First QCD results in ATLAS

Paolo Francavilla

INFN sezione di Pisa
30 November 2010
Accelerating Science

Accélérator de science

Il futuro è un buco nero

Questa informa
Jets in the LHC era

At the Large Hadron Collider (LHC), jet production is the dominant high transverse-momentum ($p_T$) process.

It gives the first glimpse of physics at the TeV scale.

Jet cross sections and properties are key observables in high-energy particle physics. Measured in $e^+e^-$, $ep$, $p\overline{p}$, and $pp$ colliders, and in $\gamma p$ and $\gamma\gamma$ collisions.

- Measurements of the strong coupling constant.
- Information about the structure of the proton and photon.
- Tools for understanding the strong interaction
- Tools for searching for physics beyond the Standard Model.
ATLAS Detector overview

**Magnetic field:** one solenoid surrounding the ID (2T), one toroid (muon spectrometer - 4T peak)

**ID** made up of three different detectors (Pixel, SCT, TRT):
High resolution tracking in $|\eta| < 2.5$

**EM calorimeter** - two sections covering up to $|\eta| \approx 3.2$.
High resolution on e/γ objects.

**HAD calorimeter** - 3 sections covering up to $|\eta| \approx 5$
Good containment, good resolution for jet measurement

**Muon system** (4 different technologies) covering up to $|\eta| = 2.7$
High precision muon momentum measurement (also standalone)
ATLAS Calorimeter System

EM LAr: $|\eta| < 3$ - Pb/LAr calorimeter, high resolution for e/$\gamma$ objects. e/h $\sim 1.7$

Central hadronic calorimeter (TileCal): $|\eta| < 1.7$: Fe(82%), scintillator (18%) - e/h = 1.36

End Cap Hadronic Calorimeter (HEC): $1.7 < |\eta| < 3.2$ - Cu/LAr

Forward calorimeter: $3 < |\eta| < 4.9$. First layer EM (Cu/LAr), the two remaining layers HAD.

Highly hermetrical ($|\eta| < 5$), non compensating calorimeters.
Data Sample

In this talk:
Performance
Trigger Efficiency
E/P calorimeter studies
Jet Calibration
Jet Resolution
Properties
Jet Shapes
Trackjet and fragmentation
$\Delta \phi$ Decorrelation
Cross Sections
Inclusive jet cross section
Di-Jet cross section
MultiJet cross section
BSM: exclusions
Exclusions: DijetMass
Exclusions: Angular

Dataset recorded by ATLAS in 2010:
~40 pb$^{-1}$ at 7 TeV
Data Sample

In this talk:
Performance
Trigger Efficiency
E/P calorimeter studies
Jet Calibration
Jet Resolution
Properties
Jet Shapes
Trackjet and fragmentation
Δφ Decorrelation
Cross Sections
Inclusive jet cross section
Di-Jet cross section
MultiJet cross section
BSM: exclusions
Exclusions: DijetMass
Exclusions: Angular

First QCD results in ATLAS
P. Francavilla
Trigger

**MBTS: Minimum Bias Trigger Scintillators**
(scintillators that detect activity in the forward region of the detector)
- In coincidence of the beam pick-up signal
- Inclusive Trigger
- **No significant bias introduced to the jet measurement**

**Level 1 Jet Trigger:**
\[ E_T \] in calorimeter elements

Element granularity:
\[ \Delta \phi \times \Delta \eta \ - 0.2 \times 0.2 \]

Jet finding:
- sliding window
  - with steps of one element
\[ E_T \] is computed in a window of configurable size.

First QCD results in ATLAS

P. Francavilla
Jet Trigger Efficiencies

**MBTS** inefficiency: Negligible from randomly triggered events

**L1 Jet Trigger**
Inclusive jet efficiency: Measured with respect to the **MBTS** trigger.

The efficiency is for jets with $p_T > 60$ GeV and $|y| < 2.8$ is above 99%.

Similar studies done for different jet algorithm sizes and different regions in rapidity.
Data Quality (DQ) used to select the periods with the nominal performance of the detector.

**Primary vertex (PV) selection:**

PV from center of ATLAS detector.

**MBTS Trigger and timing requirements:** depending on the detector and accelerator conditions of the different analyses presented here.

Effectively no bkg due to cosmic ray shower and beam related bkg left.

Negligible impact from pileup in data sample reported in these slides.
Event with high jet multiplicity

First QCD results in ATLAS

$p_T (j_1) \sim 1.3 \text{ TeV}$
$p_T (j_2) \sim 1.2 \text{ TeV}$
$M (jj) \sim 2.6 \text{ TeV}$

Uncalibrated $E$ in event display
Jet reconstruction and performance
Jet Reconstruction

Inputs:
3D Clusters:
find local cell energy maxima and cluster neighboring cells
Pro: noise suppression

Projective Towers:
All the cells in $\Delta \phi \times \Delta \eta$ - 0.1 x 0.1
Pro: Stable under extreme conditions (useful to validate the clusters)

Jet Algorithm:
The Anti-$K_T$ (infrared safe) algorithm has been taken as the default jet algorithm.

$$d_{ij} = \min(k_{t_i}^{2p}, k_{t_j}^{2p}) \Delta R_{ij}^2 / R^2$$

The Anti-$K_T$ is a sequential recombination jet algorithms with $p = -1$, ($K_t$, $p=1$) which behaves like an idealized cone algorithm.
Electromagnetic (EM) scale: Baseline cluster calibration, established using test beam with e and \( \mu \) in the calorimeters. Good estimate of the energy deposited by \( \gamma \) and e. 60-70% estimate of the energy deposited for hadrons and jets.

Hadronic Calibration. Why?: In the ATLAS Calorimeters,
- Response to hadrons lower than response to electrons.
- Energy losses in inactive regions of the detector.

Hadronic Jet Calibration driven by MC description.

Correction factor: \( p_T^{\text{Calibrated}} = C(p_T^{\text{EM}}, \eta) \cdot p_T^{\text{EM}} \)
Checks on the EM scale simulation

The simulation has been validated using test-beam and collision data.

Checks on Collisions data:
- Select isolated tracks;
- Collect the energy in the calorimeter around the track;
- Compare to MC.

\[ \langle E/P \rangle \text{ measured in} \]
- \(|\eta| < 2.3\)
- \(500 \text{ MeV} < p < 10 \text{ GeV}\)

The calorimeter response to isolated hadrons shows agreement between Data and MC at the 5% level for most of the calorimeter.
Jet Energy Scale Uncertainty

Stability of the MC response.

Variations driven by test beam and collision data

**Dominant:**
- Hadronic showers model
- Tile/LAr EM Scale
- Noise description
- Dead Material
- N_{intercalibration}

**Smaller:**
- Hadronization
- Underlying Event
- Parton Shower
- Pileup
Jet Calibration VS. $\eta$

Small (~2%) deviation at high pseudorapidity

Reference region

First QCD results in ATLAS

P. Francavilla
Jet Resolution

Di-jet Events
\[ \Delta \phi > 2.8 \text{ and } p_T[3^{rd} \text{ jet}] < 10 \text{ GeV} \]
\[ A = \frac{(p_T[1] - p_T[2])}{\langle p_T \rangle} \]
\[ \sigma(p_T)/p_T = \sqrt{2} \sigma_A \]
Estimate of the unbalance due to soft radiation.

Particle Level: \( \sigma_\psi \sim \sigma_\eta \neq 0 \) Radiation

Detector Level:
\[ \frac{\sigma(p_T)}{p_T} = \frac{\sqrt{\sigma_\psi^2 - \sigma_\eta^2}}{\sqrt{2} \langle p_T \rangle \, |\cos(\Delta \phi_{12})|} \]
Jet Resolution

Main goal of the methods: Check if the simulation does agree with data.

Differences in the methods due to unbalances (even at particle level)
Data and Simulation found to be in agreement.

The Monte Carlo simulation describes the jet energy resolution measured from data within 14 % for jets with $p_T > 20$ GeV and $|y| < 2.8$.
From the constituents to the topologies
Jet Shapes

Energy flow around the jet core

The distribution of energy within the jets is reasonably well simulated.

First QCD results in ATLAS
The tracks are a useful input to the jet clustering to study the jet fragmentation in charged particles and to improve the fragmentation models used in the MC simulations.

\[ Z_{\text{track}} = \frac{p_T^{\text{track}}}{p_T^{\text{Jet}}} \]

is the relative \( p_T \) contribution to the jet.
Azimuthal decorrelation

\[ \Delta \phi_{\text{dijet}} \]

Dijet production at leading order (LO) results in two jets with equal \( p_T \) and correlated azimuthal angles \( \Delta \phi = \pi \).

First QCD results in ATLAS

P. Francavilla
Soft radiation in dijet events starts to produce a decorrelation in $\Delta \phi$. 

First QCD results in ATLAS

P. Francavilla
Azimuthal decorrelation

ATLAS Preliminary

ALPGEN, $$\sqrt{s}=7$$ TeV

$$p_T^{\text{jet}}>100$$ GeV, $$|y^{\text{jet}}|<0.8$$

$$160<p_T^{\text{max}}<210$$ GeV

First QCD results in ATLAS

P. Francavilla
Azimuthal decorrelation

ATLAS Preliminary

ALPGEN, $\sqrt{s}=7$ TeV
$p_T^{\text{jet}}>100$ GeV $|y^{\text{jet}}|<0.8$
$160<p_T^{\text{max}}<210$ GeV

First QCD results in ATLAS

P. Francavilla
Azimuthal decorrelation

\[ \frac{1}{\sigma} \frac{d\sigma}{d\Delta\phi} \text{ [radians]^{-1}} \]

**ATLAS Preliminary**

ALPGEN, \( \sqrt{s} = 7 \text{ TeV} \)

\( p_T^{\text{jet}} > 100 \text{ GeV} \)

\( |y^{\text{jet}}| < 0.8 \)

\( 160 < p_T^{\text{max}} < 210 \text{ GeV} \)
The azimuthal decorrelation $\Delta \phi$ is a test higher-order perturbative QCD (pQCD) calculations without requiring the reconstruction of additional jets and a way to examine the transition between soft and hard QCD processes with a single observable.
Azimuthal decorrelation

Alpgen shows the best agreement with data.
(Emission of extra patrons driven by the matrix element calculation)

Similar agreement for the NLO calculation (NLOJET++)
Cross Sections
Cross Section: Inclusive Single Jet

Measurements of inclusive cross-sections are important verifications of perturbative QCD and probes of new physics (e.g. quark compositeness, etc.).

Cross Sections:
Inclusive single-jet double-differ. cross-sections as a function of $p_T$ and $y$

$$\frac{d^2\sigma}{dp_T,\text{jet} \, dy}$$

Transverse momentum: $p_T > 60$ GeV \quad Rapidity: $|y| < 2.8$

Jet Algorithm: Anti-$K_T$ jets with $R=0.4$ and $R=0.6$

Integrated Luminosity: 17 nb$^{-1}$
The cross section is corrected by the detector effects
Cross Section: Inclusive Single Jet

Bin-by-bin detector unfolding is used to correct for all detector effects.

Main contributions:
- Jet energy resolution fluctuations
- Detector efficiencies
- Jet Cleaning cuts

Pythia MC09 to derive correction factors:

Systematic uncertainties derived by:
- Worsening the jet energy resolution by 15%
- Altering the cross-section shape in Monte Carlo:
  \(< 3\% \) over the full \( p_T \) range

This is motivated by the demonstrated good modeling of trigger efficiencies, \( p_T \) spectrum shape, and energy flow around jet core in the Monte Carlo
**Cross Section: Inclusive Single Jet**

\[ P_{T,jet} \text{ max} \sim 600 \text{ GeV} \]

Data and theory are consistent

Uncertainty in data larger than in theory.

Dominated by jet energy scale.

**Rapidity Regions**

Theoretical uncertainties:

- Renormalization scale
- Factorization scale
- PDF
- \( \alpha_s \)

Fragmentation and Underlying event

First QCD results in ATLAS

P. Francavilla
The $p_T$ spectrum in data and theory are consistent in all rapidity regions.
Cross Section: Di-Jets

Cross Sections: Di-jet cross-sections as a function of di-jet mass and angle.

\[ \frac{d^2\sigma}{dM_{1,2}} \frac{d|y|_{\text{max}}}{d\chi} \]

\( M_{1,2} \) is invariant mass of first two leading jets with \( P_{T,1} > 60 \text{ GeV} \) and \( P_{T,2} > 30 \text{ GeV} \)

\( |y|_{\text{max}} = \max(|y|_1,|y|_2) \) with \( y_1 \) and \( y_2 \) rapidity of two leading jets

\[ \frac{d^2\sigma}{dM_{1,2}} \frac{d\chi}{d\chi} \]

\( \chi = \exp(|y_1-y_2|) \sim (1+\cos \theta^*)/(1-\cos \theta^*) \)

(Restricted to \( y^* = 0.5 \ |y_1-y_2| < 0.5 \log(30) \) and \( y_{\text{boost}} = 0.5 \ |y_1+y_2| < 1.1 \))

Jet Algorithm: Anti-\( K_T \) jets with \( R=0.4 \) and \( R=0.6 \)

Integrated Luminosity: 17 nb\(^{-1} \)

The cross section is corrected by the detector effects
Cross Section: Di-Jets

\[ R = 0.6 \]

**ATLAS**

anti-\( k_t \) jets, \( R = 0.6 \)
\[ \sqrt{s} = 7 \text{ TeV}, \int L \, dt = 17 \text{ nb}^{-1} \]

**Di-Jets**

\[ M_{1,2} = \text{invariant mass of first two leading jets with } P_{T,1} > 60 \text{ GeV} \]
and \( P_{T,2} > 30 \text{ GeV} \)

\[ |y|_{\text{max}} = \max(|y|_1, |y|_2) \]

\[ \chi = \exp(|y_1 - y_2|) \]

\[ \sim (1 + \cos \theta^*)/(1 - \cos \theta^*), \text{ where } \theta^* \text{ angle in cm system} \]

First QCD results in ATLAS

P. Francavilla
Exclusions: Di-jet Mass

By using the di-jet measurements, a first limit on new physics can be studied.

Search for bumps in the di-jet spectrum.

The fluctuation are not statistically significant.
Assuming a narrow di-jet spinorial resonance, the di-jet mass measurement can be used to exclude a certain cross section for the production of a resonance at a certain mass.

This result can be used to exclude regions in the plane masses/couplings for effective theories.
Exclusions: Di-jet Angles

Even the angular distribution for jets have an important role to constrain models of new physics:

i.e. contact interaction

\[ \Lambda < 3.4 \text{ TeV excluded (95\% CL.)} \]

Tevatron: 2.8 TeV (0.7 fb\(^{-1}\))
Cross Section: Multi-Jets

A first step toward the measurement of complex QCD final states

● Important as a measurement in itself
  (i.e. to extract the strong coupling constant)
● Fundamental to start the controls for the QCD background for searches.

Cross Sections:
Multi-Jet cross section:
  Multi Jet rates
  \( p_T \) spectrum for the 1\(^{st} \), 2\(^{nd} \), 3\(^{rd} \), 4\(^{th} \) jet (ordered in \( p_T \))
  \( H_T \) distribution for different multiplicity

Cuts: leading jets: \( p_T > 60 \) GeV, subleading jets \( p_T > 30 \) GeV

Jet Algorithm: Anti-\( K_T \) jets with \( R=0.6 \)

Integrated Luminosity: 17 nb\(^{-1} \)

The cross section is corrected by the detector effects
Cross Section: Multi-Jets

Alpgen describes better the data.
Pythia has a factor 0.62
Cross Section: Multi-Jets

[Graphs showing data and MC comparisons for jet distributions]
Cross Section: Multi-Jets

ATLAS Preliminary

$R=0.6, \int L \, dt=17$ nb$^{-1}$

- Data ($\sqrt{s}=7$ TeV)+syst.
- Alpgen MC+scale uncert.
- Pythia MC×0.55
  $N_{j\ell a}\geq 3$

Data/MC

$p_T$ ($3^{rd}$ leading jet) [GeV]

$\frac{d\sigma}{dp_T}$ [pb/GeV]

ATLAS Preliminary

$R=0.6, \int L \, dt=17$ nb$^{-1}$

- Data ($\sqrt{s}=7$ TeV)+syst.
- Alpgen MC+scale uncert.
- Pythia MC×0.60
  $N_{j\ell a}\geq 4$

Data/MC

$p_T$ ($4^{th}$ leading jet) [GeV]

First QCD results in ATLAS

P. Francavilla
Cross Section: Multi-Jets

$H_T = \Sigma p_T$ of selected jets

Inclusive variable to describe the events.
Cross Section: Multi-Jets

$H_T = \sum p_T$ of selected jets

Inclusive variable to describe the events.
Cross Section: Multi-Jets

$H_T = \Sigma p_T$ of selected jets

Inclusive variable to describe the events.
Cross Section: Multi-Jets

By making the ratio, part of the systematics cancel out.

Useful as an input for the strong coupling constant evaluation

(rough indication of the scaling violation).
Heavy Ions:
A first glance
Heavy Ions: A first glance

Motivation
Collisions of heavy ions at ultra-relativistic energies are expected to produce an evanescent hot, dense state.

High energy gluons and quarks are expected to transfer the energy to the medium.

-> Jet Quenching (idea from Bjorken)
   Highly unbalanced di-jet when one jet is produced at the periphery of the collision

Status and Data with Lead-Lead
LHC started the Heavy Ions Program at the beginning of November 2010.
\[ \sqrt{s_{NN}} = 2.76 \text{ TeV}, \text{Luminosity} = 17 \mu \text{b}^{-1} \]
\~ 1600 events with jets with \( p_T > 100 \text{ GeV} \)

Triggered with MBTS
Heavy Ions: A first glance

Indication for this effect in the RHIC experiments (i.e. STAR)
Studies done looking at the suppression in the particle production (i.e. charged tracks). This is an hard way to study jets.

Track-jets (¿): a natural asymmetry due to different fragmentation.
Heavy Ions: A first glance
Head-on collisions (Central collision) produce more final state activities. => The final state activity is used to separate central and peripheral collisions. To avoid biases, the events are divided in centrality bins according to the FCal $E_T$ measurement.

First QCD results in ATLAS

P. Francavilla:
Heavy Ions: A first glance


Big A = Big unbalance

Event Selection: back-to-back configuration $\Delta \phi > \pi/2$


---

Peripheral  Central

First QCD results in ATLAS  P. Francavilla
Heavy Ions: A first glance

\[ A_j = \frac{(E_T[1]-E_T[2])}{(E_T[1]+E_T[2])} \]

Big A = Big unbalance

Event Selection: back-to-back configuration \( \Delta \phi > \pi/2 \)

\( E_T[1] > 100 \text{ GeV}; \ E_T[2] > 25 \text{ GeV} \ |y| < 2.8 \)
Heavy Ions: A first glance

\[ A_j = \frac{(E_T[1]-E_T[2])}{(E_T[1]+E_T[2])} \]

Event Selection: back-to-back configuration \( \Delta \phi > \pi/2 \)


Big A = Big unbalance
Heavy Ions: A first glance


Event Selection: back-to-back configuration \( \Delta \phi > \pi/2 \)

\[ E_T[1] > 100 \text{ GeV}; \quad E_T[2] > 25 \text{ GeV} \quad |y| < 2.8 \]
Conclusions

Exciting period for the QCD analyses at LHC

A rich program of measurements begun with the LHC collisions.

Most of the analysis will be improved:

By using the complete 2010 statistics (\( p_T \sim 1.5 \) TeV)

By a deeper understanding of the detector (smaller systematics)

LHC Plans for 2011: 200 days of proton-proton (\( \sim 1\text{-}2 \text{ fb}^{-1} \))

And surprises may happens – Stay tuned.