Pramana – J. Phys. (2016) 87: 28
DOI 10.1007/s12043-016-1236-4

Momentum distribution of charged particles in jets in dijet events and comparison to perturbative QCD predictions

M E ZOMORRODIAN[1,*], M HASHEMINIA[1,4], S M ZABIHINPOUR[2] and A MIRJALILI[3]

[1]Department of Physics, Ferdowsi University of Mashhad, 91775-1436, Mashhad, Iran
[2]Department of Physics, Payame Noor University, P.O. Box 19395-3697 Tehran, Iran
[3]Physics Department, Yazd University, 89195-741, Yazd, Iran
[4]Payesh Research Institute of Fundamental Physics, Mashhad, Iran
*Corresponding author. E-mail: zomorrod@um.ac.ir

MS received 3 December 2014; revised 2 November 2015; accepted 18 November 2015; published online 19 July 2016

Abstract. Inclusive momentum distributions of charged particles are measured in dijet events. Events were produced at the AMY detector with a centre of mass energy of 60 GeV. Our results were compared, on the one hand to those obtained from other e^+e^-, ep as well as CDF data, and on the other hand to the perturbative QCD calculations carried out in the framework of the modified leading log approximation (MLLA) and assuming local parton–hadron duality (LPHD). A fit of the shape of the distributions yields $Q_{\text{eff}} = 263 \pm 13$ MeV for the AMY data. In addition, a fit to the evolution of the peak position with dijet mass using all data from different experiments gives $Q_{\text{eff}} = 226 \pm 18$ MeV. Next, α_s was extracted using the shape of the distribution at the Z^0 scale, with a value of 0.118 ±0.013. This is consistent, within the statistical errors, with many accurate measurements. We conclude that it is the success of LPHD + MLLA that the extracted value of α_s is correct. Possible explanations for all these features will be presented in this paper.

Keywords. Dijet; modified leading log approximation; coupling constant.

PACS No. 13.66.Bc

1. Introduction

e^+e^- annihilation into hadrons proves to be a wonderful laboratory for detailed experimental tests of QCD [1]. The high statistics data available from different experiments allow one to perform detailed studies of perturbative QCD and to reduce the domain of our ignorance on the physics of confinement. The data have convincingly demonstrated the dominant role of the perturbative QCD phase of jet evolution and supported the hypothesis of local parton–hadron duality (LPHD) [2].

We report the measurement of inclusive momentum distributions of charged particles in dijet events. These events were produced at the AMY detector in e^+e^- collisions with $\sqrt{S} = 60$ GeV. The results are compared with the experimental results obtained from CDF at Fermilab [3], the published data from LEP [4] and the perturbative QCD calculations carried out in the framework of the modified leading log approximation (MLLA) [5–10] and the hypothesis of local parton–hadron duality (LPHD) [11]. The MLLA evolution equations allow an analytical description of the phenomenon of a parton shower for gluon and quark jets. The LPHD hypothesis assumes that hadronization is local and occurs at the end of the parton shower phenomenon, so that properties of hadrons are closely related to those of partons. Altogether, the MLLA+LPHD scheme views jet fragmentation as a predominantly perturbative QCD process.

2. Experimental set-up

The central feature of the AMY detector is a 3 T solenoid magnet that allows the detector to be compact while maintaining good momentum resolution. Charged particles are detected efficiently over the polar angle region $\cos\theta < 0.87$ with a momentum resolution $\Delta p_{\text{T}} = 0.7\% \times [p_{\text{T}}(\text{GeV/c})]$. The detailed description of various detector components is given elsewhere [12].

3. Inclusive momentum distribution

The inclusive momentum distribution function of partons in jets, $D(\xi) = \mathrm{d}N/\mathrm{d}\xi$, in MLLA is defined in terms of the variable $\xi = \ln(1/x)$, where $x = p/E_{\text{jet}}$ and p is the parton momentum.

This distribution is predicted to have a distorted Gaussian shape [3]:

$$\frac{\mathrm{d}N}{\mathrm{d}\xi} = \frac{N}{\sigma\sqrt{2\pi}} \exp\left[\frac{1}{8}l - \frac{1}{2}s\delta - \frac{1}{4}(2+l)\delta^2 + \frac{1}{6}s\delta^3 + \frac{1}{24}l\delta^4\right], \quad (1)$$

where $\delta = \xi - \xi_0$ and ξ_0 is the position of the maximum of the distribution. The coefficients σ, s, and l respectively are the width, skewness, and kurtosis of the inclusive momentum spectrum. These coefficients are calculated to next-to-leading order and depend on Q_{eff} which is defined below.

The MLLA also predicts the energy evolution of the peak position of ξ distribution [4]:

$$\xi_0 = 0.5\tau + \sqrt{c\tau} - c, \quad (2)$$

where $\tau = \ln(Q/Q_{\text{eff}})$. Q_{eff} is the phenomenological scale and Q is the jet hardness (in this formalism, $\tau = \ln(\sqrt{S}/2Q_{\text{eff}})$) and $c = 0.2915$ (0.3190) for three (four) active flavours. Inclusive momentum spectra and the peak of the inclusive momentum distribution is shown in figure 1. The peak of the distribution is indicated by ξ_0.

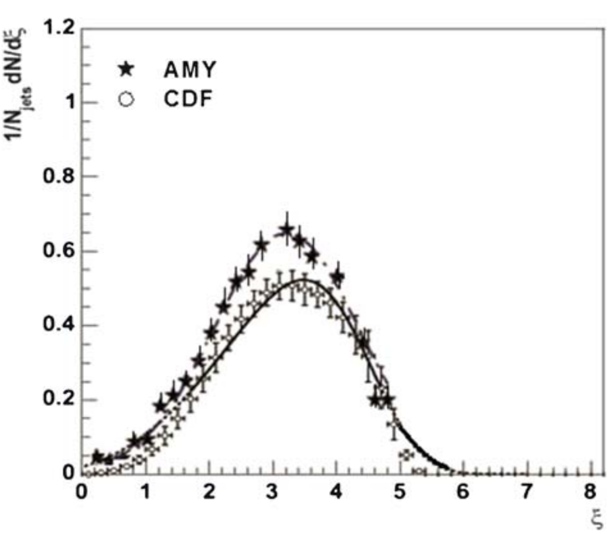

Figure 1. Inclusive momentum distributions of particles in jets with $Q = 27$ GeV for CDF [3] and $Q = 30$ GeV for AMY data. The solid curve corresponds to the fit of the CDF data and the dash–dotted curve corresponds to the fit of the AMY data.

By fitting eq. (1) to the ξ distribution measured in our AMY data, we find $\xi_0 = 3.220 \pm 0.03$. Furthermore, by applying eq. (2) to our data for three active flavours, we obtain $Q_{\text{eff}} = 263 \pm 13$ MeV. This value is consistent with the results from BES [13], OPAL [4], ZEUS [14] and CDF [15], which are 262 ± 9 (e^+e^-), 263 ± 4, 251 ± 14 (ep) and 256 ± 13($p\bar{p}$) MeV respectively. We have imposed the Origin and Mathematica softwares to fit eq. (1) on the distribution obtained from our AMY data with a (χ^2/(number of degrees of freedom (n.d.f.))) = 1.08.

Two types of systematic errors are considered, namely those coming from the differences between the data and Monte Carlo and those coming from the types of Monte Carlo used. The former is found by using the AMY data as well as the PYTHIA Monte Carlo, and the latter is found by taking the difference between the corrected distribution obtained with the PYTHIA and HERWIG Monte Carlo.

The QCD scale Q_{eff} is related to the (running) strong coupling constant (single loop) by [16]

$$\frac{\alpha_{\text{s}}}{2\pi} = \frac{1}{b\ln(E_{\text{beam}}/Q_{\text{eff}})}, \quad (3)$$

where $b = (11N_{\text{c}} - 2n_{\text{f}})/3 = 9$ for $N_{\text{c}} = 3$ and $n_{\text{f}} = 3$. The value of α_{s} extracted from the above formula for $Q_{\text{eff}} = 263$ MeV at the Z^0 scale ($E_{\text{beam}} = 91.2$ GeV) is $\alpha_{\text{s}} = 0.118 \pm 0.013$. This value is consistent within the statistical errors with many accurate measurements [17]. We conclude that it is the success of LPHD + MLLA that the extracted value of α_{s} is correct.

4. Dijet mass distribution vs. Q_{eff}

At this stage, we present the dijet distribution for our AMY data as well as for $p\bar{p}$ (CDF), e^-p, and LEP experiments. The Tevatron data (CDF), with their broad range of energies, present a good opportunity to verify the validity and consistency of the MLLA approach on an energy scale much larger than that available at other machines. Imposing some limits on the cone size which make the overlap of the energy regions of the Fermilab Tevatron and e^+e^- experiments, allows a direct comparison of experimental results in very different environment. Dijet mass is defined as

$$M_{jj} = \sqrt{(E_1 + E_2)^2 - (\vec{P}_1 + \vec{P}_2)^2}, \quad (4)$$

where E_1, $\vec{P}_1$ and E_2, $\vec{P}_2$ are the energy and momentum of jet 1 and jet 2 respectively. In CDF, the dijet mass is selected in three different cone sizes $\theta_{\text{c}} = 0.28$, 0.36, and 0.47 rad [3,15].

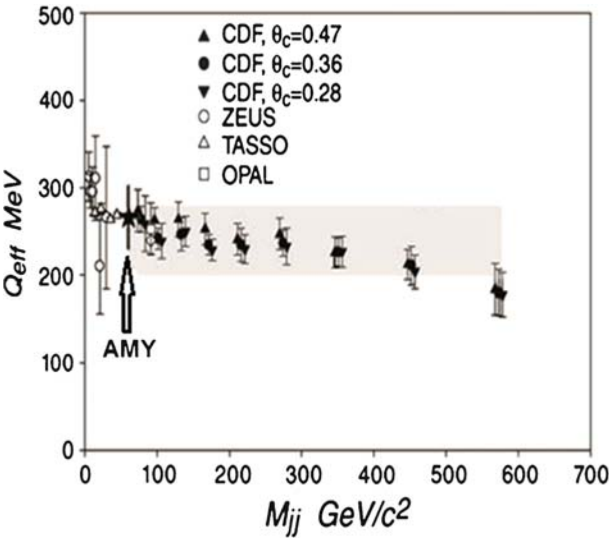

Figure 2. Fitted values of the MLLA parameter Q_{eff} as a function of dijet mass, for three cone sizes, $\theta_{\mathrm{c}} = 0.28, 0.36$, and 0.47 rad for CDF data [3]. The reported value is $Q_{\mathrm{eff}} = 230 \pm 40$ MeV and width of the shaded area shows this error. Length of the shaded area also shows the range of dijet mass used in their analysis [3]. For comparison, the data from e^+e^- [18] and *ep* [19] experiments are also shown.

One should keep in mind that in experiments with low centre of mass energies compared to the CDF data, results quoted from other experiments including our AMY data were obtained by counting all particles in the full solid angle for e^+e^- experiments or the entire jet hemisphere for *ep* experiments, which technically corresponds to the opening angle $\theta_{\mathrm{c}} = (\pi/2)$ rad.

Figure 2 shows Q_{eff} obtained from the fits to the momentum distributions against dijet energy M_{jj}, for CDF [3] and AMY, as well as, for other experiments [18,19]. Averaging over the whole range of energies for different cone angles in the CDF data, the reported value is $Q_{\mathrm{eff}} = 230 \pm 40$ MeV. Width of the shaded area shows the above error; the length of the shaded area illustrates the range of dijet mass used in CDF. One can see from the figure that Q_{eff} tends to become smaller for larger energies. The slight drift in the value of Q_{eff} may be due to the presence of higher-order contributions and/or non-perturbative effects at the hadronization stage. However, the moderate scale of these variations suggests that the overall shape of the momentum distributions is, indeed, mostly governed by the perturbative stage of jet fragmentation [3].

5. Peak position of the momentum distribution

In §3, we performed the calculations according to the MLLA prediction which considers a distorted Gaussian fit to the distribution. In this section we repeat our analysis by using a pure Gaussian fit in the vicinity of peak position of the distribution. This measurement of Q_{eff} is somewhat different from the direct fits to the MLLA-predicted function. It depends only on the momentum distribution of peak position, and does not depend on the shape of the distribution as a whole. However, as the peak position is the same for both analyses, we expect that the new method gives us results similar to the MLLA calculations.

Figure 3 shows the $\xi_0 = \ln(1/x_0)$ distribution against dijet energy, for AMY data as well as for other experiments at different energies [20–26]. As mentioned in the previous section, the results quoted for all the experiments except for CDF, corresponds to the opening angle $\theta_{\mathrm{c}} = \pi/2$. One can see that all points for different datasets, being plotted vs. dijet energy, do cluster along the same line. Assuming that Q_{eff} is a constant for different energies, a fit to all datasets (including AMY data) gives $Q_{\mathrm{eff}} = 226 \pm 18$ MeV. Our result is consistent within the statistical errors with the obtained value of $Q_{\mathrm{eff}} = 223 \pm 20$ for the CDF data [3]. We have employed a similar procedure for calculating the systematic errors as mentioned in §3, namely by considering the difference between the data and Monte Carlo on the one hand and by taking the difference between the two types of PYTHIA and HERWIG Monte Carlo on the other hand. This confirms the validity of the MLLA description of jet fragmentation in the range of jet energies.

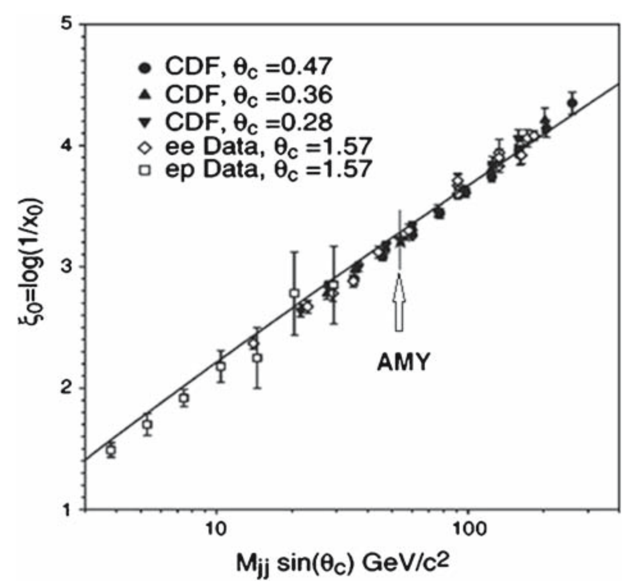

Figure 3. Momentum distribution peak position as a function of $M_{jj} \sin\theta_{\mathrm{c}} = 2E_{\mathrm{jet}} \sin\theta_{\mathrm{c}}$. Also plotted in the figure are the data points from e^+e^- [18] and *ep* [19] experiments. A fit to all datasets gives $Q_{\mathrm{eff}} = 226 \pm 18$ MeV.

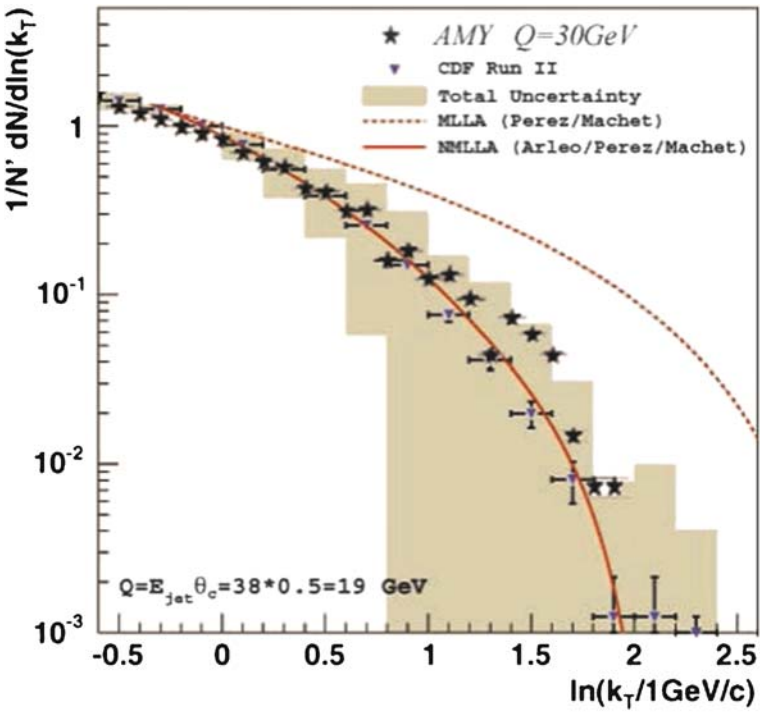

Figure 4. $\ln(k_T)$ distributions for dijet mass with $Q = 19$ GeV for CDF data [27] and $Q = 30$ GeV for AMY data. CDF data and AMY data are compared to the MLLA and NMLLA predictions.

6. Transverse momentum, k_T, distributions

Due to the recent theoretical work [27], the measurement of intrinsic k_T (transverse momenta of particles with respect to jet axis) is of particular interest because it allows us to probe particle spectra which are softer than the previously measured observables. We use the thrust as the jet axis. It directs along a line which maximizes the sum of the momenta of all particles in an event along that axis. The analysis was carried out in the dijet centre-of-mass frame. Tracks only within a cone of $\theta_c = 0.5$ rad around the jet axis for CDF are considered. For the AMY data, $\theta_c = \pi/2$. The theoretical predictions were made in the framework of MLLA and next-to-MLLA (NMLLA) [28]. Distributions were normalized to the average multiplicity of particles in jets. The goal of this study is to compare the shape of the k_T distributions of CDF with that of the AMY data. Figure 4 shows k_T distributions on top of the MLLA and NMLLA curves. The agreement between both data and MLLA predictions is fairly good in the region of low $\ln(k_T)$. However, MLLA predicts more particles with larger transverse momenta than observed in the data. The agreement between both data and NMLLA calculations is good in the entire range of $\ln(k_T)$ [28]. We conclude that these is more agreement between the data and the theory when higher-order calculations are included.

7. Summary and conclusion

We have measured inclusive momentum distributions of charged particles in jets for dijet events. The analysis was done for all particles concerned with AMY data and other e^+e^- experiments as well as ep data. The results were compared with those obtained from CDF Tevatron in Fermilab for the particles in restricted cones around the jet direction ($\theta_c = 0.28, 0.36, 0.47$ rad).

The data were compared with calculations carried out in the framework of the modified leading log approximation in conjunction with the hypothesis of local parton–hadron duality.

A fit of the shape of the distributions yields $Q_{\text{eff}} = 263 \pm 13$ MeV for the AMY data and $Q_{\text{eff}} = 230 \pm 40$ MeV for the CMF data. A fit to the evolution of the peak position with dijet mass for different data gives $Q_{\text{eff}} = 226 \pm 18$ MeV. This value is consistent within the statistical errors with the obtained value of $Q_{\text{eff}} = 223 \pm 20$ for CDF.

Next, we extracted α_s by using the shape of the distribution at the Z^0 scale with a value of 0.118 ± 0.013.

Within the statistical errors this is in good agreement with many accurate measurements [17].

The fact that measurements from different experiments nicely overlap and complement each other implies jet universality in various environments. It also confirms the validity of the MLLA description of jet fragmentation in the range of jet energies.

References

[1] Ahmed Ali and Gustav Kramer, *Eur. Phys. J. H* **36**, 245 (2011)

[2] Yu L Dokshitzer, V A Khoze, A H Mueller and S I Troyan, *Rev. Mod. Phys.* **60** (1998)
Khoze *et al*, arXiv:hep-ph/0009298 (2000)

[3] D Acosta *et al*, *Phys. Rev. D* **68**, 012003 (2003)
R P Ramos, *J. High Energy Phys.* **0606**, 019 (2006)
R P Ramos, *J. High Energy Phys.* **0609**, 014 (2006)

[4] OPAL Collaboration: G Abbiendi *et al*, *Eur. Phys. J. C* **16**, 185 (2000)

[5] Yu L Dokshitzer and S Troyan, *XIX Winter School of LNPI* **1**, 144 (1984)

[6] A H Mueller, *Nucl. Phys. B* **213**, 85 (1983); *B* **241**, 141(E) (1984)

[7] Yu L Dokshitzer, V S Fadin and V A Khoze, *Phys. Lett. B* **115**, 242 (1982)
A Basseto, M Ciafaloni, G Marchesini and A H Mueller, *Nucl. Phys. B* **207** (1982)

[8] Yu L Dokshitzer, V A Khoze and S I Troyan, *Int. J. Mod. Phys. A* **7**, 1875 (1992); *Z. Phys. C* **55**, 107 (1992)

[9] E D Malaza and B R Webber, *Phys. Lett. B* **149**, 501 (1984)

[10] Yu L Dokshitzer, A H Mueller, V A Khoze and S Troyan, *Basics of perturbative QCD* (Editions Frontieres, Paris, 1991)

[11] Ya I Azimov, Yu Dokshitzer, V Khoze and S Troyan, *Z. Phys. C* **27**, 65 (1985); **31**, 213 (1986); *Phys. Lett. B* **165** (1985)

[12] AMY Collaboration: Y K Li *et al*, *Phys. Rev. D* **41**, 2675 (1990)

[13] BES Collaboration: J Z Bai *et al*, arXiv:hep-ex0306055v2

[14] V A Jamieson, *Measurement of scaled momentum distributions in the Breit frame at HERA using the ZEUS detector*, Ph.D. thesis, *DESY F35 D-95-01*

[15] A Safonov, *Talk at 8th International Workshop on Deep Inelastic Scattering and QCD* (DIS2000), Fermilab-Conf-00-131-EM

[16] N C Brummer, hep-ex/9405001

[17] S Kluth, arXiv:1206.0065 (2012)

[18] S Catani *et al*, *Nucl. Phys. B* **377**, 445 (1992)
JADE Collaboration: W Bartel *et al*, *Z. Phys. C* **9**, 315 (1981)
CELLO Collaboration: H J Behrend *et al*, *Phys. Lett. B* **113**, 427 (1982)
TASSO Collaboration: M Althoff *et al*, *Z. Phys. C* **22**, 307 (1984)
HRS Collaboration: D Bender *et al*, *Phys. Rev. D* **31**, 1 (1985)

[19] UA1 Collaboration: G Arnison *et al*, *Nucl. Phys. B* **276**, 253 (1986)

[20] ALEPH Collaboration: D Busculik *et al*, *Z. Phys. C* **73**, 409 (1997)

[21] DELPHI Collaboration: P Abreu *et al*, *Phys. Lett. B* **275**, 231 (1992); *Z. Phys. C* **73**, 229 (1997)

[22] L3 Collaboration: M Acciarri *et al*, *Phys. Lett. B* **444**, 569 (1998)

[23] MARK II Collaboration: A Peterson *et al*, *Phys. Rev. D* **37**, 1 (1998)

[24] OPAL Collaboration: G Abiendy *et al*, *Z. Phys. C* **72**, 191 (1996); **75**, 193 (1997)

[25] TOPAZ Collaboration: R Itoh *et al*, *Phys. Lett. B* **345**, 335 (1995)

[26] ZEUS Collaboration: M Derrick *et al*, *Z. Phys. C* **67**, 93 (1995)

[27] R Perez-Ramos and B Machet, *J. High Energy Phys.* **04**, 043 (2006)
V A Khoze *et al*, arXiv:1409.8451v1 (2014)

[28] Sergo Jindariani, *Braz. J. Phys.* **37(2C)**, 830 (2007)