Jet quenching at RHIC
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Praha, 3rd of November 2008
Outline

- Jets. What is jet quenching?
- Experimental observations of jet energy loss in Heavy-Ion collisions
- Full jet reconstruction in heavy-ion collisions
- Outlook towards new methods
What is a jet?

A spray of colimated particles
- Hardly ever better defined...

Direct indication of fragmenting parton
- good assumption: approximate parton/jet energy by reconstructing energy of individual particles/constituents
- jets (unlike single hadrons) are “better” calculable within pQCD

\[ \sum p_T \text{ particles} = p_T \text{ jet} \]

Sterman and Weinberg, Phys. Rev. Lett. 39, 1436 (1977) ...
LEP: e+ e−
Jets from p+pbar at Tevatron

- Very good agreement with NLO pQCD
- Multiple algorithms used converging to consistent results
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CDF RunII Preliminary

Data/NLO prediction (CTEQ6M) corrected at hadron level

\[ \mu_R = \mu_F = \sqrt{P_T^2 + m_0^2} / 2 \]

MidPoint jets, \( R_{cone} = 0.7 \), \( f_{merge} = 0.75 \)
\( \sqrt{s} = 1.96 \text{ TeV}, \int L \sim 300 \text{ pb}^{-1} \)
\(|Y| < 0.7\)
What happens in the collision?

What really happens in hadronic collisions…

Final State Radiation (FSR)

Initial State Radiation (ISR)

Jet

Detector

{π, K, p, n, …}

Hadronization

Beam Remnants

Beam Remnants

p

(uud)

p

(¯u¯d)
What is being measured?

pQCD factorization:

parton distribution fn $f_{a/A}$
+ partonic cross section
+ fragmentation fn $D_{h/c}$
Reference: pQCD at $\sqrt{s} = 200$ GeV p+p collisions at RHIC

\[ d\sigma \propto (PDF) \otimes (Hard) \otimes (Fragm) \]

NLO: W. Vogelsang

STAR TPC Event Display

xy plane
Why to use jets in HI collisions?

- Probe early stage of the collision
- Tomographic picture of the collision zone
- Access to medium characteristics – quantifying basic QCD features of QGP
  - Partons (color charged probes) interact with the hot and dense colored medium
Heavy Ion collisions:
Jets interacting with the medium

We use the jets to probe the medium!
Describing jet quenching

Medium can be characterized by the transport coefficient \( q \):

\[
\hat{q} \sim \mu^2 / \lambda
\]

Parton loosing energy via gluon radiation - QCD Bremstrahlung

\[
E_{\text{loss}} \sim L^2
\]

\[
E_{\text{loss}} \sim \rho \sim \frac{dN_g}{dy}
\]
Suppression of high-pt hadrons

Partonic energy loss in AA:
-> substantial softening of the fragmentation function
-> suppression of hadron yield at high transverse momenta (!)

Can we quantify E-loss via suppression?
Nuclear modification factor

\[ R_{AB} = \frac{d^2 N / dp_t d\eta}{T_{AB} d^2 \sigma_{pp} / dp_t d\eta} \]

\[ T_{AB} = \langle N_{bin} \rangle / \sigma_{pp}^{inel} \]

No "Effect":  
R < 1 at small momenta  
R = 1 at higher momenta where hard processes dominate

Suppression: R < 1

Photon – color neutral probe => No suppression

Hadrons from color charged jets => Suppression
Jet suppression via di-hadron correlations

Strong modification of the recoil-jet indicates substantial partonic interaction within the medium.

Di-hadron correlations

Lowering $p_T$ assoc. recovers broad recoil correlation (momentum conservation $\sim \cos(\Delta \phi)$)

Increase of soft particle yield as compared to $p+p$ or $d+Au$!

$p_T$ assoc $> 2$ GeV/c

$p_T$ assoc $> 0.15$ GeV/c
Di-hadron correlations at high-pT

Reaperance of the away side peak at high-assoc.-pT:
- similar suppression as in the inclusive spectra
- unmodified shape

Differential measurement of jets w/o interaction
-> limitation of the LO probes

Most central

High-pT

Phys.Rev.Lett.97:162301,2006 $\Delta\phi$
Trigger Bias

Setup of the trigger (online and offline) biases studied sample towards harder fragmentation

\[ \sqrt{s_{NN}} = 200 \text{ GeV} \]

Distributions of parton production points in the transverse plane

Need more unbiased methods to constrain and reconstruct the jet energy and di-jet studies

\[ \rightarrow \text{Full jet reconstruction, gamma-jet correlations} \]

Renk and Eskola, hep-ph/0610059

Medium described by theory

Model parameters (within a given set of assumptions) are constrained within ~20%

Matter density large: ~30-50 times cold nuclear matter

Additional assumptions → different models are broadly consistent (except PQM – much larger than others)

Different modeling approaches of radiative energy loss operating with different parameters but “connected” with each-other

- $<\hat{q}> \approx 13.2 \text{ GeV}^2/fm \pm 20\% \ (PQM/ASW)$
- $\frac{dN_g}{dy} \approx 1400 \pm 20\% \ (GLV \ and \ WHDG)$
- $\epsilon_0 \approx 1.9 \text{ GeV}/fm \pm 20\% \ (ZOWW)$
- $\alpha_s \approx 0.28 \pm 8\% \ (AMY)$

Strong conclusions:
- initially generated medium is highly opaque to energetic partons
- very dense, high temperature matter has been created
Key points learned so far – onset of jet quenching

- Hard partons interact with the medium
  - High-$p_t$ hadrons are strongly suppressed in heavy-ion collisions
  - Leading hadron azimuthal correlations show strong modifications of the recoiling jet fragments at low and intermediate-$p_t$
  - At high-$p_T$: finite measurement of the recoil-jet at the expense of strong bias towards hard fragmentation and little interaction
  - **Initial gluon density constrained \(\rightarrow\) created matter is very dense and hot**

However, we would like to learn more about the interaction... Need for an unbiased and calibrated jet probe.
Parton traversing the medium: energy loss

\[
P(\Delta E) = p_0 d(\Delta E) + p(\Delta E)
\]

In realistic systems, energy loss is a broad distribution \( P(\Delta E) \)

**Single-hadron and di-hadron observables fold production spectra with \( P(\Delta E) \)**

Need more differential measurement to probe \( P(\Delta E) \)

Three techniques:

- Multi-particle correlations
- \( \gamma \)-jet
- Jet-finding

\[
\Delta E = \int d\epsilon e P(e) \]

Average energy loss:
Full jet reconstruction in heavy-ion collisions

Measure the initial parton energy

Access to unbiased fragmentation and its properties in the presence of medium

Possibly the best tool to assess and discriminate between quenching (energy loss) mechanisms

Exploration of full spectrum of jet modifications in medium
Reference jet measurement

p+p jet spectrum agree with NLO pQCD

Unbiased jet reconstruction in AuAu must result in $N_{\text{binary}}$ scaling relative to p+p – an essential test!

$$\frac{dN_{\text{jet}}^{\text{Au+Au}}}{dE_T} = T_{AA} \frac{\sigma_{\text{jet}}^{\text{p+p}}}{dE_T}$$

STAR 2007 Au+Au 200 GeV: high statistics – high reach in $p_T$ (jets up to 50 GeV!)

Experimental uncertainty $\sim 50\%$
Jet finding algorithms employed in STAR

- **Cone algorithms**
  - Leading Order High Seed Cone (LOHSC)
  - Mid Point Cone (Used in p+p only) Merging & Splitting

- **Recombination algorithms**
  - KT
  - Cambridge/ Aachen

\[ R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \]

M. Cacciari, G. Salam, G. Soyez 0802.1188 [hep-ph]
Recombination algorithms

- Colinear and infrared safe
- Improved performance
- Different algorithms -> different response to the underlying background – better control and sensitivity to quenching features
- Rigorous definition of jet area
Jets reconstructed in p+p

Raw counts of leading jets

Good agreement of various reconstruction algorithms

Seed bias clearly visible
Energy resolution

Jet Finder (Mid-point Cone Algorithm) applied to PYTHIA p+p events:

- PYTHIA particles $\rightarrow$ **PYTHIA Jets** (no detector effects)
- Reconstructed tracks and calorimeter towers $\rightarrow$ **RECO Jets** (detector effects)

Resolution: $\sim 25\%$
Jet embedded into HI collisions
- response of the algorithms

\[ \Delta E = E_{\text{PyDet}} - E_{\text{PyTrue}} \]

Shift of median due to un-measured particles (n, K^0_L) and the \( p_T \) cut.

\[ \Delta E = E_{\text{PyEmbed}} - E_{\text{pyDet}} \]

Smearing due to background subtraction in Au+Au.

\[ \Delta E = E_{\text{PyEmbed}} - E_{\text{pyTrue}} \]

Tail at positive \( \Delta E \) causes deformation in the spectrum towards higher energies.
Jet energy corrections

- An increase of the $p_T$ threshold: should reduce the effect of background fluctuations
  - jet reconstruction in 0-10% Au+Au $\sim p+p$
- The $p_T$ cut is expected to produce biases.
Jets and the heavy-ion underlying event

Main difficulty: constrain and control of the background fluctuations

-> Inhibiting background: introduction of $p_t$ cut on the input particles – source of a bias (Cone Algorithm!)

M. Cacciari, G. Salam, G. Soyez 0802.1188 [hep-ph]

$$p_T^{measured} \approx p_T^{parton} + \rho \cdot A \pm \sigma \sqrt{A}$$

$\rho =$ Diffuse noise, $\sigma =$ noise fluctuations

Background Fluctuations

Jet $E_T > 20$ GeV

$K_T$, $p_t^{cut} = 0.1$ GeV

$R=0.4$
Cross section compared to binary-scaled p+p

Inclusive spectrum correction based on PYTHIA

**MB-Trig**: Good agreement (within errors) with binary-scaled p+p → unbiased jet reconstruction?

**HT-Trig**: hardware cluster trigger (requirement of ~7.5 GeV) in EMcalorimeter -> large trigger bias persists beyond 30 GeV

**MB-Trig** is essential for unbiased measurement - good news: factor ~20 more on tape than shown here!
Scaling for sequential recomb. w/ low $p_T$ cut

Also good agreement with binary-scaled p+p
Interesting because:
- seedless algorithms: no seed bias
- $p_T>100$ MeV (!): minimal $p_T$ cut bias
- spectrum correction factors (much) closer to unity
Influence of the pT cut

Imprecise subtraction of underlying event? How sensitive are we to fragmentation model in corrections (PYTHIA)?
Fragmentation function: The Shape and Quenching

\[ \xi = \ln \left( \frac{E^{Jet}}{p_{hadron}} \right) \]

Borghini and Wiedemann, hep-ph/0506218

Jet quenching

“hump-back plateau”
Fragmentation Function in p+p @ RHIC

- Uncorrected spectra
- Different Jet Finders show similar performance for a given R
- Mean $\xi$ increases with jet energy

E. Bruna DNP meeting
Oakland October'08

$10 < p_{T,\text{jet}} < 15 \text{ GeV}$

$20 < p_{T,\text{jet}} < 30 \text{ GeV}$

$30 < p_{T,\text{jet}} < 40 \text{ GeV}$

$p_{T,\text{jet}} > 40 \text{ GeV}$
AuAu: FF for Jet energies $> 30$ GeV

Provisional conclusion: apparently no medium-induced FF modification!
but consistent with HT-trig being highly biased (require 7.5 GeV $\pi^0$ in jet)

Factor 20 more MB-trig data on tape – crucial to analyse it!
New modeling tools and hadronization

Néstor Armesto and Carlos A. Salgado  
Universidade de Santiago de Compostela 
In collaboration with Leticia Cunqueiro (Frascati) 
and Gennaro Corcella (Pisa)

qPythia: http://igfae.usc.es/qatmc/

PARTON LEVEL

HADRON LEVEL

qhat $\sim 5$ Gev$^2$/fm
qhat $\sim 50$

Evolution in length, not in energy

No evolution in length nor energy

Evolution in length and energy

vacuum

Effects reduced by hadronization -> comparison with different models (Herwig)
New modeling tools and hadronization

Effects reduced by hadronization -> comparison with different models (Herwig)

Different jet observables

- Hadron-jet correlations
  - Data driven corrections - IAA
- Gamma-jet correlations
- Di-jet measurements: energy balance, accoplanarity
  - Crucial measurements in p+p and d+Au for reference to AuAu (!)
- jT and pout distributions
- Sub-jet distributions (JEWEL – new MC quenching model)
New jet observable: subjet distributions

Look at multiplicity of “subjets” as fn of Durham/Cambridge metric:

\[ y_{ij} = 2 \cdot \min \left( \frac{E_i^2}{E_{CM}^2}, \frac{E_j^2}{E_{CM}^2} \right) \left( 1 - \cos \theta_{ij} \right) / E_{CM}^2 \]


medium-enhanced jet splitting
New jet observable: subjet distributions

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\[ y_{ij} = 2 \cdot \min \left( E_i^2, E_j^2 \right) \left( 1 - \cos \theta_{ij} \right) / E_{CM}^2 \]


medium-enhanced jet splitting

Jet rates for a single 100 GeV quark jet

\( E_{\text{cut}} = 2 \text{ GeV} \)

\( f_{\text{med}} = 3, \ L = 5 \text{ fm} \)
Jets in Heavy-Ions at LHC

Huge cross-section for jet production

Large kinematic reach

-> Very good lever arm for energy dependence of partonic energy loss
ALICE

with EMCAL – first module next year(?)

Lead-Scintillator sampling calorimeter

$|\eta|<0.7$, $\Delta\phi\sim110^\circ$

Shashlik geometry, APD photo-sensor

$\sim13k$ towers ($\Delta\eta\times\Delta\phi\sim0.014\times0.014$)

$\frac{\sigma_E}{E} \sim \frac{11\%}{\sqrt{E}}$
Summary

Leading hadron studies in Heavy-Ion collisions at RHIC show a strong evidence of jet quenching – constrain theoretical understanding of the medium density and temperature.

Studies of parton energy loss in hot QCD medium (Quark Gluon Plasma) require unbiased probes.

Full jet reconstruction in HI collisions works extremely well - gamma-jet, di-jet studies are under way, access to the fragmentation function and other promising observables.

Theoretical developments, MC models including quenching will provide understanding of the energy loss mechanisms – in case of strongly coupled QGP we may explore unique access and sensitivity to non-perturbative QCD dynamics.

Important studies at RHIC may prove useful for LHC(!)
Additional material
qPythia in 1 slide

We modify PYTHIA FSR routine PYSHOW, for t-ordered branching, introducing the medium-modified splittings

\[ P_{\text{tot}} = P_{\text{vac}}(z) + \Delta P(z, t, \hat{q}, L, E) \]

\[ \Delta(t) \equiv \exp \left[ - \int_{t_0}^{t} \frac{dt'}{t'} \int dz \frac{\alpha_s}{2\pi} \left[ P(z) + \Delta P(z, t', \hat{q}, L) \right] \right] \]

Probability of no emission between \( t_{\text{max}} = E^2 = 10^2 \text{ GeV}^2 \) and \( t \)

- lines/markers: with/without large x correction
- upper/lower curves: quarks/gluons
- \( t_{\text{min}} = 2t_0 = 2 \text{ GeV}^2, L = 2 \text{ fm} \)
- red: \( \hat{q}L = 10 \text{ GeV}^2 \)
- green: \( \hat{q}L = 1 \text{ GeV}^2 \)
- black: \( \hat{q}L = 0 \)

The medium is here

\( E = 10 \text{ GeV} \)

[Armesto, Cunqueiro, Salgado, Xiang 2007]
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Model parameters (within a given set of assumptions) are constrained within \(\sim 20\%\).

Matter density large: \(\sim 30\text{-}50\) times cold nuclear matter

Additional assumptions → different models are broadly consistent (except PQM – much larger than others)

Strong conclusions:
• initially generated medium is highly opaque to energetic partons
• very dense, high temperature matter has been created

Different modeling approaches of radiative energy loss operating with different parameters but “connected” with each-other

\[
\begin{align*}
\text{PQM/ASW} & \quad \langle \hat{q} \rangle = 13.2^{+2.1}_{-3.2} \text{GeV}^2/\text{fm} \\
\text{GLV} & \quad \frac{dN}{dy} = 1400^{+270}_{-150} \\
\text{WHDG} & \quad \frac{dN}{dy} = 1400^{+200}_{-375} \\
\text{ZOWW} & \quad \varepsilon_0 = 1.9^{+0.2}_{-0.5} \text{GeV/fm}^3 \\
\text{AMY} & \quad \alpha_s = 0.280^{+0.016}_{-0.012}
\end{align*}
\]
Qualitative to quantitative: radiative energy loss


Medium-induced gluon radiation spectrum:

\[ \frac{dI_{\text{LPM}}}{d\omega d\tau} = \left( \frac{\lambda}{l_{\text{coherent}}} \right) \frac{dI_{\text{BetheHeitler}}}{d\omega d\tau} = \sqrt{\hat{q} \frac{\alpha_s N_C}{\omega \pi}} \]

Total medium-induced energy loss:

\[ \Delta E_{\text{med}} = \int dz \int d\omega \omega \frac{dI_{\text{LPM}}}{d\omega d\tau} \sim \alpha_s \sqrt{\hat{q} \omega_c} L \sim \alpha_s \hat{q} L^2 \]

\[ t_{\text{formation}} < L \iff \omega < \omega_c \]
kt algorithmics

http://www.lpthe.jussieu.fr/~salam/repository/software/fastjet/fastjet-doc-2.3.3.pdf

1.1 $k_t$ jet algorithm

The definition of the inclusive $k_t$ jet algorithm that is coded is as follows:

1. For each pair of particles $i$, $j$ work out the $k_t$ distance

$$d_{ij} = \min(k_{ti}^2, k_{tj}^2) \Delta R_{ij}^2 / R^2$$

with $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$, where $k_{ti}$, $y_i$ and $\phi_i$ are the transverse momentum, rapidity and azimuth of particle $i$ and $R$ is a jet-radius parameter usually taken of order 1; for each parton $i$ also work out the beam distance $d_{iB} = k_{ti}^2$.

2. Find the minimum $d_{\text{min}}$ of all the $d_{ij}, d_{iB}$. If $d_{\text{min}}$ is a $d_{ij}$ merge particles $i$ and $j$ into a single particle, summing their four-momenta (this is $E$-scheme recombination); if it is a $d_{iB}$ then declare particle $i$ to be a final jet and remove it from the list.

3. Repeat from step 1 until no particles are left.
1.2 Cambridge/Aachen jet algorithm

Currently the Cambridge/Aachen jet algorithm is provided only in an inclusive version [5], whose formulation is identical to that of the \( k_t \) jet algorithm, except as regards the distance measures, which are:

\[
d_{ij} = \frac{\Delta R_{ij}^2}{R^2}, \quad (2a)
\]

\[
d_{iB} = 1. \quad (2b)
\]
**Figure 10.** The single inclusive distribution $dN/d\xi$ for a single medium-modified quark jet ($E_q = 100$ GeV) before ($Q_0 = 1$ GeV) and after hadronisation. On the parton level (left hand side), all partons are shown, but on the hadron level (right hand side), only charged hadrons are included. Collisional energy loss is calculated for $T = 500$ MeV and $L = 5$ fm, with recoil partons either hadronised together with the cascade (‘all’) or not included in the hadronisation (‘cascade’). Medium induced radiation is calculated for $f_{\text{med}} = 3$ and $L = 5$ fm.