Jet Physics in Heavy Ion Collisions with ALICE

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Heavy Ions at LHC: the actors ...

2010/11: p+p collisions @ 7 TeV
Nov 2010 hot switch to
PbPb collisions @ 2.76 TeV
4 weeks in 2010 and 2011
It is really happening
Di-Jet Event

Reconstructed Jets UA1 Cone R = 0.4:
Jet 1: $\eta = 0.02$, $\phi = 306^\circ$, $p_T = 71$ GeV, Tracks 15
Jet 2: $\eta = 0.84$, $\phi = 132^\circ$, $p_T = 47$ GeV, Tracks 9
$\Delta \phi = 174^\circ$
Total Tracks 108
Some more patience needed:
Early Heavy Ion Runs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Early (2010/11)</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( s_{NN} ) (per colliding nucleon pair)</td>
<td>2.76 TeV</td>
<td>5.5</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>62 s/10^6 s</td>
<td>592</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>1350 ns</td>
<td>99.8</td>
</tr>
<tr>
<td>( \beta^* )</td>
<td>2 \rightarrow 3.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Pb ions/bunch</td>
<td>7 \times 10^7</td>
<td>7 \times 10^7</td>
</tr>
<tr>
<td>Transverse norm. emittance</td>
<td>1.5 \mu m</td>
<td>1.5</td>
</tr>
<tr>
<td>Initial Luminosity ( (L_0) )</td>
<td>(1.25 \rightarrow 0.7) \times 10^{25}</td>
<td>10^{27}</td>
</tr>
<tr>
<td>Stored energy ( (W) )</td>
<td>0.2 MJ</td>
<td>3.8</td>
</tr>
<tr>
<td>Luminosity half life ( (1,2,3 \text{ expts.}) )</td>
<td>( \tau_{IBS}=7-30 )</td>
<td>8, 4.5, 3</td>
</tr>
</tbody>
</table>

Initial interaction rate: 50 Hz (5 Hz central collisions \( b = 0 - 5 \text{ fm} \))
\(~5 \times 10^7\) interaction/10^6 s (~1 month)
In 2010: integrated luminosity 1-3 \( \mu b^{-1} \)
The rare becomes profuse
**Expected rates**

- **First PbPb run** at 2.76 TeV
  - Jet x-section reduced by factor 10
  - $10^6$ central events
  - Measure $R_{AA}^{Jet}$ up to 110 GeV

- 10$^7$ central events at 5.5 TeV
  - Measure $R_{AA}^{Jet}$ up to 150 GeV
  - Jet structure up to 100 GeV

- **Nominal 1 month runs** with EMCAL trigger
  - Jet structure up to 200 GeV

- Some important reference measurements only possible with EMCal trigger

**Charged jets**: $10^9$ evts pp

**Central events PbPb**: $10^7$ evts

**Di-Jets (charged only)**

**Central events PbPb**: $10^7$ evts
As compared to RHIC...

- Cross-section falls with a smaller (power-law) exponent
  - \( n = 5.9 \) (LHC) / 8 (RHIC)
  - Reduced sensitivity to energy scale
  - Reduced selection bias on fragmentation

- Different \( x_T \) range
  - LHC: 0.02 - 0.2
  - RHIC: 0.15 – 0.45

- LHC (RHIC) gluon (quark) dominated

Jets in Nucleus-Nucleus Collisions

- High-$p_T$ partons produced in hard interactions in the initial state of nucleus-nucleus collisions undergo multiple interaction inside the collision region prior to hadronisation.
- In particular they lose energy through medium induced gluon radiation and this so called “jet quenching” has been suggested to behave very differently in cold nuclear matter and in QGP.

\[ \Delta E \propto \alpha_s C_R <\hat{q}> L^2 f(E, m_q) \]
Consequences for the Jet Structure

- Decrease of leading particle $p_T$ (energy loss)
- Increase of number of low momentum particles (radiated energy)
- Increase of $p_T$ relative to jet axis ($j_T$)
  - Broadening of the jet
  - Out of cone radiation (decrease of jet rate)
- Increased di-jet energy imbalance and acoplanarity.

Simplistically: \( \text{Jet}(E) \rightarrow \text{Jet}(E-\Delta E) + \text{soft gluons (}\Delta E) \)
Background from the UE also important at LHC

Jet($E$) → Jet($E - \Delta E$) + soft gluons ($\Delta E$) + soft hadrons from UE

... and this has important consequences for
- Jet identification
- Jet energy reconstruction
  - Resolution
  - Bias
- Low-$p_t$ background for the jet structure observables

In Cone of $R=1$
- 0.25 TeV (RHIC, cen. AuAu)
- 0.8 - 1.9 TeV (LHC, cen. PbPb)
  - Higher bound from HIJING
- High energy jets are more collimated
ALICE Detector Systems for Jet and $\gamma$-Identification

- **ITS+TPC+(TOF, TRD)**
  - Charged particles $|\eta| < 0.9$
  - Excellent momentum resolution up to 100 GeV/c ($\Delta p/p < 6\%$)
  - Tracking down to 100 MeV/c
  - Excellent Particle ID and heavy flavor tagging

- **EMCal**
  - Energy from neutral particles
  - Pb-scintillator, 13k towers
  - $\Delta\phi = 107^\circ$, $|\eta| < 0.7$
  - *Energy resolution* $\sim 10\%/\sqrt{E_{\gamma}}$
  - Trigger capabilities
DCal complements EMCal for Dijet and hadron-Jet Correlation Measurements
Sequence of key measurement

- Characterization of the soft background
  - Background fluctuations in typical jet cone areas
    - Correlated and uncorrelated
  - Elliptic flow

- Modification of the transverse jet structure
  - $R^{AA}_{Jet}(E_T, R)$
  - Jet shape $\psi(r)$
  - $j_T$

- Modification of the longitudinal jet structure
  - Fragmentation function $1/N_{jet} \, dN/dz$
More technically ...

- Determine Resolution Matrix $R(E_{\text{rec}} \mid E_{\text{true}} ; \text{FF, JF, ...})$
  - FF: Fragmentation
  - JF: Jet Finder
- Unfold measured spectrum
- Determine Smearing Matrix $R(E_{\text{true}}, E_{\text{bg}} \mid E_{\text{rec}} ; \text{FF, JF, ...})$
- Measure jet shape and correcting for soft BG (splash-in)
- Evaluate bias from splash-out
- Measure longitudinal fragmentation
  - Correct for splash in and splash out

MC Consistency check
Without modification standard jet finders used in pp (e⁺e⁻) collisions will not work in a heavy ion environment.

The main modification consists in determining the mean underlying event cell energy from cells outside a jet cone. It is recalculated after each iteration and subtracted from the energy inside the jet area.

Large interest and progress in Jet Reconstruction in high multiplicity environment

FASTJet package (Cacciari, Salam)
- Fast ($N \ln N$) implementation of $k_\perp$ and Cambridge/Aachen
- Implementation of an IRC safe cone algorithm (SIScone)
- New soft-resilient algorithm: anti-$k_\perp$
- Quantitative definition of jet area beyond leading order
Jet Reconstruction: Underlying Event

- Background energy fluctuations limit jet energy resolution at low energies
- In addition, they add a soft component to the jet structure observables (splash in)
- \( \Delta E \sim \sqrt{\text{Jet Area}} \)
  - Cone Algorithm: fixed area \( R^2 \)
  - \( k_T \): minimizes splash-out, however back-reaction from soft particles dominates systematics when comparing PbPb to more elementary collisions (pp, pA)
  - Anti-\( k_T \): regular jet-areas, small back-reaction
- At LHC background has hard component
  - \( O(10) \) Jets > 10 GeV per central collision

Splash-in can only be quantified once input spectrum has been measured and carries part of its systematic uncertainty.
Background Fluctuations

\[ \Delta E = \sqrt{N} \sqrt{[<p_T>^2 + \Delta p_T^2]} \]

- "non-Poissonian" behavior at medium \( p_T \) and in the tails of the pdf
- Small but significant systematics of the mean value
- Characterization of the soft correlated and uncorrelated background for high \( E_T \) QCD jets is an important LHC day-1 measurement.

\[ \Delta E_{bg} = \sqrt{\langle p_T \rangle^2 + \Delta p_T^2} \]

\( p_T > 2 \text{ GeV/c} \)

```
<table>
<thead>
<tr>
<th>Method</th>
<th>( \sigma ) GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random Cones</td>
<td>11.8 ± 0.1</td>
</tr>
<tr>
<td>Single ( \pi )</td>
<td>12.5 ± 0.1</td>
</tr>
<tr>
<td>PYTHIA jet</td>
<td>12.2 ± 0.05</td>
</tr>
</tbody>
</table>
```

Difference between real and estimated background energy

Jet Finder systematics with monochromatic jets.

ALICE EMCal PPR
Energy Resolution: EMCAL+tracking

Instrumental effects and fluctuating unmeasured contribution of $K_0^L$ and neutrons.
Jet Cross-Section Measurement: Systematic Error

**Graphs:**
- Two graphs showing data for jet cross-section measurements.
- One for p+p collisions with $\sqrt{s}=5.5$ TeV and $R=0.4$, 3 pb$^{-1}$.
- Another for Pb+Pb collisions with $\sqrt{s_{NN}}=5.5$ TeV, 10% Central, 0.5 nb$^{-1}$.

**Systematic effect table:**

<table>
<thead>
<tr>
<th>Effect</th>
<th>Incl. cross section sys. uncert.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common in p-p and A-A</td>
<td></td>
</tr>
<tr>
<td>Tracking distortions (space charge etc.)</td>
<td>unknown</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>1%</td>
</tr>
<tr>
<td>Hadronic and electron energy double counting</td>
<td>3-4%</td>
</tr>
<tr>
<td>EMCal energy scale</td>
<td>8-10%</td>
</tr>
<tr>
<td>Unobserved neutral energy</td>
<td>13-15%</td>
</tr>
<tr>
<td>Underlying event (central Pb–Pb)</td>
<td></td>
</tr>
<tr>
<td>Fluctuations</td>
<td>20% (75 GeV/c), 3% (150 GeV/c)</td>
</tr>
<tr>
<td>False Jets</td>
<td>small (&gt;50 GeV/c)</td>
</tr>
</tbody>
</table>
Reduced Jet Area (Splash-Out)

- Trigger bias towards more collimated jets
- Part of the medium induced soft radiation will be outside the jet cone and/or indistinguishable from the underlying event.
  - This introduces a systematic difference in the energy scale when comparing measurements in central PbPb to a baseline (pp or peripheral PbPb)
  - Energy scale enters directly into longitudinal fragmentation function ($z = p_L/E_{jet}$)
  - Bias towards less quenched jets
- Measurement of the $R_{AA}^{Jet}(R)$ allows to quantify the effect
  - (see STAR and PHENIX)
Large Out-of-cone radiation also expected at LHC

\[ R_{Jet}^{AA}(p_T) = \frac{d^2 \sigma_{Jet}^{AA} / dp_T d\eta}{T_{AA} d^2 \sigma_{pp} / dp_T d\eta} \]

jets (R=0.5), |\eta|^{jet}<3

PYQUEN (I. Lokhtin)
Jet $R_{AA}$ and Jet Broadening
Splash in/out systematics on jet structure

• Splash-in
  – Softening, widening
  – Quench-bias

• Splash-out
  – Collimation, hardening
  – Anti-quench bias

• Examples on the following slides ...
Modification of the Fragmentation Function

\[ \frac{1}{N_{\text{jet}}} dN/d\xi \]

Ideal: No background

1/N_{\text{jet}} dN/d\xi for E_{\text{jet}}=90+/-5GeV

PbPb

pp

UE soft background
\[ R_{AA}(\xi) = \frac{1/N_{jet}^{AA} dN_{AA}^{AA}/d\xi}{1/N_{jet}^{pp} dN_{pp}^{pp}/d\xi} \]

\[ \sqrt{S+B+0.002 B} \]
Systematic Effects

- Jet reconstruction pre-selects jets with larger than average soft UE contribution. Needs correction.

- Robust signal but underestimation of jet energy biases $\xi$ to lower values.
  - Depends on cone size $R$ and $p_T$ cut
  - Measurement has to be complemented by measurement of the
    - jet shape (out of cone radiation)
    - $R_{AA}(E_{\text{jet}})$
    - Calibration using $\gamma$-jet events

\[ Y = x_0 + x_1 X + x_2 X^2 \]

Fitting results:

<table>
<thead>
<tr>
<th>NO.</th>
<th>VALUE</th>
<th>ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8.846016e-01</td>
<td>8.235385e-01</td>
</tr>
<tr>
<td>1</td>
<td>-2.263853e-03</td>
<td>7.499791e-01</td>
</tr>
<tr>
<td>2</td>
<td>1.786685e-02</td>
<td>1.468557e-01</td>
</tr>
</tbody>
</table>

\[ \xi = \ln\left(\frac{E_{\text{cor}}}{p_T}\right) \]

- Splash-In
- Splash-Out

**Annual ALICE run statistics**

- $<E_{\text{input}}>$ ~ 175 GeV
- Pb+Pb 0-10%: $<\hat{q}>$=50 GeV$^2$/fm

[AQM]
PID and Jets

Measure $K_0^s$ spectrum much harder wrt to any Pythia Tune!
Look more differential into this effect:
- $K_0$ yield inside jets
- $K_0$ in underlying event
PID and Jets

Jet Composition

\[ \frac{dN}{d\xi} \]

- \( \pi^\pm \) (vacuum)
- \( K^\pm \) (vacuum) \times 2.5
- \( p(\bar{p}) \) (vacuum) \times 2.5
- \( \pi^\pm \) (medium)
- \( K^\pm \) (medium) \times 2.5
- \( p(\bar{p}) \) (medium) \times 2.5

\[ E_{jet} = 14.5 \text{ GeV} \quad \Theta_c = \pi/2 \]

\( \xi = \ln(E_{jet}/p_h) \)

100 GeV Jet

ALICE PID Range

Sapeta, Wiedemann EPJ C55 293 (2008)
only effect of enhanced parton splitting
Where do we stand today?

Reconstructed Jets UA1 Cone R = 0.4:
Jet 1: $\eta = 0.02$, $\phi = 306^\circ$, $p_T = 71$ GeV, Tracks 15
Jet 2: $\eta = 0.84$, $\phi = 132^\circ$, $p_T = 47$ GeV, Tracks 9
$\Delta\phi = 174^\circ$
Total Tracks 108
Di-Hadron Correlation

See talk J. Ulery
Jet-like properties from Di-Hadron Correlations

See talk J. Ulery

Di-Hadron $p_T$
Raw Min Bias Jet Spectrum \( pp@900 \text{ GeV} \)

Jets within \( |\eta| < 0.5 \), Tracks within \( |\eta| < 0.9 \)
Raw Min Bias Jet Spectrum pp@7 TeV

Jets within |\eta| < 0.5, Tracks within |\eta| < 0.9

p+p \sqrt{s} = 7 TeV

128 M selected events
Some ideas for non-standard jet measurements

• Energy flow relative to thrust-major axis
• Jet mass modifications
• High $j_T$ suppression
Energy flow relative to Thrust-Major

Jet axis ~ (single jet) Thrust

- Jet reconstruction sensitive to modifications of longitudinal and transverse energy flow. However, it should be insensitive to redistributions in the tangential direction.

- How to measure this?
  - In parton showers $\phi$-symmetry in plane perpendicular to jet axis is broken after first “hard” splitting. Defines Thrust Major Axis.
  - Determine this axis from particles near to the jet axis with relatively high $p_t$.
  - Look for correlations at higher $R$ and lower $p_t$. 

Sphericity Matrix in plane perpendicular to jet axis

\[ S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |p_i|^2} \]

\[ p_i^x = p_i T \cos(\delta) \]
\[ p_i^y = p_i T \sin(\delta) \]

\[ \delta = \tan^{-1}(\Delta \Phi / \Delta \eta) \]

Find largest eigenvalue and corresponding eigenvector. Eigenvector = x-axis of new coordinate system.
pp

Quenched (Q-Pythia)

$\Delta \phi$

$\Delta \eta$

$10^{-2}$

$10^{-1}$

$1$
Effects intimately related to enhanced splitting!
Jet Mass

Will approximate scaling $\sim R E_1$ persist in QGP?
Possible LHC Scenario

Limit for uncorrelated background

- $R = 0.4$
- $\sqrt{\langle M^2_{\text{jet}} \rangle} / (E_{\text{jet}} R)$
- $E_{\text{jet}}$ [GeV]
- Pyquen
- Pythia 6.4

$R = 0.4$
The Measurement: Background Correction

- Determine expected \((E, p_x, 0, 0)\) at \(y = 0\) from background
- Rotate and boost in the jet direction.
- Subtract jet by jet.

Scaled Jet Mass

![Graph showing Scaled Jet Mass with labels and axes](image)

- Unquenched
- Quenched

\(E_T = 150\) GeV

Solid: MC truth Dotted: Measured
Suppression of large $j_T$?

- Relation between $R$ and formation time of hard final state radiation.
  - Early emitted final state radiation will also suffer energy loss.
  - Look for $R$ – dependence of $\langle j_\parallel \rangle$!

$$t_{\text{form}} = \frac{1}{\Theta j_T}$$
Summary

We can look forward to very interesting physics with reconstructed jets in Heavy Ion collisions with ALICE
- High rates providing sufficient energy lever-arm to map out the energy dependence of jet quenching.
- Large effects: Jet structure changes due to energy loss and the additional radiated gluons.
- Experiments suited for jet measurements in Heavy Ion Collisions
  - ATLAS and CMS: larger acceptance, higher energy reach
  - ALICE: excellent PID and low-$p_T$ capabilities

Three unconventional jet observables have been discussed. They might help to distinguish between different jet quenching models.
- Energy flow relative to thrust-minor axis
- Jet mass modifications
- High $j_T$ suppression