Recent ATLAS results on HI collisions

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on behalf of the ATLAS Collaboration

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Heavy ion physics at ATLAS

• **Soft physics** – lesson from RHIC: hot and dense QCD matter created in heavy ion collisions can be described by viscous hydrodynamics and it exhibits behavior of nearly perfect fluid. ATLAS confirms and extends this view by:
  - measurements of higher order flow harmonics
  - measurements of flow fluctuations
  - correlations in p+Pb events

• **Hard physics** – lesson from RHIC: high-pt hadrons are strongly suppressed due to the jet quenching = energy loss of partons passing through the dense colored medium. ATLAS further extends this view by:
  - various measurements of fully reconstructed jets,
  - measurements of high-pt photons and vector bosons,
  - measurements of jet internal structure

Talk by Jiangyong Jia

... this talk
ATLAS Detector

Muon Detectors

|\eta| < 2.7

Tile Calorimeter

|\eta| < 4.9

Liquid Argon Calorimeter

|\eta| < 2.5

... calorimetry

muons ...

... tracking

Toroid Magnets

Solenoid Magnet

SCT Tracker

Pixel Detector

TRT Tracker
Data-taking

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

- **LHC Delivered (Pb+Pb)**
- **ATLAS Recorded**

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

- **LHC Delivered (Pb+Pb)**
- **ATLAS Recorded**

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

ATLAS Online Luminosity $\sqrt{s_{NN}} = 5.0$ TeV

- **LHC Delivered (p+Pb)**
- **ATLAS Recorded**

Total Delivered: 31.2 nb$^{-1}$
Total Recorded: 29.8 nb$^{-1}$
How does the parton lose its energy? How does the parton lose its energy? To answer this fundamental question we need to ask further detailed questions:

- How are the inclusive jet yields suppressed?
- How does the suppression depend on jet energy and collisions centrality?
- Does the suppression depend on the size of the jet?
- Can we quantify the impact of initial state effects on jet the suppression? Can we see the jet suppression in other final states as well?
- Does the suppression depend on the flavor of initial parton?
- Does the suppression depend on the path-length of a parton traversing the medium?
- What is the jet $v_2$?
- Is the structure of jets modified? How do the spectra of particles inside jets differ in central HI collisions?
Q: How are the inclusive jet yields suppressed?

- Jet $R_{CP}$ – ratio of central to peripheral collisions,

$$R_{CP} = \frac{\frac{1}{N_{coll}} \frac{1}{N_{evt}} \frac{dN}{dp_T}}{\frac{1}{N_{coll}} \frac{1}{N_{evt}} \frac{dN}{dp_T}} |_{60-80\%}$$

- Result unfolded using SVD unfolding to remove detector effects (e.g. jet energy resolution).

- Systematic uncertainties:
  - black band: fully bin-wise correlated ($R_{coll}$, jet energy scale, jet energy resolution, efficiency, parametrization of truth distribution)
  - red boxes: partially correlated (choice of regularization parameter in unfolding)

- Statistical uncertainty by error bars.
Jet $R_{CP}$ vs $p_T$

A: Suppression by a factor of 2 in central comparing to peripheral collisions. Suppression is almost independent on $p_T$. 
Q: Does the suppression depend on the jet radius?
Jet $R_{CP}$ vs jet size

A: Clear evidence for stronger suppression of smaller jets.
(Consistent with a picture of energy being recovered out of cone.)
Is suppression final state effect?

Q: Can we verify that the jet suppression is really the final state effect?
Is suppression final state effect?

A: Yes. Yields of high-pt $\gamma$ are not suppressed.
Q: Can we see the jet suppression in other final states as well?  
A: Yes. Measuring the jet suppression in final states with vector bosons can help us to quantify the size of the jet energy loss.

Di-jets in vacuum  
Di-jets in medium  
$\gamma/Z^0$-jets in medium

on average jets are balanced  
both jets are be modified  
medium is transparent for EW vector bosons

Imbalance in momentum between $\gamma$ and jet can be quantified by:

$$x J_\gamma = \frac{p_T, Jet}{p_T, \gamma}$$
Jet suppression in other final states

- Per-photon normalized distributions, fully unfolded.
- Sizable suppression of jets in g-jet events seen.

\[ x_{J\gamma} = \frac{p_{T,\text{Jet}}}{p_{T,\gamma}} \]
Jet suppression
in other final states

... similar behavior seen in $Z^0$-jet events, though the statistics is limited
Q: Does the suppression depend on the flavor?
Q: Does the suppression depend on the flavor?

- Measurement of direct muons with $p_T=4-14$ GeV.
- Two component template fitting to separate the prompt muons from non-prompt.
A: $R_{CP}$ of HF decreases smoothly from peripheral to central collisions.

- $R_{CP}$ is $p_T$ independent.
- $R_{CP}$ in 0-10%/60-80% of 0.45 – comparable result to $R_{CP}$ measured in jets.
Q: Does the jet suppression depend on the azimuthal distance from the reaction plane? What is the jet $v_2$?
\[ R_{\Delta \phi} = \left( \frac{d^2 N_{\text{jet}}}{dp_T d\Delta \phi} \bigg|_{\Delta \phi = 2, 3, 4} \right) \left/ \left( \frac{d^2 N_{\text{jet}}}{dp_T d\Delta \phi} \bigg|_{\Delta \phi = 1} \right) \right. \]

\[ \Psi \text{ dependence of jet suppression} \]
A suppression by as much as 15% seen for out-of-plane jets comparing to in-plane jets.
Q: If the suppression is different for in-plane and out-of-plane jets, what is the jet $v_2$?

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_2)$$
Ψ dependence of jet suppression

A: – jet $v_2$ of 0.02-0.04
– no jet $p_T$ dependence observed for $v_2$

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_2)$$

Small quenching
Small eccentricity

ATLAS

5 - 10 % anti-$k_t$ $R = 0.2$
10 - 20 %
20 - 30 % $L dt = 0.14 \text{ nb}^{-1}$
40 - 50 %

$\langle N_{\text{part}} \rangle$

60 < $p_T$ < 80 GeV
Jet fragmentation

Spectra of charged particles in jets

“Fragmentation function”

\[ D(p_T)(p_T^{jet}) = \frac{1}{N_{jet}} \frac{1}{\epsilon} \frac{dN}{dp_T} (p_T^{jet}) = \]

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

Upstream efficiency corrected

Underlying event subtracted

\[ D(z)(p_T^{jet}) = \frac{1}{N_{jet}} \frac{1}{\epsilon} \frac{dN}{dz} (p_T^{jet}) = \]

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

\[ z = \frac{p_T}{p_T^{jet}} \cos \Delta R \]
Jet fragmentation

\[ D(p_T)(p_T^{\text{jet}}) = \frac{1}{N_{\text{jet}}} \frac{1}{\epsilon} \frac{dN}{dp_T} (p_T^{\text{jet}}) = \]

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

Spectra of charged particles in jets

“Fragmentation function”

\[ D(z)(p_T^{\text{jet}}) = \frac{1}{N_{\text{jet}}} \frac{1}{\epsilon} \frac{dN}{d\Delta} (p_T^{\text{jet}}) = \]

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

Q: Is the jet structure modified?
Jet fragmentation

- Result unfolded using SVD unfolding to remove detector effects (e.g. jet energy resolution, tracking momentum resolution).

- Systematic uncertainties:
  - gray band: fully bin-wise correlated (tracking efficiency)
  - yellow boxes: partially correlated (jet energy scale and resolution, tracking efficiency, choice of regularization parameter in unfolding, parametrization of truth distributions, ...)

- Statistical error by error bars.
Jet fragmentation

**ATLAS Preliminary**

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

$L_{int}$ = 0.14 nb$^{-1}$

$R = 0.4$

- $0$-$10\% \times 2^6$
- $10$-$20\% \times 2^5$
- $20$-$30\% \times 2^4$
- $30$-$40\% \times 2^3$
- $40$-$50\% \times 2^2$
- $50$-$60\% \times 2^1$
- $60$-$80\%$

$D(z)$ vs $z$

$D(p_T)$ vs $p_T$ [GeV]
Jet fragmentation

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

\[ R_D(p_T) = \frac{D(p_T)|_{\text{cent}}}{D(p_T)|_{60-80\%}} \]
Jet fragmentation

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

\[ R_D(p_T) = \frac{D(p_T)|_{\text{cent}}}{D(p_T)|_{60-80\%}} \]

**ATLAS Preliminary**

Pb+Pb \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

\( L_{\text{int}} = 0.14 \text{ nb}^{-1} \)

- anti-\( k_T \) \( R=0.4 \)
- \( p_T^{\text{jet}} > 100 \text{ GeV} \)
- 0-10%/60-80%
Jet fragmentation

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

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

**ATLAS Preliminary**

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

$L_{\text{int}} = 0.14$ nb$^{-1}$

anti-$k_T$ $R = 0.4$

$p_T^{\text{jet}} > 100$ GeV

0-10%/60-80%

Enhancement at low-z (or low- $p_T$)

Suppression at intermediate-z (or $p_T$)

No sizable modification at high-z (or $p_T$)
Jet fragmentation
Jet fragmentation

=> A: Clear modification of jet fragmentation with increasing centrality
Conclusions

• No modification of high-pt photons and electroweak vector bosons.
• Suppression of inclusive jet yields by a factor of two in central compared to peripheral collisions.
• Suppression of jets in γ-jet events.
• Indirect measurement of suppression of b-jets consistent with the measurement of the suppression of inclusive jets.
• Suppression of ~15% of jets oriented out-of-plane comparing to jets oriented in plane.
• Enhancement of particles in jets at low-$p_T$, suppression of particles at intermediate $p_T$, no sizable modification of particles in jets at high-$p_T$.
• … many more to come
Additional Information
Jet reconstruction

- Jets reconstructed using anti-\(k_T\) algorithm with different distance parameters \(R=0.2-0.5\).
- The underlying event contribution ("background") subtracted from jets on an event-by-event basis.

\[
E_{T,j}^{\text{sub}} = E_{T,j} - A_j \rho_j(\eta_j)(1 + 2v_{2,i} \cos[2(\phi_j - \Psi_2)])
\]

- Jets are corrected for the elliptic flow contribution.
- The subtraction is done in two iterations to avoid a bias of the background estimate by the presence of jets.
Performance

- Detailed evaluation of the performance.

- Data-driven checks of jet energy resolution using the evaluation of fluctuations in minimum bias event and HIJING.

- Data-driven check of jet energy scale using jets reconstructed from tracks (“track jets”).

- Fake rejection using track jets or electromagnetic clusters.

Jet energy resolution

Jet energy scale

\[ \frac{\Delta E_T}{E_T^{\text{truth}}} \text{ or } \sigma \left[ \frac{\Delta E_T}{E_T^{\text{truth}}} \right] \]

\[ E_T^{\text{truth}} \text{ [GeV]} \]
Performance

Jet energy resolution

Jet energy scale

R=0.2 jets: very small difference in the performance between central and peripheral collisions

ATLAS simulation

anti-\(k_t\) \(R = 0.2\)

\[ \langle \frac{\Delta E_T}{E_T^{\text{truth}}} \rangle or \sigma \left[ \frac{\Delta E_T}{E_T^{\text{truth}}} \right] \]

\[ \text{Efficiency} \]

\[ E_T^{\text{truth}} \text{ [GeV]} \]

\[ E_T^{\text{truth}} \text{ [GeV]} \]

\[ \sigma \left[ \frac{\Delta E_T}{E_T^{\text{truth}}} \right] + \text{fit, 0-10\%} \]

\[ \sigma \left[ \frac{\Delta E_T}{E_T^{\text{truth}}} \right] + \text{fit, 60-80\%} \]

\[ \langle \frac{\Delta E_T}{E_T^{\text{truth}}} \rangle, 0-10\% \]

\[ \langle \frac{\Delta E_T}{E_T^{\text{truth}}} \rangle, 60-80\% \]

\[ \varepsilon, 0-10\% \]

\[ \varepsilon', 0-10\% \]

\[ \varepsilon, 60-80\% \]

\[ \varepsilon', 60-80\% \]
First observation of jet quenching at LHC

Dijet asymmetry => imbalance in $E_T$

Dijet $|\Delta \phi|$ => balance in $E_T$

Original observation measurement of dijet asymmetry using $\sim 2 \mu b^{-1}$ of 2010 Pb+Pb collisions
Jet $v_2$

\[ \frac{dN}{d\phi} = A (1 + 2v_2 \cos [2(\phi - \Psi_2)]) \]
Jet $v_2$

ATLAS preliminary

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

- 2010 MB, $\int L \, dt = 8 \mu b^{-1}$
- 2011 jets, $\int L \, dt = 0.14 \text{ nb}^{-1}$

\[
\Psi_2 = \frac{1}{2} \tan^{-1} \left( \frac{\sum w_i E_{T_i} \sin 2\phi_i}{\sum w_i E_{T_i} \cos 2\phi_i} \right)
\]
Jet $v_2$

ATLAS preliminary simulation

45 < $p_T$ < 60 GeV

60 < $p_T$ < 80 GeV

80 < $p_T$ < 110 GeV

anti-$k_t$ $R = 0.2$

10 - 20 %

$\langle \Delta p_T / p_T \rangle$ vs $\Delta \phi$
Jet $v_2$

ATLAS preliminary
Jet $v_2$

$\textbf{ATLAS preliminary}$

Anti-$k_t$, $R = 0.2$

Pb+Pb $\sqrt{s_{NN}} = 2.76 \text{ TeV}$
$L \, dt = 0.14 \text{ nb}^{-1}$

$5 - 10 \%$

$10 - 20 \%$

$20 - 30 \%$

$30 - 40 \%$

$40 - 50 \%$

$50 - 60 \%$

- Jet energy resolution
- Event plane resolution
- Spectral shape

$p_T$ [GeV]
Jet $v_2$

$\int L \, dt = 0.14 \, \text{nb}^{-1}$

$\text{Pb+Pb} \sqrt{s_{NN}} = 2.76 \, \text{TeV}$

$\text{anti-}k_t R = 0.2$

$\text{ATLAS preliminary}$

$45 < p_T < 60 \, \text{GeV}$

$60 < p_T < 80 \, \text{GeV}$

$80 < p_T < 110 \, \text{GeV}$

$110 < p_T < 160 \, \text{GeV}$
Jet Fragmentation

\[ 5 < p_T < 7 \text{ GeV} \]

Data 2011
MC 2011

ATLAS Preliminary
Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV, $L_{\text{int}}$=0.14 nb^{-1}

ATLAS Preliminary
Data/MC

\[ \frac{N}{N_{\text{MC}}} \]

ATLAS Preliminary
Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV, $L_{\text{int}}$=0.14 nb^{-1}

ATLAS Preliminary
Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV, $L_{\text{int}}$=0.14 nb^{-1}

Efficiency

ATLAS Preliminary Simulation
Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV
PYTHIA Overlay
$|\eta|<1$

\[ p_T \text{ [GeV]} \]

0-10% + fit
60-80% + fit

ISMD 2013, Martin Spousta, ATLAS Collaboration
Jet Fragmentation

ATLAS Preliminary

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

$L_{\text{int}} = 0.14\text{ nb}^{-1}$

anti-$k_T$ $R = 0.4$

- 0-10% Raw $\times 10$
- 0-10% Unfolded $\times 10$
- 60-80% Raw
- 60-80% Unfolded

ATLAS Preliminary

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

$L_{\text{int}} = 0.14\text{ nb}^{-1}$

anti-$k_T$ $R = 0.4$

- Raw
- Unfolded

Raw/Unfolded

- 0-10% + 1
- 60-80%

Raw/Unfolded
Jet Fragmentation

**ATLAS Preliminary**

- **Pb+Pb**\(\sqrt{s_{NN}}=2.76\text{ TeV}\)
- **L\text{\textsubscript{int}}=0.14\text{ nb}\textsuperscript{-1}\)
- **anti-k\textsubscript{t}** \(R=0.4\)
- **p\textsubscript{T}\textsuperscript{jet}>100\text{ GeV}\)

**Legend:**
- **0-10%/60-80%**
- **10-20%/60-80%**
- **20-30%/60-80%**
- **30-40%/60-80%**
- **40-50%/60-80%**
- **50-60%/60-80%**

**Graphs:**

1. Left:
   - **p\textsubscript{T} [GeV]** range from 10 to 10^2
   - **R\textsubscript{D(A)}** range from 0.8 to 1.6

2. Middle:
   - **p\textsubscript{T} [GeV]** range from 10 to 10^2
   - **R\textsubscript{D(A)}** range from 0.8 to 1.6

3. Right:
   - **p\textsubscript{T} [GeV]** range from 10 to 10^2
   - **R\textsubscript{D(A)}** range from 0.8 to 1.6
Jet Fragmentation
Heavy Flavor

\[
\frac{\Delta p_{\text{loss}}}{p_{\text{ID}}} = \frac{p_{\text{ID}} - p_{\text{MS}} - \Delta p_{\text{calo}}(p, \eta, \phi)}{p_{\text{ID}}}
\]

\[
S(k) = \frac{1}{\sqrt{n}} \left( \sum_{i=1}^{k} s_i - \sum_{j=k+1}^{n} s_j \right)
\]

\[
S = \max \left\{ |S(k)|, k = 1, 2, \ldots \right\}
\]

\[
s_i = q \frac{\Delta \phi_i}{\phi_{\text{msc}}}
\]

\[
C = \left| \frac{\Delta p_{\text{loss}}}{p_{\text{ID}}} \right| + r S
\]

\[
r = 0.07
\]
Gamma-jet
Gamma-jet

\[ \langle x \rangle_j \]

\( N_{\text{part}} \)

- **R=0.2 Data**
- **R=0.2 PYTHIA+Data**

**ATLAS Preliminary**

Pb+Pb \( L_{\text{int}} = 0.13 \text{ nb}^{-1} \)

\( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \)

\[ \langle x \rangle_j \]

\( N_{\text{part}} \)

- **R=0.3 Data**
- **R=0.3 PYTHIA+Data**

**ATLAS Preliminary**

Pb+Pb \( L_{\text{int}} = 0.13 \text{ nb}^{-1} \)

\( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \)
Gamma-jet
Z-jet