RECENT HARD QCD RESULTS FROM ATLAS

Mathieu Plamondon
on behalf of the ATLAS Collaboration

University of Victoria

PLHC 2011
Physics at LHC 2011
June 6 - 11th, 2011
Congress Center GIO, PERUGIA (Italy)

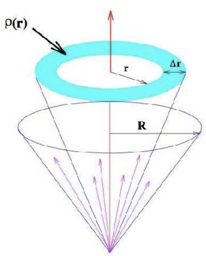
Hard QCD in ATLAS

Hard QCD is the physics of high-p_T jets

Why study this in ATLAS?
- Test pQCD in still unexplored phase space regions

→ in depth probes of α_S and PDFs
- Is a dominant background to searches for new physics (MC tuning needed)

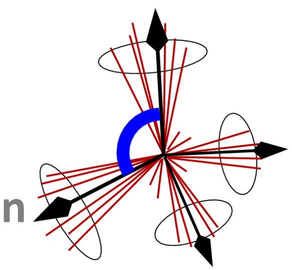
Many observables…



Jet shapes

W/Z + jets

Angular decorrelation



Jet substructure

HARD QCD

Many cross sections…

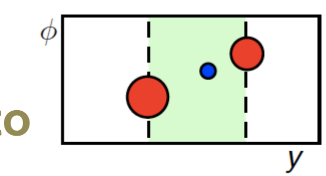
Multi-jets

Inclusive

Prompt photons

Dijets

with jets veto



with b-jets

ATLAS Calorimeters and Inner detectors

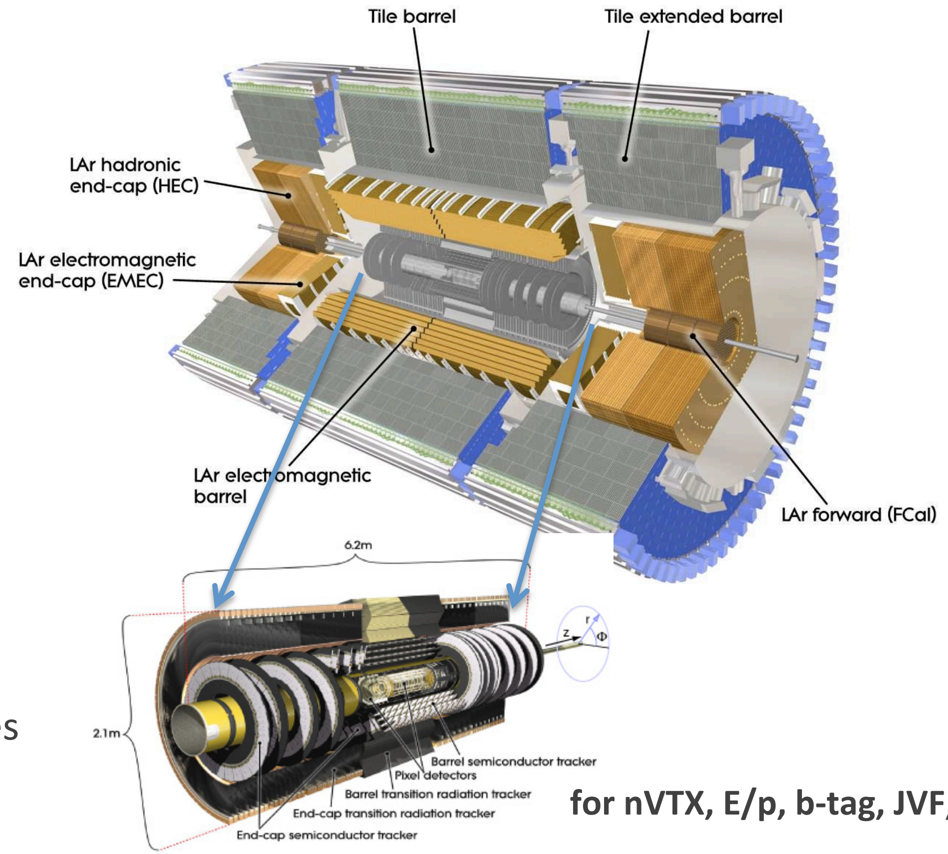
Sampling Calorimeters

- High granularity
- Longitudinal segmentation (3-4)
- Non-compensating
  (jet calibration performed offline)
- Coverage

EM: LAr(act.) / Pb(abs.)
$|\eta| < 1.475$ (barrel)
$1.375 < |\eta| < 3.2$ (endcap)

HAD
Barrel region $|\eta|<1.4$:
Organic scintillator(act.) / steel(abs.) tiles
Endcap region $1.4<|\eta|<3.2$: LAr/Cu

FORWARD
$3.2<|\eta|<5.0$
LAr/Cu (EM) and LAr/W (HAD)



for nVTX, E/p, b-tag, JVF,…

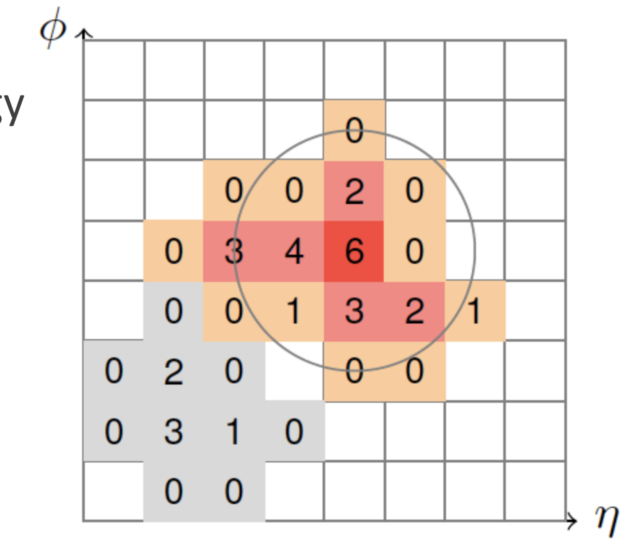
Inner Detector

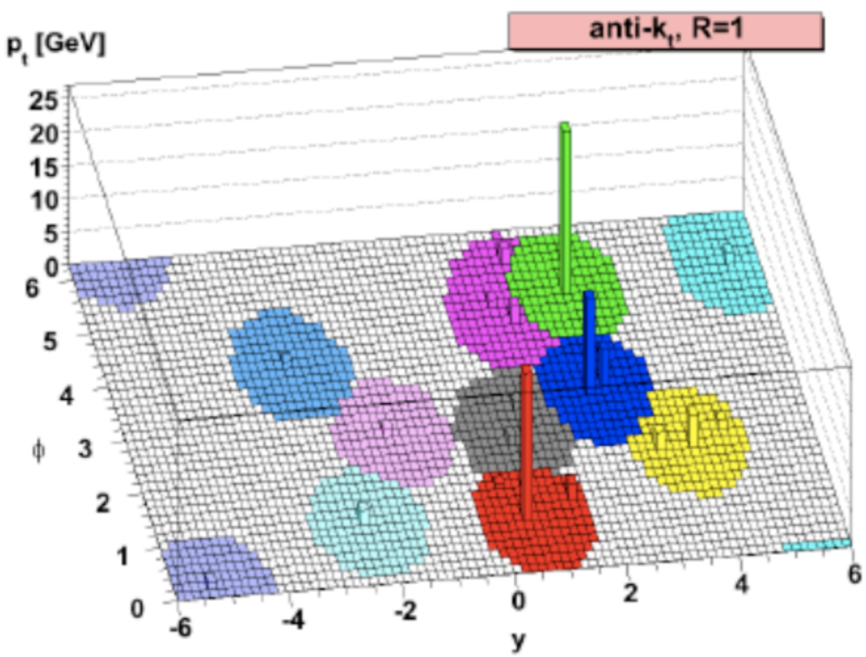
Pixel detectors, semiconductor tracker (SCT), transition radiation tracker (TRT)
87M readout channels, coverage up to $\eta = 2.5$
Immersed in 2T solenoidal magnetic field

Jet Reconstruction

Jets built from 3-D topological clusters

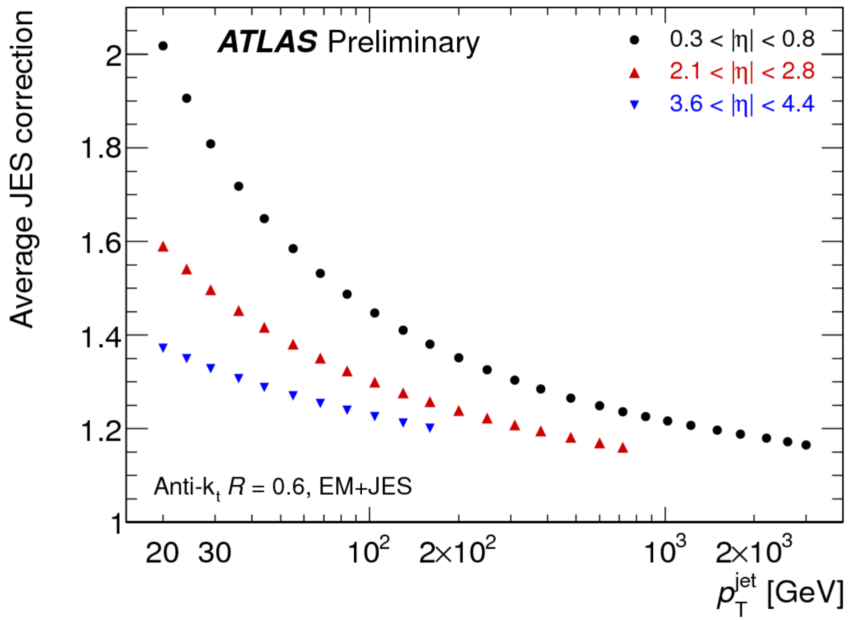
1. Start with a seed cell which has the highest energy deposit among its neighbors and |E|>4σ
2. Add neighboring cells with |E|>2σ
3. Add all adjacent cells with |E|>0



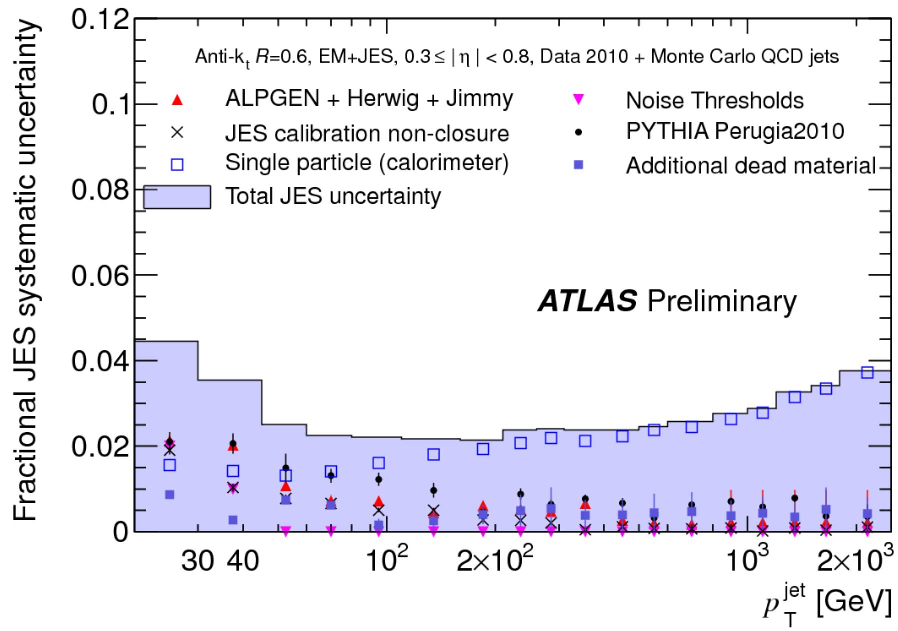


Jet reconstruction: combine the clusters's 4-momentum using the anti-kt algorithm with parameter R = 0.4, **0.6** or 1.0

Jet energy scale



- Calorimeter response corrected for inactive material, out-of-cone and leakage effects, non-compensation and pile-up
- EM+JES calibration scheme (default) apply MC-based corrections as a function of the jet energy and η

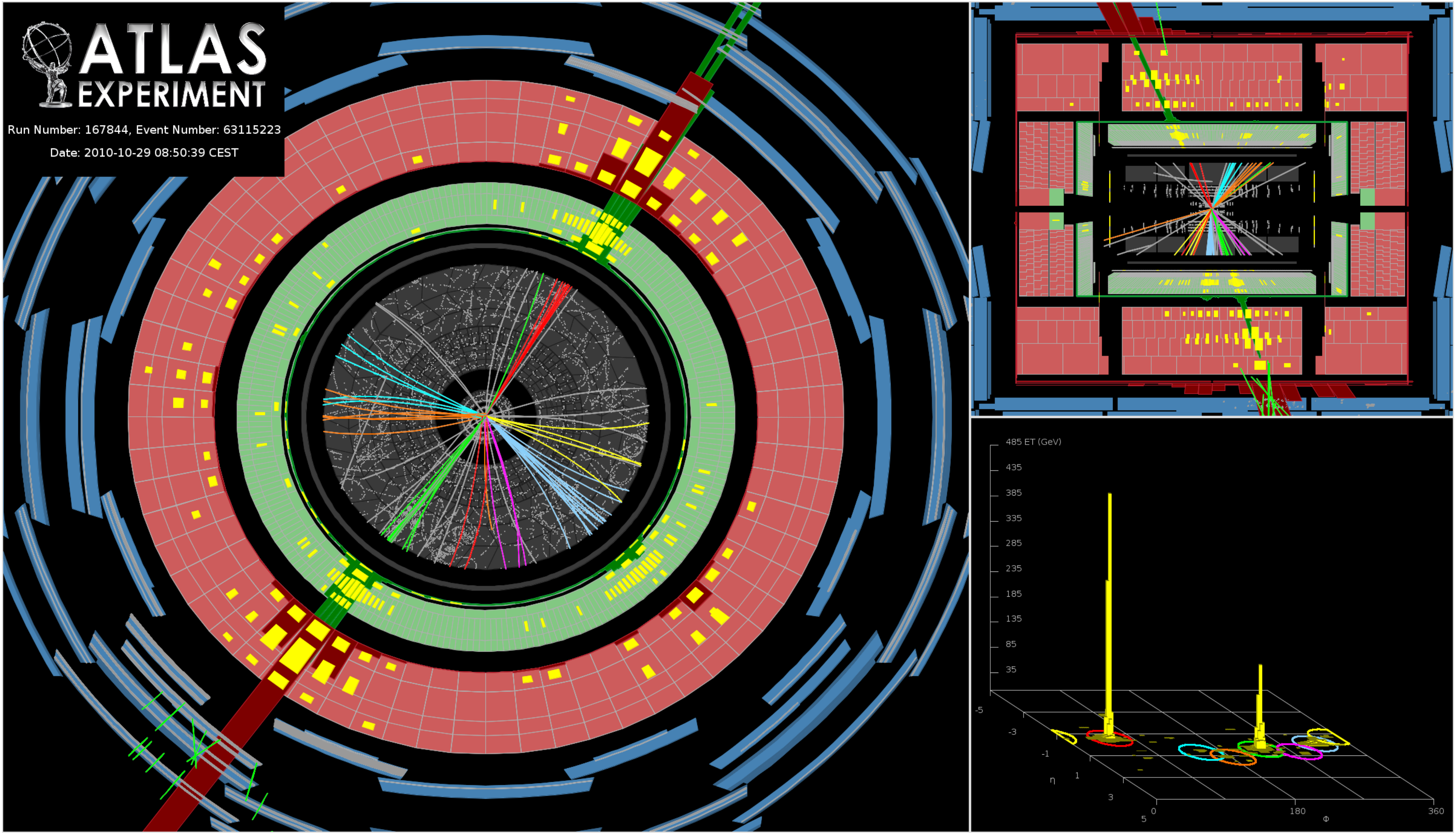


Uncertainties

- 2.5% for ≈100 GeV central jets
- dominated by shower shape description at high p_T
- determined from test-beam, in-situ data measurements and MC simulations

ATLAS-CONF-2011-032

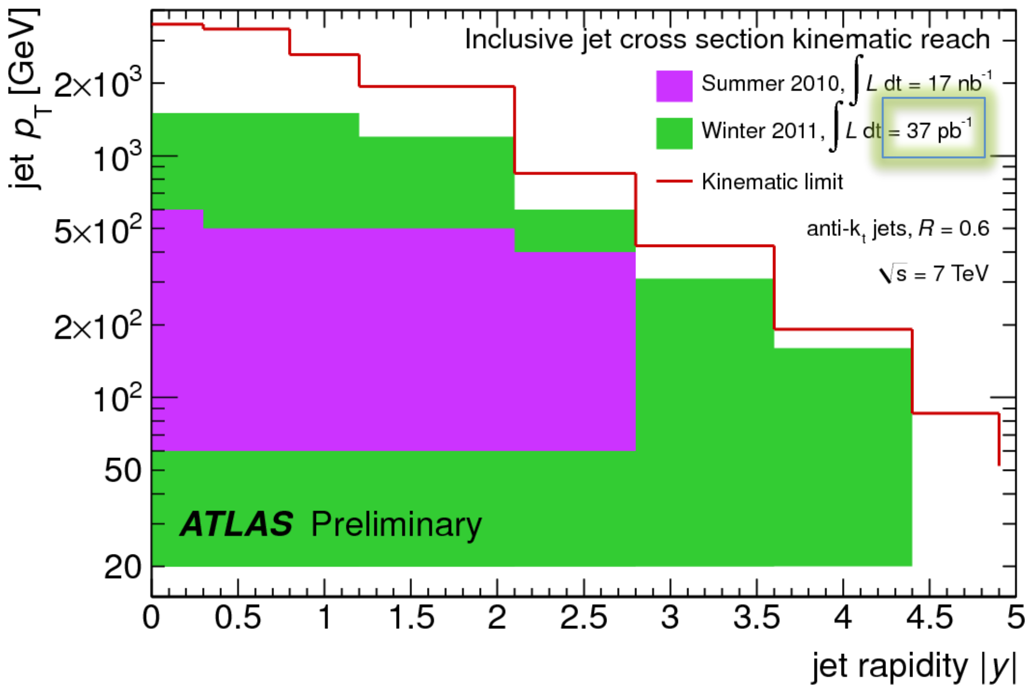
Jet cross sections



Highest-p_T jet collected in 2010: 1.5 TeV

Jet cross sections: highlights

With just 10 pb^{-1} of data, the reach in jet transverse momentum at the LHC is twice that obtained by other collider experiments



Kinematic range of the inclusive jet cross section measured in this analysis compared to that of the previous study

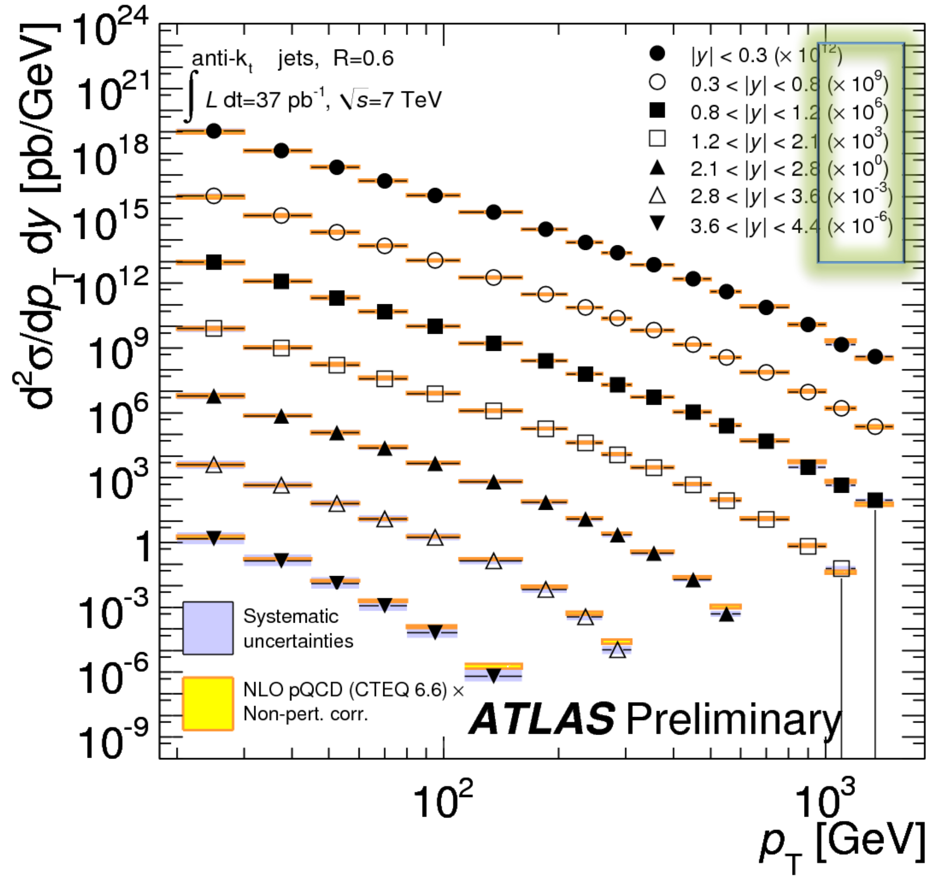
Forward jet measurements at the LHC cover a phase space region that is currently largely unexplored, out to **|y| = 4.4**

- Uncertainty on the collected luminosity is reduced from 11% to **3.4%**
- Improved understanding of the detector performance has reduced several systematics (JES)
- Compare data with recently available **NLOJET++** predictions

More details in Felix Mueller's talk Jet production measurement with the ATLAS detector

ATLAS-CONF-2011-047

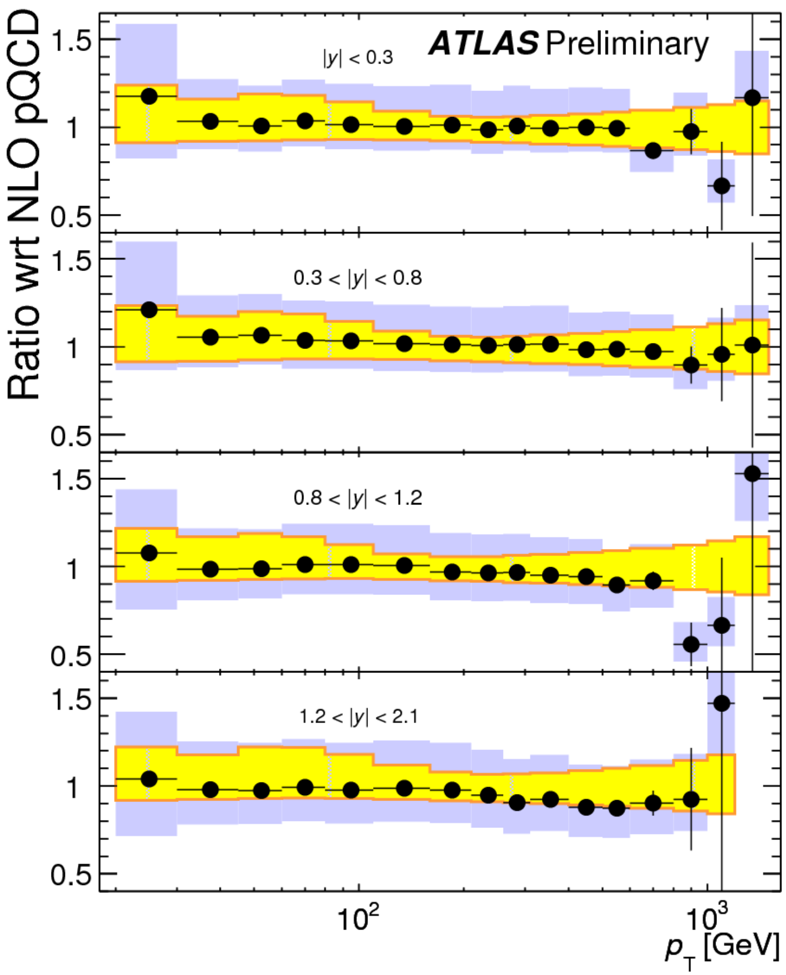
Inclusive jet cross section

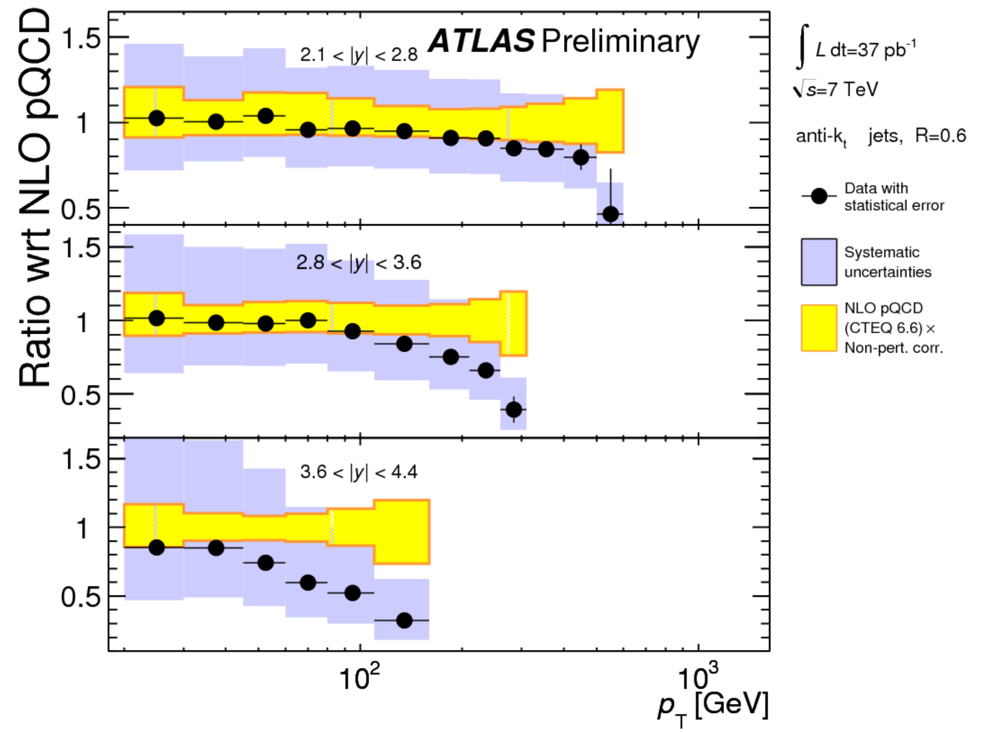


Spanning 2 orders of magnitude in p_T , 7-9 orders of magnitude in cross section!
For data points: Pythia-derived bin-by-bin unfolding with uncertainties from spectrum shape and measurement resolution

ATLAS-CONF-2011-047

Inclusive jet cross section





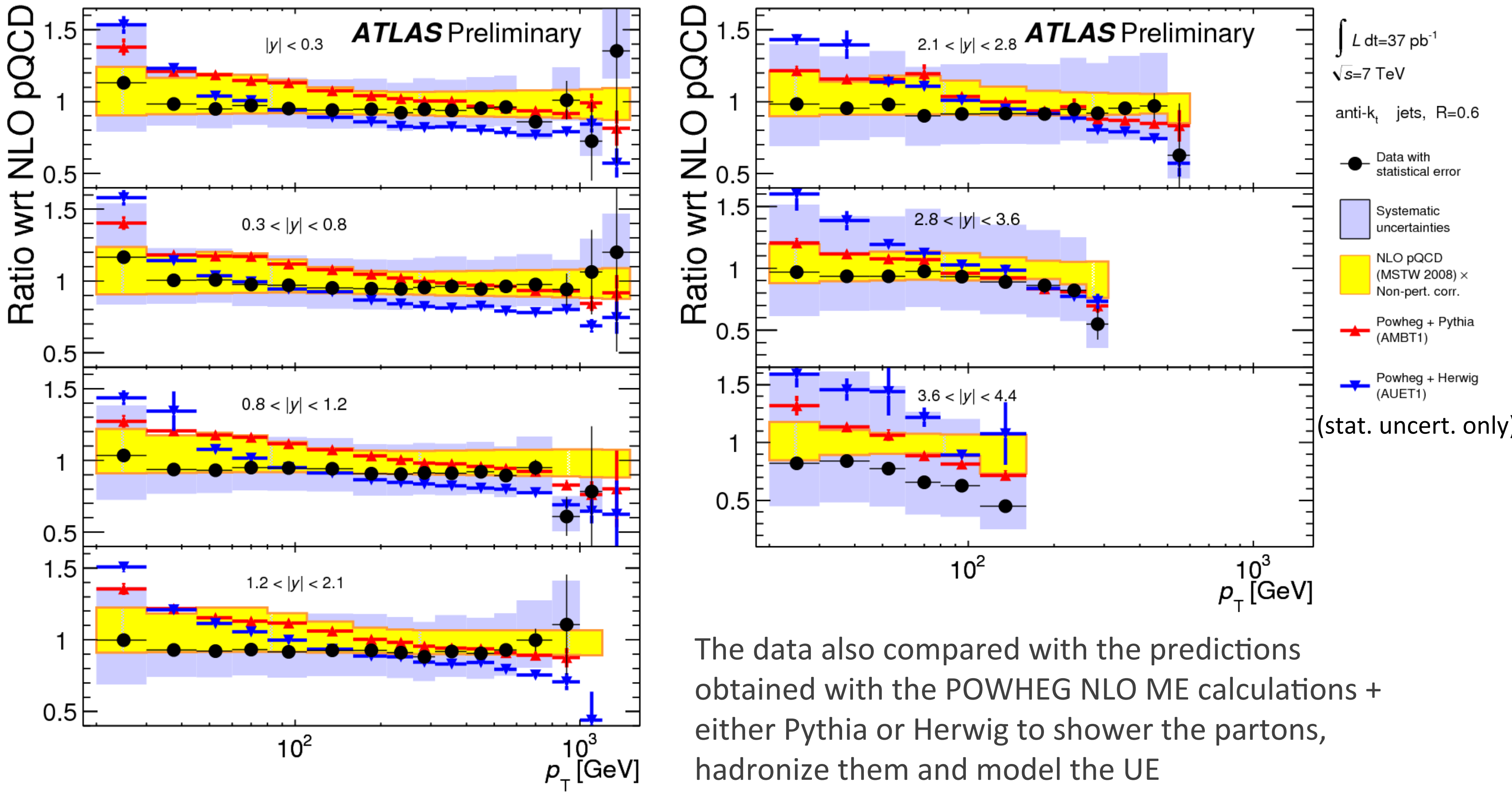
data and theory predictions of NLOJET++ with non-perturbative corrections in reasonable agreement within the experimental and theoretical uncertainties

some differences observed at high p_T and large |y|

NLO prediction: theoretical uncertainty shown includes contributions from scales, PDFs, α_s and non-perturbative effects

ATLAS-CONF-2011-047

Inclusive jet cross section



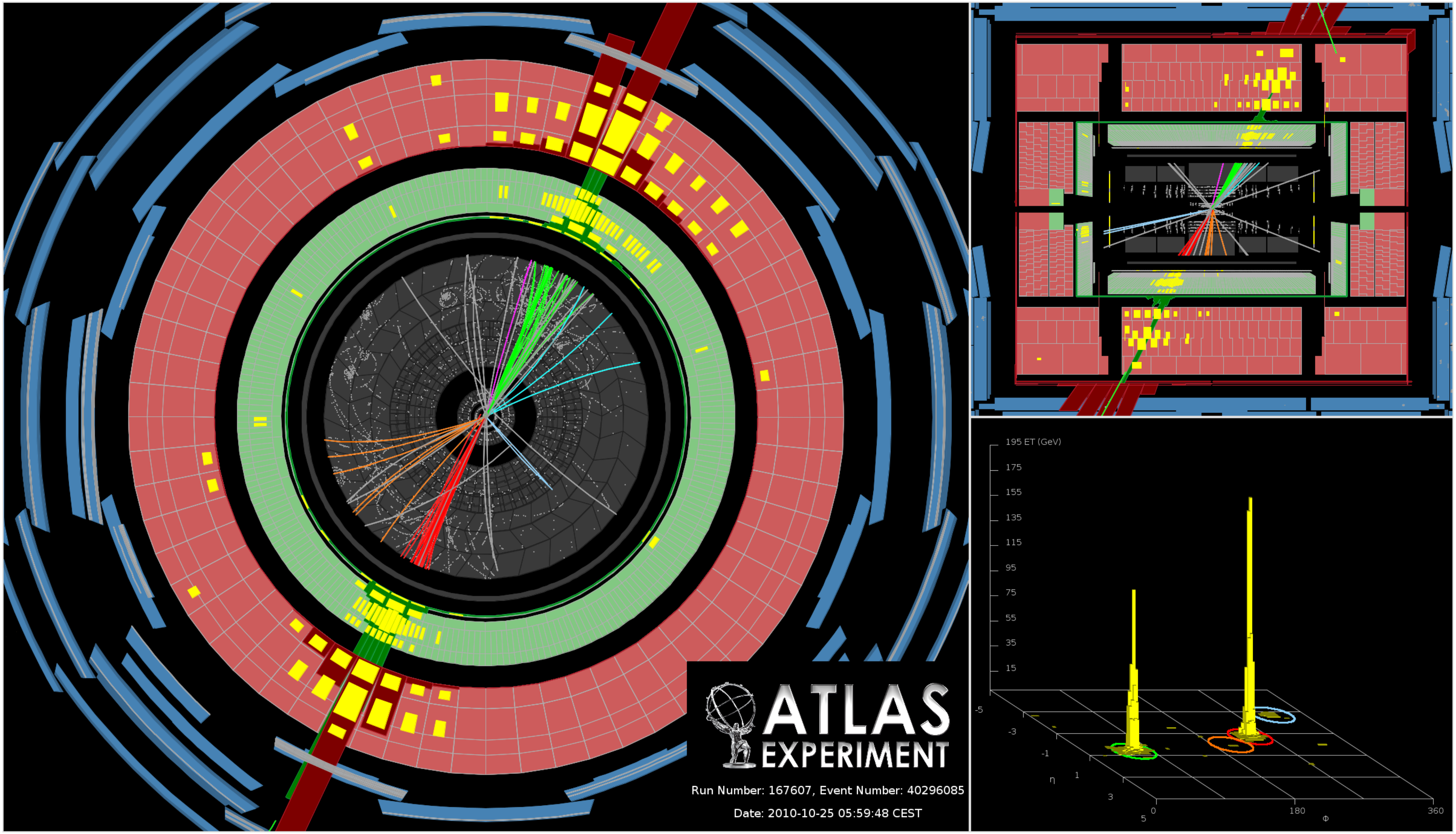
The data also compared with the predictions obtained with the POWHEG NLO ME calculations + either Pythia or Herwig to shower the partons, hadronize them and model the UE

Within the present uncertainties, the POWHEG predictions are consistent with the data and NLOJET++ but:

- Low p_T: trend to predict larger cross sections
- High p_T: predict smaller cross sections than NLOJET++ (but closer to the data)

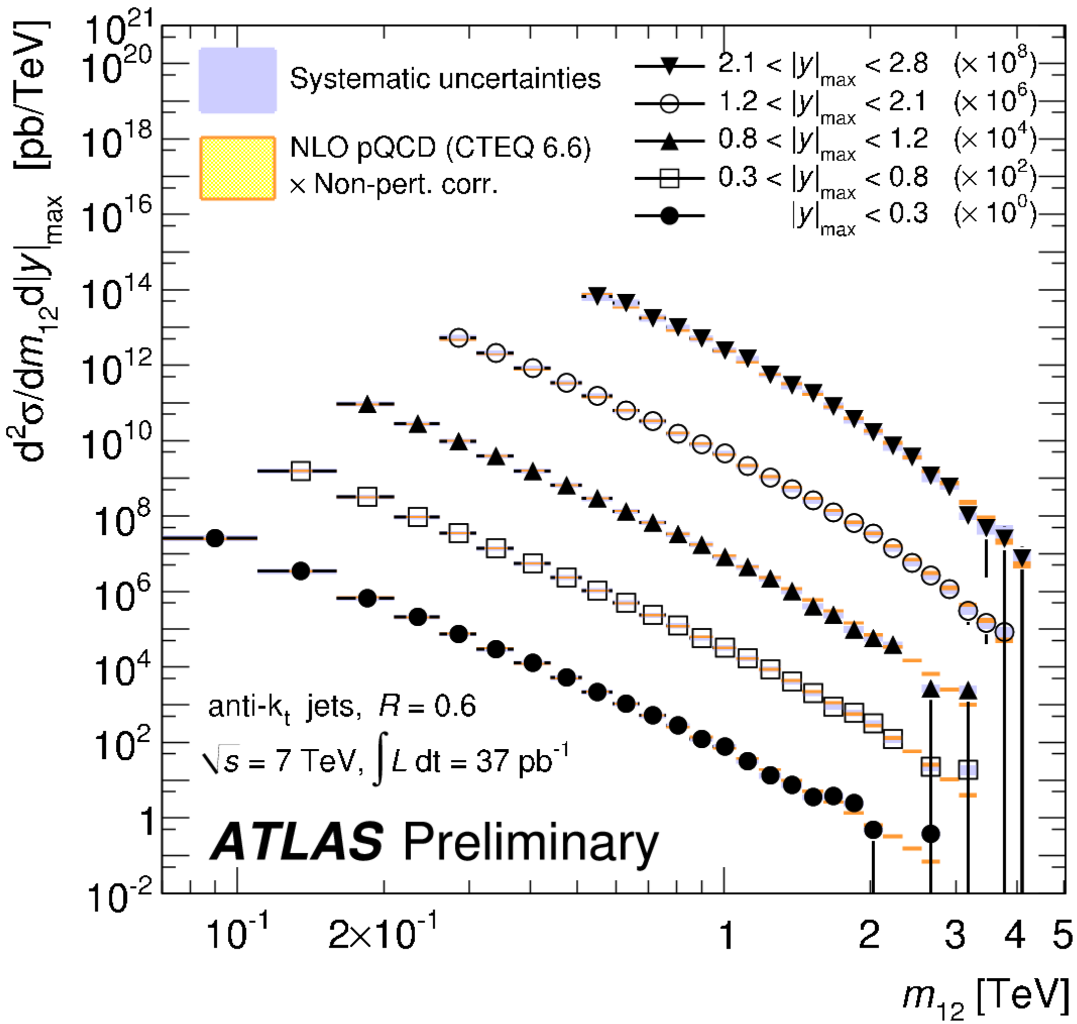
ATLAS-CONF-2011-047

Dijets cross sections



Highest-mass (3.1TeV) central dijet event collected in 2010

Dijets cross section



Measured as a function of the dijet invariant mass m_{12} for various bins of the maximum rapidity $|y|_{max}$ of the two leading jets with $|y| < 2.8$

The cross section falls rapidly with m_{12}
Probe up to m_{12}=4.1 TeV

Not included here:

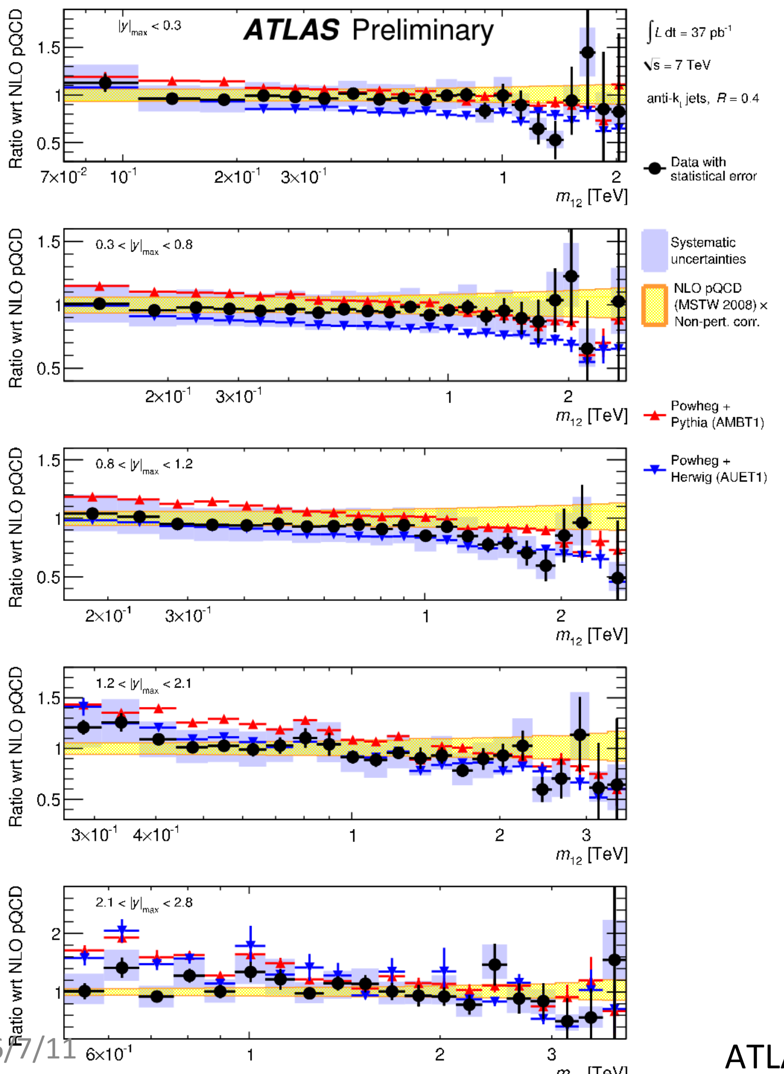
- overall uncertainty of 3.4% due to the luminosity measurement
- uncertainties from the renormalization and factorization scales

ATLAS-CONF-2011-047

Dijets cross section

Compare POWHEG to NLO pQCD and data

good agreement, data appear to be roughly bracketed by the predictions using Pythia and Herwig for showering



|y|<0.3

0.3<|y|<0.8

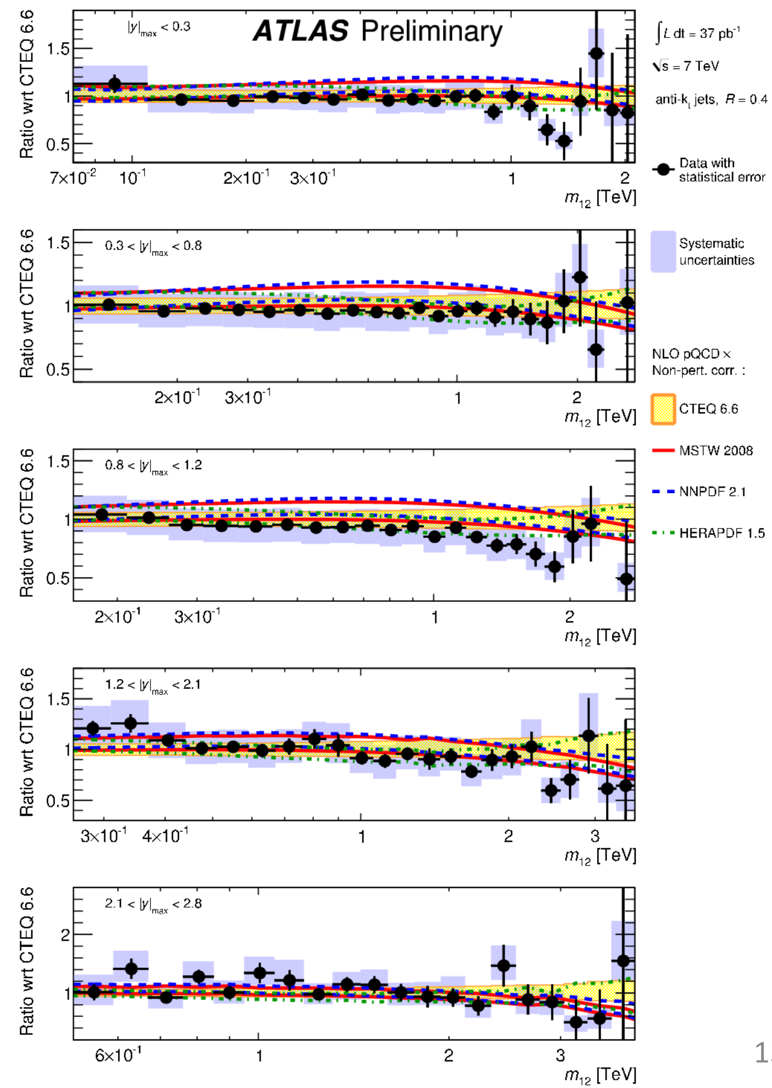
0.8<|y|<1.2

1.2<|y|<2.1

2.1<|y|<2.8

Compare PDF sets

best agreement with data is obtained using HERAPDF 1.5, followed by the CTEQ 6.6 PDF set



ATLAS-CONF-2011-047

Cross sections of b-jets

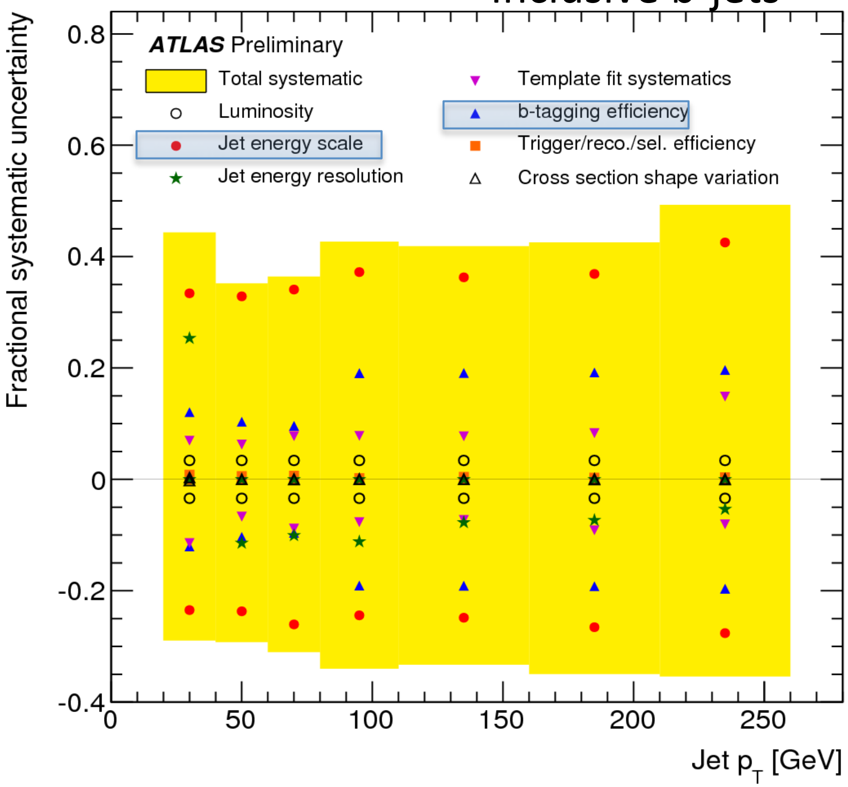
First step in understanding other processes involving the production of b-quarks (substantial BG in many BSM searches)

SV0 algorithm reconstructs the displaced vertex from the charged decay products of the long-lived b-hadron in a jet

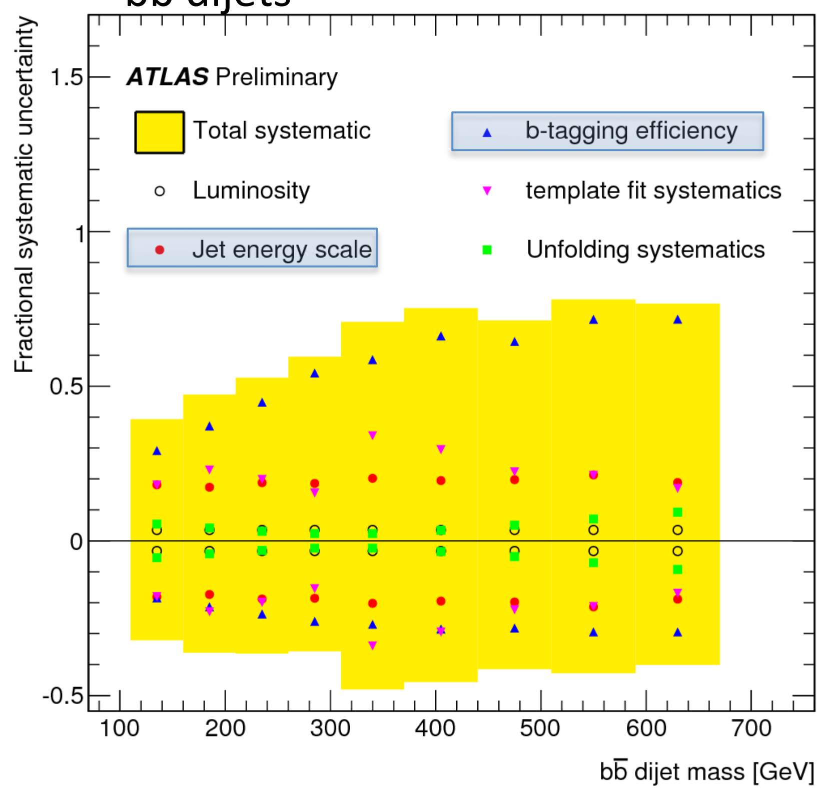
Enriched sample: an operating point chosen that yields a 50% b-tagging efficiency

Invariant mass distribution of tracks in the secondary vertex was fitted to extract the fraction of b-jets in the sample

Inclusive b-jets



$b\bar{b}$ dijets



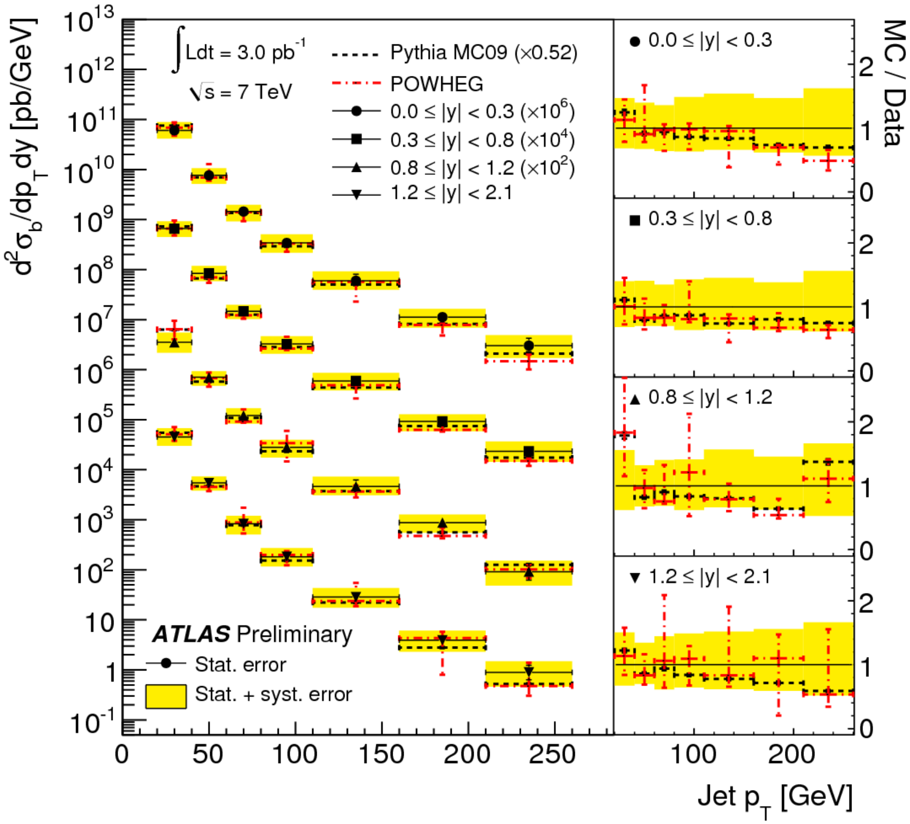
ATLAS-CONF-2011-056

Cross section of b-jets

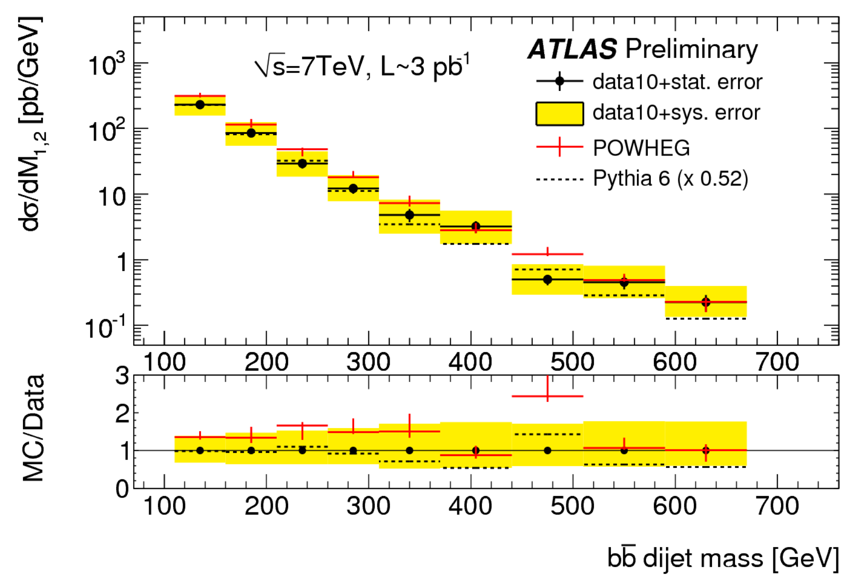
General agreement, but POWHEG predictions show a steeper drop as a function of jet p_T

POWHEG predicts a higher cross section at lower dijet masses

Inclusive b-jet cross section

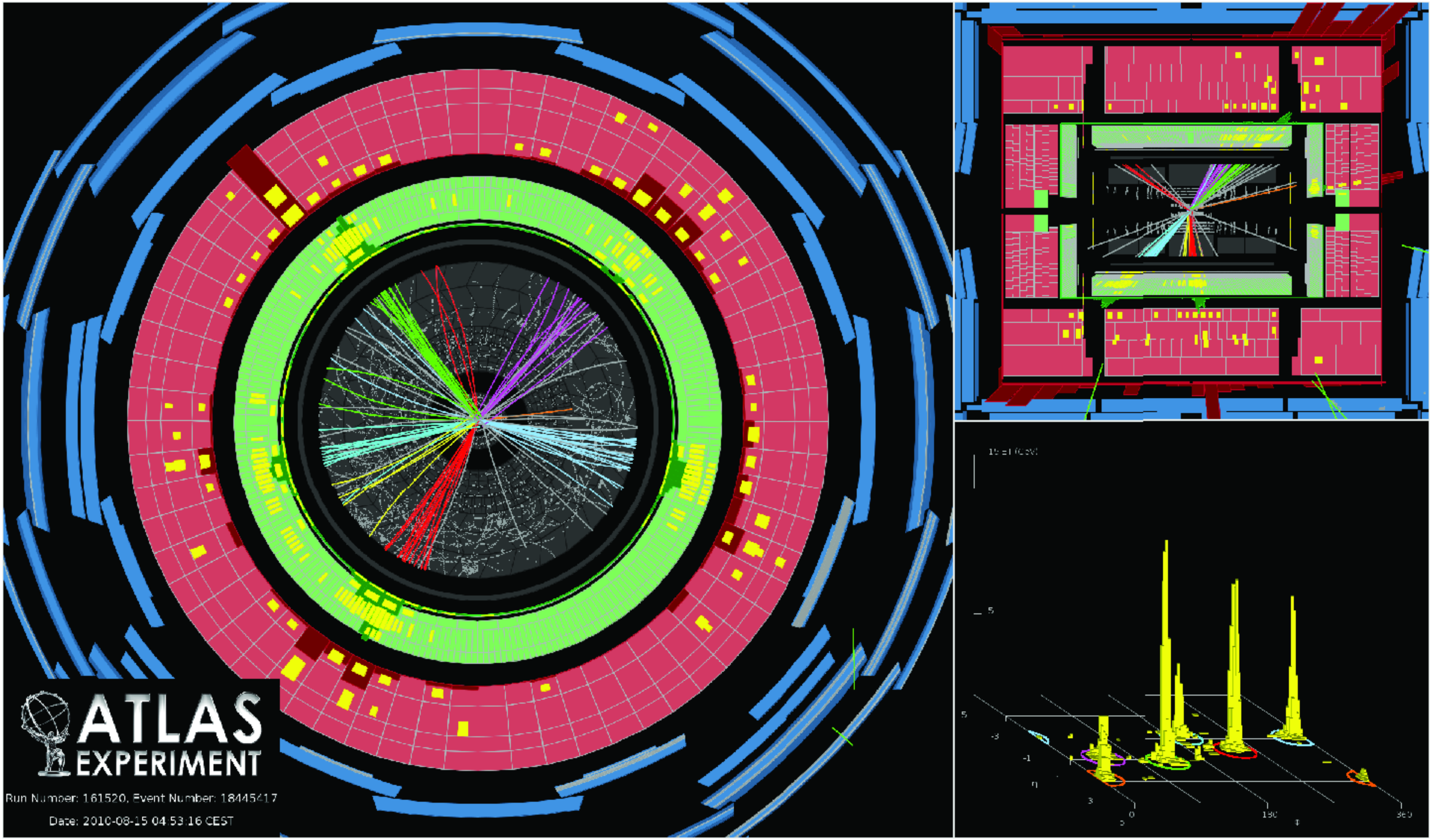


$b\bar{b}$ dijet cross section



ATLAS-CONF-2011-056

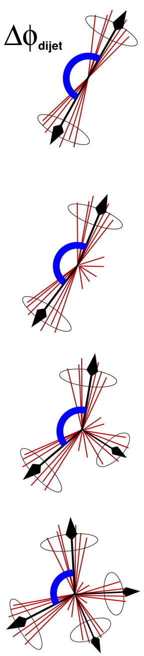
And >2 jets

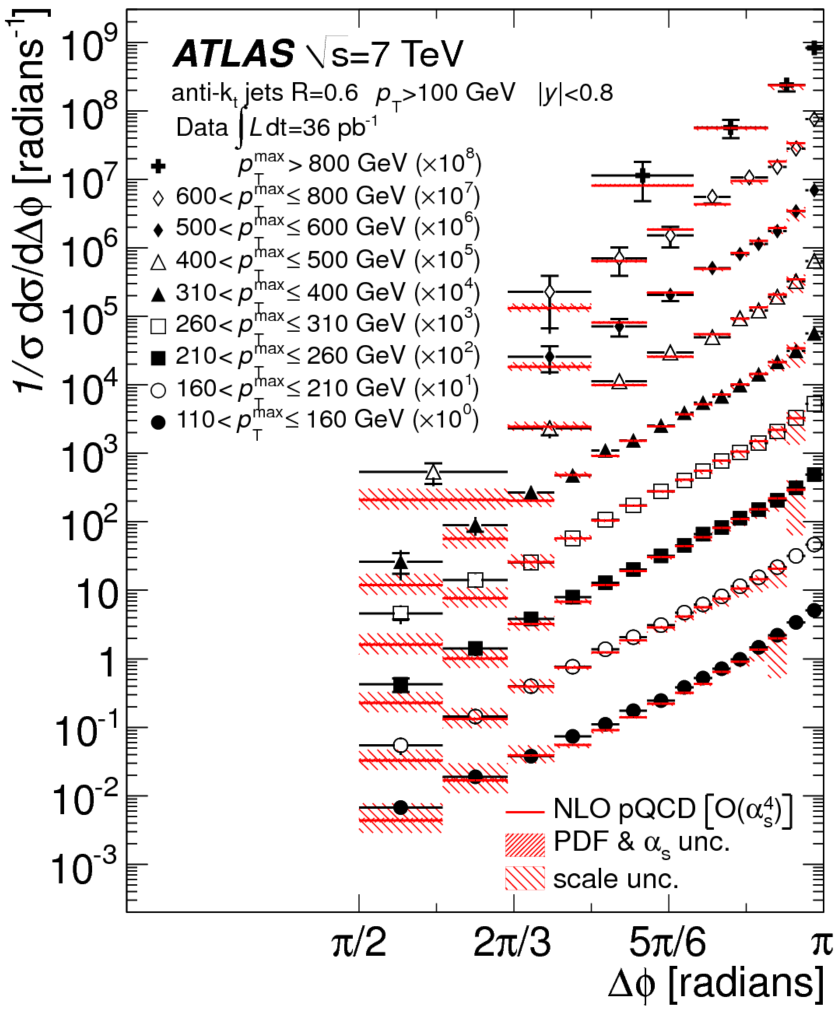


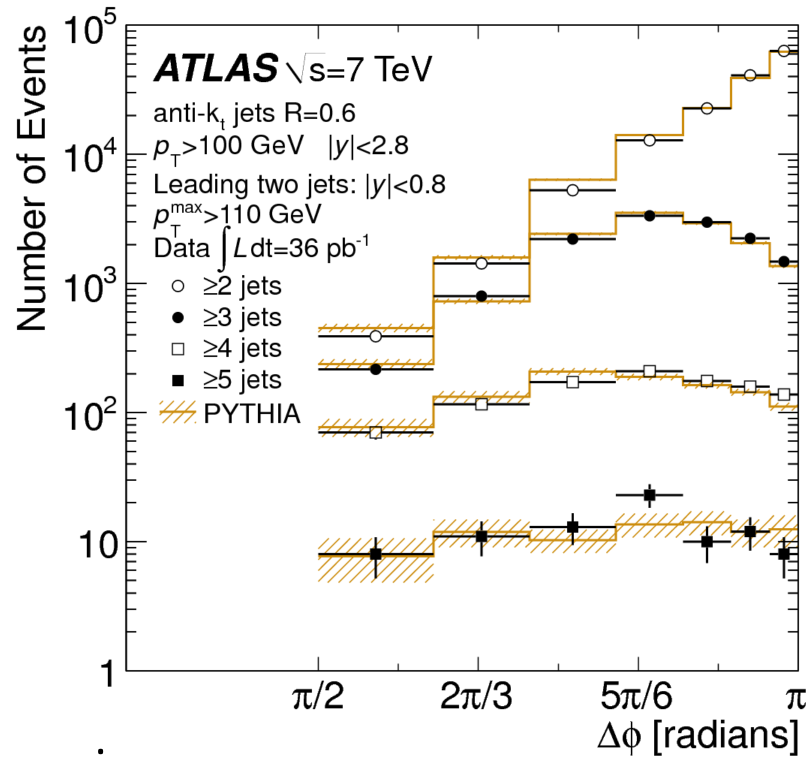
6-jets event

Dijet Azimuthal Decorrelations

Distributions in Δϕ test pQCD calculations for multiple jet production without requiring the measurement of additional jets



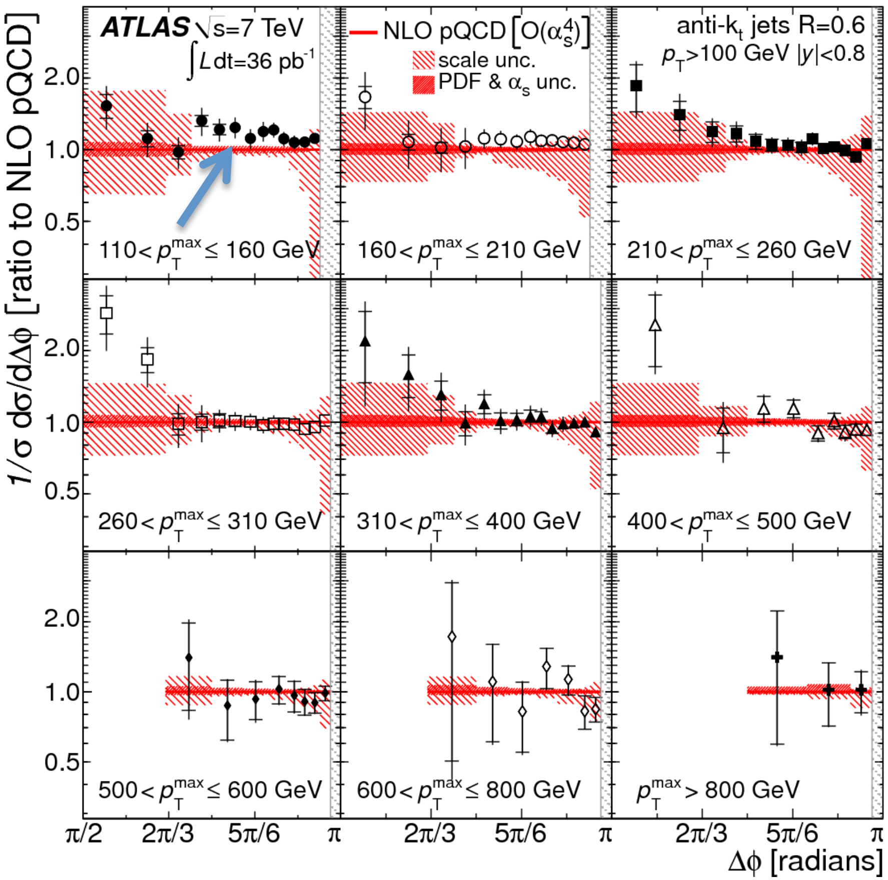


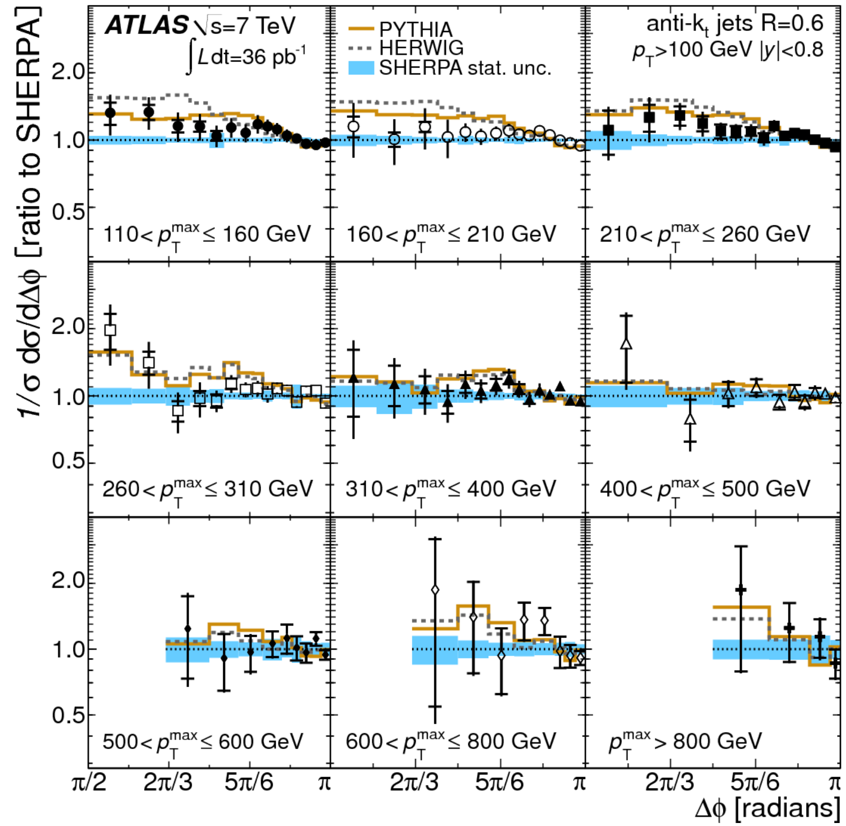


A detailed understanding of events with large azimuthal decorrelations is important to searches for new physical phenomena with dijet signatures

Phys. Rev. Lett. 106, 172002 (2011)

Dijet Azimuthal Decorrelations





phenomenological parameters have been adjusted to previous ATLAS measurements

In most regions, the theory is consistent with the data
The prediction in the range $110 < p_T^{max} < 160$ GeV is relatively low in the central region of $\Delta\phi$ where the scale uncertainties are small

SHERPA, which explicitly includes higher order tree-level diagrams, performs well in most $\Delta\phi$ and p_T^{max} regions

Phys. Rev. Lett. 106, 172002 (2011)

Dijets with jet veto

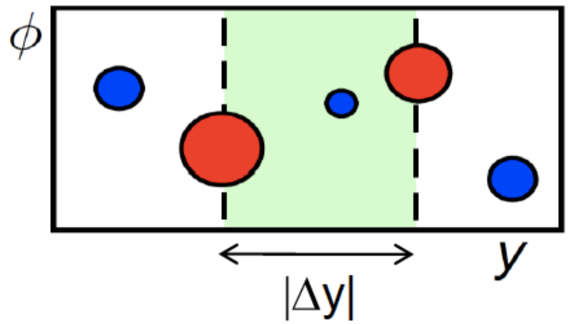
Measure the effect of imposing a third jet veto on dijet systems

Two variables

Gap-fraction: fraction of dijet events that do <u>not</u> have an additional jet with a p_T greater than a given veto scale Q_0 in the rapidity region bounded by the dijet system

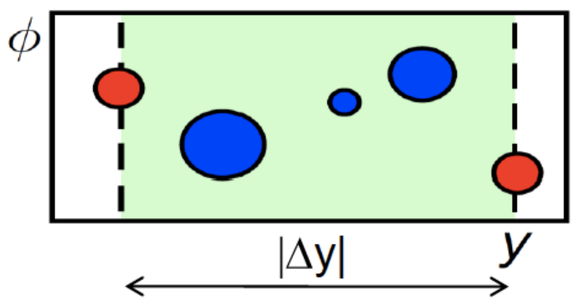
$\langle n_{jet} \rangle_{gap}$: mean number of jets in the rapidity region bounded by the dijet system

Two boundary conditions



Selection A: considers the two leading jets in the event to be the boundary jets

jet $p_T \gg Q_0$ examines wide-angle gluon radiation



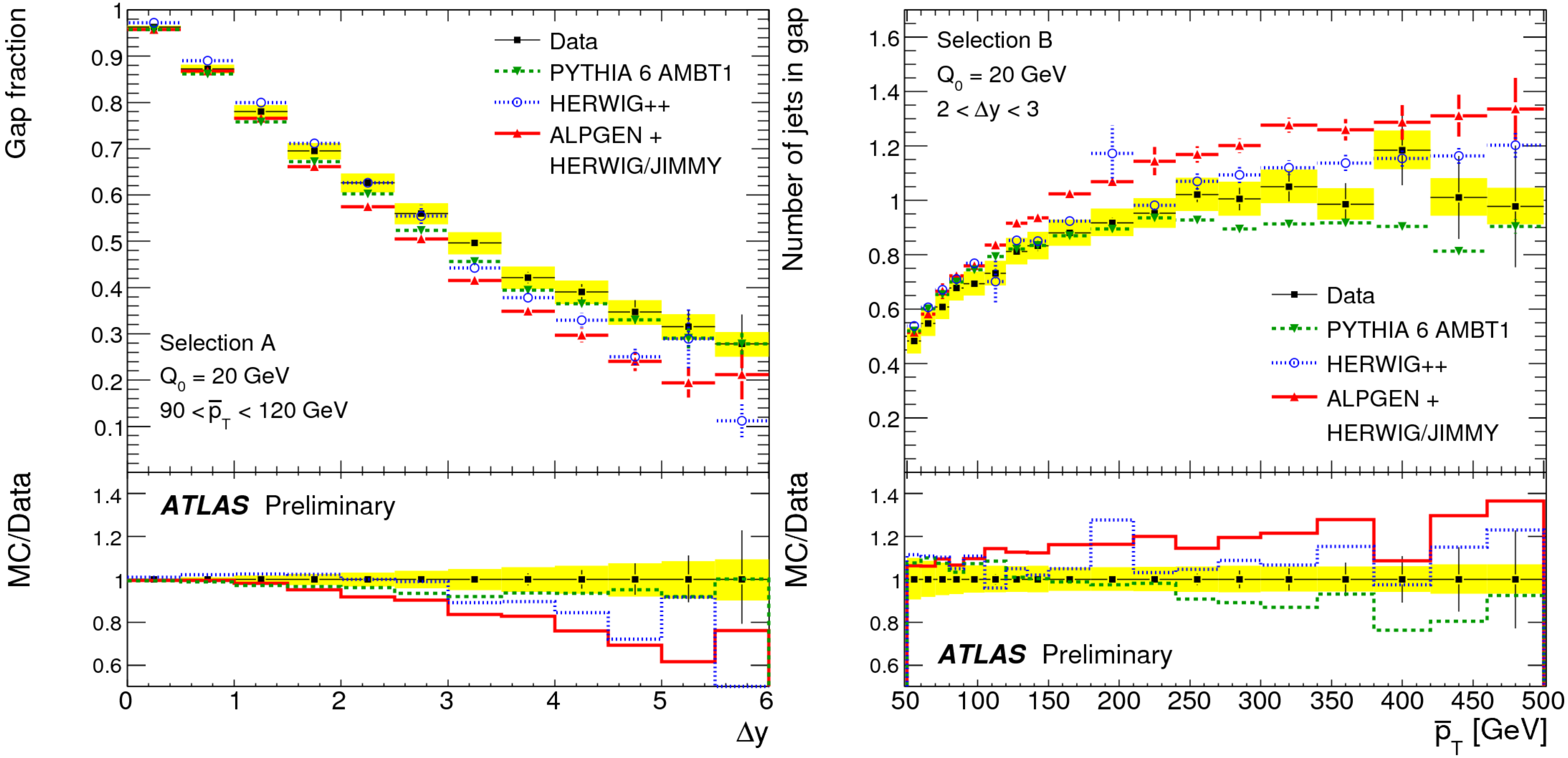
Selection B: considers the two boundary jets as those with the largest absolute rapidity

test of BFKL-like dynamics with wide gaps

Extra motivation: jet veto used in Higgs production via VBF (H+2 jets) to reject background

ATLAS-CONF-2011-038

Dijets with jet veto: MC generators



- Expected behavior of a reduction of gap events for harder jets or for larger rapidity gaps
- PYTHIA 6 tends to underestimate the gap-fraction at low Δy and low $\bar{p}_T$, but gives the best description
- ALPGEN shows the largest deviation from data
- MC event generators have dramatically different predictions of the jet activity for large $\bar{p}_T$ and Δy experimental uncertainty is much smaller than this spread

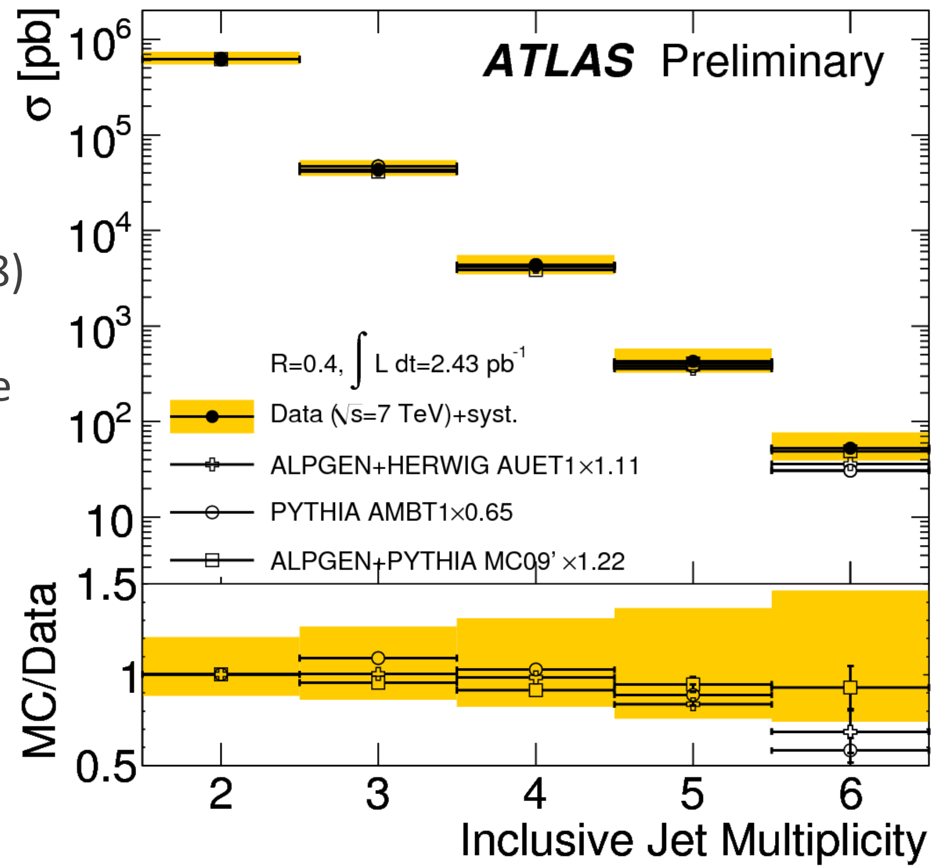
ATLAS-CONF-2011-038

Multi-jets

Evaluate and understand how robust the LO theoretical predictions are for representing the high jet multiplicity

Compare to LO+ME predictions and parton-shower tunes

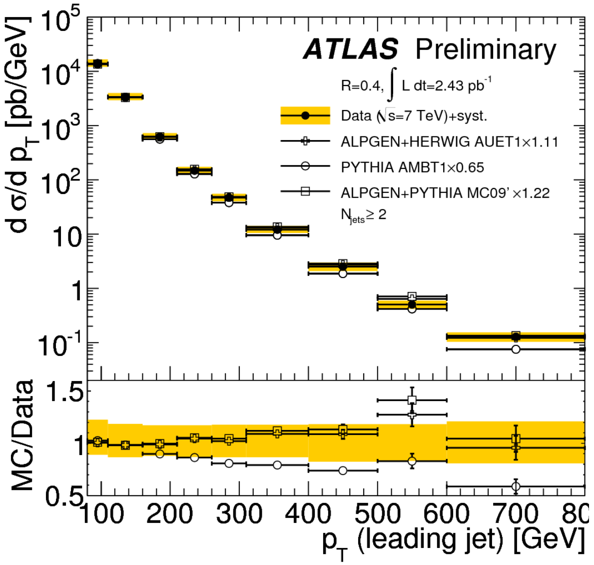
- total cross section for multi-jet events as a function of the jet multiplicity (p_T >60 GeV and |y|< 2.8)
- ask at least one jet with p_T > 80 GeV
- LO MC predictions normalized to the measured 2-jet bin
- measurement systematics are dominated by the JES uncertainty

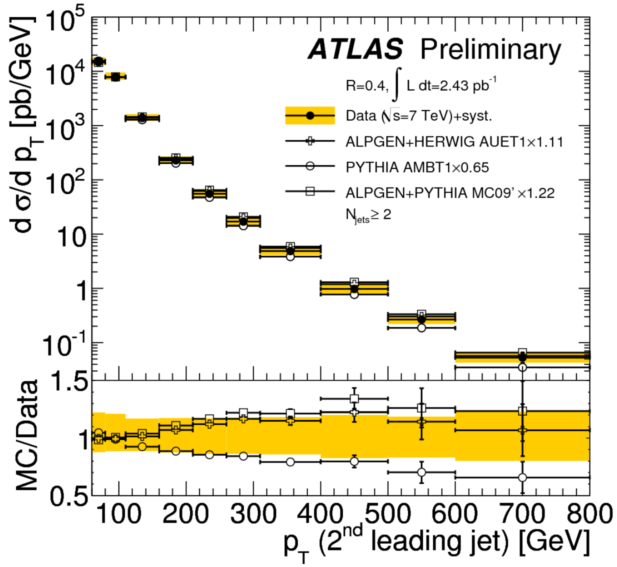


Contribution from JES uncertainty: 10-20% → 40-50%

ATLAS-CONF-2011-043

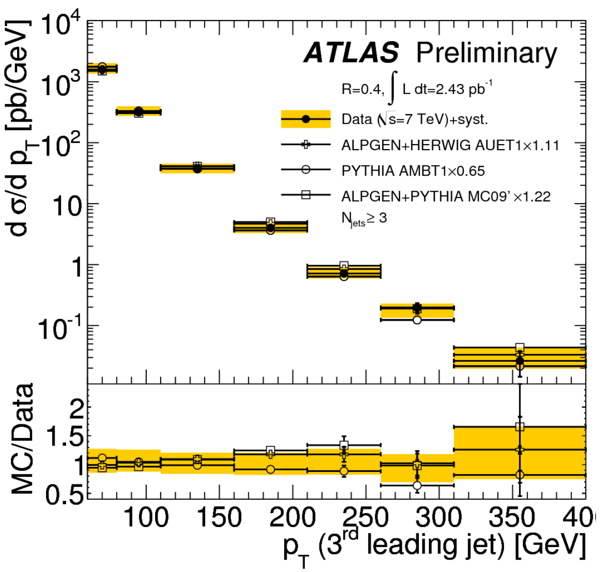
Multi-jets

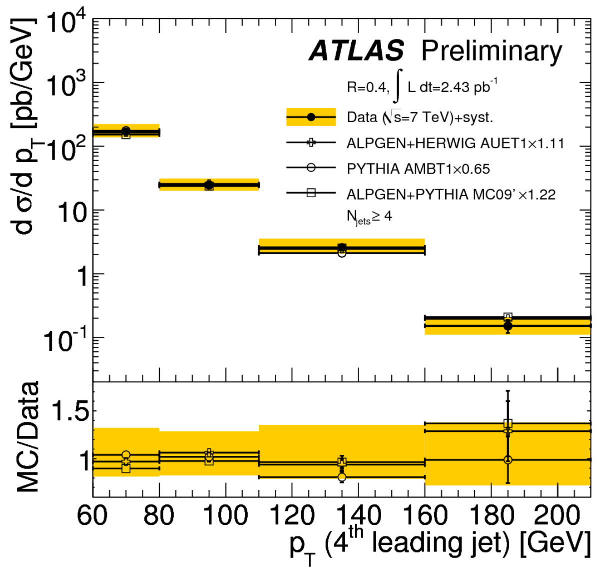




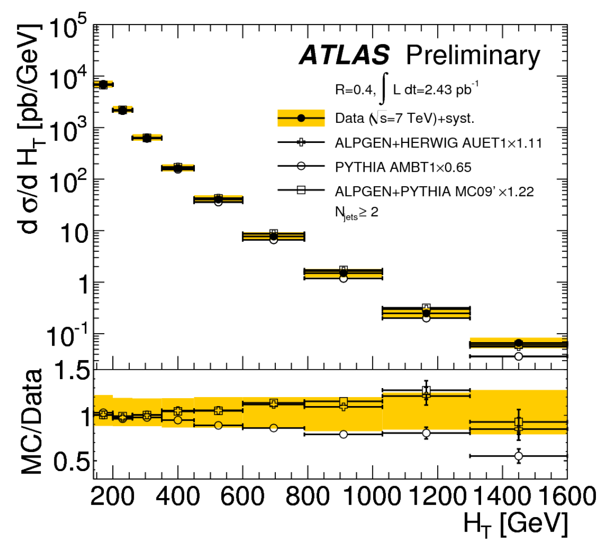
Differential cross sections as a function of the jet p_T

The shape of PYTHIA AMBT1 is steeper than in data





Same conclusion with the total transverse energy H_T of the jets in the event

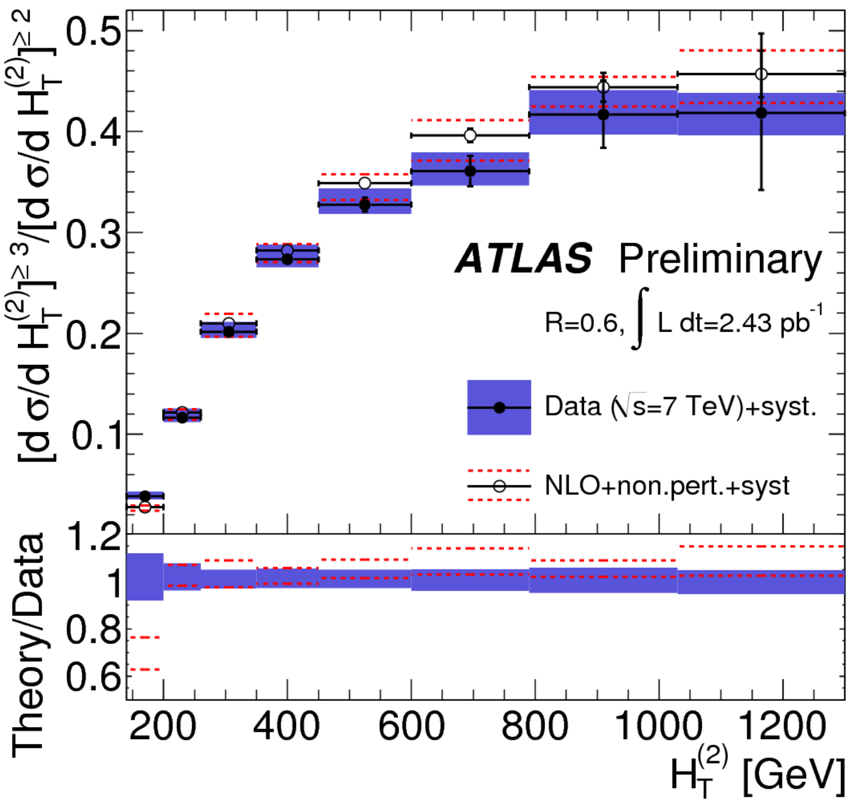


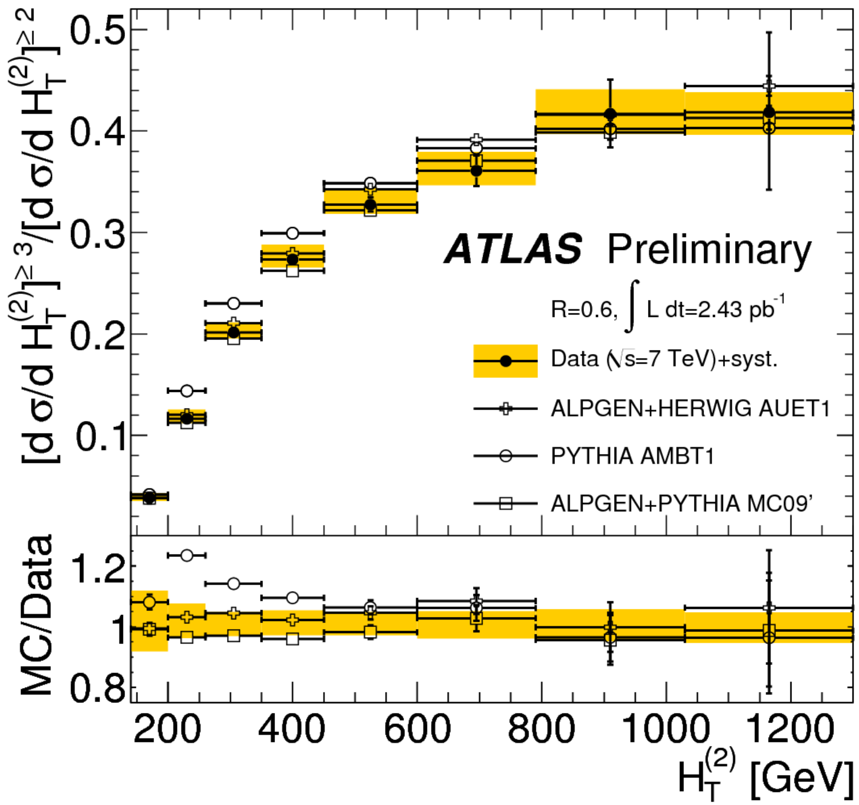
ATLAS-CONF-2011-043

Multi-jets

Test NLO pQCD predictions and MC generators with an observable in which many systematic uncertainties cancel

3-jets to 2-jets cross section ratio as a function of a characteristic p_T of the event

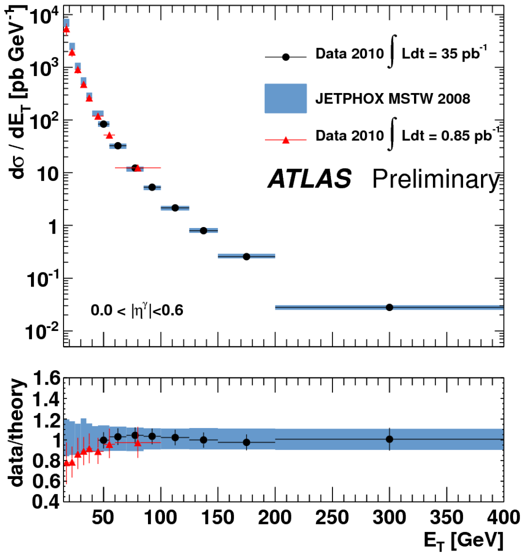


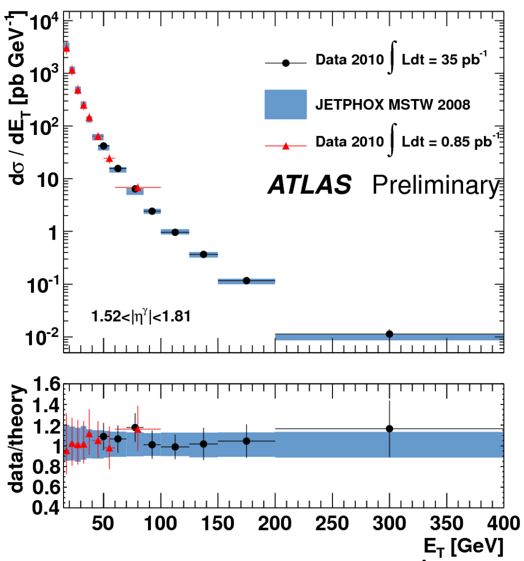


may be useful to constrain parameters entering the NLO calculation, such as PDFs or the value of $\alpha_S(M_Z)$ given the small measurement uncertainties

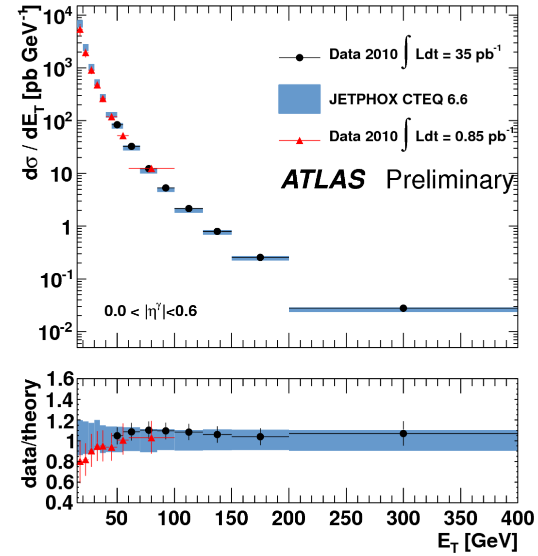
ATLAS-CONF-2011-043

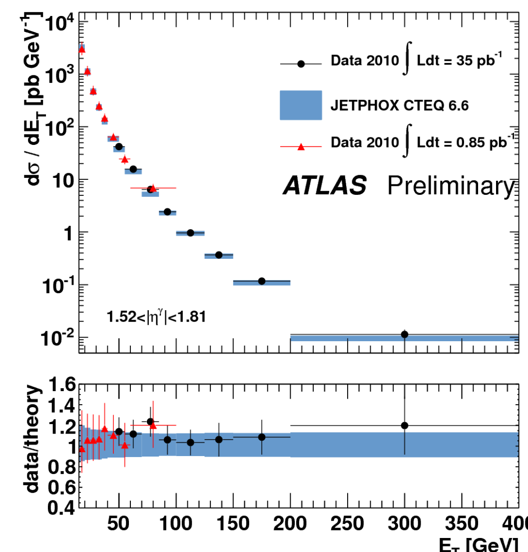
Prompt photon production





- Prompt photons are produced by qg->qγ Compton scattering and the annihilation subprocess $q\bar{q}$->gγ
- Colorless probe of the hard-scattering process: can also be used to constrain the relatively poorly measured **gluon density** of the proton
- JETPHOX theoretical computation
  - full NLO QCD of both the direct and fragmentation contributions
  - parton-level isolation cut of ΔR=0.4 around the photon
- Good agreement observed for both CTEQ6.6 (right) and MSTW2008 (left)
  - previous cross section measurement is also shown extending the overall energy coverage down to 15 GeV
  - limited statistics in the higher transverse-energy regions (E_T > 150 GeV)





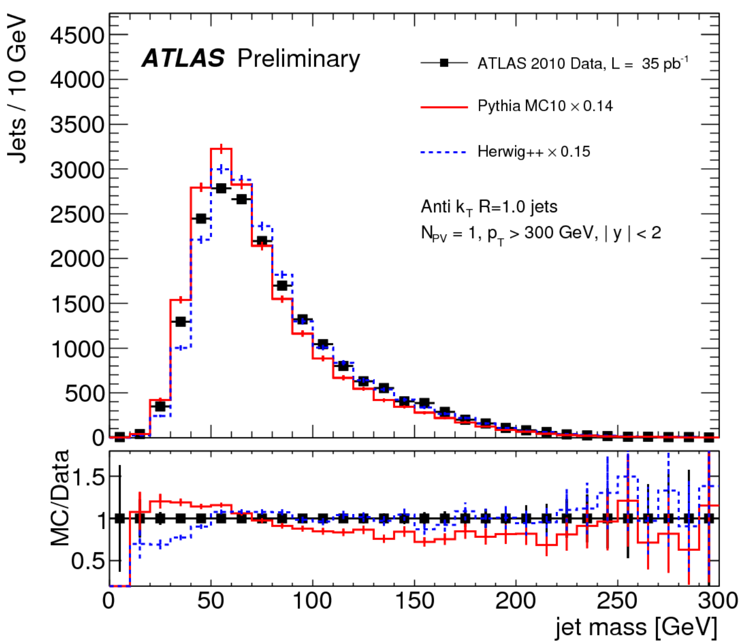
See Ruggero Turra's poster Measurements of isolated prompt photons in pp collisions with the ATLAS detector

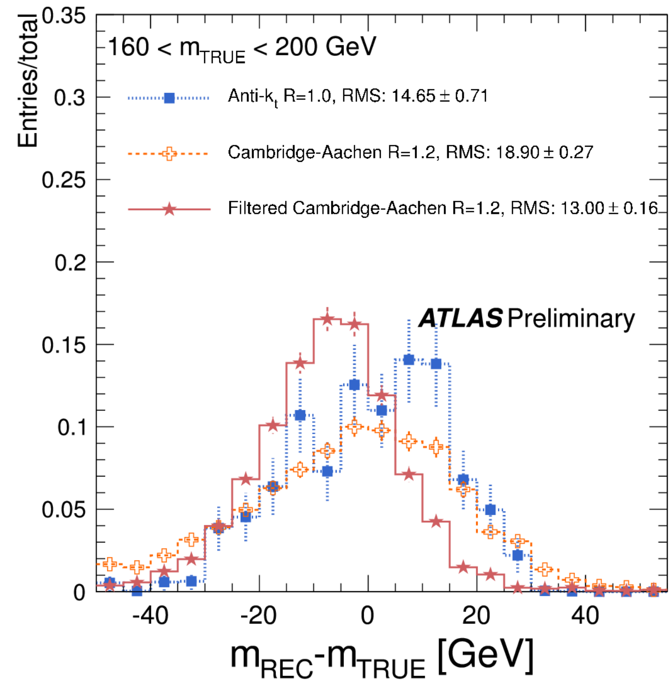
ATLAS-CONF-2011-058

Jet substructure

- Use jet substructure techniques to identify e.g. decays of electroweak-scale objects created well above threshold (i.e. boosted)
- If they decay hadronically their decay products may be contained in a single jet
  i.e. jets can be complex composite objects
- Their internal substructure can reveal additional information and the granularity of the ATLAS calorimeter makes these studies possible
- Has never been tried with real data and rely on the assumption that it is well modeled by MC

Jet invariant mass



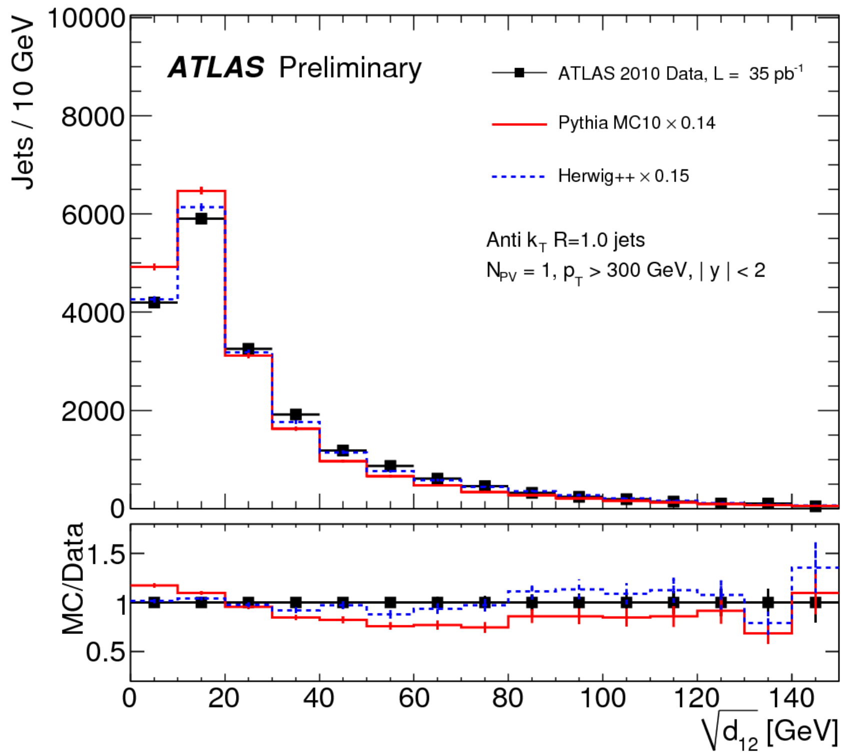


ATLAS-CONF-2011-073

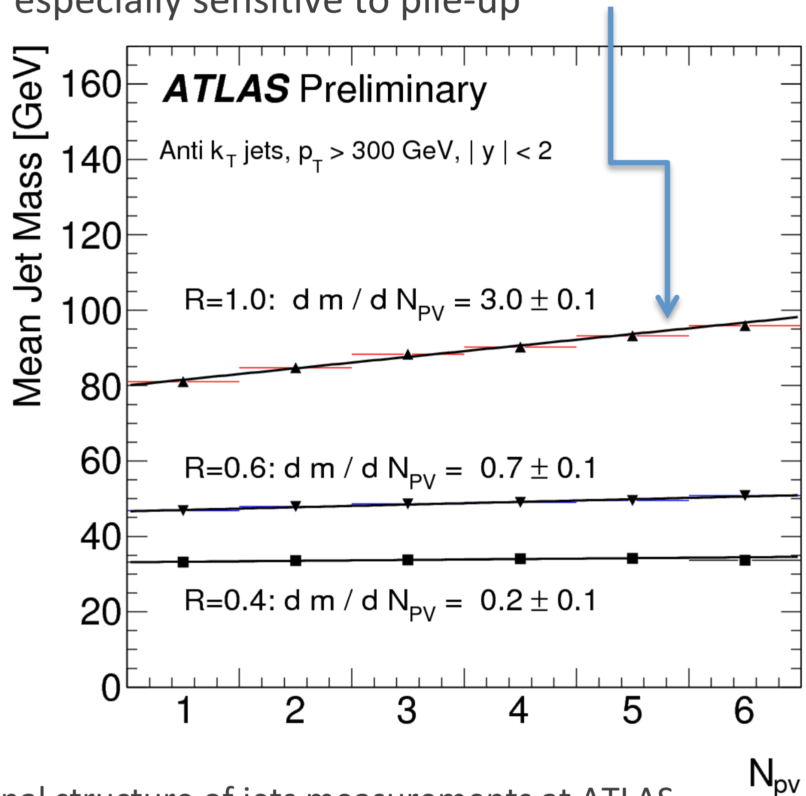
Jet substructure

1st k_t splitting scale defined as $\sqrt{d_{12}} = \min(p_{Ta}, p_{Tb}) \times \sqrt{d\phi_{a,b}^2 + dy_{a,b}^2}$
where a and b are the two jets before the final clustering step

Distinguish heavy particle decays, which tend to be symmetric, from largely asymmetric QCD splittings



Substructure observables are expected to be especially sensitive to pile-up



See Bilge Demirkoz's talk Multijets and the internal structure of jets measurements at ATLAS

ATLAS-CONF-2011-073

Conclusions

A vast effort in place to understand SM high-energy/high-multiplicity jets physics

Conclusions

A vast effort in place to understand SM high-energy/high-multiplicity jets physics

Jet p_T range already exceeds Tevatron measurements and with the increased statistics, the uncertainties on jet quantities have considerably dropped

Conclusions

A vast effort in place to understand SM high-energy/high-multiplicity jets physics

Jet p_T range already exceeds Tevatron measurements and with the increased statistics, the uncertainties on jet quantities have considerably dropped

pQCD describes generally well the jet quantities in the new energy regime

Conclusions

A vast effort in place to understand SM high-energy/high-multiplicity jets physics

Jet p_T range already exceeds Tevatron measurements and with the increased statistics, the uncertainties on jet quantities have considerably dropped

pQCD describes generally well the jet quantities in the new energy regime

Stay tuned for in depth probes of α_S or PDFs (some observables already sensitive)

Conclusions

A vast effort in place to understand SM high-energy/high-multiplicity jets physics

Jet p_T range already exceeds Tevatron measurements and with the increased statistics, the uncertainties on jet quantities have considerably dropped

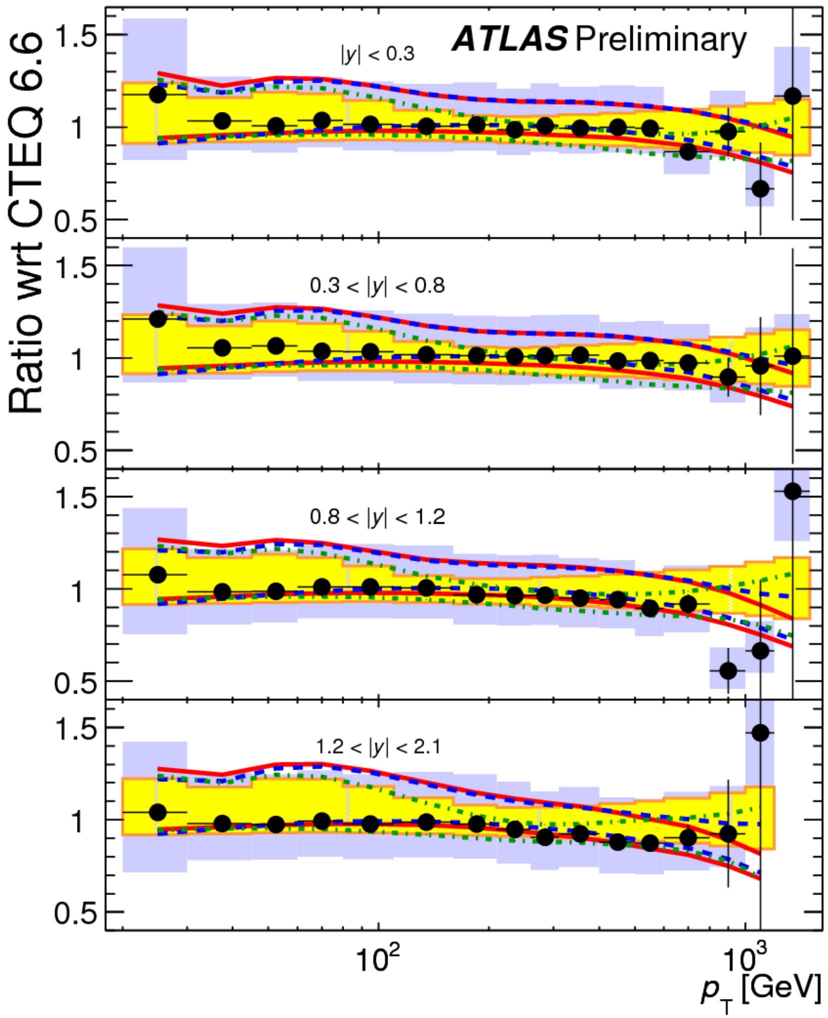
pQCD describes generally well the jet quantities in the new energy regime

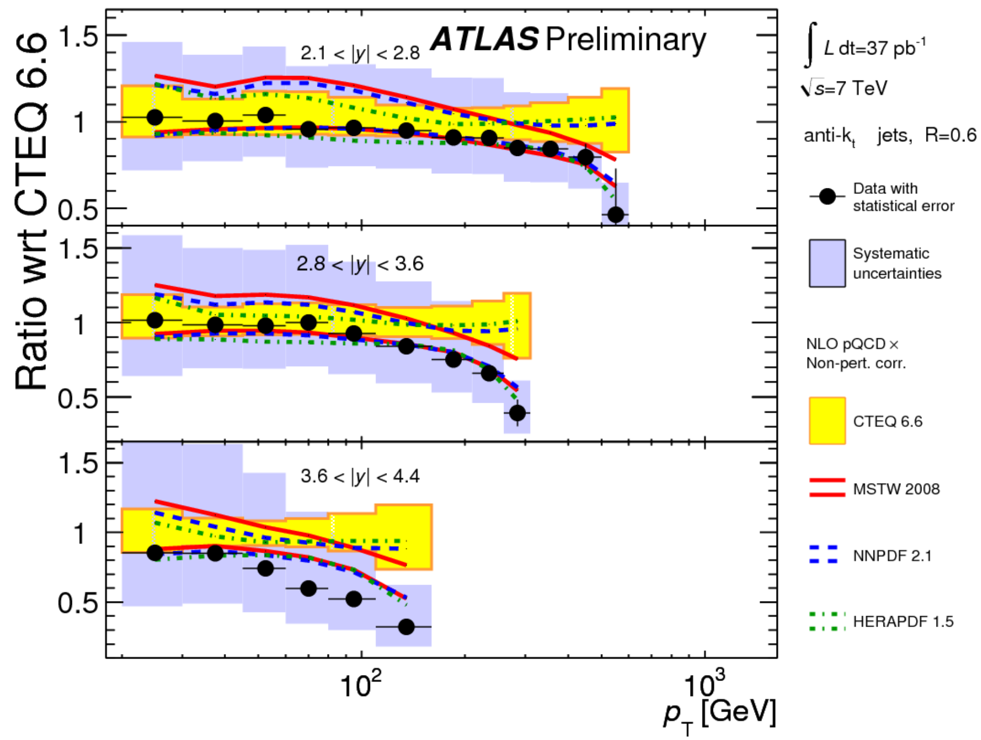
Stay tuned for in depth probes of α_S or PDFs (some observables already sensitive)

And all this work is paving the way for BSM searches

Backup

Inclusive cross section: compare PDFs

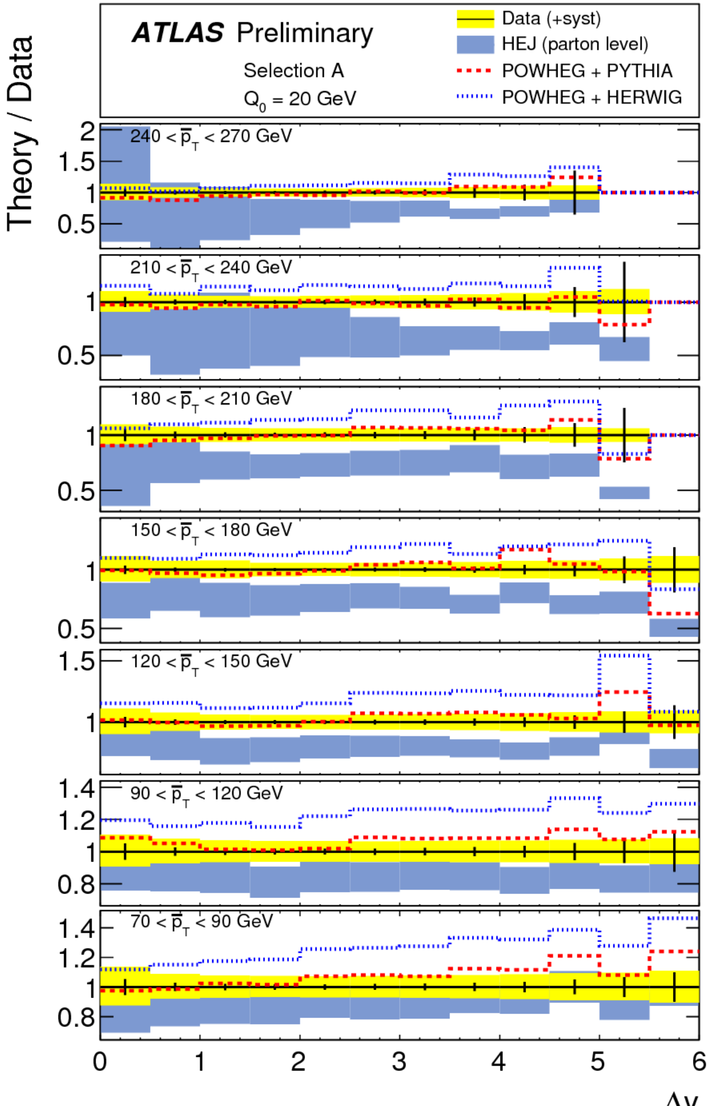




Predictions using HERAPDF 1.5 appeared to follow the data most closely, though consistency within experimental and theoretical uncertainties with most other PDF sets is observed

ATLAS-CONF-2011-047

Dijets with jet veto: NLO predictions



Gap fraction

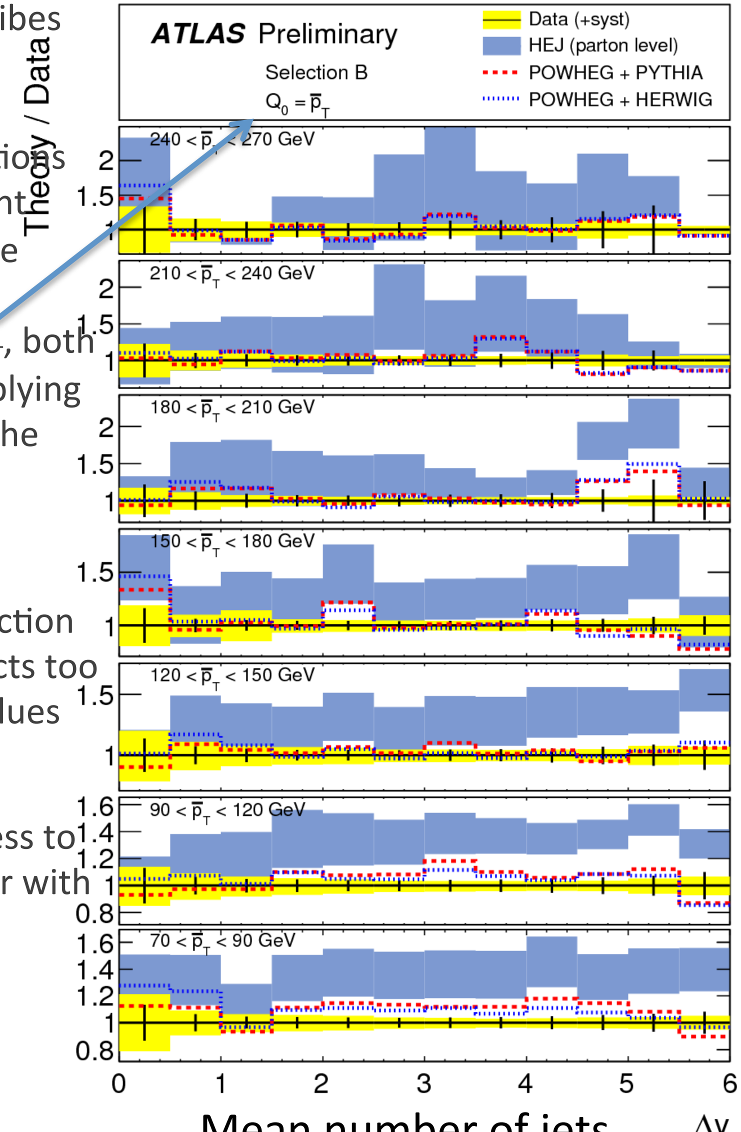
In general, POWHEG describes the data well

POWHEG+HERWIG predictions showing a better agreement for most of the phase space

With the veto scale $Q_0 = p_T$, both describe the data well, implying a smaller dependence on the generator modelling of PS, hadronisation and UE

The parton-level HEJ prediction (BFKL resummation) predicts too little jet activity at large values of p_T/Q_0

Work is currently in progress to interface the HEJ generator with PS and hadronisation

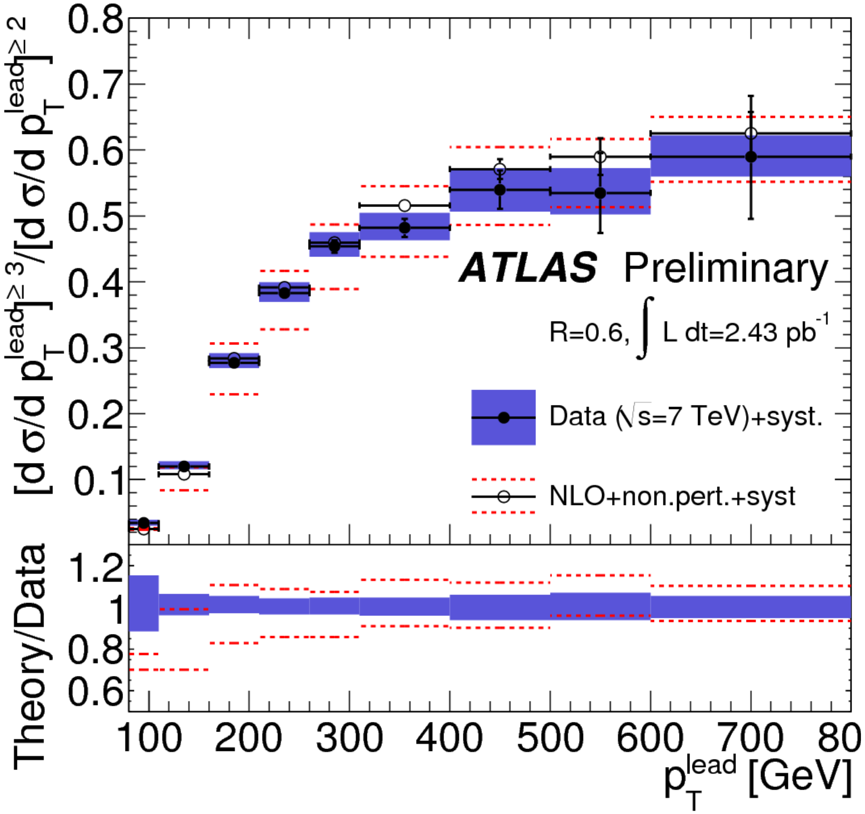


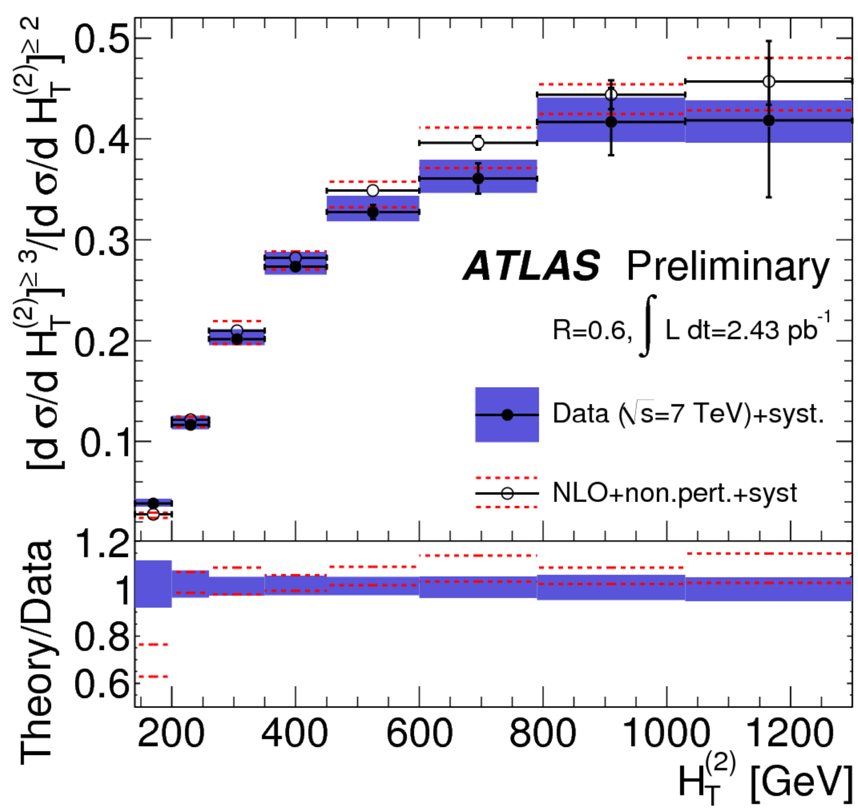
Mean number of jets

ATLAS-CONF-2011-038

Multi-jets

Test NLO pQCD predictions with an observable in which many systematic uncertainties cancel



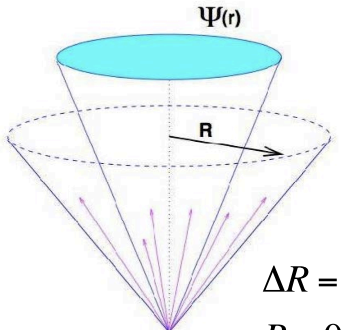


ratio as a function of p_T^{lead} is of interest for the tuning of final state radiation

$H_T^{(2)}$ more stable under renormalization scale variations in the NLO calculation

Jet shapes

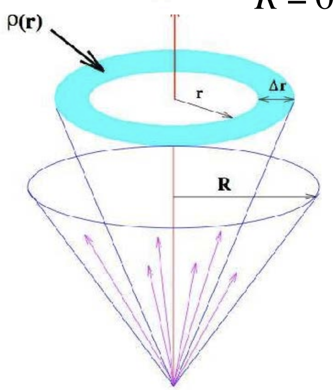
Jet shapes in proton-proton collisions provide information about the details of the parton-to-jet fragmentation



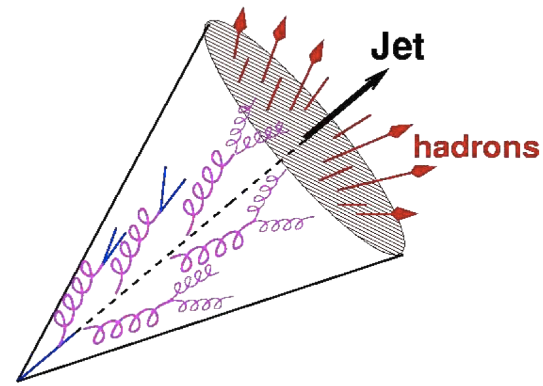
$$\Psi(r) = \frac{1}{N^{\text{jet}}} \sum_{\text{jets}} \frac{p_T(0,r)}{p_T(0,R)}, \quad 0 \le r \le R$$

$\Delta R = 0.1$

$R = 0.6$



$$\rho(r) = \frac{1}{\Delta r} \frac{1}{N^{\text{jet}}} \sum_{\text{jets}} \frac{p_T(r - \Delta r/2, r + \Delta r/2)}{p_T(0,R)}, \quad \Delta r/2 \le r \le R - \Delta r/2$$



The shape of the jet depends on the type of partons (quark or gluon) that give rise to jets in the final state, and is also sensitive to non-perturbative fragmentation effects and underlying event (UE) contributions from the interaction between proton remnants

Phys. Rev. D 83, 052003 (2011)