Precision QCD at hadron colliders (LHC)

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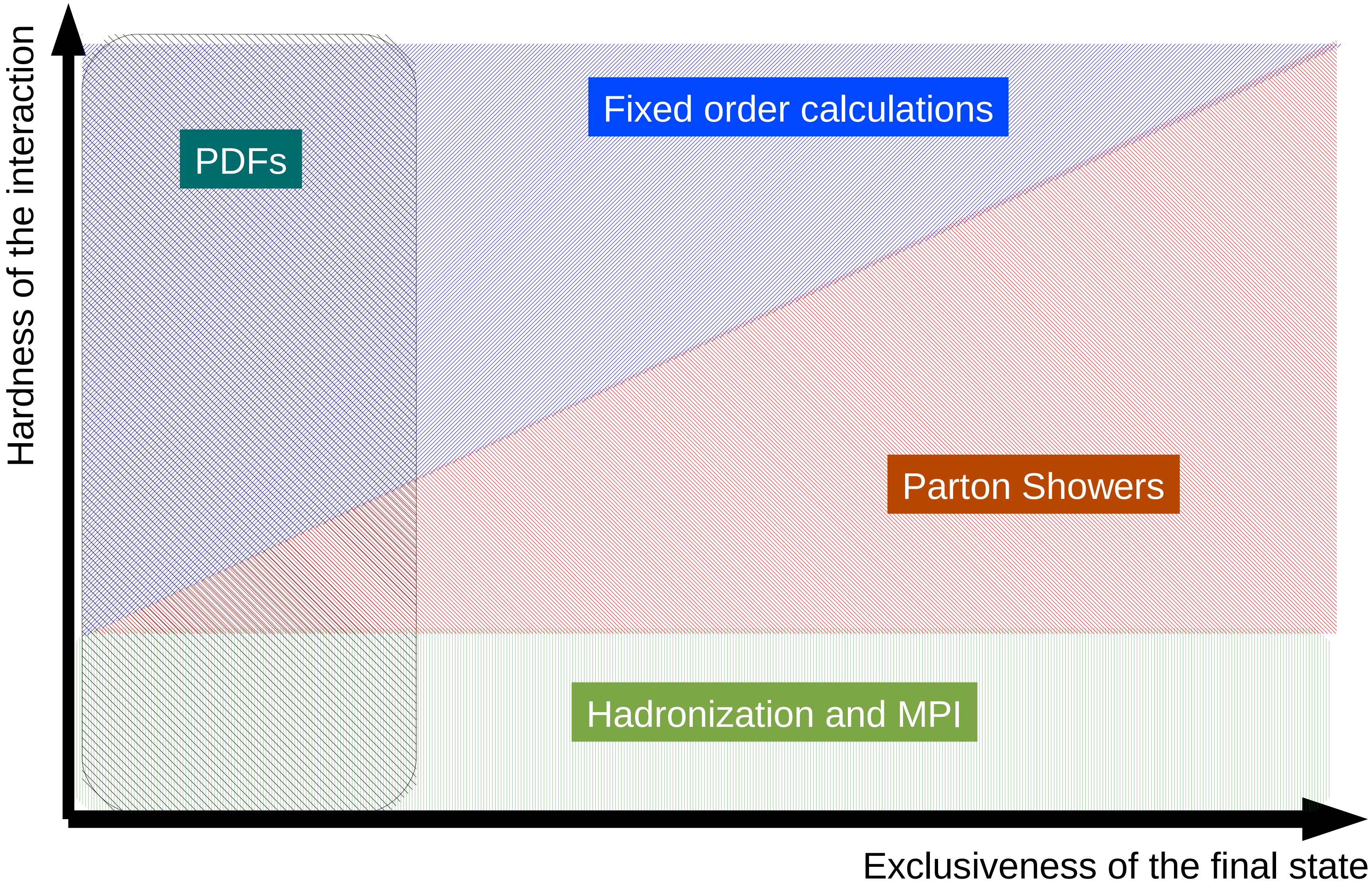
DIS 2013

QCD at LHC

- The study of QCD processes at the LHC is important for two broad classes of reasons
  - They provide a tool to test the theoretical predictions at the energy frontier
    - The current understanding of our detectors allows both ATLAS and CMS collaborations to do <u>precision</u> QCD measurements
  - They represent a ubiquitous source of background for virtually any signal at a hadron collider

The landscape of QCD

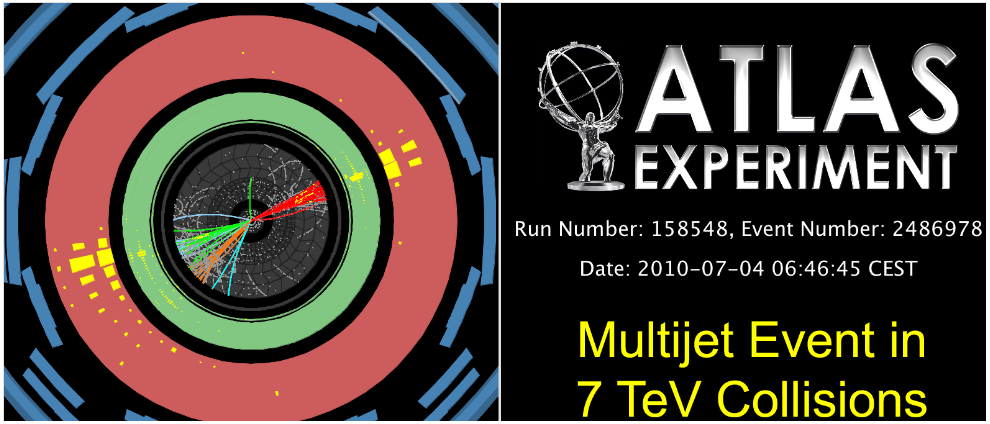


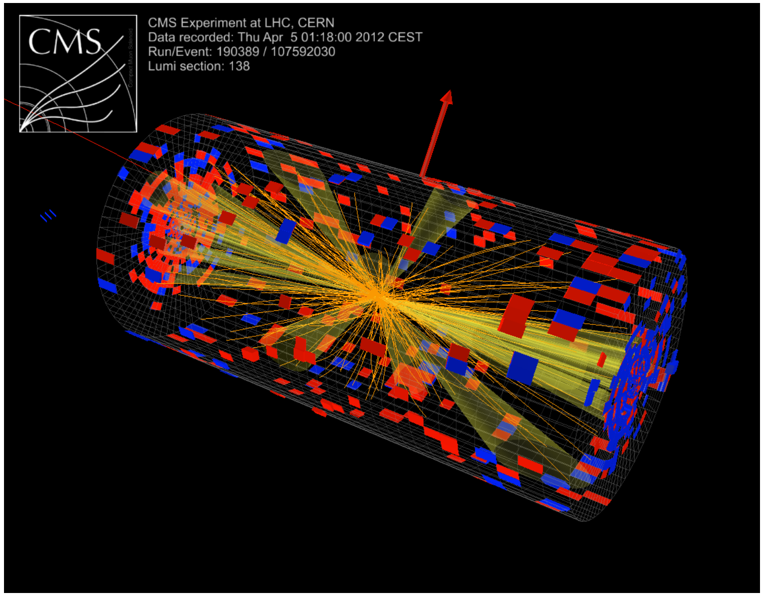
Theoretical predictions

- A lot of progress have been made in phenomenology in recent years
- Many modern generators and analytical predictions have been used to compare to measurements
  - Monte Carlo event generators
    - Pure shower models
      - Pythia, Herwig
    - LO multi leg + Parton Shower
      - Madgraph + Pythia, Alpgen + Pythia/Herwig, Sherpa
    - NLO+Parton Shower
      - POWHEG+Pythia/Herwig, MC@NLO+Herwig
  - Parton level codes
    - Fixed order calculations (Blackhat)
    - BFKL inspired models (HEJ)

Outline

- Inclusive jets
- Event shapes
- Di-jets
- Forward jets
- Inclusive photons
- Photons+jets
- W/Z+jets





In many cases very similar measurements have been performed by ATLAS and CMS. In all those cases I will show the results from one experiment, unless there are differences to notice.

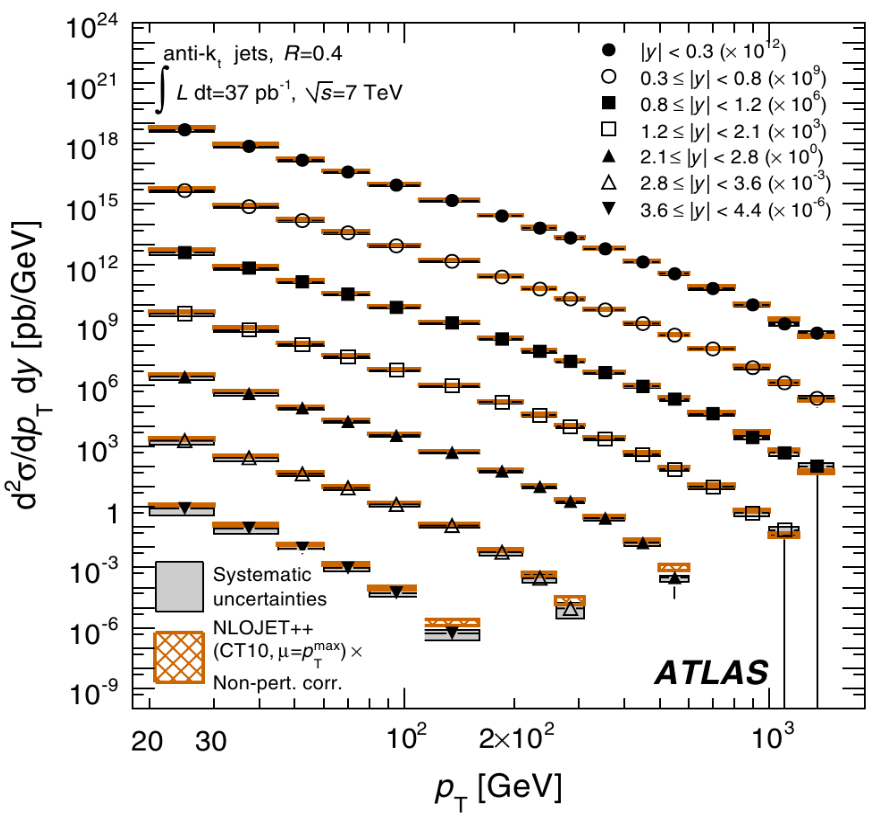
Inclusive jet observables

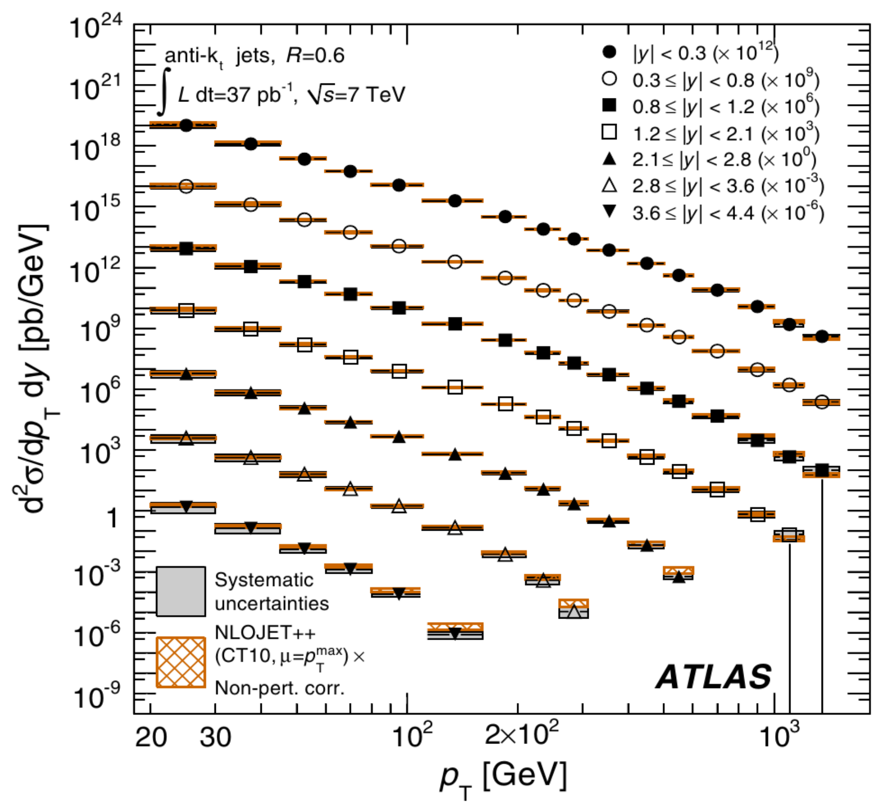
- Event shapes
- Inclusive jets
- Di-jets
- Jets, forward jets, rapidity gaps

Inclusive jets

Phys. Rev. D 86, 014022 (2012)

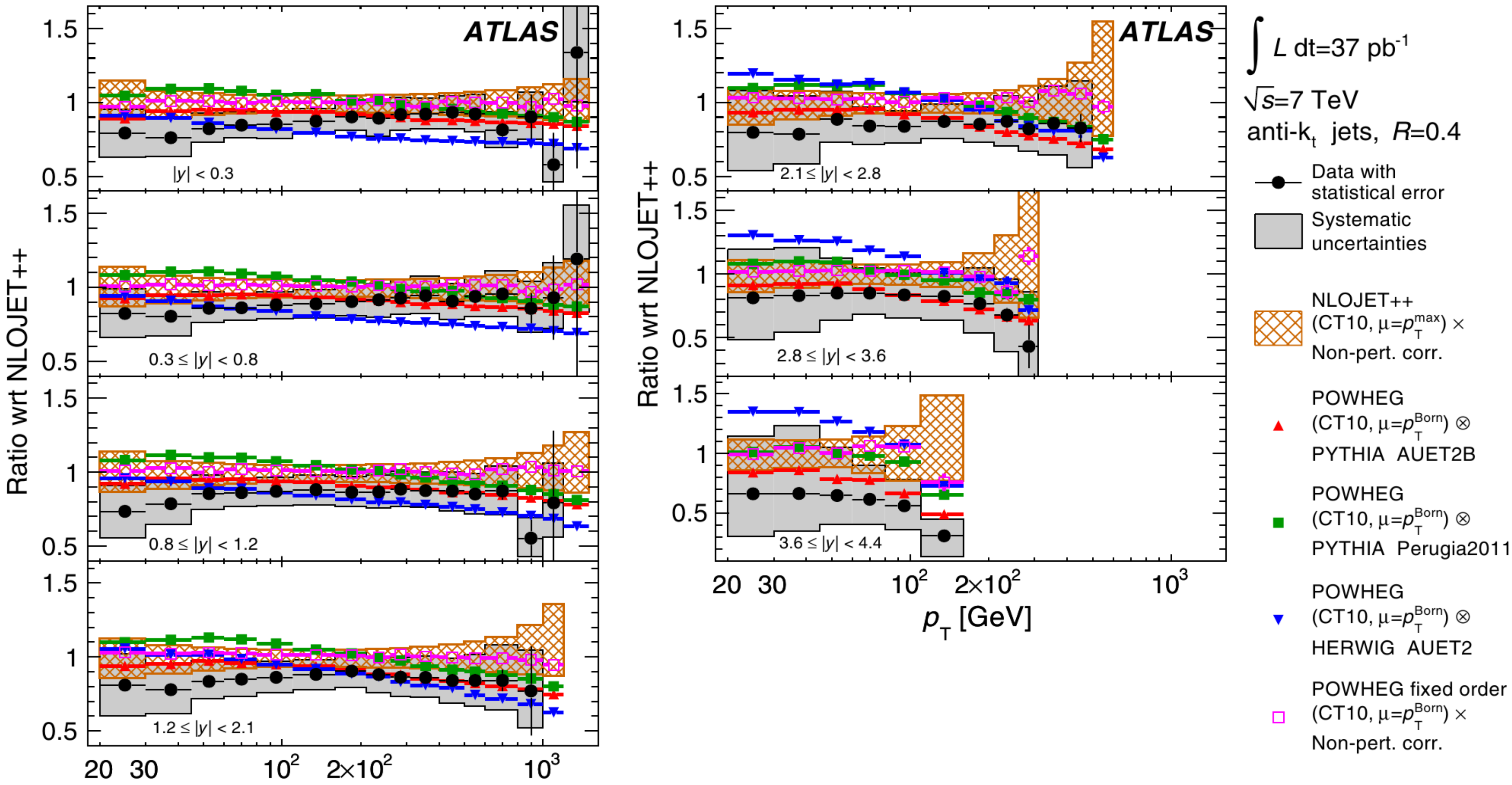
- Measurement of inclusive jets for two jet sizes
  - Difference contribution of hadronization and UE corrections
- Data are compared with the predictions at NLO, including non-perturbative (NP) corrections obtained with a shower MC





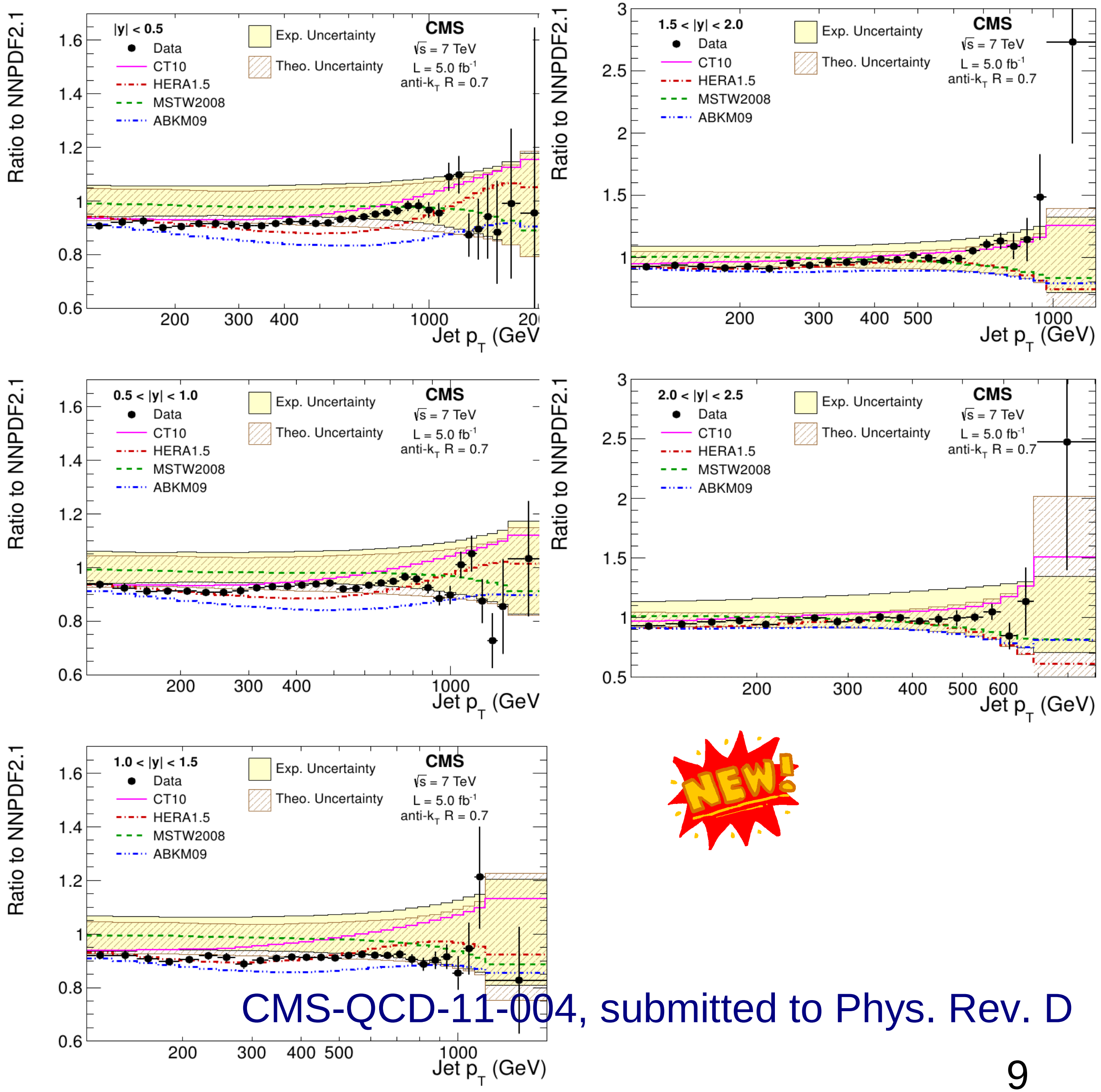
Inclusive jets

- Comparison with several MC generators
- General good agreement
- POWHEG NLO dijet predictions show dependency on the shower used
    - Improved in newer versions



Inclusive jets

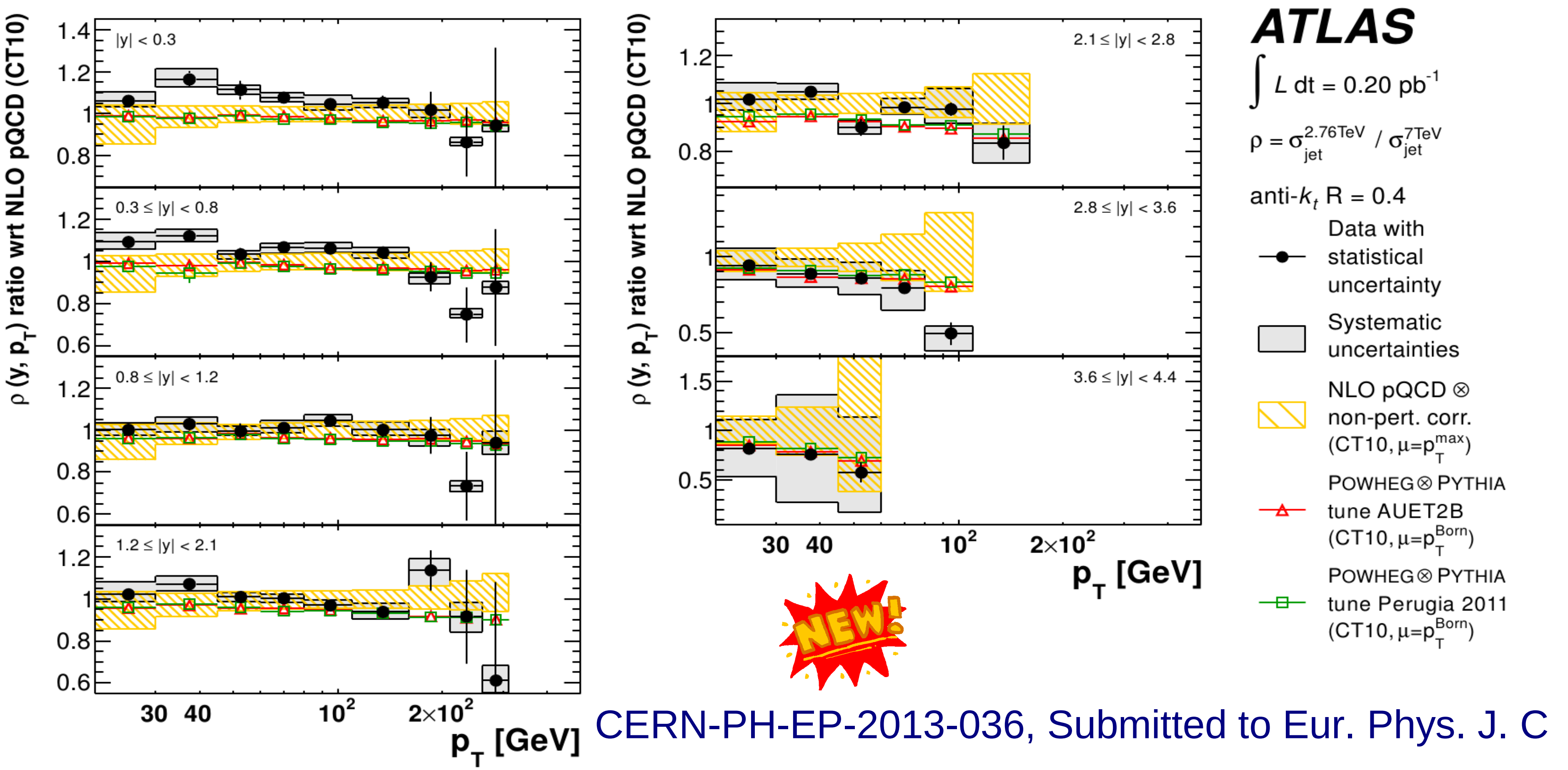
- Similar result from CMS with larger statistics highlighting the PDF sensitivity
- More on PDFs in the talk from Voica Radescu



CMS-QCD-11-004, submitted to Phys. Rev. D

Inclusive jets

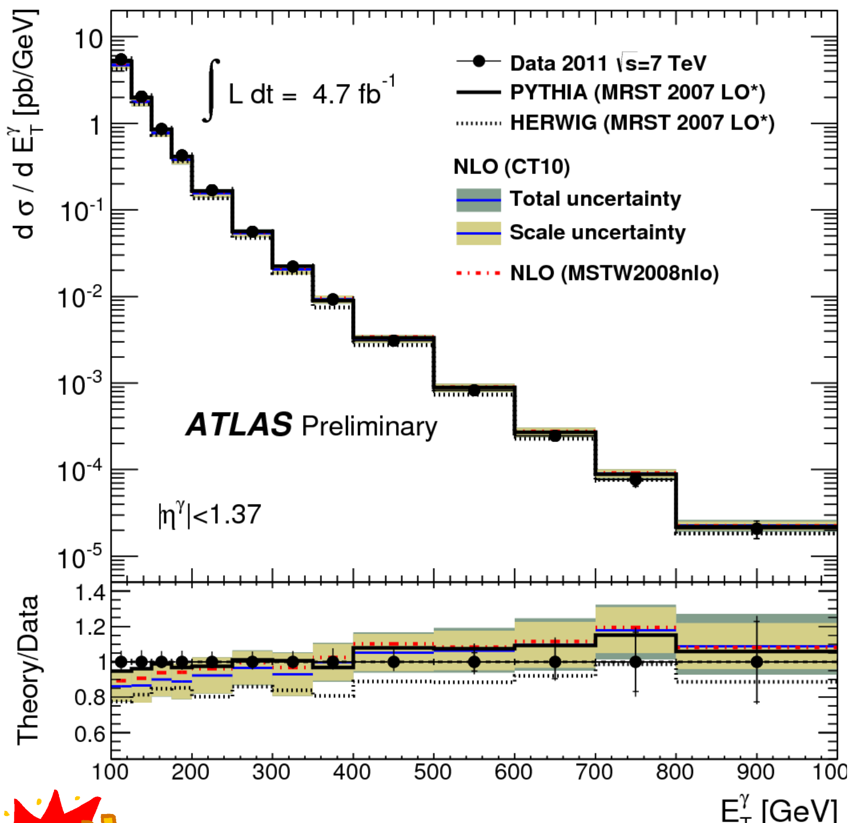
- Very interesting comparison between 7 TeV and 2.76 TeV
- No significant differences between the two Pythia tunes used on top of NLO dijet powheg
- Powheg is slightly below the data in the central region while the agreement is very good in the forward region



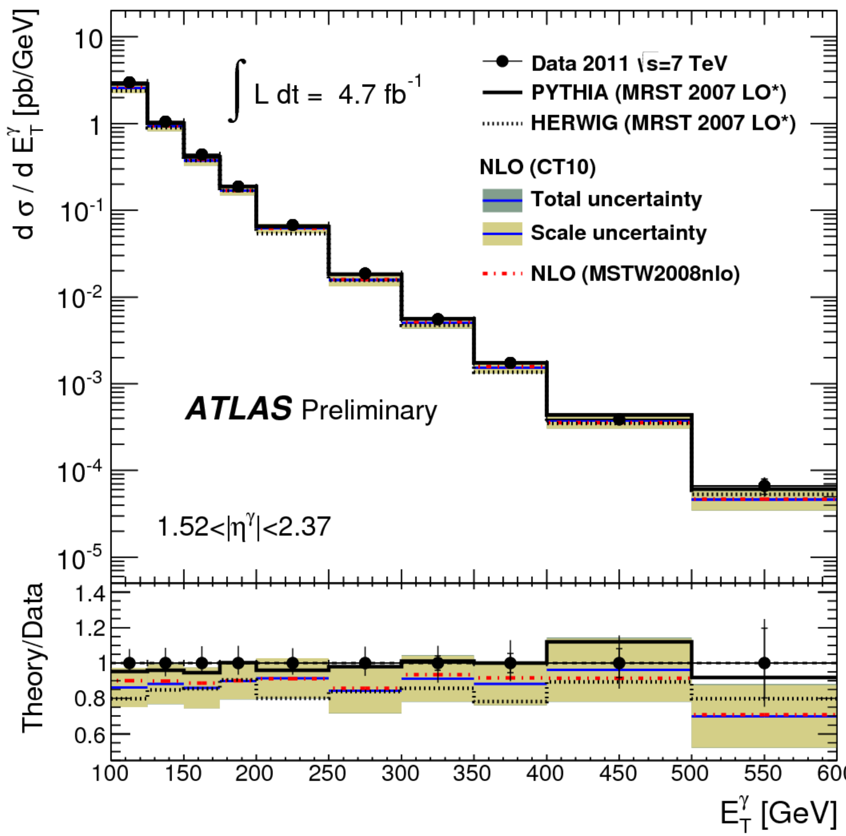
CERN-PH-EP-2013-036, Submitted to Eur. Phys. J. C

Inclusive photons

- Measurement of inclusive photon production up to 1 TeV
- Slight underestimation of the cross section by the NLO calculation at low pT
- Pure shower models also describe the shape of the data very well

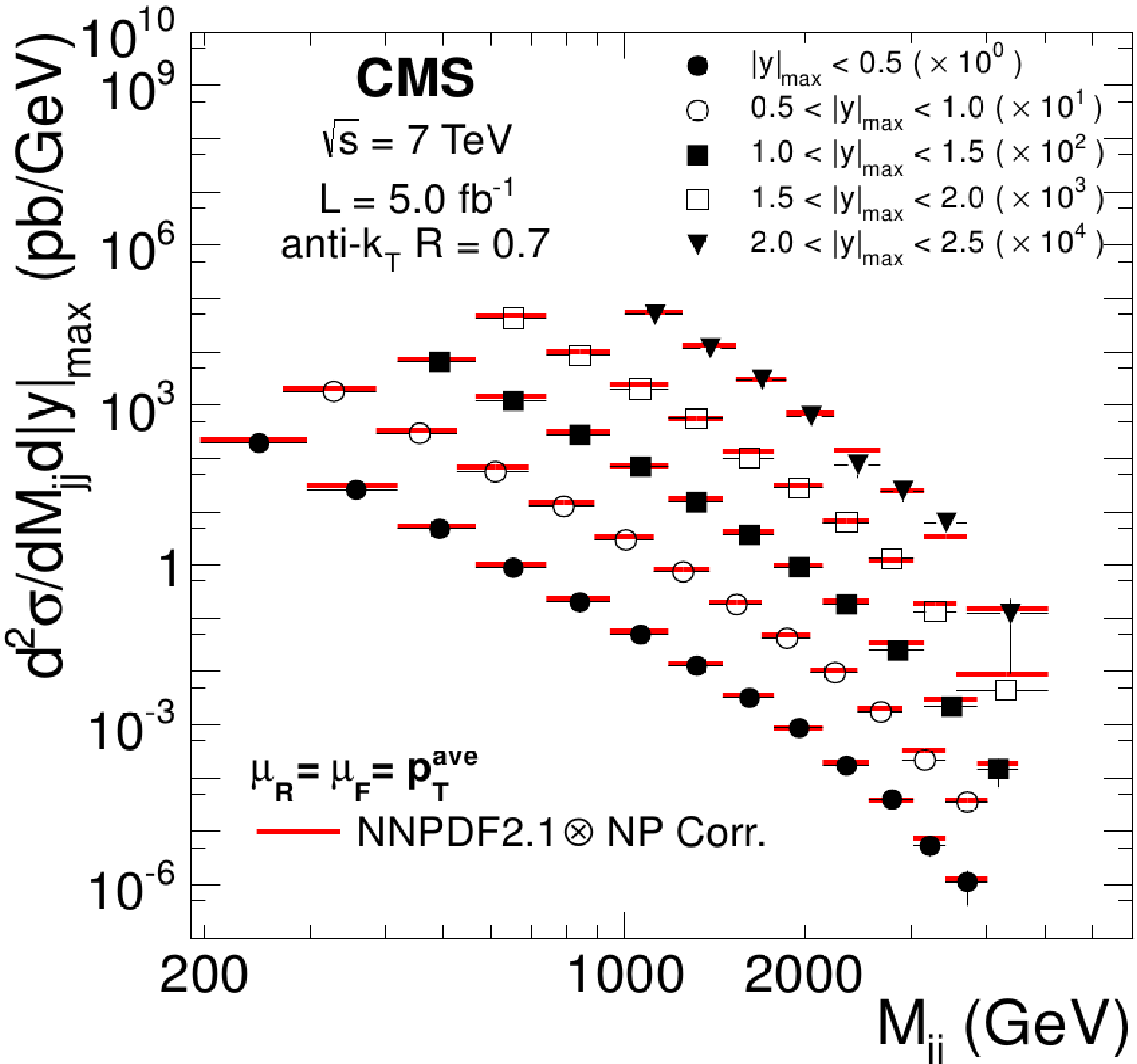


ATLAS-CONF-2013-022



Phys. Rev. D 84, 052011 (2011)

Di-jet mass

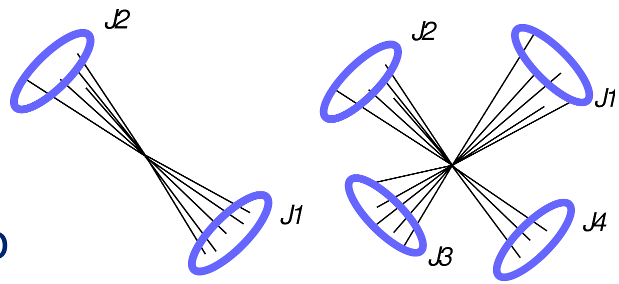


CMS-QCD-11-004, submitted to Phys. Rev. D

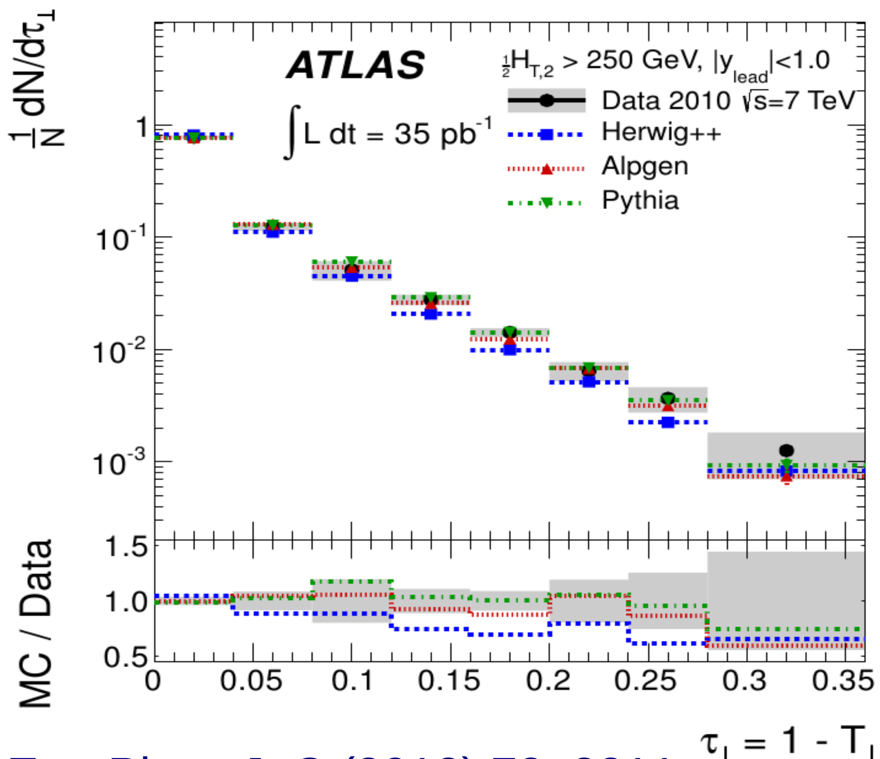
Event shapes

- Distributions of central transverse thrust and thrust minor, using central jets as input, in the transverse plane

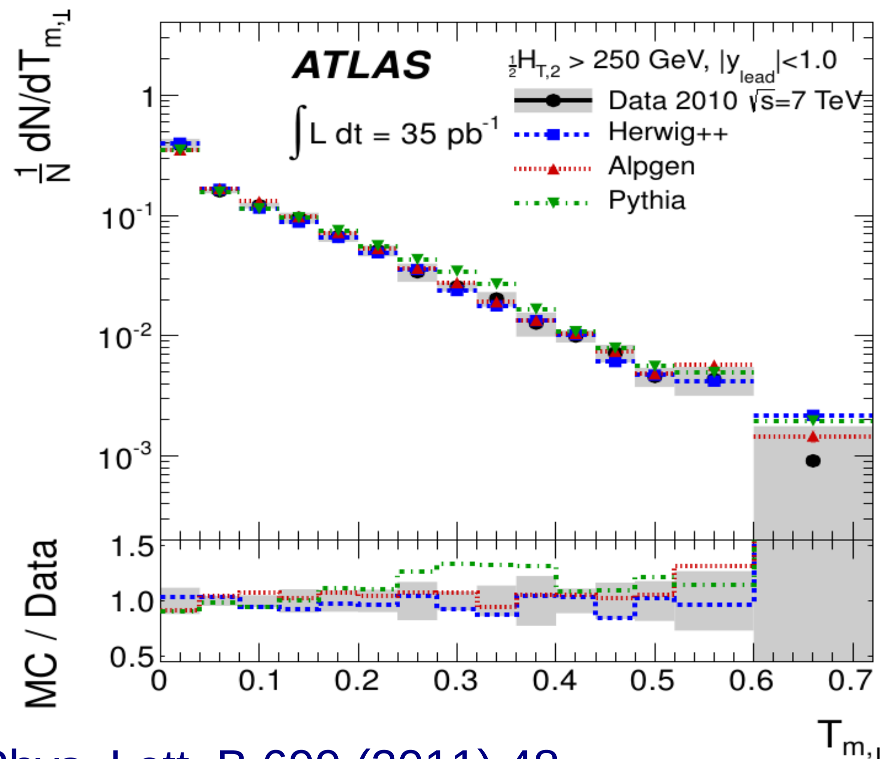
$$\tau_{\perp,\mathcal{C}} \equiv 1 - \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \hat{n}_T|}{\sum_i p_{\perp,i}}$$



- The modeling of Pythia and Alpgen seem to be better than that of Herwig in this observable



Eur. Phys. J. C (2012) 72: 2211



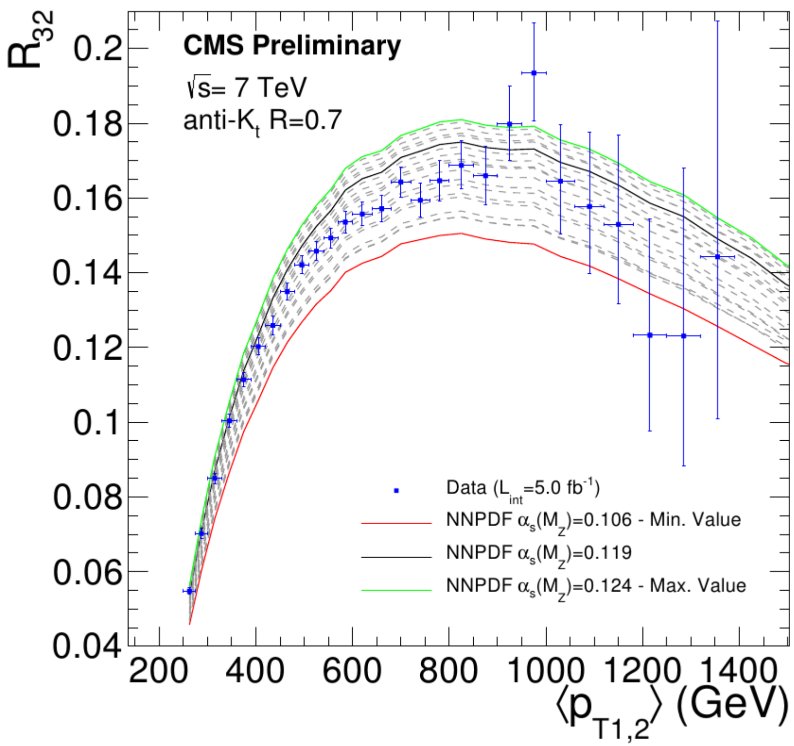
Phys. Lett. B 699 (2011) 48

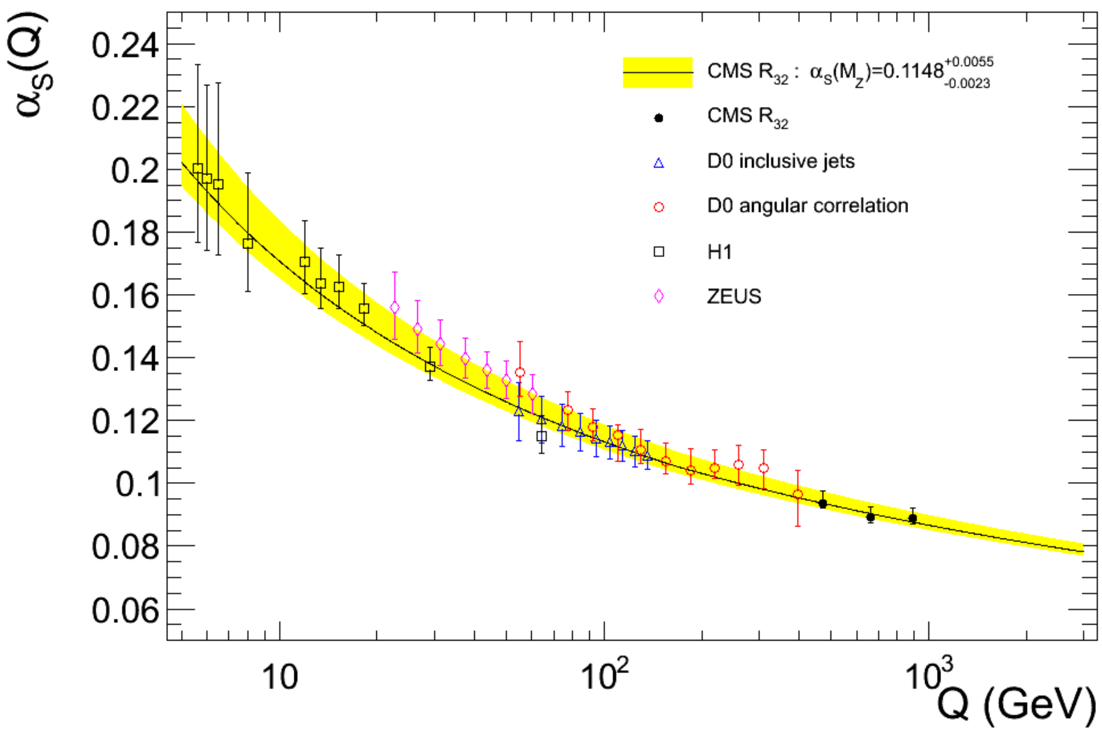
3-jets over 2-jets ratio

- Measurement of the ratio of events with 3 or more jets over events with 2 or more jets, as a function of average pt of the di-jet system
  - Jets: pT > 150 GeV, |y|<2.5

CMS-QCD-11-003

- Provides a stringent test of hard gluon radiation and higher order effects
- It is used to evaluate α_s



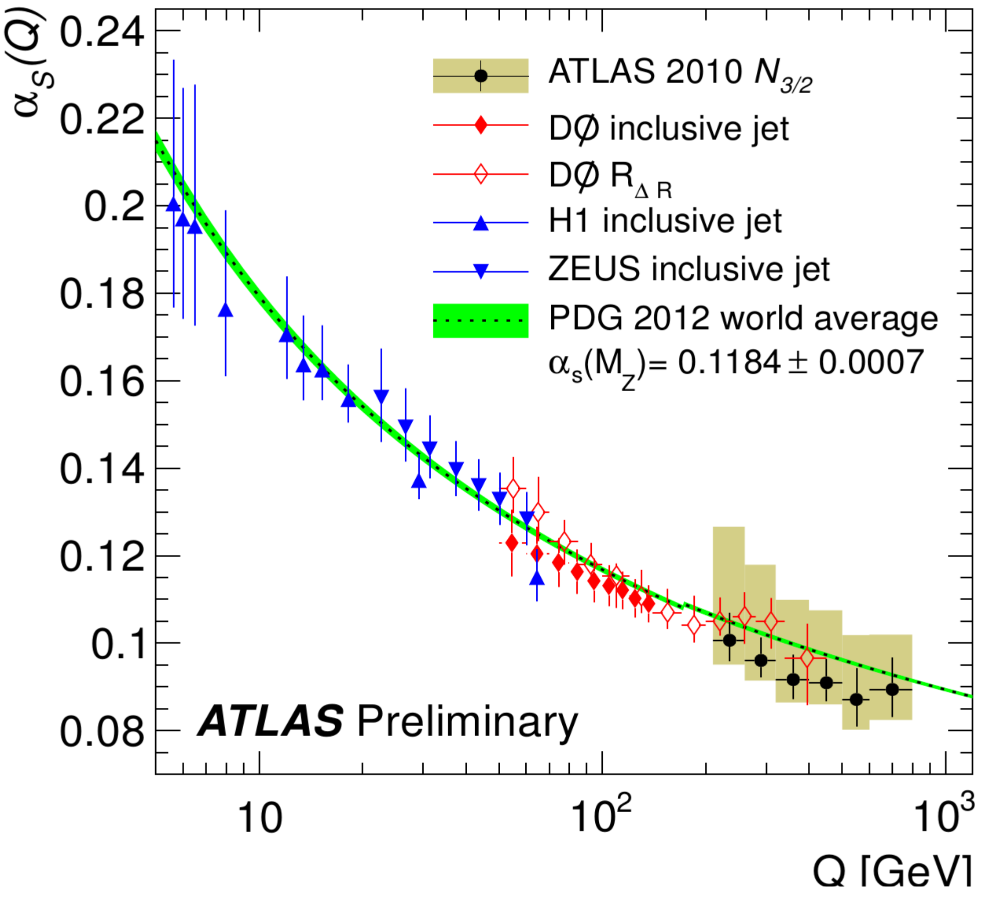


$\alpha_s(MZ) = 0.1148 \pm 0.0014\ (\text{exp.}) \pm 0.0018\ (\text{PDF})\ ^{+0.0050}_{-0.0000}\ (\text{scale})$

3-jets over 2-jets ratio

- Similar result from ATLAS

ATLAS-CONF-2013-041



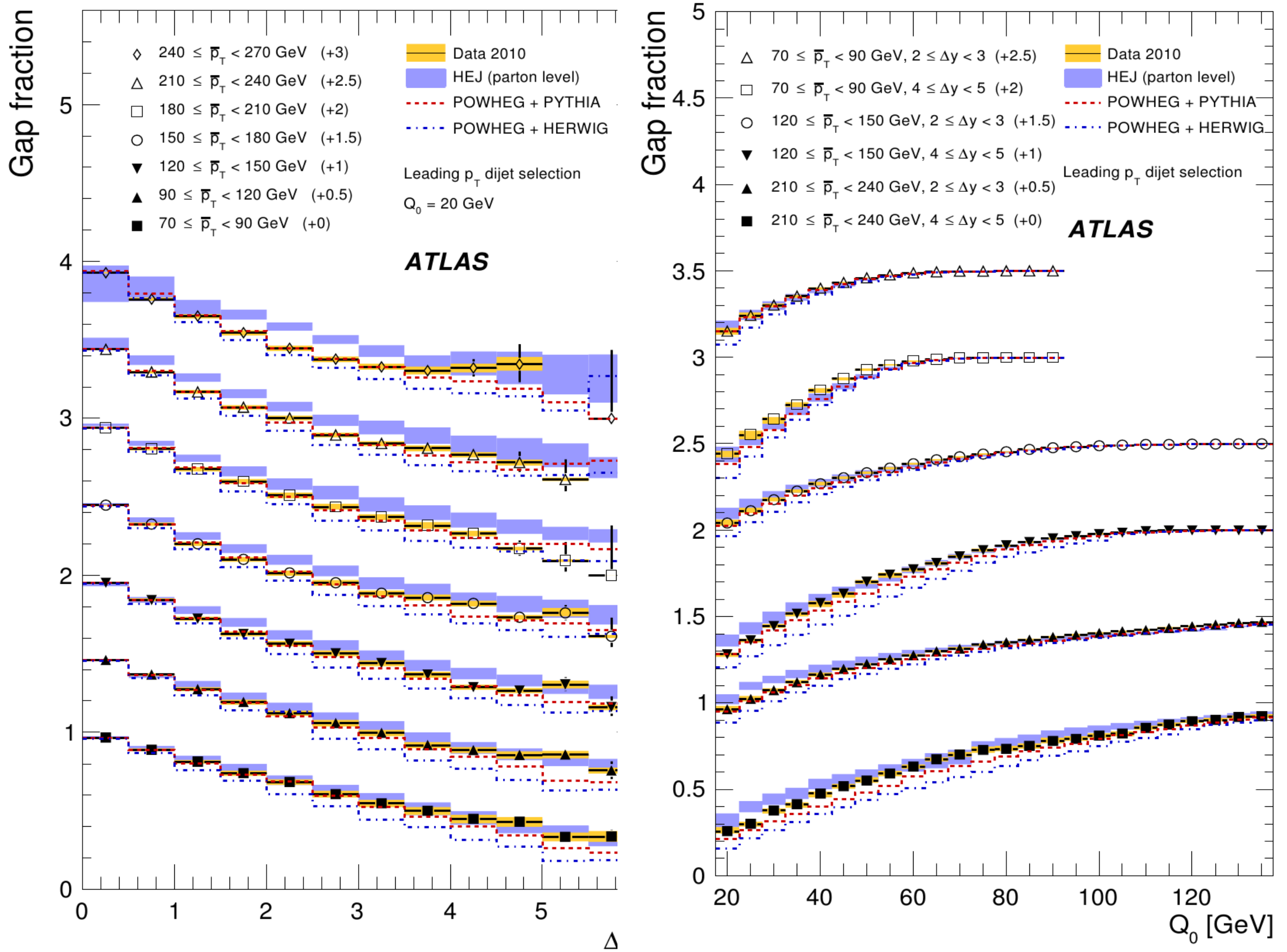
$$\alpha_s(M_Z) = 0.111 \pm 0.006(\text{exp.})\ ^{+0.016}_{-0.003}(\text{theory})$$

Di-jets with rapidity gaps

- ATLAS studied di-jet events as a function of the activity between them

  Observables: fraction of events with additional jets above a threshold Q_0

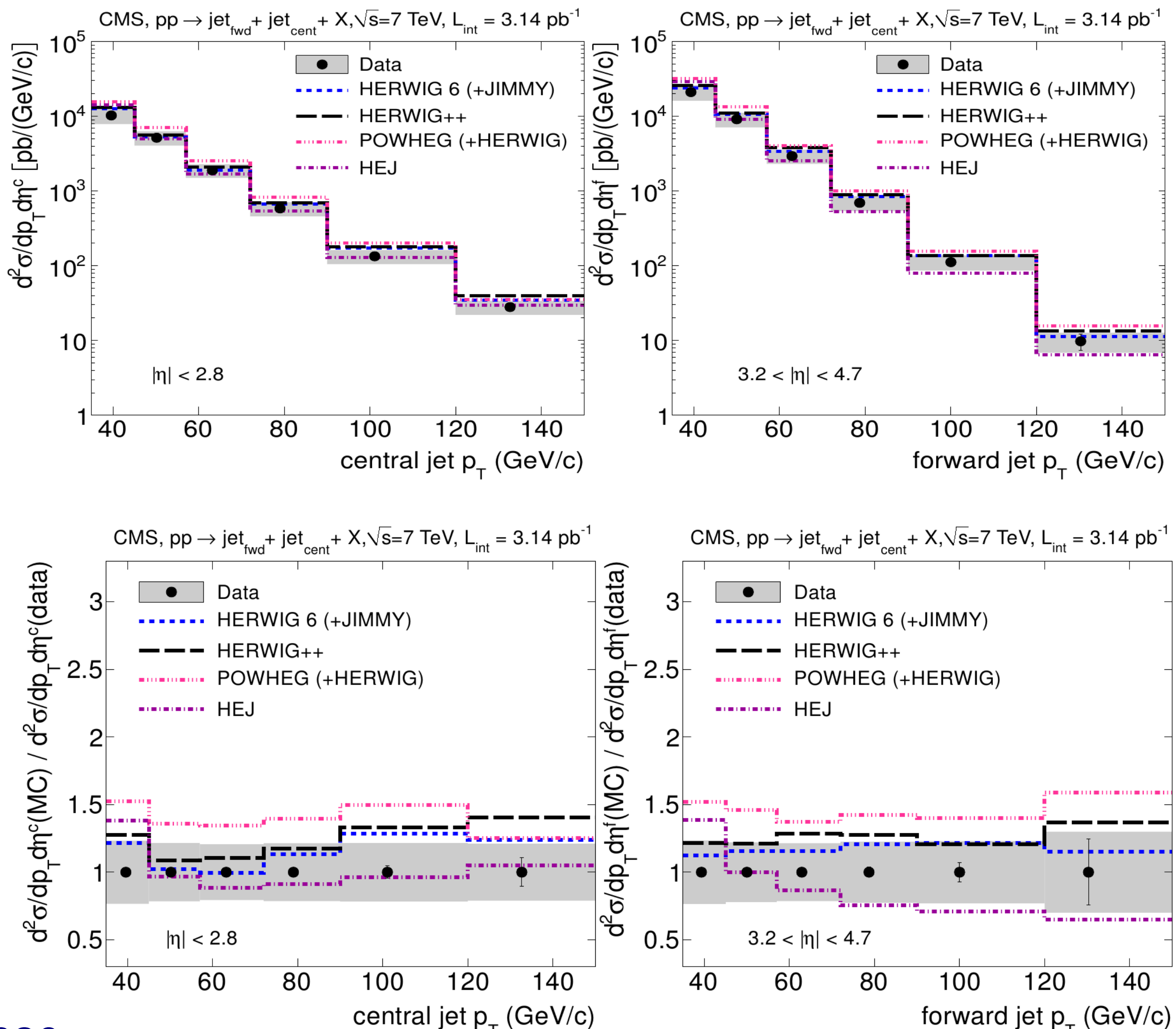
- Powheg NLO di-jet gives a generally good description of data
  - The agreement becomes worse as the rapidity gap increases
- The all order, BFKL inspired description of HEJ gets better and better as the threshold Q_0 is increased



JHEP 1109 (2011) 053

Di-jets with rapidity gaps

- Configuration with a central and a forward jet
- Best comparison is obtained with angular ordered Parton Shower (Herwig and Herwig++)
- The normalization is overestimated in NLO di-jet powheg
- Good description from all order BFKL inspired HEJ



JHEP06(2012)036

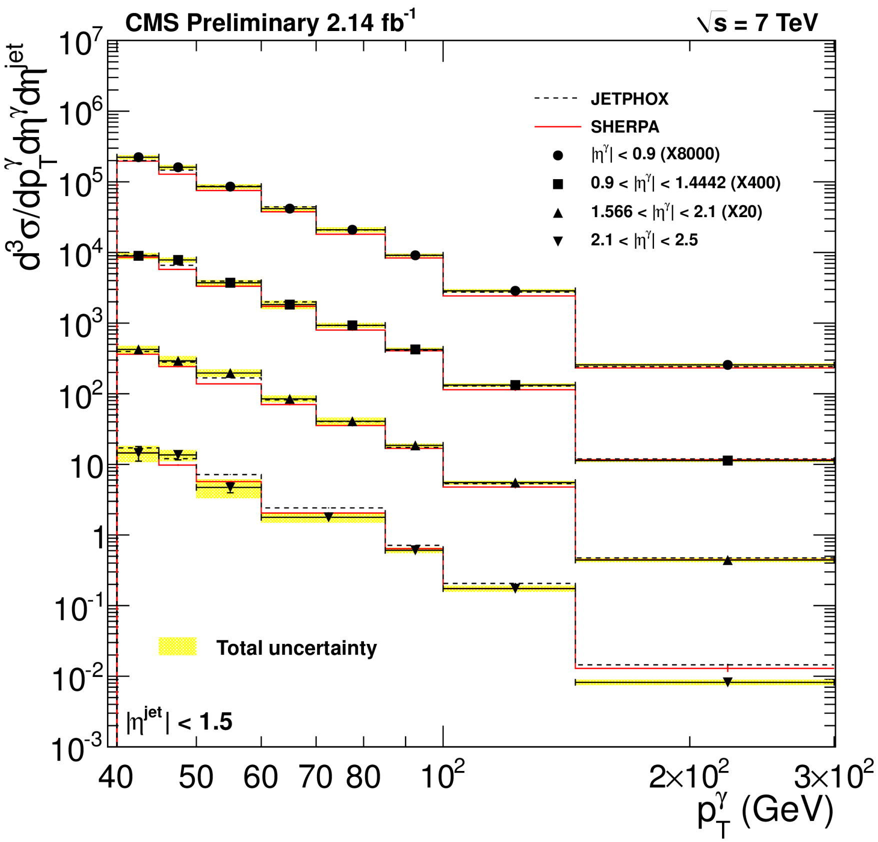
Vector boson + jets

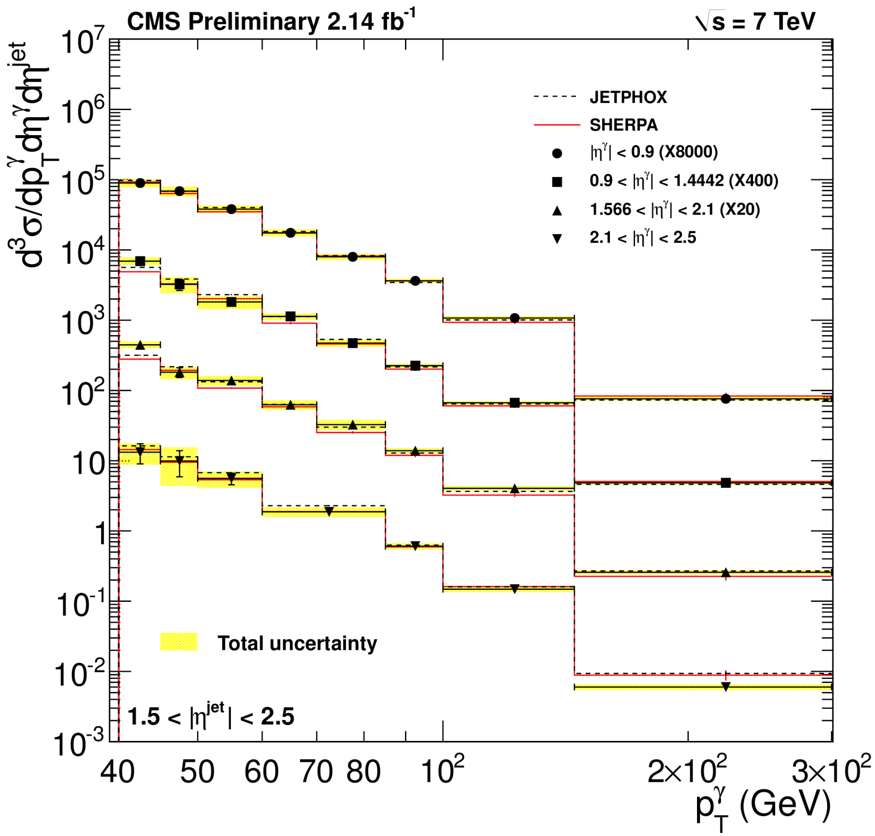
- DY phi*
- Photon + jets
- W/Z + jets
- Jet substructure in W/Z+jets
- W/Z+b jets

Photon + jets

- Jet pt > 30 GeV, |η|<2.4
- Good agreement with NLO QCD
- Also good agreement with Sherpa
  - Including extended matrix element + parton shower approach to photons

CMS-QCD-11-005

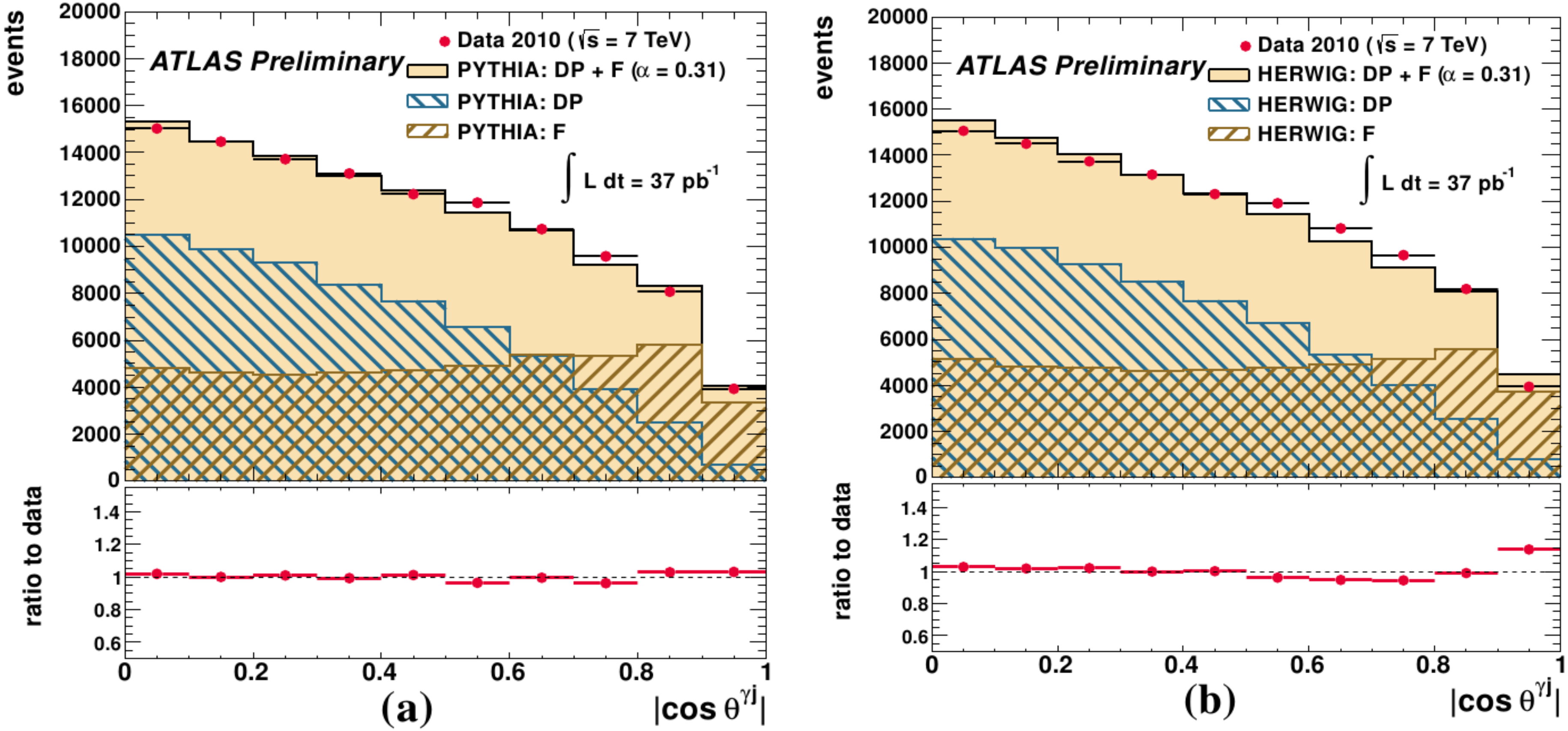




Photon + jets

- The contribution of fragmentation versus direct photons was studied in detail as a function of scattering angle $\theta^{\gamma j}$ in the photon-jet rest frame
- Shower MC can get the right differential shape with tuning of the two contributions

PYTHIA HERWIG

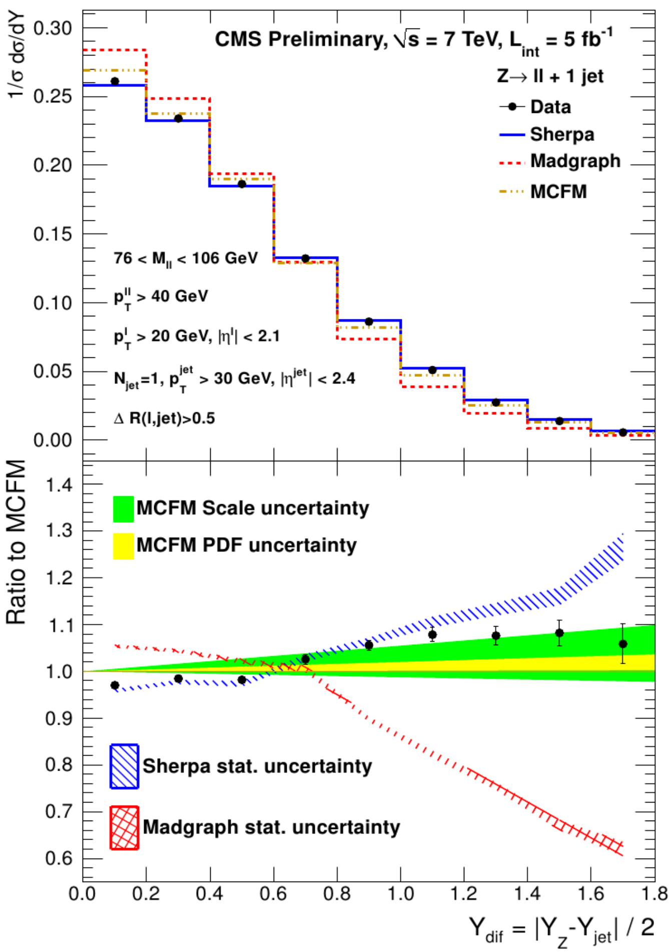


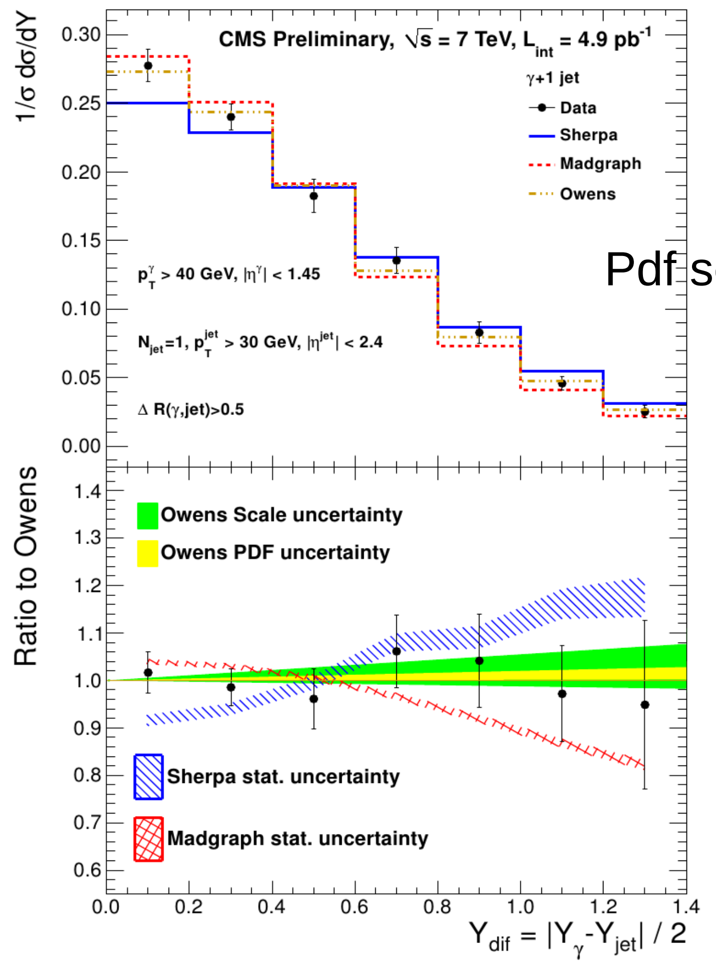
ATLAS-CONF-2013-023

Photon + jets

CMS-SMP-12-004

- Rapidity measurements in Z or γ + jet
- Significant differences between Sherpa and Madgraph
  - maybe due to the different matrix element-parton shower matching prescription?





Pdf set CTEQ6.6M

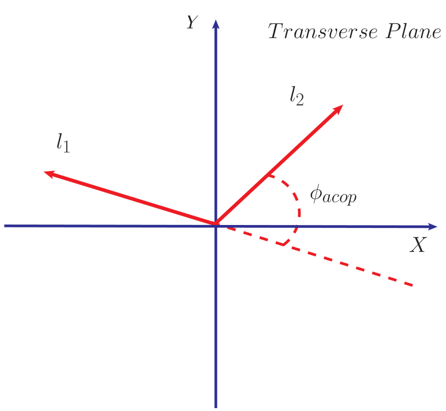
Drell-Yan phi*

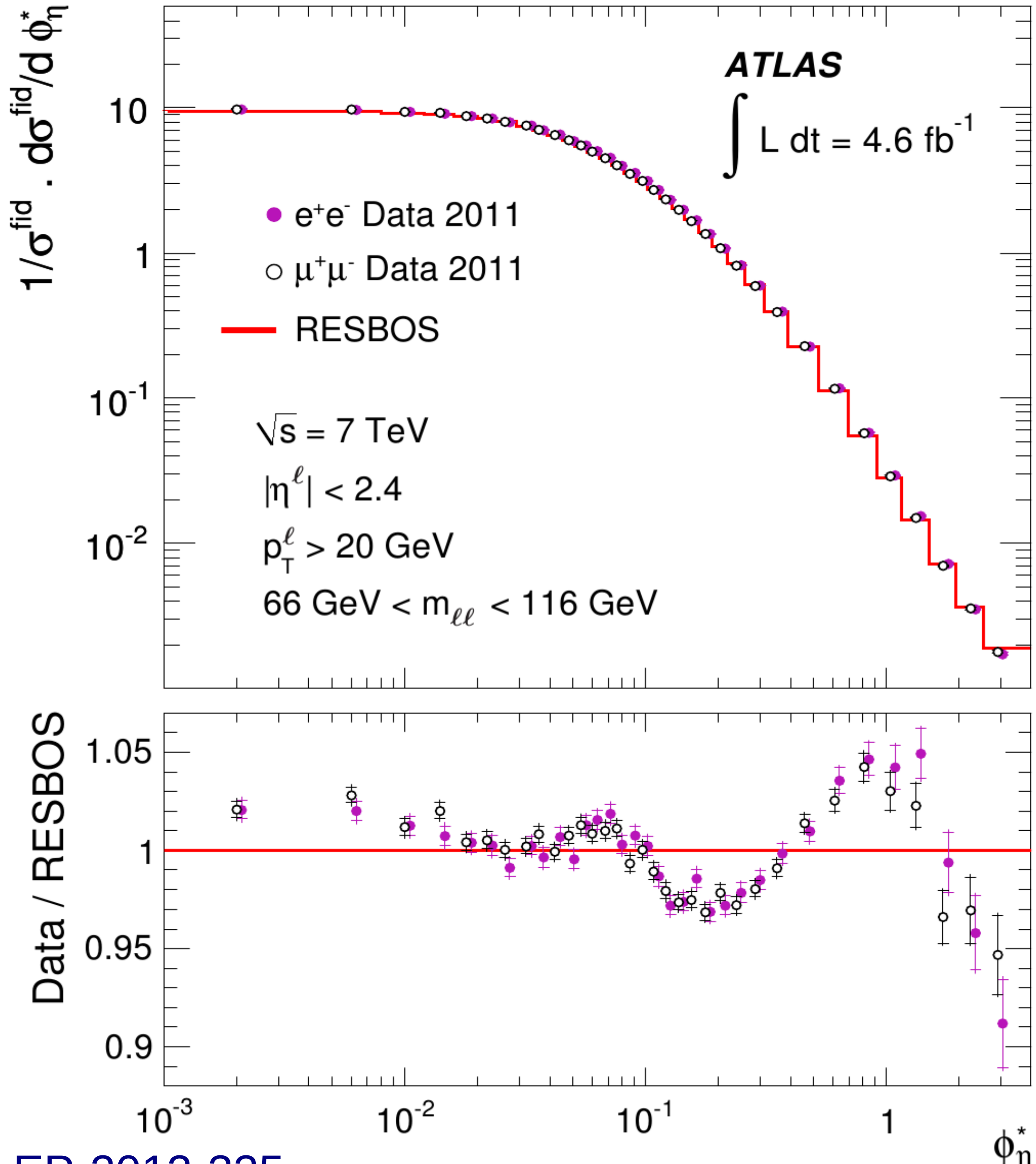
- It is strongly correlated with Pt, but uses only angular variables
  - It probes the same physics as the Drell-Yan pT, in an experimentally more precise way
  - It is defined as follows

$$\phi^*_\eta \equiv \tan(\phi_{acop}/2) \cdot \sin(\theta^*_\eta)$$

$$\cos(\theta^*_\eta) \equiv \tanh[(\eta^- - \eta^+)/2]$$

- It is a measurement of the scattering angle of the leptons wrt the beam line in the Z rest frame

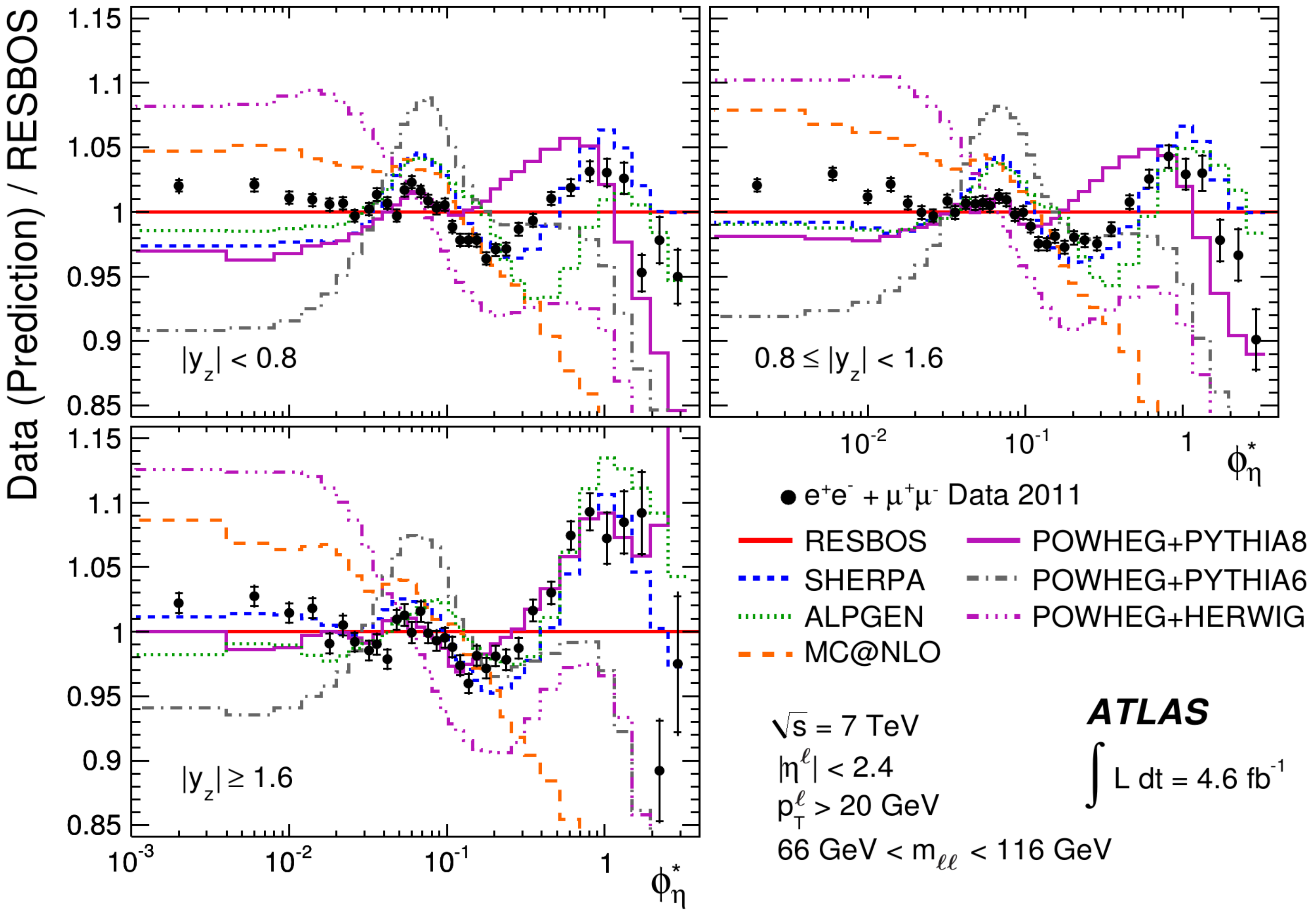




CERN-PH-EP-2012-325

Drell-Yan phi*

- Compared to RESBOS and different MC
  - Sherpa gives the best comparison to data over the entire range, with the exception of very low values of phi*
  - Powheg interfaced with Pythia8 is significantly different from Powheg+Pythia6



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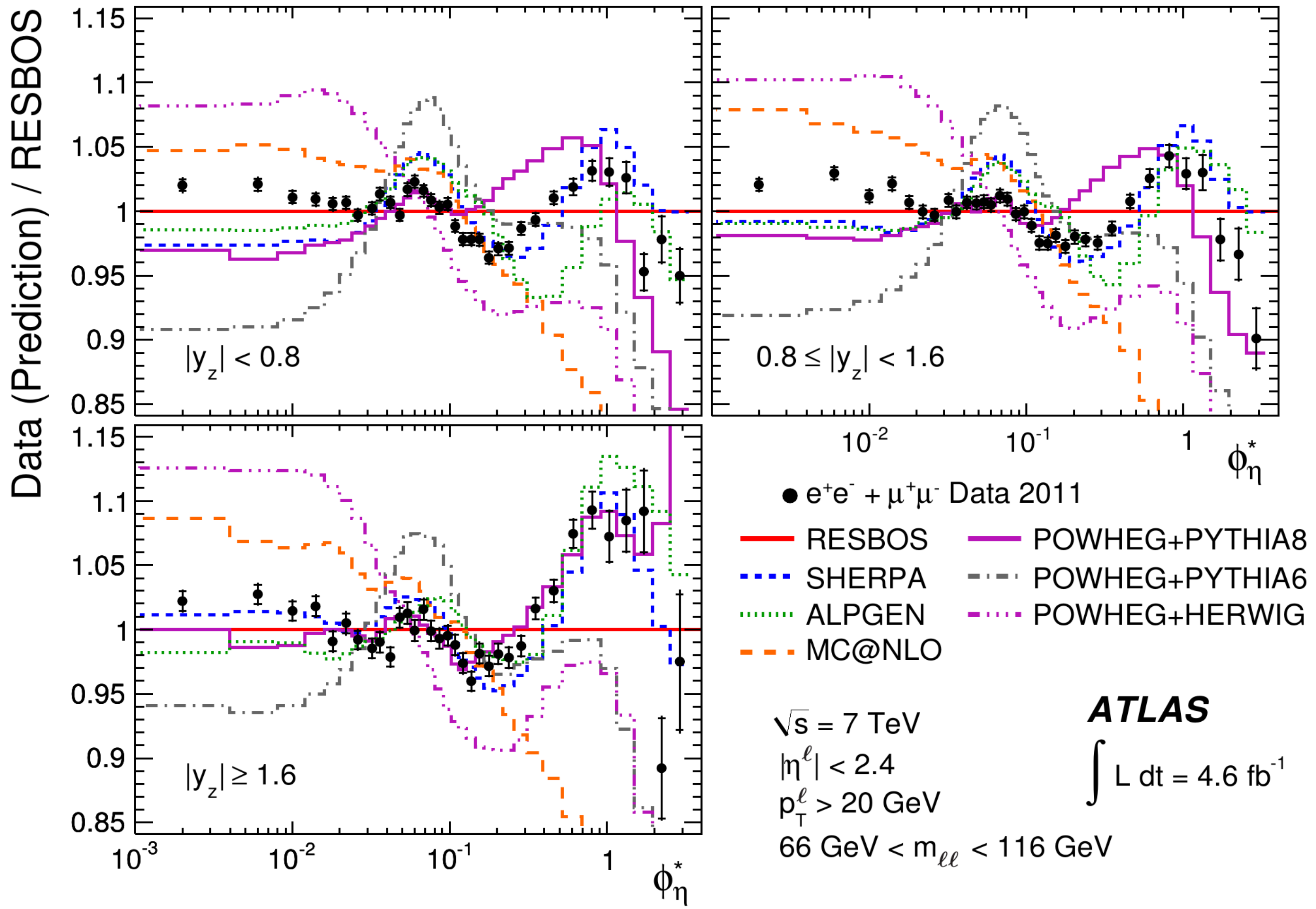
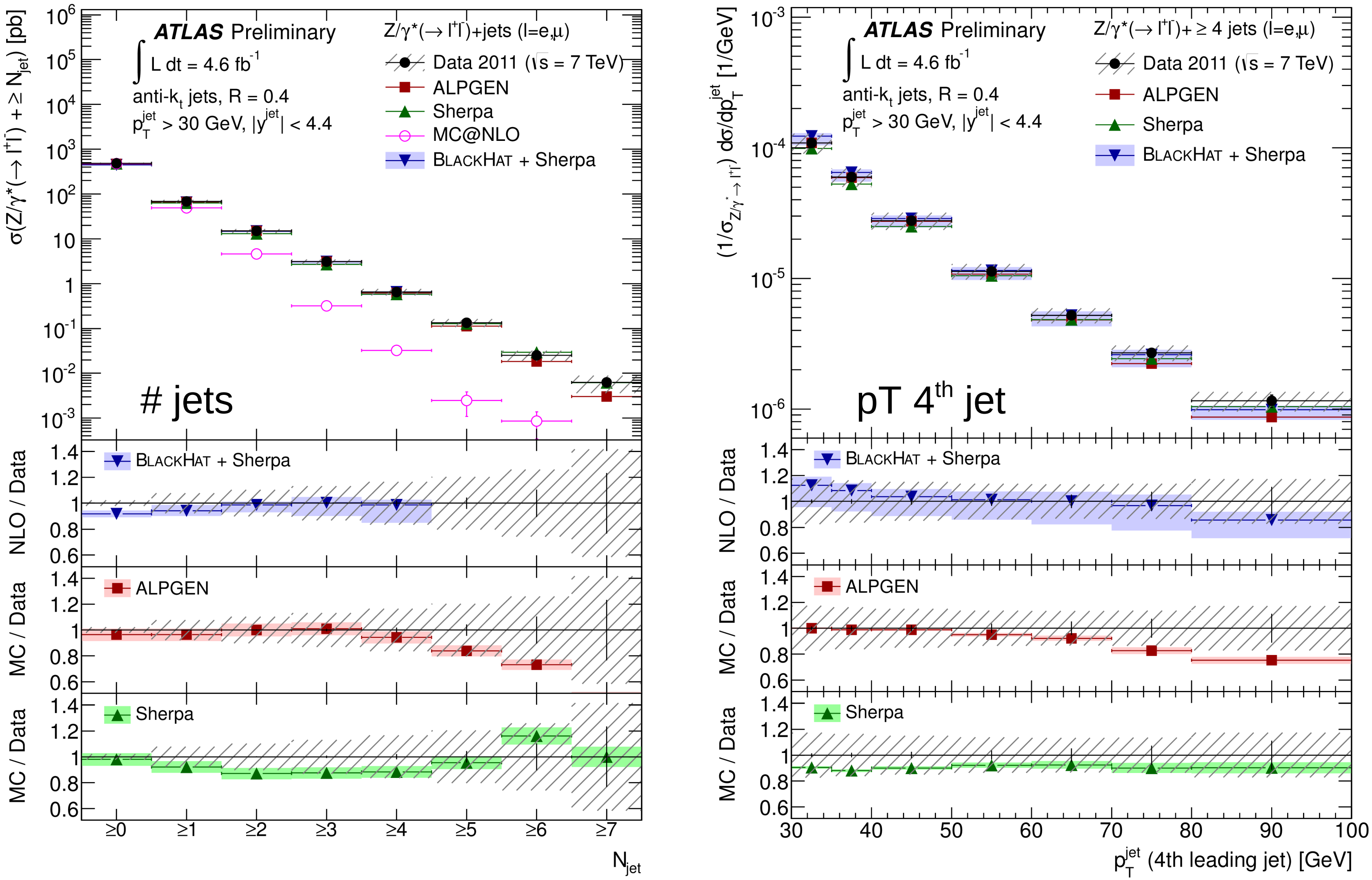


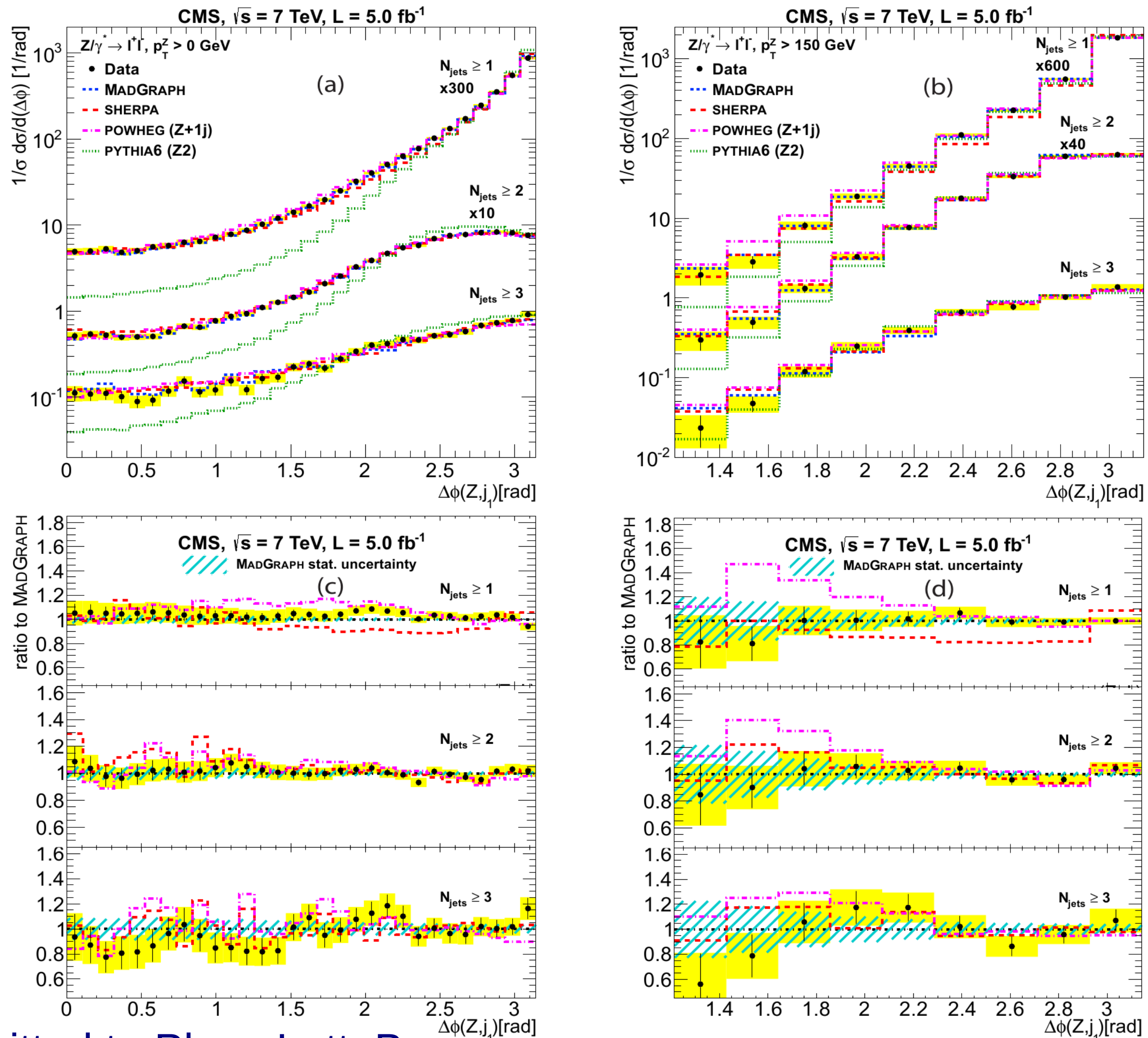
Z+jets

- Very nice agreement with NLO multileg calculations (Blackhat)
- Shows the power of the LO+PS methods in describing multi-leg final states



Azimuthal correlation in Z+jets

- ΔΦ between the Z and the leading jet
- Jet reconstruction: jet pT > 50 GeV, |η|<2.4
- Good agreement with LO+PS
- Also very nice agreement with NLO+PS

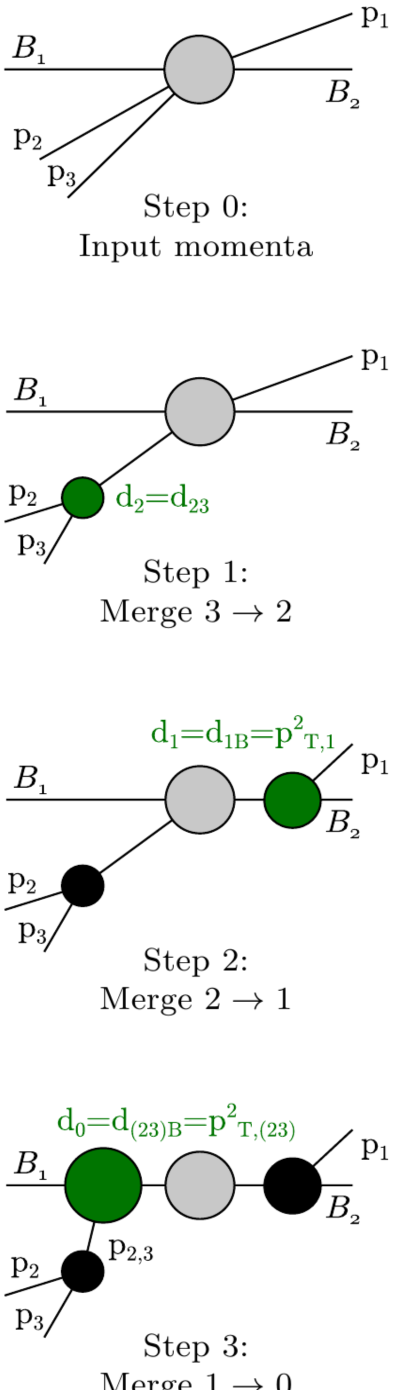


CMS-EWK-11-021, submitted to Phys. Lett. B

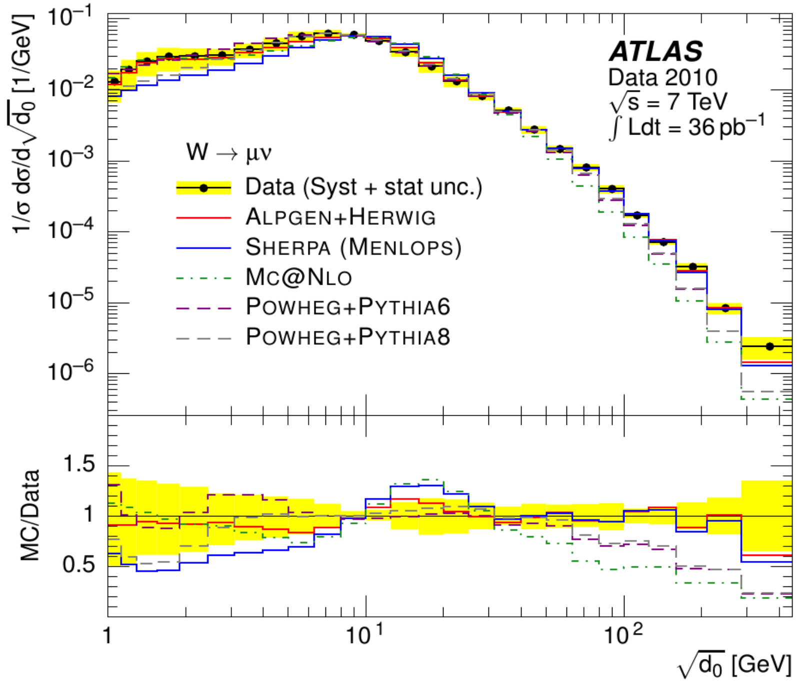
Event shapes in V+jets

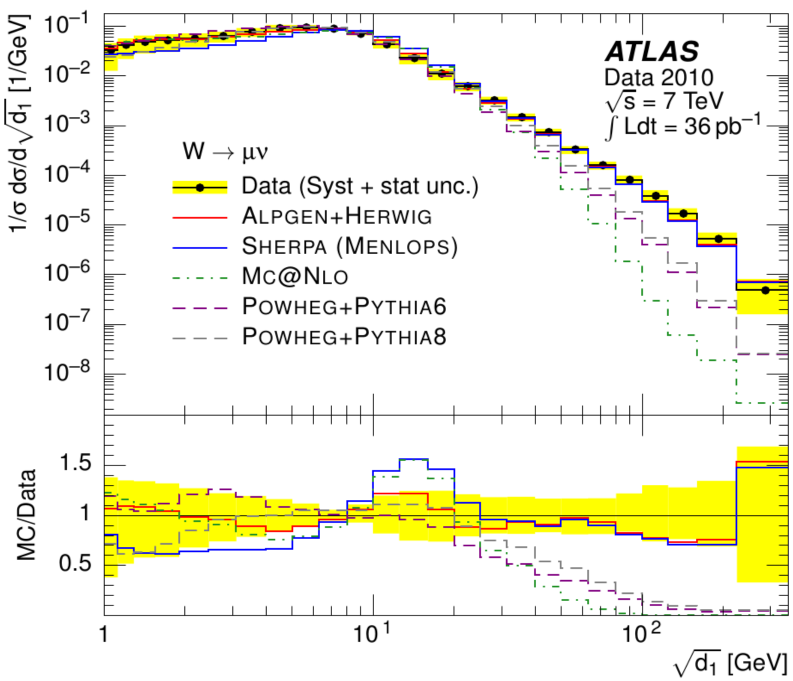
CERN-PH-EP-2013-003

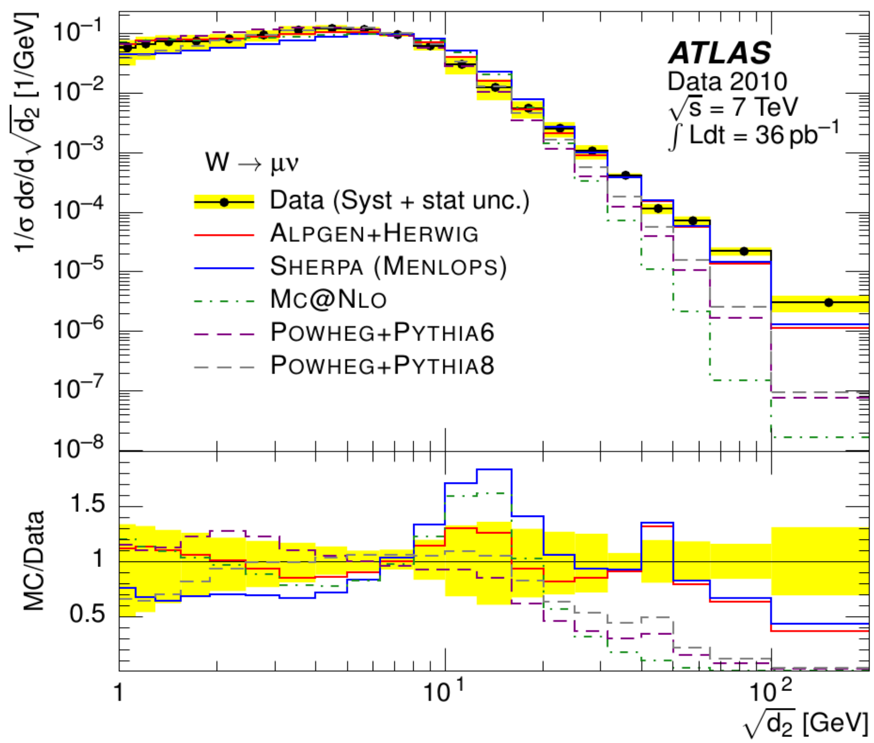
- KT splitting scales in W+jets
  - Aka differential jet rates
- The kT algorithm works with sequential recombination of particle momenta, based on the kT distance
- The recombination goes on until all kT distances of the resulting jets are above a given threshold
- This is a measurement of the value of such thresholds that need to be set to make an event look like an n-jet event
- In depth characterization of the hadronic component of W+jets
  - High end is sensitive to hard emission
  - Low end is sensitive to jet substructure
-



- LO+PS agrees well with the data
- All NLO+PS show less hard activity than the data
  - Expected due to missing multi-leg matrix elements
- The low end of the spectra, sensitive to the parton shower is very well described by Herwig





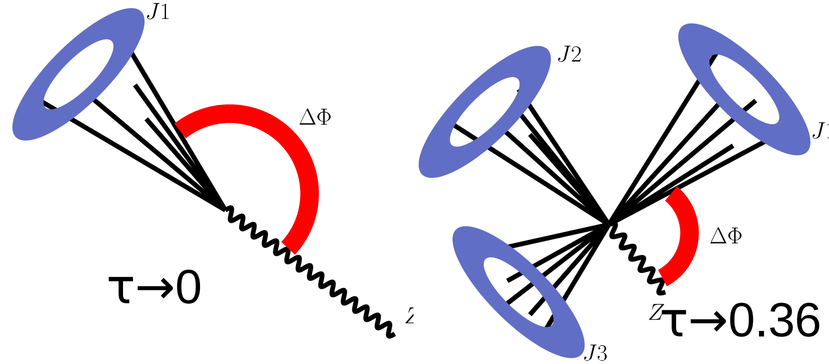


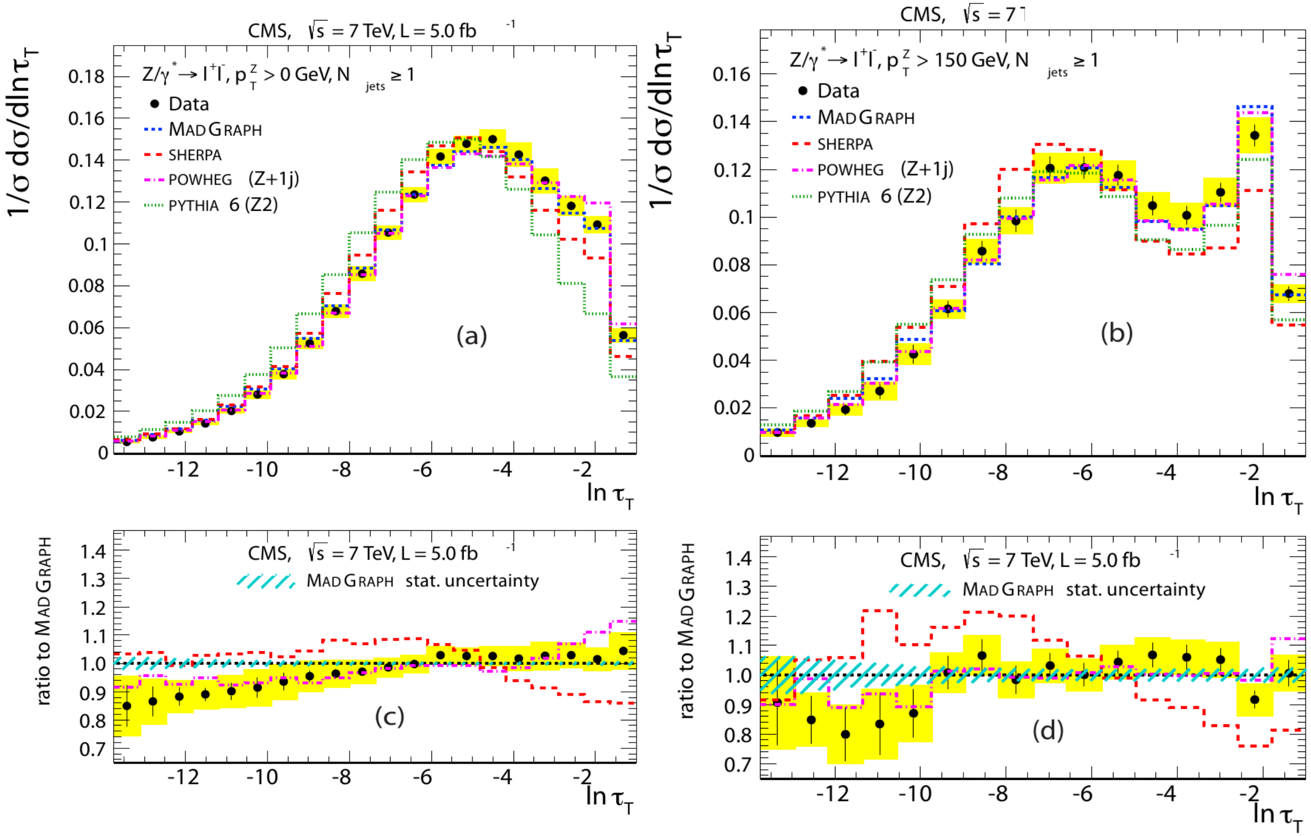
Event shapes in V+jets

CMS-EWK-11-021

- Central transverse thrust in Z+jets
- Built out of the Z and the jets with pT >50 GeV, |η|<2.4
- Both inclusively, and in a boosted topology where pt(Z)>150 GeV

$$\tau_\perp \equiv 1 - \max_{\vec{n}_T} \frac{\sum_i}{}$$





- The region dominated by multijet topologies shows agreement with LO+PS (Madgraph)
- NLO +PS is also good, with a slight tendency to overshoot
- Instead, in pencil-like topologies powheg shows best agreement

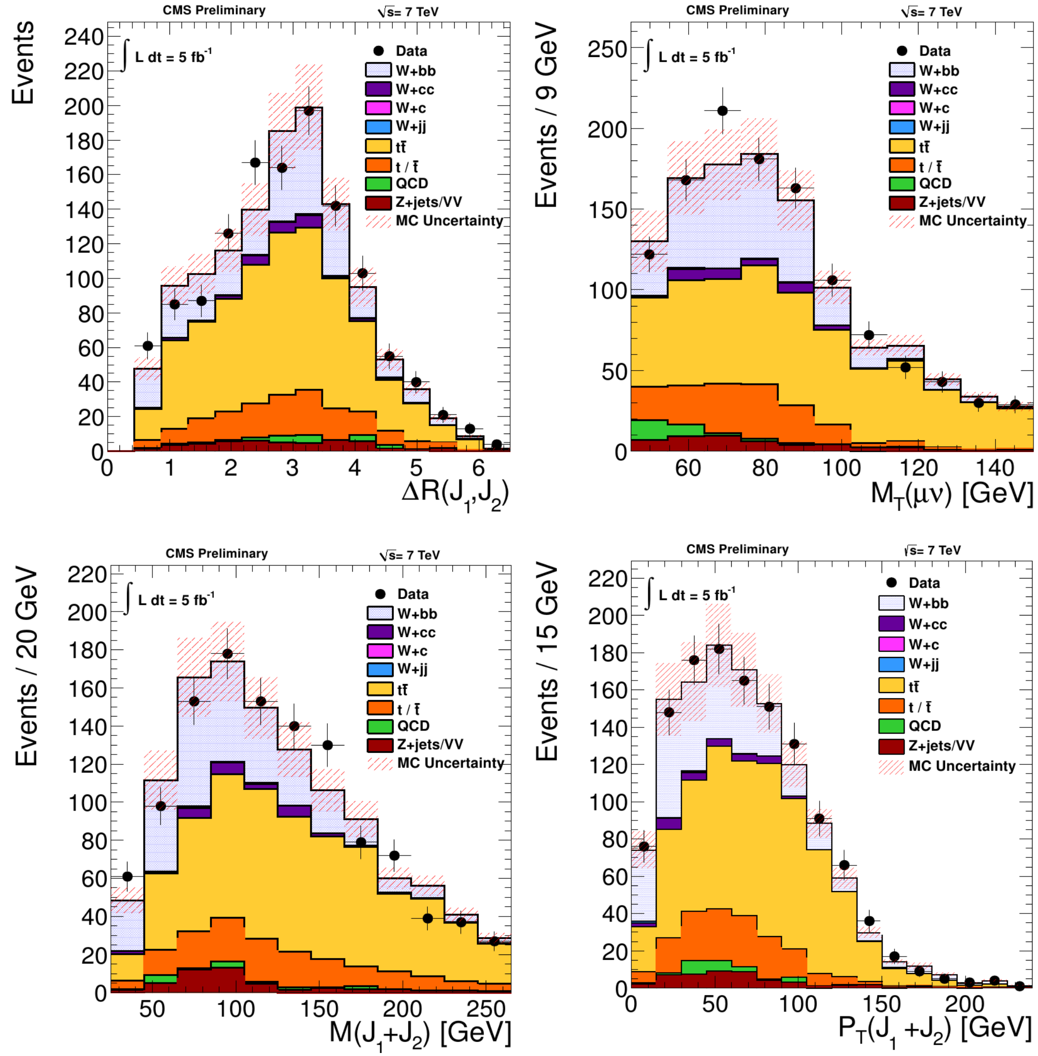
W/Z+heavy flavor

$$\sigma(pp \to \mathrm{W} + \mathrm{b}\bar{\mathrm{b}}, p_T^{\mathrm{b}} > 25\ \mathrm{GeV}, |\eta^{\mathrm{b}}| < 2.4) \times \mathcal{B}(\mathrm{W} \to \mu\nu, p_T^{\mu} > 25\ \mathrm{GeV}, |\eta^{\mu}| < 2.1) =$$
$$= 0.53 \pm 0.05\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{syst.}) \pm 0.06\,(\mathrm{theo.}) \pm 0.01\,(\mathrm{lum.})\ \mathrm{pb}.$$

- Wbb cross section and differential distribution
  - Very good agreemer with simulations
  - Consistent with NLO calculation with MSTW2008 PDFs

$0.52 \pm 0.03\ \mathrm{pb}$

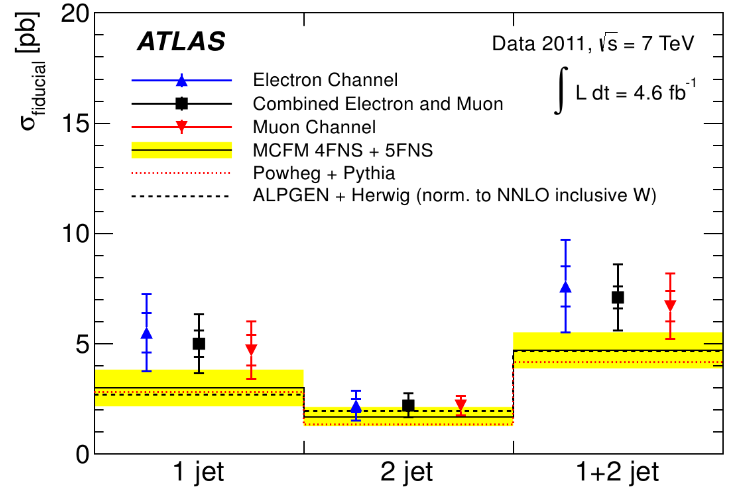
CMS-SMP-12-026



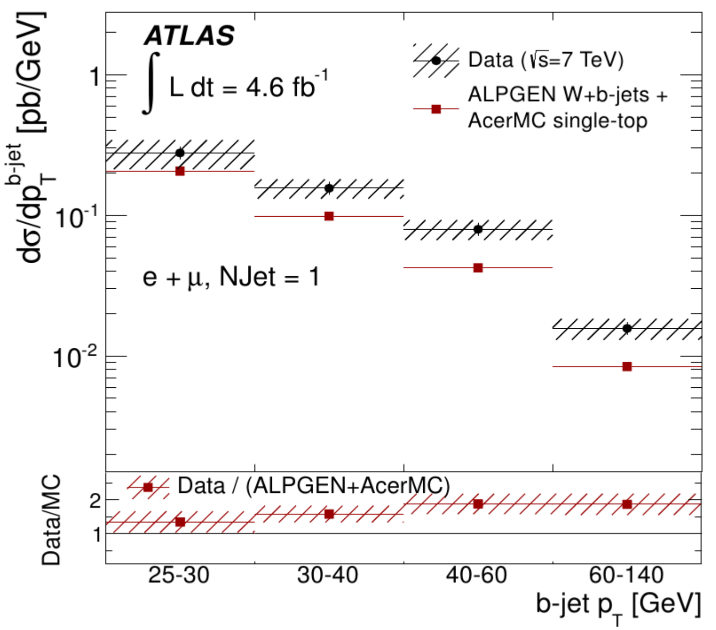
W/Z+heavy flavor

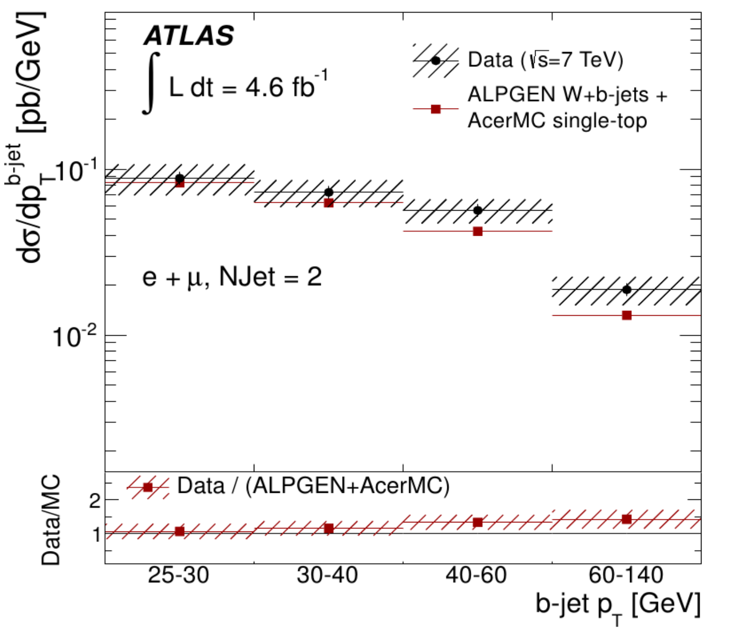
- W+>=1 b cross section and differential distributions, measured in a fiducial region in the 1 jet and 2 jet channel
  - Alpgen and Powheg: 4F scheme
  - MCFM: 5F scheme

STDM-2012-11, submitted to JHEP



- Differential distributions are also compared to predictions without the subtraction of single top background
  - Same final state

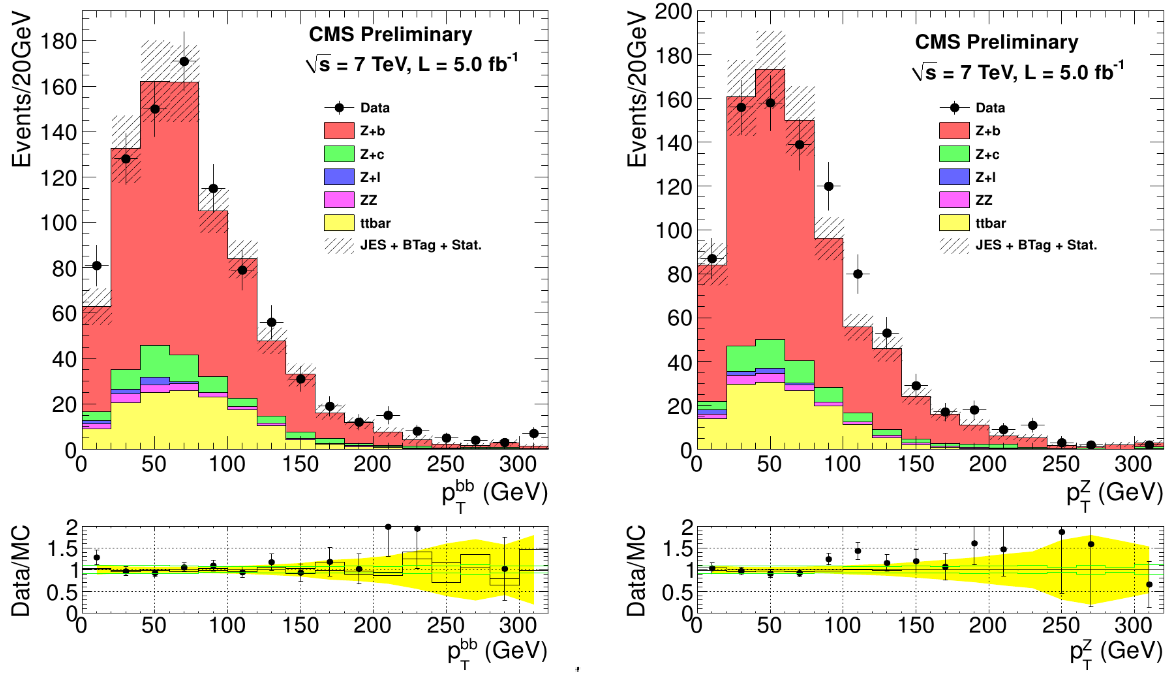




W/Z+heavy flavor

SMP-13-004
Phys.Lett.B 706 (2012) 295-313

- Z(ll)+b cross section and differential distributions
  - Fair agreement with simulations (5F scheme)
  - Total cross section compared to Madgraph prediction in both 5f and 4F schemes
    - After normalization to NLO of total DY cross section



$p_T^\ell > 20$ GeV, $|\eta^\ell| < 2.4$ $\quad 76 < M_{\ell\ell} < 106$ GeV, $\quad p_T^j > 25$ GeV

stat syst

Multiplicity bin	Measured	MadGraph 5F	MadGraph 4F
$\sigma(Z(\ell\ell)+1b)$ (pb)	$3.52 \pm 0.02 \pm 0.20$	3.66 ± 0.02	3.11 ± 0.03
$\sigma(Z(\ell\ell)+2b)$ (pb)	$0.36 \pm 0.01 \pm 0.07$	0.37 ± 0.01	0.38 ± 0.01
$\sigma(Z(\ell\ell)+b)$ (pb)	$3.88 \pm 0.02 \pm 0.22$	4.03 ± 0.02	3.49 ± 0.03
$\sigma(Z(\ell\ell)+b)/\sigma(Z(\ell\ell)+j)$ (%)	$5.15 \pm 0.03 \pm 0.25$	5.35 ± 0.02	4.60 ± 0.03

Conclusion

- ATLAS and CMS exploited the LHC Run 1 to make a large amount of QCD precision measurements
  - Ranging from low pt to high pt and from inclusive to exclusive observables
- Still more measurements are in the works
- These measurements have improved significantly out understanding of QCD in several ways
  - Comparison to the recent, most precise event generators
    - With experimental errors that in several cases are comparable or smaller than the corresponding theoretical predictions

Backup

Jet reconstruction

- Jets are reconstructed with the anti-kt algorithm, with radius of 0.5 or 0.7
- 3 available algorithms for jet reconstruction
  - Calo-Jets: use only the calorimeter towers
  - Jet-Plus-Track Jets: improve the calorimeter jets using the tracks in the jet cone
  - Particle-Flow jets: uses particle flow candidates as input to the clustering algorithm
    - Particle flow reconstruction:
      - global event reconstruction
      - Identifies muons, electrons, taus, photons, charged hadron, neutral hadrons
      - Combines the information from all detectors

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Jet energy scale

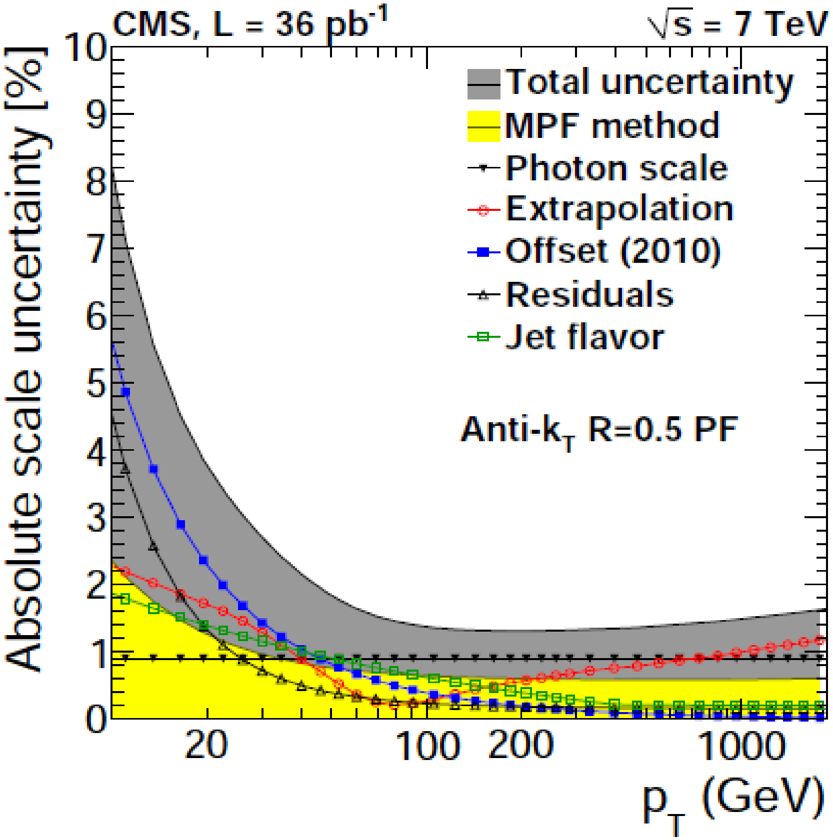
- We use a multi-step procedure to correct the energy of our jets

$$p_{\mu}^{cor} = \mathcal{C} \cdot p_{\mu}^{raw}. \qquad \mathcal{C} = C_{\text{offset}}(p_T^{raw}) \cdot C_{\text{MC}}(p'_T, \eta) \cdot C_{\text{rel}}(\eta) \cdot C_{\text{abs}}(p''_T)$$

  - C_{offset} accounts for detector noise and pile-up
  - The method uses correction factors extracted from the full simulation of CMS, C_{MC}
  - Residual differences with respect to data are accounted for as further scaling factors
    - C_{rel} accounts for non-uniformity in eta. It is obtained applying on data and MC the di-jet balance method
    - C_{abs} accounts for residual absolute scale differences between data and MC. It is obtained applying on data and MC the γ+jet and Z +jet pT balancing
  - In this MC + residual method effects like the presence of additional radiation spoiling dijet or γ+jet and Z +jet balancing enter only at second order

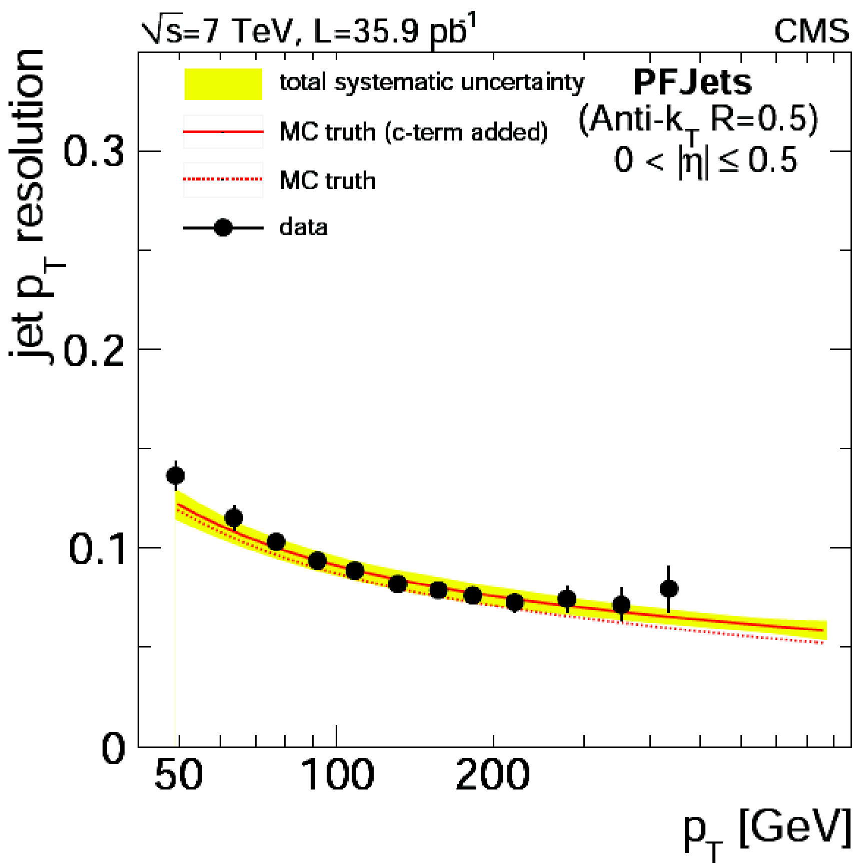
Jet energy scale

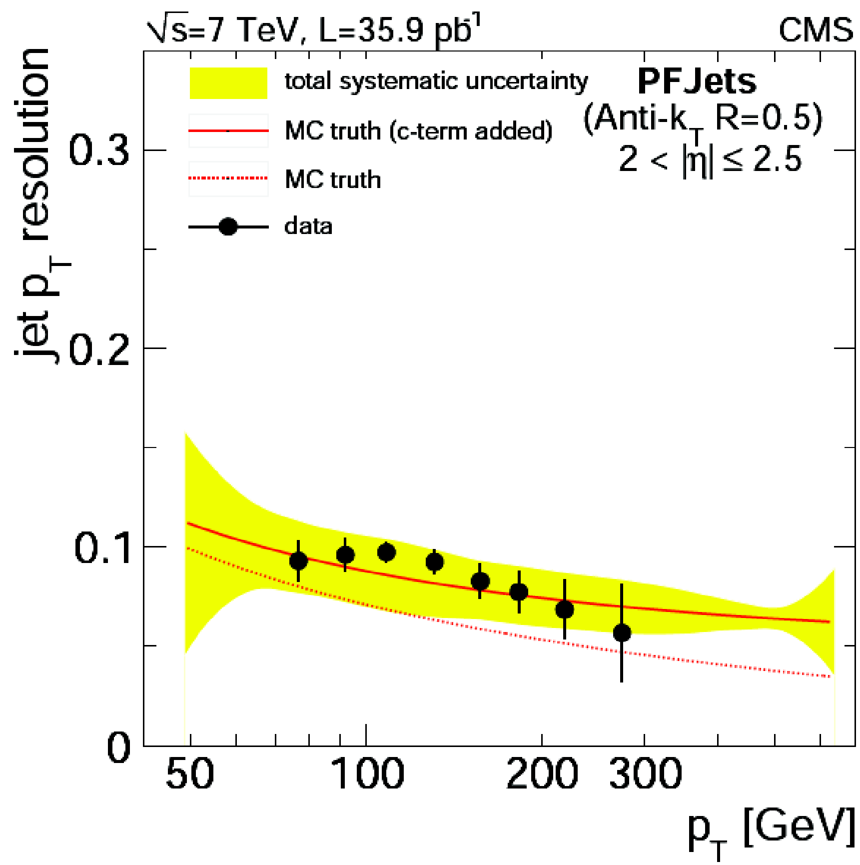
- Total systematic uncertainty on the energy scale for particle-flow jets
- The main sources of uncertainty are:
  - The photon energy scale, known at 1%
  - The relative response across detector regions
  - Pile-up effects
  - Extrapolations down to 0 for the additional activity in the balance methods
  - Dependency on jet flavor in the MC used



Jet energy resolution

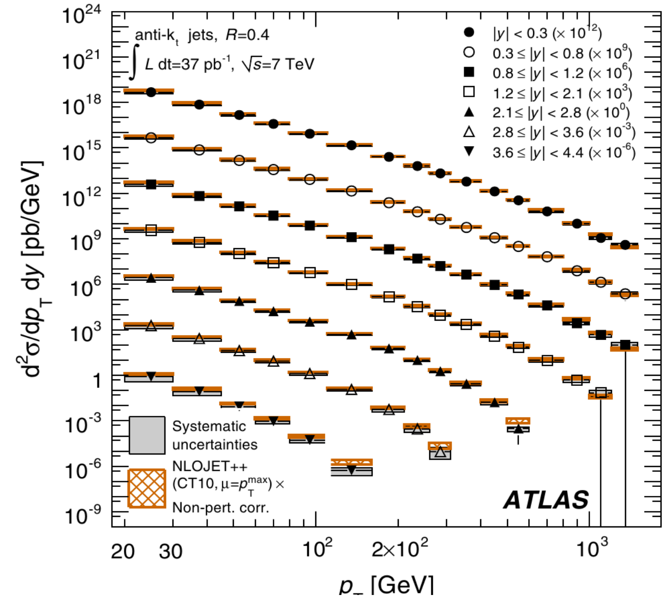
- Determined with di-jet and γ+jet pT balance
  - Plots show two example regions in η
  - Resolution is of the order of 10% around 50 GeV

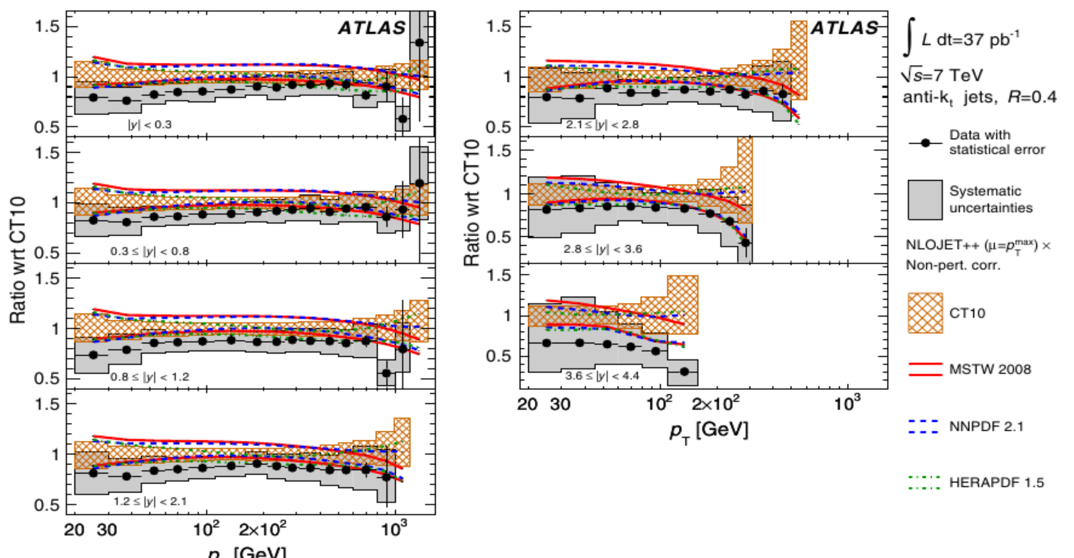


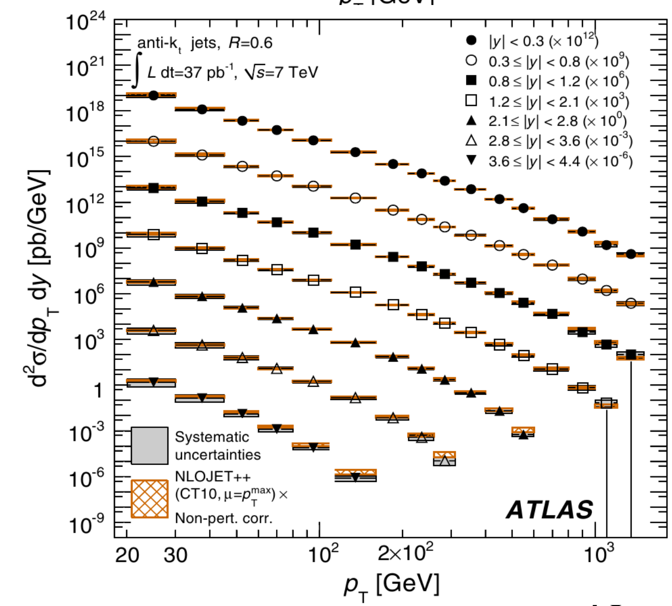


Inclusive jets

- From 20 GeV to 1.5 TeV
- It is interesting to compare different jets sizes
  - Difference contribution of hadronization and UE corrections
- Main systematic: jet energy scale
- Data are compared with the predictions at NLO, including non-perturbative (NP) corrections obtained with a shower MC
- Good agreements NNPDF and CT10
- MSTW better at large rapidities

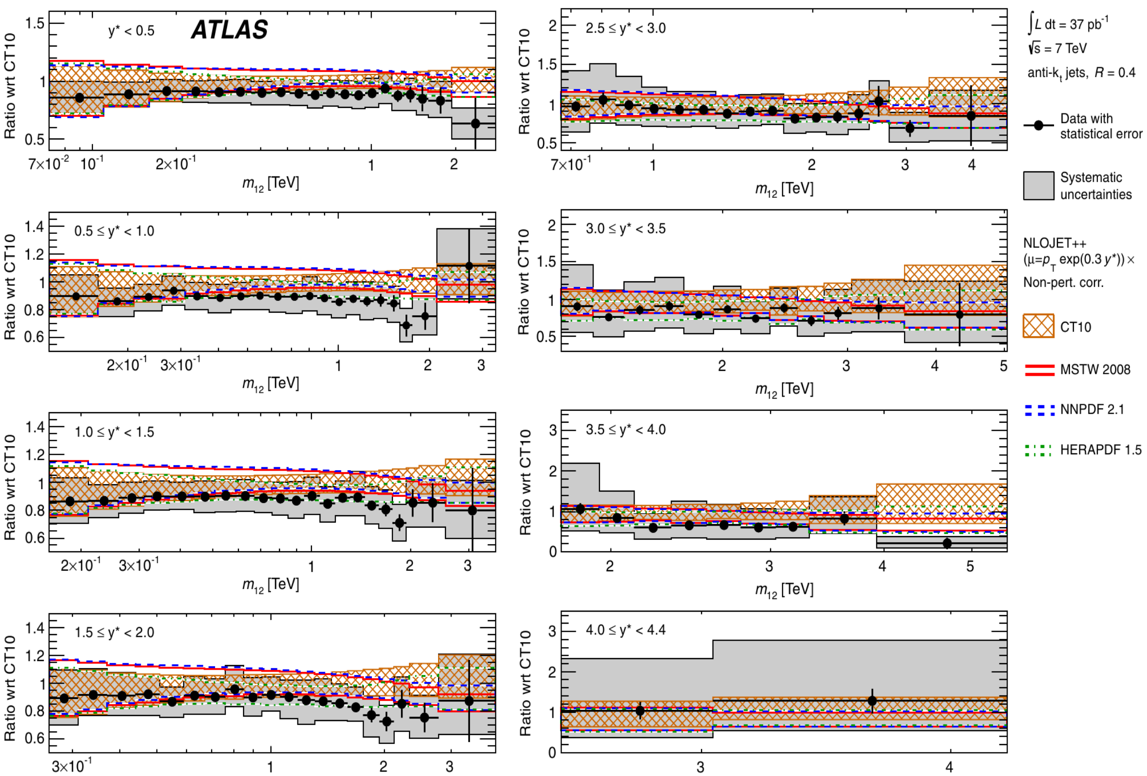


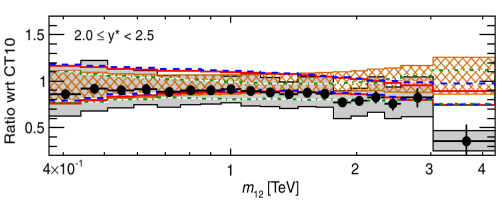




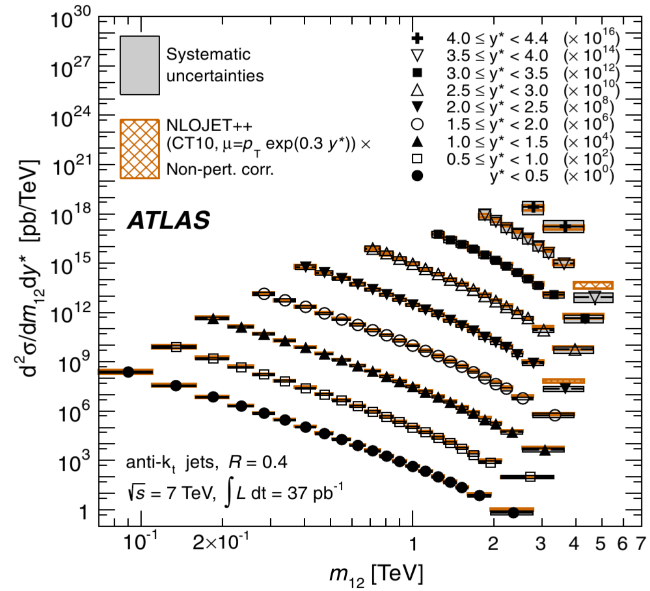
Di-jet mass

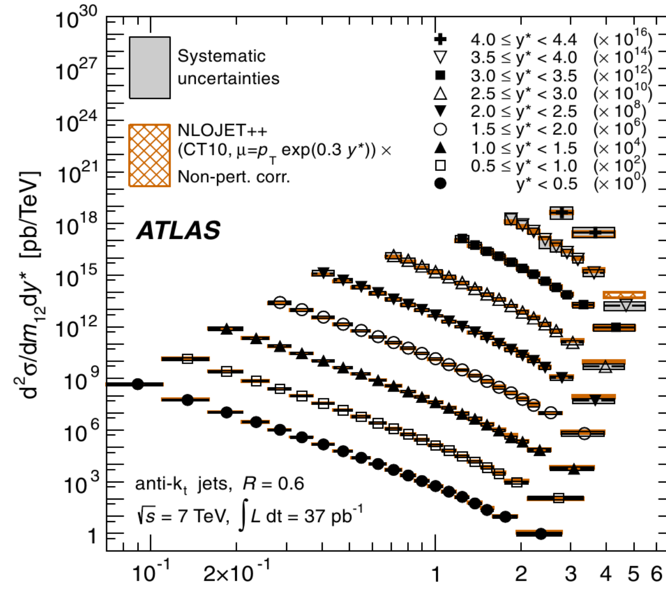
- Measured in up to 5 TeV in bins of rapidity
- Jet pT > 20 GeV, |η|<4.4





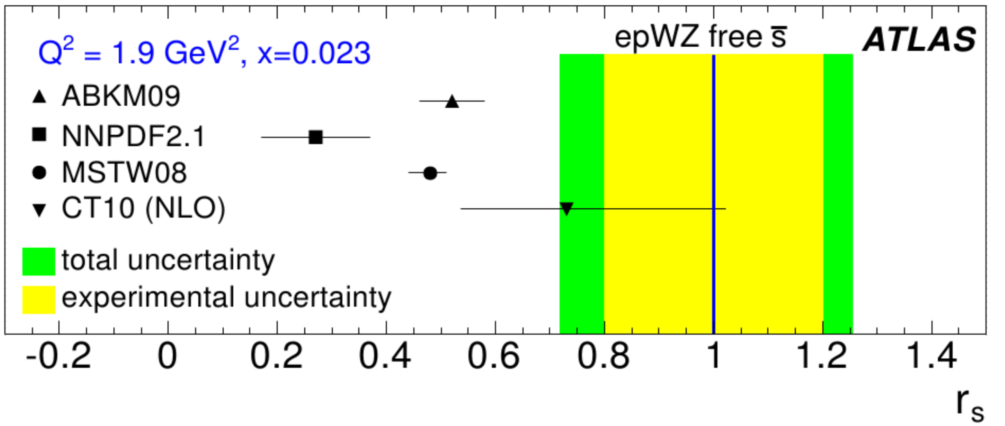
- Good agreement with several PDF sets

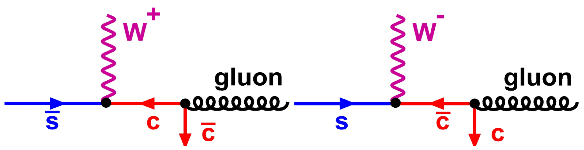


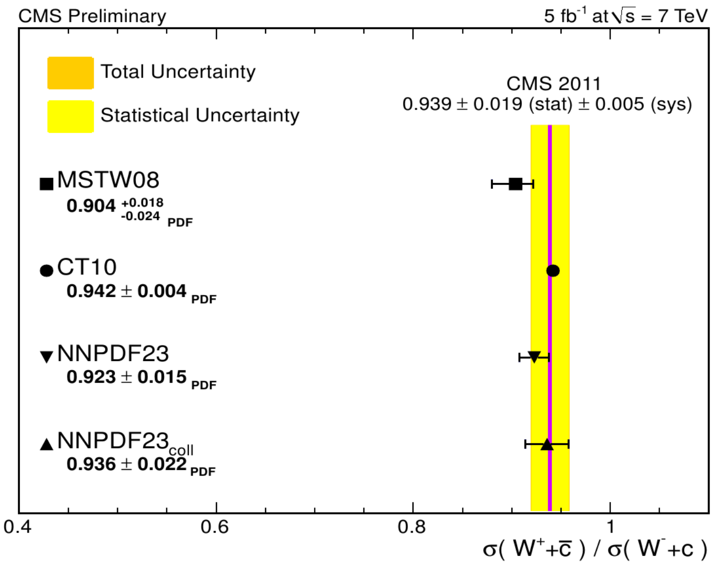


Constraints of strange quark content

- ATLAS studied the ratio of (s+sbar)/d using W and Z cross section measurements
- CMS measured W+c cross sections to constraint s and sbar density

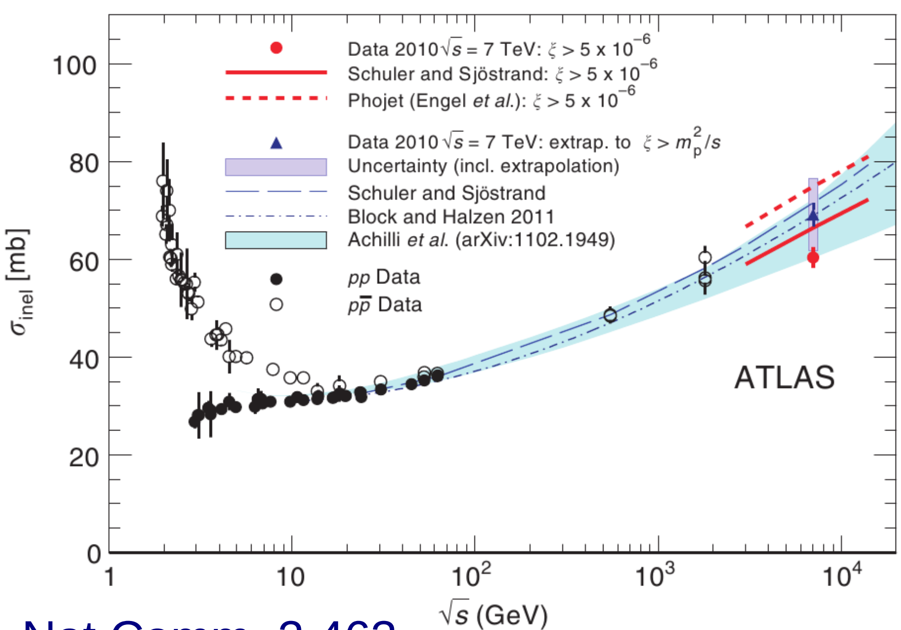






Inelastic pp cross section

- Both ATLAS and CMS measured the inelastic cross section using forward calorimeters
  - An additional measurement, using a of a poissonian to the number of vertices is derived in CMS
- Results are compared to several models
  - Agreement is very good especially when compared to models for cosmic ray interactions like EPOS and QGSjet



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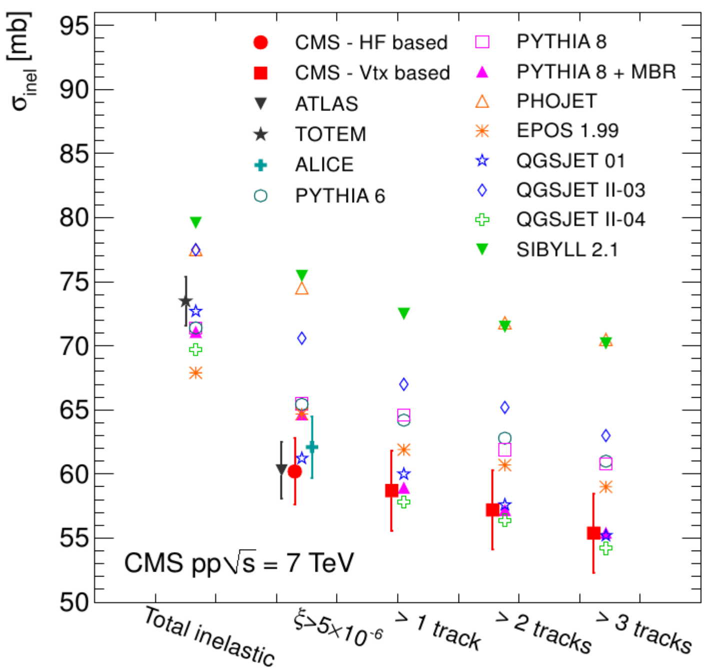


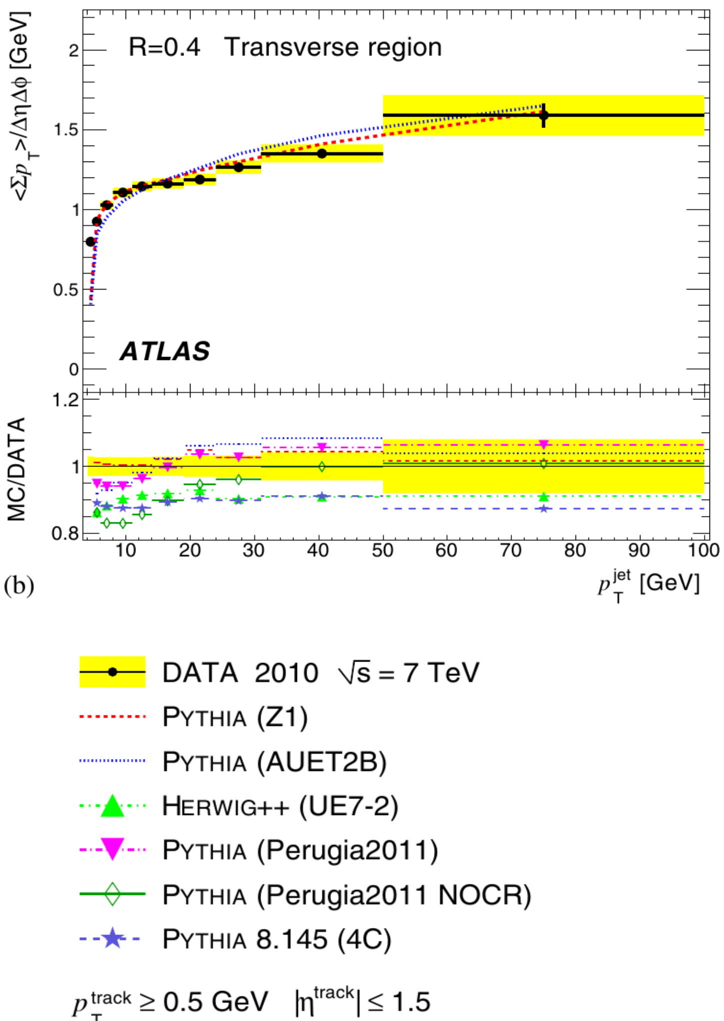
CMS-FWD-11-001

Underlying event

- Addressed in several different ways:
  - Rick Field-like observables
    - Inclusive
    - In events with a hard scatterer
- Aspects studied:
  - Energy dependence
  - Dependence on jet size

UE: Rick Field observables

- Event is sub-divided into 3 regions in the transverse plane wrt a “leading object”



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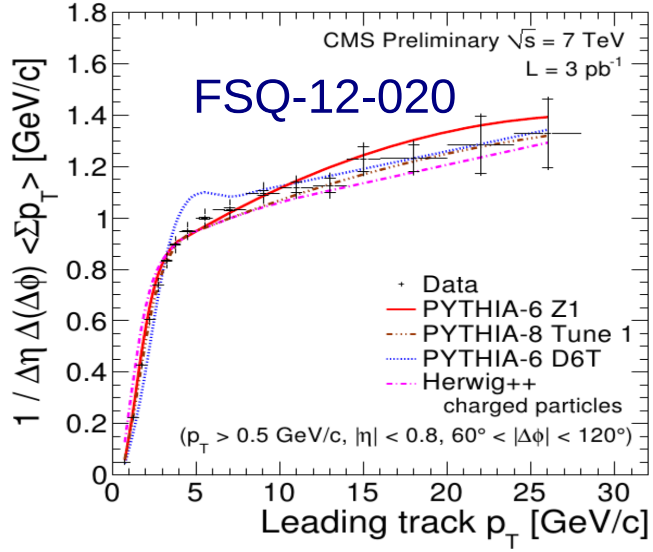
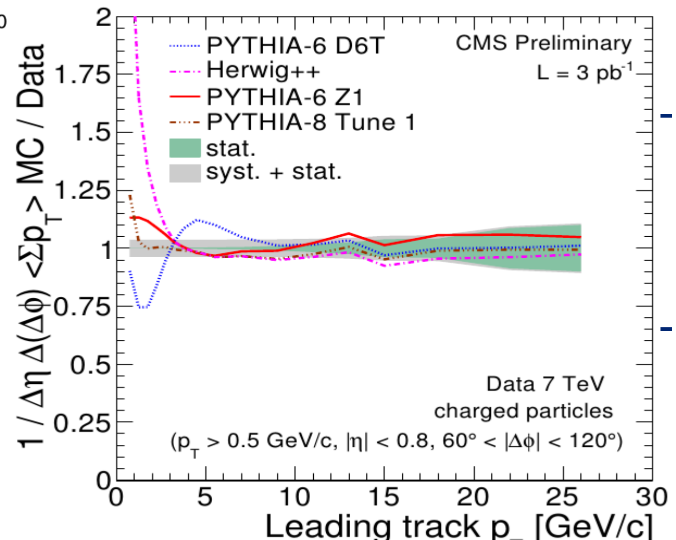
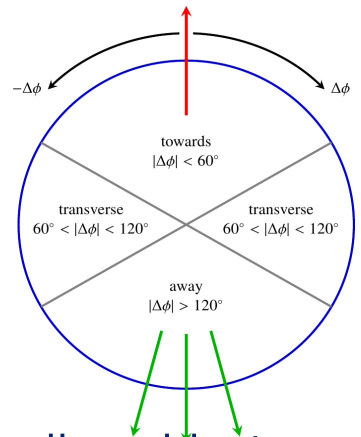


FSQ-12-020

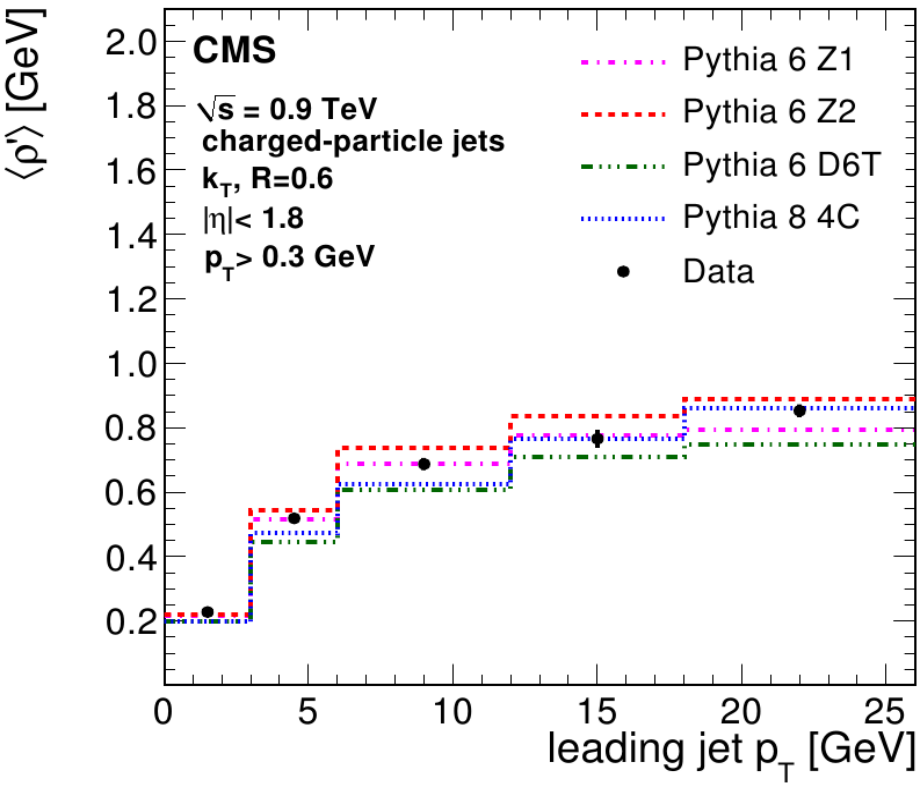


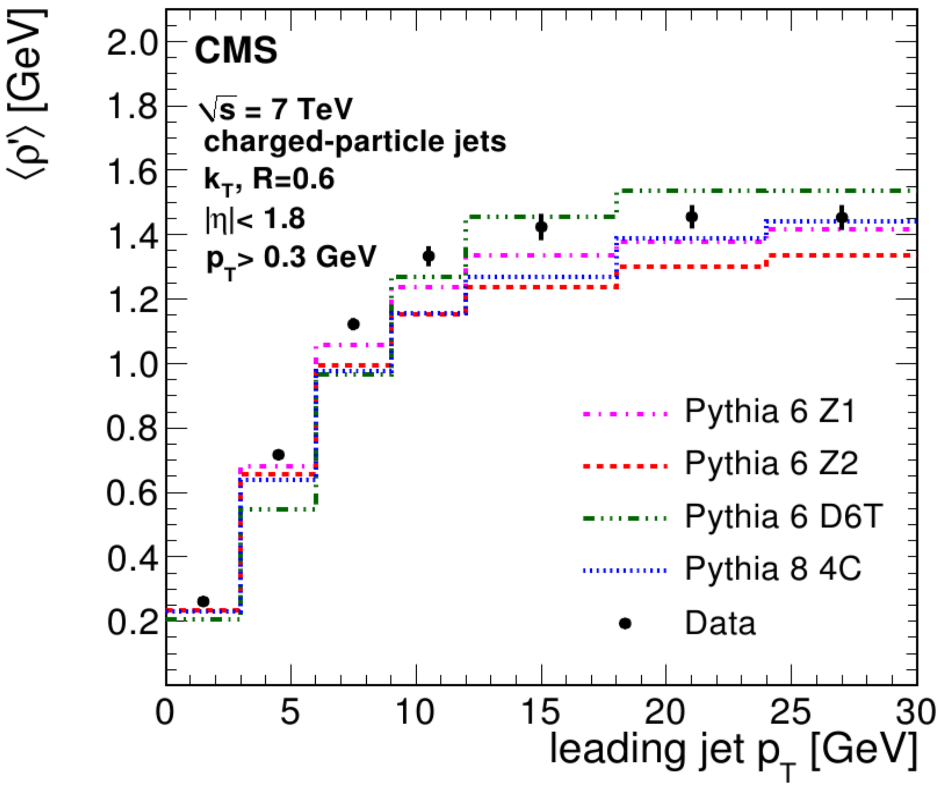


- Leading object definition is different in ATLAS and CMS
  - Leading charged jet for ATLAS
  - Leading track for CMS
- Both ATLAS and CMS used these measurements to derive MC tunes
- Both Pythia6 and Pythia8 with dedicated tunes give good description of the observables

UE: jet area/median approach

- It uses the FastJet definition of jet area and median activity
  - Slightly modified definition of median, including only jets with at least 1 charged particle





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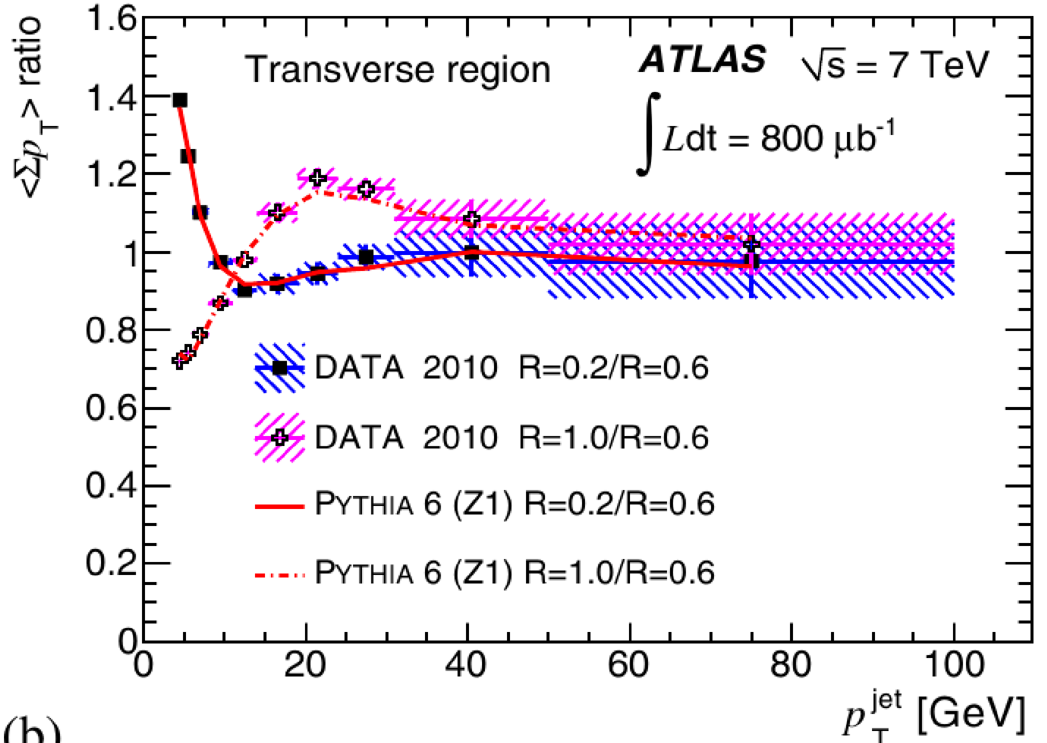
UE energy and jet size dependence

- Both the dependency on jet size and on energy is well descried with dedicated tunes



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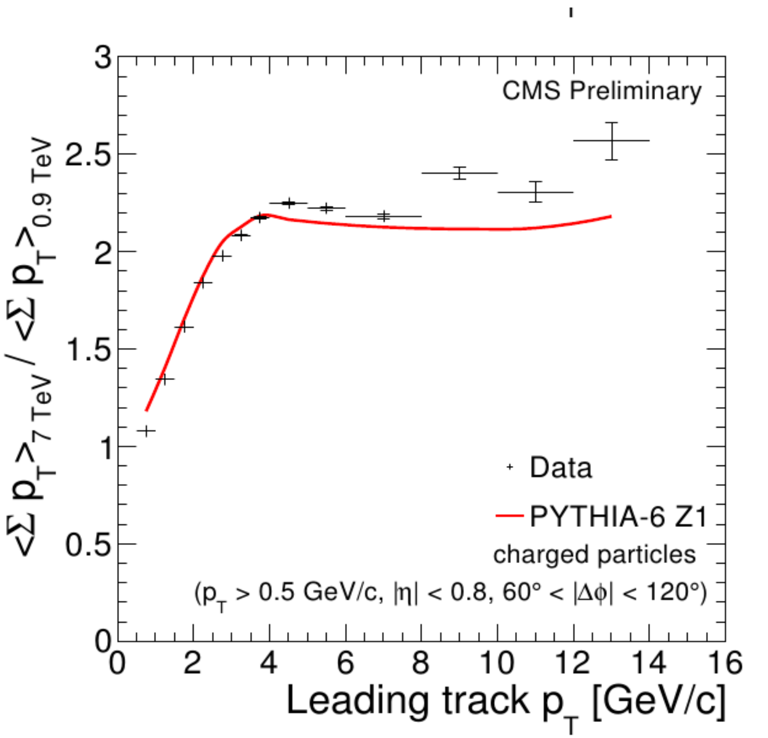
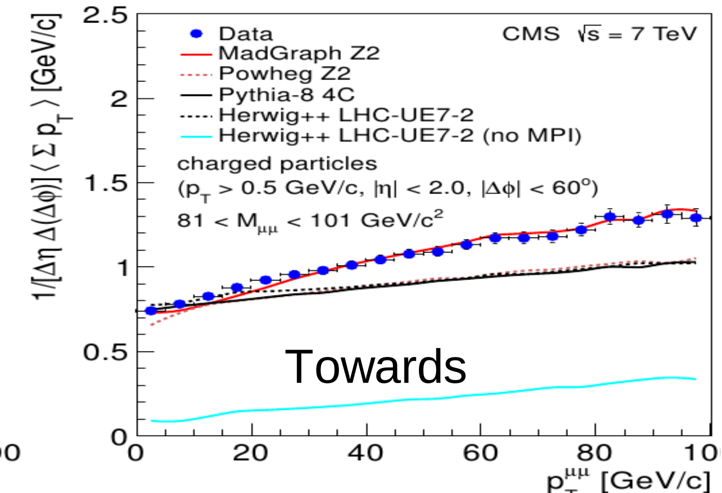
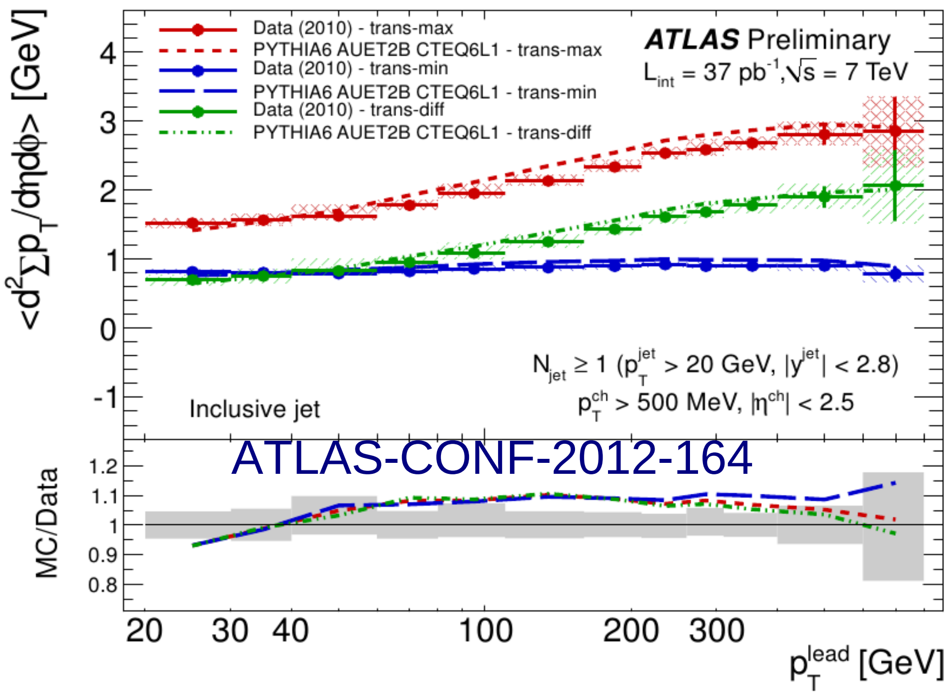


UE in events with a hard scatterer

- ATLAS UE in events with a hard jet
  - The transverse region is the most sensitive to UE
  - It is divided in a region of max and min activity
    - Region with max activity is likely to be influenced by hard jets
    - Region with min activity and (max-min) is UE dominated
- CMS UE in events with a Z boson
  - The Z boson defines the leading object direction



Eur. Phys. J. C 72 (2012) 2080



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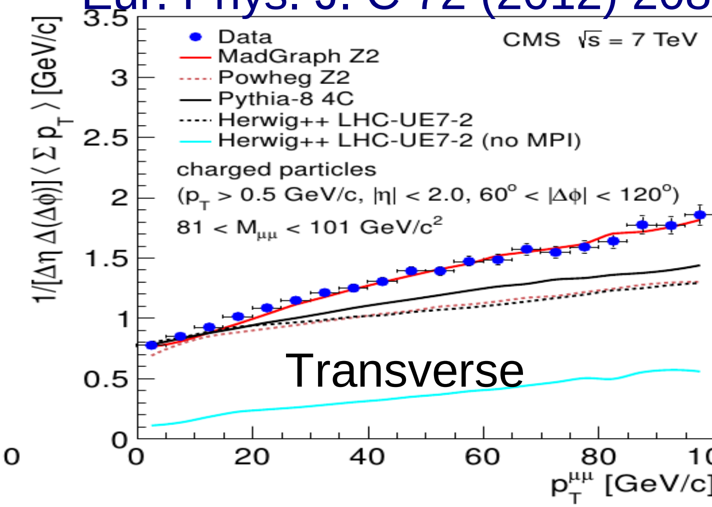
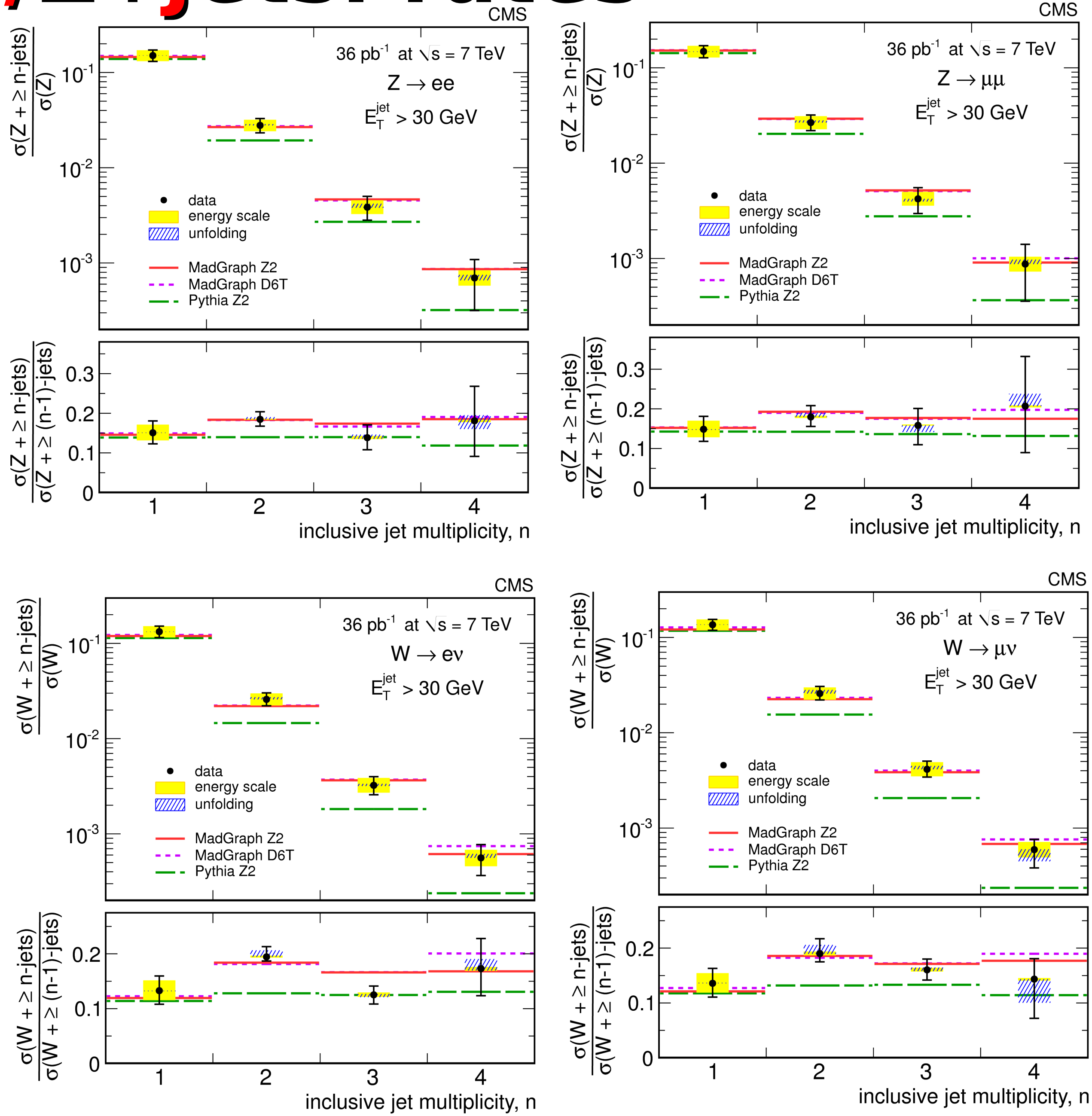


W/Z+jets: rates

JHEP01(2012)010

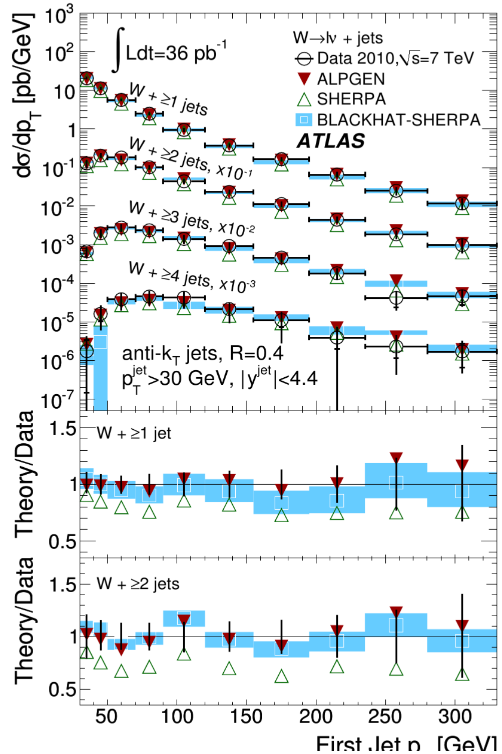
- Jet rates
  - Normalized to the inclusive cross section
  - n/(n-1) jets
- The comparison to the predictions of multi-leg matrix element + parton shower (Madgraph) shows good agreement
  - Pure parton shower (pythia) fails to predict multi-jet final states
- Given the pT threshold the sensitivity to underlying event is negligible

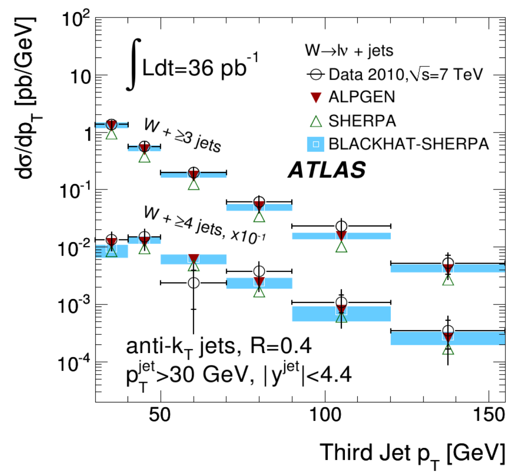


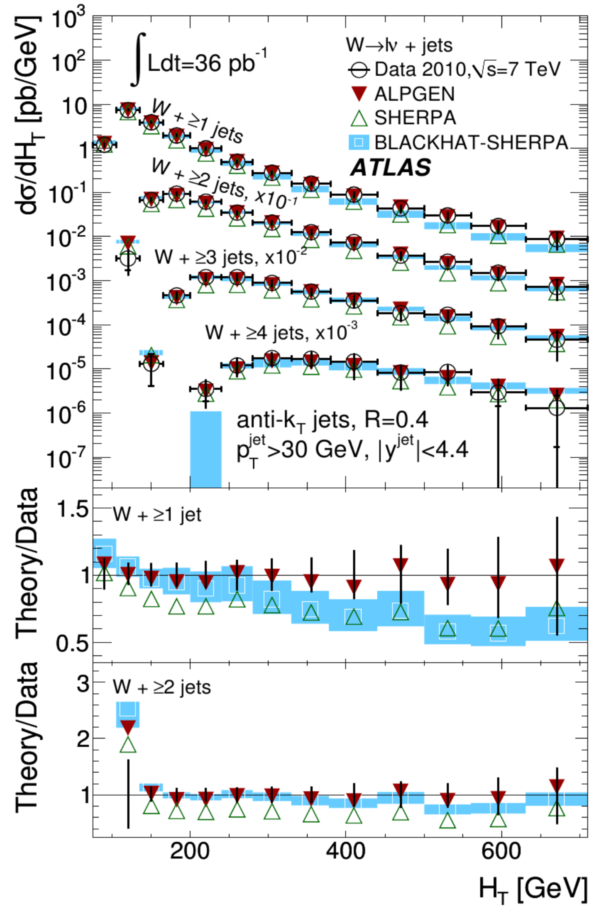
W/Z+jets differential distributions

- Remarkably good agreement with Alpgen
- Agreement with Sherpa slightly worse
- Very good agreement with NLO multi-jet predictions
  - Slight underestimation of hight HT tail

Phys. Rev. D85 (2012) 092002

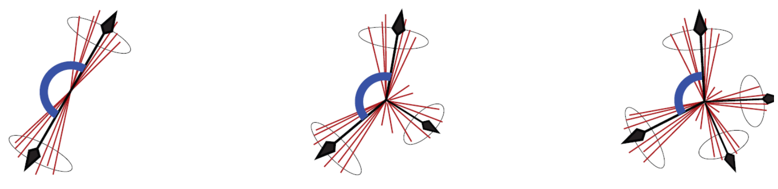






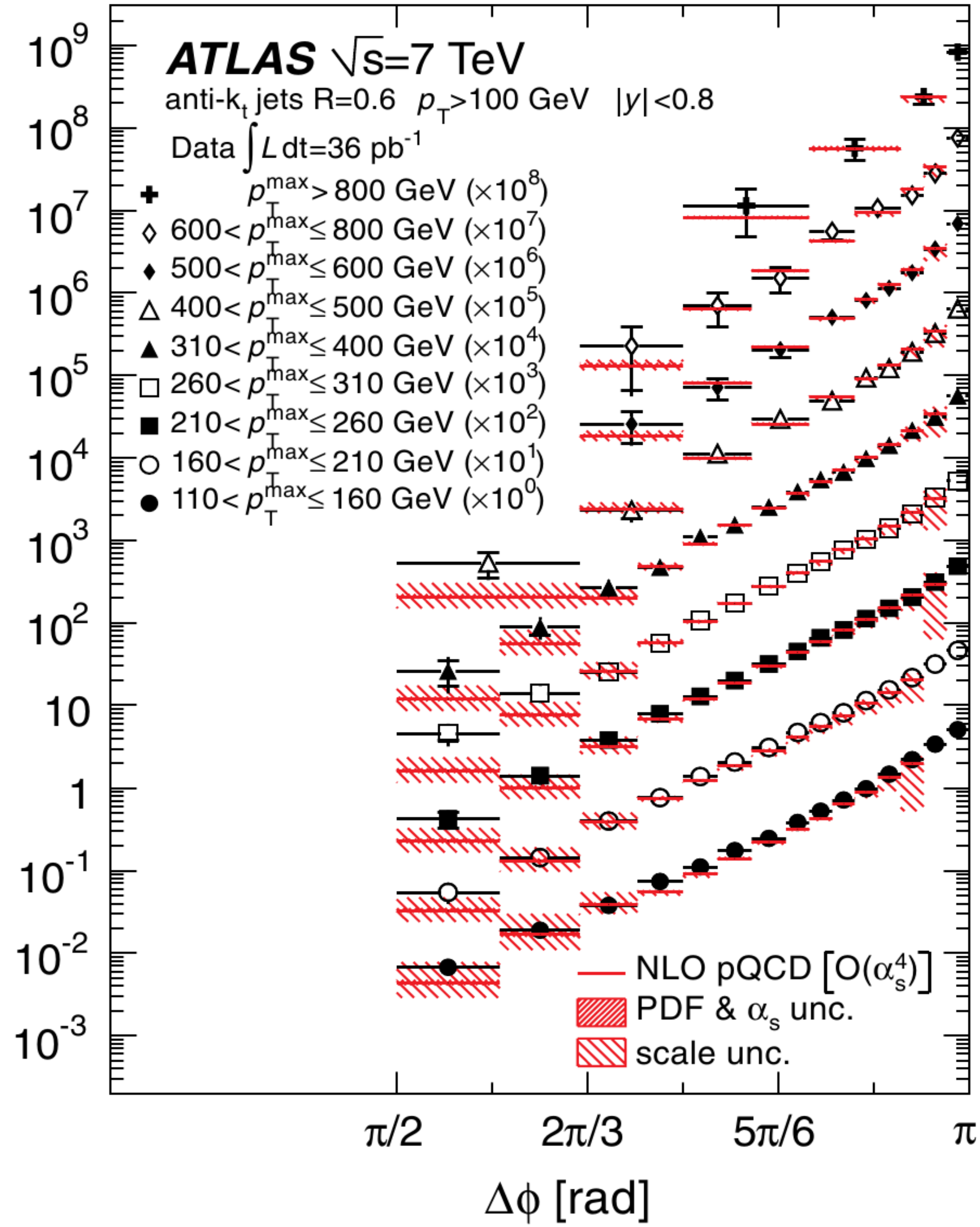
Azimuthal decorrelation

- $\Delta\varphi$ between the two leading jets in the event
  - It is very sensitive to additional radiation effects (hence to higher order corrections) but also to MPI and hadronization



- Comparison to NLO QCD
  - Good agreement over the entire range

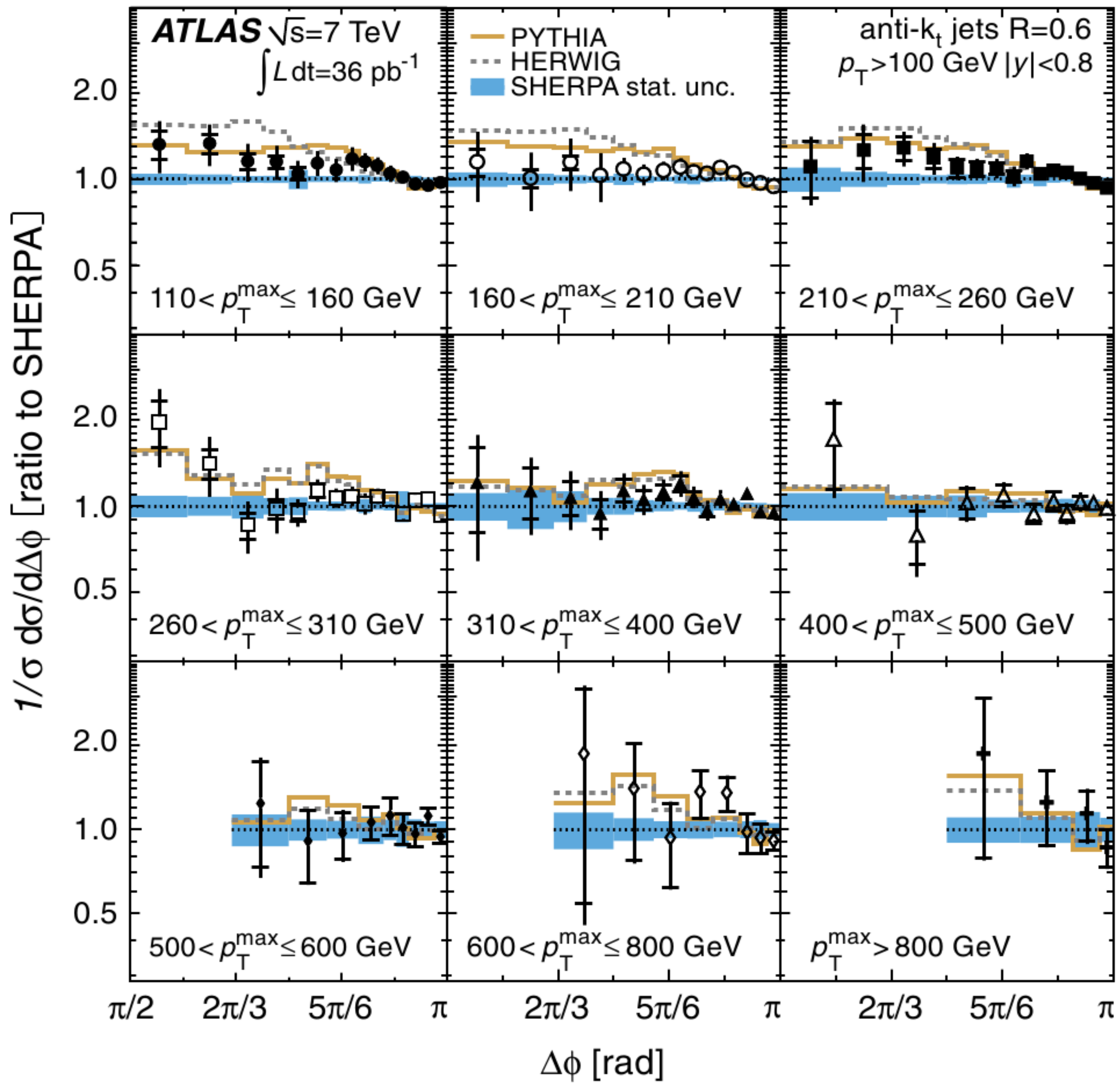
Phys. Rev. Lett. 106 (2011) 12200



Azimuthal decorrelation

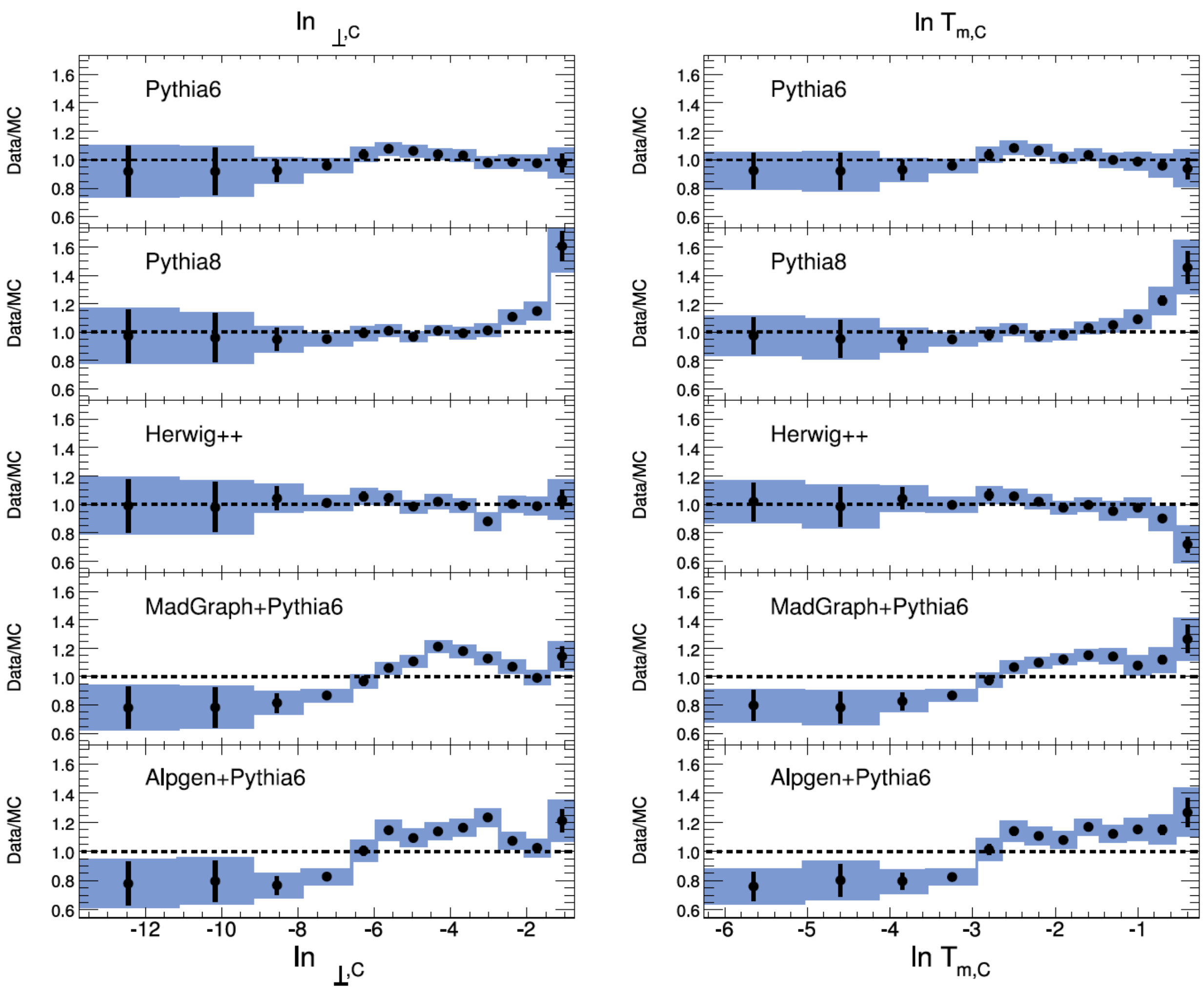
- Comparison to shower MC
  - Good description of all models chosen
  - Sherpa, with LO multileg matrix elements agrees very well with the data in the high end of the spectrum
  - Also pure shower models (Pythia8, Herwig) tuned to previous measurements agree well with the data

PRL 106 (2011) 172002



Event shapes

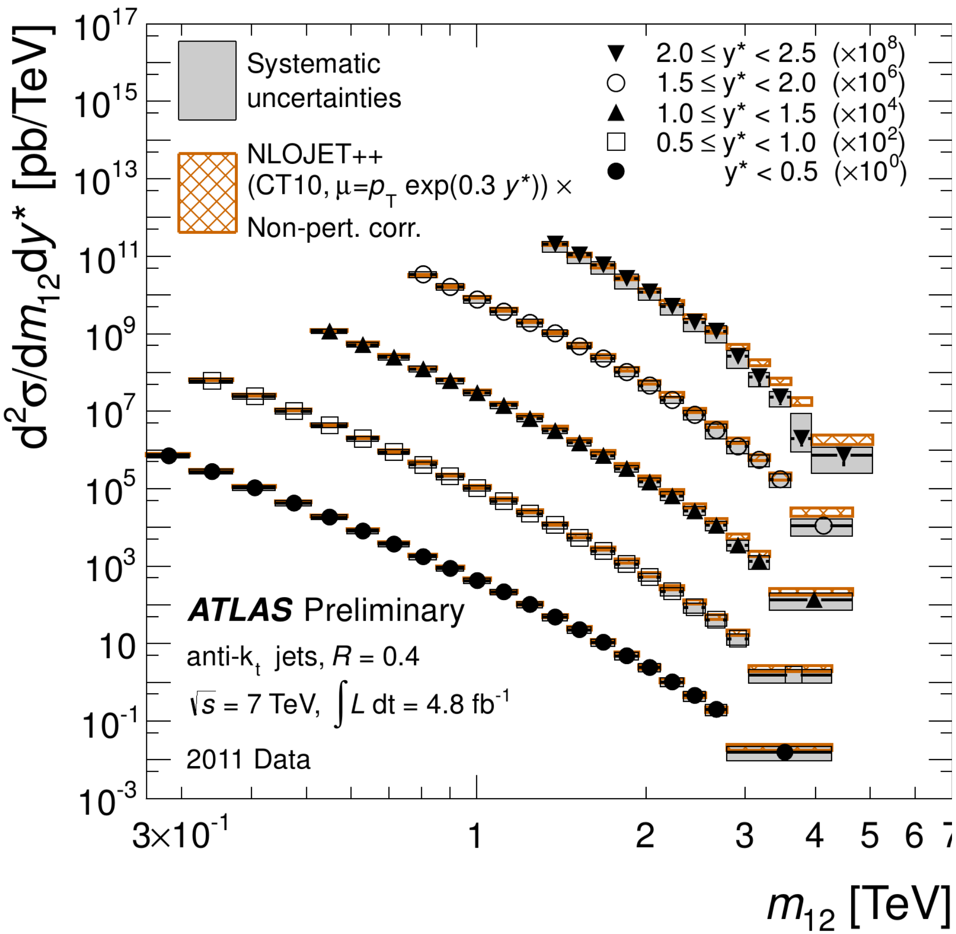
- Very nice agreement with pyre shower models, like Herwig and Pythia6
- Comparison to LO + PS programs, like AlpGen and Madgraph shows deviation from the data
    - Overtuning of the standalone Parton Shower?

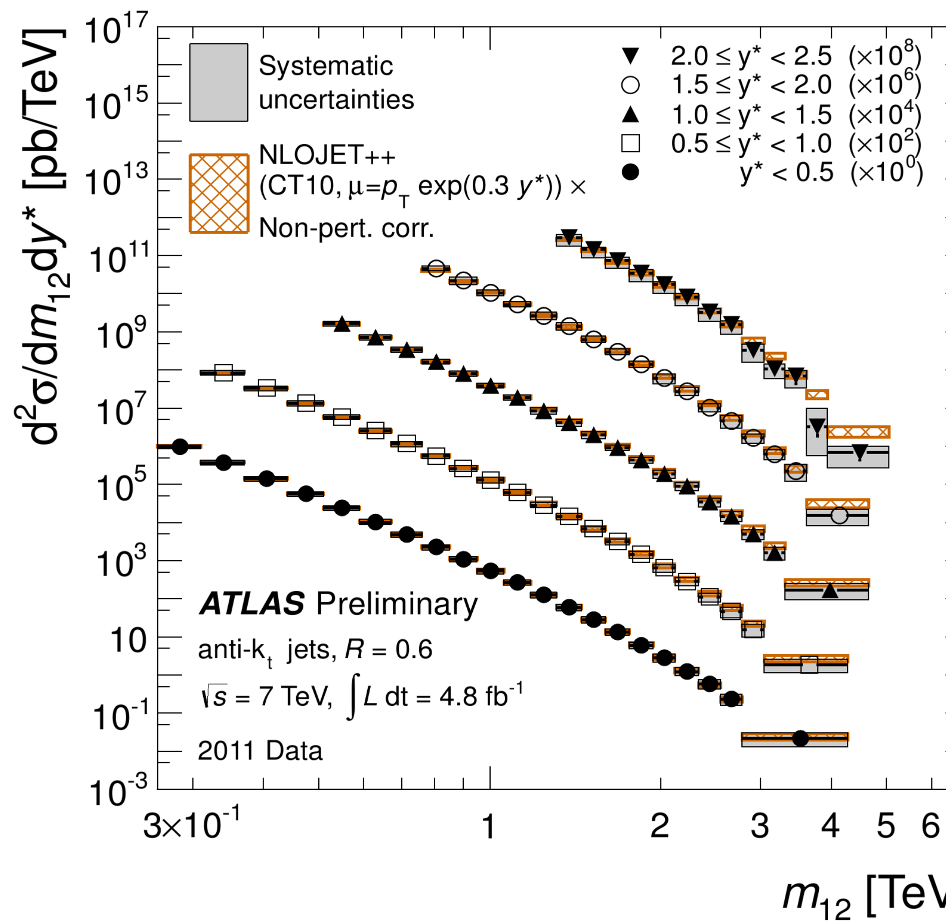


Di-jet mass

- Measured in up to 5 TeV in bins of rapidity
- Jet pT > 20 GeV, |η|<4.4
- Two Jet sizes

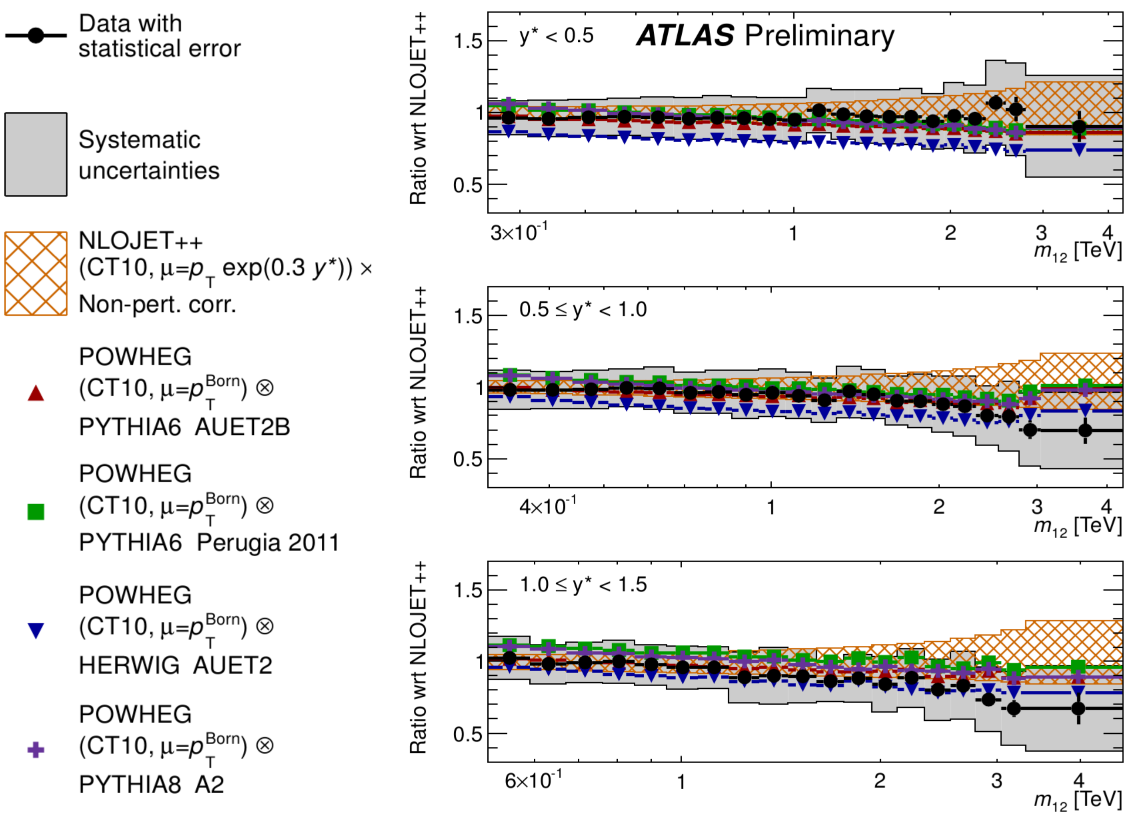
ATLAS-CONF-2012-021

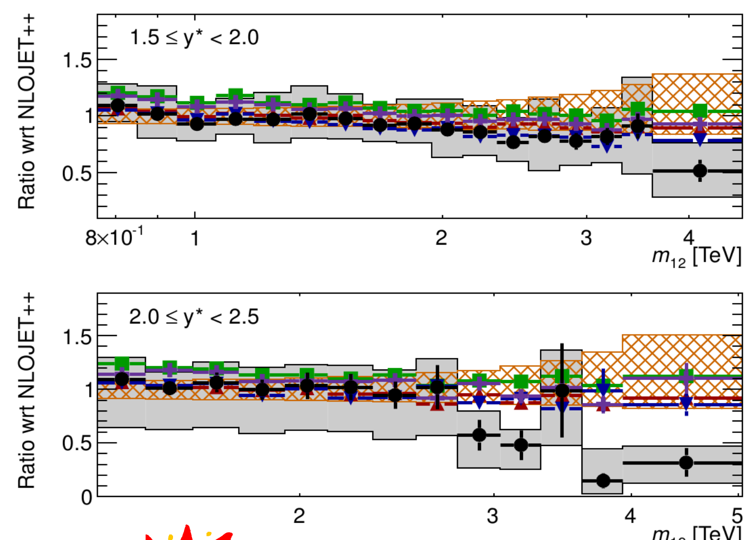




Di-jet mass

- Powheg NLO dijet showered with Pythia6 with dedicated LHC tune gives the best description of data
- Fixed order NLO tends to slightly overestimate large masses





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CMS-QCD-11-004, submitted to Phys. Rev. D