Fermi National Accelerator Laboratory

FERMILAB-Pub-91/217

Distributions of Charged Hadrons Observed in Deep-Inelastic Muon-Deuterium Scattering at 490 GeV

The Fermilab E665 Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

August 1991

* Submitted to *Physics Letters B*.

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

Distributions of Charged Hadrons Observed in Deep–Inelastic Muon–Deuterium Scattering at 490 GeV

THE FERMILAB E665 COLLABORATION

August 20, 1991

Abstract

Longitudinal and transverse momentum spectra of final state hadrons produced in deep–inelastic muon–deuterium scattering at incident muon energy of 490 GeV have been measured up to a hadronic center of mass energy of 30 GeV. The longitudinal distributions agree well with data from earlier muon-nucleon scattering experiments; these distributions tend to increase in steepness as the center of mass energy increases. Comparisons with e^+e^- data at comparable center of mass energies indicate slight differences. The transverse momentum distributions show an increase in mean p_T^2 with an increase in the center of mass energy.

Submitted to Physics Letters B

THE FERMILAB E665 COLLABORATION

M. R. Adams[6], S. Aïd[9], P. L. Anthony[10,a], M. D. Baker[10], J. Bartlett[4], A. A. Bhatti[13,b], H. M. Braun[14], W. Busza[10], J. M. Conrad[5], G. Coutrakon[4,c], R. Davisson[13], I. Derado[11], S. K. Dhawan[15], W. Dougherty[13], T. Dreyer[1], K. Dziunikowska[8], V. Eckardt[11], U. Ecker[14], M. Erdmann[1,e], A. Eskreys[7], J. Figiel[7], H. J. Gebauer[11], D. F. Geesaman[2], R. Gilman[2,d], M. C. Green[2,f], J. Haas[1], C. Halliwell[6], J. Hanlon[4], D. Hantke[11], V. W. Hughes[15], H. E. Jackson[2], D. E. Jaffe[6], G. Jancso[11], D. M. Jansen[13], S. Kaufman[2], R. D. Kennedy[3], T. Kirk[4,g], H. G. E. Kobrak[3], S. Krzywdzinski[4], S. Kunori[9], J. J. Lord[13], H. J. Lubatti[13], D. McLeod[6], S. Magill[6,g], P. Malecki[7], A. Manz[11], H. Melanson[4], D. G. Michael[5,h], W. Mohr[1], H. E. Montgomery[4], J. G. Morfin[4], R. B. Nickerson[5,i], S. O'Day[9,j], K. Olkiewicz[7], L. Osborne[10], V. Papavassiliou[15,g], B. Pawlik[7], F. M. Pipkin[5], E. J. Ramberg[9,j], A. Röser[14,k], J. J. Ryan[10], A. Salvarani[3,k], H. Schellman[12], M. Schmitt[5], N. Schmitz[11], K. P. Schüler[15], H. J. Seyerlein[11], A. Skuja[9], G. A. Snow[9], S. Söldner-Rembold[11], P. H. Steinberg[9,l], H. E. Stier[1,l], P. Stopa[7], R. A. Swanson[3], R. Talaga[9,g], S. Tentindo-Repond[2,m], H.-J. Trost[2], M. Vidal[11] M. Wilhelm[1], J. Wilkes[13], H. Venkataramania[15], Richard Wilson[5], W. Wittek[11], S. A. Wolbers[4], T. Zhao[13]

[1] Albert-Ludwigs-Universität Freiburg i. Br., Germany
[2] Argonne National Laboratory, Argonne IL USA
[3] University of California, San Diego, CA USA
[4] Fermi National Accelerator Laboratory, Batavia, IL US A
[5] Harvard University, Cambridge, MA USA
[6] University of Illinois, Chicago, IL USA
[7] Institute for Nuclear Physics, Krakow, Poland
[8] Institute for Nuclear Physics, Academy of Mining and Metallurgy, Krakow, Poland
[9] University of Maryland, College Park, MD USA
[10] Massachusetts Institute of Technology, Cambridge, M A USA
[11] Max-Planck-Institute, Munich, Germany
[12] Northwestern University, Evanston, IL USA
[13] University of Washington, Seattle, WA USA
[14] University of Wuppertal, Wuppertal, Germany
[15] Yale University, New Haven, CT USA

In the measurements reported here, charged final state hadrons produced in deep–inelastic muon–deuterium scattering have been studied. The final state in muon scattering is dominated by light quarks, the charm and bottom content is small. Muon scattering thus provides a clean insight into light quark fragmentation and Quantum Chromodynamic(QCD) effects. The measurements were performed with positive muons of mean energy 490 GeV in the NM beamline at the Fermilab Tevatron. The apparatus used in the experiment, Fermilab E665, has been described extensively elsewhere[1]. The muons impinged on a target vessel, which was approximately one meter long and contained liquid deuterium, located inside a dipole vertex magnet. A second magnet, downstream of the vertex magnet and with an opposing field, provided the primary measurement of the momenta of the scattered muons and produced hadrons; their energies, E_μ and E_h, were calculated assuming muon and pion masses, respectively. The momentum of each incident muon was measured in a conventional beam spectrometer.

The kinematics of the muon scattering process, described by the exchange of a single virtual photon, for a fixed beam energy E, is defined by two Lorentz invariant variables. We have used Q^2, the modulus of the square of the virtual photon four–momentum, and W^2, the total hadronic center of mass energy-squared, which is given by $W^2 = M^2 + 2M\nu - Q^2$, where $\nu = E - E_\mu$ is the energy exchanged in the lab system and M is the mass of the target nucleon which is assumed to be at rest. x_{Bj} is given by $x_{Bj} = Q^2/2M\nu$. The variables used to describe the hadron kinematics are z_h and p_T; $z_h \equiv E_h/\nu$ is the fraction of the exchanged energy carried by the hadron, and p_T is the hadron transverse momentum, defined with respect to the direction of the exchanged virtual photon. An alternative hadron variable, the Feynman-x (x_F), describes the longitudinal momentum fraction of the hadron; for the muon scattering kinematics of this sample and for hadrons with $z_h > 0.1$, the two variables z_h and x_F agree to within 3%.

The results are based on the charged hadrons produced in the forward hemisphere of the total hadronic center of mass system, from a sample of ~11,000 muon–deuterium scattering events which survived cuts. A minimum ν of 100 GeV was required to ensure good resolution in the kinematic variables. A kinematic restriction of $y \leq 0.85$ ($y = \nu/E$) avoided the region where radiative corrections increase rapidly. An explicit lower limit of $Q^2 > 2$ GeV^2/c^2 was imposed; this was motivated by the minimum acceptance angle of 3 milliradians of the trigger used for these data.

All hadron tracks found and fitted by the reconstruction programs — pattern recognition, track fitting, and vertex fitting — were required to satisfy basic selection criteria before being included in the distributions. The requirement on the hadronic energy fraction, $z_h > 0.1$, limited the sample of tracks to those which had adequate acceptance in the forward spectrometer. The distance of closest approach between the fitted hadronic tracks and the primary muon scattering vertex had to be less than 1 cm; this minimized the number of tracks with mismeasured hadron transverse momentum component. Additional requirements on track quality parameters, χ^2-probability, and relative error on momentum measurement were imposed[5].

The selection criteria listed above, as well as the corrections applied to the data described below, were derived using an extensive simulation program. The generation of deep–inelastic muon scattering events and hadron fragmentation, using quark distribution functions from Morfin and Tung [2], was realized with a Monte Carlo (MC) model developed by the Lund group [3]. This model provides an adequate description of the particle distributions for use in the calculation of acceptance. The generated particles were traced through a detailed model of the detector, accounting for particle decays, secondary strong and electromagnetic interactions as well as chamber efficiencies and noise. The MC event information was structured identically to data information to allow a full event reconstruction using the same reconstruction programs on both sets. The comparison of MC event information between generated and reconstructed values determined corrections for the geometric acceptance as well as the reconstruction acceptance. In addition, corrections for secondary interactions, K^0 and Λ decays were obtained. The combination of these *acceptance* corrections affected the uncorrected hadron distributions by up to 20–30%. Contamination of the hadron sample by electrons originating from bremsstrahlung, which occurs mainly for $z_h > 0.8$, was not removed explicitly from the hadronic distributions but has been estimated to be less than 10%.

Radiative corrections, based on calculations by Mo & Tsai [4], have been applied to the data. The procedure corrects for the modification of the event kinematics due to photon emission associated with either the incident or scattered muon. It also accounts for the modification of the yields as a function of the muon scattering variables. These corrections increase with z_h and p_T^2 up to a maximum of $\sim 20\%$, depending on the event kinematics; they are well understood and contribute little to the uncertainty of the derived distributions.

Particular effort has been expended to estimate the magnitude of systematic errors. If the MC model of the apparatus and the physics were to reproduce reality perfectly, the fully corrected data distributions, in a fixed kinematic bin, would not depend on any of the selection criteria. In practice, variations of the selection criteria imposed on the data have lead to slightly different final hadron distributions; the magnitudes of these differences have been employed as an estimate of the relevant systematic errors associated with the final distributions. We quote an error of $\sim 15\%$ for the $(1/N_\mu)(dN^h/dz_h)$ distributions. For $p_T^2 > 3.5$ GeV^2/c^2, an uncertainty of $\sim$20% is estimated for $(1/N_\mu)(dN^h/dp_T^2)$ and 3%–9% for $\langle p_T^2 \rangle$. A complete discussion of this analysis method is given in reference [5].

Within the quark parton model, the normalized z_h distribution is the result of the convolution of light quark fragmentation functions with the quark densities, weighted by the charge-squared of the quarks [6]. The fragmentation functions are postulated to be independent of the underlying hard scatter, which permits comparisons between lepton scattering and other interactions, to the extent that the participating quark species are the same. Within this model, there is also no dependence on the event kinematics. A calculation based on QCD suggests deviations from this behavior leading to a steepening of the z_h distribution as W^2 increases[7]. Such steepening has been observed in muon scattering [8] and e^+e^- [9] interactions.

Figure 1a shows the scaled energy distribution (z_h) for charged hadrons measured in this experiment. The average W^2 of the data set is 420 GeV^2. The error bars represent the statistical errors only. For comparison, data at somewhat lower W, measured by the EMC [10] and by earlier muon scattering experiments at Fermilab [11] are included. There are no obvious differences among the deep–inelastic muon scattering data sets. The data are well represented by a simple exponential in z_h for $z_h > 0.1$. In Figure 1c we show the results of fitting our data, in several ranges of W, with a simple exponential in z_h. The absolute value of the slope increases slightly as W increases. In Figure 1b the μd data are compared to those from e^+e^- annihilation at a comparable center of mass energy, taken from reference [12] and scaled by a factor 0.5 to ensure a comparison for one hemisphere only. In the interval $0.1 < z_h < 0.75$, the distribution measured in e^+e^- annihilation is slightly steeper. One should remark that neither the variables nor the analyses are identical, since the event axis is not known *a priori* for the e^+e^- data. Such effects were studied at lower energies and were found not to debase the conclusion that the e^+e^- data are steeper; it was suggested that this is due to the difference in the mix of quarks involved [10]. The results of exponential fits to the TASSO [12] data are also included in Figure 1c; in both data sets the slopes of the distributions become steeper as W^2 increases. Such a dependence would be expected as a result of QCD[7]; it is analogous to the QCD evolution of the structure functions.

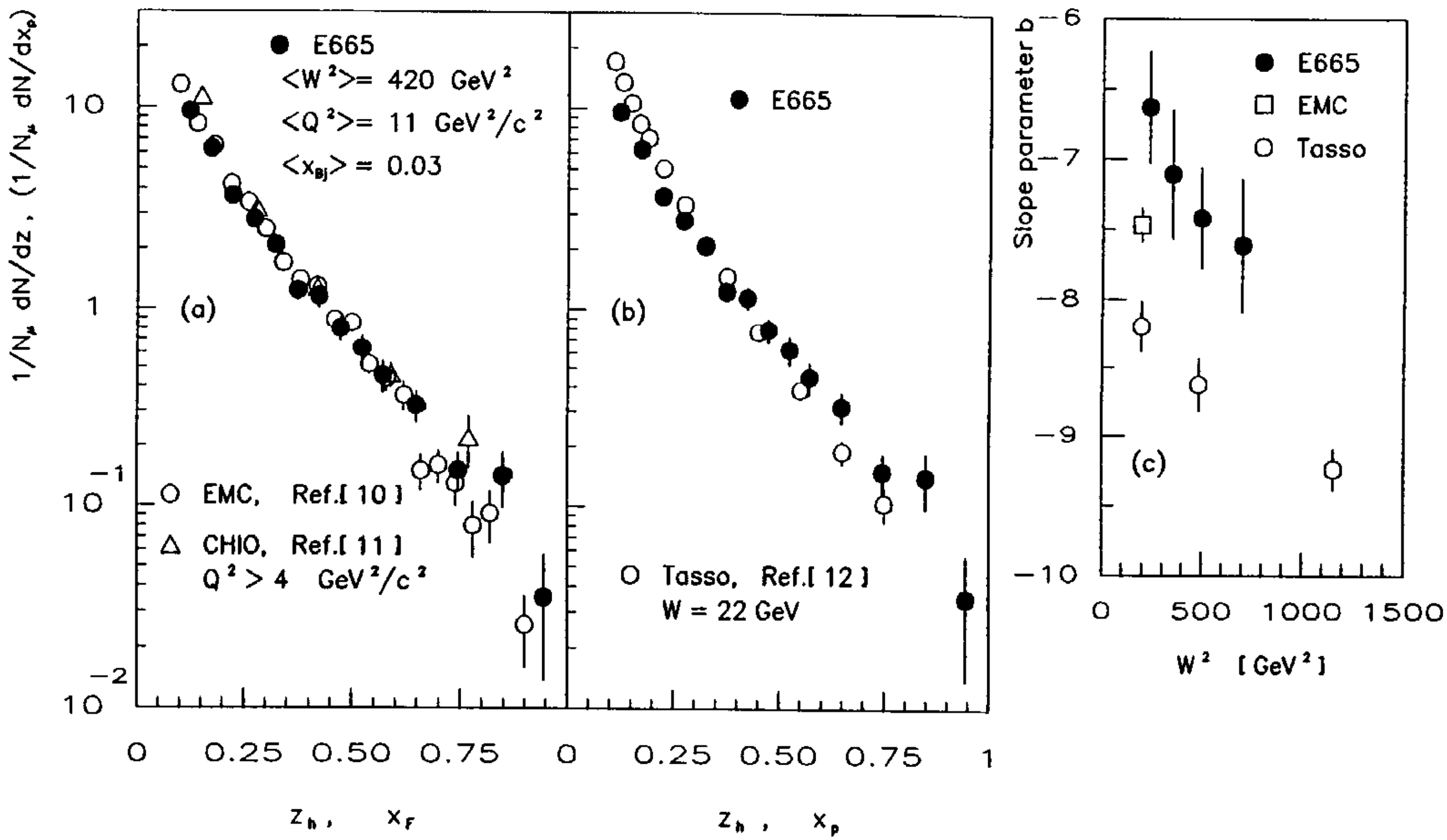

Figure 1: Scaled energy distribution (z_h) measured in this experiment in comparison to earlier μp scattering experiments (a) and to e^+e^- annihilation interactions (b) and the W dependence of the slope parameter (see text) of the scaled energy distributions (c). The variables $x_F = 2P_L/W$ and $x_P = 2P/W$ are very similar to z_h in the range shown.

In Figure 2 we display the p_T^2 distributions, $(1/N_\mu)(dN^h/dp_T^2)$, measured in this experiment for three different ranges in W^2. The distribution at low p_T^2 shows the typical exponential decrease but is much flatter at high p_T^2, which is consistent with descriptions of such QCD processes as gluon bremsstrahlung. This feature is especially marked for the highest W^2 data. For comparison, some data from a recent EMC analysis are included, which used a merged data set of μp and μd interactions[13].

The average p_T^2 in lepton scattering has been understood in simple terms as the quadratic sum of terms from three sources: the intrinsic momentum of the quarks in the nucleon, the p_T introduced by the fragmentation process, and the p_T introduced by perturbative QCD processes which may be either gluon emission by the participant quark or the photon gluon fusion mechanism. The first of these is expected to lead to an increase of the $\langle p_T^2\rangle$ with z_h, as the hadron takes a fraction z_h of the initial quark transverse momentum. The second contribution, from fragmentation, is approximately constant in most models. The QCD contribution is expected to grow proportionally with W^2 [14], as the phase space available for gluon emission grows. We plot, in Figure 3, the average p_T^2 versus W^2 for three different z_h ranges: $0.1 < z_h < 0.2$ (a), $0.2 < z_h < 0.4$ (b), and $0.4 < z_h < 1.0$ (c). The W^2 range in Figure 3c is limited to $W^2 < 700$ GeV^2, to limit systematic uncertainties. We also include measurements from both muon[13] and neutrino[15, 16, 17] scattering experiments although [17] the latter are not expected to be identical. The expected behavior is clearly seen; there is an increase of $\langle p_T^2\rangle$ with W^2 as well as with z_h, and the higher energy data from this experiment connect smoothly to the lower energy data. The rise as a function of W^2 appears to be weaker if only the higher W^2 data are considered, perhaps because the higher W^2 data tend to be at lower x_{Bj}.

Deep–inelastic muon scattering data have been presented from a previously unexplored kinematic region of center-of-mass energies of up to ~30 GeV. The data smoothly connect to those from lower energy lepton scattering, in terms of both their scaled energy and transverse momentum characteristics. A small difference in the scaled energy distribution is observed in the comparison of μN and e^+e^- data possibly due to the different quark content in the two processes. A steepening of these distributions as a function of W^2 is observed, which is the result expected from QCD gluon emission effects. The increase of $\langle p_T^2\rangle$ with W^2, which was observed in previous data at lower energies, persists to these higher W^2 data although with somewhat shallower slope.

We wish to thank all those personnel, both at Fermilab and at the participating

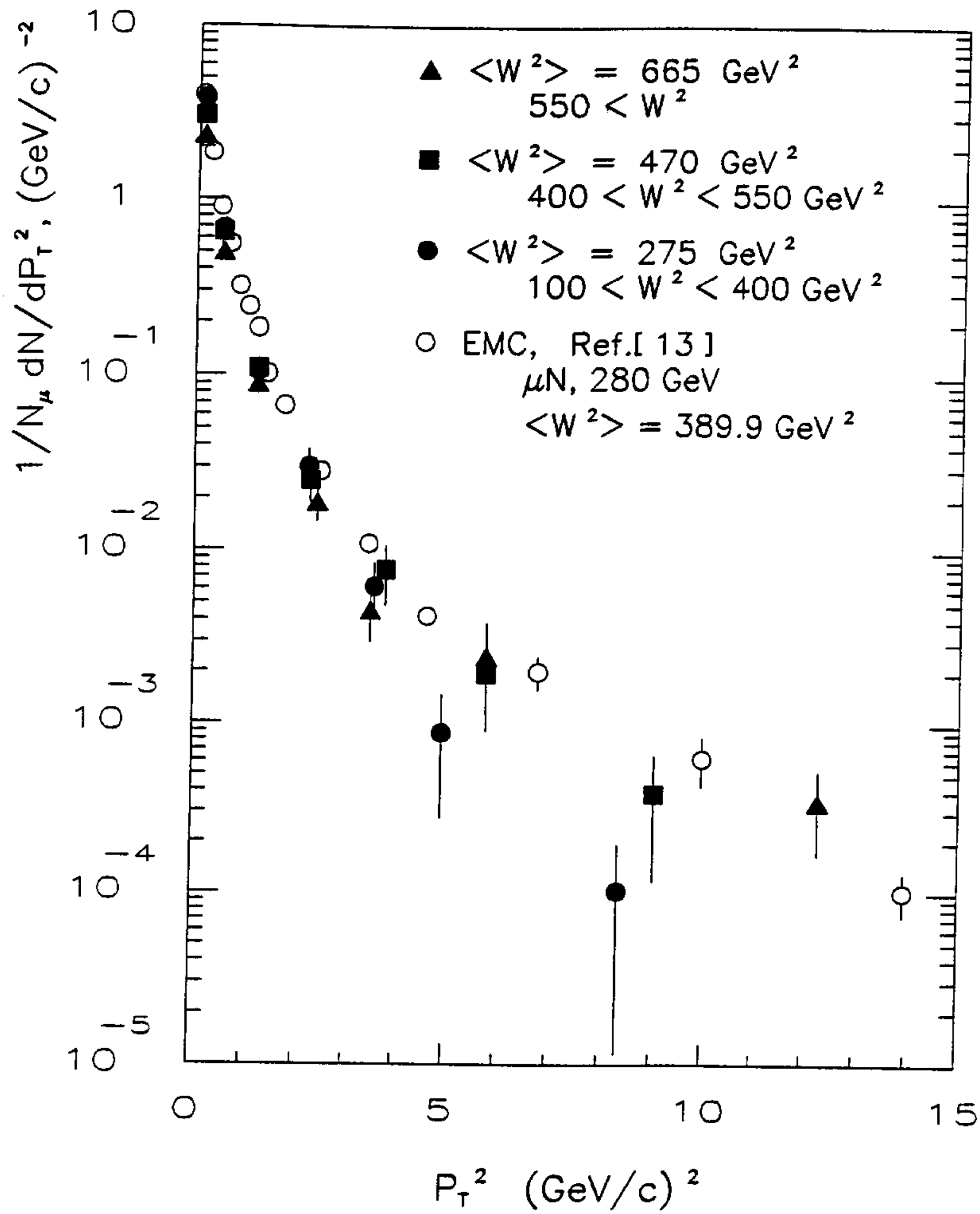

Figure 2: Normalized p_T^2 distribution $(1/N_\mu)(dN^h/dp_T^2)$ measured in this experiment in three different ranges of W^2 and in [13] at the lower W^2.

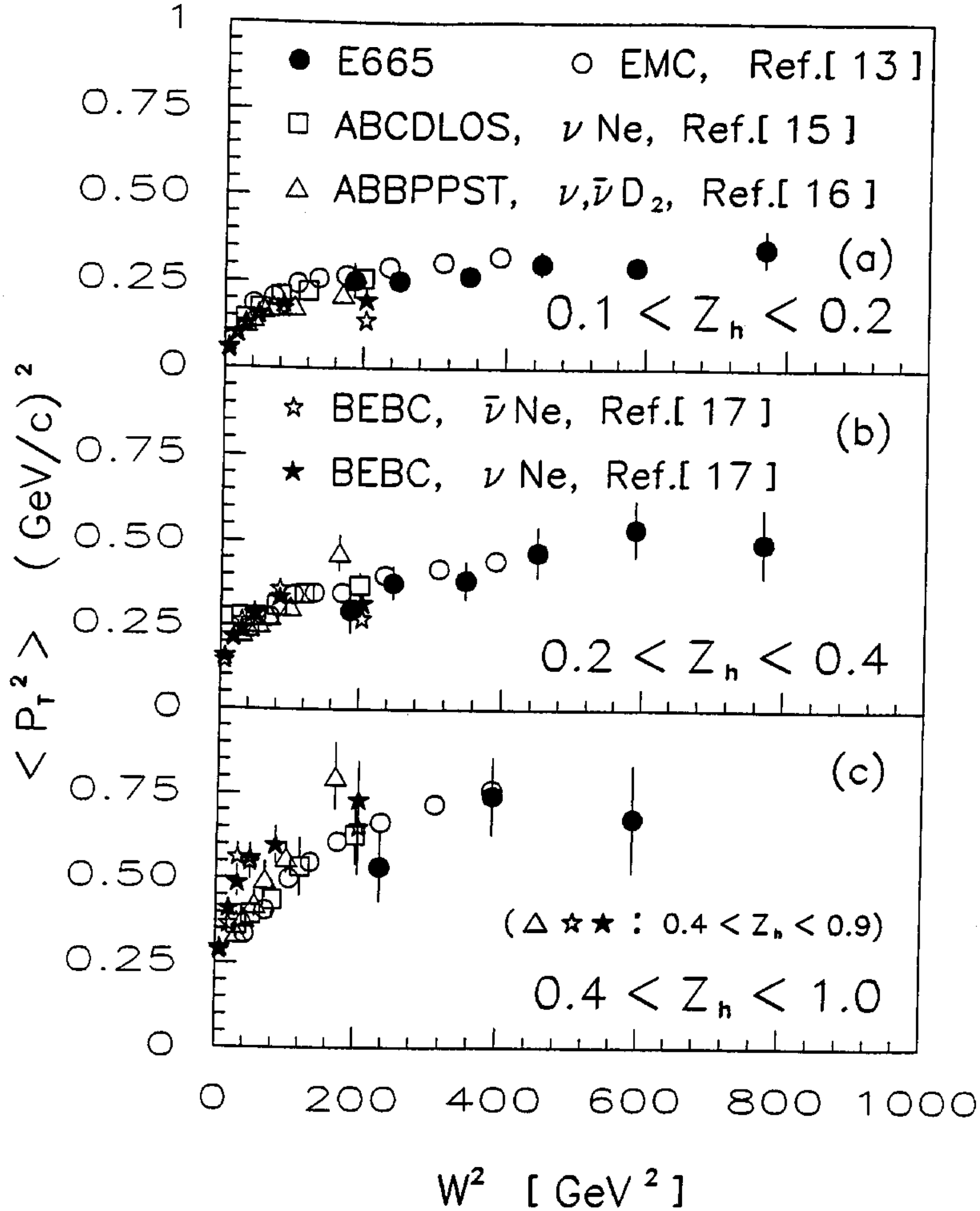

Figure 3: Mean p_T^2 versus W^2 for three different z_h intervals in comparison with other leptoproduction measurements [13,15,16,17].

institutions, who have contributed to the success of this experiment. The work of the University of California, San Diego was supported in part by the National Science Foundation, contract numbers PHY82-05900, PHY85-11584 and PHY88-10221; the University of Illinois at Chicago by NSF contract PHY88-11164; and the University of Washington by NSF contract numbers PHY83-13347 and PHY86-13003. The University of Washington was also supported by the U. S. Department of Energy. The work of Argonne National Laboratory was supported by the Department of Energy, Nuclear Physics Division, under Contract No. W-31-109-ENGGG-38. The Department of Energy, High Energy Physics Division, supported the work of Harvard University, the Unversity of Maryland, the Massachussetts Institute of Technology under Contract No. DE-AC02-76ER03069 and Yale University. The Albert-Ludwigs-Universität and the University of Wuppertal were supported in part by the Bundesministerium für Forschung and Technologie.

[a] Current address: Lawrence Livermore National Laboratory, Livermore, CA 94550, USA.

[b] Current address: The Rockefeller University, New York NY 10021, USA.

[c] Current address: Loma Linda University Medical Center, Loma Linda CA 92350 USA.

[d] Current address: Rutgers University, Piscataway, NJ 08855, USA.

[e] Current address: LeCroy Research Systems, Spring Valley, NY 10977, USA.

[f] Current address: DESY, Notkestr.85,2000 Hamburg, Germany.

[g] Current address: Argonne National Laboratory, Argonne, IL 60439, USA.

[h] Current address: California Institute of Technology, Pasadena, CA 91125, USA.

[i] Current address: Oxford University, Oxford, UK.

[j] Current address: Fermi National Accelerator Laboratory, Batavia, IL 60510, USA.

[k] Current Address A. T. & T, Bell Labs. 2000 North Naperville Road, Naperville, IL, USA.

[l] Deceased.

[m] Current address: Northern Illinios University, Dekalb, IL 60115, USA.

References

[1] M.R. Adams et al., Nucl. Inst. and Meth. **A291** (1990) 533.

[2] J.G. Morfin and Wu-Ki Tung, FERMILAB-Pub-90/74; April, 1990.

[3] T. Sjöstrand, Comp. Phys. Comm. **27** (1982) 243.

[4] L.W. Mo, Y.S. Tsai, Rev. Mod. Phys. **41** (1969) 205; Y.S. Tsai, SLAC-PUB-848 (1971); J. Drees, EMC/78/24; Wuppertal University Preprint WU - B 78 - 16, April 1978.

[5] U. Ecker, Ph.D. Thesis, University of Wuppertal, WUB–DIS 91–1, January 1991.

[6] For leptoproduction the quark parton model of hadron production is succinctly summarized in: L.M. Sehgal, *Hadron Production by Leptons,* Proceedings of the 1977 International Symposium on Lepton and Photon Interactions at High Energies (Hamburg, August, 1977), 837.

[7] R. Baier, K. Fey, Z. Physik C, Particles and Fields **2** (1979) 339.

[8] M. Arneodo et al., Phys. Lett. **165B** (1985) 222; J.J. Aubert et al., Phys. Lett. **114B** (1982) 373.

[9] D.H. Saxon, *Quark and Gluon Fragmentation in High Energy* e^+e^-*–Annihilation,* Rutherford Appleton Laboratory, RAL–86–057, July 1986.

[10] M. Arneodo et al., Z. Phys. C - Particles and Fields **35**, (1987) 417.

[11] W.A. Loomis et al., Phys. Rev. **D19**, (1979) 2543.

[12] M. Althoff et al., Z. Phys. **C22** (1984) 307, (Table 4f and Figure 40).

[13] J. Ashman et al., CERN-PPE-53(1991) to be submitted to Zeitschrift für Physik.

[14] G. Altarelli, G. Martinelli, Phys. Lett. **76B**, (1978) 89.

[15] H. Deden et al., Nucl. Phys. **B181**, (1981) 375.

[16] D. Allasia et al., Z. Phys. **C27**, (1985) 239.

[17] M. Berggren et al., Z. Phys. **C50**, (1991) 427.