QCD RESULTS USING JETS AND PHOTONS IN ATLAS
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Outline

- Motivation
- The building blocks
- Benchmark measurements
- Completing the picture
- Summary
- Prospects
Motivation

- Fundamental test of QCD in a new energy regime
- Feedback to searches of new physics
Photon Reconstruction and Identification

- Energy measurement: all layers

- Photon identification:
  - Granularity in all layers exploited
  - First layer eta granularity helpful for $\pi^0$ rejection
Photon Purity Calculation

- Isolation energy to increase purity
- Purity uses template fits, templates extracted from control regions
- Cross checks with additional methods
• High purity at high $p_T$

• Systematics dominated by identification control region definition

• Signal leakage into control regions also important systematic

Systematic Uncertainties in the Jet Energy Scale

• Jet energy scale uncertainty primarily from single-particle analyses

• Additional uncertainties from \( \eta \) intercalibration results
• Data and NLO calculation agree

• Measurements cover $E_T^{\gamma}$ from 15 to 400 GeV (and up to $|\eta|=2.37$)

• Systematic uncertainties comparable to NLO calculation accuracy ($\sim 10\%$)
• Divide phase space to change different contributions

• Results consistent with prompt photon measurement
Data agree with NLO calculations in $p_T^{\gamma\gamma}$ and $m^{\gamma\gamma}$ distributions.

NLO/NNLL calculations predict narrower $\Delta\phi^{\gamma\gamma}$.
Inclusive and Dijet Analyses: Important Considerations

- 2010 final inclusive jet analysis close to reaching kinematic limit

- Dijet cross section is binned in

\[ y^* = \frac{|y_1 - y_2|}{2} \]

- Enters choice of renormalization scale

(*) arXiv:1112.6297
Inclusive Jet Cross Section Results

\[ \int L \, dt \cdot 37 \, \text{pb}^{-1}, \sqrt{s} = 7 \, \text{TeV} \]

\[ \frac{d^2 \sigma}{d \rho_T \, dy} \, [\text{pb/GeV}] \]

- \( y \leq 0.3 \times 10^{-5} \)
- \( 0.3 \leq y < 0.6 \times 10^{-5} \)
- \( 0.8 \leq y < 1.2 \times 10^{-5} \)
- \( 1.2 \leq y < 2.1 \times 10^{-5} \)
- \( 2.1 \leq y < 2.8 \times 10^{-5} \)
- \( 2.8 \leq y < 3.6 \times 10^{-5} \)
- \( 3.6 \leq y < 4.4 \times 10^{-5} \)

Systematic uncertainties
NLOJET++ (CT10, \( \mu = \mu_{\text{max}} \) ×
Non-perl. corr.

\( \text{ATLAS} \)

\( \text{arXiv:1112.6297} \)
Inclusive Jet Cross Section Results

![Graphs showing inclusive jet cross section results from ATLAS experiment. The graphs display the ratio of ATLAS data to CT10 predictions for different rapidity bins. The plots include comparisons with NLOJET++ and other PDF sets. The graphs are labeled with various kinematic regions and show data with statistical errors, systematic uncertainties, and non-perfect correlation corrections. The theoretical predictions from MSTW 2008, NNPDF 2.1, and HERAPDF 1.5 are also included for comparison.]
NLO+Parton Shower Comparisons to Data

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

Data with statistical error
Systematic uncertainties
NLOJET++
\( \text{(CT10, } \mu_n^{\text{max}}) \times \)
Non-perl. corr.
POWHEG
\( \text{(CT10, } \mu_n^{\text{ext}}) \times \)
PYTHIA AUET2B
POWHEG
\( \text{(CT10, } \mu_n^{\text{ext}}) \circ \)
PYTHIA Perugia2011
POWHEG
\( \text{(CT10, } \mu_n^{\text{ext}}) \circ \)
HERWIG AUET2
POWHEG fixed order
\( \text{(CT10, } \mu_n^{\text{ext}}) \times \)
Non-perl. corr.
Dijet Cross Section Results

\[ \frac{d^2\sigma}{dm_{12}dy^*} \text{ [pb/TeV]} \]

- Systematic uncertainties
- NLOJET++ (CT10, $\mu = p_T \exp(0.3 y^*)$) × Non-pert. corr.

- $4.0 \leq y^* < 4.4$ (× 10^{15})
- $3.5 \leq y^* < 4.0$ (× 10^{14})
- $3.0 \leq y^* < 3.5$ (× 10^{13})
- $2.5 \leq y^* < 3.0$ (× 10^{12})
- $2.0 \leq y^* < 2.5$ (× 10^{11})
- $1.5 \leq y^* < 2.0$ (× 10^{10})
- $1.0 \leq y^* < 1.5$ (× 10^{9})
- $0.5 \leq y^* < 1.0$ (× 10^{8})
- $y^* < 0.5$ (× 10^{7})

ATLAS

- anti-$k_T$ jets, $R = 0.4$
- $\sqrt{s} = 7$ TeV, $\int L dt = 37$ pb^{-1}

arXiv:1112.6297
Dijet Cross Section Results

\[ \text{ATLAS} \]

\[ \left[ \text{L} = 27 \, \text{pb}^{-1} \right] \]
\[ \sqrt{s} = 7 \, \text{TeV} \]
\[ \text{anti-}k_t \text{ jets, } R = 0.4 \]

\[ \text{Data with statistical error} \]

\[ \text{Systematic uncertainties} \]

\[ \frac{\text{NLOJOET++}}{(\text{NLOJOET++})} \times \]
\[ \text{Non-pert. corr.} \]

\[ \text{POWHEG} \]
\[ (\text{CT10, } \gamma = \text{exp}(0.3 \, y^*)): \]
\[ \text{PYTHIA AUEET2B} \]

\[ \text{POWHEG} \]
\[ (\text{CT10, } \gamma = \text{exp}(0.0)): \]
\[ \text{POWHEG} \]
\[ (\text{CT10, } \gamma = \text{exp}(0.3)): \]
\[ \text{HERWIG AUEET2} \]

\[ \text{POWHEG fixed-order} \]
\[ (\text{CT10, } \gamma = \text{exp}(0.0)): \]
\[ \text{Non-pert. corr.} \]
Other Measurements: \textit{b}-jet and Multijet Cross Sections

- \textit{b}-jet cross section consistent with POWHEG (but not with MC@NLO)

\begin{itemize}
  \item Inclusive jet multiplicity distribution not well described by many tunes
\end{itemize}

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  \item Inclusive jet multiplicity distribution not well described by many tunes
\end{itemize}
NLO Comparisons for Measurements with Multiple Jets

- 3-jet to 2-jet cross-section ratios compared to NLO

- Number of jets as a function of rapidity gap seem to favor NLO calculations
What We Have Learned About QCD with Jets and Photons

- Systematic comparisons with NLO and NLO+parton shower

- Generally, agreement between data and MC is found

- Measurement uncertainties comparable to theoretical uncertainties

- Comparisons with NLO+parton shower underline importance of parton shower tunes
Prospects

• Theoretical work in NLO+parton shower matching to understand importance of the parton shower tune for NLO calculations

• Measurements to be used for PDF fits, $\alpha_s$ measurements

• Improvements in object performance developed in QCD analyses

• Jet substructure QCD measurements coming up as techniques are commissioned for searches
BACK-UP SLIDES
Jet Reconstruction and Performance

- Jet reconstruction uses clusters as inputs

- Clusters built using cells above noise (seeded with $4\sigma$, grown with $2\sigma$ cells)

- Use anti-$k_t$ algorithm with $R=0.4$ or $R=0.6$ to build jets from clusters

- Jets calibrated with simple correction (EM+JES)

- More sophisticated calibrations also available

- Constant term of EM+JES calibration $\sim5\%$ ($\sim3\%$ for others)
Photon Shower Shapes

\[ \text{ATLAS Preliminary} \]

Data 2010, \( \sqrt{s}=7 \text{ TeV}, \int L dt=40 \text{ pb}^{-1} \)

- Data
  - G4.9.2
  - G4.9.4, new geo.
  - AFII

\( R_\eta \)

\( \sigma \) arXiv:1110.3174

seed
energy
position
Photon Shower Shape Variables

• For loose identification:
  - Leakage $R_{\text{had}}$ (into first hadronic layer)
  - $R_\eta$ (see previous slide)
  - $w_2$ (RMS of energy distribution along $\eta$ in 2\textsuperscript{nd} layer)

• For tight identification:
  - $R_\phi$ (like $R_\eta$ in $\phi$ direction)
  - $w_{s,\text{tot}}$ (RMS of energy distribution along $\eta$ in 1\textsuperscript{st} layer)
  - $E_{\text{ratio}}$ between first and second maxima in energy profile along $\eta$
  - $\Delta E$ between the second maximum and the minimum between maxima
  - $F_{\text{side}}$ (like $R_\eta$ in 1\textsuperscript{st} layer)
  - $w_{s,3}$ (RMS of energy distribution along $\eta$ in 1\textsuperscript{st} layer using 3 core strips)
Systematic Uncertainties in Photon Energy Scale

• Systematic uncertainties in photon scale and resolution extrapolated from $Z \rightarrow ee$

• Studies use data/MC comparisons and different MCs to understand different effects (material, hardware failures, pile-up...)

(*) arXiv:1110.3174
Photon Identification Efficiency and Systematic Uncertainties

- Identification efficiency calculated after correcting MC shower shapes to data
- Uncertainties estimated varying criteria for identification and material description
- Cross-checked in $Z \rightarrow ee$ data

ATLAS

$|\eta^\gamma| < 0.6$

$E_T^{iso} < 3 \text{ GeV}$

- Simulation $\sqrt{s} = 7 \text{ TeV}$

systematic uncertainty

Photon Triggers

ATLAS
\sqrt{s} = 7 \text{ TeV}

- Data 2010, \int L dt = 880 \text{ nb}^{-1}
- Minimum Bias MC

Efficiency vs. \text{E}_{T}^{\gamma}[\text{GeV}]

ATLAS

- MC
- Data

Efficiency vs. cluster \text{E}_{T}[\text{GeV}]
Photon+jet Non-perturbative Corrections

ATLAS Simulation

|\gamma|^<1.2, y^\gamma \eta^\gamma\geq0

E^\gamma_T [GeV]
Diphoton Invariant Mass

Data 2010, $\sqrt{s}=7$ TeV, $\int Ldt=37$ pb$^{-1}$

$p_T>16$ GeV, $E_T^{\text{soft}}<4$ GeV, $\Delta R>0.4$

$|\eta|<2.37$ excluding $1.37<|\eta|<1.52$

+ measured (stat)
+ measured (stat $\oplus$ syst)

DIPHOX
ResBos

ATLAS

$\frac{d\sigma}{dm_{\gamma\gamma}}$ [pb GeV$^{-1}$]

$10^{-1}$

$1$

$0.5$

$0$

$-0.5$

$-1$

$0$

$20$

$40$

$60$

$80$

$100$

$120$

$140$

$160$

$180$

$200$

$220$

$m_{\gamma\gamma}$ [GeV]
Inclusive Jet and Di-jet Triggers

\( s = 7 \text{ TeV}, \int L \, dt = 37 \text{ pb}^{-1} \)

anti-\( k_t \) jets, \( R = 0.6 \)

\( 1.2 \leq |y| < 2.1 \)

- \( L2 \ E_T^{EM} > 15 \text{ GeV} \)
- \( L2 \ E_T^{EM} > 30 \text{ GeV} \)
- \( L2 \ E_T^{EM} > 45 \text{ GeV} \)
- \( L2 \ E_T^{EM} > 70 \text{ GeV} \)
- \( L2 \ E_T^{EM} > 90 \text{ GeV} \)
- \( L1 \ E_T^{EM} > 95 \text{ GeV} \)

\( \sqrt{s} = 7 \text{ TeV}, \int L \, dt = 34 \text{ pb}^{-1} \)

anti-\( k_t \) jets, \( R = 0.6 \)

\( p_T > 60 \text{ GeV} \)

- central trigger, \( L1 \ E_T^{EM} > 10 \text{ GeV} \)
- forward trigger, \( L1 \ E_T^{EM} > 10 \text{ GeV} \)
- central OR forward
Inclusive Jet Cross Section for $R=0.6$

\[ \int L \, dt = 37 \, \text{pb}^{-1} \]
\[ \sqrt{s} = 7 \, \text{TeV} \]
anti-$k_T$ jets, $R=0.6$

- Data with statistical error
- Systematic uncertainties
- NLOJET++ $(\mu - \mu_{\text{max}}) \times$ Non-pert. corr.
- CT10
- MSTW 2008
- NNPDF 2.1
- HERAPDF 1.5
Inclusive Jet Cross Section
Systematic Uncertainties

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

\[ \text{anti-}k_t \text{ jets, } R=0.6 \]
Non-perturbative Corrections to Inclusive Jet Cross Section
b-jet Cross Section Compared with MC@NLO

ATLAS

Data / MC

- Vertex-based
- Muon-based
- MC@NLO + Herwig

\( \sqrt{s} = 7 \text{ TeV}, \int L dt = 34 \text{ pb}^{-1} \)

\(|y| < 0.3\)

\(|y| < 0.8\)

\(|y| < 1.2\)

\(|y| < 2.1\)

Jet \( p_T \) [GeV]