QCD Results from ATLAS and CMS

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(on behalf of the ATLAS and CMS collaborations)

30th International Workshop on High Energy Physics
IHEP, Protvino, Russia
24 June 2014
Outline

• Introduction
• QCD, Jets, MC modeling
• Measurements
  • Soft-QCD
  • Inclusive and di-jet cross sections
  • Color coherence
  • PDF sensitivity
  • Photon + jets cross sections
  • Multi-jet cross sections
  • Extraction of $\alpha_s$
• Summary

Strong interactions are responsible for the bulk of production cross sections at the LHC
The Large Hadron Collider

Compact Muon Solenoid

A Toroidal LHC ApparatuS
\[ \eta = -\ln(\tan \theta/2) \]

<table>
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<th>ATLAS</th>
<th>CMS</th>
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<td>Tracker:</td>
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<td>EM calorimeter:</td>
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<tr>
<th>Run-I</th>
<th>(\sqrt{s}) (TeV)</th>
<th>(&lt;\mu&gt;)</th>
<th>(L_{\text{int}})</th>
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<tbody>
<tr>
<td>2010</td>
<td>7</td>
<td>2</td>
<td>(~ 40 \text{ pb}^{-1})</td>
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<tr>
<td>2011</td>
<td>7</td>
<td>9</td>
<td>(~ 5 \text{ fb}^{-1})</td>
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<td>2011</td>
<td>2.76</td>
<td>(~ 1)</td>
<td>0.2 \text{ pb}^{-1}</td>
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<td>2012</td>
<td>8</td>
<td>21</td>
<td>(~ 20 \text{ fb}^{-1})</td>
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\(<\mu> = \text{average number of interactions per bunch crossing}\)
QCD in \textit{pp} collisions

A proton-proton collision consists of:

- Soft processes (non-perturbative QCD)
  - Underlying event (UE)
  - Fragmentation of spectator partons
  - Initial- and final-state radiation (ISR/FSR)
  - Multiple parton interactions (MPI)

- Hard processes (perturbative QCD)
  - $\sigma_{pp\to X}$
    - PDFs
    - Matrix element
Jet reconstruction

- Jet algorithms cluster a spray of particles into a single object
- This object can act as a proxy for the partons from the hard process
- **ATLAS** and **CMS** primarily use anti-k$_T$ algorithm
  - Sequential recombination algorithm
  - Longitudinally invariant
  - Infrared and collinear safe to all orders in pQCD
  - Better control on shape and area (wrt other algorithms)
    $\rightarrow$ essential for calibrating jet energy

$R = 0.4, 0.6$

$R = 0.5, 0.7$
Modeling the data

Data is modeled using Monte Carlo generators:

- **Matrix element**: exact part up to the stated accuracy (e.g. LO or NLO)
- **Parton shower**: a good approximation to describe radiative QCD
- **Hadronization**: a model to describe non-perturbative effects
- **Underlying event**: describes how the rest of the colliding protons interact with the event and each other
Underlying Event (UE)

- Motivation: more accurate phenomenological modeling of soft and semi-hard parton interactions
  
- Classic definition of event topology, oriented by highest $p_T$ object in the event ($p_T^{\text{lead}}$)
  
  - Azimuthal segmentation of events
  
  - Transverse regions less affected by hard scatter process and most sensitive to UE
  
- Observables: $\Sigma E_T$, $n_{\text{ch}}$, $\Sigma p_T$, $<p_T>$ vs. $n_{\text{ch}}$
  
  - Studied as function of $p_T^{\text{lead}}$ (inversely proportional to impact parameter)
  
- All data distributions corrected to particle level and compared to MC models

arXiv:1406.0392, sub. to EPJC
Underlying Event

- Using the calorimeters allows the inclusion of neutral particles
- Relatively well described by the MC generators, but Pythia tuned to ATLAS UE data gives worse agreement

Inclusive (≥ 1 jet): Increase indicates contribution from wide-angle emissions from the hard scattering

Exclusive (= 2 jets with $p_T$ balance): flat, slightly decreasing with $p_T^{lead}$, indicates rate of MPI reaches plateau
Underlying Event in Drell-Yan

- Dependence of UE on di-muon invariant mass and transverse momentum

- UE activity independent of $M_{\mu\mu}$
- Well described by Pythia and Herwig++
- Illustrates universality of UE

- Slow increase with increasing $p_T^{\mu\mu}$
- Accurately described by MadGraph, which simulates multiple hard emissions
Double parton interactions (DPI)

Production of $W + 2$ associated jets vs. DPI producing a $W$ and a dijet


\[ \sigma_{\text{eff}} = 15 \pm 3 \text{ (stat.)} +^{5}_{-3} \text{ (syst.)} \text{ mb} \]

\[ \sigma_{\text{eff}} = 20.7 \pm 0.8 \text{ (stat.)} \pm 6.6 \text{ (syst.)} \text{ mb} \]

Comparable to values measured at other CM energies at other experiments

DPI-produced jets expected to be back-to-back $\rightarrow$ require jet-jet $p_T$ balance

DPI-sensitive kinematical distributions studied at particle level and a template method used to extract fraction of DPI events

arXiv: 1312.5729
Cross section measurements

- General motivation:
  - Test of pQCD
  - Constrain proton PDFs
  - Strong coupling measurement
  - Constraints on physics beyond the SM

- Basic strategy:
  - Select anti-$k_T$ jets, $R = 0.4, 0.5, 0.6, \text{ or } 0.7$
  - Unfold to particle level
  - Compare to NLO predictions
  - Dominant systematic uncertainty typically due to jet energy scale
Inclusive jet cross section

**ATLAS**

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

- anti-\(k_T\), jets, \(R=0.4\)
- \(|y| < 0.3 \times 10^5\)
- \(0.3 \leq |y| < 0.8 \times 10^6\)
- \(0.8 \leq |y| < 1.2 \times 10^6\)
- \(1.2 \leq |y| < 2.1 \times 10^6\)
- \(2.1 \leq |y| < 2.8 \times 10^6\)
- \(2.8 \leq |y| < 3.6 \times 10^6\)
- \(3.6 \leq |y| < 4.4 \times 10^6\)

**CMS**

\[
\sqrt{s} = 7 \text{ TeV}
\]

- \(|y| < 0.5 \times 10^4\)
- \(0.5 < |y| < 1.0 \times 10^3\)
- \(1.0 < |y| < 1.5 \times 10^2\)
- \(1.5 < |y| < 2.0 \times 10^1\)
- \(2.0 < |y| < 2.5 \times 10^0\)

\(L = 5.0 \text{ fb}^{-1}\)

anti-\(k_T\), \(R = 0.7\)

**Systematic uncertainties**

- Non-port. corr.

**PRD 86 (2012) 014022**

**PRD 87 (2013) 112002**
Inclusive jet cross section

Via inclusive cross section measurements, QCD has been tested at 3 CM energies and over 7 orders of magnitude!
Measurements generally well described by NLO, except for high \( m_{12} \) and large \( y^* \).
Sensitivity to physics beyond the SM

- Implement contact interaction (CI) in CIJET
- Restrict study to where theory predicts largest effect:
  \[ m_{12} > 1.31 \text{ TeV}, \ y^* < 0.5, \ R = 0.6 \]
- CI exclusion limit:
  - Create pseudo-experiments for both SM and SM + CI
  - Calculate generalized \( \chi^2 \), taking into account asymmetric uncertainties and their correlations
  - Scan CLs over compositeness scale \( \Lambda \)

Exclusion of \( \Lambda < 6.9–7.7 \text{ TeV} \) at 95% CL, depending on PDF set used
Color coherence

- Event selection: \( N_{\text{jet}} \geq 3 \) and two back-to-back leading jets

- The emission of a colored object depends on other colored objects in the event \( \rightarrow \) color coherence

- Look at direction of emission of third jet (quantified by \( \beta \))

- None of the examined MC give an adequate description of the data

\[ \tan \beta = \Delta \phi_{23} / \Delta \eta_{23} \]

arXiv:1311.5815 (accepted by EPJC)
PDF sensitivity

- HERA data tightly constrain distributions for $x < 0.01$
- Combined fit using HERA-1 and ATLAS/CMS data leads to improved shape constraints
  - Both ATLAS and CMS data favor harder gluons (and softer sea quarks)

EPJC (2013) 73:2509
CMS-PAS-SMP-12-028
**Inclusive isolated prompt photon cross section**

- **Motivation:**
  - Precise test of pQCD
  - Photons provide a cleaner environment than jets
  - Sensitive to gluons: dominant process is \( qg \rightarrow q\gamma \)
- NLO Jetphox: good agreement up to highest photon energies
- LO parton shower MCs
  - Pythia describes data well
  - Herwig 10-20% lower than data

Potential to constrain shape and uncertainty of gluon PDF in \( 0.03 < x < 0.3 \) (see backup)
(Isolated) photon + jet production

- Measure cross section as functions of $E_T$, $p_T$, $y$, $\Delta\varphi$, $|\cos \theta^{\gamma j}|$
  - $\theta^{\gamma j}$ is polar angle between photon and jet in their rest frame
- Good test of dominance of the quark exchange channel
- Good agreement between data and Jetphox NLO prediction

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arXiv:1311.6141 (accepted by JHEP)
$R_{3/2}$: ratio of three-jet cross section ($\sim \alpha_s^3$) over two-jet cross section ($\sim \alpha_s^2$) as a function of $p_T^{\text{lead}}$. 

**ATLAS Preliminary**

\( I_s = 7 \text{ TeV} \)

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

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**ATLAS-CONF-2013-041**
\( N_{3/2} \): ratio of three-jet cross section (\( \sim \alpha_s^3 \)) over two-jet cross section (\( \sim \alpha_s^2 \)) as a function of \( p_T^{\text{all jets}} \)

- \( N_{3/2} \) has a smaller dependence on scale choice and theoretical prediction

- Dominant uncertainty comes from theory
Measuring $\alpha_s$

Extracted using $N_{3/2}$ since it is less sensitive to choice of renormalization and factorization scales

$$\alpha_s(M_Z) = 0.111 \pm 0.006 \text{(exp.) } +0.016 \ -0.003 \text{ (theory)}$$

Extracted using $R_{3/2}$, but also inclusive jet cross section spectrum up to 2 TeV

$$\alpha_s(M_Z) = 0.1185 \pm 0.0019 \text{ (exp.) } \pm 0.0028 \text{ (PDF) } \pm 0.0004 \text{ (NP) } \pm 0.0019 \text{ (exp.) } +0.0055 \ -0.0022 \text{ (scale)}$$
Measuring $\alpha_s$

Both are consistent with world average and renormalization group equation (RGE)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
Summary

• QCD has been tested across a range of energies and phase spaces
  • Broadly speaking, it is performing remarkably well
  • Disagreement when looking into extreme areas of phase space

• Soft-QCD results help us to better understand the underlying event processes in pp collisions

• New pQCD measurements are providing powerful constraints on PDFs

• More results can be found here:
  • https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
  • https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

• 8 TeV analyses ongoing → expect new results soon!
BACKUP
Jet energy scale uncertainty

The jet energy scale uncertainty is the accuracy with which the calorimeters have been calibrated.

• Determined by:
  • Looking for a jet recoiling off EM objects (photon or Z)
  • Test-beam data
  • MC simulation

• Typical range of systematic uncertainty (for \( p_T > 20 \) GeV):
  1-3% (ATLAS)
  1-5% (CMS)
Jet energy resolution

The jet energy resolution is the inherent accuracy with which a jet can be measured.

- Measured by looking for two objects with the same $p_T$ and looking at the spread of their measured $p_T$.
- Typical range of systematic uncertainty (for $p_T > 20$ GeV):
  
  10-20%  
  (ATLAS and CMS)
Underlying event (UE)

- Inclusive selection shows rising activity with $p_T^{\text{lead}}$, but exclusive selection gives flat behavior.
- Relatively well described by the MC generators, but Pythia tuned to ATLAS UE data gives worse agreement.

arXiv:1406.0392, sub to EPJC
**Φ(1020) cross section**

- Measure cross section of $\Phi \rightarrow K^+K^-$ in MB events
- Probe the strangeness production and hadronization models at a scale of $\sim 1$ GeV
- Discriminating power among MC models: data best described by Pythia6 tune DW and EPOS-LHC

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**ATLAS**  
$\sqrt{s} = 7$ TeV, $L = 383 \mu$b$^{-1}$

$$ \frac{d\sigma(\Phi \rightarrow K^+K^-)}{dp_T} [\mu$b/MeV] $$

- $|y| < 0.8$, $p_{T,K} > 230$ MeV, $p_K < 800$ MeV
- $500 < p_{T,\phi} < 1200$ MeV

**ATLAS**  
$\sqrt{s} = 7$ TeV, $L = 383 \mu$b$^{-1}$

$$ \frac{d\sigma(\Phi \rightarrow K^+K^-)}{dy}\text{[}\mu$b\text{]} $$

- $p_{T,K} > 230$ MeV, $p_K < 800$ MeV

**arXiv:1402.6162**, sub to EPJC
Inclusive jet cross section

- Theory predicts a larger cross section than seen in data
- **ATLAS** 7 TeV data indicates the CT10 PDF description becomes worse at high $p_T$
- To some extent, MSTW 2008 predicts the trend seen in the data
- **CMS** 8 TeV data favors the high-$p_T$ description from CT10
Ratio of inclusive jet cross sections

Many correlated uncertainties cancel when measuring ratio of cross sections at different CM energies

→ Strong constraint on the PDFs
Dijet cross section
Jet flavor in dijet events

- Unfolded fractions compared to MC at particle level
- Good data/MC agreement except for BU at high $p_T$
Jet substructure

• Boosted objects and jet substructure provide a new tool for separating QCD from the decay of heavy objects
• Several ways to examine jet substructure, which are all reasonably described in simulation
• In some cases, the more aggressive substructure techniques produce a better agreement between data and simulation
PDF sensitivity

- HERA data tightly constrain distributions for $x < 0.01$
- Combined fit using HERA-1 and ATLAS/CMS data leads to improved shape constraints
  - Both ATLAS and CMS data favor harder gluons (and softer sea quarks)

EPJC (2013) 73:2509

CMS-PAS-SMP-12-028
PDF sensitivity of the photon cross section

- Gluon PDF difference between different sets larger than quoted uncertainties
- NLO theory calculated using Jetphox and MCFM for different PDF sets
- $\chi^2$ using all uncertainties from the experiment and theory (and correlations) using HERAFitter

$Q^2 = 2.0 \text{ GeV}^2$

- CT10
- MSTW2008
- ABM11_5N
- HERAPDF1.5
- NNPDF2.3

ATL-PHYS-PUB-2013-018
Four-jet cross section

- First attempt at measuring $N_{\text{jet}} = 4$ double differential cross sections.
- Softer jets poorly described by MC generators.

CMS, $\sqrt{s} = 7$ TeV, $L = 36$ pb$^{-1}$, pp $\to 4j+X$

$|\eta| < 4.7$
- $2j$: $p_T > 50$ GeV
- $2j$: $p_T > 20$ GeV

arXiv:1312.6440