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

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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 $t\bar{t}$ 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 $1\text{fb}^{-1} = 7 \times 10^{13}$ inel. int. of pp

This talk: only results based on 7 TeV data

Level of pileup

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: $p_T > 100 \text{ GeV}$ ($> 50 \text{ GeV}$).
- ✓ Only events collected during stable beam conditions - at least one primary vertex, reconstructed ≥ 2 tracks with $p_T > 400 \text{ MeV}$.
- ✓ 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 $\eta = 0.5$ and $\eta = 2.0$.

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: $\mu = \mu_R = \mu_F = p_T^{\max} e^{0.3 y^*}$.

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.

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 ($\gg m_{\text{quark}}$) $\Rightarrow$ at energies $\ll \Lambda$: 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 $m_{12} > 1.31 \text{ TeV}$ in the range $y^* < 0.5$ (CIs: events preferentially produced at smaller y^*).

PDF set / $\Lambda[\text{TeV}]$	R=0.6	
	Exp	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
 $< 3 \cdot 10^{-20} \text{ m}$

Measured cross section vs NLO QCD (yellow line)
and NLO QCD + CIs with $\Lambda=6.5 \text{ TeV}$ (red line) predictions, CT10 PDF set used.

Dijet flavour decomposition

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

Heavy quarks participating in the hard scattering:

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

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

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

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 $|\eta| < 2.1$.

Dijet flavour: predictions and reconstruction

Classification $\Rightarrow$

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: $\Pi = \frac{m_{\text{vertex}} - 0.4 \text{ GeV}}{m_B} \cdot \frac{\sum_{\text{vertex}} E_i}{\sum_{\text{jet}} E_i},$

$$B = \frac{\sqrt{m_B} \cdot \sum_{\text{vertex}} |\vec{p}_{Ti}|}{m_{\text{vertex}} \cdot \sqrt{p_{T\text{jet}}}}$$

Dijet flavour: results

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

(a)

(b)

(c)

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.

- ✓ 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% -

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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 $\Rightarrow$ 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 $t\bar{t}$ 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** ($t \rightarrow Wb$), in lepton+jets and di-lepton channels, and light jets from $W^+ \rightarrow u\bar{d}, c\bar{s} + \text{C.C.}$

Two sample of jets selected:

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

Jet purities

- $l + \text{jets}$: **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 $t\bar{t}$ -bar events in pp at 7 TeV

Differential jet shape

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

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

Integrated jet shape

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

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

$\langle 1 - \Psi(r = 0.2) \rangle \equiv$ 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 $\langle \rho(r) \rangle$ ($\langle \Psi(r) \rangle$) vs r for light jets (triangles) and **b-jets** (squares). The data vs different MC for $30 \text{ GeV} < p_T < 40 \text{ GeV}$.

The uncertainties: statistical $\oplus$ 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 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 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 ($\gg m_{\text{quark}}$) $\Rightarrow$ at energies $\ll \Lambda$: 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 $m_{12} > 1.31 \text{ TeV}$ in the range $y^* < 0.5$ (CIs: events preferentially produced at smaller y^*).

PDF set / Λ [TeV]	R=0.4	
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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 $\sqrt{s} = 7\text{TeV}$, $L_{\text{int}} = 39 \text{ pb}^{-1}$.

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