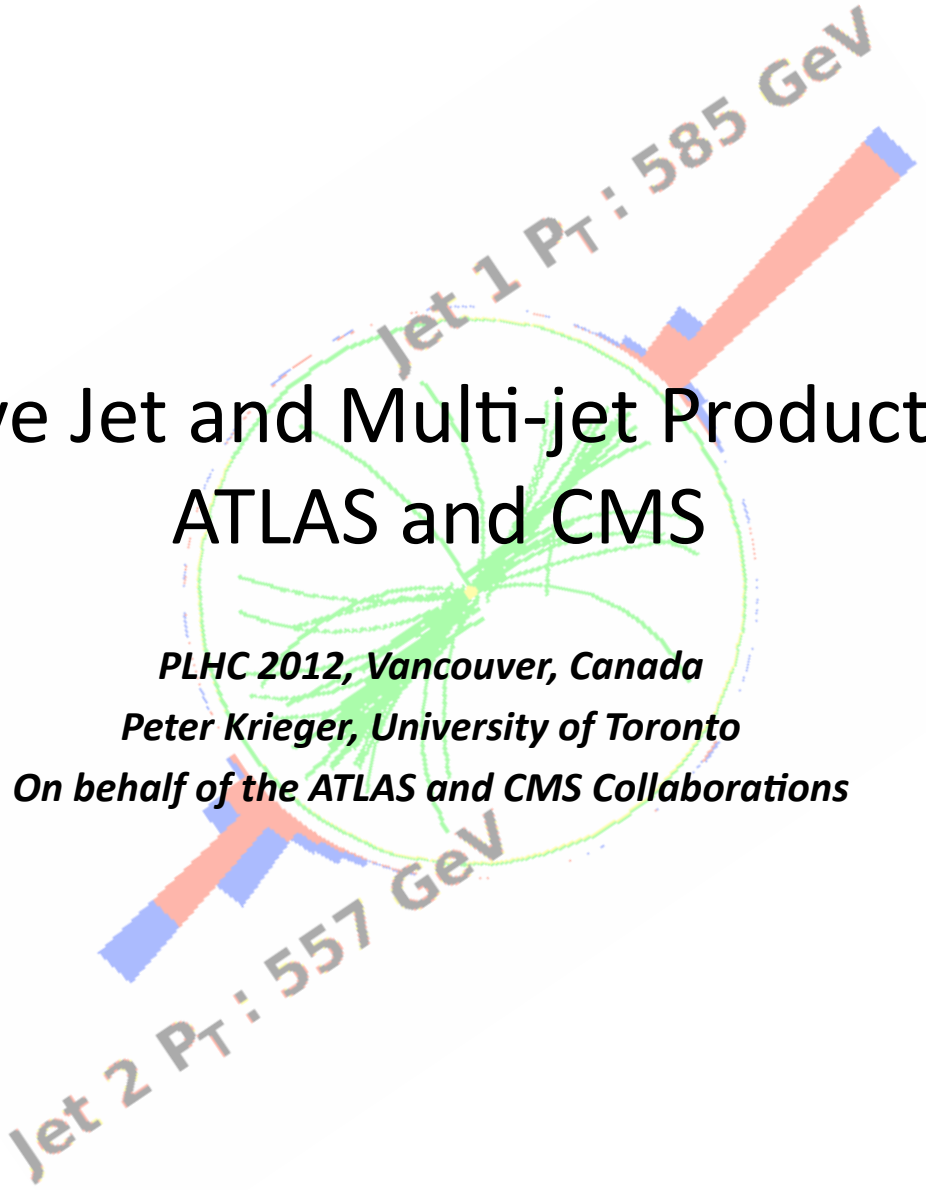
Inclusive Jet and Multi-jet Production at ATLAS and CMS



PLHC 2012, Vancouver, Canada

Peter Krieger, University of Toronto

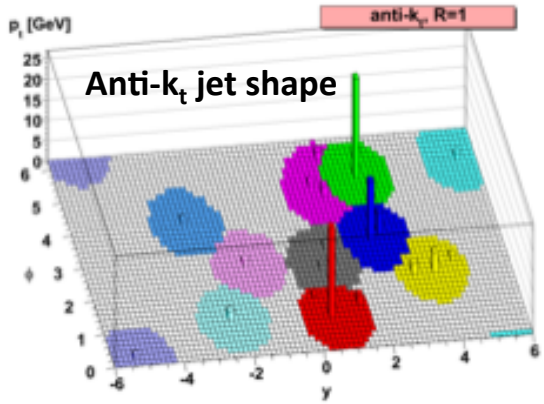
On behalf of the ATLAS and CMS Collaborations

Overview

- Event selection and jet reconstruction
- Performance:
  - Jet energy scale uncertainties (dominant systematic uncertainty)
- **Inclusive Jet cross-sections**:
  - some updates since PLHC 2011
- **Dijet cross-sections**:
  - some updates since PLHC 2011
- **Multi-jet production**:
  - fewer updates: preliminary results finalized.
- In each case, for data / theory comparisons:
  - Results unfolded to particle-level to allow comparison with theory.
  - Comparisons to Parton Shower Monte Carlos:
    - Different models (PYTHIA, HERWIG,…..), tunes, PDFs etc.
  - Comparisons to NLO pQCD (various PDFs)
    - + non-perturbative (NP) corrections or interfaced to parton shower generator.

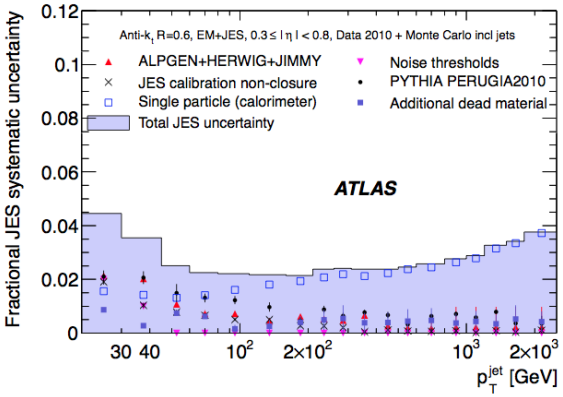
[see also backup slides]

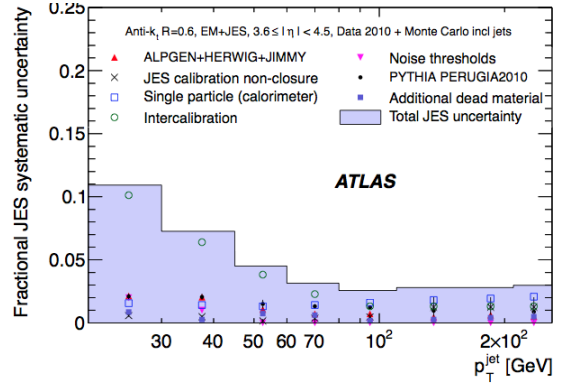
Event Selection / Jet Reconstruction Overview

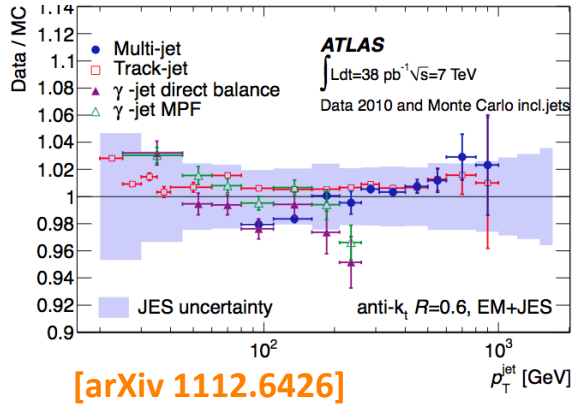


- Jet algorithm: anti-k_t (infrared & collinear safe, good jet shape)
- Jet size: R = 0.4, 0.5, 0.6, 0.7 (ATLAS, CMS)
- Selected triggers used on plateau where ε ≥ 99%.
- Primary vertex requirement to ensure collision event
- Jet quality cuts (to suppress jets from non-collision backgrounds):
  - typically ~ 100% efficient for real jets
- ATLAS & CMS detectors (see backup slides)
  - Tracking coverage for region $|\eta| < 2.5$
  - Calorimetry coverage for (approx.) $|\eta| < 5$
- Jet algorithm inputs (for analyses discussed here):
  - ATLAS: topological clusters of calorimeter cells at the EM scale
  - CMS: Calibrated Particle-flow candidates (PF)
  - CMS: Calorimeter towers (CALO)

Performance: ATLAS JES Uncertainties







[arXiv 1112.6426]

JES is the dominant experimental uncertainty in the measurements presented here (except in some cases where ratios are used).

JES uncertainty < 5% for central region

JES in forward region has additional uncertainty from dijet balance used to extrapolate into endcap/forward regions.

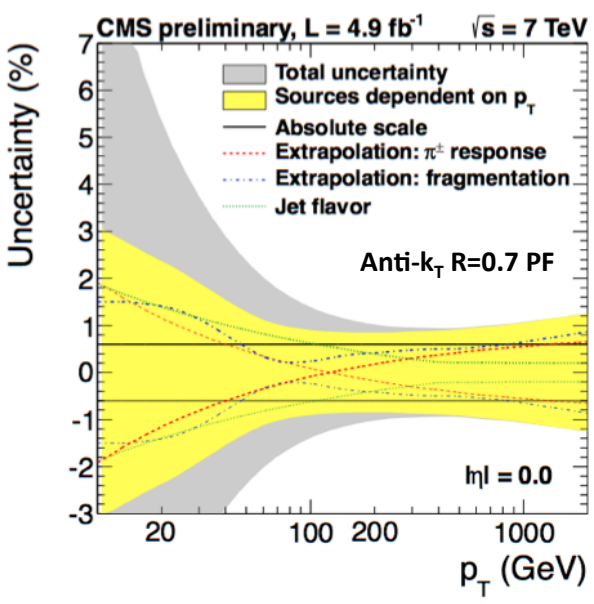
Validated with in-situ checks using p_T balance with well-calibrated objects. Results compared here with the JES uncertainties.

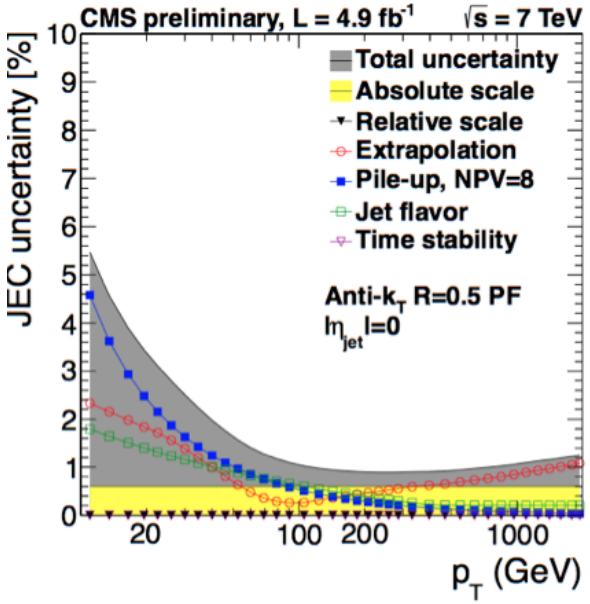
Contribution due to pile-up depends on N_{PV}.

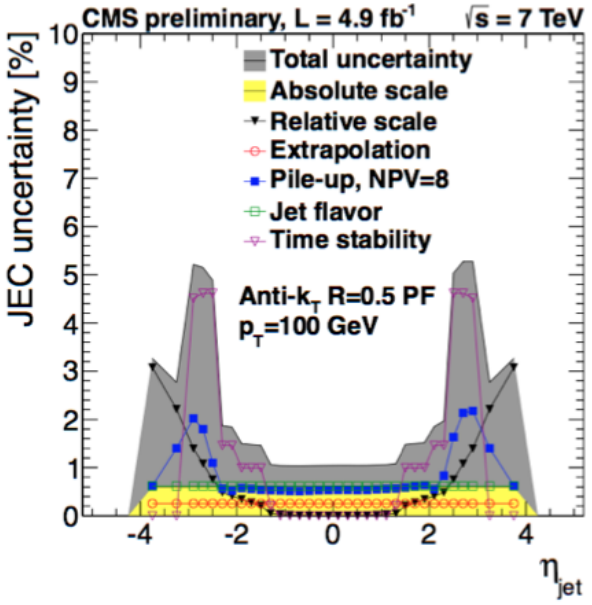
JES from 2011 data in progress.

Performance: CMS JES Uncertainties (2011)

- JES uncertainty depends on constituents input to jet algorithm
- Best performance is for particle flow (PF) jets.
- JES from 2010 data (backup slides) updated for PF jets with 2011 data.
- CMS results involving the forward region use EM-scale CALO jets: these higher p_T thresholds and larger (2010) JES uncertainties.



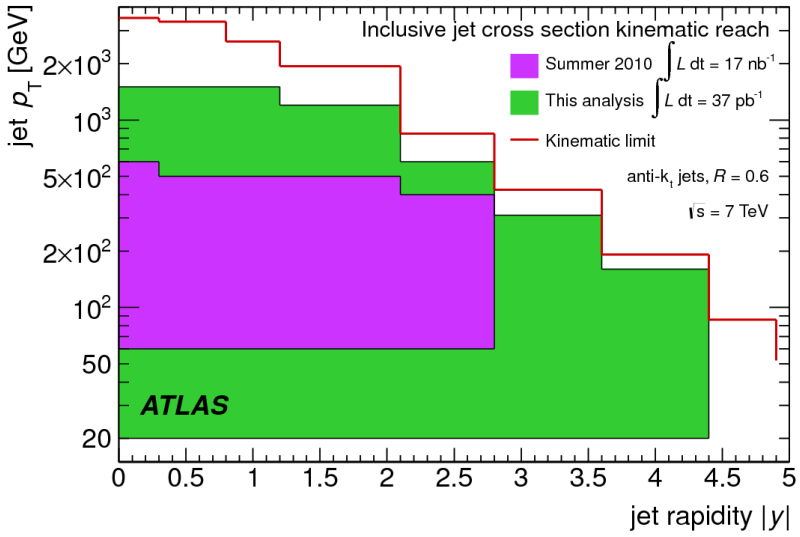


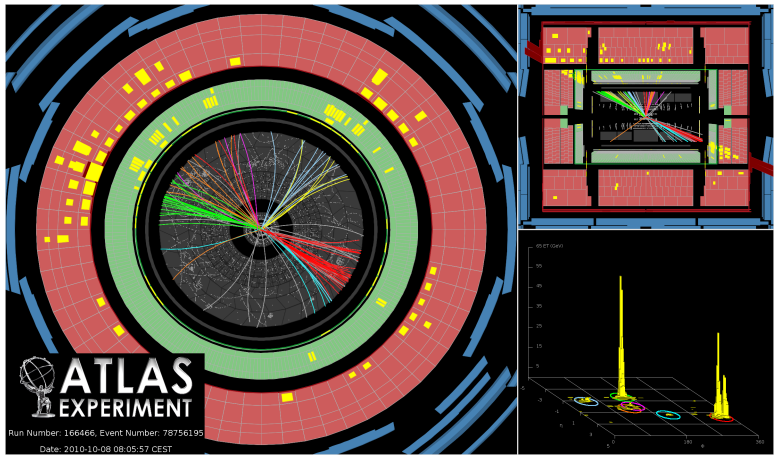


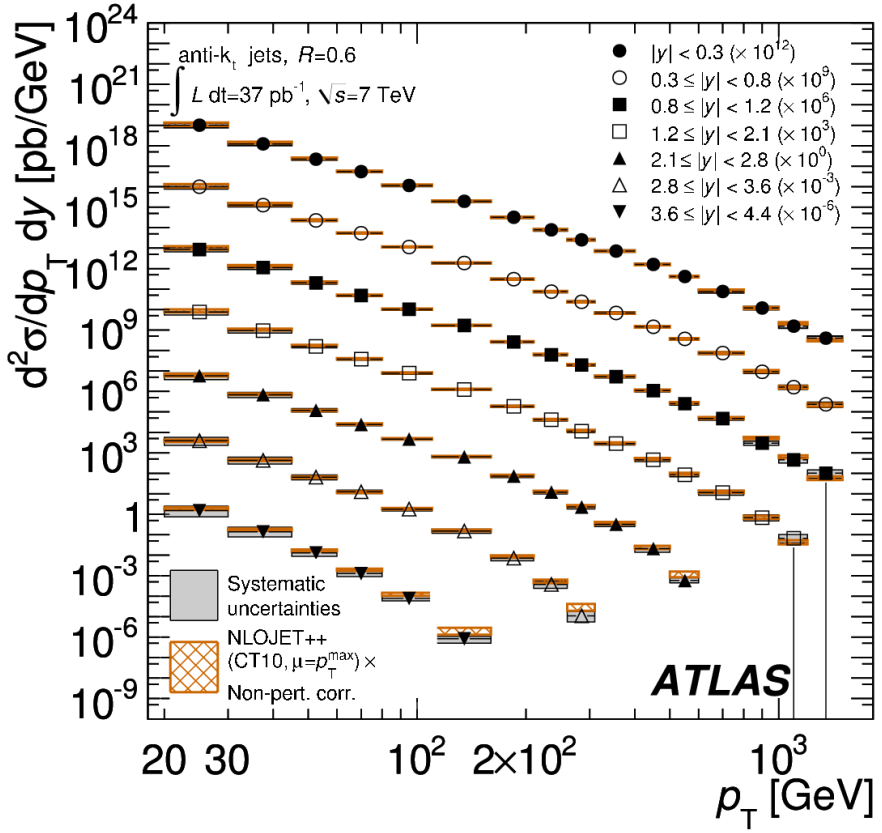
These uncertainties apply to the 2011 inclusive jet and dijet cross section measurements

Inclusive Jet Cross-section ATLAS (2010)

ATLAS 2010 data: rapidity coverage |y|<4.4, p_T coverage 20 GeV to 1.5 TeV







[arXiv 1112.6297]

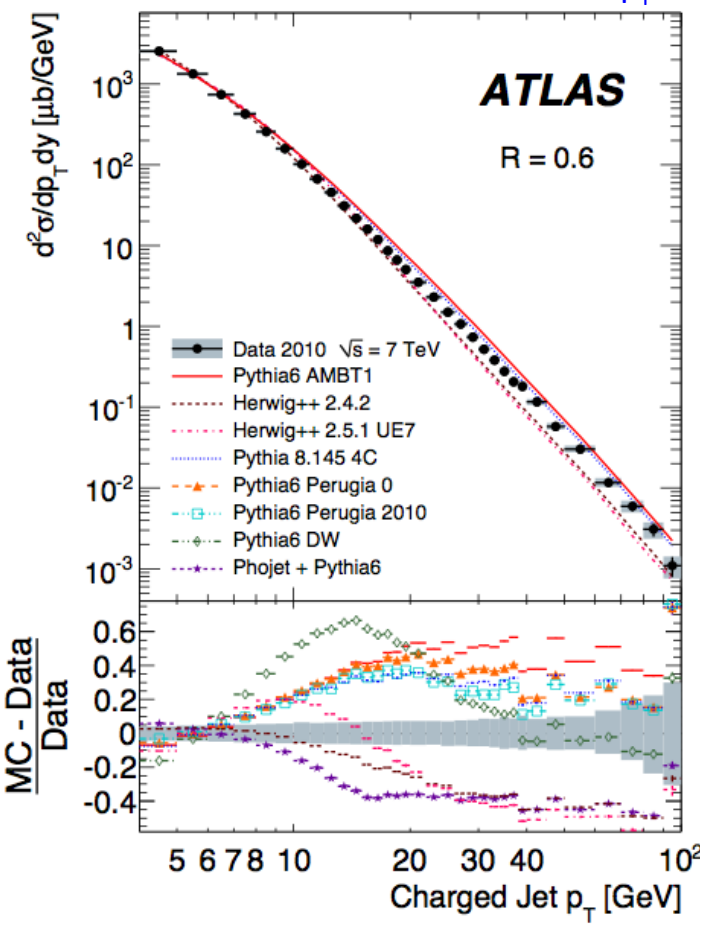
Good agreement with NLO pQCD calculations + non-pert. corrections.
Other PDFs: MSTW2008, NNPDF2.1 (100), HERAPDF1.5 (see backup slide)

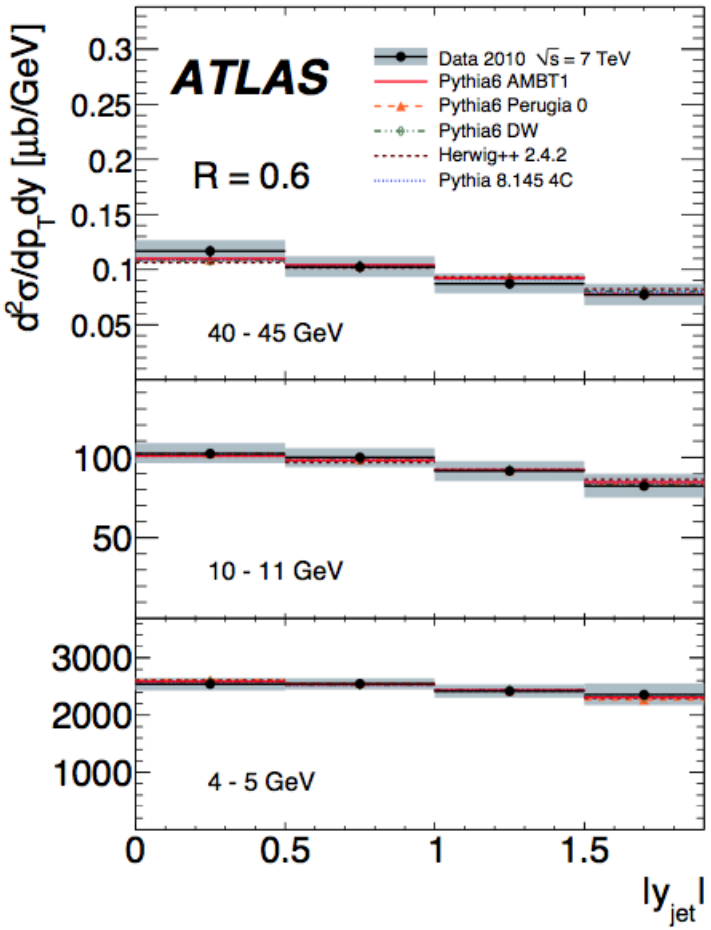
Cross-section for Inclusive Track Jets (ATLAS)

Track jets used to test Monte Carlo models to lower p_T, here down to 4 GeV.

$|y_{jet}| < 1.9$ (ensures R=0.6 jet contained within tracking acceptance)

MC normalized to data at low p_T.





MC normalized to data separately for each bin of p_T.

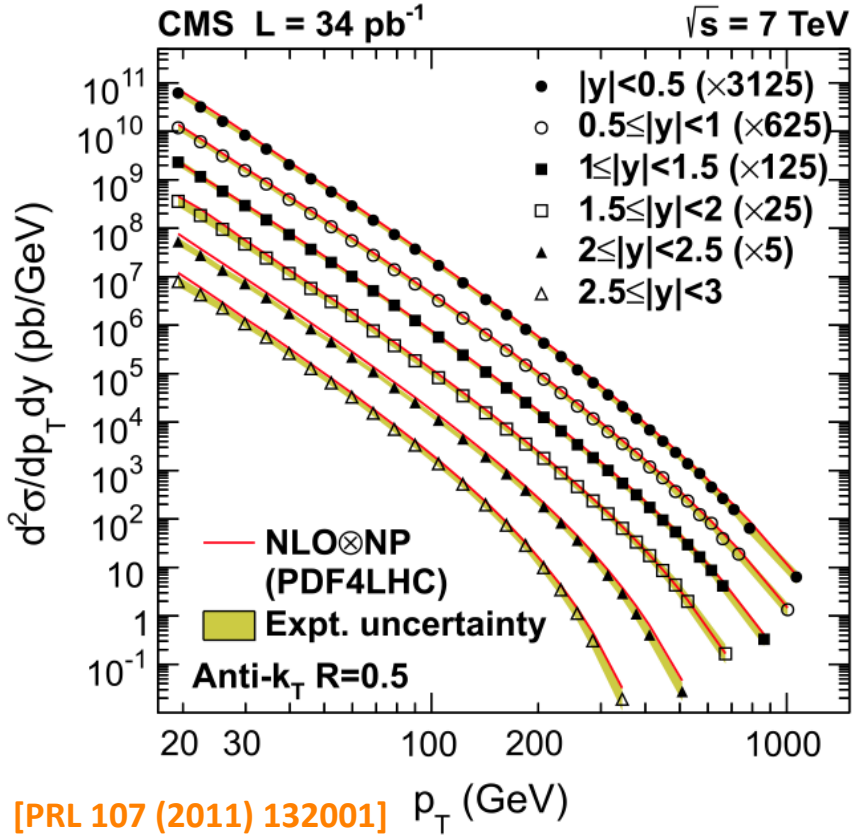
MC models all have difficulty in the low p_T region

[PRD 84 (2011) 054001]

Inclusive Jet Cross-section (CMS) – Central Region

2010 data: Anti-k_t R=0.5, |y|<3.0

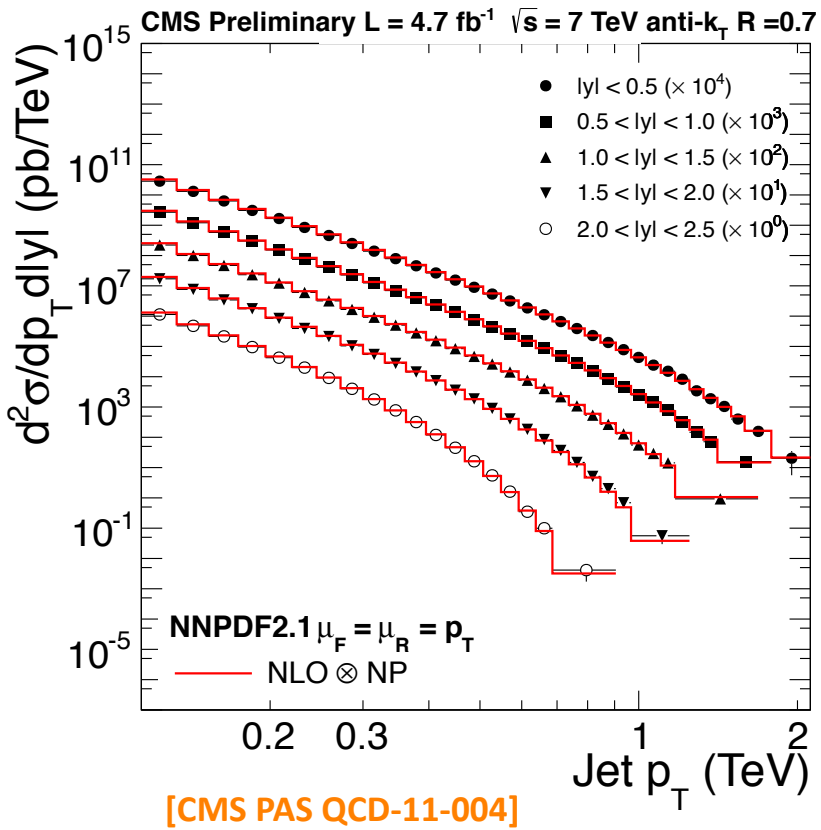
p_T > 18 GeV



[PRL 107 (2011) 132001]

2011 data: Anti-k_t R=0.7, |y|<2.5

p_T > 114 GeV



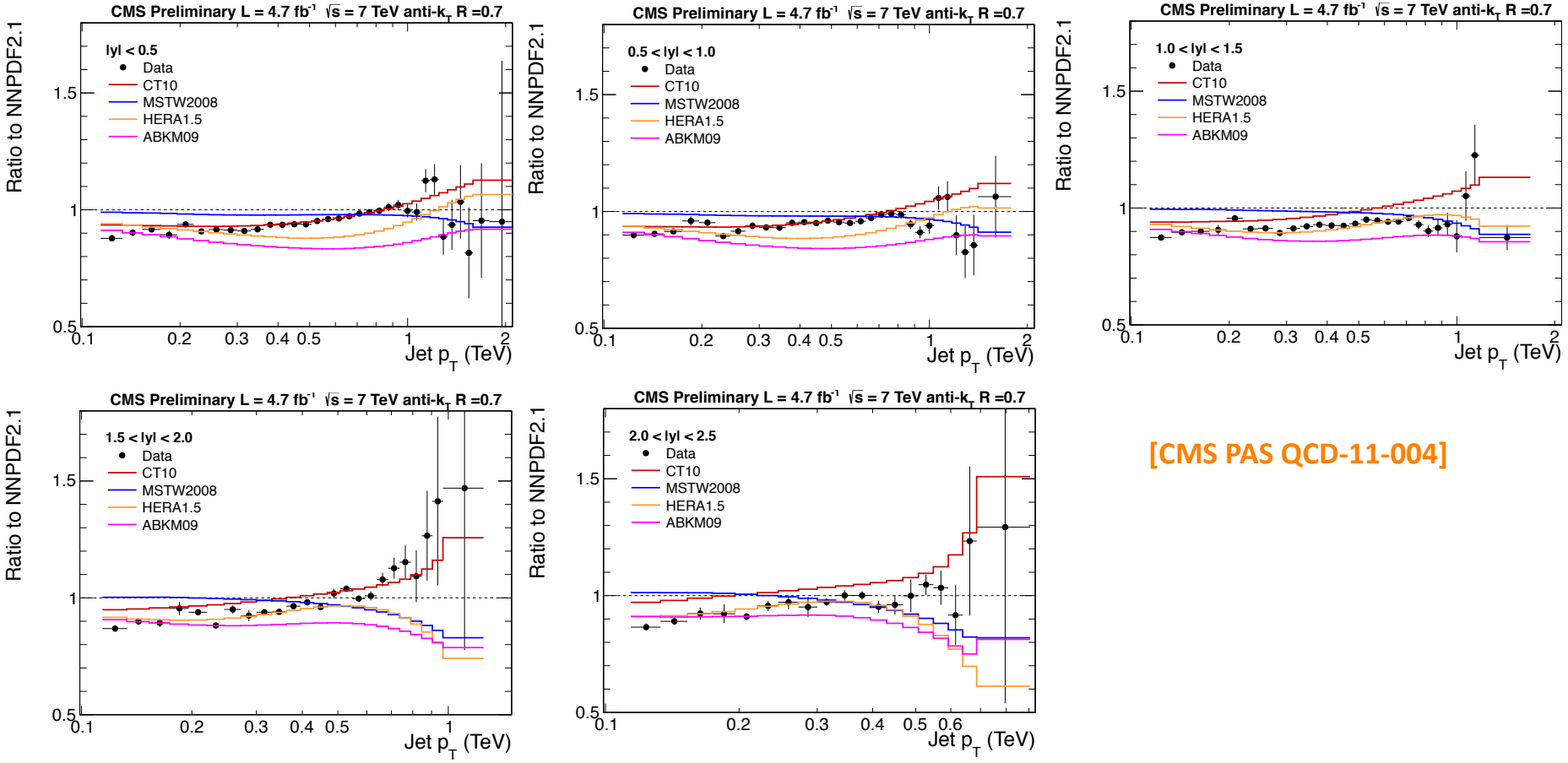
[CMS PAS QCD-11-004]

Particle-flow (PF) jets. Theory prediction from NLOJET++ with NP corrections. Checked for a variety of PDF sets (next slide). Agreement generally good.

CMS Inclusive Jets (Central, 2011) Data/Theory

Data to theory ratio for the five bins of y: NLOJET++ (NNPDF2.1) plus NP corrections

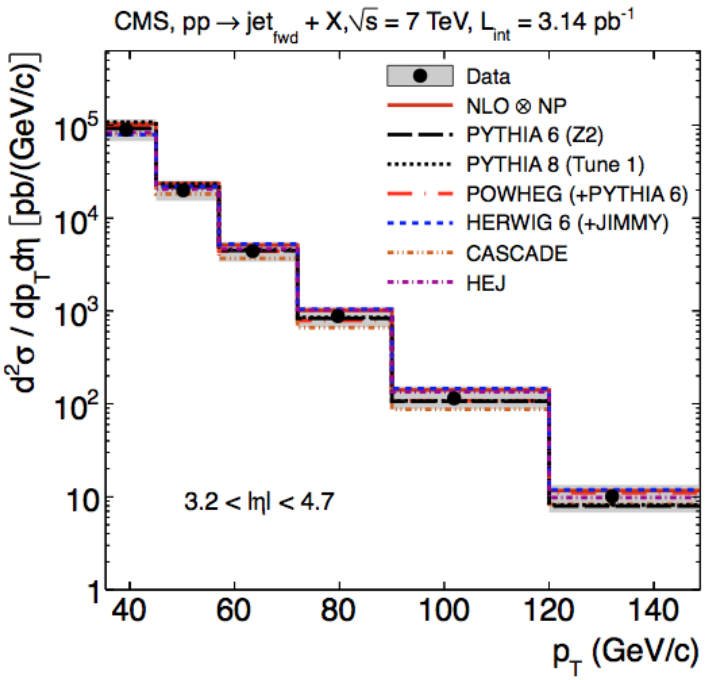
Ratio also shown of NLO prediction with differing PDFs, to default NLO prediction.

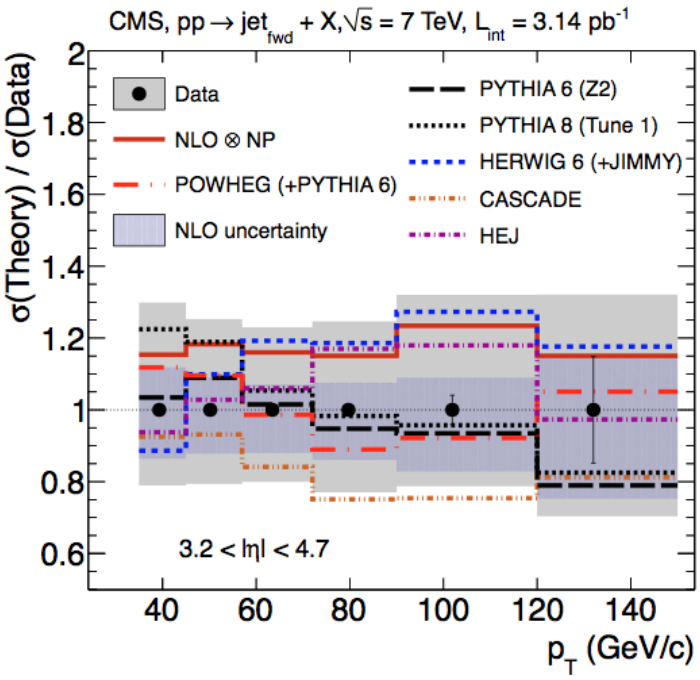


[CMS PAS QCD-11-004]

Inclusive Jets Cross-section (CMS) – Forward Region

- Anti-k_t 0.5, CALO jets, $3.2<|\eta|<4.7$, p_T 35-150 GeV (CMS FCal coverage is 3.0-5.2).
- Single pseudorapidity (η) bin used for the forward region: cross-section shown vs. p_T.
- 2010 data 3.14 pb^{-1} (special dijet trigger)
- Approx. 30 % uncertainties dominated by JES uncertainty.





Use of different PDFs in NLO calculations gives similar results

[CMS-FWD-11-002]

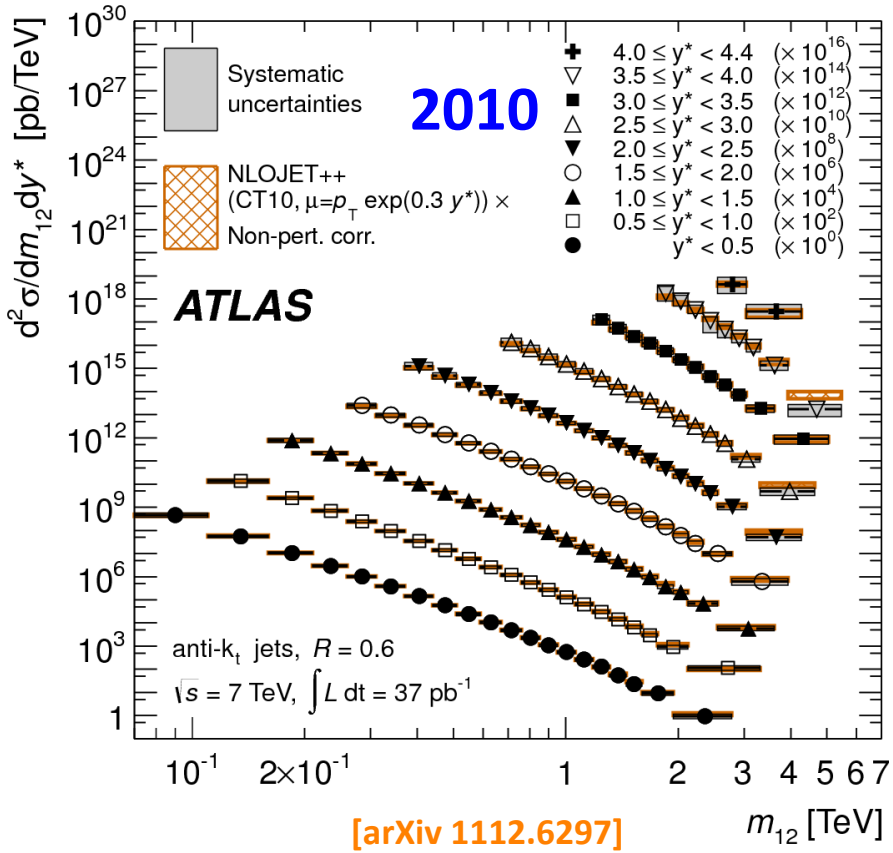
Most models consistent within experimental uncertainties. No preference for BFKL/CCFM-inspired models (HEJ, CASCADE) which are expected to become relevant for large rapidity separations.

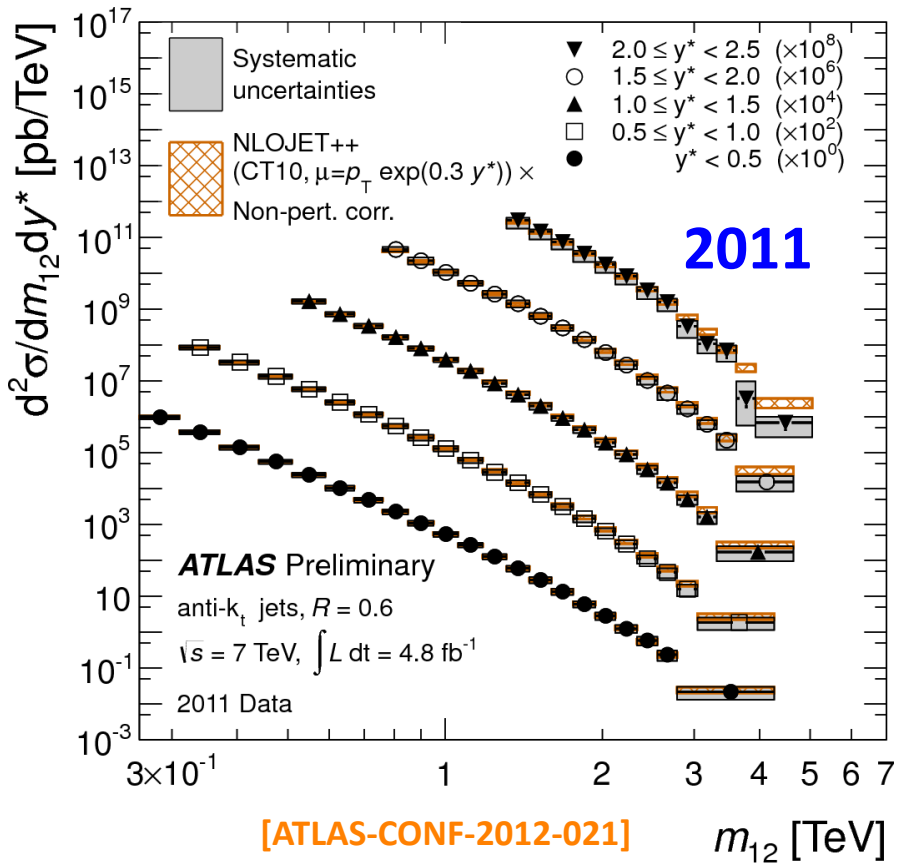
Dijet Cross-section measurements (ATLAS)

Rapidity coverage $|y|<4.4$, p_{T1} (leading jet) > 30GeV, p_{T2} (sub-leading jet) > 20 GeV.

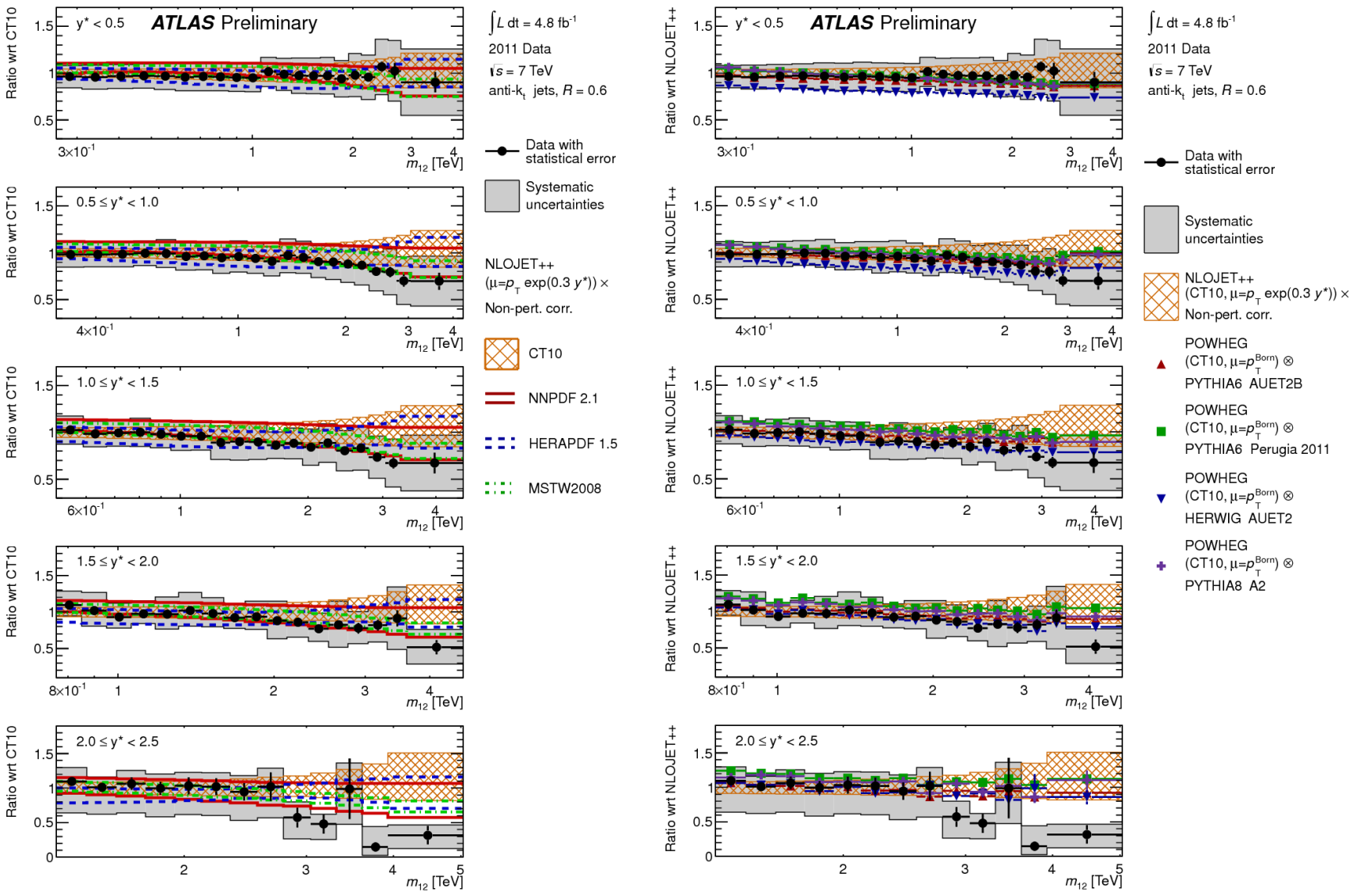
Cross-section binned in m_{12} = invariant mass of dijet system $y^* = |y_1 - y_2|/2$

Published 2010 results updated with full 2011 dataset, for $y^* < 2.5$ region p_T cuts 100, 50GeV.





Data/Theory Comparisons for ATLAS 2011 Dijet Results



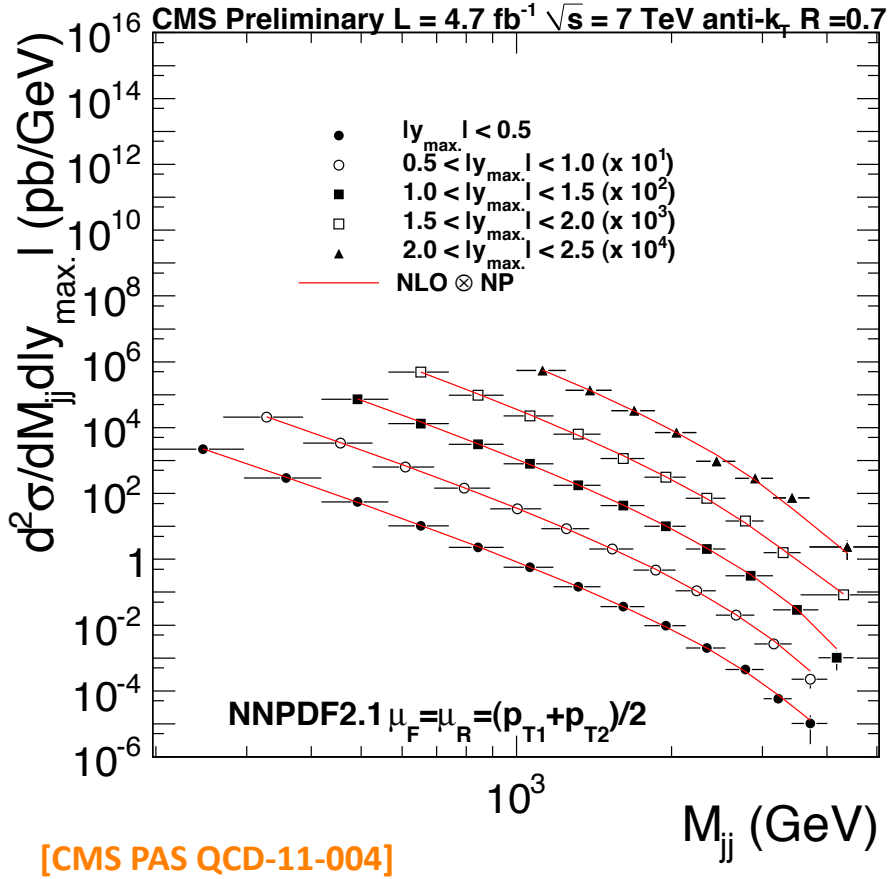
[ATLAS-CONF-2012-021]

CMS Dijet Cross-section (2011) - Central region

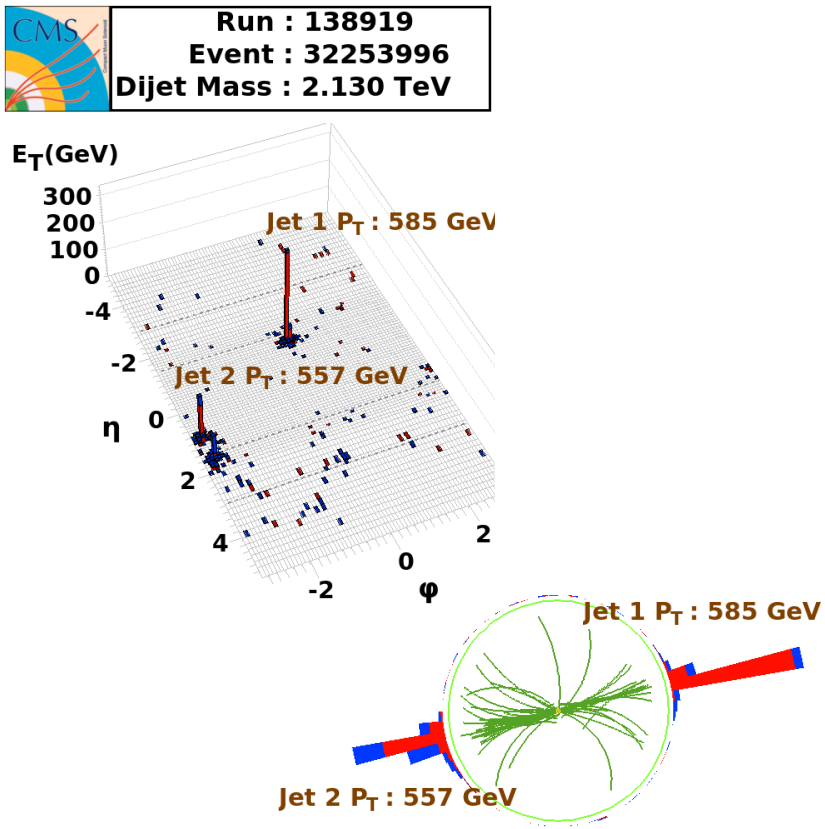
Kinematic coverage: $|y|<2.5$, p_{T1} (leading jet) > 60 GeV, p_{T2} (sub-leading jet) >30 GeV.

Cross-section binned in $m_{jj} = m_{12}$ and $|y_{max}| = \max(|y_1|, |y_2|)$. Dijet masses up to 5 TeV

Anti-k_t R=0.7 Particle Flow jets (as for inclusive jet cross-section analyses).



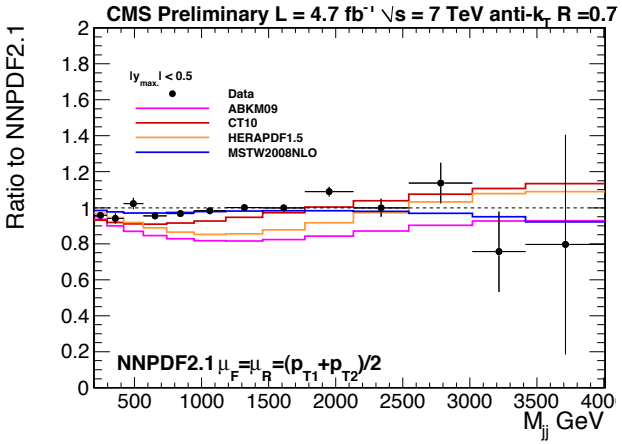
[CMS PAS QCD-11-004]

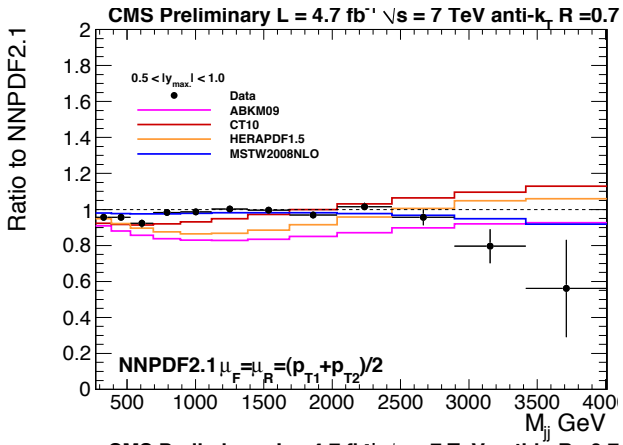


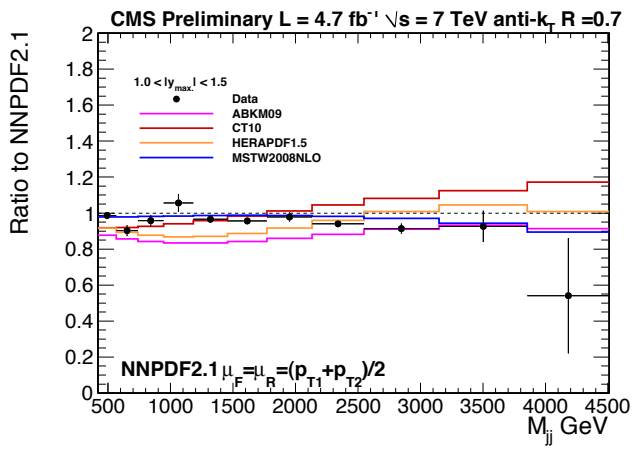
CMS Central Dijets (2011) Data/Theory

Data to theory ratio for the five bins of y_{max}: NLOJET++ (NNPDF2.1) + NP corrections.

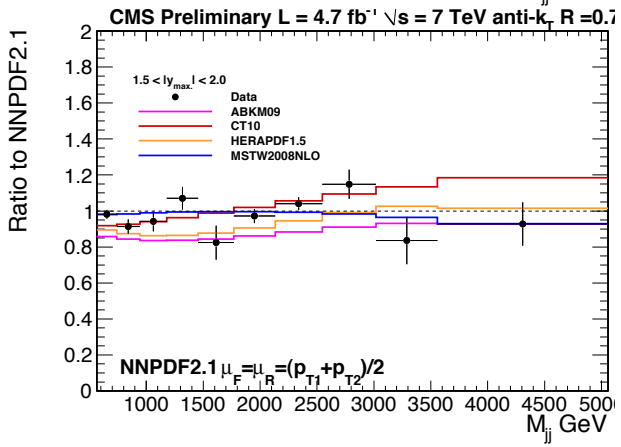
Ratios also shown of NLO predictions with various PDFs, to default NLO prediction.

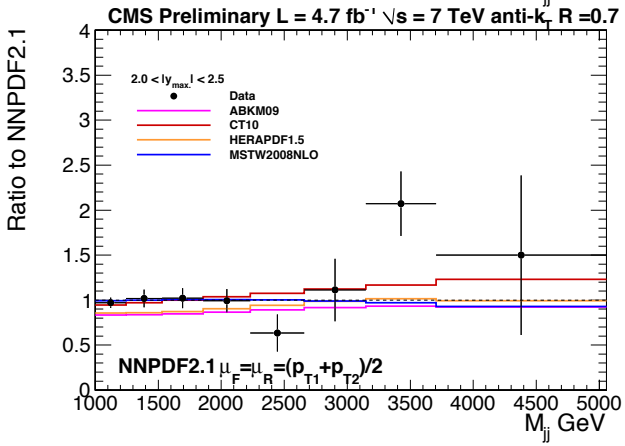






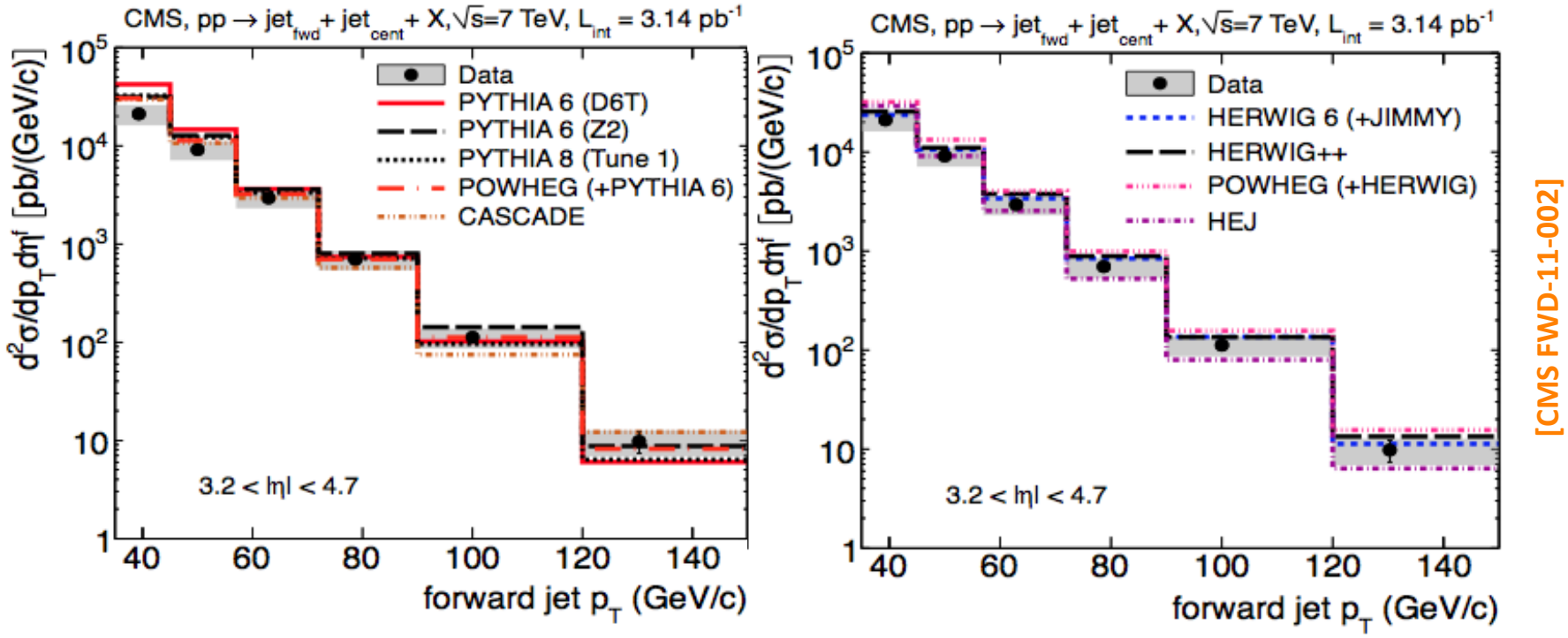
[CMS PAS QCD-11-004]





CMS Central-Forward Dijets

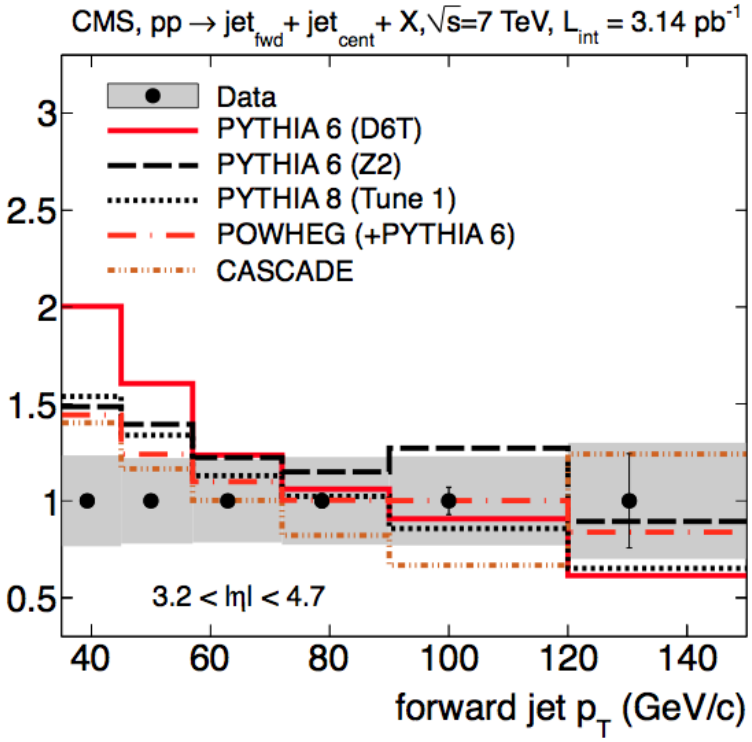
- Forward: $3.2 < |\eta| < 4.7$, Central $|\eta| < 2.8$, CALO Jets, $\Delta\eta \leq 6$, $p_T > 35$ GeV, anti-k_t R=0.5 (differs from central dijet measument).
- Dijet trigger: 2 jets with $p_T > 30$ GeV within $|\eta|<5.2$. Fully efficient for jets with $p_T > 35$ GeV (calibrated scale)

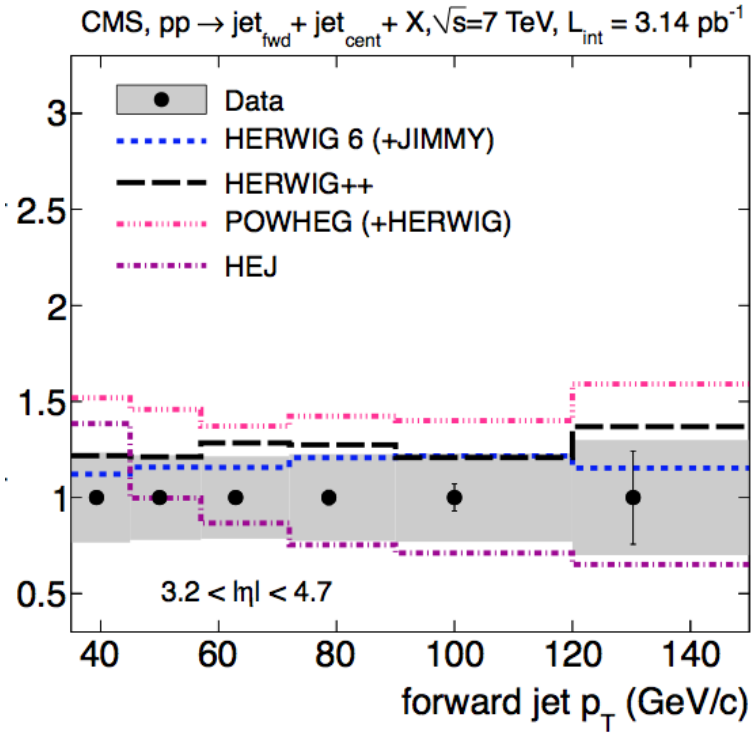


[CMS FWD-11-002]

CMS Central-Forward Dijets

- Forward: 3.2 < |η| < 4.7, Central |η| < 2.8, CALO Jets, Δη≤6, Anti-k_t R=0.5 (differs from central dijet measument).
- Dijet trigger: 2 jets with p_T > 30 GeV within |η|<5.2. Fully efficient for jets with p_T > 35 GeV (calibrated scale)





[CMS FWD-11-002]

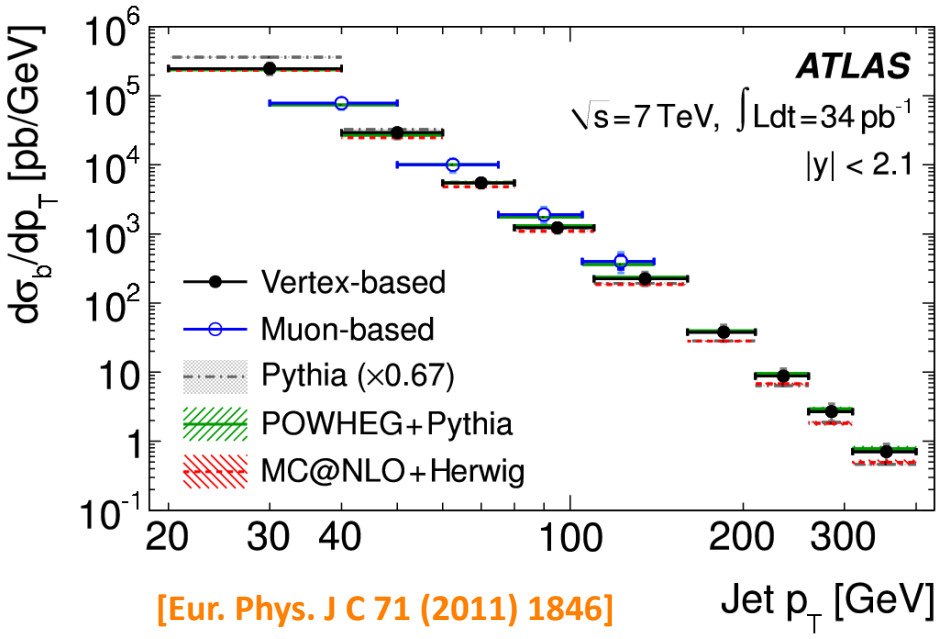
HERWIG OK for shape. No preference for HEJ or CASCADE. Only the forward region is shown here. Level of data / theory agreement similar for the central jets [backup slides].

Inclusive b-jet production cross-section

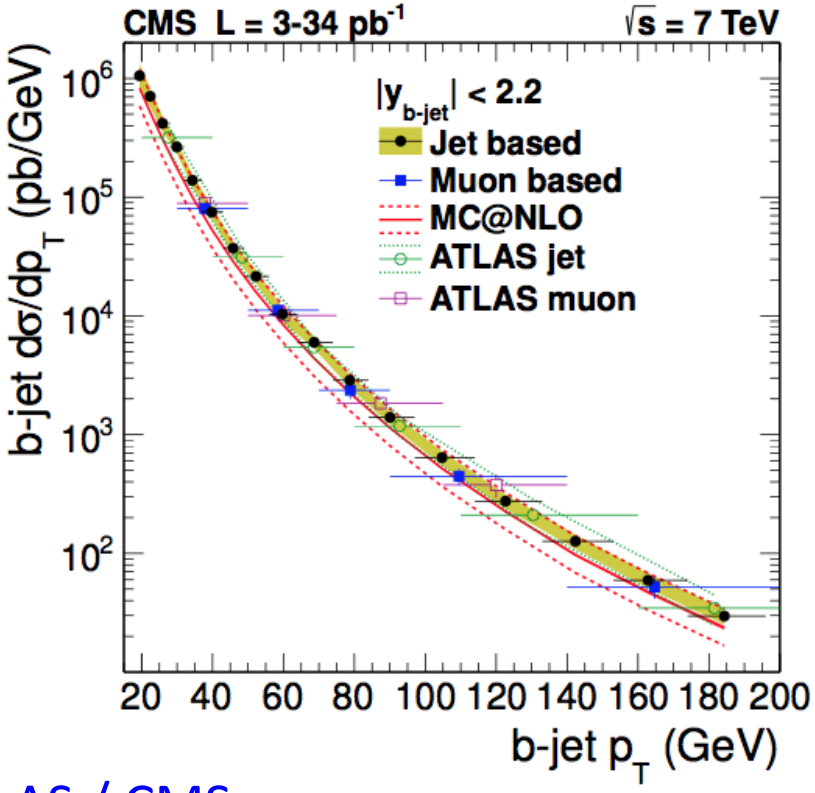
Identification of b-jets: secondary-vertex tag and / or muon tag.

Separation from c, light jets based on vertex mass or muon p_T^{rel}

Central region only (need tracker)



[Eur. Phys. J C 71 (2011) 1846]

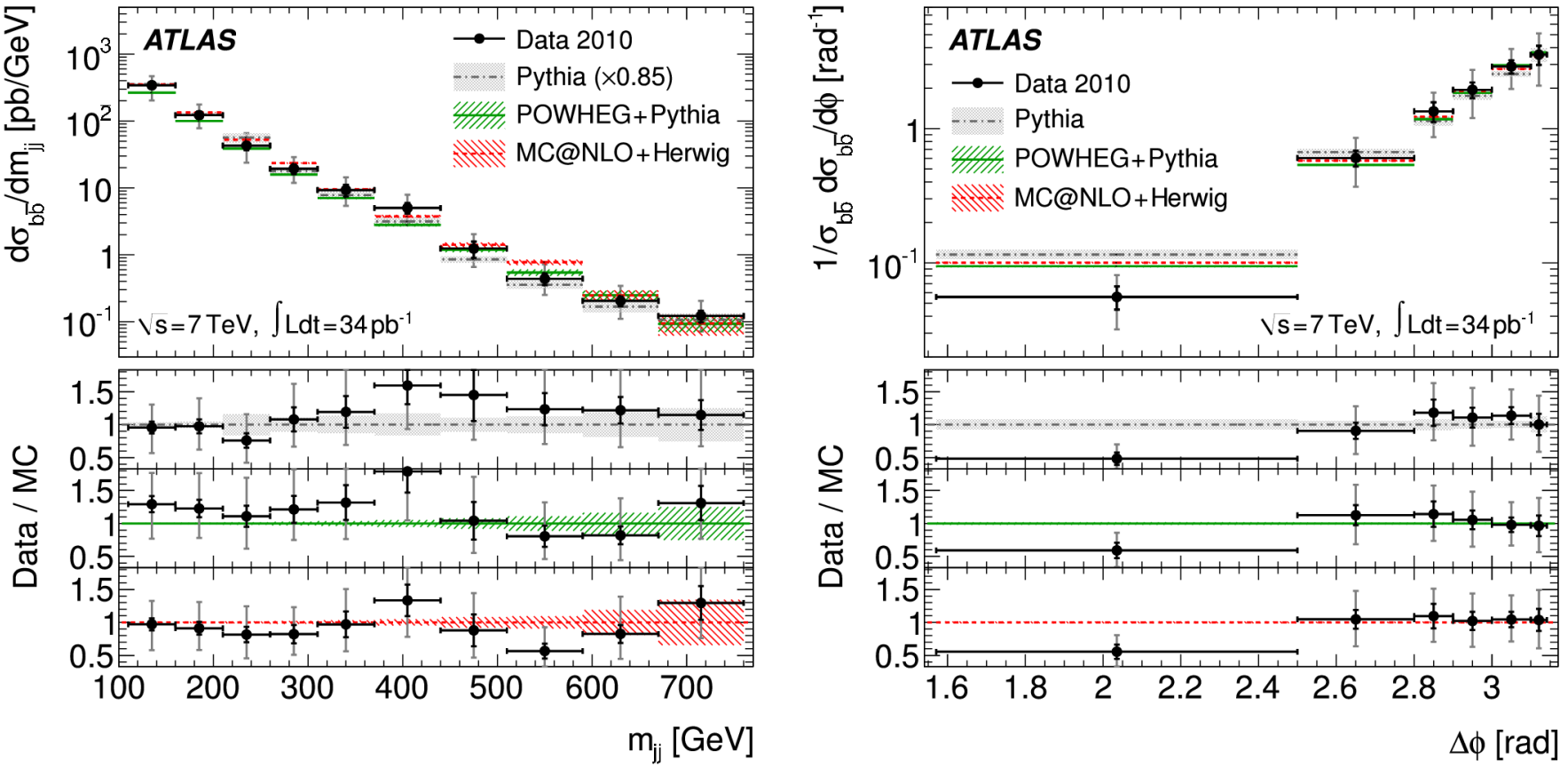


[JHEP 04 (2012) 084]

Good agreement between separate analyses as well as with theory and ATLAS / CMS

$b\bar{b}$-dijet production cross-section

Measured as function of m_{jj} (110-760 GeV) and $\Delta\phi$

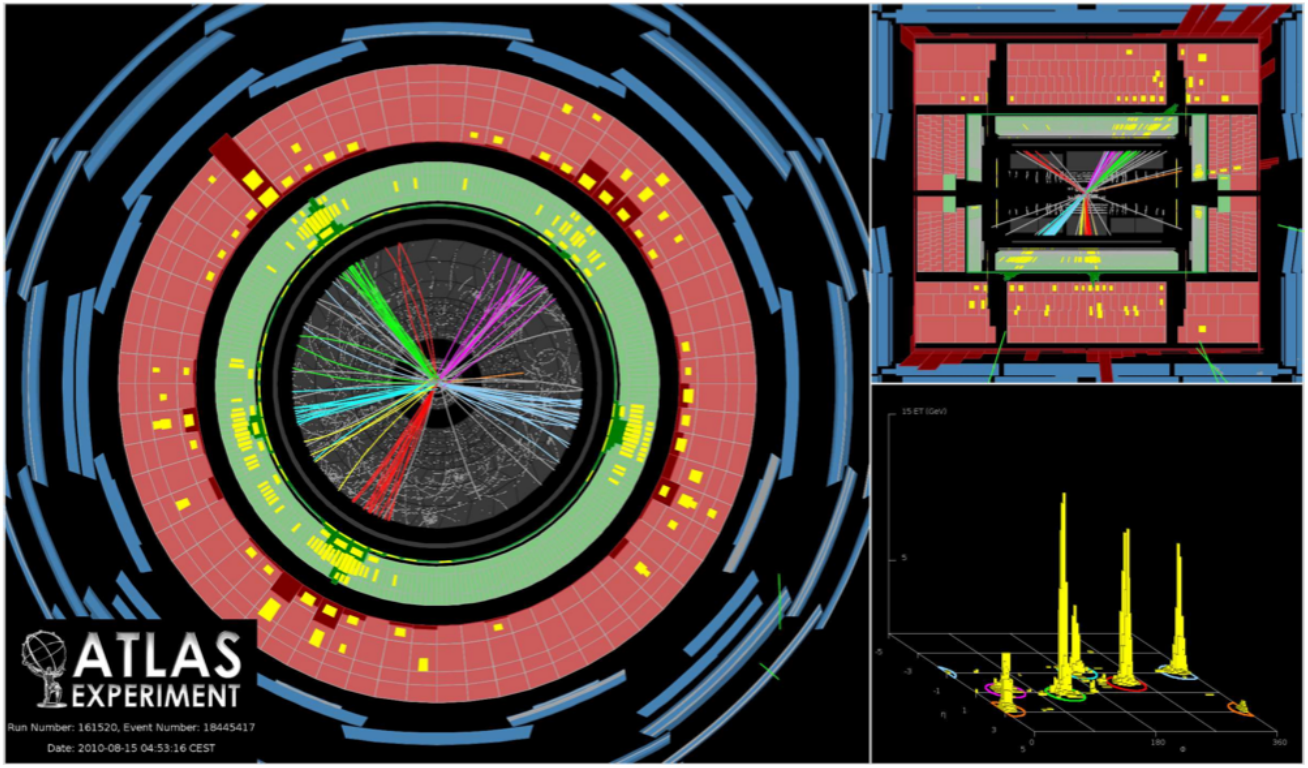


[Eur. Phys. J C 71 (2011) 1846]

Also measured as a function of $\chi = \exp|y_1 - y_2|$ for two region of m_{jj} (not shown).

Results on Multi-jet Production

- Many results seen in preliminary form at PLHC 2011.
  - Dijet aziumthal decorrelations (no updates – see backup slides).
  - Jet activity between dijet pairs (as function of p_T, $|\Delta y|$).
  - Multi-jet production, cross-sections, inclusive 3 to 2 jet ratio.



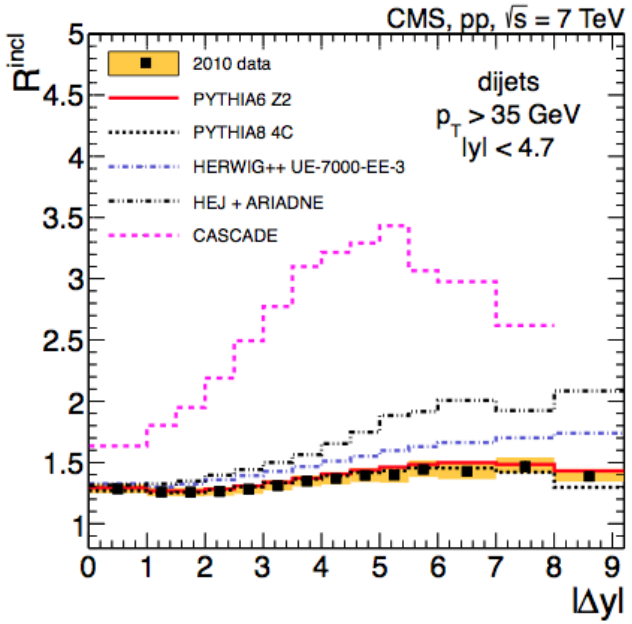
Candidate 8-jet event at ATLAS [Oct. 5, 2010]

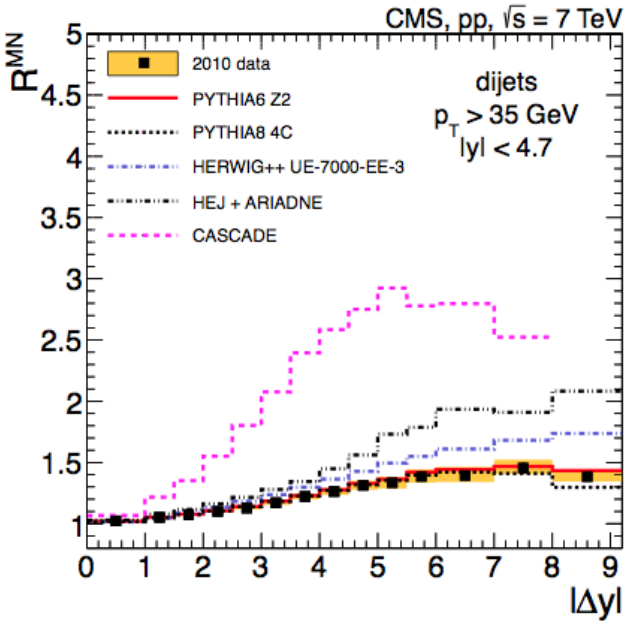
Jet Activity between Dijets (CMS)

Examine ratio of "inclusive dijet cross-section" ($N_{jet} \geq 2$) to "exclusive dijet cross-section" ($N_{jet}=2$) as a function of the rapidity separation $|\Delta y|$ of the dijet system.

For inclusive case, each pairwise combination of jets (above threshold) considered.

Two choices for dijet system: leading and sub-leading p_T or system with maximal $|\Delta y|$





Pythia provides a good description.

Other models have problems.

HEJ, CASCADE models deviate the most from observations.

Anti-k_t $R = 0.5$, $p_T > 35$ GeV, $|y| < 4.7$ 2010 data **[CMS-FWD-10-014, CERN-PH-EP-2012-088]**

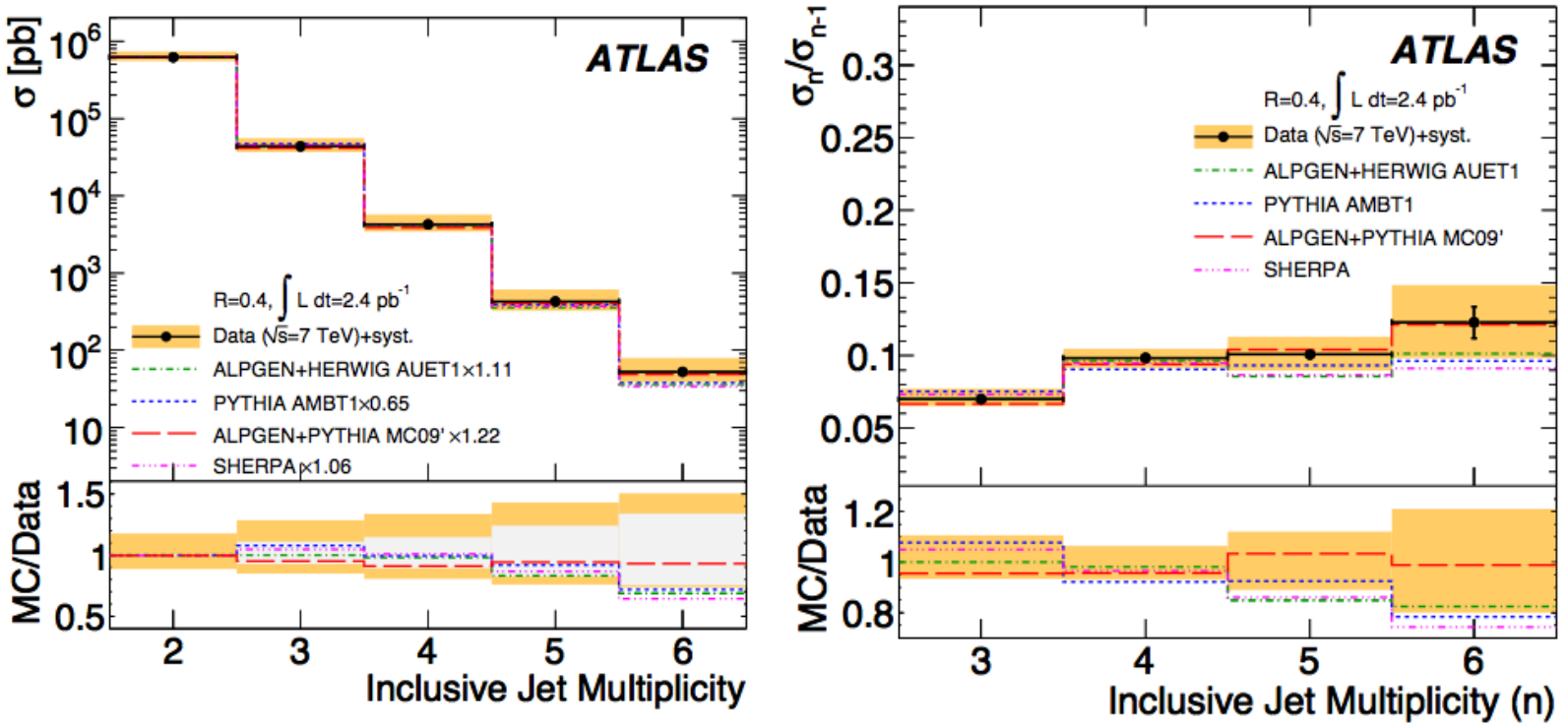
Similar published results (see backup) from ATLAS. **[JHEP 09 (2011) 053]**

Multi-jet Production (ATLAS)

Fundamental QCD measurement. But also motivated by desire to understand multi-jet backgrounds to BSM searches (SUSY etc.)

2010 data, 2.4 pb^{-1} $p_T > 60$ GeV, $|y|<2.8$, Anti-k_t R=0.4, p_T (leading jet) > 80 GeV.

[Eur. Phys. J C 71 (2011) 1763]

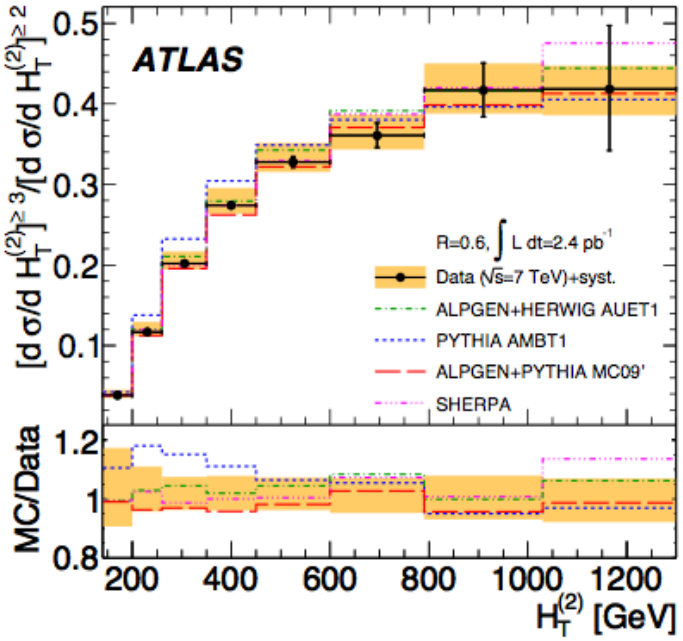


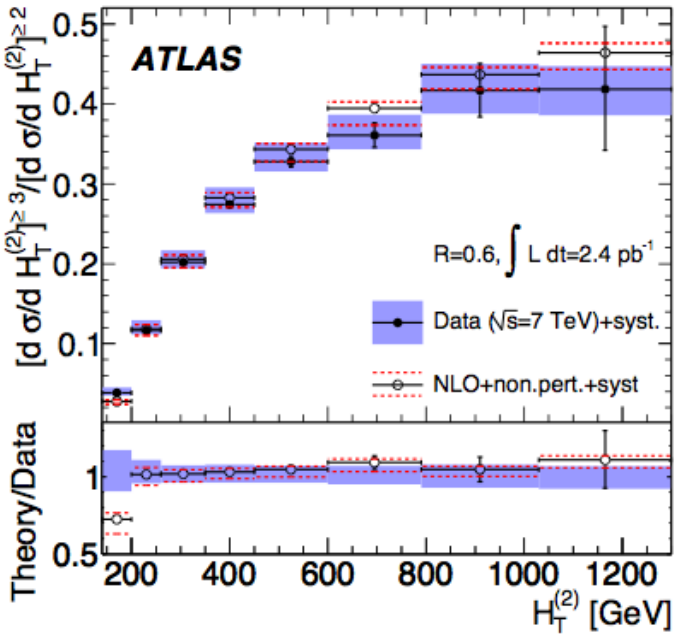
Monte Carlo shape predictions consistent with data: normalized to σ(2-jet).

Multi-jet Production: Inclusive 3-jet to 2-jet ratio (ATLAS)

2010 data, 2.4 pb^{-1} p_T > 60 GeV, |y|<2.8, Anti-k_t R=0.6, p_T (leading jet) > 80 GeV.
$H_T^{(2)}$ defined using only the leading and sub-leading jet.

[Eur. Phys. J C 71 (2011) 1763]





$$H_T^{(2)} = \sum_{i=1}^{2} p_{\mathrm{T}i}$$

LO Monte Carlo models do a good job

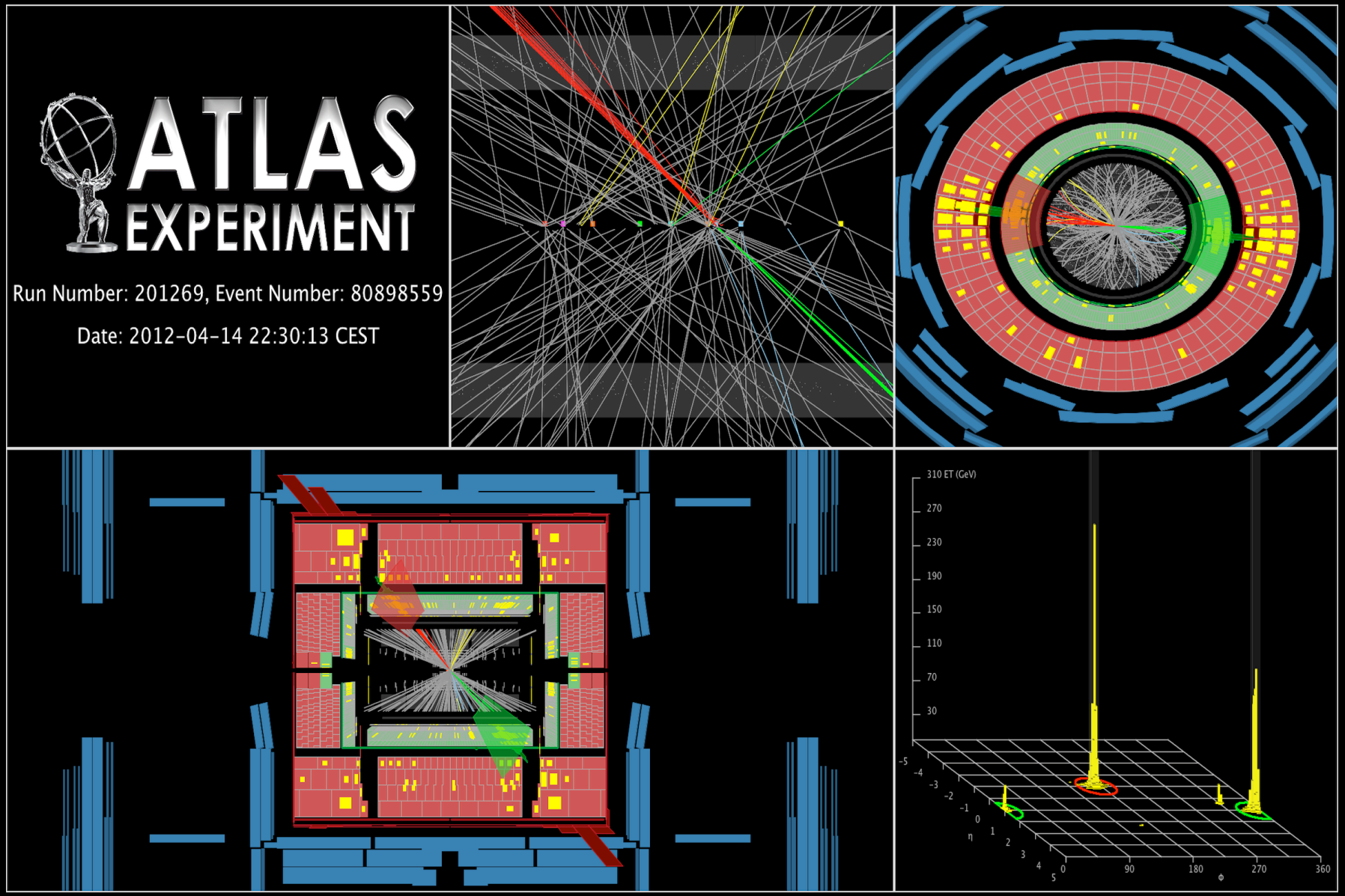
Also used to test NLO pQCD (NLOJET++ with NP corrections). Disagreement at low $H_T^{(2)}$ may be due to effect of kinematic cuts on NLO prediction in this low $H_T^{(2)}$ region.

Published CMS measurement (see backup) shown last year: **[Phys. Lett. B 702 (2011) 336]**

Summary

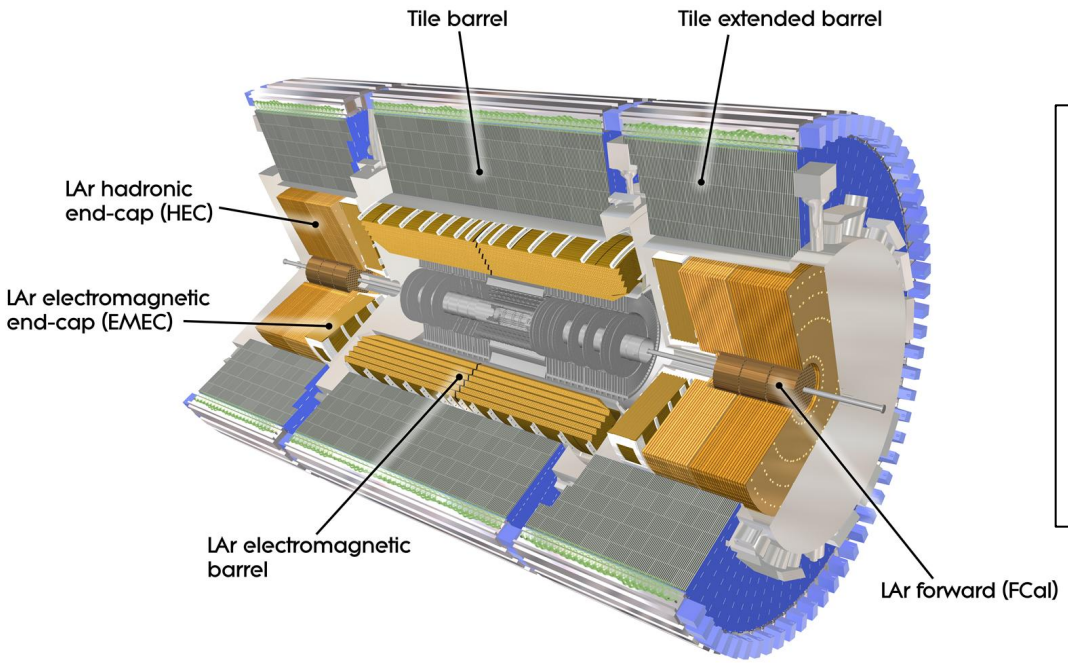
- Many results for inclusive-jet, dijet and multijet production at 7 TeV.
- Includes results at large rapidity or with large rapidity separations.
- Generally good data/theory agreement over much of the kinematic reach of these analyses:
  - Inclusive-jet and dijet theoretical NLO predictions with various PDF sets consistent with experimental results.
  - LO parton shower Monte Carlos still provide an adequate description, even in kinematic regions (e.g. large rapidity separation) where this is not necessarily expected.
- Detailed studies of jet properties also available:
  - See e.g. talk by S. Gibson (Thurs., 4F).
- We are again entering a new kinematic regime: awaiting 8 TeV results.

ATLAS $\sqrt{s}$ = 8 TeV High Mass Dijet Event (4.23 TeV)



Backup Slides

The ATLAS Calorimeter



Main technology: Liquid Argon (LAr)

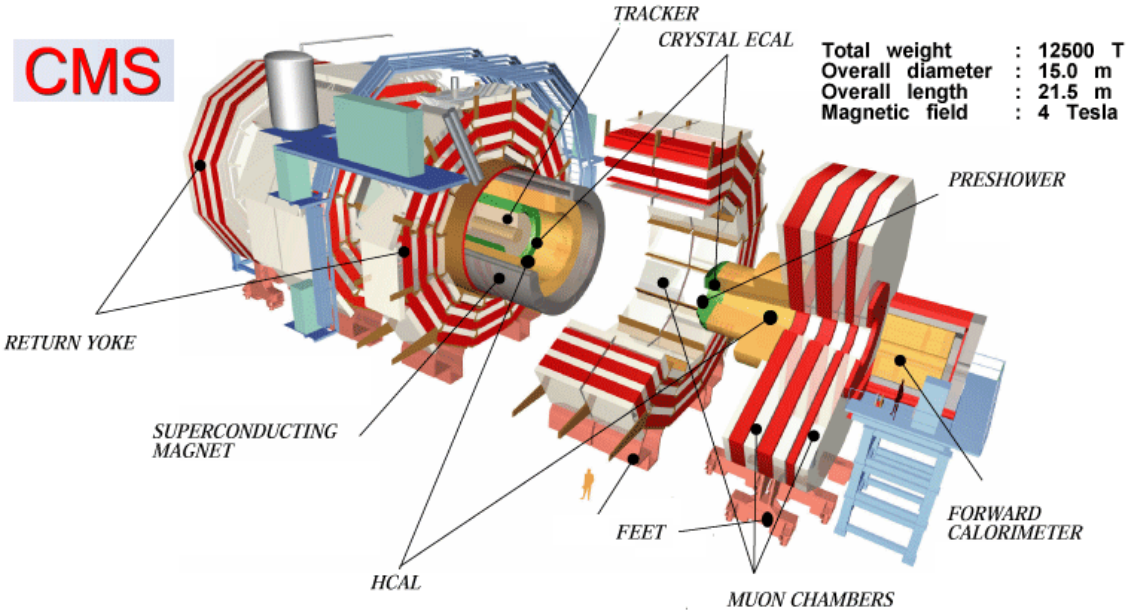
LAr EM Barrel	$\eta < 1.475$
LAr EM Endcap	$1.375 < \eta < 3.2$
Tile Calorimeter	$\eta < 1.7$
LAr Hadronic Endcap	$1.5 < \eta < 3.2$
LAr Forward	$3.1 < \eta < 4.9$

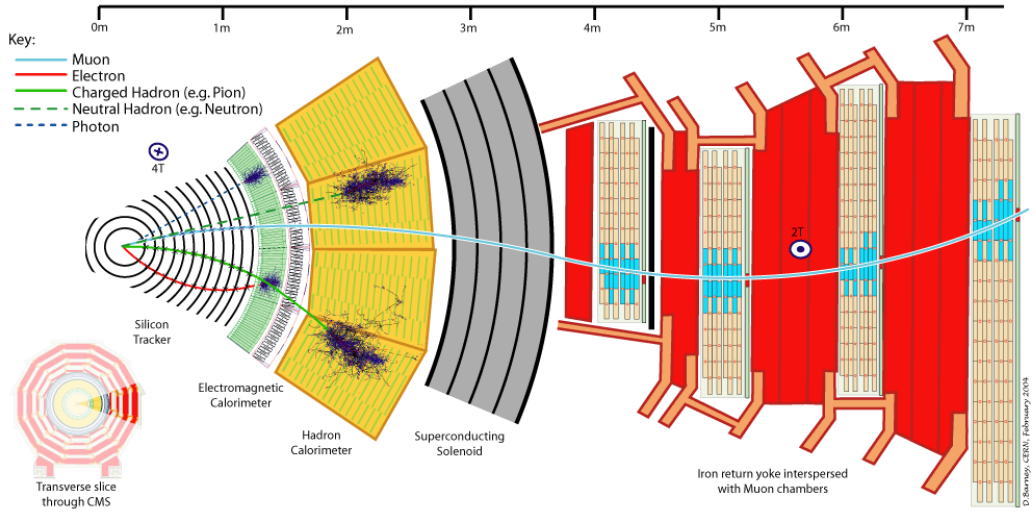
Readout granularity varies with region pseudorapidity (η) and layer (sampling).

ATLAS inputs to jet algorithm are either calorimeter towers, or 3-dimensional EM-scale topological clusters built from calorimeter cells. (Represents attempt to reconstruct individual particles)

All ATLAS results presented here use the jets formed from topological clusters.

The CMS Detector





Lead-tungstate ECAL
Brass-scintillator HCAL
} $|\eta| < 3.0$
Steel-quartz-fibre fibre FCAL
Forward coverage: $3.0 < |\eta| < 5.2$

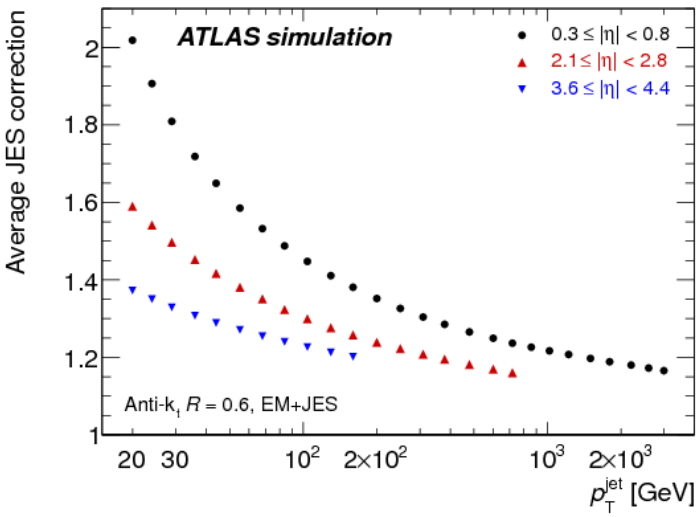
Particle Flow (PF) produces calibrated particles that can be clustered into jets. Yields the best performance.

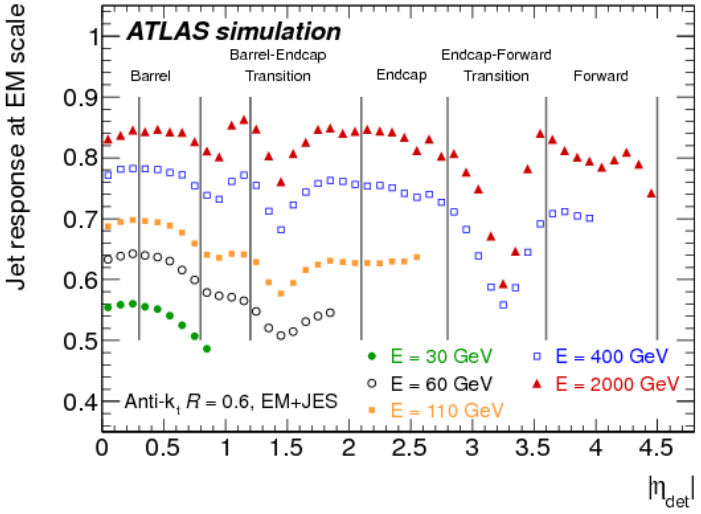
Also use jets built from calorimeter towers (CALO jets). Current analyses involving the forward region use these.

Performance: Jet Energy Scale Corrections (2010)

ATLAS JES based on simulation. In situ checks for validations and JES uncertainties

[arXiv 1112.6426]

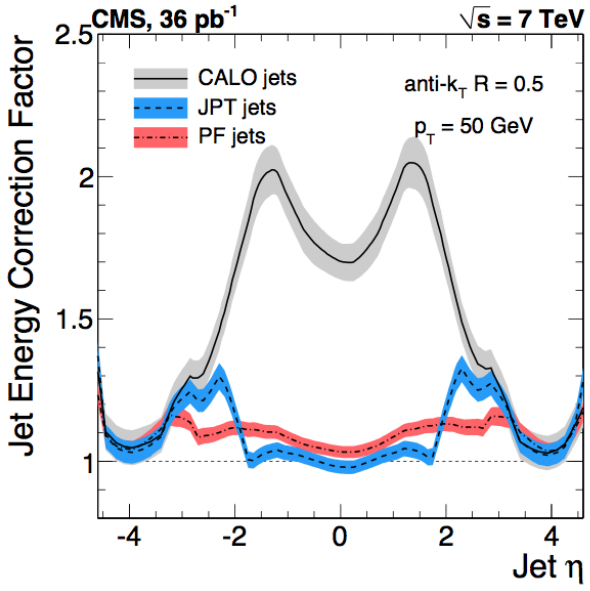


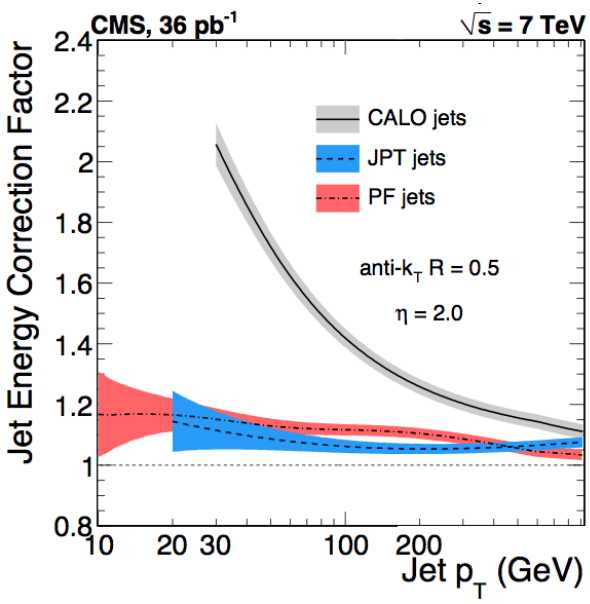


CMS JES derived from in-situ studies (data)

In each case, pileup offset needs to be applied first.

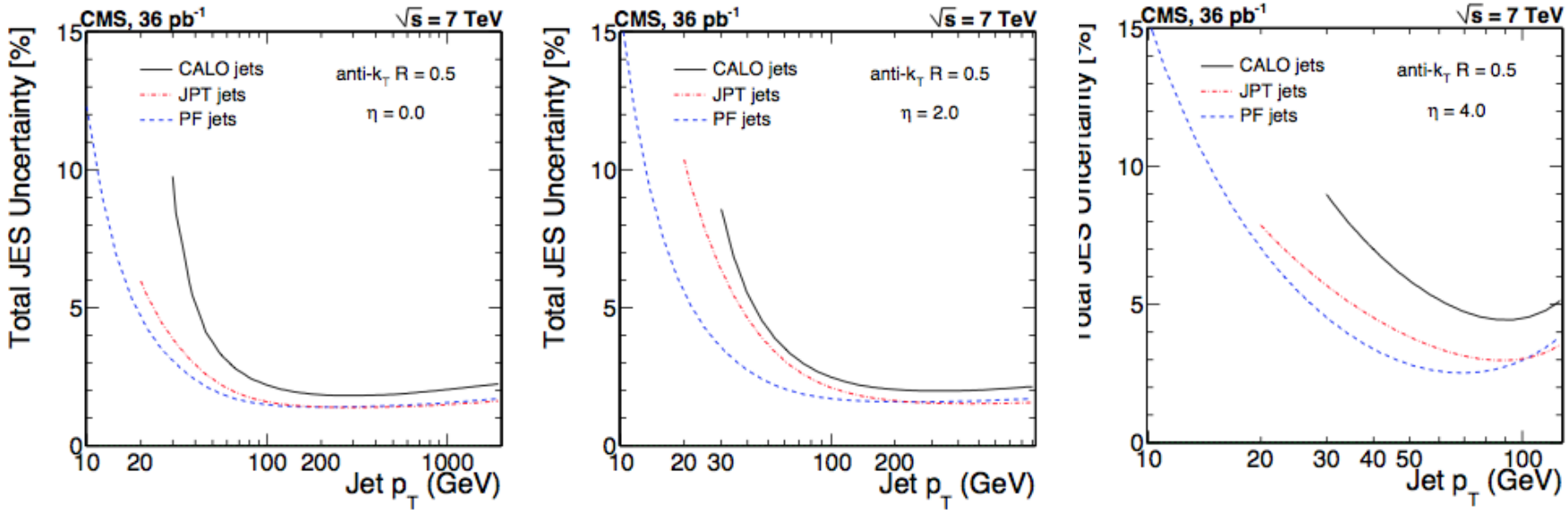
[JINST 6 (2011) P11002]





Performance: CMS JES Uncertainties (2010)

- JES uncertainty depends on constituents input to jet algorithm (3 types)



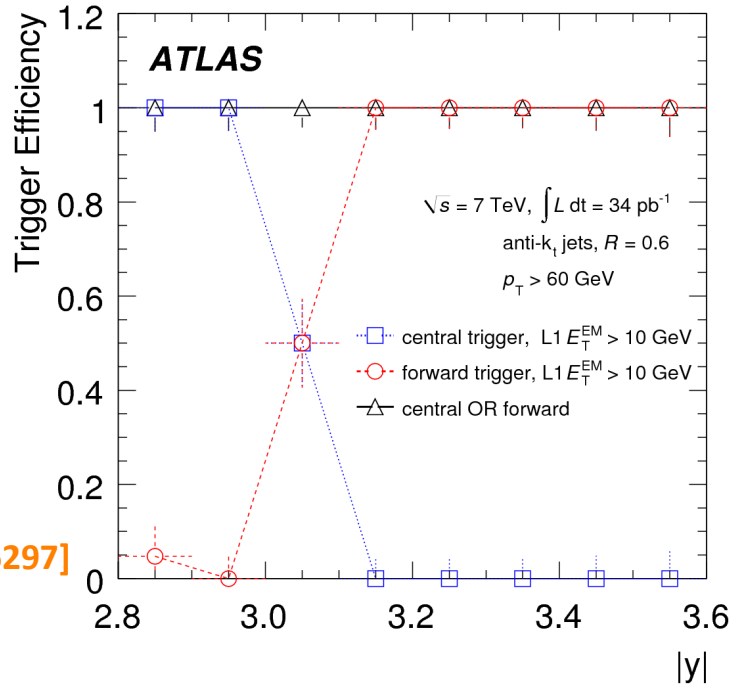
[JINST 6 (2011) P11002]

- Best performance is for particle flow (PF) jets which take as input calibrated particles from the particle-flow algorithm.
- For studies involving the forward region, EM-scale CALO jets are used, which have higher p_T thresholds and larger JES uncertainties.

Triggering

- Multiple jet triggers needed to cover large kinematic region. Most pre-scaled.
- CMS: dedicated forward-backward dijet trigger (opp. hemispheres and $|\eta| > 3$).
- Single or multi-jet triggers. Minimum-bias scintillator triggers also used for low p_T jets and jet-trigger efficiency studies.
- Efficiencies measured w.r.t. minbias trigger or lower-threshold jet triggers.
- Inclusive-jet analysis typically populate a given kinematic bin in the cross-section using the lowest-pre-scale trigger that provides for > 99% efficiency. Usually but not always a single trigger per kinematic region – e.g. ATLAS inclusive jet cross-section measurement in overlap region between the endcap and forward calorimeters:

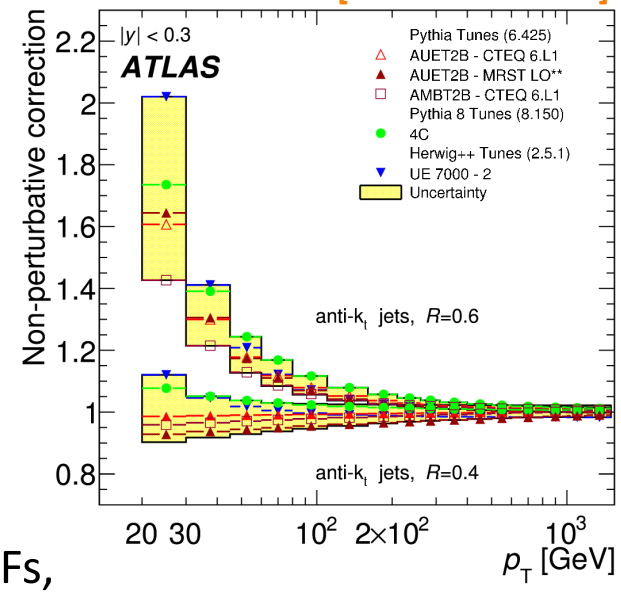
[arXiv 1112.6297]



Monte Carlo Simulations and pQCD Calculations

- Results compared to Monte Carlo simulations:
  - Various generators (Pythia6, Herwig, Pythia8, Herwig++, Alpgen……)
  - Various tunes
  - Default pdf sets, strong coupling α_s : varied for systematic studies
- NLO pQCD calculations
  - NLOJET++ (and others, e.g. POWHEG) with non-perturbative (NP) corrections or interfaced to PS Monte Carlo (Pythia, Herwig)
    - Typically using a variety of models and tunes
      - Default generation / generation with MPI and hadronization switched off.
    - For smaller jet sizes dominated by hadronization effects, for larger by UE.
    - Corrections decrease as p_T and rapidity increase.

[arXiv 1112.6297]

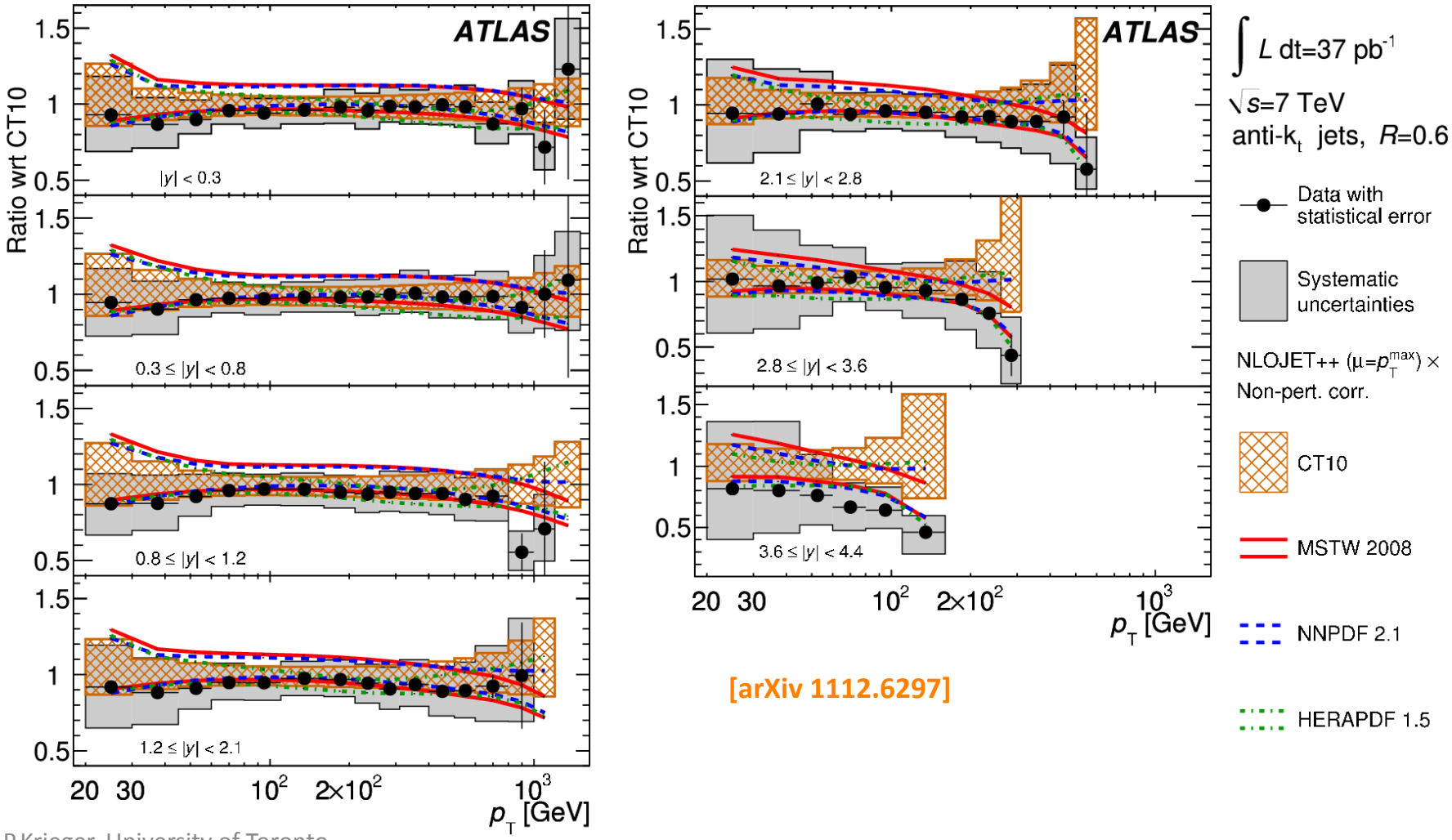


  - Main theoretical uncertainties due to choice of PDFs, renormalization and factorization scales, value of strong coupling constant. Generally dealt with as per PDF4LHC recommendations. These dominate at higher p_T. At low p_T NP correction uncertainties larger.

ATLAS Inclusive Jet Cross-section (PDF comparisons)

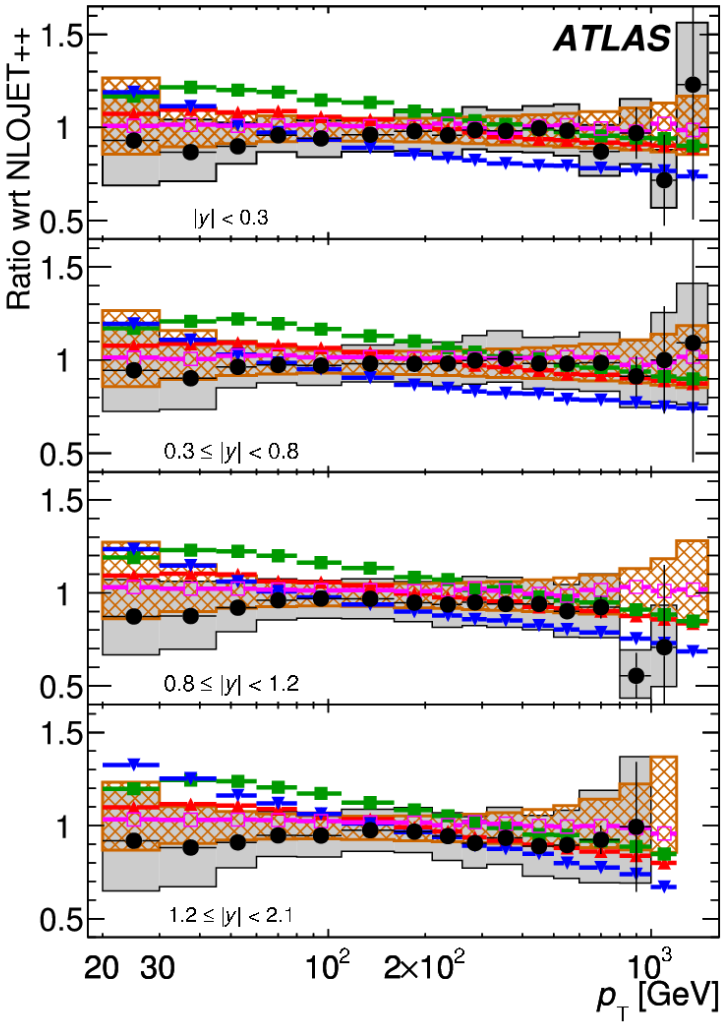
Corrected NLO pQCD prediction consistently higher than the measurements.

Consistency within experimental and theoretical uncertainties.

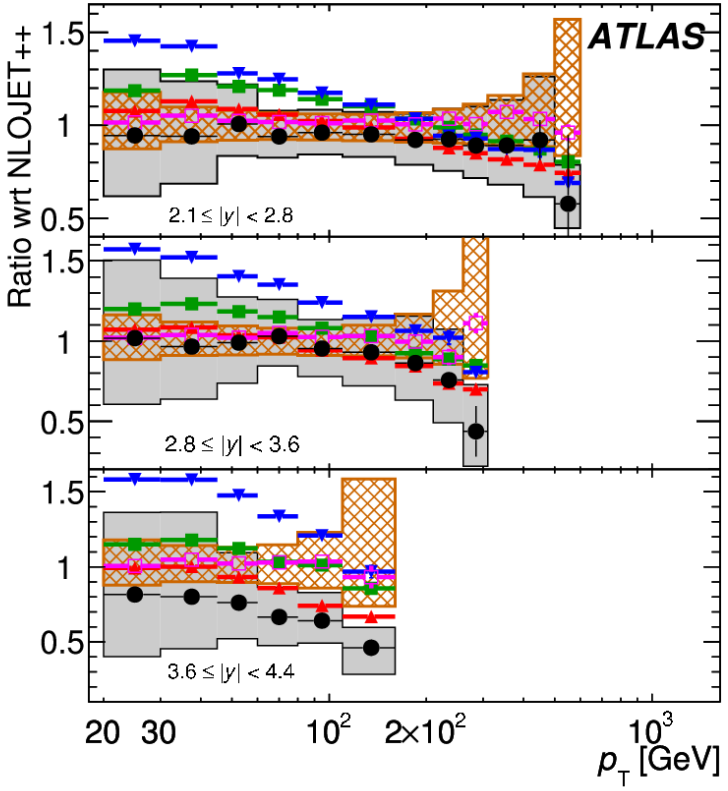


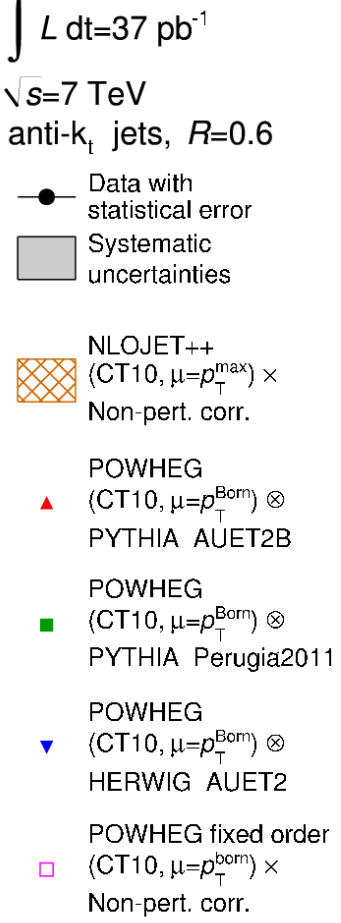
[arXiv 1112.6297]

ATLAS Inclusive Jet Cross-Section (POWHEG)



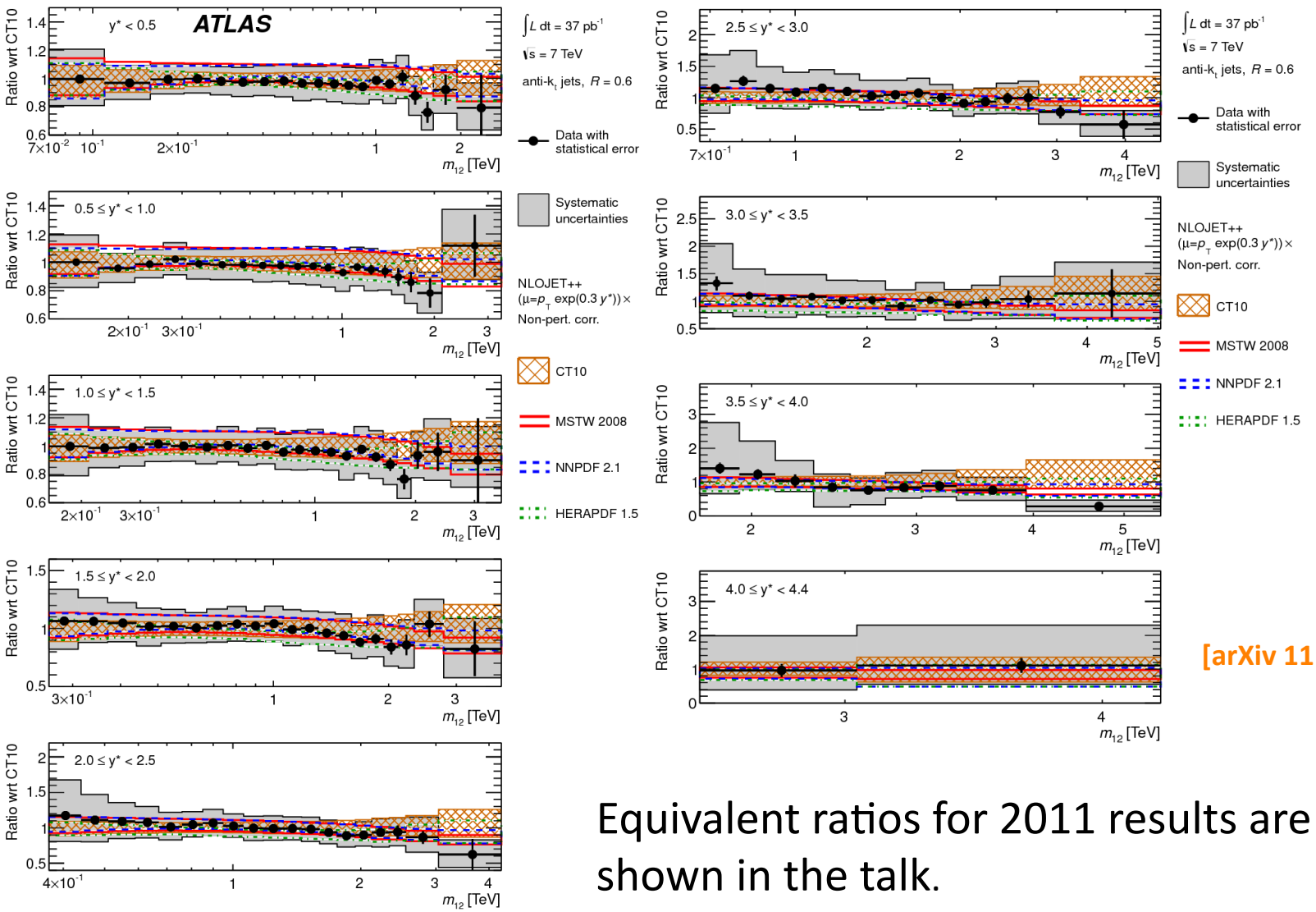
[arXiv 1112.6297]





POWHEG+HERWIG gives a poor description.

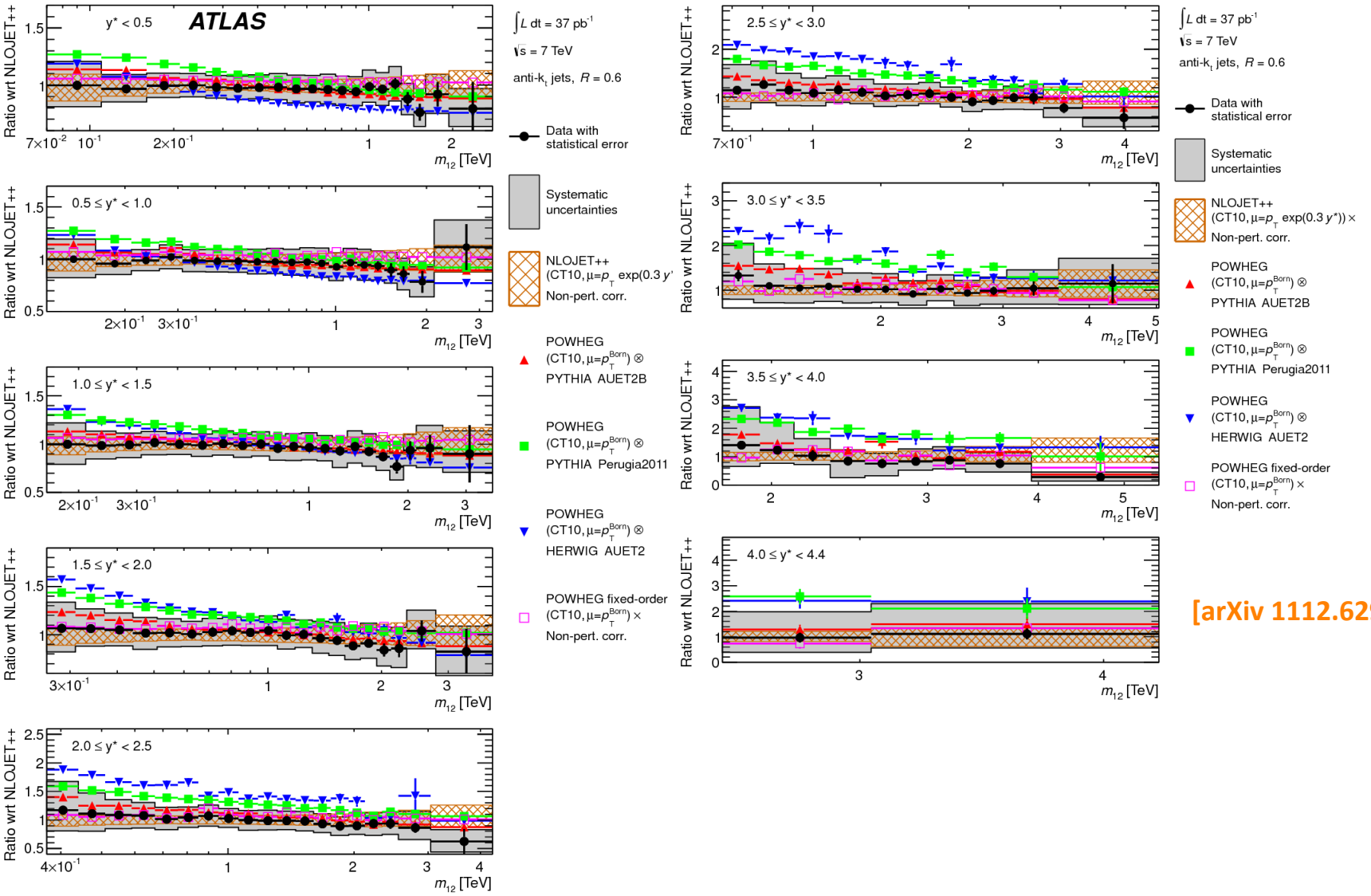
Data/Theory ATLAS 2010 Dijets (PDFs)



[arXiv 1112.6297]

Equivalent ratios for 2011 results are shown in the talk.

Data/Theory ATLAS 2010 Dijets (POWHEG)



[arXiv 1112.6297]

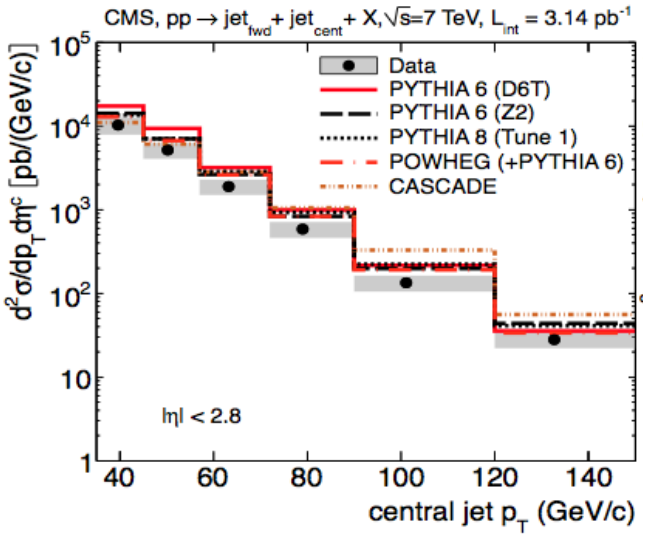
CMS Central-Forward Dijets: central & forward jets

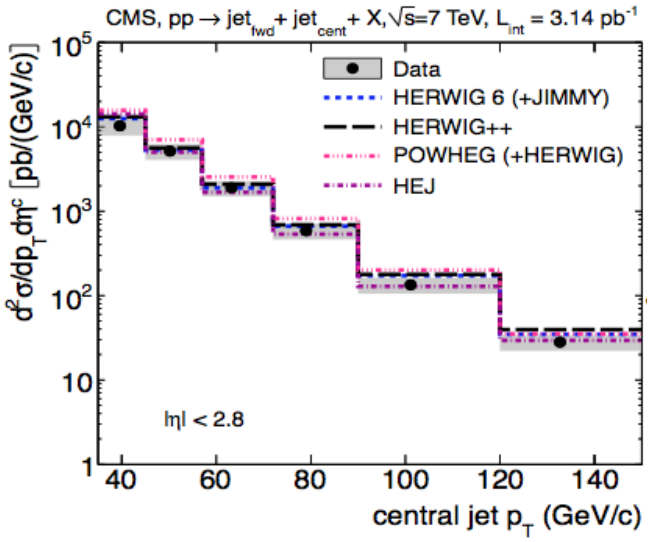
Central jet distributions

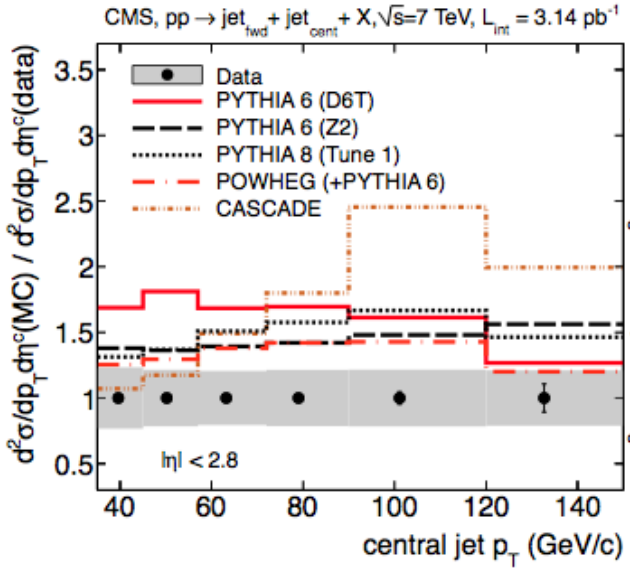
Forward jet distributions shown in talk

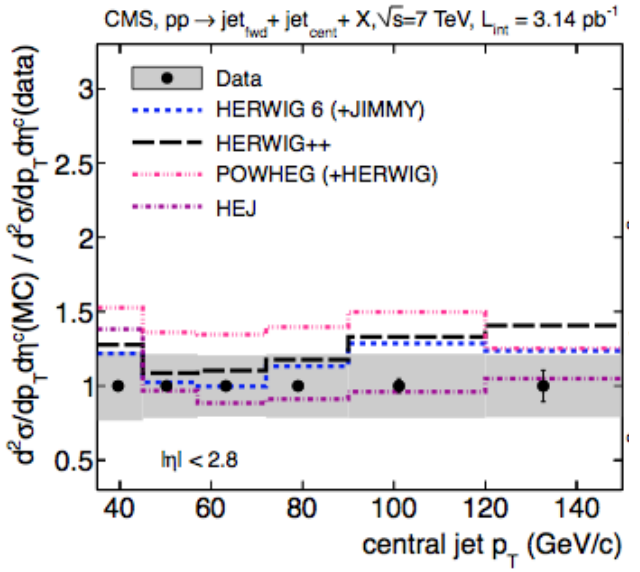
Some models have difficulties.

[CMS FWD-11-002]

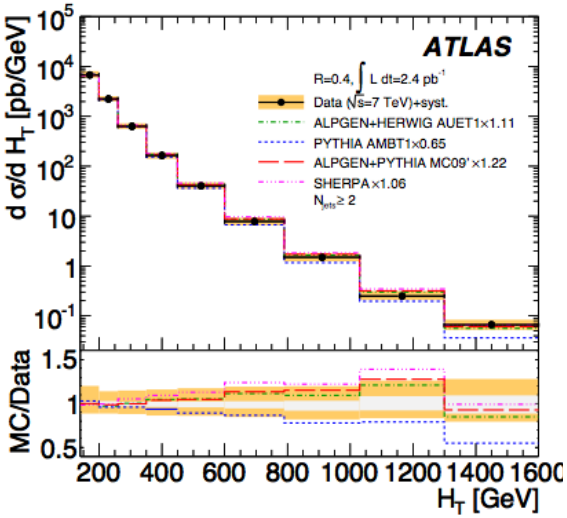


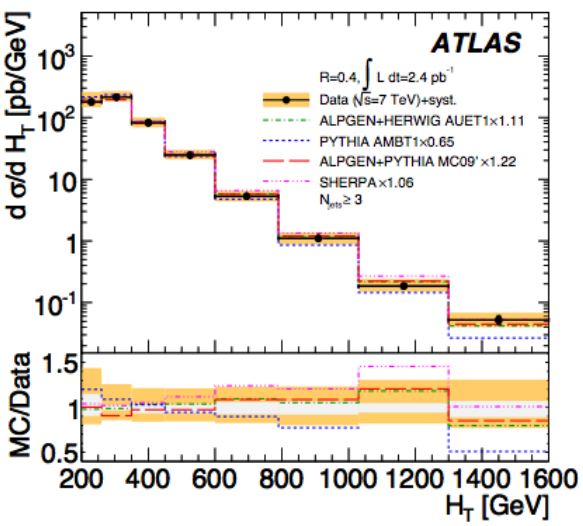




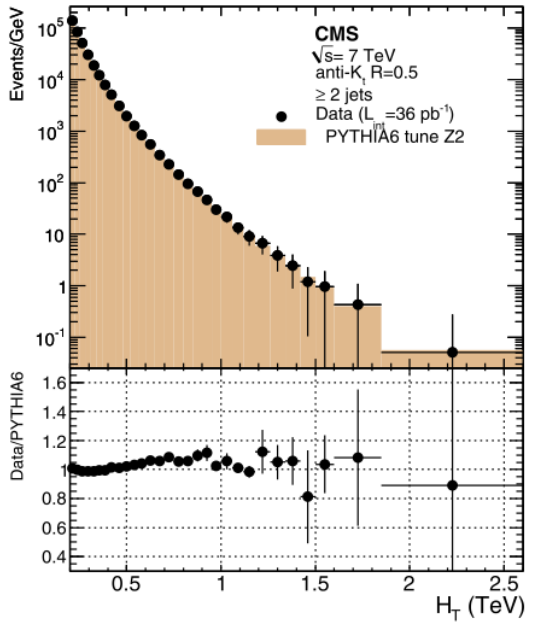


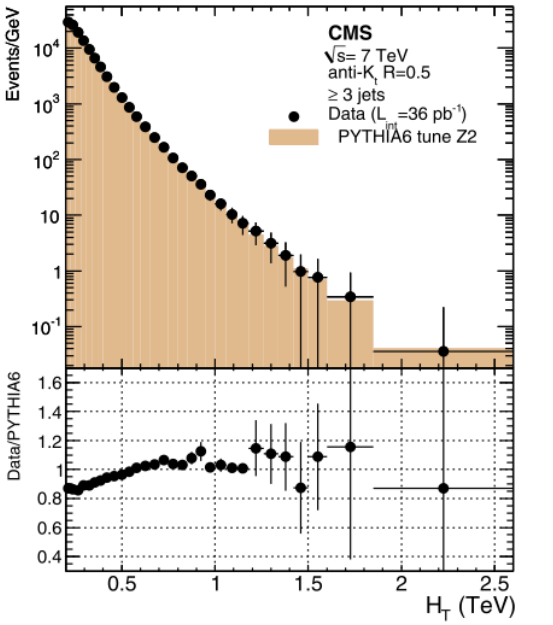
H_T Spectra from ATLAS/CMS Multi-jet Events





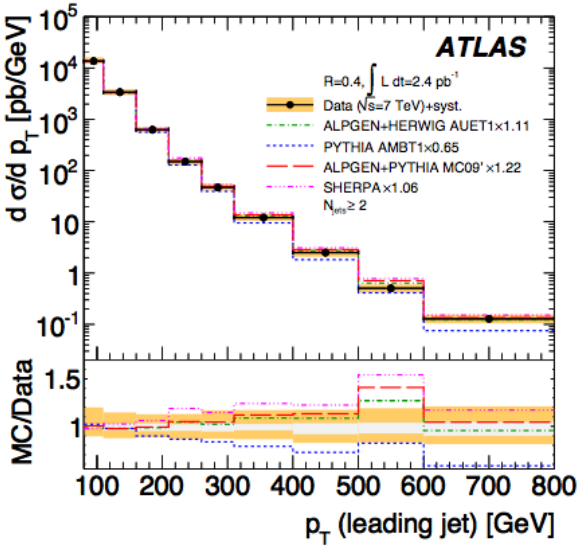
[Eur. Phys. J C 71 (2011) 1763]

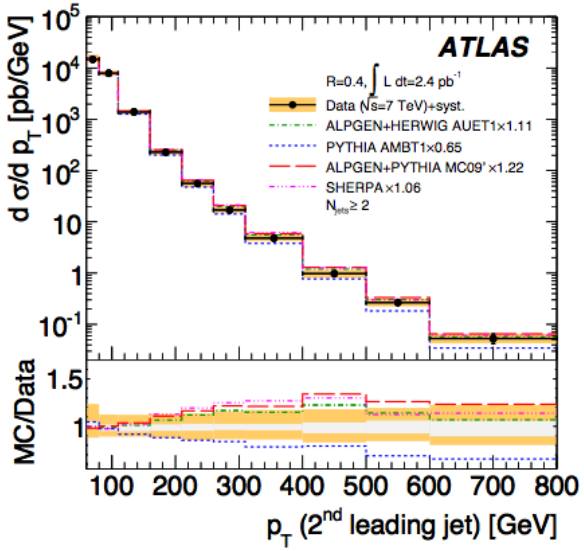


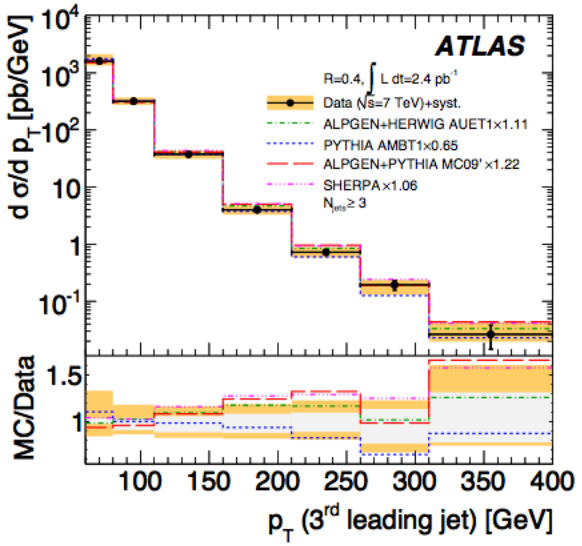


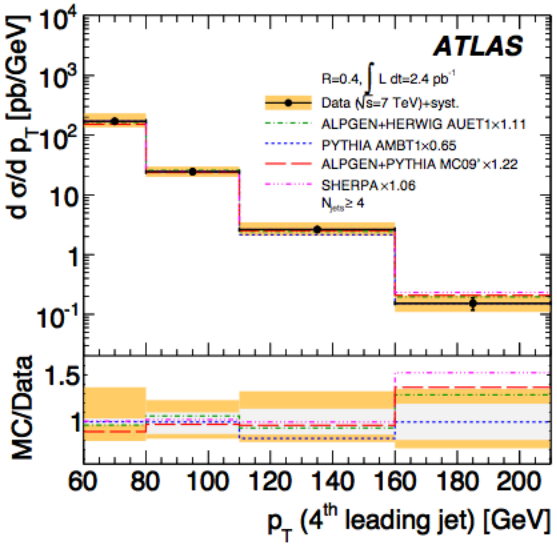
[Phys. Lett. B 702 (2011) 336]

Kinematic Distributions from ATLAS Multi-jet Study









Pythia (and other 2->2) ME calculations predict too steep a slope for the two leading jet.

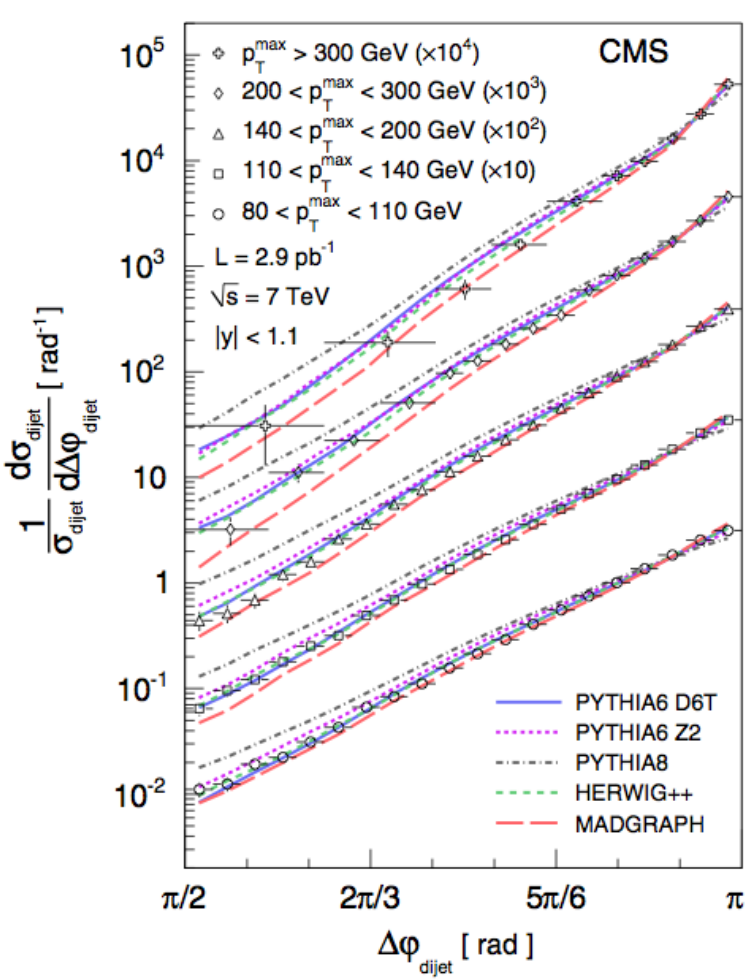
2->n ME calculations predict less steeply falling spectra than seen in the data.

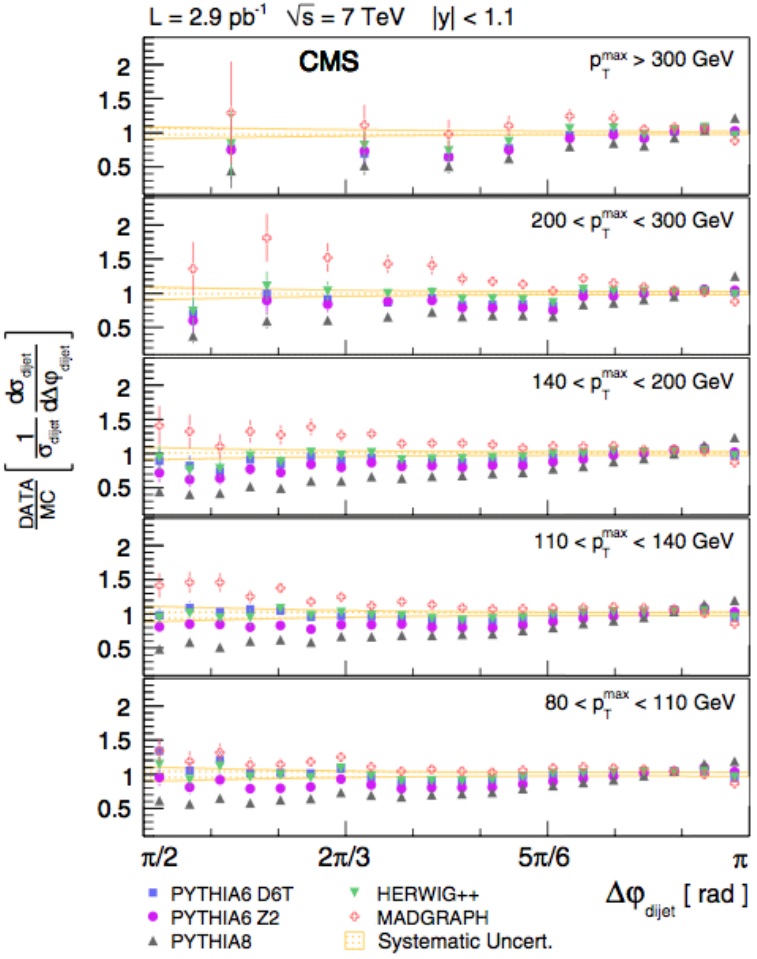
Similar conclusions for H_T spectra (in paper but not shown here).

[Eur. Phys. J C 71 (2011) 1763]

Multi-jet Production: Azimuthal Decorrelations (CMS)

- Azimuthal decorrelations in dijet events: sensitive to multi-jet production but requires reconstruction of only the two (leading) jets.

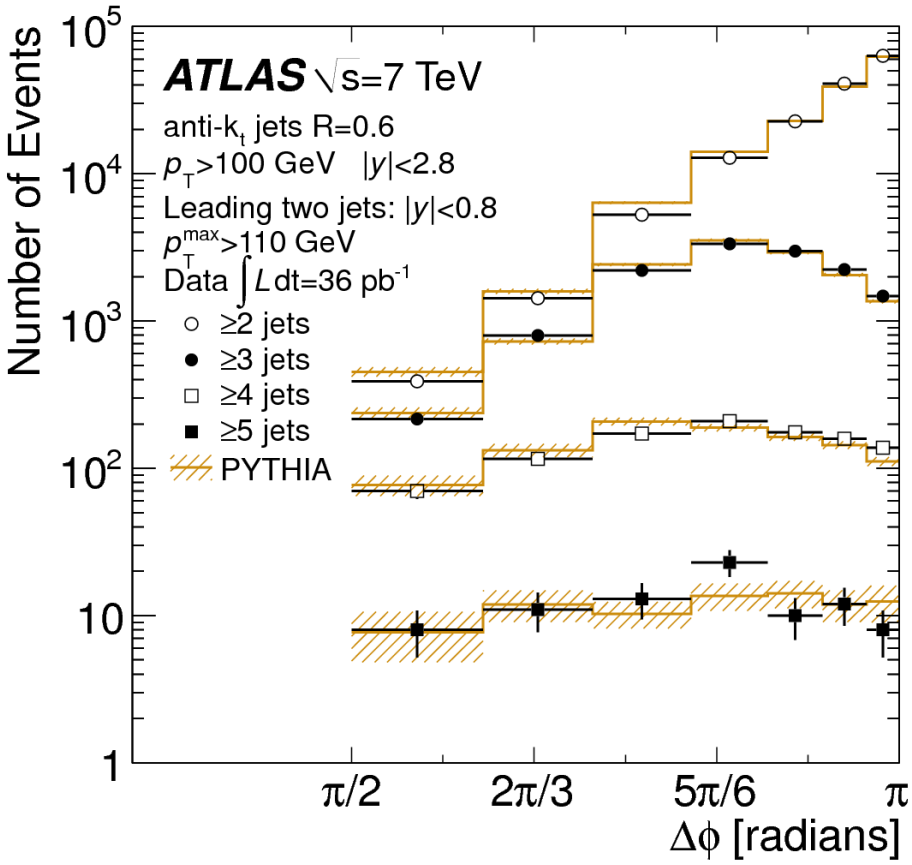


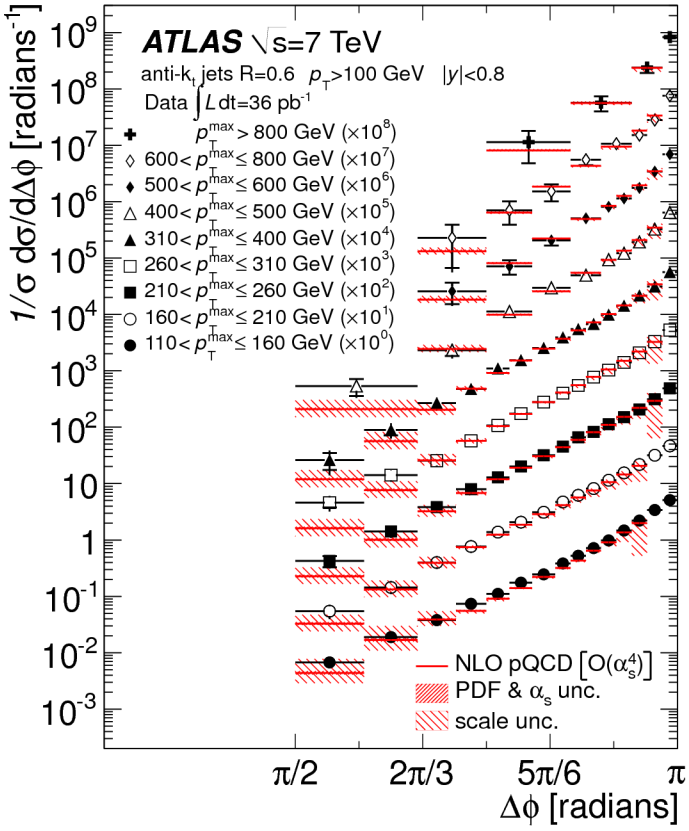


[PRL 106 (2011) 122003]

Multi-jet Production: Azimuthal Decorrelations (ATLAS)

- Azimuthal decorrelations in dijet events: sensitive to multi-jet production but requires reconstruction of only the two (leading) jets.



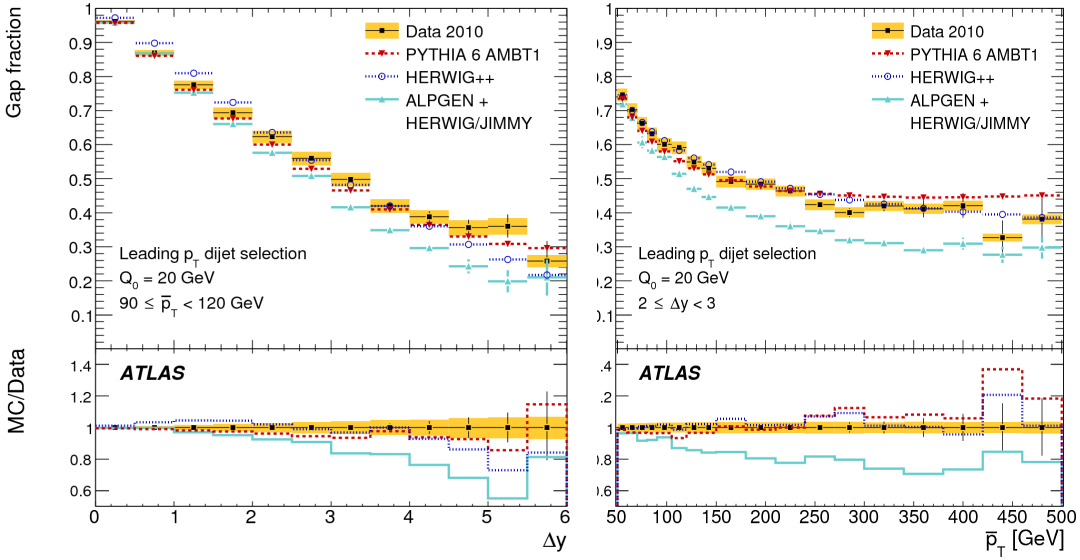


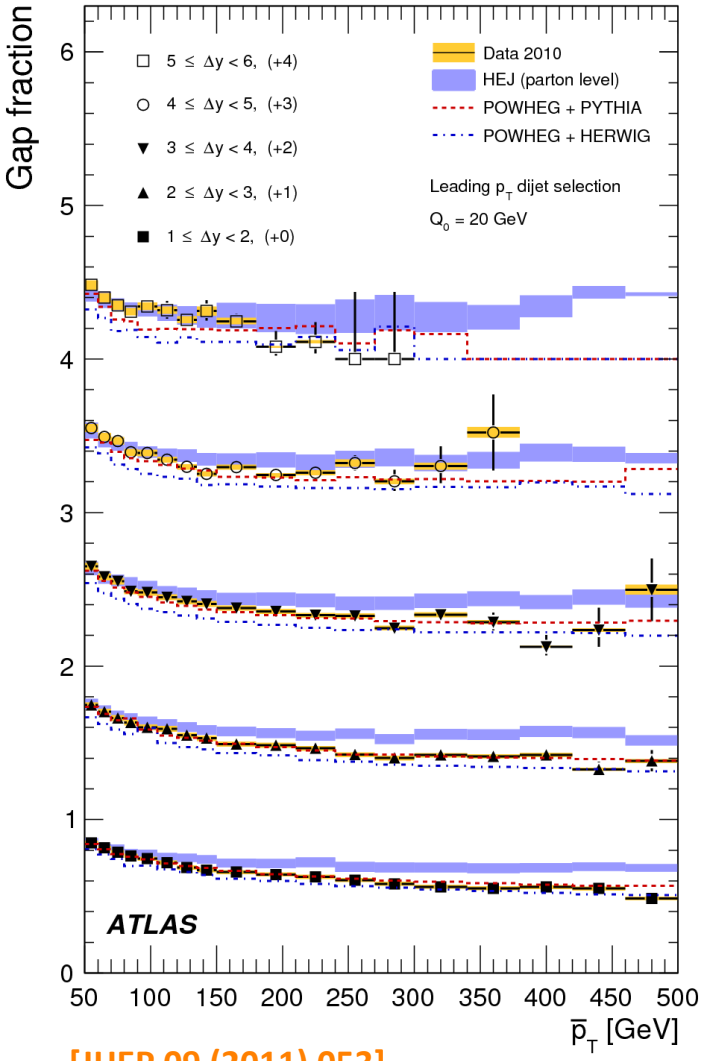
[PRL 106 (2011) 172002]

Jet Activity between Dijets: ATLAS

"**Gap fraction**": fraction of dijet events ($N_{jet} \geq 2$) without a jet with $p_T > Q_0$ (= 20 GeV) in rapidity interval between two highest p_T jets in the event (also system with maximal $|\Delta y|$).

HEJ underestimates the activity between the two jets (so too large a gap fraction).

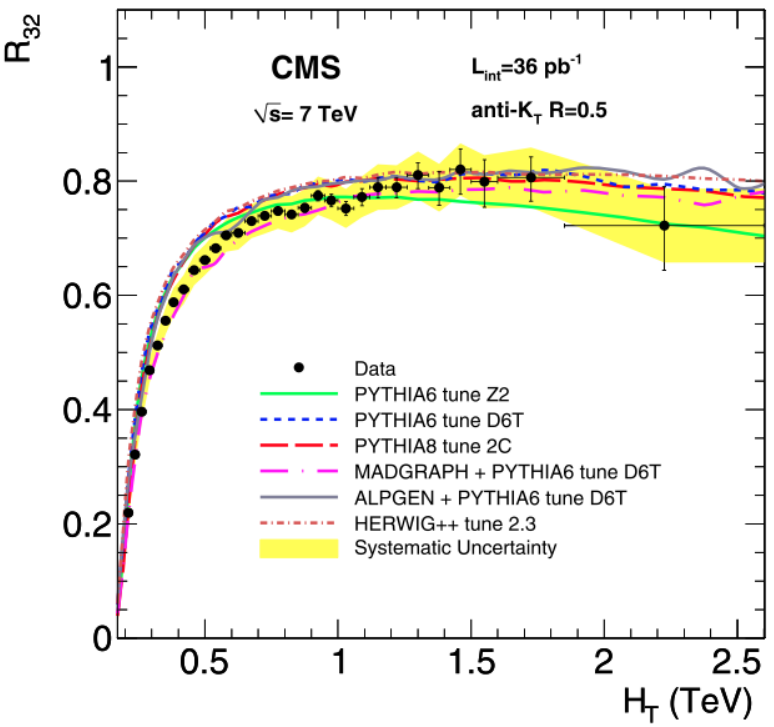


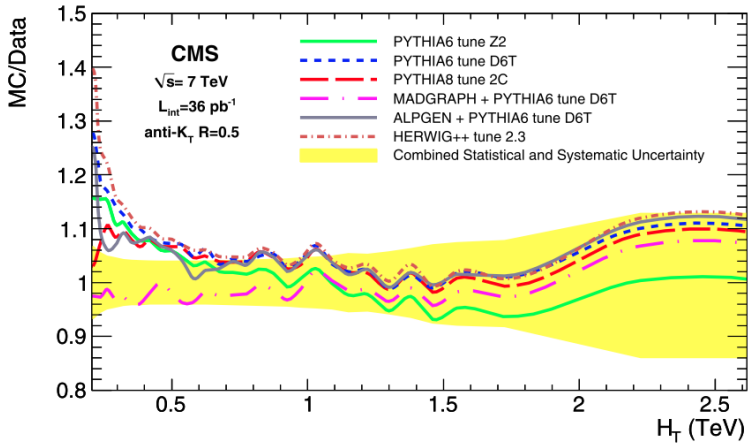


Anti-k_t $R = 0.6$, $p_T > 20$ GeV, $|y| < 4.4$ 2010 data

[JHEP 09 (2011) 053]

Multi-jet Production: Inclusive 3-jet to 2-jet ratio





2010 data, $p_T > 50$ GeV, $|y|<2.5$, anti-k_t R=0.5

$$H_T = \sum_{i=1}^{N_{jet}} p_{Ti}$$

Shape of H_T spectra for 2-jet, 3-jet events well described (within 20%) by Monte Carlo models.

Most MC generators high at low H_T.
Best description from Madgraph + Pythia

Note that Madgraph does NOT do a good job with azimuthal decorrelations (backup slides).

Similar analysis has been done by ATLAS as part of a more general investigation of multi-jet events (following slides).

[Phys. Lett. B 702 (2011) 336]