Measurement of the jet production properties at the LHC with the ATLAS Detector

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On behalf of the ATLAS collaboration

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Borgo, Corsica, France 2015

Outline of the talk

- Jet physics motivation
- ATLAS detector
- Dijet cross section in pp collisions at 7 TeV
- Limits on contact interaction
- Dijet flavour decomposition
- Inclusive jet cross section in pp collisions at 7 TeV
- Three-jet production in pp collision at 7 TeV
- Jet shapes in ttbar events
- Conclusions

Jet physics motivation

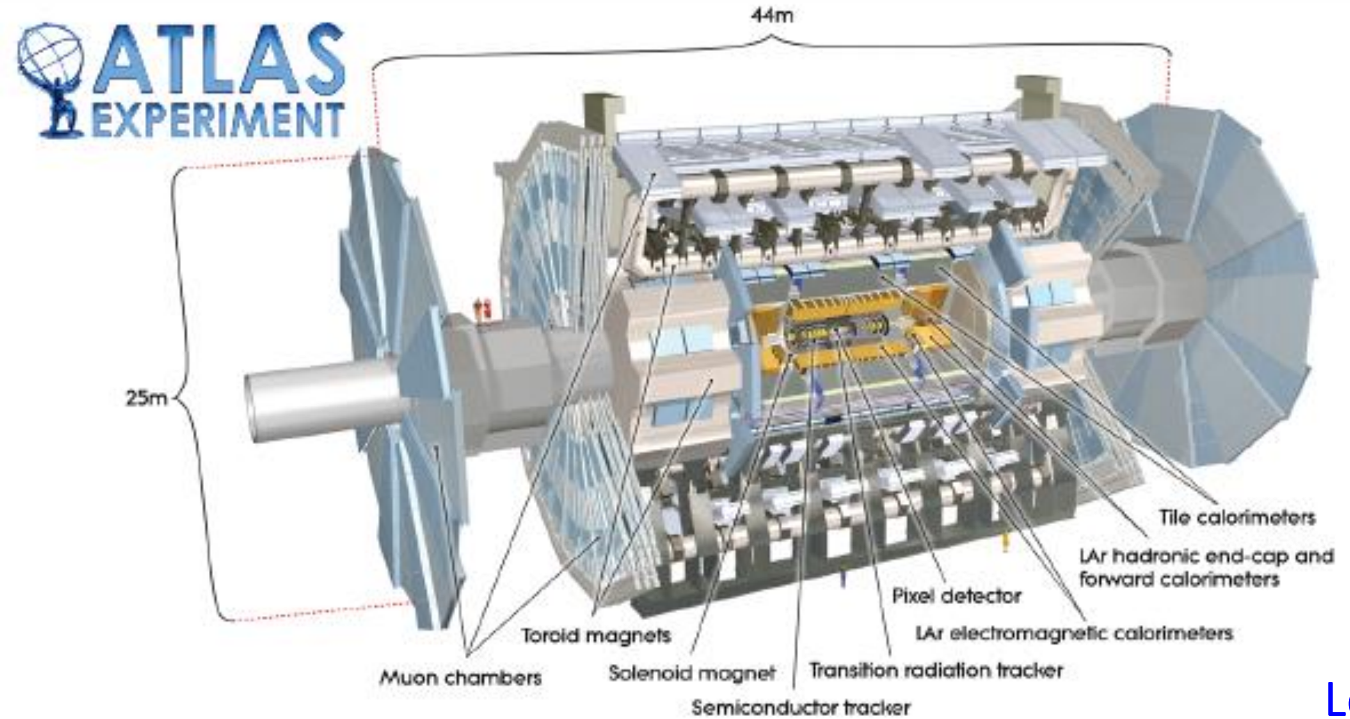
Test of the quantum chromodynamics (QCD): jets are the result of fragmentation of partons produced in a scattering process.

In high-energy particle collisions - two main phases:

- ✓ Perturbative phase: partons with high-transverse momentum (p_T) are produced in a hard-scattering process at a scale Q.
- ✓ Non-perturbative phase: partons convert in hadrons emitting gluons and $q\bar{q}$-pairs – non-perturbative part of jet evolution is an interplay between hadronisation process (HP) and underlying event (UE).
  - Hadronisation process: transition from partons to hadrons
  - Underlying event: initial-state radiation, multiple-parton interactions and colour-reconnection effects.
  - Effects of HP and UE vary strongly with the jet radius parameter and are most pronounced at low p_T.

All these aspects of high energy collisions can be probed in the jet physics!

Atlas experiment



3 levels of detectors:

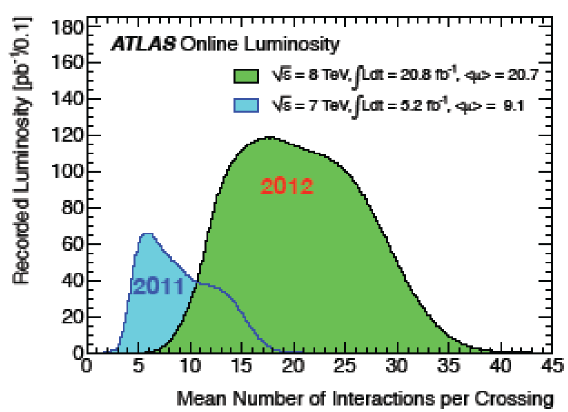
- ✓ Inner detector
- ✓ Calorimetric system
- ✓ Muon system

Integrated luminosity:

- ✓ 2011 (7TeV): $5fb^{-1}$
- ✓ 2012 (8TeV): $21fb^{-1}$

Sample of $1fb^{-1}$ = 7×10^{13} inel. int. of *pp*

Level of pileup



This talk: only results based on 7 TeV data

Dijet cross-sections in *pp* at 7 TeV

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- ✓ Jets reconstructed by the anti-k_t algorithm - jets are clustered using two different values of R: 0.4 and 0.6.
- ✓ Measured cross-sections are corrected for all experimental effects and are defined at the particle-level final state (unfolding to particle level jets).
- ✓ A set of single-jet triggers with different thresholds used to collect data. Offline: Leading (subleading) jet required: $p_T > 100$ GeV (> 50 GeV).
- ✓ Only events collected during stable beam conditions - at least one primary vertex, reconstructed ≥ 2 tracks with $p_T > 400$ MeV.
- ✓ Primary vertex with the highest $\sum {p_T}^2$ of associated tracks is selected as the hard-scatter vertex.
- ✓ Dominant uncertainties: jet energy calibration – from balance in Z/γ-jet , dijet intercalibration, multijet balance and single hadron response.

Dominant uncertainty: Jet Energy Scale

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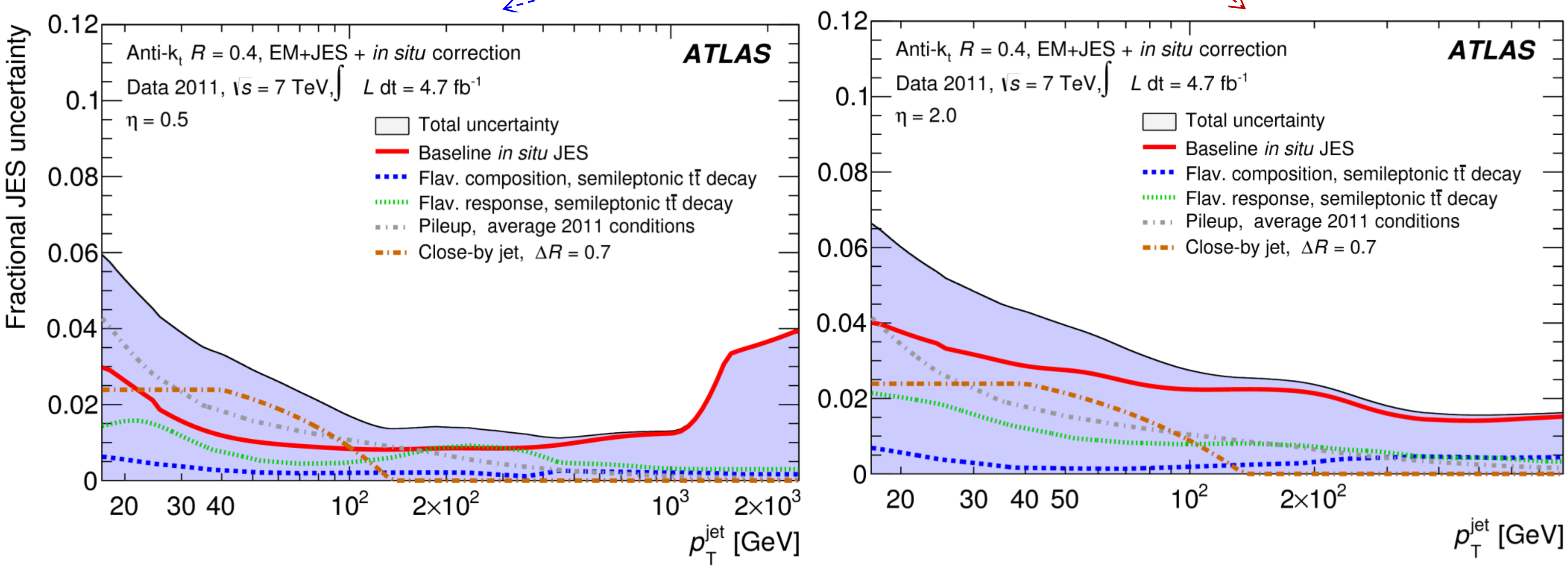
- ✓ Jets reconstructed by the anti-k_t algorithm - and clustered using R = 0.4.
- ✓ Fractional JES uncertainty vs jet p_T for η = 0.5 and η = 2.0.

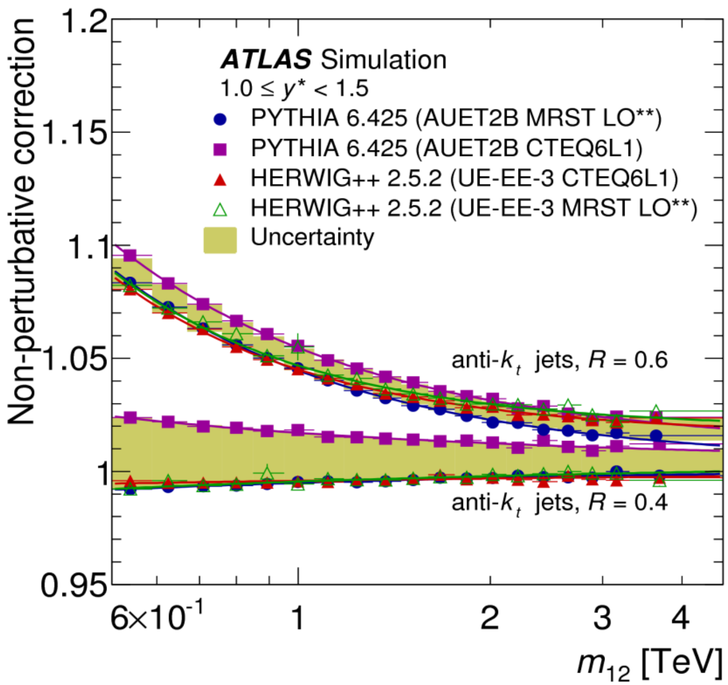


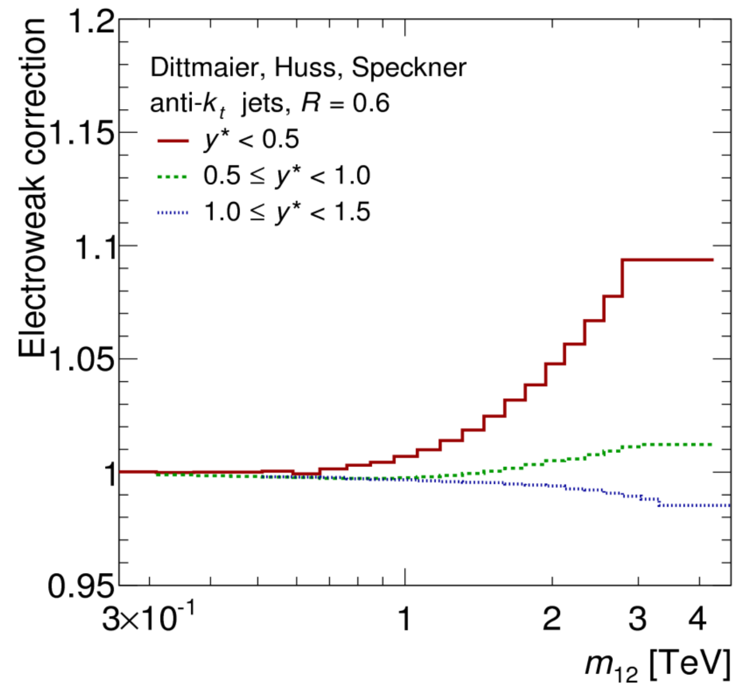
In situ JES uncertainty comes from measurements of Z+jets, γ +jets, multijet balance, η-intercalibration, single hadron.

Particle level vs parton level X-sections

Measured X-sec are compared to NLO QCD predictions corrected for

- ✓ non-perturbative effects in fragmentation process and in underlying event.
- ✓ NLO electroweak effects.



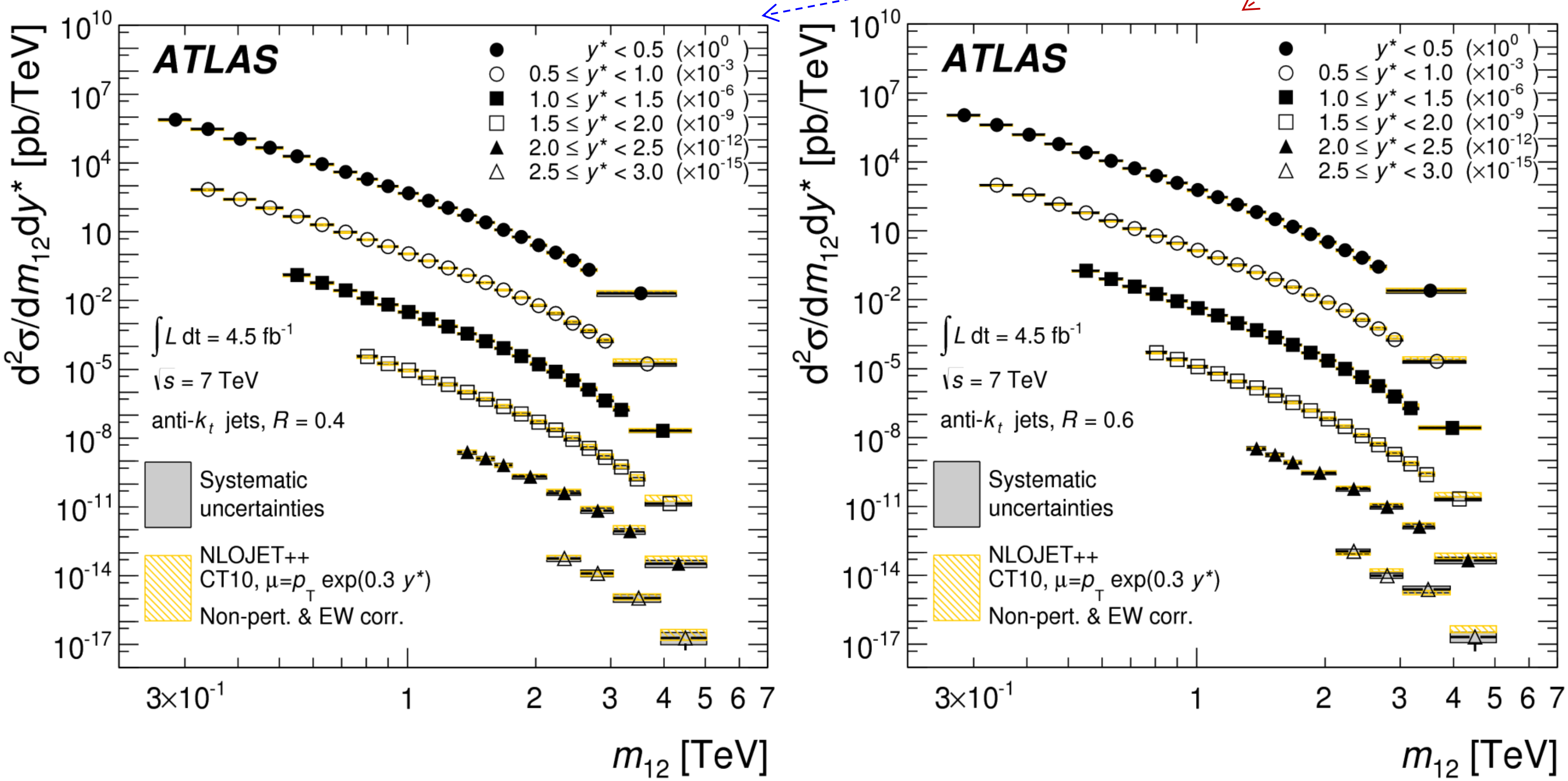


Non-perturbative effects (depending on the jet R): evaluated using leading-log generator (Pythia 6.425...)

EW corrections for tree-level + weak loop effects are applied to the NLOJet++ and POWHEG predictions

Dijet cross section

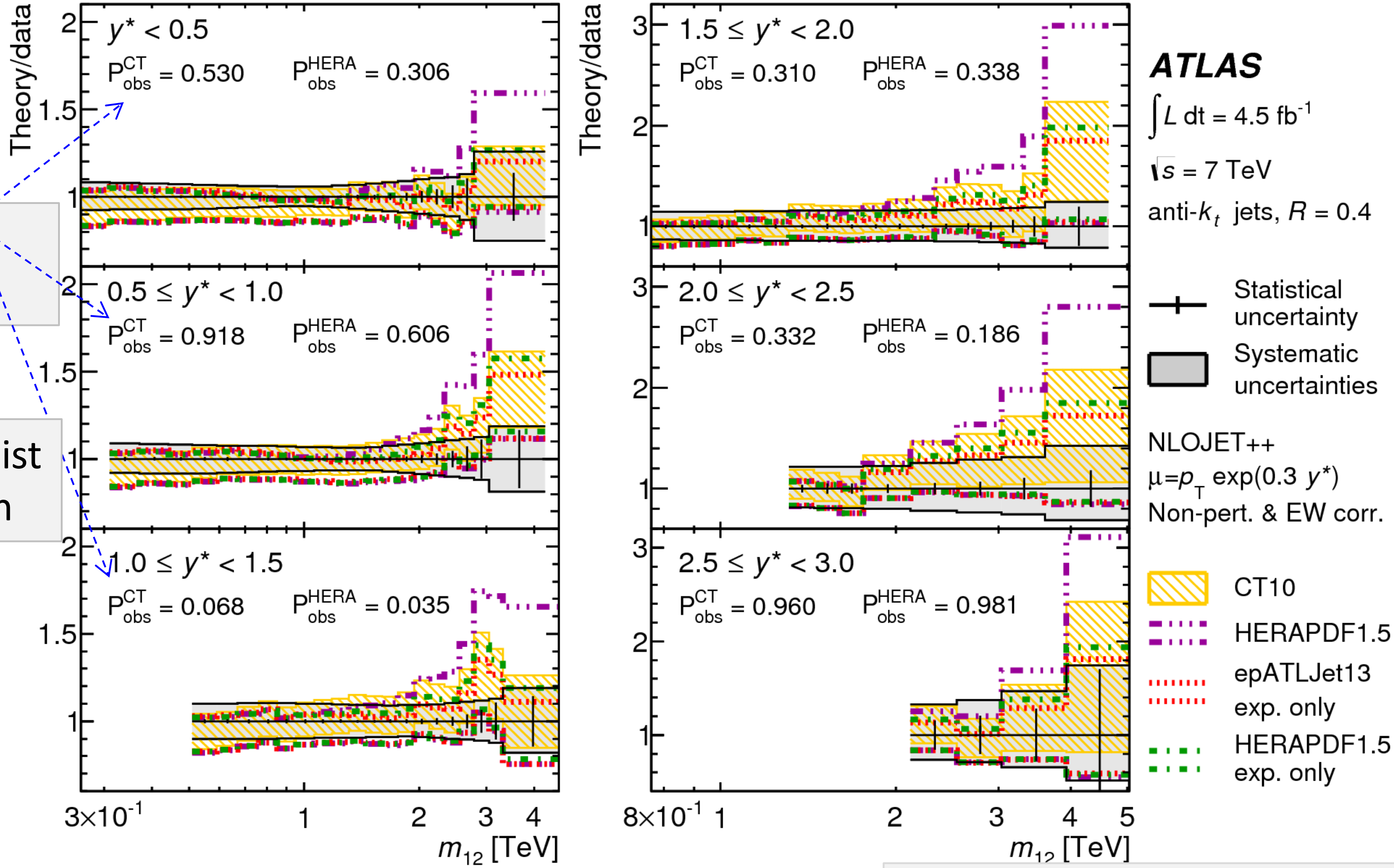
Measurements of the dijet double-diff. cross-sections vs dijet mass and rapidity separation ($y^*=|y_1-y_2|/2$) - anti-k_t jets with R = 0.4 and R = 0.6.



Data are compared to NLOJet++ predictions with various PDFs (CT10), corrected for non-perturbative and EW effects, scale: $\mu = \mu_R = \mu_F = p_T^{max} e^{0.3y^*}$.

Dijet cross section

Ratio of NLOJet++ prediction to measurements of dijet double-diff. X-sec vs dijet mass and y* - PDF sets used: CT10, HERAPDF1.5, and epATLJet13.



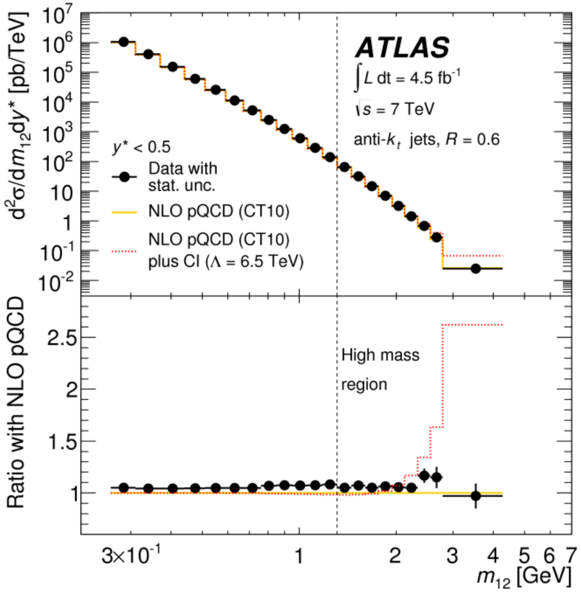
p-values for PDFs

frequentist approach

Potential for PDF improvement

Exclusion of contact interactions

- ✓ If quarks are composed of more fundamental particles with new strong interactions at a composite scale Λ (>> m_{quark}) $\Rightarrow$ at energies <<Λ: contact interaction from the underlying strong dynamics $\rightarrow$ observable effect.
- ✓ Model of QCD + contact interactions (CIs) with left–left coupling and destructive interference between CIs and QCD is considered.
- ✓ Measurement is restricted to the high dijet-mass m_{12} > 1.31 TeV in the range $y^* < 0.5$ (CIs: events preferentially produced at smaller y*).



PDF set / Λ[TeV]	R=0.6 Exp	R=0.6 Obs
CT10	7.1	7.1
HERAPDF1.5	7.3	7.7
MSTW 2008	7.1	6.9
NNPDF2.1	7.2	7.0

Quark size < $3{\cdot}10^{-20}$m

Measured cross section vs NLO QCD (yelow line) and NLO QCD + CIs with Λ=6.5 TeV (red line) predictions, CT10 PDF set used.

Dijet flavour decomposition

Flavor decomposition measurement: pp collision at $\sqrt{s}$ = 7TeV, L_{int}= 39 pb^{-1} .
Decomposition determined in 6 jet pT bins

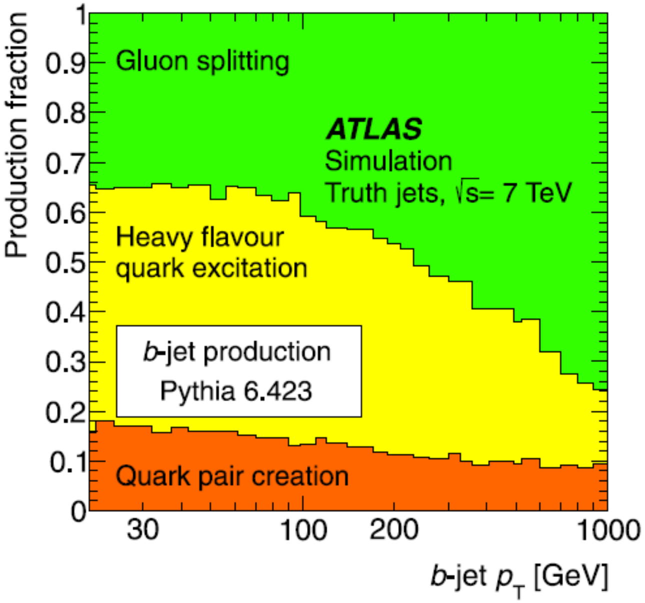
Heavy quarks participating in the hard scattering:

- ✓ Quark pair creation: $gg \to Q\bar{Q}$ and $q\bar{q} \to Q\bar{Q}$.
- ✓ Heavy flavour quark excitation: a single heavy quark from the sea of one hadron scatters on a parton from another hadron: $gQ \to gQ$ and $qQ \to qQ$.

Additional motivation $\Rightarrow$ sensitivity to proton sea heavy quarks

- ✓ Gluon splitting: $g \to Q\bar{Q}$.

PYTHIA 6.423:
The relative contributions of the different heavy flavor quark production mechanisms to inclusive *b*-jet production for simulated pp collisions at 7 TeV ; jets in $|y| < 2.1$.



Dijet flavour: predictions and reconstruction

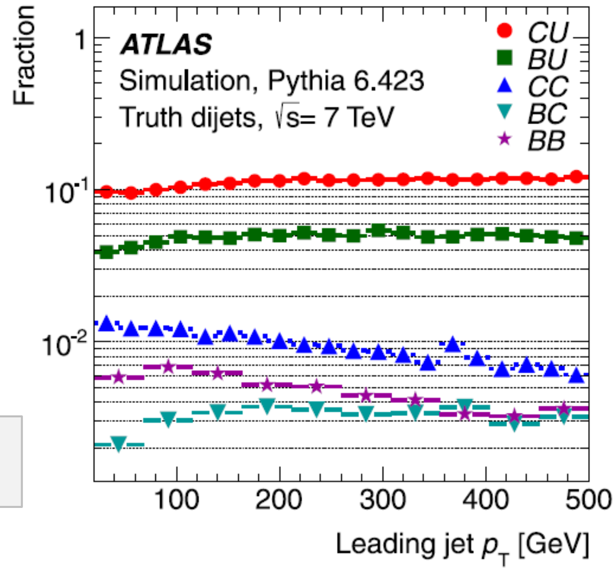
Classification ⇒

Light quarks (U): up, down and strange,

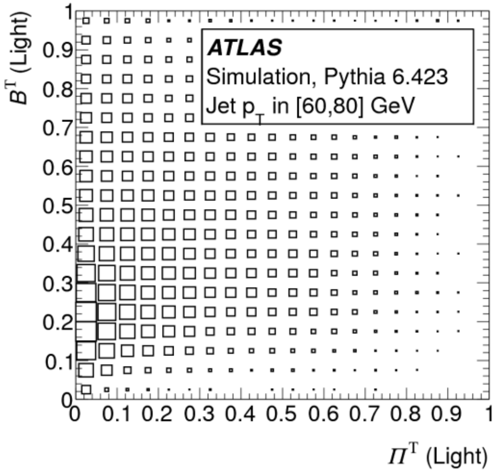
Heavy quarks: charm (C) and bottom (B)

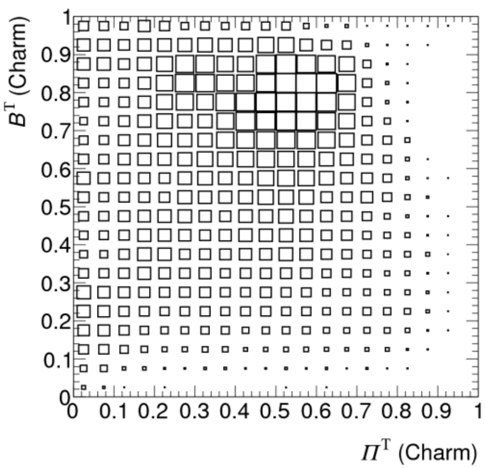
- Kinematic properties of the produced partons are mostly flavour independent .

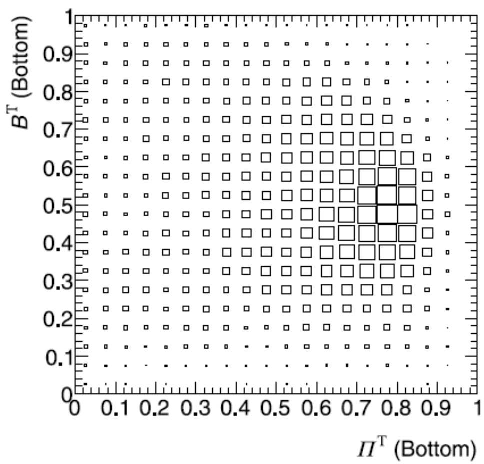
- A single secondary vertex is fitted for each jet.



To distinguish jet flavour: $$\Pi = \frac{m_{\text{vertex}} - 0.4\ \text{GeV}}{m_B} \cdot \frac{\sum_{\text{vertex}} E_i}{\sum_{\text{jet}} E_i}, \qquad B = \frac{\sqrt{m_B} \cdot \sum_{\text{vertex}} |\vec{p}_{\text{T}i}|}{m_{\text{vertex}} \cdot \sqrt{p_{\text{T jet}}}}$$

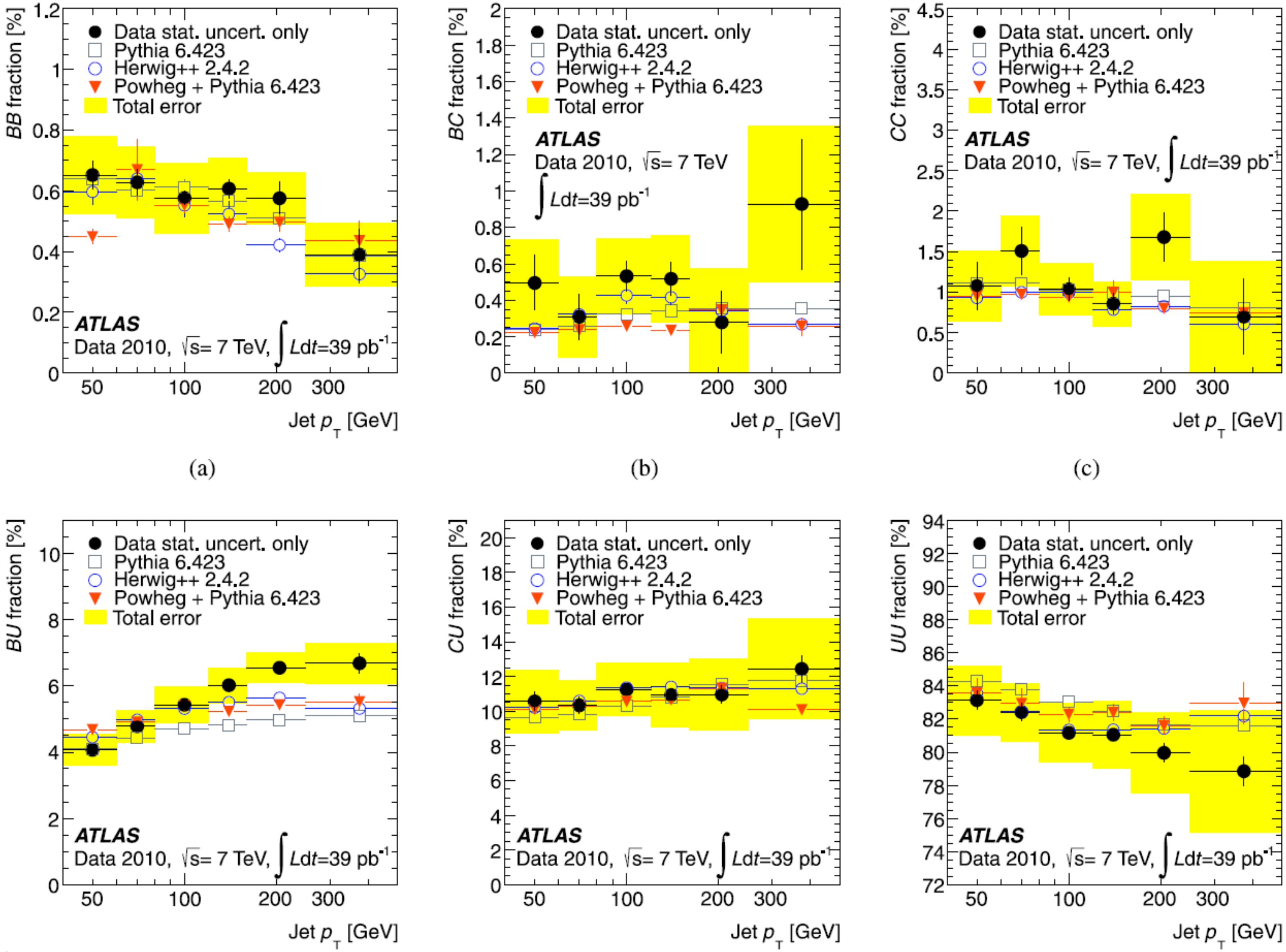






Dijet flavour: results

Dijet production fraction: Data vs MC (Pythia 6.423, Herwig++ 2.4.2, Powheg+Pythia)



Inclusive jet cross-section in *pp* at 7 TeV

⇒ Motivation: a test of validity of pQCD and probing of the parton distribution functions (PDFs) in the proton.

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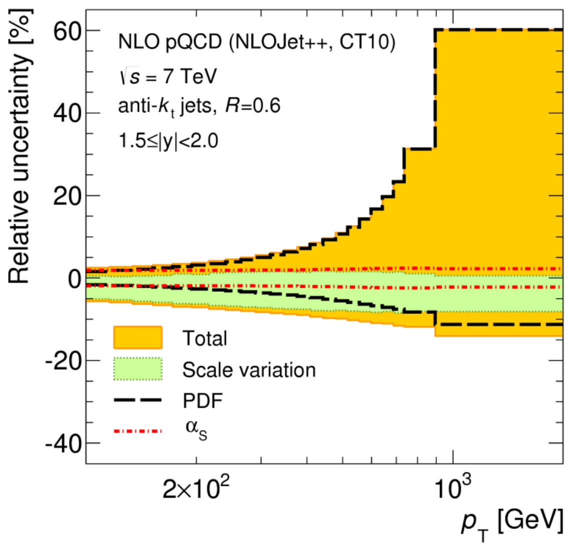
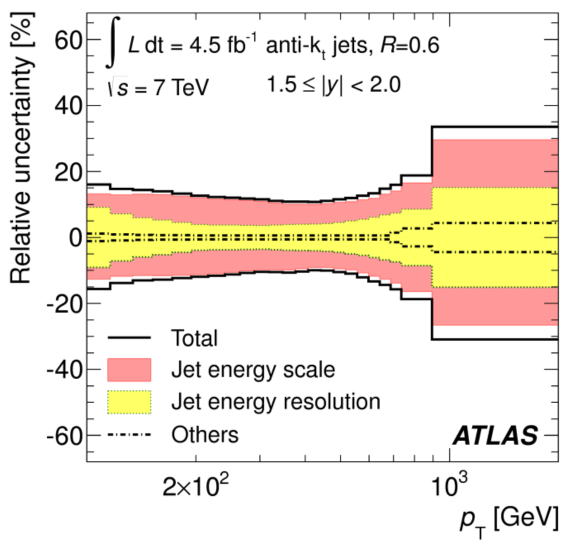
- ✓ Uncertainty in the NLO pQCD prediction of incl. Xsec vs jet p_T.
- ✓ Jet cross section unfolded to particle-level jets - to compare them with NLO pQCD: corrections for non-perturbative and EW effects is done.
- ✓ Theoretical predictions: NLO pQCD calculated by NLOJET++ 4.1.2 with several PDFs and different μ_R and μ_F – to cover missing high.-o. corrections.
- ✓ Experimental systematic uncertainties: Main sources: JES and jet energy resolution. For $|y|< 0.5$ and $p_T < 1$ TeV less than 10% -





Inclusive jet cross-section in *pp* at 7 TeV

Double-diff. inclusive jet X-sections for jets with R=0.4 vs jet p_T and rapidities
$\Rightarrow$ data vs NLO pQCD prediction corrected for non-perturb. and EW effects

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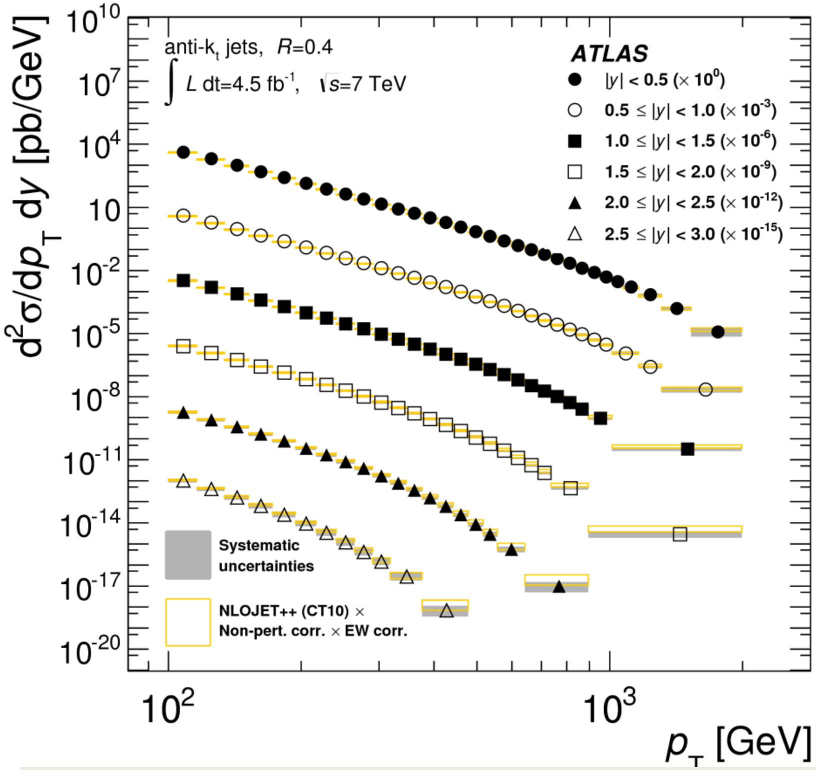

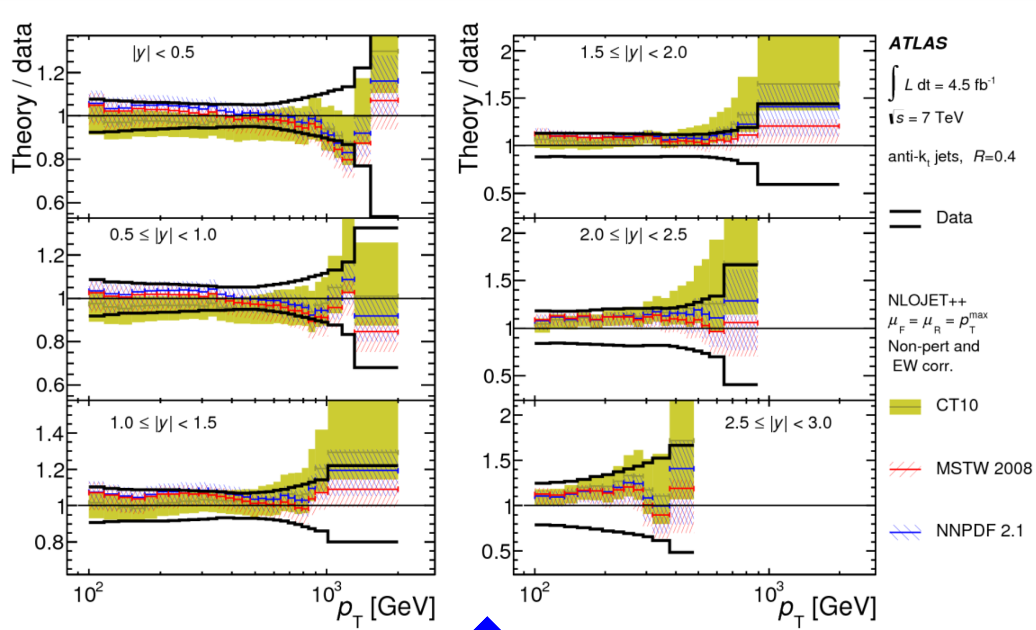

Ratio of NLO pQCD predictions to measured double-diff. inclusive jet X-section vs jet p_T and jet rapidity - different NLO PDF sets used: CT10, MSTW2008 and NNPDF 2.1.

3-jet production cross-section in *pp* at 7 TeV

Motivation: study of higher order effects of *p*QCD

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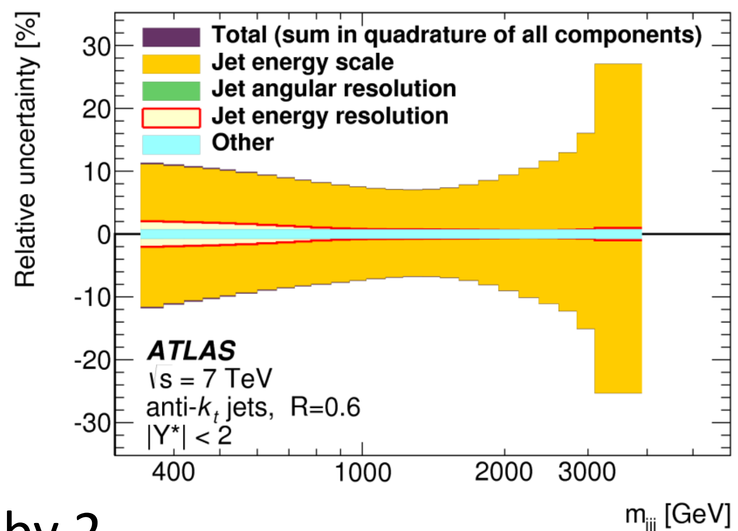
- 3-level jet trigger used: events with ≥ 3 jets – leading, subleading and sub-subleading jets are required: p_T >150 GeV, p_T >100 GeV and p_T > 50 GeV.
- 3-jet x-sections vs m_{jjj} in 5 bins of |Y*| (= $|y_1-y_2| + |y_2-y_3| + |y_1-y_3|$) < 10 - obtained by unfolding the data distributions to particle level.

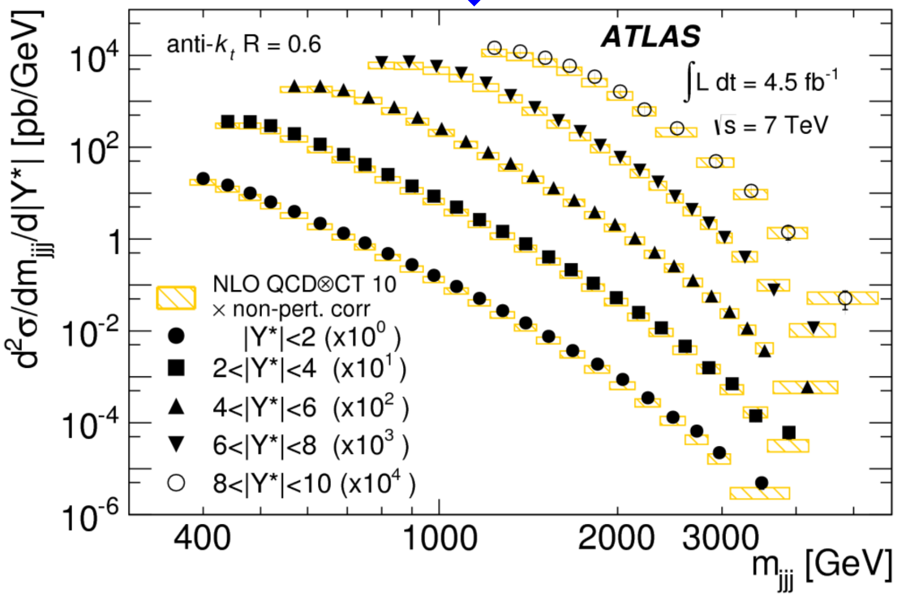
Experimental uncertainties: dominant is JES, jet energy and angular resolution ⇒ 8-10% for low m_{jjj}, 28% at high m_{jjj} at |Y*|< 6.

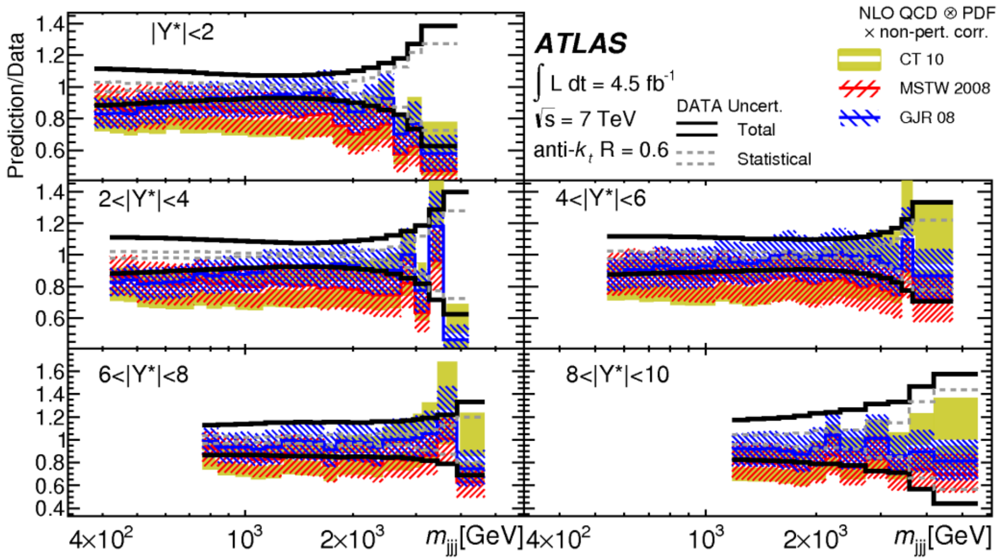


Theo. predictions and uncertainties: NLO QCD predictions (NLOJET++). Scale: $\mu_R = \mu_F = m_{jjj}$. Uncertainty due to missing h.o.: scale up/down by 2.

3-jet production cross-section at *pp* 7 TeV

3-jet double diff. x-sec vs m_{jjj} in 5 bins of |Y*| for jets with R= 0.6 compared with NLOJET++ prediction with CT 10 PDF corrected for non-perturb. effects





The ratio of NLO QCD predictions, obtained by using NLOJET++ with different PDF sets (CT 10, MSTW 2008, GJR 08) and corrected for non-perturbative effects, to data as a function of m_{jjj} in 5 bins of $|Y^*|$.

Jet shapes in tt-bar events in *pp* at 7 TeV

Motivation: in $t\bar{t}$ events jets are observed at large momentum-transfer $\Rightarrow$ a good place for study of jet shapes - to understand perturbative and non-perturbative phase of jet evolution.

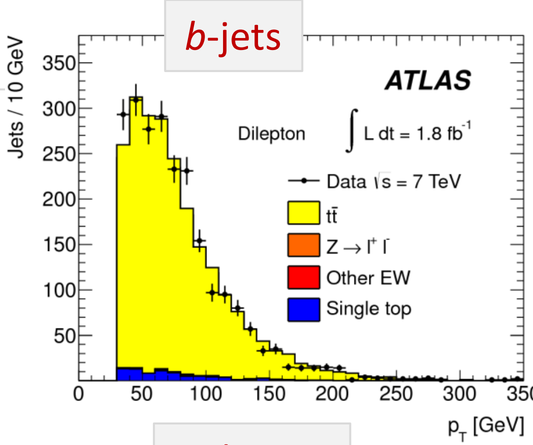
Aimed at $t\bar{t}$ final state *b*-jets (t→Wb), in lepton+jets and di-lepton channels, and light jets from $W^+ \to u\bar{d}, c\bar{s}$ + C.C.

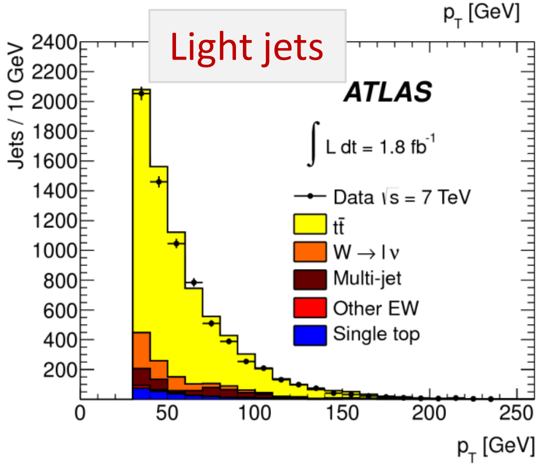
Two sample of jets selected:

- ✓ b-jet sample – b-tagging procedure based on NN algorithm (secondary vertex, impact parameter...)
- ✓ Light quark jet sample (decays $W \to q\bar{q}'$)

Jet purities

- ***l*** + jets: ***b***-jets $(88.5 \pm 5.7)\%$, light jets $(66.2 \pm 4.1)\%$
- Dilepton: ***b***-jets $(99.3\ ^{+0.7}_{-6.5})\ \%$





Jet shapes in tt-bar events in *pp* at 7 TeV

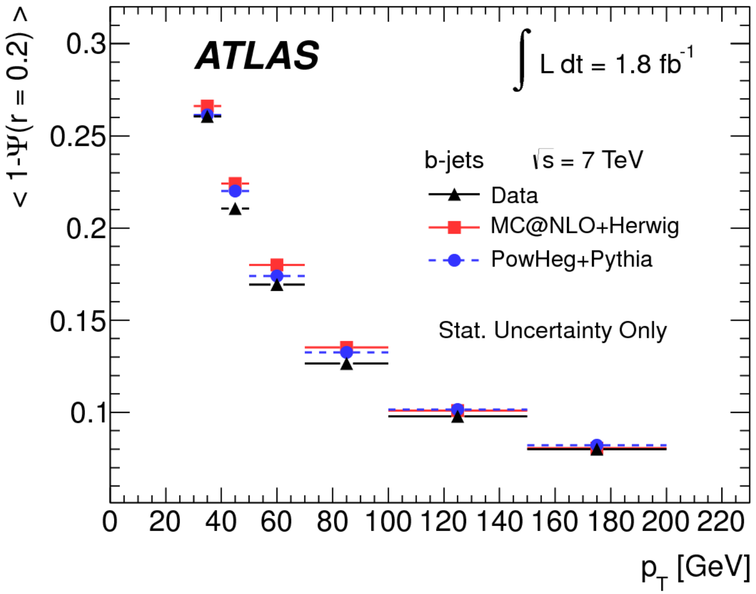
Differential jet shape

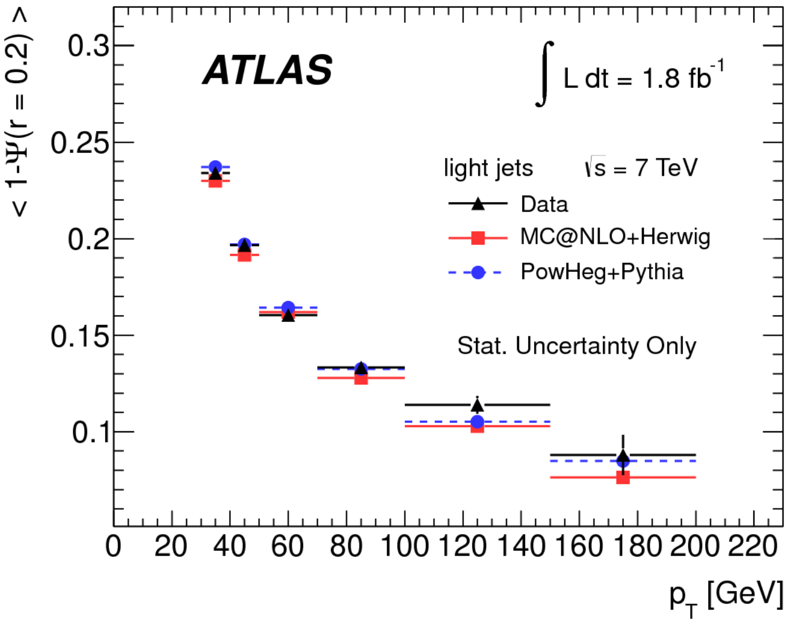
$$\rho(r) = \frac{1}{\Delta r}\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)}$$

Integrated jet shape

$$\Psi(r) = \frac{p_T(0,r)}{p_T(0,R)}, r < R$$

r ≡ distance to the jet axis in the η-φ plane and $p_T(r_1, r_2)$ ≡ scalar sum of the p_T of the jet constituents with radii between r_1 and r_2 .

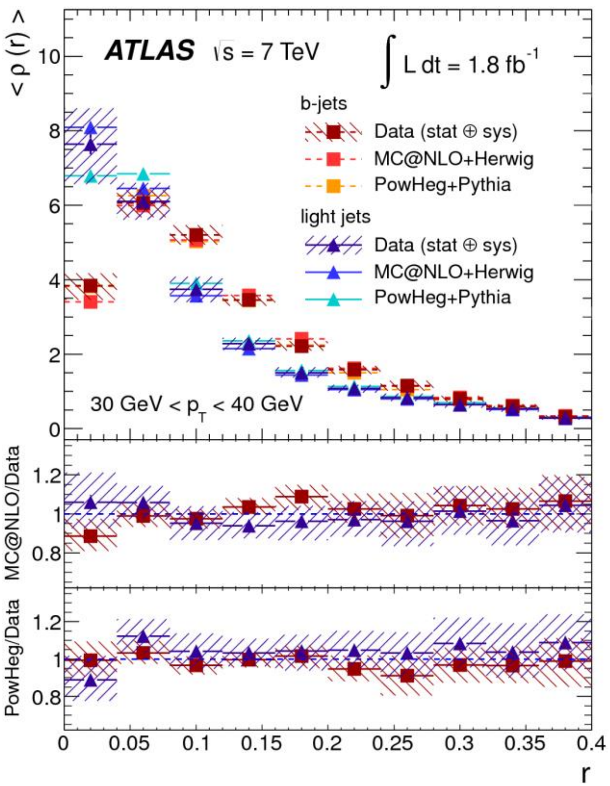


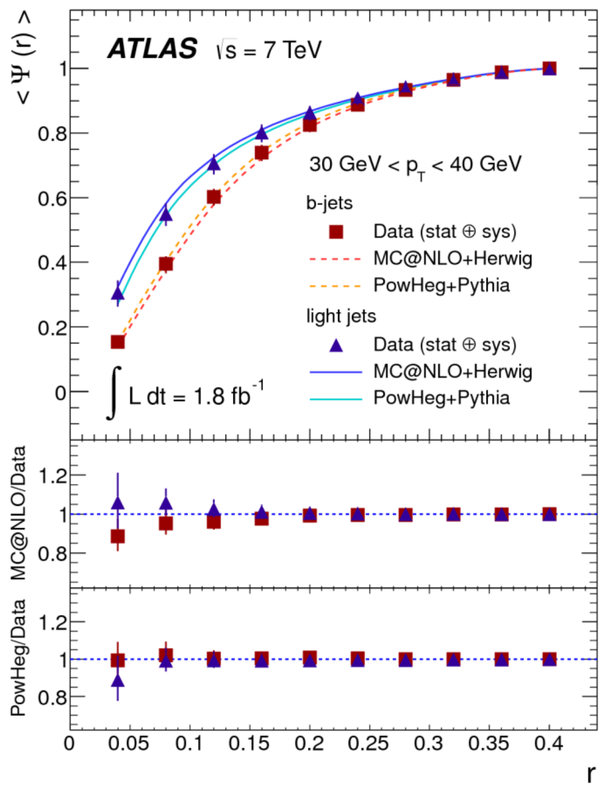


Dependence of the *b*-jet (*left*) and light-jet (*right*) shapes on the jet p_T.

<1 – $\Psi(r = 0.2)$> ≡ fraction of energy in the outer part of jet cone (***l***+jets events).

Jet shapes and uncertainties





Data vs theory:
good agreement
(see also p. 24)

Diff. shape systematics:

- ✓ energy of individual clusters inside jet is varied : 2-10%.
- ✓ et energy resolution: 5%.
- ✓ Pile-up (vs r): 2-10%.
- ✓ Unfolding (3 MC generators used): 1 - 8%.

Differential (integrated) jet shapes *<ρ(r)>* (<Ψ(r)>) *vs* ***r*** for **light jets** (*triangles*) and ***b*-jets** (*squares*). The data vs different MC for 30 GeV < p_T < 40 GeV.

The uncertainties: statistical ⊕ systematic sources.

Conclusions

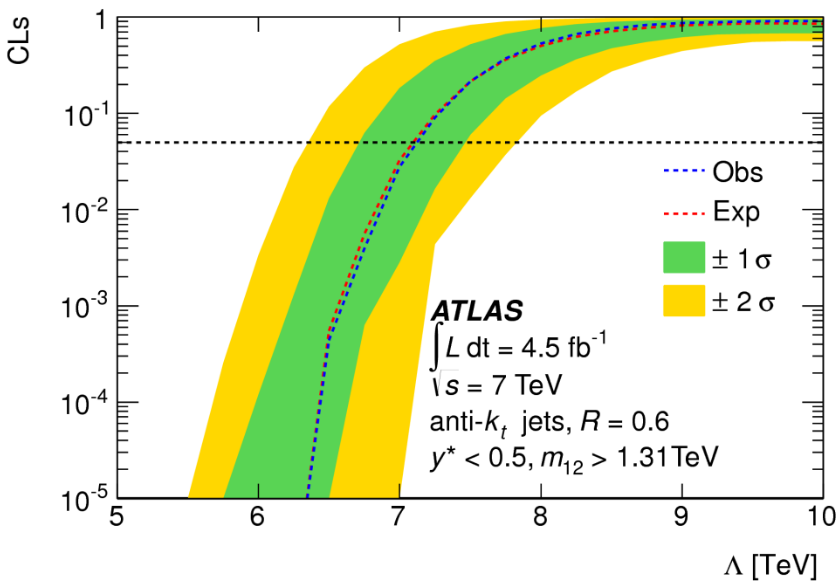
- Jet physics provide us with powerful means for testing QCD – a lot of interesting results at 7TeV obtained.
- Measured differential cross section for
  - Dijet production *vs* dijet mass and rapidity.
  - Inclusive jet production *vs* jet $\boldsymbol{p_T}$ and **y.**
  - Three-jet production vs m_{jjj} and |Y*|.

  Good consistency between the data and SM predictions found.
- Using di-jet events the quark composite scale Λ, excluded below 7 TeV.
- Flavor dijet decomposition for different jet combinations measured – giving good agreement with the SM predictions.
- Using $t\bar{t}$ events the b-jet and light jet shapes *vs* distance to jet axis and jet $\boldsymbol{p_T}$ were measured – good agreement with SM expectations.

Back up

Exclusion of contact interactions

- ✓ If quarks are composed of more fundamental particles with new strong interactions at a composite scale Λ (>> m_{quark}) $\Rightarrow$ at energies <<Λ: contact interaction from the underlying strong dynamics $\rightarrow$ observable effect.
- ✓ Model of QCD + contact interactions (CIs) with left–left coupling and destructive interference between CIs and QCD is considered.
- ✓ Measurement is restricted to the high dijet-mass m_{12} > 1.31 TeV in the range y^* < 0.5 (CIs: events preferentially produced at smaller y*).



PDF set / Λ[TeV]	R=0.4 Exp	Obs
CT10	7.3	7.2
HERAPDF1.5	7.5	7.7
MSTW 2008	7.3	7.0
NNPDF2.1	7.3	7.2

Measured cross section vs NLO QCD + CIs predictions: scan of CLs value for NLO QCD + CIs as a function of Λ, using the CT10 PDF set….

Dijet flavour decomposition

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Flavour decomposition measurement: pp collision at $\sqrt{s}$ = 7TeV, L_{int}= 39 pb^{-1} .

- ✓ 3-level single jet trigger: events with jet $\boldsymbol{p}_{\mathrm{T}}$ over a threshold for $|\eta|<3.2$.
- ✓ At least one reconstructed primary vertex candidate.
- ✓ A candidate vertex: at least 10 tracks with p_{T} > 150 MeV associated to it.
- ✓ Jets: used anti-k_t algorithm with R = 0.4 , jets with p_{T} > 30 GeV + |y|<2.1 and 2 highest p_{T} jets with back-to-back topology: $\Delta\varphi$ > 2.1.
- ✓ Investigated jet p_{T} intervals:

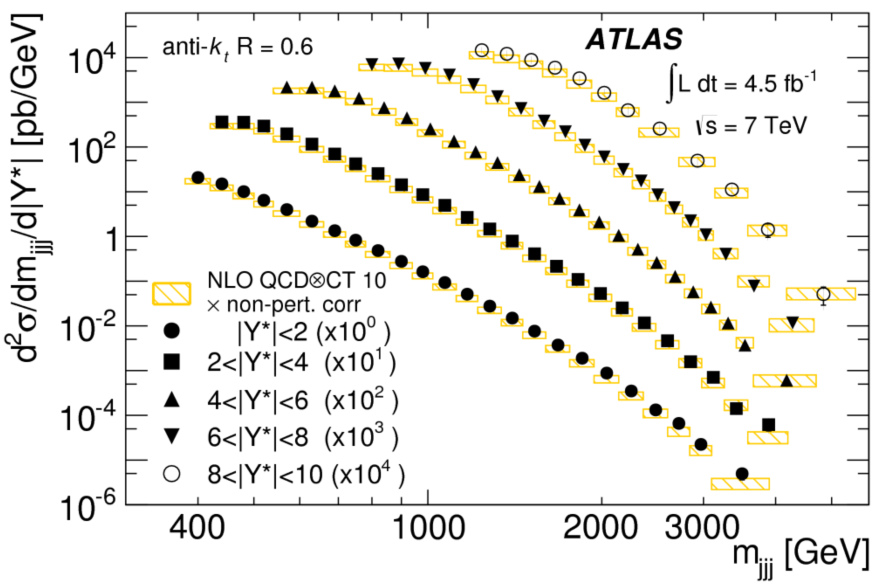
Lead. jet p_{T}[GeV]	40 - 60	60 - 80	80 – 120	120 – 160	160 – 250	250 – 500
sLead. Jet p_{T}[GeV]	30 - 60	40 - 80	50 – 120	75 – 160	100 – 250	140 – 500

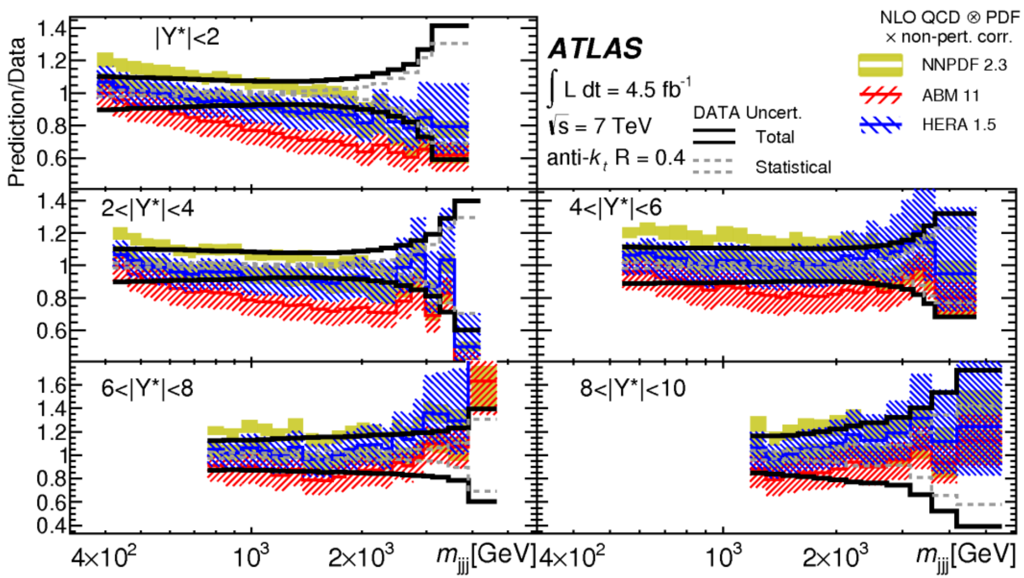
MC generators:

- Pythia 6.423 (LO parton matrix element for 2$\rightarrow$2 processes) for template construction.
- NLO generator Powheg for interpretation of the analysis results.

3-jet production cross-section at *pp* 7 TeV

3-jet double diff. x-sec vs m_{jjj} in 5 bins of $|Y^*|$ for jets with R= 0.6 compared with NLOJET++ prediction with CT 10 PDF corrected for non-perturb. effects





The ratio of NLO QCD predictions, obtained by using NLOJET++ with different PDF sets (NNPDF 2.3, ABM 11, HERA 1.5) and corrected for non-perturbative effects, to data as a function of m_{jjj} in 5 bins of $|Y^*|$.

Diff. and integral jet shapes for jet p_T intervals