Recent Heavy Ion Results with the ATLAS Detector at the LHC

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The ATLAS Detector

- Muon Detectors: $|\eta| < 2.7$
- Tile Calorimeter: $|\eta| < 4.9$
- Liquid Argon Calorimeter: $|\eta| < 2.5$

- Toroid Magnets
- Solenoid Magnet
- SCT Tracker
- Pixel Detector
- TRT Tracker
Integrated luminosity for 2010 Pb+Pb run

10 \mu b^{-1} delivered, 9 \mu b^{-1} recorded by ATLAS, \sim 8 \mu b^{-1} w/ solenoid
Survey of basic properties of heavy ions @ LHC

• **Global properties**
  • Multiplicity
  • Collective flow (& connection to correlations)

• **How do high $p_T$ processes vary with centrality?**
  • Measurement of jet energy loss in hot, dense medium

• **We have addressed this with a large sample of minimum bias events**
  • Triggered on combination of forward scintillators and zero degree calorimeters
  • No high $p_T$ triggers (jets, muons, etc.) used to select events
Centrality estimation

Energy sum in FCal (3.2<|η|<4.9) compared with Glauber MC ⊗ p+p data

Integrals of normalized data & MC distributions agree to 2% above & below range of fiducial $\Sigma E_T$ cut, consistent with sampling $f=100\pm2\%$ of inelastic total cross section. We calculate $<N_{\text{part}}>$ and $<N_{\text{coll}}>$ by binning in the simulated FCal variable.
Charged particle multiplicity

Pixel “tracklets” in solenoid-off data, to measure down to $p_T>0$

Yield per participant pair increases by factor of two relative to RHIC, in agreement with ALICE measurement

Similar centrality dependence to that found at RHIC (which itself was similar to top SPS energies):

Confirmation of what appears to be a robust scaling feature in HI
Flow measurements

Elliptic flow at RHIC showed that spatial deformations in the initial overlap region closely correlated with momentum anisotropies:

ATLAS has new measurements with increased $\eta$ dependence, and at high $p_T$

With the high multiplicities & large acceptance of ATLAS, we are also studying higher order components of the transverse flow

Do $v_n$ directly reflect higher order deformations in initial state? Higher modes should be more sensitive to viscous effects
Higher order moments vs. $p_T$ and centrality

Similar $p_T$ dependence for all flow coefficients. Weak centrality dependence observed for $v_3$-$v_6$. For the 5% most central events $v_2 < v_3$.
Two particle correlations

Two-particle correlations studied using discrete Fourier transform (DFT): $v_{n,n} \sim v_n^2$

$$C(\Delta \phi) = \frac{\int N_s(\Delta \phi, \Delta \eta) d\Delta \eta}{\int N_m(\Delta \phi, \Delta \eta) d\Delta \eta}$$

$$v_{n,n} = \langle \cos(n \Delta \phi) \rangle = \frac{\sum_{m=1}^{N} \cos(n \Delta \phi_m) C(\Delta \phi_m)}{\sum_{m=1}^{N} C(\Delta \phi_m)}$$

Complementary approach to event plane, to check consistency:
at long range, no more jet & resonance correlations (but non-trivial structure)
We find excellent agreement of DFT and EP results. In fact, event plane measurements provide nearly-identical information as 2 particle correlations: “ridge” and “cone” at large $\Delta \eta$ should no longer be seen as “jet related” phenomena.
Charged particle spectra

Corrected for efficiency, secondaries, fakes, resolution. Cutoff at 30 GeV due to small, systematic differences in track errors between data and MC (under investigation).
At fixed centrality, the $p_T$ dependence seems to scale (within large errors for PHENIX at high $p_T$): differential parton energy loss?

$v_2$ at high $p_T$
Quantitative comparisons between energy loss calculations and $v_2$ at high momentum, reflecting differential energy loss. Impressive agreement, despite predicting too-low $R_{AA}$.
Quantitative comparisons between energy loss calculations and $v_2$ at high momentum, reflecting differential energy loss. Impressive agreement, despite predicting too-low $R_{AA}$.
In most central events, see discrepancies possibly arising from lack of fluctuations in theoretical calculation.
Hard probes of heavy ion collisions

The LHC provides much higher rates of hard processes than provided previously: new opportunities for studying the microscopic properties of the medium

ATLAS published first observations of the centrality dependence of dijet asymmetries

ATLAS also first measured suppression of $J/\psi$ & observed production of $Z$ bosons


Hard probes: $N_{\text{coll}}$ scaling from $W^\pm$ production

$W$ yields extracted using an empirical fit to single muon spectra: heavy flavor (adapted from p+p) and simulated PYTHIA $W^\pm$ template

Pinned to most central events ($R_{PC}$), $\sim N_{\text{coll}}$ scaling observed.
Out of large variety of algorithms, ATLAS uses “anti-$k_t$”: consistent jet shape (e.g. $R=0.4$), widely used in HEP & HI
Subtracting the underlying background

• **ATLAS has excellent longitudinal segmentation**
  - Underlying event estimated and subtracted for each layer, and in 100 slices of $\Delta \eta = 0.1$
  - $\rho$ is estimated event by event, averaged over full azimuth

\[
E_{T_{sub}}^{cell} = E_{T}^{cell} - \rho^{layer}(\eta) \times A^{cell}
\]

• **Remove jets from the averaging**
  - We use the anti-$k_t$ algorithm to remove jets which have a large “core” region
  - Cross checked with a standard “sliding window” algorithm

\[
D = \frac{E_{T_{max}}^{tower}}{\langle E_{T}^{tower} \rangle} > 5
\]

• **NB: No jets are removed - but only real jets will have a large energy above the background level!**
Jet yields in HI

• **First ATLAS results** were an observation of asymmetric dijets, with a relative rate that increased with collision centrality

• **Recent work involves more detailed background subtraction**
  - Elliptic flow
  - Iterative method to remove bias of jet on background
  - Systematic comparison of jets of different sizes
    - *R=0.2 without flow correction used. $E_T(R=0.2) \sim 0.7 \times E_T(R=0.4)$*

• **Extensive MC studies of jet performance**
  - jet energy scale (JES) and jet energy resolution (JER) based on PYTHIA dijets embedded into HIJING with a flow afterburner

• **Centrality-dependent spectral unfolding**
Jet Spectra $R=0.4 \& R=0.2$

$\frac{1}{N_{\text{evt}}} \frac{dN_{\text{jet}}}{dE_T}$

Centrality
- 0-10 %
- 10-20 %
- 20-30 %
- 30-40 %
- 40-50 %
- 50-60 %
- 60-80 %

$\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$

$L_{\text{int}} = 7 \mu \text{ b}^{-1}$

$R = 0.4$

$R = 0.2$
Scaled by $N_{\text{coll}}$ (selected bins)

Pb+Pb $\sqrt{s_{\text{NN}}}=2.76$ TeV
$L_{\text{int}} = 7 \, \mu \text{b}^{-1}$

$R=0.4$

$R=0.2$
$R_{CP}$ vs. centrality in $E_T$ bins

Suppression characterized by central/peripheral ratio (pinned on 60-80%)

$$R_{CP} = \frac{1}{N_{coll}^{cent}} \frac{E \frac{d^3 N^{cent}}{dp^3}}{E \frac{d^3 N^{periph}}{dp^3}}$$

tends to ~0.5 in central bin
$R_{CP}$ vs. $E_T$ in centrality bins

No appreciable $E_T$ dependence of $R_{CP}$ for $R=0.4$ & 0.2
Fragmentation Functions

$p_T$ cut to suppress underlying event, and background subtracted using region outside jet cone
Yellow bands represent uncertainties from background subtraction

No strong modification of fragmentation functions between peripheral and central: surprising in a radiative energy loss scenario?
Charged particle $R_{CP}$

Strong suppression seen in more central events via charged $R_{CP}$

No $\eta$ dependence observed
Centrality dependence of charged hadron $R_{CP}$

$R_{CP}(p_T>20 \text{ GeV})$ shows systematic suppression, very similar to jets (but $R_{CP}$ still rising with $p_T$ at 30 GeV)

Pseudorapidity dependence dominated by statistics in 60-80%
The first ATLAS asymmetry measurement

Asymmetry defined as:

\[ A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \]

for \( \Delta \phi > \pi/2 \)

\( E_{T1} > 100\text{GeV} \)
\( E_{T2} > 25\text{GeV} \)

First measurements: broad asymmetry distribution, back-to-back angular distribution
New results incorporate a flow-sensitive background, better control of jet energy, higher statistics.
Asymmetry results robust, persist for R=0.2 jets, with much less sensitivity to background fluctuations
Asymmetry, updated

Dijets are produced back-to-back at all centralities, even when asymmetry distribution has been modified. Possible small contribution from fake jets in central events at large $\Delta\phi$. 
Modeling jet asymmetry

Young, Schenke, Gale, Jeon (2011 v2)

Theory community is already making use of this data.

**MARTINI** (jet quenching, radiative and collisions E-loss)
using **MUSIC** (hydro) background

can model salient features of asymmetry data:

"flat" $A_J$ distribution and peaked $\Delta \phi$ distribution
Conclusions

• **Global observables**
  - Centrality dependence of inclusive multiplicity scales with beam energy
  - Transverse momentum dependence of $v_2$ scales out to highest $p_T$ (modulo large errors at RHIC).
    - *New comparisons with energy loss calculations.*
  - Detailed study of higher order flow coefficients challenges ridge & cone interpretation. New information to help constrain viscous hydro models.

• **High $p_T$ observables**
  - $W^\pm$ production consistent with simple scaling with $N_{\text{coll}}$
  - Jet production systematic suppressed by a factor of $\sim 2$ relative to peripheral collision.
  - Charged hadron $R_{CP}$ measured out to 30 GeV: centrality dependence of suppression similar to jets
  - Asymmetries robust, and being successfully modeled in recent calculations
Plans

• Looking forward to a productive 2011
  • Quark Matter publications imminent
  • More systematic studies of jets, high $p_T$ charged particles, heavy flavor
  • Electromagnetic processes (especially photons)

• 2011 LHC Pb+Pb run expected to begin mid-November
  • Higher luminosities, requiring careful triggering on high $p_T$ jets, muons and electromagnetic processes
  • Will allow more detailed studies of hard processes & quarkonia with improved statistics

• Exciting time for HI physics: two machines and 5 experiments!
Heavy ion collisions: the first $3 \times 10^{-23}$ seconds

The goal of heavy ion physics is to “rewind the movie” to study the hot, dense medium formed in the early moments.
Heavy Ion Collision Event with 2 Jets
Minimum bias triggering

• The 2010 data set was taken with a minimum bias trigger configuration
  • Coincidence of minimum bias trigger scintillators (2.1<|\eta|<3.9)
  • Coincidence of neutrons in Zero Degree Calorimeters

• Offline requirements of
  • MBTS time difference |\Delta t|<3 ns
  • Coincidence in ZDC
  • Reconstructed vertex in Inner Detector

• Efficient rejection of
  • Beam-gas events
  • Inelastic photonuclear events

• No physics triggers (e.g. jets, muons) used in event selection
Underlying event fluctuations

Detailed look at variable-size square patches in data and MC. After 15% adjustment of FCal $\Sigma E_T$ scale, good agreement over nearly full centrality range.
Elliptic flow measurements

\[ R = \sqrt{\langle \cos[2(\Psi_2^N - \Psi_2^P)] \rangle}; \]

ATLAS forward calorimeter used for event plane determination.
Resolution correction factor for subevents \( \sim 75-85\% \) in mid-central events.
Tested in subregions of calorimeter acceptance.
Higher order moments vs. $p_T$ and centrality

At all moderate $p_T$ values (only 2-3 GeV shown here) weak centrality dependence for $v_3$-$v_6$

$v_2$ is not the largest component for central events.
Transverse momentum dependence of $v_2$:

Centrality and $p_T$ dependence of $v_2$:
Rapid rise up to 3-4 GeV, less rapid decrease to 8-9 GeV, and then weak $p_T$ dependence out to 20 GeV.

\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]
\[ L_{\text{int}} = 7 \mu\text{b}^{-1} \]

**ATLAS** Preliminary
Pseudorapidity dependence

Very weak \( \eta \) dependence above 500 MeV

Measurements out to \( |\eta| = 2.5 \) show systematic, but small decrease of \( v_2 \)

Very different than RHIC which had a strong \( \eta \) dependence