Discussion on Hard Scattering at RHIC
(with John Harris)

May 15, 17, 2002 ITP/UCSB

Miklos Gyulassy
1) Jet Quenching
2) Elliptic Flow at 5 GeV pt

based on work with Ivan Vitev, Peter Levai, Xin-mian Wang

Five New p_{T}~2-6 GeV Phenomena
Discovered in Au+Au E_{cm} = 130 AGeV

"Jet Quenching"
Azimuthal Collectivity

PHENIX: PRL88(02) 022301

STAR: Jets+Flow

Preliminary

charged particles
Hydro pions

STAR nucl-ex/0104006
Two Particle Correlations at High $p_T$

- Trigger particle $p_T > 4$ GeV/c, $|\eta| < 0.7$
- azimuthal correlations for $p_T > 2$ GeV/c
- short range $\eta$ correlation: jets + elliptic flow
- long range $\eta$ correlation: elliptic flow

⇒ subtract correlation at $|\eta_1 - \eta_2| > 0.5$
- NB: also eliminates the away-side jet correlations

- extracted $v_2$ consistent with reaction-plane method

- what remains has jet-like structure ⇒ first indication of jets at RHIC!

April 9, 2002

QCD in the RHIC Era

First direct evidence for jettyness at RHIC at moderate $p_T$!

A + A Tomography with Jets

X-ray Tomography

Jet Tomography, GLVW

$\Delta E_{\text{GLV}} \sim C_2 \alpha_s^3 E_0^5 \int dt \tau_\text{glue} (\tau, r(\tau))$
Gluon Double Differential Distributions to All Orders in Opacity

1. Add up all Direct and Virtual FSI at order \( \left( \frac{\alpha_s}{\lambda_g} \right)^n \)
2. Use GLV Reaction Operator Formalism to solve recursion relations algebraically

\[
\frac{dN^{(n)}}{dx \, dk^2} = \frac{C_R \alpha_s}{\pi} \left( \frac{L}{\lambda_g} \right)^n \prod_{i=1}^n dq_i \left\{ \mu_i^2 (q_i^2 + \mu_i^2)^2 - \delta^2 (q_i) \right\}
\]

\[
-2 \sum_{j=1}^n B_{(j+1, \ldots, n)_{(j, \ldots, n)}}
\]

LPM effect

\[
\left( \cos \left( \sum_{k=2}^j \omega_{(k, \ldots, n)} \Delta z_k \right) - \cos \left( \sum_{k=1}^j \omega_{(k, \ldots, n)} \Delta z_k \right) \right)
\]

where\[
\omega_{(j, \ldots, n)} = \frac{(k - q_j - \ldots - q_n)^2}{2xE}
\]

Inverse Formation Times

Scatt amplitudes

GLV: First Order Radiative Energy Loss

\[
\Delta E^{(i)} = \int_0^1 dx \frac{d\Gamma^{(i)}}{dx} = E_0 \frac{2C_R \alpha_s}{\pi} \int_0^1 dx \int_0^\infty dz \sigma(z) \rho(z, z) f(Z(x, z))
\]

Formation parameter

\[
Z(x, z) = \frac{\mu^2(z)}{2xE} (z - z_0) = \frac{\Delta z}{\tau_{\text{form}}}
\]

Linear Regime: "Thin Plasma"

\[
Z(x, z) \ll 1 \Rightarrow x_c = \frac{\mu^2(z)}{2E} (z - z_0) \ll x \ll 1
\]

\[
\Delta E^{(i)} = \frac{2C_R \alpha_s}{\pi} \int_{x_c}^\infty \frac{dz}{\lambda_g(z)} \left\{ \int_0^{x_c} \frac{dx}{x} \frac{\mu^2(z)(z - z_0)}{4} + E_0 \int_0^{x_c} dx \log \left[ \frac{x_c}{x} \right] \right\}
\]

\[
= \frac{C_R \alpha_s}{2} \int_{z_0}^\infty dz \mu^2(z)(z - z_0) \left\{ \log \frac{2E}{\mu^2(z)(z - z_0)} + \frac{2}{\pi} \right\}
\]
Bjorken expansion

\[ \rho \tau \approx \frac{dN}{dy} \propto \frac{1}{R^2} \]

Scaling Expansion

\[ \frac{d}{d\tau} \rho(\tau) \tau^\alpha = 0 \]

Transport Property

\[ \mu^2 / \lambda_0 \propto \alpha_s^2 \rho \]

BDMS

Baier, Dokshitzer, Mueller, Schiff 1996
B.G. Zakharov 2000
U. Wiedemann 2000

Jet Energy Loss \( \propto L^2 \rightarrow L^1 \). Expansion Dependent Reduction.

Asymptotic Leading Log Approx

GLV Opacity Expansion in LLA same as BDMS (mod Log \( E/\mu^2 L \))

\[ \Delta E_\alpha (L) = \frac{C_R \alpha_s^2 (L) L^\alpha L^{2-\alpha}}{2} \log \frac{2E}{\mu^2 L} \]

For Bjorken 1+1D Expansion

\[ \Delta E_{\alpha=1} (L) = \frac{9C_R \pi \alpha_s^3}{4} \left( \frac{1}{\pi R^2} \frac{dN}{dy} \right) L \log \frac{2E}{\mu^2 L} \]

For static medium

\[ \Delta E_{\alpha=0} (L) = \frac{9C_R \pi \alpha_s^3}{8} \left( \frac{1}{\pi R^2} \frac{dN}{dy} \right) L^2 \log \frac{2E}{\mu^2 L} \]

For initial condition driven energy loss there is a factor of \( L/2z_0 \) reduction for the expanding medium relative to the static one.

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PHENIX / RHIC

WA98 / SPS

Fig. 12. Ratios of invariant multiplicity distributions of neutral pions to the proton in the nuclear collisions normalized to the number of binary collisions also called the nuclear modification factor. The gray band shows the estimate of the systematic errors due to the calculation of the number of collisions and the absolute cross section normalization relative to \( p+p \).
Pion \(^0\) Tomography

Three approximations:
1) \(P(\xi, E)\) including Poisson fluctuations
2) \(P(\xi, E) \approx \delta(\xi - \Delta E/E)\) Average Energy Loss
3) \(P(\xi, E) \approx \delta(\xi - \Delta E/E)\) Renormalized \(\Delta E\)
**pQCD p+p Baseline**

Current AA data → 2002 RHIC data → ?

- GRV98 LO
  - $<k_t^2> = 1.8$ GeV$^2$
  - $K = 1.5, Q^2 = P_T^2/2$

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**Additional Effects that Influence E-Loss**

- **Absorption effects important** for small $E_{xy} < 5$ GeV

- **Multi-gluon fluctuations**
  - Renormalize $\Delta E$ by $\sim 1/2$

GLV nucl-th/0112071; BDMS; Wang

\[
P(\varepsilon, E) = \sum_{n=0}^{\infty} P_n(\varepsilon, E) \quad \frac{\Delta E}{E} = \int_0^\infty d\varepsilon \varepsilon P(\varepsilon, E)
\]

\[
P_{n+1}(\varepsilon, E) = \frac{1}{n+1} \int_{x_0}^{1-x_0} dx_n \rho(x_n, E) P_n(\varepsilon - x_n, E)
\]

\[
P_1(\varepsilon, E) = e^{-\langle x \rangle} \rho(\varepsilon, E)
\]
Effect of Fluctuating En-loss GLV (02)

Similar shape of spectrum renormalization density by factor $Z \sim 0.4-0.5$ at RHIC

$$\frac{dE}{d^3p} = \sum_{\text{final}} \int dx_1 dx_2 dq_1 dq_2 g_1(q_1) g_2(q_2) \Delta x_1 \Delta x_2 \Delta Q_1 \Delta Q_2$$

Compare

$$P(\epsilon) = \left\{ \frac{\delta(\epsilon - Z \Delta E/E)}{\pi^2} \right\}$$

Cronin + Shadow effects

PHENIX data at 130 AGeV

$P(\epsilon) \rightarrow \rho_0$ at 130 AGeV

$1/N_{jet}$ (Jψ)
Elliptic Collective Flow at RHIC

\[ \frac{dN}{dydp_T^2d\phi} \propto 1 + 2v_2(p_T) \cos(2\phi) \]

\[ \frac{dN(0)}{dN(\frac{\pi}{2})} \approx \frac{13}{a_7} \approx 2 \]

Huge Asymmetry In Momentum Space!

Saturated \( p_T > 2 \text{GeV} \)

STAR Preliminary

Raimond Snellings QM01

A hydro calculation of elliptic flow

P. Kolb, J. Sollfrank, and U. Heinz

Pb + Pb, \( b = 7 \text{ fm} \)

Equal energy density lines

8/24/2000 R. Snelling LBNL
Dr. Miklos Gyulassy (Columbia Univ) [ITP QCD-RHIC Program 5-15-02] Discussion on Hard Scattering and its Use at RHIC

**Pasi Huovinen**

**Euler Hydrodynamics**

\[ \nu_2 @ \text{RHIC} \]

- Charged particles
- Min. Bias
- EoS A \( T_c = 165 \text{ MeV} \)
- \( T_c \text{ I} \) \( T_c = 140 \text{ MeV} \)
- \( T_c \text{ II} \) \( T_c = 125 \text{ MeV} \)

**Collective Flow or Final State Interactions?**

Up to how high \( p_t \) can dissipation \( 1/R \) be neglected?

**Elliptic Flow from Parton Cascade**

\[ \frac{dN_{\text{ch}}}{dy} = \nu_2 + 2\nu_3 \cos 2\phi + \ldots \]

Bin Zhang, c.m. ko, mg
PLB 455 (99) 43

\[ \nu_2 \text{ develops early + sensitive to } \sigma_{gg} \]
a) hadronization via parton-hadron duality

- Impact parameter averaged $v_2(P_T)$

b) independent fragmentation

- $80\times$ more opaque plasma needed than from HIJING to reproduce data
- not enough for equilibrium $\sim 30$ but rapid expansion
- too opaque for Eikonal dynamics to hold
- little sensitivity to hadronization scheme

Non-Central Collisions

\[ \text{X.N. Wang} \]

\[ \text{\[L(\phi)\]_{max}} \]

\[ \text{\[<L(\phi)\]_{mean}} \]

\[ r = 3 - 4 \text{fm} \]

\[ \text{7-8} \]

\[ \text{9-10} \]
**Soft Hydro + GLV Quenched Hard**

\[ E \frac{dN_{AB}(b)}{d^3p} = N_{\text{part}}(b) \frac{dN_{s}(b)}{dyd^2p_T} + T_{AB}(b) \frac{d\sigma_{h}(b)}{dyd^2p_T} \]

(1) pQCD computable "hard" part:

\[ E_h \frac{d\sigma_{h}}{d^3p} = K \sum_{abcd} \int dx_a dx_b f_{a/p}(x_a, Q^2_a) f_{b/p}(x_b, Q^2_b) \]

\[
\frac{d\sigma}{dt}(ab \to cd) \frac{D'_{h/c}(z_c, Q^2_c)}{\pi z_c}
\]

Medium modified fragmentation

\[ z_c D'_{h/c}(z_c, Q^2_c) = z'_c D_{h/c}(z'_c, Q^2_c) + N_g z_g D_{h/g}(z_g, Q^2_g) \]

\[ z'_c = \frac{p_h}{p_c - \Delta E_c(p_c, \phi)}/N_g \]

(2) Soft phenom. "hydro" part (P. Huovinen)

\[ \frac{dN_{s}(b)}{dyd^2p_T} \approx \frac{dn_s e^{-4p_T}}{dy} \frac{8\pi}{1 + 2v_{2s}(p_T) \cos(2\phi)} \]

\[ v_{2s}(p_T) \approx \tanh(p_T/(10 \pm 2 \text{ GeV})) \]