Overview of ATLAS
Heavy Ions Results

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Outline

ATLAS detector

Pb+Pb data samples

Jets
  Jet suppression
  Jet fragmentation

Photons and Z bosons

Photons, Z – jet correlations

Azimuthal anisotropy
  Event plane method
  Event by Event method
  Event plane correlations
ATLAS Detector

**Inner Detector** – Tracking $|\eta|<2.5$

**Calorimetry** – $|\eta|<4.9$

**Muon Spectrometer** - $|\eta|<2.7$
Pb+Pb Data Samples

2010

ATLAS Online Luminosity $\sqrt{s_{NN}} = 2.76$ TeV

- LHC Delivered (Pb+Pb)
- ATLAS Recorded

Total Delivered: 9.69 $\text{ub}^{-1}$
Total Recorded: 9.17 $\text{ub}^{-1}$

Day in 2010

2011

ATLAS Online Luminosity $\sqrt{s_{NN}} = 2.76$ TeV

- LHC Delivered (Pb+Pb)
- ATLAS Recorded

Total Delivered: 166 $\text{ub}^{-1}$
Total Recorded: 158 $\text{ub}^{-1}$

Day in 2011

$L_{\text{int}}$ 8 $\mu\text{b}^{-1}$ 0.15 $\text{nb}^{-1}$

Detector efficiency $> 97%$ $> 97%$

Triggers Minimum Bias (MB) MB, e, $\mu$, $\gamma$, jets, UPC

Events [$X 10^6$] $\sim 50$ $\sim 1000$
Pb+Pb Collision Centrality

Characterize centrality by percentiles of the total cross-section using forward calorimeter (FCal) $\Sigma E_T$ ($3.2<|\eta|<4.9$)

Energy sum in FCal compared with Glauber MC $\otimes$ 2.76 TeV p+p data

Sampling fraction $f = 98 \pm 2\%$ of total inelastic cross-section

Centrality parameters $<N_{\text{part}}>$, $<N_{\text{coll}}>$ calculated from Glauber MC (binning in the simulated FCal $\Sigma E_T$)
Up to 8,000 charged particles in ATLAS tracking @ $\sqrt{s_{NN}}=2.76$ TeV

Twice more particles per participant pair compared to p+p

5% increase of yield from $\eta\sim0$ to $\eta\sim1$ in peripheral events (30-80% centrality class)
Jets
Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS Detector at the LHC

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \quad \Delta \phi > \frac{\pi}{2}$$

$E_{T1} > 100$ GeV
$E_{T2} > 25$ GeV

Significant fraction of events with enhanced dijet asymmetry imbalance in $E_T$...

...preserving the back-to-back angular correlation: dijet $|\Delta \phi|$ balance in $E_T$
Jet $R_{CP}$

Asymmetry alone cannot provide information about the details of parton energy loss for radiative energy loss, jet energies can be reduced by greater “out of cone” radiation depending on the jet radii, according theoretical calculations (e.g., Y. He et al. arXiv:1105.2566).

Single inclusive jet spectra and central to peripheral ratio $R_{CP}$:

\[
R_{CP} = \frac{\frac{1}{N_{coll}} \frac{1}{N_{evt}} \frac{dN}{dp_T}}{\frac{1}{N_{coll}} \frac{1}{N_{evt}} \frac{dN}{dp_T}} \bigg|_{cent}^{60-80}
\]

use anti-$k_t$ algorithm with $R=0.2$, 0.3, 0.4 and 0.5; result using SVD unfolding to remove detector effects; ~ 50 million events from 2010 PbPb data.

First LHC result on jet suppression (submitted to PLB arXiv:1208.1967)

Suppression by a factor of 2 in central comparing to peripheral collisions. $R_{CP}$ for all centralities and for both radii show weak variation with $p_T$. 

ATLAS

anti-$k_t$ $R=0.2$  
$\int L dt = 7 \mu b^{-1}$

Pb+Pb $s_{NN} = 2.76$ TeV

$0 - 10 \%$

$10 - 20 \%$

$30 - 40 \%$

$50 - 60 \%$
Jet $R_{CP}$ versus jet size


Ratio of $R_{CP}$ values between $R=0.3$, 0.4 and 0.5 jets and $R=0.2$ jets

significant dependence of $R_{CP}$ on jet radius!
Jet fragmentation

Asymmetry alone cannot provide information about the details of parton energy loss. A modification of jet internal structure was predicted by different theoretical models N. Armesto et al., JHEP0802 (2008) 048.

R = 0.4

SVD unfolding was used to correct detector effects and to reduce the effect of statistical fluctuations:
- D(z) unfolding accounts for track momentum and jet energy resolution;
- D(pT) for track momentum resolution.

D(z) and D(pT) distributions have similar shape in all centrality bins.
D(z) centrality dependence

Ratios are needed to study centrality dependence

\[ R_{D(z)} = \frac{D(z)_{\text{cent}}}{D(z)_{60-80\%}} \]

~15% suppression at intermediate z (~0.1) and 25% enhancement at very low z (~0.02)
no strong modification at large z in central collisions with respect to peripheral ones
similar results found for R=0.2 and 0.3 jets
$Z \rightarrow e^+ e^-$

$Z \rightarrow \mu^+ \mu^-$

Z bosons,

Photons and

Z, photons - jet correlations
Z boson distributions

(submitted to PRL, arXiv: 1210.6486)

**invariant mass**

- **Z → e+ e−**
  - $E_T > 20$ GeV, $|\eta| < 2.5$
  - Background ~5%

- **Z → μ+μ−**
  - $p_T > 10$ GeV, $|\eta| < 2.5$
  - Background ~1%

Simulation weighted to match centrality distribution in data and normalized in the region of vertical dashed lines: $66 < m_\| < 102$ GeV

**per event rapidity**

Data consistent with PYTHIA simulations in p+p scaled to NNLO cross section $\times <T_{AA}>$
Photons

yields scaled by $<T_{AA}>$ and compared to JETPHOX predictions

ratio: Data/JETPHOX $\approx 1$

Z’s

transverse momentum distribution averaged over $|y|<2.5$
spectral shape is centrality independent
consistent with PYTHIA simulations in p+p scaled to NNLO cross section $\times <T_{AA}>$

(submitted to PRL, arXiv: 1210.6486)
Photon per-event yields

no centrality dependence in any of the measured $p_T$ intervals

photon yields in HI collisions scale linearly with $<T_{AA}>$ or equivalently with $<N_{coll}>$

photon production rates are not affected by QGP

isolated direct photons seem to be a perfect probe to help in understanding of the jet quenching phenomenon

Z boson per-event yields

integrated yields show a clear scaling with number of binary collisions

same dependence observed for three momentum ranges (<10, 10-30, >30 GeV)

(submitted to PRL, arXiv: 1210.6486)
Photon- jet $x_{J\gamma}$ distributions

$E_\gamma > 60$ GeV: 60-90 GeV, $|\eta|<1.3$

Jet: anti-$k_T$, R=0.2, 0.3, $p_T>25$ GeV, $|\eta|<2.1$

$\gamma$-jet separation $\Delta \varphi > 7\pi/8$ (back-to-back)

$$x_{J\gamma} = \frac{p_T^{\text{jet}}}{p_T^\gamma}$$

Shape and integral compatible with PYTHIA for peripheral collisions.

With increasing centrality shift towards smaller $x_{J\gamma}$ and reduction of the integral.
Photon-jet $\Delta \Phi$ distributions

$\Delta \Phi$ between photon and jet (normalized by integral). Shapes are consistent between data and simulation in all centrality, jet cone size.
**Z - jet correlations**

**0-20 % centrality**

ATLAS Preliminary

Pb+Pb $\sqrt{s_{NN}}=2.76$ TeV, $L_{int}=0.15$ nb$^{-1}$

Anti-$k_t$, Jet $R=0.3$, $p_T^{\text{jet}}>25$, $p_T^{Z}>60$ GeV, $p_T^{\text{jet}}/p_T^{Z}>25/60$

- PYTHIA: Mean = 0.82±0.01
- Pb+Pb: Mean = 0.62±0.04±0.04
  0-20% Centrality

**R = 0.3**

![Graph 1](image1)

**R = 0.4**

![Graph 2](image2)

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**20-80 % centrality**

ATLAS Preliminary

Pb+Pb $\sqrt{s_{NN}}=2.76$ TeV, $L_{int}=0.15$ nb$^{-1}$

Anti-$k_t$, Jet $R=0.4$, $p_T^{\text{jet}}>25$, $p_T^{Z}>60$ GeV, $p_T^{\text{jet}}/p_T^{Z}>25/60$

- PYTHIA: Mean = 0.84±0.01
- Pb+Pb: Mean = 0.68±0.05±0.03
  20-80% Centrality

**R = 0.3**

![Graph 3](image3)

**R = 0.4**

![Graph 4](image4)
Z’s-jets

Extracted \( <p_T^{\text{jet}}/p_T^{Z}> \) relative to MC simulations with no energy loss (PYTHIA: Z+jet events).

Stronger suppression for more central collisions.

The blue points refer to 0-80% centrality, and therefore are not independent relative to the black points.

Photons-jets

Downward shift of \( <x_{jY}> \) (jets more quenched).
The fraction of events with a Z boson ($p_T^Z > 60$ GeV) that also have a jet reconstructed ($p_T^{\text{jet}} > 25$ GeV, $p_T^{\text{jet}}/p_T^Z > 25/60$).

Most peripheral events consistent with PYTHIA truth, and strong centrality dependence: nearly half of the photons in central events do not have a matching jet: downward shift of $R_{j\gamma}$.
Azimuthal anisotropy

Spatial deformations in the initial overlap region are transformed into the final state momentum anisotropy studied via Fourier decomposition of the azimuthal angle distribution measured relative to the initial symmetry plane $\Phi_n$


$$E \frac{d^3 N}{dp^3} = \frac{1}{2\pi p_T} \frac{d^2 N}{dp_T d\eta} \left( 1 + 2 \sum_{n=1}^{\infty} v_n(p_T, \eta) \cos[n(\phi - \Phi_n)] \right)$$

phase of $v_n$ accumulated over many events;

this event-averaged $v_n$ mostly reflects the hydrodynamic response of the created matter to the average collision geometry in the initial state.

$$v_n = \langle \cos[n(\phi - \Phi_n)] \rangle$$

Event plane is measured based on energy deposition in the first sampling layer of FCal

Fourier harmonics are reconstructed in inner detector from charged particle tracks:

- $p_T > 0.5$ GeV
- $|\eta| < 2.5$

Reaction plane ($\Psi_{RP}$) is approximated by event plane ($\Psi_{n, EP}$) measured in FCal:

$$\Psi_{n, EP} = \frac{1}{n} \tan^{-1} \left( \sum_i E_{tower}^i w_i \sin(n\phi_i) / \sum_i E_{tower}^i w_i \cos(n\phi_i) \right)$$
Significant $v_2$ – $v_6$ are measured in broad range of $p_T$, $\eta$ and centrality.

$p_T$ dependence for all measured amplitudes show similar trend.

Stronger centrality dependence of $v_2$ than higher order harmonics.

In most central collisions (0-5%): $v_3$, $v_4$ can be larger than $v_2$. 
Event-by-event flow harmonics

New technique – direct measure of flow harmonics fluctuations!
Event-by-event unfolded $v_n$ distributions normalized to unit, for $n=2 – 4$

Lines represent radial projections of 2D Gaussians, rescaled to $\langle v_n \rangle$ for $v_2$ only in the 0-2% of most central collisions
for $v_3$ and $v_4$ over all centralities

Quantities calculated directly from these distributions:
- mean $\langle v_n \rangle$
- width $\sigma_{v_n}$
- ratio $\sigma_{v_n} / \langle v_n \rangle$
- RMS value: $\sqrt{\langle v_n^2 \rangle} \equiv \sqrt{\langle v_n^2 \rangle + \sigma_{v_n}^2}$
The values of $\sigma_{vn}/\langle v_n \rangle$:

- The values of $\sigma_{vn}/\langle v_n \rangle$ are found to be independent of $p_T$, suggesting that the hydrodynamic response to the eccentricity of the initial geometry has little $p_T$ dependence.
- $\sigma_{v2}/\langle v_2 \rangle$ shows significant centrality dependence.
- $\sigma_{v3}/\langle v_3 \rangle$, $\sigma_{v4}/\langle v_4 \rangle$ are consistent with Gaussian fluctuations.

found to reach a minimum of 0.34 for $v_2$ around $\langle N_{\text{part}} \rangle \sim 200$. 
Event plane correlations

The resolution corrected correlations between EP of different orders: \((\Phi_n, \Phi_m)\), \((\Phi_n, \Phi_m, \Phi_k)\)

Study non-linear response of the medium to initial fluctuations.

Model predicts even planes to be correlated.
Data shows strong correlation of \(\Phi_2\) and \(\Phi_4\), stronger than expected
Correlations between even and odd planes is not expected
Data shows significant correlations between \(\Phi_2\) and \(\Phi_3\)
Jet yields suppressed by a factor of 2 in central collisions.
Jet suppression depends on the jet size in central collisions.
Jet fragmentation function shows no modification at high z, but significant suppression with centrality at $z\approx 0.1$ and enhancement at very low z is observed.
Jet quenching also studied with $Z, \gamma$ - jet correlations.
$Z$ and $\gamma$ production consistent with Ncoll scaling.
ATLAS measured significant flow harmonics of charged particles in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.
New results on flow harmonics fluctuations.
Mixed reaction plane correlations were obtained.

Thank you!
Additional Slides
Jet fragmentation

Spectra of charged particles in jets

\[ D(p_T)(p_T^{\text{jet}}) = \frac{1}{N_{\text{jet}}(p_T^{\text{jet}})} \frac{1}{\epsilon(p_T, \eta)} \left( \frac{\Delta N_{\text{ch}}(p_T, p_T^{\text{jet}})}{\Delta p_T} - \frac{\Delta N_{\text{UE}}(p_T, p_T^{\text{jet}})}{\Delta p_T} \right) \]

Underlying event subtracted

Tracking efficiency corrected

\[ D(z)(p_T^{\text{jet}}) = \frac{1}{N_{\text{jet}}(p_T^{\text{jet}})} \frac{1}{\epsilon(p_T, \eta)} \left( \frac{\Delta N_{\text{ch}}(z, p_T^{\text{jet}})}{\Delta z} - \frac{\Delta N_{\text{UE}}(z, p_T^{\text{jet}})}{\Delta z} \right) \]

\[ z = \frac{p_T}{p_T^{\text{jet}}} \cos \Delta R \]
$D(p_T)$ centrality dependence

Ratios are needed to study centrality dependence.

Similar behaviour as for $D(z)$ distribution.
Event selection and triggers

Photons and electrons
based on EM calorimeter

efficiency $> 98\%$ for $E_T > 20$ GeV

Muons
L1 $\mu$ trigger with $p_T > 4$ GeV, HLT (MS OR MS + ID), additional $p_T > 10$ GeV $\mu$ scan

efficiency $> 90\%$ above 10 GeV
0.13 nb\(^{-1}\) of 2011 data

Trigger: EM cluster with \(E_T > 16\) GeV at L1

100% efficient for photons with \(E_T > 20\) GeV

Underlying-event background (UE) is subtracted event-by-event

Photon reconstruction with a sliding window algorithm seeded by clusters of at least 2.5 GeV in the second sampling layer.

Photon energy using all three layers and the presampler.

Photon conversions are not reconstructed in the HI environment.

Nine shower-shape variables used to choose high-quality photons (tight photons).
6435 tight photon candidates with $p_T > 45$ GeV and $|\eta| < 1.3$ before applying the isolation requirement. 

Isolation criterion optimized for HI photons: $E_T(R_{iso} = 0.3)$ – transverse energy in a cone of $R_{iso}$ around the photon axis.

Enhancement of data for $E_T(R_{iso} = 0.3) > 0$ due to two components: UE energy fluctuations and di-jet background.

Width of $E_T(R_{iso} = 0.3)$ in 0-10% photon+jet events is 6 GeV.

Isolation requirement: $E_T(R_{iso} = 0.3) < 6$ GeV.
Double side banded method

used for background subtraction. All photon candidates classified to one of four regions:

A: Primary signal region
B: Photons which happen to be in the vicinity of a jet or an UE fluctuation
C: Isolated jet fragments or photons which have shower shape fluctuations which fail the cuts
D: Primary background region

Leak of the signal to other regions is evaluated using MC

Leakage factors $c_i = N_{\text{sig} i} / N_{\text{sig} A}$

c_i range from 0.005-0.06, no dependence on centrality
Photon purity and efficiency

Efficiencies extracted from MC and normalized to all PYTHIA isolated photons with $E_T(R_{iso}=0.3)<6\text{GeV}$ (the isolation removes 1.5% photons)

Purity is determined by double side band method: fraction of di-jet background in photon sample: 20-30% in low $p_T$ bins
Z - jet correlations

\[ Z \rightarrow e^+e^- + \text{jet event candidate} \]

\[ Z \rightarrow \mu^+\mu^- + \text{jet event candidate} \]
Z boson efficiencies

electrons

muons
**Z - jet correlations 0-80% centrality**

- **Ratio of jet and Z boson transverse momenta.**
- **Normalized per Z boson.**
- **Inset $\Delta\phi$ distribution, normalized to unity.**
- **Low statistics but data distributions in the momentum ratio are different from PYTHIA null hypothesis.**

**Graphs:**
- **$R = 0.2$:**
  - ATLAS Preliminary
  - $\text{Pb+Pb | } s_{NN}=2.76 \text{ TeV, } L_{int}=0.15 \text{ nb}^{-1}$
  - Anti-$k_T$ Jet $R=0.2$, $p_T^{jett}>25$, $p_T^Z>60 \text{ GeV}$, $p_T^{jett}/p_T^Z>25/60$
  - PYTHIA: Mean=$0.79\pm0.01$
  - Pb+Pb: Mean=$0.65\pm0.04\pm0.03$
  - 0-80% Centrality

- **$R = 0.3$:**
  - ATLAS Preliminary
  - $\text{Pb+Pb | } s_{NN}=2.76 \text{ TeV, } L_{int}=0.15 \text{ nb}^{-1}$
  - Anti-$k_T$ Jet $R=0.3$, $p_T^{jett}>25$, $p_T^Z>60 \text{ GeV}$, $p_T^{jett}/p_T^Z>25/60$
  - PYTHIA: Mean=$0.82\pm0.01$
  - Pb+Pb: Mean=$0.67\pm0.03\pm0.05$
  - 0-80% Centrality

- **$R = 0.4$:**
  - ATLAS Preliminary
  - $\text{Pb+Pb | } s_{NN}=2.76 \text{ TeV, } L_{int}=0.15 \text{ nb}^{-1}$
  - Anti-$k_T$ Jet $R=0.4$, $p_T^{jett}>25$, $p_T^Z>60 \text{ GeV}$, $p_T^{jett}/p_T^Z>25/60$
  - PYTHIA: Mean=$0.84\pm0.01$
  - Pb+Pb: Mean=$0.72\pm0.04\pm0.03$
  - 0-80% Centrality
Z production – e, μ selection and efficiencies

electrons:
identified at L1 as a cluster of cells in the electromagnetic calorimeter, formed into
\((\Delta \phi \times \Delta \eta) = 0.1 \times 0.1\) trigger towers;
\(|\eta| < 2.5\), excluding the transition region between calorimeter sections\((1.37 < |\eta| < 1.52)\)
\(E_T > 14\) GeV.

muons:
selected using all three trigger levels;
(combination of MS and/or ID):
“high quality” MS & ID, combined: \(p_T > 10\) GeV required for both,
“low quality”, \(p_T > 20\) GeV required for both

weak centrality dependence:
Photon-jet correlations

Jet quenching physics:
- opening angle between leading jet and photon, $\Delta \phi$;
- transverse momentum ratio, $x_{j\gamma} = p_{Tj} / p_{T\gamma}$;
- $R_{j\gamma} = (1/N_{\gamma})dN_{j\gamma}/dx_{j\gamma}$, fraction of photon events that have a jet.

Correlation between the photon and the leading jet with:
- $p_{Tj} > 25$ GeV, $|\eta_{j}| < 2.1$;
- $60 < p_{T\gamma} < 90$ GeV, $|\eta_{\gamma}| < 1.3$;
- (For $x_{j\gamma}$ and $R_{j\gamma}$) $\Delta \phi > 7/8 \pi$, and $x_{j\gamma} > 25/60$.

Background subtraction
- “double sideband” method to find the background.

Unfold jet spectrum
- unfolding matrix for inclusive jets (SVD) from PYTHIA embedded into data;
- apply to single events;
- $p_{Tj}$ mapped to different values with different weights;
- fill $x_{j\gamma}$ distribution.

Photon efficiency

Jet reconstruction efficiency in photon-jet events.
Jets reconstructed using standard iterative background subtraction.

Above 50-60 GeV jet and Z are emitted back to back.

Fake rejection (based on track jet or EM cluster within jet), removes uncorrelated jets (esp. in R=0.3).

Similar to photon – jet analysis

- Lower statistics
- Higher purity

Correlation between Z boson and leading jet with:

- $p_T^{\text{jet}} > 25$ GeV, $|\eta^{\text{jet}}| < 2.1$
- $p_T^Z > 60$ GeV
- $\Delta \phi > 1/2\pi$, and $x_{jZ} > 25/60$
The result: 2PC compared to EP

Measurement of the azimuthal anisotropy for charged particle production in $\sqrt{s_{NN}} = 2.76$ TeV lead-lead collisions with the ATLAS detector.

$1<p_T^a, p_T^b<2$ GeV

$2<p_T^a, p_T^b<3$ GeV

Centrality [%]
for v3 e v4 the values of $v_n^{EP}$ are almost identical to RMS $\sqrt{\langle v_n^2 \rangle}$; 

for v2 the values of $v_n^{EP}$ are in between $\langle v_n \rangle$ and $\sqrt{\langle v_n^2 \rangle}$: they are closer to $\langle v_n \rangle$ in mid-central collisions where the EP resolution factor is close to one, and approach $\sqrt{\langle v_n^2 \rangle}$ in peripheral collisions where the resolution factor is small.