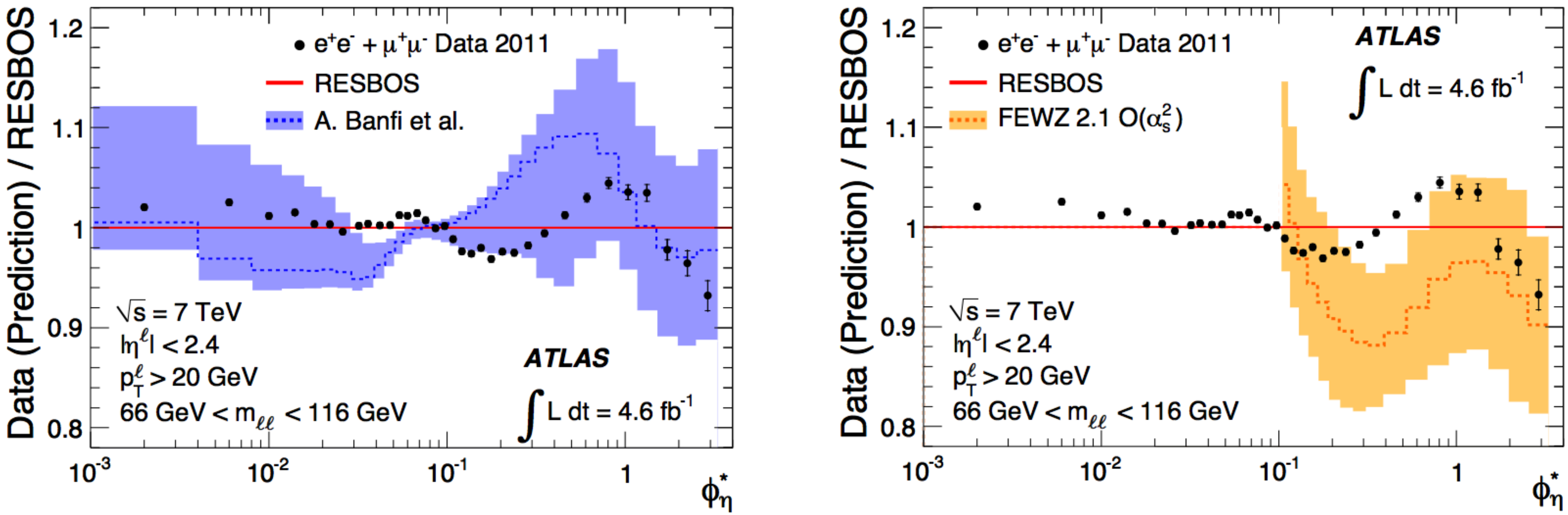
Calculations using RESBOS provide the best description of the data

- NNLL resummation (scale M_Z) matched to $O(\alpha_s)$, corrected to $O(\alpha_s^2)$ using k-factors depending on Z p_T and y.
- **but unable to reproduce the detailed shape to better than 4%**

- ~3 x 10^6 di-lepton candidates
- angular resolution:
  - 0.4-0.6 mrad in φ
  - 0.0010-0.0012 in η
- 0.6% background, half from multi-jet, dominating at low $\Phi\eta^*$
- dominant experimental systematics
  - background 0.3%
  - angular resolution: 0.2%
- Total uncertainties:
  - 0.5% (low $\Phi\eta^*$), stat ≈ sys
  - 0.8% (high $\Phi\eta^*$), stat dominating

Z Φ_η^* - comparison with theory

Phys. Lett. B720 (2013) 32-51



- Difference between RESBOS and data smaller than PDF uncertainty (4-6%)
- Experimental uncertainty an order of magnitude more precise than predictions

- Banfi et al:
  - NNLL matched to NLO from MCFM
  - Phys. Lett. B 715 (2012) 152
- Uncertainty includes:
  - Resummation, μ_R, μ_F : × 2 around M_Z
  - PDF CTEQ6m error eigenvectors

- Fixed order calculations not expected to be adequate in low Z p_T region
  - FEWZ not shown for $\Phi_\eta^* < 0.1$
- FEWZ uncertainty include
  - μ_R, μ_F : × 2 around M_Z
  - PDF CT10 error eigenvectors
  - vary α_s within range (90%CL)

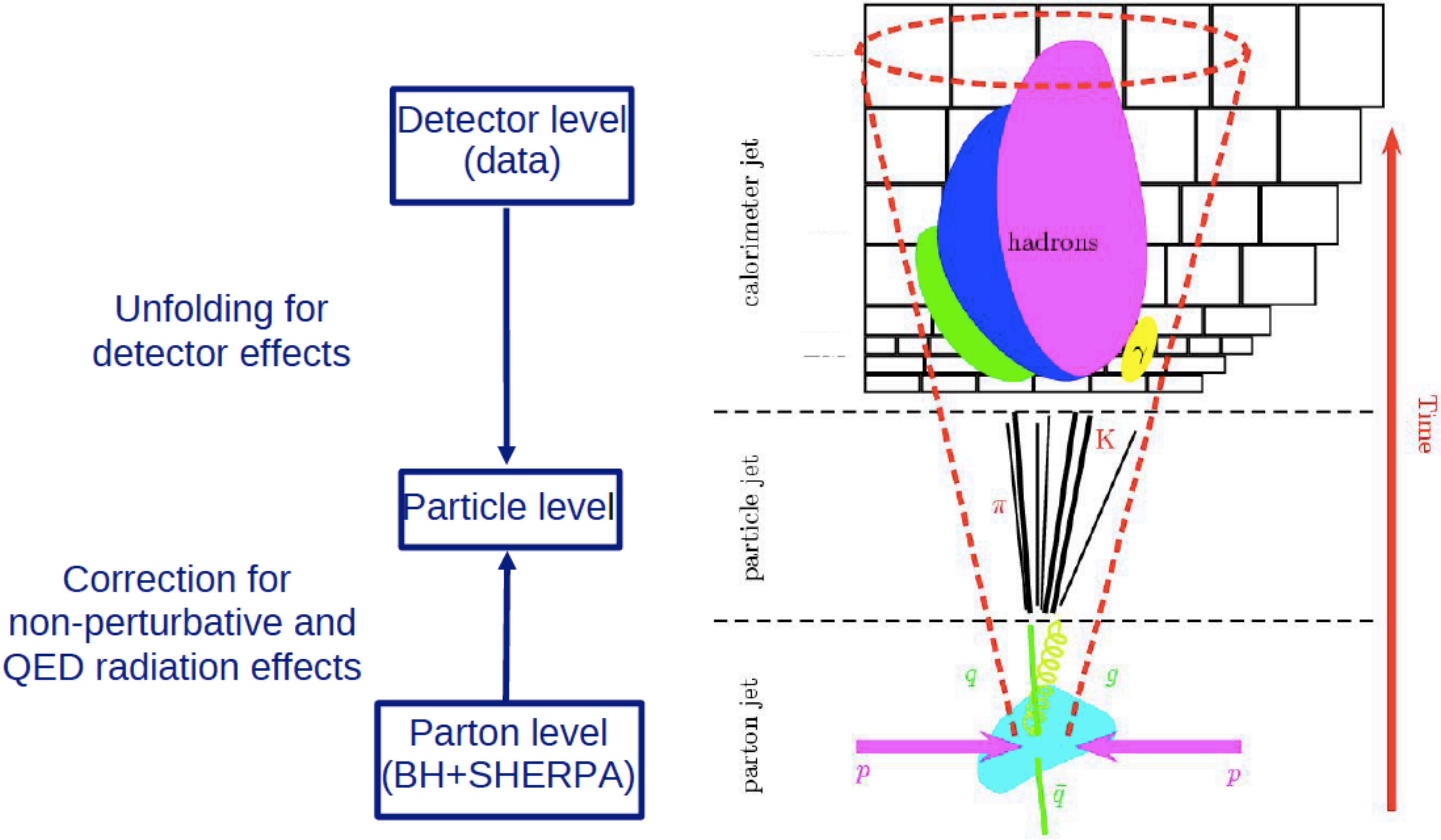
Conclusions W/Z + jets

- ATLAS and CMS have performed a wide range of W/Z + (light) jets measurements at the LHC
  - stringent tests of pQCD
- In general, good agreement between data and predictions
  - but discrepancies observed in several regions
    - fixed order NLO + PS fails to describe the data: missing higher order effects
      - challenges for certain types of observables, such as H_T
    - tension with very precise Z Φ_η^* distribution
  - LO ME or NLO, interfaces with parton shower models, provide input for generator tuning
    - needed for background predictions
- W + 2 jets study of double parton interactions
  - successful measurement of σ_{eff} and of DPI sensitive observables
- Stay tuned: more data being analyzed!

Backup Slides

Z+jets - analysis strategy

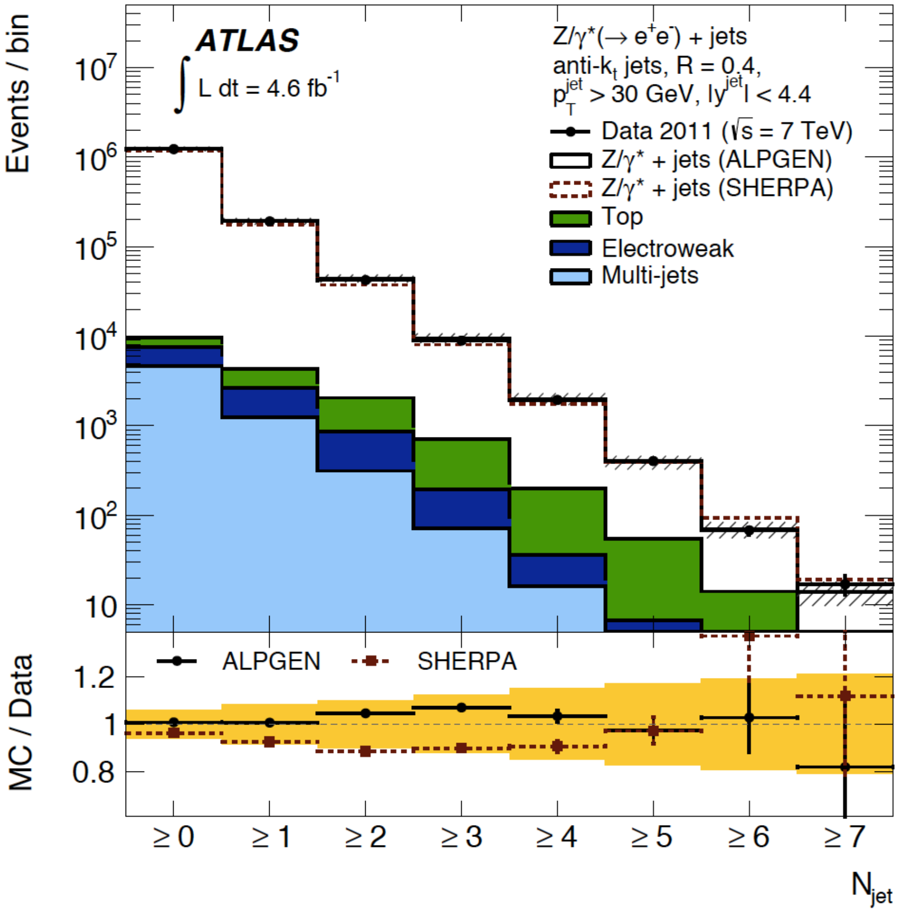
JHEP07(2013)032

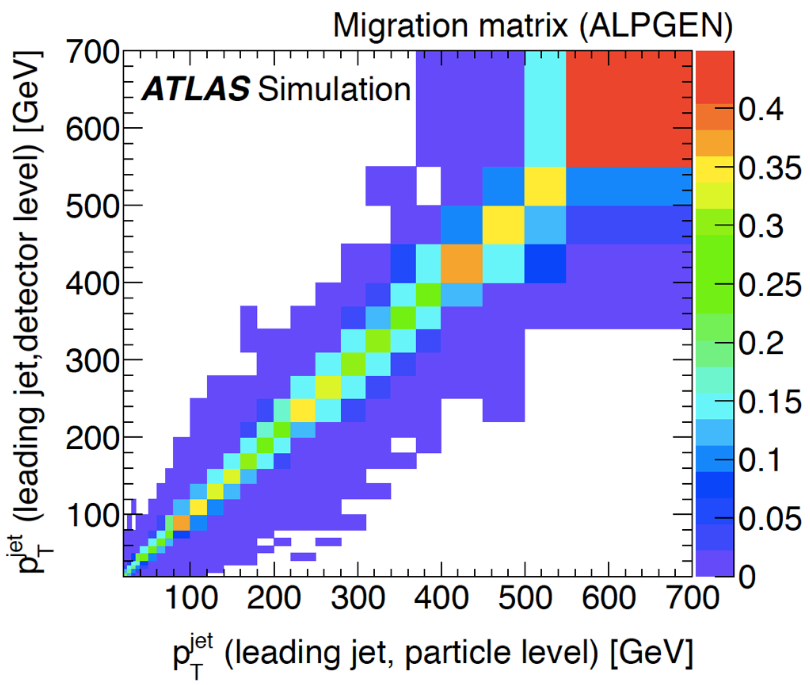


Z+jets - cross section

JHEP07(2013)032

- Main backgrounds
  - multi-jets in situ (0.4 - 1.5%)
  - ttbar in situ (0.2 - 26%)
  - diboson (0.2 - 1.2%)
- Iterative Bayesian unfolding method
  - NIM A362 (1995) 487
- Differential measurements on dressed level, separately for e and μ channels
- Results from each channel extrapolated to common phase space region:
  - e, μ: $p_T > 20$ GeV, $|\eta| < 2.5$
    dressed: add photon in $\Delta R < 0.1$
  - Z: opposite sign leptons
    $66 < M_{\ell\ell} < 116$ GeV
  - jets: anti-kt, R=0.4, $p_T > 30$ GeV
    $|y| < 4.4$, $\Delta R(j, \ell) > 0.5$





Z + jets - MC signal events and NLO calculations

JHEP07(2013)032

- MC signal event samples: Z (→ee or →μμ) + jets (VBF production neglected)
  - ALPGEN 2.13 (0 ≤ Npartons ≤ 5)
    - HERWIG v6.520 (PS) + JIMMY v4.31 (UE AUET2-CTEQ6L1 tune)
    - PDF: CTEQ6L1 (LO)
    - QED FSR: PHOTOS
  - ALPGEN 2.14 (0 ≤ Npartons ≤ 5)
    - PYTHIA v6.425 (PERUGIA2011C tune)
    - PDF: CTEQ6L1 (LO)
    - QED FSR: PHOTOS
  - SHERPA 1.4.1 (0 ≤ Npartons ≤ 5)
    - PDF: CT10
    - MEnloPS approach
    - QED FSR: YFS method
  - MC@NLO v4.01
    - HERWIG
  - normalized to NNLO inclusive W production
  - Pileup events: minimum bias event from PYTHIA with AMBT1 tune
    - events reweighted to ensure the same distribution on the number of primary vertices as for data, average number of nine interactions per bunch crossing

- NLO pQCD predictions
  - BLACKHAT-SHERPA fixed order
    - Z+≥0j, Z+≥1j, Z+≥2j, Z+≥3j, Z+≥4j,
    - PDF: CT10
  - renormalization and factorization scales set to $H_T/2$
  - anti-kt R=0.4 at parton level
  - corrected for fragmentation, QED-FSR, UE
    - (distributions for particle-level jets)/(distribution for parton-level jets with no UE)

Z+jets - systematic uncertainties

JHEP07(2013)032

$Z\ (\rightarrow ee)$	≥ 1 jet	≥ 2 jets	≥ 3 jets	≥ 4 jets	p_T^{jet} in [30–500 GeV]
electron reconstruction	2.8%	2.8%	2.8%	2.8%	2.6–2.9%
jet energy scale, resol.	7.4%	10.1%	13%	17%	4.3–9.0%
backgrounds	0.26%	0.34%	0.44%	0.50%	0.2–3.2%
unfolding	0.22%	0.94%	1.2%	1.9%	1.4–6.8%
total	7.9%	10.5%	13%	17%	5.5–12.0%
$Z\ (\rightarrow \mu\mu)$	≥ 1 jet	≥ 2 jets	≥ 3 jets	≥ 4 jets	p_T^{jet} in [30–500 GeV]
muon reconstruction	0.86%	0.87%	0.87%	0.88%	0.8–1.0%
jet energy scale, resol.	7.5%	9.9%	13%	16%	3.2–8.7%
backgrounds	0.093%	0.20%	0.41%	0.66%	0.1–1.9%
unfolding	0.30%	0.68%	0.52%	1.3%	0.5–6.2%
total	7.6%	10.0%	13%	16%	4.4–10.2%

- Jet energy scale dominant component of the total uncertainty
  - in particular in the forward region: 20 - 30%

QCD Scaling

E. Gerwick, T. Plehn, S. Schumann and P. Schichtel, Scaling Patterns for QCD Jets , JHEP 10 (2012) 162

Figure 1. Simplest primary (left) and secondary contributions (right) assuming a core process with a hard quark line.

x. For hadron collider processes involving two parton densities $f(x, Q)$ we define the PDF correction factor to the ratio of successive jet ratios $R_{(n+1)/n}/R_{(n+2)/(n+1)}$

$$B_n = \left| \frac{\dfrac{f(x^{(n+1)}, Q)}{f(x^{(n)}, Q)}}{\dfrac{f(x^{(n+2)}, Q)}{f(x^{(n+1)}, Q)}} \right|^2 . \tag{3.9}$$

The square in the definition of B_n reflects the two PDFs in hadron collisions. If for example the partonic ratio of two successive jet ratios is $R_{(n+1)/n}/R_{(n+2)/(n+1)} \sim c$ then the proper hadronic ratio becomes $B_n c$. We fix Q for simplicity, but this only mildly affects our results.

QCD Scaling

E. Gerwick, T. Plehn, S. Schumann and P. Schichtel, Scaling Patterns for QCD Jets , JHEP 10 (2012) 162

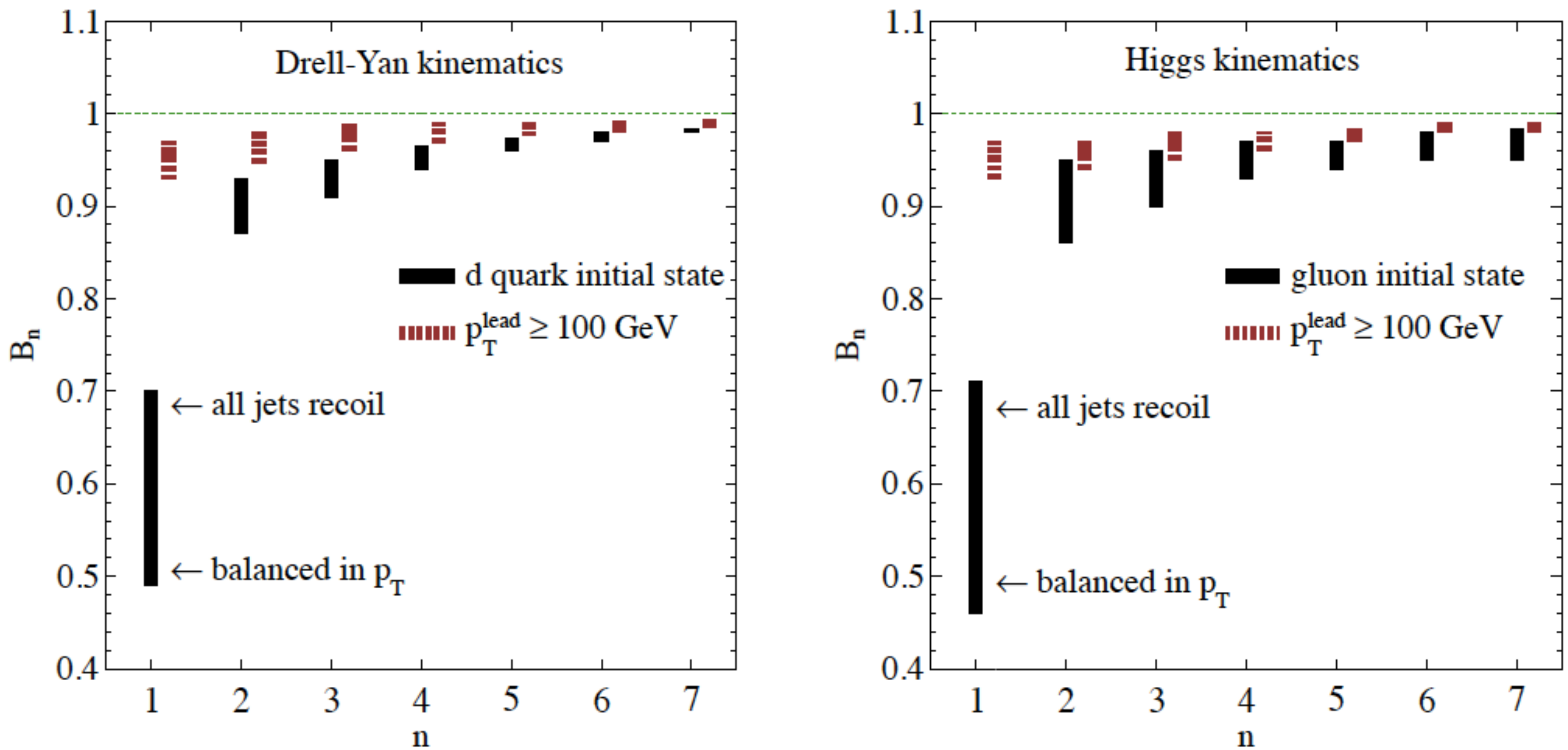
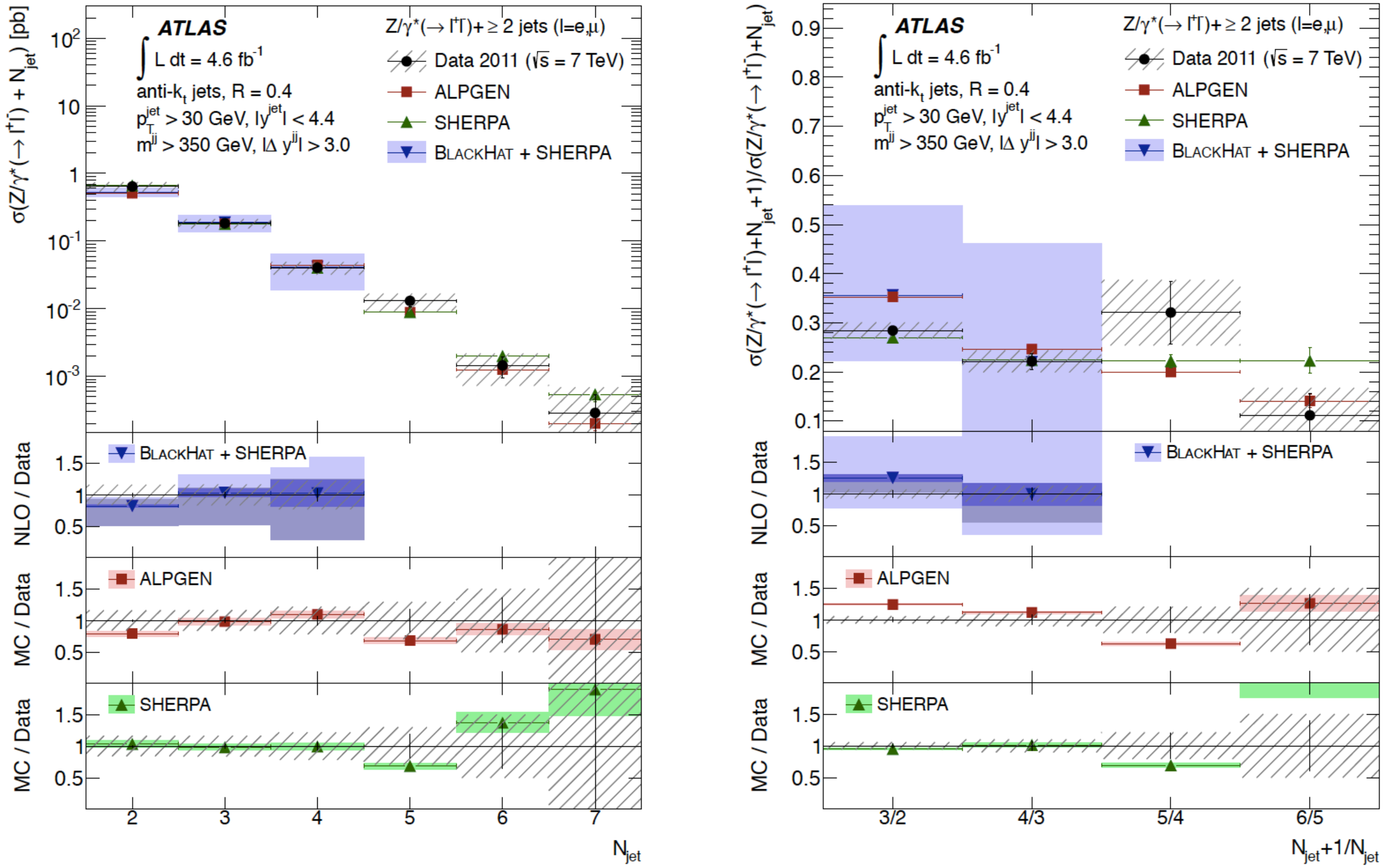


Figure 5. Left panel: estimated PDF suppression for inclusive (solid) and jet-associated (dashed, $p_T^{\text{lead}} \geq 100$ GeV) Drell-Yan kinematics. We assume an initial state with d-quarks only. Right panel: same for Higgs production in gluon fusion with $m_H = 125$ GeV. The uncertainty encompasses two representative kinematical limits of the multi-jet final state, described in the text.

Z + jets - exclusive jet multiplicities

JHEP07(2013)032

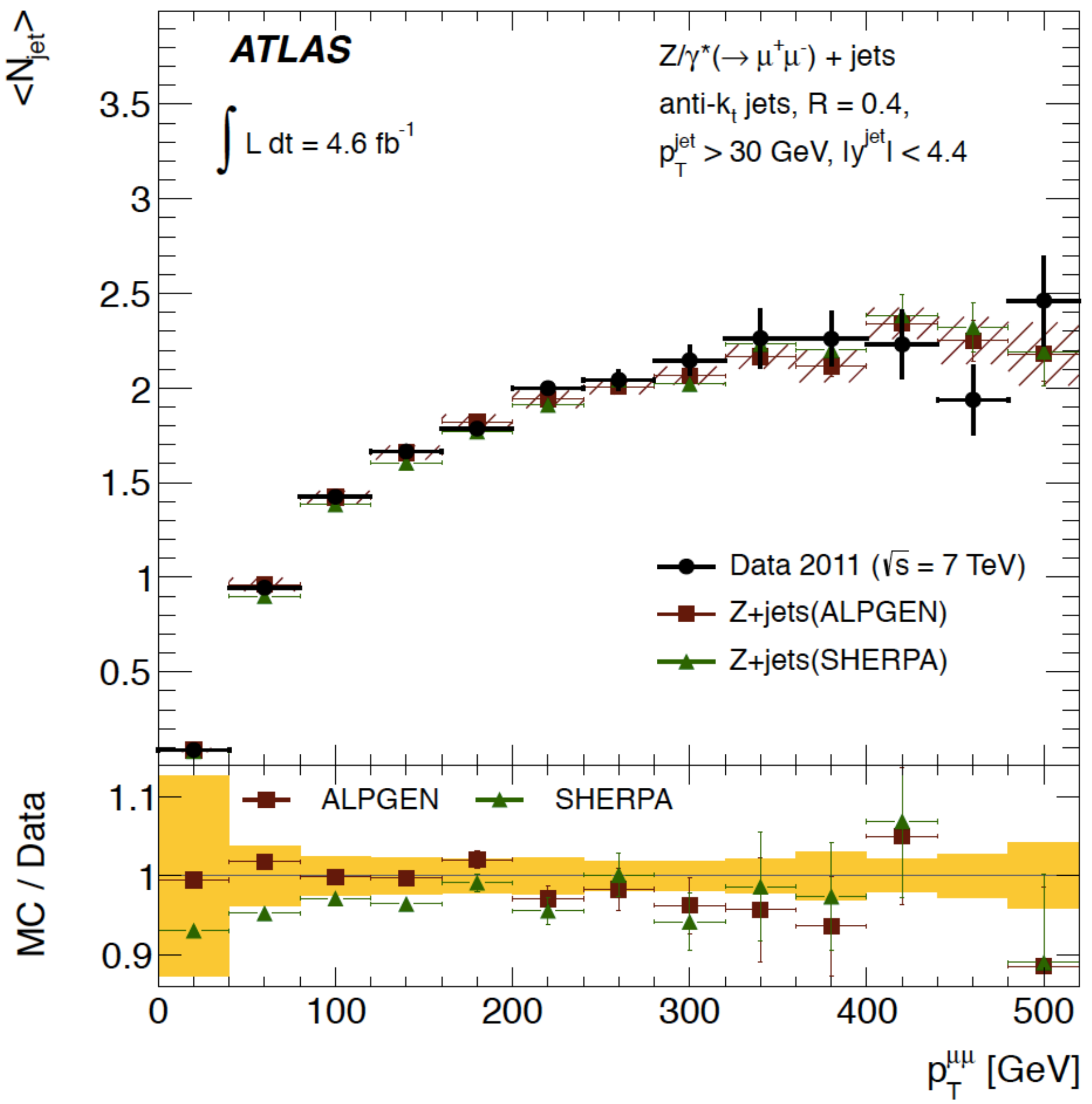
- Exclusive jet multiplicities for VBF pre-selection

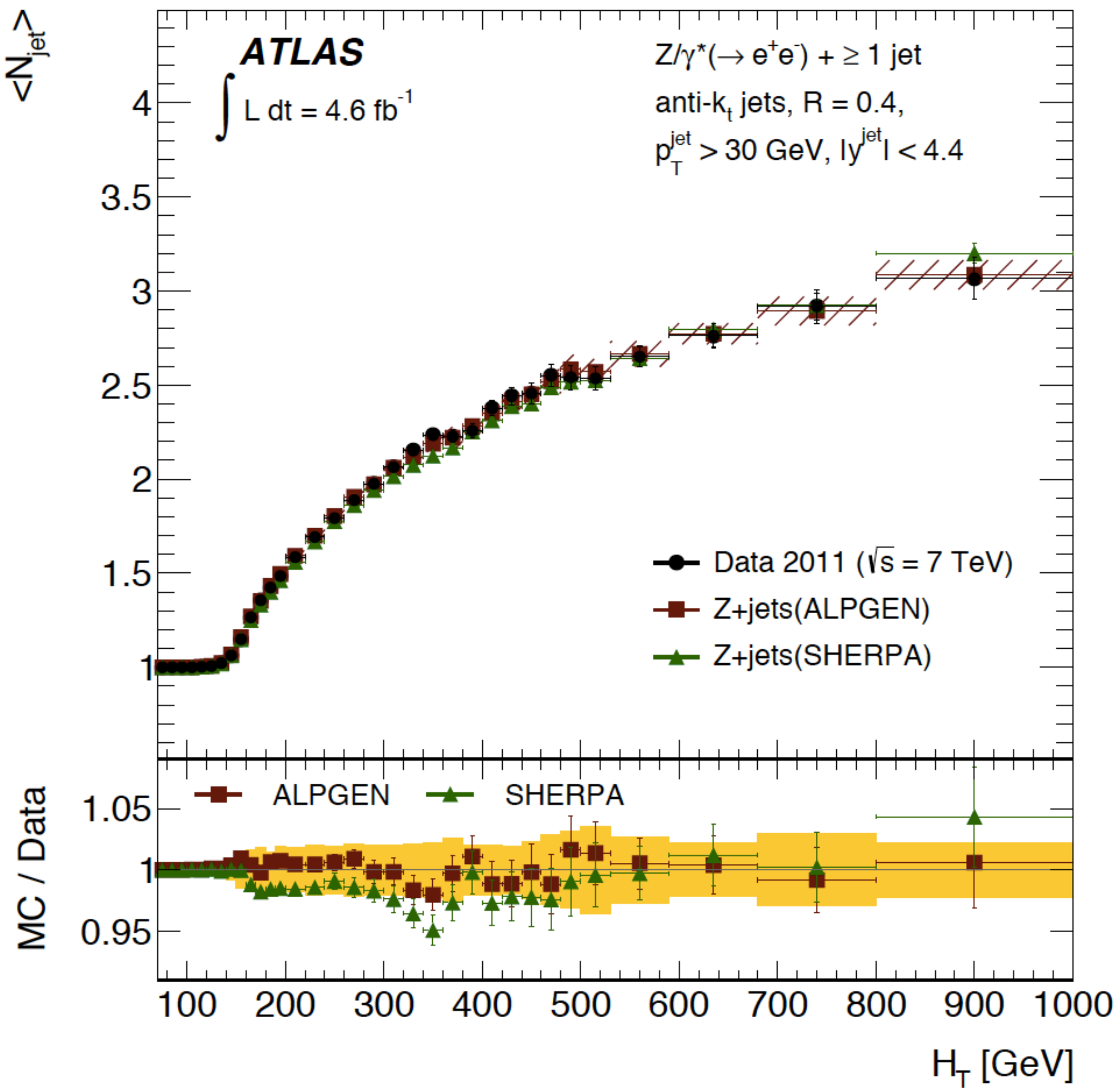


- Scaling properties useful in analyses using jet vetoes
- data consistent with BLACKHAT+SHERPA, and SHERPA
- ALPGEN overestimates $R_{3/2}$

Z + jets - average jet multiplicities

JHEP07(2013)032

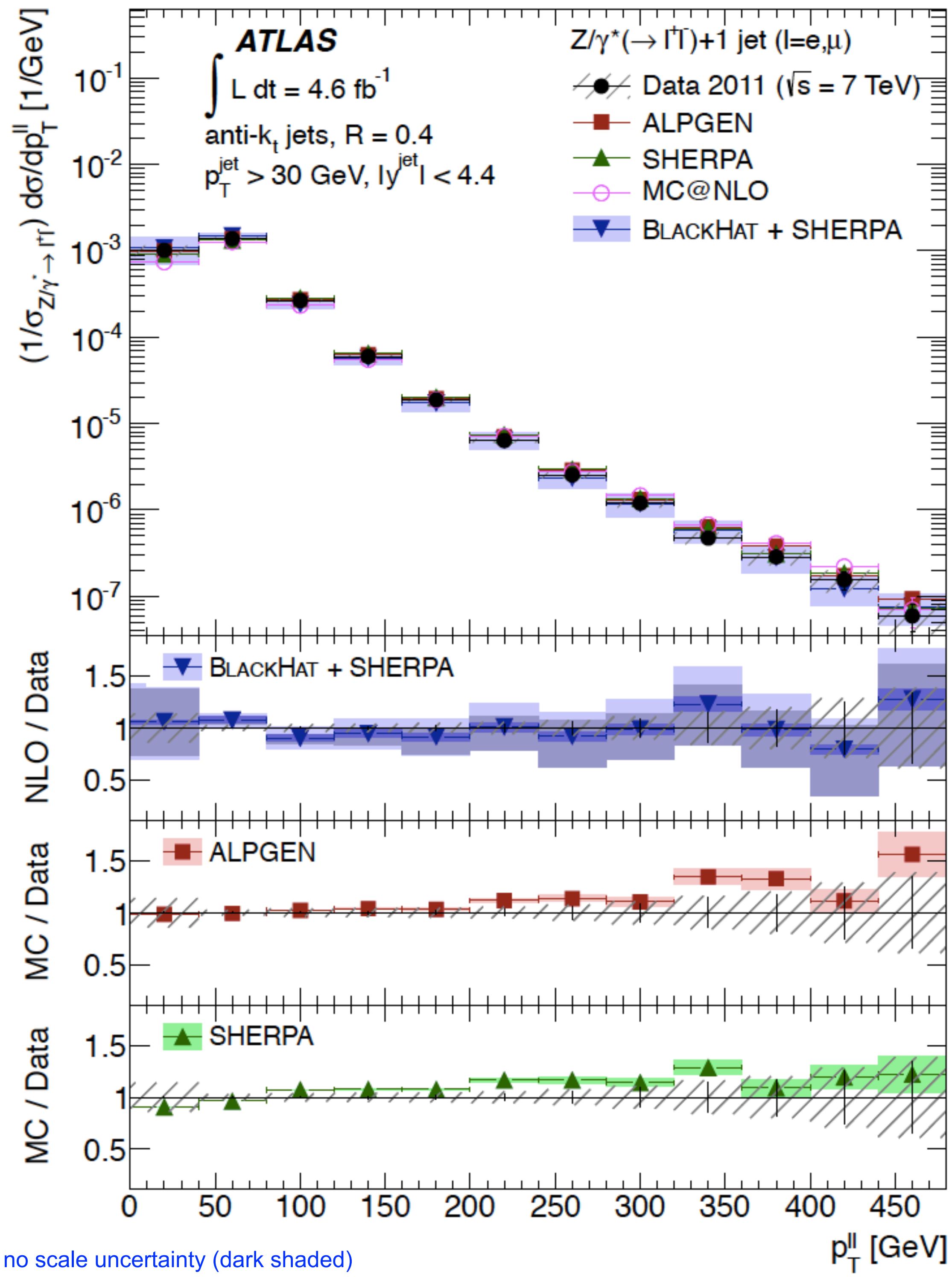


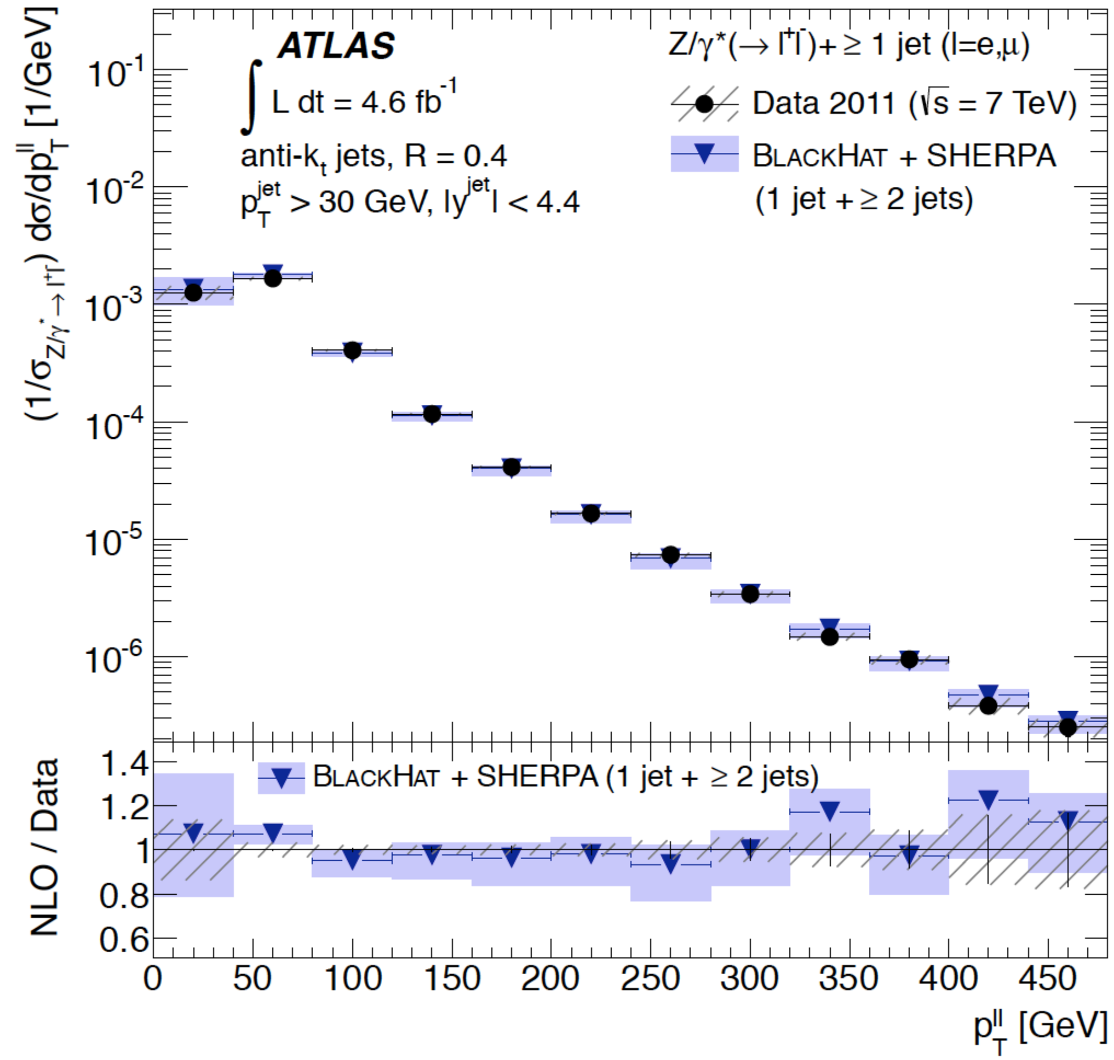


Z + jets - Z transverse momentum

JHEP07(2013)032

exclusive 1 jet | normalized to inclusive cross section | **inclusive ≥ 1 jet**



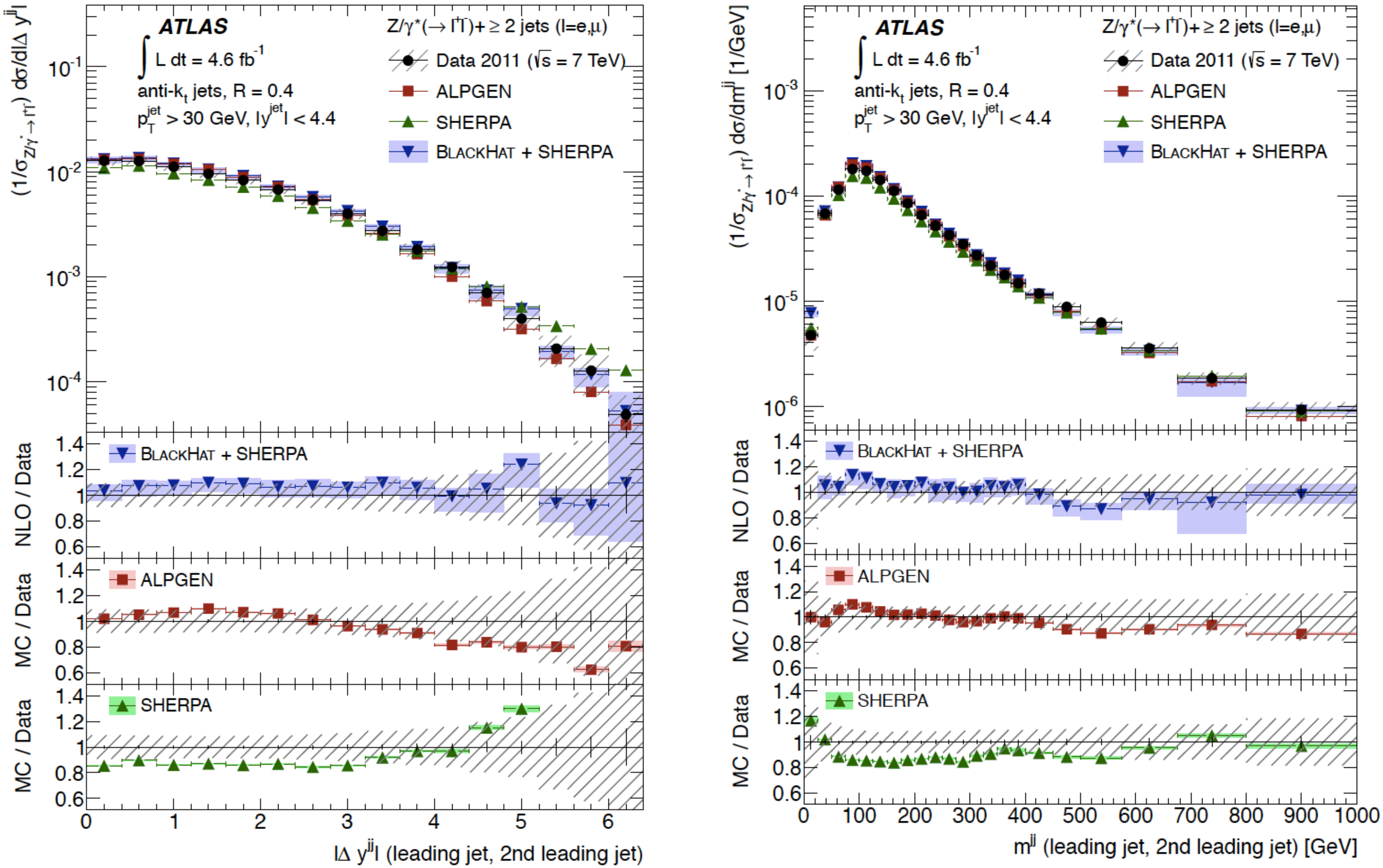


- Better agreement with data if inclusive final state in calculations is replaced by **exclusive sums**

exclusive sum:
Z + ≥ 1 = (Z + 1) + (Z + ≥ 2)

- no scale uncertainty (dark shaded)
- correlated between multiplicity bins (medium shaded)
- uncorrelated (light shaded), as prescribed in Phys.Rev.D85 (2012) 034011

Z + jets - two leading jets Δy and invariant mass

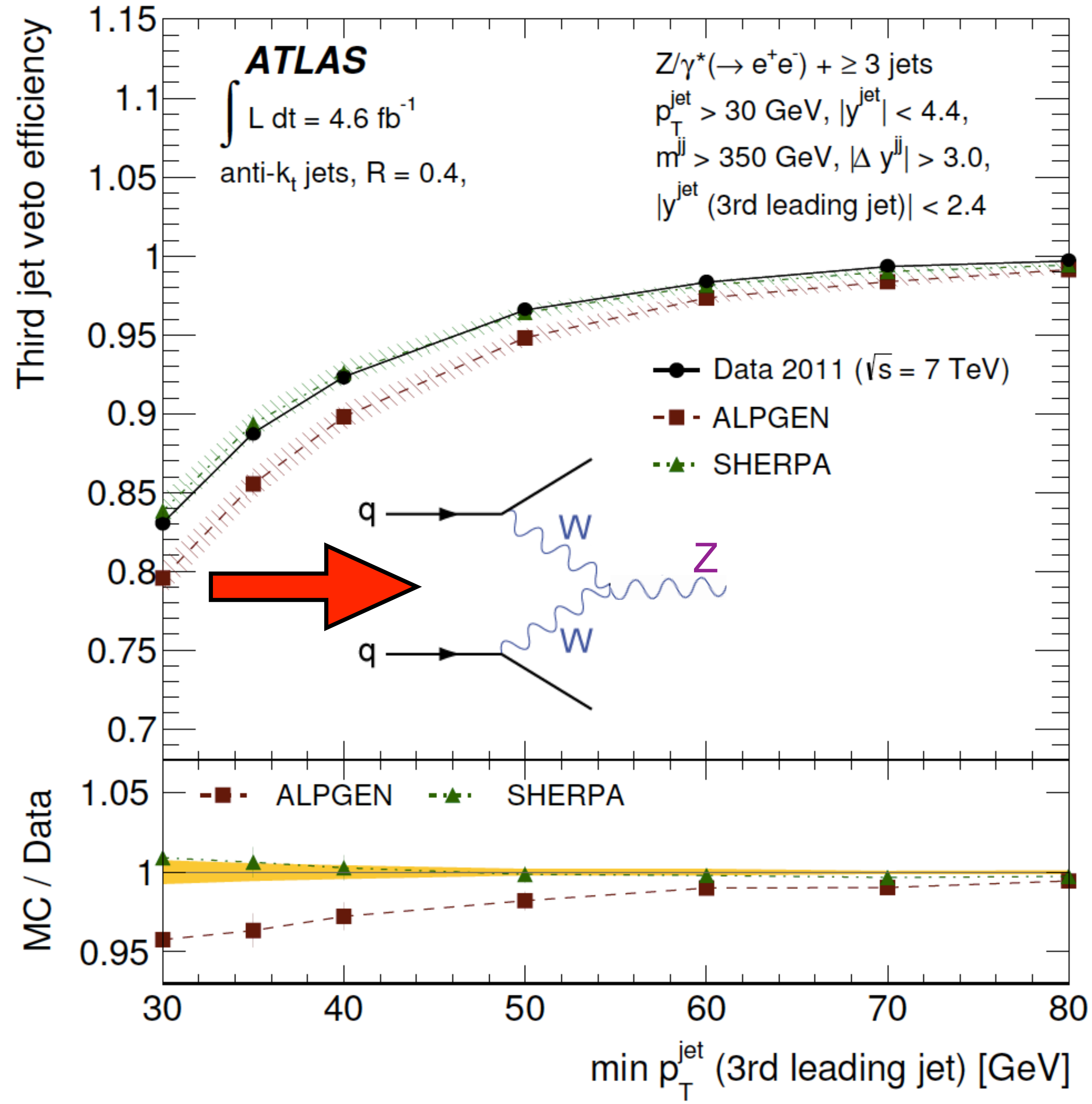


- Important for VBF Higgs analysis!
- BLACKHAT+SHERPA and ALPGEN predictions are in agreement with the data

Z + jets - VBF preselection 3rd jet veto efficiency

JHEP07(2013)032

- W/Z + jets are irreducible backgrounds to Higgs analyses, in particular through VBF production
- VBF signature
  - two forward jets (large |Δy|)
  - high dijet mass
  - central jet gap
- Study of Z+jets events with a VBF preselection
  - test Z+jets modeling
  - test of ME and PS matching
- 3rd jet veto efficiency
  - fraction of events passing veto requirement on 3rd jet in central region $|\eta| < 2.4$ as function of veto scale

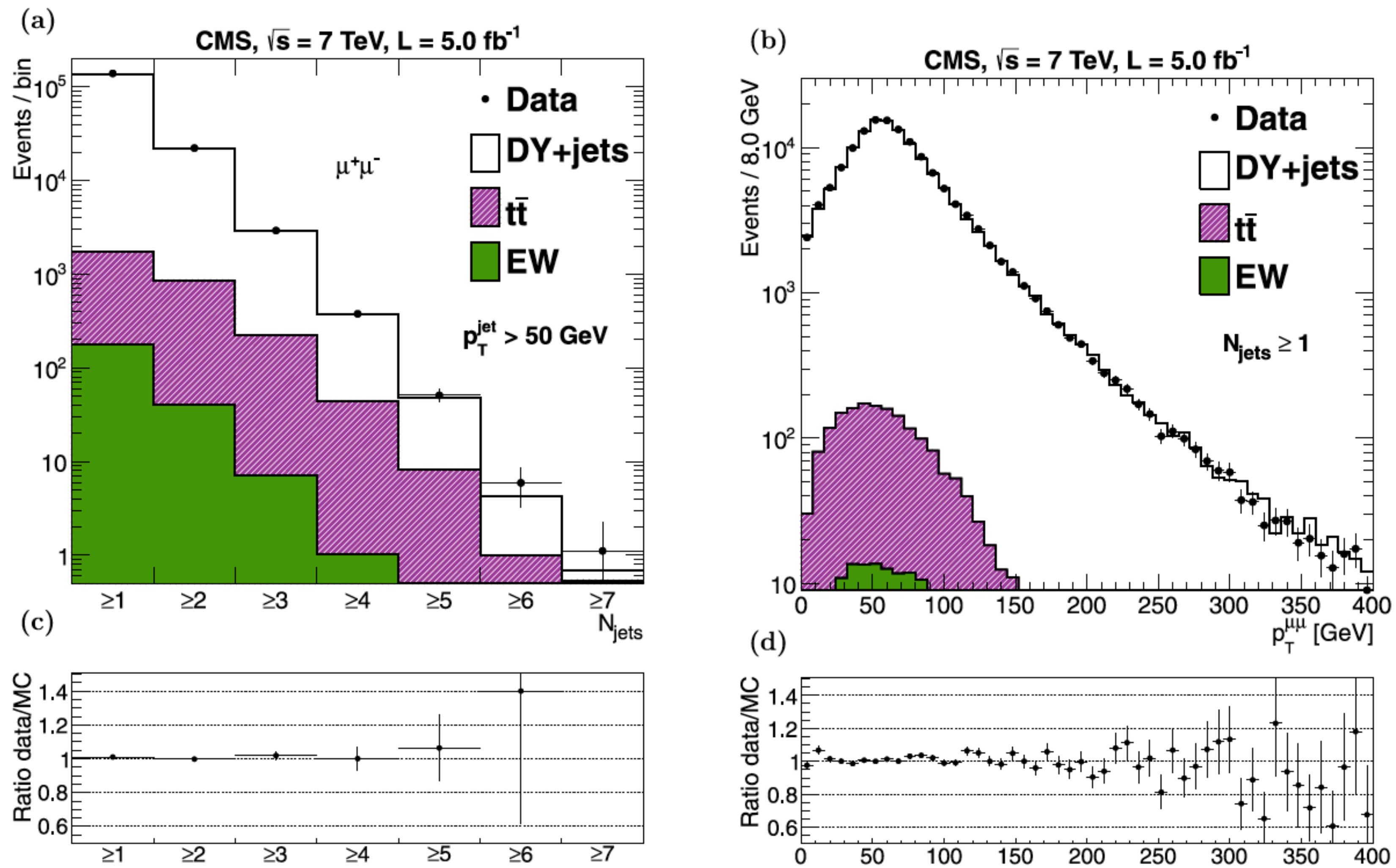


- BLACKHAT+SHERPA and SHERPA predictions are in agreement with the data
- ALPGEN underestimate the veto efficiency (due to overestimate of $R_{3/2}$)

Z+jets - event shapes and azimuthal correlations

Phys. Lett. B722 (2013) 238

- Leptons
  - p_T > 20 GeV
  - $|\eta|$ < 2.4
  - isolated
- $71 < m_{\ell\ell} < 111$ GeV
- Jets from particle flow
  - p_T > 50 GeV
  - $|\eta|$ < 2.5
  - $\Delta R_{j\ell} > 0.4$
- Analysis procedure
  - select $Z \rightarrow \ell\ell$
  - subtract background
  - unfold to particle level
  - combined channels
- Dominant systematics
  - jet energy scale
  - jet pT resolution
  - background subtraction
  - unfolding procedure
- ttbar dominant background
  - 1.1% for $N_{jets} \geq 1$
  - 8 % for $N_{jets} \geq 3$

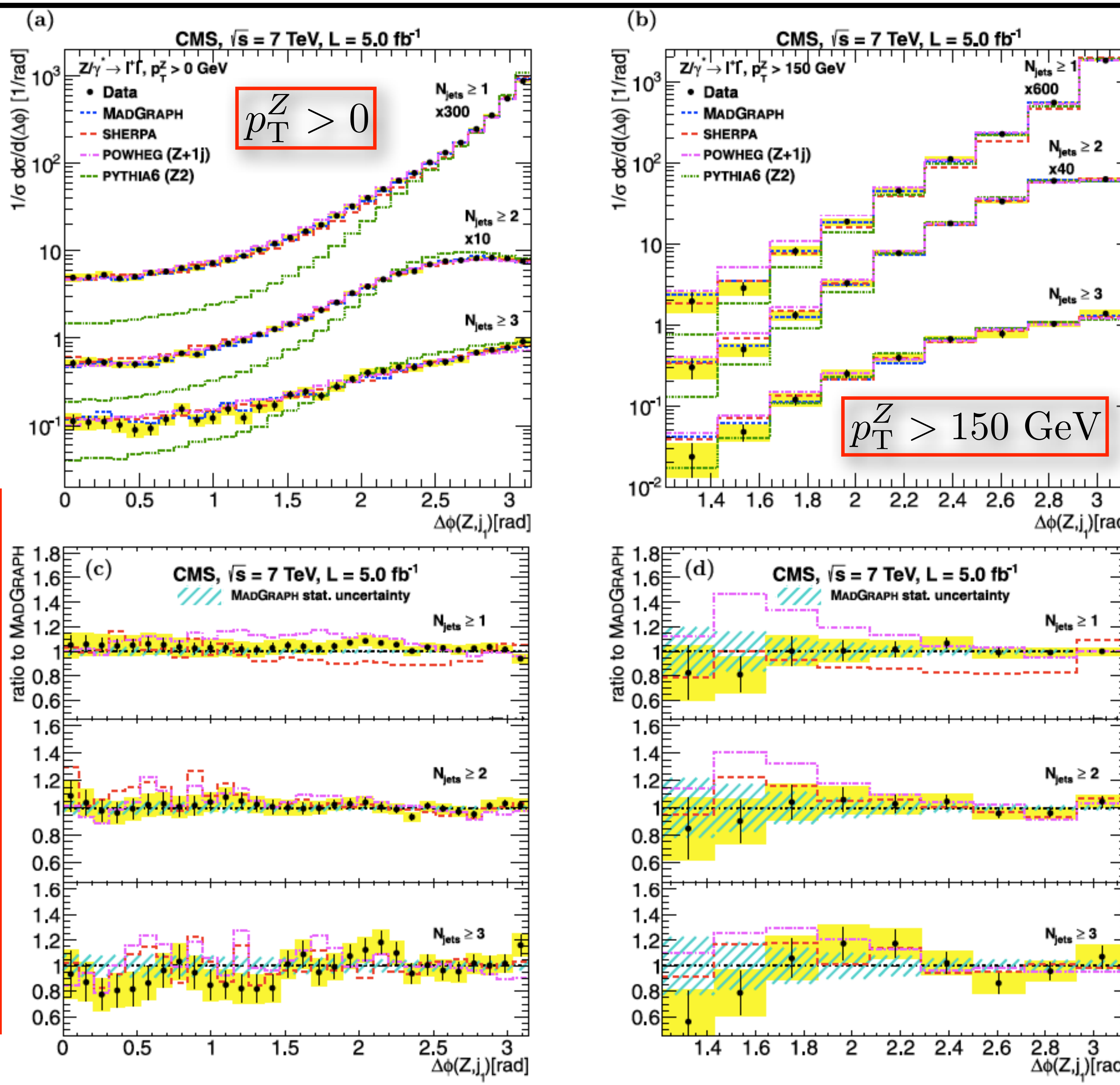


- Z+jets signal generators considered
  - MadGraph 5.1.1.0 + PYTHIA 6.4.2.4 + Z2 tune + CTEQ6L1
    LO up to 4 final state partons
  - SHERPA 1.3.1 + default tune + CTEQ6m
    LO up to 4 final state partons
  - POWHEG + PYTHIA 6.4.2.4 + Z2 tune + CT10
    NLO Z+1 jet
  - PYTHIA 6.4.2.4 + Z2 tune

Z+jets - azimuthal correlations ΔΦ(Z, j1)

Phys. Lett. B722 (2013) 238

- ΔΦ(Z, j1): ΔΦ between the Z and the leading jet for the inclusive multiplicities
  - $N_{jets} \geq 1, \geq 2, \geq 3$
  - normalized to unity
  - ratios to MadGraph
- ΔΦ observable with largest systematics
  - 5-6% near 0, to 2% near π

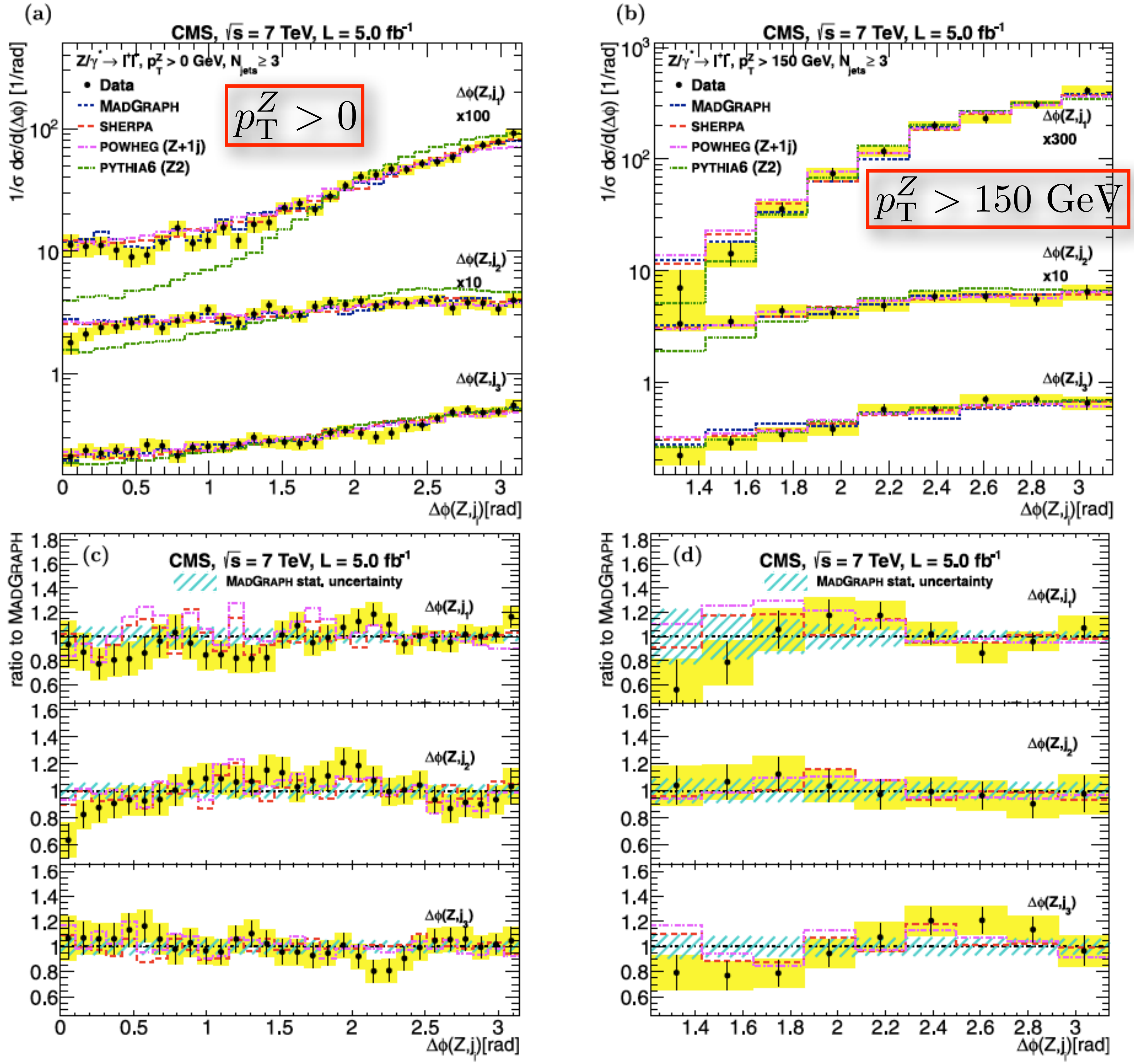


- Agreement with POWHEG and SHERPA improve for larger multiplicities
- For N_{jets} = 1, ΔΦ(Z, j1) ≈ π
  - large N_{jets}: more isotropic
  - also for p_T^Z > 150 GeV
- Multi-parton LO + PS do better than LO + PS !!
  - see ΔΦ(Z, j1)
- PS important for NLO 1 jet in multijet environment

Z+jets - azimuthal correlations ΔΦ(Z, j_i)

Phys. Lett. B722 (2013) 238

- $N_{jets} \geq 3$
  - ΔΦ(Z, j_i)
  - normalized to unity
  - ratios to MadGraph

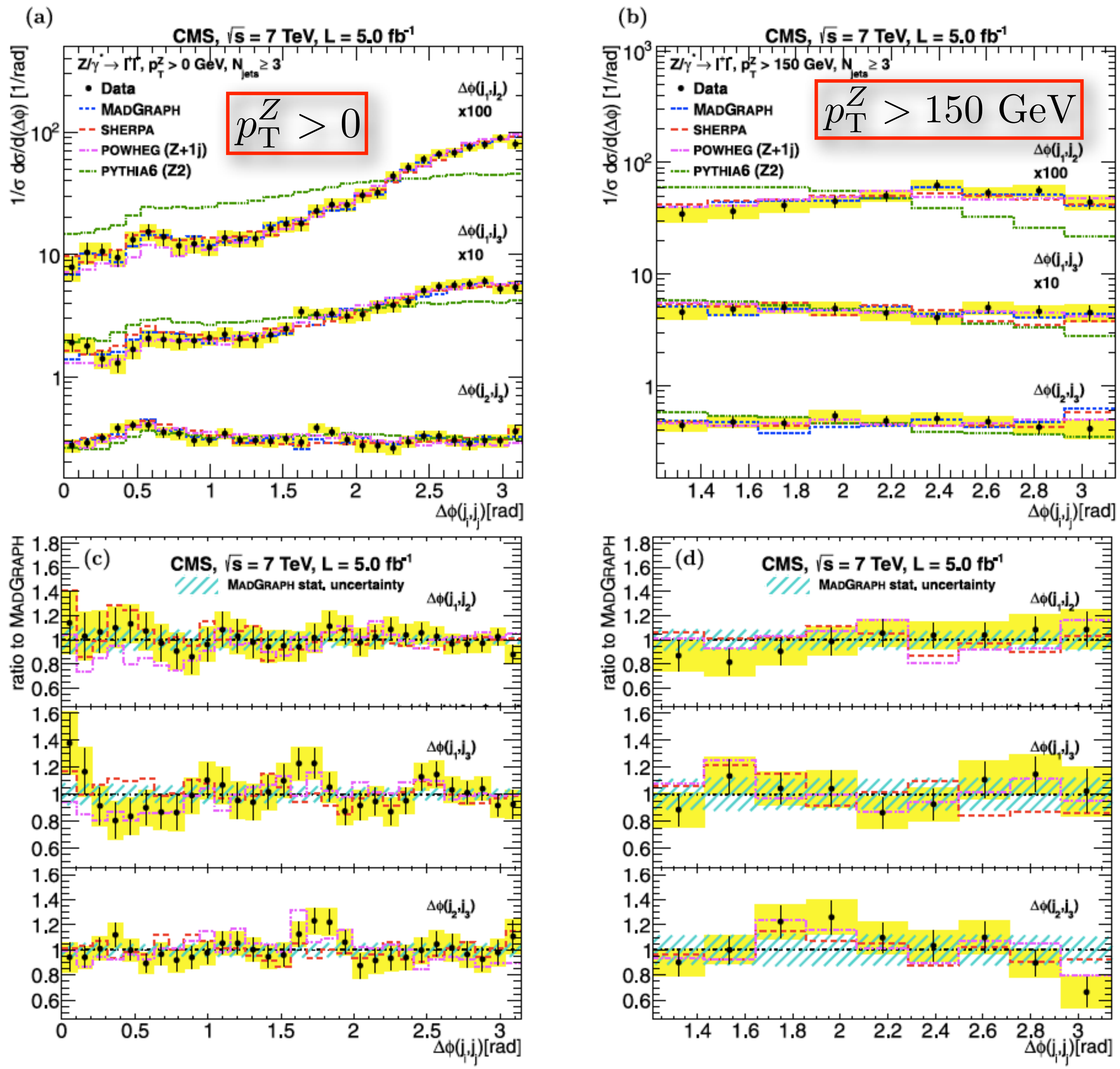


- Good agreement with MadGraph, POWHEG and SHERPA
- For ΔΦ(Z, j_3), PYTHIA LO + PS agrees with data
  - PS contribution

Z+jets - azimuthal correlations $\Delta\Phi(j_i, j_k)$

Phys. Lett. B722 (2013) 238

- $N_{jets} \geq 3$
  - $\Delta\Phi(j_1, j_2)$
  - $\Delta\Phi(j_1, j_3)$
  - $\Delta\Phi(j_2, j_3)$
  - normalized to unity
  - ratios to MadGraph

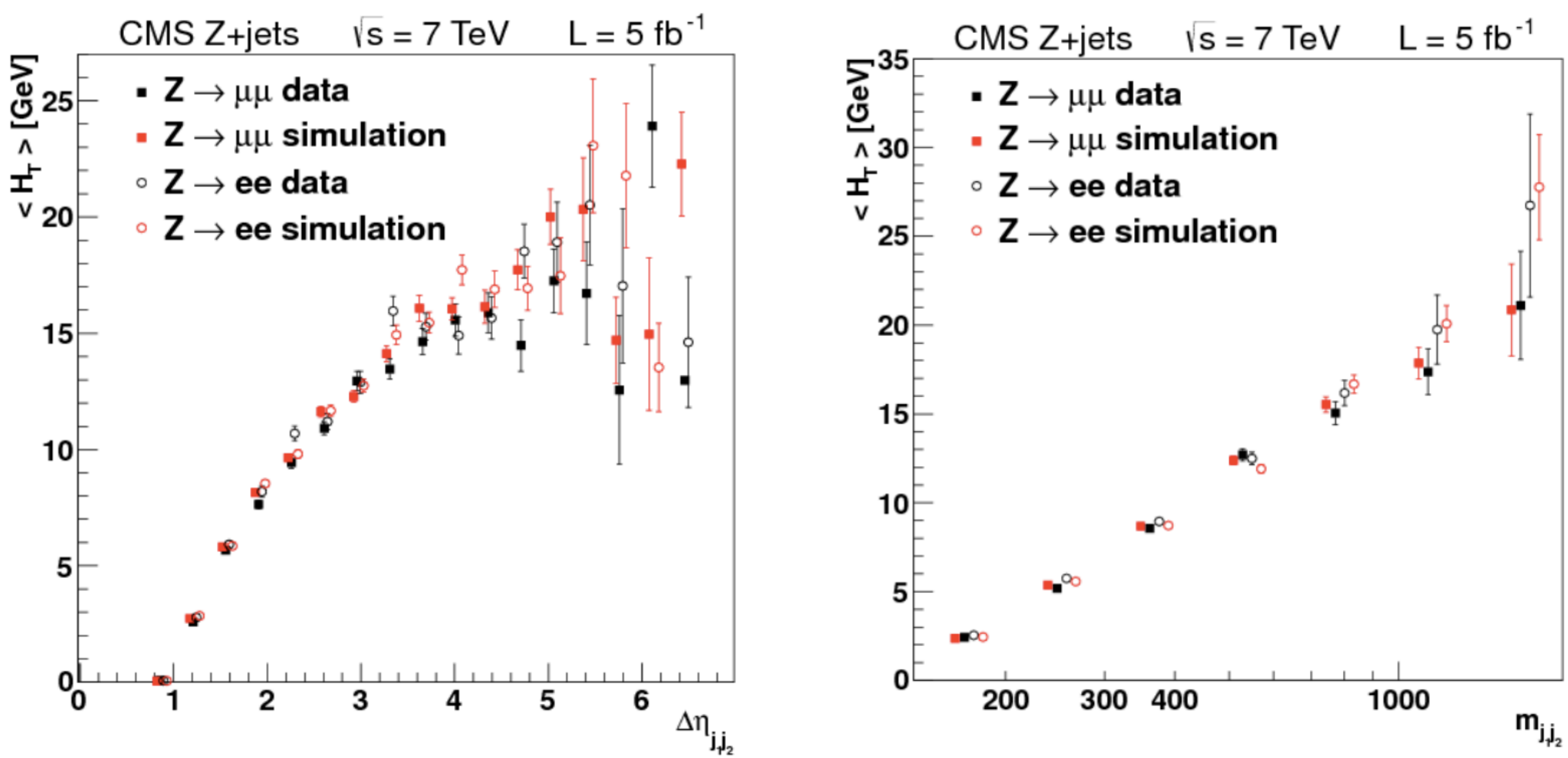


- Isotropic for $p_T^Z > 150$ GeV
  - improved agreement with PYTHIA consistent with increased phase space available for parton emission

Z+jets - EW Z+2 forward jets

CMS-FSQ-12-019
arXiv:1305.7389

- Correlation between soft hadronic activity (H_T) and dijet rapidity span and M_{jj} (reco level)
  - H_T = scalar sum of jet p_T's for $|\eta_j| > 4.7$
  - reco level: no background subtraction, no unfolding
  - tagged jets: $p_{T1} > 65$ GeV; $p_{T2} > 40$ GeV in $|\eta_j| < 3.6$

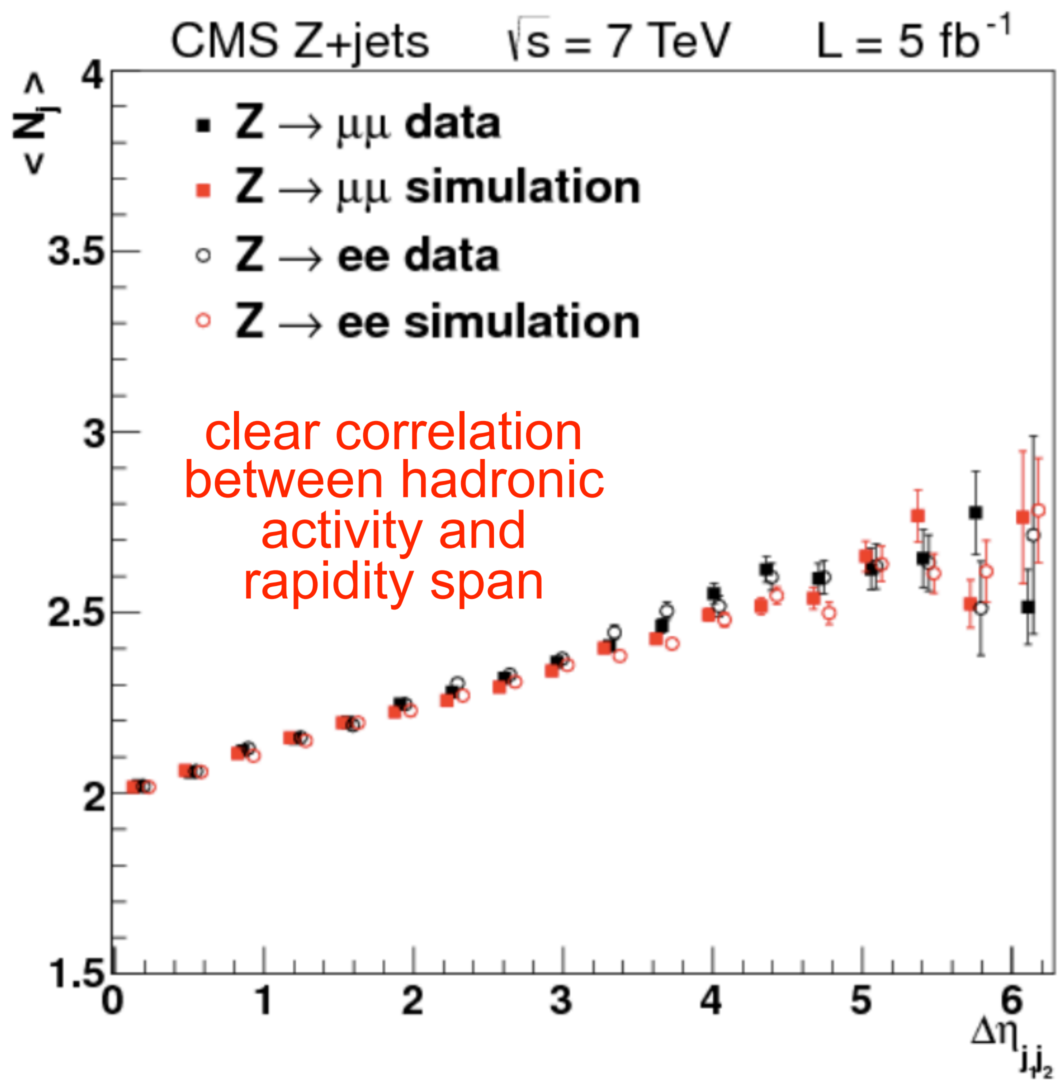


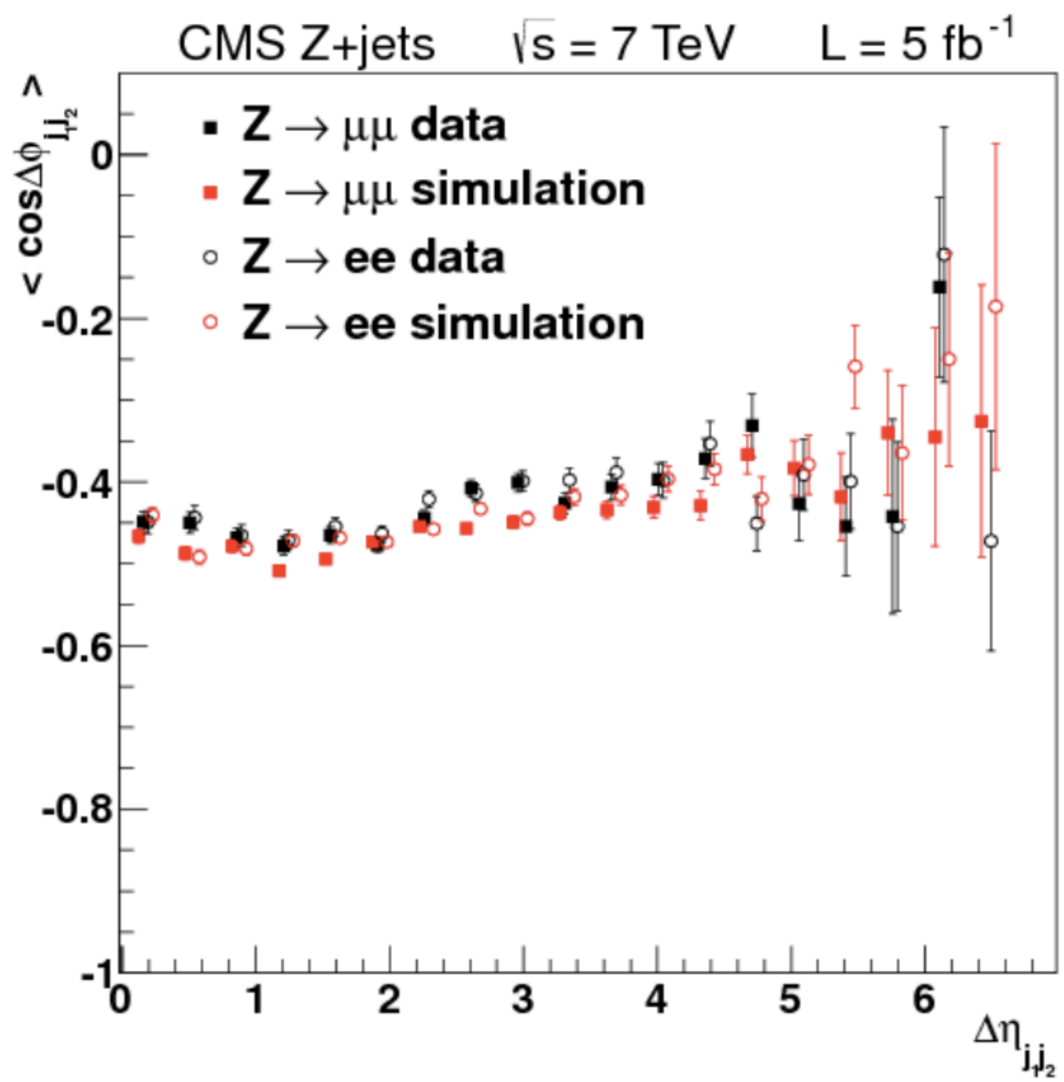
- MadGraph-based predictions in agreement with data

Z+jets - EW Z+2 forward jets

CMS-FSQ-12-019
arXiv:1305.7389

- Radiation pattern as a function of the dijet rapidity span
  - reco level: no background subtraction, no unfolding
  - $p_{Tj} > 40$ GeV





- MadGraph-based predictions in agreement with data

W + jets

Phys. Rev. D85 (2012) 092002

- Probe NLO pQCD properties by studying H_T
- Missing transverse momentum
  - E_T^{miss} calculated from the energy deposits in calorimeter cells inside 3D clusters with $|\eta| < 4.5$ The clusters are calibrated to hadronic scale including corrections to account for dead material and out-of-cluster energy losses. It is also corrected for the muon momentum and its energy deposited in the calorimeter
  - $m_T(W)$ is given by $\sqrt{2p_T^{\ell}p_T^{\nu}\left(1-\cos\left(\phi^{\ell}-\phi^{\nu}\right)\right)}$

    where the neutrino momentum components are the corresponding E_T^{miss} components
- Unfolding of efficiency and resolution effects
  - iterative Bayesian method

W + jets - systematics

Phys. Rev. D85 (2012) 092002

- W+jets complementary to Z+jets
- Large background contamination
  - multi-jets at low N_{jets}: 5-10% (e); 5% (μ)
  - ttbar at $N_{jets} \geq 3$: ~4-60% for N_{jets} = 1 to 4
- Systematic dominated
  - 10% stat and 40% sys for N_{jets} = 4
- Main systematic uncertainties
  - Jet energy scale (2.5%-14%, p_T, η dependent)
    - 10% on cross section for N_{jets} = 1
    - 40% on cross section for N_{jets} = 4
  - Jet energy resolution (10%)
    - 1-6% on cross section
  - top background
    - 20% on cross section for N_{jets} = 4
  - QCD background
    - 11-20% on cross section for N_{jets} = 4
- NLO theoretical uncertainties (BLACKHAT)
  - μ_R and μ_F: 4-15%
  - PDF + α_S: 2-6%
  - Hadronization and underlying event model: 2-5%

Fiducial Phase Space

$p_T^l > 20$ GeV, $|\eta| < 2.5$

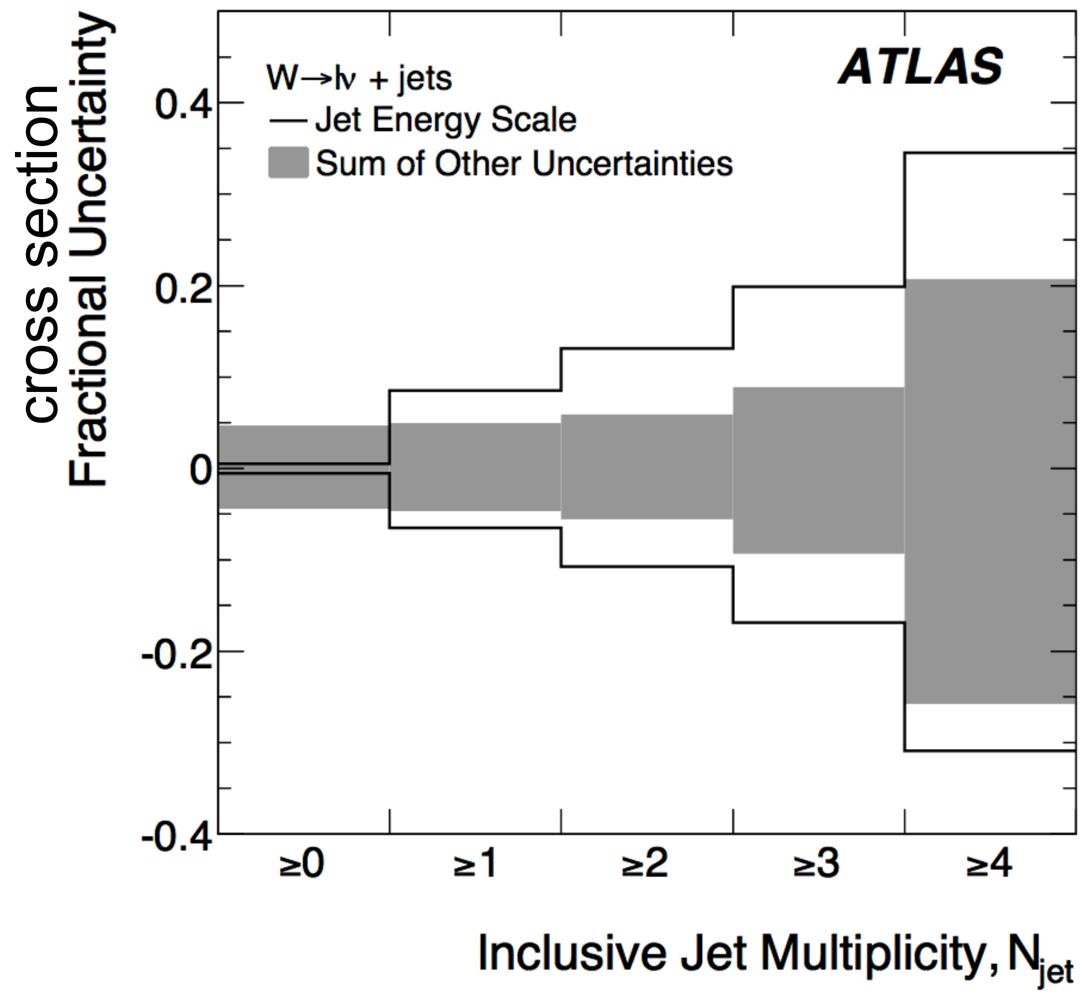
$E_T^{miss} > 25$ GeV

$m_T(W) > 40$ GeV

$p_T^{jet} > 30$ GeV

$|y^{jet}| < 4.4$

$\Delta R^{lj} > 0.5$



W + jets - MC signal events and NLO calculations

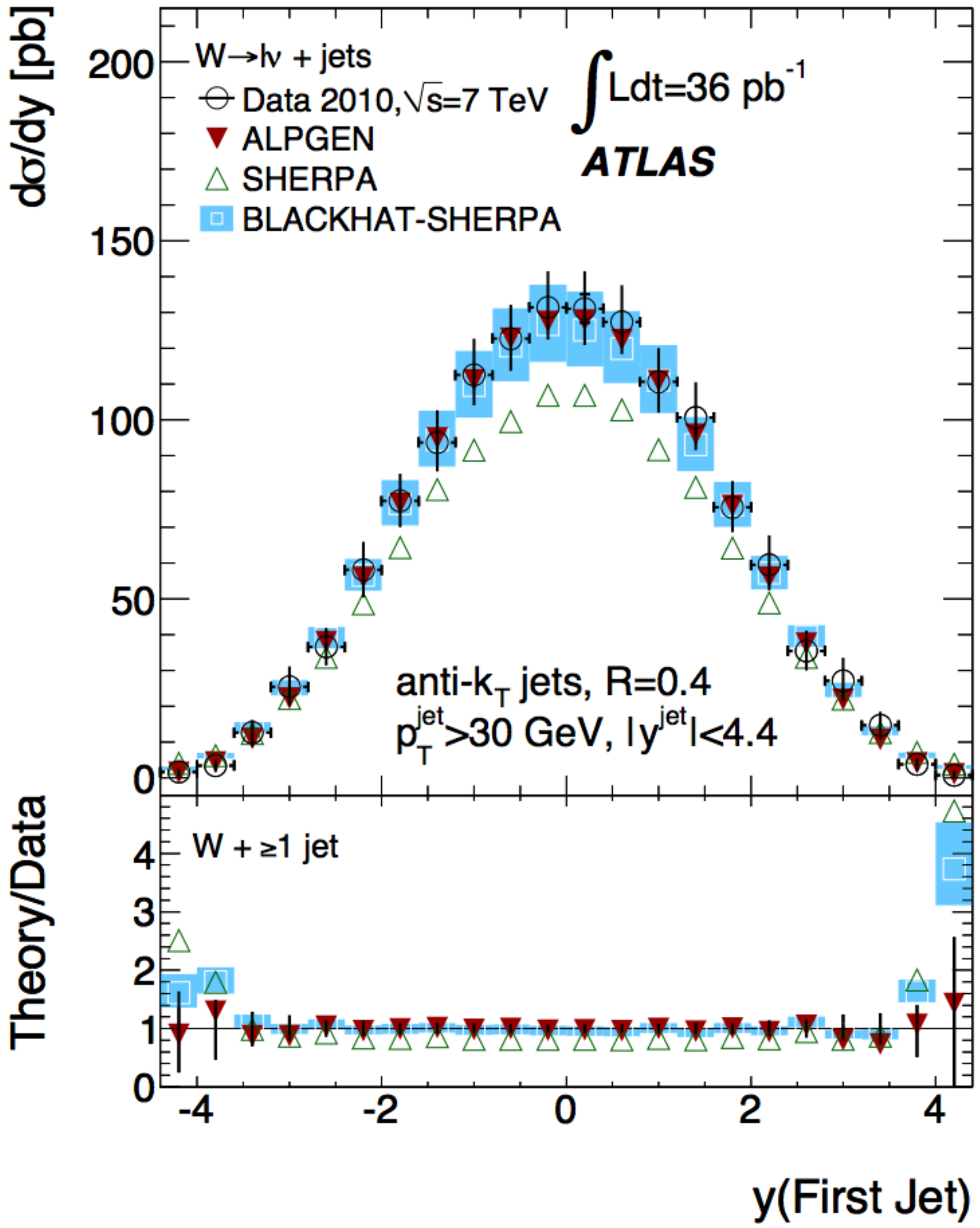
Phys. Rev. D85 (2012) 092002

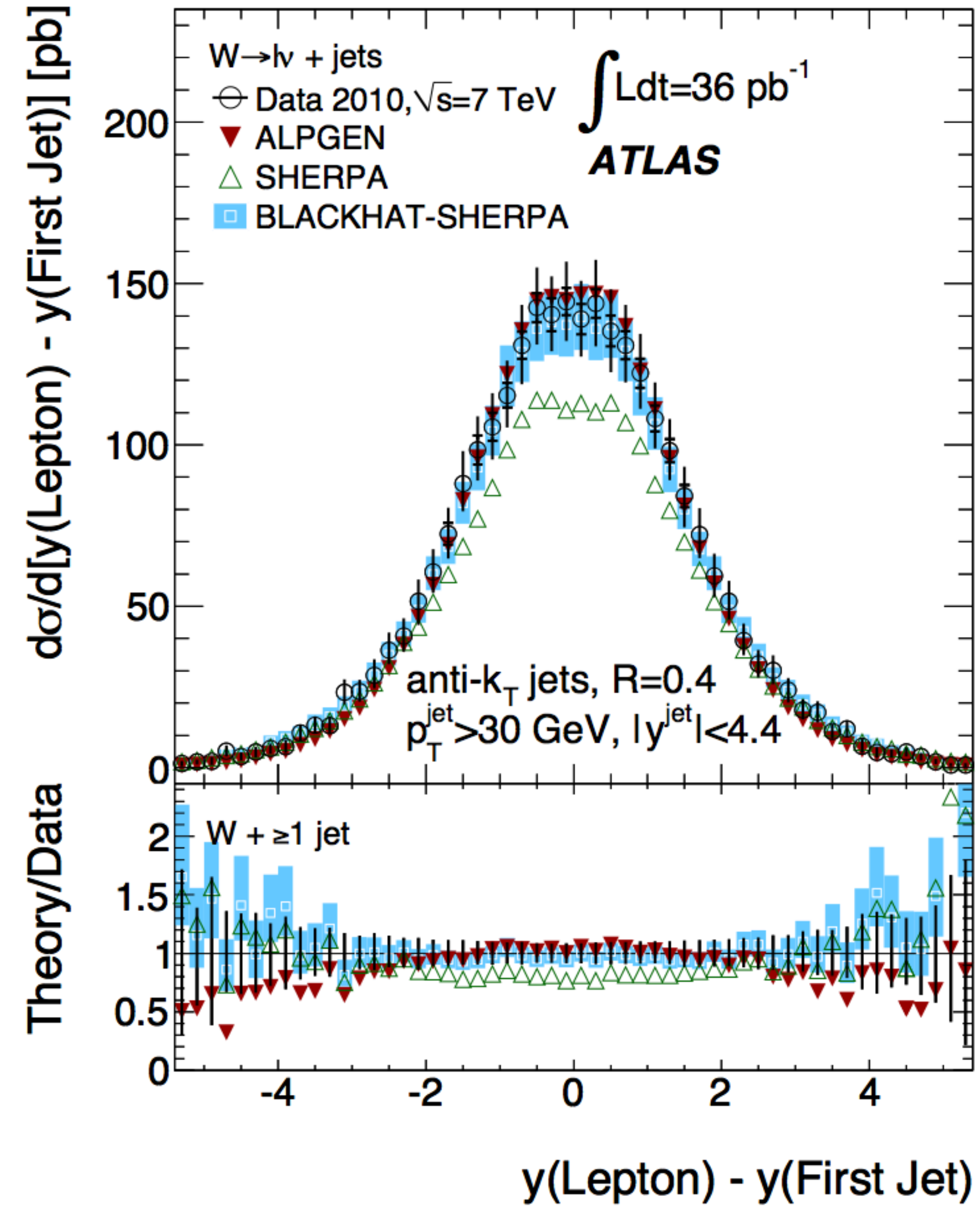
- MC signal event samples: W + jets ($0 \leq N_{partons} \leq 5$)
  - ALPGEN 2.13
    - HERWIG (PS) + JIMMY v4.31 (UE AUET1)
    - PDF: CTEQ6L1 (LO)
    - factorization scale set to $Q^2 = M_W^2$ + sum of all partons p_T^2
    - MLM parton-jet matching scheme performed at $p_T^{jet} = 20$ GeV (cone R = 0.7)
  - SHERPA 1.3.1
    - CTEQ6.6M (NLO)
    - CKKW parton-jet matching scheme
    - default μ_R and μ_F and UE tune
  - normalized to NNLO inclusive W production
  - Pileup events: minimum bias event from PYTHIA with AMBT1 tune
    - events reweighted to ensure the same distribution on the number of primary vertices as for data
- NLO QCD predictions
  - BLACKHAT-SHERPA (for $N_{jet} \leq 4$)
    - PDF: CTEQ6.6M (used for both LO and NLO calculations)
  - MCFM v5.8 (for $N_{jet} \leq 2$)
    - PDF: CTEQ6L1 (LO) and CTEQ6.6M (NLO)
  - renormalization and factorization scales set to $H_T/2$
  - corrected for non-pQCD effects, hadronization, UE
    - (distributions for particle-level jets)/(distribution for parton-level jets with no UE)

W + jets - first jet y and Δy to lepton

Phys. Rev. D85 (2012) 092002

- Distributions sensitive to the PDFs used for the LO and NLO ME.



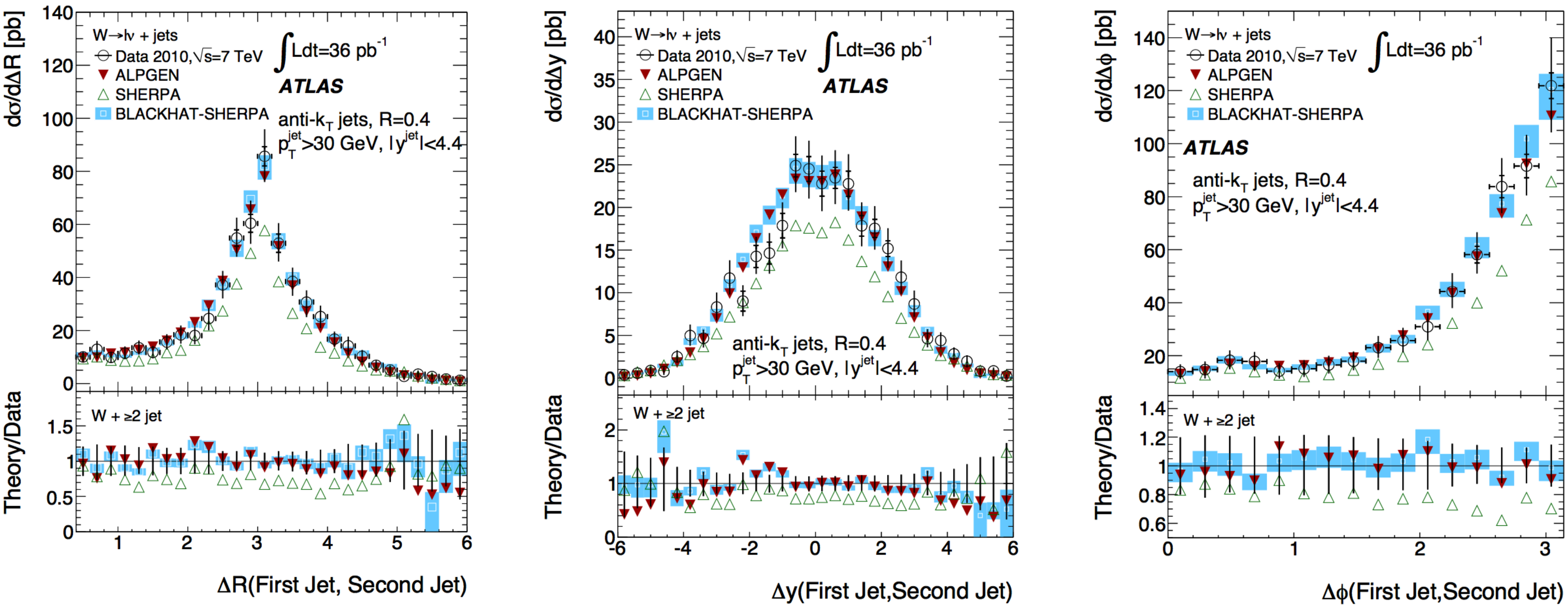


- BLACKHAT-SHERPA deviation at high y may be caused by issues with gluon PDF at high x.

- ALPGEN has a different distribution

W + jets - distances between first two jets

Phys. Rev. D85 (2012) 092002



- Test of hard parton radiation at large angles and of matrix element to parton shower matching schemes
  - $\Delta R \sim \Delta\Phi \sim \pi$: most jets modeled via ME calculation
  - ΔR small (collinear radiation): most jets modeled via the parton shower

- ALPGEN and BLACKHAT+SHERPA agree well with data
- SHERPA worse agreement (attributed to differences in PDFs, α_s and factorization scales)

W + jets - k_T splitting

Eur. Phys. J. C, 73 5 (2013) 2432

- k_T clustering sequence mimics the reverse QCD evolution
  - measurement probes QCD evolution
  - test of LO and NLO MC generators and analytical calculations
- k_T distance measure
  - distance between two particle momenta p_i, p_j
  - distance p_i to beam

$$d_{ij} = \min\left(p_{\mathrm{T}i}^2, p_{\mathrm{T}j}^2\right) \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = p_{\mathrm{T}i}^2$$

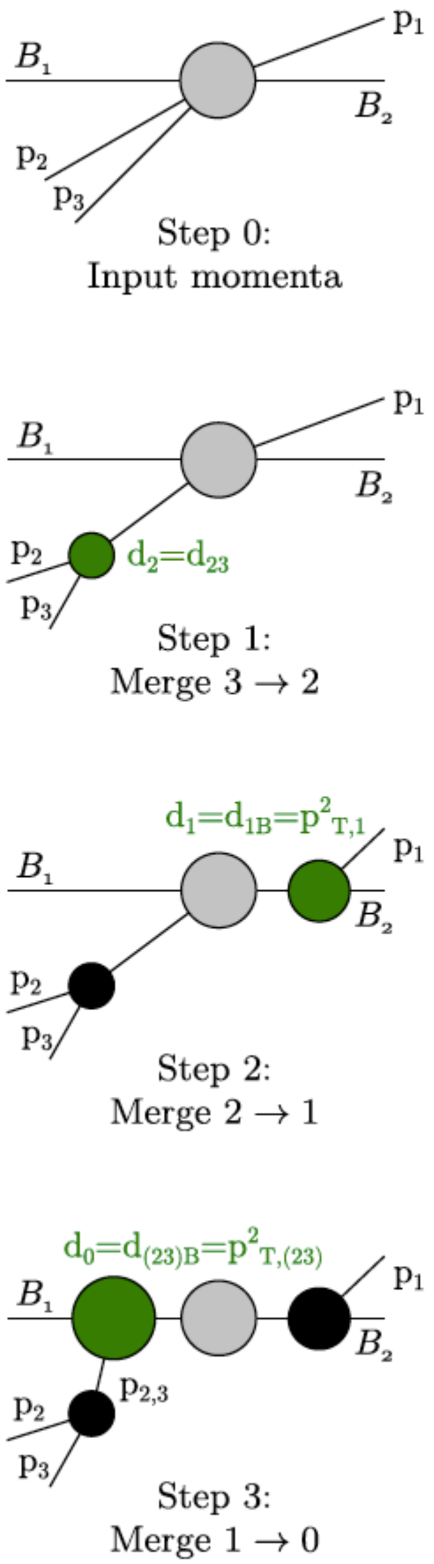
$$R = 0.6$$

- Clustering sequence

1. Calculate all d_{ij} and d_{iB}
2. Find their minimum, $d_{\min}$
   (a) If $d_{\min}$ is a d_{ij}, combine i and j: $p_{ij} = p_i + p_j$
   (b) If $d_{\min}$ is a d_{iB}, remove i from the list and declare it a jet
3. Return to step 1 or stop if no particle remains

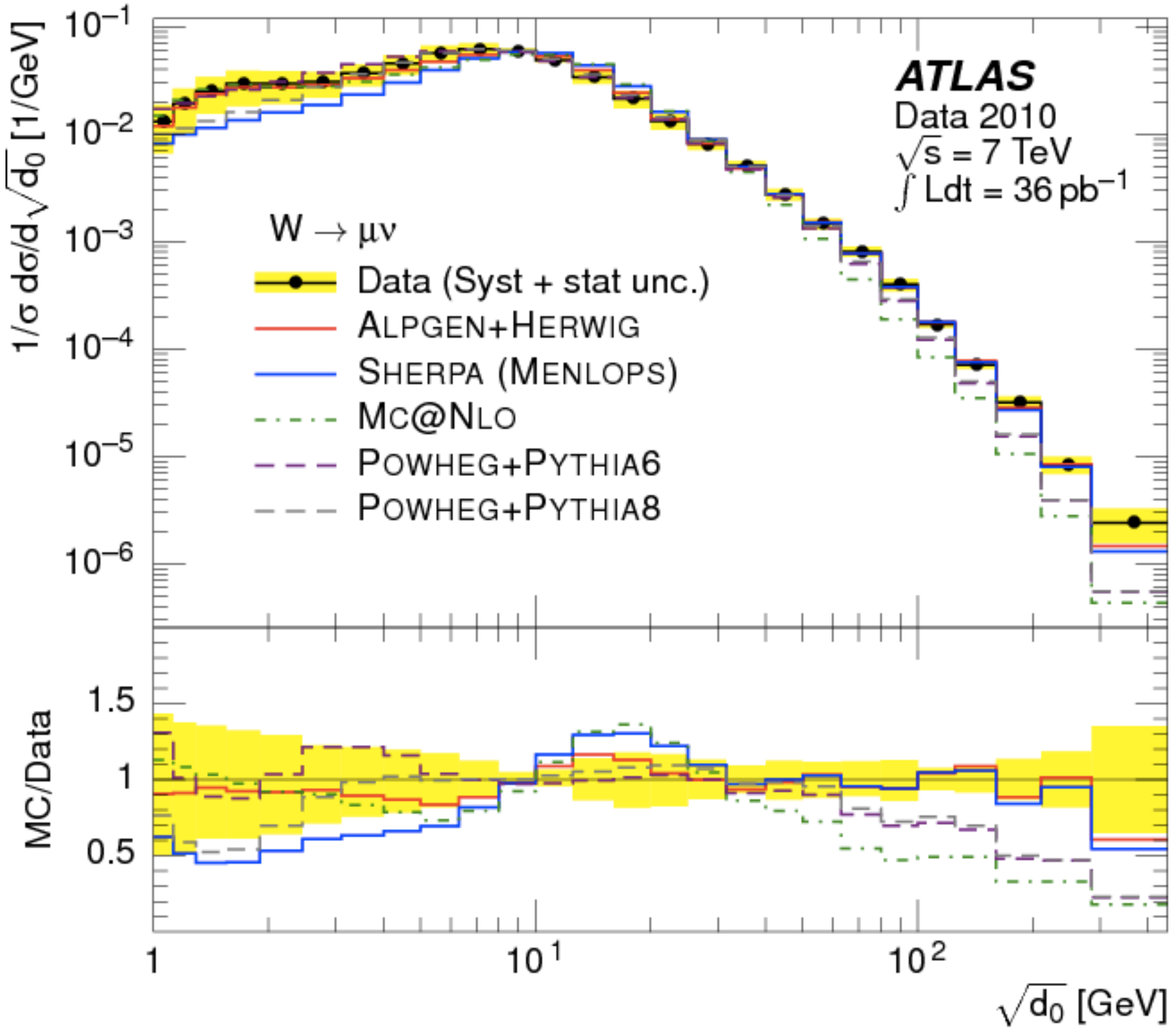
- Define $\mathbf{d_k}$ as $d_{\min}$ found when clustering k+1 to k particles
  - $\sqrt{d_0}$ corresponds to p_T of highest p_T jet (last step)

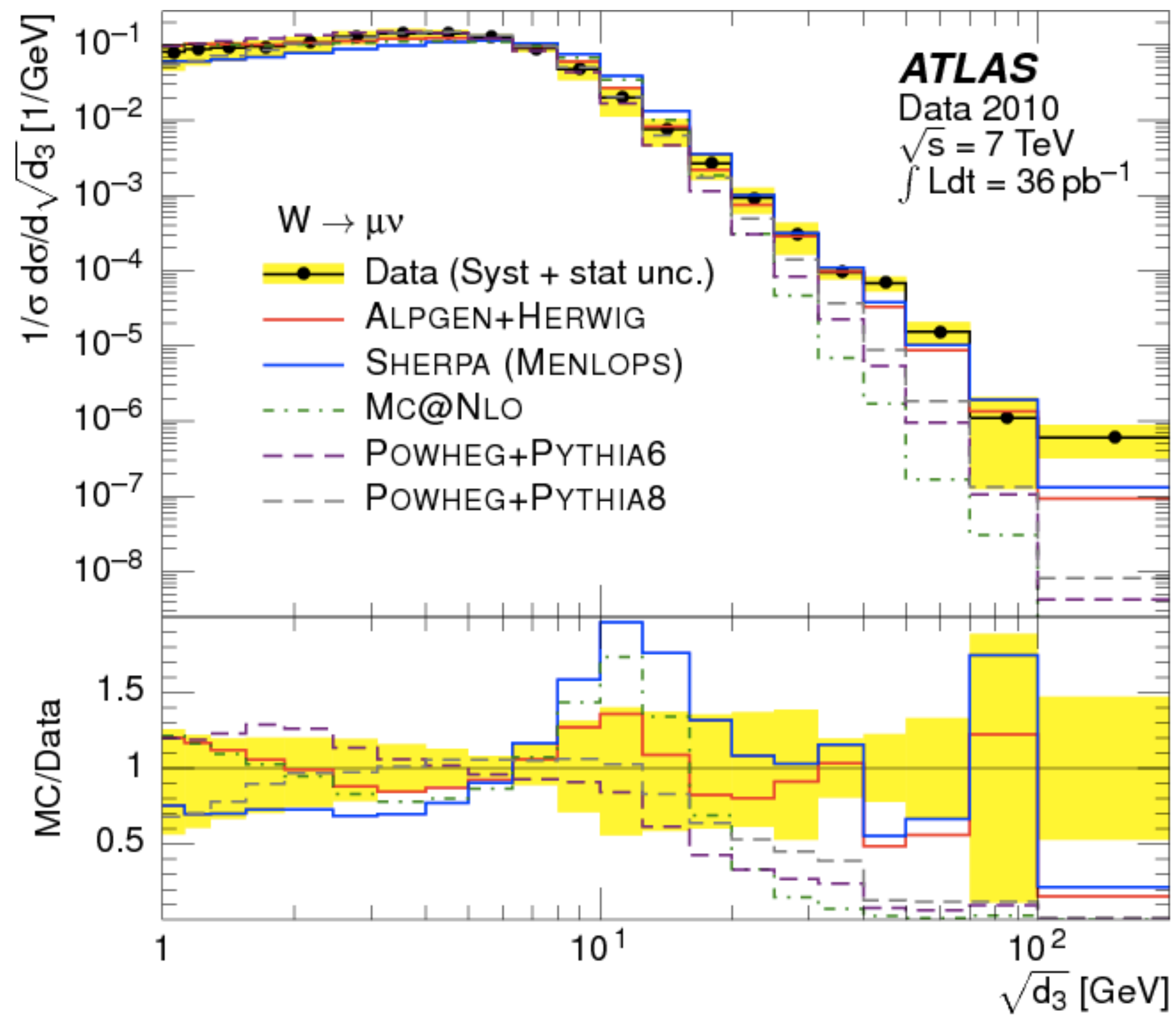
example



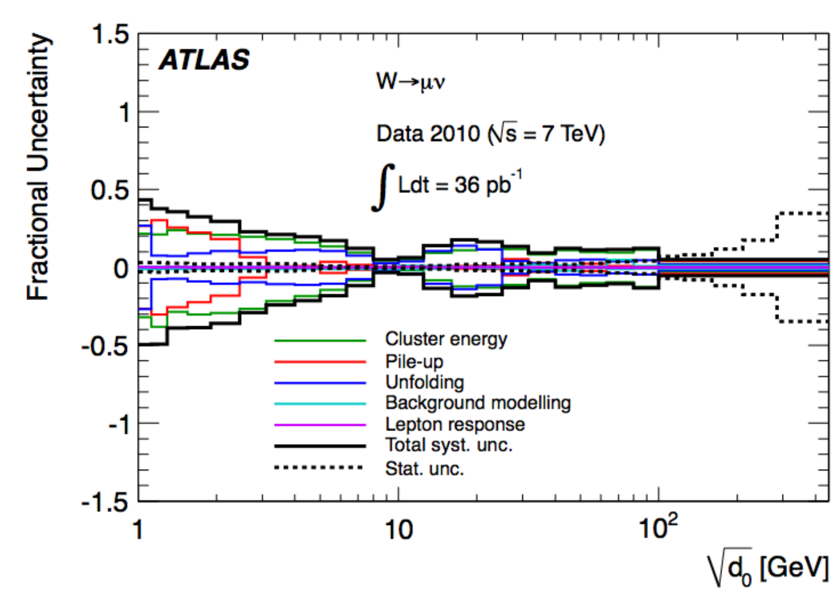
W + jets - k_T splitting

Eur. Phys. J. C, 73 5 (2013) 2432



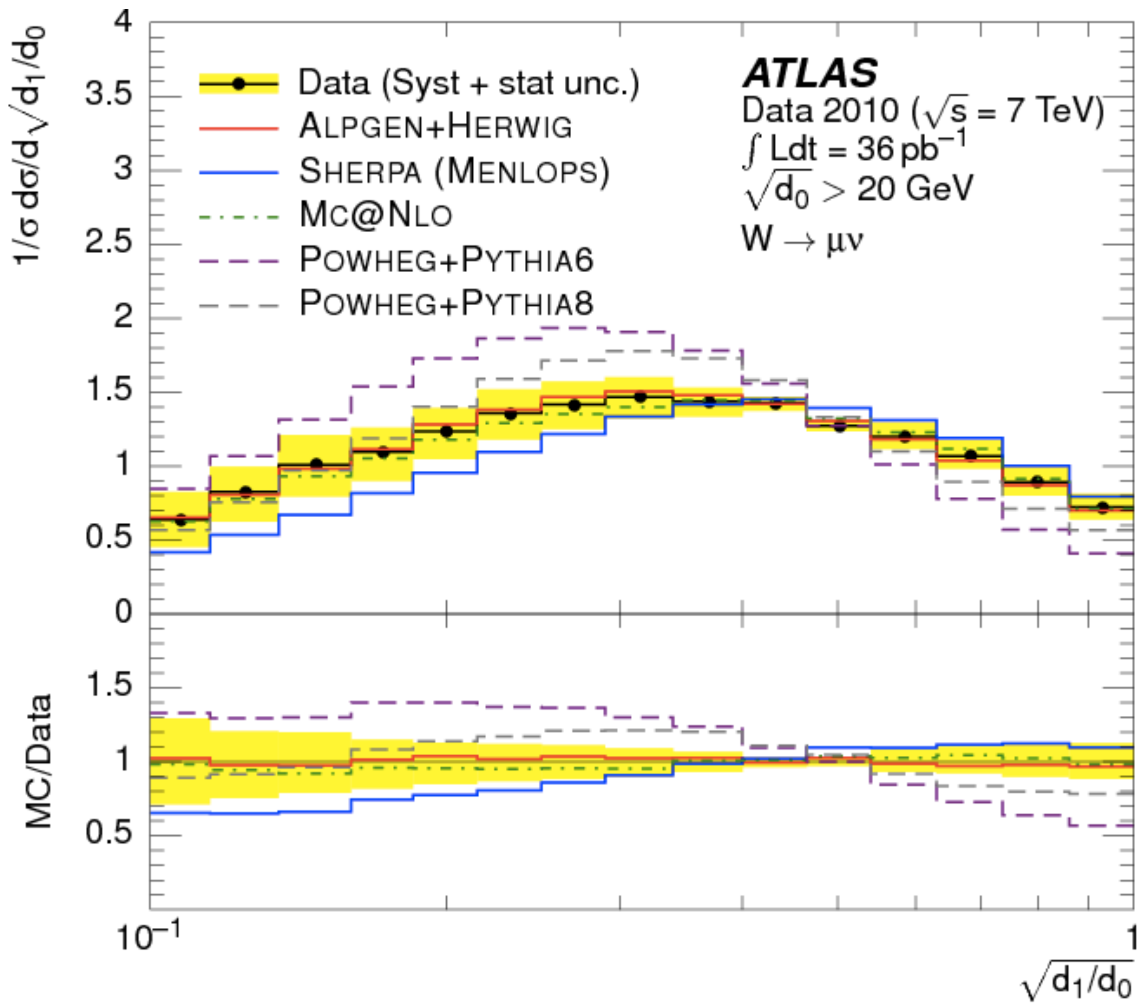


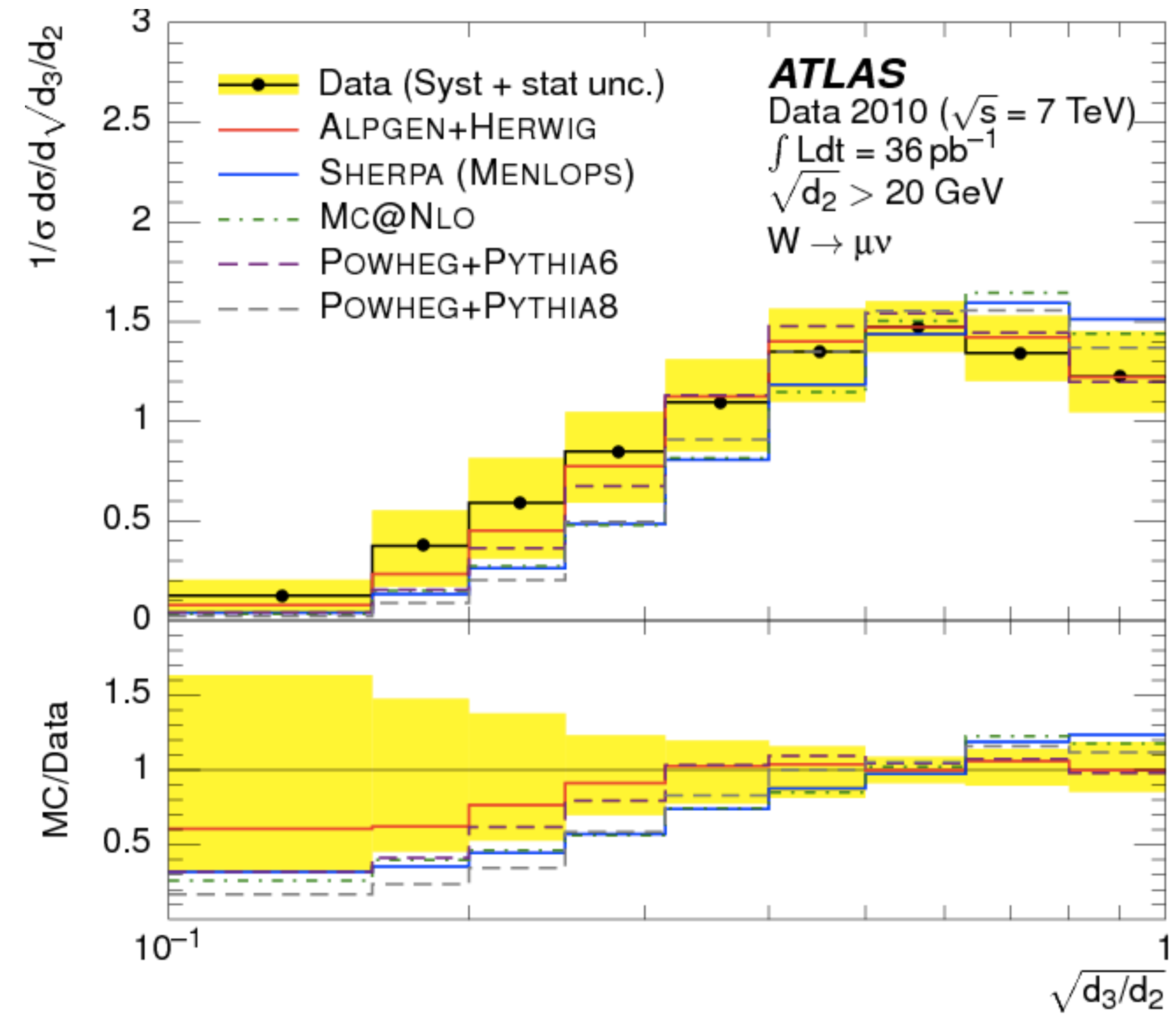
- LO multi-leg predictions (ALPGEN, SHERPA) perform better than NLO+PS generators (MC@NLO, POWHEG) in hard region
- Significant differences also in soft region, probing QCD resummation
- Largest experimental uncertainty: cluster energy scale and pileup
  - Statistical uncertainty dominating only in hard region



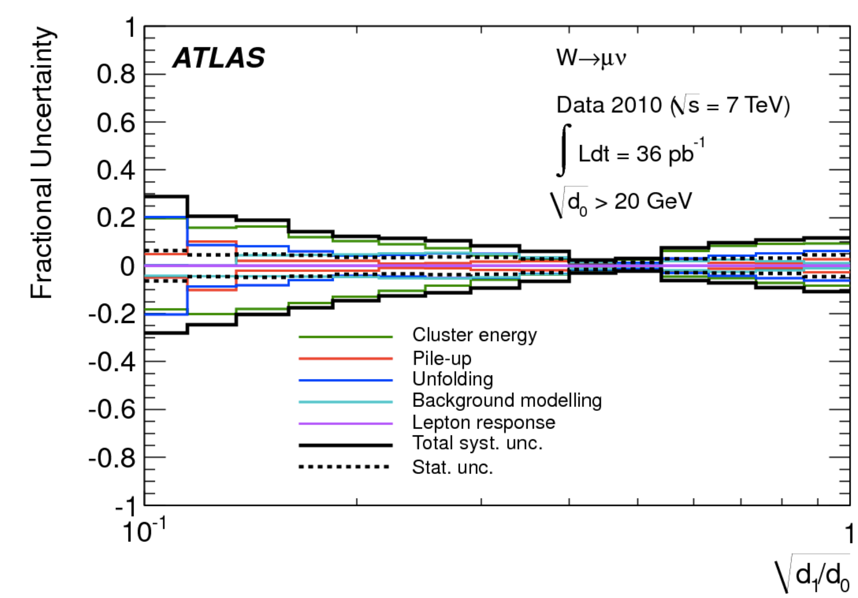
W + jets - k_T splitting

Eur. Phys. J. C, 73 5 (2013) 2432





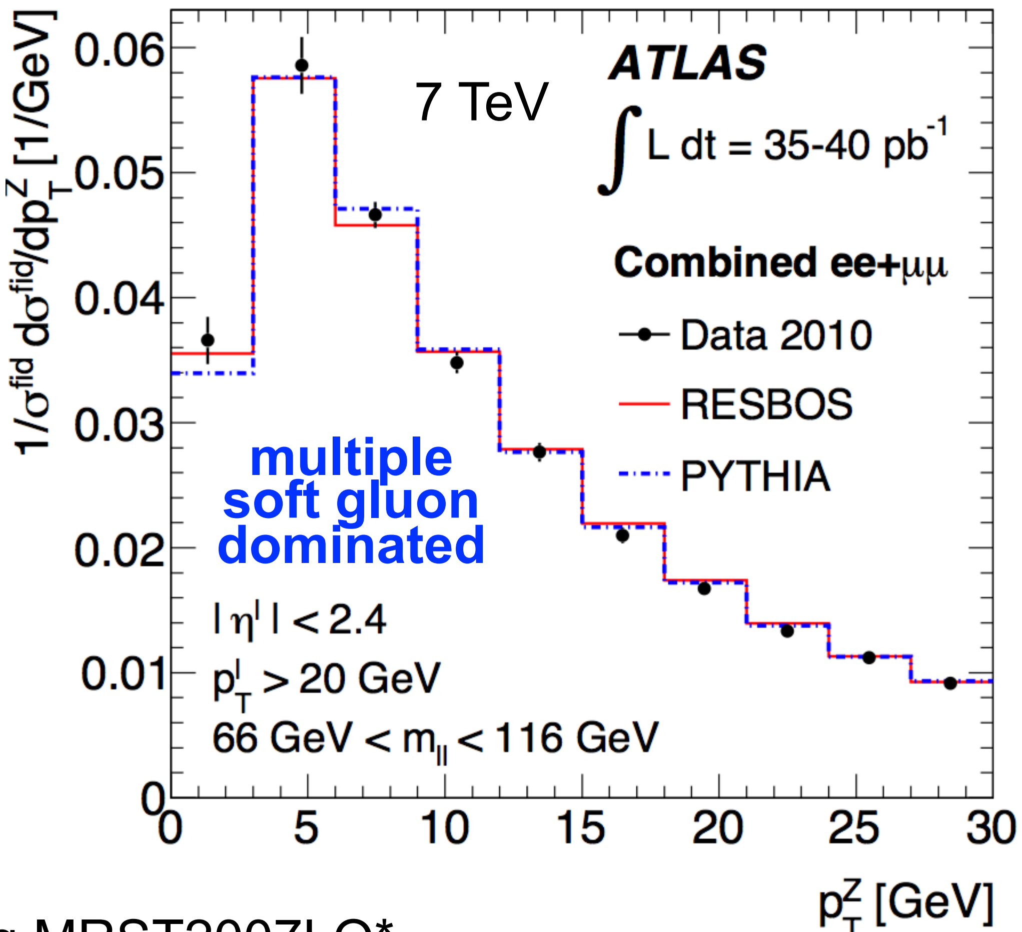
- d_{k+1}/d_k ratio: most generators just outside experimental uncertainty band
- Best description with HERWIG-based generators (ALPGEN, MC@NLO)
- Largest experimental uncertainty: cluster energy scale and unfolding
  - Systematics dominated

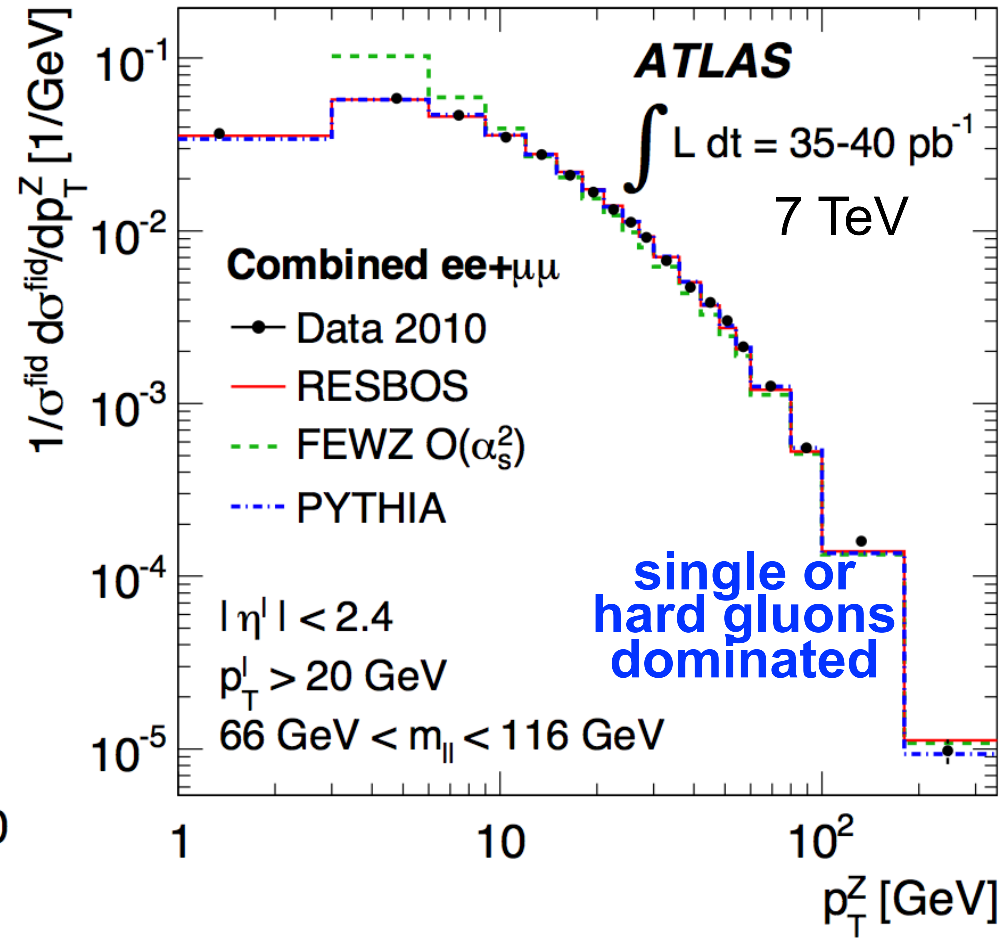


Z p_T

Phys. Lett. B705 (2011) 415-434

- Total background: 0.4% (mu) 1.5% (e), up to 3.5% at high Z p_T
- Dominant exp uncertainties:
  - lepton ID and reconstruction: 1-3%
  - lepton energy scale and resolution: 0.7-4.4% (smaller for mu-channel)
  - unfolding (mainly Z p_T modeling used in efficiency correction): 1.3-4.7%





- PYTHIA 6.4 using MRST2007LO*
  - LO + PS
- SHERPA v1.2.3 using CTEQ6.6 and
  - LO with up to 5 additional hard partons + PS
- ALPGEN v2.13 using CTEQ6L1 and
  - LO with up to 5 additional hard partons
  - interfaced to HERWIG v6.510 (PS) and Jimmy (UE)
- MC@NLO using CTEQ6.6
  - NLO
  - HERWIG v6.510 (PS) and Jimmy (UE)
- POWHEG v1.0 using CTEQ6.6
  - NLO
  - PYTHIA 6.4 (PS + UE)

- MC Generators
  - All interfaced to PHOTOS (QED FSR)
  - Pileup: overlay of simulated minimum bias events
  - GEANT4 simulation of ATLAS
  - Pileup and resolution corrected to data
- FEWZ v2.0 using MSTW2008
  - $O(\alpha_s) + O(\alpha_s^2)$
- RESBOS using CTEQ6.6
  - NNLL resummation (scale MZ) (Collins-Soper-Sterman)
  - $+ O(\alpha_s) + O(\alpha_s^2)$ corrections

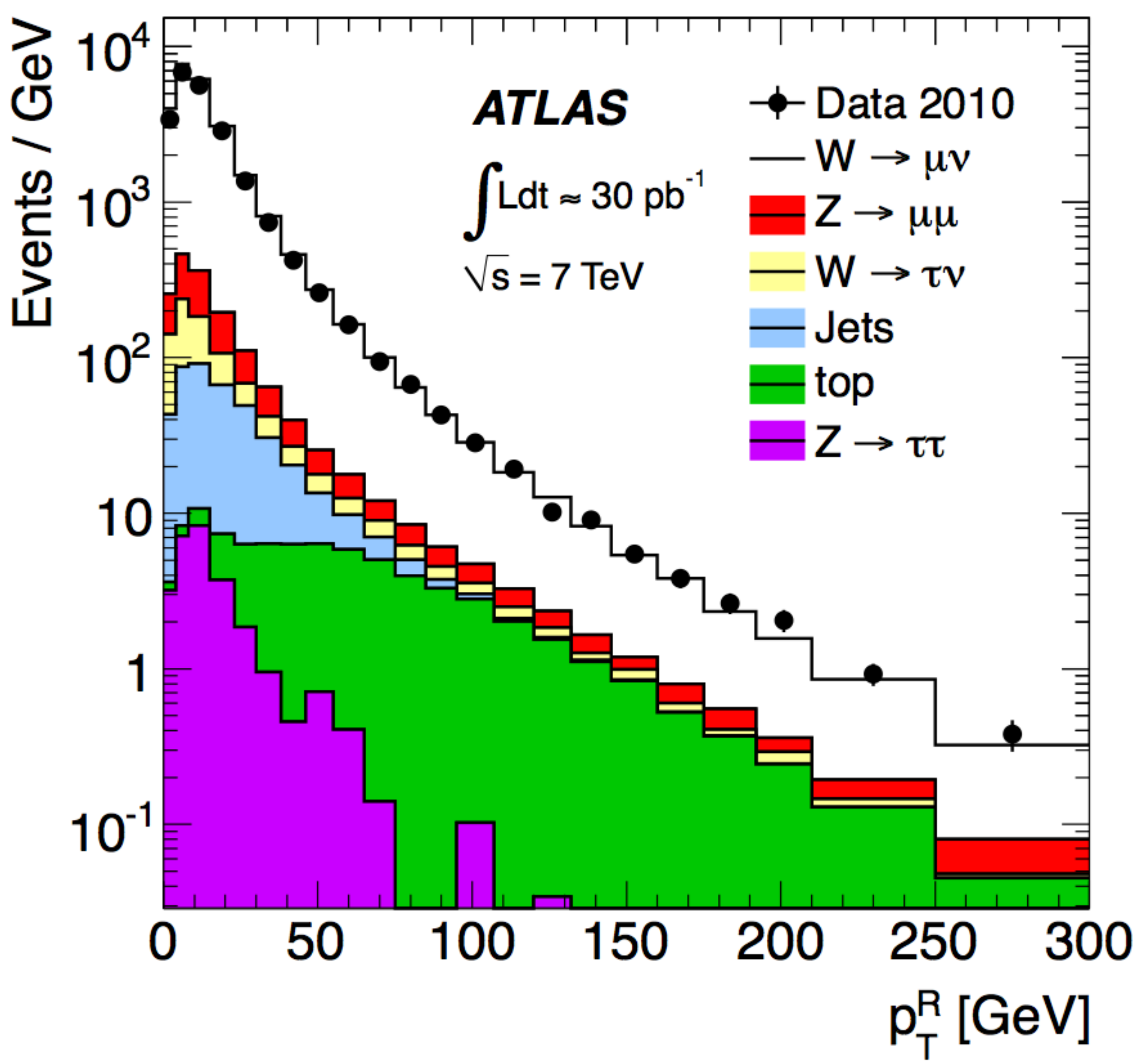
W p_T - MC generators

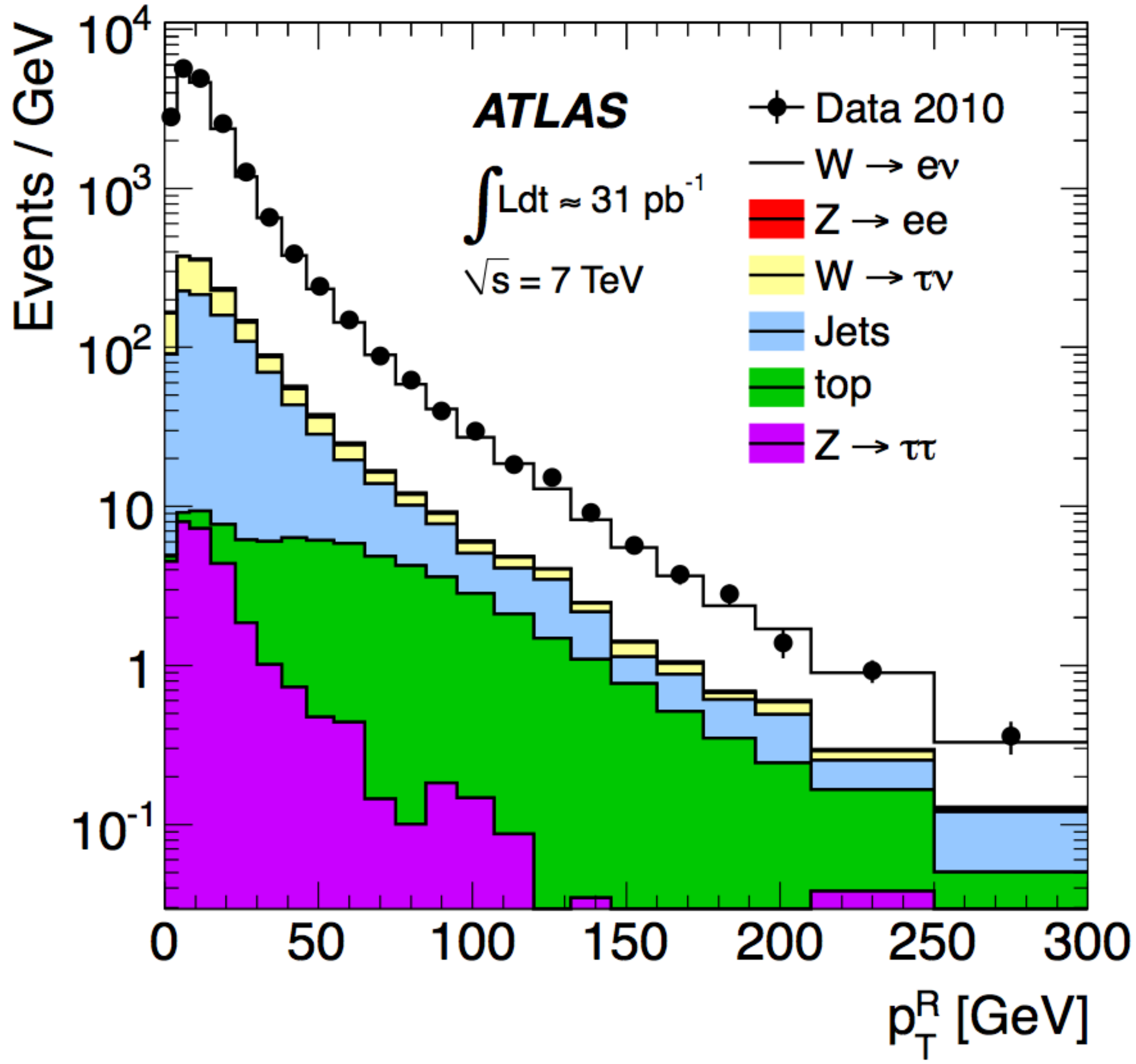
Phys. Rev. D85 (2012) 012005

- Pythia 6.421 using MRST2007LO*
  - LO + PS
- MC@NLO v3.41 using CTEQ6.6
  - NLO
  - Herwig v6.510 (PS) and Jimmy v4.1 (UE)
- Powheg v1.0 using CTEQ6.6
  - NLO
  - Pythia 6.4 (PS + UE)
- Alpgen v2.13 using CTEQ6L1
  - LO with up to 5 additional hard partons
  - interfaced to Herwig v6.510 (PS) and Jimmy v4.31 (UE)
- Sherpa v1.3.0 using CTEQ6L1
  - LO with up to 5 additional hard partons + PS
    - Catani-Seymour subtraction based parton shower model
    - matrix element merging withtruncated showers
    - high multiplicity matrix elements generated by COMIX
- MC Generators
  - All interfaced to Photos v2.15.4 (QED FSR)
  - taus decayed by TAUOLA v1.0.2
  - Pileup: overlay of simulated minimum bias events (ATLAS MC09 tunes)
  - GEANT4 simulation of ATLAS
  - Pileup and resolution corrected to data
- RESBOS using CTEQ6.6
  - NNLL resummation (scale MZ) + $O(\alpha_s)$ + $O(\alpha_s^2)$ correction
  - renormalization and factorization scale set to MW
- DYNNLO v1.1 and MCFM v5.8 for W + 1 parton
  - LO $O(\alpha_s)$ uses MSTW2008 NLO
  - NLO $O(\alpha_s^2)$ uses MSTW2008 NNLO
  - renormalization and factorization scale set to MW
  - do not include resummation effects: not expected to do well at very low W p_T
- FEWZ v2.0 using MSTW2008
  - $O(\alpha_s)$

W p_T - reconstructed p_T

Phys. Rev. D85 (2012) 012005

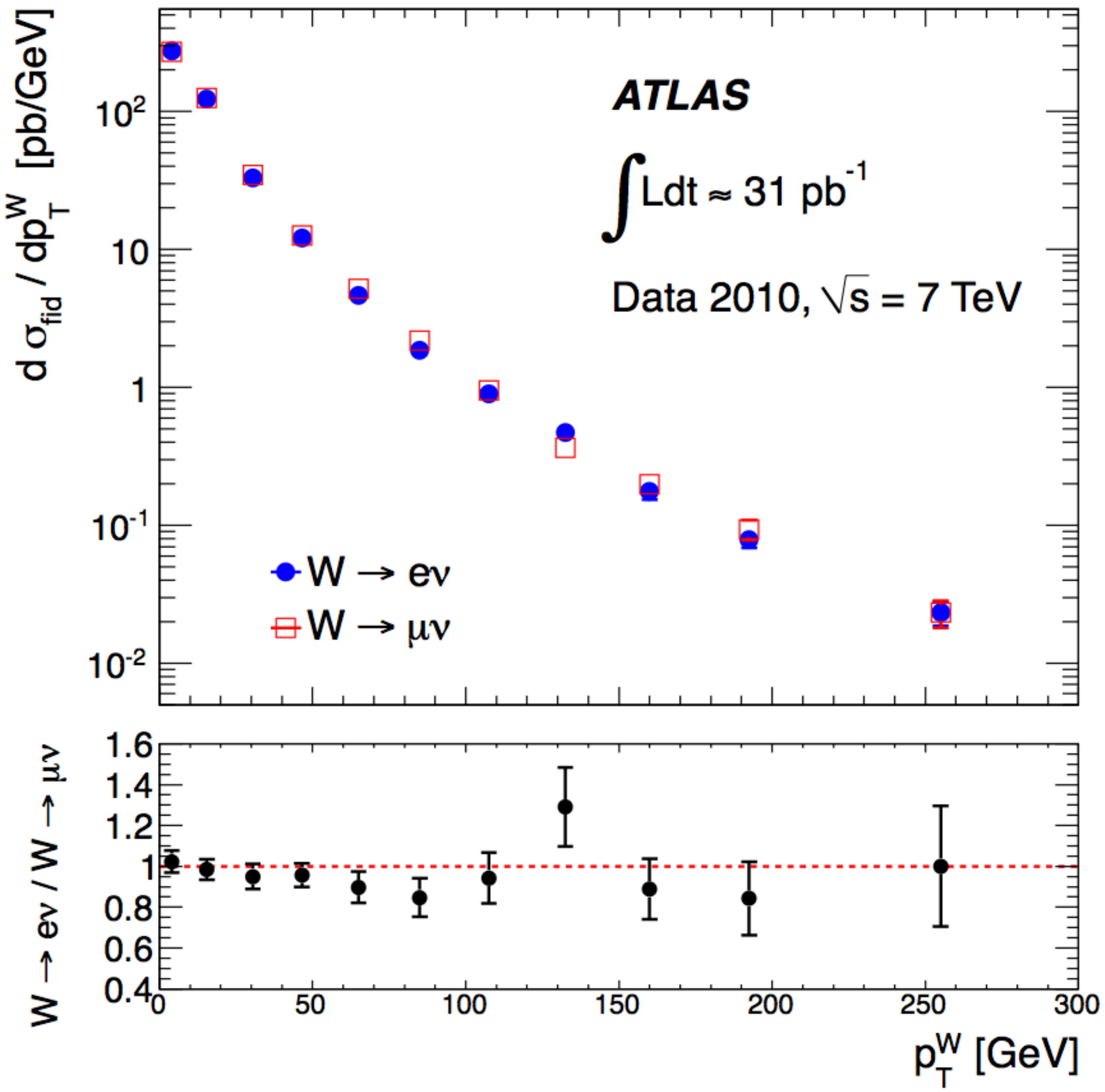


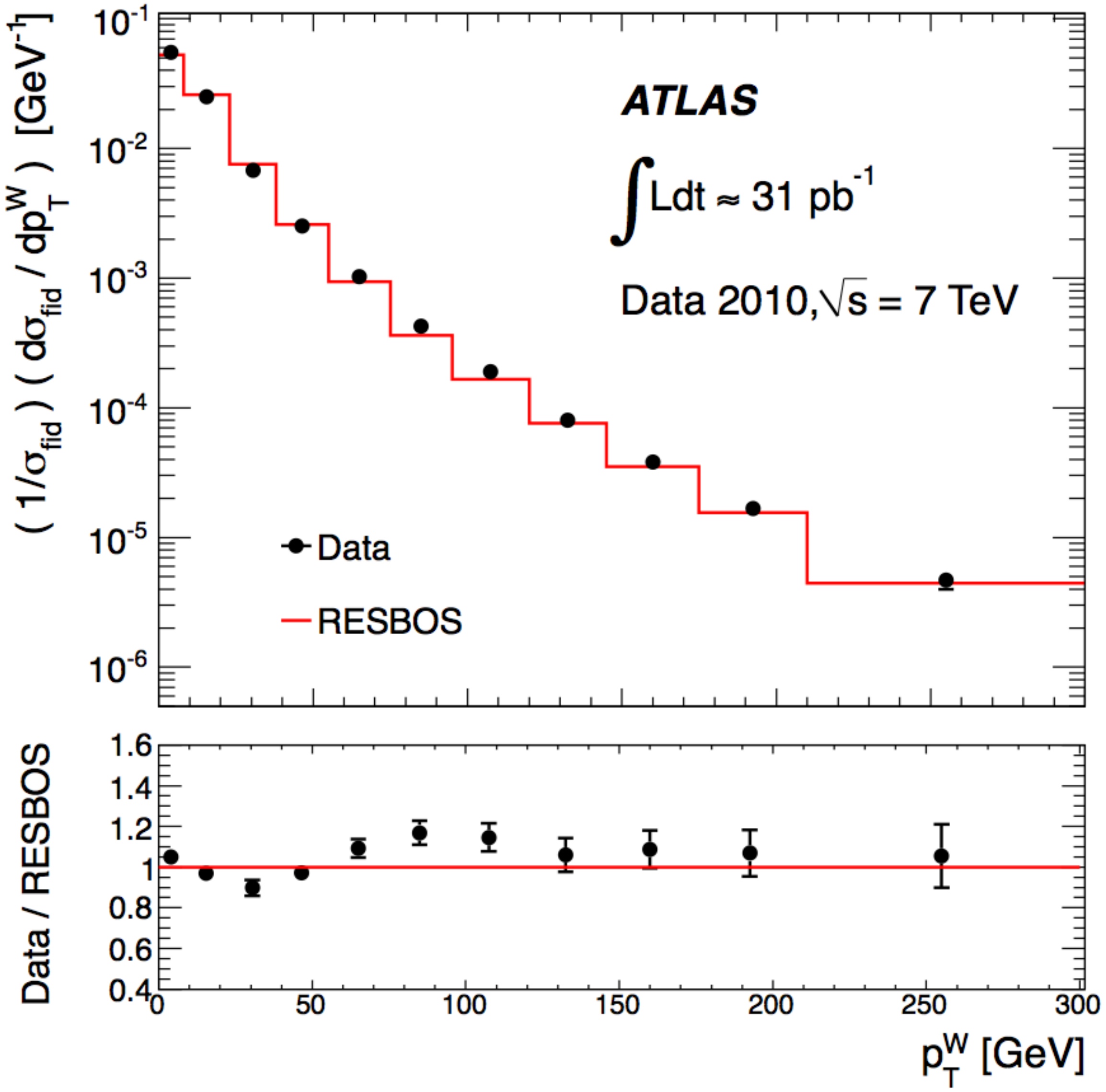


- p_T^R is the reconstructed p_T^W from the hadronic recoil

W p_T - unfolded true p_T

Phys. Rev. D85 (2012) 012005

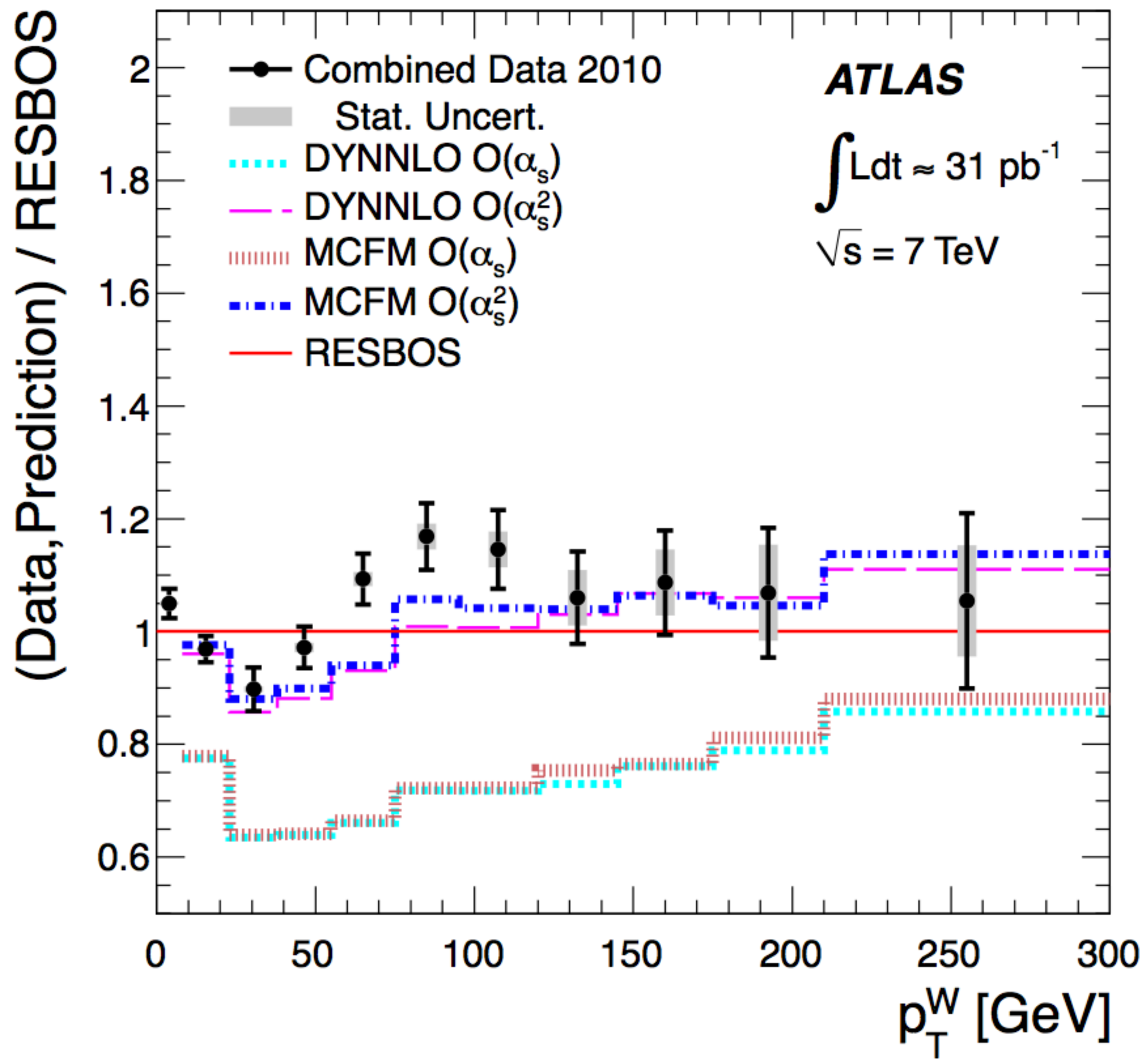


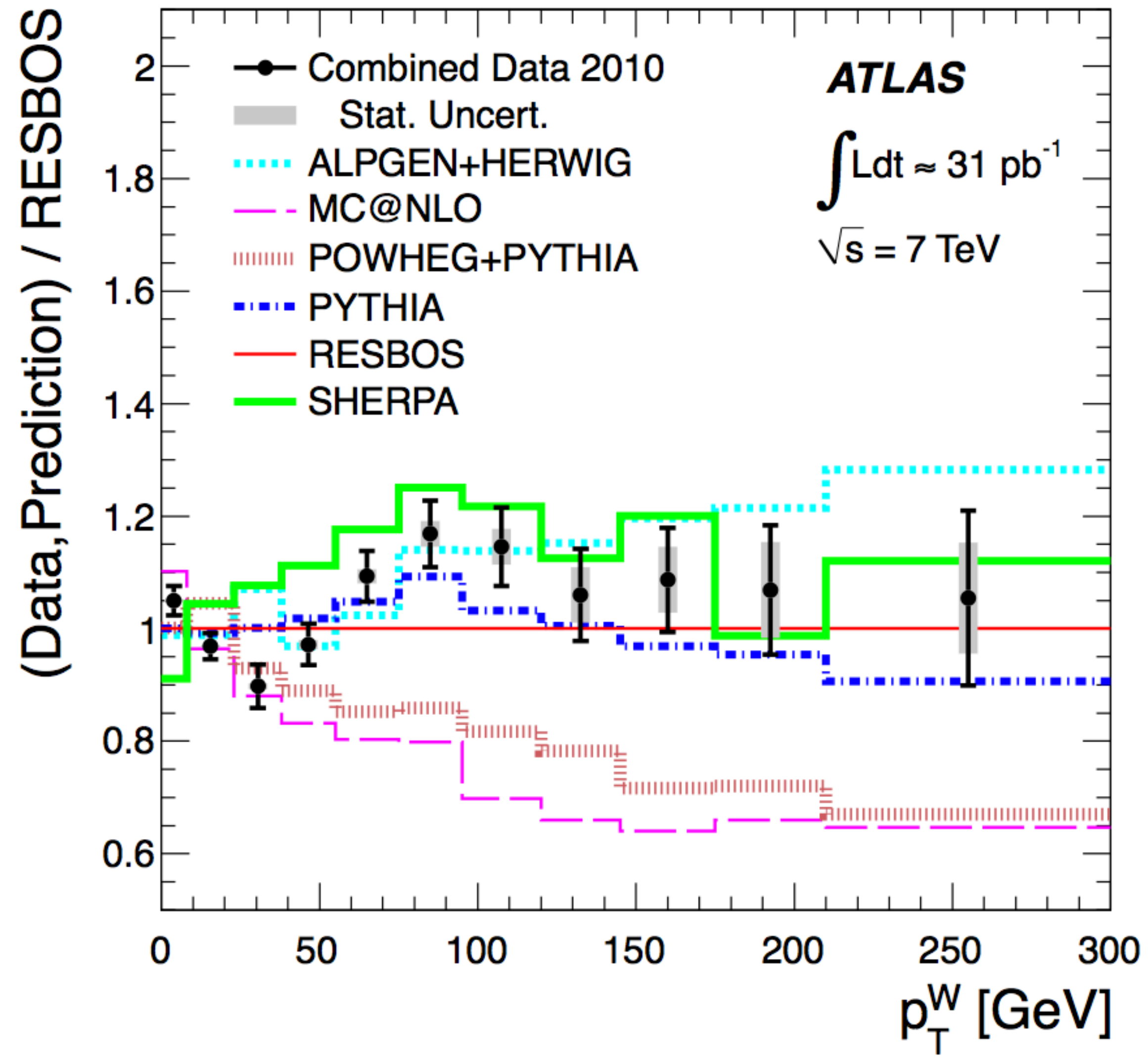


- p_T^W is the true p_T^W unfolded from p_T^R
  - by default it is defined from the Born level W propagator

W p_T - unfolded true p_T

Phys. Rev. D85 (2012) 012005



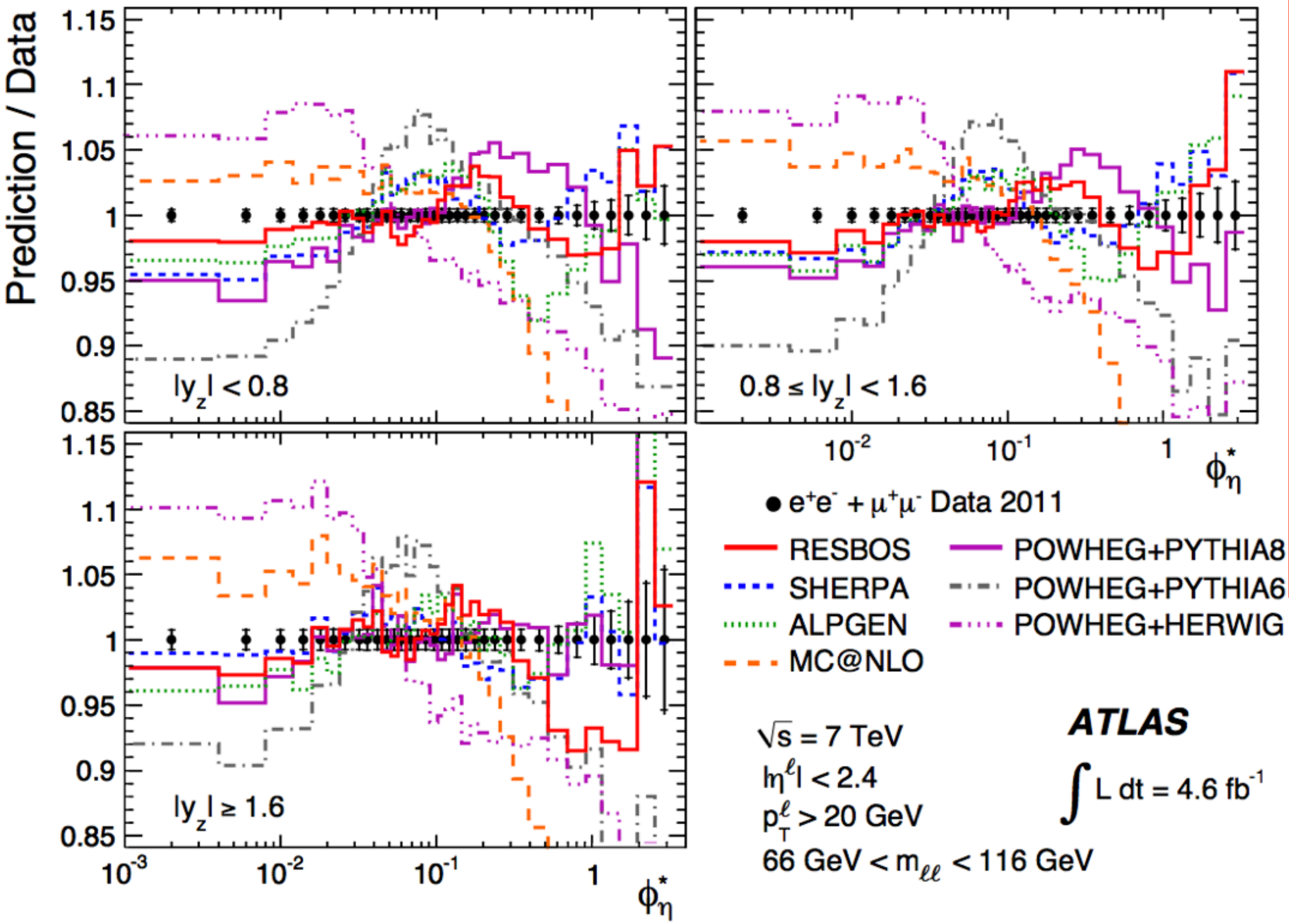


RESBOS, DYNNLO and MCFM at $O(\alpha_s^2)$, Sherpa, Alpgen, Pythia describes the spectrum well (within 10-20%) over the entire range

$O(\alpha_s)$ approximation insufficient to describe the data

Z Φ_η^* - comparison with MC generators

Phys. Lett. B720 (2013) 32-51



MC Generators

- at $\Phi_\eta^* < 0.1$ best description from **SHERPA** and **ALPGEN**
- at low Φ_η^*, best description from **RESBOS**
- Pythia8 best parton shower description when interfaced to **POWHEG**

- Useful information for MC tuning