D+Au and Au+Au Reactions at RHIC: Manifestation of Multiparton Dynamics in Dense Nuclear Matter

Ivan Vitev

Iowa State University, Ames, IA 50011

INT – First Three Years at RHIC

June 09, 2003

Institute for Nuclear Theory, Seattle, WA
Approximations to \textbf{QCD}

\begin{align*}
  L &= -\frac{1}{4} F_{\mu\nu, a} F^{\mu\nu, a} + \bar{\Psi}_q (i\gamma^\mu D^\mu) \Psi_q \\
  &\quad \text{Lattice QCD}
\end{align*}

- Deconfinement phase transition
- Chiral symmetry restoration
- Thermal equilibration of the partonic medium

1. Supershadowed classical QCD
   \[ x_c < 10^{-2} - 10^{-3} \]
   May have relevance for total multiplicities
   \[ dN^{ch} / dy = c_{part} A^1 + c_{bin} A^{4/3} \]

2. Perturbative QCD & QCD in nuclear matter

The subject of the talk

\[ T_c ; 170 \text{ MeV} \quad e ; 1 \text{ GeV} / \text{fm}^3 \]

AGS, SPS, RHIC, LHC
High-$p_T$ Hadronic Signatures of Jet Quenching

**Binary scaling**

Jet Quenching

Cronin Effect

PHENIX Phys.Rev.Lett to be published

Predictions


High-p\textsubscript{T} Hadronic Signatures of Jet Quenching

Interplay of non-perturbative and perturbative effects


T.Hirano and Y.Nara, nucl-th/0301042

June 09, 2003

T. Hirano and Y. Nara, nucl-th/0301042

STAR

High-\(p_T\) Hadron Production from LO pQCD

\[
f_{a/N}(x, Q^2) \quad \text{Parton distribution functions}
\]

\[
D_h(z_c, Q^2) \quad \text{Fragmentation functions}
\]

\[
g(k_T) ; \quad \text{Exp}\left(-\frac{k_T^2}{\langle k_T^2 \rangle}\right) / \langle p \langle k_T^2 \rangle \rangle \quad \text{(generalized PDFs)}
\]

\[
x_a = \frac{p_a}{P_a}
\]

\[
x_b = \frac{p_b}{P_b}
\]

\[
z_c = \frac{p_c}{P_c}
\]

\[
E_h \frac{dS}{d^3p} = K_{NLO} \hat{\alpha}_abcd dx_a dx_b d^2k_a d^2k_b g(k_a)g(k_b)
\]

\[
\frac{dS}{dt} = f_a/A(x_a, Q^2)f_b/B(x_b, Q^2) D_{h/c}(z_c, Q^2) \frac{D_{h/c}(z_c, Q^2)}{p z_c}
\]
The Cronin Effect – a Qualitative Discussion

Faster than linear scaling of the \( p+A \) cross section with the number of binary collisions

\[
\frac{d\sigma^{p+A}}{dpT} \propto \frac{d\sigma^{p+p}}{dpT} \left( N_{\text{coll}} \right)^{\alpha}, \quad \alpha = \alpha(p_T)
\]

\[
R_{pA}(p_T, b) = A^{\alpha(p_T, b)-1}
\]

Relation between the 2 measures

**Experimental Facts**

- Includes both enhancement and suppression
- The effect decreases with \( \sqrt{s} \)
- The peak and intercept are \( p_T \)-stable, i.e. \( x_T \)-dependent
  (Excludes a wavefunction nature)


\[\text{J.Cronin et al.}\]

June 09, 2003

Ivan Vitev
Tensorial Book-keeping of Classes of Amplitudes

\[ A_{i_1 \cdots i_{n-1},0} \equiv \hat{1} \ A_{i_1 \cdots i_{n-1}} = \]

\[ A_{i_1 \cdots i_{n-1},1} \equiv \hat{D}_n \ A_{i_1 \cdots i_{n-1}} = \]

\[ A_{i_1 \cdots i_{n-1},2} \equiv \hat{V}_n \ A_{i_1 \cdots i_{n-1}} = \]

Amplitude and its complementary

\[ A_{i_1 \cdots i_n} = (\delta_{0,i_n} \hat{1} + \delta_{1,i_n} \hat{D}_n + \delta_{2,i_n} \hat{V}_n) \ A_{i_1 \cdots i_{n-1}} = \prod_{k=1}^{n} (\delta_{0,i_k} \hat{1} + \delta_{1,i_k} \hat{D}_k + \delta_{2,i_k} \hat{V}_k) \ A_0 \]

\[ \bar{A}^{i_1 \cdots i_n} = \left\{ \prod_{k=1}^{n} (\delta_{0,i_k} \hat{V}_k + \delta_{1,i_k} \hat{D}_k + \delta_{2,i_k} \hat{1}) \ A_0 \right\}^\dagger = \left\{ A_{2-i_1,\ldots,2-i_n} \right\}^\dagger \]


June 09, 2003

Ivan Vitev
Direct vs Virtual Contribution to $\chi = L/\lambda$

\[
d^3N_1 = \int \frac{d^4q}{(2\pi)^4} \frac{d^4q'}{(2\pi)^4} \int d_R \ j(p-q) j^*(p-q')
\]

\[
\times \frac{v(q)\Gamma(2p-q)}{(p-q)^2 + i\epsilon} \times \frac{v^*(q')\Gamma(2p-q')}{(p-q')^2 + i\epsilon} \times \frac{C_RC_2(T)}{d_A} \times \left( \sum_{j=1}^{N} e^{i(q-q')(x_j-x_0)} \right) x_i
\]

Off Diagonal in $q, q'$
Diag in Color
Average over $x_i=(z_i, b_i)$

\[
\frac{1}{d_T} \text{Tr} \langle M_2 M_0^* \rangle = \int \frac{d^4q}{(2\pi)^4} \frac{d^4q'}{(2\pi)^4} \int d_R \ j(p-q-q') j^*(p)
\]

\[
\times \frac{v(q)\Gamma(2p-q-2q')}{(p-q-q')^2 + i\epsilon} \times \frac{v(q')\Gamma(2p-q')}{(p-q')^2 + i\epsilon} \times \frac{C_RC_2(T)}{d_A} \times \left( \sum_{j=1}^{N} e^{i(q+q')(x_j-x_0)} \right) x_i
\]

Off Diagonal in $q, q'$
Diag in Color
Average over $x_i=(z_i, b_i)$

Main diff.
The **Reaction Operator Approach to Multiple Elastic and Inelastic Scatterings**

**Reaction Operator** = all possible on-shell cuts through a new Double Born interaction with the propagating system

\[
R_n = D_n^\dagger D_n + \hat{V}_n + \hat{V}_n^\dagger
\]

\[
\bar{n} = c = \frac{L}{l}
\]

For the **elastic scattering case** illustrated here by iteration:

\[
dN^f(p) = \hat{\mathcal{A}} \left( \sum_{n=0}^{\infty} \frac{c^n}{n!} \frac{1}{s_{el}} \frac{ds_{el}}{d^2q_i} \left( e^{-q_i \cdot N_{pb}} \hat{A} e^{-q_i \cdot p_{pb}} - 1 \right) \right) dN^i(p)
\]

\[
\frac{ds_{el}(b)}{d^2q} = \frac{nb}{4p^2} K_i(nb) \equiv \frac{1}{4p^2} \frac{\mathcal{A}}{\hat{\mathcal{O}}} - \frac{m^2b^2}{2} x + O(b^3) \frac{\hat{\mathcal{O}}}{\hat{\mathcal{O}}}
\]

\[
dN(k) = \frac{1}{2p} e^{-\frac{c m^2 x}{2}}, \quad \langle D k^2 \rangle = c m^2 x
\]

\[x = \log 2 / (1.08 mb)\]
Understanding the Systematics of Low Energy Data

Include nuclear-induced parton broadening

\[ \left\langle \Delta k^2_\perp \right\rangle_{\text{tot.}} = \left\langle k^2_\perp \right\rangle_{pp} + \left\langle \Delta k^2_\perp \right\rangle_{pA} \]

Slight increase of \( \left\langle \Delta k^2_\perp \right\rangle_{\text{tot.}} \) with increasing fraction of gluons

1. EKS'98
   shadowing/antishadowing/EMC effect
2. No strong antishadowing/EMC effect

- Better agreement may be reached in case 2
- The constant \( R_{pA} \text{ max} \) and \( R_{pAu}(p_T) = 1 \) is recovered
- Including initial state elastic E-loss requires ~20% increase of the transport coefficients
  \( \mu^2 / \lambda_q = 0.06 \text{ GeV}^2/\text{fm}, \mu^2 / \lambda_g = 0.14 \text{ GeV}^2/\text{fm} \)
Impact Parameter Dependence of the Cronin Effect at RHIC

The Cronin peak is located at $p_T = 3 - 4 \text{ GeV}$

Antishadowing plays an important role for $p_T = 3 - 4 \text{ GeV}$ - an approximately constant contribution (experiments can constrain it)

The maximum Cronin enhancement for the total invariant cross section is 20%

The Cronin effect decreases in going from central to peripheral reactions

In contrast: D. Kharzeev et al., PLB 561 (2003)

If it is initial wave-function $R_{dAu} = \sqrt{R_{AuAu}}$

$R_{dAu} \not< 0.5$ since $R_{AuAu} \not< 0.2 - 0.4$

Experimental Confirmation (and Resolution)

AGS and RHIC users’ meeting,

CIPANP 2003 conference

PHENIX Preliminary

20% at $p_T=4$ GeV, l. V.

1σ errors

PHOBOS Preliminary

June 09, 2003
Gluon Radiation in Hard Processes

Hard Jet Production

Soft Gluon Radiation

DGLAP evolution

BFKL evolution

Modified vacuum radiation

M. Djordjevic, M. Gyulassy

\[ M_J = J(P)e^{ipx_0}, \]

\[ M_0 = -2ig_s \frac{\vec{e}_1 \cdot \vec{k}_1}{k_1^2} e^{i\theta_0 \frac{k_1^2}{2E_0 c}} \]

\[ \frac{d^3N_g^{(0)}}{dx \, dk^2} \approx \frac{C_R \alpha_s}{\pi^2} \frac{1}{k_1^2} \]

\[ dN_g^{(0)} = \frac{C_R \alpha_s}{\pi} \frac{dx}{x} \frac{dk^2}{k_1^2} \]

NOT what we are interested in

\[ k^\mu = \left[ xE^+, \frac{k_1^2}{xE^+}, k_\perp \right] \]

\[ p^\mu = \left[ (1-x)E^+, \frac{p_1^2}{(1-x)E^+}, p_\perp \right] \]

Medium independent

\( x \gg 1 \) and \( k_\perp \ll E_0 \)
Medium Induced Radiation
(What we ARE interested in)

Similar algebraic recursive method (Reaction Operator) is needed!

\[ \hat{R} = \sum_{q_n a_n} Z_n \hat{q}_n a_n + \sum_{\bar{q}_n a_n} -\bar{q}_n a_n + \sum_{\bar{q}_n a_n} -\bar{q}_n a_n \]


June 09, 2003
Direct Insertion Operator

\[ \hat{D}_n = \alpha_n + \hat{S}_n + \hat{B}_n \]

Interference phases

\[ \omega_n = \frac{(k - q_n)^2}{2\varepsilon E_0} \approx |f|^{-1} \]

Gunion-Bertsch elastic

\[ B_i = \frac{k}{k^2} - \frac{k - \bar{q}_i}{(k - q_i)^2} \]

Internal substructure of the Direct operator

\[ \hat{S}_n A_{i_1 \cdots i_{n-1}}(x, k, c) = i \left\{ e^{i(\omega_0 - \omega_n)z_n} e^{iq_n \hat{b}} \right\} f^{cbn} A_{i_1 \cdots i_{n-1}}(x, k, b) \]

\[ \hat{B}_n A_{i_1 \cdots i_{n-1}}(x, k, c) = -i \left\{ B^n e^{i\omega_0 z_n} \right\} f^{cbn} \left\{ b \prod_{m=1}^{n-1} \left( -\frac{1}{2} \right)^{\delta_2/\delta_m} (a_m)^m \right\} \]
Virtual Insertion Operator

\[ \hat{V}_n = -\frac{1}{2}(C_A + C_R) - \alpha_n (\hat{S}_n + \hat{B}_n) \]
\[ = -\alpha_n \hat{D}_n - \frac{1}{2}(C_A - C_R) \]

Key Identity for Induced Gluon Radiation

Inelastic Reaction Operator

\[ \hat{R}_n = \hat{D}_n^\dagger \hat{D}_n + \hat{V}_n + \hat{V}_n^\dagger \]
\[ = (\hat{D}_n - a_n)^\dagger (\hat{D}_n - a_n) - C_A \]
\[ = (\hat{S}_n + \hat{B}_n)^\dagger (\hat{S}_n + \hat{B}_n) - C_A \]

- Only the $C_R C_A^n$ second order Casimir combination appears at order $n$!
- Because both $S$ and $B$ are proportional to $f^{abc}$
  \[ f^{abc} f^{abc'} = C_A \Omega_{cc'} \]

June 09, 2003

16

Ivan Vitev
**Gluon Double Differential Distributions to All Orders in Opacity**

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

\[
x \frac{dN^{(n)}}{dx dk^2} = C_R \alpha_s \left(\frac{L}{\lambda_g}\right)^n \prod_{i=1}^{n} d\xi_i \left(\bar{\sigma}^2(q_i) - \delta^2(q_i)\right)
\]

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

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

where

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

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

\[
B_{(j+1,\ldots,n)(j,\ldots,n)} = C_{(j+1,\ldots,n)} - C_{(j,\ldots,n)}
\]


**Normalized q distributions**

**Color current propagators**

**LPM destructive interference in QCD**

**All kinematic bounds, i.e. \(k_\perp, \omega, q_\perp\)**

Gluon Probability Density

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

\[ P_{n+1}(e, E) = \frac{1}{n+1} \int_{0}^{1} dx_n r(x_n, E) P_n(e - x_n, E) \]

\[ P_1(e, E) = e^{-(\langle N_g \rangle/\langle T \rangle)} r(e, E) \]

- Poisson approximation
- Non-negligible \( d(e) \) contribution

\[ D_{\text{eff}}^e (z, Q^2) = \int d\varepsilon P(\varepsilon) \frac{1}{1 - \varepsilon} D\left(\frac{1}{1 - \varepsilon} z, Q^2\right) \]

However:
Dependence on \( A, \sqrt{s}, p_T \)

Medium effects: Braaten and Pisarski

R. Baier et al., JHEP (2001)
1. At SPS $\sqrt{s_{NN}} = 17 GeV$ Cronin effect dominates. Even with energy loss $\pi^0$ exhibit noticeable enhancement.

2. Cronin effect, shadowing, and jet quenching conspire to give flat suppression pattern out to the highest $p_T$ at RHIC $\sqrt{s_{NN}} = 200 GeV$

$$R_{AA}(p_T) = 0.2 - 0.3$$

3. At LHC $\sqrt{s_{NN}} = 5500 GeV$ the nuclear modification is completely dominated by energy loss. Predicts below $N_{part}$ quenching, strong $p_T$ dependence.
Differential Comparison and Discussion

- There is no need (room) for "down-and-up" models.
- The shape of $R_{AA}$, $R_{CP}$ is a function of the interplay of the known nuclear effects.
- One needs to compute the energy loss for the non-asymptotic RHIC.

Known issues

a) The hydro feedback at low $p_T$, See e.g.
   - P. Kolb, R. Rapp, hep-ph/0210222
   - Z. Lin, C. M. Ko, S. Pal, nucl-th/0205056
   - E. Wang, X. N. Wang, PRL 87 (2001)

b) The baryons. See e.g.
   - D. Teaney, J. Lauret, E. Shuryak, nucl-th/0110037
Stability of the Centrality Dependence of $R_{AA}$ in GLV E-loss

\[ \frac{dN_{pp}^h}{dyd^3p_T} \propto \frac{1}{p_T^{n_{eff}}} D_{n/p}(\langle z \rangle), \quad \frac{dN_{AA}^h}{dyd^3p_T} \propto \frac{1}{(p_T + Z\Delta p_T)^{n_{eff}}} D_{n/p}(\langle z \rangle) \]

\[ R_{AA} = \frac{1}{(1 + Z\Delta p_T / p_T)^{n_{eff}}} \]

\[ \Delta E \propto N_{part}^{2/3}, \quad 1+1D \]


June 09, 2003

X. N. Wang, nucl-th/0305010

Ivan Vitev
Measures of Energy Loss

From GLV energy loss

$$\sum \int dz \int d^2 j_T D(z) g(j_T) \Delta - \text{const.} N_{\text{part}}^{2/3}$$

Correspondence can be established between the different measures of E-loss


June 09, 2003

Ivan Vitev
Medium-induced Jet Acoplanarity

\[ \langle k_{\perp}^2 \rangle = \langle k_{\perp}^2 \rangle_{\text{vac}} + \frac{\mu^2}{\lambda} \langle L \rangle_{\text{nucl}} + 2\langle \cos^2 \alpha \rangle K_{FS} \frac{\mu^2}{\lambda} \langle L \rangle_{FS \text{ nucl}} \]

\[ \langle |j_{\perp y}| \rangle = \text{the mean transverse momentum of the hadron with respect to the jet axis in the plane perpendicular to the beam axis.} \]

\[ \langle |k_{\perp y}| \rangle = \text{the mean effective transverse momentum of two colliding partons in the plane perpendicular to the beam axis (FS contribution in d+Au).} \]

\[ \langle |j_{\perp y}| \rangle = \frac{1}{\sqrt{\pi}} \sqrt{\langle j_{\perp}^2 \rangle} = \langle p_{\perp} \rangle \sin \frac{\sigma_N}{\sqrt{\pi}} \]

\[ \langle k_{\perp y} \rangle = \frac{1}{\sqrt{\pi}} \sqrt{\langle k_{\perp}^2 \rangle} = \langle p_{\perp} \rangle \cos \left( \frac{\sigma_N}{\sqrt{\pi}} \right) \sqrt{\frac{1}{2} \tan^2 \left( \frac{2}{\sqrt{\pi}} \sigma_F \right)} - \tan^2 \left( \frac{\sigma_N}{\sqrt{\pi}} \right) \]

Credit: P. Constantin, J. Rak, J. Lajoie, C. Ogilvie
M. Tannenbaum
**Experimental Back-to-Back Correlations**

True monojets? $|M|^2$

Regge-Muller cut diagrams

---

**NO true monojets at RHIC**

---

I.V., J.W.Qiu, to be published

---

T. Hirano and Y. Nara, nucl-th/0301042
The combined evidence from p+p, d+Au, Au+Au (consistent between the experiments) suggests that Au+Au reactions at RHIC differ significantly in many aspects from lower energies or other systems (p+p, p+A). Most notably in strong final state interactions.

Jet tomographic analysis indicates that the density of the matter created at RHIC is 30-50 times normal nuclear matter density. This is well in excess of the critical temperature and energy density calculated on the lattice and in strong support of the QGP formation hypothesis.

Di-hadron correlations provide valuable complementary information for the strength of final state interactions. In particular the striking similarity in the near-side cone shape in $e^+ + e^-$, $p + p$, $p + A$, $A + A$ is a signature of jet fragmentation outside the medium. The away-side correlations can also quantify the difference between p+A and A+A.