Inclusive and Dijet Jet Production Measured with the ATLAS Detector

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Overview

• Introduction
• Theory predictions and Jet Reconstruction
• High Mass Dijet cross sections
  • up to invariant mass 4.6 TeV
• Inclusive jet cross sections
  • $\sqrt{s} = 7$ and $\sqrt{s} = 2.76$ TeV
• Conclusions
Introduction

- **QCD Jet Production** is a **dominant process** at the LHC
  - Probes the TeV scale

- **Many reasons to study the production of jets:**
  - Test of QCD predictions at high energy
  - Constraints for Parton Distribution Functions
  - Measurement of strong coupling strength
  - Important backgrounds for many analyses

- Many analyses study jets and jet production at ATLAS
  - Presented here: **inclusive and dijet cross section** measurements

2011 dijet event: invariant mass 4.0 TeV
Theory Predictions

Jet cross sections and ratios compared to NLO theory predictions

• **NLOJET++**
  - pQCD calculations at NLO
  - CT10 NLO Parton Distribution Functions as nominal
  - Also compare to MSTW2008, NNPDF2.1, HERAPDF1.5 PDFs, ABM 11 NLO
  - Bin-by-bin multiplicative factors applied for hadronisation and underlying event
    - Pythia 6.425 with AUET2B tune

• **POWHEG**
  - NLO matrix element calculation
  - CT10 NLO PDFs
  - Parton shower matched to Pythia or Herwig
    - Improved theoretical predictions expected
    - Additional uncertainties due to matching and tuning of parton shower

Results in **data are unfolded to particle level** for comparison to theory
Jet Reconstruction and Calibration

- Jets reconstructed from electromagnetic clusters of calorimeter cells using **Anti-\(k_t\) algorithm with \(R = 0.4\) and \(R = 0.6\)**

- Jet Energy Scale calibration applied:
  - Pile-up offset correction
  - Origin correction
  - JES & \(\eta\) calibration
  - Calorimeter jets (EM+JES or LCW+JES scale)

- Jet Energy Scale (JES) **dominant experimental uncertainty**

Uncertainties derived from single hadron response and Monte Carlo simulation

Uncertainties confirmed using insitu response measurements
Dijet production at $\sqrt{s} = 7$ TeV

- $\sqrt{s} = 7$ TeV, luminosity 4.8 fb$^{-1}$
- $260 \text{ GeV} \leq m_{12} \leq 4.6$ TeV
- Binned in $y^* = \frac{|y_1 - y_2|}{2}$, $y^* < 2.5$

ATLAS Preliminary

anti-$k_t$ jets, $R = 0.6$

$\sqrt{s} = 7$ TeV, $\int L \, dt = 4.8$ fb$^{-1}$

2011 Data
Dijet production at $\sqrt{s} = 7$ TeV

- Ratios to NLOJET++ with CT10 PDF
- In general data is in agreement with theory predictions
  - Differences up to 40% at high $y^*$ & dijet mass: theory predictions overestimate cross section

**ATLAS CONF-2012-021**

NLOJET++ and POWHEG

NLOJET++ with different PDFs
Inclusive jet cross section measurements at two different $\sqrt{s}$

- $\sqrt{s} = 7$ TeV, luminosity $37$ pb$^{-1}$
  - $20$ GeV $\leq$ Jet $p_T$ $\leq$ $1.5$ TeV, $|y| < 4.4$
- $\sqrt{s} = 2.76$ TeV, luminosity $0.20$ pb$^{-1}$
  - Close to highest energy $p\bar{p}$ collisions
  - $20 \leq p_T \leq 430$ GeV, $|y| < 4.4$

Comparison to NLOJET++ with different PDF sets

- Ratio with respect to NLOJET++, CT10 PDFs
- Good agreement within systematic uncertainties
- Data systematically lower than theory prediction
  - Particularly at high pt and rapidity
  - MSTW follows trend better

\[ \int L \, dt = 37 \, \text{pb}^{-1} \]
\[ \sqrt{s} = 7 \, \text{TeV} \]
\[ \text{anti-}k_t \text{ jets, } R=0.4 \]

\[ \int L \, dt = 0.20 \, \text{pb}^{-1} \]
\[ \sqrt{s} = 2.76 \, \text{TeV} \]
\[ \text{anti-}k_t \text{, } R=0.4 \]

Data with statistical error
Systematic uncertainties

MSTW 2008
NLO pQCD ⊗ non-pert. corrections

NLOJET ++ (μ=ρ_rk)
Non-pert. corr.

CT10
NNPDF 2.1
HERAPDF 1.5

CT10
MSTW 2008


Anti – \( k_t \) R = 0.4 jets
New version of POWHEG BOX used for $\sqrt{s} = 2.76$ TeV predictions

- At $\sqrt{s} = 7$ TeV problem with parton shower matching caused fluctuations in final observables
- New version with modified matching scale released by POWHEG BOX authors (arXiv:1303.3922v1)

Old version: used for $\sqrt{s} = 7$ TeV

New version: used for $\sqrt{s} = 2.76$ TeV

Comparison to POWHEG with different parton showers and tunes

- Ratio with respect to NLOJET++, CT10 PDFs
- Best agreement with POWHEG + Pythia AUET2B
- New matching parameters in POWHEG for $\sqrt{s} = 2.76$ TeV
- Agreement with data within uncertainties

\[ \int L \, dt = 0.20 \text{ pb}^{-1} \]
\[ \sqrt{s} = 2.76 \text{ TeV} \]
\[ \text{anti-}k_t \, R = 0.4 \]

Data with statistical error
Systematic uncertainties
NLOJET++ (CT10, $\mu = p_T^{\text{beam}}$) ×
Non-pert. corr.
POWHEG (CT10, $\mu = p_T^{\text{beam}}$) ⊗
PYTHIA Perugia 2011
POWHEG (CT10, $\mu = p_T^{\text{beam}}$) ⊗
HERWIG AUET2
POWHEG fixed order (CT10, $\mu = p_T^{\text{beam}}$) ×
Non-pert. corr.

\[ p_T [\text{GeV}] \]
\[ \text{Ratio wrt NLO pQCD (CT10)} \]
\[ |y| < 0.3 \]
\[ 7 \text{ TeV} \]

\[ |y| < 0.3 \]
\[ 2.76 \text{ TeV} \]

\[ p_T [\text{GeV}] \]
\[ \text{Ratio wrt NLO pQCD (CT10)} \]
\[ 3.6 \leq |y| < 4.4 \]

\[ \text{EPSHEP 2013: Inclusive and Dijet production measured with the ATLAS detector} \]

Inclusive jets: ratio of $\sqrt{s} = 7$ and 2.76 TeV

- Jet cross sections as function of jet $p_T$ and $x_T = \frac{2p_T}{\sqrt{s}}$
- Ratios of cross sections at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 2.76$ TeV reduce uncertainties:

$$\rho(y, x_T) = \left(\frac{2.76 \text{ TeV}}{7 \text{ TeV}}\right)^3 \frac{\sigma(y,x_T,2.76 \text{ TeV})}{\sigma(y,x_T,7 \text{ TeV})}$$

$$\rho(y, p_T) = \frac{\sigma(y,p_T,2.76 \text{ TeV})}{\sigma(y,p_T,7 \text{ TeV})}$$

theoretical uncertainties reduced

experimental uncertainties reduced

arXiv:1304.4739
• $\rho(y, x_T)$ ratio shows very **good agreement** with NLOJET++ and POWHEG
  - Constant behaviour with $x_T$
    => QCD asymptotic freedom and evolution of gluon PDF with QCD scale
  - Differences between different tunes are small
  - Theory uncertainties are very small

• $\rho(y, p_T)$ ratio shows **differences in central region** up to 10%
  - POWHEG follows data well in forward region
  - Experimental uncertainties are very small

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**Cross section ratio theory comparison**

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EPSHEP 2013: Inclusive and Dijet production measured with the ATLAS detector

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arXiv:1304.4739

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Cross section ratio PDF comparisons

$\rho(y, p_T)$ ratio compared to different PDFs:

- Data higher in central region and lower in forward region
  - larger deviation for ABM11 NLO

- Systematic uncertainty smaller than theory uncertainty

$\Rightarrow \sqrt{s} = 7$ TeV and $\sqrt{s} = 2.76$ TeV inclusive cross sections can be used to constrain PDFs
Conclusions

- Jet cross sections have been measured with the ATLAS detector and compared to NLO pQCD predictions

- **Dijet cross sections** measured at $\sqrt{s} = 7$ TeV
  - Good agreement with theoretical predictions
  - Differences at high energies and rapidities of up to 40%

- **Inclusive jet cross sections** measured at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 2.76$ TeV
  - In general good agreement with theoretical predictions
  - Cross sections can be used to constrain PDFs
Back-up slides
The ATLAS Detector

EPSHEP 2013: Inclusive and Dijet production measured with the ATLAS detector
Triggers : Inclusive jet Cross section

- Triggers used:
  - Minimum-Bias trigger scintillators for jets 20 – 60 GeV
  - Central jet trigger : $|\eta| < 3.2$
  - Forward jet trigger : $3.1 < |\eta| < 4.9$
- Different trigger in each $p_T$ bin
  efficiency > 99 % with smallest possible prescale

Combined L1 + L2 trigger efficiencies
Triggers: Dijet Cross section

- Central jet triggers $|\eta| < 3.2$
- Jet energy fully contained in central trigger towers => trigger is unbiased
- Highest $E_{T}^{EM}$ trigger unprescaled
- Different threshold for each trigger in the analysis
  > 99% efficiency with the smallest possible prescale
Inclusive Jets: $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 2.76 \text{ TeV}$

Inclusive jet cross section measurements at two different $\sqrt{s}$

- $\sqrt{s} = 7 \text{ TeV}$, luminosity 37 pb$^{-1}$
  - $20 \text{ GeV} \leq \text{Jet } p_T \leq 1.5 \text{ TeV}, \ |y| < 4.4$

- $\sqrt{s} = 2.76 \text{ TeV}$, luminosity 0.20 pb$^{-1}$
  - Similar $\sqrt{s}$ as at Tevatron
  - $20 \leq p_T \leq 430 \text{ GeV}, \ |y| < 4.4$


Anti – kt $R = 0.4$ jets
Comparison to NLOJET++ with different PDF sets

- Ratio with respect to NLOJET++, CT10 PDFs
- Good agreement within systematic uncertainties
- Data systematically lower than theory prediction
  - Particularly at high pt and rapidity
  - MSTW follows trend better

2.76 TeV

ATLAS

\[ \int L d^2 \rho = 0.20 \text{ pb}^{-1} \]
\[ \sqrt{s} = 2.76 \text{ TeV} \]
\( \text{ Anti-kt } R = 0.4 \text{ jets} \)

ATLAS

\[ \int L d^2 \rho = 37 \text{ pb}^{-1} \]
\( \sqrt{s} = 7 \text{ TeV} \)
\( \text{ Anti-kt } R = 0.4 \text{ jets} \)

Data with statistical error

Systematic uncertainties

NLOJET++ [3+PDF]
Non-pert. corr.

CT10

MSTW 2008

NNPDF 2.1

HERAPDF 1.5

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Inclusive Jets: Cross section with NLOJET++

Comparison to NLOJET++ with different PDF sets

- Ratio with respect to NLOJET++, CT10 PDFs
- Good agreement within statistical uncertainties
- Data systematically lower
  - Particularly at high pt and rapidity

\[ \int \text{d}^2 \mathbf{p}_t \, \frac{\text{d} \sigma}{\text{d} \mathbf{p}_t} \]

Anti – kt R = 0.6 jets

Inclusive Jets: Cross section with POWHEG

Comparison to POWHEG with different parton showers and tunes

- Ratio with respect to NLOJET++, CT10 PDFs
- Best agreement with POWHEG + Pythia AUET2B
- New matching parameters in POWHEG for $\sqrt{s} = 2.76$ TeV
  - Agreement with data within uncertainties


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Comparison to POWHEG with different parton showers and tunes

- Ratio with respect to NLOJET++, CT10 PDFs
- Best agreement with Pythia AUET2B
- New matching parameters in POWHEG for $\sqrt{s} = 2.76$ TeV
  - Agreement with data within uncertainties

ATLAS

$\int L \, dt = 37 \text{ pb}^{-1}$

$\sqrt{s} = 7$ TeV

$\text{anti-kt, } R = 0.6$

Data with statistical error

Systematic uncertainties

- NLOJET++
- Powheg $\mu_F = 2 \text{ GeV}$
- Pythia AUET2B
- Powheg $\mu_F = 2 \text{ GeV}$
- Pythia Augeas2011
- Powheg

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http://arxiv.org/abs/1304.4739

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Anti – kt $R = 0.6$ jets
Cross section ratio theory comparison

- $\rho(y, x_T)$ ratio shows very **good agreement** with NLOJET++ and POWHEG
  - Constant behaviour with $x_T$
    => QCD asymptotic freedom and evolution of gluon PDF with QCD scale
  - Differences between different tunes are small
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- $\rho(y, p_T)$ ratio shows **differences in central region** up to 10%
  - POWHEG follows data well in forward region
  - Experimental uncertainties are very small

**ATLAS**

\[
\int L \, dt = 0.20 \, \text{pb}^{-1}
\]
\[
p = \frac{e^{2.75 \, \text{y} / \sigma_{\text{jet}}}}{\sigma_{\text{jet}}}
\]
anti-$k_t$, $R = 0.6$

Data with statistical uncertainty

- Systematic uncertainties

- NLO pQCD
  - non-perf. corr. ($\text{CT10, } \mu = \mu_F$)

- POWHEG: PYTHIA
  - tune A/JET2B ($\text{CT10, } \mu = \mu_F$)
  - tune Perugia 2011 ($\text{CT10, } \mu = \mu_F$)

**arXiv:1304.4739**

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Cross section ratio theory comparison

- $\rho(y, x_T)$ ratio shows very **good agreement** with NLOJET++ and POWHEG
  - Constant behaviour with $x_T$
    - $\Rightarrow$ QCD asymptotic freedom and evolution of gluon PDF with QCD scale
  - Differences between different tunes are small
  - Theory uncertainties are very small

- $\rho(y, p_T)$ ratio shows **differences in central region** up to 10%
  - POWHEG follows data well in forward region
  - Experimental uncertainties are very small

http://arxiv.org/abs/1304.4739
Inclusive jets: HERA + ATLAS PDFs

- **ATLAS jet cross sections** at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV used to constrain PDFs
  - HERA + ATLAS PDF set
  - Comparison to inclusive jet cross section at $\sqrt{s} = 2.76$ TeV and $\rho(y, p_T)$
- **Good agreement** is seen with HERA + ATLAS PDF
  - Particularly in the forward region

Inclusive jet cross section

$\rho(y, p_T)$

[Graphs and data plots showing comparisons and ratios]

http://arxiv.org/abs/1304.4739

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Cross section ratio PDF comparisons

$\rho(y, p_T)$ ratio compared to different PDFs:

- Data higher in central region and lower in forward region
  - larger deviation for ABM11 NLO
- Systematic uncertainty smaller than theory uncertainty

$\Rightarrow \sqrt{s} = 7$ TeV and $\sqrt{s} = 2.76$ TeV inclusive cross sections can be used to constrain PDFs

**ATLAS**

\[
\int L \, dt = 0.20 \text{ pb}^{-1}
\]

\[
\rho = \frac{\sigma_{2.76 \text{ TeV}}}{\sigma_{7 \text{ TeV}}}
\]

anti-$k_t$, $R = 0.6$

Data with statistical uncertainty

Systematic uncertainties

NLO pQCD @ non-pert. corrections

- CT10
- MSTW 2008
- NNPDF 2.1
- HERAPDF 1.5
- ABM 11 NLO

arXiv:1304.4739
Inclusive jets: experiment comparisons

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http://arxiv.org/abs/1304.4739
Dijet production at $\sqrt{s} = 7$ TeV

- Ratios to NLOJET++ with CT10 PDF
- In general data is in agreement with theory predictions
  - Differences up to 40% at high $y^*$ & dijet mass: theory predictions overestimate cross section

ATLAS-CONF-2012-021

Anti – $kt$ $R = 0.6$ jets

NLOJET++ and POWHEG

NLOJET++ with different PDFs
Dijet production at $\sqrt{s} = 7$TeV

- Ratios to NLOJET++ with CT10 PDF
- In general, data is in agreement with theory predictions
  - Differences up to 40% at high $y^*$ & dijet mass: theory predictions overestimate cross section

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Anti – kt $R = 0.4$ jets

NLOJET++ and POWHEG

NLOJET++ with different PDFs
Jet Energy Scale with 2011 data

• 2010 Jet Energy Scale and uncertainties used for all analyses presented here

• 2011 Jet Energy Scale calibration scheme:

  - Calorimeter jets (EM or LCW scale)
  - Pile-up offset correction
    - Corrects for the energy offset introduced by pile-up.
    - Depends on $\mu$ and $N_\text{vtx}$.
    - Derived from MC.
  - Origin correction
    - Changes the jet direction to point to the primary vertex.
    - Does not affect the energy.
  - Energy & $\eta$ calibration
    - Calibrates the jet energy and pseudorapidity to the particle jet scale.
    - Derived from MC.
  - Residual $in situ$ calibration
    - Residual calibration derived using $in situ$ measurements.
    - Derived in data and MC.
    - Applied only to data.
  - Calorimeter jets (EM+JES or LCW+JES scale)

• Jet Energy Scale (JES) uncertainties in 2011 derived from insitu analyses

![Graph showing fractional JES uncertainty vs. $p_T^{\text{jet}}$](graph.png)

- Anti-$k\, R=0.4$, EM+JES $in situ$ correction
- Data 2011, $\sqrt{s}=7 \text{ TeV}$, $L=4.7 \text{ fb}^{-1}$
- $\eta = 0.5$