Jets in Heavy Ion Collisions Measured by ATLAS
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Unknowns:

How do parton showers in hot and dense medium differ from those in vacuum?

How much is the jet yield suppressed?
How does the suppression depend on jet radius?
Is the fragmentation function modified?
Is the partons angular distribution broadened?

What is the physics responsible for this modification?
Expectations:

Medium interactions induce additional radiations modifying usual fragmentation in vacuum. Medium-induced radiation may cause energy deposition outside jet cone.

Predictions of radiative energy loss suggest that energy can be recovered by expanding jet cone.

\[ \hat{q} = 50 \text{ GeV}^2\text{fm}^{-1} \]
\[ \hat{q} = 10 \text{ GeV}^2\text{fm}^{-1} \]

• Transverse energy in FCal compared to Glauber MC model \( \otimes \) p+p data

• Sampling fraction \( f = 98 \pm 2\% \), after all trigger and selection cuts

• Data are divided in 10% centrality intervals
Jets are reconstructed using anti-k$_T$ algorithm with four choices of R parameter (R=0.2, 0.3, 0.4 and 0.5)

Inputs are 0.1x0.1 ($\Delta\eta \times \Delta\phi$) calorimeter towers (piled cells)

Average background estimated event-by-event per calorimeter sampling layer and per 0.1 $\eta$ strip

$$E_{T,\text{subt}}^\text{cell} = E_T^\text{cell} - \rho x A^\text{cell}$$

Background modulated by elliptic flow before subtraction

Define jet seeds and exclude them from cell's energy density ($\rho$) and elliptic flow estimates
Jet energy resolution
• Low ET: dominated by underlying event fluctuations
• High ET: limited by intrinsic detector resolution

Jet energy scale evaluated from the mean fractional energy shift

Efficiencies for finding jets before and after removing jets from the underlying event
Enhancement of asymmetric di-jets, relatively to p+p and PYTHIA+HIJING → first indication of jet suppression

\[ A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \quad E_{T1} > 100 \text{ GeV} \]
\[ E_{T2} > 25 \text{ GeV} \]
\[ |\eta| < 2.8 \]

Flatter distribution for R=0.2 jets

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$\Delta \phi = \pi$ acoplanarity remains, while $A_J$ is changing.

Consistent with combinatoric contribution to $R=0.4$ di-jet $\Delta \phi$ distribution

- 2nd jet “missing” and uncorrelated jet used

• But, combinatoric contribution much smaller for $R=0.2$
  - Yet, equally strong asymmetry modification
Electroweak bosons are unaffected by the medium, allowing calibrate scale of the hard process and directly probe jet energy loss

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

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Beyond Asymmetry

Di-jet asymmetry and unbalanced photon-jet transverse momentum are direct probes of parton energy loss but cannot account for the details. A deeper insight is needed:

- 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?
- Is the structure of jets modified? How do the spectra of particles inside jets differ in central collisions?

And more (not covered in this talk)
- Does the suppression depend on the path-length of a parton traversing the medium?
- Does the suppression depend on the flavor of initial parton?

More...?
Jet $p_T$ Spectra

Not corrected for detector effects
Steep falling spectra independently on collisions centrality, but how does the ratio between a given centrality interval and the most peripheral one?
- Increasing jet suppression with centrality, up to a factor of 2 in the most central collisions, well beyond statistical and systematic errors
- Weak dependence on jet $p_T$
$R_{cp}$ for most central collisions as a function of $p_T$ ranges and jet cone size

The suppression is higher for narrower jets, which is consistent with a scenario of energy recovered out of cone.
$R_{cp}$ for most central collisions as a function of $p_T$ ranges and jet cone size

The suppression is higher for narrower jets, which is consistent with a scenario of energy recovered out of cone (cf. slide 3).
Jet Fragmentation - $D(z)$ and $D(p_T)$

$D(z[p_T]) = \frac{1}{N_{jet}} \frac{1}{\epsilon} \frac{\Delta N_{ch}(z[p_T])}{\Delta z[p_T]}$

$z \equiv \left( \frac{p_{T,\text{had}}}{p_{T,\text{jet}}} \right) \cos \Delta R$

$D(z)$ measures the $p_T$ of the charged particles parallel to the jet axis.

$D(p_T)$ is the $p_T$ spectrum of charged particles inside the jet.
Jet Fragmentation – $R_D(z)$ and $R_D(p_T)$

- Enhancement at low $z$ and low $p_T$
- Suppression at intermediate $z$ and $p_T$
- No modification at high $z$ or high $p_T$

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

$R_D(p_T) = \frac{D(p_T)|_{\text{cent}}}{D(p_T)|_{60-80\%}}$
Jet Fragmentation – $R_D(z)$

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

**ATLAS Preliminary**

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

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

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

- Enhancement at low z and low $p_T$
- Suppression at intermediate z and $p_T$
- No modification at high z or high $p_T$

$\hat{q} = 50$ GeV$^2$fm$^{-1}$
$\hat{q} = 10$ GeV$^2$fm$^{-1}$

Jet Fragmentation – $R_{D(z)}$

Reference is the D(z) in the 60-80% centrality interval

The jet structure modification is higher as the centrality of the collisions increases.
Jet Fragmentation – $R_D(p_T)$

Reference is the $D(z)$ in the 60-80% centrality interval.

The jet structure modification is higher as the centrality of the collisions increases.
Conclusions

1 - Di-jet balance in peripheral collisions well compatible with p+p collisions and non-quenching based MC; Di-jet asymmetry increases with increasing centrality.

2 - No broadening of Δφ.

3 - The same conclusions for photon-jet balance
Conclusions

4 - Jet production suppressed by a factor of 2 in central collisions w.r.t. peripheral; tiny dependence with jet $p_T$ is observed.

5 - The suppression is larger for narrower jets. This is consistent with radiation-dominated energy loss scenario.
Conclusions

The jet structure is modified: enhancement of particles at low $z$ and $p_T$; suppression at intermediate $z$ and $p_T$. The modification increases as the centrality of the collisions increases. Predictions of high suppression at high $z$ are not confirmed.
2011 Pb+Pb Run

- $\sqrt{s_{NN}} = 2.76$ TeV
- ATLAS recorded 158 $\mu$b$^{-1}$ of Pb+Pb data
- Data recording efficiency > 97%
- Triggers: MB, $e$, $\mu$, $\gamma$, jet, UPC
- $1 \times 10^9$ events!
Calorimeter fluctuations

Fluctuations are measured in single towers and also in larger windows comparable to the area of jet:

4x3 towers ~ R = 0.2 jets

7x7 towers ~ R = 0.4 jets

The agreement between data and MC is better than 5% for R=0.2 jets.

Fluctuations in data are at most 5% higher than in MC for R=0.4 jets.

Fluctuations are higher in MC in the most central events.
Detecting Particles