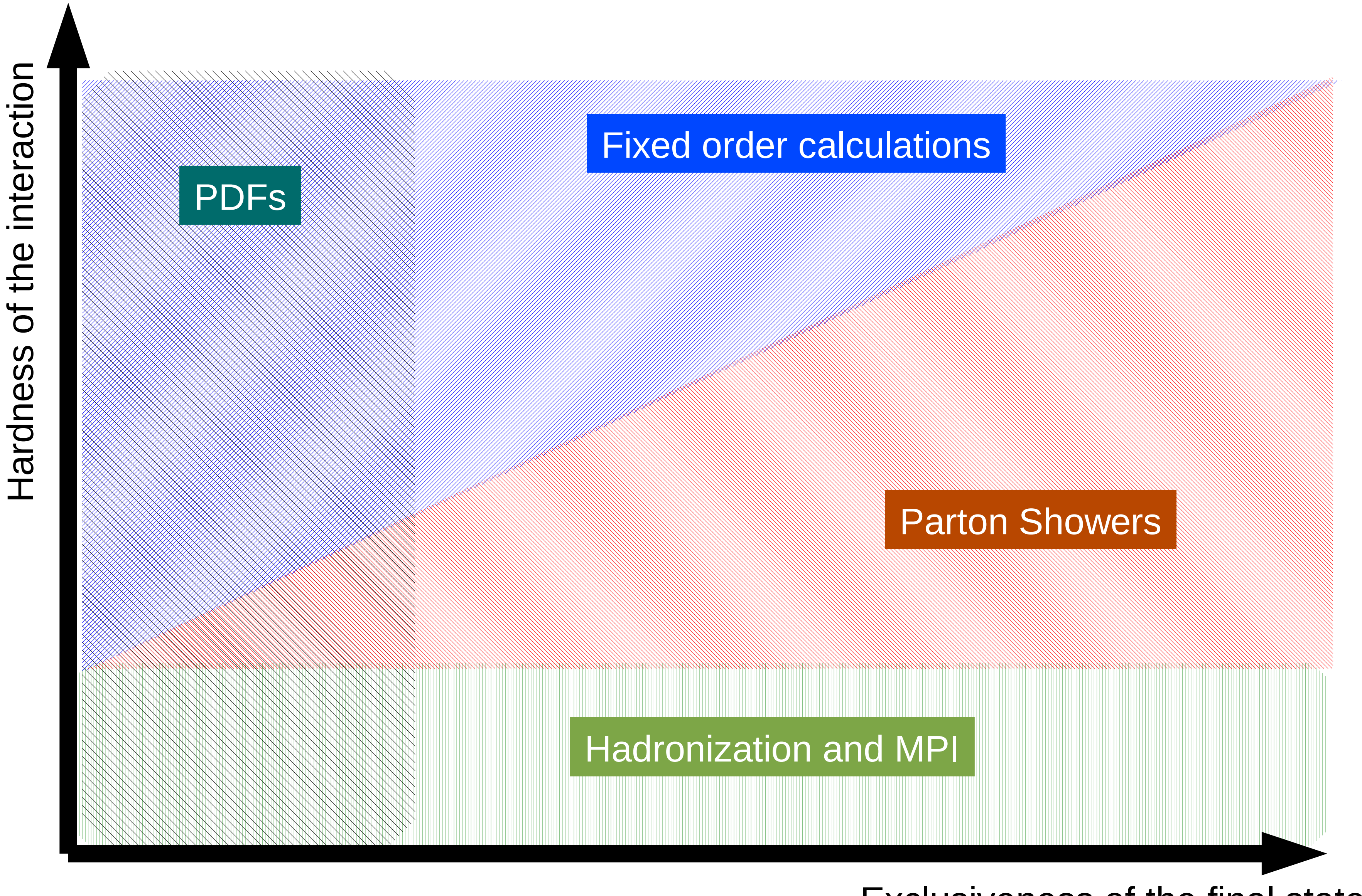
Photon and jet measurements at the LHC

Leonardo Carminati – INFN Milano
Piergiulio Lenzi – INFN Firenze

The landscape of QCD

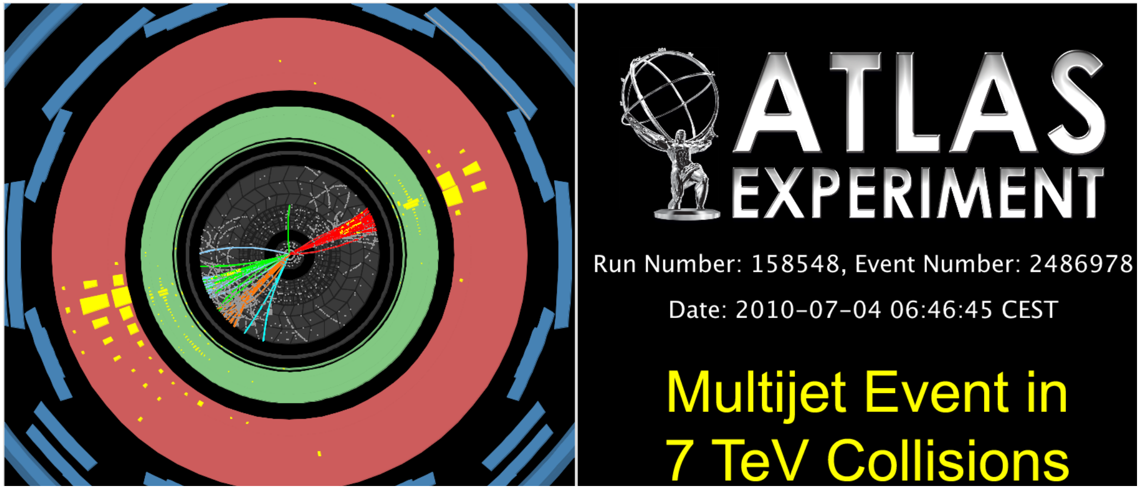


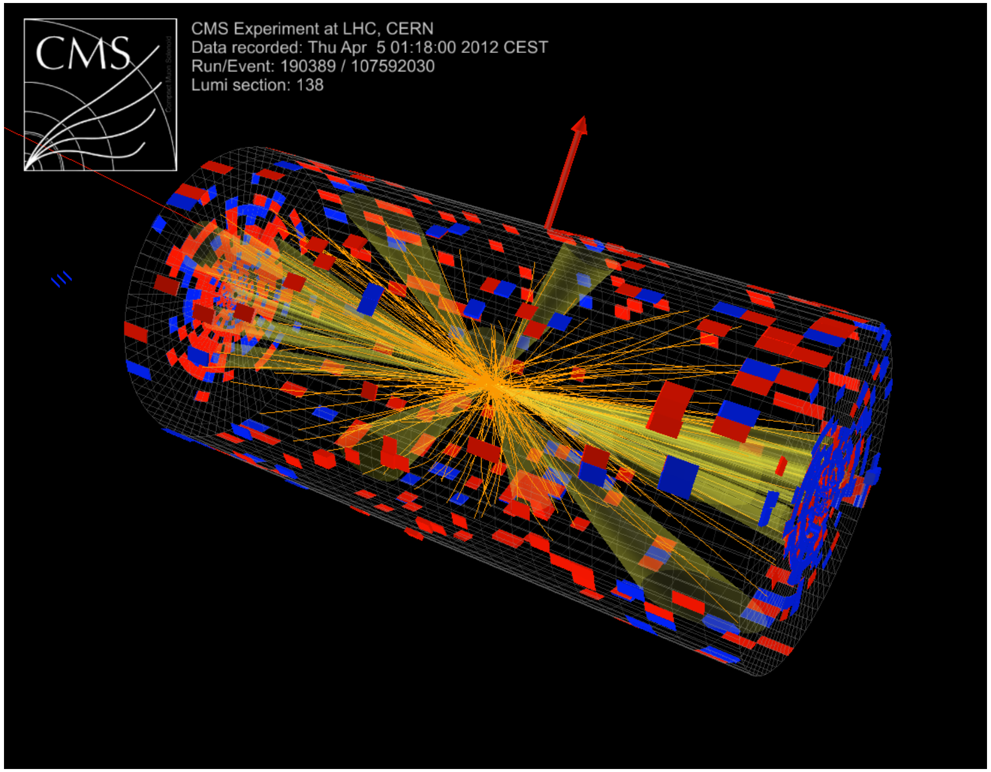
Theoretical predictions

- 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 (NLOJet++, Blackhat, JetPhox)
    - BFKL inspired models (HEJ)

Outline

- Inclusive jets
- Di-jets
- Forward jets
- Inclusive photons
- Photons+jets
- Di-photons

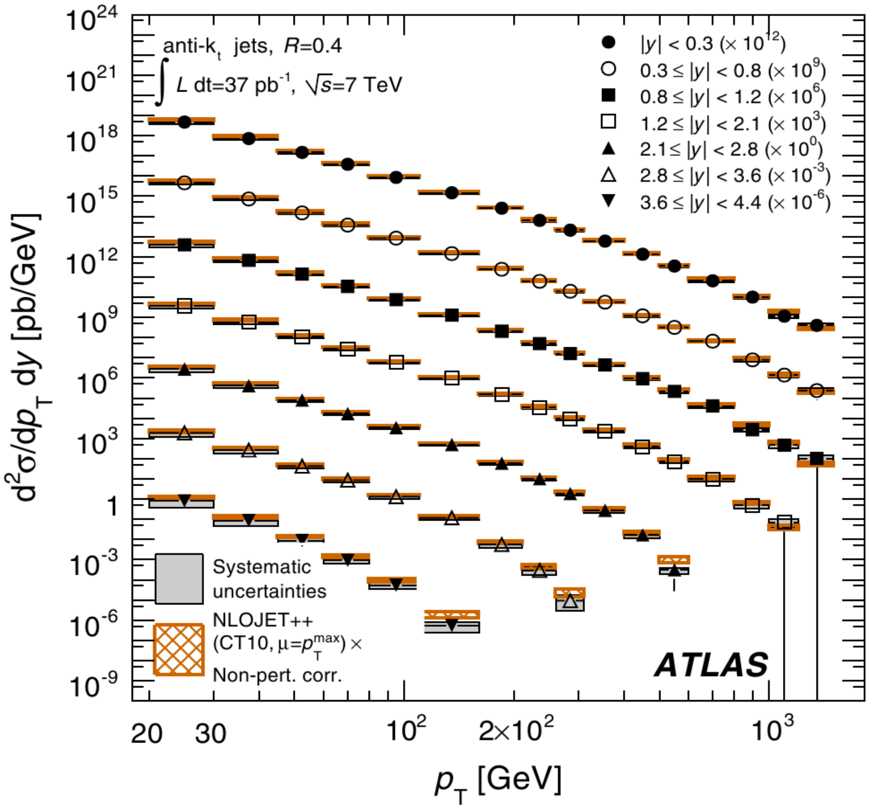


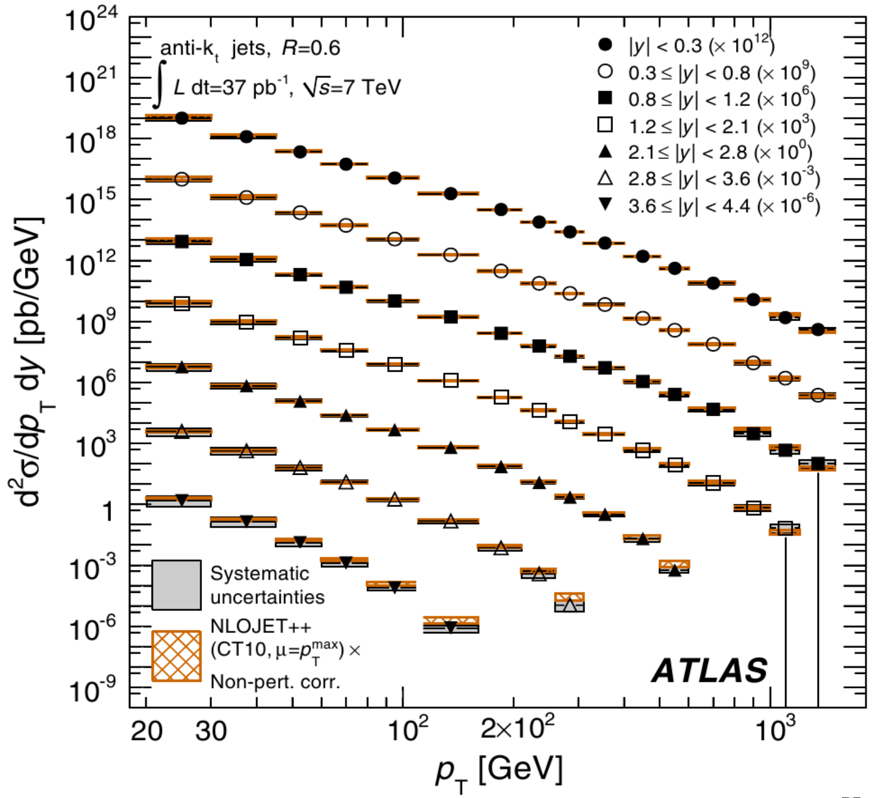


Inclusive jets

Phys. Rev. D 86, 014022 (2012)

- Measurement of inclusive jets for two jet sizes (antiKt)
  - Difference contribution of hadronization and UE corrections
    - At 30 GeV NP~60% for 0.6, NP~10% for 0.4
- Jet Energy Scale is the main source of systematic uncertainty
- Data are compared with the predictions at NLO, including non-perturbative (NP) corrections obtained with a shower MC



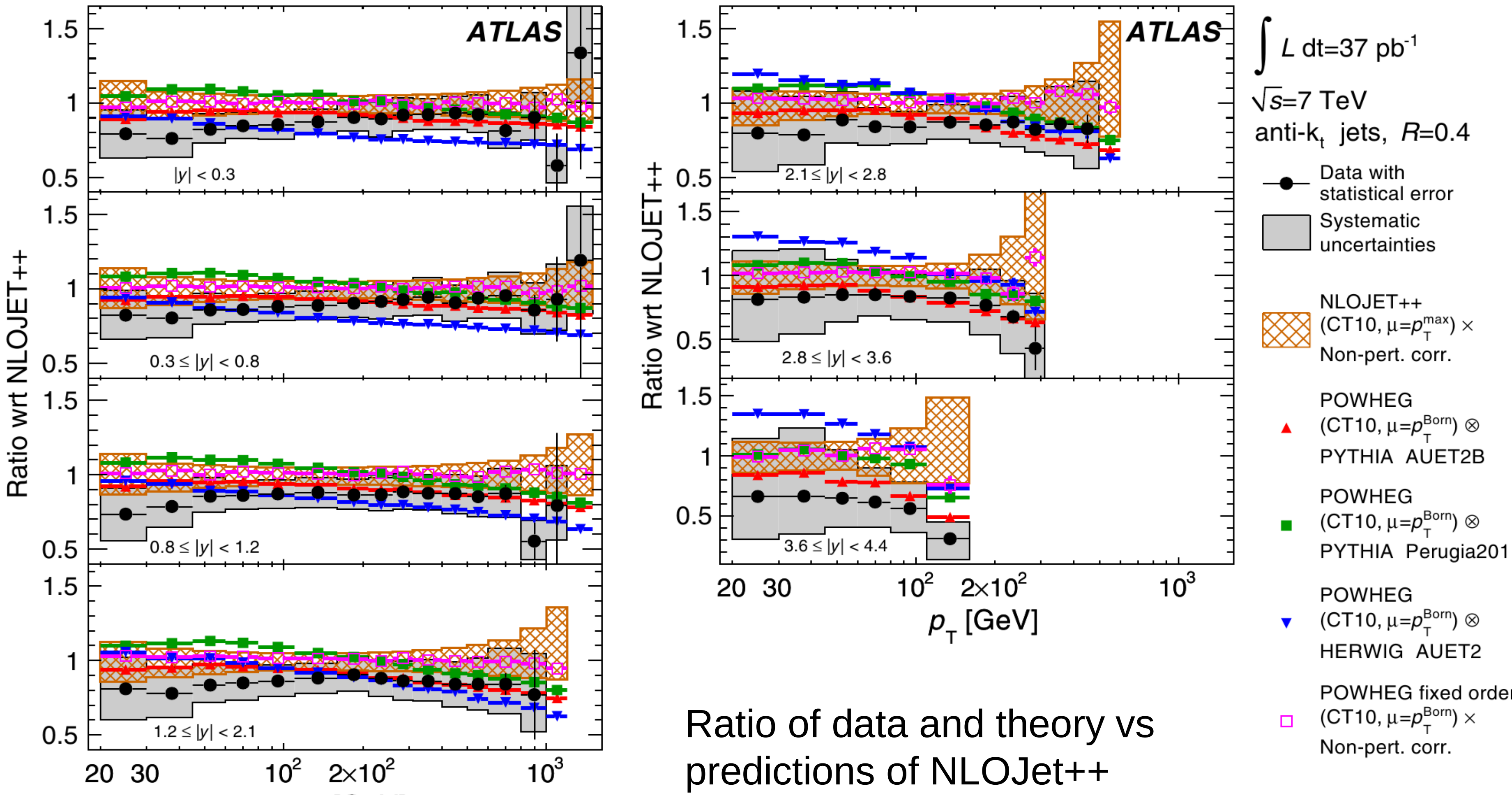


Inclusive jets

- Comparison with several MC generators
- General good agreement

Phys. Rev. D 86, 014022 (2012)

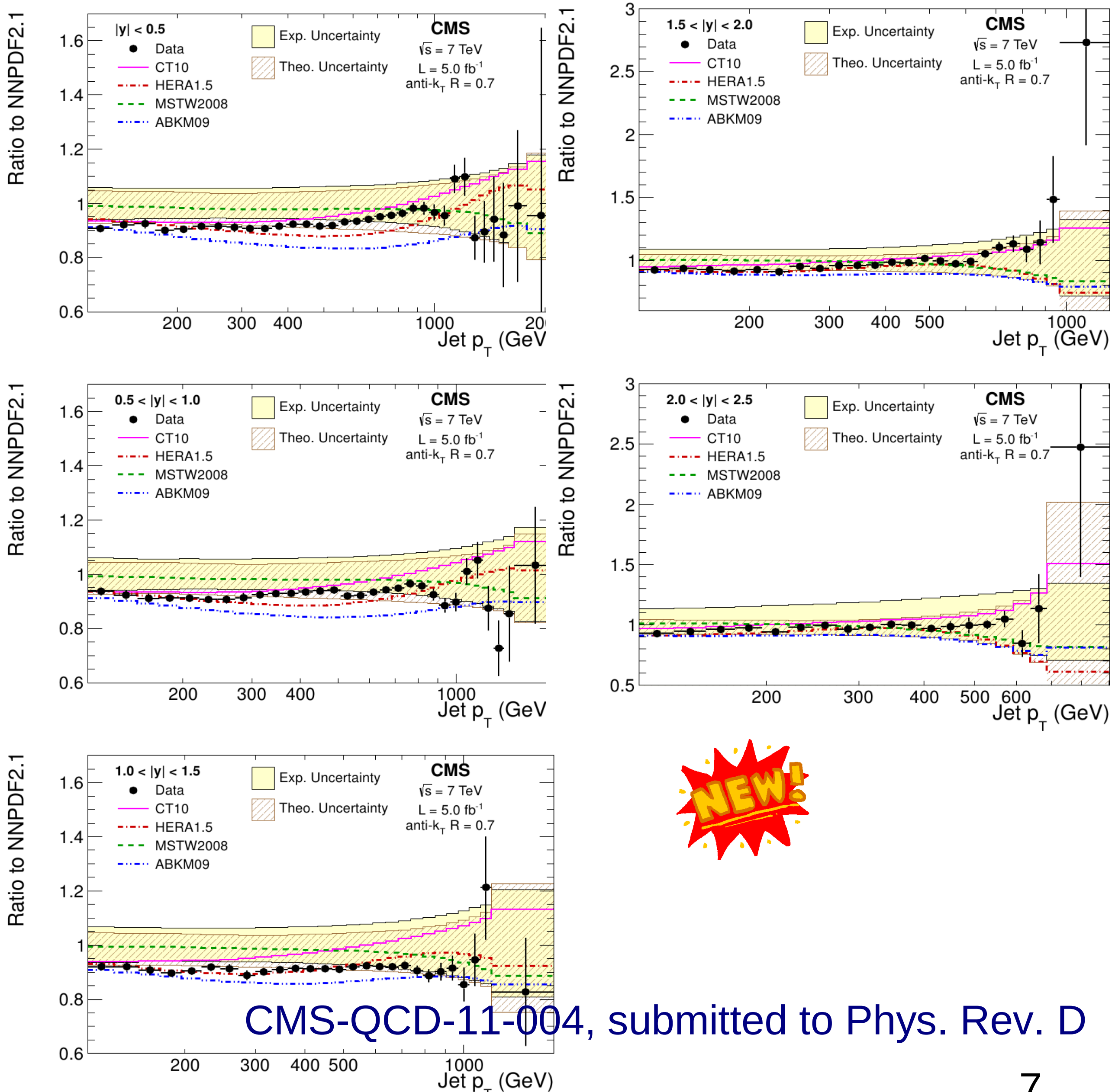
- POWHEG NLO dijet predictions show dependency on the shower used
    - Improved in newer versions



Ratio of data and theory vs predictions of NLOJet++

Inclusive jets

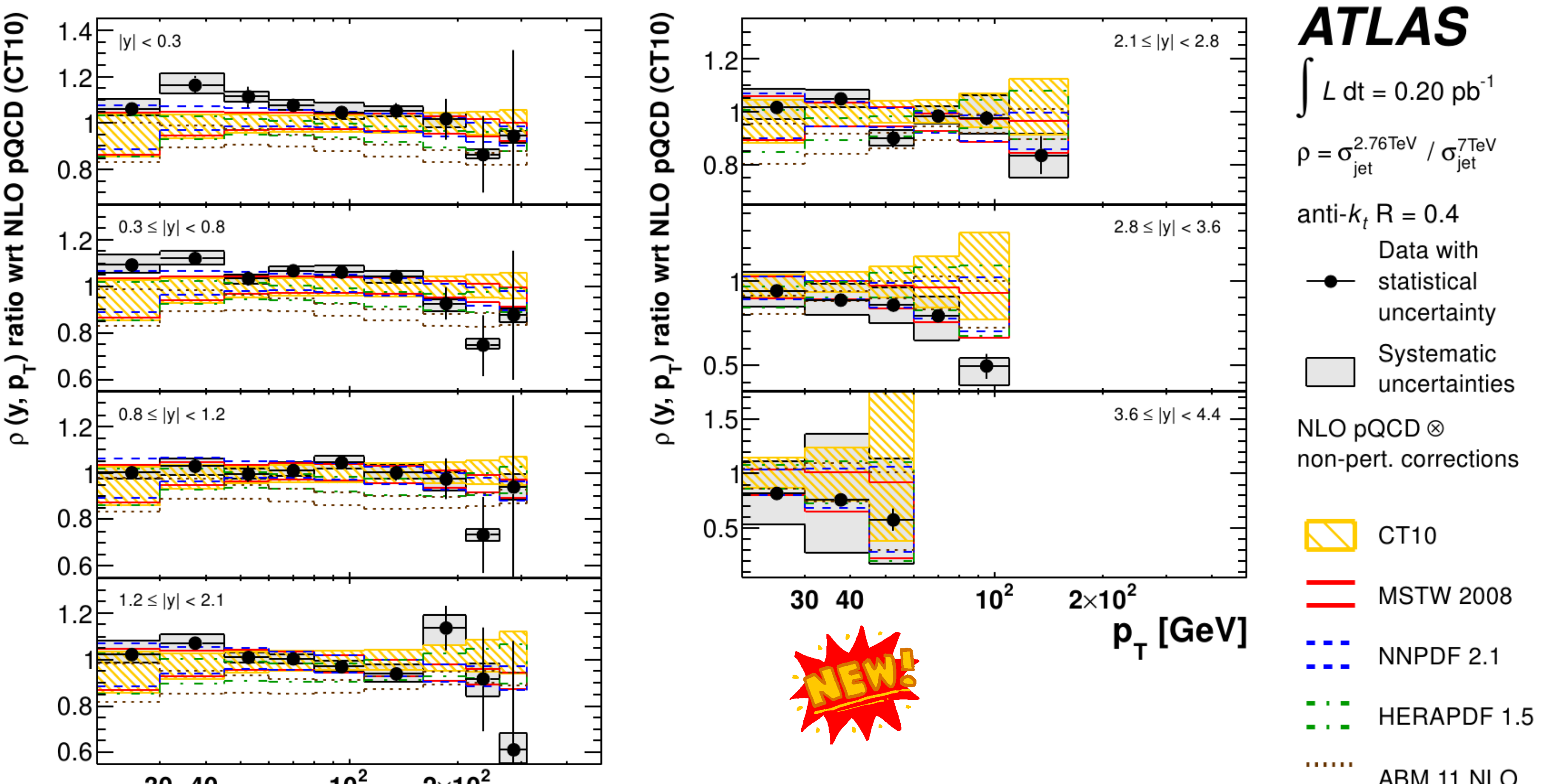
- Similar result from CMS with larger statistics highlighting the PDF sensitivity
- Particularly sensitive to high x gluon
- Comparison to the same PDFs fro ATLAS shows similar results



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

Inclusive jets

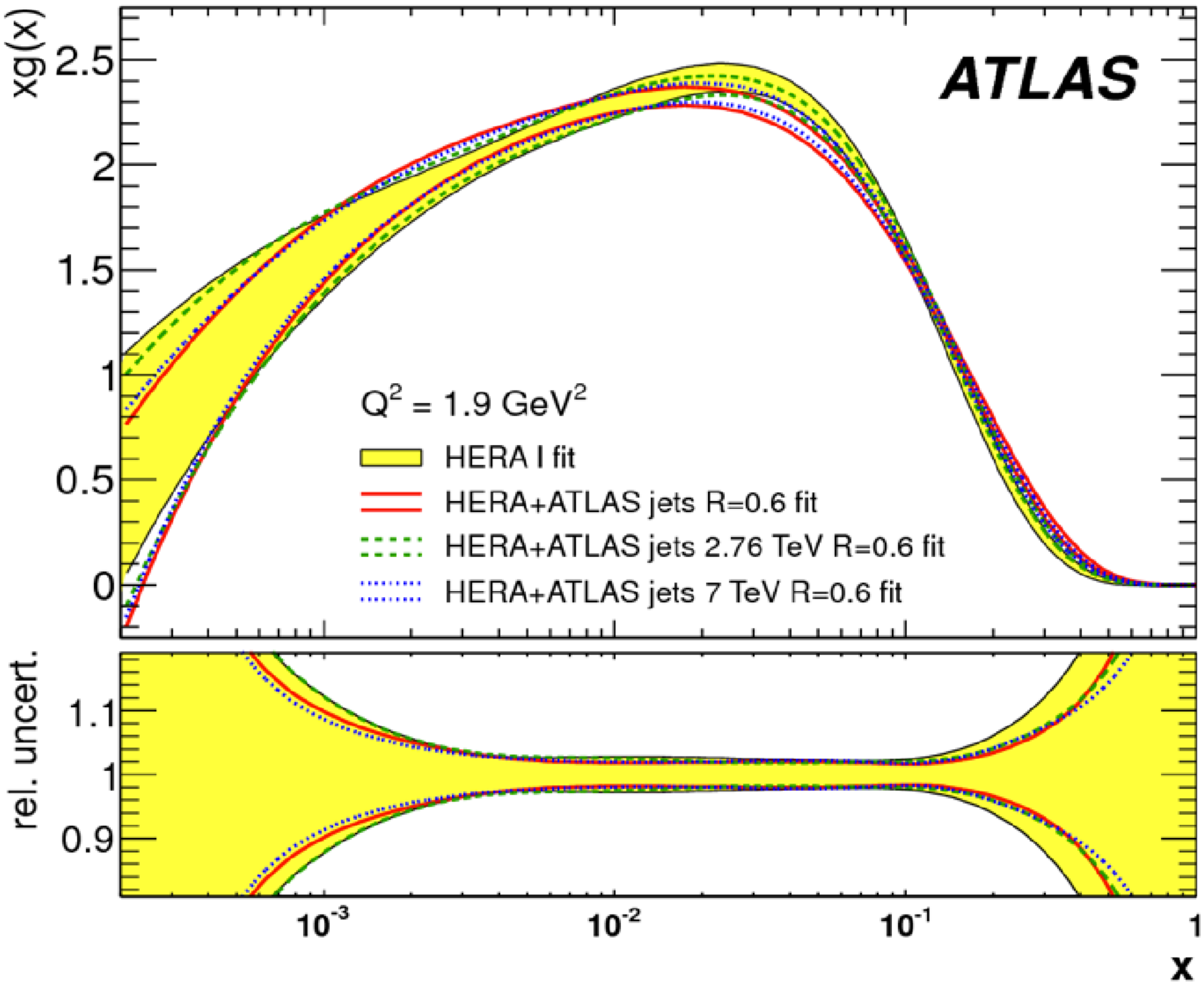
- Very interesting comparison between 7 TeV and 2.76 TeV
    - JES uncertainty cancel to large extent in the ratio
- Powheg is slightly below the data in the central region while the agreement is very good in the forward region



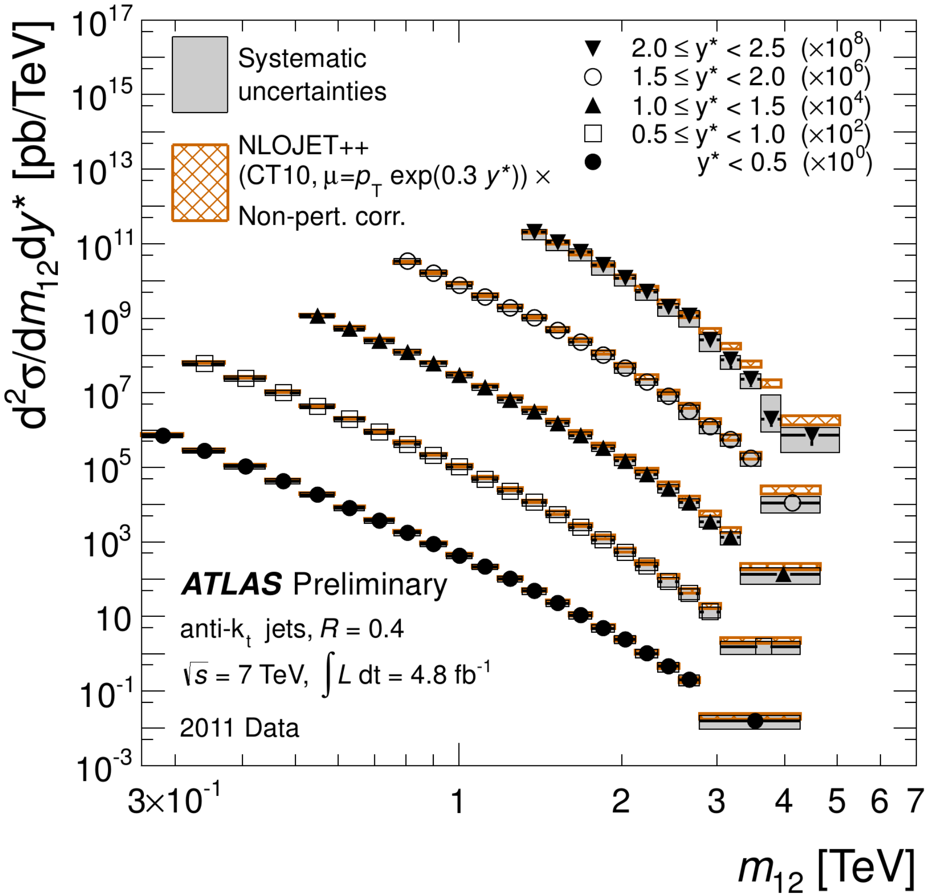
p_T [GeV] CERN-PH-EP-2013-036, Submitted to Eur. Phys. J. C

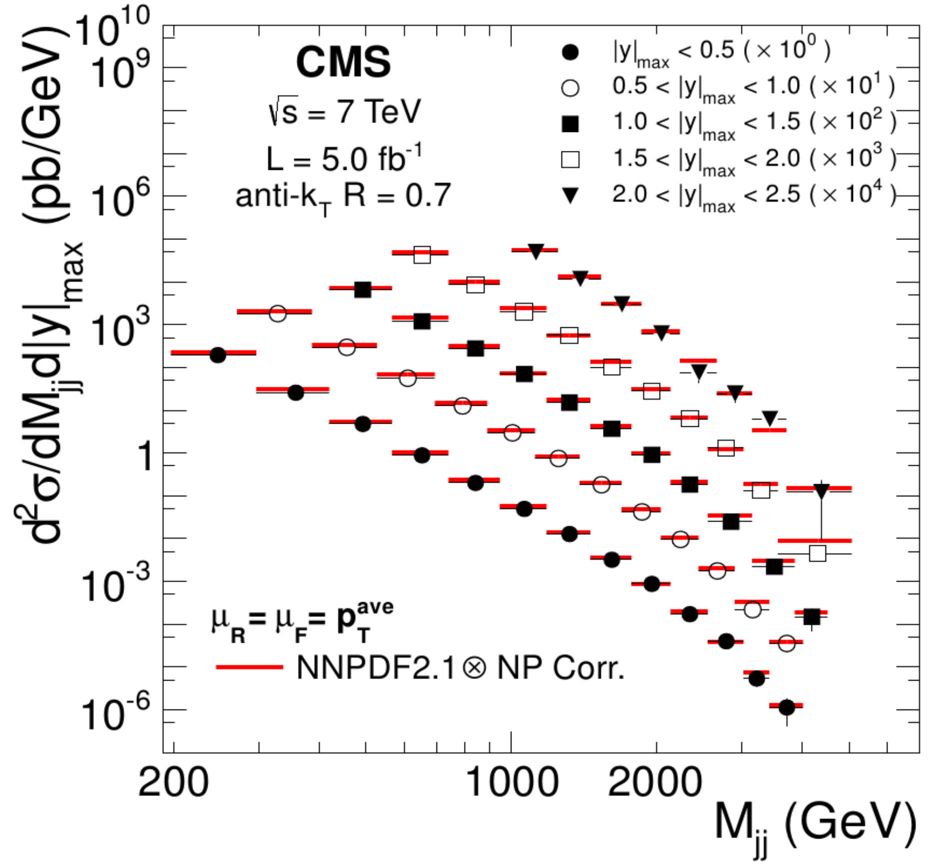
Inclusive jets

- This ratio had constraining power for PDFs
- Gluon becomes harder and the uncertainty gets smaller



Di-jet mass





ATLAS-CONF-2012-021

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

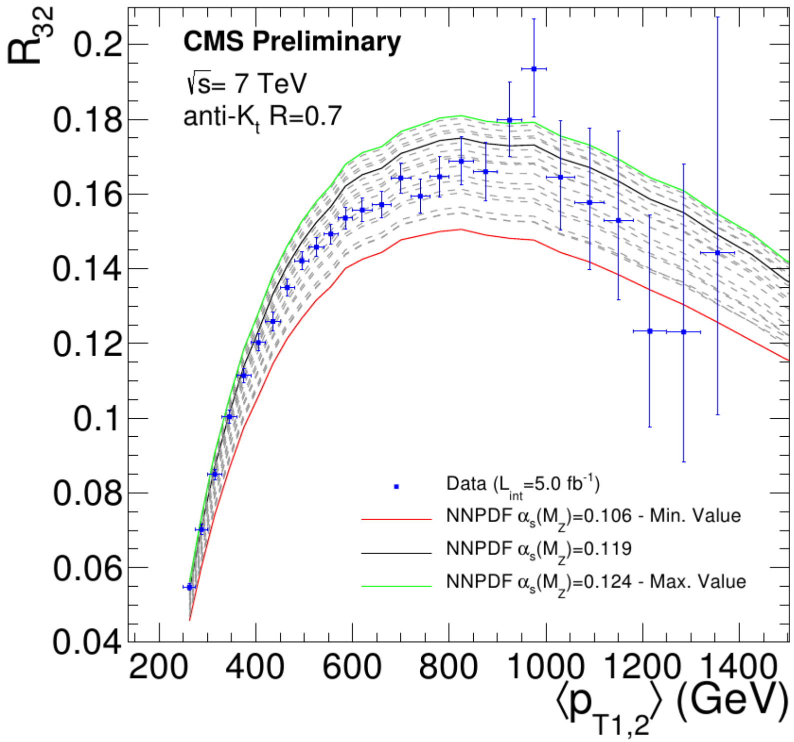
3-jets over 2-jets ratio

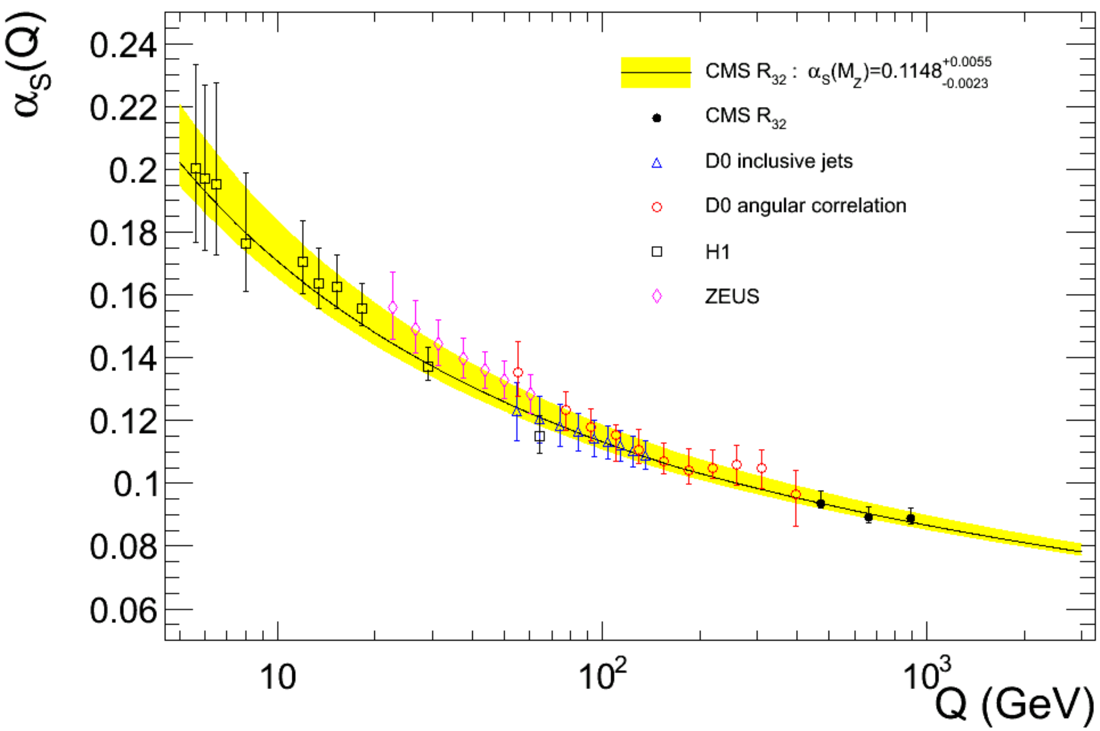
- Measurement of the ratio of events with 3 or more jets over events with 2 or more jets, as a function of average pt of the di-jet system
  - Jets: pT > 150 GeV, $|y|<2.5$

CMS-QCD-11-003

NEW!

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

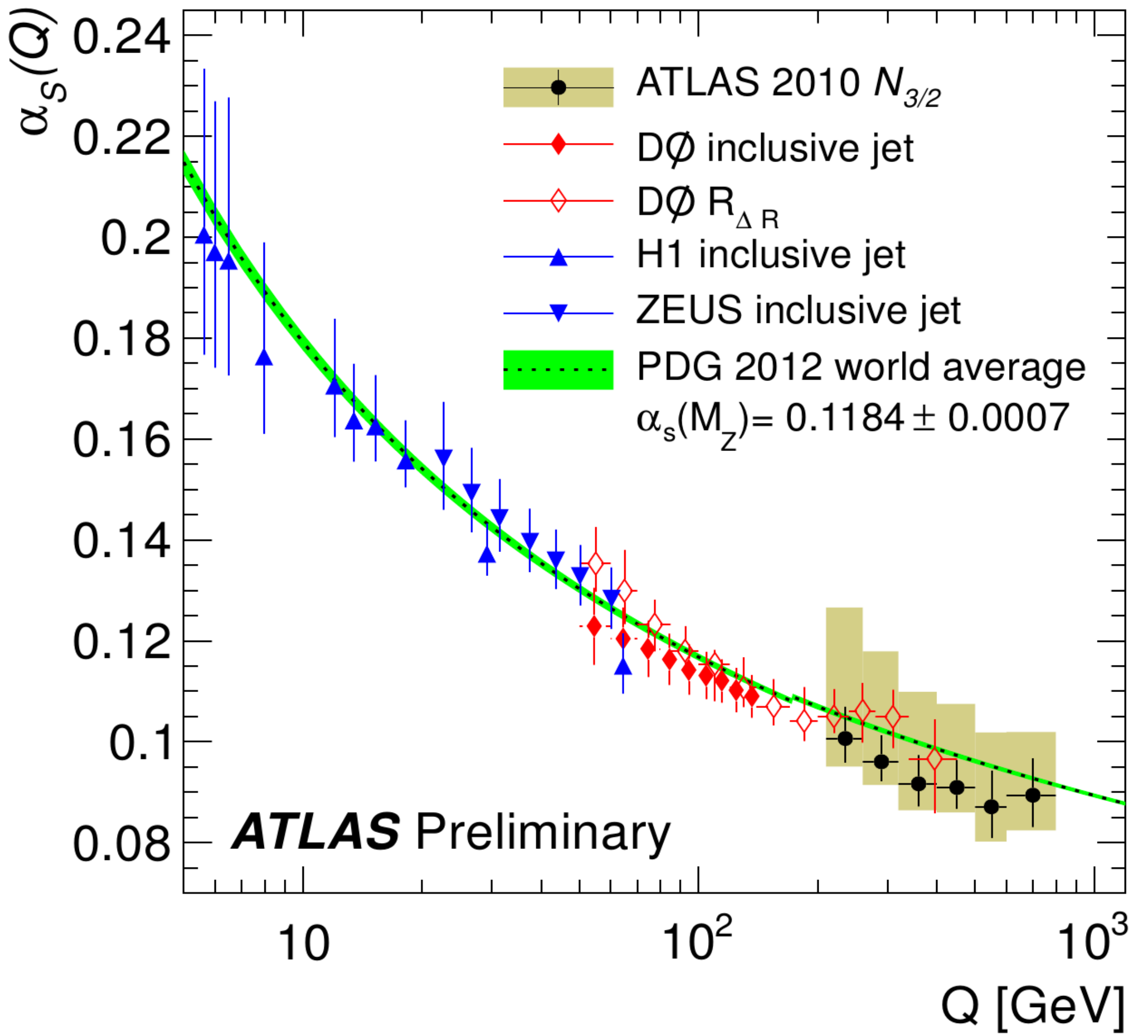




$\alpha_s(MZ) = 0.1148 \pm 0.0014\ (\text{exp.}) \pm 0.0018\ (\text{PDF})\ ^{+0.0050}_{-0.0000}\ (\text{scale})$

3-jets over 2-jets ratio

- Similar result from ATLAS
- Using a smaller sample, with lower jet pT threshold
  - Leading jet pT > 60GeV
  - All jets pT > 40 GeV
- The observable is also slightly different:
  - This is the ratio between the inclusive pT spectrum for events with 3 jets divided by the inclusive spectrum for events with 2 jets
    - i.e. more than 1 entry per event



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

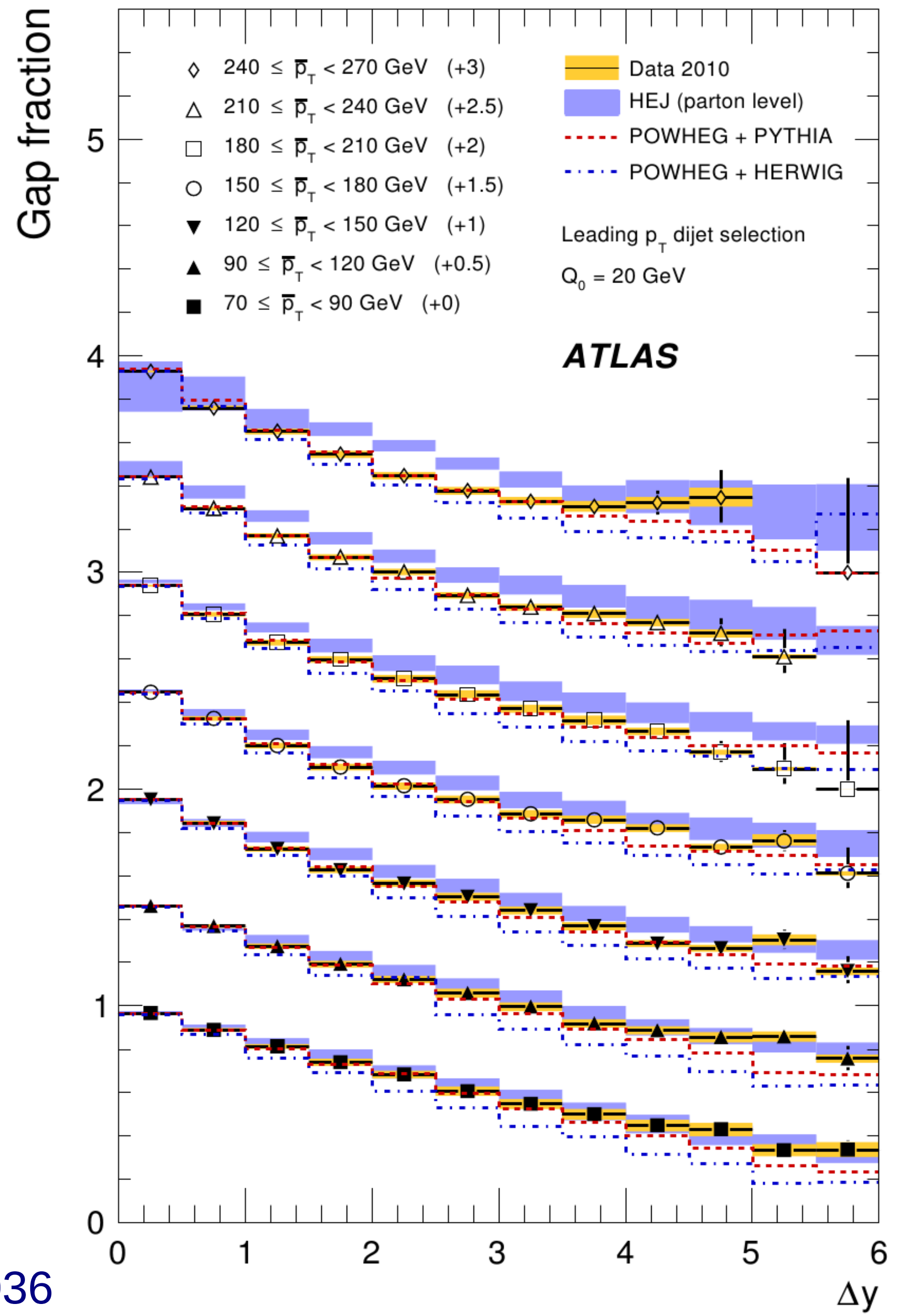
- ATLAS studied di-jet events as a function of the activity between them

  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

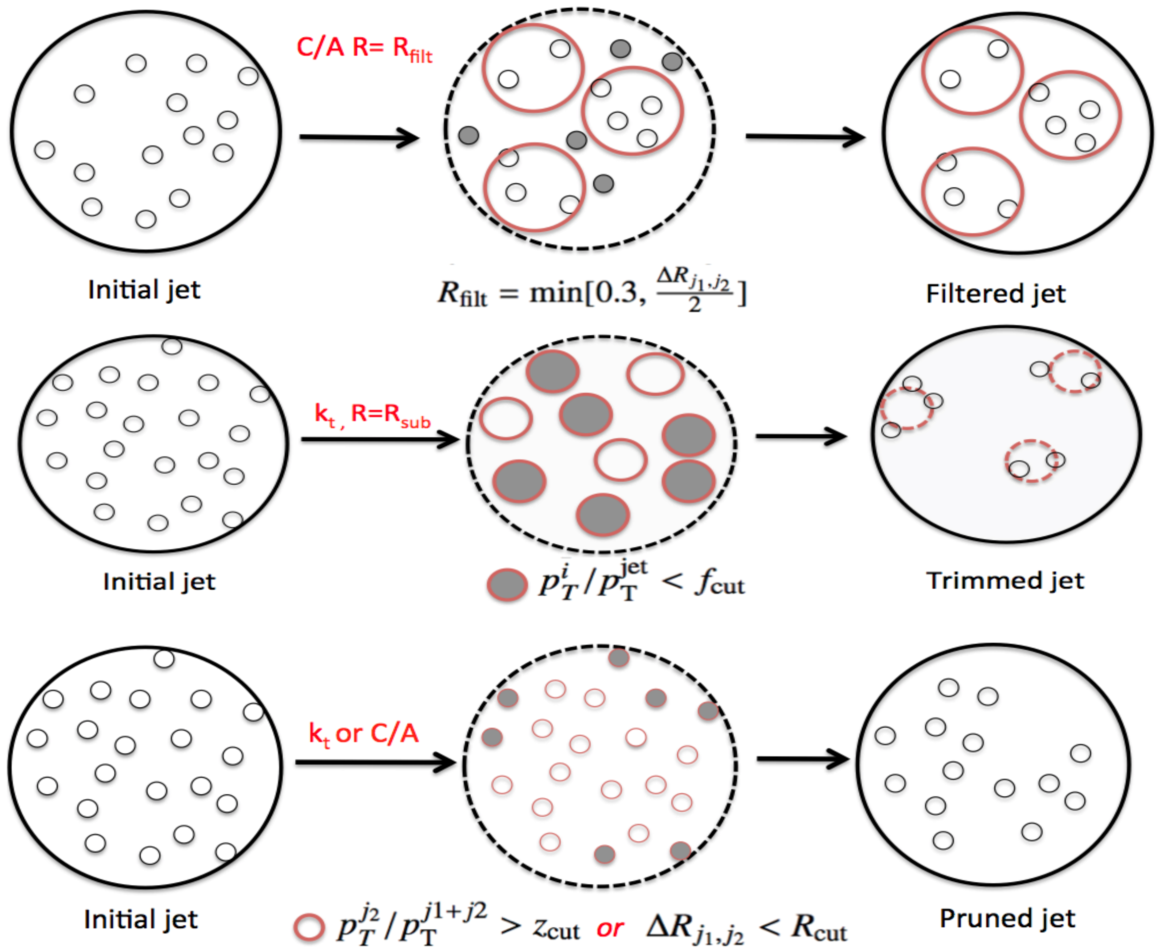
JHEP06(2012)036



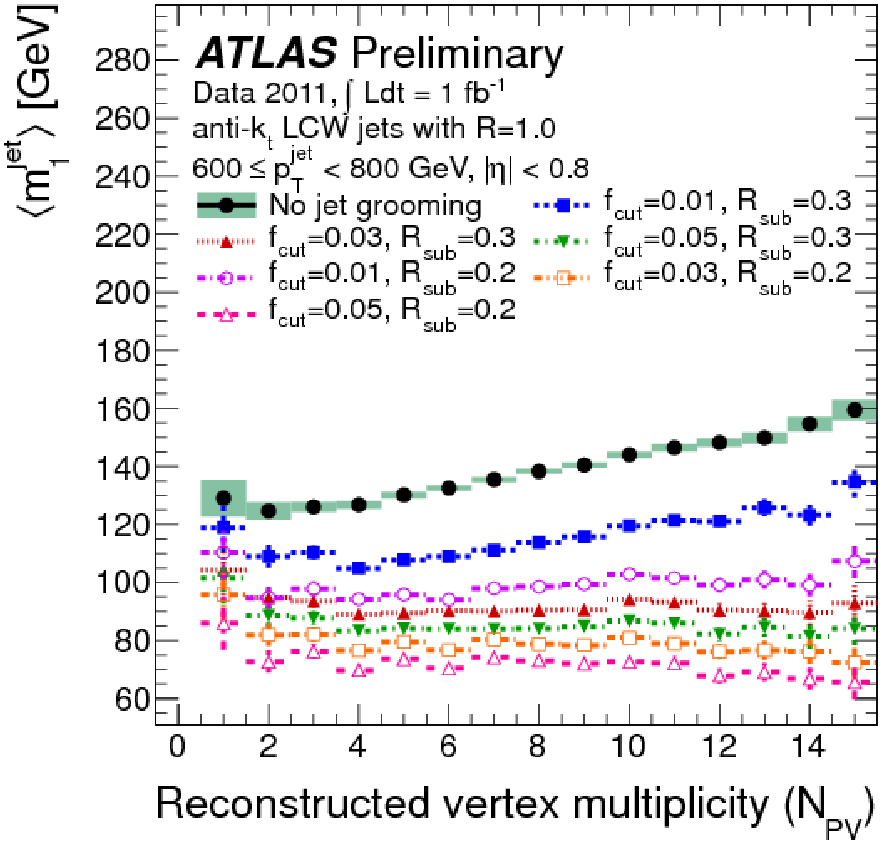
Jet substructure

- Study of jet mass via jet-substructure resolution techniques
- Three techniques studied, that are aimed at resolving boosted objects decays
  - Jet Filtering:
  - Jet Trimming:

  J
  - Jet Pruning:

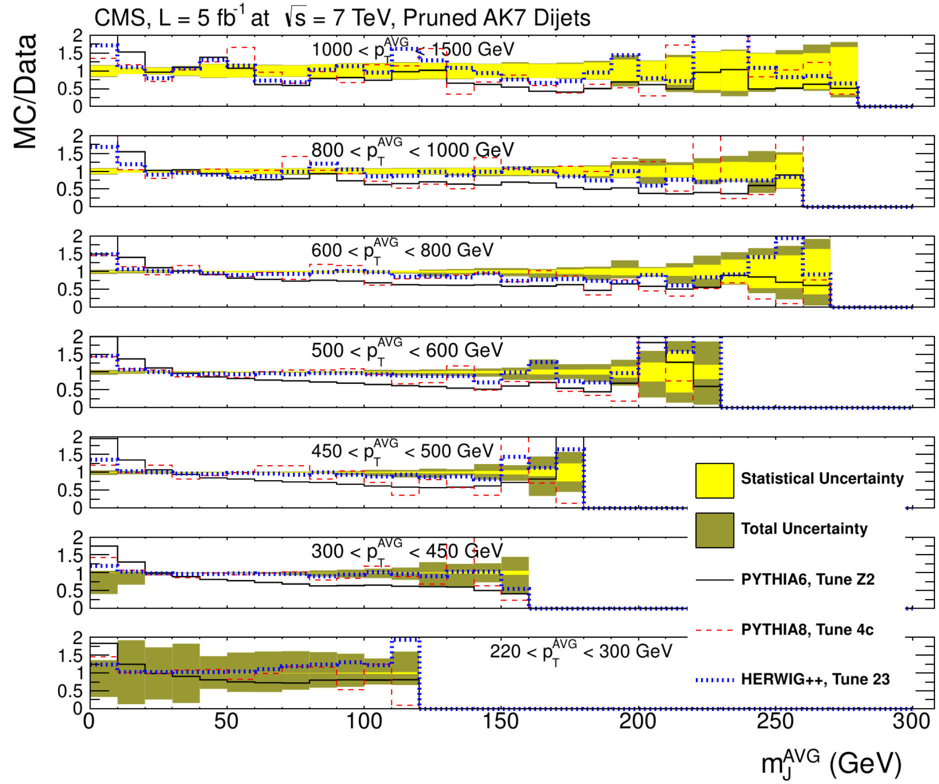


- Relevant because they probe the accuracy of the shower



- Effect of reduction of PU dependence

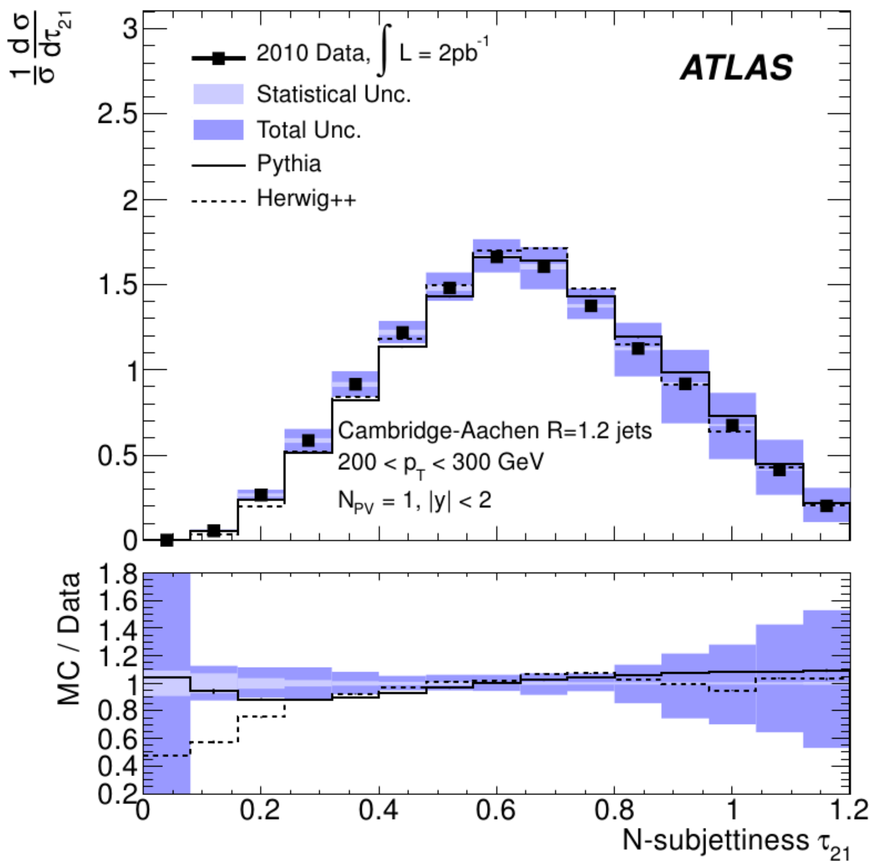
ATLAS-CONF-2012-066

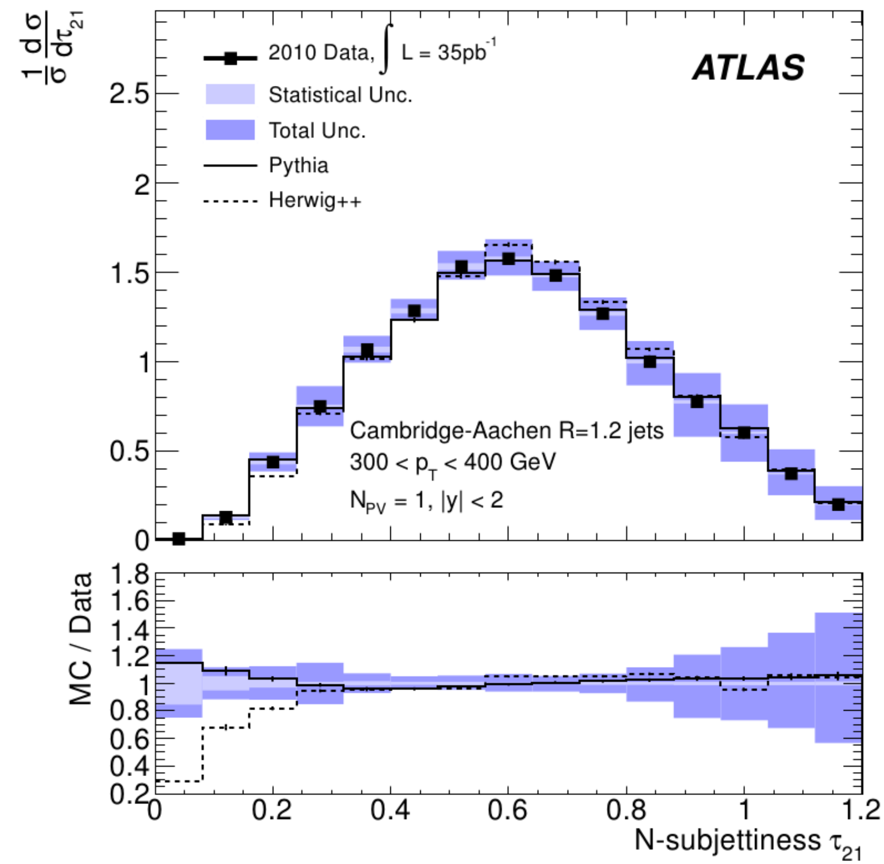


- Measurement of jet shapes in di-jet events
- Herwig++ shows nice agreement with the data, especially for jet pT above 300 GeV
- The agreement is worse for softer jets

CMS-SMP-12-019

- Other substructure variables
  - N-subjettiness: a measure of how much a jet looks like made of N sub-jets
    - Constituents are reconstructed with kT algorithm forcing N jets
- MC tools are able to give nice description of jet substructure

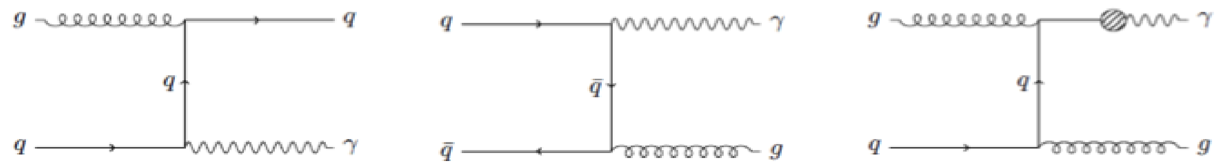




JHEP05(2012)128

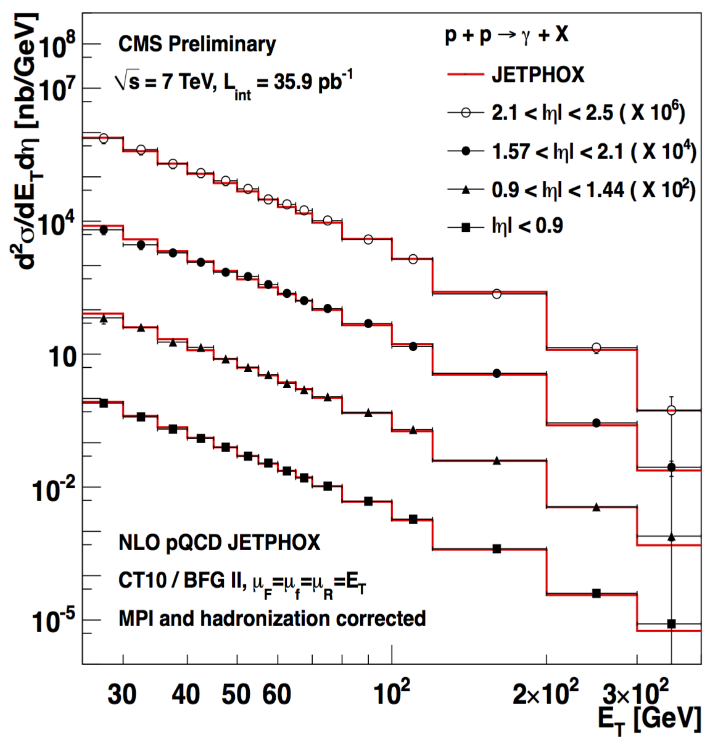
Inclusive photons

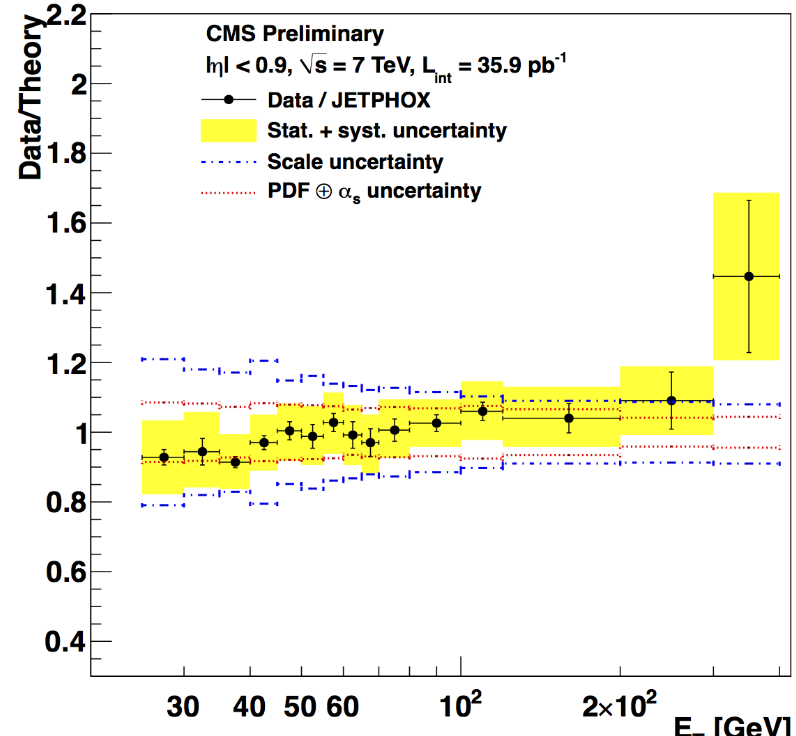
- Test of QCD predictions with colorless (clean !) final state
- Large compton scattering contribution probes gluon PDF
- Measurement extracted from fit to the photon isolation or using converted photons
- Main systematics
  - Background shape
  - Photon Id



Compton Scattering   Annihilation   Fragmentation

Phys. Rev. D 85(2012)

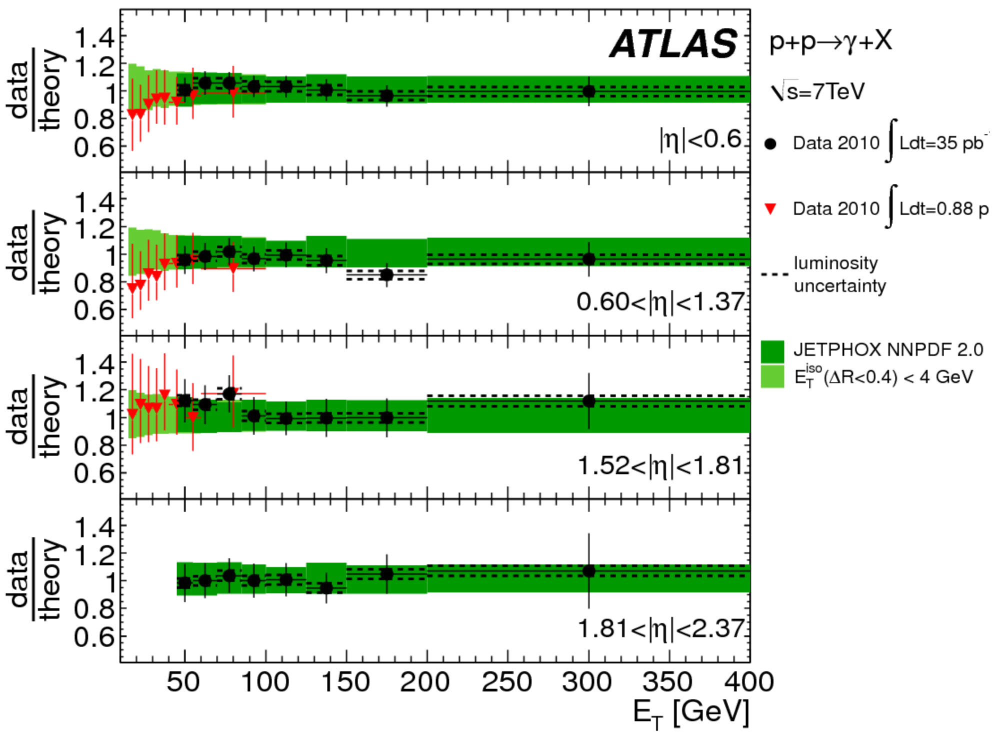




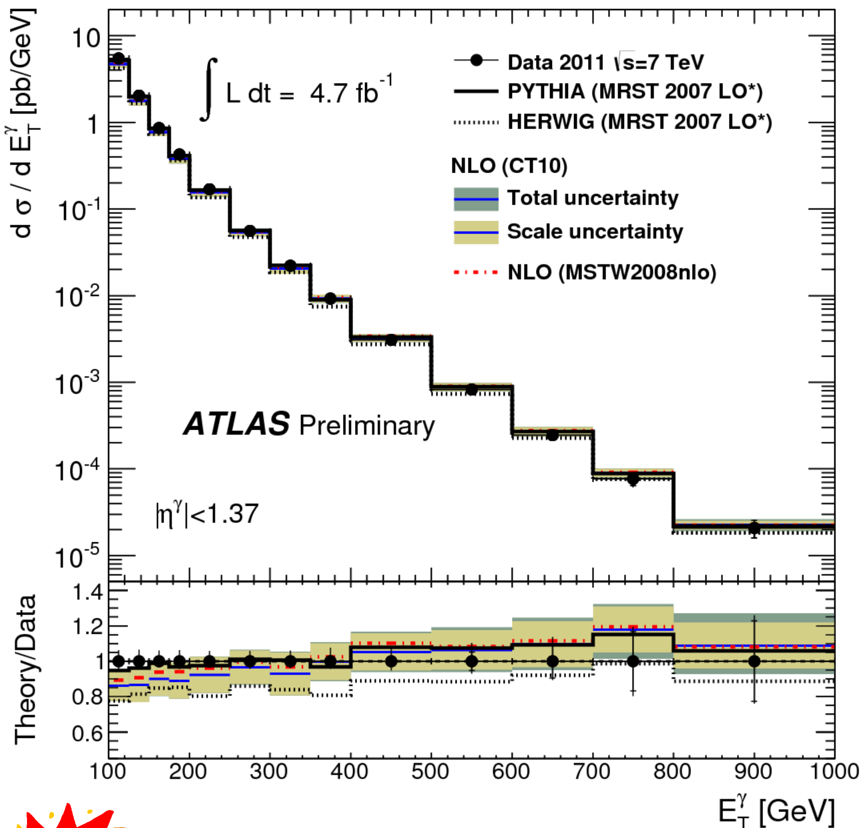
Phys. Rev. D 84, 052011 (2011)

Inclusive photons

- Measurement of inclusive photon production extended up to 1 TeV
- Slight underestimation of the cross section by the NLO calculation at low pT



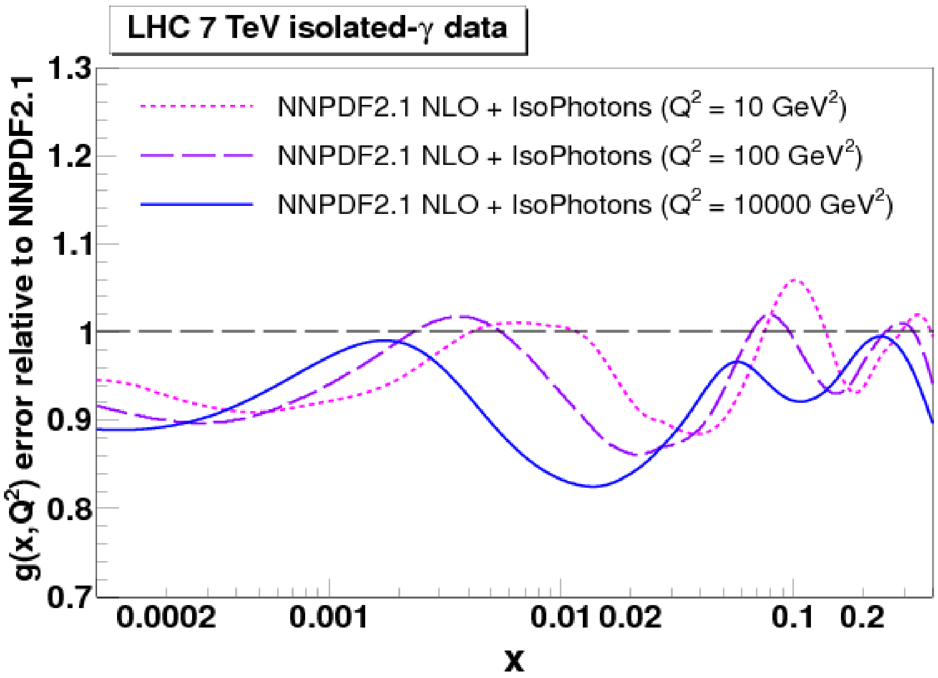
ATL-PHYS-PUB-2011-013

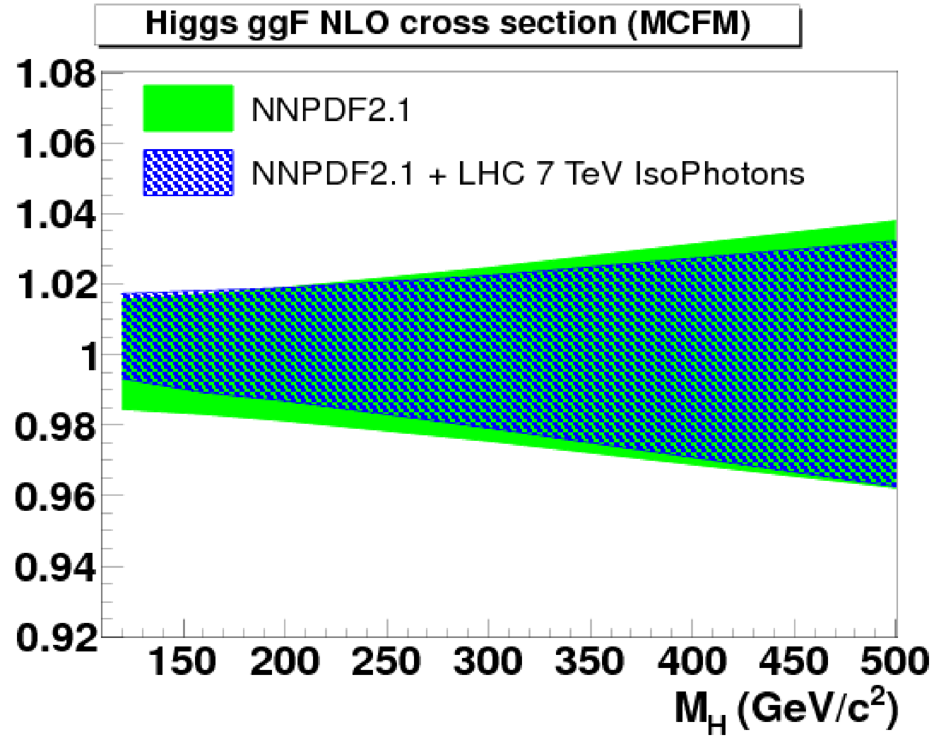


NEW! ATLAS-CONF-2013-022

Inclusive photons

- New LHC data (with RHIC, Tevatron...) can be used to reduce the uncertainty on the gluon PDF.
- This turns out in a potential reduction of one of the main source of theoretical uncertainty in many LHC analyses



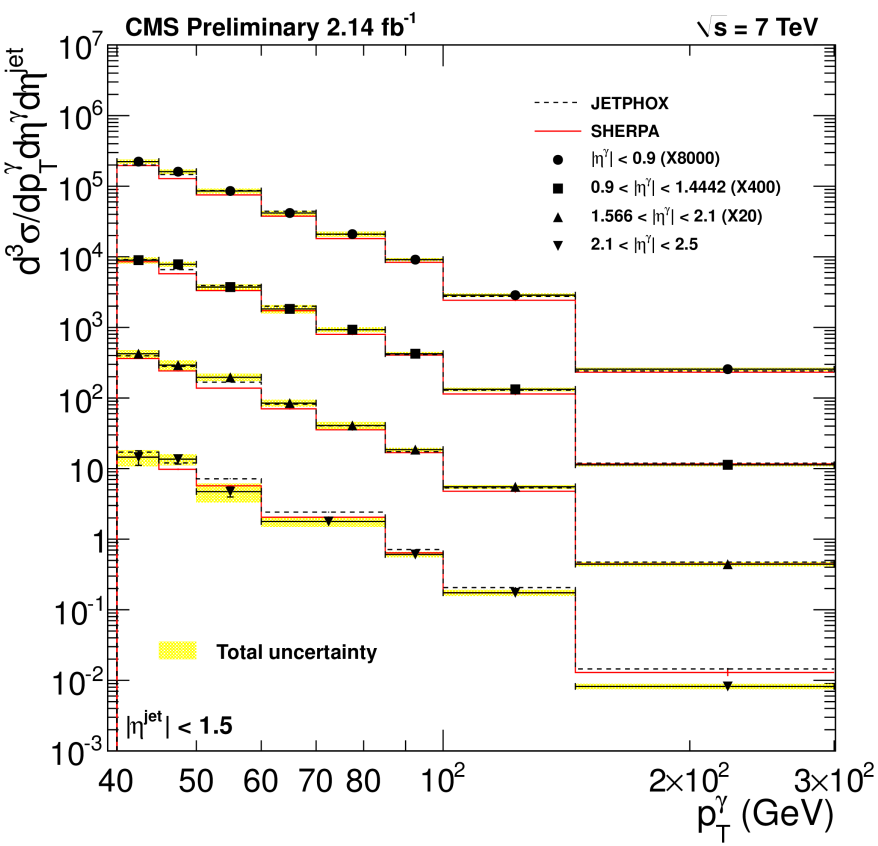


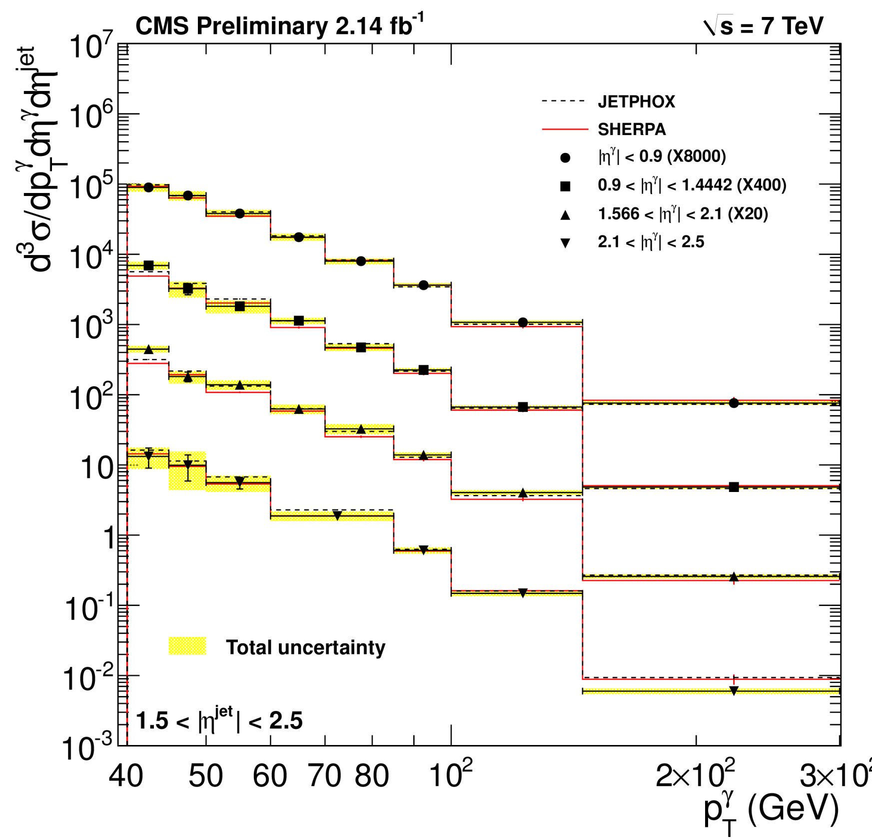
D'Enterria et. al. Nucl. Phys. B860(2012)

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

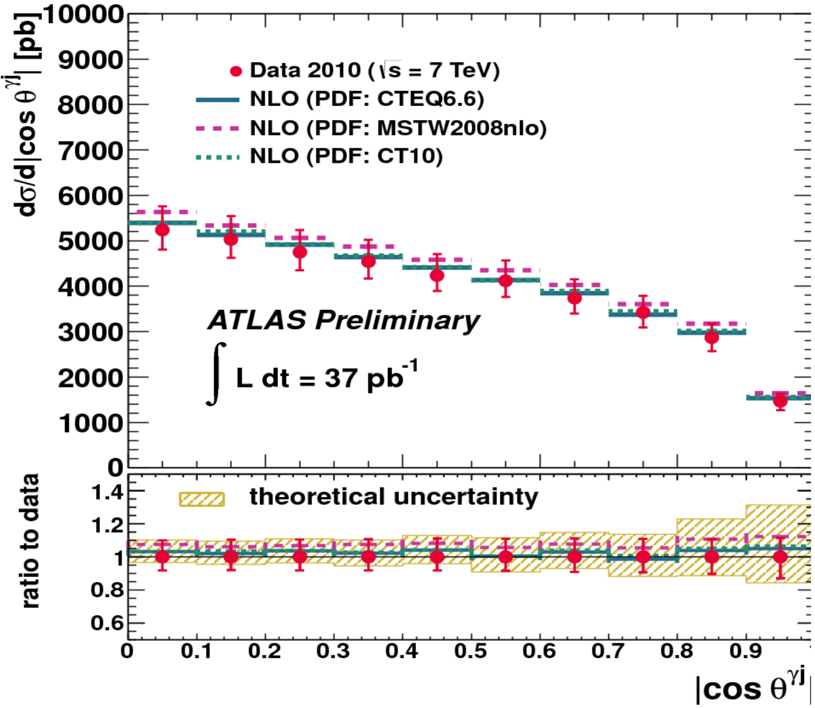


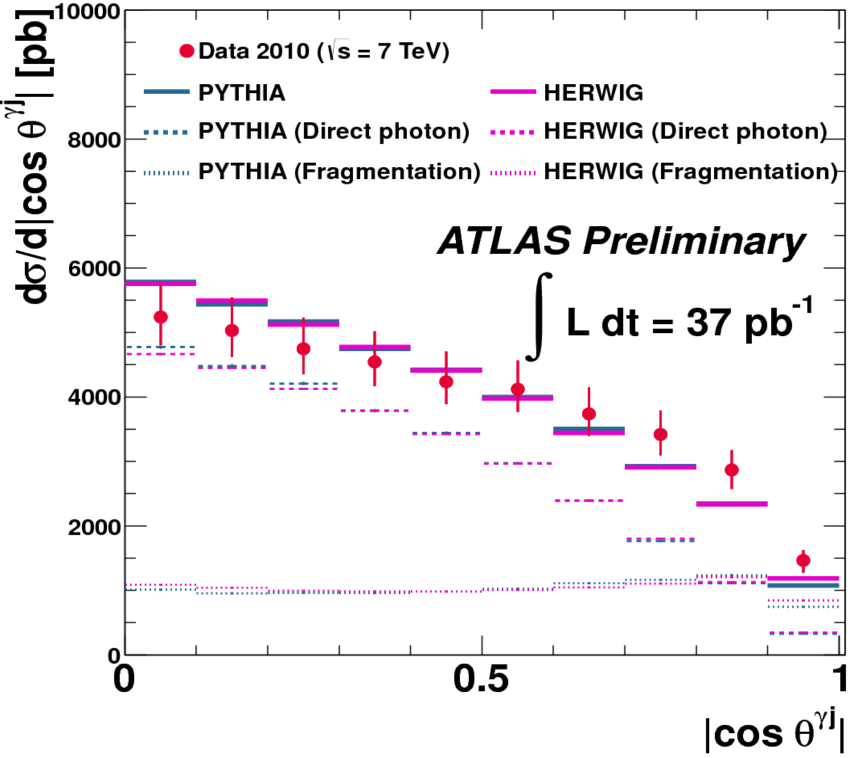


Photon + jets

- 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 or $m\gamma\varphi$
- Shower MC can get the right differential shape with tuning of the two contributions

ATLAS-CONF-2013-023

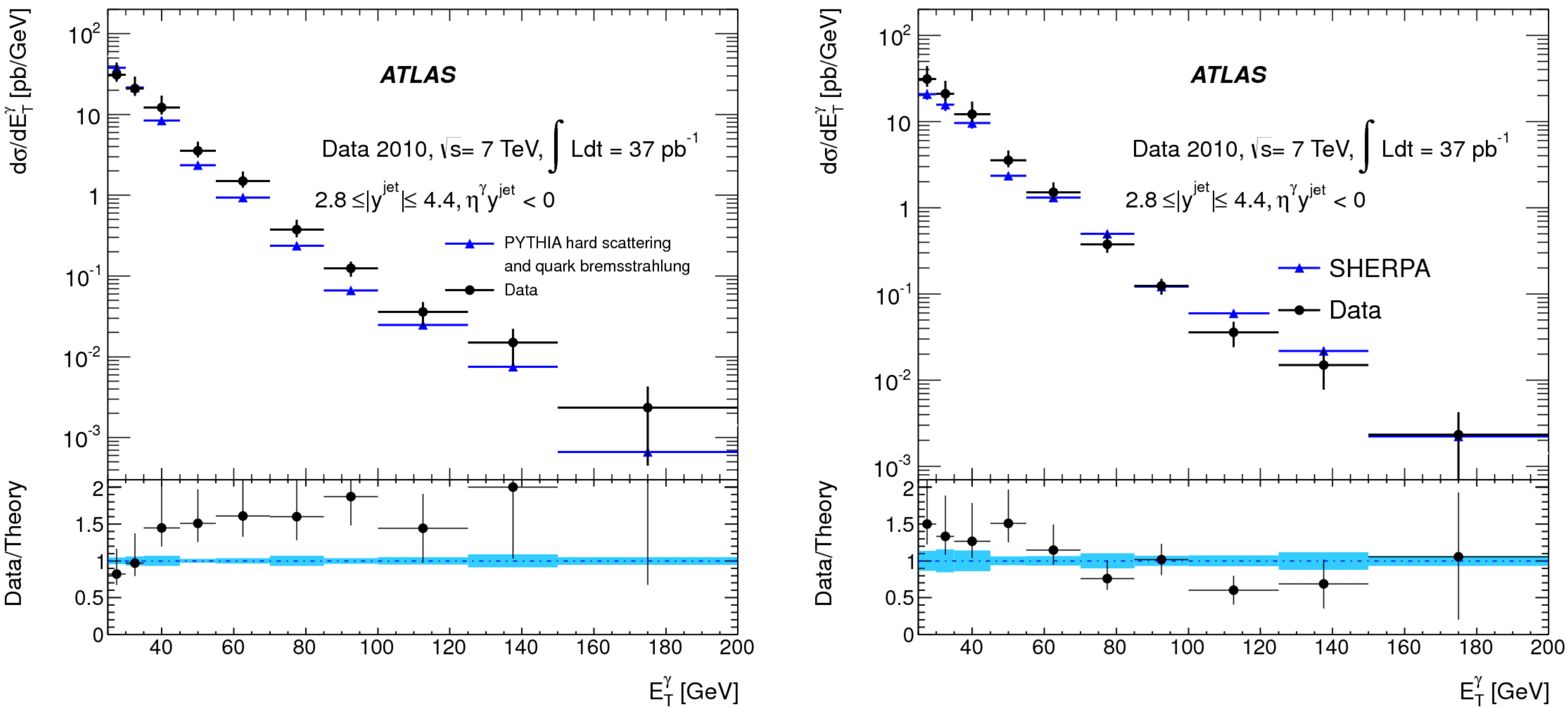




Photon + jets

- Effects of fragmentation are also put into evidence by requiring the jet and the photon to have opposite rapidity signs

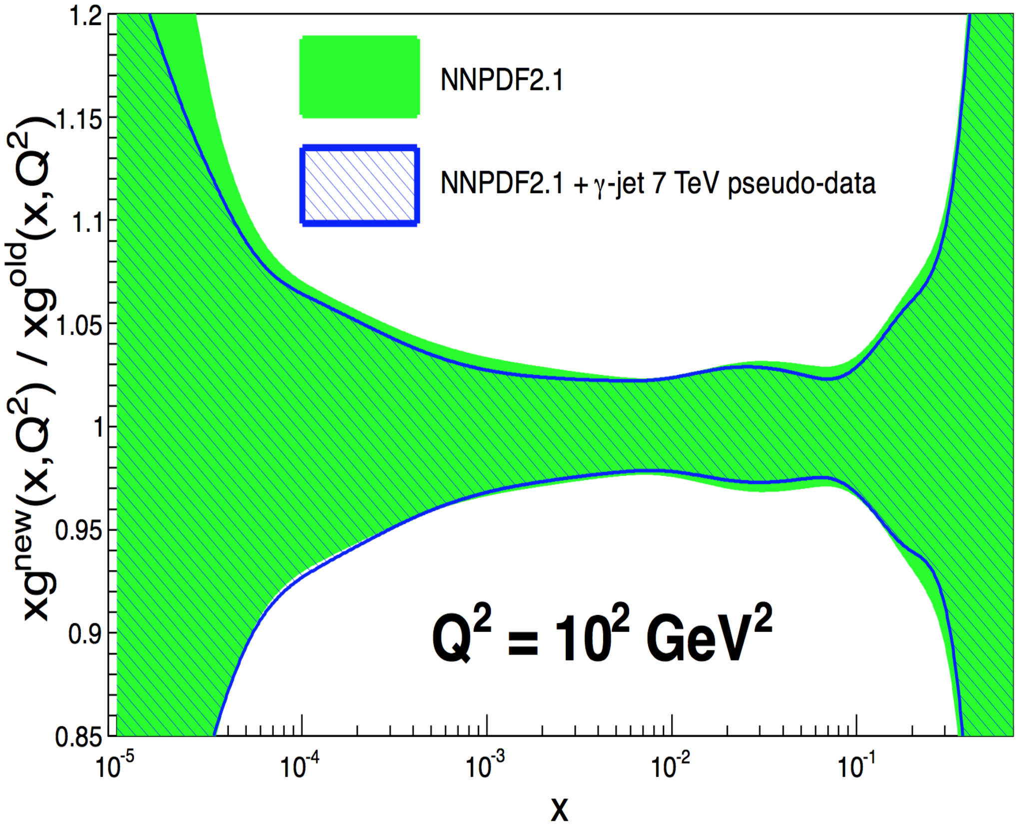
Phys. Rev. D 85(2012)



photon+jet

- The effect of including ATLAS photon+jet data in the PDF fit is negligible due to the large uncertainties on jet energy scale
- An exercise assuming half the current uncertainty shows a potential of further reduce the gluon PDF uncertainty

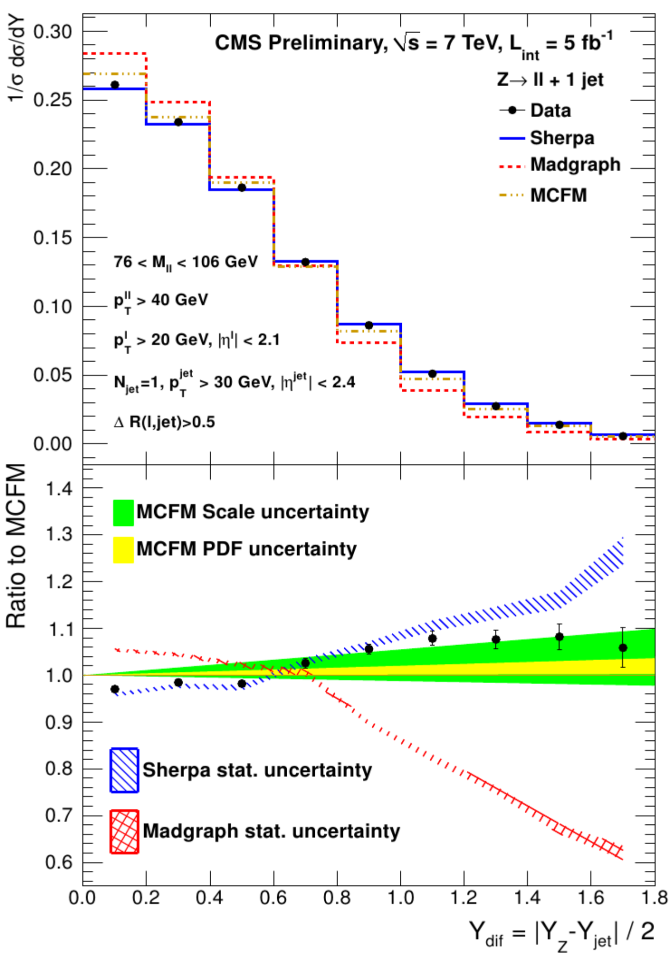
EPL 101(2013) 61002

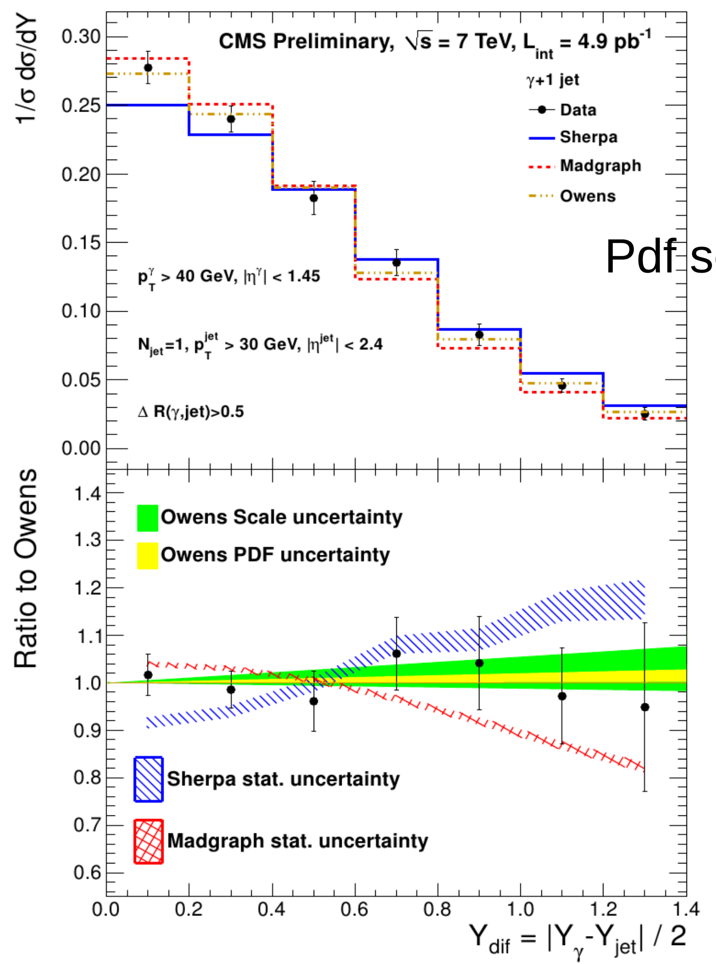


Photon + jets

CMS-SMP-12-004

- Rapidity measurements in Z or γ + jet
  - In case of γ, probes very similar physics as ATLAS $\theta^{\gamma j}$
- Significant differences between Sherpa and Madgraph
  - maybe due to the different matrix element-parton shower matching prescription?





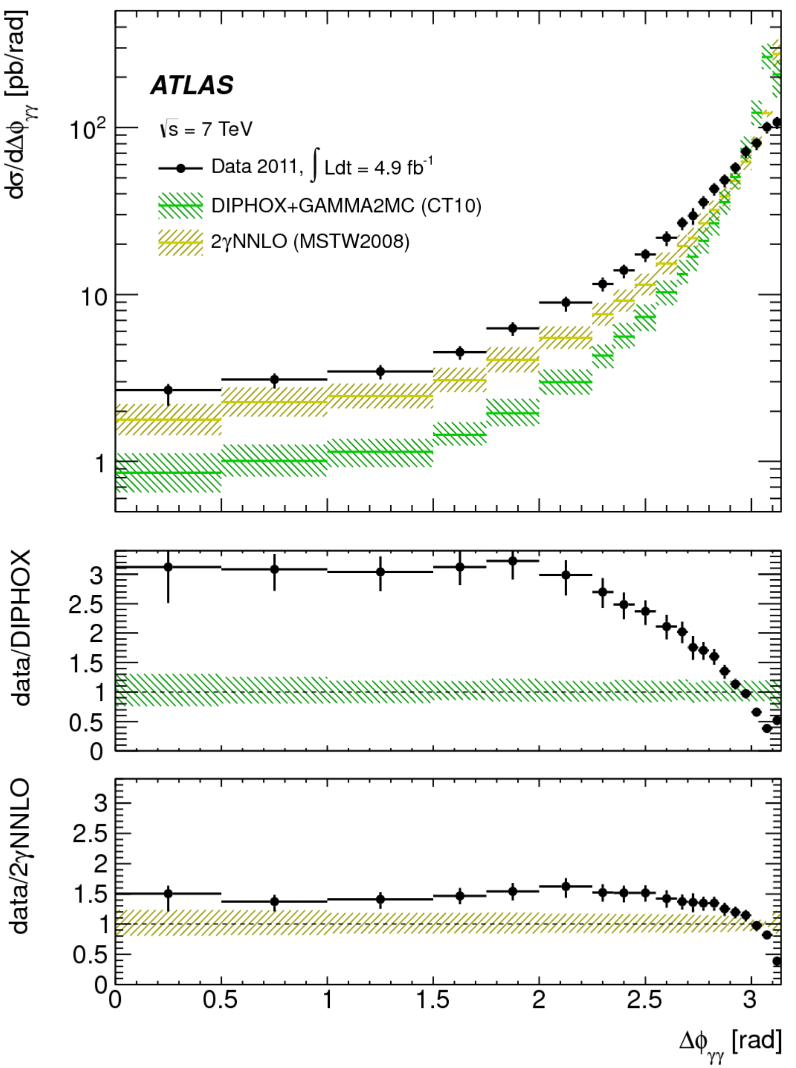
Pdf set CTEQ6.6M

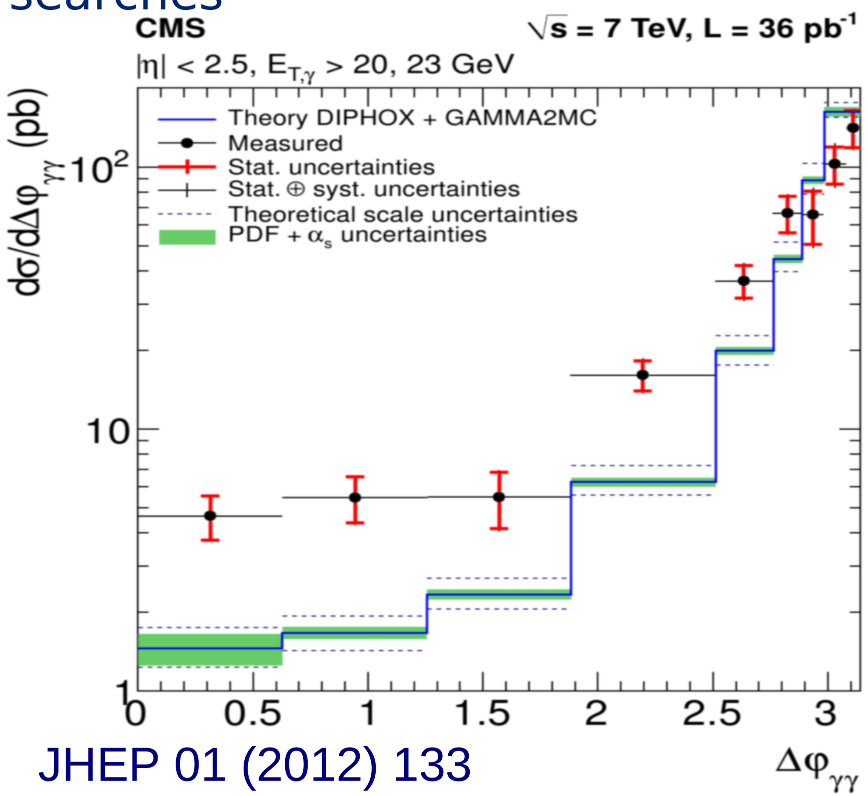
NEW!

Diphoton

- Both ATLAS and CMS measured the diphoton differential cross section as a function of $\Delta\Phi\gamma\gamma$ $m\gamma\gamma$ $PT\gamma\gamma$ and $|\cos\theta*|$ using 4.9 fb-1 and 36 pb-1 of 7 TeV data respectively
- Main background in the SM H-> diphoton searches

JHEP01 (2013) 086



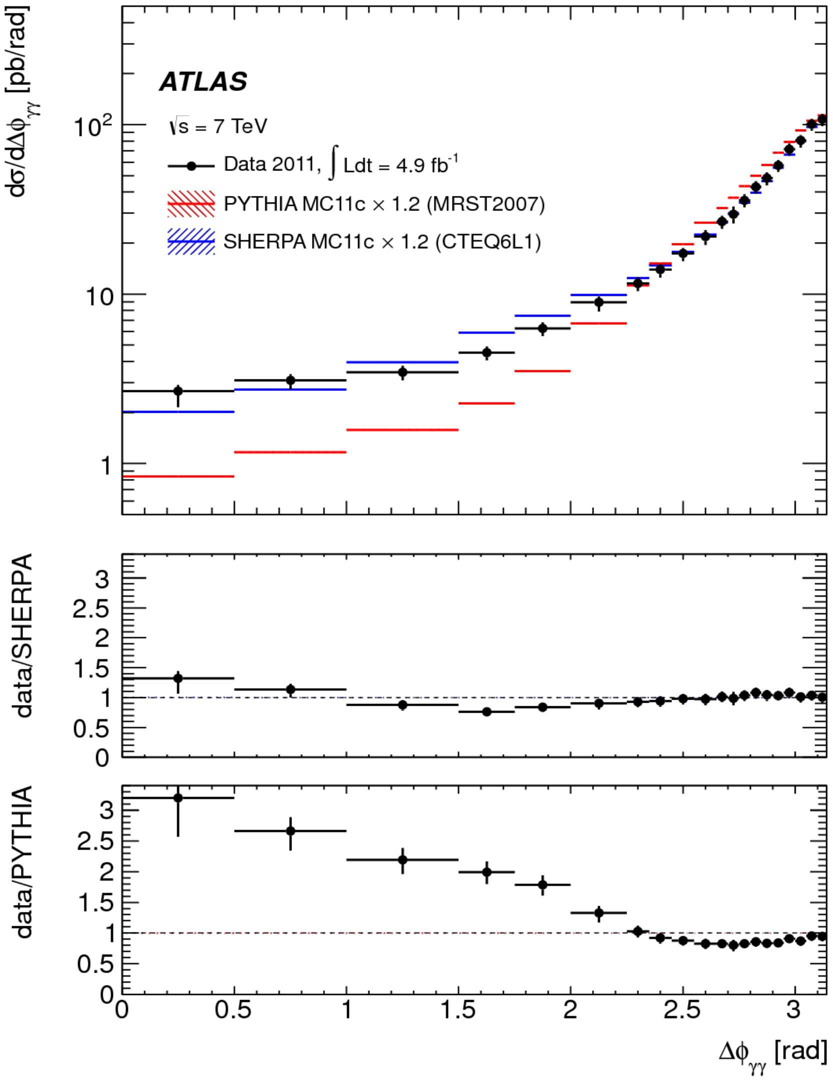


JHEP 01 (2012) 133

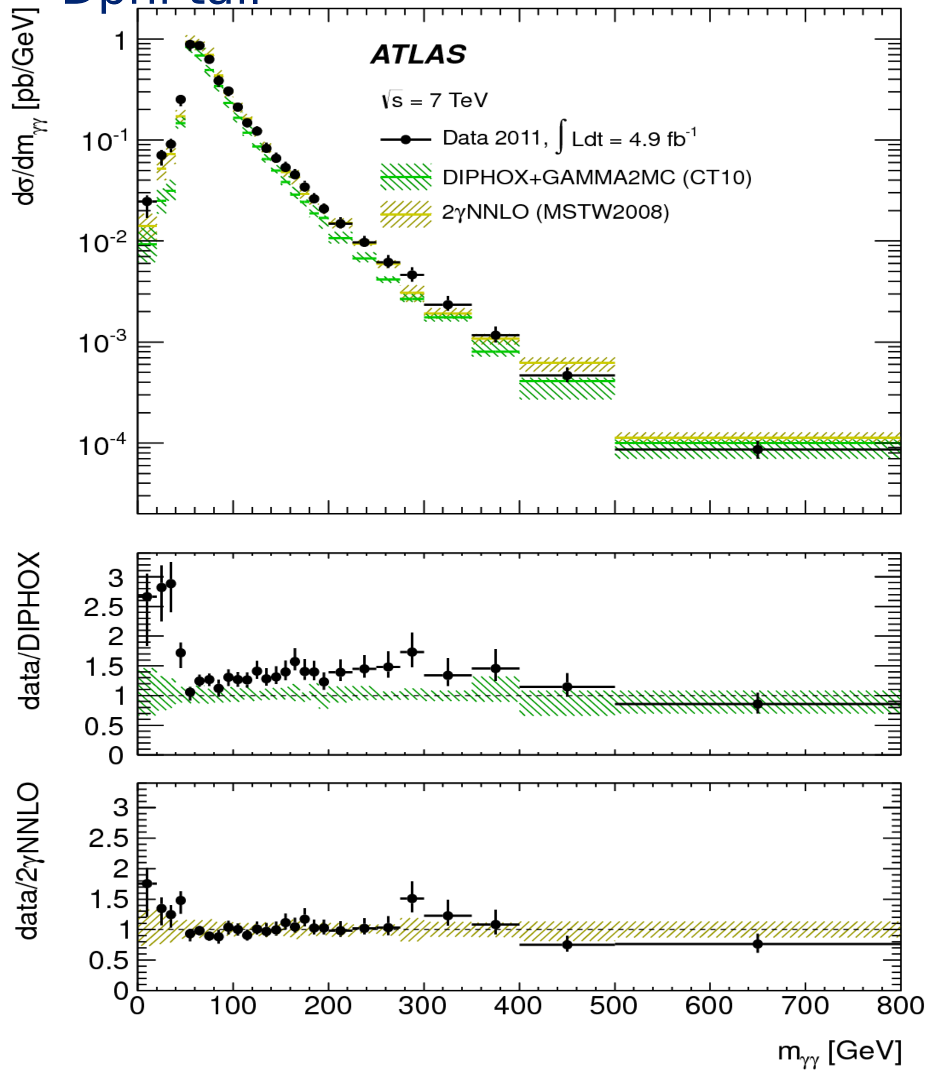
Diphoton

JHEP01 (2013) 086

Fair description SHERPA, PYTHIA fails



Deficit at low mgg consisten with Dphi tail



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 our 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
  - Improvement on our knowledge of PDFs

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

Jet reconstruction

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Jet energy scale

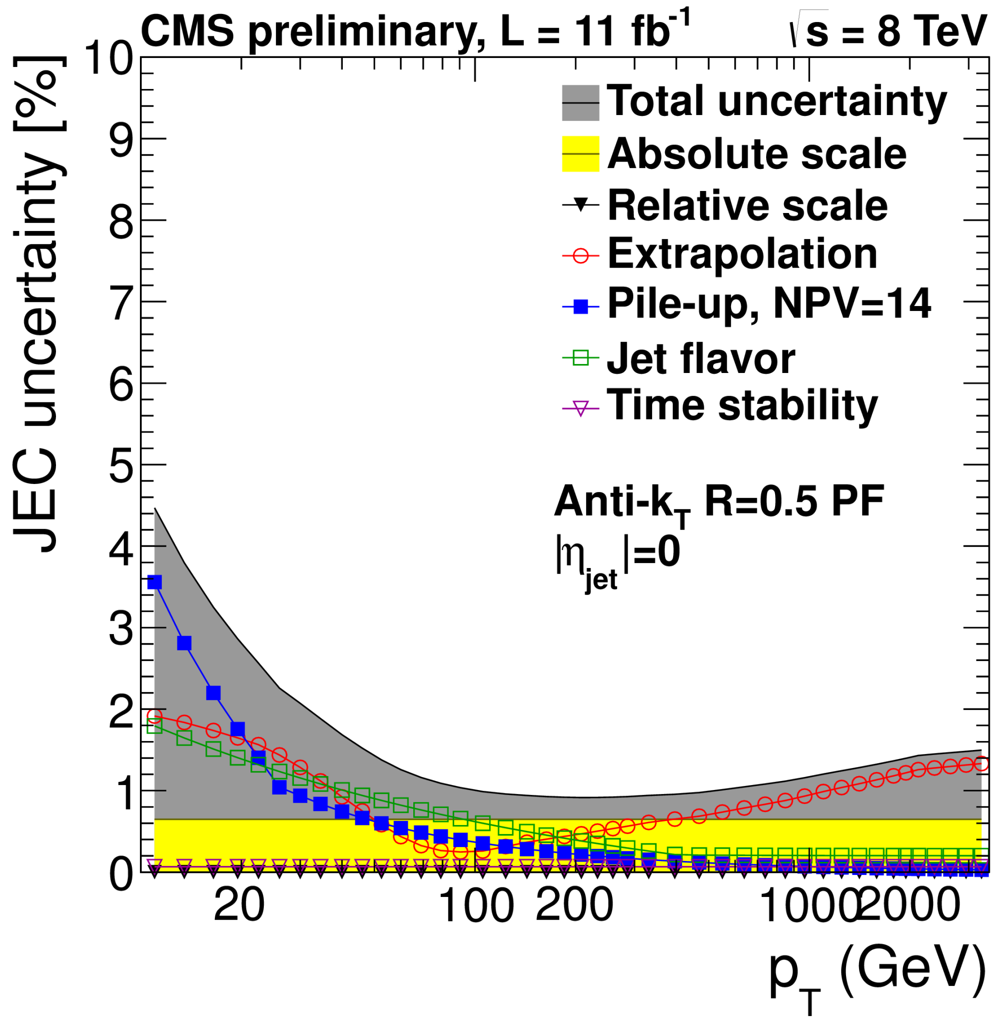
- We use a multi-step procedure to correct the energy of our jets

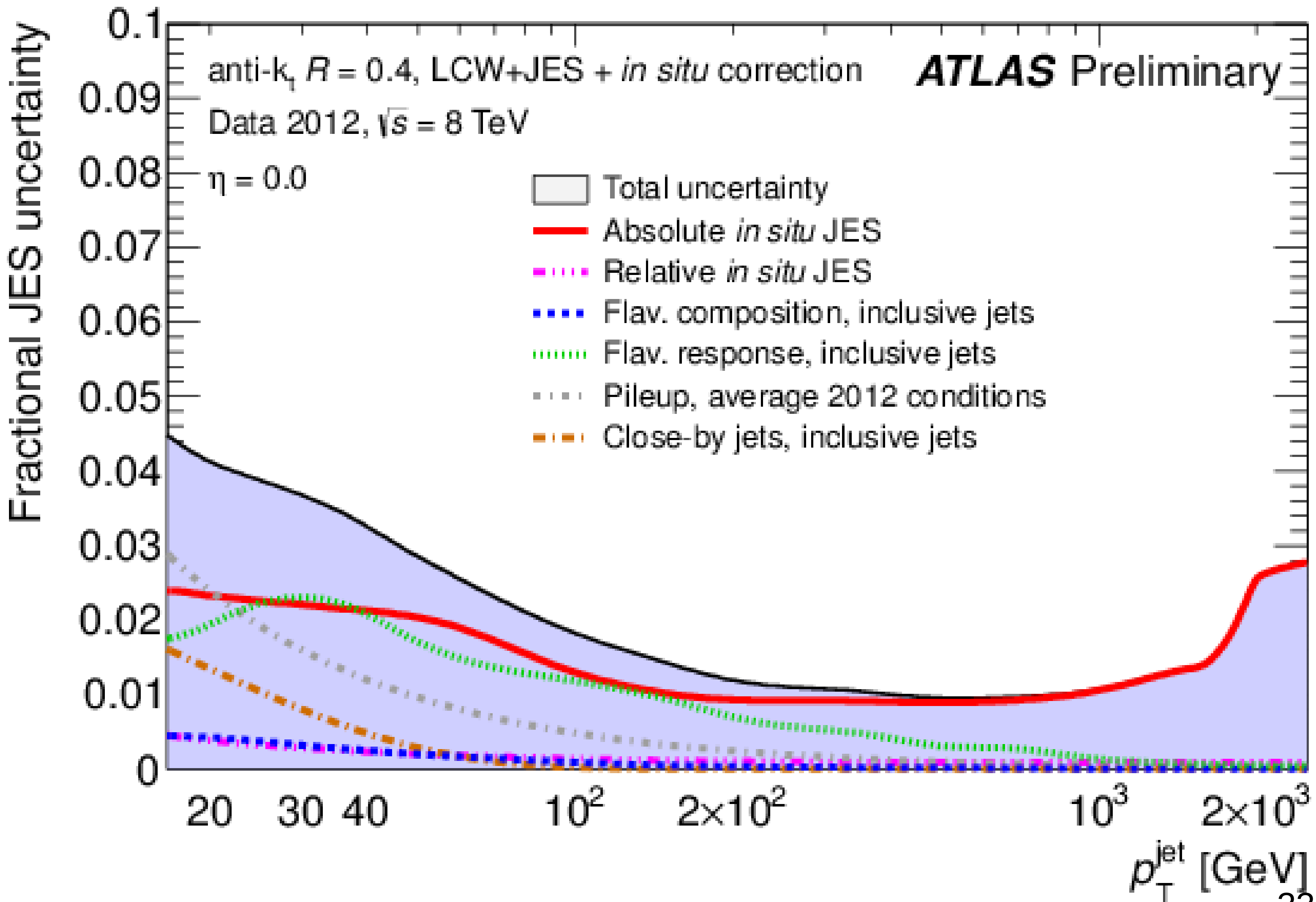
$$p_{\mu}^{cor} = \mathcal{C} \cdot p_{\mu}^{raw}. \qquad \mathcal{C} = C_{\text{offset}}(p_T^{raw}) \cdot C_{\text{MC}}(p'_T, \eta) \cdot C_{\text{rel}}(\eta) \cdot C_{\text{abs}}(p''_T)$$

  - 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

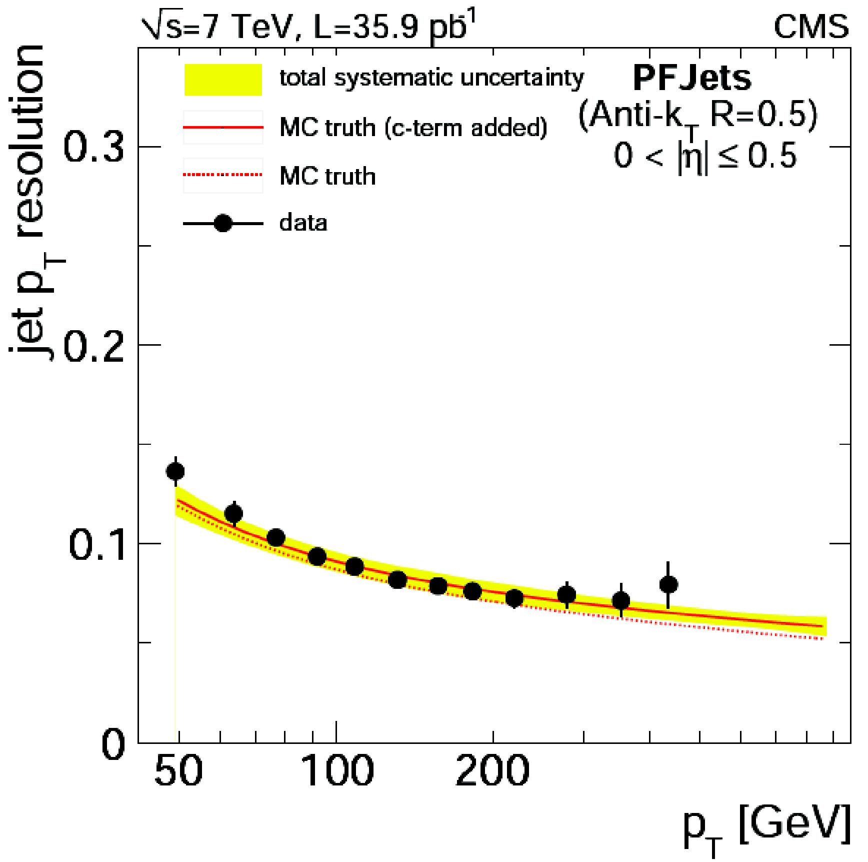


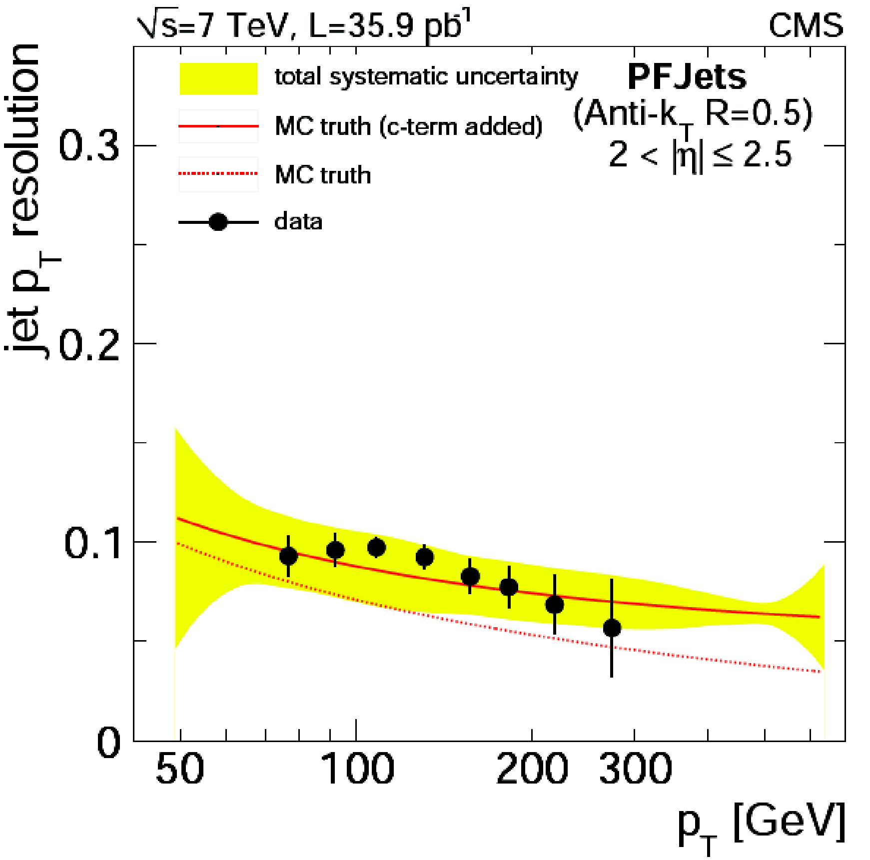


Fractional JES uncertainty
anti-k$_t$ R = 0.4, LCW+JES + *in situ* correction
Data 2012, $\sqrt{s}$ = 8 TeV
η = 0.0
ATLAS Preliminary
Total uncertainty
Absolute *in situ* JES
Relative *in situ* JES
Flav. composition, inclusive jets
Flav. response, inclusive jets
Pileup, average 2012 conditions
Close-by jets, inclusive jets
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
20
30
40
10^2
2×10^2
10^3
2×10^3
p_T^{jet} [GeV]

Jet energy resolution

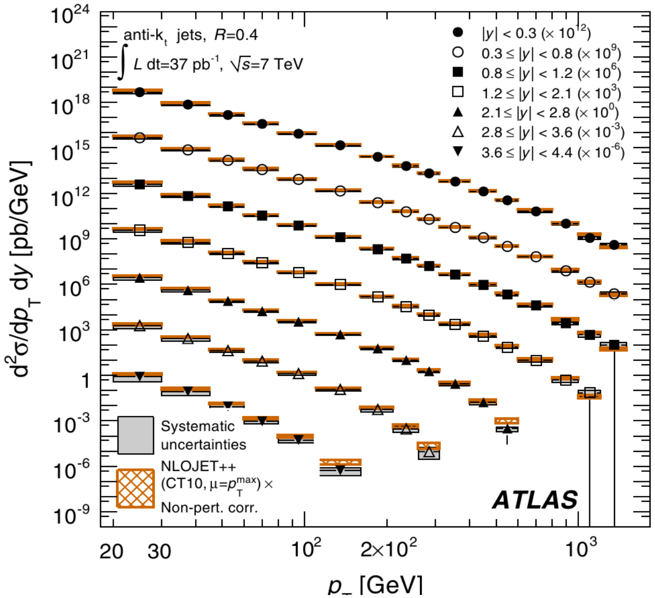
- Determined with di-jet and γ+jet pT balance
  - Plots show two example regions in η
  - Resolution is of the order of 10% around 50 GeV

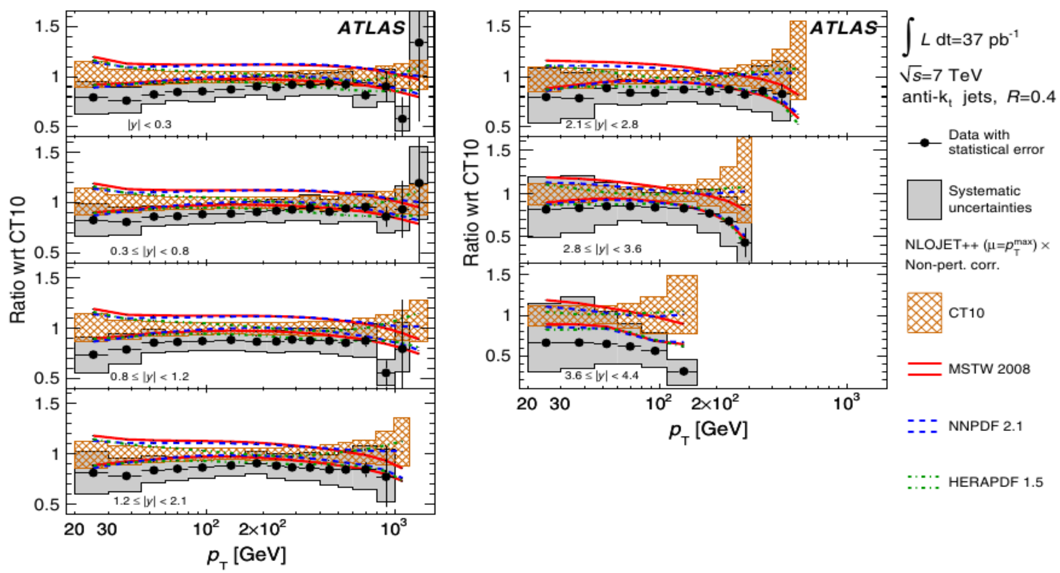


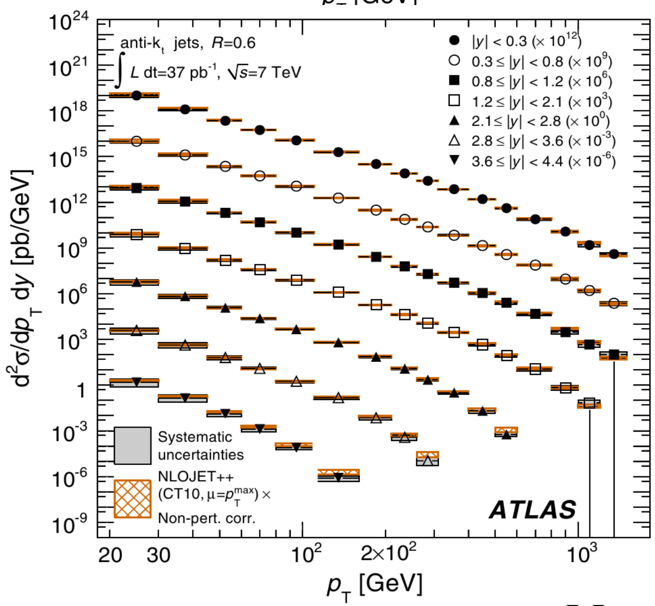


Inclusive jets

- 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

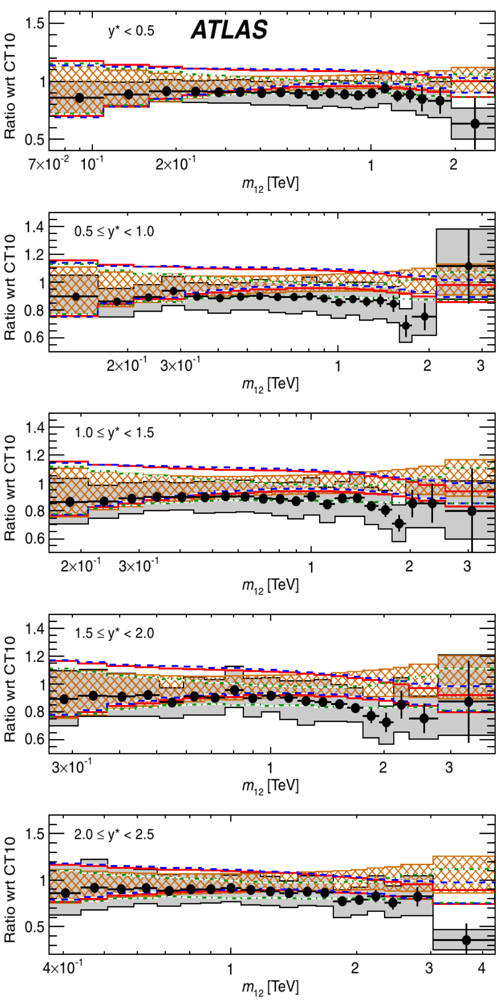


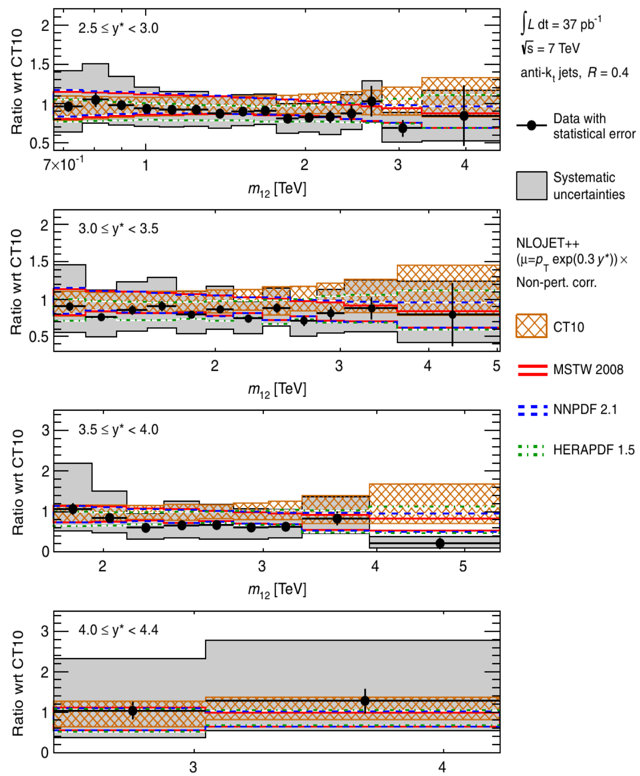


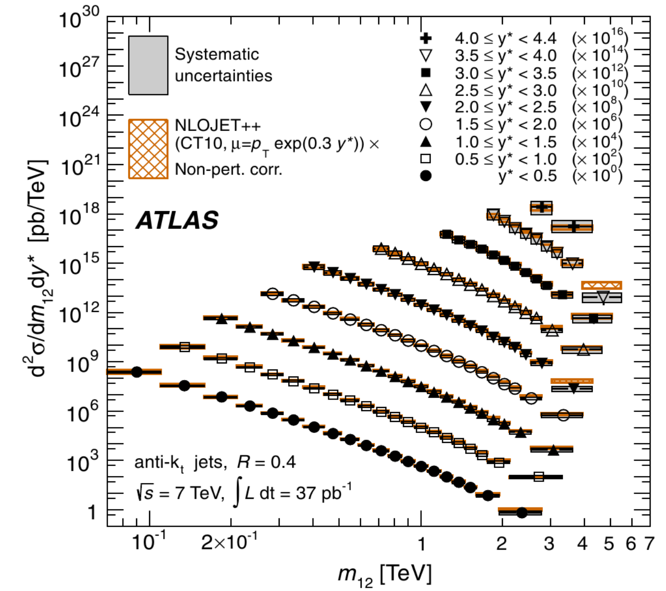


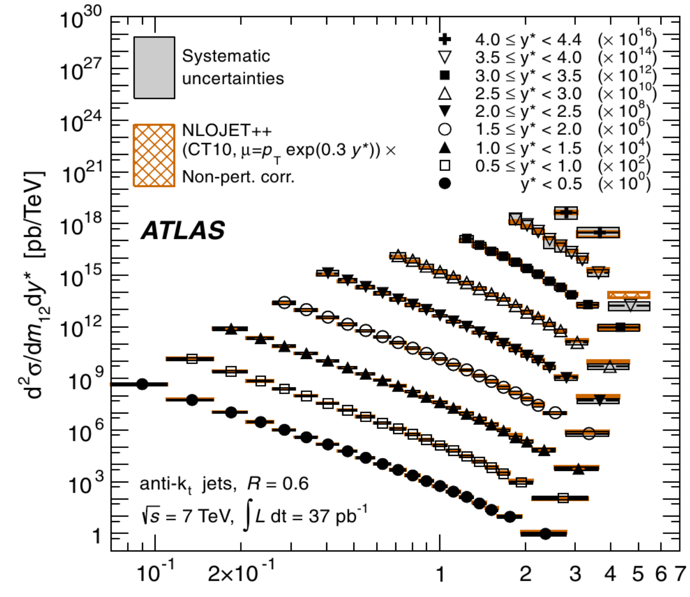
Di-jet mass

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





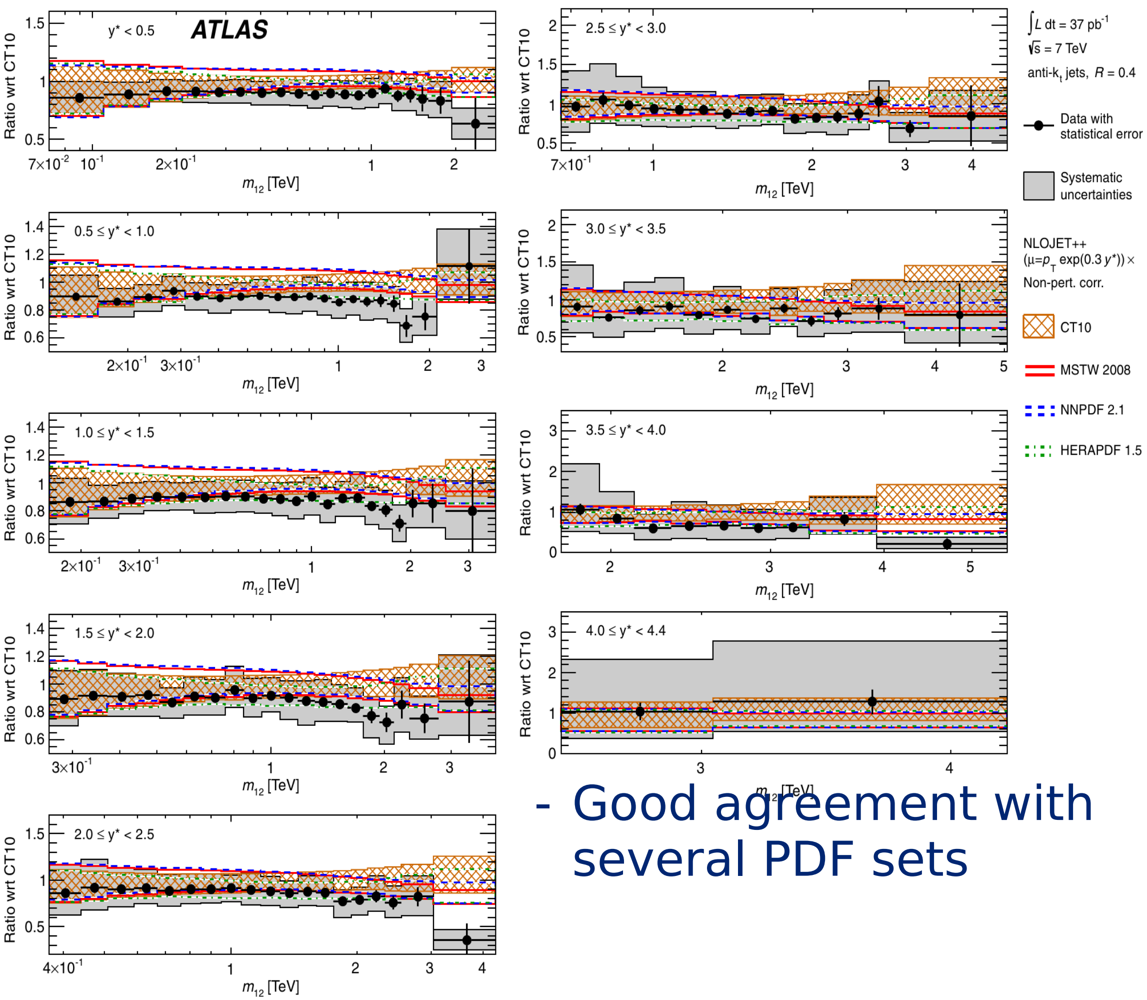




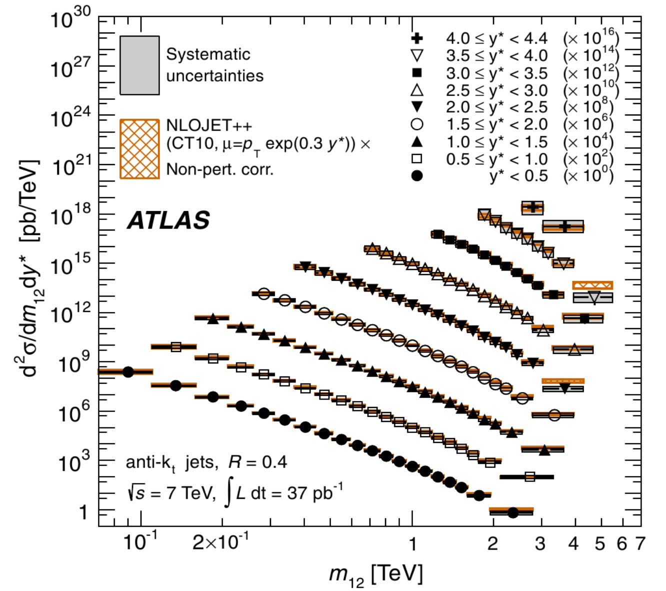
- Good agreement with several PDF sets

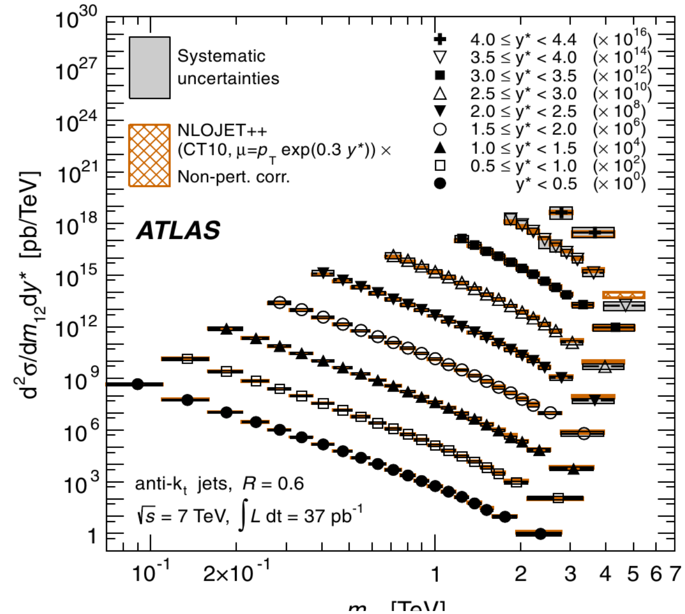
Di-jet mass

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



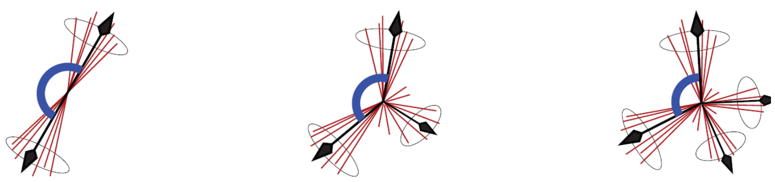
- Good agreement with several PDF sets





Azimuthal decorrelation

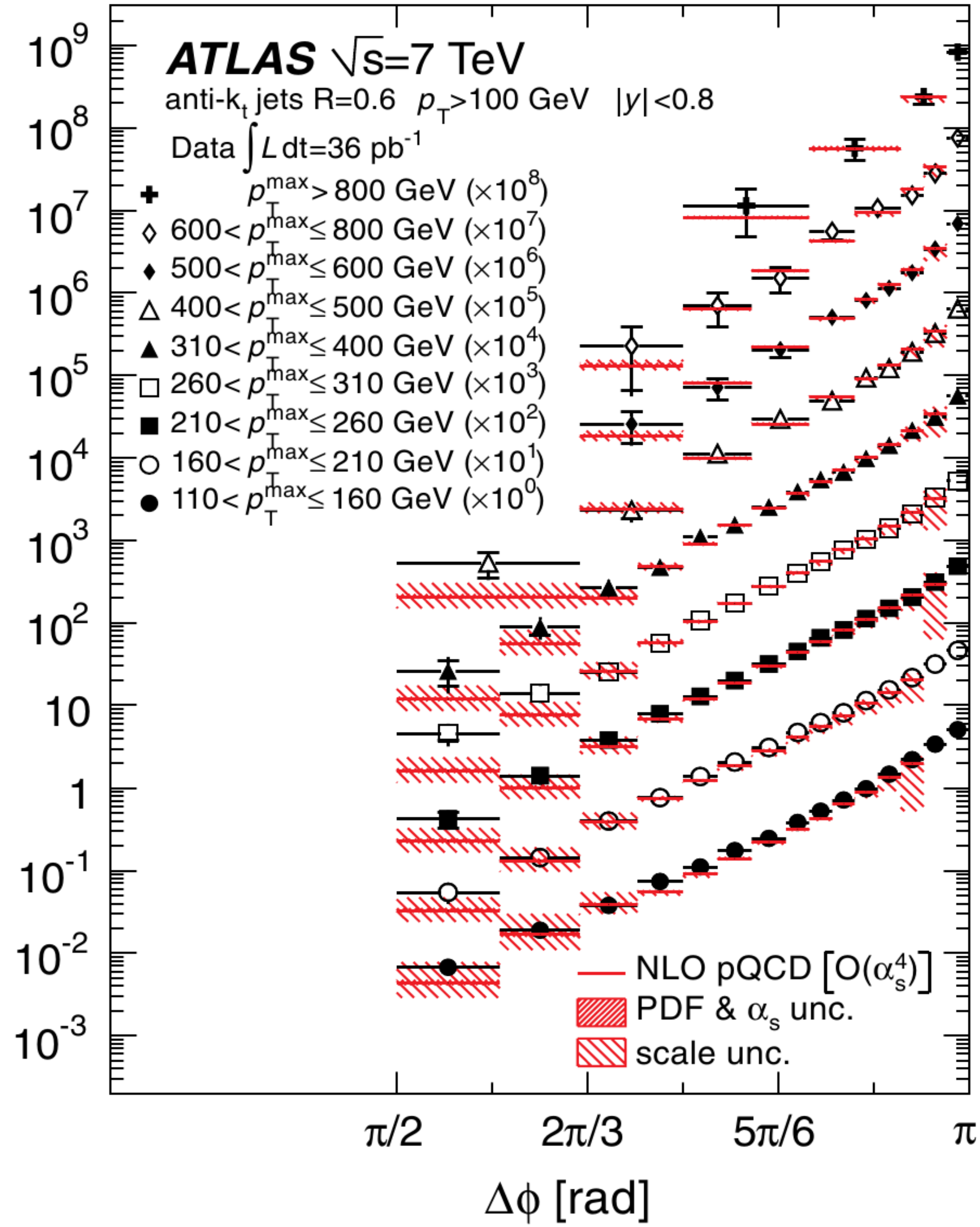
- $\Delta\varphi$ between the two leading jets in the event
  - It is very sensitive to additional radiation effects (hence to higher order corrections) but also to MPI and hadronization



$\Delta\varphi_{dijet} = \pi$ $\Delta\varphi_{dijet} < \pi$ $\Delta\varphi_{dijet} << \pi$

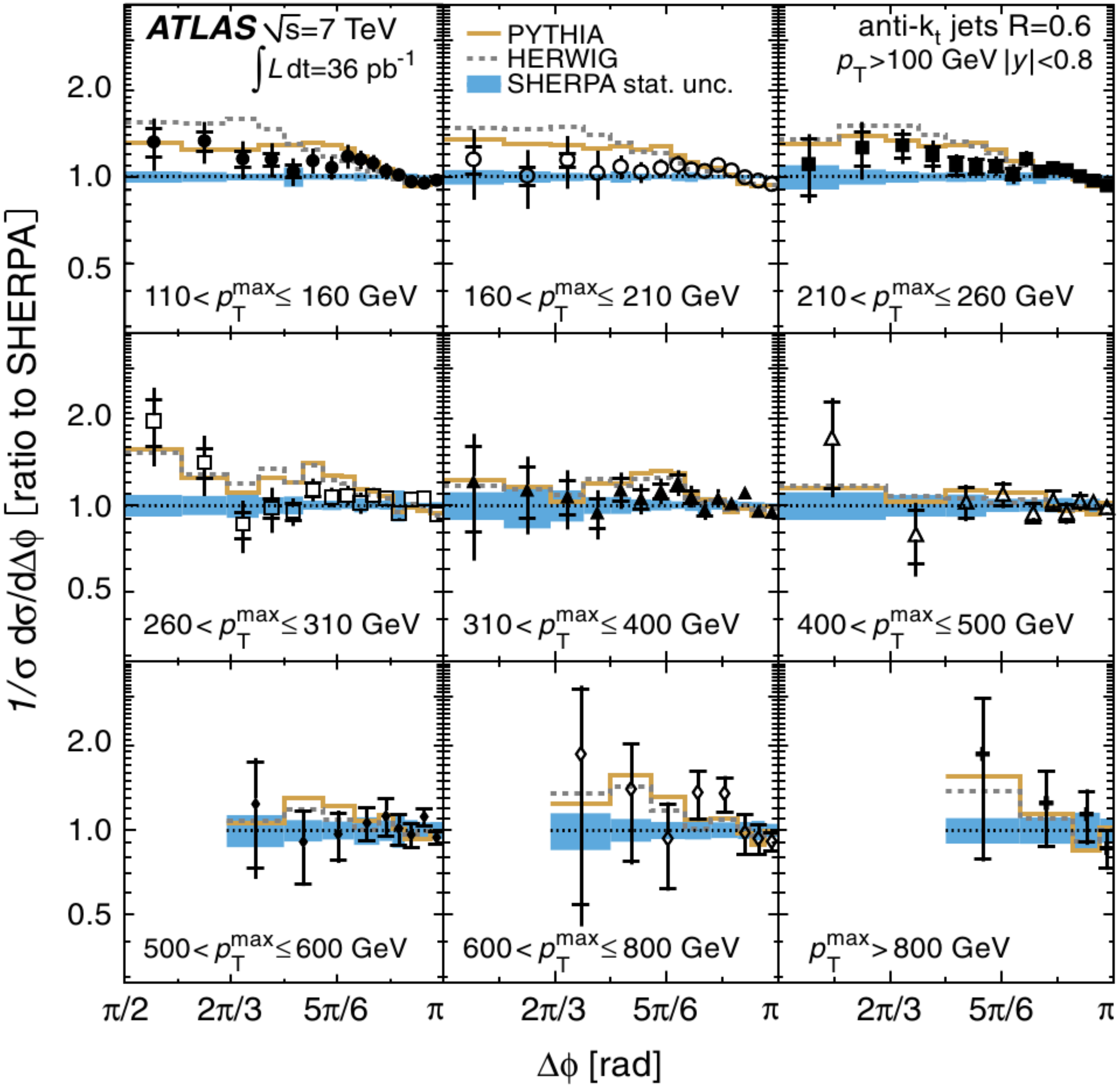
- Comparison to NLO QCD
  - Good agreement over the entire range

Phys. Rev. Lett. 106 (2011) 12200



Azimuthal decorrelation

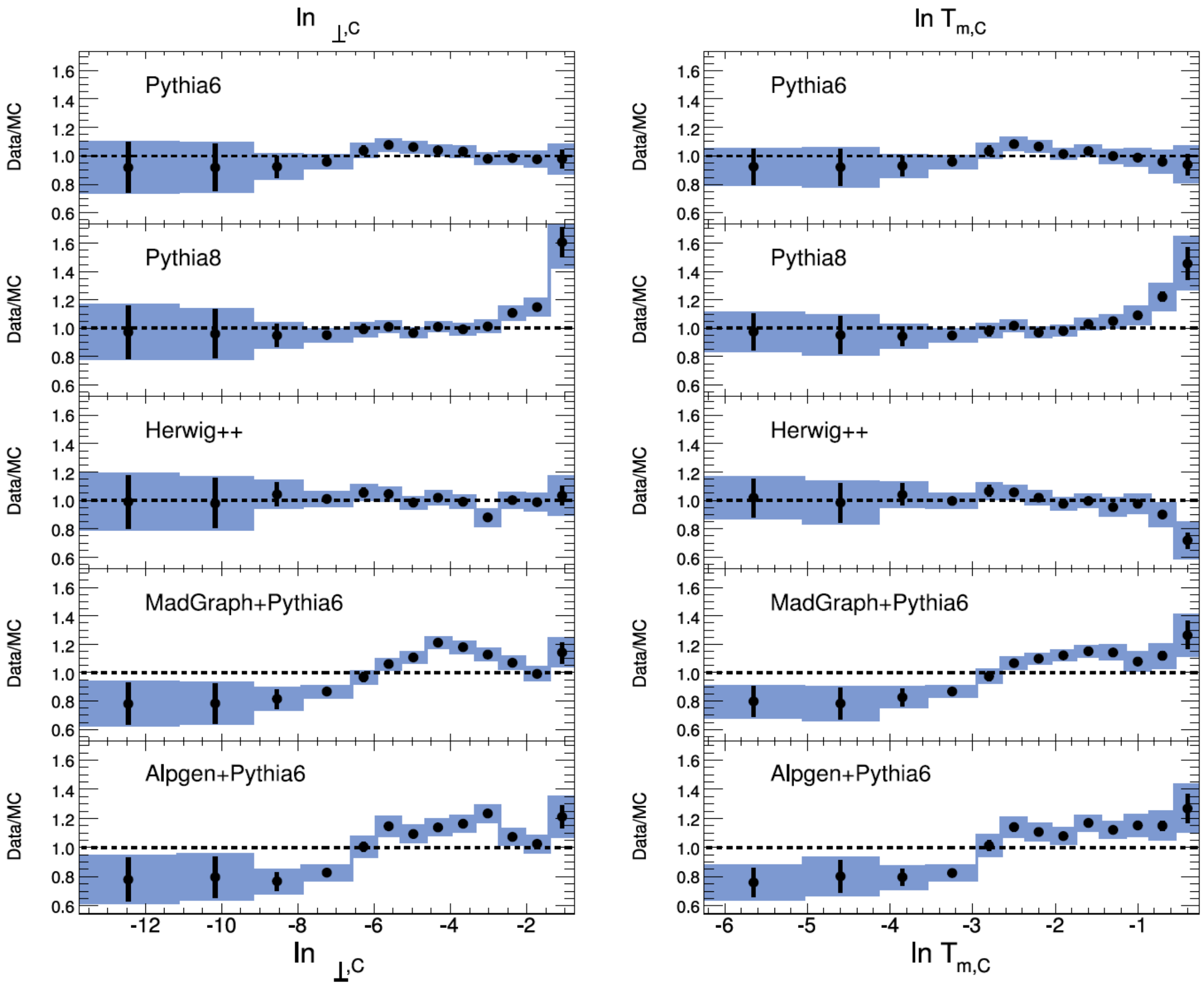
- Comparison to shower MC
  - Good description of all models chosen
  - Sherpa, with LO multileg matrix elements agrees very well with the data in the high end of the spectrum
  - Also pure shower models (Pythia8, Herwig) tuned to previous measurements agree well with the data



PRL 106 (2011) 172002

Event shapes

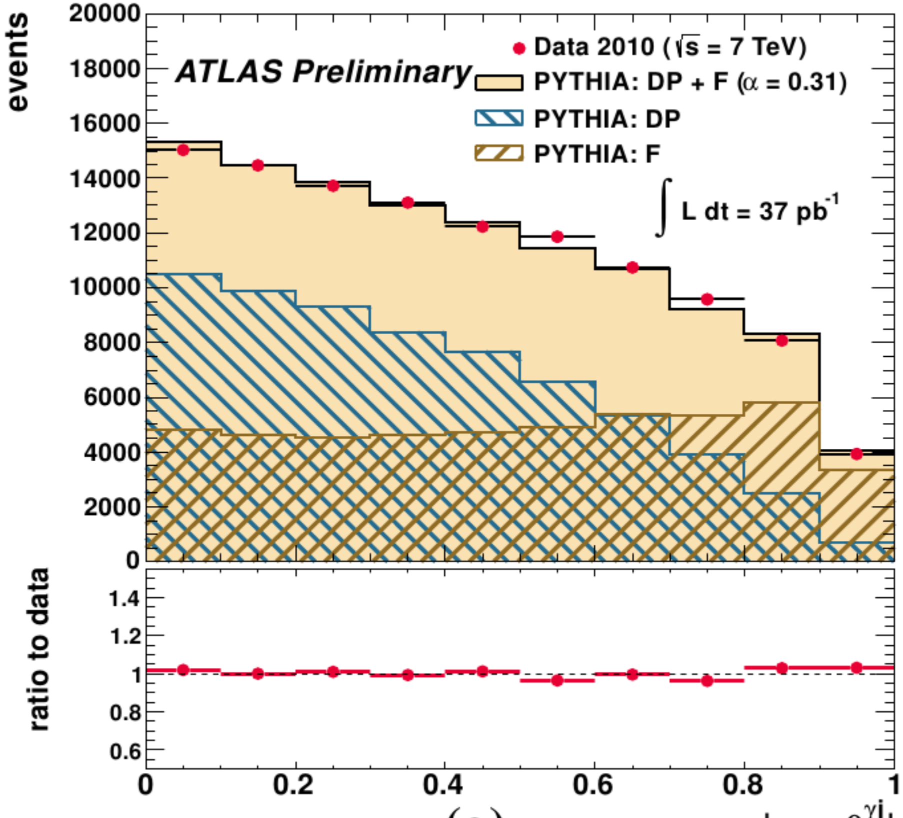
- Very nice agreement with pyre shower models, like Herwig and Pythia6
- Comparison to LO + PS programs, like AlpGen and Madgraph shows deviation from the data
  - Overtuning of the standalone Parton Shower?



Photon + jets

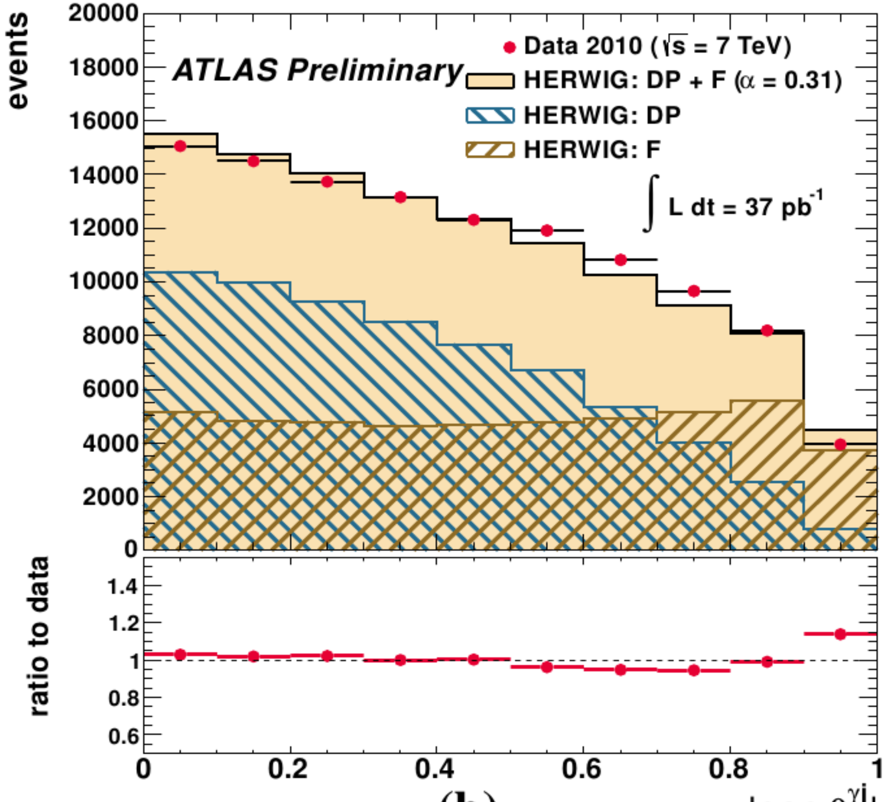
- The contribution of fragmentation versus direct photons was studied in detail as a function of scattering angle $\theta^{\gamma j}$ in the photon-jet rest frame
- Shower MC can get the right differential shape with tuning of the two contributions

PYTHIA



(a)

HERWIG

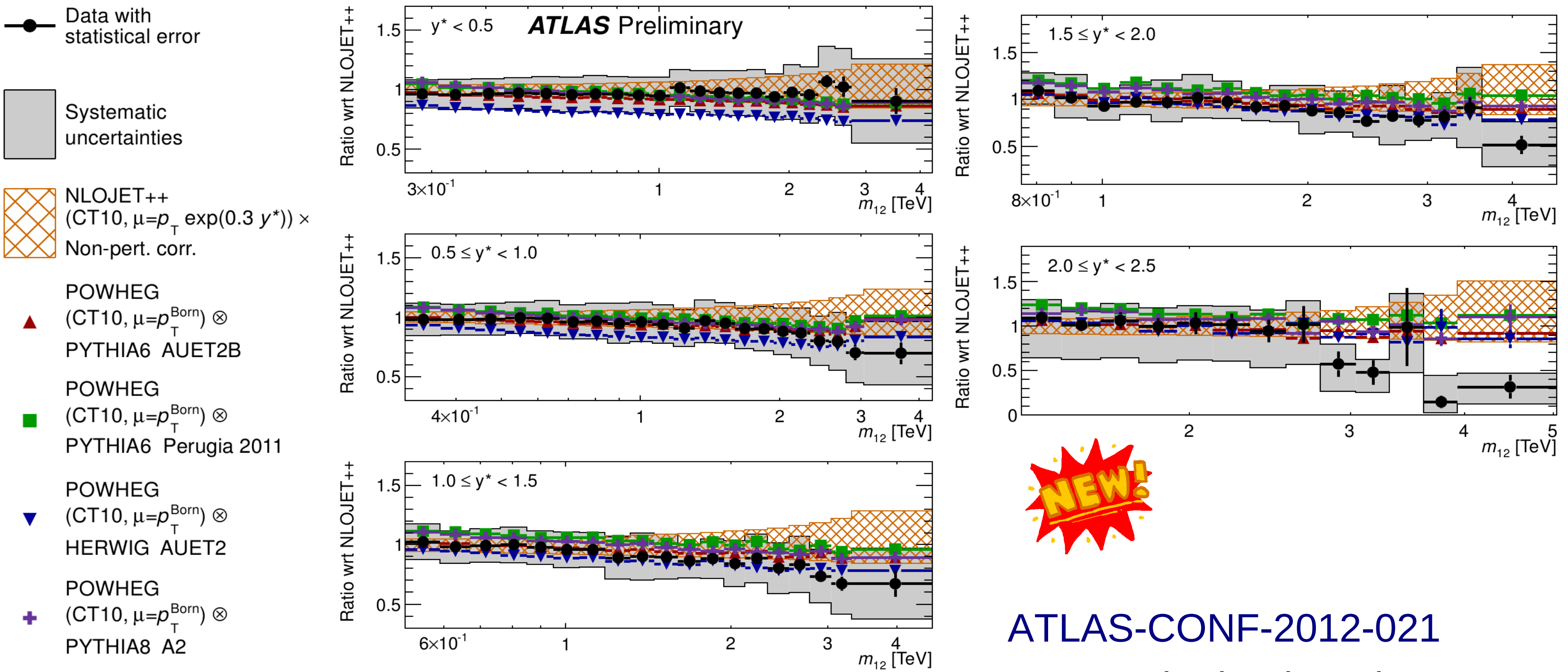


(b)

ATLAS-CONF-2013-023

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



ATLAS-CONF-2012-021

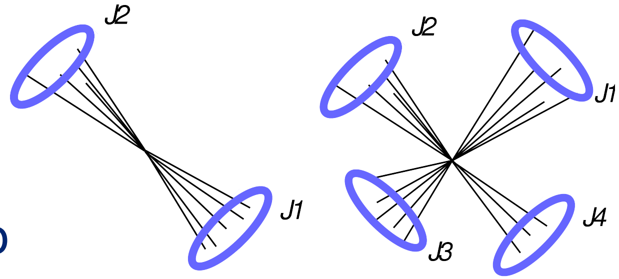
CMS-QCD-11-004, submitted to Phys. Rev. D

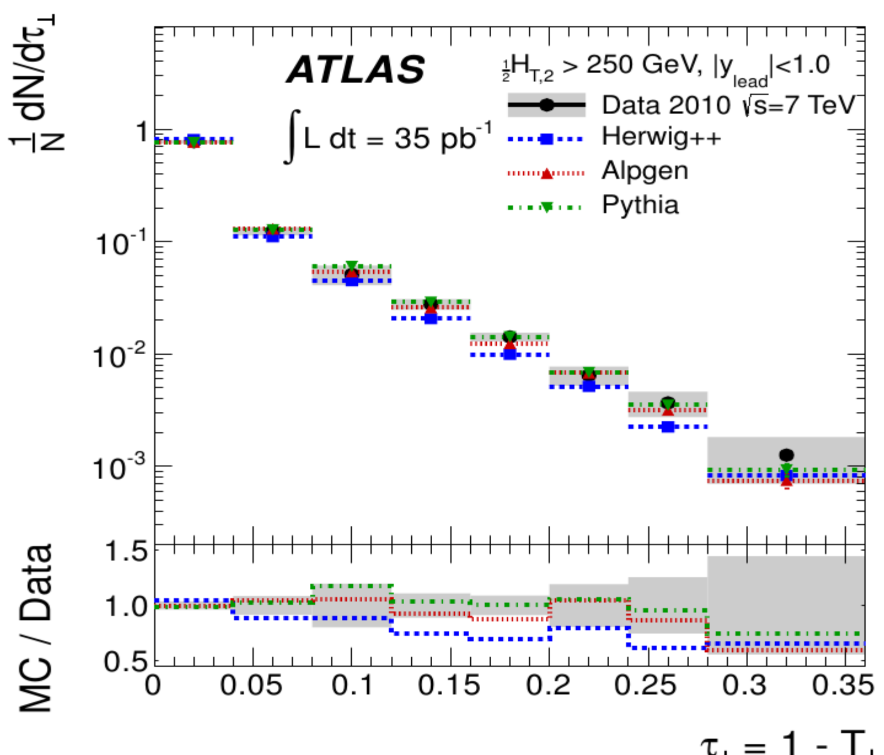
Event shapes

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

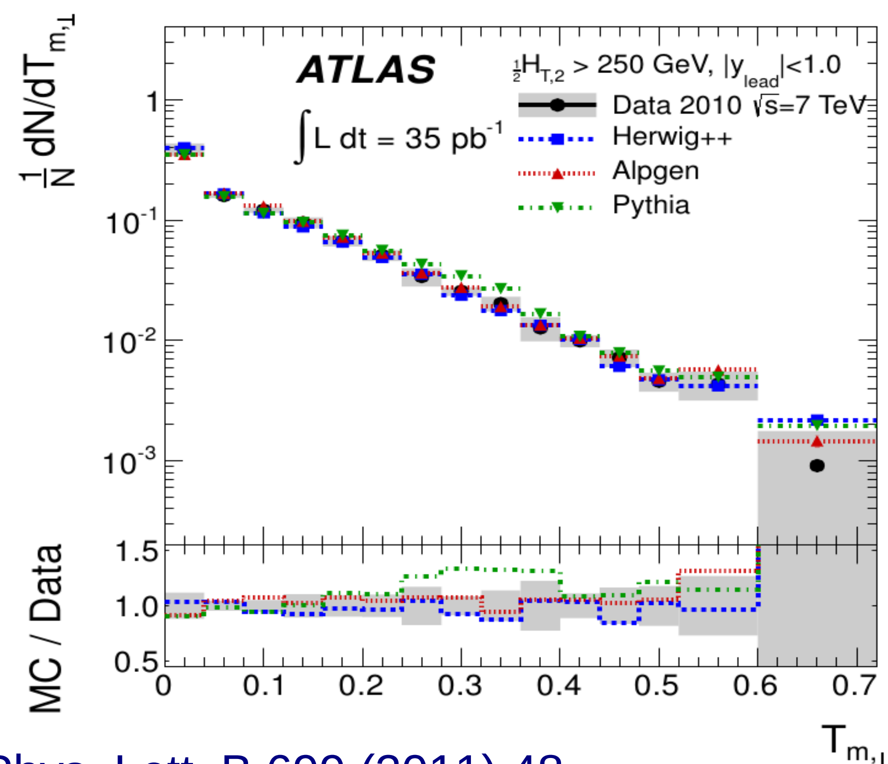
$$\tau_{\perp,\mathcal{C}} \equiv 1 - \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \hat{n}_T|}{\sum_i p_{\perp,i}}$$

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





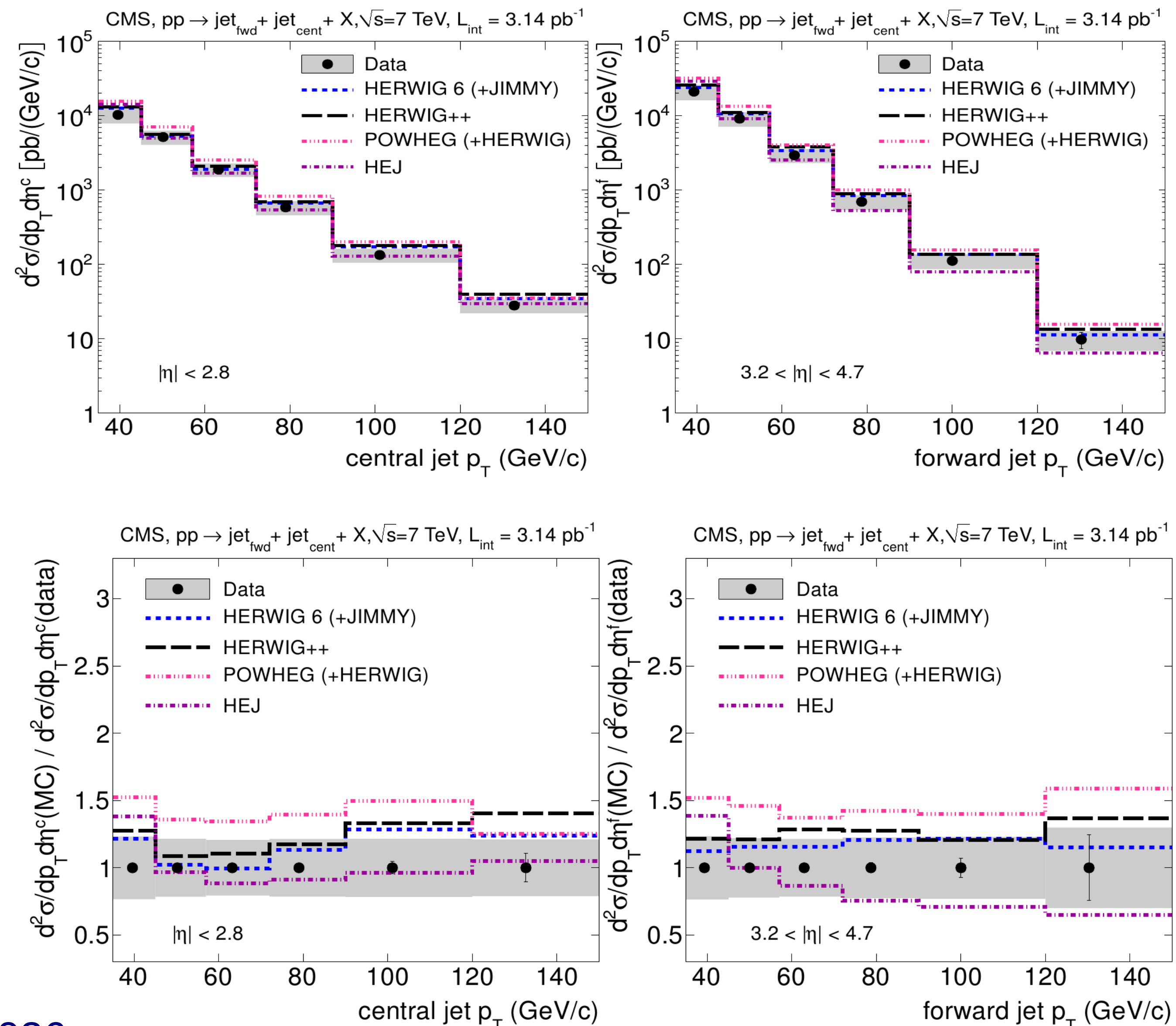
Eur. Phys. J. C (2012) 72: 2211



Phys. Lett. B 699 (2011) 48

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

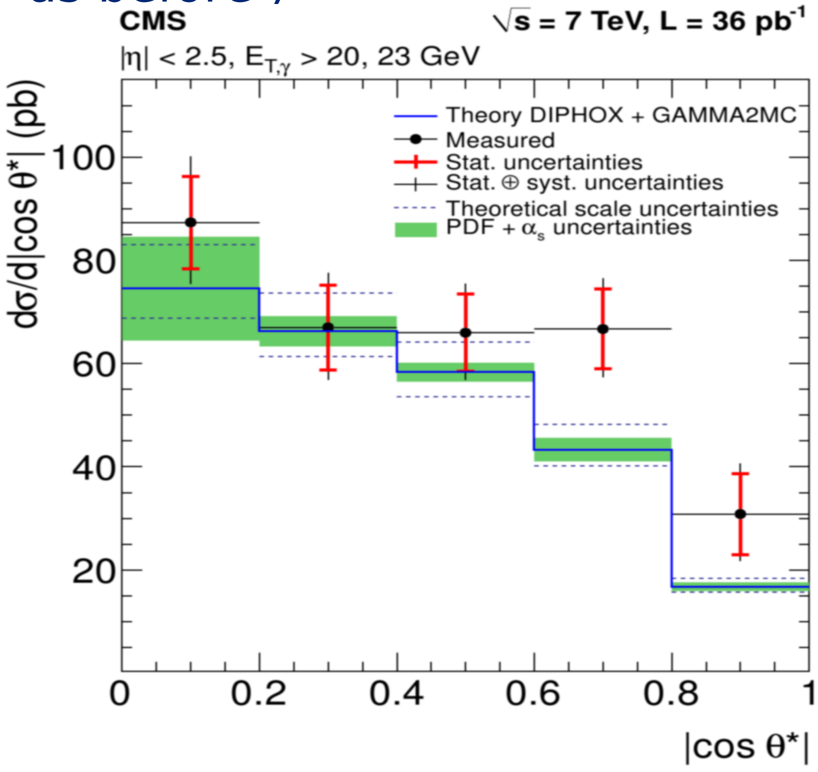


JHEP06(2012)036

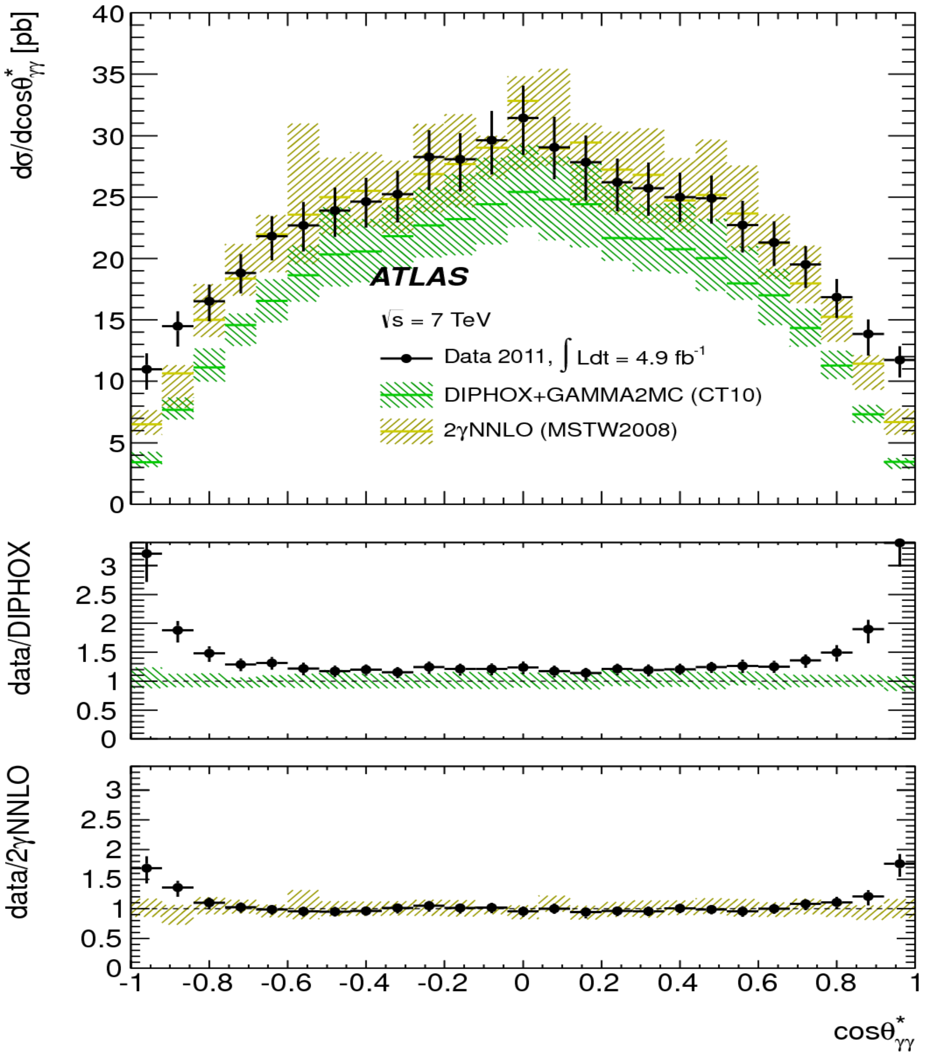
Diphoton

CMS-SMP-12-004

- Fragmentation enhanced regions (costheta*->1) not well described
- SHERPA does a reasonable job (as before)



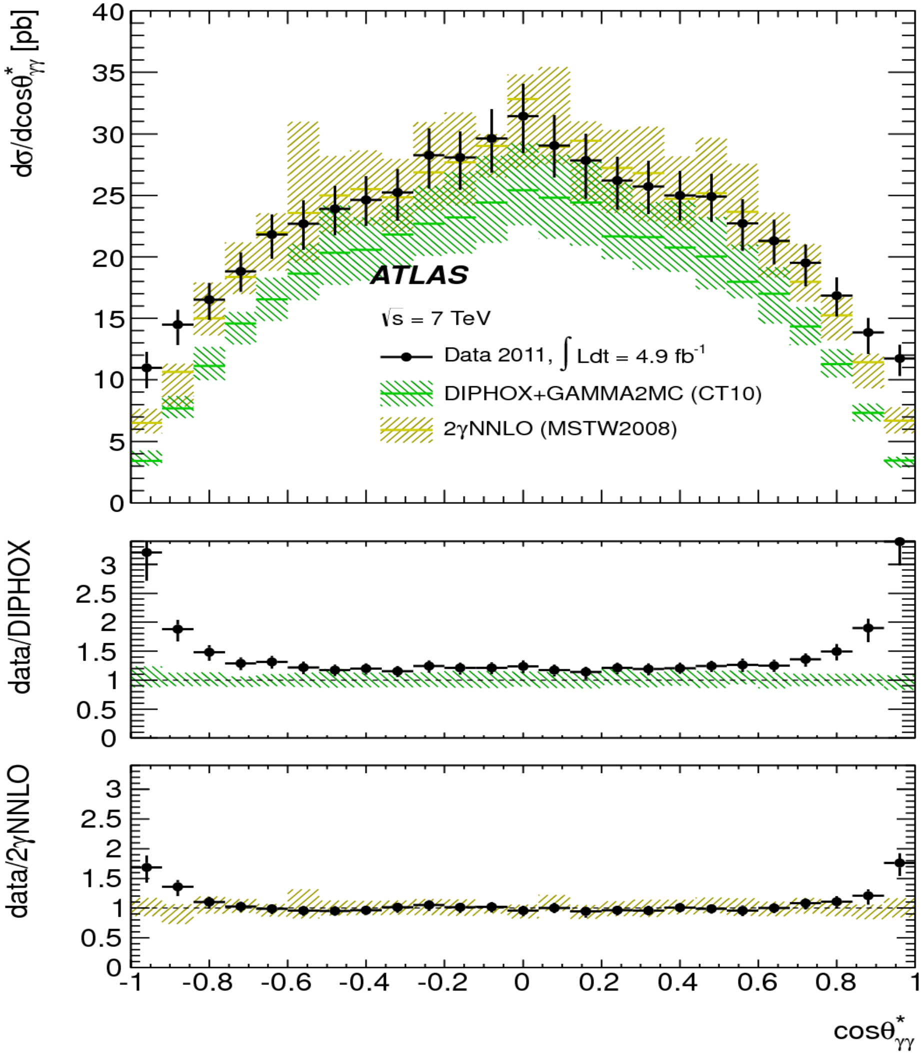
JHEP 01 (2012) 133



JHEP01 (2013) 086

Diphoton

- Fragmentation enhanced regions (costheta*->1) not well described
- SHERPA does a reasonable job (as before)
- Especially relevant for the measurement of spin in $\gamma\gamma$



JHEP 01 (2012) 133

JHEP01 (2013) 086