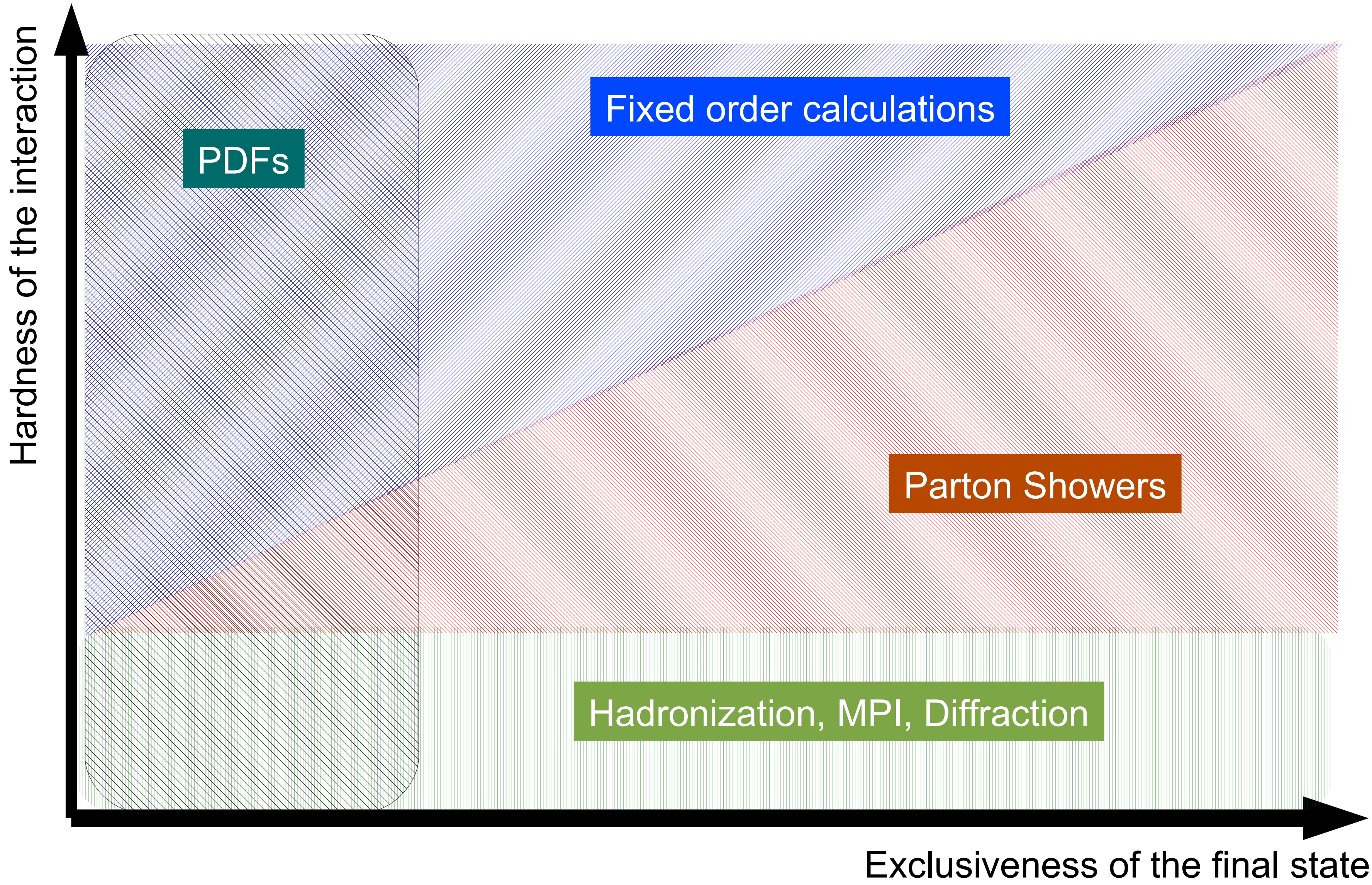
QCD at the LHC:
experimental status and prospects

Piergiulio Lenzi – INFN, CMS experiment

QCD at LHC

- The study of QCD processes at the LHC is important for 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 precision QCD measurements
  - They represent a ubiquitous source of background for virtually any signal at a hadron collider

The landscape of QCD

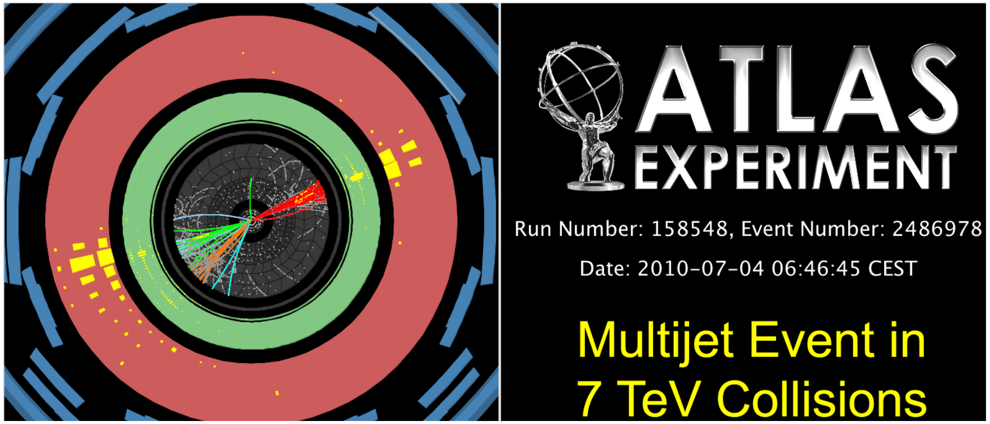


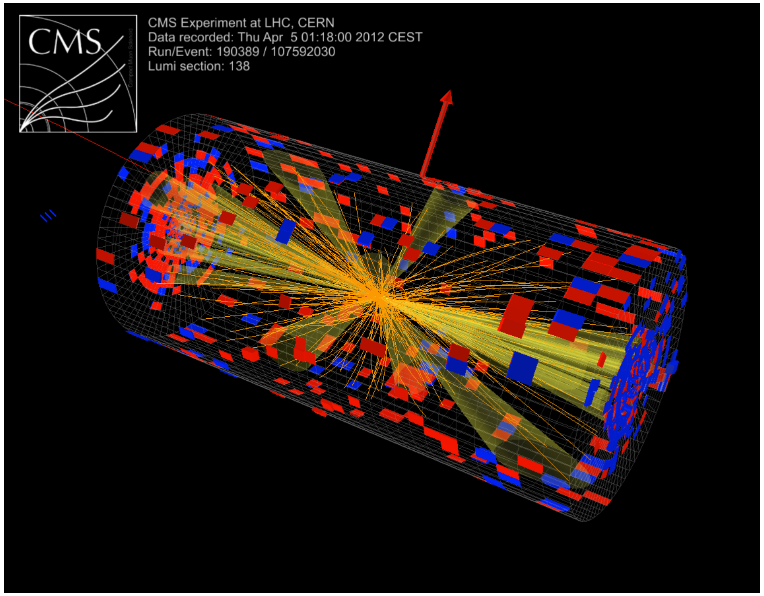
Theoretical predictions

- 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, aMC@NLO+Pythia/Herwig
    - NLO muti leg +Parton Shower
      - Sherpa, aMC@NLO + MadFKS
    - Regge-Gribov based generators
      - EPOS, QGSJetII
  - Parton level codes
    - Fixed order calculations (NLOJet++, Blackhat, JetPhox)
    - BFKL inspired models (HEJ)

Outline

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





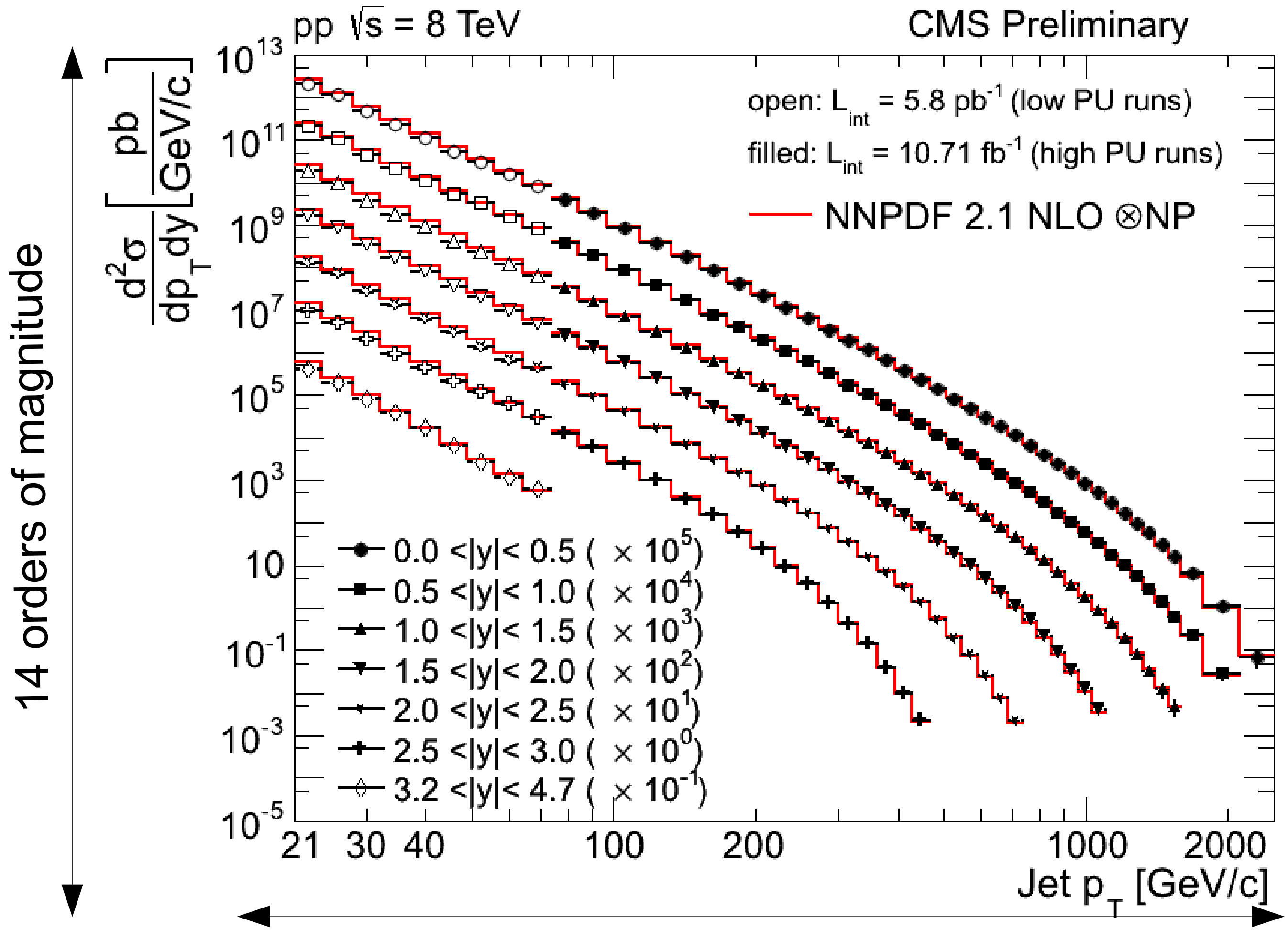
Notice that often very similar measurements have been performed by ATLAS and CMS. In all those cases I will show the results from one experiment, unless there are differences to notice.

Inclusive jets

CMS-SMP-12-012

CMS-FSQ-12-031

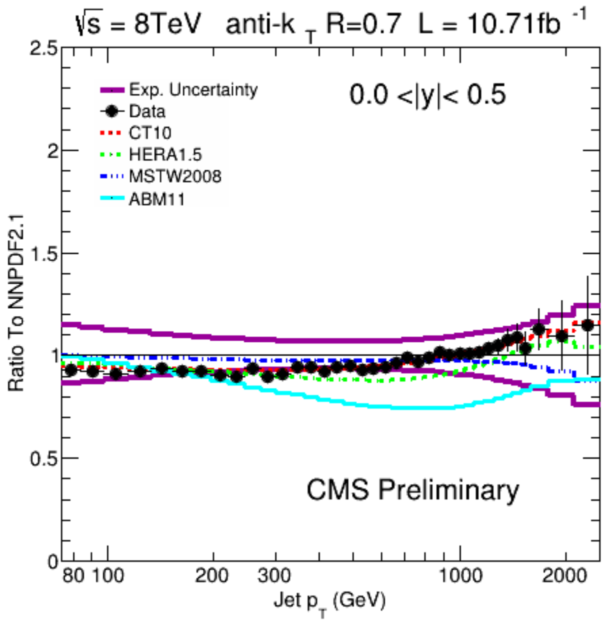
- Measurement of inclusive jets at 8 TeV
- Data are compared with the predictions at NLO (NLOJet++), including non-perturbative (NP) corrections obtained with a shower MC

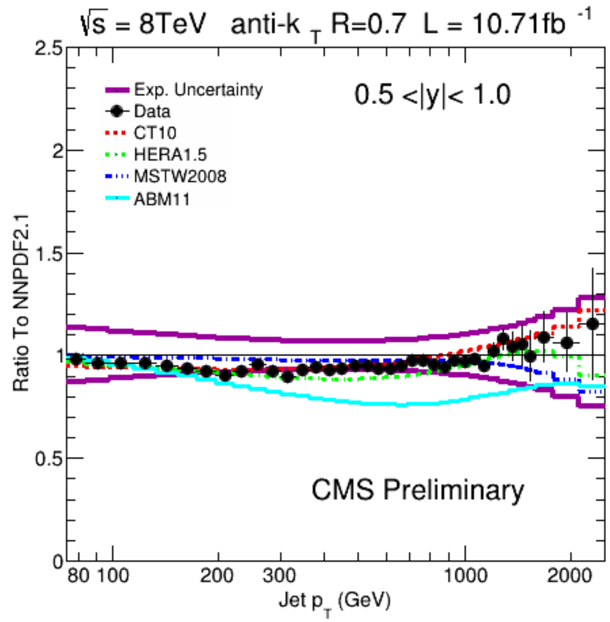


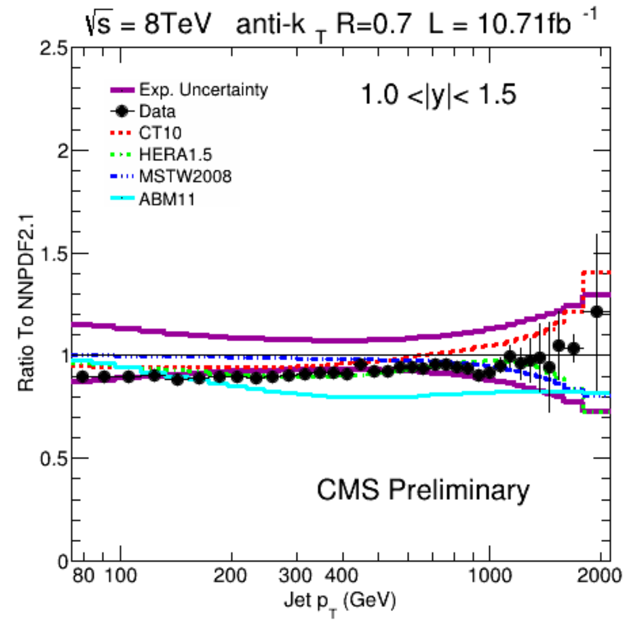
Phys.Rev. D86 (2012) 014022 (ATLAS)

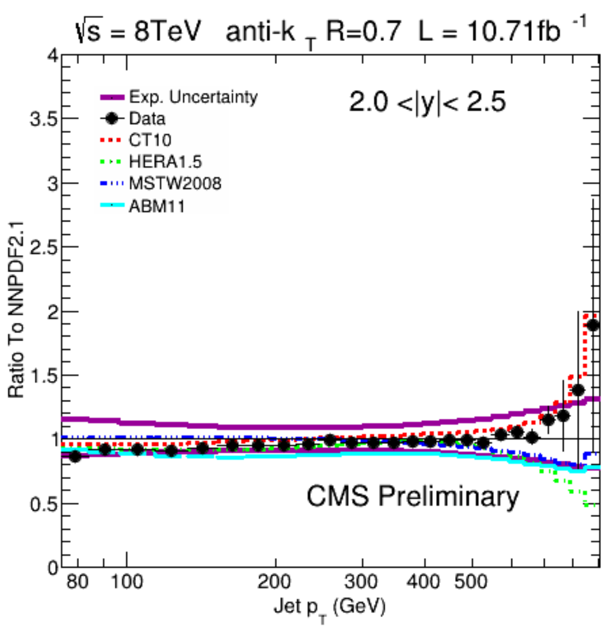
3 orders of magnitude

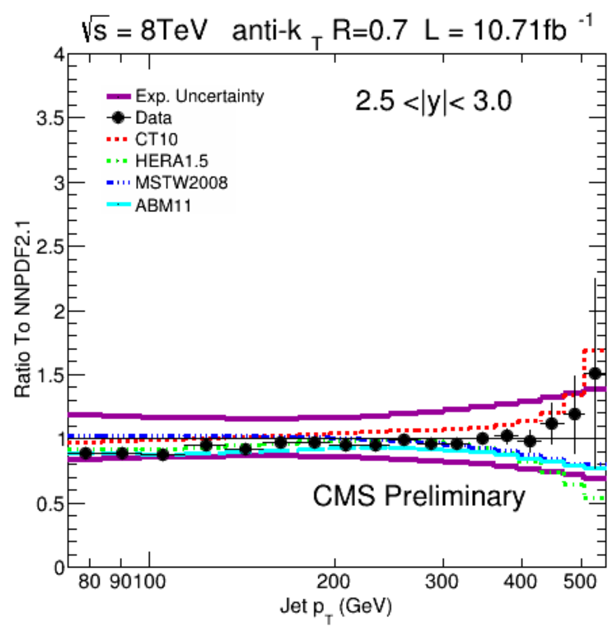
Inclusive jets







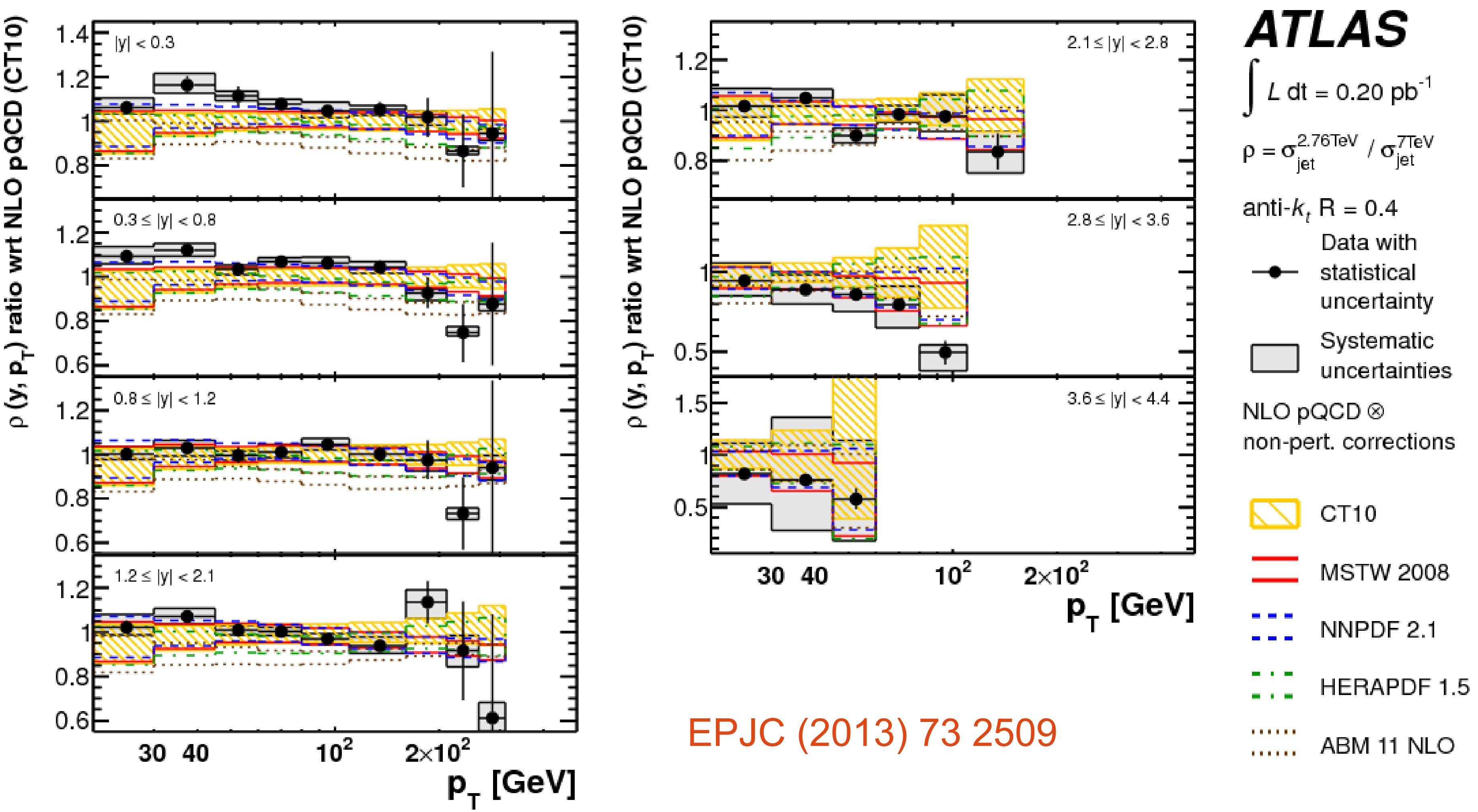




- Sensitive to PDFs
- Good agreement with several PDF sets
- Predictions disagree mainly at very high pT

Inclusive jets

- Very interesting comparison between 7 TeV and 2.76 TeV
- Has power to constrain PDFs in the central region



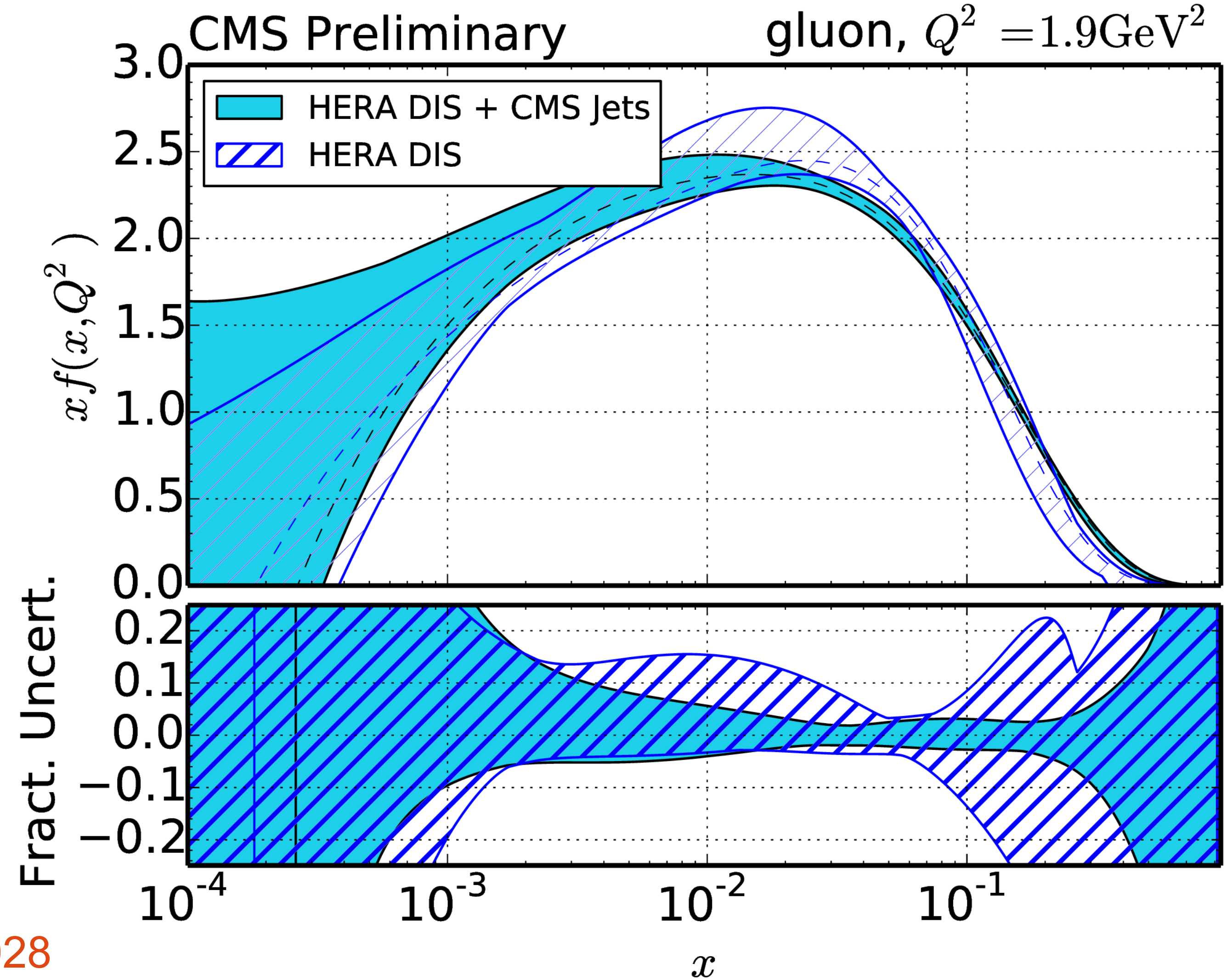
EPJC (2013) 73 2509

Gluon PDF

Central rapidities are particularly relevant for gluon PDF

Forward rapidities and high pT are expected to have an impact on quark PDFs

Inclusion of jet data predicts a significantly harder gluon

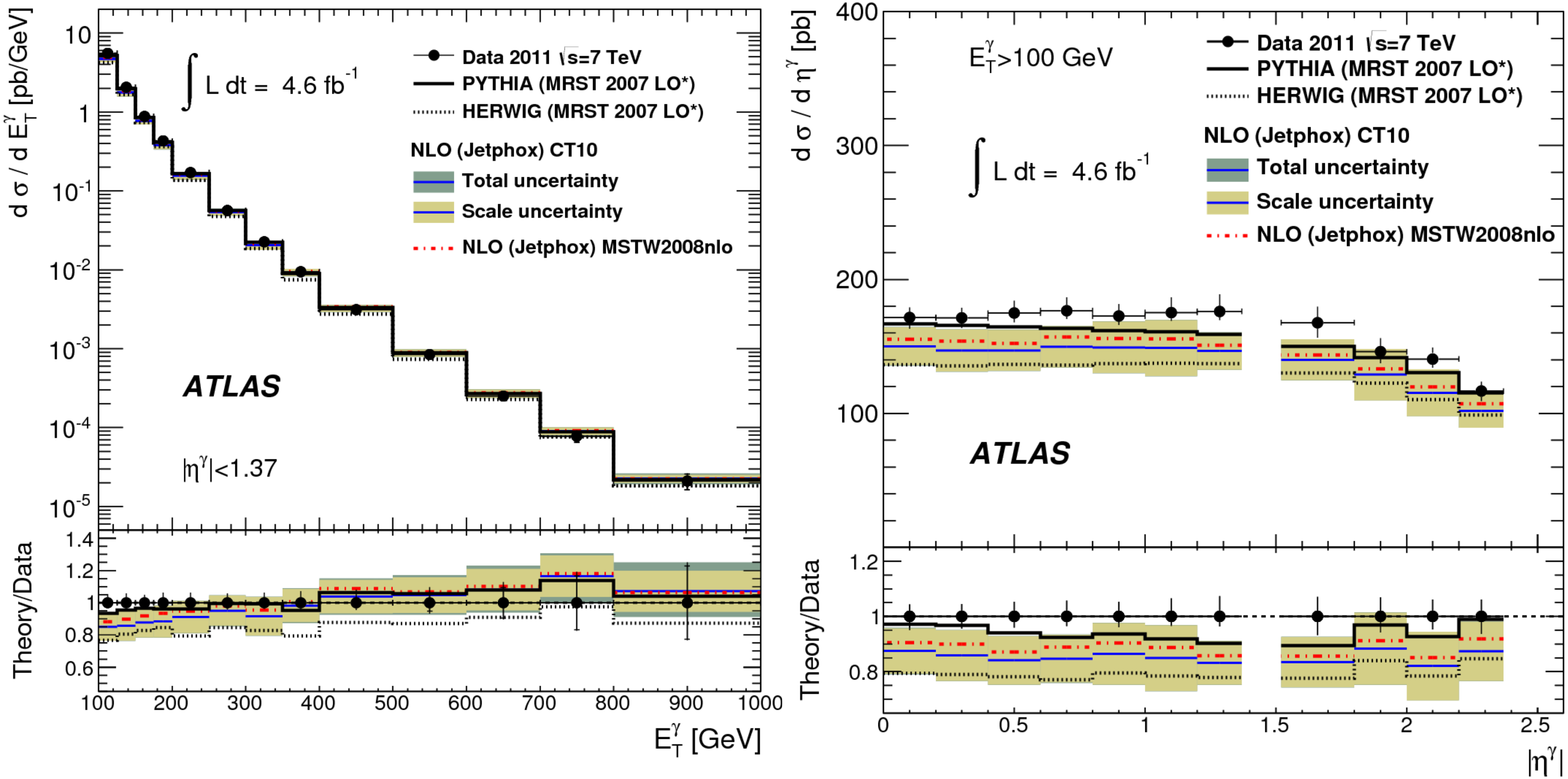


CMS-SMP-12-028

Isolated Photons

Useful for gluon constraint

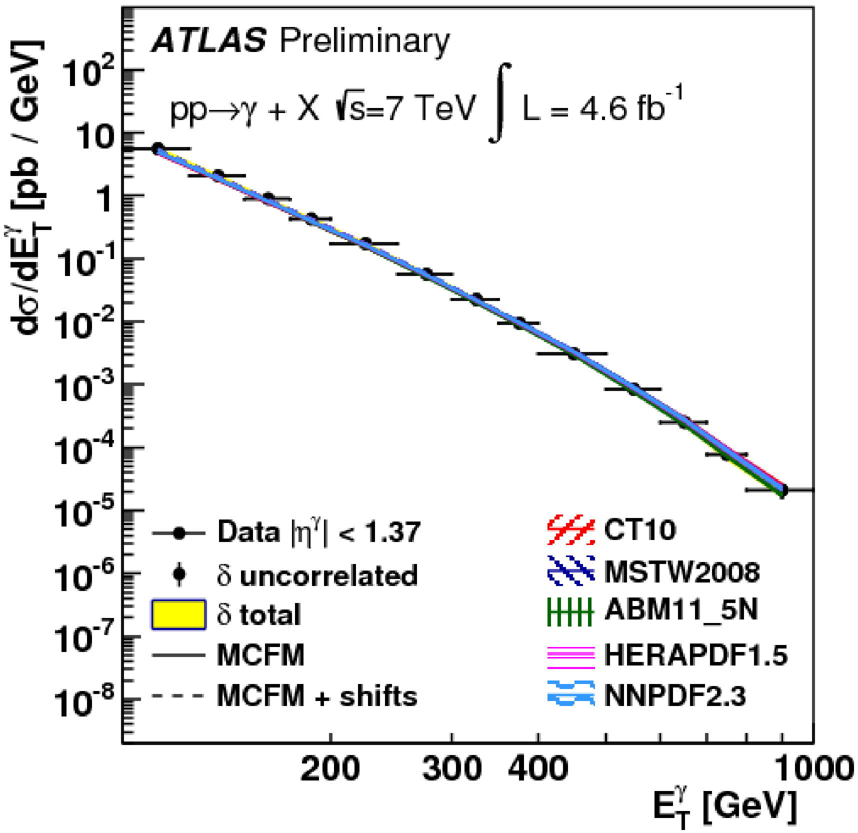
Phys. Rev. D 89, 052004 (2014)

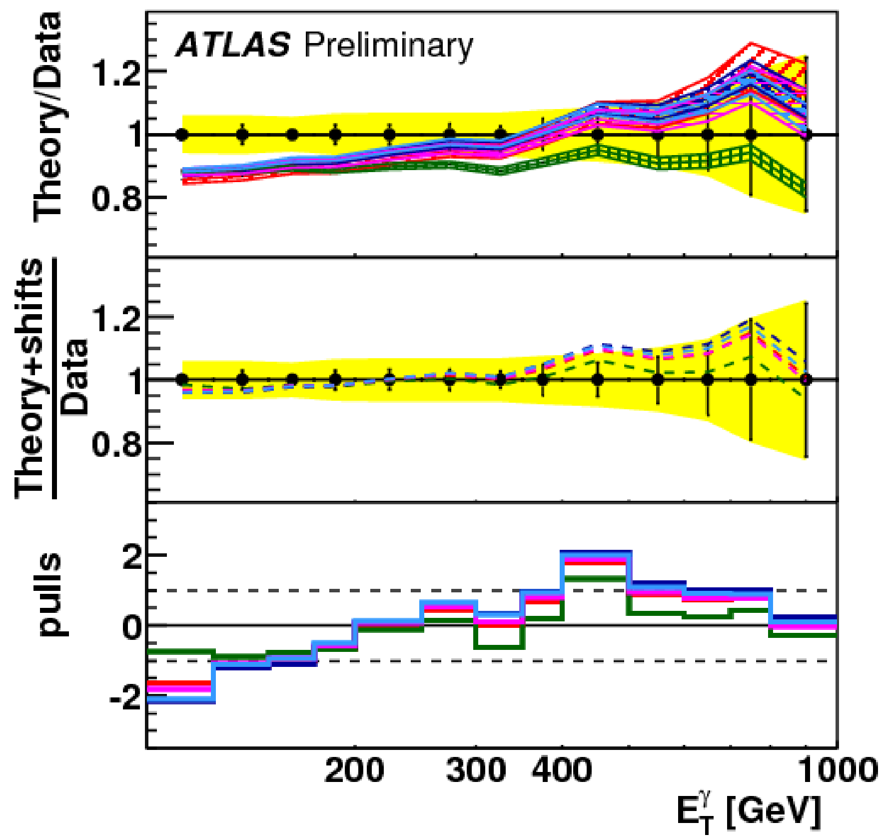


Photons and PDFs

Prompt photon data also have a significant impact on gluon PDF

ATL-PHYS-PUB-2013-018

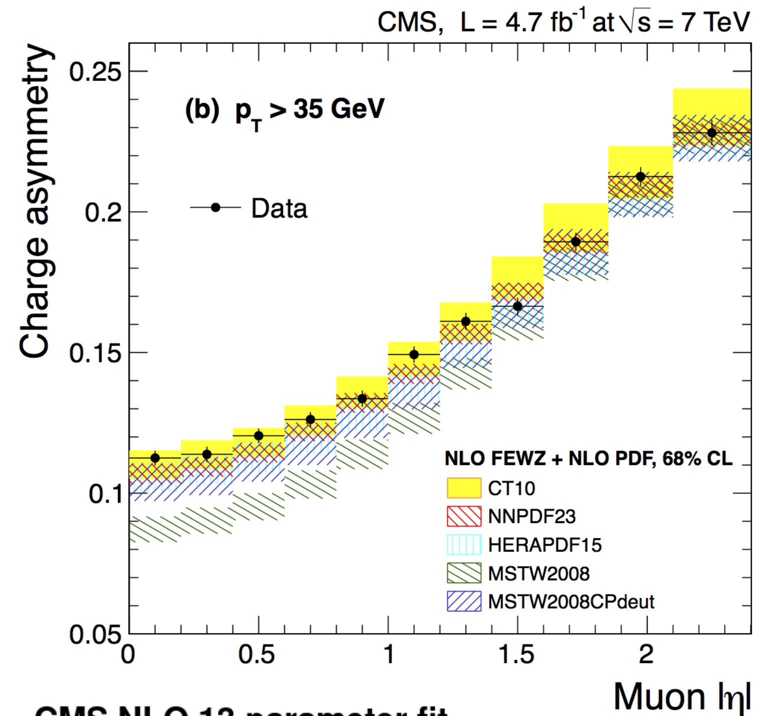


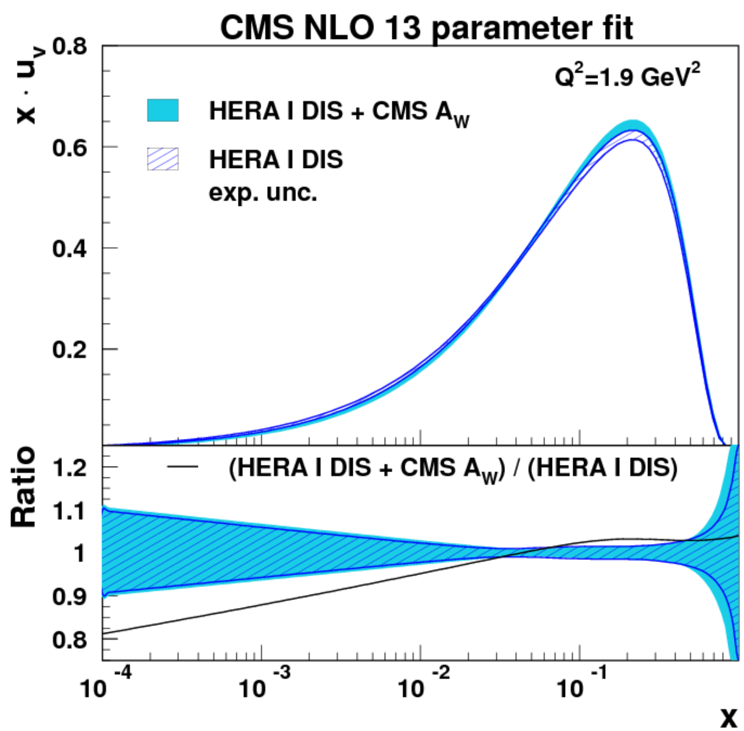


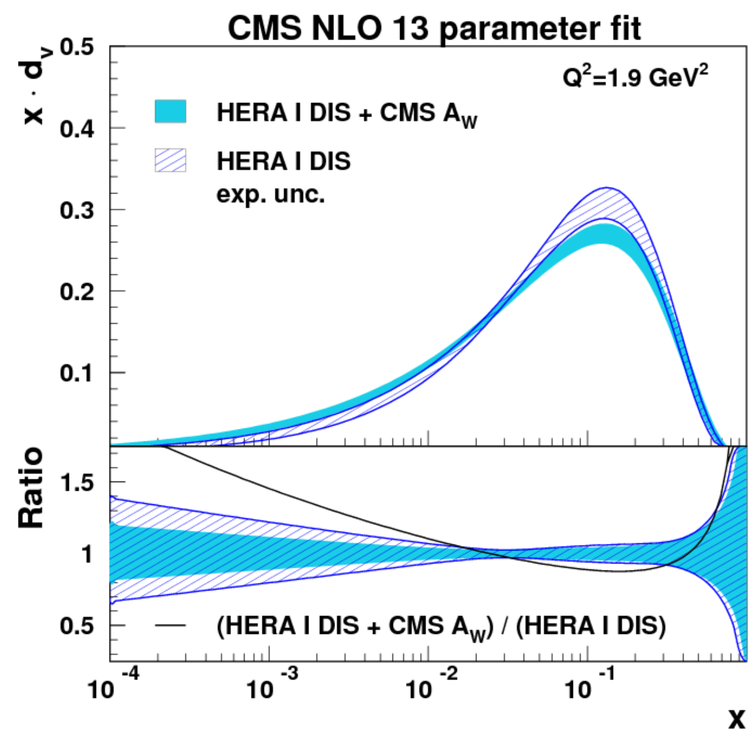
W charge asymmetry

- Probe of valence quarks
- Including CMS data predicts slightly more u and less d

PRD 90 (2014) 032004

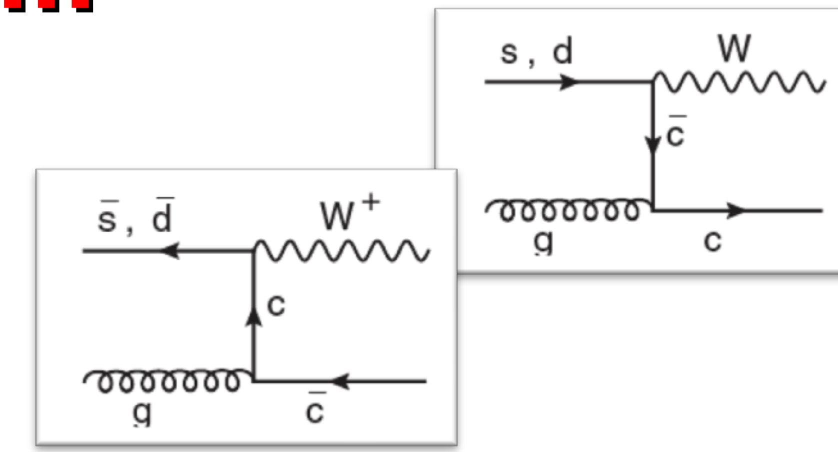




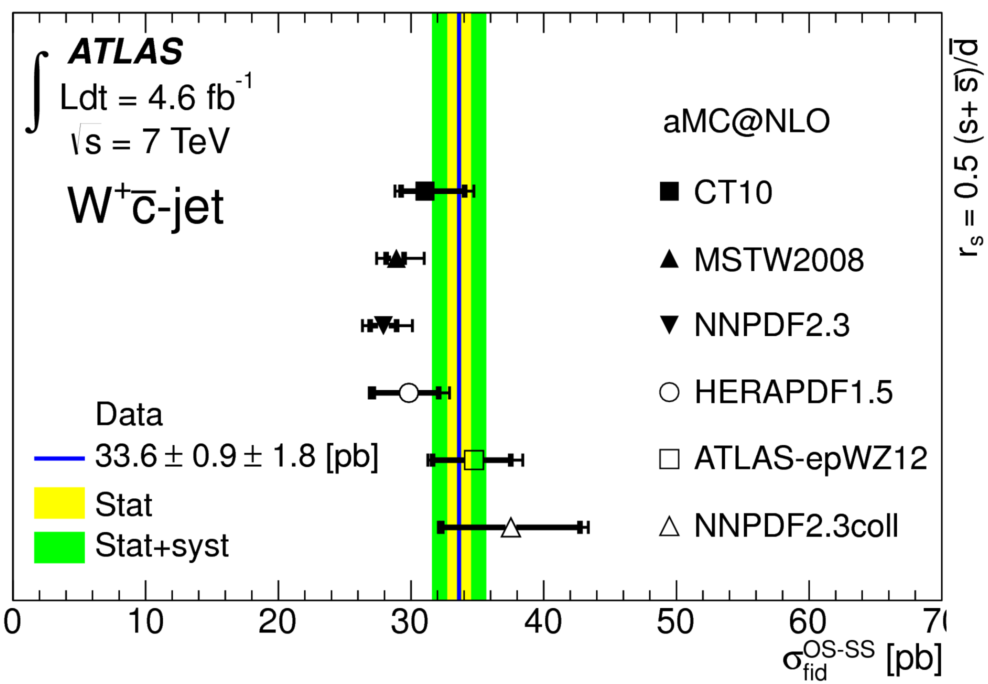


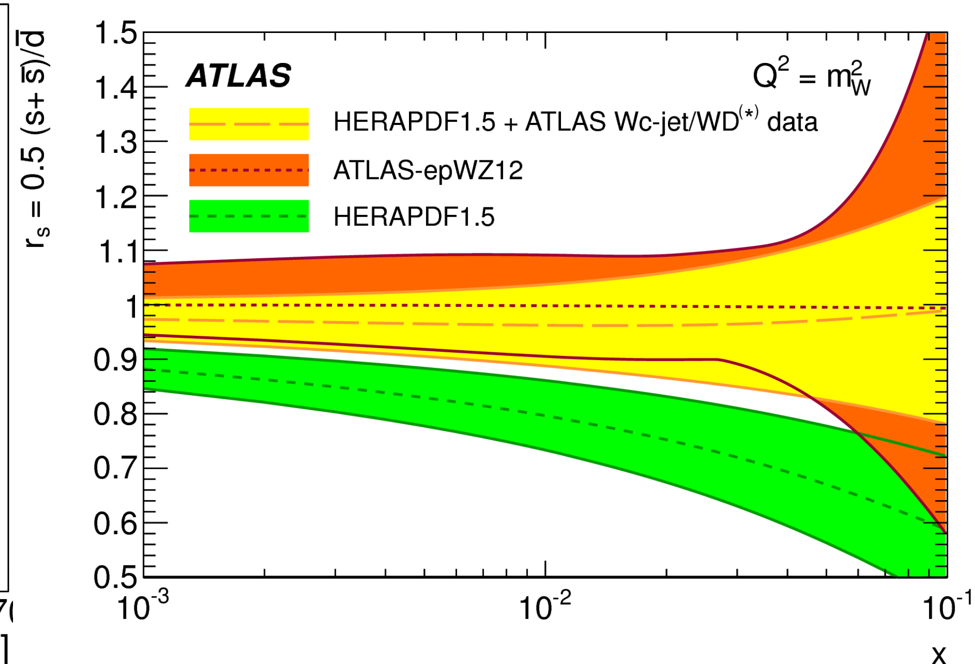
W+charm

- Probes the strange quark pdf
- Different PDFs predict different suppressions of s quark w.r.t. d quark
  - ATLAS data consistent with no or small suppression



JHEP05(2014)068

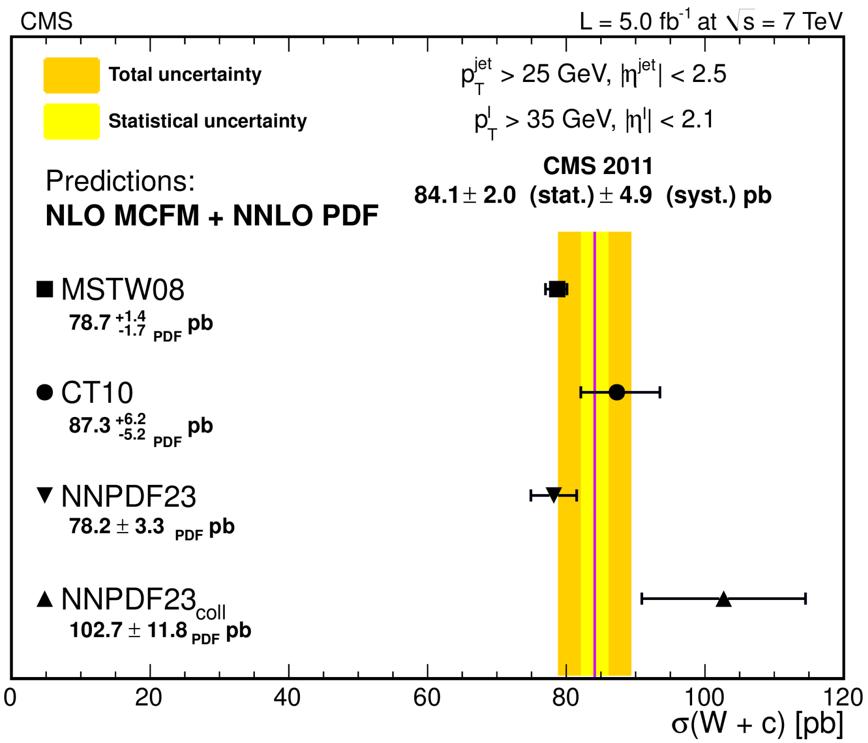


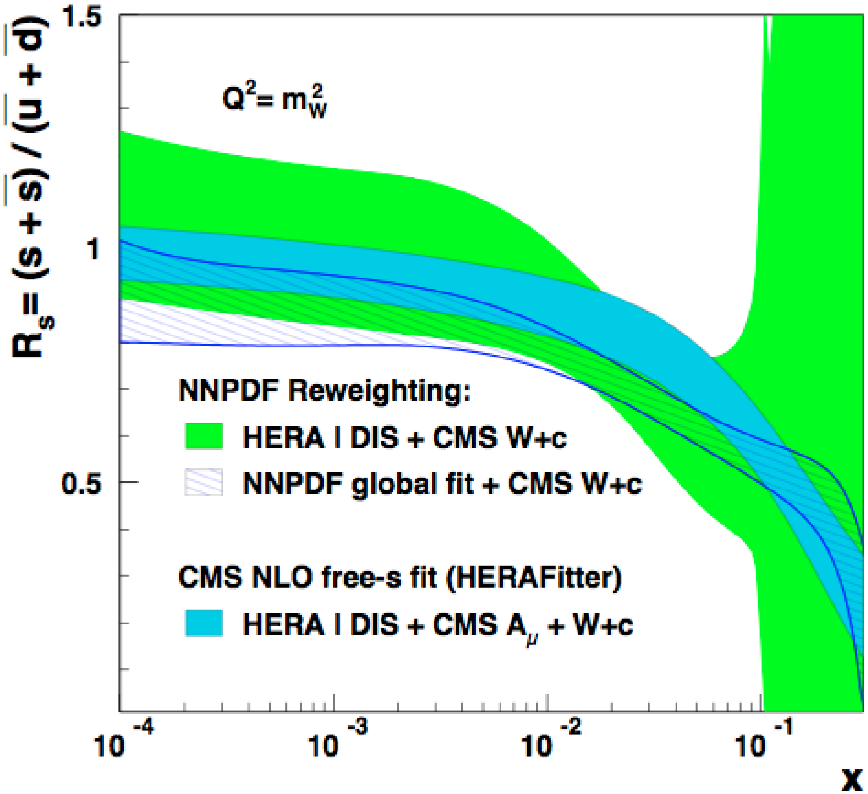


W+charm

- CMS tends to favor s suppression
  - Some tension between CMS and ATLAS on this measurement

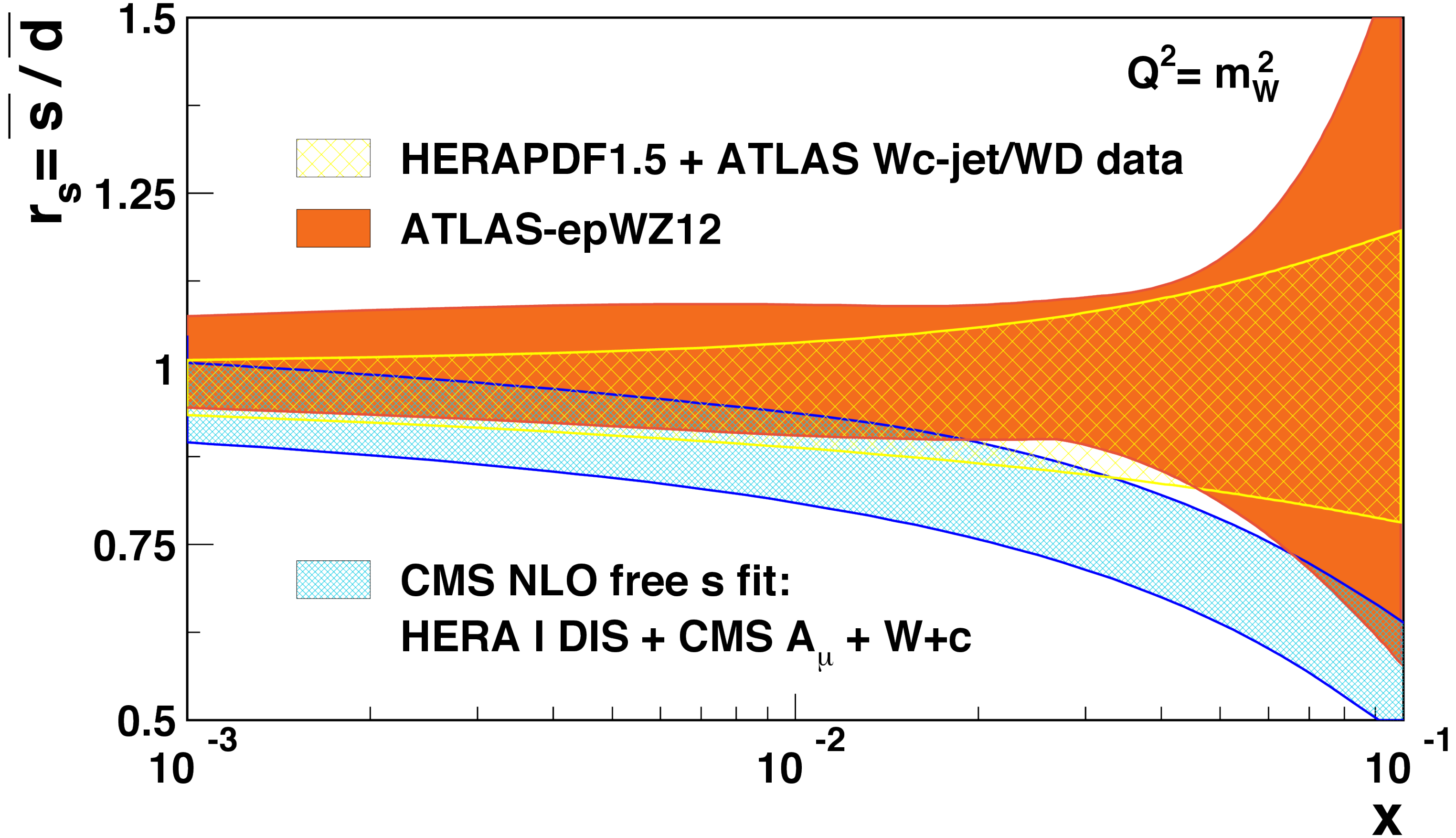
JHEP02(2014)013





W+charm

- CMS tends to favor s suppression
  - Some tension between CMS and ATLAS on this measurement



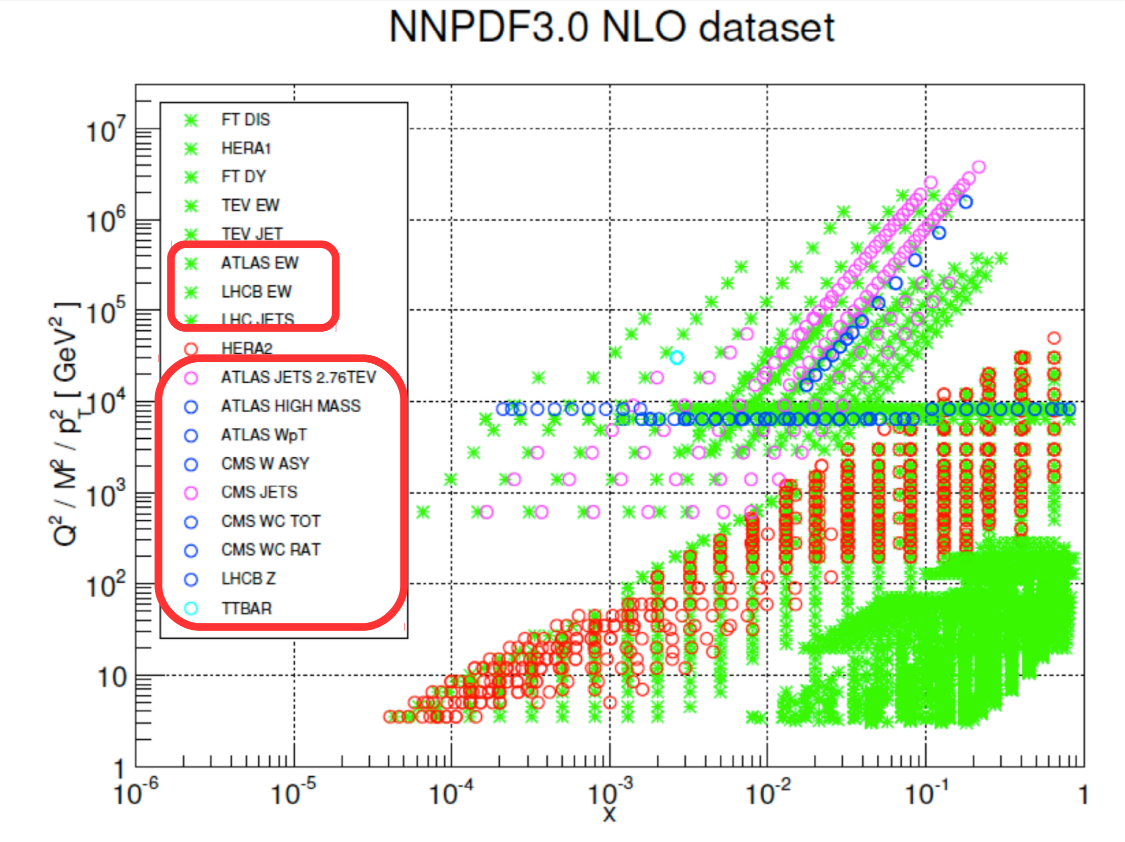
Impact of LHC on PDF

New experimental data

J. Rojo

- More than **1000 new data points** from new HERA and LHC **data**

  - ☑ **HERA structure function data:** HERA-II structure functions from H1 and ZEUS, combined HERA F_{2c} cross-sections
  - ☑ **LHC jet data:** CMS **7 TeV inclusive jets** from 2011, ATLAS **2.76 TeV jets** including their correlation with the 7 TeV jet data
  - ☑ **LHC electroweak data:** CMS **muon asymmetries** from 2011, LHCb **Z rapidity distributions** from 2011, CMS **W+charm** production data, ATLAS and CMS **Drell-Yan production**, ATLAS **W** p_T distributions
  - ☑ **ATLAS and CMS top quark pair production data**

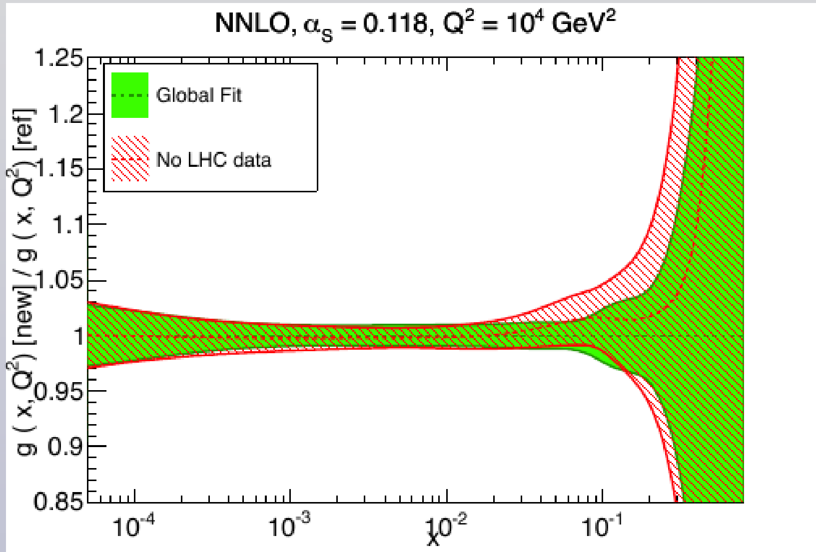


All these datasets **already reasonably well described by NNPDF2.3**

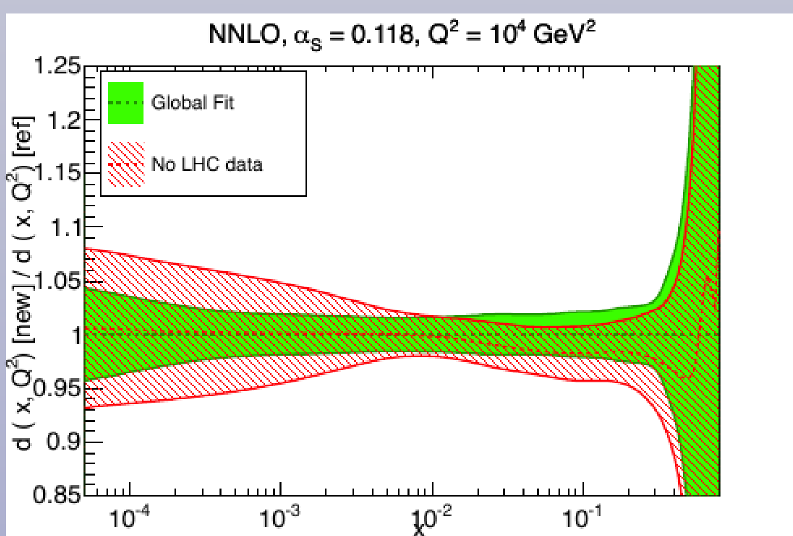
Impact of LHC on PDF

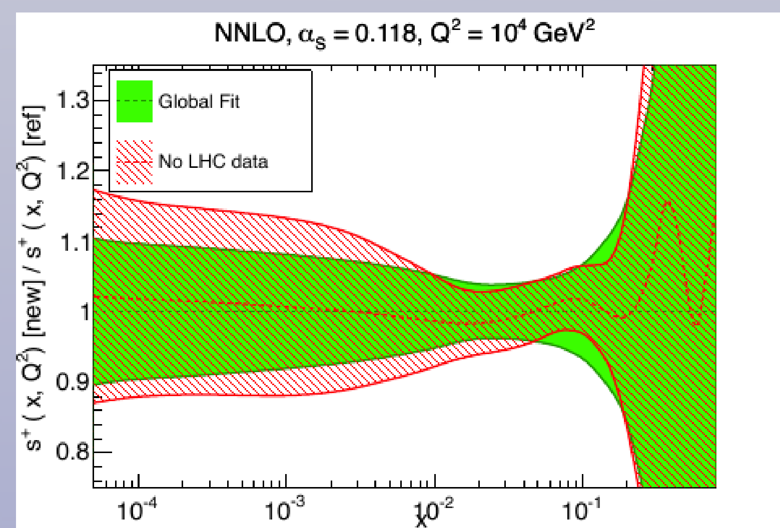
Impact of LHC data

J. Rojo

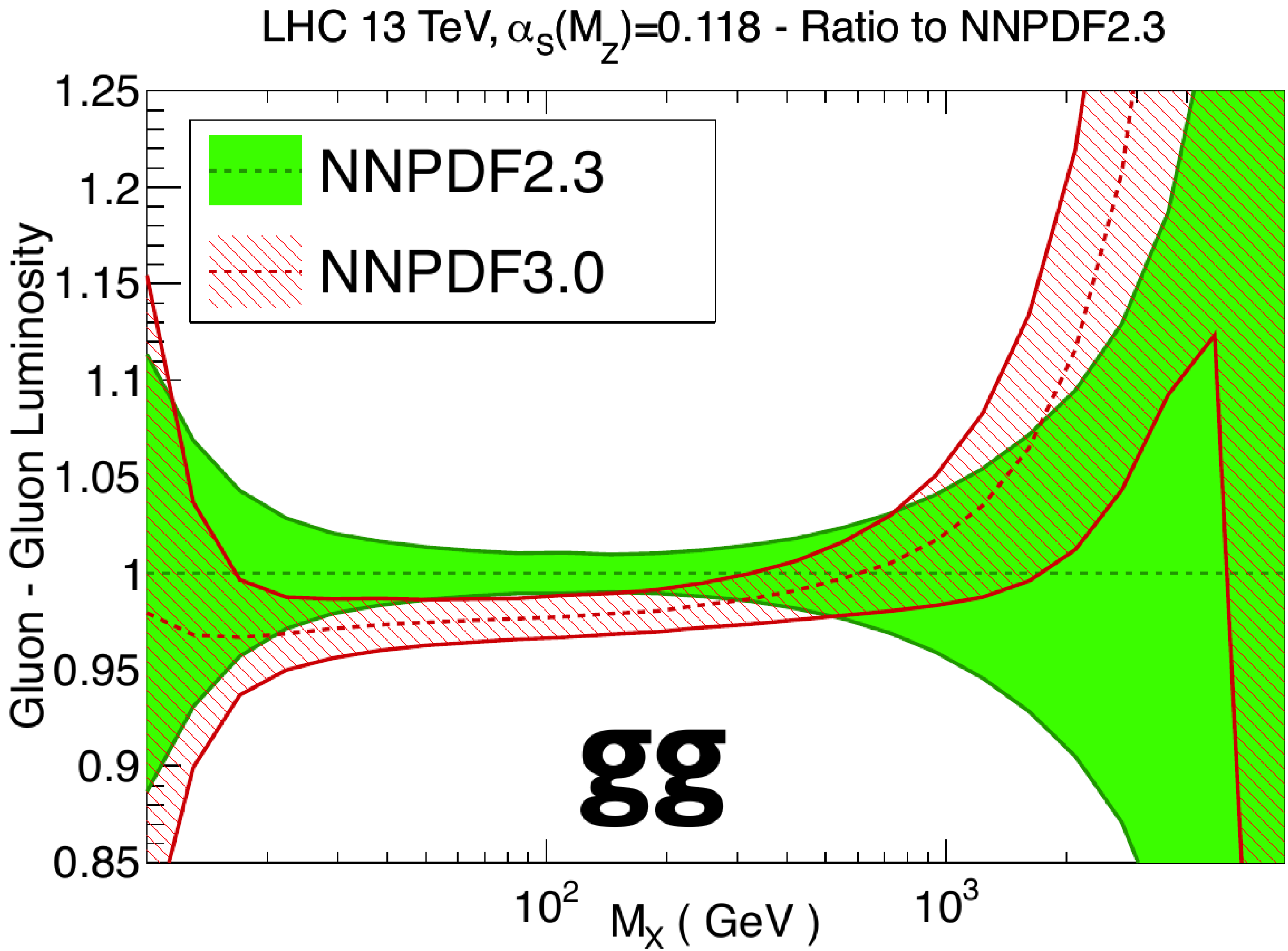


- Compare global NNPDF3.0 fit with a fit **without LHC data**
- PDF uncertainties on **large-x gluon** reduced due to **top quark and jet data**
- PDF uncertainties on **light quarks** reduced from the **Drell-Yan** and **W+charm data**
- The **description of all new LHC data**, already good in NNPDF2.3, is further improved in NNPDF3.0



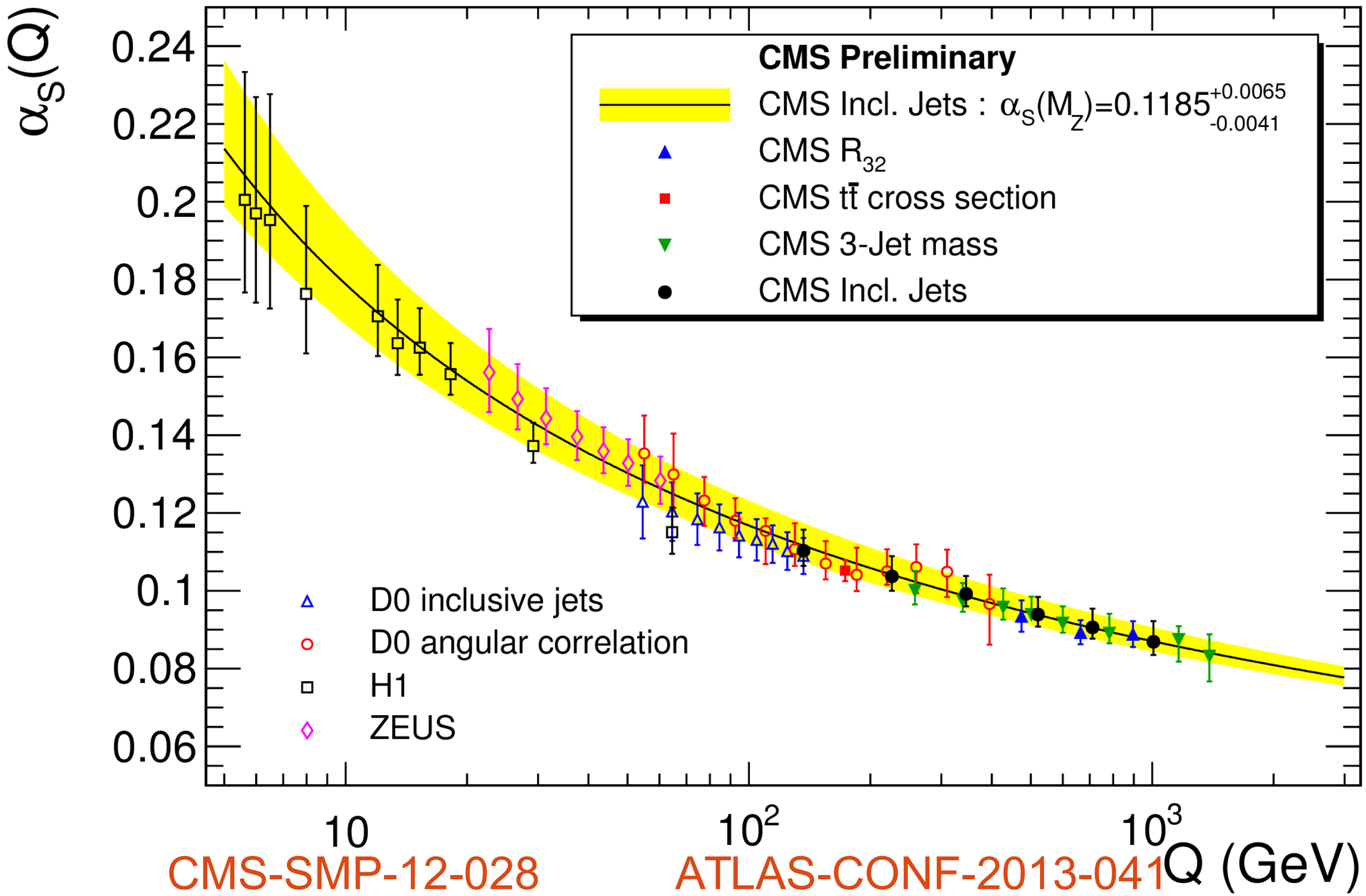


Impact of LHC on PDF



α_s determination

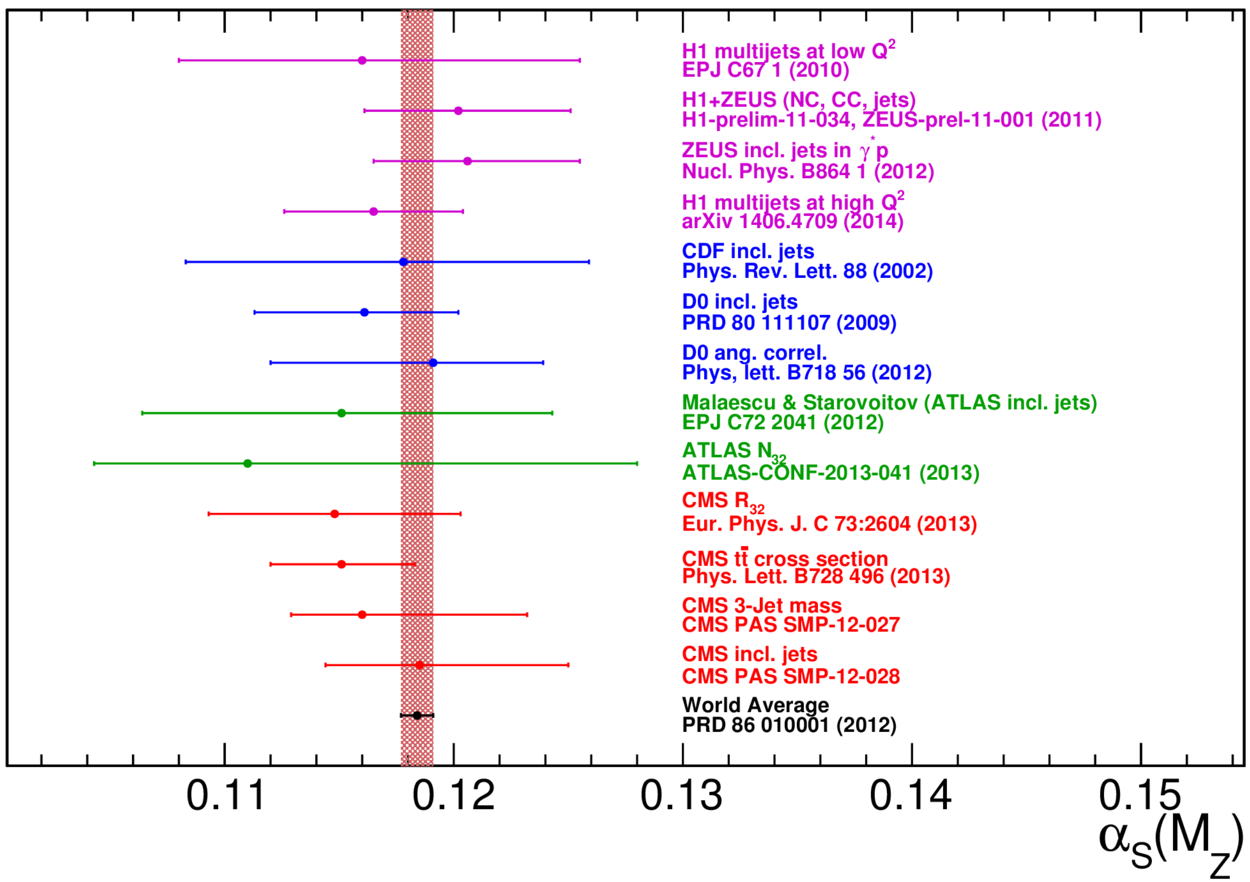
- Several measurements using different observables
  - Inclusive jets, R32, 3-jet mass $t\bar{t}$ cross section
  - Running probed up to the TeV scale



CMS-SMP-12-028 ATLAS-CONF-2013-041

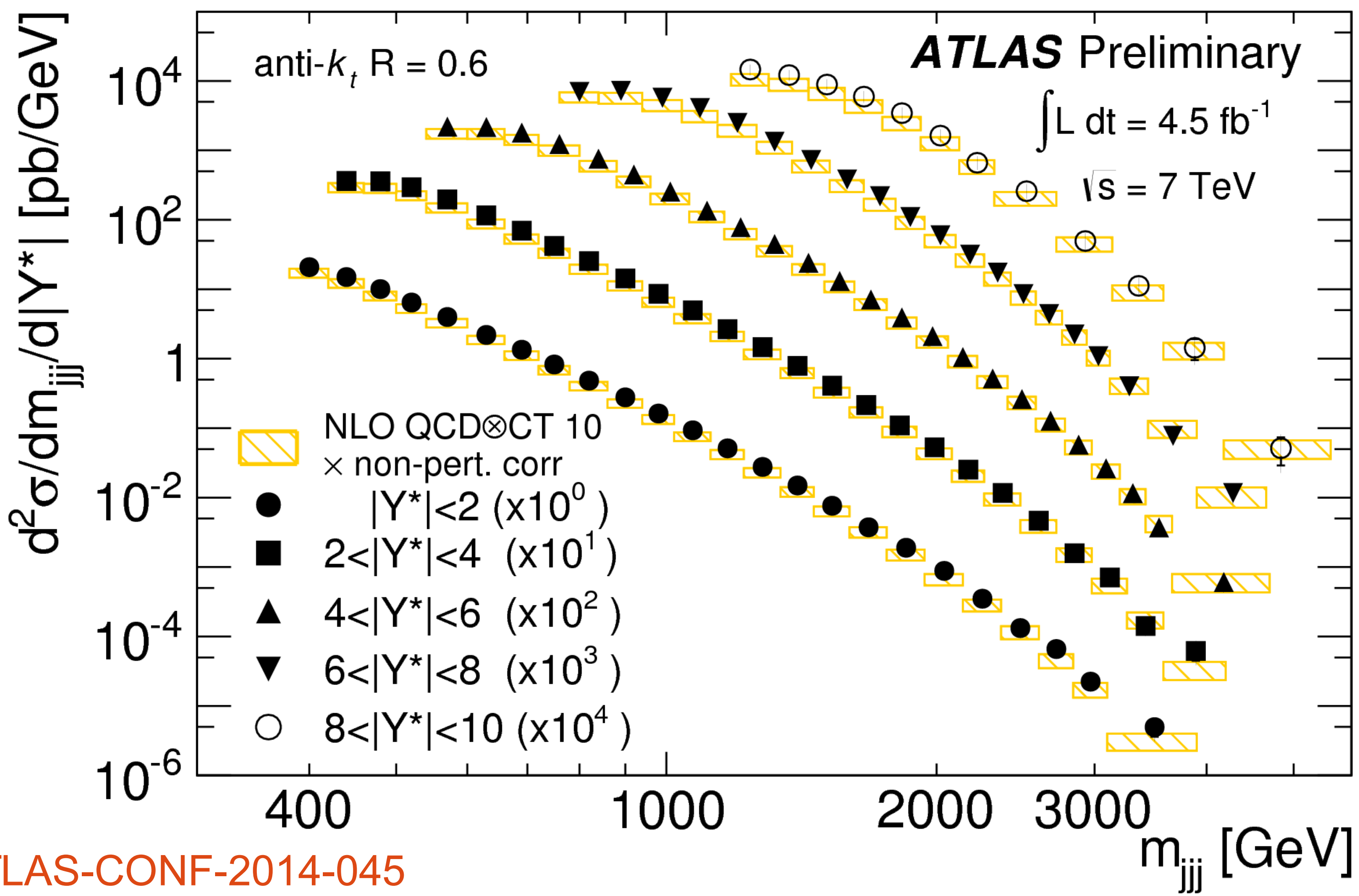
α_s determination

- Several measurements using different observables
  - Inclusive jets, R32, 3-jet mass $t\bar{t}$ cross section
  - Running probed up to the TeV scale



Multi-jet final states

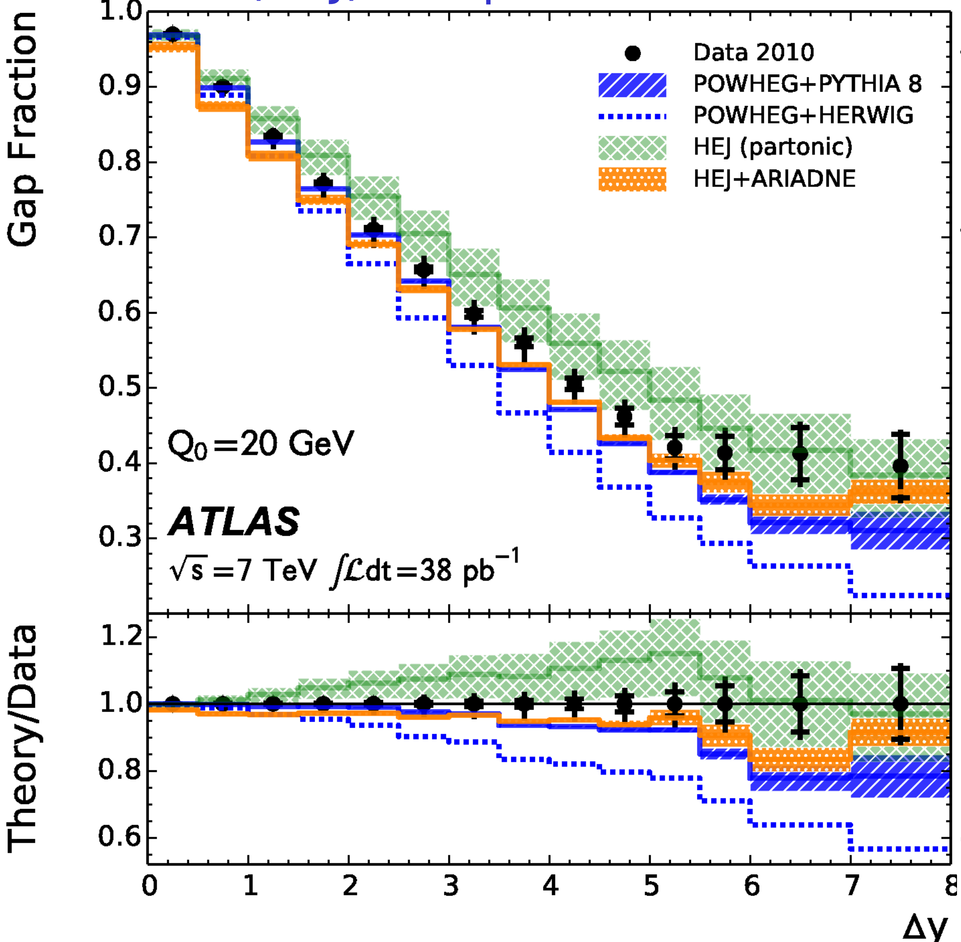
Going more exclusive

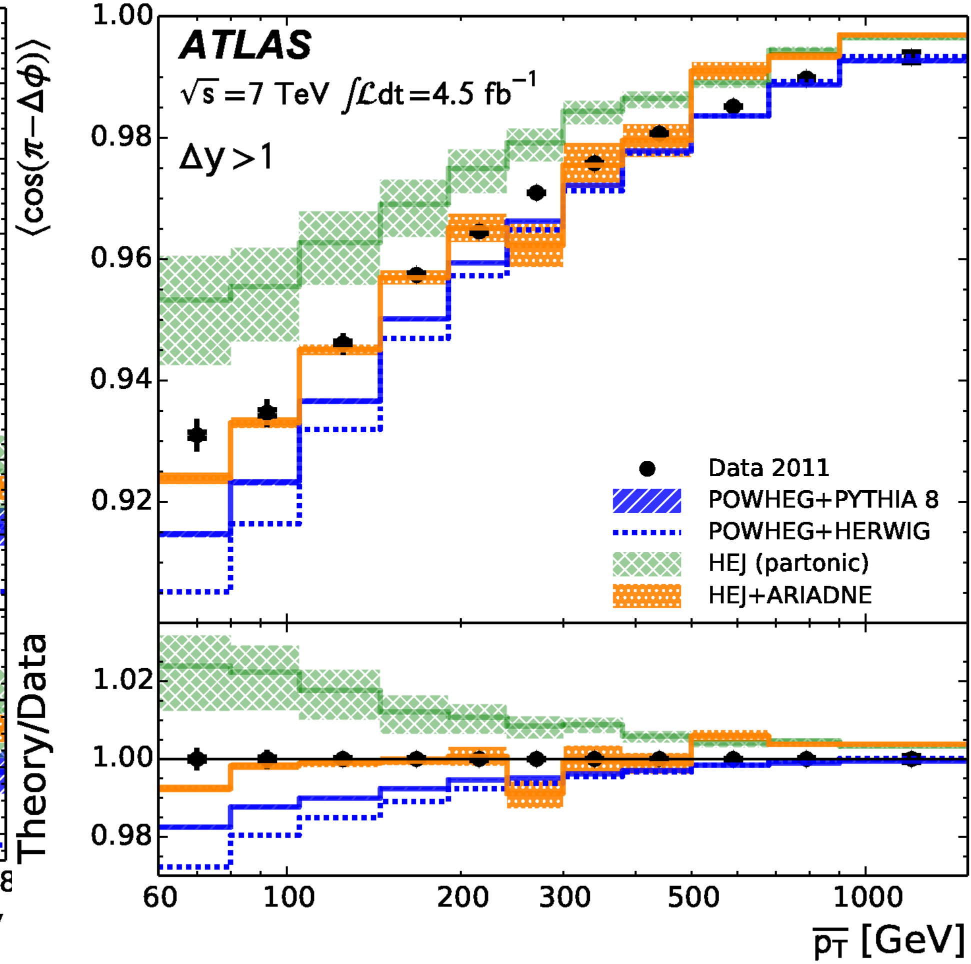


ATLAS-CONF-2014-045

Multi-jets and rapidity gaps

- Evaluate activity in rapidity gaps
- Sensitive to BFKL dynamics
  - Both NLO dijet+PS (powheg) and a BFKL inspired model + PS (HEJ) compared to the data with similar performances



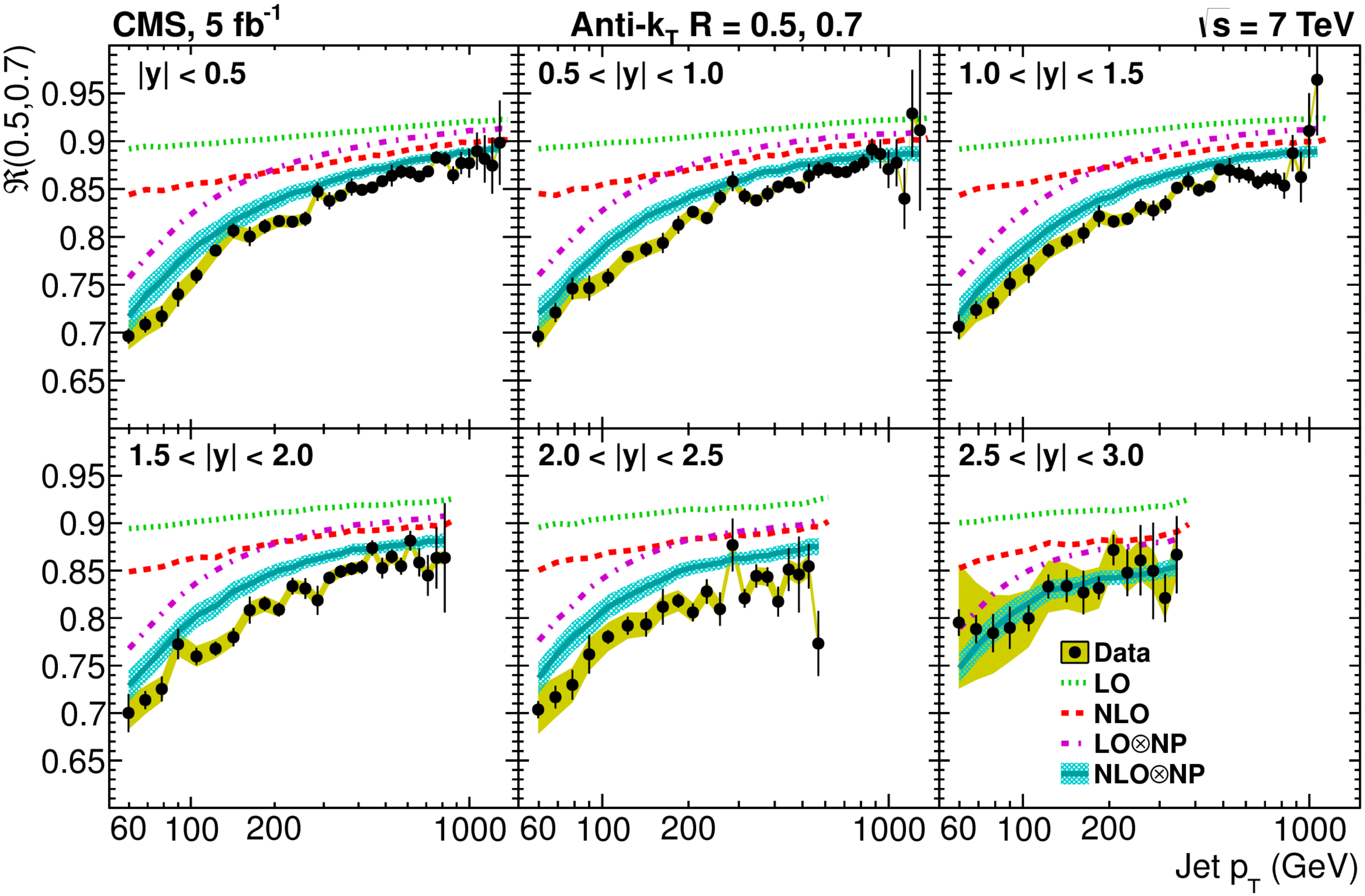


arXiv:1407.5756

Different jet sizes

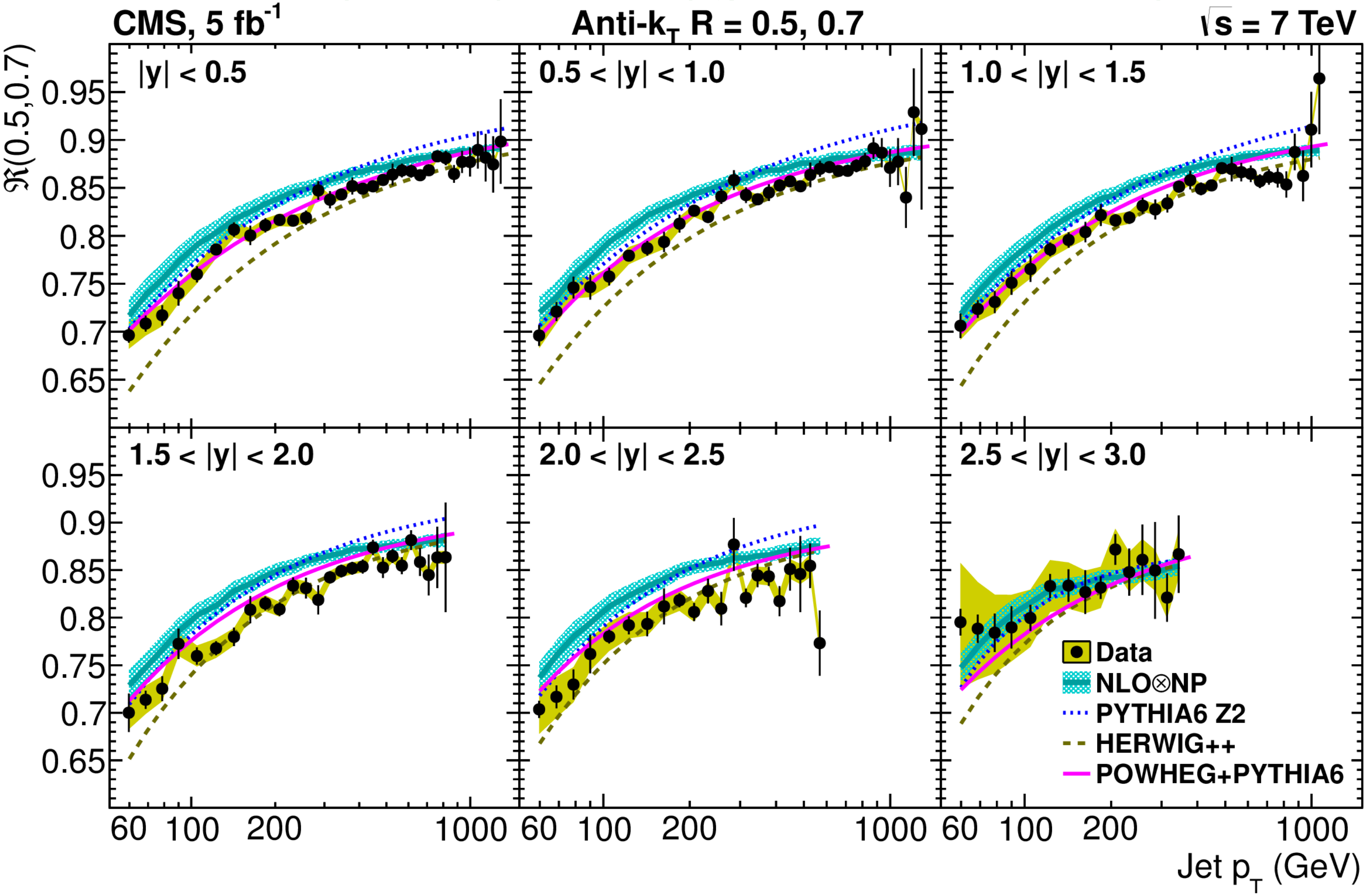
- Ratio of inclusive jet spectra with R-0.5 and 0.7. What do we learn?
  - Importance of non-perturbative corrections on parton level predictions

arXiv:1406.0324



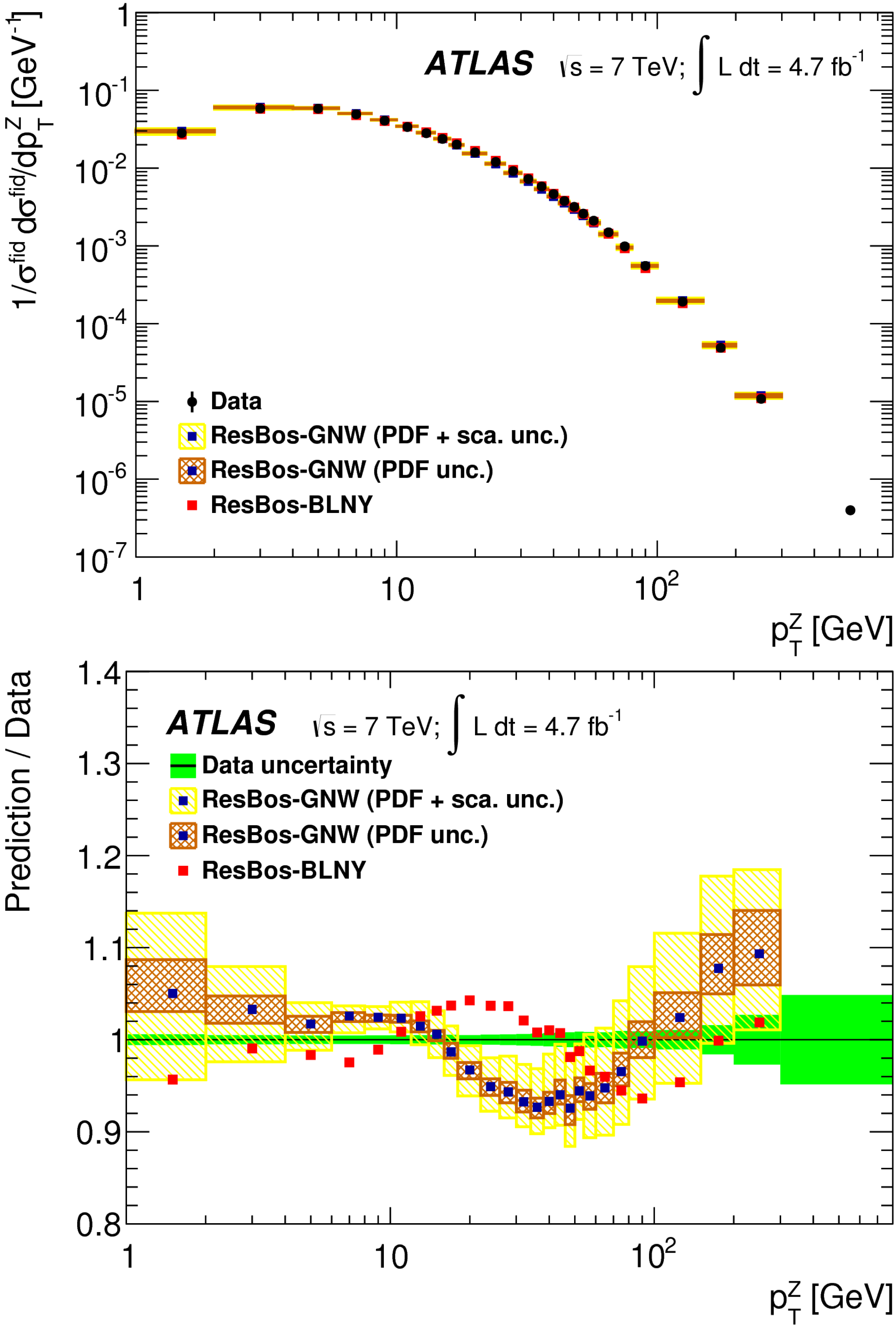
Different jet sizes

- Ratio of inclusive jet spectra with R-0.5 and 0.7. What do we learn?
  - Importance of Parton Shower
    - NLO dijet+PS (POWHEG) gives the best descrioption



Z pT

- A tough one.
- Important for W mass
- Measured inclusively and in rapidity bins
- Compared to different predictions
  - RESBOS-GNW
    - NNLO+NNLL
  - RESBOS-BLNY
    - NLO+NNLL
  - Agreement is withing 5-7% with some structures



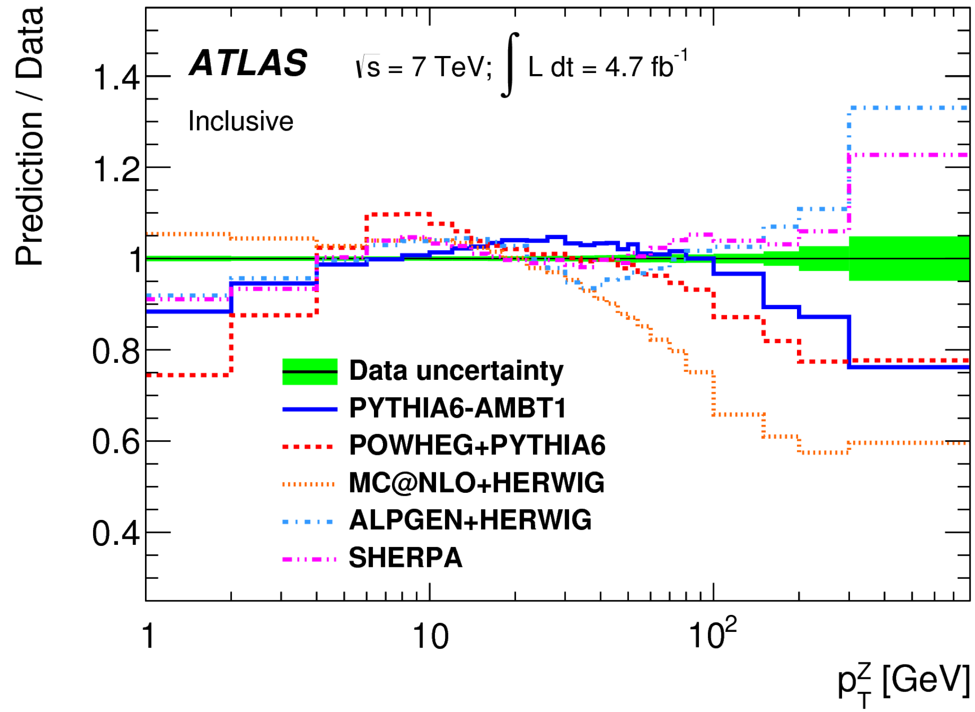
arXiv:1406.3660

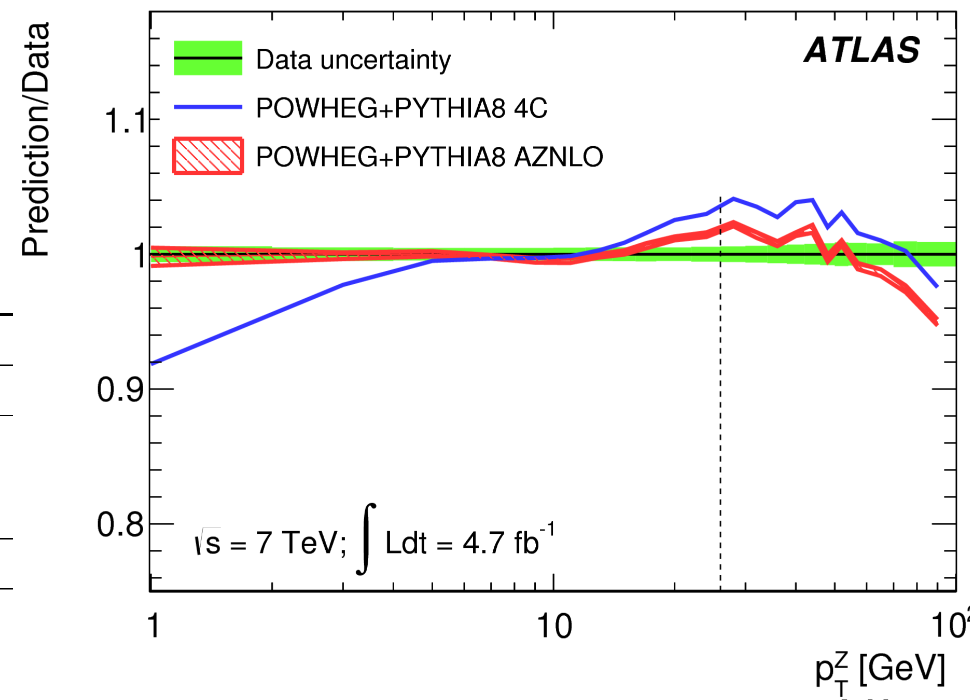
Z pT

- A tough one.
- Important for W mass
- Measured inclusively and in rapidity bins
- Compared to different predictions
  - Different MC generators
  - Data below 15 GeV were used for a tuning of POWHEG+Pythia8
    - Reduced primordial kT

	Pythia8	Powheg+Pythia8	Base tune
Tune Name	AZ	AZNLO	4C
Primordial k_T [GeV]	1.71 ± 0.03	1.75 ± 0.03	2.0
ISR $\alpha_S^{ISR}(m_Z)$	0.1237 ± 0.0002	0.118 (fixed)	0.137
ISR cut-off [GeV]	0.59 ± 0.08	1.92 ± 0.12	2.0
χ^2_{min}/dof	45.4/32	46.0/33	-

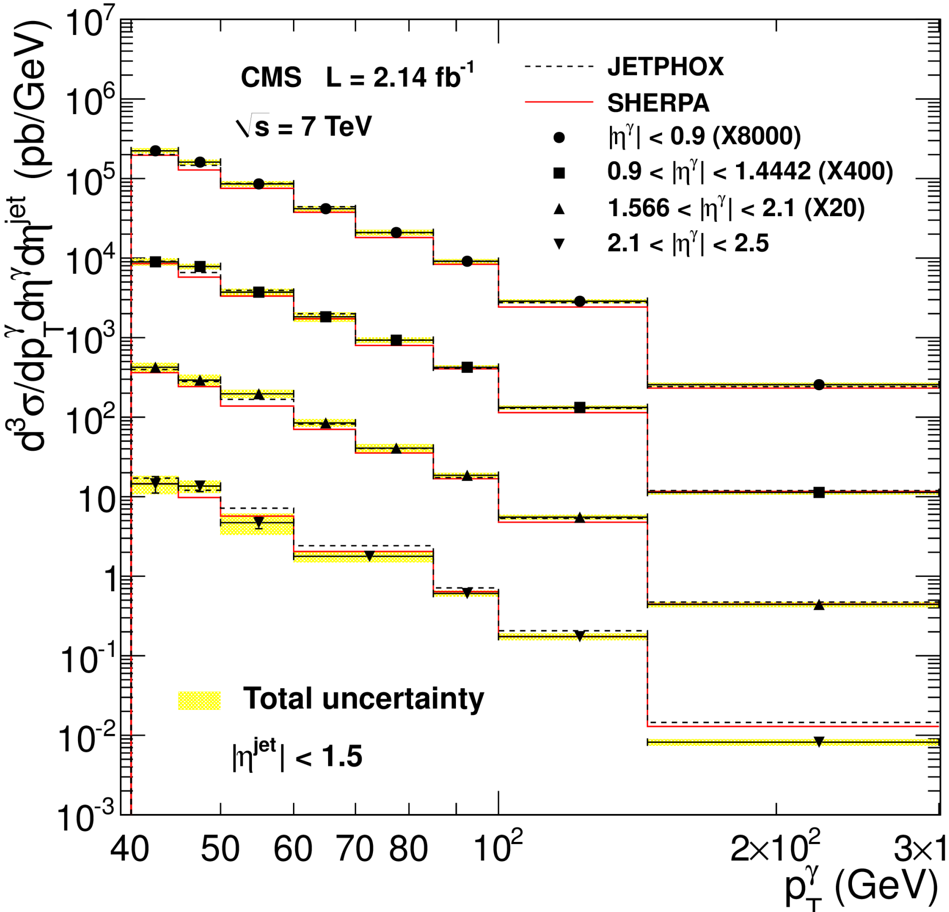
arXiv:1406.3660

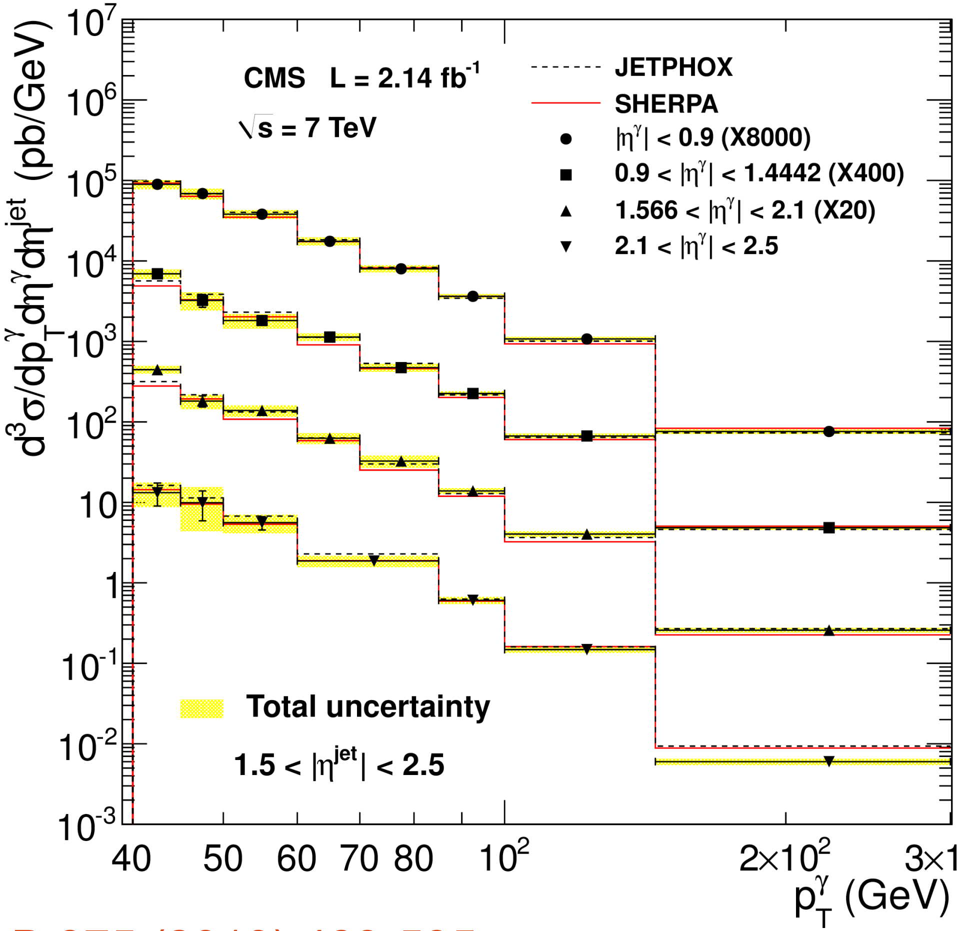




Photon + jets

- 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





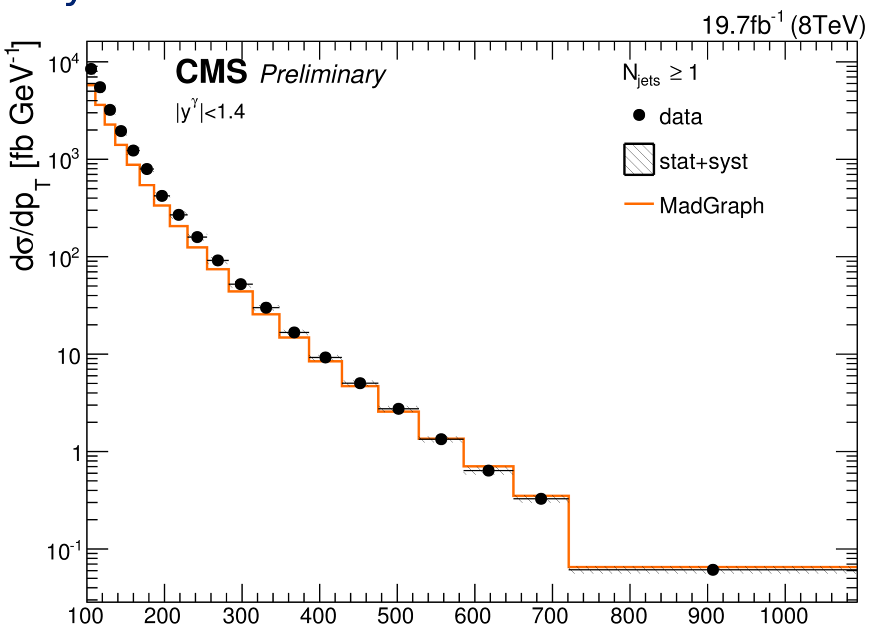
JHEP06(2014)009

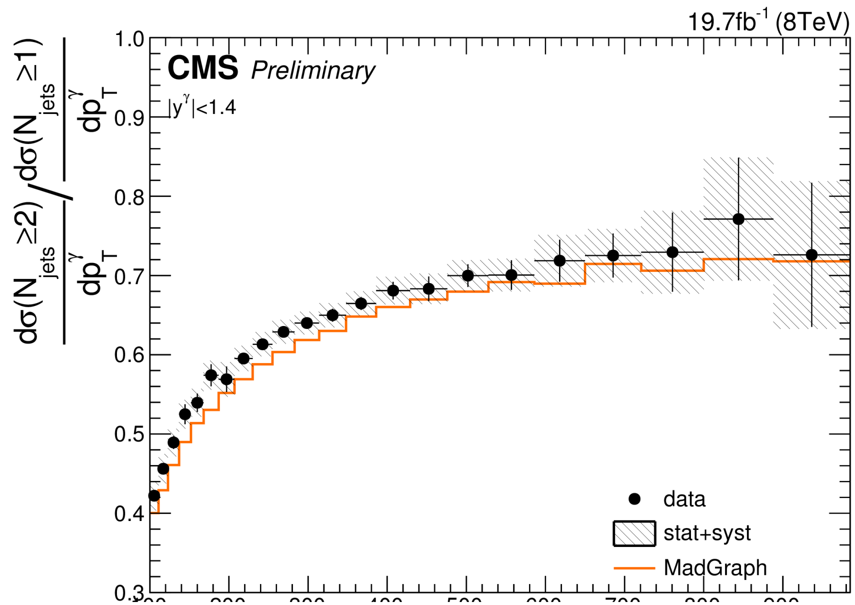
Nucl. Phys, B 875 (2013) 483-535

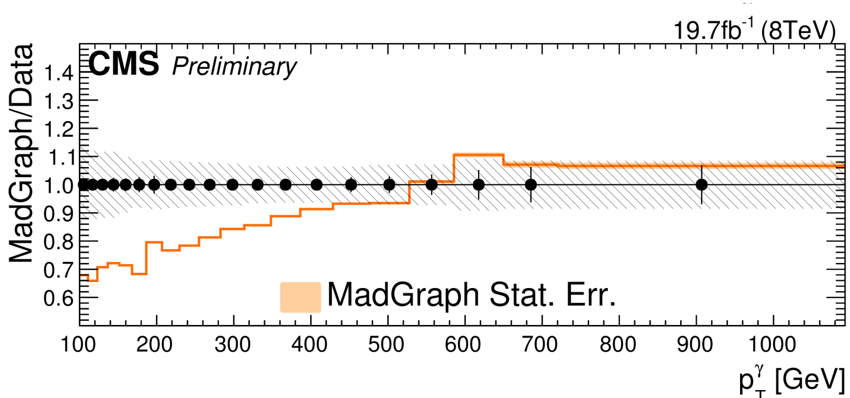
Photon+jets

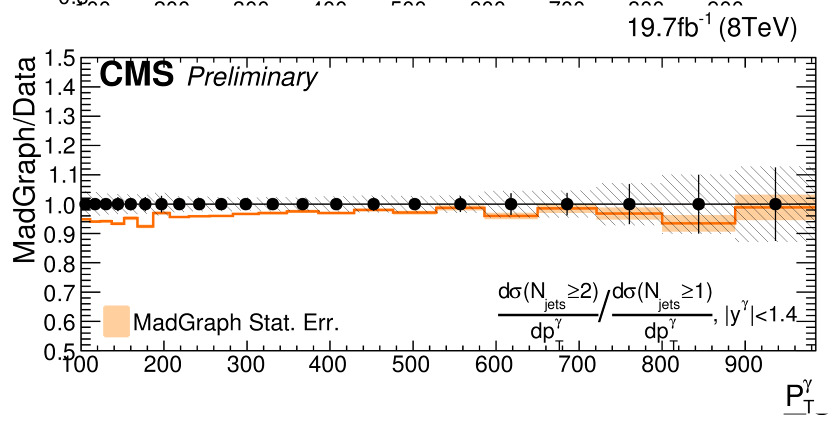
- Differential in jet multiplicity and HT
- Interesting test for ME+PS
- Studied ratios also, reduced experimental (and theoretical) systematics
- ~30% discrepancy, not flat in photon pT
  - Better description of the 2j over 1 jet ratio

CMS-SMP-14-005





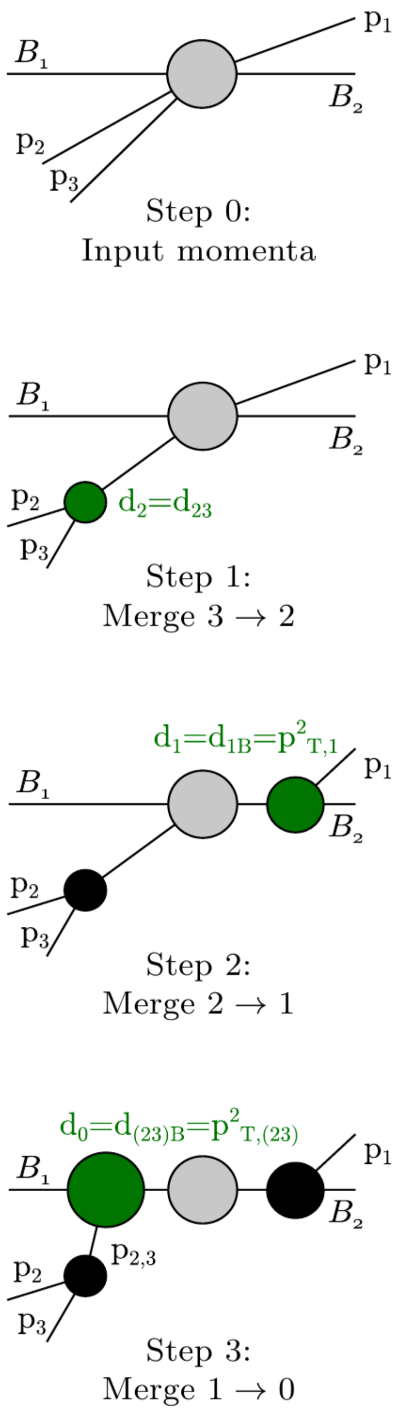




Event shapes in V+jets

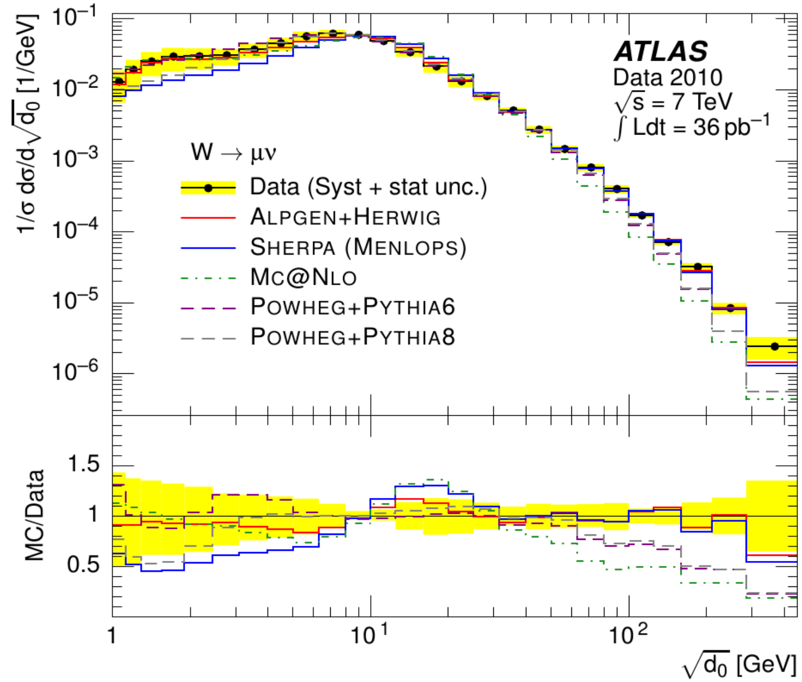
CERN-PH-EP-2013-003

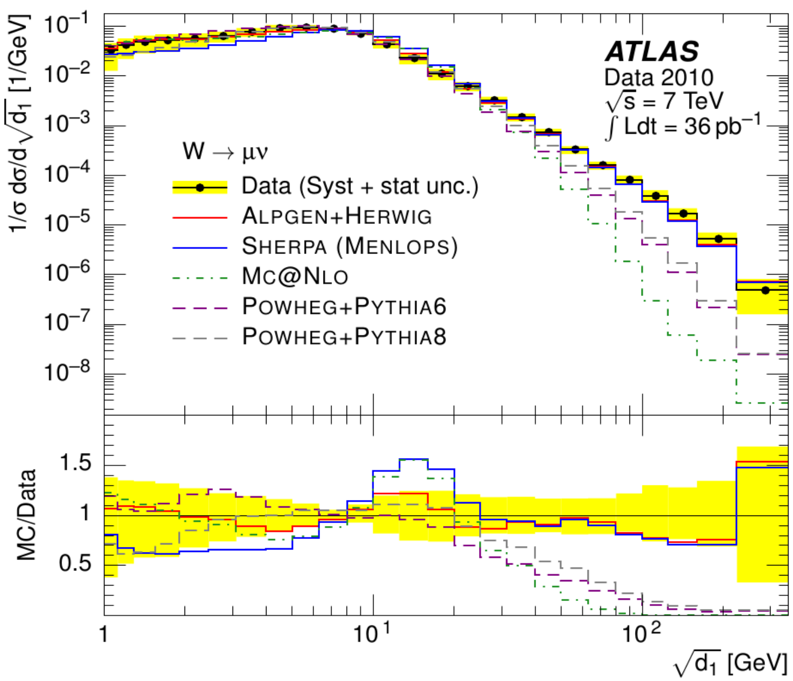
- KT splitting scales in W+jets
  - Aka differential jet rates
- The kT algorithm works with sequential recombination of particle momenta, based on the kT distance
- The recombination goes on until all kT distances of the resulting jets are above a given threshold
- This is a measurement of the value 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

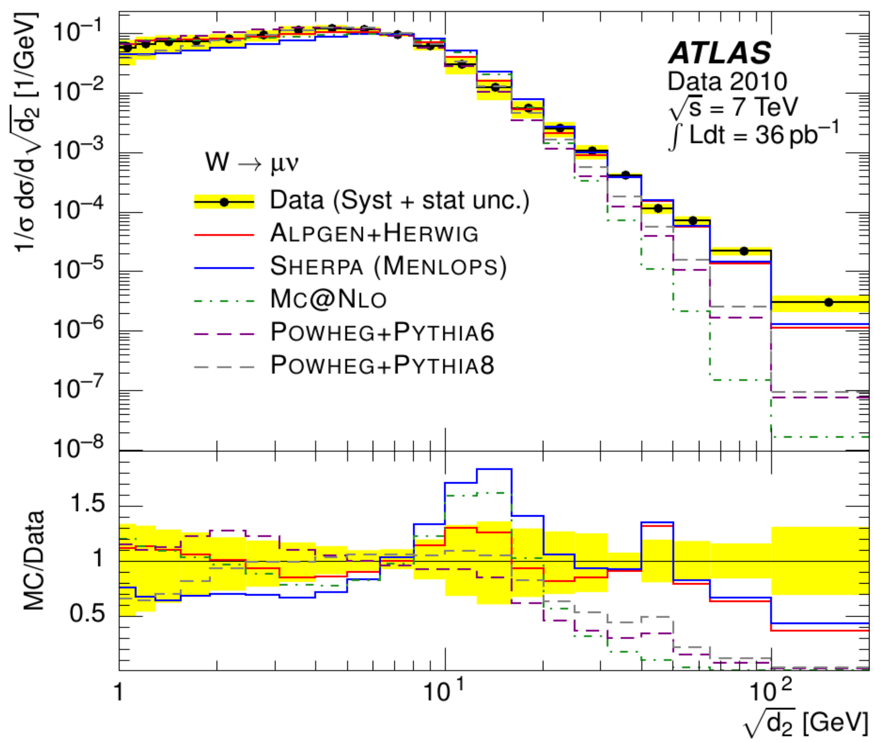


- LO+PS agrees well with the data
- All NLO+PS show less hard activity than the data
    - Expected due to missing multi-leg matrix elements
- The low end of the spectra, sensitive to the parton shower is very well described by Herwig

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



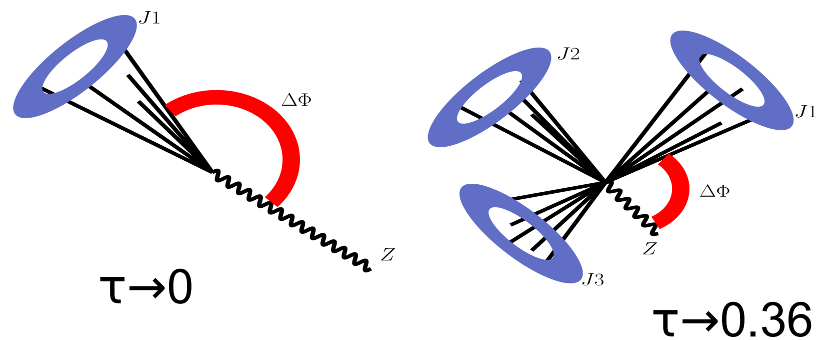




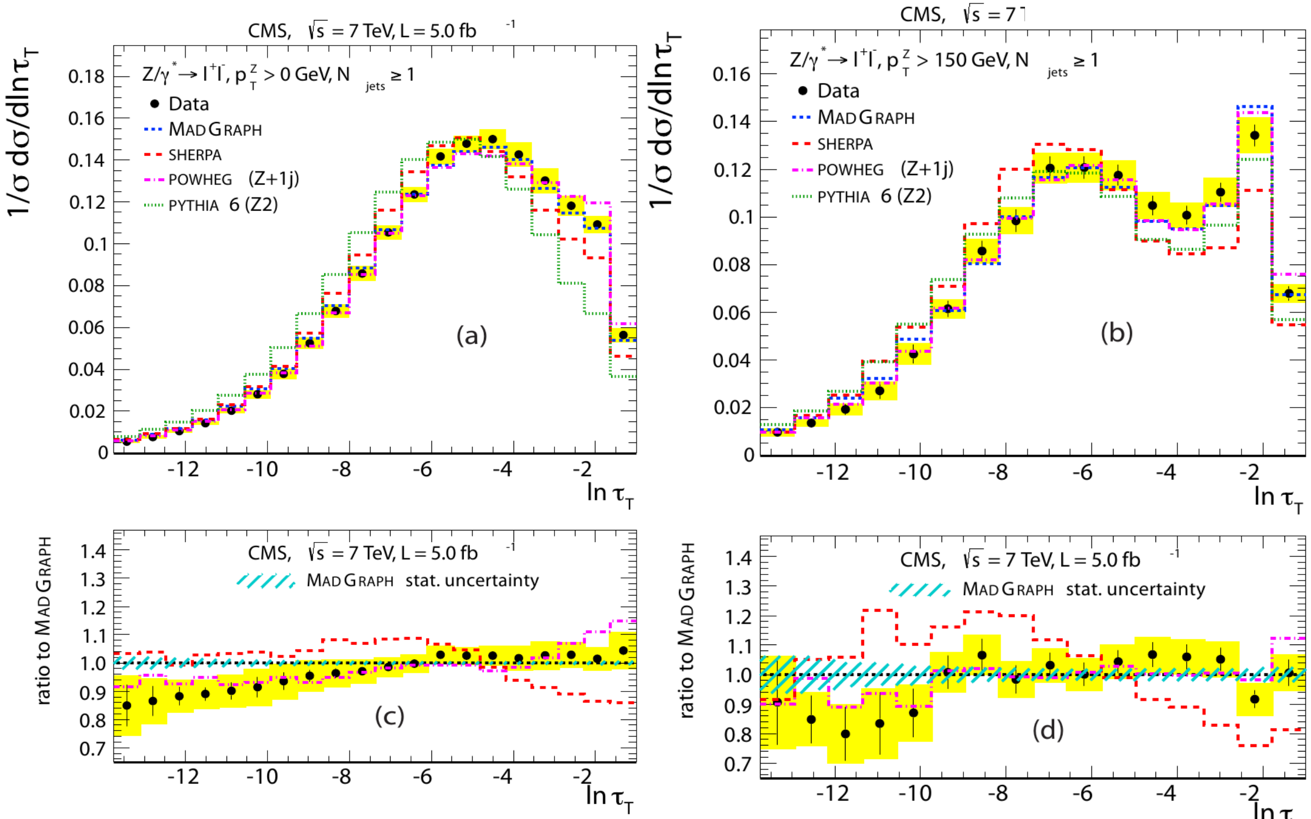
Event shapes in V+jets

Phys. Lett. B 722 (2013) 238–261

- 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



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



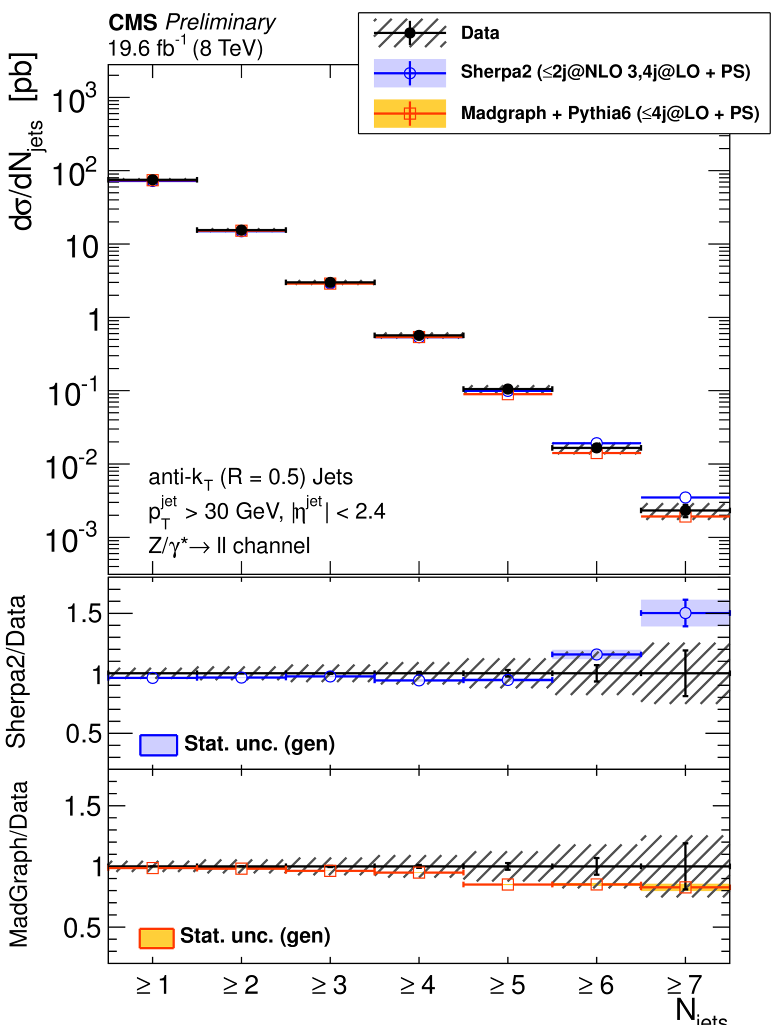
The region dominated by multijet topologies shows agreement with LO+PS (Madgraph)

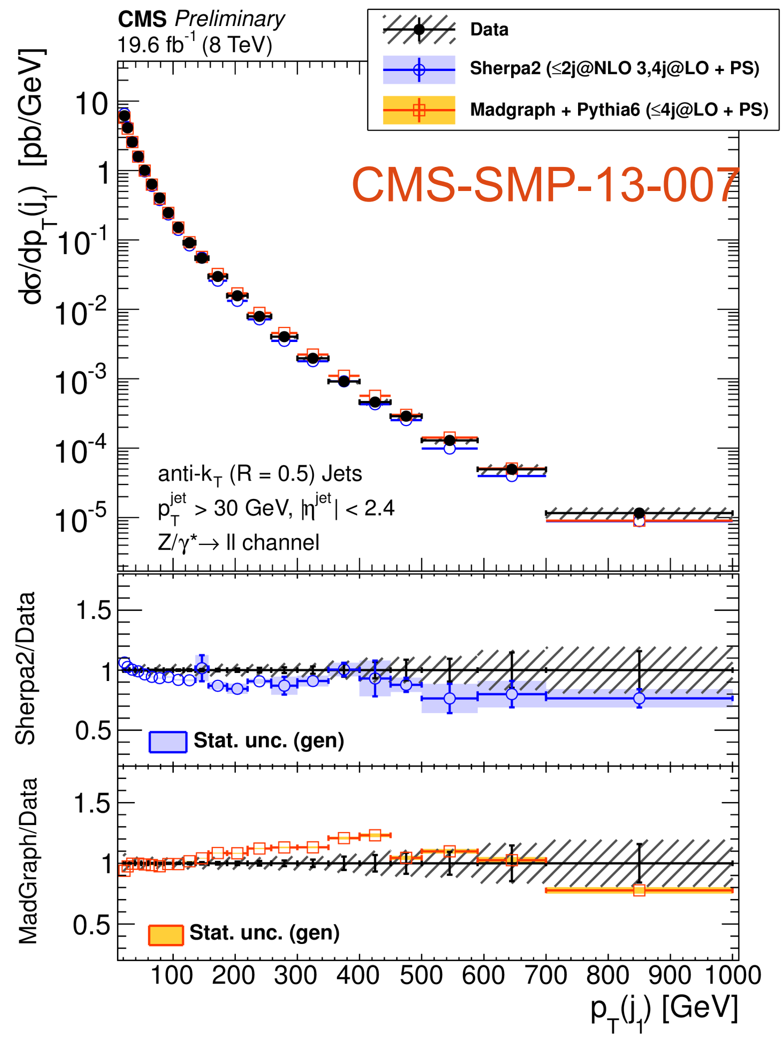
NLO +PS is also good, with a slight tendency to overshoot

Instead, in pencil-like topologies powheg shows best agreement

Z+jets

- Several measurements, differential, up to 7-8 jets with full Run1 stat!
  - Comparison with LO ME+PS and multi leg NLO +PS
  - Nice agreement with ME+PS for multiplicity
  - Some discrepancies in jet pT spectra below 300-400 GeV

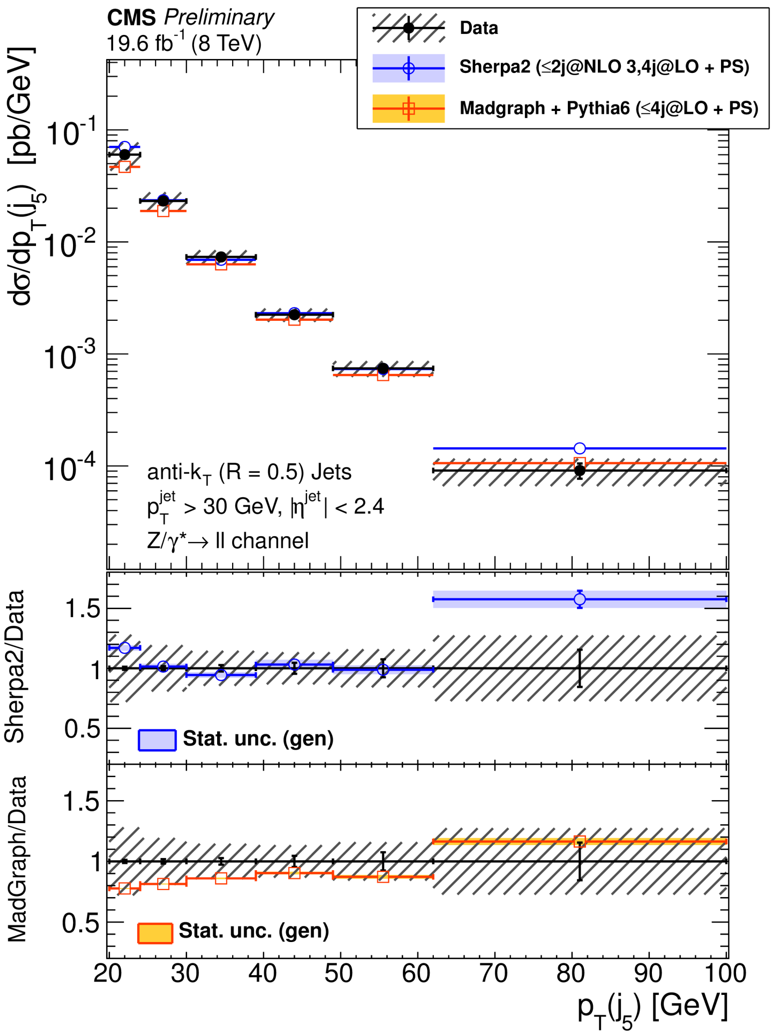


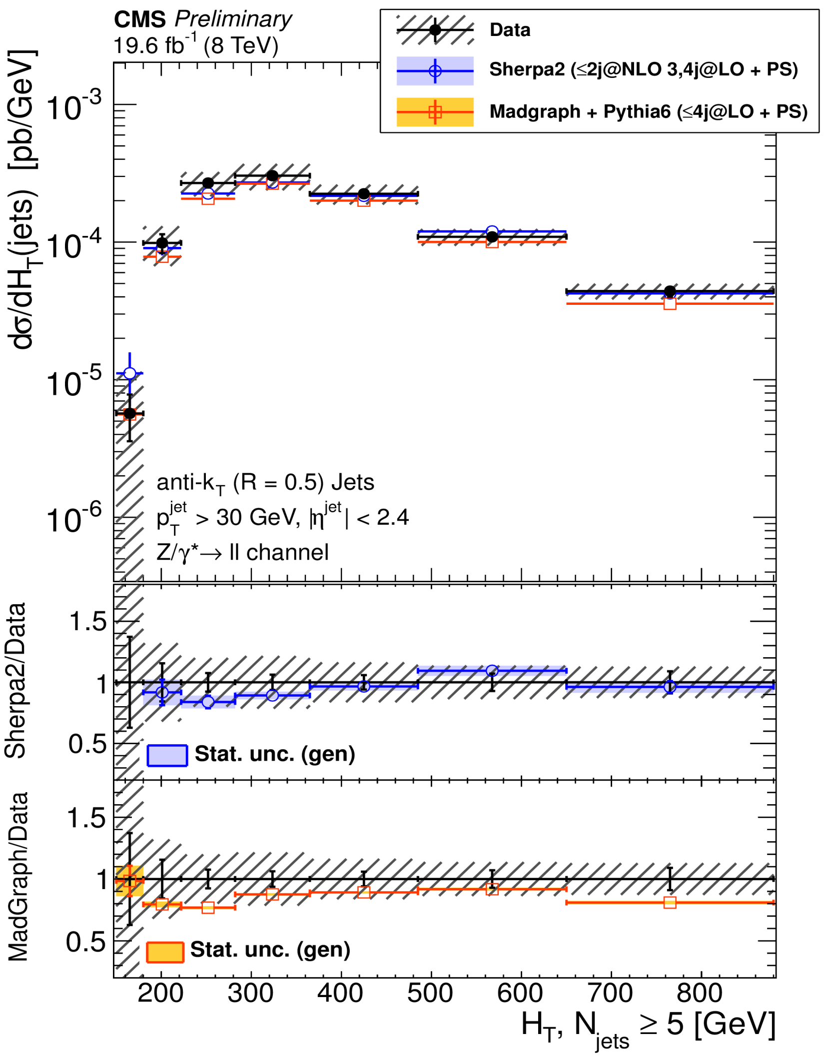


Z+jets

CMS-SMP-13-007

- Remarkable agreement also at very high multiplicity
  - Data/Theory rather flat

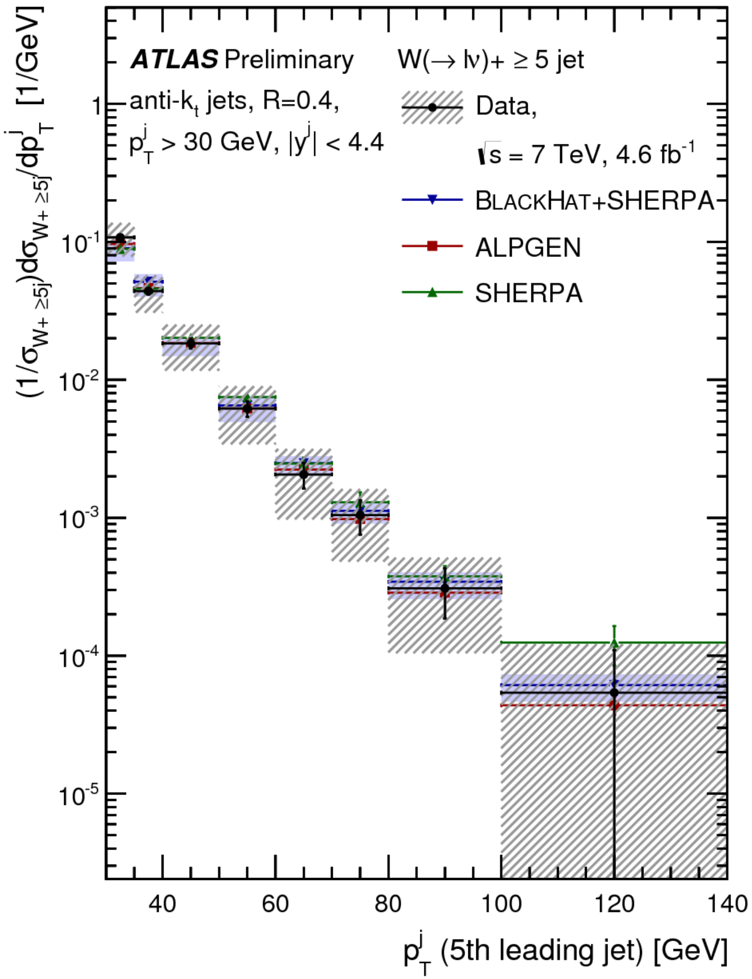


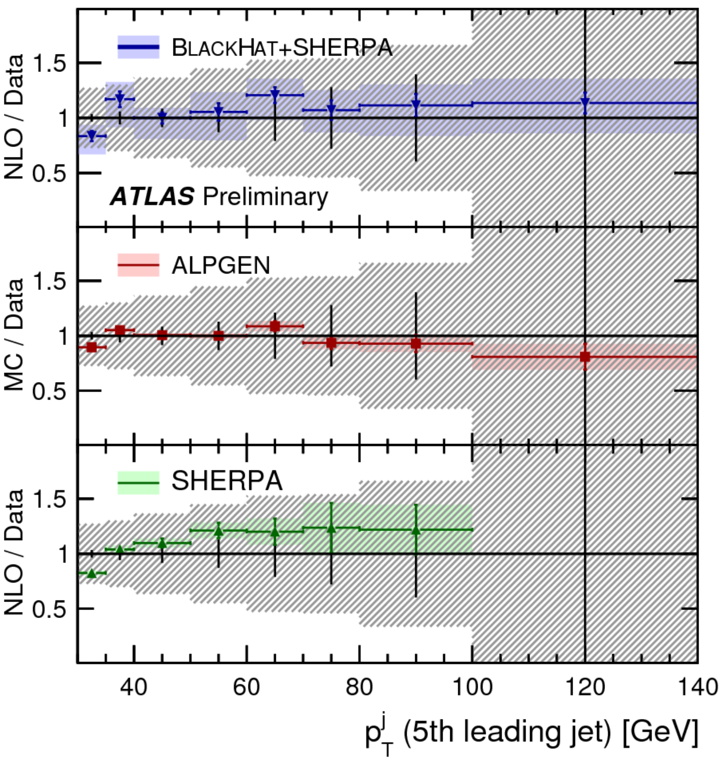


W+jets

ATLAS-CONF-2014-035

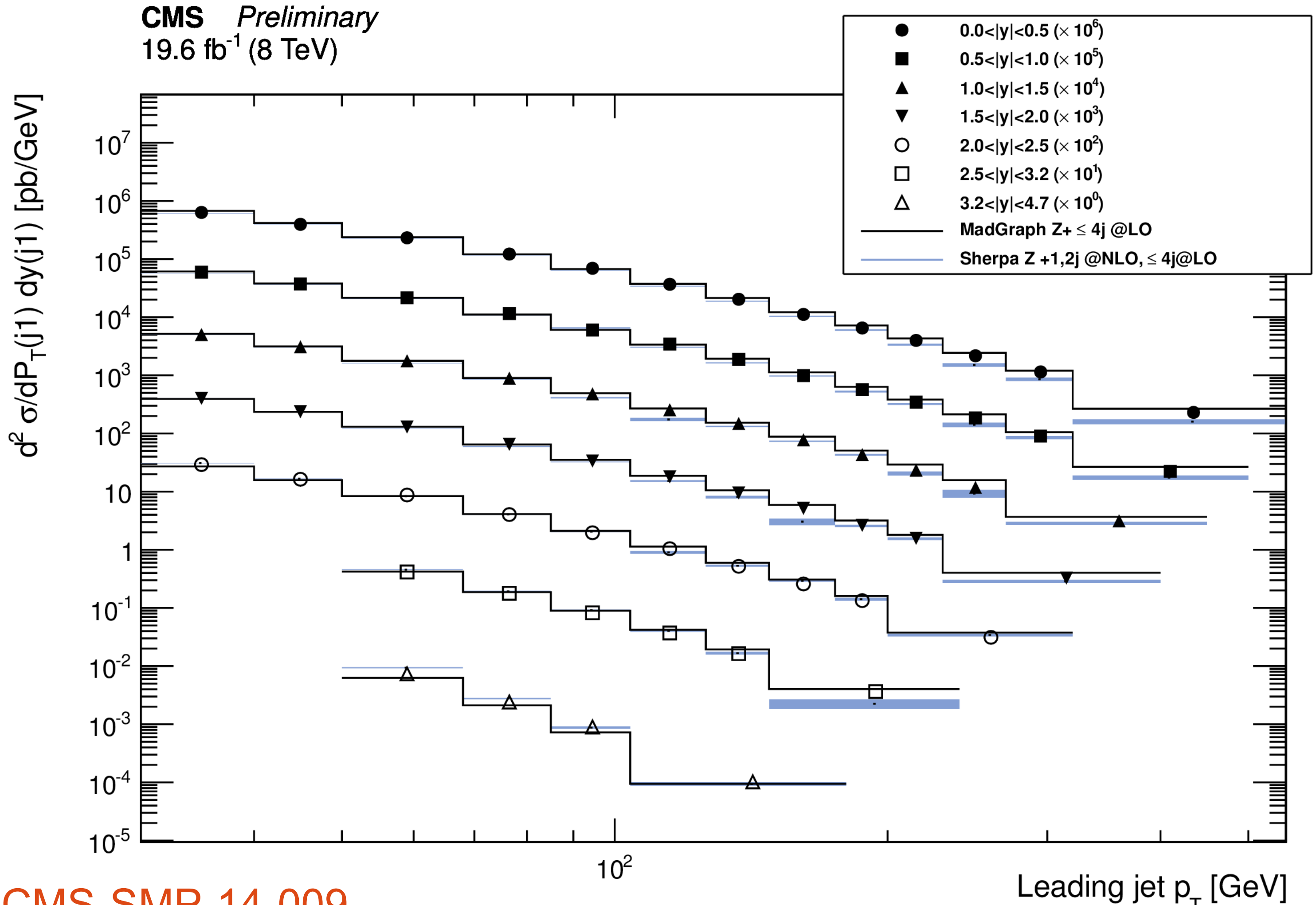
- Similar conclusions
  - Very nice description of jet spectra even at high multiplicity





Z+jets

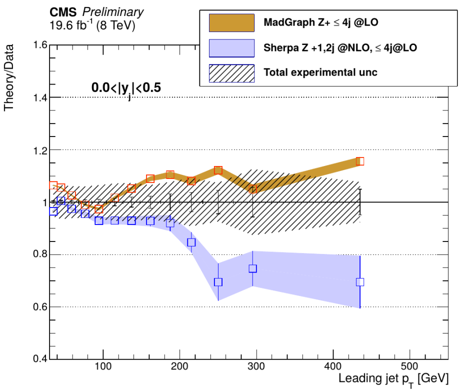
- Leading jet pT in Z+jets
  - Differential in jet rapidity: some discrepancies begin to arise

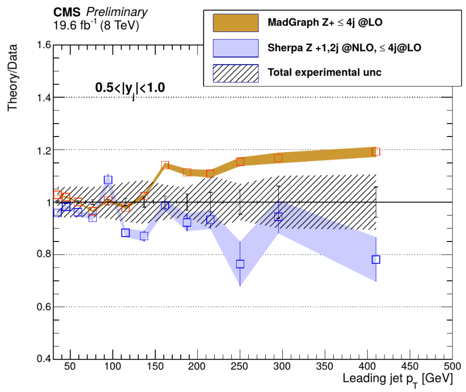


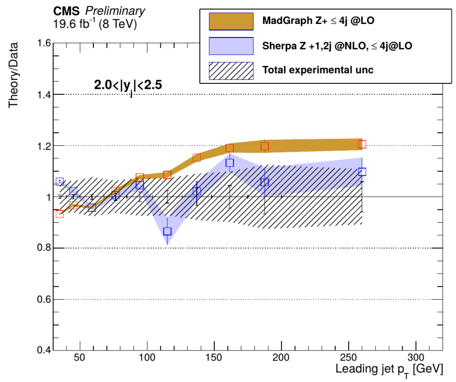
CMS-SMP-14-009

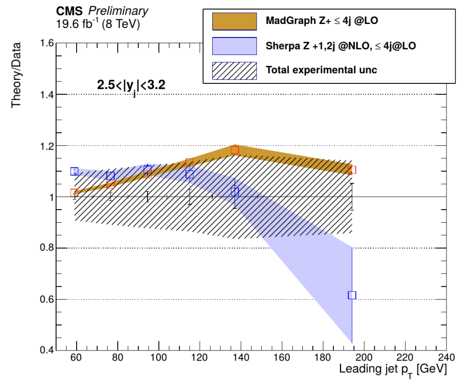
Z+jets

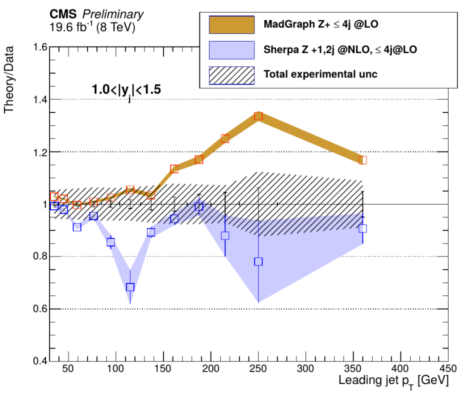
- Madgraph+Pythia tends to predict harder spectra above ~100GeV
- Sherpa (NLO up to the second jet) shows a few single bin discrepancies

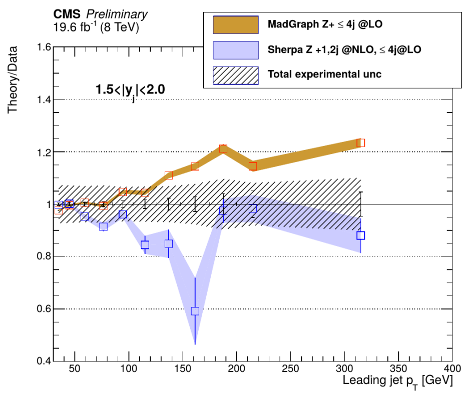


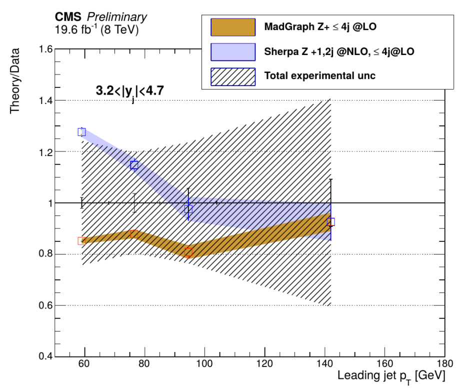










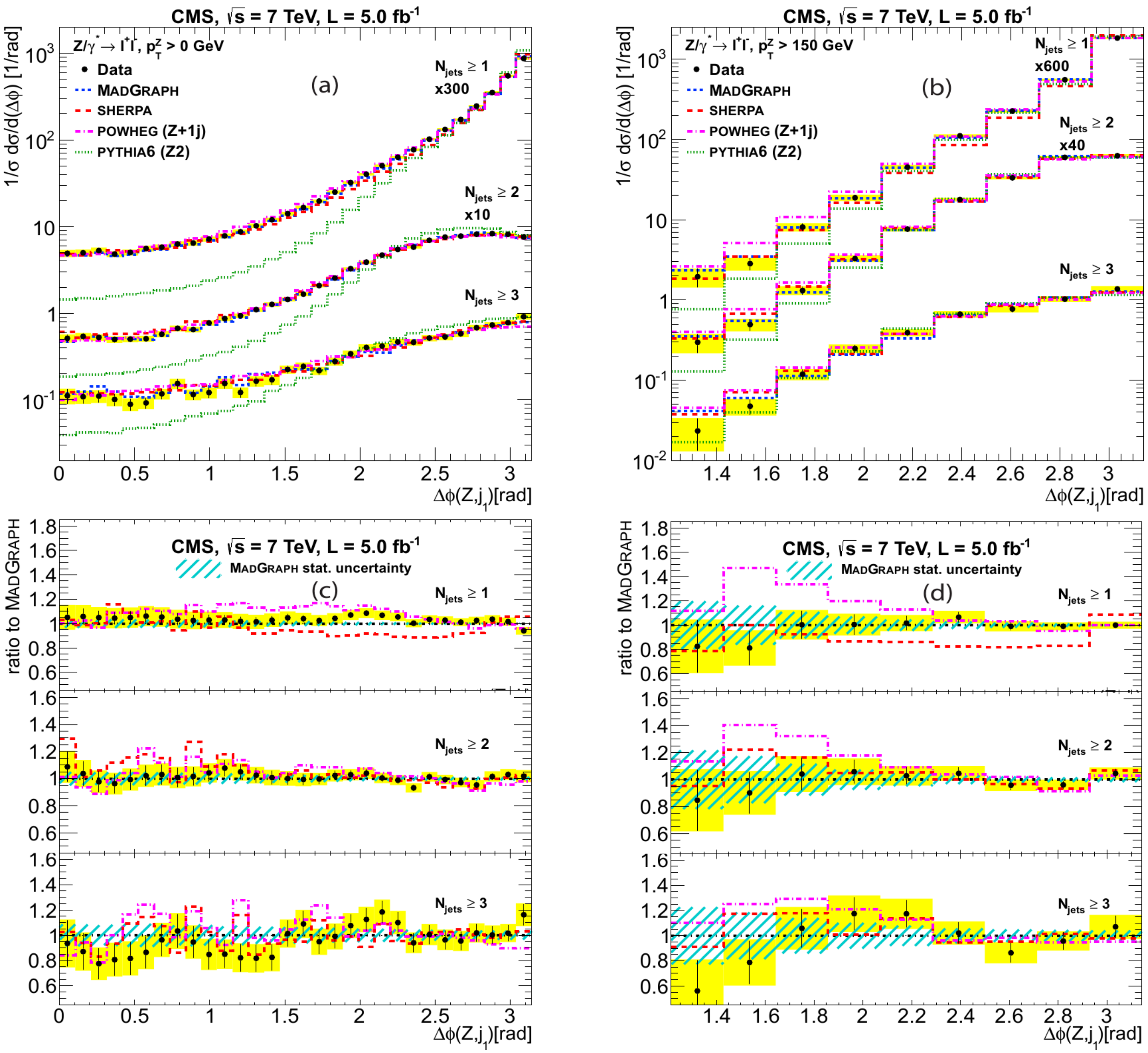


CMS-SMP-14-009

Z+jets

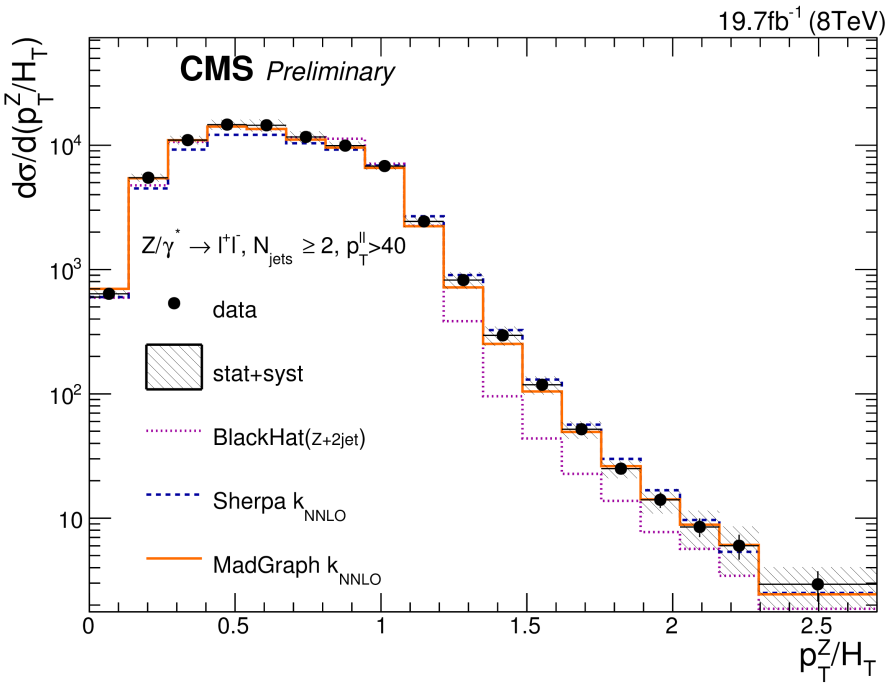
Phys. Lett. B 722 (2013) 238–261

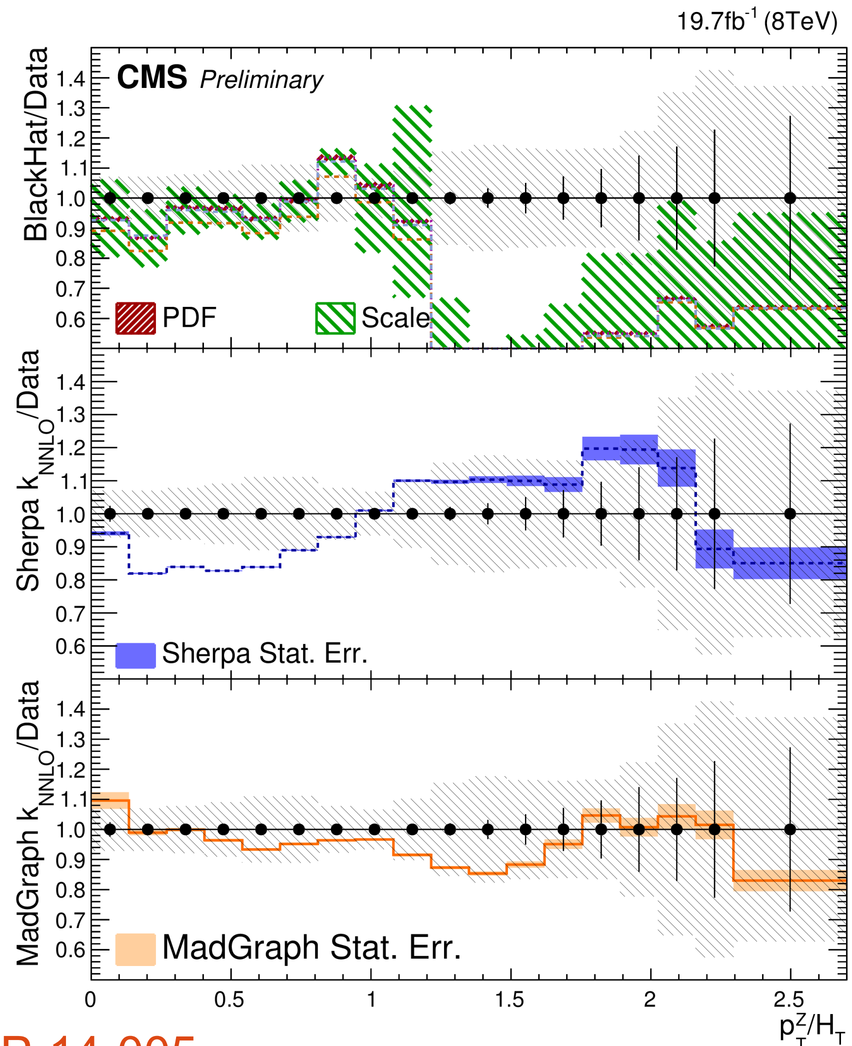
- ΔΦ between the Z and the leading jet
- Jet reconstruction: jet pT > 50 GeV, |η|<2.4
- Good agreement with LO+PS
- Also very nice agreement with NLO+PS



Z+jets

- Ratios pt(Z)/HT or pt(Z)/pt(j) are important for searches and are challenging to predict
  - Large logarithms, missing higher orders



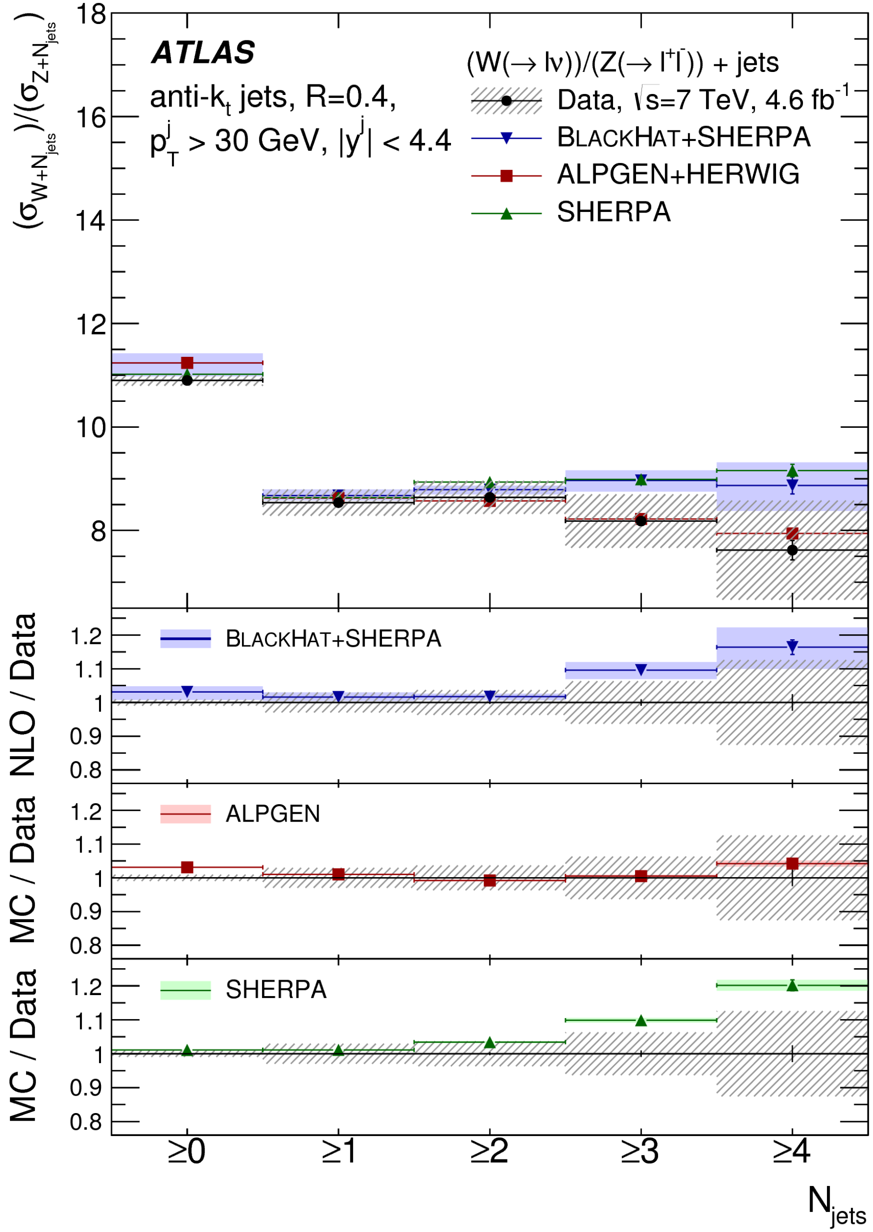


- Fixed order fails in the high pt(Z)/HT region
  - Possibly due to more jets with pT < than the analysis cut

CMS-SMP-14-005

W/Z+jet ratio

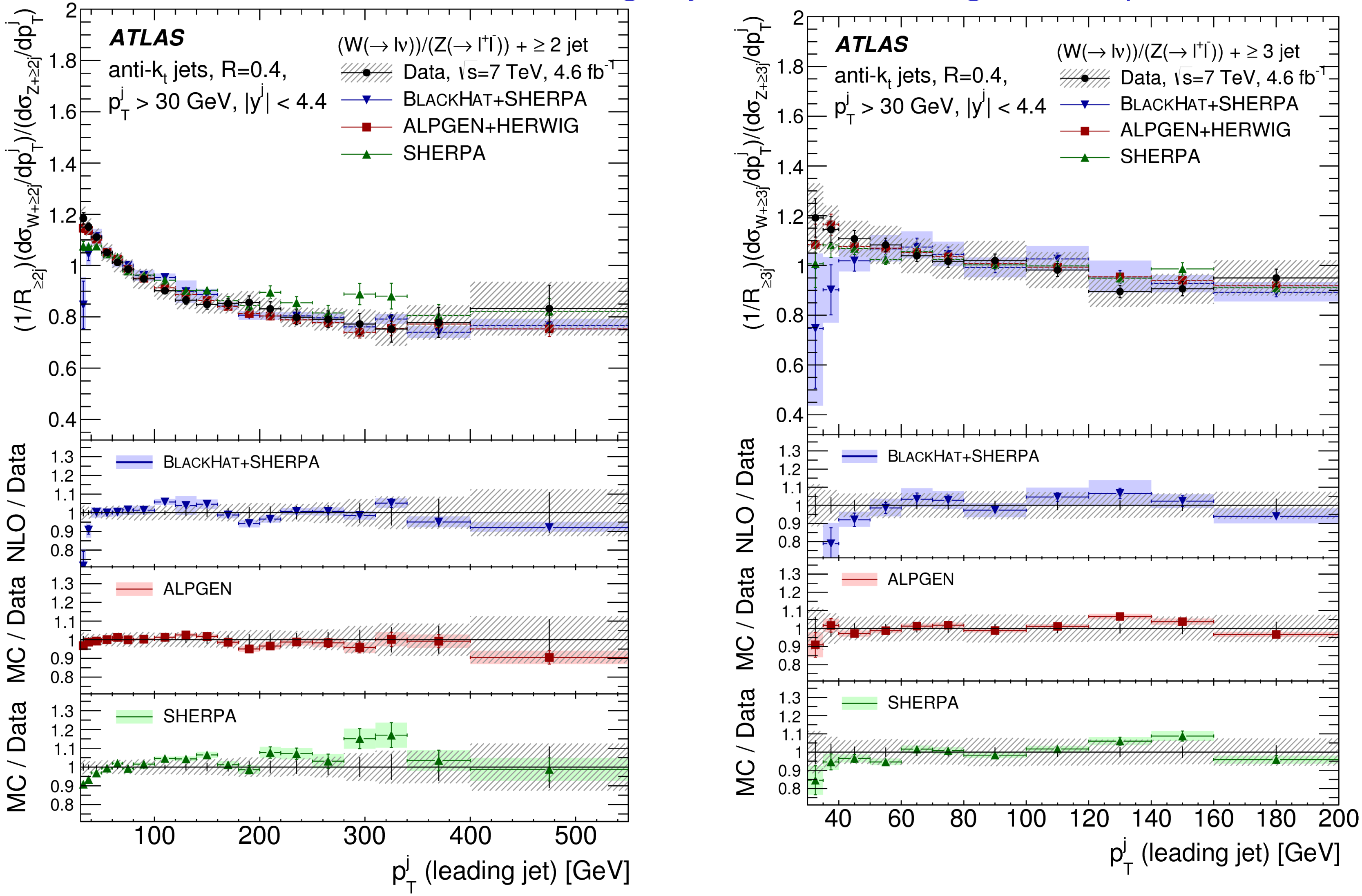
- Cancellation of several experimental uncertainties
- (Partial) cancellation of non-perturbative effects
- Sensitive to different effects
  - Low energies: sensitive to PDFs and to the W/Z mass difference and polarization effects
  - At High energies the ratios are expected to flatten



arXiv:1408.6510

W/Z+jet ratio

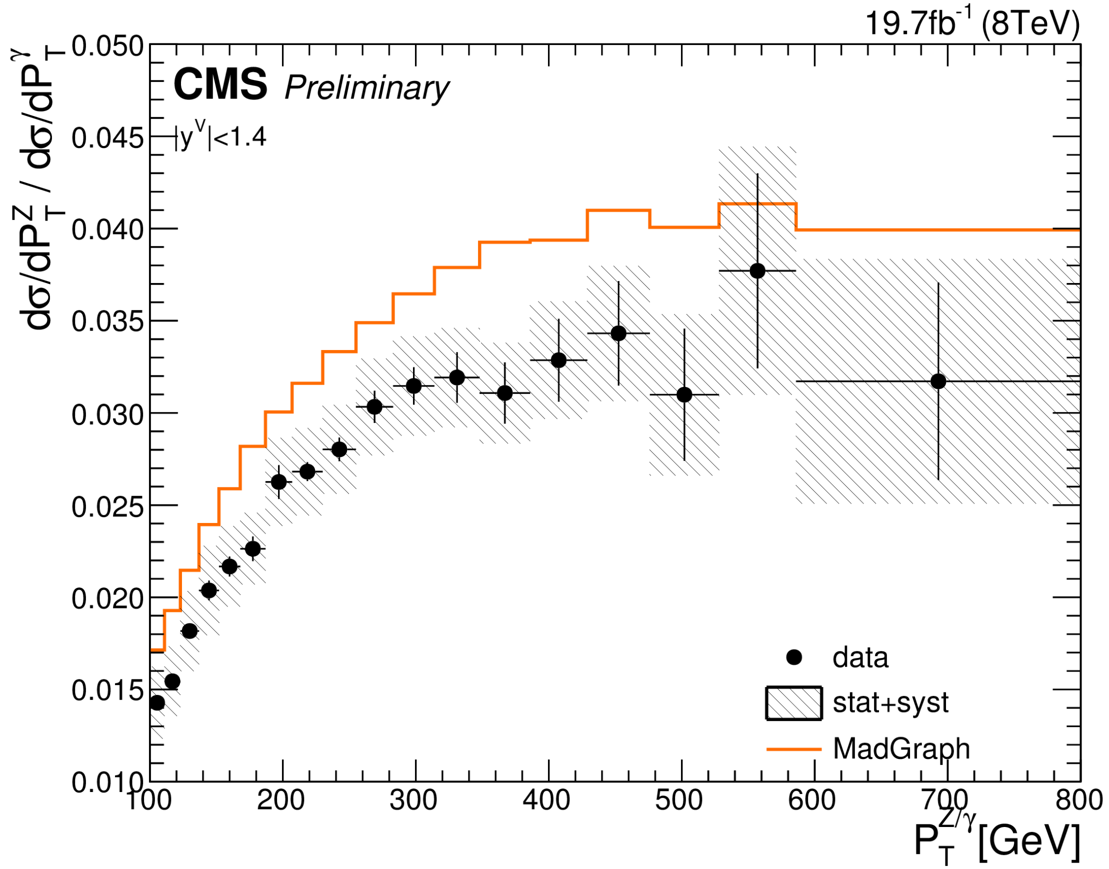
- W/Z ratio as a function of leading jet pT in events with at least one or at least 3 jets
  - Deviation from one larger at low jet pT (different mass)
  - Less deviation with increasing # jets (lower average boson pT)

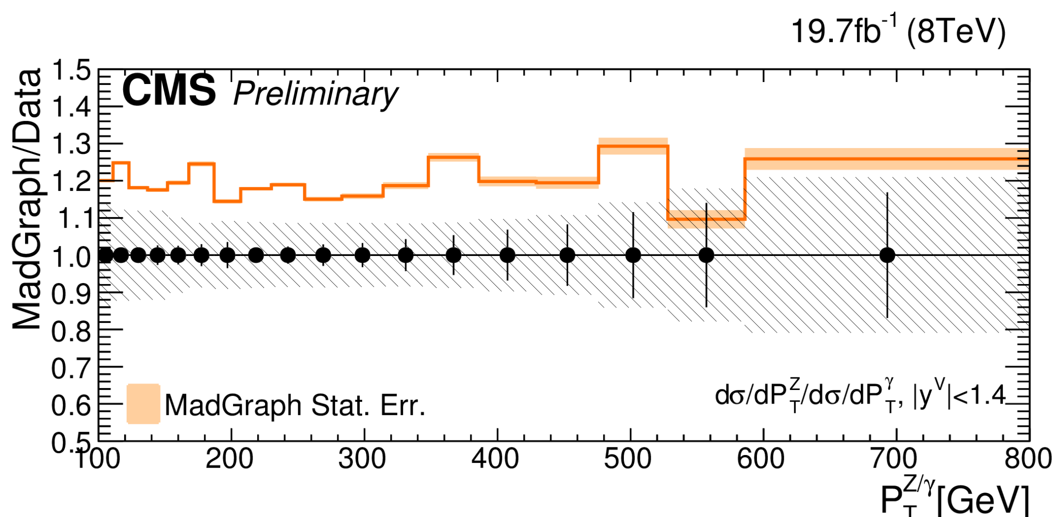


Z+jets over γ+jets

- Important for searches
- At large momenta effects due to the Z mass can be neglected and ratios should flatten
- Measurement in 4 bins
  - >1,2,3 jets and HT>300 GeV
- Comparison with ME+PS is rather flat
  - ~20% off
  - It will be interesting to see how NLO+PS does

CMS-SMP-14-005

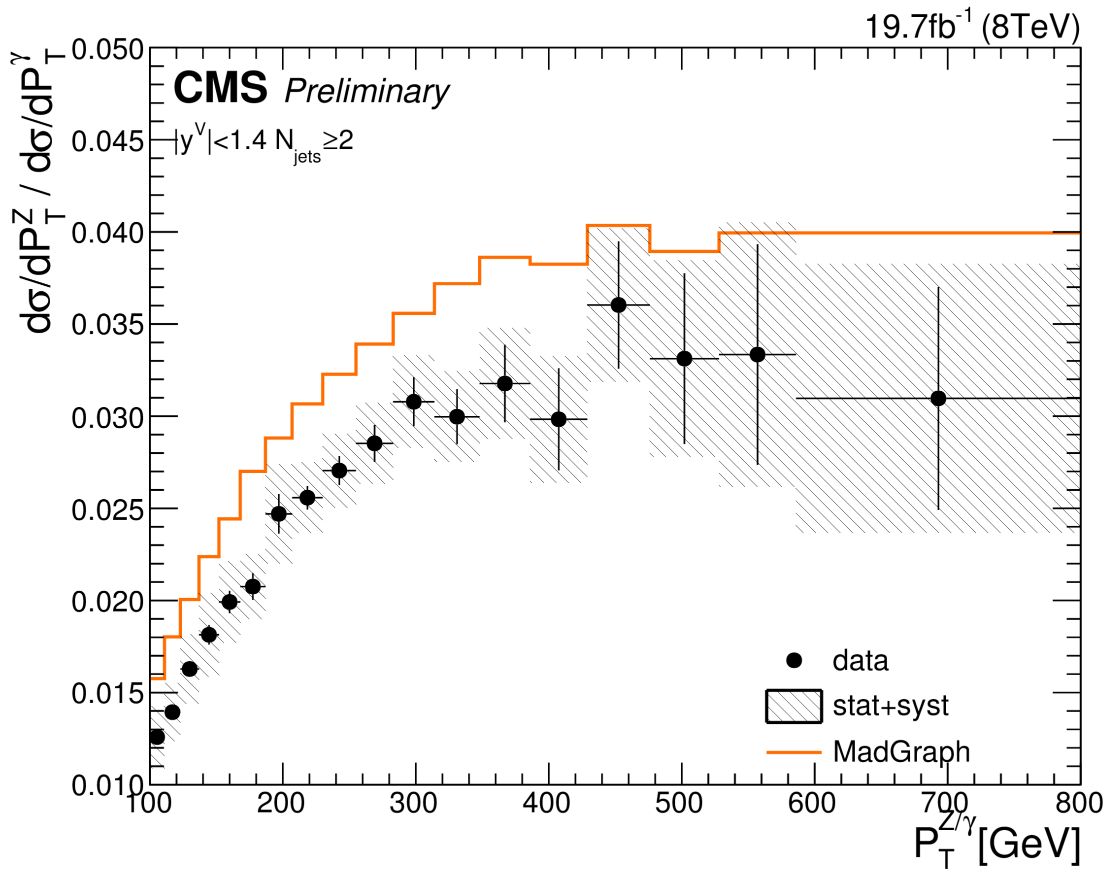


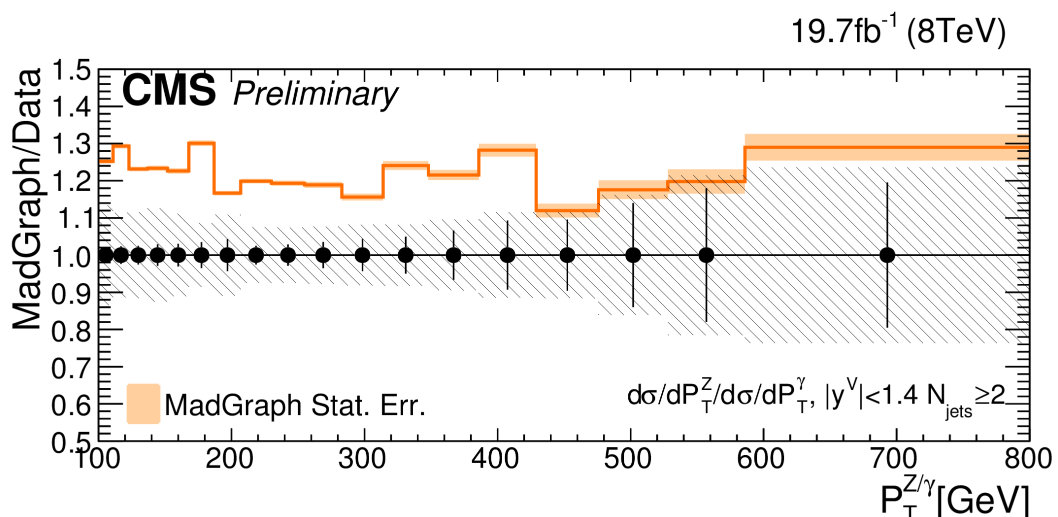


Z+jets over γ+jets

- Important for searches
- At large momenta effects due to the Z mass can be neglected and ratios should flatten
- Measurement in 4 bins
  - >1,2,3 jets and HT>300 GeV
- Comparison with ME+PS is rather flat
  - ~20% off
  - It will be interesting to see how NLO+PS does

CMS-SMP-14-005

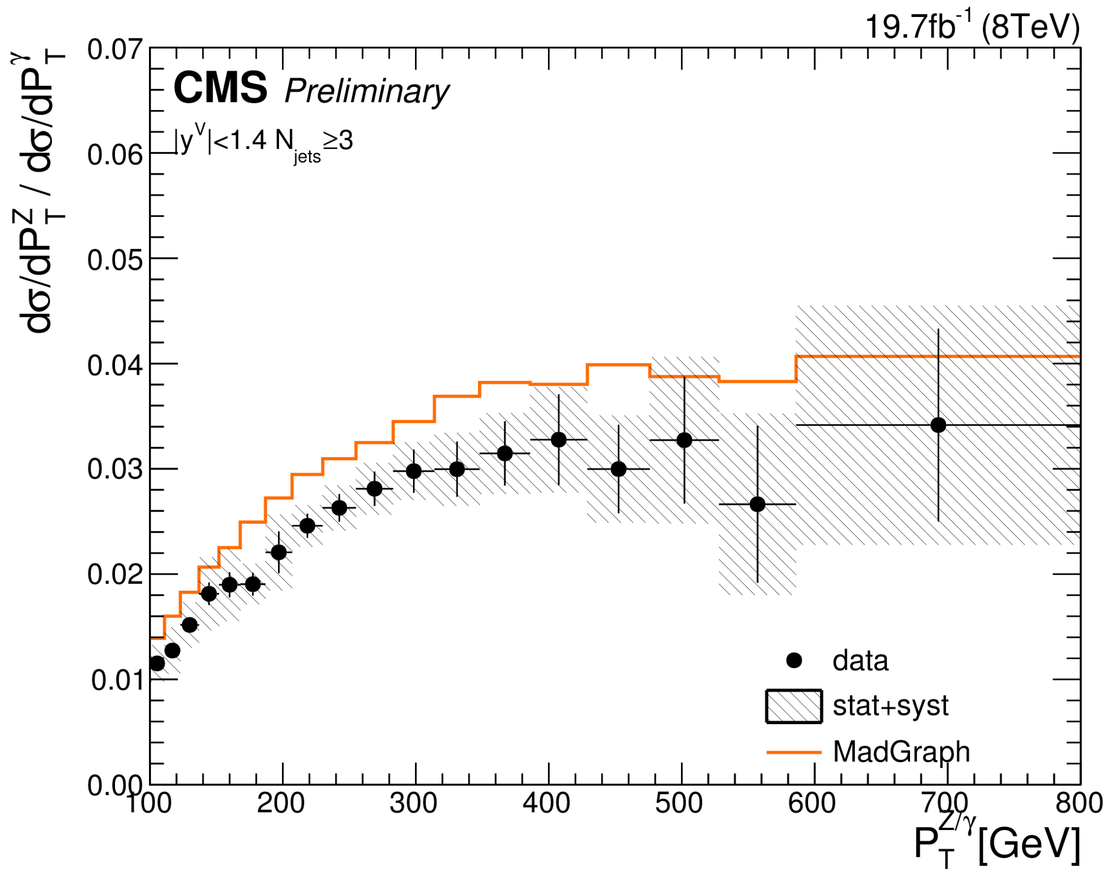


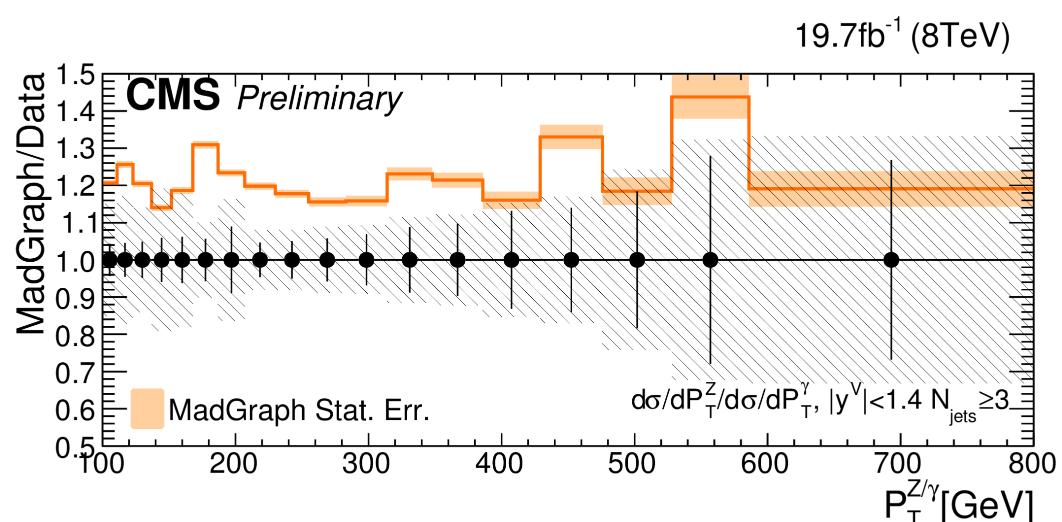


Z+jets over γ+jets

- Important for searches
- At large momenta effects due to the Z mass can be neglected and ratios should flatten
- Measurement in 4 bins
  - >1,2,3 jets and HT>300 GeV
- Comparison with ME+PS is rather flat
  - ~20% off
  - It will be interesting to see how NLO+PS does

CMS-SMP-14-005

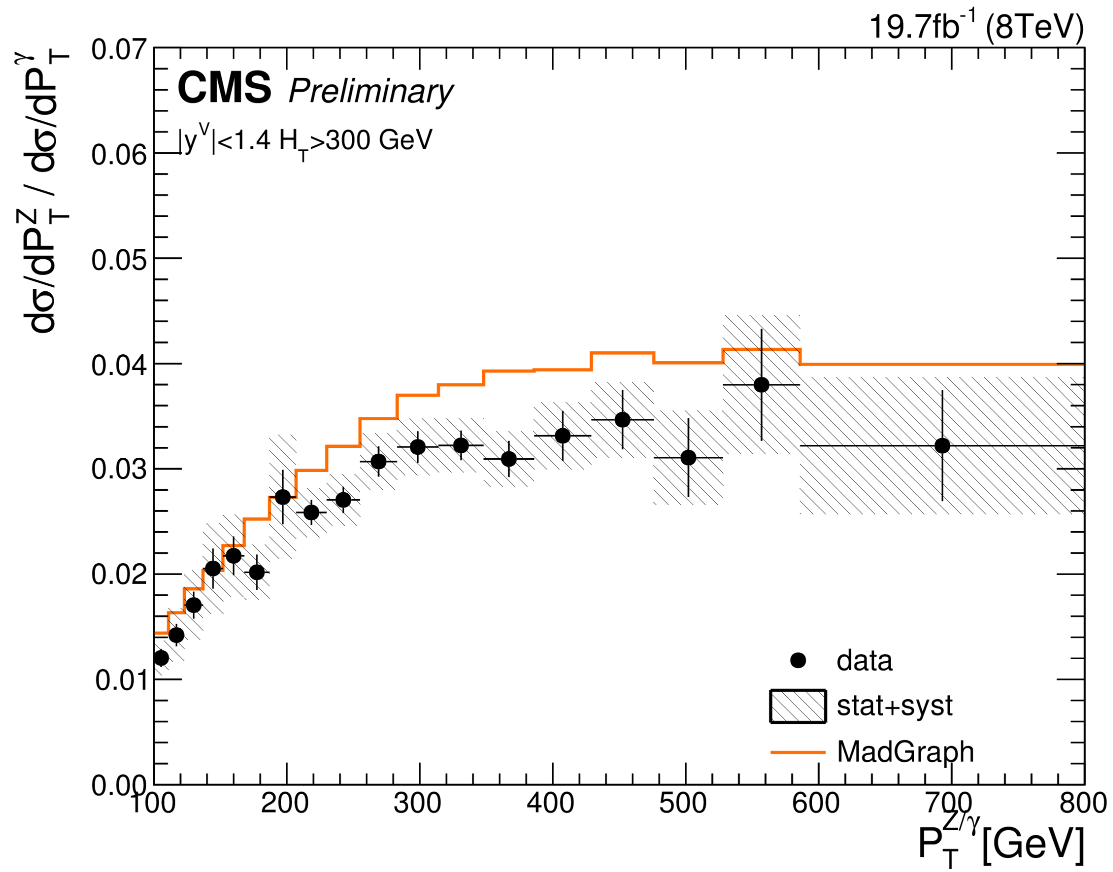


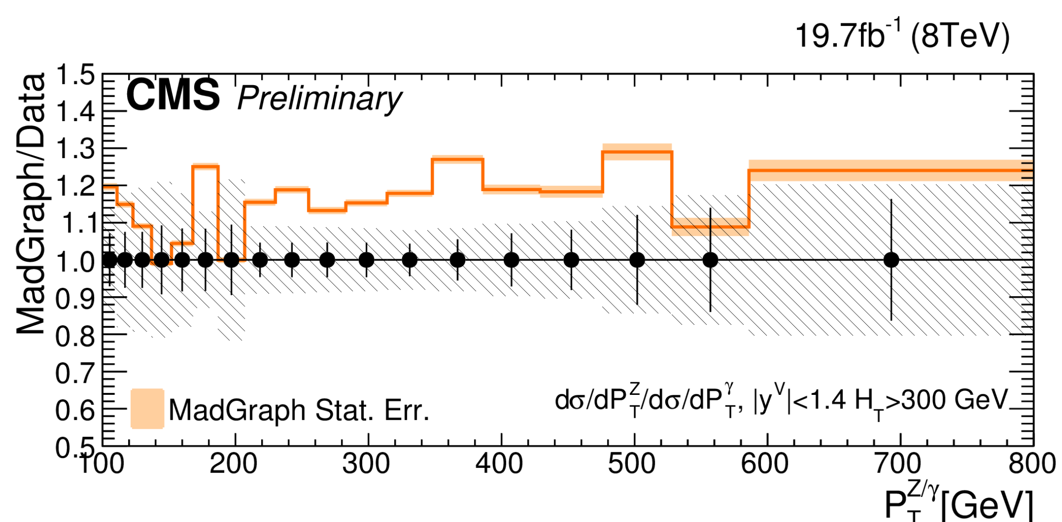


Z+jets over γ+jets

- Important for searches
- At large momenta effects due to the Z mass can be neglected and ratios should flatten
- Measurement in 4 bins
  - >1,2,3 jets and HT>300 GeV
- Comparison with ME+PS is rather flat
  - ~20% off
  - It will be interesting to see how NLO+PS does

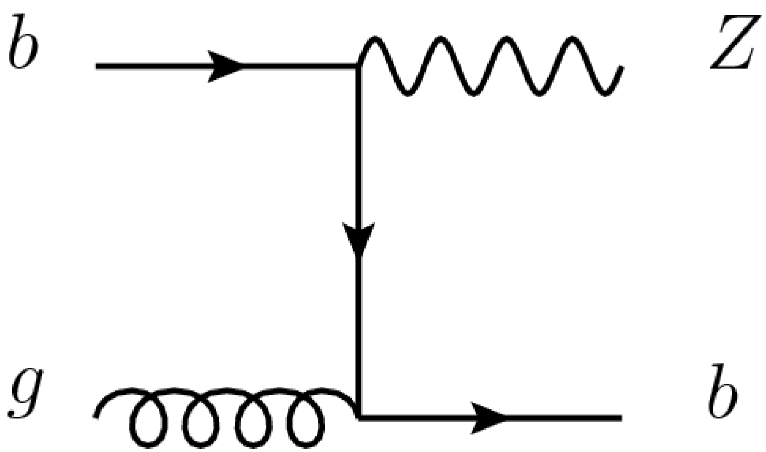
CMS-SMP-14-005



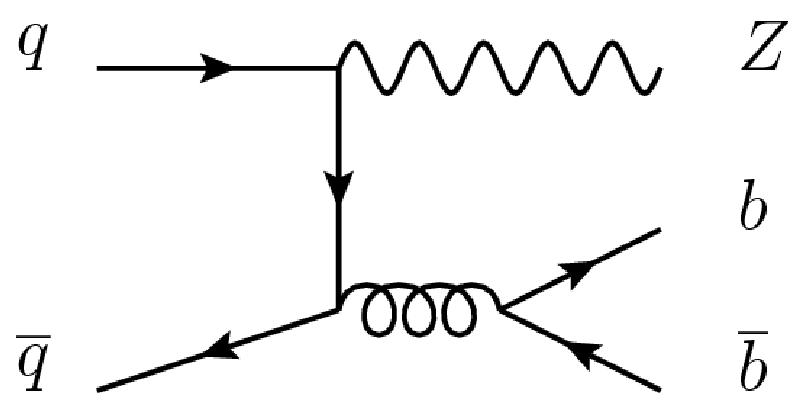


Z+heavy flavor

- Large theoretical uncertainties
- Important for searches
- Two main approaches
  - 4-flavor scheme: use PDFs without a b quark and produce all b quarks via matrix element
  - 5-flavor scheme: b quarks allowed in the initial state

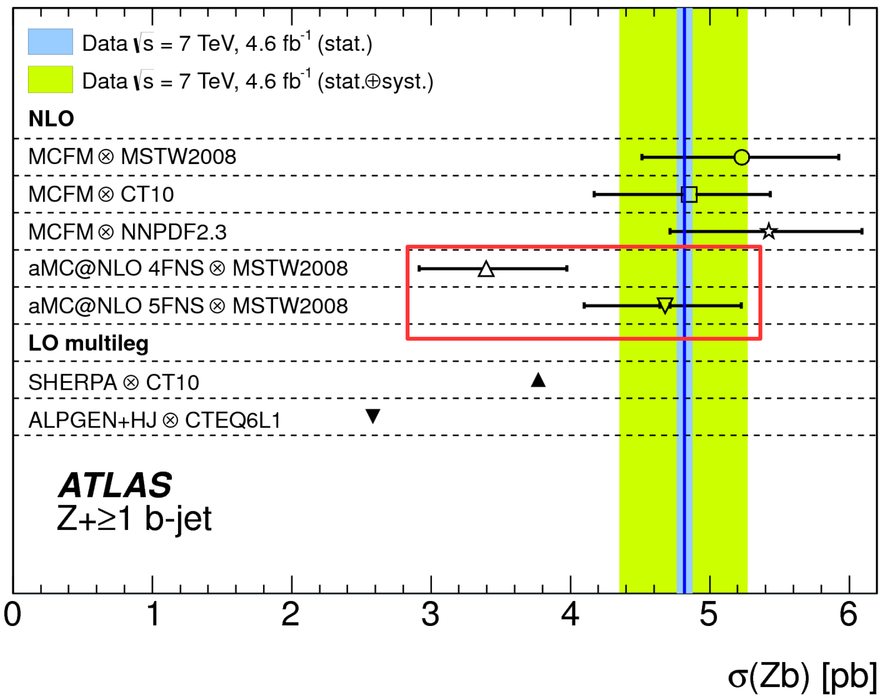


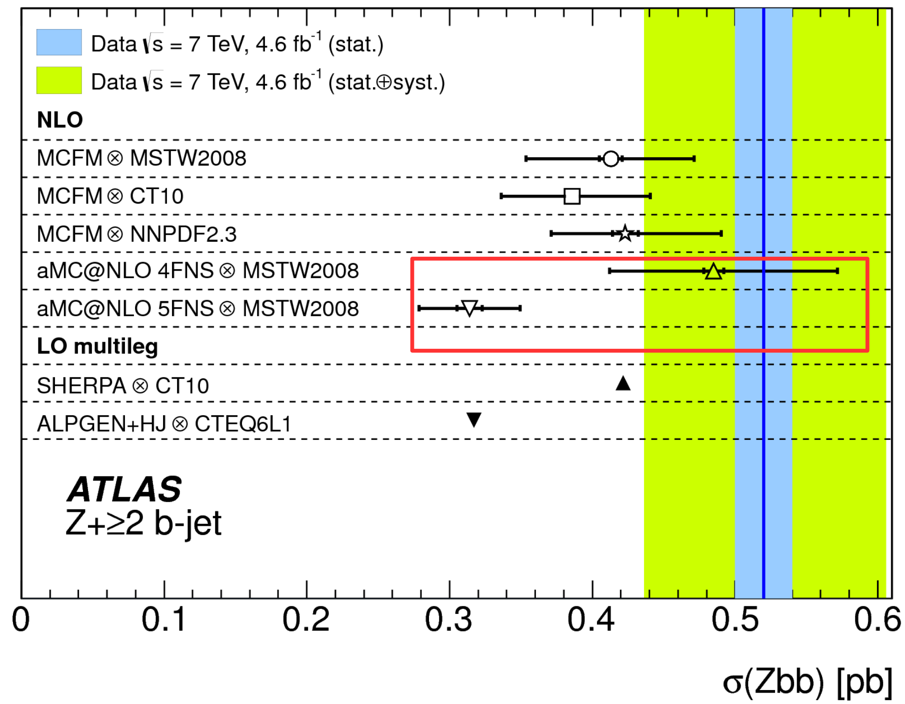
LO for Z+>=1b in 5-f



LO for Z+>=1b in 4-f

Z+heavy flavor





- 5-F scheme gives the best description of Z+>=1b jet
  - Unclear why, for Z+1b both 4F and 5F should correspond to the same order
- 4-F scheme gives the best description of Z+>=2b jets

arXiv:1407.3643 J. High Energy Phys. 12 (2013) 39

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 (CMS)

- 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 (CMS)

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 energy scale (CMS)

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

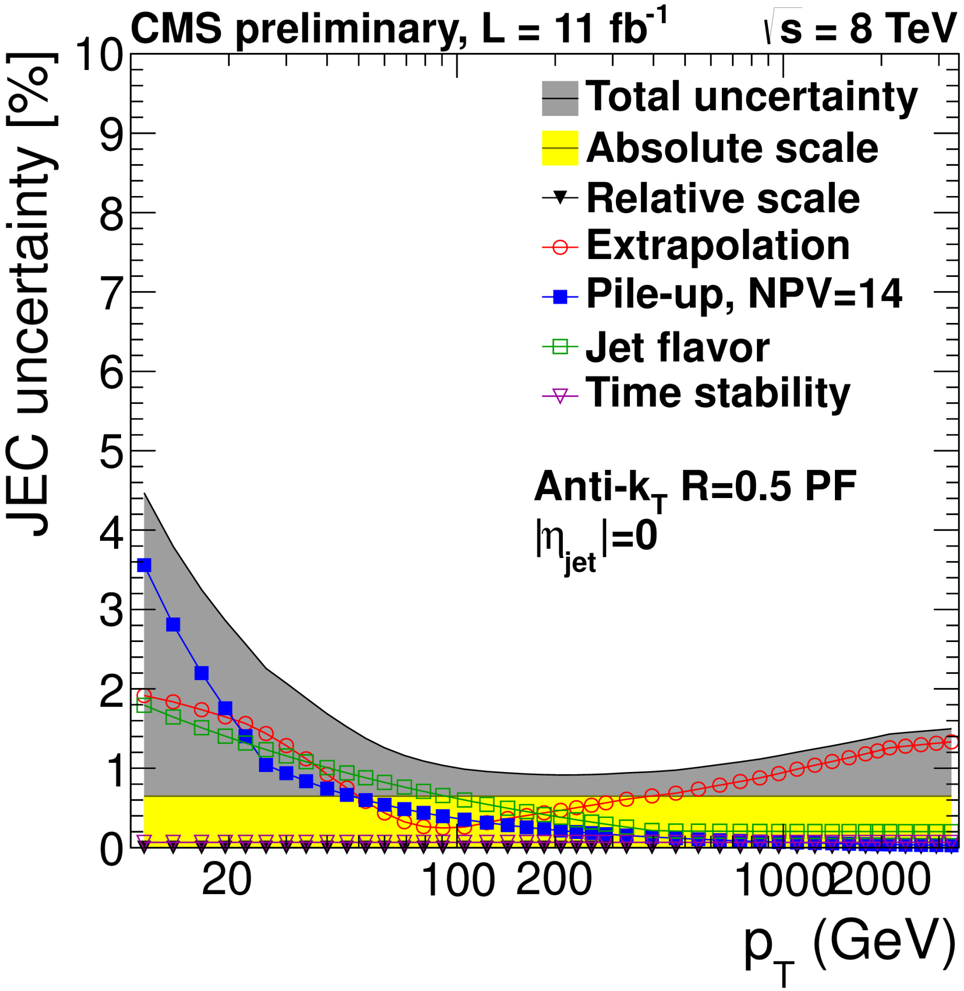
In this MC + residual method effects like the presence of additional radiation spoiling dijet or γ+jet and Z +jet balancing enter only at second order

Jet energy scale (CMS)

Total systematic uncertainty on the energy scale for particle-flow jets

The main sources of uncertainty are:

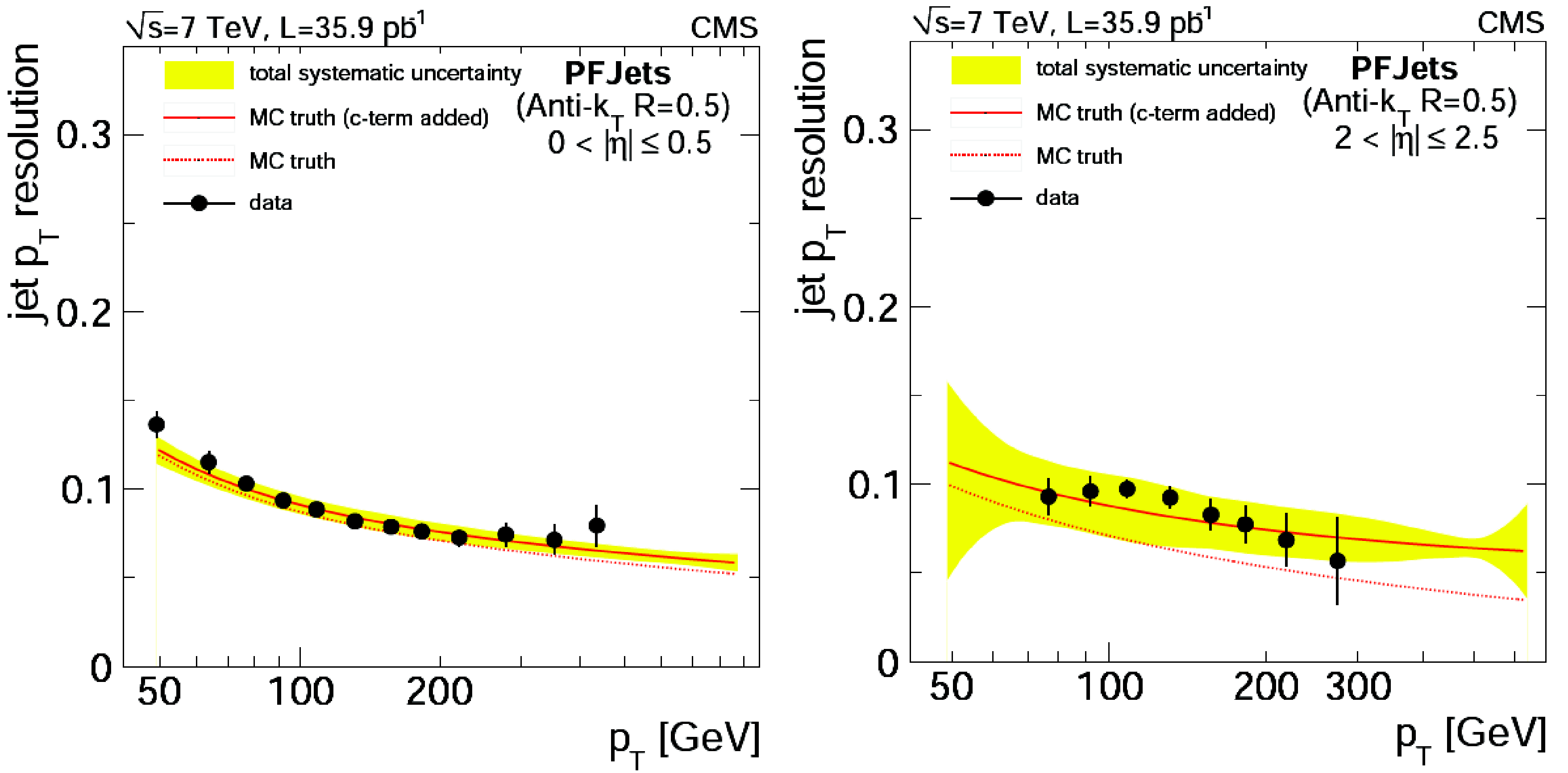
- The photon energy scal known at 1%
- The relative response across detector regions
- Pile-up effects
- Extrapolations down to (for the additional activit in the balance methods
- Dependency on jet flavo in the MC used



Jet energy resolution (CMS)

Determined with di-jet and γ+jet pT balance

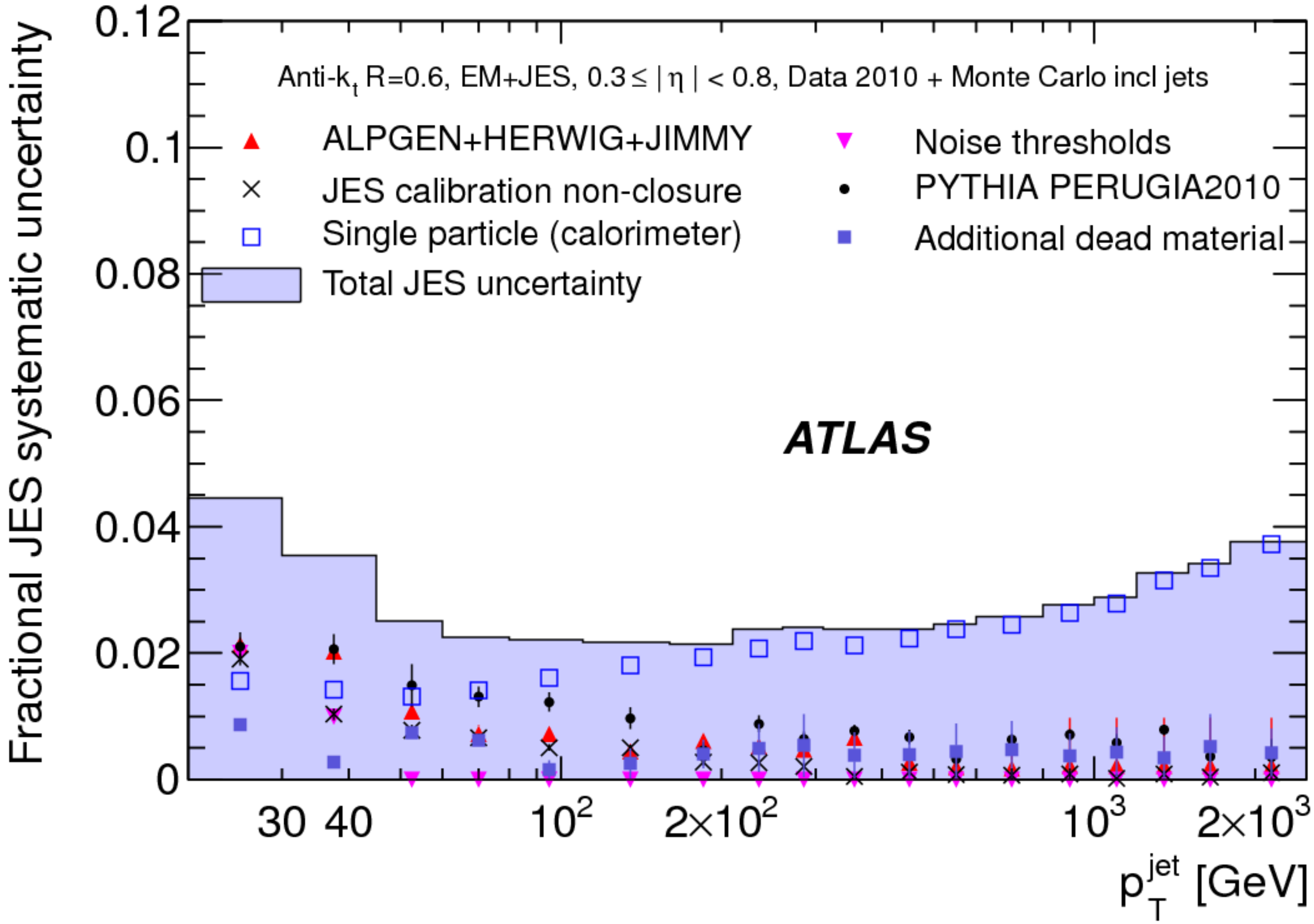
- Plots show two example regions in η
- Resolution is of the order of 10% around 50 GeV



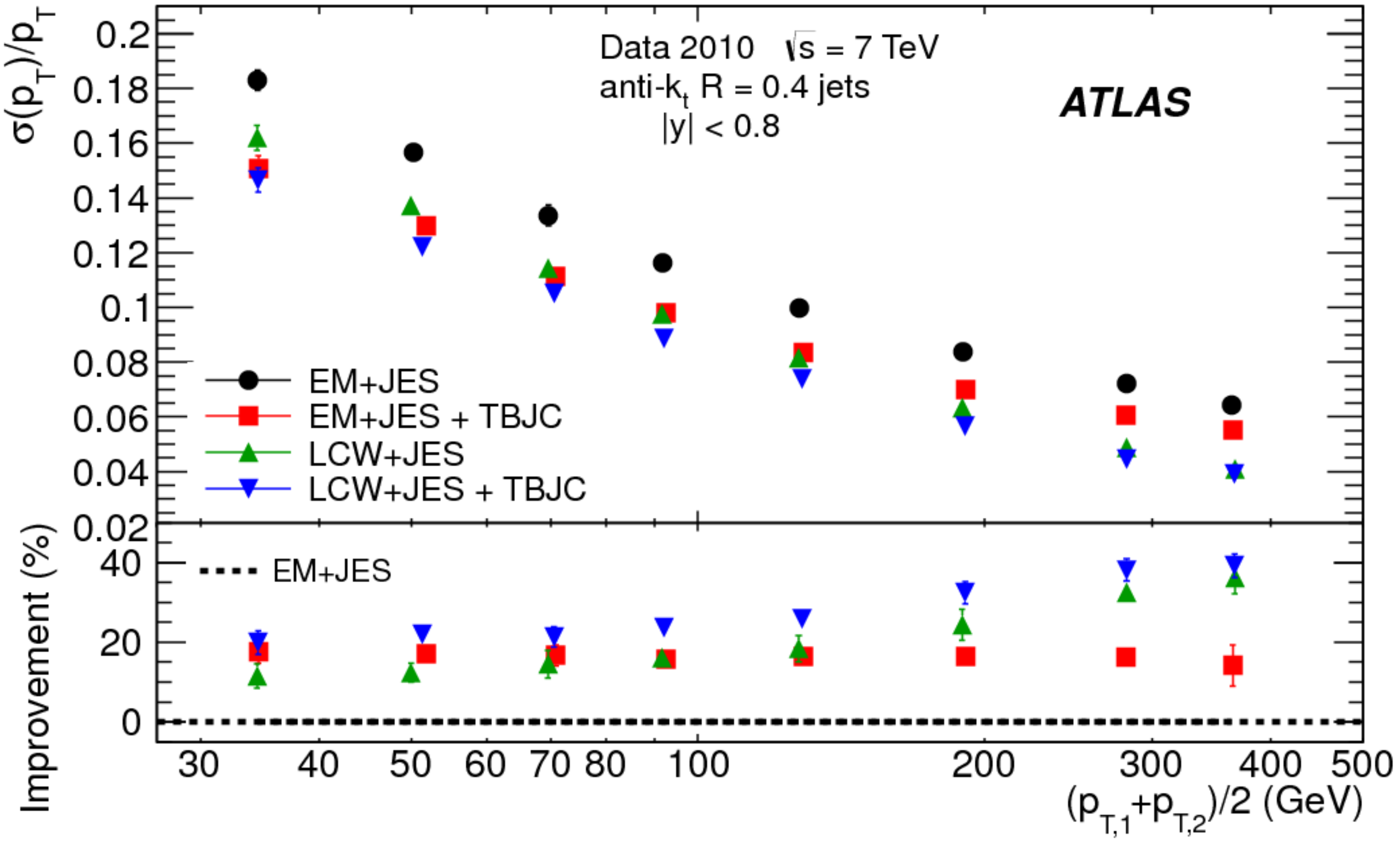
Jet Reconstruction ATLAS

- Jets are reconstructed from calorimeter topo-clusters
  - Topo-clusters are groups of calorimeter cells build with an algorithm that follows the shower development
  - Topo-cluster algorithm is able to identify deposits from close-by particles

Jet energy scale (ATLAS)

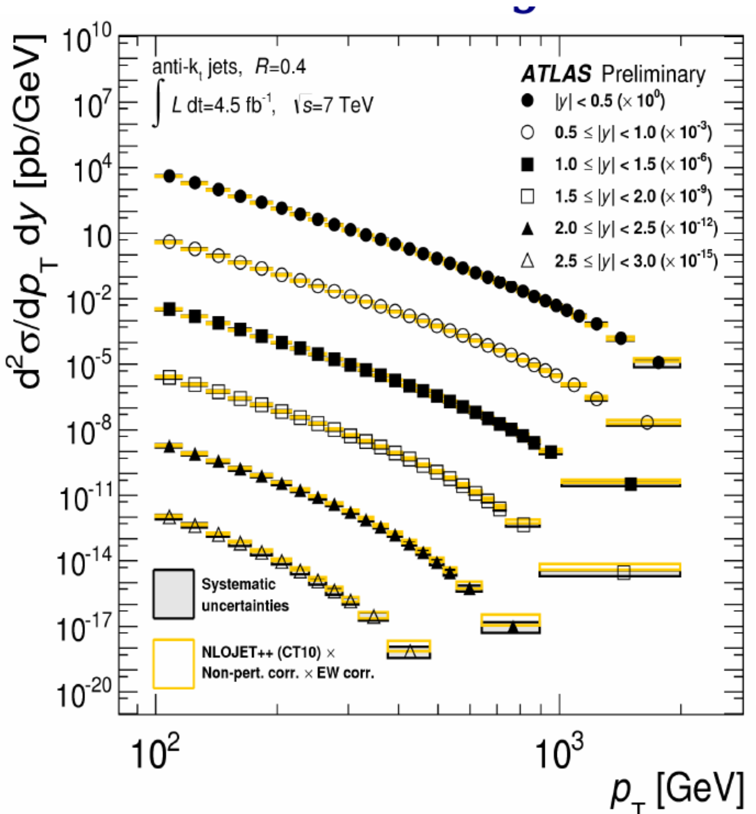


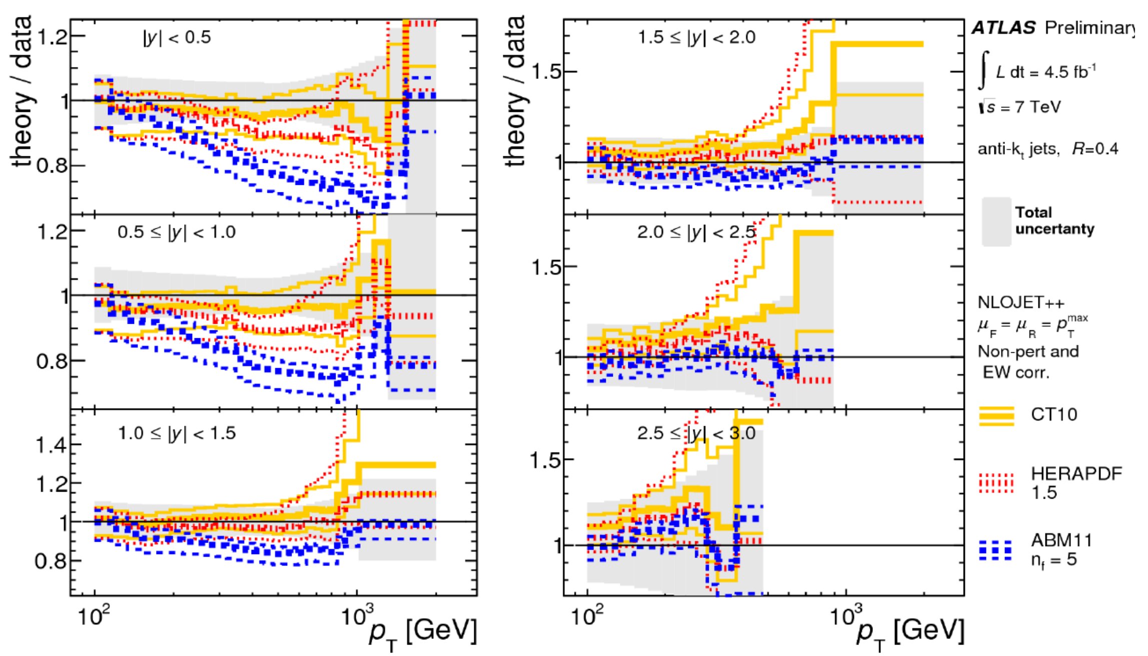
Jet energy resolution (ATLAS)



Inclusive jets

- 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 agreement with CT10, HERAPDF
  - Discrepancies with ABM11 especially at central rapidity

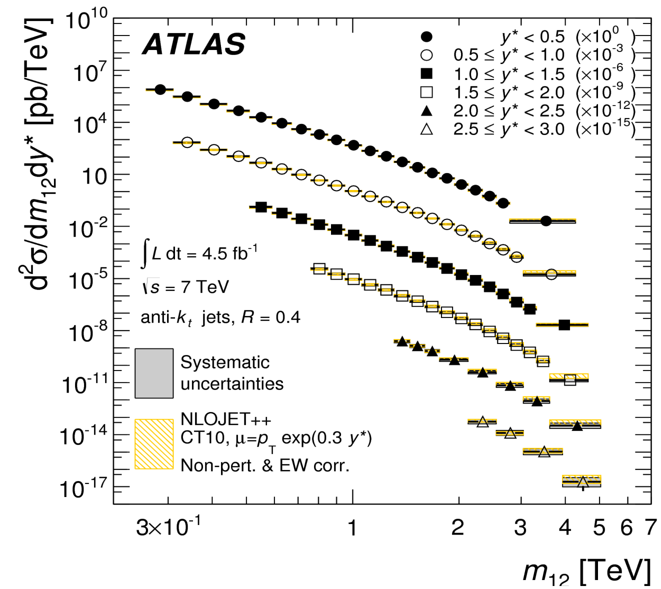


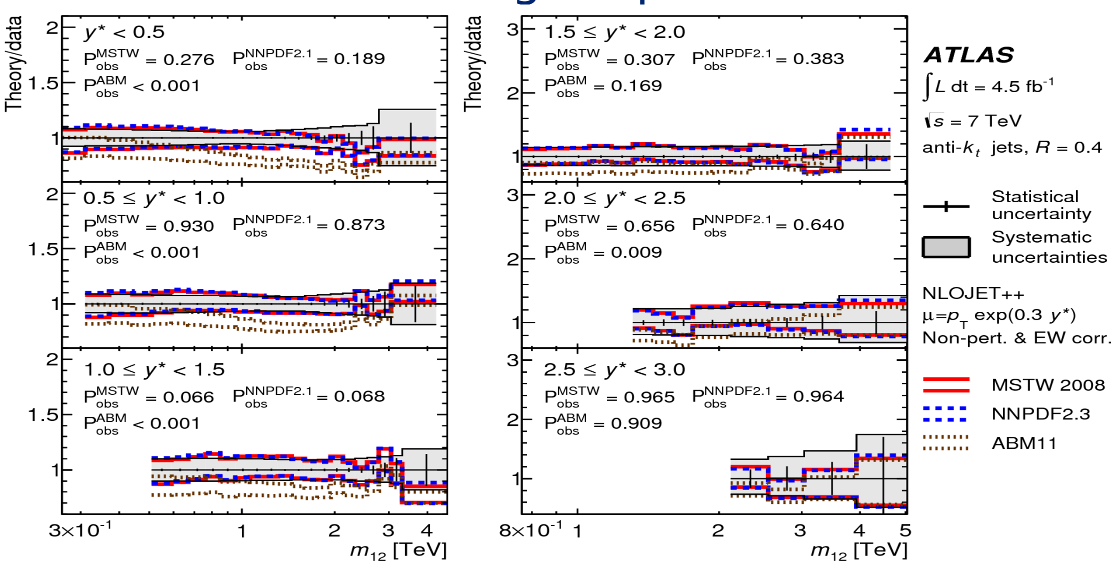


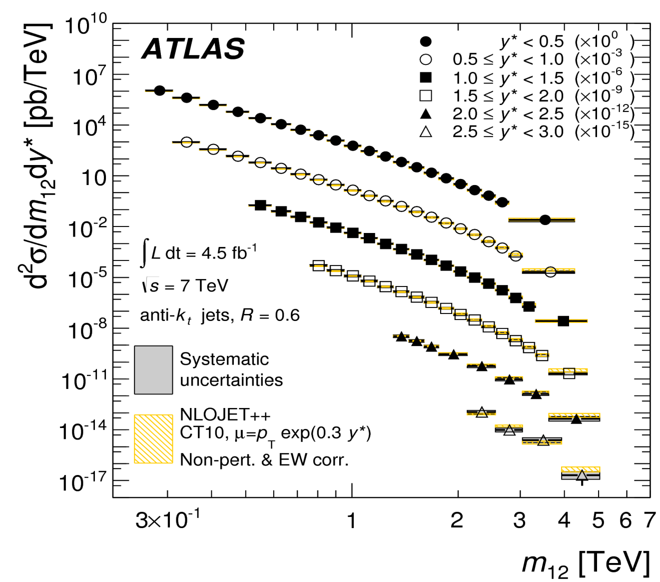
Inclusive jets

JHEP05(2014)059

- 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



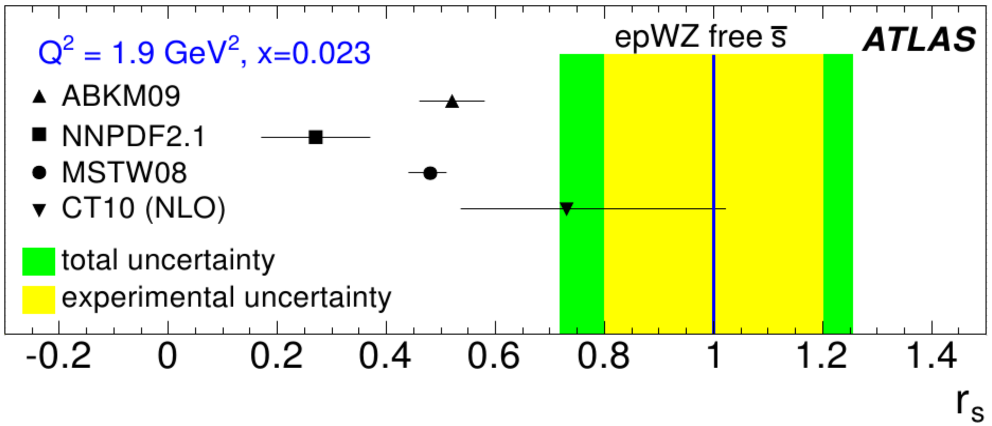


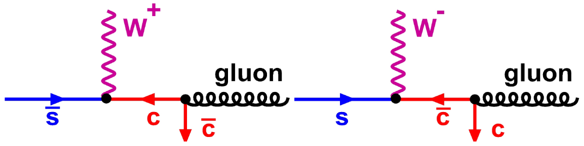


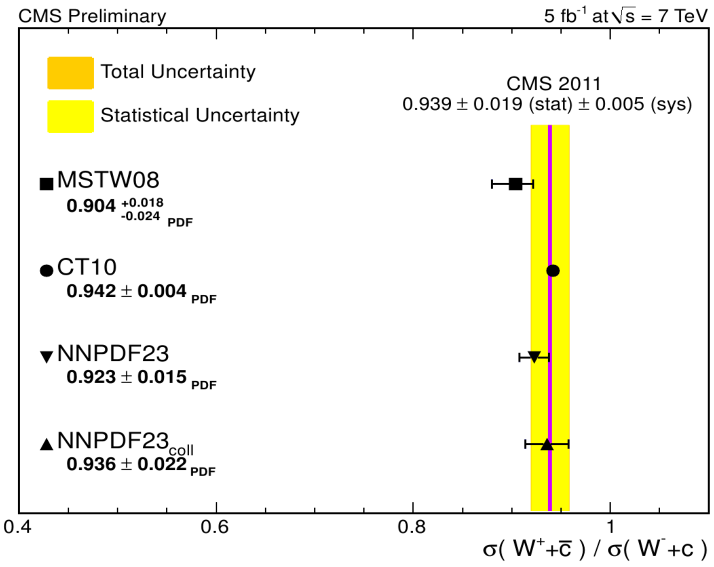
Constraints of strange quark content

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

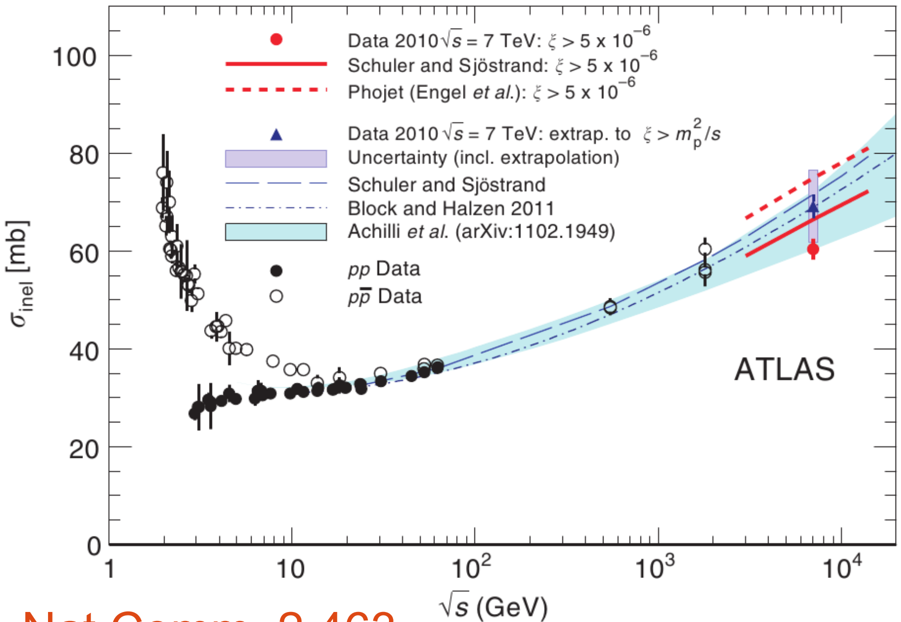




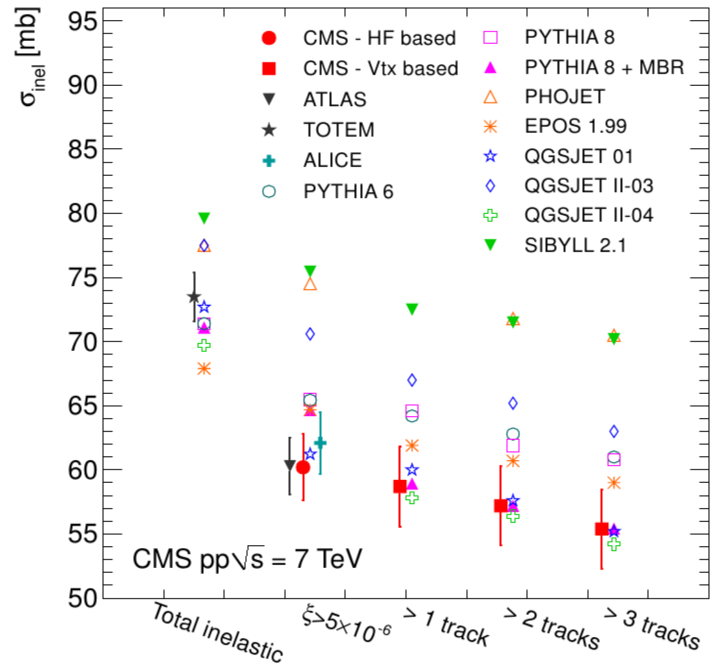


Inelastic pp cross section

- 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



Nat.Comm. 2 463



CMS-FWD-11-001

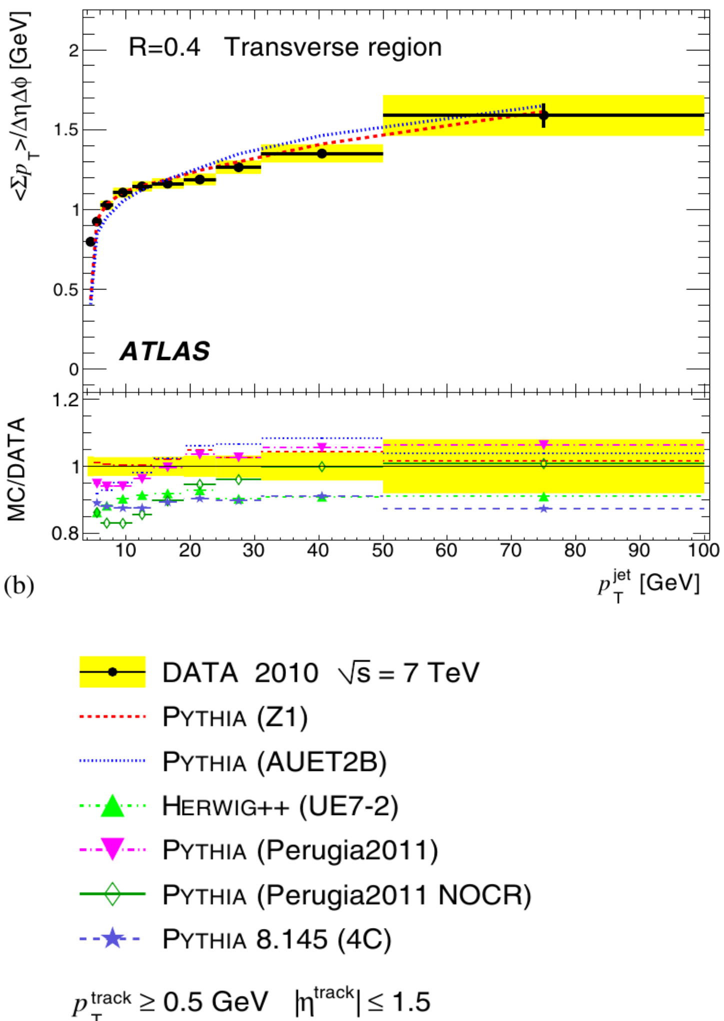
Underlying event

Addressed in several different ways:
- Rick Field-like observables
  - Inclusive
  - In events with a hard scatterer

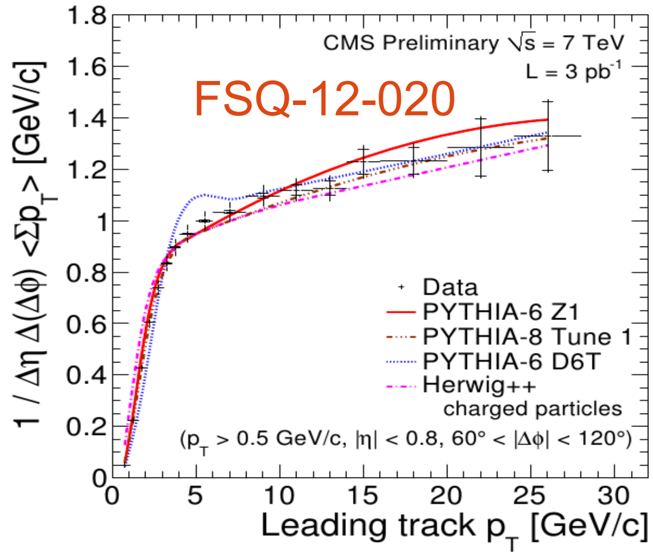
Aspects studied:
- Energy dependence
- Dependence on jet size

UE: Rick Field observables

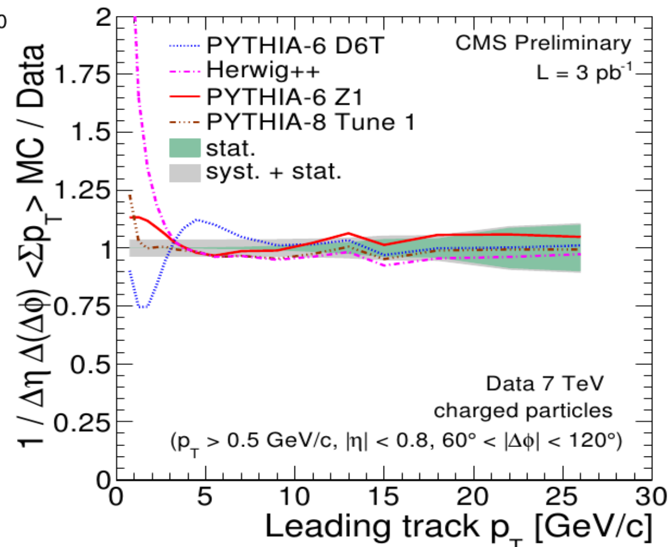
Event is sub-divided into 3 regions in the transverse plane wrt a “leading object”

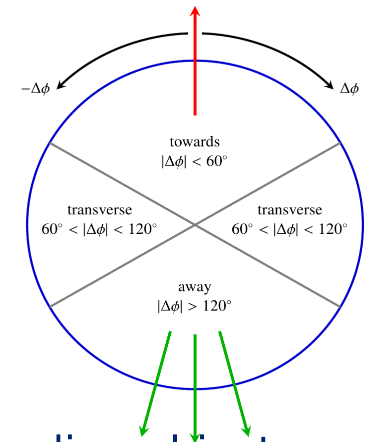


PRD 86 072004



FSQ-12-020





Leading object definition is different in ATLAS and CMS

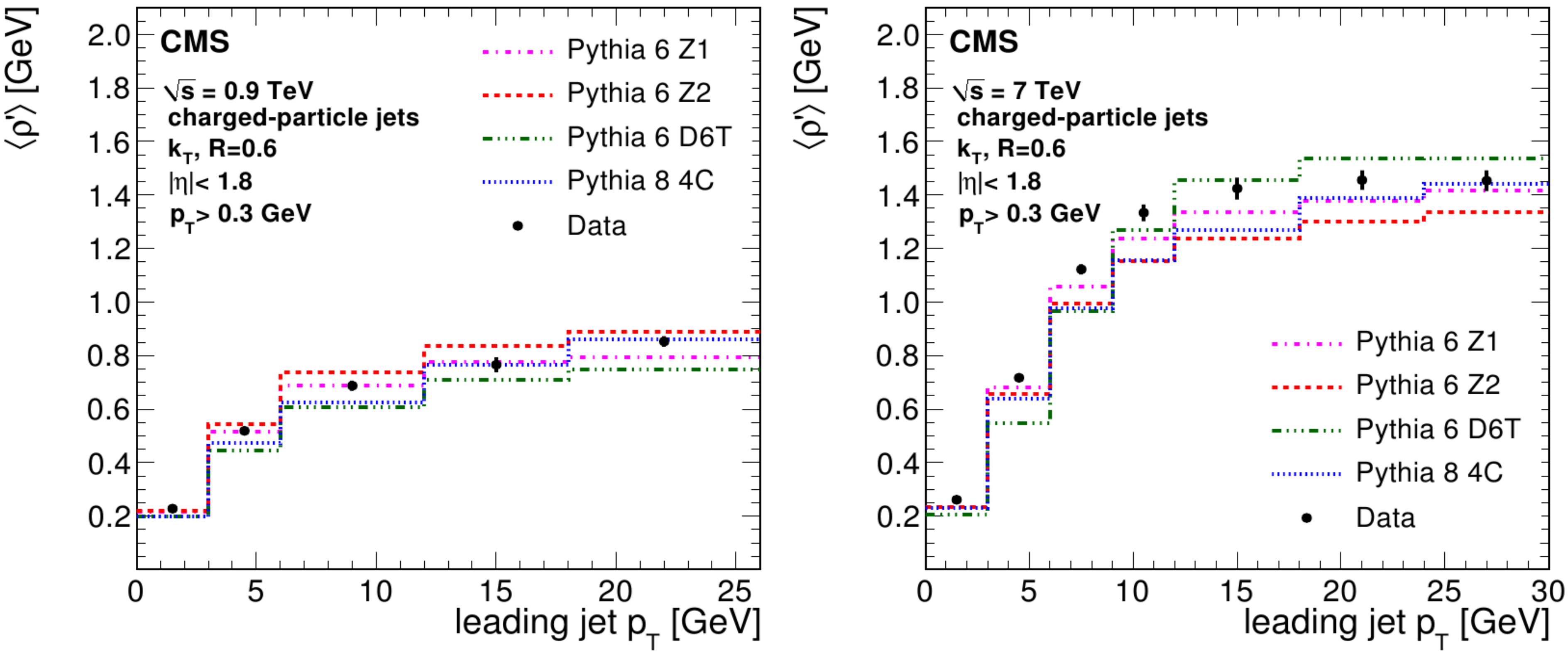
- Leading charged jet for ATLAS
- Leading track for CMS

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

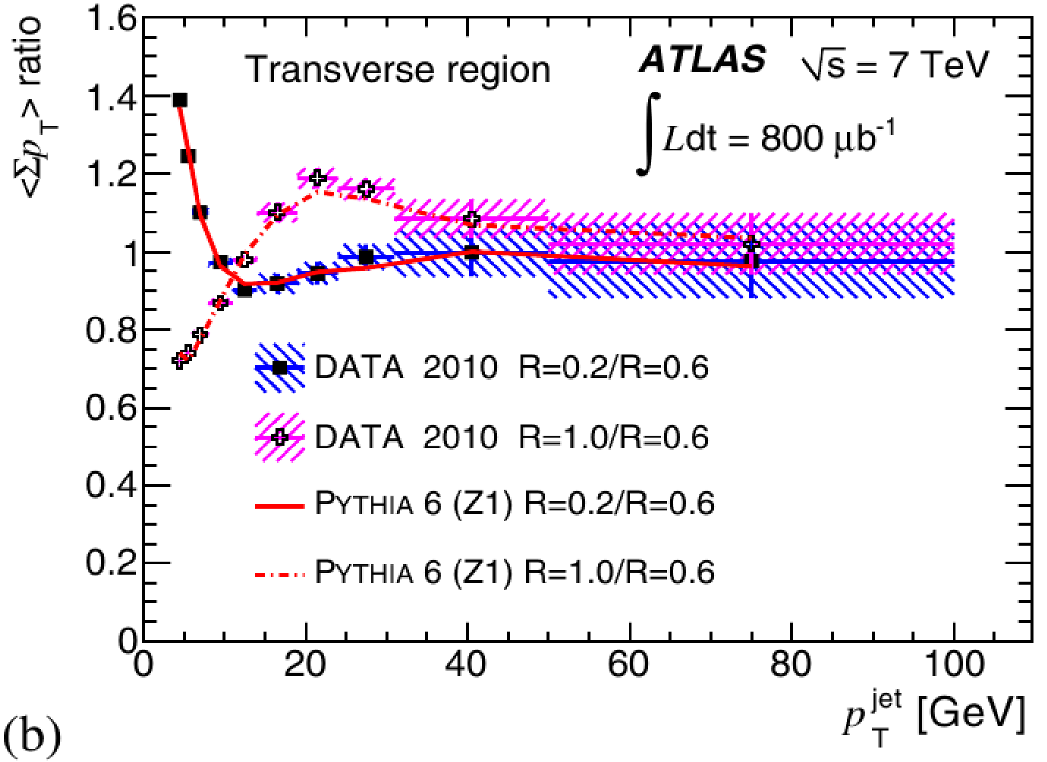
- It uses the FastJet definition of jet area and median activity
  - Slightly modified definition of median, including only jets with at least 1 charged particle



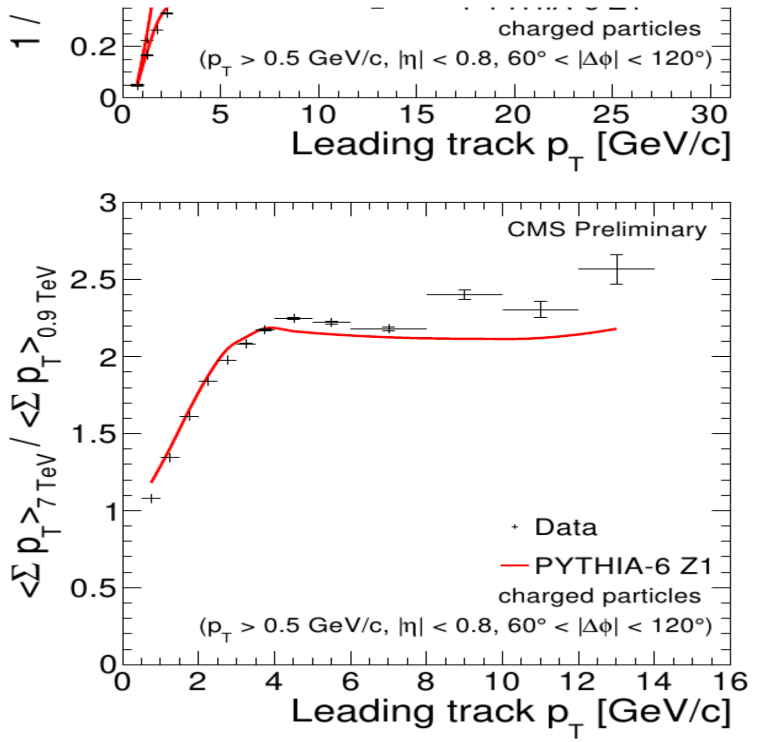
JHEP 08 (2012) 130

UE energy and jet size dependence

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



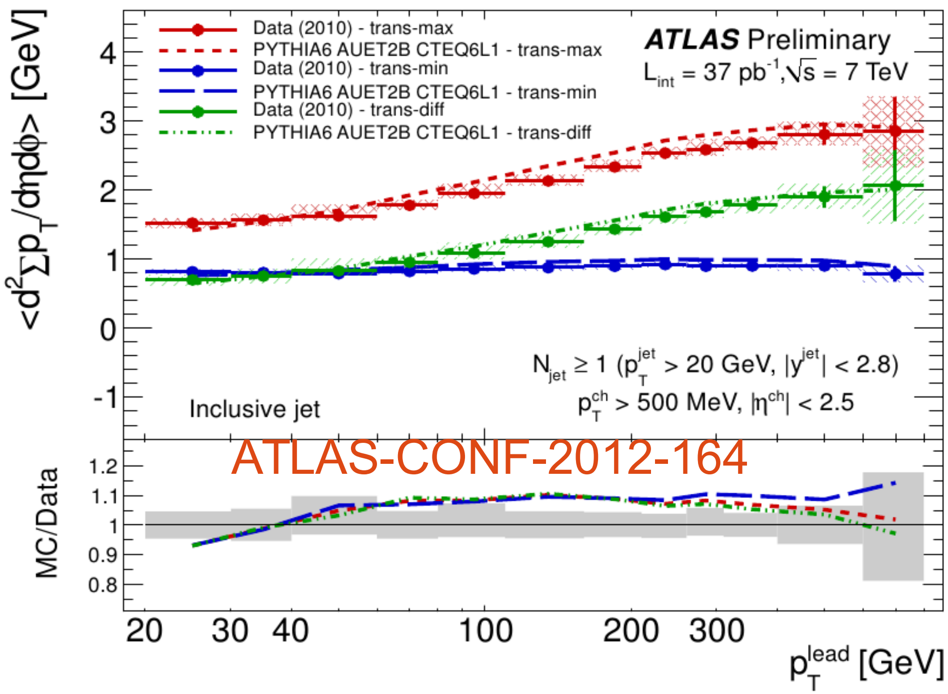
(b)



UE in events with a hard scatterer

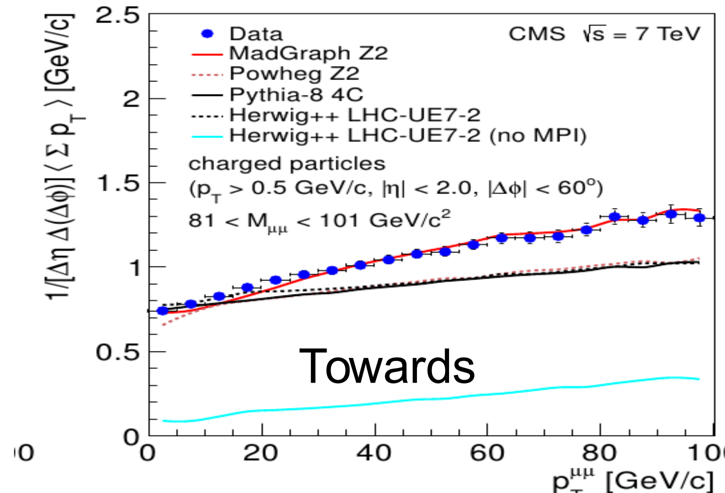
ATLAS UE in events with a hard jet

- 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

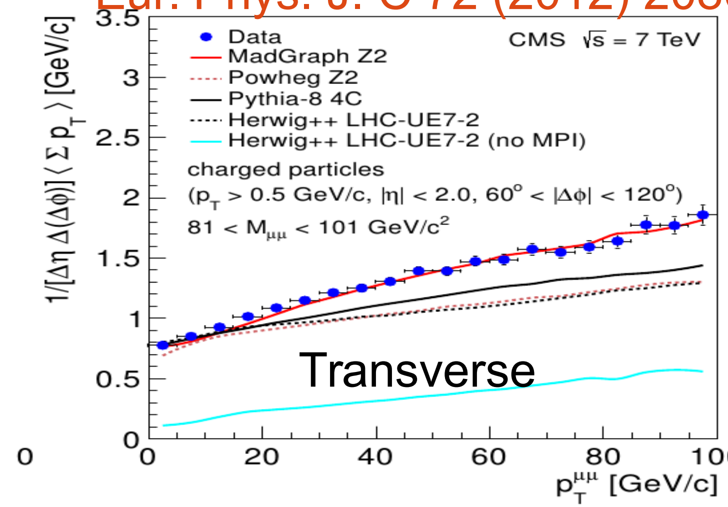


CMS UE in events with a Z boson

- The Z boson defines the leading object direction



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



W/Z+jets: rates

JHEP01(2012)010

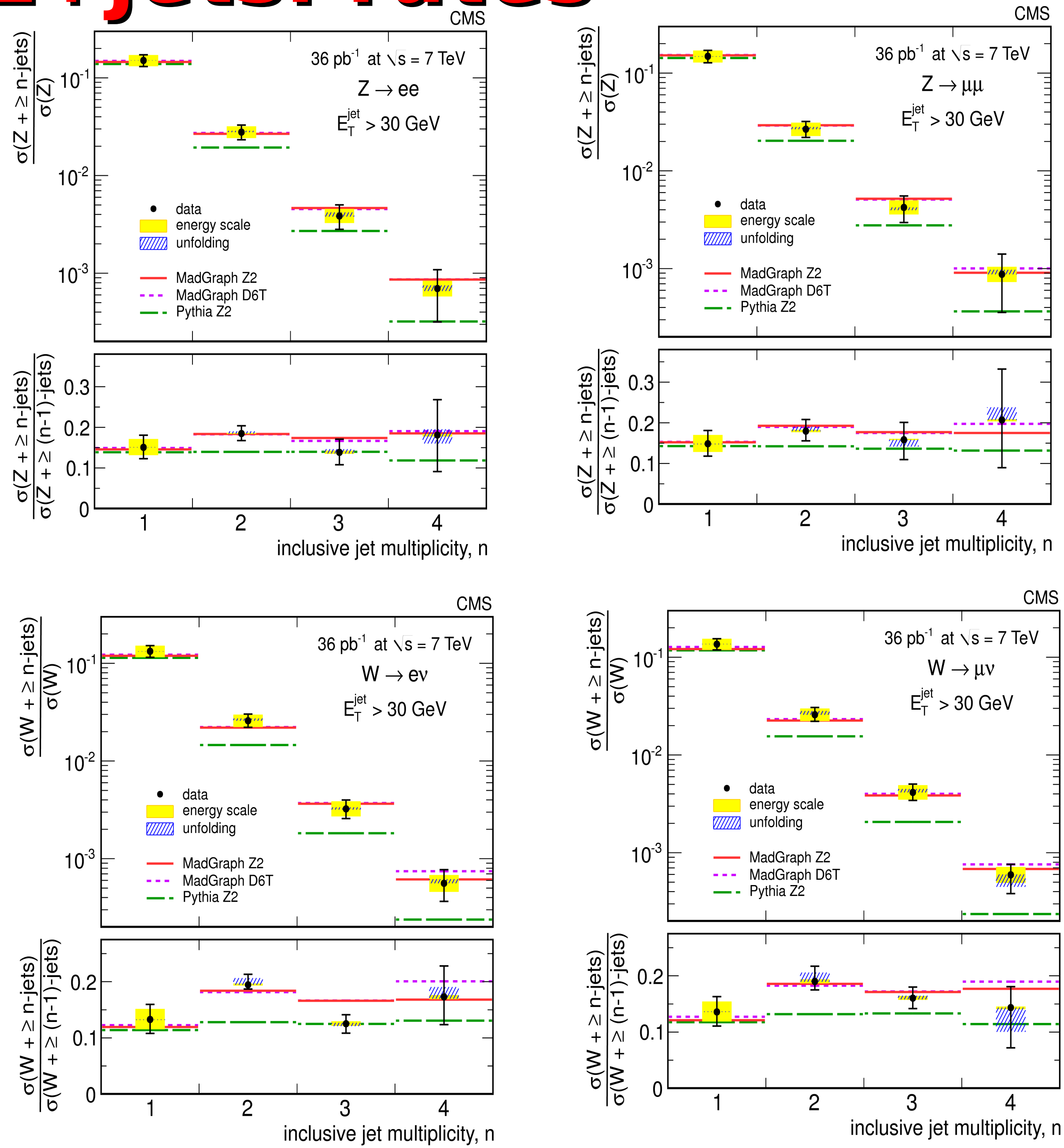
Jet rates

- 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

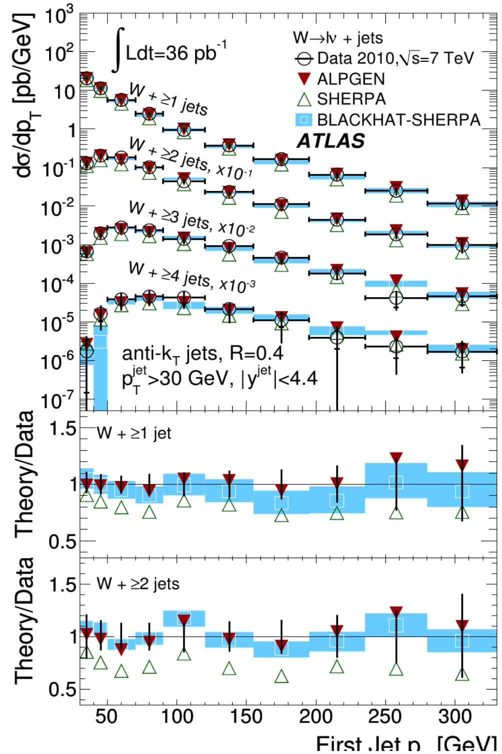
Given the pT threshold the sensitivity to underlying event is negligible

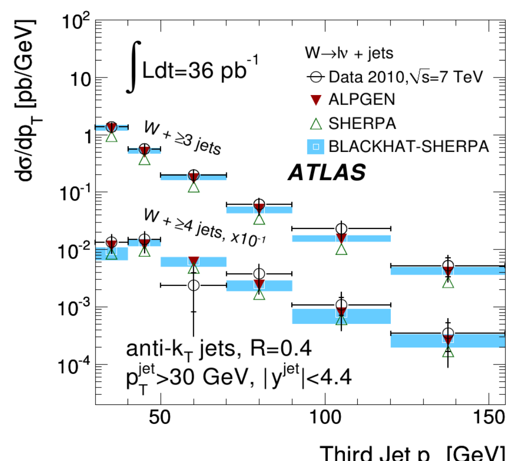


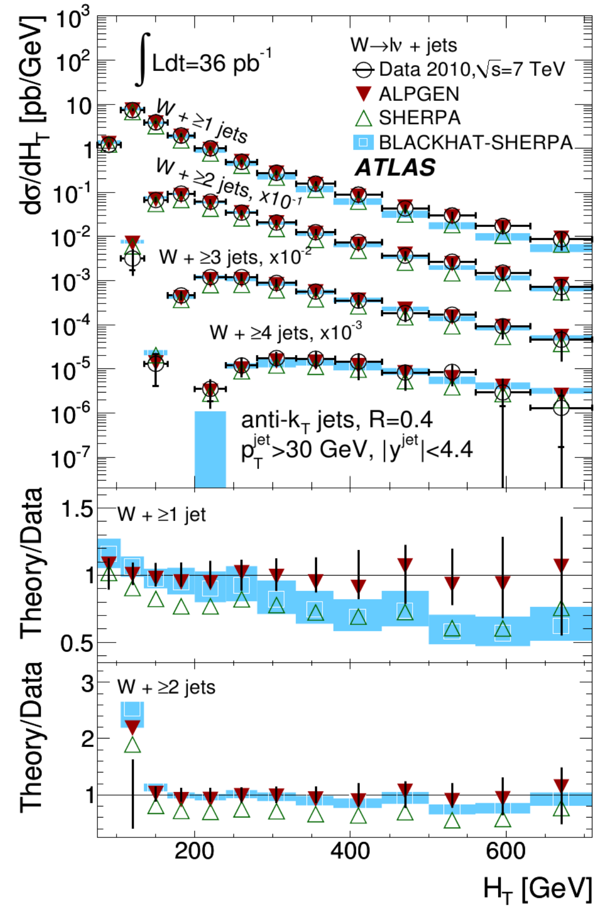
W/Z+jets differential distributions

- 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



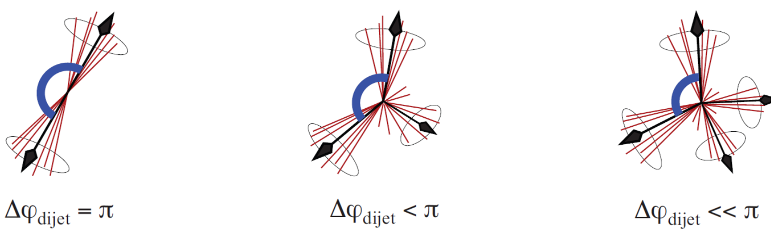




Azimuthal decorrelation

$\Delta\varphi$ between the two leading jets in the event

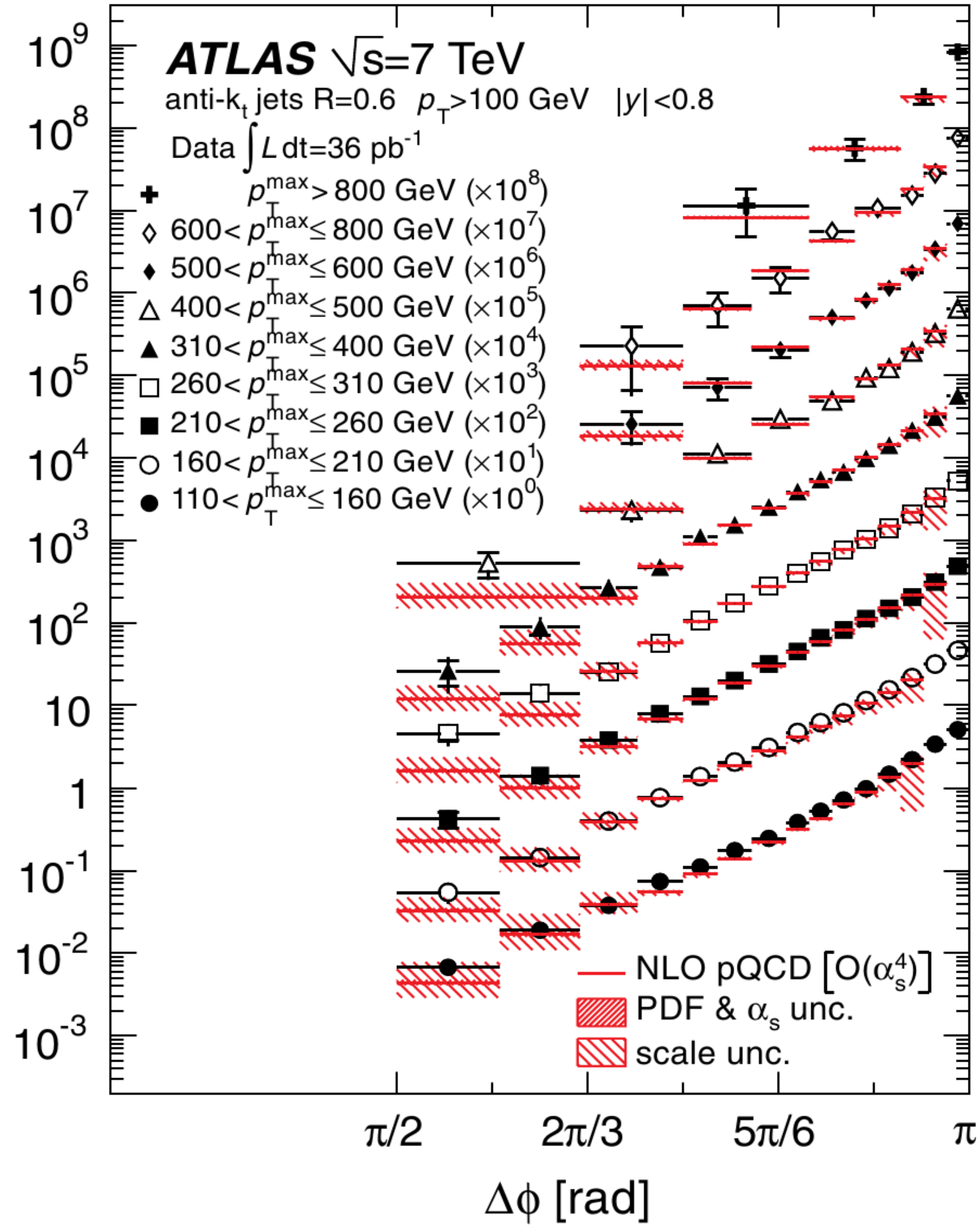
- It is very sensitive to additional radiation effects (hence to higher order corrections) but also to MPI and hadronization



Comparison to NLO QCD

- Good agreement over the entire range

Phys. Rev. Lett. 106 (2011) 12200?

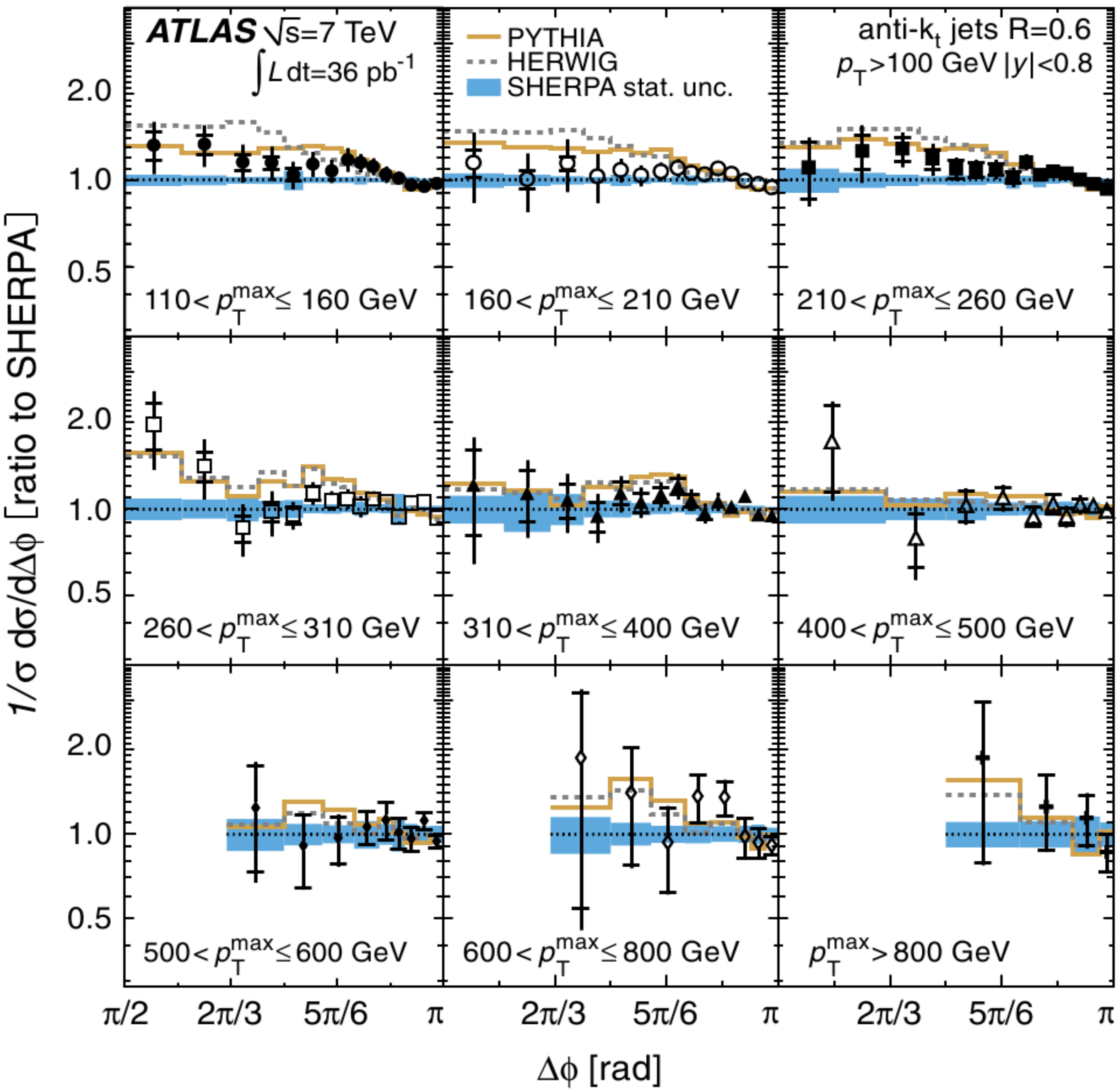


Azimuthal decorrelation

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

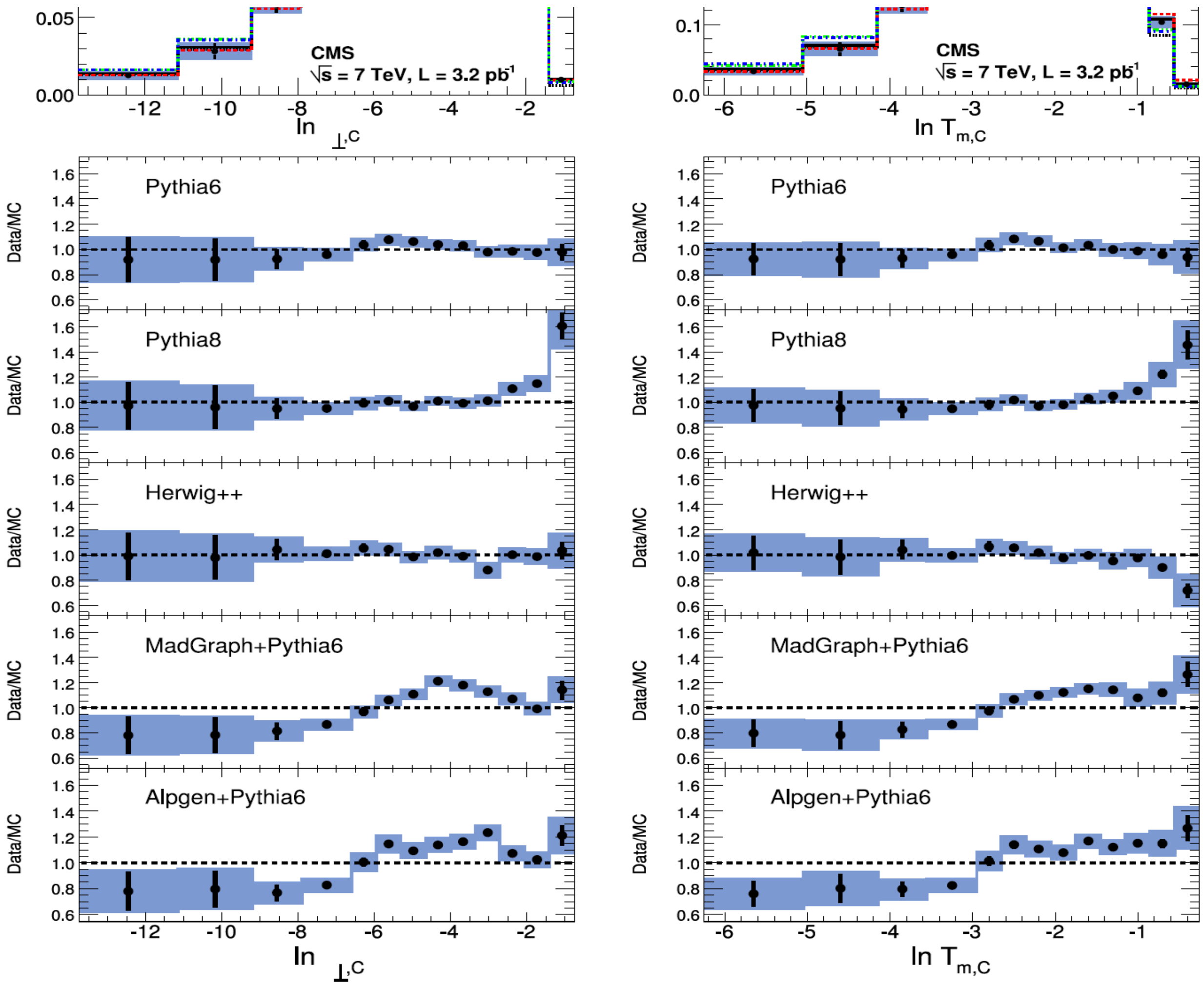


Event shapes

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?



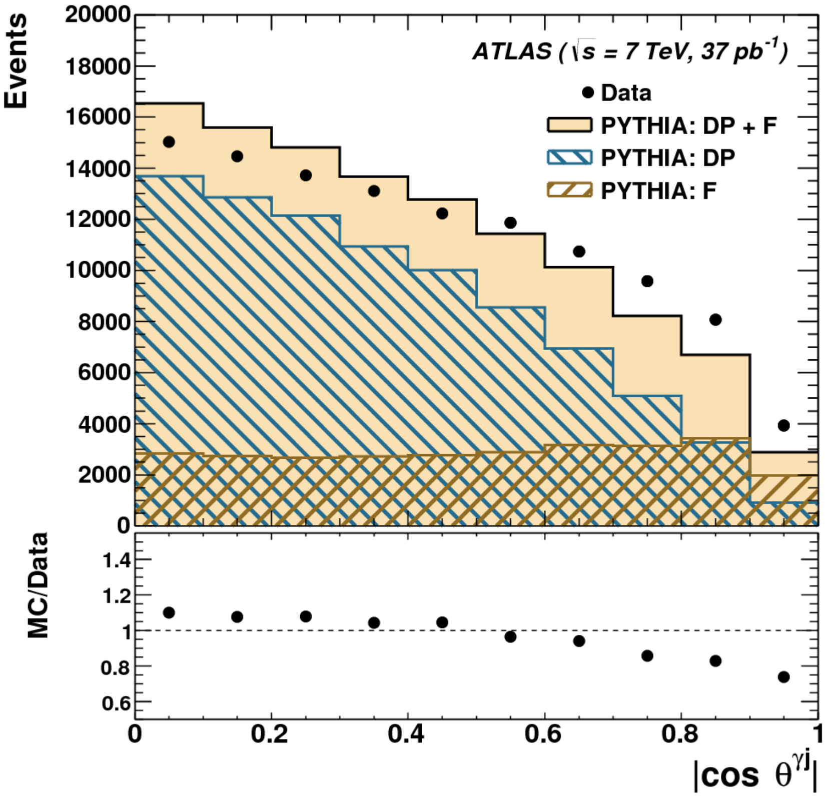
Photon + jets

Nucl. Phys, B 875 (2013) 483-535

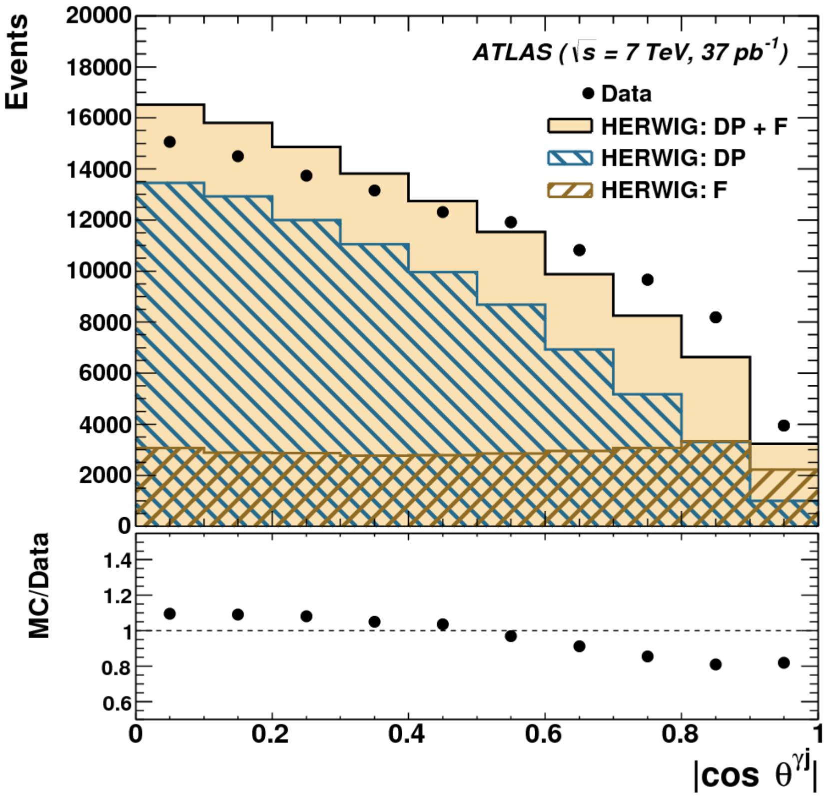
The contribution of fragmentation versus direct photons was studied in detail as a function of scattering angle $\theta^{\gamma j}$ in the photon-jet rest frame

Shower MC can get the right differential shape with tuning of the two contributions

PYTHIA

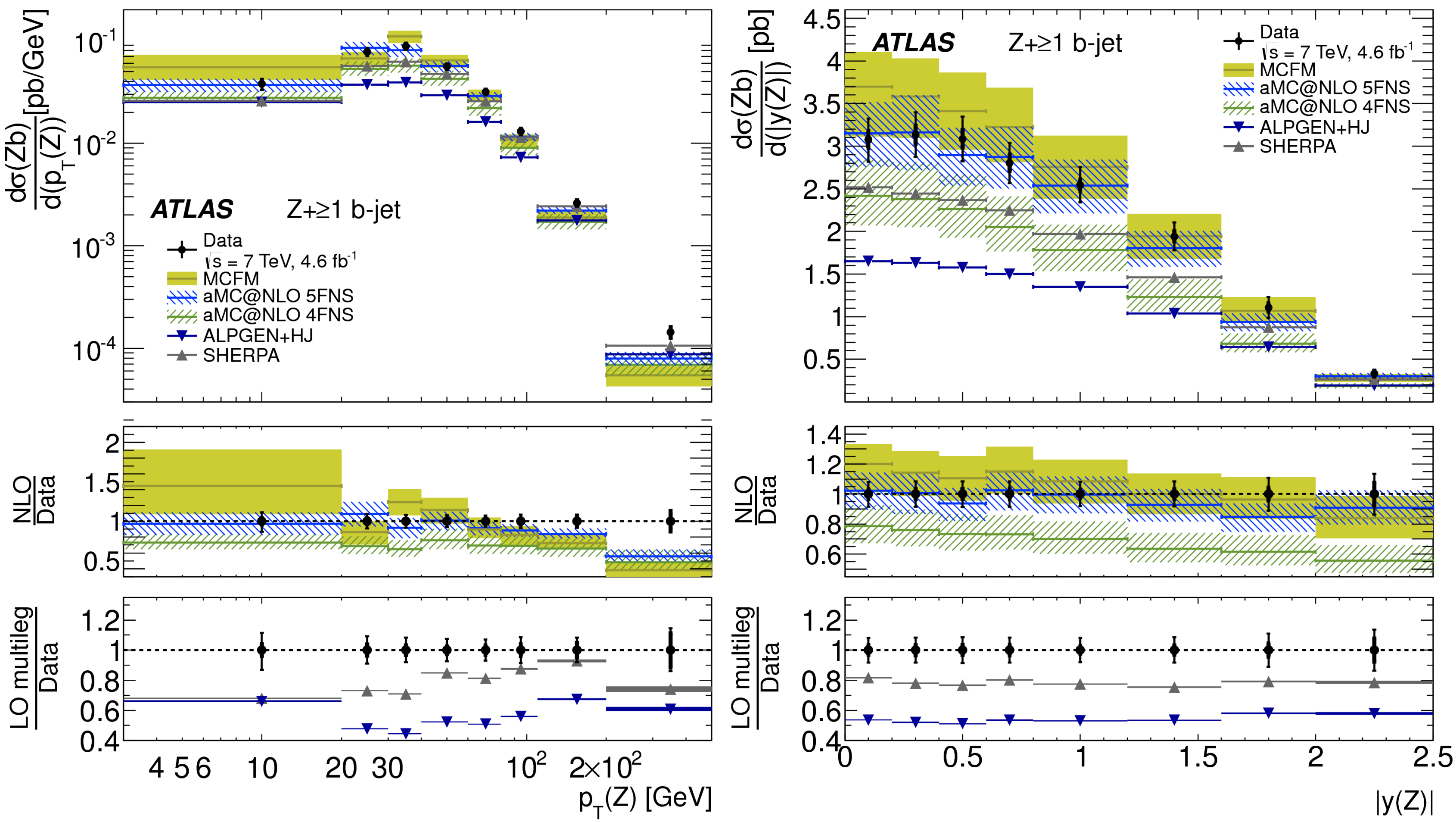


HERWIG



Z+heavy flavor

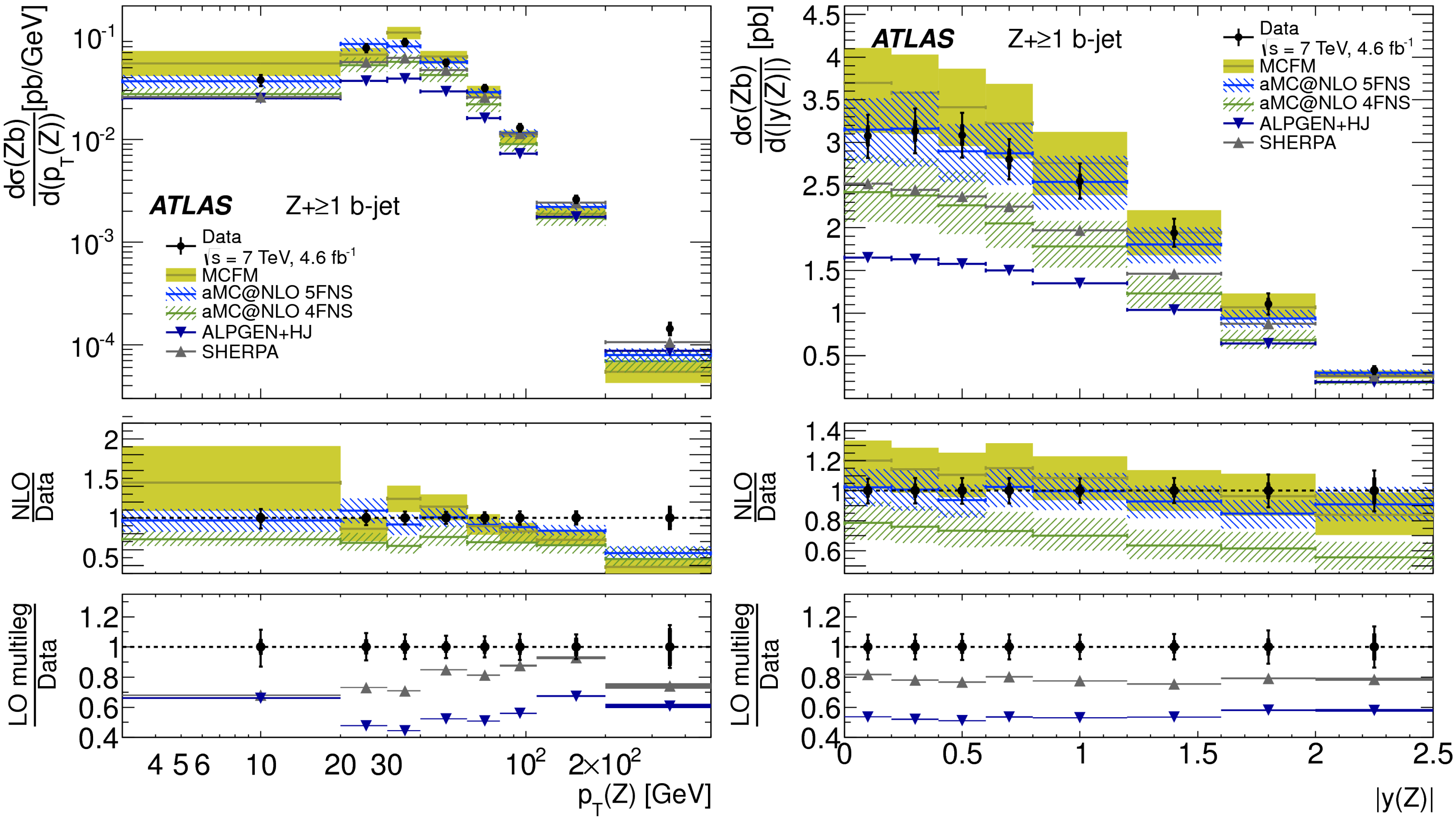
Z+>=1 jet aMC@NLO in the 5-F scheme gives a remarkably good description



CERN-PH-EP-2014-118

Z+heavy flavor

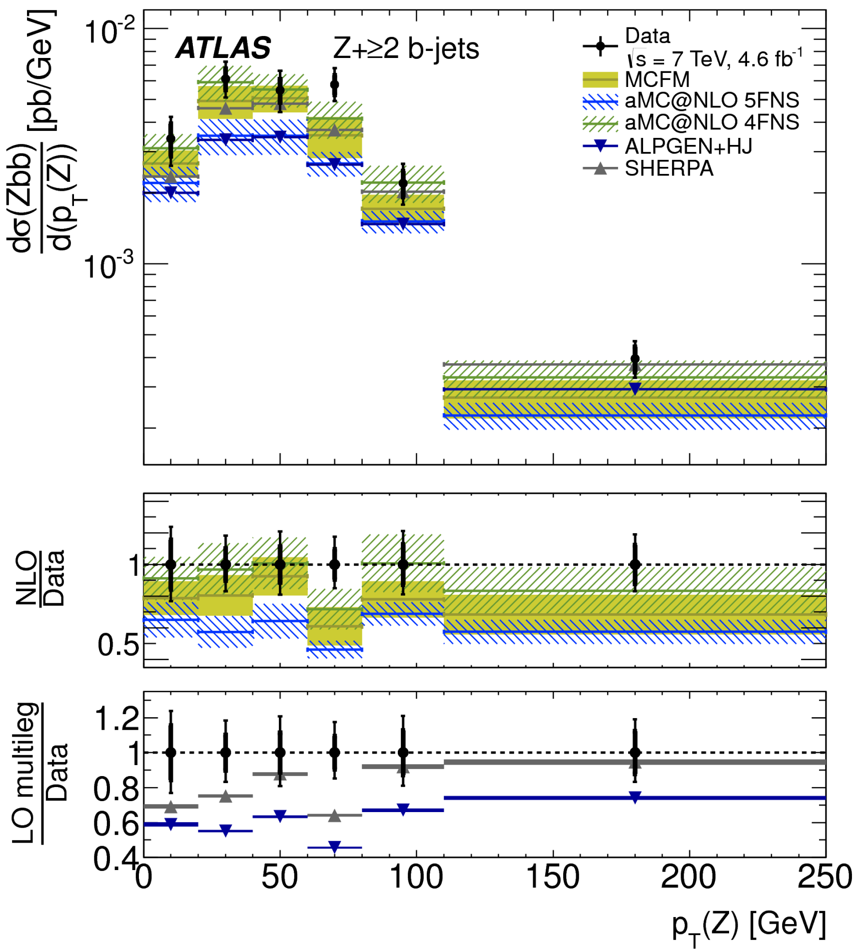
Z+>=1 jet aMC@NLO in the 5-F scheme gives a remarkably good description

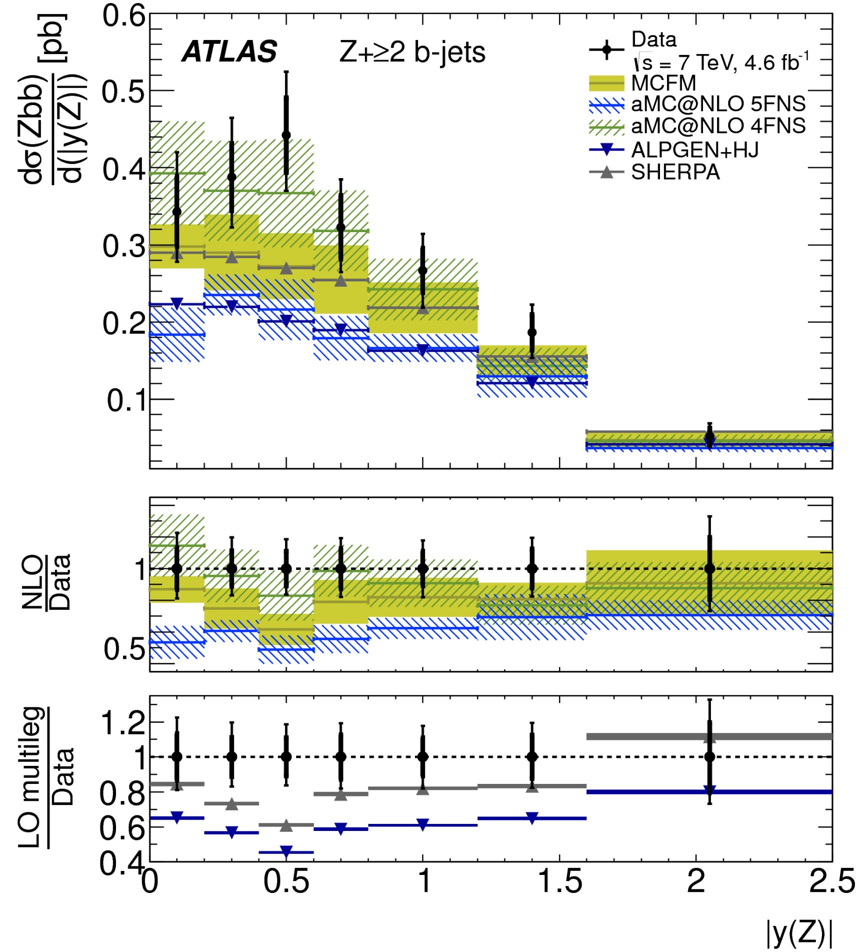


CERN-PH-EP-2014-118

Z+heavy flavor

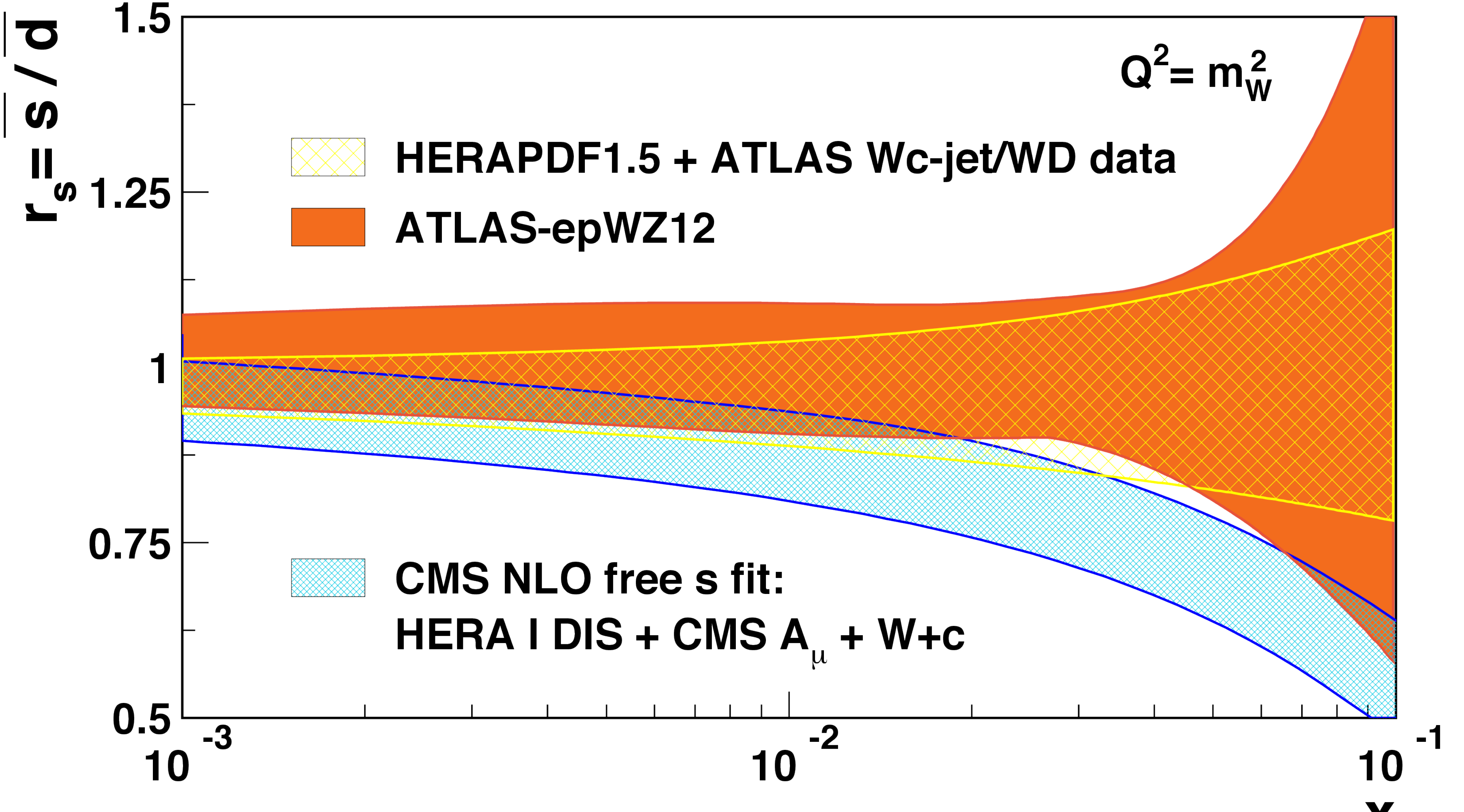
Z+>=2 jets aMC@NLO with 4-F is now best





CERN-PH-EP-2014-118

JHEP12(2013)039



$r_s = \bar{s} / \bar{d}$
1.5
1.25
1
0.75
0.5
$Q^2 = m_W^2$
HERAPDF1.5 + ATLAS Wc-jet/WD data
ATLAS-epWZ12
CMS NLO free s fit:
HERA I DIS + CMS A_μ + W+c
10^{-3}
10^{-2}
10^{-1}
x