On a Possible Use of Hadron Jets to Test Quark-Qluon Plasma Formation in Nucleus-Nucleus Interactions

Aleksei Pavlinov

Experimental Physics Division, Institute for High Energy Physics, Protvino, Russia

March 12, 1997

A possibility of hadron jets separation in the central collisions of heavy nuclei ($A \simeq 200$) at $\sqrt{s}$=200 GeV and $\sqrt{s}$ = 5500 GeV is discussed. An estimate of the transverse jet energy E_0^J is given above which a background processes can be neglected.

Introduction

A Quark-Gluon Plasma(QGP) search in nucleus-nucleus interactions will be one of basic tasks in experiments on new hadron colliders RHIC and LHC. At present many varios siqnatures for registration of QGP are suggested [1]. It is supposed especially that the study of jets, produced in a QGP collision, will give information about basic properties of plasma [2]. However the jets separation in nucleus-nucleus collisions has a number of special features when compared with hadron-hadron collisions.

As follows from results obtained from hadron-hadron colliders (hh) (ISR and S$p\overline{p}$S) and FNAL (Tevatron) [3, 4, 5], the processes of quasielastic scattering of partons(quarks, anti-quarks and gluons) at $p_t \geq 5$ Gev(hard scattering) are well described by Pertubation Theory of Quantum Chromodinamics(PT QCD)in the first order approach. Partons with large scattering angles are observed as hadron jets, i.e. separable groups of hadrons. The double jet dominancy is observed with the increase of the sum of transverse energies of all final particles $\sum E_t$ [6]. Jets separations in hh-collisions usually takes place at a low background (some particles per unit of pseudorapidity)

The situations changes in nucleus-nucleus collisions. In $(S - W)$ central collisions at 200 GeV per nucleus $dE_t/d\eta \approx 150$ GeV [7] though at energies $\sqrt{s} \leq 20$ GeV the deposition of hard processes is small. The relative contribution of a hard component increases with energy yielding approximately a half of cross section value at RHIC energies and dominating at Tevatron energies, which leads to increase of $\sum E_t$. In $(Au + Au)$ collisions at RHIC energies [8] $\sum E_t$ increases up to $\approx$400 times compared with hh-collisions. Jets separation methods developed for hadron collisions [9] become unacceptable for RHIC [10] even in the case of central collisions of medium nuclei $(A \geq 30 - 50)$ and jet transverse energy $E_t^J \geq 10 \div 30$ GeV. The main reason is transverse energy fluctuation the which magnitude prohibits jets separation with $E_t^J \geq 10 \div 30$ GeV.

By the same reason in events where hard parton scattering is absent the fluctuations would produce "false" jets just presenting a background for "real" jets. The transverse energy E_t^J must be such that the production cross section for "false" jets would be less than the production cross section for "true" jets. A question of estimation of E_0^J above which "true" jets separation is possible is considered in this note.

Sections 1-3 describe the method of calculation of $d\sigma/dE_t$ taking into account soft and hard processes in high energy nucleus-nucleus collisions using the results from [12]. Section 4 gives an estimate of a ratio of production cross section of a "false" jets to "real" jets in dependence on transverse energy and also an estimate of E_0^J is analysed.

1 An Inclusive Cross Section of Parton Hard Scattering

We suppose that $2 \to 2$ parton hard scattering (quasielastic parton scattering at large angles) is the dominating process in jets production with large transverse momenta, and that the cross section is well described in a lowest order of PT QCD. The data are present for $p_t > 5.5$ GeV/c [3]. It is supposed that PT QCD is applicable for $p_t > 2$ GeV/c. In a lowest order of PT QCD the inclusive production cross section of two partons with rapidities y_1 and y_2 and transverse momentum p_t is defined as

$$\frac{d\sigma_h}{dp_t^2 dy_1 dy_2} = K\, x_1 f(x_1, p_t^2)\, x_2 f(x_2, p_t^2)\, \frac{d\sigma^{gg}}{d\hat{t}}, \tag{1.1}$$

where

$$x_1 = \frac{x_t}{2}(e^{y_1} + e^{y_2}), \qquad x_2 = \frac{x_t}{2}(e^{-y_1} + e^{-y_2}), x_t = 2p_t/\sqrt{s}, \tag{1.2}$$

$$\frac{d\sigma^{gg}}{d\hat{t}} = \frac{9\pi\alpha_s^2(p_t^2)}{2p_t^4}\left[1 - \frac{p_t^2}{x_1 x_2 s}\right]^3, \qquad \alpha_s(p_t^2) = 4\pi/9\ln(p_t^2/\Lambda^2). \tag{1.3}$$

$f(x, p_t^2)$ is the effective structure function, which can be written as

$$f = g + \frac{4}{9}\sum_f (q_f + \bar{q}_f), \tag{1.4}$$

where g, q_f and $\bar{q}_f$ are the structure functions of gluons, quarks and antiquarks respectively. The formula (1.1) is written in assumption that the processes of quasielastic parton scattering have a similar angular dependence [13]. The range of rapidities y_1 and y_2 at fixed p_t is given by formulaes

$$-\ln(2/x_t - e^{-y_1}) \leq y_2 \leq \ln(2/x_t - e^{y_1}), \tag{1.5}$$

$$\mid y_1 \mid \leq \ln\left(1/x_t + \sqrt{1/x_t^2 - 1}\right). \tag{1.6}$$

The $K-$factor takes into account the highest order corrections of PT QCD. $K-$factor value depends on experimental jets definition, absolute detector calibration, Q^2 scale used and on the structure functions selection. We used structure function from [11] with the soft gluon structure functions with $\Lambda = 200$ MeV and p_t as a scale for hard scattering (DO set 1).

In Fig.1a and 1b the inclusive hard scattering cross sections $d^2\sigma/dp_t dy(y = 0)$, calculated using formulaes (1.1)-(1.6), is compared with a UA1 data [3] at 5.5 GeV/c$< p_t <$ 25 GeV/c and with CDF data [5] at 35 GeV/c$< p_t <$ 300 GeV/c. At $\sqrt{s} = 200$ GeV $K \simeq 2,5$ which is a bit more of $K-$value $K = 2$ from [3]. At $\sqrt{s} = 1800$ GeV $K \simeq 1,4$. This comparison shows that the PT QCD has a good agreement with the experiment and that the $K-$factor has a strong dependence on $\sqrt{s}$.

With the same set of structure functions we can calculate a quasielastic scattering cross section for partons with $p_t > p_0$:

$$d\sigma_h^{pp} \equiv d\sigma_h^{pp}(p_0, \sqrt{s}) = \int_{p_0^2}^{s/4} dp_t^2 dy_1 dy_2 \frac{1}{2} \frac{d\sigma_h^{pp}}{dp_t^2 dy_1 dy_2}. \tag{1.7}$$

For a calculation of transverse energy distribution in a hard scattering of partons for a concrete detector it is necessary to define an acceptance function because either two ($E_t = 2p_t$) partons or one ($E_t = p_t$) parton can hit into detector or none of them ($E_t = 0$). If parton's momenta are stretched in opposite directions in transverse plane then $p_1 \equiv (p_t, \phi, y_1)$, $p_2 \equiv (p_t, \phi + \pi, y_1)$. The acceptance function $\epsilon(p) = 1$ if parton with the momentum p hits the detector and $\epsilon(p) = 0$ if parton hasn't been detected.

E_t-distribution of a single process of a quasielastic parton scattering can be written as ($\epsilon_1 \equiv \epsilon(\phi, y_1), \epsilon_2 \equiv \epsilon(\phi + \pi, y_2)$)

$$\frac{d\sigma_h^{pp}}{dE_t} = \int dp_t dy_1 dy_2 \frac{d\phi}{2\pi}\, \delta(E_t - (\epsilon_1 + \epsilon_2)p_t)\, \frac{1}{2}\, \frac{d\sigma_h^{pp}}{dp_t dy_1 dy_2}. \tag{1.8}$$

The first moment of equation (1.8) is just the equation (1.7) and it doesn't depend on acceptance function. E_t- и E_t^2-moments are derived as

$$\langle E_t \rangle_h^{pp} \sigma_h^{pp}(p_0) = \int dp_t dy_1 dy_2\, \frac{d\phi}{2\pi}\, \frac{1}{2}\, \frac{d\sigma_h^{pp}}{dp_t dy_1 dy_2}\, (\epsilon_1 + \epsilon_2)\, p_t,$$

$$\langle E_t^2 \rangle_h^{pp} \sigma_h^{pp}(p_0) = \int dp_t dy_1 dy_2\, \frac{d\phi}{2\pi}\, \frac{1}{2}\, \frac{d\sigma_h^{pp}}{dp_t dy_1 dy_2}\, (\epsilon_1 + \epsilon_2)^2\, p_t^2. \tag{1.9}$$

2 E_t-distribution of Hard Partons in a Heavy Ions Collisions

As we proceed to nucleus-nucleus interactions we suppose that the nuclei interaction is an independent interaction between nucleons and that the nucleus structure function is additive

$$f^A(x, p_t^2) = A\, f(x, p_t^2), \tag{2.1}$$

so we obtain

$$d\sigma_h^{AB} = AB\, d\sigma_h^{pp} \tag{2.2}$$

for inclusive cross section. We neglect shadowing of structure functions in a nucleus.

In accordance with equation (2.1) the hard component in $(A+B)$-collision is composed by independent $(p+p)$-collisions. The average value of hard collisions for a nucleon passing through the nucleus A with impact parameter $\vec{b}$ is equal to $T_A(\vec{b})\sigma_h^{pp}$ where $T_A(\vec{b})$ is the function of nucleus thickness. The average value of hard collisions in $(A+B)$-collision with the impact parameter $\vec{b}$ is given by equation

$$\bar{N}^{AB}(\vec{b}) = T_{AB}(\vec{b})\ \sigma_h^{pp}(p_0), \tag{2.3}$$

where $T_{AB}(\vec{b}) = \int d^2\vec{s}\, T_A(\vec{s})\ T_B(\vec{b}-\vec{s})$ is the overlap function for a nucleus (see application in [12]). From that one can obtain an expression for E_t-distribution:

$$\frac{d\sigma_h^{AB}}{dE_t} = \int d^2\vec{b} \sum_{N=1}^{\infty} \frac{[\bar{N}(\vec{b})]^N}{N!} \exp[-[\bar{N}(\vec{b})] \times$$
$$\times \int \prod_{i=1}^{N} dE_{T_i} \frac{1}{\sigma_h^{pp}} \frac{d\sigma_h^{pp}}{dE_{T_i}} \delta(E_t - \sum_{i=1}^{N} E_{T_i}). \tag{2.4}$$

Substituting $\delta(E_t - \sum E_{T_i}) = \frac{1}{2\pi} \int\limits_{-\infty}^{+\infty} e^{i\tau(E_t - \sum E_{T_i})} d\tau$ and making sum over N one obtains

$$\frac{d\sigma_h^{AB}}{dE_t} = \int\limits_{-\infty}^{+\infty} \frac{d\tau}{2\pi} \int d^2\vec{b} \times$$
$$\times \exp\left\{ i\tau E_t + T_{AB}(\vec{b}) \int dy_1 dy_2 dp_t \frac{1}{2} \frac{d\sigma_h}{dp_t dy_1 dy_2} [\exp[-i\tau(\epsilon_1+\epsilon_2)p_t] - 1] \right\} -$$
$$-\delta(E_t) \int d^2\vec{b} \exp[-\bar{N}^{AB}(\vec{b})]. \tag{2.5}$$

The last term is the contribution from $(A+B)$-collisions without hard parton-parton collisions. For $E_t \gg p_0$ we can expand $[\exp[-i\,\tau\,(\,\epsilon_1+\epsilon_2)\,p_t]-1]$ by powers of τ up to quadratic term inclusive, and, integrating over τ, we obtain for $E_t > 0$

$$\frac{d\sigma_h^{AB}}{dE_t} = \int d^2\vec{b} \frac{1}{\sqrt{2\pi\sigma^2(\vec{b})}} \exp\left\{ -\frac{[E_t - \bar{E}_t^{AB}(\vec{b})]^2}{2\sigma^2(\vec{b})} \right\}, \tag{2.6}$$

where

$$\bar{E}_t^{AB}(\vec{b}) = T_{AB}(\vec{b})\sigma_h^{pp}(p_0)\langle E_t\rangle_h^{pp},$$
$$\sigma^2(\vec{b}) = T_{AB}(\vec{b})\sigma_h^{pp}(p_0)\langle E_t^2\rangle_h^{pp}. \tag{2.7}$$

Equations (2.3) and (2.7) demonstrate that the number of partons, the average value and dispersion for E_t-distribution in ion collisions are equal to the overlap function $T_{AB}(\vec{b})$ times the hard parton cross section and times the E_t- and E_t^2-moments from (1.9).

Integrating by E_t in equation (2.5) we obtain an expression for inclusive cross-section

$$\sigma_h^{AB}(p_0) = \int d^2\vec{b}\,[1 - \exp[-T_{AB}(\vec{b})\,\sigma_h^{pp}(p_0)]]. \tag{2.8}$$

3 The Contribution from Soft Processes

From the analysis of experimental data [7, 14, 15] at $\sqrt{s}$ = 20 GeV two important conclusions follow:

- There's no need to include hard processes to describe experimental data because it's share is negligible;
- Experimental data are satisfactorily described supposing independent nucleon-nucleon interaction.

Further we suppose for pp-collisions:

- Soft and hard processes occur independently;
- Soft component does not depend on $\sqrt{s}$ and E_t-moments values for soft processes will be defined from experimental data analysis at $\sqrt{s} =$ 20 GeV.

Then at fixed $\vec{b}$ the E_t-distribution is given by equation (2.6) with relationships:

$$\bar{E}_t^{AB}(\vec{b}) = T_{AB}(\vec{b})[\sigma_h^{pp}(p_0)\langle E_t\rangle_h^{pp} + \sigma_s^{pp}\langle E_t\rangle_s^{pp}],$$
$$\sigma^2(\vec{b}) = T_{AB}(\vec{b})[\sigma_h^{pp}(p_0)\langle E_t^2\rangle_h^{pp} + \sigma_s^{pp}\langle E_t^2\rangle_s^{pp}]. \tag{3.1}$$

The hard component in equation (3.1) is taken from equation (2.2), the soft – from HELIOS collaboration data [7]. An analysis was done in terms of equations (2.6) and (3.1) where only soft component was included. For $(S+Pb)$-collisions $\langle E_t\rangle_s^{pp} = 1.04$ GeV and $\langle E_t^2\rangle_s^{pp} = 3.57$ GeV^2 for $-2.9 < y < 0.1$. Multiplying by $\sigma_s^{pp} = 32$ mb and dividing by factor 2/3 for the range $|y| < 1.0$ we obtain the next values for E_t-moments:

$$\sigma_s^{pp}\langle E_t\rangle_s^{pp} = 15 \text{ mb GeV}, \quad \sigma_s^{pp}\langle E_t^2\rangle_s^{pp} = 50 \text{ mb GeV}^2. \tag{3.2}$$

4 Jets as Probe for Quark-Gluon Plasma

From HELIOS data [7] follows that in central region $|\eta| \leq 1$ E_t has a weak dependence on pseudorapidity and, henceforce, does not depent on polar angle ϕ. Then the transverse energy distribution in a circle of radius R_J in $\eta * \phi$ space at a fixed impact parameter $\vec{b}$ and $E_t > 0$(see (2.6)) will obey to Gauss distribution with the following parameters:

$$\bar{E}_t^J = \bar{E}_t^{AB}(\vec{b})\frac{S_J}{S_D}, \qquad \sigma_J^2 = \sigma^2(\vec{b})\frac{S_J}{S_D}, \tag{4.1}$$

where $S_J = \pi R_J^2$ and $S_D = 2\pi\ 2\eta_D$, and $\bar{E}_t^{AB}(\vec{b})$ and $\sigma^2(\vec{b})$ are taken from formulae (2.7). For calculation of E_t- and E_t^2-moments in (2.2) for hard processes and in (3.2) for soft processes η_D was taken as 0.5.

Then the probability for a "false" jet production with energy E_t^J and radius R_J in an event with fixed impact parameter $\vec{b}$ is the probability of the fact that the transverse energy E_t exceeds the average transverse energy $\bar{E}_t^J$ by E_t^J. Using (2.8) we obtain an expression for "false" jet production cross-section with the transvers energy greater than E_t^J:

$$\Delta\sigma_f(\vec{b}) \approx d^2\vec{b}\left\{1 - \exp[-T_{AB}(\vec{b})(\sigma_h^{pp}(p_0) + \sigma_s^{pp})]\right\} P(E_t > \bar{E}_t^J + E_t^J) * N_J, \tag{4.2}$$

where $N_J = S_D/S_J$ and $\eta_D = 1.0 - R_J$.

"True" jet production cross-section with transverse energy greater than E_t^J equals

$$\Delta\sigma_t(\vec{b}) = d^2\vec{b}\left\{1 - \exp[-T_{AB}(\vec{b})\,\sigma_{hD}^{pp}(E_t^J)]\right\}, \tag{4.3}$$

where the cross-section $\sigma_{hD}^{pp}(E_t^J)$ is calculated taking into account acceptance function similar to formulae (1.9) for E_t-moments

$$\sigma_{hD}^{pp}(E_t^J) = \int dp_t^2 dy_1 dy_2 \frac{d\phi}{2\pi}\frac{1}{2}\frac{d\sigma_h^{pp}}{dp_t^2 dy_1 dy_2}(\epsilon_1 + \epsilon_2). \tag{4.4}$$

We define a purity factor C as a ratio of "false" cross-section to "true" cross-section

$$C = \frac{\Delta\sigma_f}{\Delta\sigma_t}. \tag{4.5}$$

From the general considerations it is clear that for experimental selection of "true" jets a purity factor must be a little value. This can be realized in collisions of light nuclei or in collisions of heavy nuclei at big impact parameters. From a theoretical estimates it follows that the most favourable conditions for QGP production [1] are realized in central collisions of heavy nuclei. In this case for C decrease we have only two degrees of freedom – a possibility of variation of jet transverse energy and jet radius.

The jet transverse energy is limited above by the luminosity value. For STAR detector [16] in central $AuAu$-collisions at integral luminosity $\int Ldt = 2 \times 10^{33}$ cm^{-2} an expected boundary transverse energy is $50 \div 60$ GeV. Fig.2 shows the curves of purity factor at $\sqrt{s} = 200$ GeV and $K = 2.5$ for central $AuAu$-collisions for three values of jet radius R_J=0.3; 0.5; 0.7.

As it seen for $R_J = 0.3$ we reach the lowest value for C ($C \approx 300 \div 500$) at $E_t^J = 50 \div 60$ GeV. Fig.3 differs from Fig.2 only by the value of $K = 1.0$. The value C strongly depends on $K-$factor ($C \approx 2 \div 20$) at $E_t^J = 50 \div 60$ GeV. But it must be noted that for pp-interactions at $\sqrt{s} = 200$ GeV the experimental data are well described with $K = 2.5$. Hence it follows that for an extraction of "true" jets at $\sqrt{s} = 200$ GeV we need an extra suppresion of "false" jets by $3 \div 4$ orders of magnitude.

The situation changes when we proceed from RHIC energies ($\sqrt{s} = 200$ GeV) to LHC energies ($\sqrt{s} = 5500$ GeV). For $|\eta| \leq 0.5$ in central $PbPb$-collisions at integral luminosity $\int Ldt = 2 \times 10^{34}$cm^{-2} an expected boundary transverse energy is $200 \div 250$ GeV. As it seen from fig.4 at such energies $C \leq 0.1$ at $R_J \leq 0.5$ and $C \simeq 1$ at $R_J = 0.7$ which is essentially less than at $\sqrt{s} = 200$ GeV.

Conclusion

The jets separation in central nucleus-nucleus collisions as a distinct observable objects is complicated compared to hadron-hadron collisions. One of main reasons of this are transverse energy fluctuations. At rather high E_t^J values the jets separation is possible but E_t^J is limited by integral luminosity. For $\sqrt{s} = 200$ GeV and $E_t^J = 40 \div 60$ GeV an additive information is necessary to suppress "false" jets. It is worth noting that transverse energy fluctuations deteriorate the energy resolution and are comparable by order of magnitude with the energy resolution itself.

Acknowledgements

I would like to thank A.A.Derevshikov and A.N.Vasiliev for support, V.I.Belousov for helping at all stages of this work. I acknowledge stimulating discussions with S.I.Striganov.

References

[1] QM88. / Ed. G.Baym et al.// Nucl.Phys. 1989, v. A**498**, p. 1;
QM90. / Ed. J.P.Blaizot et al.// Nucl.Phys. 1991, v. A**525**, p. 1.

[2] Bjorken J.D. Fermilab report No.Fermilab.Pub-82/59-THY(1982);
Appel D.A.// Phys.Rev. 1986, v. D33, p. 717.

[3] UA1 Collab. Albajar C. et al.// Nucl.Phys., 1988, v. B**309**, p. 405.

[4] UA2 Collab. Alitti J. et al.// Phys.Lett., 1985, v. B**165**, p. 441.

[5] CDF Collab. Abe F. et al.// Phys.Rev.Lett. 1992, v. **68**, p. 1105.

[6] Banner M. et al.// Phys.Lett. 1982, v. B**118**, p. 203;
Arnison G. et al.// Phys.Lett. 1983, v. B**123**, p. 115;
Appel J. et al.// Phys.Lett. 1985, v. B**165**, p. 441.

[7] HELIOS Collab. Åkesson T. et al.// Phys.Lett. 1985, v. B**214**, p. 295;
HELIOS Collab. Åkesson T. et al. CERN preprint CERN-EP/88-21.

[8] Wang X.N., Gyulassy M.// Phys.Rev. 1991, v. D**44**, p. 3501;
Wang X.N., Gyulassy M.// Phys.Rev.Lett. 1992, v. **68**, p. 1480.

[9] Flaugher B., Meier K. FERMILAB-Conf-90/248-E.

[10] STAR Collab. Pavlinov A. Star Note 183;
STAR Collab. Christie B., Shestermanov K. Star Note 196.

[11] Duke D.W. and Owens J.F.// Phys.Rev. 1984, v. D**30**, p. 49.

[12] Eskola K.J., Kajantie K. and Lindfors J.// Nucl.Phys., 1989, v. B**323**, p. 37;
Eskola K.J. In: Large Hardron Colider Workshop, 1990. CERN 90-10, vol.II, p. 1195.

[13] Combridge B.L. and Maxwell J.C.// Nucl.Phys. 1984, v. **239**, p. 429;
Halzen F. and Hoyer P.// Phys.Lett., 1983, v. **130**, p. 326.

[14] Jackson A.D. and Bøqqild H.B.// Nucl.Phys., 1987, v. A**470**, p. 669.

[15] Ochiai T.// Z.Phys. 1987, v. C**35**, p. 741; Prog.Theor.Phys. 1987, v. **78**, p. 741.

[16] Conceptual Design Report for the Solenoidal Tracker at RHIC.
The STAR Collaboration, PUB-5347(1992).

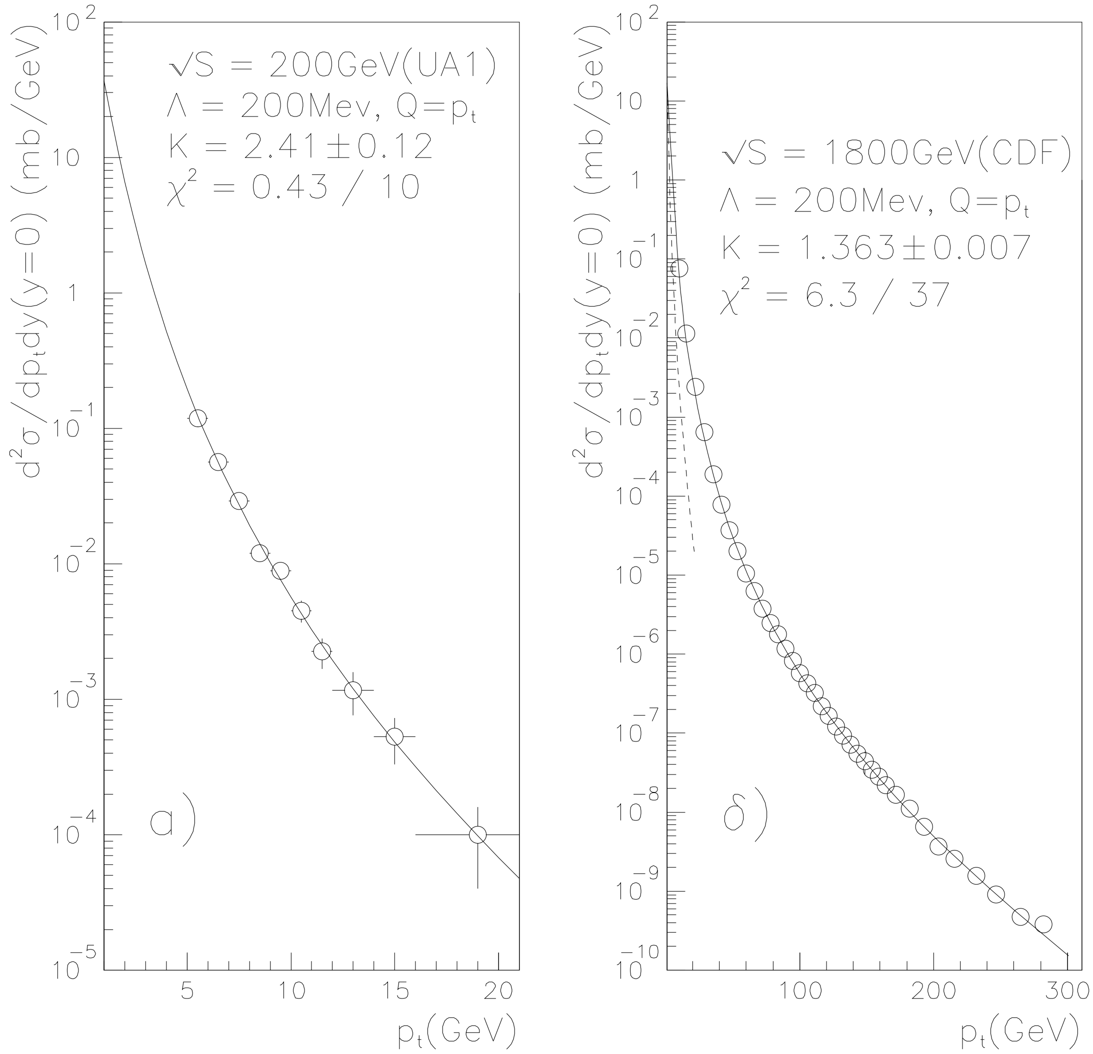

Fig.1 The comparison of inclusive hard scattering cross sections of a partons $d^2\sigma/dp_t dy(y=0)$, calculated in a lowest order PT QCD for pp-collisions by formulaes (1.1)-(1.6) with experiment: a) UA1 data [3], $\sqrt{s}=200$ GeV; b) CDF data [6], $\sqrt{s}=1800$ GeV. $K-$ factor value is defined from fit.

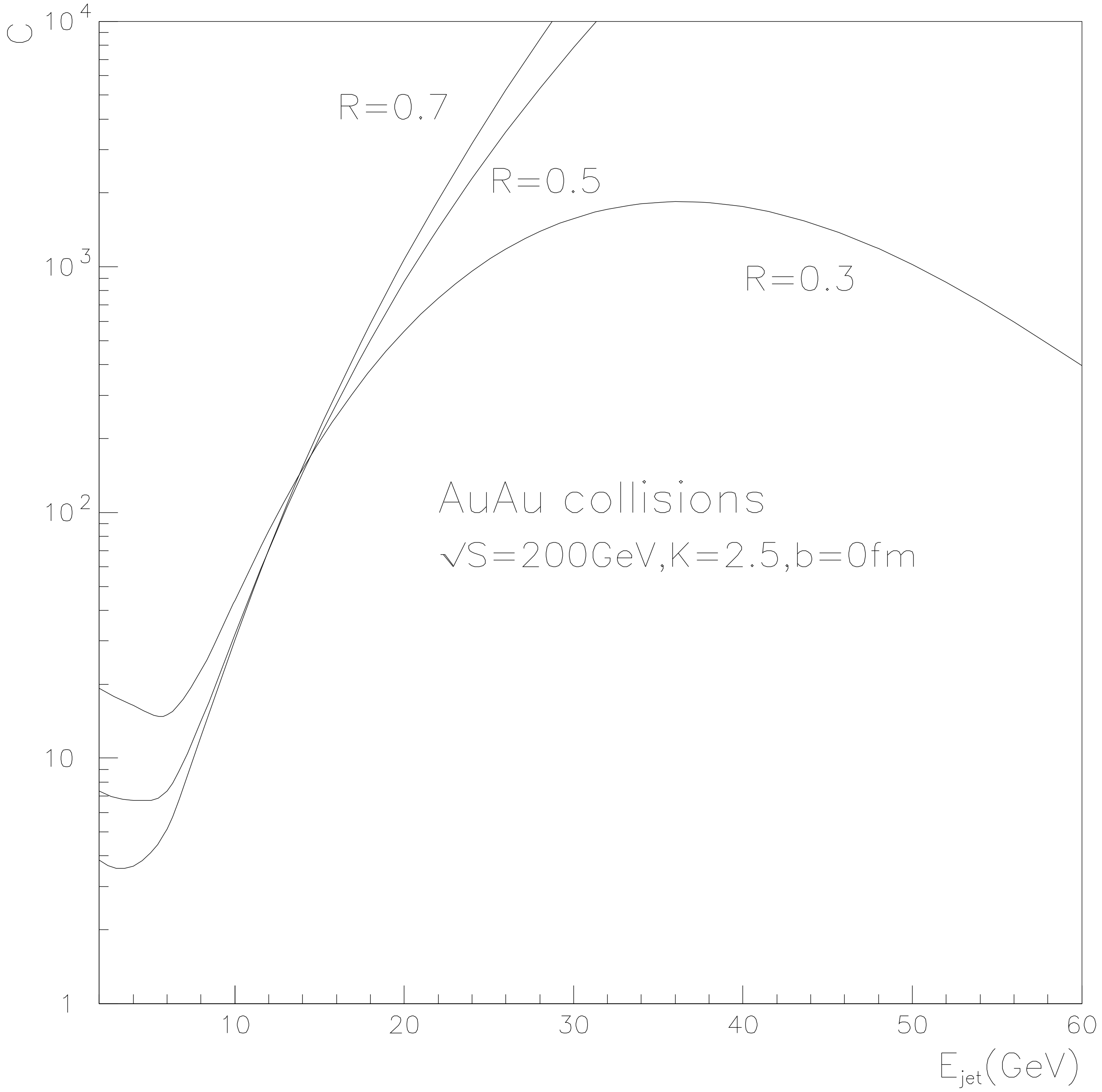

Fig.2 A purity factor C dependence on jet transverse energy E_t for central $AuAu$-collisions at $\sqrt{s} = 200$ GeV and $K = 2.5$ for three values of jet radius $R = 0.3; 0.5; 0.7$.

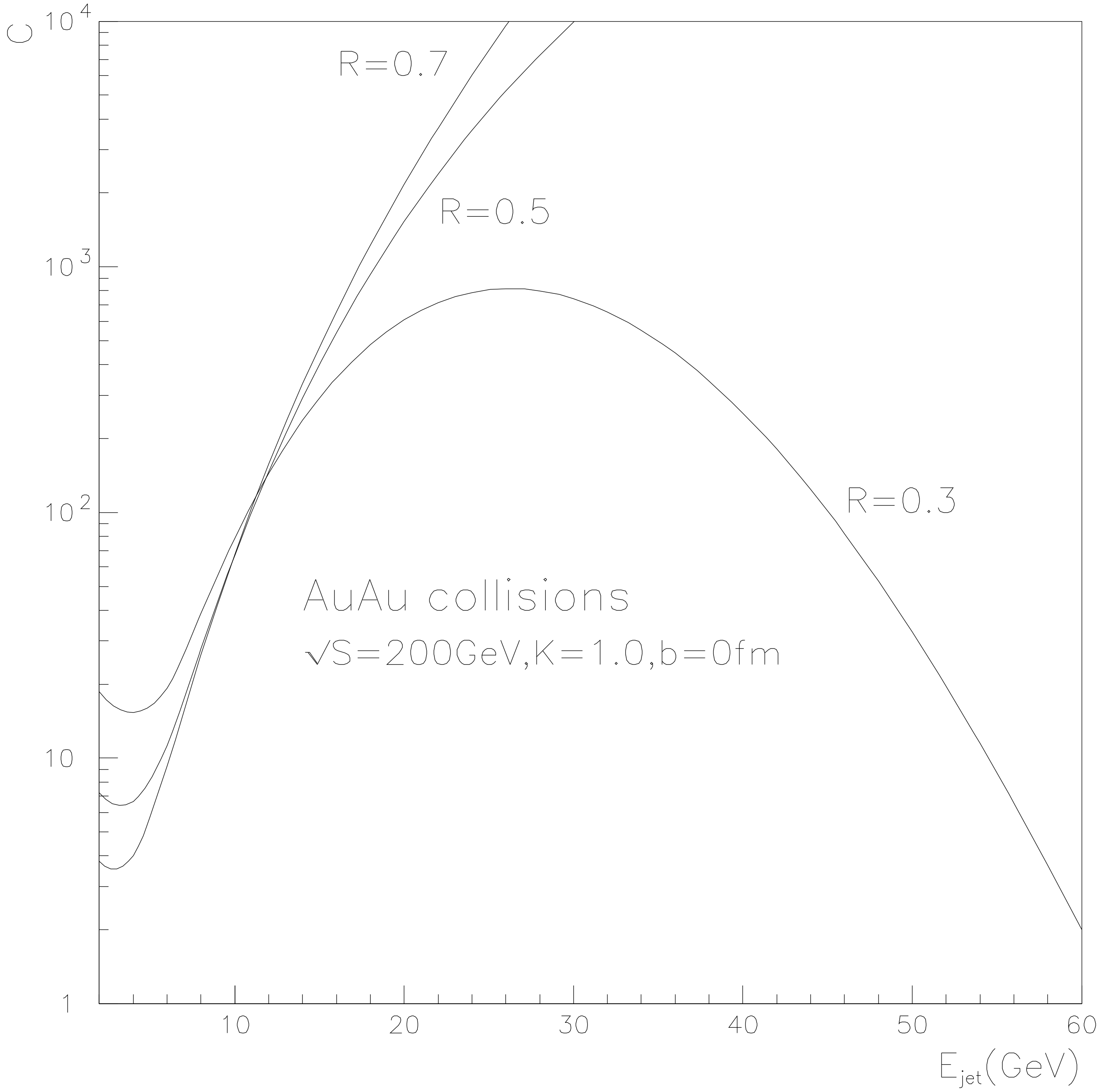

Fig.3 A purity factor C dependence on jet transverse energy E_t for central $AuAu$-collisions at $\sqrt{s} = 200$ GeV and $K = 1.0$ for three values of jet radius $R = 0.3; 0.5; 0.7$.

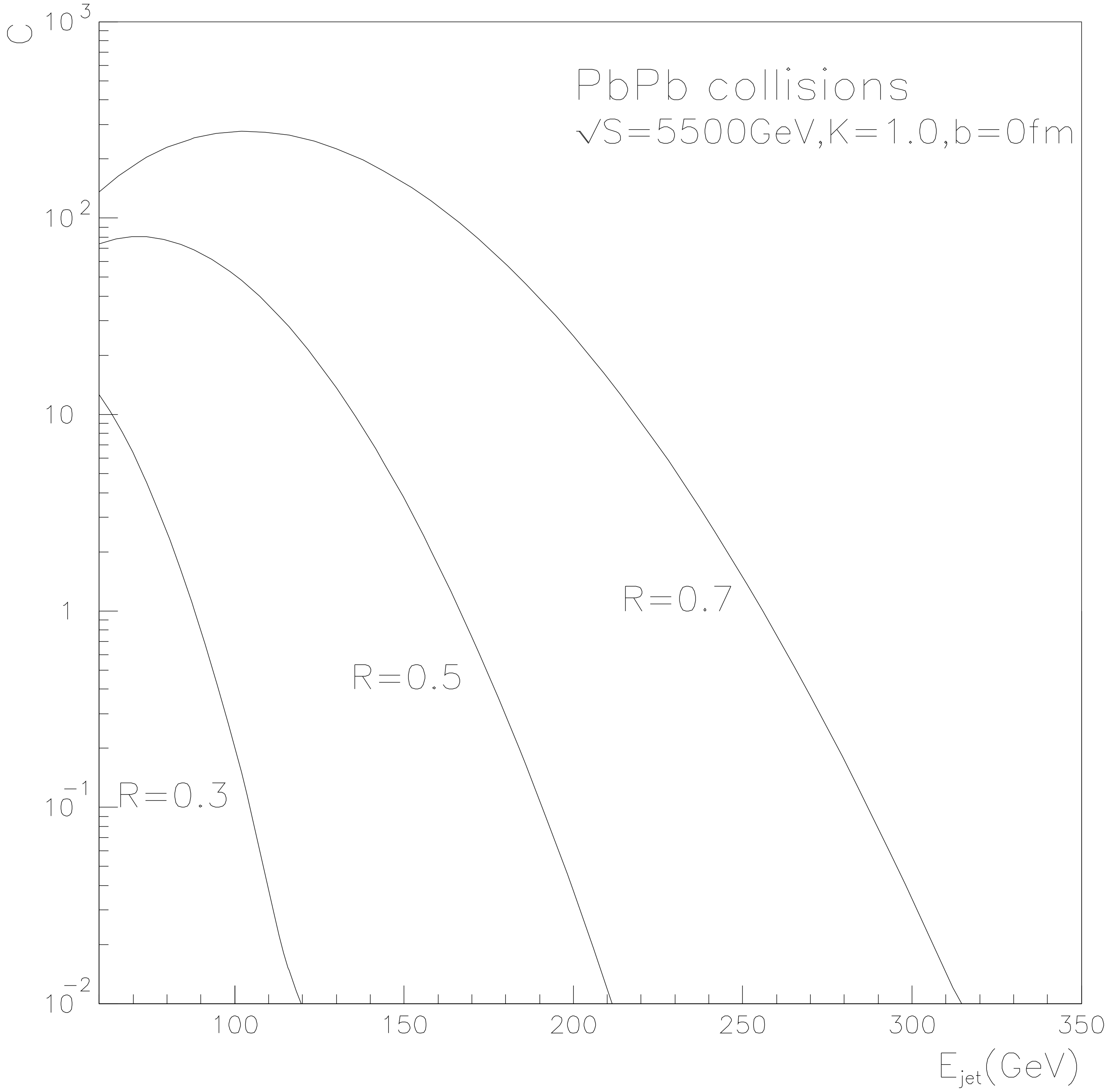

Fig.4 A purity factor C dependence on jet transverse energy E_t for central $PbPb$-collisions at $\sqrt{s} = 200$ GeV and $K = 1.0$ for three values of jet radius $R = 0.3; 0.5; 0.7$.