

## JETS IN NUCLEAR COLLISIONS\*

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Ultra-relativistic heavy ion collisions at RHIC and the LHC open exciting new possibilities for jet physics studies in the presence of hot and dense nuclear matter. Recent theoretical advances in understanding the QCD multi-parton dynamics provide a good description of the quenching in the single and double inclusive high- $p_T$  hadron spectra. Measurement of the redistribution of the lost energy and the corresponding increase in the soft hadron multiplicities is the next critical step in elucidating the modification of the jet properties in the nuclear environment.

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**1. Introduction**

Jet production [1, 2] is among the most robust high- $Q^2$  processes, calculable within the pQCD factorization approach [3]. In the case of heavy ion reactions the interactions of the hard probe with the bulk partonic matter lead to elastic, inelastic and coherent modifications to the cross section that can be systematically incorporated in the perturbative formalism [4].

At large center of mass energies jet production may probe the parton distribution functions  $\phi(x, \mu_f)$  at small momentum fractions  $x \leq 0.1$ . In the case of heavy ion reactions nuclear size enhanced power corrections generate dynamical parton mass and lead to nuclear shadowing [5]. While these are relevant for low- and moderate- $Q^2$  (or  $t$ ) processes, large  $E_T$  jet production  $Q^2$  (or  $t$ )  $\gg m_{\text{dyn}}^2$  remains unaffected [5].

Before we investigate the consequences of medium-induced acoplanarity and non-Abelian bremsstrahlung some basic characteristics of jets in  $e^+ + e^-$  and  $p + p(\bar{p})$  collisions should be reviewed. The virtuality  $Q/2 \sim \sqrt{t}$  of a hard perturbative process is reduced to a limiting value  $t_0 \ll t$  via

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soft gluon radiation. In the simple case of independent Poisson emission the induced parton multiplicities scale with average squared color charge of quarks and gluons  $C_R = \{C_A, C_F\}$ . In the presence of color coherence [6, 7] parts of the phase for soft gluon bremsstrahlung are excluded due to destructive interference effects. For the limiting case of factorizable exact double ordering [7], both in terms of the lightcone momentum fractions  $z_i$  and the virtualities  $t_i$ , one finds significant corrections for the predicted soft hadron multiplicities. Let  $\alpha_s(t) = \frac{4\pi}{\beta_0} \left( \ln \frac{t}{\Lambda_{\text{QCD}}^2} \right)^{-1}$  and  $\kappa = \frac{2}{\beta_0} \ln \frac{\alpha_s(t_0)}{\alpha_s(t)}$ . The exclusive probability for  $n$ -gluon emission is given by  $P_n(t; t_0, z_0) = \left( 2C_R \kappa \ln \frac{1}{z_0} \right)^n (n!n!)^{-1}$ . Standard first moment evaluation yields an average gluon multiplicity

$$\langle N_g \rangle = \left( \frac{\rho}{2} \right) \frac{I_1(\rho)}{I_0(\rho)}, \quad \rho = 2\sqrt{2C_R \kappa \ln \frac{1}{z_0}}. \quad (1)$$

It is easy to verify that in the small  $z_0$  or  $\alpha_s(t) \lim_{z_0 \rightarrow 0} \lim_{\alpha_s \rightarrow 0} \langle N_g \rangle = \rho/2$ . While  $\langle N_g \rangle$  depends on the choice of  $z_0$  and  $t_0$ , assuming isospin symmetry,  $N_{\text{ch}} = 2/3 N_{\text{tot}}$ , and local parton-hadron duality [8] we find

$$\frac{\langle N_{\text{ch}} \rangle_{g\text{-jet}}}{\langle N_{\text{ch}} \rangle_{q\text{-jet}}} \simeq \lim_{z_0 \rightarrow 0} \lim_{\alpha_s \rightarrow 0} \frac{\langle N_g \rangle_{g\text{-jet}}}{\langle N_g \rangle_{q\text{-jet}}} = \sqrt{\frac{C_A}{C_F}} = \frac{3}{2}. \quad (2)$$

The left panel of Fig. 1 shows the ratio of the charged hadron multiplicities for quark and gluon jets measured by the OPAL collaboration [9]. Over a wide range of energies  $E_g^* = p_{Tg}$  the experimental results fall in the range  $\frac{\langle N_{\text{ch}} \rangle_{g\text{-jet}}}{\langle N_{\text{ch}} \rangle_{q\text{-jet}}} = 1.4\text{--}1.6$ , which has to be compared with the analytic expectation of 1.5 from Eq. (2). The typical charge hadron multiplicity for gluon jets of  $E_g^* = 10\text{--}20$  GeV is  $\langle N_{\text{ch}} \rangle_{g\text{-jet}} = 6\text{--}10$  [9].

Parton broadening relative to the axis of propagation and the shape of the transverse momentum distributions can be roughly estimated in the leading double log approximation (LDLA). The normalized  $\mathbf{k}_T$  probability from vacuum radiation and including Sudakov form factors [11] is given by

$$\frac{1}{\sigma_0} \frac{d\sigma}{d\mathbf{k}_T^2} \Big|_{\text{LDLA}} = -2 \frac{C_R \alpha_s}{2\pi} \frac{1}{\mathbf{k}_T^2} \log \frac{\mathbf{k}_T^2}{Q^2} \exp \left( -\frac{C_R \alpha_s}{2\pi} \log^2 \frac{\mathbf{k}_T^2}{Q^2} \right). \quad (3)$$

The simple analytic form, Eq. (3), has definite shortcomings. It forgoes important kinematic constraints, assigns  $\equiv 0$  probability to  $\sum_i \mathbf{k}_{Ti} = 0$  type configurations and thus suggests that back-to-back leading hadrons always disfavor the  $\Delta\phi = \pi$  topology. Experimentally, large away-side correlations have been measured in  $p + p$  and  $d + \text{Au}$  reactions at  $\Delta\phi = \pi$  [12].

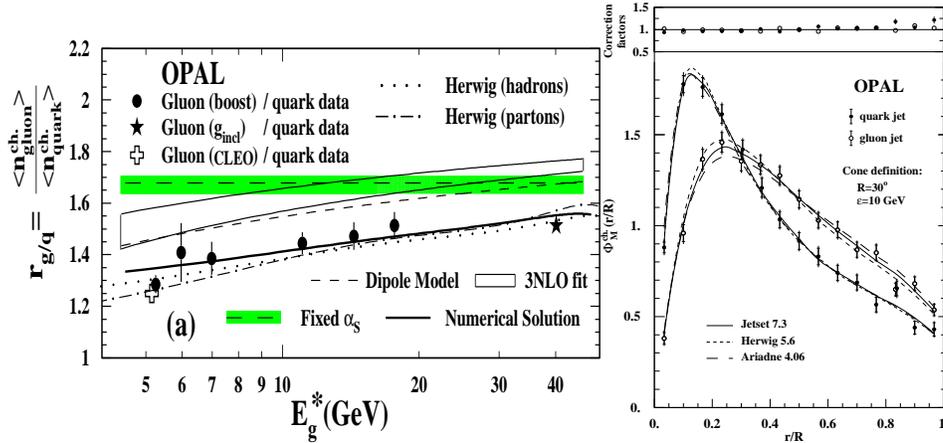


Fig. 1. Left panel from [9]: the ratio of charged hadron multiplicities associated with gluon and quark jets in the range  $E_g^* = 5\text{--}40$  GeV. Right panel from [10]: the distribution of charged hadrons in  $r/R$  with  $R = 30^\circ$ . Note the broader distribution for gluon jets.

The mean transverse momentum broadening from Eq. (3) reads

$$\langle \mathbf{k}_T^2 \rangle_{pp} = \left( 1 - \frac{\pi}{\sqrt{2C_R\alpha_s}} e^{\frac{\pi}{2C_R\alpha_s}} \left[ 1 - \text{Erf} \left( \sqrt{\frac{\pi}{2C_R\alpha_s}} \right) \right] \right) Q^2, \quad (4)$$

and is proportional to the only dimensionful scale in the problem  $Q^2$ . In the small coupling limit  $\langle \mathbf{k}_T^2 \rangle_{pp} = \frac{C_R\alpha_s}{\pi} (1 + \mathcal{O}(\alpha_s)) Q^2$ . As emphasized above, correction will reduce the  $Q^2$  dependence of these estimates. Nevertheless, one still expects a strong correlation between the acoplanarity momentum projection  $\langle k_{Ty} \rangle$  [12] and the hardness of the process. The ratio of the broadening and the width of the jet cone for quark and gluon jets is approximately given by

$$\lim_{\alpha_s \rightarrow 0} \frac{\theta_g}{\theta_q} \sim \sqrt{\frac{\langle \mathbf{k}_T^2 \rangle_{g\text{-jet}}}{\langle \mathbf{k}_T^2 \rangle_{q\text{-jet}}} = \sqrt{\frac{C_A}{C_F}} = \frac{3}{2}. \quad (5)$$

Differences in the angular distribution of hadrons in quark and gluon jets from the OPAL experiment are shown in the right-hand side of Fig. 1.

## 2. Modification of the jet properties in nuclear collisions

In dense nuclear matter one of the anticipated modifications of the jet properties is the accumulation of transverse momentum from elastic multi-parton interactions in addition to the vacuum acoplanarity discussed in Sec. 1

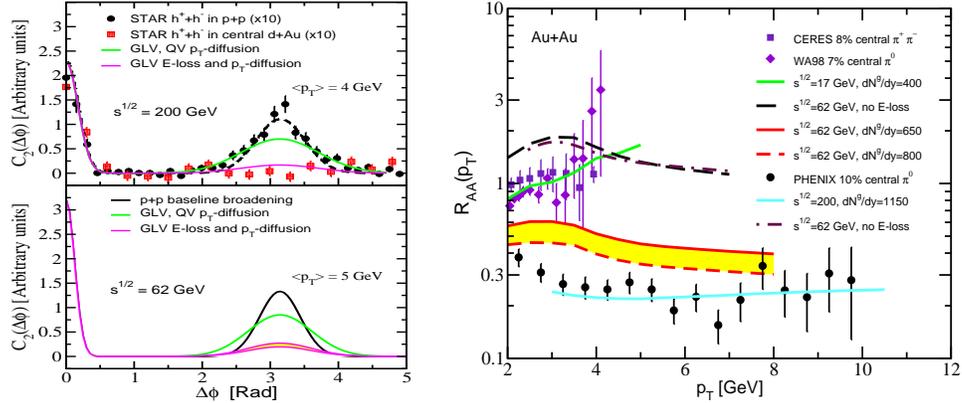


Fig. 2. Left panel: the away-side correlation function  $C_2(\Delta\phi)$  in  $p + p$  and central Au+Au reactions with transverse momentum diffusion and with and without jet energy loss. Data is from STAR [12]. Right panel from [20]: predicted suppression ratio  $R_{AA}^{h_1}(p_T)$  for neutral pions at  $\sqrt{s_{NN}} = 17, 62$  and  $200$  GeV. SPS and RHIC data [21] is shown for comparison.

$$\langle \mathbf{k}_T^2 \rangle_{\text{tot}} = \langle \mathbf{k}_T^2 \rangle_{\text{pp}} + \langle \mathbf{k}_T^2 \rangle_{\text{nucl}}. \quad (6)$$

Transverse momentum diffusion [13], amplified by the underlying steep partonic slope, results in the Cronin effect observed in  $p + A$  reactions [14]. Constraints from fits to low energy data [15] suggest that in cold nuclear matter at midrapidity  $\langle \mathbf{k}_T^2 \rangle \simeq 0.7 \text{ GeV}^2$  per jet [5]. Such broadening is relatively small compared to the acoplanarity from vacuum bremsstrahlung, Eq. (4), especially in hard processes.

Significantly stronger  $p_T$ -diffusion is expected in hot nuclear matter of initial effective gluon rapidity density  $\frac{dN_g}{dy} \sim 1000$  and  $\rho_g(\tau) = \frac{1}{\tau A_\perp} \frac{dN_g}{dy}$ , as shown in the left-hand side of Fig. 2. Comparisons to existing data [12, 16] on di-hadron correlations  $C_2(\Delta\phi) = \frac{1}{N_{\text{trig}}} \frac{dN^{h_1 h_2}}{d\Delta\phi}$ , however, demonstrate that this is *not* the dominant nuclear effect. Inelastic final state parton scattering, manifest in the multi-hadron attenuation ratio [5]

$$R_{AB}^{(n)} = \frac{d\sigma_{AB}^{h_1 \dots h_n} / dy_1 \dots dy_n d^2 p_{T_1} \dots d^2 p_{T_n}}{\langle N_{AB}^{\text{coll}} \rangle d\sigma_{NN}^{h_1 \dots h_n} / dy_1 \dots dy_n d^2 p_{T_1} \dots d^2 p_{T_n}}, \quad (7)$$

is the signature difference between the  $p + A$  and  $A + A$  dynamics in the high- $p_T$  sector.

The non-Abelian energy loss of jets can be calculated using the GLV approach [17]. In the physical case of 1+1D Bjorken expansion to first order in opacity [18]

$$\Delta E \approx \int dz \frac{9C_R\pi\alpha_s^3}{4} \rho^g(z) \ln \frac{2E}{\mu^2 \langle L \rangle} = \frac{9C_R\pi\alpha_s^3}{4} \frac{1}{A_\perp} \frac{dN^g}{dy} \langle L \rangle \ln \frac{2E}{\mu^2 \langle L \rangle}. \quad (8)$$

Current jet quenching calculations go beyond the mean  $\Delta E$  approximation, Eq. (8), but assume independent Poisson medium-induced emission [19]. The corresponding *increase* in the soft hadron multiplicities then scales as  $\frac{C_A}{C_F}$  in contrast to the vacuum bremsstrahlung result, Eq. (2). The right-hand side of Fig. 2 shows the predicted nuclear modification  $R_{AA}^{h_1}$  in central Au+Au collisions at  $\sqrt{s_{NN}} = 17, 62$  and  $200$  GeV [14, 20], which is dominated by parton energy loss. The theoretical calculation is in good agreement with the moderate- and high- $p_T$  dependence of the measured nuclear suppression [21]. Critical test of jet tomography [14] will be provided by the upcoming  $\sqrt{s_{NN}} = 62$  GeV pion attenuation data. Parton energy loss also leads to the suppression of the double inclusive hadron production  $R_{AA}^{h_1 h_2}$  and is experimentally manifest as a reduction of the area  $A_{\text{Far}}$  of the away-side correlation function  $C_2(\Delta\phi)$ . Such attenuation is 25%–50% larger than the suppression in the single inclusive spectra. Numerical results are shown in the left-hand side of Fig. 2.

An emerging novel aspect of jet tomography of the dense quark–gluon plasma (QGP) is the study of the redistribution of the lost energy, Eq. (8), back into the partonic system [22]. With suppressed gluon propagation for  $\omega < \omega_{\text{pl}}$ , the medium-induced virtuality is irradiated into fewer harder quanta above the plasmon frequency [17, 23]. For perfect angular acceptance, as a function of the experimental  $p_{T \text{ cut}}$  for the measured hadrons the induced multiplicities and the total energy recovered in the jet are given by

$$N(p_{T \text{ cut}}) = 1 \Big|_{E - \Delta E \geq p_{T \text{ cut}}} + \sum_n n P_n(\bar{N}_g) \Big|_{\frac{\Delta E}{n} \geq p_{T \text{ cut}}}, \quad (9)$$

$$E(p_{T \text{ cut}}) = E - \Delta E \Big|_{E - \Delta E \geq p_{T \text{ cut}}} + \frac{\Delta E}{1 - P_0(\bar{N}_g)} \sum_n P_n(\bar{N}_g) \Big|_{\frac{\Delta E}{n} \geq p_{T \text{ cut}}}. \quad (10)$$

In Eqs. (9) and (10)  $\bar{N}_g$  and the probability distribution  $P_n(\bar{N}_g)$  are computed as in [14, 19]. The left panel of Fig. 3 shows numerical estimates for  $p_T = 8$  and  $20$  GeV quark jets at RHIC and  $p_T = 20$  and  $100$  GeV quark jets at the LHC. A large part of the lost energy reappears already at  $p_T \simeq 1.5$  GeV at RHIC and  $p_T \simeq 3$  GeV at the LHC. For ideal reconstruction of the jet-related soft hadrons  $\lim_{p_{T \text{ cut}} \rightarrow 0} E(p_T) = E_{\text{jet}}^{\text{tot}}$  and  $\lim_{p_{T \text{ cut}} \rightarrow 0} N_{\text{parton}}(p_{T \text{ cut}}) = \bar{N}_g(E_{\text{jet}}) + 1$ . The medium-induced increase in the parton multiplicity is  $\sim 25$ – $35\%$  relative to the vacuum bremsstrahlung result [9].

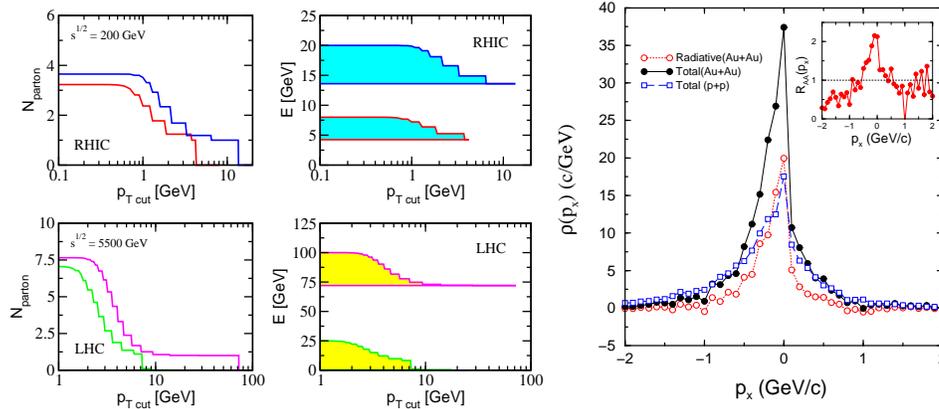


Fig. 3. Left panel from [14]: medium-induced partonic multiplicity as a function of the experimental  $p_{T,\text{cut}}$  for energetic quark jets at RHIC and the LHC. Right panel from [22]: momentum density of hadrons associated with energetic back-to-back jets with and without medium-induced bremsstrahlung. Secondary rescattering leads to gluon transverse momenta  $\sim 600$  MeV.

If the radiative gluons reinteract with the QGP, their momentum will be further degraded [22]. For complete thermalization  $N_g(\mathbf{r}, \Delta\tau) \approx \frac{1}{4} \Delta S = \frac{1}{4} \frac{\Delta E(\mathbf{r}, \Delta\tau)}{T(\mathbf{r}, \tau)}$ . Numerical simulations based on a parton cascade model [22] are shown in the right-hand side of Fig. 3. The growth of the soft multiplicity per jet is close to a factor of two and the bremsstrahlung gluons appear at transverse momenta  $p_T \sim 600$  MeV.

### 3. Conclusions

The study of jets in nuclear collisions is a natural extension of the calculable perturbative QCD dynamics to a complex strongly interacting many-body system. Elastic, inelastic and coherent multiple scattering [4] can modify the jet and hadronic cross sections, the multi-hadron correlations, the energy flow of jets and the associated soft particle multiplicities relative to measurements in baseline systems such as  $e^+ + e^-$  and  $p + p(\bar{p})$ . For large  $E_T$  processes it is the medium-induced non-Abelian bremsstrahlung that dominates the observable nuclear effects. At present, the quenching of the single inclusive spectra and the di-hadron correlations is well established experimentally and understood theoretically. The balance between the lost energy and the per jet growth of the soft particle production is the emerging novel aspect of jet tomography of dense nuclear matter. Preliminary results on this class of observables at RHIC are encouraging [24] and hint at the redistribution of the energy lost by the parent parton of the away-side jet into

$p_T \leq 2\text{--}3\text{ GeV}$  hadrons. Improved jet reconstruction techniques for heavy ion collisions at RHIC and the LHC, extended  $E_T$ -reach and larger cross sections will greatly facilitate the studies of the modification of the energy flow and hadron multiplicities associated with jets in the nuclear environment.

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## REFERENCES

- [1] G. Hanson *et al.*, *Phys. Rev. Lett.* **35**, 1609 (1975); M. Della Negra *et al.*, *Nucl. Phys.* **B127**, 1 (1977).
- [2] G. Sterman, S. Weinberg, *Phys. Rev. Lett.* **39**, 1436 (1977); R.K. Ellis, D.A. Ross, A.E. Terrano, *Nucl. Phys.* **B178**, 421 (1981).
- [3] J.C. Collins, D.E. Soper, G. Sterman, *Adv. Ser. Direct. High Energy Phys.* **5**, 1 (1988); *Nucl. Phys.* **B308**, 833 (1988); J.C. Collins, D.E. Soper, *Nucl. Phys.* **B194**, 445 (1982).
- [4] I. Vitev, [hep-ph/0409297](#).
- [5] J.W. Qiu, I. Vitev, *Phys. Rev. Lett.* in press, [hep-ph/0309094](#); *Phys. Lett.* **B587**, 52 (2004); [hep-ph/0405068](#).
- [6] Y.L. Dokshitzer, D. Diakonov, S.I. Troian, *Phys. Rep.* **58**, 269 (1980); Y.I. Azimov *et al.*, *Phys. Lett.* **B165**, 147 (1985).
- [7] R.D. Field, *Applications of perturbative QCD*, Addison–Wesley publishing Co., 1989.
- [8] Y.L. Dokshitzer, V.A. Khoze, S.I. Troian, *J. Phys. G* **17**, 1585 (1991).
- [9] G. Abbiendi *et al.*, *Phys. Rev.* **D69**, 032002 (2004).
- [10] R. Akers *et al.*, *Z. Phys.* **C68**, 179 (1995).
- [11] V.V. Sudakov, *Sov. Phys. JETP* **3**, 65 (1956).
- [12] C. Adler *et al.*, *Phys. Rev. Lett.* **90**, 082302 (2003); J. Rak, *J. Phys. G* **30**, S1309 (2004).
- [13] J.W. Qiu, I. Vitev, *Phys. Lett.* **570**, 161 (2003); M. Gyulassy, P. Levai, I. Vitev, *Phys. Rev.* **D66**, 014005 (2002).
- [14] I. Vitev, M. Gyulassy, *Phys. Rev. Lett.* **89**, 252301 (2002); I. Vitev, *Phys. Lett.* **B562**, 36 (2003);
- [15] J.W. Cronin *et al.*, *Phys. Rev.* **D11**, 3105 (1975).
- [16] M.L. Miller, D.H. Hardtke, *AIP Conf. Proc.* **698**, 729 (2004); M.L. Miller, *Acta Phys. Pol. B* **36** 559 (2005), these proceedings; R. Seto, *Acta Phys. Pol. B* **36** 525 (2005), these proceedings; K. Filimonov, *J. Phys. G* **30**, S919 (2004).
- [17] M. Gyulassy, P. Levai, I. Vitev, *Nucl. Phys.* **B594**, 371 (2001); *Phys. Rev. Lett.* **85**, 5535 (2000); *Nucl. Phys.* **B571**, 197 (2000).

- [18] M. Gyulassy, I. Vitev, X.N. Wang, *Phys. Rev. Lett.* **86**, 2537 (2001).
- [19] R. Baier *et al.*, *J. High Energy Phys.* **0109**, 033 (2001); M. Gyulassy, P. Levai, I. Vitev, *Phys. Lett.* **B538**, 282 (2002).
- [20] I. Vitev, [nucl-th/0404052](#).
- [21] D. d'Enterria, *Phys. Lett.* **B596**, 32 (2004); S.S. Adler *et al.*, *Phys. Rev. Lett.* **91**, 072301 (2003).
- [22] S. Pal, S. Pratt, *Phys. Lett.* **B574**, 21 (2003).
- [23] M. Djordjevic, M. Gyulassy, *Phys. Rev.* **C68**, 034914 (2003); M. Djordjevic, M. Gyulassy, *J. Phys. G* **30**, S1183 (2004).
- [24] F. Wang, *J. Phys. G* **30**, S1299 (2004).