Hard QCD studies with the ATLAS detector

QCD@LHC Workshop, St Andrews, Scotland

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August 22, 2011

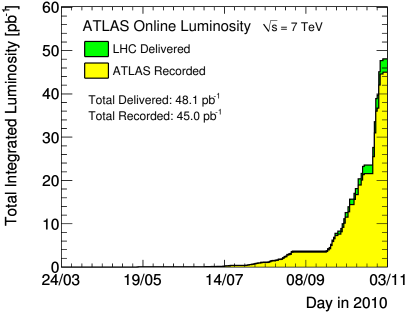
Outline

- The LHC has delivered an unexpected amount of data, and the ATLAS collaboration has produced an amazing number of results.
- Events with jets in final state are copiously produced at hadron machines
  - LHC is new energy frontier and fertile ground for many tests of QCD theory
- Must be selective in what I present, apologies to those results not included here today
  - Jet cross sections
  - Angular decorrelation, Dijets with jet veto
  - Jet substructure
  - b-jet cross sections
  - W and Z production - see also talk by E. Devetak

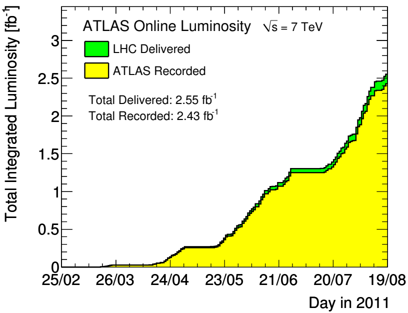
Unprecedented Luminosity

The LHC has outdone itself with the smooth running of the accelerator.

2010 Data Run
$45pb^{-1}$

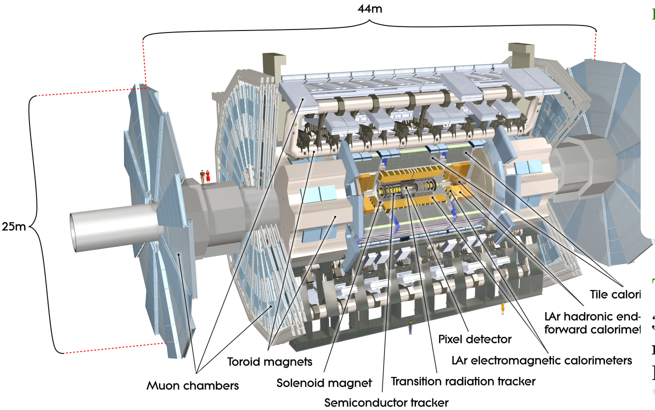


2011 Data Run
$> 2fb^{-1}$ and growing!



ATLAS-CONF-2011-116 : Luminosity systematic uncertainty 3.7%

ATLAS Trigger System



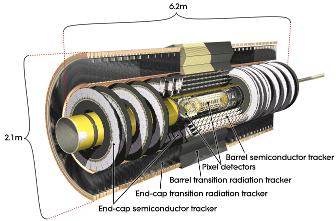
The ATLAS Detector is really big!

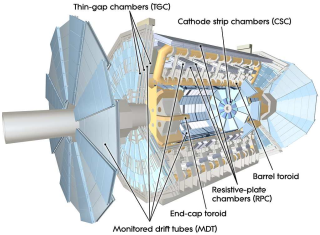
- Length : $\sim$ 46 m
- Radius : $\sim$ 12 m
- Weight : $\sim$ 7000 tons
- $\sim 10^8$ electronic channels
- 3000 km of cables

Trigger System

3-level trigger reducing the rate from 20 MHz to $\approx$ 200 Hz

ATLAS Inner Detector and Muon System





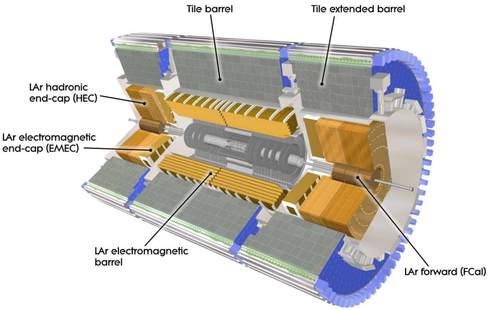
The inner detector $|\eta| < 2.5$ consists of

- Pixel detectors, semi-conductor tracker (SCT), transition radiation tracker
  - $\approx$ 87 million readout channels
  - Immersed in 2T solenoidal magnetic field
- Resolution of $\sigma/p_T = 5 \times 10^{-4} \oplus 0.015$

Muon Spectrometer ($|\eta| < 2.7$)

- 4T Air-core toroids with gas-based muon chambers
  - MDT, CSC for triggering, RPC, TGC for measurement
- Muon measurement with design momentum resolution $\Delta p_T/p_T <$ 10% up to E $\sim$ 1 TeV

ATLAS Calorimeters



Electromagnetic and hadronic calorimeters

- Subsystem technology and granularity $\leftrightarrow$ shower characteristics
- Transverse and longitudinal sampling $\approx$ 200000 readout cells up to $|\eta| < 4.9$

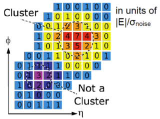
Electromagnetic Calorimeters:

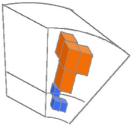
- Fine granularity $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ in central region
- Energy resolution $10\%/\sqrt{E}$

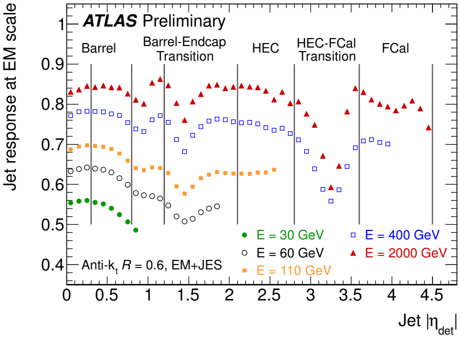
Hadronic Calorimeters:

- Granularity $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in central region, less segmented in forward region
- Energy resolution $50\%/\sqrt{E} \oplus 0.03$

Jet Reconstruction in ATLAS







Transitions between separate calorimeters evident.

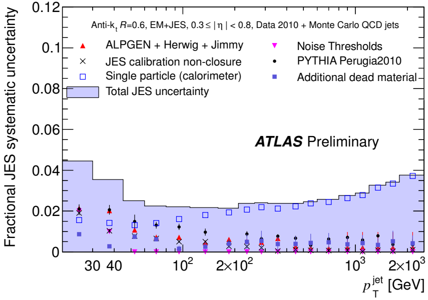
η-dependent jet calib corrects for response diffs in η

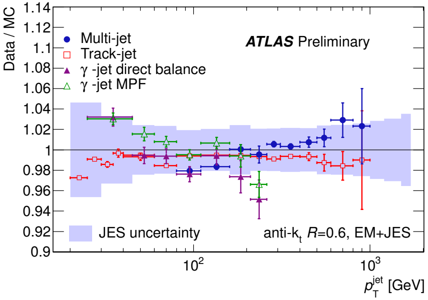
- Clustering seeded with $|E| > 4\sigma$ cells
  - Iteratively adds neighbours with different noise levels (4,2,0 scheme default)
  - Use resulting 3D topological clusters as input to jet clustering algorithm
- Topo cluster masses assumed to be zero
- Jet clustering uses the *AntiKt* algorithm with $R = 0.6$

Jet Energy Calibration

Jet measurements require calibration of the jet energy

- Derives a calibration which restore average JES with (η, E)-dependent calibration constants from MC
- Validated using *in-situ* techniques using γ-jet, track-jets, multi-jet events

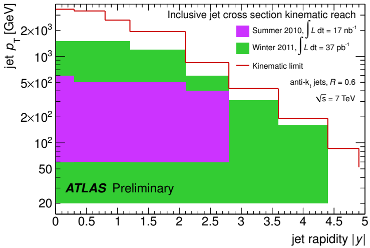


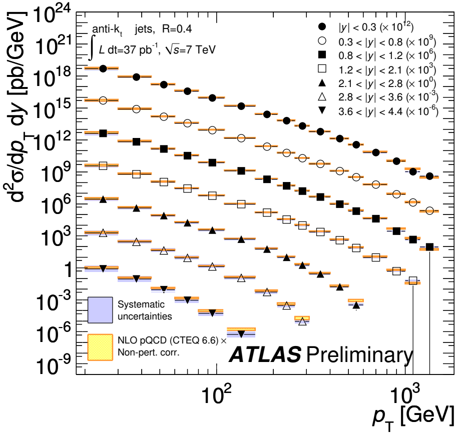


Inclusive jet cross section

ATLAS-CONF-2011-047

Using 37 pb^{-1} pb of data, increasing the kinematic range of previous measurements

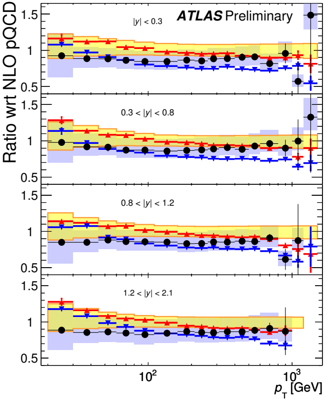


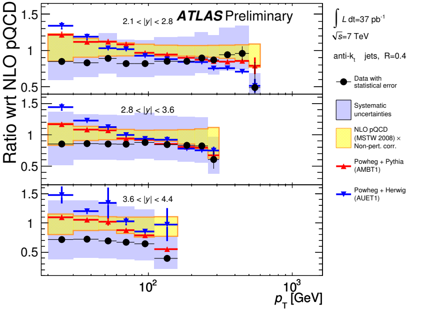


- Cross section out to $|y| < 4.4$
- p_T up to 1.5 TeV

Comparison of data to NLO pQCD predictions with CTEQ 6.6.

Inclusive jet cross section





Prediction w.r.t NLOJet++ MC

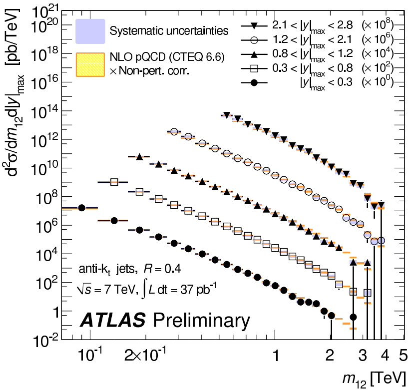
$AMBT1$, $AUET1$ are different detector tunes

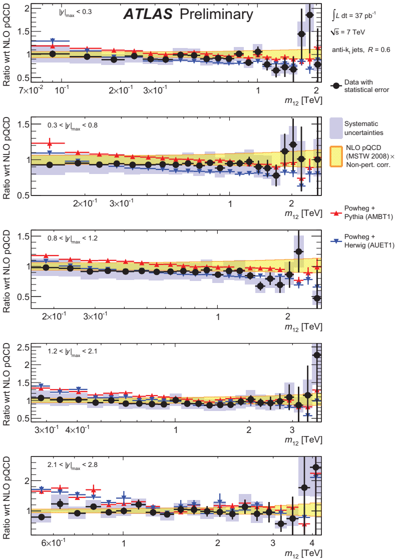
Powheg predictions are consistent with data and NLOJet++, with present uncertainties

Trend for Powheg to predict different slope to cross section

DIJET CROSS SECTION

$R = 0.4$





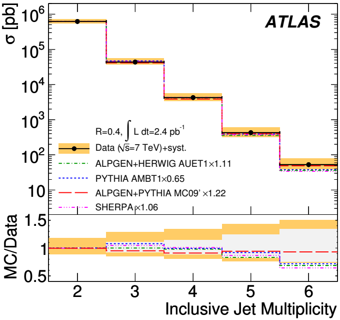
Observing masses up to 4.1 TeV, new energy range!

Powheg systematically predicts higher cross sections at low mass, and lower prediction at high mass, than NLOJet++

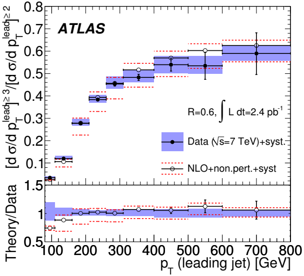
Multijet cross section

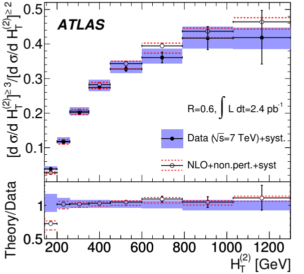
CERN-PH-EP-2011-098,
hep-ex/arXiv:1107.2092,
Submitted to EurPhysJ C

Fundamental and direct test of QCD



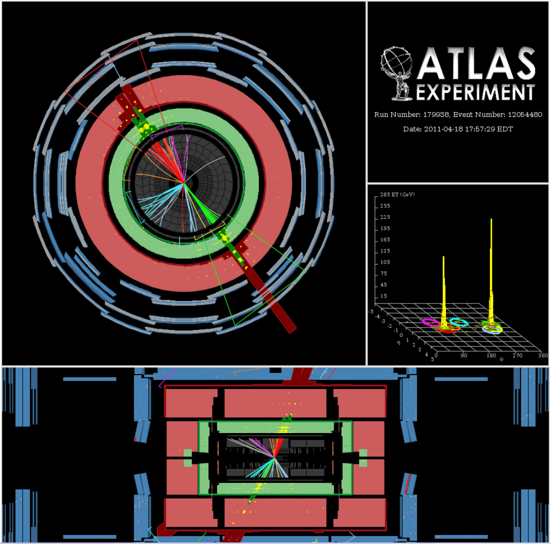
Find ALPGEN better describes data





ATLAS High Mass Dijet Event

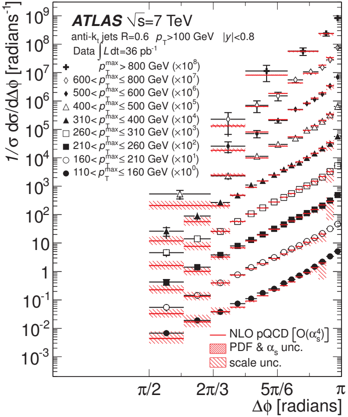
2011 data event with dijet mass of 4040 GeV

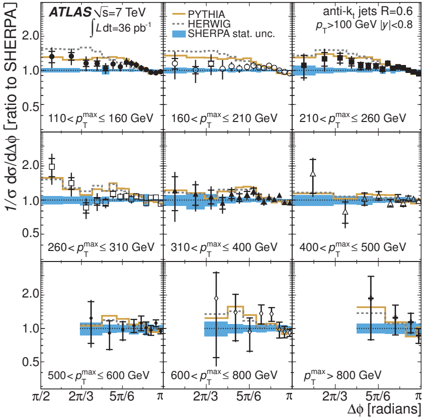


Dijet Azimuthal Decorrelation

CERN-PH-EP-2011, Submitted to PRL

Testing pQCD for multijet production without measuring additional jets

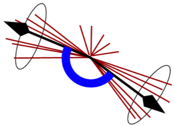




Ratio of data to PYTHIA, HERWIG, SHERPA

All describe data, SHERPA does best, expected result as SHERPA explicitly includes higher-order tree level diagrams

Dijet with Jet Veto



CERN-PH-EP-2011-100, Submission to JHEP

Rapidity gap measurement, no color flow between jets

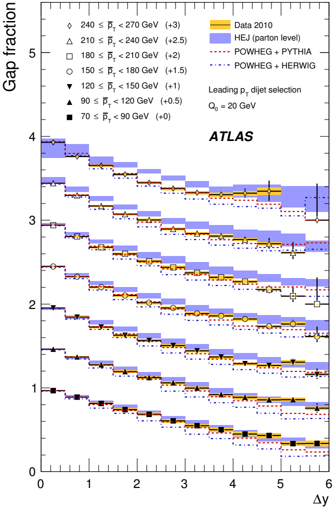
$f_{gap} = N_{passGapVeto}/N_{all}$

POWHEG + PYTHIA Generally agree with data

HEJ Agreement better in some places than others

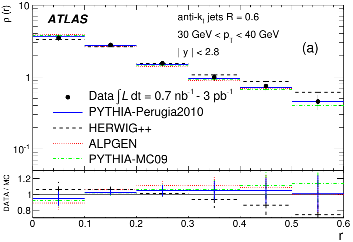
Quick theory reaction R.M. Duran Delgado at al, arXiv:1107.2084:

"The message is clear: the accuracy of the ATLAS data already demands better theoretical calculations"



Jet Substructure, Shapes

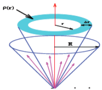
ATL-PHYS-PUB-2011-010, Phys. Rev. D 83, 052003 (2011)



Differential jet shape

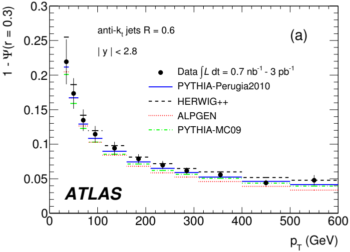
$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N_{jet}}\Sigma_{jets}\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)}$$

Differential jet shape demonstrates clear jet-like structure. Data/MC shows different levels of agreement, but no clear outliers

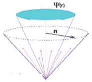


Integral jet shape

$$\Psi(r) = \frac{1}{N_{jet}}\Sigma_{jet}\frac{p_T(0,r)}{p_T(0,R)}$$



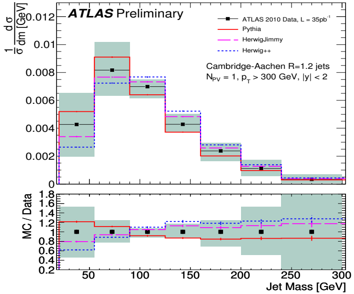
Integral jet shape shows an underestimate of the amount of soft, wide-angle contributions to the jet by PYTHIA, ALPGEN. Herwig overestimates.

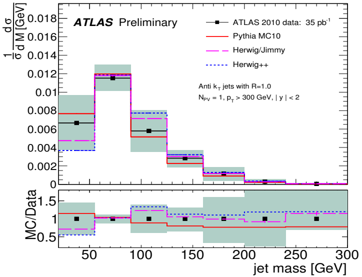


Jet Substructure, "Fat" Jets

ATLAS-CONF-2011-073

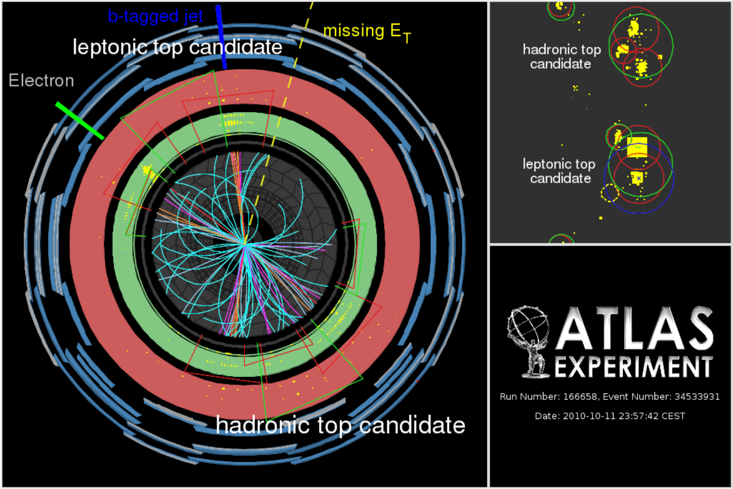
- Jets are both complete 4-vectors and complex composite objects.
- At LHC, decays of t, W, H, etc decays can be collimated into a jet
- Knowledge of the internal jet substructure is important in distinguishing these decays from gluon or light-quark initiated jets
- Jet mass encodes information about both the parton shower and the potential presence of heavy particle decays within the jet.





Jet mass is unfolded to the particle level to correct for detector effects.

Candidate Boosted Top Decay

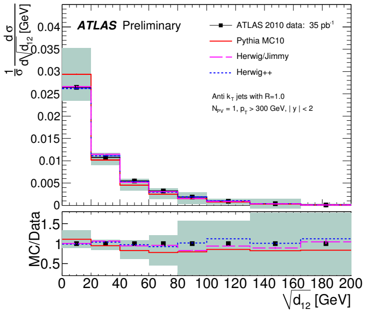


Jet Substructure, "Fat" Jets

ATLAS-CONF-2011-073

$$\sqrt{d_{1,2}} = min(p_T^1, p_T^2)\delta R_{1,2},$$
$$\delta R_{1,2} = \sqrt{{d\phi_{1,2}}^2 + {dy_{1,2}}^2}$$

- Splitting scale is threshold at which jets can be broken into sub-components, structure starts to form
- Expected to be different for hadronic jets and boosted signal (V, t, etc.)
  - Heavy particle decays expected to be reasonably symmetric
  - QCD splittings generally asymmetric

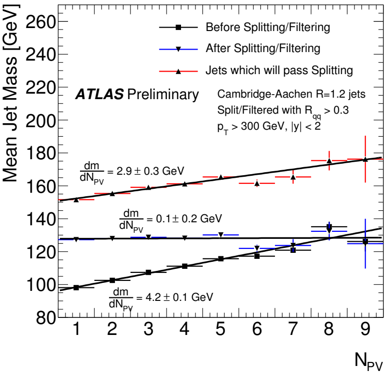


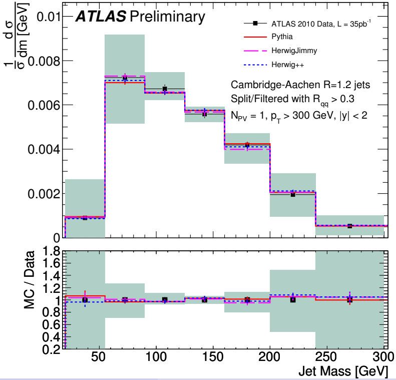
- Corrected to particle level for detector effects
- Data well predicted by MC+detector simulation

Jet Substructure, “Fat” Jets

ATLAS-CONF-2011-073

- Currently work ongoing in $H \to b\bar{b}$ channel, studying jet structure, ways to distinguish H decay from QCD
- By applying the jet filtering algorithm generator differences are reduced and impact of pile-up is removed.
- Data/MC agreement very good after filtering





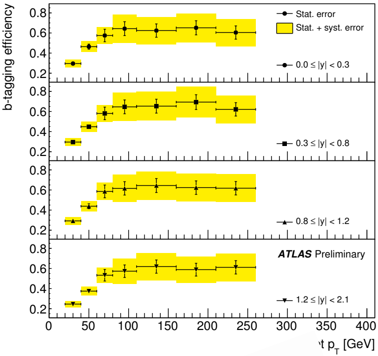
b-jet Cross Section

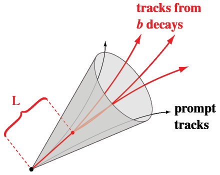
b-jet tagger "SV0"

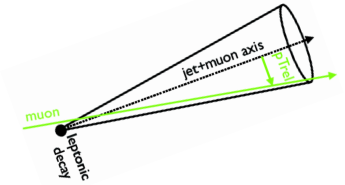
- Iterative secondary vertex seeding from track pairs
- separation power from decay length significance

Also tag b-jets with muon decay

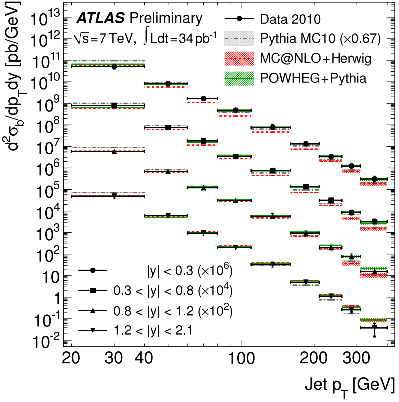
- Determine the relative distance between jet axis and muon
- Fit templates for b-jet contribution

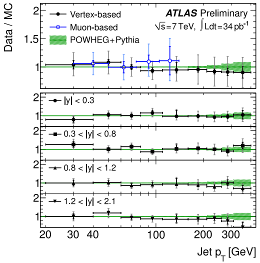


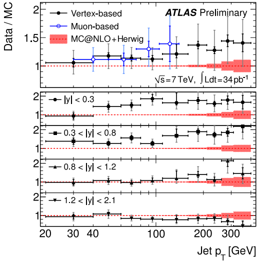




b-jet Cross Section

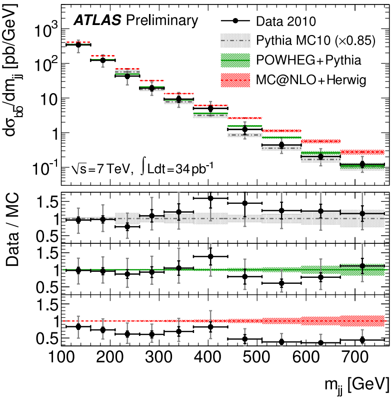




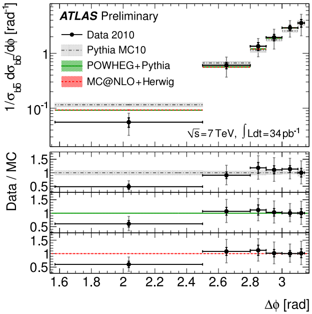


- Good agreement with Powheg+PYTHIA
- MC@NLO+Herwig predicts too few central jets, too many forward jets

Inclusive $b\bar{b}$ Jet Cross Section



- PYTHIA MC10 and Powheg show good agreement
- MC@NLO does not model the data, especially at high dijet mass



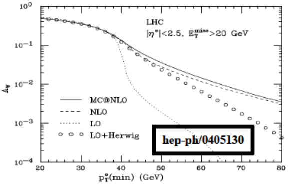
W and Z Production

Precision studies of W and Z production at LHC serve several purposes:

- Important to re-establish the standard model
- Understand main backgrounds to searches for new physics, Higgs sector

Although these points are often quoted and true, they ignore the reasons why W and Z are important in their own right

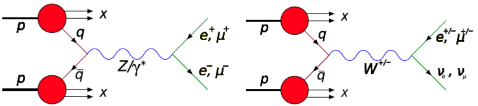
- Leptonic decay channels are among the cleanest final states that we can exploit at hadron colliders
- Higher order QCD corrections modify the cross sections by 30-40% and have a visible effect on kinematics.
- Experimentally able to test new tools available:



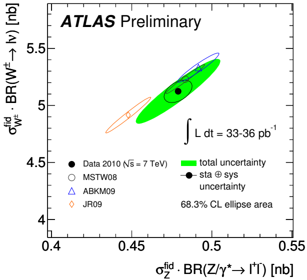
- NLO QCD MC generators (MC@NLO, POWHEG,)
- LO-matched multi-jet generators (ALPGEN, MADGRAPH, SHERPA), which will become NLO-matched in the near future.
- NNLO Drell Yan predictions with FEWZ, DYNNLO

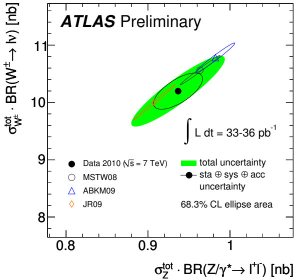
W and Z Cross Sections

ATLAS-CONF-2011-041



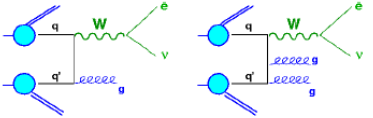
- **Fiducial cross section** corrected for efficiency factor, adjusted to data/MC differences
  - Comparing the fiducial region disentangles theor. and exp. effects
  - Provides most precise comparison with theory
- **Total cross section** corrected for acceptance based on MC
  - Comparing total cross sections, acceptance uncertainty accounts for effects of different PDFs on unmeasured phase space



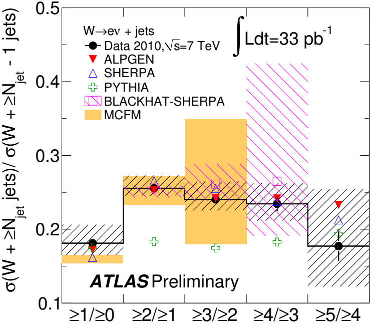


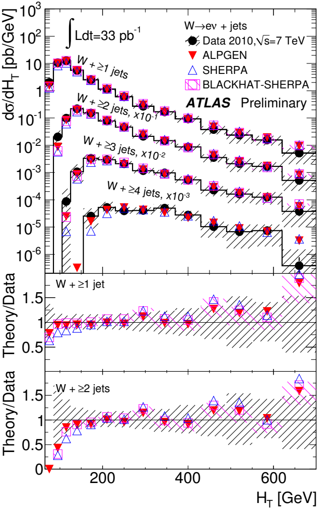
W+jets Production

ATLAS-CONF-2011-060



W+jets, sensitive to pQCD predictions

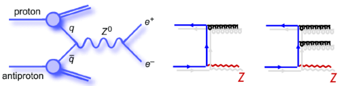


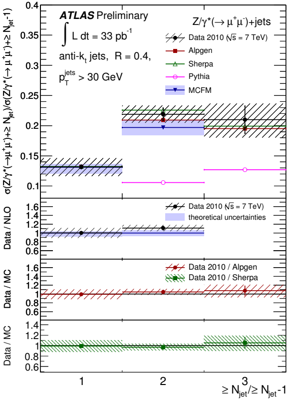


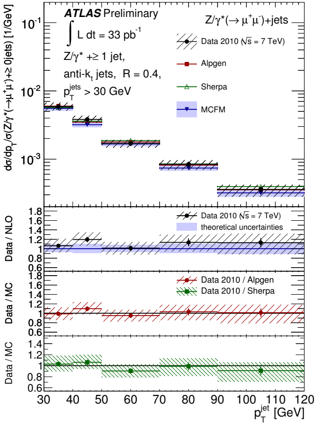
H_T is a common choice for factorization and renormalization scale, important variable

Z+jets Production

ATLAS-CONF-2011-042







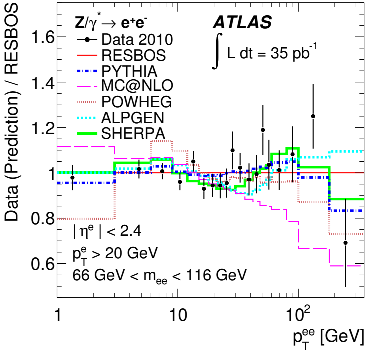
Good agreement with matched LO prediction from ALPGEN and Sherpa.

Poor agreement with LO PYTHIA at high jet multiplicity

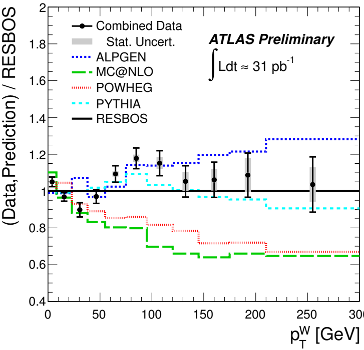
W and Z p_T

The measurement of the boson p_T is sensitive to dynamic effects of strong interaction, complementary to associated production of bosons with jets.

CERN-PH-EP-2011-095



Resbos shows good agreement with data, indicating importance of resummation.



For $p_T^W > 120$ GeV Pythia and Resbos agree in predicting a softer spectrum than Alpgen and Sherpa

First corrected p_T^W measurement, precision comparable to p_T^Z

Summary

- As promised, the LHC era has allowed us to test QCD in new kinematic regimes, good testing ground for predictions.
- Already ATLAS data is able to discriminate between different MC predictions.
  - Theorists are eager to compare predictions against our data, and are writing papers about our data!
- Breaking new ground in techniques to identify boosted final states.
- There is LOTS more data to analyse, more to learn.
- Looking forward to fruitful interactions between the theory and experimental viewpoints
- Exciting times are upon us!

Additional Material

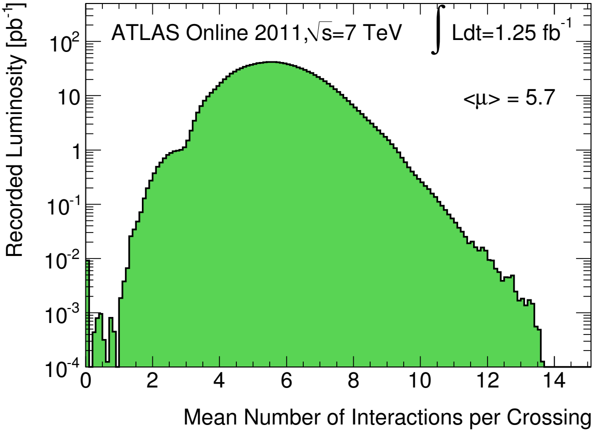
A word on simulation

Jet production is the most common process at the LHC, and leads to an enormous number of diagrams at higher orders.

- LO generators like Pythia and Herwig have $2 \to 2$ process at matrix element, plus some leading logs terms to match with parton shower.
- A full NLO calculation for $2 \to 2$ and $2 \to 3$ parton processes available with NLO++, but no matching with PS. Partons are however clustered into jets, then soft corrections coming from unfolding
- ALPGEN contains $2 \to n$ LO matrix elements, so it should be well-suited for multiple final states
- POWHEG box now includes 2 parton final states at NLO, with matching to both Pythia and Herwig PS.
- HEJ is a new fully-resummed MonteCarlo for wide-angle emission of similar momentum partons. Recently interfaced to ARIADNE + Pythia, just used at parton level here

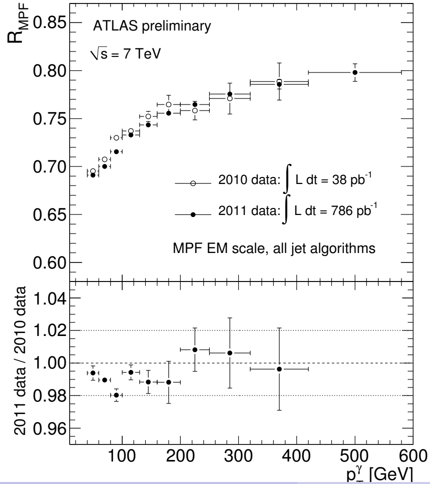
Pileup in 2011 data

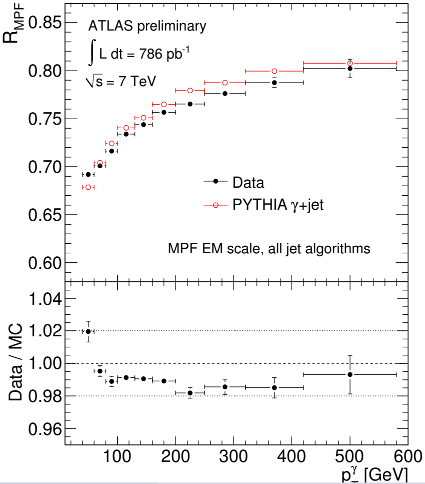
Mean number of interactions per bunch crossing in 2011 data run



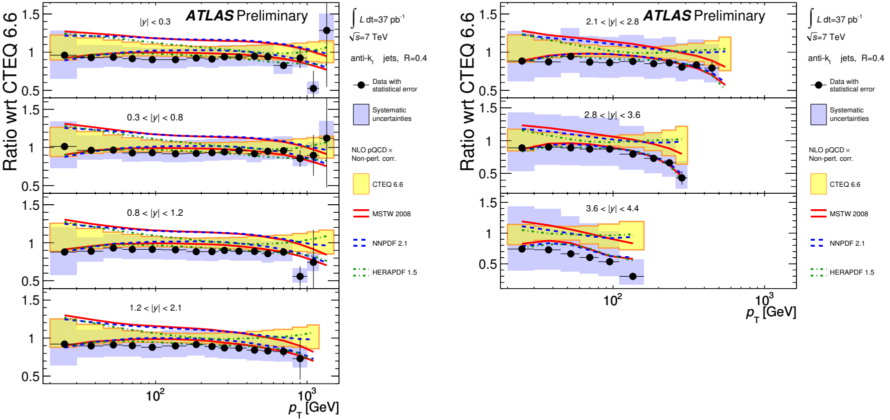
In-situ Jet Calibration with 2011 data

In 2011 with additional event activity (pileup) the jet calibration using the MPF technique appears robust





Inclusive jet cross section - PDF variation

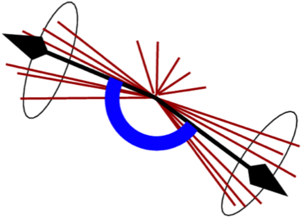


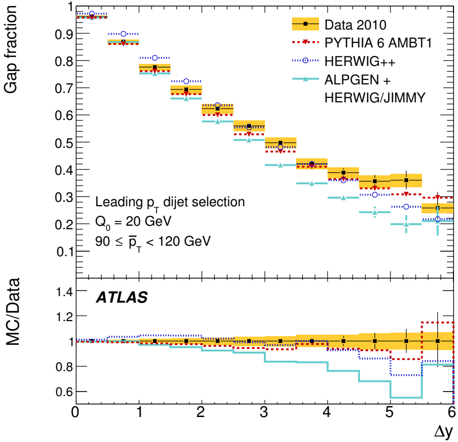
Ratio of inclusive jet cross section measurement in data and MC, with various PDFs

Dijet with Jet Veto

CERN-PH-EP-2011-100, Submission to JHEP

- Historically measurement has been a search for colour singlet exchange
- Increased c.m. energy of LHC
- Testing ground for experimental techniques to search for VBF Higgs





Gap fraction= (# events passing the Gap veto) / (all events)

Dijet with Jet Veto

POWHEG + PYTHIA

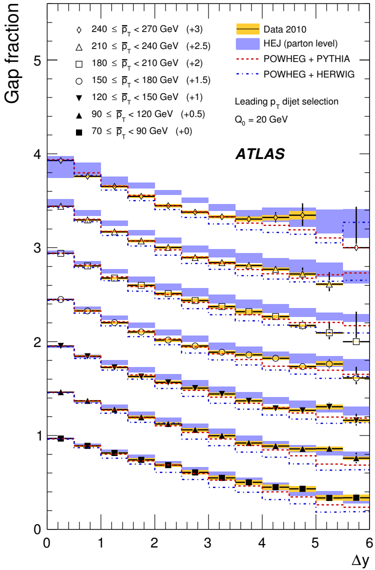
Generally agree with data

HEJ

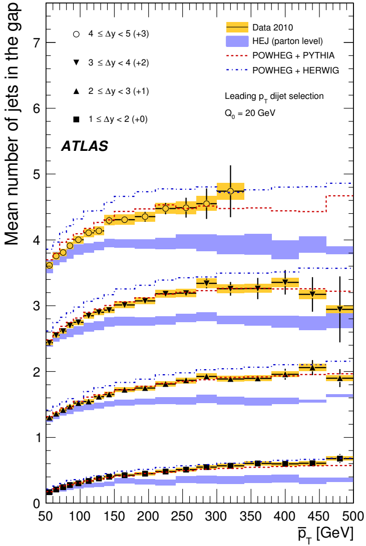
Agreement better in some places than others

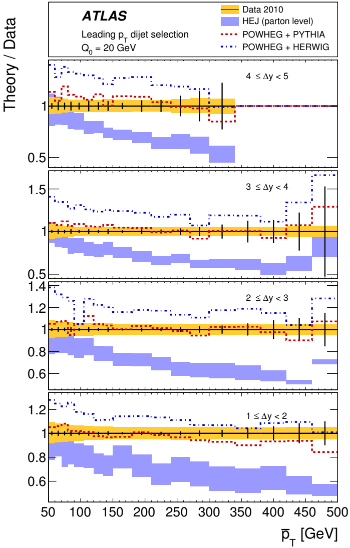
Quick theory reaction R.M. Duran Delgado at al, arXiv:1107.2084:

"The message is clear: the accuracy of the ATLAS data already demands better theoretical calculations"



Dijet with Jet Veto

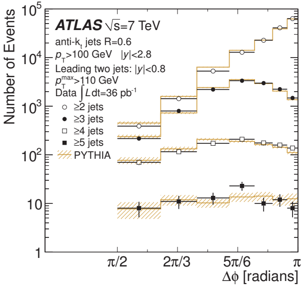




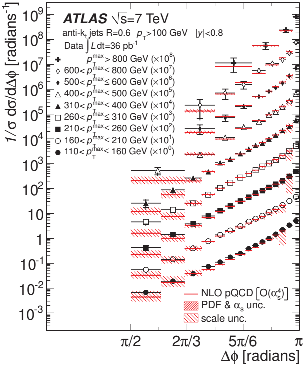
Dijet Azimuthal Decorrelation

CERN-PH-EP-2011, Submitted to PRL

Testing pQCD for multijet production without measuring additional jets

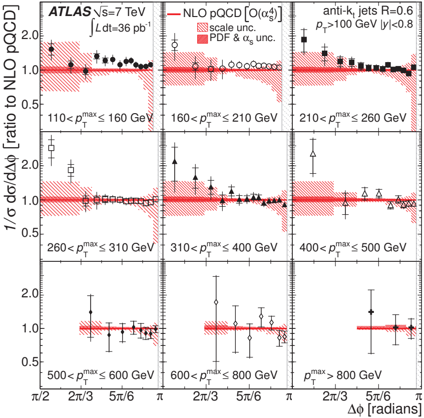


Decorrelation increases when additional jets are required

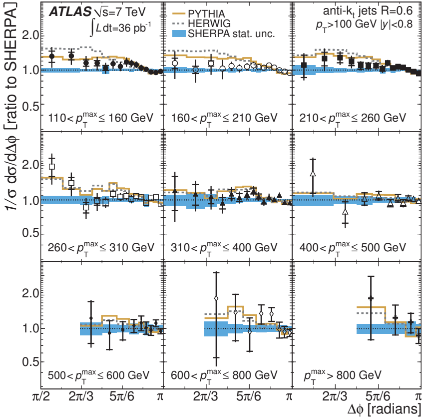


Differential cross section in data and NLO pQCD (NLOJET++, MSTW 2008 PDF)

Dijet Azimuthal Decorrelation



Ratio of data to NLO pQCD
Theory consistent with data

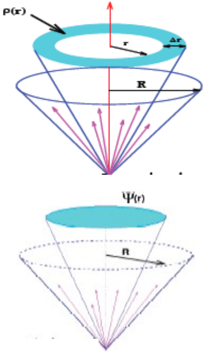


Ratio of data to PYTHIA, HERWIG, SHERPA
All describe data, SHERPA does best

Jet Substructure

ATL-PHYS-PUB-2011-010

- Jets are both complete 4-vectors and complex composite objects.
- At LHC energy decays of top, W, etc decays can be collimated into one jet
- Knowledge of the internal jet substructure is important in distinguishing these decays from gluon or quark initiated jets
- Internal structure of energetic jets is mainly dictated by emission of multiple gluons from primary parton
    - Calculable in pQCD



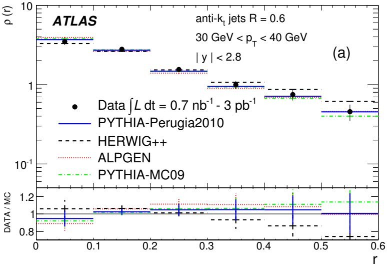
Differential jet shape

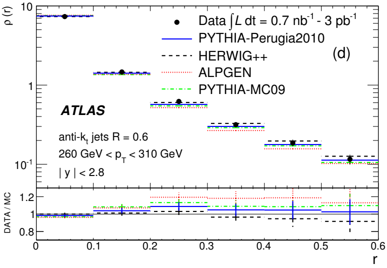
$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N_{jet}}\Sigma_{jets}\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)}, \Delta r/2 \le r \le R - \Delta r/2 \qquad (1)$$

Integral jet shape

$$\Psi(r) = \frac{1}{N_{jet}}\Sigma_{jet}\frac{p_T(0,r)}{p_T(0,R)}, 0 \le r \le R \qquad (2)$$

Jet Substructure

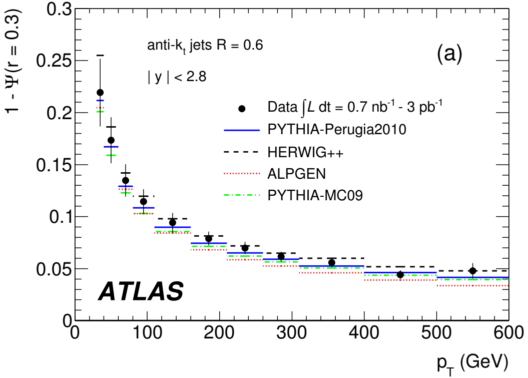




Differential jet shapes vs jet p_T, integrated over $|y| < 2.8$

- As expected, jet narrows with increasing p_T
- Data compared to various MC predictions
  - PYTHIA-Perugia2010
  - PYTHIA-MC09
  - Herwig++
  - Alpgen (with Herwig+Jimmy)
- General agreement, although Herwig++ predicts jets too narrow

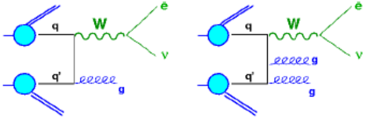
Jet Substructure



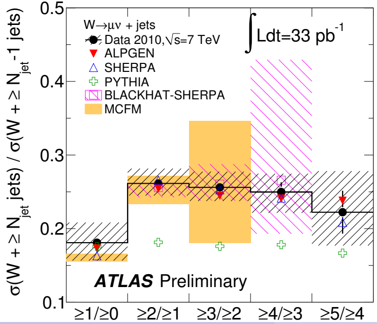
- PYTHIA-Perugia 2010 provides reasonable description of data
- Herwig++ broader than data
- Alpgen predictions too narrow at high p_T
- PYTHIA-MC09 produces jets which are too narrow in the whole kinematic range (possibly due to soft QCD mismodeling)

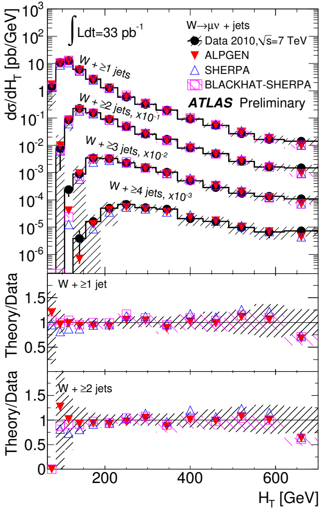
W+jets Production, muon channel

ATLAS-CONF-2011-060



W+jets, sensitive to pQCD predictions

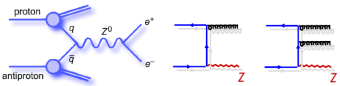


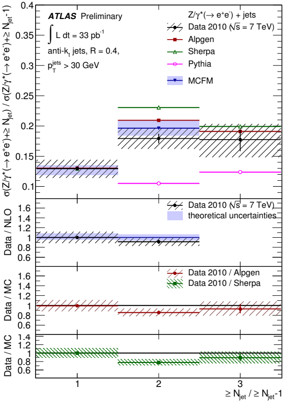


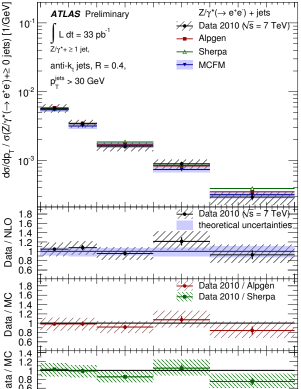
H_T is a common choice for factorization and renormalization scale, important variable

Z+jets Production, muon channel

ATLAS-CONF-2011-042







Good agreement with matched LO prediction from ALPGEN and Sherpa.

Poor agreement with LO PYTHIA at high jet multiplicity