Jet Physics
in Heavy Ion Collisions at the LHC

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- LHC Heavy Ion Program
- Jet Physics at LHC: Introduction and motivation
- Emphasis on expectations and requirements
  - Jet rates at the LHC
  - Energy resolution
  - Jet structure observables
- In short: The experiments.

ECT Workshop on Parton Propagation through Strongly Interacting Systems
**Nuclear collisions at the LHC**

- LHC on track for start-up of pp operations in April 2007
- Pb-Pb scheduled for 2008
  - Each year several weeks of HI beams ($10^6$ s effective running time)
- Future includes other ion species and pA collisions.
  - LHC is equipped with two separate timing systems.

<table>
<thead>
<tr>
<th>System</th>
<th>$\mathcal{L}_0$ [cm$^{-2}$s$^{-1}$]</th>
<th>$\sqrt{s}_{NN \text{ max}}$ [TeV]</th>
<th>$\Delta y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb+Pb</td>
<td>$1 \times 10^{27}$</td>
<td>5.5</td>
<td>0</td>
</tr>
<tr>
<td>Ar+Ar</td>
<td>$6 \times 10^{28}$</td>
<td>6.3</td>
<td>0</td>
</tr>
<tr>
<td>O+O</td>
<td>$2 \times 10^{29}$</td>
<td>7.0</td>
<td>0</td>
</tr>
<tr>
<td>pPb</td>
<td>$1 \times 10^{30}$</td>
<td>8.8</td>
<td>0.5</td>
</tr>
<tr>
<td>pp</td>
<td>$1 \times 10^{34}$</td>
<td>14</td>
<td>0</td>
</tr>
</tbody>
</table>

**First 5-6 years**
- 2-3y Pb-Pb (highest energy density)
- 2y Ar-Ar (vary energy density)
- 1y p-Pb (nucl. pdf, ref. data)
Pb-Pb Collisions at LHC

- As compared to RHIC
  - Energy density 4-10 higher
  - Larger volume (x 3)
  - Longer life-time (2.5 x)
- High rate of hard processes
  - Produced in on year of running for |y| < 1
    - $5 \times 10^{10}$ Open charm pairs
    - $2 \times 10^9$ Open beauty pairs
    - $1 \times 10^9$ Jets ($E_T > 20$ GeV)

<table>
<thead>
<tr>
<th>Central collisions</th>
<th>SPS</th>
<th>RHIC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s^{1/2}$ (GeV)</td>
<td>17</td>
<td>200</td>
<td>5500</td>
</tr>
<tr>
<td>$dN_{ch}/dy$</td>
<td>500</td>
<td>650</td>
<td>3-8 x10³</td>
</tr>
<tr>
<td>$\varepsilon$ (GeV/fm³)</td>
<td>2.5</td>
<td>3.5</td>
<td>15-40</td>
</tr>
<tr>
<td>$V_s$(fm³)</td>
<td>$10^3$</td>
<td>$7x10^3$</td>
<td>$2x10^4$</td>
</tr>
<tr>
<td>$\tau_{QGP}$ (fm/c)</td>
<td>&lt;1</td>
<td>1.5-4.0</td>
<td>4-10</td>
</tr>
<tr>
<td>$\tau_0$ (fm/c)</td>
<td>~1</td>
<td>~0.5</td>
<td>&lt;0.2</td>
</tr>
</tbody>
</table>
High rates, however challenging ... 

Study jet structure ... 

... inside the underlying event of a Pb-Pb collision.
Evidence for energy loss in nuclear collisions has been seen at RHIC. Measurements are consistent with pQCD-based energy loss simulations and provide a lower bound to initial color charge density. However, more detailed studies at higher $p_T$ at RHIC and higher energies (LHC) are necessary to further constrain model parameters. This has triggered substantial interest in Jet Physics in nuclear collisions at the LHC at which

- Medium and low-$p_T$
  - Dominated by hard processes
  - Several Jets $E_T < 20$ GeV / central PbPb collision
- At high-$p_T$
  - Jet rates are high at energies at which jets can be identified over the background of the underlying event.
The leading particle as a probe becomes fragile in several respects:

- Surface emission “trigger bias” leading to
  - Small sensitivity of $R_{AA}$ to variations of transport parameter $q_{\text{sat}}$.
  - Yields only lower limit on color charge density.
- For increasing in medium path length $L$ leading particle is less and less correlated with jet 4-momentum.

Ideally, the analysis of reconstructed jets will allow us to measure the original parton 4-momentum and the jet structure (longitudinal and transverse). From this analysis a higher sensitivity to the medium parameters (transport coefficient) is expected.
Part II

- What are the expected jet production rates at the LHC?
- How to identify jets knowing that a typical jet cone contains 1 TeV of energy from the underlying event?
- What are the intrinsic limitations on the energy resolution?
Jet rates at LHC

NLO by N. Arnesto
Jet rates at LHC

Copious production:
Several jets per central PbPb collisions for $E_T > 20$ GeV

However, for measuring the jet fragmentation function close to $z = 1$, $>10^4$ jets are needed. In addition you want to bin, i.e. perform studies relative to reaction plane to map out $L$ dependence.
Jet identification

- It has been shown (by embedding Pythia jets into HIJING) that even jets of moderate energies \( (E_T > 50 \text{ GeV}) \) can be identified over the huge background energy of the underlying HIJING event of central PbPb.

- Reasons:
  - Angular ordering: Sizable fraction \((\sim 50\%)\) of the jet energy is concentrated around jet axis \((R < 0.1)\).
  - Background energy in cone of size \(R\) is \(\sim R^2\) and background fluctuations \(\sim R\).

For \(dN_{ch}/dy = 5000\):

Energy in \(R = \sqrt{(\Delta \eta^2 + \Delta \phi^2)} < 0.7\):

1 TeV!
Jet Reconstruction with reduced cone-size

- Identify and reconstruct jets using small cone sizes $R = 0.3 - 0.4$
- Subtract energy from underlying event and correct using measured jet profiles.
- Reconstruction possible for $E_{\text{jet}} \gg \Delta E_{\text{Bg}}$
- Caveat:
  - The fact that energy is carried by a small number of particles and some is carried by hard final state radiation leads to out-of-cone fluctuation.
    - Reconstructed energy decreased.
    - Hence increase of $\Delta E/E$
  - Additional out-of-cone radiation due to medium induced radiation possible.
In analogy with heavy flavor physics:

- Fully contained jet.
- Reconstructed resonance.
- Hard final state radiation at large $R$ lost.
- Radiative losses, i.e. bremsstrahlung.
- Leading particle analysis
- Semileptonic decays.
Intrinsic resolution: Effect of cuts

$E_T = 100$ GeV

Counts / $2 \text{ GeV}$

$E_{\text{cone}} \text{ [GeV]}$

- $R < 0.4$
- $R < 0.4, p_T > 1 \text{ GeV}$
- $R < 0.4, p_T > 2 \text{ GeV}$
Intrinsic resolution

$E_T = 100 \text{ GeV}$
More quantitatively ...

Intrinsic resolution limit for $E_T = 100$ GeV

For $R < 0.3$:

$\Delta E/E = 16\%$ from Background
(conservative $dN/dy = 5000$)

14\% from out-of-cone fluctuations

Jet reconstruction for $E_{Jet} > 50$ GeV should be possible at LHC.

Not included in this estimate: Expected “quenching” or even thermalisation of the underlying event.
Production rate weighted resolution function

- Intrinsic resolution limited to $\Delta E/E \sim (15-20)\%$
- Production rate changes factor of 3 within $\Delta E$
- Production rate weighted resolution function has to be studied.
Production spectrum induced bias

Leading Particles

charged jets

TPC+EMCAL

R < 0.4 p_T > 2 GeV
Part III

- The transverse structure
  - Do jets survive?
  - Transverse Heating.

- Longitudinal structure
  - Leading parton remnant
  - Radiated energy
Central question

- Does the collimated structure of the jets survive so that they can be reconstructed event by event?
  - Study nuclear suppression factor $R_{AA}^{Jet}(E_T, R)$
  - Total suppression (i.e. surface emission only) or do we reconstruct modified jets?

Have the observed jets a modified transverse structure?

- Measure jet shape $dE/dR$
- Measure momentum distribution perpendicular to the jet axis $dN/dk_T$ ("Transverse Heating")
Transverse Structure

\[ \Delta E = 20 \text{ GeV} \]

Salgado, Wiedemann, hep-ph/0310079
Longitudinal structure

- Measure parton energy as the energy of the reconstructed jet
- Measure energy loss
  - Remnant of leading partons in the high-z part of the fragmentation function
- Measure radiated energy
  - Additional low-z particles
Longitudinal structure

- No trivial relation between energy loss and jet observables
  - Intrinsic to the system
    - Path length is not constant
    - Need measurements relative to reaction plane and as a function of $b$.
  - More importantly: Intrinsic to the physics
    - Finite probability to have no loss or on the contrary complete loss
  - Reduced cone size
    - Out-of-cone fluctuations and radiation
- To relate observables to energy loss we need shower MC combining consistently parton shower evolution and in-medium gluon radiation.

[code for Quenching Weights from C. Salgado and U. Wiedemann]
Toy Models

Two extreme approaches

- Quenching of the final jet system and radiation of 1-5 gluons. (AliPythia::Quench + Salgado/Wiedemann - Quenching weights with $q = 1.5 \text{ GeV}^2/\text{fm}$)
- Quenching of all final state partons and radiation of many (~40) gluons (I. Lokhtin: Pyquen)

Jet (E) $\rightarrow$ Jet (E-$\Delta E$) + n gluons (“Mini Jets”)

footnotes:

\footnotesize

- I.P. Lokhtin et al., e-print hep-ph/0406038
- http://lokhtin.home.cern.ch/lokhtin/pyquen/
Example: Hump-backed Plateau

\[ \frac{d\mathcal{N}}{d\xi}(\xi, \tau) \]

N. Borghini, U. Wiedemann

- OPAL, \( \sqrt{s} = 192-209 \) GeV
- in vacuum, \( E_{\text{jet}} = 100 \) GeV
- in medium, \( E_{\text{jet}} = 100 \) GeV
- TASSO, \( \sqrt{s} = 14 \) GeV
- in vacuum, \( E_{\text{jet}} = 7 \) GeV
- in medium, \( E_{\text{jet}} = 7 \) GeV

\( \xi = \ln\left(\frac{1}{x}\right) \)

\[ 1 \mathcal{N}_{\text{jet}} \frac{d\mathcal{N}}{d\xi} \]

AliPythia

Pyquench

\[ \xi = \ln\left(\frac{E_{\text{jet}}}{p_T}\right) \]
Transverse Heating: $k_T$ - Broadening

- Unmodified jets characterized by $\langle k_T \rangle = 600$ MeV $\sim \text{const}(R)$.
- Partonic energy loss alone would lead to no effect or even a decrease of $\langle k_T \rangle$.
  - Transverse heating is an important signal on its own.

Salgado, Wiedemann, hep-ph/0310079

Unquenched
Quenched (AliPythia)
Quenched (Pyquen)
Suppression of large $k_T$?

- 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 $\langle j_T \rangle$!
Interpretation of Fragmentation Functions

- Intrinsic limit on sensitivity due to higher moments of the expected $\Delta E/E$ distribution.
- Possible additional bias due to out-of-cone radiation.
  - $E_{\text{rec}} < E_{\text{parton}}$
  - $z_{\text{rec}} = p/E_{\text{rec}} > z_{\text{hadron}}$

Energy-Loss Spectrum

$E = 100 \text{ GeV}$

$\Delta E = 20 \text{ GeV}$

$z = p_L/E$

Unquenched
Quenched (AliPythia)
Quenched (Pyquen)
Limit experimental bias ...

- By measuring the jet profile inclusively.
  - Low-\(p_T\) capabilities are important since for quenched jets sizeable fraction of energy will be carried by particles with \(p_T < 2\) GeV.

- Exploit \(\gamma\)-jet correlation
  - \(E_\gamma = E_{\text{jet}}\)
  - Caveat: limited statistics
    - \(O(10^3)\) smaller than jet production
  - Does the decreased systematic error compensate the increased statistical error?
  - Certainly important in the intermediate energy region \(20 < E_T < 50\) GeV.
ALICE Jet Data Challenge

- Embed Pythia jets in central Pb-Pb HIJING events
- Pass through full detector simulation
  - Geant3 transport and detailed detector simulation
- Reconstruct tracks in central detectors
- Reconstruct charged jets ($E_T > 10\text{GeV}$)
  - Statistics: $\sim 3000$ jets for $E_T > 100\text{ GeV}$
  - $\sim 1$ month, un-triggered
- Study jet structure
ALICE Jet Data Challenge

![Graph showing differential cross-sections for different energy ranges.]

- $30 < E_{\text{cone}} < 40 \text{ GeV}$
- $70 < E_{\text{cone}} < 80 \text{ GeV}$
- $110 < E_{\text{cone}} < 120 \text{ GeV}$

- Pythia
- Pythia + Hijing
Hump-backed plateau

High z (low $\xi$): Needs good resolution
Low z (high $\xi$): Systematics is a challenge, needs reliable tracking.
Also good statistics (trigger is needed)
EMCAL for ALICE

- EM Sampling Calorimeter (STAR Design)
- Pb-scintillator linear response
  - $-0.7 < \eta < 0.7$
  - $\pi/3 < \Phi < \pi$
- 12 super-modules
- 19152 towers
- Energy resolution $\sim 15\%/\sqrt{E}$
Complementarities and Redundancy

- ATLAS, CMS
  - Full calorimetry
  - Large coverage (hermeticity)
  - Optimized for high-$p_T$
- ALICE
  - TPC + proposed EMCAL
  - Low- and high-$p_T$ capability
    - 100 MeV – 100 GeV
  - Particle identification
Conclusions

- Copious production of jets in PbPb collisions at the LHC
  - < 20 GeV many overlapping jets/event
    - Inclusive leading particle correlation
- Background conditions require jet identification and reconstruction in reduced cone $R < 0.3-0.5$
- At LHC we will measure jet structure observables ($k_T$, fragmentation function, jet-shape) for reconstructed jets.
  - High-$p_T$ capabilities (calorimetry) needed to reconstruct parton energy
  - Good low-$p_T$ capabilities are needed to measure particles from medium induced radiation.
- ALICE needs calorimetry (EMCAL) for triggering and jet reconstruction
  - ... and this would make it the ideal detector for jet physics at the LHC covering the needed low and high-$p_T$ capabilities + particle ID.
- Community needs MC combining consistently in medium energy loss and parton showers.