QCD Results with the ATLAS Detector

J. Pilcher

- for the ATLAS Collaboration
Outline

- Overview of experiment
- Early QCD results
  - Non-perturbative QCD
    - Minimum bias interactions
    - Underlying event
  - Perturbative QCD
    - High $p_t$ inclusive jet and dijet production
    - Azimuthal decorrelation
    - Multijet production
    - Rapidity Gaps
    - Weak boson production
- Expected evolution
Muon Spectrometer ($|\eta|<2.7$): air-core toroids with drift-tube muon chambers
Muon trigger and measurement with momentum resolution < 10% up to $E_\mu \sim 1$ TeV

Length : \(~ 46 \text{ m}\)
Radius : \(~ 12 \text{ m}\)
Weight : \(~ 7000 \text{ tons}\)
\(~10^8\) electronic channels
3000 km of cables

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing $E_T$
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

EM calorimeter: Pb-LAr Accordion
$e/\gamma$ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

Inner Detector ($|\eta|<2.5$, $B=2T$):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing, $e/\pi$ separation
Momentum resolution:
$\sigma/p_T \sim 3.8 \times 10^{-4} p_T (GeV) \oplus 0.015$
First Collisions  30-Nov-09!
Peak luminosity began at \( \sim 10^{27} \) on March 30 and is now \( \sim 10^{31} \) cm\(^{-2}\) s\(^{-1}\). Luminosities known to 11\% from van der Meer scans

- one beam swept through the other to determine size

Present limitation from knowledge of beam current
Charged Particle Tracking

Photon Conversions

ATLAS Preliminary

Minimum Bias Stream, Data 2010 (\(\sqrt{s} = 7\) TeV)

Entries / MeV

\(M_{\pi\pi} [\text{MeV}]\)

X [mm]

Y [mm]
Calorimetry

$p_t$ balance for dijet events

\[ A = \frac{p_{t1} - p_{t2}}{p_{t1} + p_{t2}} \]

\(< p_t > \sim 20 \text{ GeV} \)

\(< p_t > \sim 30 \text{ GeV} \)
Non-perturbative QCD

- “Minimum bias” interactions
  - Soft pp collisions
  - Unbiased by detector trigger and analysis selection
  - Background for hard collisions with multiple interactions in the same bunch crossing
    - Currently ~1.8 interactions per crossing
    - Ultimately ~25 interactions per crossing
  - Measurements include
    - charge particle production
      - multiplicities, $p_t$ spectra, rapidity spectra, correlations
    - $\pi^0$, $\eta$, $K^0$, $\phi$, $\Lambda$, $\Xi$ production
Event with 4 pp interactions in the same bunch-crossing

~10-45 tracks with $p_T > 150$ MeV per vertex
Vertex z-positions: $-3.2, -2.3, 0.5, 1.9$ cm (vertex resolution better than $\sim 200 \, \mu$m)
Corrections to Measurements

- Secondary interactions, efficiency, resolution smearing
  - Knowledge of inert material is essential
    - Use photon conversions and hadronic interactions
- We do not remove any diffractive component
  - Model dependent
  - Complicates comparisons with some other measurements
Results for $p_t > 100$ MeV, $|\eta| < 2.5$, $E_{cm} = 7$ TeV

- ~ 6 charged particles per unit rapidity
- $p_t$ spectrum observed to fall over 11 orders of magnitude between 0.1 and 40 GeV
- Multiplicities to over 90 charged particles per event
  - Note discrepancies with models at low multiplicity
- $< p_t >$ of tracks increases slowly with multiplicity

Similar measurements at $E_{cm}$ of 0.9 TeV
Energy Dependence

- Early publication of results at 0.9 TeV reported on $p_t > 500$ MeV
  - Now $p_t > 100$ MeV
- Increase of rapidity density with $E_{cm}$
- Broadening of $p_t$ spectrum with $E_{cm}$
- Broadened multiplicity spectrum
Energy Dependence

- Diffractive contributions predicted to be larger for $p_T > 100$ MeV (22%) compared to $p_T > 500$ MeV (14%)
- Little data for tuning diffractive properties
  - Models appear to work best where diffractive contributions are small
  - Predictions normalized to total signal
    - Poor modeling diffractive component affects comparison in non-diffractive regions
Diffraction-suppressed Comparisons

- Require $n_{ch} \geq 6$ to suppress diffractive component
- Retune Pythia MC in this region

$E_{cm} = 7$ TeV
Other energies similar
Retune Pythia MC to better describe data for \( n_{ch} \geq 6 \) (AMBT1)

- Better descriptions of data obtained at both 0.9 and 7 TeV
Underlying Event Studies

- Soft debris in a hard pp interaction
  - From remnants of initial state protons and multi-parton interactions

- A background in measurements of hard processes
  - Needs to be included in simulation of detector response

- Non-perturbative processes
  - Several phenomenological models in generators
  - May need tuning in new energy regime
Underlying Event Studies

- Define a reference direction as the $p_t$ of the leading track
- Look at level of activity in “toward,” “away,” and “transverse” regions
- Activity measured as $d^2n_{ch}/d\eta d\phi$ and $d^2\Sigma p_t/d\eta d\phi$
- All measurements corrected for detection efficiency and resolution effects

Plane perpendicular to beam
Underlying Event Studies

- More activity in “transverse” region than predicted by models
- “Toward” and “away” regions reasonably modeled for this comparison
- Significant increase of activity with energy for all regions
- Other comparisons of $<n_{ch}>$, $<p_t>$, fluctuations of these variables (RMS)
- For more details see our conference note ATLAS-CONF-2010-081
Hard processes are rather well described by QCD

- Quantitative descriptions for $Q^2$ scales above $\sim 10$ GeV$^2$
- Decades of earlier work have taught us how to make useful predictions and what questions to ask of the data

Extend measurements into a new $Q^2$ range

- Gain confidence in the predictions and our ability to confront them with data

Hard scattering is the domain of new physics

- Essential that we understand the standard model processes if we are to be able to identify new physics
Inclusive Jet and Dijet Production

- Classic channels for studying hard scattering
  - Believed to be well described by perturbative QCD with the parton probability density functions (PDF) for the proton
    - Application of these tools to a new $Q^2$ regime
  - Sensitive to new-physics effects
    - Jet-jet resonances
    - Contact terms in interaction

- This data sample requires at least one jet with $p_t > 60$ GeV, $|y| < 2.8$
  - Trigger more than 99% efficient
  - Dijet measurement requires a second jet with $p_t > 30$ GeV and $|y| < 2.8$
  - First 17 nb$^{-1}$ data sample
    - Currently $\sim 3.5$ pb$^{-1}$ are available (200 times more)

- Define jets with anti-$k_t$ jet algorithm
  - A clustering algorithm
  - Stable under infra-red and collinear radiation
  - Leads to regular jet shapes (“cone-like”)
  - Use jet resolution parameter $R=0.6$ and $R=0.4$
Jet energy scale (JES) is critical

- Based on test beam calibration of production detector elements with monochromatic beams of electrons and hadrons
- Extra complications in final detector
  - More dead material (supports, cables, pipes, etc.)
  - Hadrons are in jets rather than isolated single particles
    - Spectrum of hadron energies
    - Mixture of EM ($\pi^0 \rightarrow \gamma\gamma$) and hadronic energy deposition ($\pi^\pm$, $K^\pm$, p, n, etc.)
- These complications are captured in Geant4 Monte Carlo program
  - Used for both the test beam and final detector
  - Detector response fully simulated for final states of events from physics generators (Pythia, Herwig, Alpgen, etc.)
- In-situ cross checks done with data
  - Calorimeter response for isolated hadrons
  - $p_t$ balance for dijet final states
  - $p_t$ balance for $\gamma$-jet final states
Current jet energy scale uncertainty

- A mild function of $p_t$ and $\eta$
- Based on cross checks from first few months of data
  - Workshop underway this week to reassess these uncertainties
  - Ultimate goal is $\sim 1\%$ by using the data itself
Model comparisons

- **Pythia 6.4**
  - Leading order matrix elements for $2 \rightarrow 2$ processes
  - $p_T$-ordered parton showers in leading-log approximation
  - Lund string model for hadronization
  - Underlying event modeled by multiple parton interactions

- **Herwig 6**
  - Leading order matrix elements for $2 \rightarrow 2$ processes
  - Angle-ordered parton showers
  - Cluster hadronization model
  - Underlying event using the Jimmy package

- PDFs from MRST2007LO*

- Also NLO cross sections from NLOJET++
Inclusive Jet and Dijet Production

- Inclusive single jet cross section measured to $p_t$ of 550 GeV
- Excellent agreement with NLO prediction over 5 orders of magnitude
- The dominant systematic uncertainty for the data is the JES
Inclusive Jet and Dijet Production

- Inclusive dijet cross section measured to $M \sim 2$ TeV
  - Leading jet $p_t > 60$ GeV
  - Subleading jet $p_t > 30$ GeV
  - $|y| < 2.8$
- Excellent agreement with NLO predictions
Inclusive Jet and Dijet Production

\[ p_{t1} = 890 \text{ GeV}, \ y_1 = -0.6; \quad p_{t2} = 760 \text{ GeV}, \ y_2 = 0.6; \quad p_{t3} = 30 \text{ GeV}, \ y_3 = 1.5 \]

\[ M_{12} = 1.9 \text{ TeV} \]
Current mass reach with 1 pb$^{-1}$

- Full analysis still in progress
Azimuthal Decorrelation in Dijet Events

- Inclusive dijet events are not back-to-back in $\phi$
  - Additional jets in final state
  - How large is the effect?
  - Do MC models describe it properly?

ALPGEN

110 < $p_t$ < 160 GeV

160 < $p_t$ < 210 GeV

210 < $p_t$ < 310 GeV

$p_t$ > 310 GeV
Azimuthal Decorrelation in Dijet Events

- Alpgen works well over 3 orders of magnitude
  - Also NLO pQCD (NLOJET++) (not shown)
- Data is well described by the appropriate models
Multijet Production

- Can we count and characterize the additional jets?
  - Essential to understand for new-particle searches
  - Prediction requires higher order QCD corrections
- Count jets with $p_t > 30$ GeV, $|y| < 2.8$
  - Jet energy scale (JES) crucial because of steeply falling $p_t$ spectrum
  - Correct for detector smearing effects
  - Corrections depend on proximity of jets (overlap)
    - MC dependent (additional systematic)
- Plot ratio of cross sections for successive multiplicities
  - Many systematic errors cancel
  - Uncertainties significantly reduced
Do we understand the $p_t$ spectrum of the extra jets?

- Pythia spectrum renormalized to data for each jet multiplicity
- Results in quite good agreement with Alpgen

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**ATLAS Preliminary**

![Graph showing $d\sigma/dp_T$ for different jet multiplicities](image)

- $R=0.6$, $L = 17$ nb$^{-1}$
- Data ($\sqrt{s} = 7$ TeV) + syst.
- Alpgen MC + scale uncert.
- Pythia MC $> 0.55$
- $N_{jets} \geq 3$
- $N_{jets} \geq 4$
Many new-particle searches use the $H_t$ variable to characterize the level of high-$p_t$ activity in an event

- Scalar sum of jet $p_t$ values
  $$H_t = \sum p_t$$

- Overall spectrum well described (top)
  - Ratio for successive multiplicities reduces uncertainties to \(~10\%\) level

Quantitative aspects of multijet final states very well described by Alpgen MC model

- Comparisons with higher statistics in the future
- Many checks already at 10\% level
Level of activity in rapidity gap between leading jets is important at LHC

- Vector boson fusion production of the Higgs expected to yield two forward jets with “quiet” color-free central region except for the Higgs
- How well do we understand the rapidity gap activity for QCD events (the background)?

CDF, D0, ZEUS, H1 observe a special class of QCD events with very little activity in the gap

- Very low multiplicity or $E_t$ in gap ($E_t < 2$ GeV)
- Interpreted as color-singlet exchange
- ~1% of events for $\bar{p}p$ collisions (CDF/D0)
- ~10% of photoproduced dijet events for $ep$ collisions (H1/ZEUS)

At present we just try to understand the activity in the gap
Rapidity Gap Studies

$p_t$ spectrum of leading jet in the rapidity gap between jets

Boundary jets have maximum rapidity separation and $p_t > 30$ GeV

Boundary jets are the two highest $p_t$ jets in event with $p_t > 30$ GeV

Reasonable agreement between data and Pythia 6 Monte Carlo

- will be important to extend this comparison to Alpgen
Rapidity Gap Studies

Probability of no jet with $p_t > 30$ GeV in the gap, vs $\langle p_t \rangle$ of boundary jets

Boundary is the two highest $p_t$ jets

Probability of no jet with $p_t > 30$ GeV in the gap, vs $\Delta y$ between boundary jets

Boundary is the two highest $p_t$ jets
Rapidity Gap Studies

- Data in good agreement with leading-order MC predictions of Pythia 6 for no jets in the gap with $p_t > 30$ GeV

- In future
  - Increase statistics
  - Explore lower $p_t$ threshold for vetoing jets in gap
    - Need to be at level of few GeV to see color-singlet exchange
  - Compare with other predictions for gap activity
  - Extend $\Delta y$ range of gap
    - For this analysis one jet always has $|\eta| < 3.2$
Inclusive Weak Boson Production

- Hard processes since $M_w = 80.4$ GeV and $M_z = 91.2$ GeV
  - Leading order processes very simple
  - NLO and NNLO calculations available for some observables
Measurement involves charged lepton detection

- Plus missing energy for the $W^\pm$
- Experimental challenges very different between electron channels and muon channels
  - i.e. $W^\pm \rightarrow e^\pm \nu$ and $Z \rightarrow e^+e^-$ versus $W^\pm \rightarrow \mu^\pm\nu$ and $Z \rightarrow \mu^+\mu^-$
- Detector systems and backgrounds different
  - Systematic effects are changed
  - Comparison of results from the two channels is very important
**Inclusive Weak Boson Production**

- W cross section measurement for 17 nb\(^{-1}\)
  - Require charged lepton candidate with \(p_t > 20\) GeV and \(|y| < 2.47\) for electrons, \(|y| < 2.4\) for muon
  - Use \(E_{\text{miss}}\) and \(m_T\) to separate signal from background

\[
m_T = \sqrt{2p_T^\ell p_T^\nu (1 - \cos(\phi^\ell - \phi^\nu))}
\]

![Graph showing \(E_{\text{miss}}\) vs. \(m_T\) for electrons and muons](image)

**Electrons**  
**Muons**
W cross section measurement

- Final candidate event samples with $E_{\text{tmiss}} > 25$ GeV and $m_t > 40$ GeV
- Estimated backgrounds are 3% for $e^\pm$ case, 6% $\mu^\pm$ case
Inclusive Weak Boson Production

- $W$ cross section comparisons vs $E_{cm}$
  - Electron and muon channels in good agreement
  - $W^+$ cross section larger because of quark PDFs ($u$ vs $d$)
  - Cross sections $\sim 3$ times larger than at the Tevatron
Inclusive Weak Boson Production

- Z cross section measurement for 220 nb\(^{-1}\)
- Backgrounds 1% for ee, 0.2% for \(\mu\mu\)
  - Resolutions and masses consistent with current calibration uncertainties
Z cross section comparisons with $E_{cm}$
- Cross section ~ 3 times larger than at the Tevatron
Inclusive Weak Boson Production

\[ Z \rightarrow \mu^- \mu^+ + 3 \text{ jets} \]

Run Number 158466, Event Number 4174272
Date: 2010-07-02 17:49:13 CEST
Larger data samples now under analysis

\[ W \rightarrow e\nu \]
\[ W \rightarrow \mu\nu \]
\[ Z \rightarrow e\bar{e} \]
\[ Z \rightarrow \mu\bar{\mu} \]
Expected Evolution

- Recent operation has typically been with 36 proton bunches colliding
  - Close to nominal number of protons per bunch
  - Design is 2808 bunches
  - Currently adding crossing angle to beams to avoid parasitic collisions with more bunches
- Plan to run pp collisions until late October
  - Peak luminosity goal $10^{32}$ cm$^{-2}$s$^{-1}$ (10 times above current)
  - Heavy ion run with Pb-Pb collisions for 4 weeks before Christmas shutdown
- Luminosity goal for pp collisions by end of 2011 is 1 fb$^{-1}$
  - Year-long shutdown in 2012 to repair bus bar splices between magnets
- Initial program is off to an outstanding start!
Jet proximity
- Plot fraction of events with $\Delta R < 1.5$ units in $\eta$-$\phi$
- Compare data with Pythia and Alpgen

![Graph showing jet multiplicity vs. fraction with close-by jets for ATLAS Preliminary data and simulations with Pythia and Alpgen.](image)
Anti-$k_t$ Algorithm

- Infra-red and collinear safe
  - Resultant jets stable under these effects

- Two general classes
  - Cone algorithms around seeds
    - Require split-merge if overlapping cones
  - Clustering algorithms
    - May give irregular shapes with complicated background corrections

- Anti-$k_t$ is a clustering algorithm
  - $p=1$ for $k_t$ clustering, $p=0$ for Cambridge/Aachen, $p=-1$ for anti-$k_t$
  - Cluster smallest distance and recompute

\[ d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2} \]
\[ \Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2 \]

\[ d_{iB} = k_{ti}^{2p} \]

arXiv:0802.1189v2
Faulty joint between two magnets opened with substantial stored energy in the magnet

- Power dissipation in 200 nΩ residual resistance melted solder holding joint together