Confronting QCD with ATLAS Inclusive Jet & Dijet Measurements

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Confronting Theory with Experiment:
Puzzles, Challenges and Opportunities in the LHC Era

Fermilab

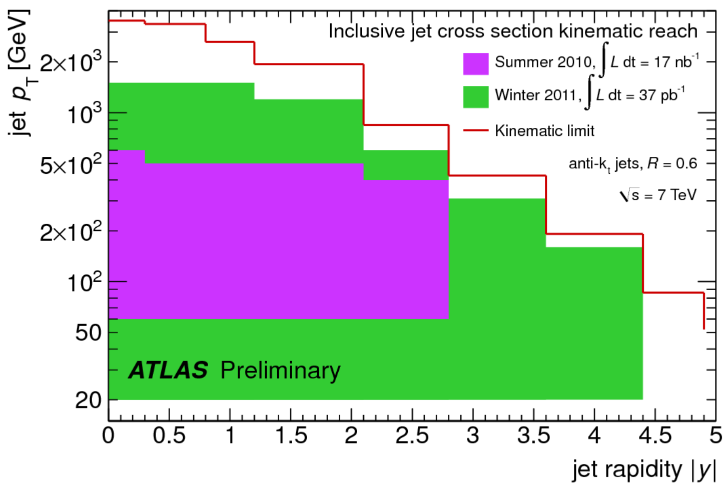
November 17, 2011

A (Partial) History of ATLAS Jet Cross-Section Measurements

- **June 2010:** First observation of energetic jets, 1 nb^{-1}
  PLHC (ATLAS-CONF-2010-043)
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CON
- **July 2010:** First measurement of jet cross-sections, 17 nb^{-1}
  ICHEP (ATLAS-CONF-2010-050)
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CON
- **Sept 2010:** First published jet cross-sections, 17 nb^{-1}
  Eur. Phys. J. C (71.1512)
  http://www.springer.com/physics/particle+and+nuclear+physics/journal/100
- **March 2011:** Full 2010 data sample, 37 pb^{-1}
  Moriond QCD (ATLAS-CONF-2011-047)
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CON
- ***Nov 2011:*** *This analysis, 37 pb^{-1}*
  In ATLAS internal review, to be submitted to Phys. Rev. D in a couple weeks

Kinematic reach of this analysis

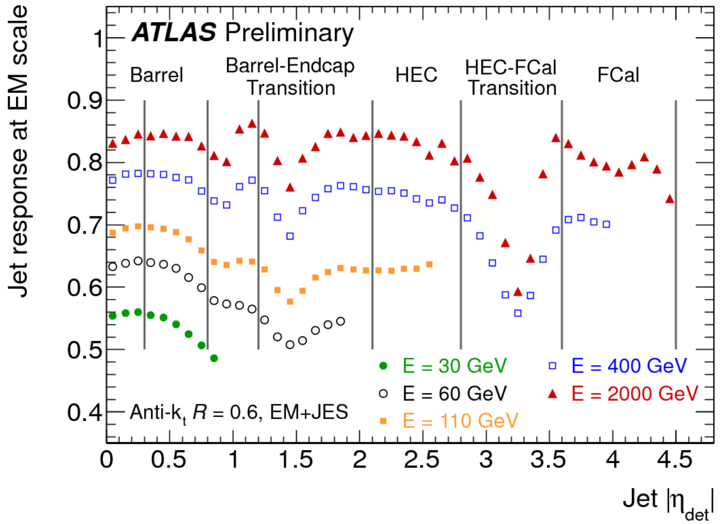
- 2200 more integrated lumi than EPJC:
  17 nb^{-1} → 37 pb^{-1}
- Max jet p_T: **600 GeV → 1.5 TeV**
- Max dijet mass m_{12}: **1.8 TeV → 5 TeV**
- Extension to low p_T and mass:
  p_T: **60 GeV → 20 GeV**
  m_{12}: **110 GeV → 70 GeV**
- Forward rapidity:
  |y| < 2.8 → 4.4



- **Probes perturbative QCD in huge new kinematic regime**
  - 2 orders of magnitude in jet p_T and dijet mass
  - 10 orders of magnitude in cross-section
- Encountered many theoretical puzzles along the way...

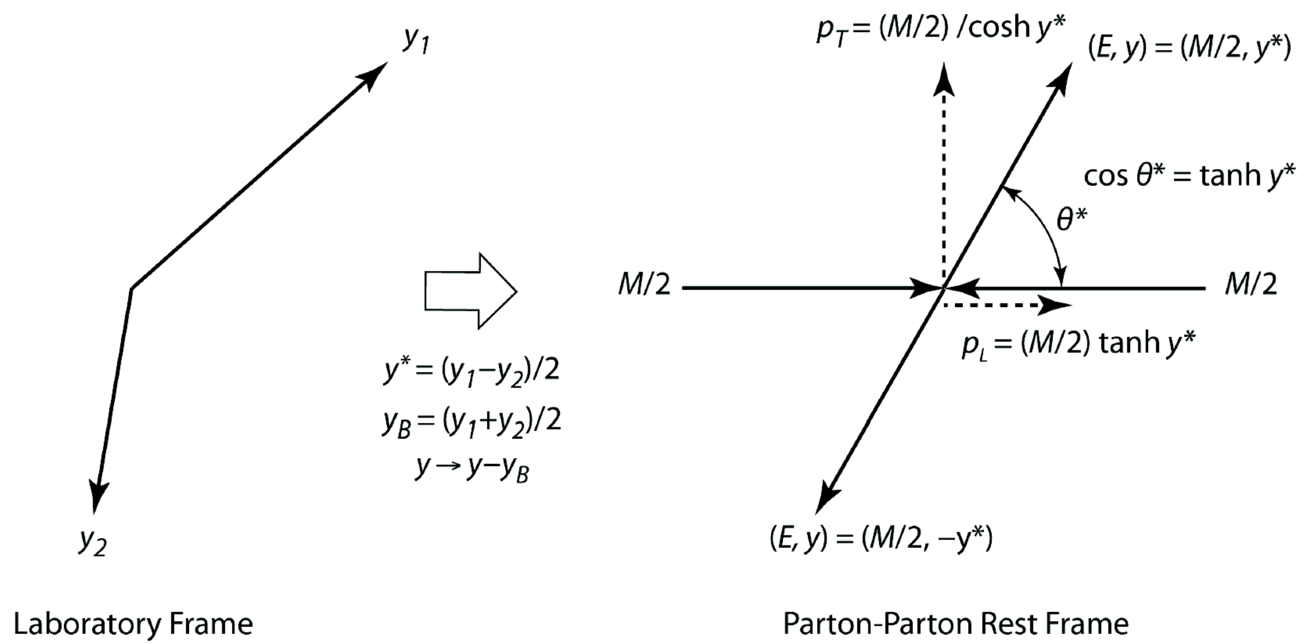
Jet observables

- Anti-k_T jets with R=0.4 and R=0.6, calibrated to hadron-level
- Inclusive jet pT spectrum (all jets):
  - **Jet p_T > 20 GeV binned in $|y|<4.4$**
- Dijet mass spectrum (two leading jets):
  - **Dijet invariant mass m_{12} binned in $y^*<4.4$, where $y^* = (y_1-y_2)/2$**
    - Replaces $y_{max} = \max(|y_1|, |y_2|)$
    - More details on kinematics on next slide
  - p_{T1} > 30 GeV, p_{T2} > 20 GeV
- Will be first inclusive jet and dijet cross-sections published at these large rapidities from a hadron collider



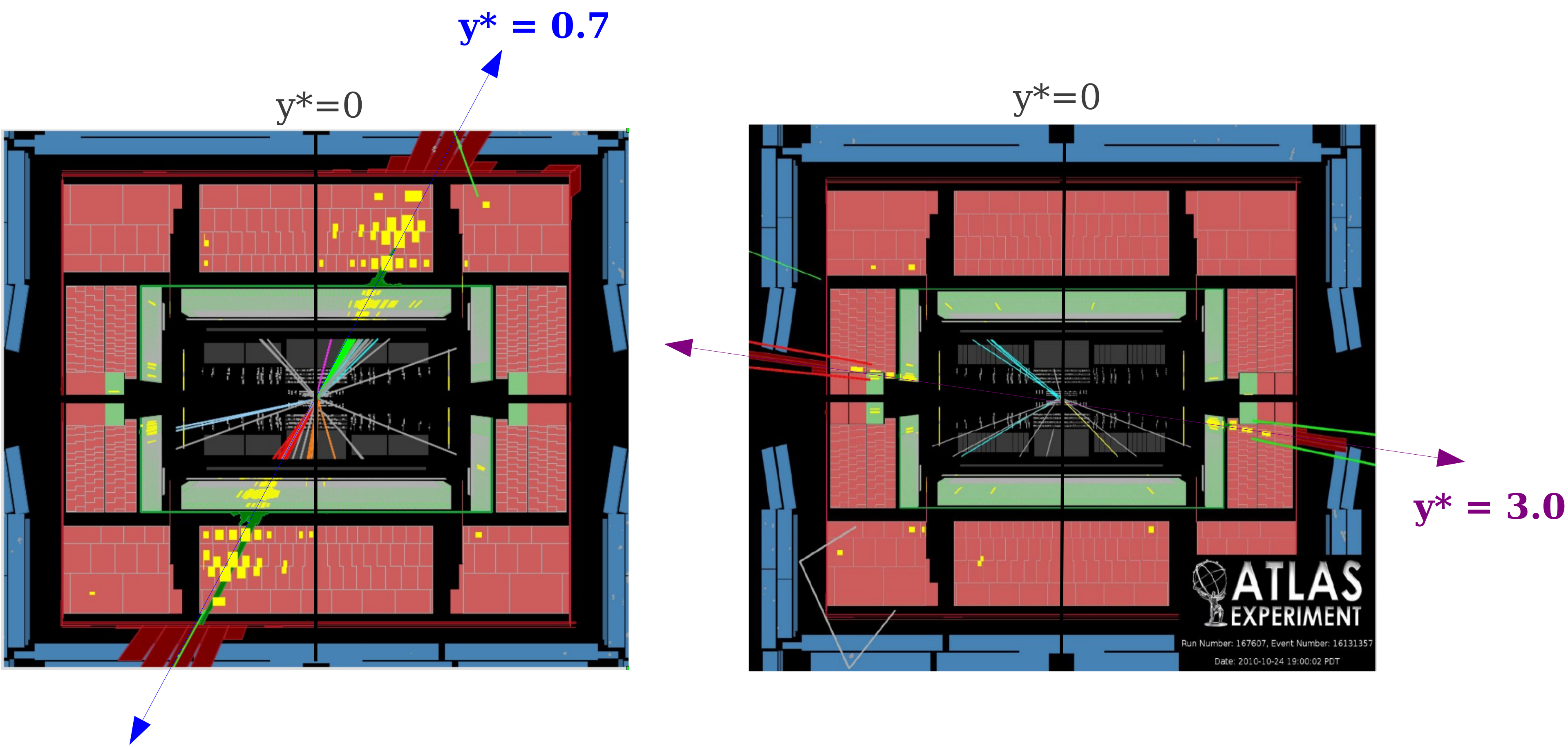
Brief aside on dijet kinematics

- In the two-parton center-of-mass frame (massless limit):
  - θ* is the polar scattering angle wrt beamline
  - $y^* = \mathrm{arctanh}(\cos(\theta^*))$ is the rapidity
    - Superior observable to $|y|_{max}$ because mass and y* (along with y_B) uniquely determine the kinematics for a dijet event
- Large (small) angle θ* wrt beamline translates to small (large) y*



Small vs. large y*

- Two high-mass dijet events
  - m_{12} = 3.1 TeV, y* = 0.7 (left)
  - m_{12} = 4.1 TeV, y* = 3.0 (right)

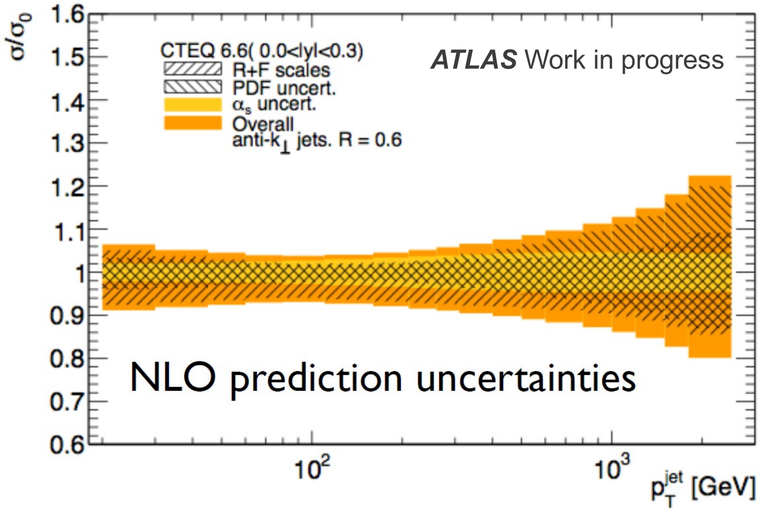


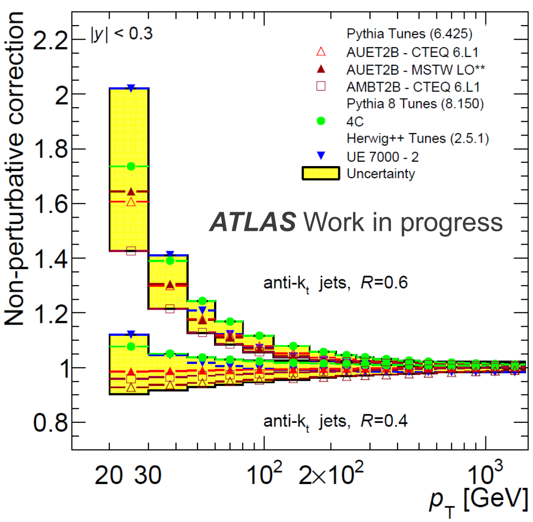
NLO pQCD calculations

- NLOJET++ is a fixed-order NLO parton-level calculation for QCD
  - Benchmark theory prediction for inclusive jet and dijet production for years
- POWHEG is the first NLO ME + parton shower Monte Carlo for inclusive jets and dijets
  - Introduced last year and expected to eventually supercede NLOJet++
  - Gladly welcomed by experimental community, including ATLAS
- However some issues for both NLOJET++ and POWHEG that are not understood yet

Fixed order NLO predictions

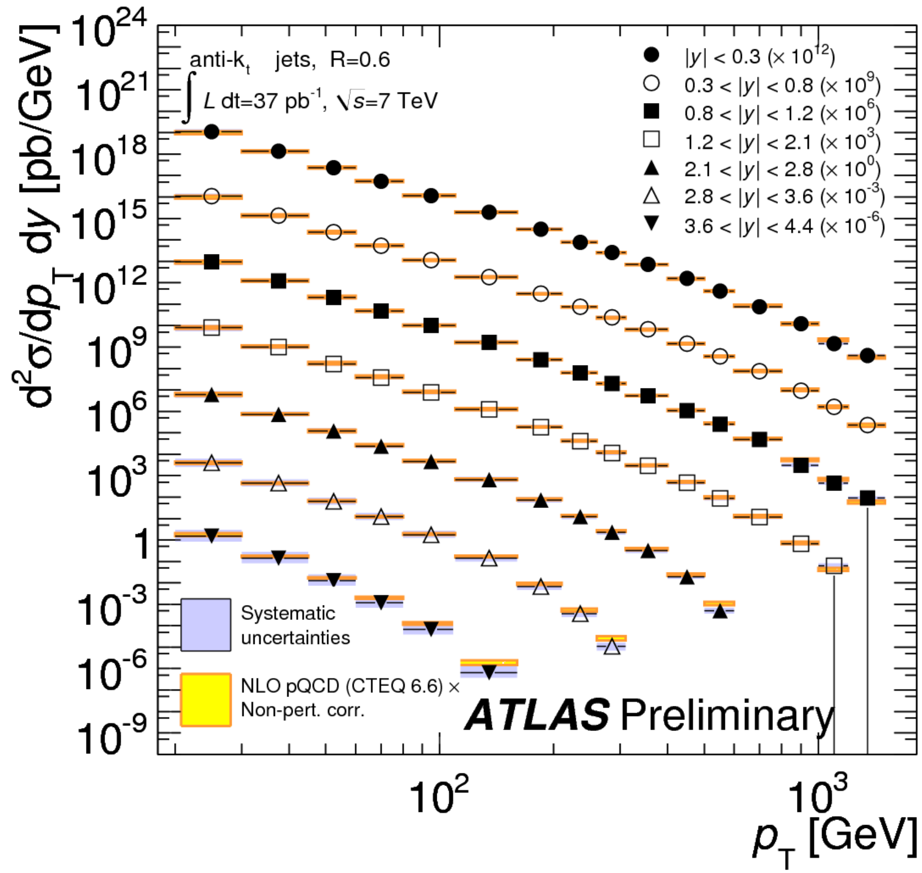
- Baseline QCD predictions from NLOJET++ (fixed order calculation)
- Uncertainties from renormalization and factorization scales, PDF, and α_S derived using APPLGRID (left)
- Non-perturbative correction applied to bring parton-level NLO cross sections to truth particle level accounting for hadronization and UE
  - Derived using PYTHIA (AUET2B tune)
  - Uncertainties derived using envelope of generators and tunes (right)





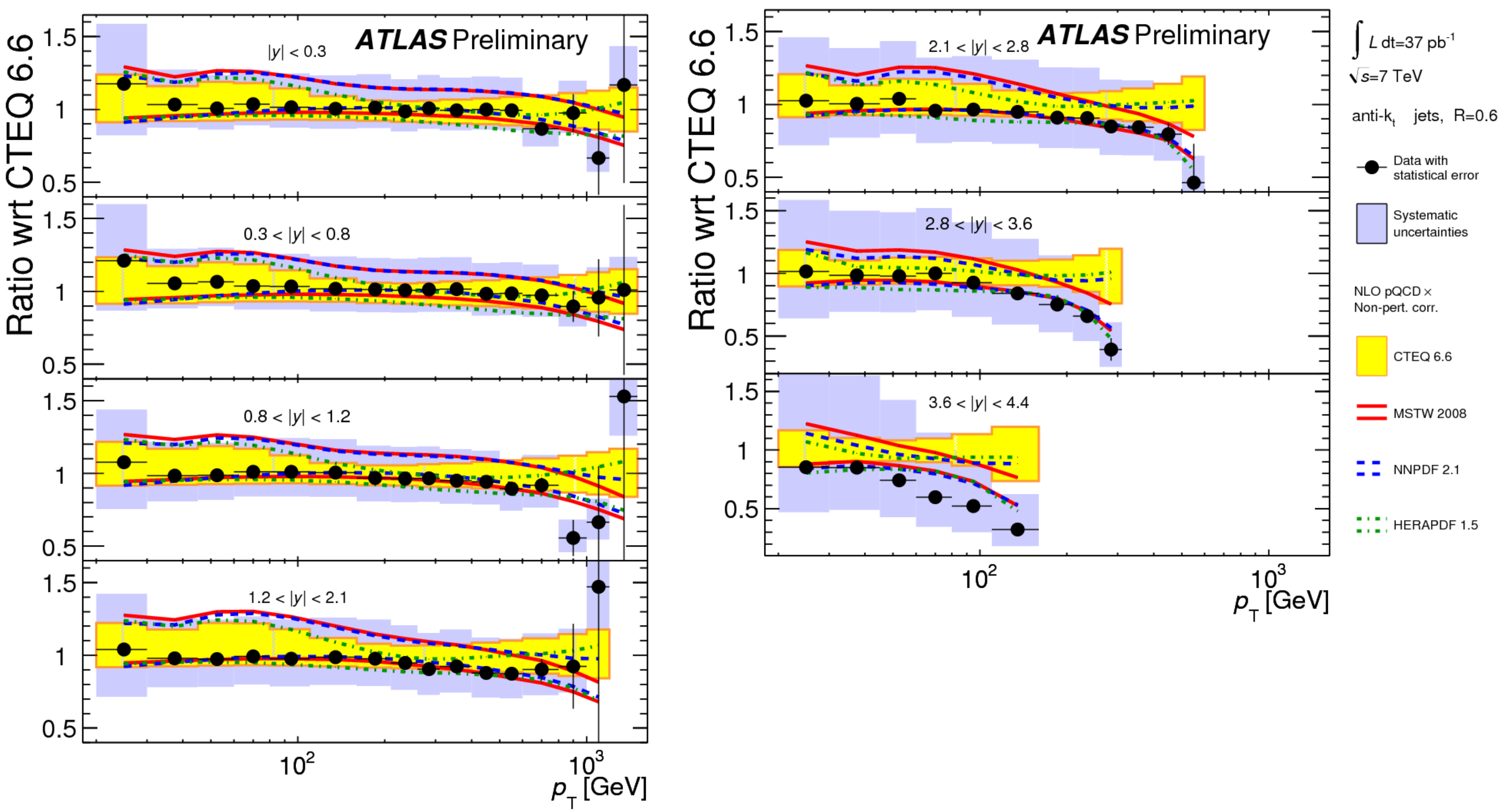
Inclusive jet cross section

- Inclusive jet p_T cross-section compared to NLOJET++ with non-perturbative corrections
- All cross-sections measured with both R=0.4 and R=0.6



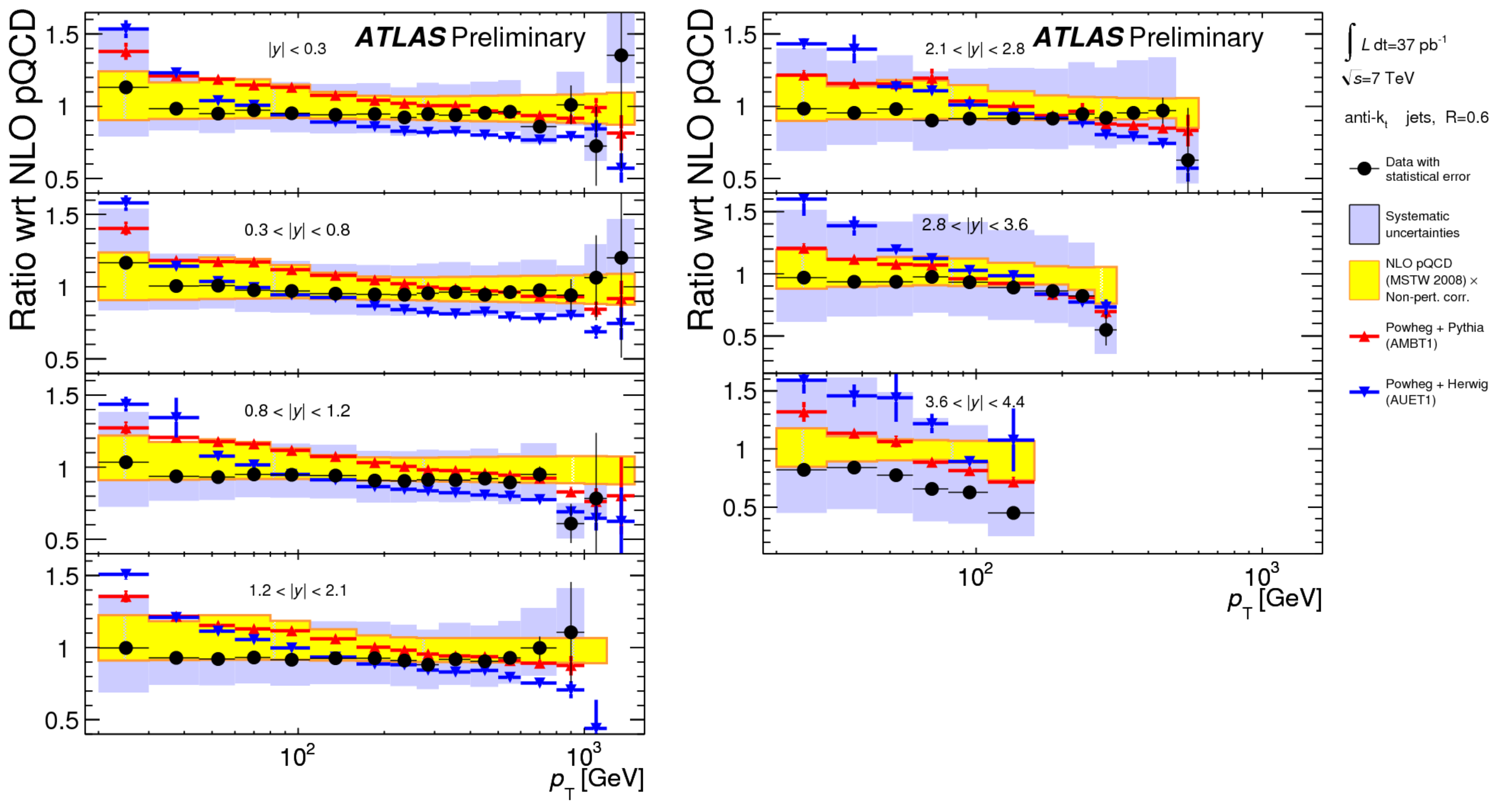
PDF comparisons

- Comparisons to CT10, CTEQ 6.6, MSTW 2008, NNPDF 2.1, and HERAPDF 1.5 (following PDF4LHC recommendations)
- Data dives below NLOJET++ prediction at high p_T, particularly in forward region
  - At the edge of PDF predictions



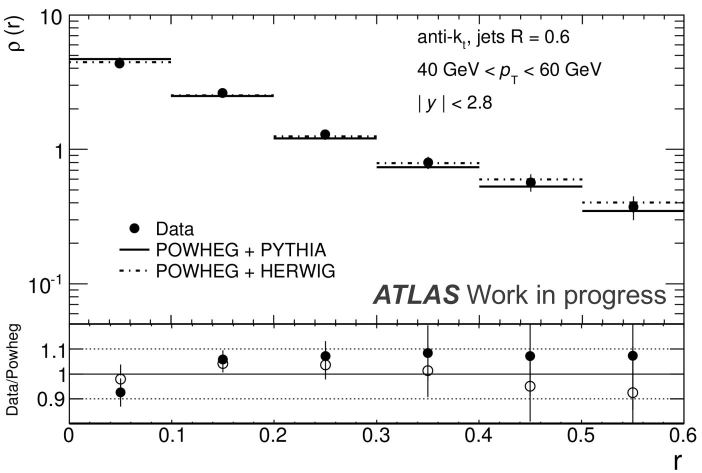
POWHEG comparisons

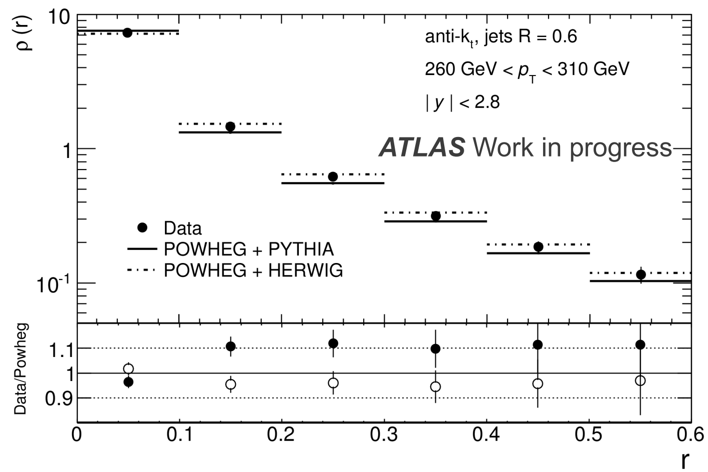
- Comparisons to POWHEG BOX, showered with PYTHIA / HERWIG
  - POHWEG also exhibits slope wrt NLOJET++, but also strong disagreement with data at low p_T
  - Why is the effect of the parton shower (POWHEG vs. NLOJET++) so large even at high p_T?



Jet shape comparisons to POWHEG

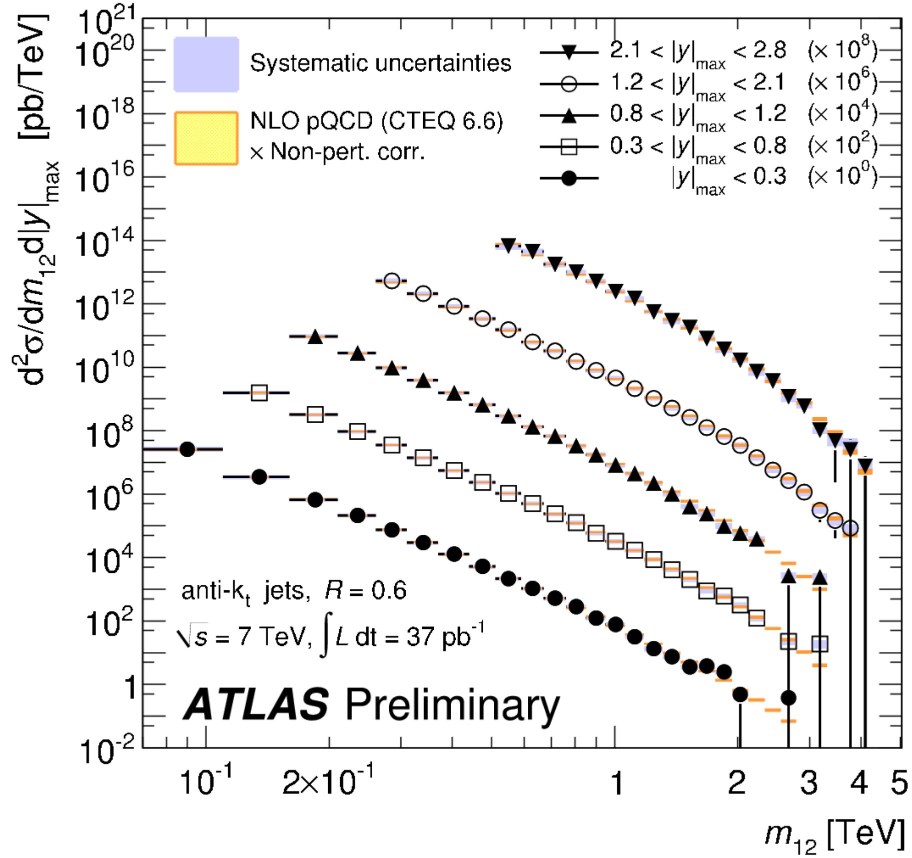
- Detector-level jet shape
- Why are POWHEG cross-section predictions so different for two parton showers?
    - Neither PYTHIA (AMBT1) nor HERWIG (AUET1) prediction is consistently higher/lower than the other
- POWHEG + PYTHIA jet shape is systematically harder than that with HERWIG
    - Not clear whether explains difference in cross-sections





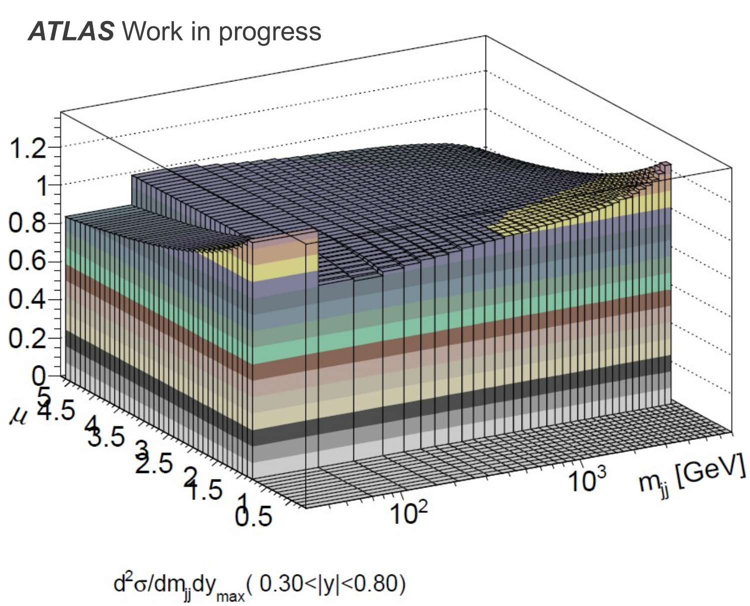
Dijet NLO pQCD

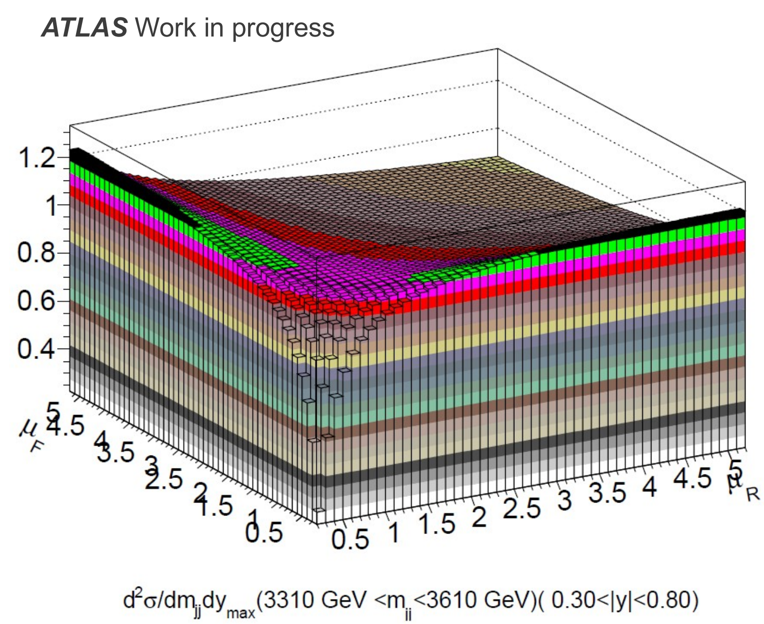
- Dijet mass spectrum, compared to NLOJET++ (mu = pT) with non-perturbative corrections
- Only reported up to $|y|_{max}$<2.8 at Moriond precisely due to problems with theory calculation
- NLOJET++ predicts negative cross-sections in the forward region beyond this!



Scale for central dijet mass spectrum

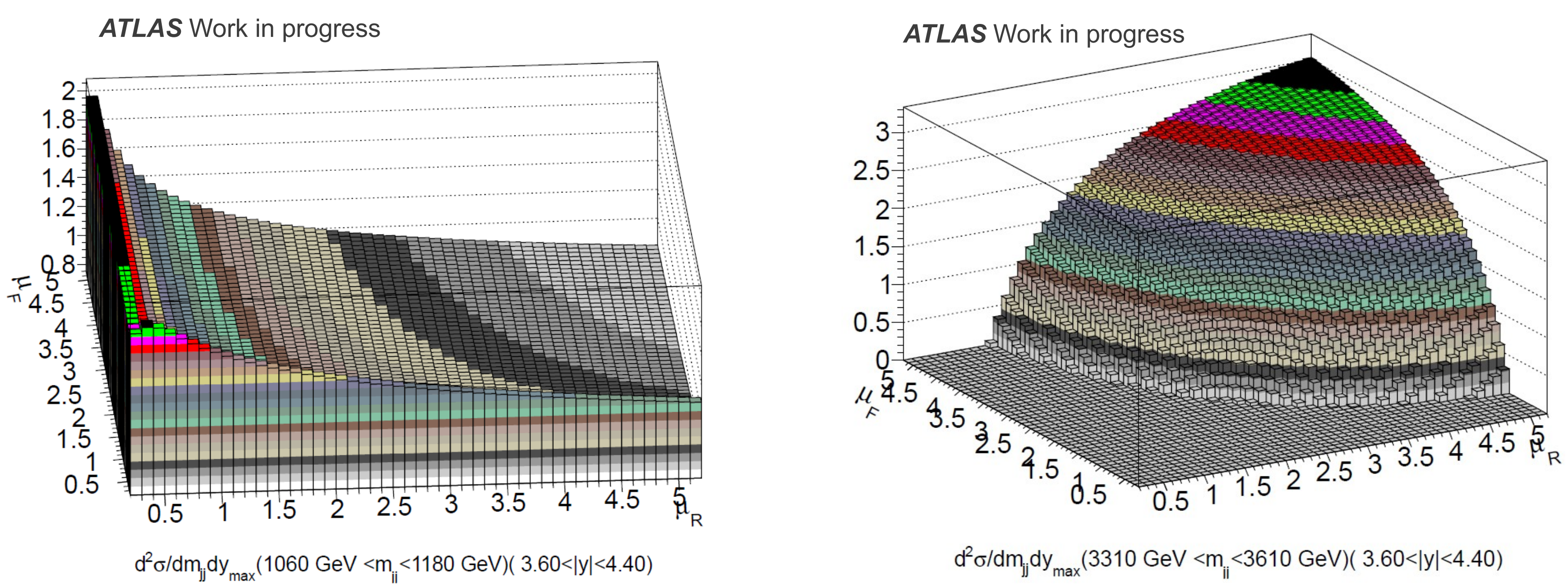
- Finite cross-sections predicted by NLOJET++ for central dijet mass spectrum at small $|y|_{ymax}$ using leading jet p_T as scale
  - Similar for small y*, or equivalently large θ*
  - Note right plot shows mass = 3.3 TeV ↔ jet pT ~ 1.2 TeV
    - Scale of leading jet p_T would be large





Scale for forward dijet mass spectrum

- Negative cross-sections predicted by NLOJET++ for high-mass forward dijet events (at large $|y|_{max}$) when leading jet p_T used as scale
  - Similar for large y*, or equivalently large θ*
  - Note y* = 4.4 on right plot, so mass = 3.3 TeV ↔ jet pT ~ 40 GeV
    - Scale is very small when set to leading jet p_T
      - *Is this the cause of the problem?*



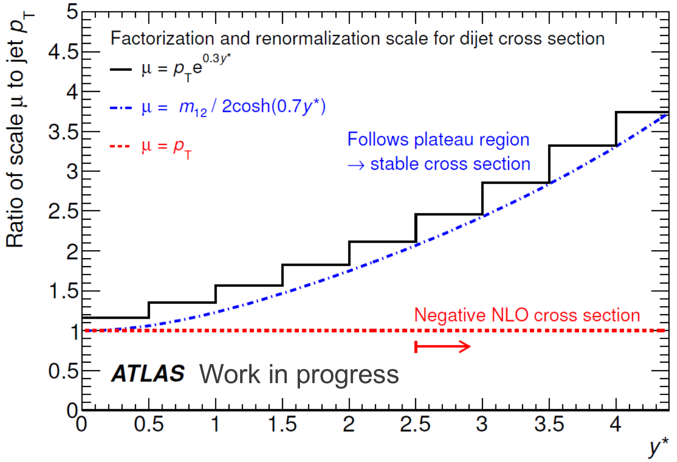
Forward dijet production with NLOJET++

- NLOJET++ predictions for inclusive jet p_T calculated using renormalization & factorization scales set to leading jet p_T:
  $\mu = \mu_R = \mu_F = p_T$

- However, with this scale NLOJET++ predicts negative cross-sections for dijet mass spectrum at y*>3.0
  - Scale of:
    $\mu = m_{12} / 2 \cosh(0.7y^*)$

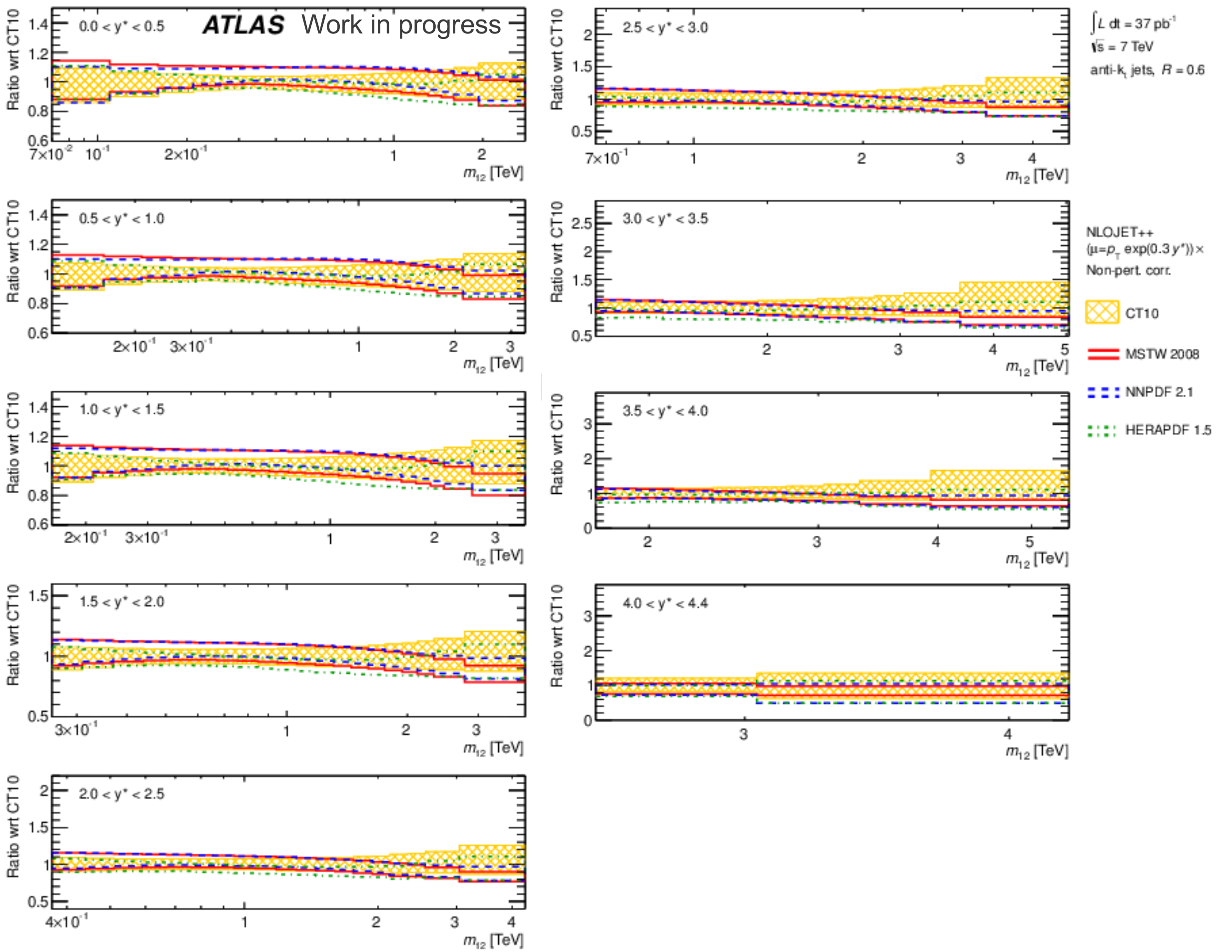
    proposed by Ellis et al.:

    http://inspirebeta.net/record/336137
    - Appears to be hybrid of $p_T = m_{12}/2\cosh(y^*)$ and m_{12}
    - Coefficient of 0.7 was optimized in paper for narrower |y| acceptance
  - We used numerical approximation $\mu = p_T \exp(0.3y^*)$, which is very similar
    - Yields positive predictions that are in reasonable agreement with data



Dijet PDF comparisons

- NLOJET++ produces finite predictions for forward dijets using y*-dependent scale proposed by Ellis et al.
- Measurements to be submitted to Phys. Rev. D shortly → only theory shown below

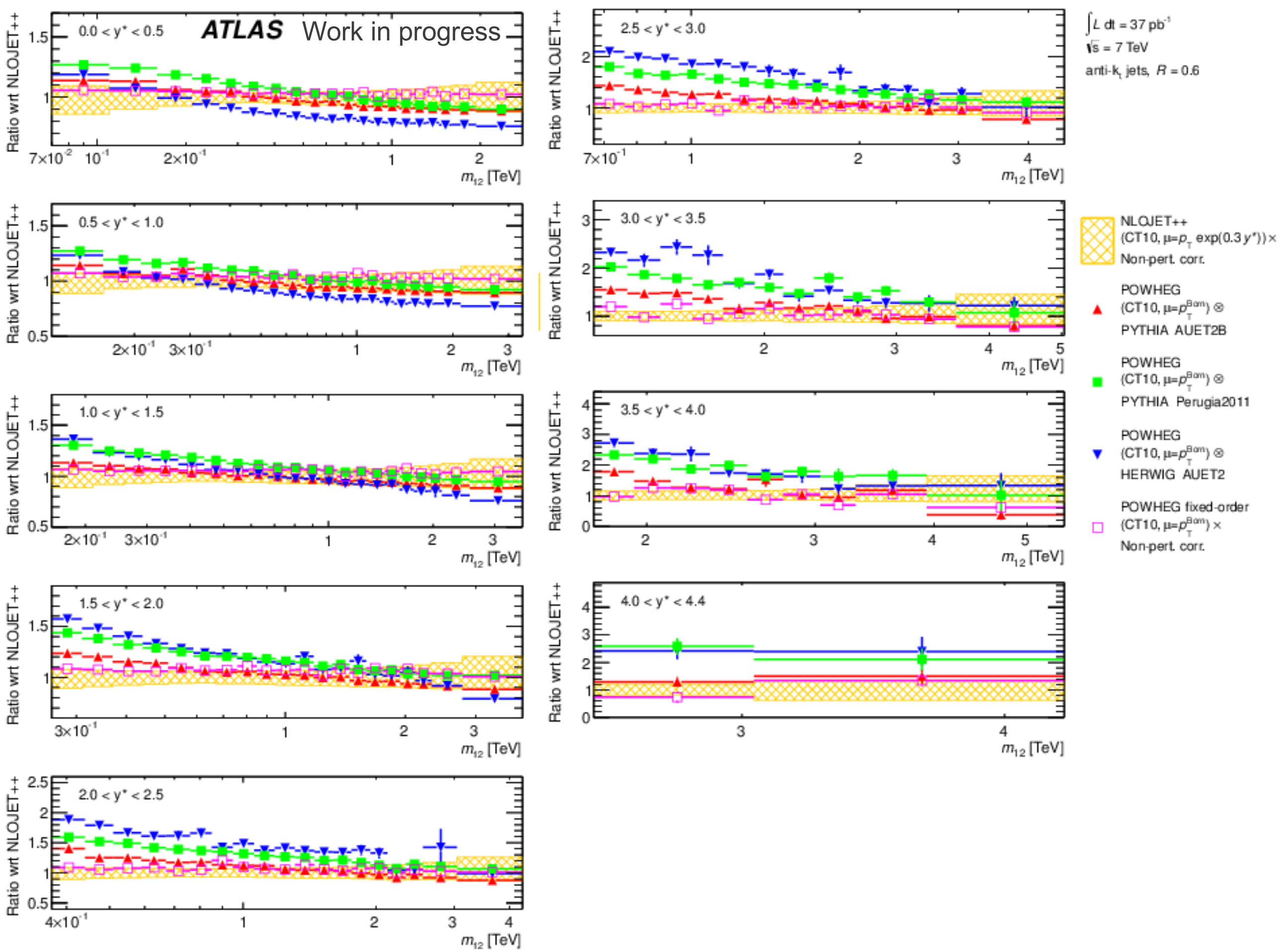


How to define the scale

- Not clear how to uniquely define hardness (Q^2) of interaction
  - Jet p_T apparently works fine for small y* (large scattering angle θ*)
    - Seems natural measure of the momentum transfer, i.e. "hardness" of collision
  - But jet pT fails at large y*, where dijet mass (or hybrid) apparently works
    - *Since dijet mass ~ twice the jet energy, implies energy (rather than pT) characterizes the hardness better?*
- *Is there any relation to s-hat (dijet mass) vs. t-hat (jet p_T)?*
  - t-channel diagrams dominate for all y*, but relative contribution of s-channel is larger for small y* (large θ*)
    - Seems to be opposite relationship to that we see here
  - Also u-channel (back scattering) production of forward dijets would seem to prefer dijet mass as well, since the jet pT is small
  - So not clear if this scale problem has anything to do with s-, t-, u-hat
- And more general questions about whether μ_R and μ_F need to be tied together, how much to vary them (factor of 2?) to assign uncertainties, etc.

Dijet POWHEG comparisons

- POWHEG fixed order (pink) uses μ = Born p_T but is non-negative for forward dijets!
- As for inclusive jets, see large slope of all POWHEG NLO+PS curves wrt NLOJET++
- POWHEG showered predictions depend strongly on parton shower and tune used
- Measurements to be submitted to Phys. Rev. D shortly → only theory shown below



Forward dijet production with POWHEG

- No such divergences seen for large y* using POWHEG operated at fixed order NLO (no resummation nor parton shower), i.e. “pure NLO mode”
  - Uses scale $\mu=p_T^{Born}$ (equivalent to leading jet p_T at Born level)
  - NLOJET++ and POWHEG calculations consistent at small y*
- *Why aren't NLOJET++ and POWHEG calculations identical at large y*?*
  - *Is this due to numerical differences in the subtraction scheme?*
    - NLOJet++ uses color dipole scheme, whereas POWHEG uses FKS-style
  - *Is it due to slight difference in the scale choice?*
    - NLOJet++ uses leading jet p_T at NLO (real term includes 3 jets)
    - POWHEG uses LO jet p_T

POWHEG dependence on parton shower and tune

- *Again why is the effect of the parton shower (NLOJet++ vs. POWHEG) so large even at high mass?*
  - Note that for each y* slice, higher mass ↔ higher p_T
- POWHEG prediction very sensitive to parton shower and tune used:
  - Large differences between using PYTHIA vs. HERWIG shower
  - Large differences between AUET2b vs. Perugia2011 tunes (both for PYTHIA shower)
- Basic assumption was that standalone tunes for generator (PYTHIA, HERWIG) should be fine for use with POWHEG
  - *But perhaps a dedicated tune of POWHEG (together with each parton shower) to the minimum bias or underlying event data is required?*

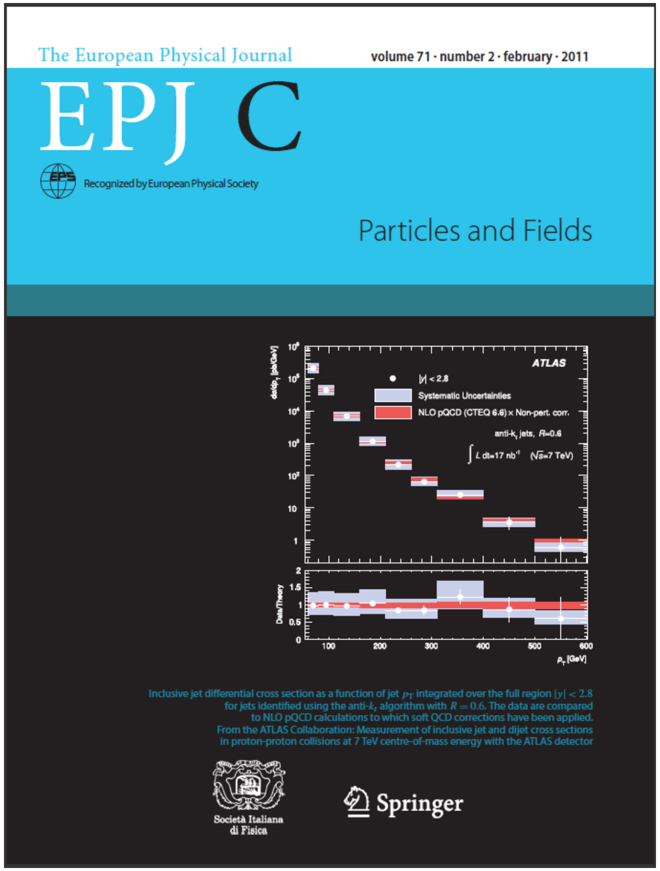
Conclusions

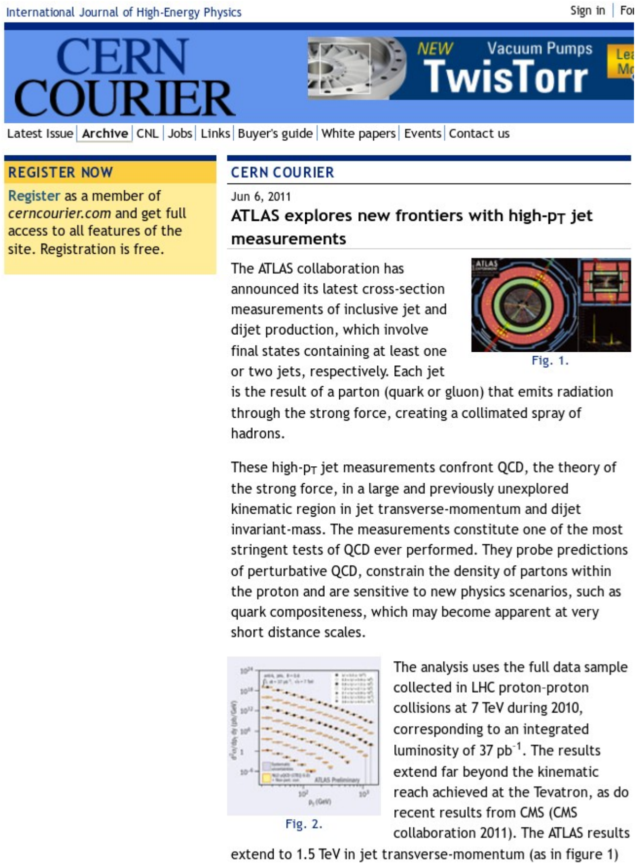
- Measurements of inclusive jet p_T and dijet mass cross-sections performed using full 2010 ATLAS dataset of 37 pb^{-1}
  - Major extension at low & high jet p_T & dijet mass, as well as forward rapidity
  - To be submitted to Phys. Rev. D in a couple weeks
- Many puzzles with theory calculations encountered along the way
  - For forward dijets, NLOJET++ (NLO fixed order calculation) predicts negative cross-sections if scale is set to leading jet pT
    - Solved by switching to scale that is hybrid of pT & dijet mass
    - POWHEG (fixed order) has no such divergence even with μ = Born pT
      - *Why aren't the NLOJET++ and POWHEG calculations identical?*
      - *How to define the scale appropriately and uniquely?*
  - Large difference between NLOJET++ (fixed-order NLO) and POWHEG (NLO+PS)
    - *Why does the parton shower have such a large effect even at high p_T and large dijet mass (well as a low pT/mass)?*
  - POWHEG (NLO+PS) prediction very sensitive to parton shower & tune used
    - *Is a dedicated tune needed for POWHEG?*
- **ATLAS jet measurements performed in a large new kinematic regime are challenging QCD theory predictions!**

ADDITIONAL MATERIAL

In the public eye

- 17 nb^{-1} analysis chosen for EPJC cover in Feb 2011 (left)
- Moriond analysis in June 2011 issue of CERN Courier (right)





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Jun 6, 2011

ATLAS explores new frontiers with high-p_T jet measurements

The ATLAS collaboration has announced its latest cross-section measurements of inclusive jet and dijet production, which involve final states containing at least one or two jets, respectively. Each jet is the result of a parton (quark or gluon) that emits radiation through the strong force, creating a collimated spray of hadrons.

Fig. 1.

These high-p_T jet measurements confront QCD, the theory of the strong force, in a large and previously unexplored kinematic region in jet transverse-momentum and dijet invariant-mass. The measurements constitute one of the most stringent tests of QCD ever performed. They probe predictions of perturbative QCD, constrain the density of partons within the proton and are sensitive to new physics scenarios, such as quark compositeness, which may become apparent at very short distance scales.

Fig. 2.

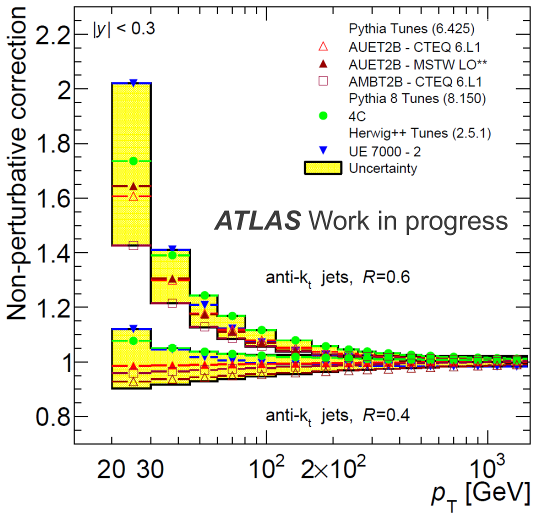
The analysis uses the full data sample collected in LHC proton-proton collisions at 7 TeV during 2010, corresponding to an integrated luminosity of 37 pb^{-1}. The results extend far beyond the kinematic reach achieved at the Tevatron, as do recent results from CMS (CMS collaboration 2011). The ATLAS results extend to 1.5 TeV in jet transverse-momentum (as in figure 1)

Parton distribution functions

- Differences between different PDF sets (e.g. CTEQ vs. MSTW) are sometimes larger than the uncertainty within a given set (determined via eigenvectors, replicas, etc.)
  - *Should the envelope be assigned as a theoretical uncertainty, or comparisons made to each PDF set separately with their respective uncertainties?*
  - ATLAS generally does the latter for jet measurements

Non-perturbative corrections

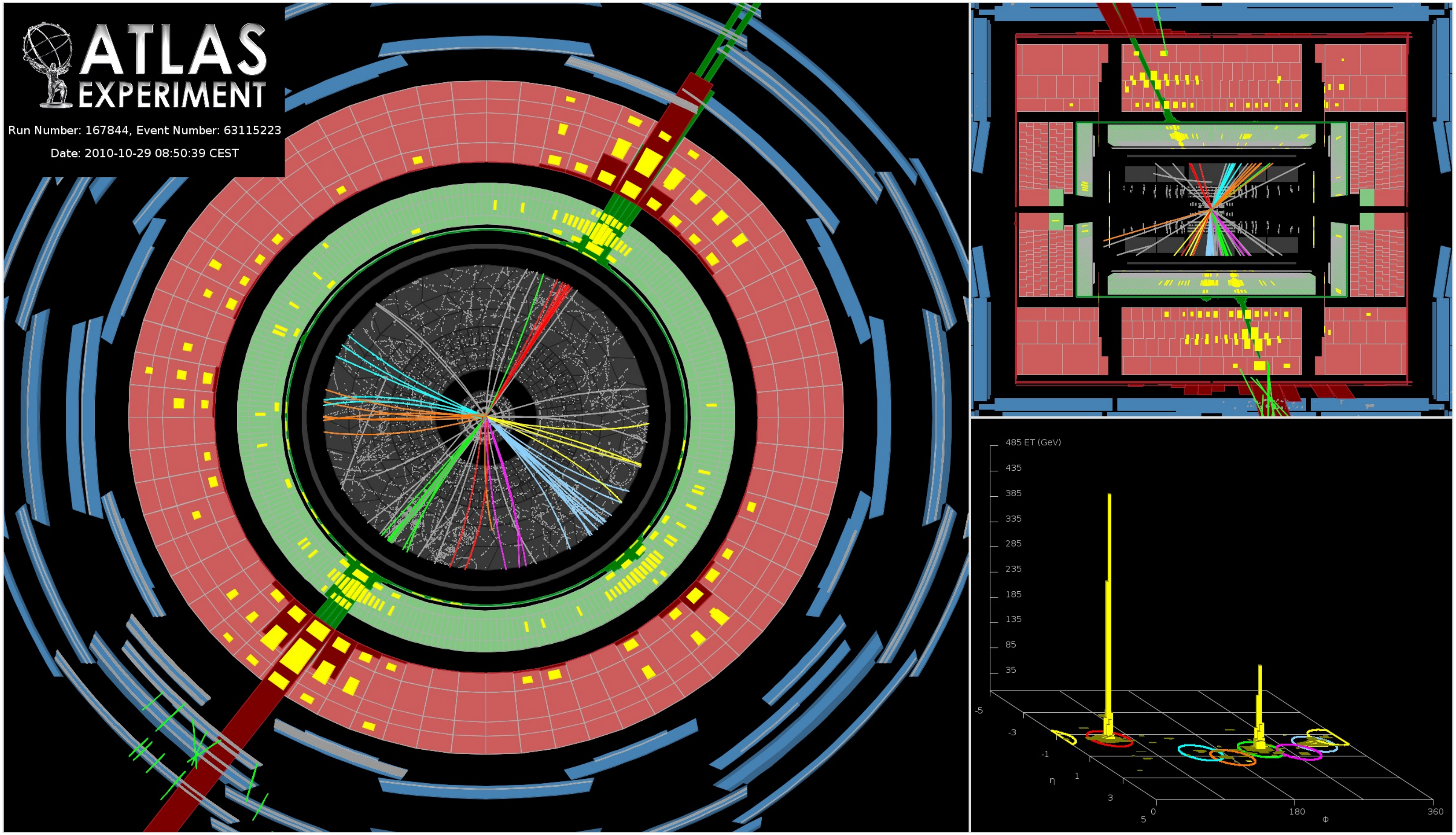
- Convention to run Monte Carlo with hadronization and UE each turned on/off to calculate "non-perturbative corrections"
  - $\sigma^{\text{UE on, had on}} / \sigma^{\text{UE off, had off}}$
  - Correction to cross-section that needs to be applied to NLO parton-level calculation to account for effect of hadronization and underlying event



- However this is calculated with LO+PS Monte Carlo
  - Mis-match to NLO matrix element with no PS
- In principle POWHEG (via PYTHIA or HERWIG) should be able to include such effects coherently

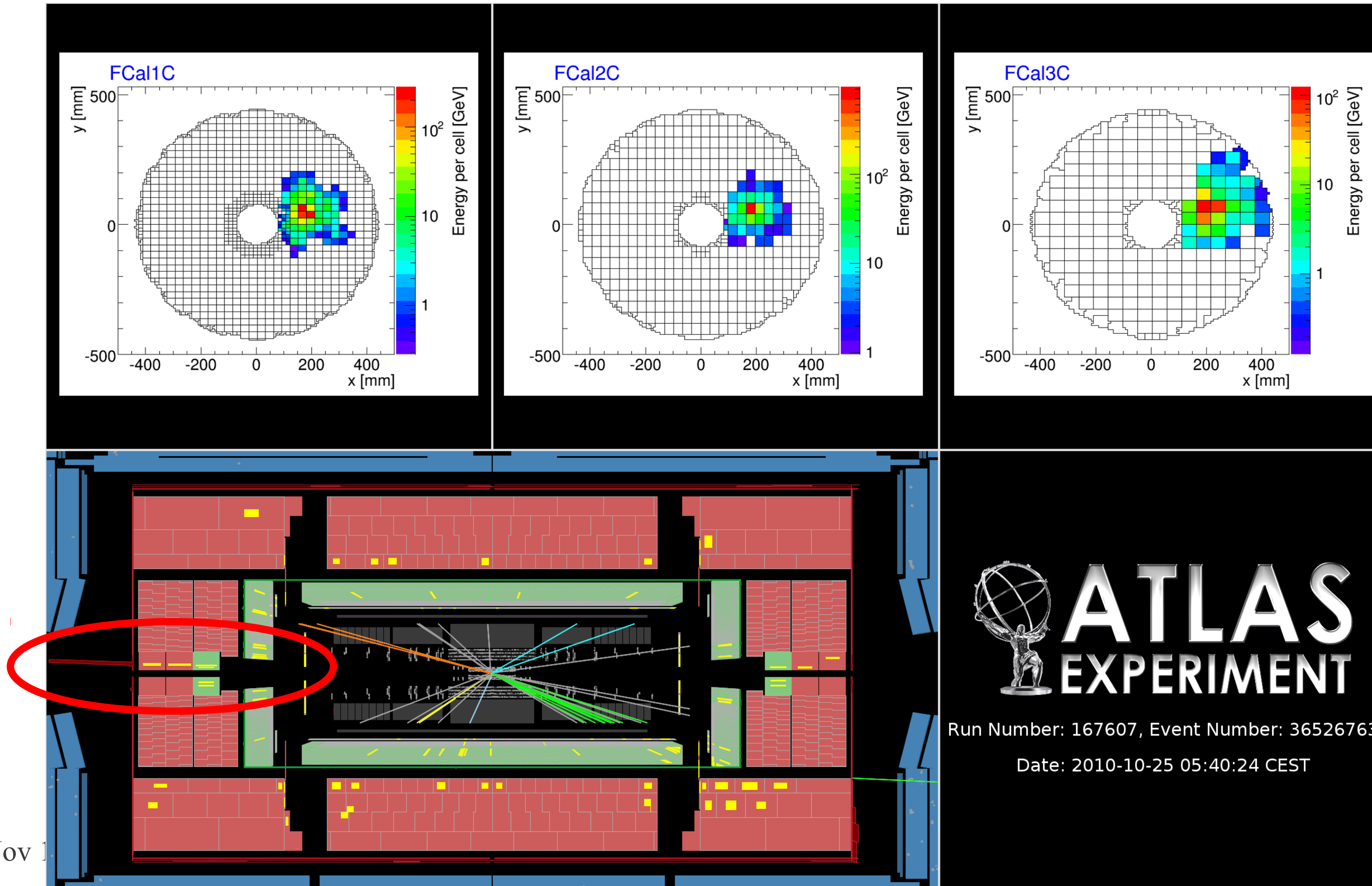
High p_T jet = 1.5 TeV

- Run 167607, Event 63115223
- Dijet mass m_{12} = 2.8 TeV



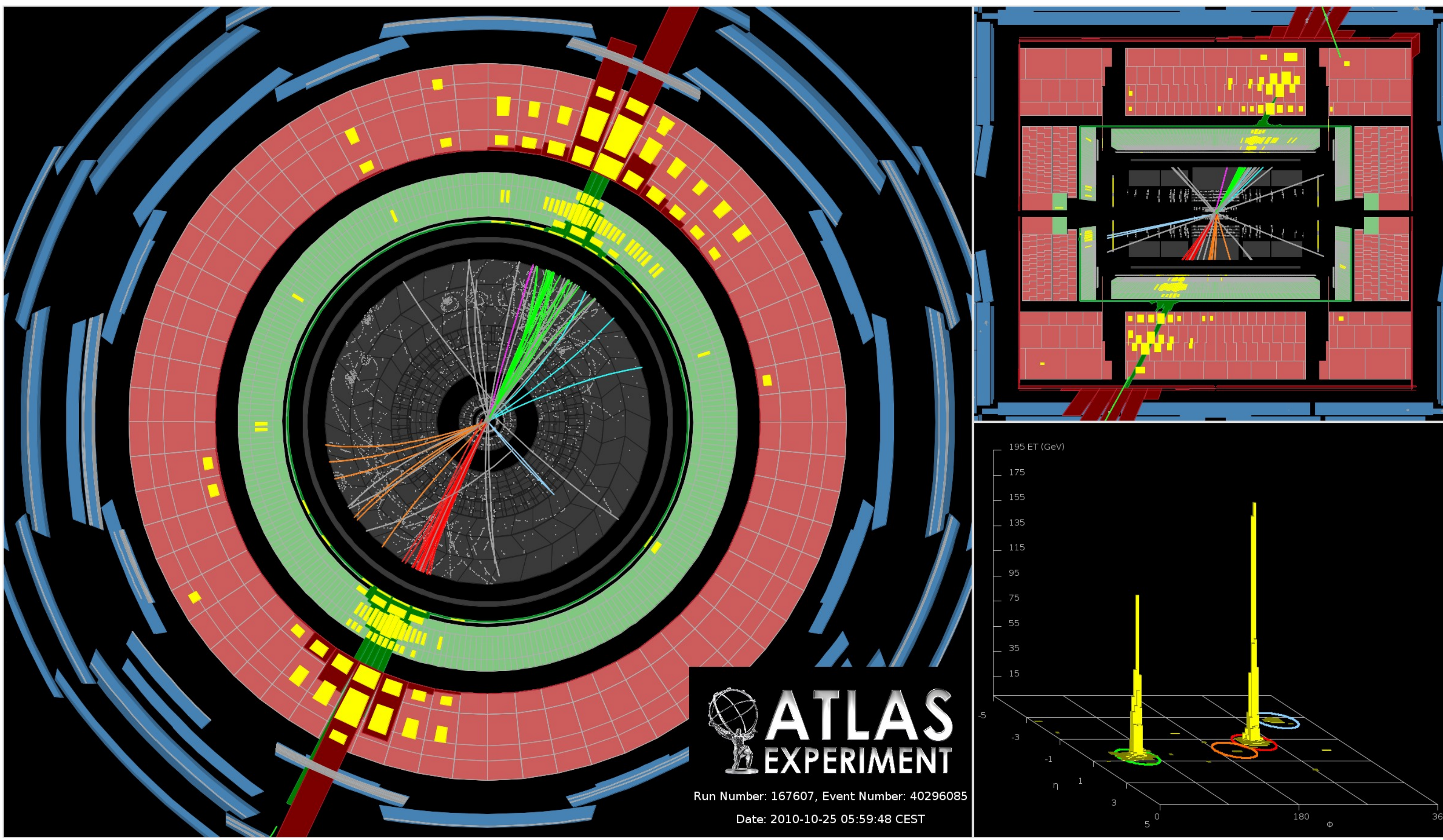
High-energy forward jet: E = 3.4 TeV

- Run 167607, Event 3652763



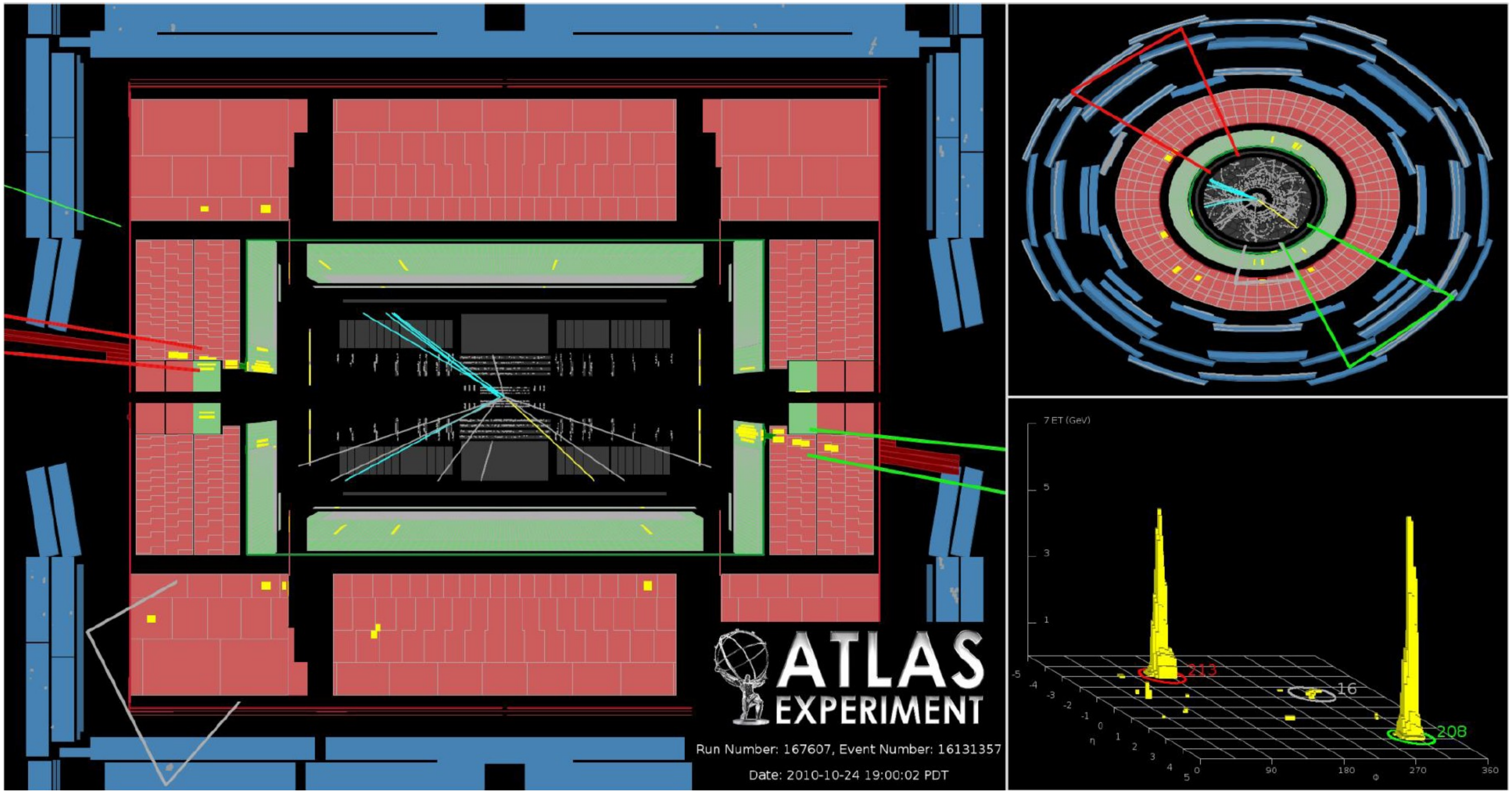
High-mass central dijet event

- Run 167607, Event 40296085
- Dijet mass m_{12} = 3.1 TeV, y^* = 0.7



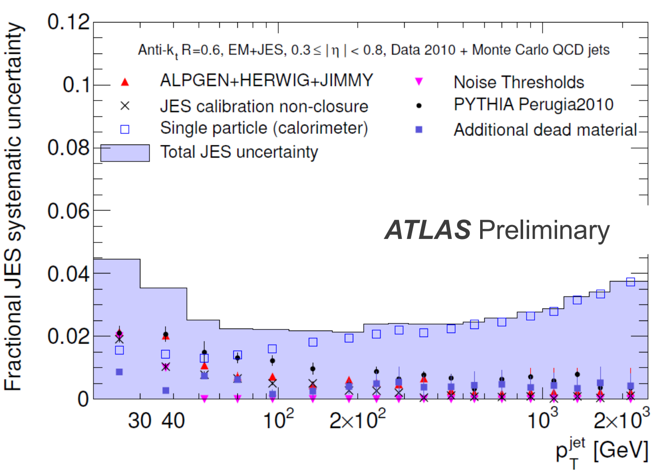
High-mass forward dijet event

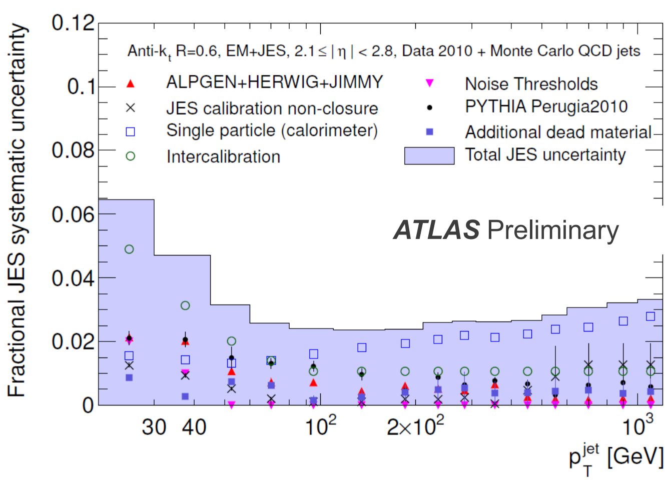
- Run 167607, Event 16131357
- Dijet mass m_{12} = 4.1 TeV, y* = 3.0

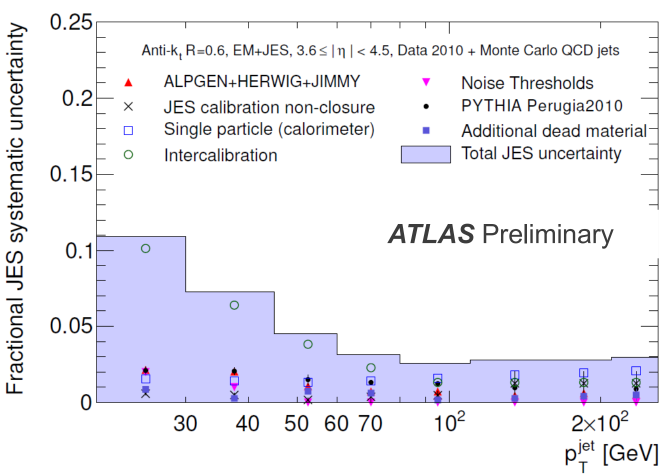


Absolute JES Uncertainty

- Much reduced compared to EPJC:
  - Less than 2.5% in central region for 60-800 GeV jets
  - Calorimeter component dominant in central region (from test beam and single particle response)
- Forward jet energy scale determined wrt central via dijet balance
  - η intercalibration component due to MC modeling uncertainty is dominant in forward region

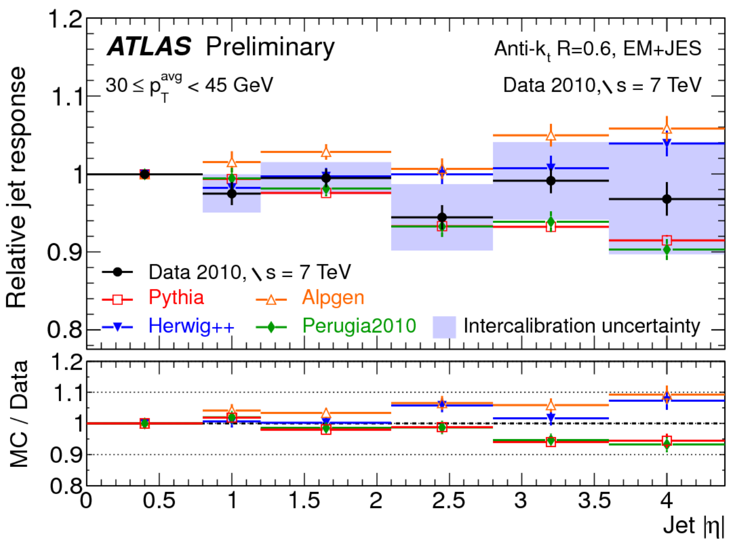


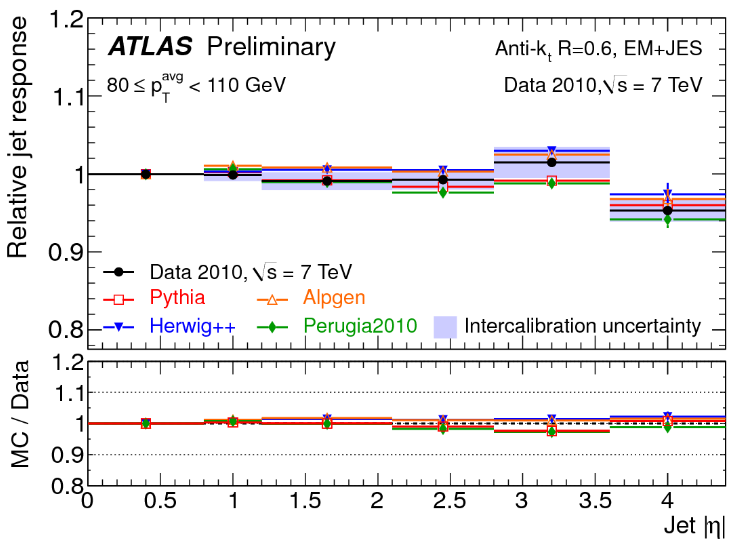




Forward JES Uncertainty

- Forward jet energy scale determined wrt central via dijet balance
  - At low p_T, energy scale of forward jets wrt central jets described by MC within a few percent (up to ~10% in the forward region)
  - Better agreement at high p_T
  - Uncertainty mainly due to HERWIG vs. PYTHIA differences





Forward jet shapes

- Detector-level jet shapes in forward region
- Energy distribution within jet reasonably well-modeled (agreement within 20%)
  - Differences between data and MC are fully covered by unfolding uncertainty due to shape of measured spectrum