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Abstract

We report on the first experimental study of the hadronic final state in de
inelastic electron-proton scattering with the H1 detector at HERA. Energy fl
and transverse momentum characteristics are measured and presented both in t
laboratory and in the hadronic center of mass frames. Comparison is made wi
QCD models distinguished by their different treatment of parton emission.

1 Introduction

Since May 1992 when the first electron-proton (ep) collisions were observed at the
storage ring, a new kinematic domain of ep physics has become accessible experim
In this paper we report on first results of an analysis of the hadronic final state
inelastic scattering (DIS) of 26.7 GeV electrons and 820 GeV protons. The da
collected in July 1992 and amount to an integrated luminosity of about 1.6 nb^{-}

It is already well established from analyses of previous lower energy lepton-
DIS measurements [1,2,3] that an understanding of the topological characteri
hadron production requires QCD corrections to the naive quark-parton model.
ticular, the observed event shapes and the transverse momentum (p_T) distribu
final state hadrons were described in terms of $O(\alpha_s)$ QCD matrix elements, ad
effects of soft gluons, and fragmentation [4].

In the present rather small sample of data, the bulk of events are at mor
transfers Q^2 that have already been observed in previous experiments. However,
the average invariant mass W of the hadronic final state is about 100 GeV, ro
times greater than in the previous experiments, the data presented here are in
DIS kinematic domain, namely Bjorken x down to 10^{-4}. In the H1 detector we
the scattered electron and the current jet, as can be seen in the event displ
fig. 1a) and b), while the fragments from the proton remnants and from initial
radiation tend to remain inside the beam pipe. Therefore we are sensitive m
gluon emission associated with the current quark and to large p_T quark pair pro
in photon gluon fusion.

We compare our data in terms of hadronic energy flow and p_T both in the lab
and hadronic center of mass systems with several QCD models which differ i
treatment of parton radiation processes.

2 Detector description

We describe here briefly only the components of the H1 detector used in this a
(see fig. 1a), referring to [5] for details.

The interaction region is surrounded by the central tracker (CT). It consists
cylindrical "jet" drift chambers for charged track reconstruction in the plane
verse to the beam interleaved with "z" drift chambers to improve track polar an

measurement. The uniform 1.2 T field is provided in the CT region by a large superconducting solenoidal magnet which surrounds the trackers and the central calorimeter. In the "backward" direction (the electron beam and $-z$ direction) the backward multiwire proportional chamber (BPC) measures the polar angle θ_e of the scattered electron and is used in the scattered electron identification and kinematic reconstruction.

Outside the track detectors are calorimeters for electromagnetic and hadronic energy measurement. A finely segmented liquid argon (LAr) calorimeter covers the forward (the proton beam and $+z$ direction) and central regions ($4^0 < \theta < 155^0$). It consists of an electromagnetic section (EMC) of between 20 and 30 radiation lengths (X_0) depth followed by an hadronic section (HAC). The total depth of the LAr calorimeter varies between 4.5 and 8 interaction lengths.

The initial calibration of the LAr calorimeter was achieved with test beam measurements using electrons and pions at CERN. The absolute scale of the energy response at HERA has been verified with charged particles by comparing their momentum measured in the CT with associated energy deposited in the calorimeter. With electrons and positrons produced by cosmic ray muons, the electromagnetic scale has been checked to $\pm 2\%$ [6]. Using negatively charged particle tracks originating from the ep interaction region, the hadronic scale has been checked to $\pm 10\%$. Furthermore, a study of the balance of transverse momentum between the scattered electron measured in the backward calorimeter and the recoiling hadronic system measured in the LAr calorimeter has so far verified that the overall hadronic energy scale of the LAr calorimeter is understood to within $\pm 7\%$.

The backward region ($154^0 < \theta < 176^0$) is covered by a 22 X_0 deep lead-scintillator electromagnetic calorimeter (BEMC). The overall calibration of the BEMC calorimeter to $\pm 2\%$ was achieved by using kinematic constraints in DIS events [7]. A hodoscope consisting of 2 planes of scintillators (TOF) is placed behind the BEMC. It provides time-of-flight information to reject out of time proton beam background originating upstream.

A luminosity detector which measures the reaction $ep \rightarrow e\gamma p$ is placed in the backward direction with components at $z = -33$ m to tag electrons scattered at small angles and at $z = -103$ m to measure photons.

3 Event Selection

For this analysis only a subsample of our DIS candidate events is used in which the electron is scattered into the BEMC calorimeter and substantial hadronic energy deposition is observed in the detector.

The hardware trigger requires an energy cluster with more than 4 GeV deposited in the BEMC and no time of flight veto from the scintillator hodoscope. The trigger efficiency is $> 99\%$ for the final sample of selected events because an energetic BEMC cluster is required [7]. After reconstruction, the data are subjected to the following selection criteria:

1. the scattered electron, defined as the most energetic BEMC cluster, mu
energy greater than 14 GeV and be associated within 15 cm with a hi
BPC; to ensure a precise energy measurement, the cluster center of gravity
must not be too close to the beam pipe, i.e. $|x_{c.o.g}| > 16$ cm or $|y_{c.o.g}| > 1$
2. the BPC hit must lie between 18 and 60 cm from the beam line, i.e. the
scattering angle is between 173° and 157° when the collision occurs at the n
ep interaction point;
3. the invariant mass squared W^2 of the hadronic system must be greater th
GeV^2;
4. the event vertex, determined from central charged tracks, must lie within
of the nominal ep interaction point (the event vertex distribution is spre
with a FWHM of 40 cm due to the length of the proton bunches in HERA

Selection 1 eliminates the background from photoproduction in which an en
π^0 fakes a DIS electron [7]. Selection 2 ensures good containment of the electron
in the BEMC. Selection 3 ensures substantial hadronic energy flow into the H1 de
Selection 4 ensures that a meaningful determination of kinematic variables is po
Fig. 1c shows the distribution in x and Q^2 for the final sample of 88 events after
identification and rejection of 6 remaining background events (p-gas or p-bea
interaction).

For the hadron analysis only tracks other than the electron which meet the fol
requirements are used:

- they must be measured in the central tracking chamber with at least 10 hi
of a maximum of 56) and have a polar angle between 22° and 160°;
- after being constrained to the average beam position in the transverse plane
must have a transverse momentum p_T of more than 100 MeV and a frac
momentum error $\sigma(p)/p$ of less than 0.5.

The reconstruction efficiency for tracks fulfilling these conditions in our DIS san
$95 \pm 2\%$ obtained from the visual scan.

For the calorimetric measurement of the hadronic energy flow we use the c
the liquid argon and BEMC calorimeters. Electronic noise is included in the de
simulation using H1 events recorded with random triggers. After off-line reconstru
the summed contribution of the electronic noise in all LAr calorimeter cells to the e
measurement is 0.3 GeV with an *r.m.s.* of 0.9 GeV.

4 Kinematics of the DIS Events

In DIS events, kinematic variables can be determined from either the scattered ele
or the produced hadrons. A comparison of the two is a good check that the data s
the kinematic constraints of energy and momentum conservation. Such a check is

effectively carried out by comparing estimates of both the momentum transverse to the beam axis p_T and the DIS scaling variable y.

Both p_T and y are determined from the energy E'_e and polar angle θ_e of the scattered electron using the expressions

$$p_{Te} = E'_e \sin\theta_e \qquad\qquad y_e = 1 - \frac{E'_e}{E_e}\sin^2\frac{\theta_e}{2}$$

where E_e is the incident electron energy taken to be the beam energy.

For the measurement of y from the hadronic system we use the Jacquet-Blondel method [8], namely

$$y_h = \sum_{hadrons} \frac{E_h - p_{zh}}{2E_e},$$

where E_h is the energy of a hadron and p_{zh} its momentum component along the $+z$ direction. y_h can be determined either by summing over all calorimeter cells or over a combination of tracks and calorimeter cells. Since in our data sample most of the events are at low Q^2 with correspondingly low particle energies and multiplicities, we find that the combined method is more precise, and so we use it for the determination of y_h.

The electron/hadron comparison of p_T and y can be summarized by examining the means and widths of the distributions of the ratios p_{Th}/p_{Te} and y_h/y_e.

	$< p_{Th}/p_{Te} >$	r.m.s.	$< y_h/y_e >$	r.m.s.
data	0.83 ± 0.04	0.34	0.86 ± 0.04	0.31
MC	0.86 ± 0.01	0.34	0.87 ± 0.01	0.34

For the comparison of transverse momenta a cut in the electron transverse momentum of $p_{Te} > 3$ GeV is applied. p_{Th} is the negative transverse component of the hadronic momentum vector projected onto the electron direction and is measured with calorimeter energies. The ratio y_h/y_e is studied here for a subsample of events satisfying $y_e > 0.1$ to allow a good determination of y_e. The data are compared with a detailed simulation of DIS events after the same selection criteria have been applied. With our present statistics, the reconstruction of kinematics is not sensitive to the QCD model used. We conclude from these comparisons that the selected sample of DIS events is consistent with kinematic expectation. The discrepancies of the mean values of the ratios quoted above from unity are expected because, for the low Q^2 of these data, the hadronic energies are low and sometimes not visible in the LAr calorimeter. These discrepancies are however well reproduced by MC simulation demonstrating that the measurement of tracks and calorimetric energy flow in this kinematic region is well understood.

In the following, we will use the scaling variable x and the hadronic invariant mass W determined using

$$x = \frac{Q^2}{s y_h} \qquad\qquad W^2 = s y_h - Q^2 + M^2$$

where s is the ep center of mass energy (87600 GeV^2), M is the proton mass and Q^2 is obtained from the electron with

$$Q^2 = 4E'_e E_e \cos^2\frac{\theta_e}{2}\,.$$

The Lorentz transformation from the laboratory system to the hadronic center of mass (CMS) is performed using y_h and the direction and energy of the scattered electron, since this combination is relatively insensitive to QED radiation effects.

5 QCD Models and Simulation

In the comparison of our data with theoretical models, we investigate three d
prescriptions for the simulation of QCD effects in deep inelastic scattering. We
ourselves to one model for soft parton fragmentation, namely the Lund string m
implemented in JETSET [9], and to a parametrization of the proton structure f
(MRSD0 [10]) which describes data [11] at values of $x > 8 \cdot 10^{-3}$ and is consiste
our data at lower values of x [7]. The QCD prescriptions are as follows.

Leading log parton showers (PS)
In ep collisions two parton cascades are generated, one from the time-like sc
parton, and one from the space-like initial parton in the proton. The amou
hardness of the gluon radiation depend sensitively on the virtuality of the parton
and after the quark-photon vertex. In ep scattering Q^2 or W^2 or some function
can be chosen as the scale for the maximum of the allowed virtuality. In this expe
we investigate for the first time the kinematic region where $< Q^2 > \approx 15$ Ge
$< W^2 > \approx 10^4$ GeV^2, in which significantly more gluon radiation is predicted us
higher W^2 scale. For comparison with data, we have chosen the two scales
W^2. Distributions for each of these two cases we denote with PS(Q^2) and PS(W^2
corresponding events have been generated using **HERACLES** 3.1 [12] for the elect
interaction, including first order radiative corrections, followed by LEPTO 5.2
the simulation of QCD processes.

Color dipole model (CDM)
In contrast to the bremsstrahlung-like parton shower model, the CDM does not
guish between initial and final state radiation. It assumes that gluon emission
described by a chain of radiating color dipoles starting with a dipole formed b
the scattered point-like quark and the extended proton remnant. In this model
plemented in ARIADNE [15], the scale is given by the p_T^2 of the radiated glu
its maximum is proportional to $W^{4/3}$. Distributions labelled with CDM are ba
events generated with LEPTO 6.1 [14] for the electroweak interaction and photon
fusion in first order QCD, followed by ARIADNE 4.03 for parton emission in C

$O(\alpha_s)$ matrix element and parton showers (ME+PS)
Here the photon gluon fusion and gluon radiation processes are simulated usin
order α_s matrix elements, and additional softer emissions are added using the
shower model. In the approach adopted in LEPTO 6.1 [14] the maximum vir
scale is related to the first order matrix element. Distributions generated wi
program are labelled with ME+PS.

The implementations of CDM and ME+PS do not include QED radiative
tions. The requirement of $E'_e > 14$ GeV for the scattered electron implies y_e
Therefore the radiative corrections are small ($< 5\%$) for the distributions which
cuss below. This has been verified using HERACLES. The effect of choosing M
a different parametrization of the structure function which in our kinematic regi
a more steeply falling x dependence ($\propto 1/\sqrt{x}$), gives rise to changes in some
distributions of typically less than 15%. Both effects however have no impact
conclusions.

The results of the event generation are fed into the H1 detector simulation program, which is based on the GEANT package [16] and contains a precise description of the H1 geometry. The calorimetric response of this program has been extensively compared and tuned to test-beam results [17]. The resulting simulated events are subject to the same reconstruction and analysis chain as the real data.

6 Results

The distributions shown are not corrected for detector acceptance and resolution. They are compared with model calculations including a full simulation of the H1 detector. The detector effects are small because the simulated distributions differ by less than 20% from the generated ones[1]. It is important to note that in all subsequent figures each event contributes to more than one data point, and therefore that there exist correlations between data points.

In a study of experimental systematic effects the criteria for event and track selection as well as the details of the calorimetric energy reconstruction and noise suppression scheme have been varied within reasonable bounds. A possible degradation of the track momentum resolution by 10% and the calibration uncertainty of the BEMC ($\pm 2\%$ to date) have a negligible influence on the results. The biggest source of systematic error is the absolute hadronic calibration of the liquid argon calorimeter ($\pm 7\%$ uncertainty to date), which enters linearly in all calorimetric energy flow measurements. All these systematic effects are small when compared with the differences between the models which our statistical sensitivity allows us to distinguish. As a further check, all calorimetric measurements are confirmed when tracks in the central tracker only are used, though with larger error and over a smaller rapidity range.

Within the chosen acceptance cuts of the central tracker ($22° < \theta < 160°, p_T > 0.1$ GeV) we observe on average about four charged particles per event. Their distribution in transverse momentum p_T with respect to the beam axis falls steeply (fig. 2). The flow of energy measured in the calorimeter transverse to the beam axis, E_T, is shown in fig. 3a as a function of pseudorapidity $\eta = -\ln \tan \frac{\theta}{2}$. Here θ is the polar angle of the energy deposition with respect to the proton beam axis. Fig. 3b shows the flow of E_T, measured with the calorimeter in the rapidity interval $-3 < \eta < 3$, as a function of ϕ. Here ϕ is the angle in the plane transverse to the beam direction between the scattered electron and the energy deposition. We observe the current jet as collimated energy flow balancing the p_T of the electron at $\phi = \pi$.

The most natural frame to study the hadronic final state is its center of mass system (CMS). In this frame we define the z^* axis[2] as the direction of the exchanged virtual photon. In the naive quark parton model the current and target jet fragmentation regions then correspond to the $+z^*$ and $-z^*$ hemispheres. In fig. 4 the energy flow measured with the calorimeter as a function of θ^* is shown, where θ^* is the angle with respect to the $+z^*$ direction. A well collimated current jet is evident. In the

[1]This is not so for calorimetric measurements in the forward region (rapidity > 2) where the difference increases to 50% because particles at small polar angles hit the beam pipe and spray energy into the forward calorimeters.

[2]The transformed variables are denoted with a * as superscript.

hadronic CMS the distribution of particle momenta transverse to the virtual direction as function of Feynman x, $x_F = p_z^*/p_z^{*max}$ is particularly sensitive to d QCD models [2]. Here $p_z^{*max} = W/2$ is the maximum of the kinematically longitudinal momentum carried by a single particle. Fig. 5 displays the x_F distr and the mean transverse momentum squared $< p_T^{*2} >$ of the charged partic function of x_F ("seagull" plot). We are not sensitive to negative x_F because of th angle cut used in this analysis.

In all the above distributions both the ME+PS and the CDM models are agreement with the data, and are indistinguishable with the available statisti cision. Both the distributions of transverse energy (figs. 3a, b) and the width current jet (figs. 3b, 4, 5) are described correctly. However the parton shower ev with the large scale, PS(W^2), predicts too much transverse energy, and the ev with the small scale, PS(Q^2), predicts too little (figs. 3,4). The same effect is the "seagull" plot (fig. 5), where PS(W^2) is found to overestimate the averag the produced particles while PS(Q^2) underestimates it. Varying Λ_{QCD} between 800 MeV for PS(Q^2) and PS(W^2) does not lead to an adequate description of ou The prediction of the simple quark parton model without QCD corrections is fo be similar to the PS(Q^2) model and can thus also be excluded. This is true eve increase the parameter governing the p_T generated in the fragmentation proce factor of 2.

Conclusions

The hadronic final state in deep inelastic ep scattering has been measured for t time at HERA in a new kinematic domain. The data are in good agreement wit expectations. The observed widening of the current jet is described when in parton emission. The models based on first order matrix element calculation additional parton shower evolution and on color dipole radiation are both abl produce the data at the present level of statistical sensitivity without any adju of parameters from values which describe parton processes in lower energy DI The leading log parton shower approach fails if either W^2 or Q^2 is chosen as th governing the amount and hardness of gluon radiation, although an intermedia may still be compatible with our data. Forthcoming, more precise data, will allo stringent comparison as well as other QCD tests.

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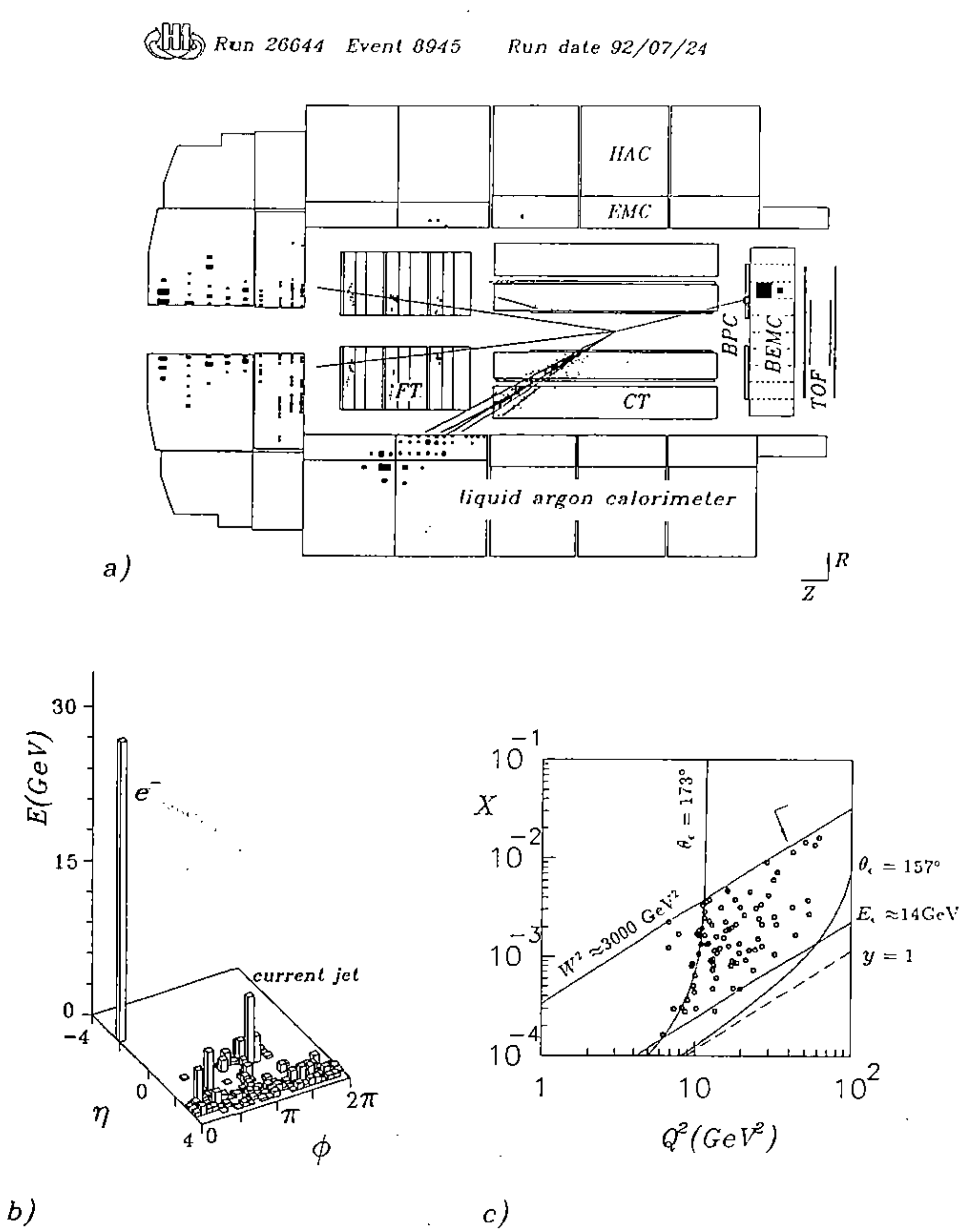
Figure 1:
A deep inelastic scattering event in the H1 detector: shown are a) side view of c
ters (EMC,HAC,BEMC), forward (FT) and central (CT) trackers, backward
tional chamber (BPC), and scintillator hodoscope (TOF), and b) energy flow
sured in the calorimeters as a function of pseudorapidity η and azimuthal ang
shows the distribution of the event sample in the x, Q^2 plane. The arrow point
event shown in a) and b). Contours of $\theta_e = 157°, 173°$ and of constant y corres
to $W^2 \approx 3000$ GeV^2, $E_e' \approx 14$ GeV and the kinematic limit ($y = 1$) are indicate

Figure 2:
Transverse momentum p_T distribution for charged particles with respect to th
axis in the laboratory frame. Superimposed are the expectations of the differen
based models. The distribution is normalized to the number of events N, and
to the number of tracks.

Figure 3:
Transverse energy flow E_T in the laboratory frame measured with the calorim
as a function of pseudorapidity η; b) as a function of azimuthal angle ϕ with
to the scattered electron direction in the plane transverse to the beam directi
predictions of the different models are also given.

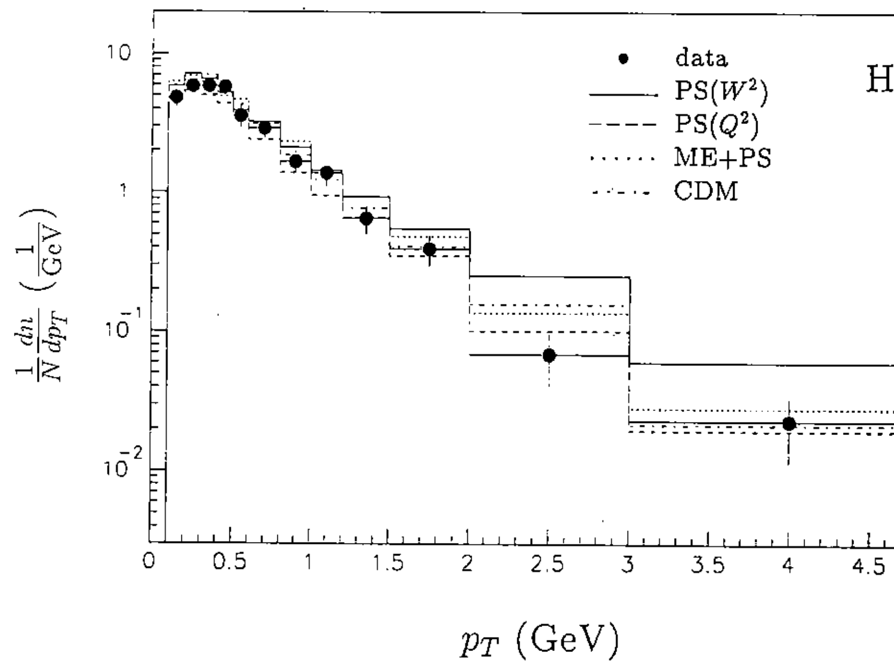
Figure 4:
Calorimetric energy flow as a function of angle θ^* with respect to the virtual
direction in the hadronic CMS. The predictions of the various models are superim

Figure 5:
a) Feynman x, x_F, distribution and b) average p_T^{*2} as a function of x_F ("seagull"
for charged particles in the hadronic CMS. The model predictions are also show



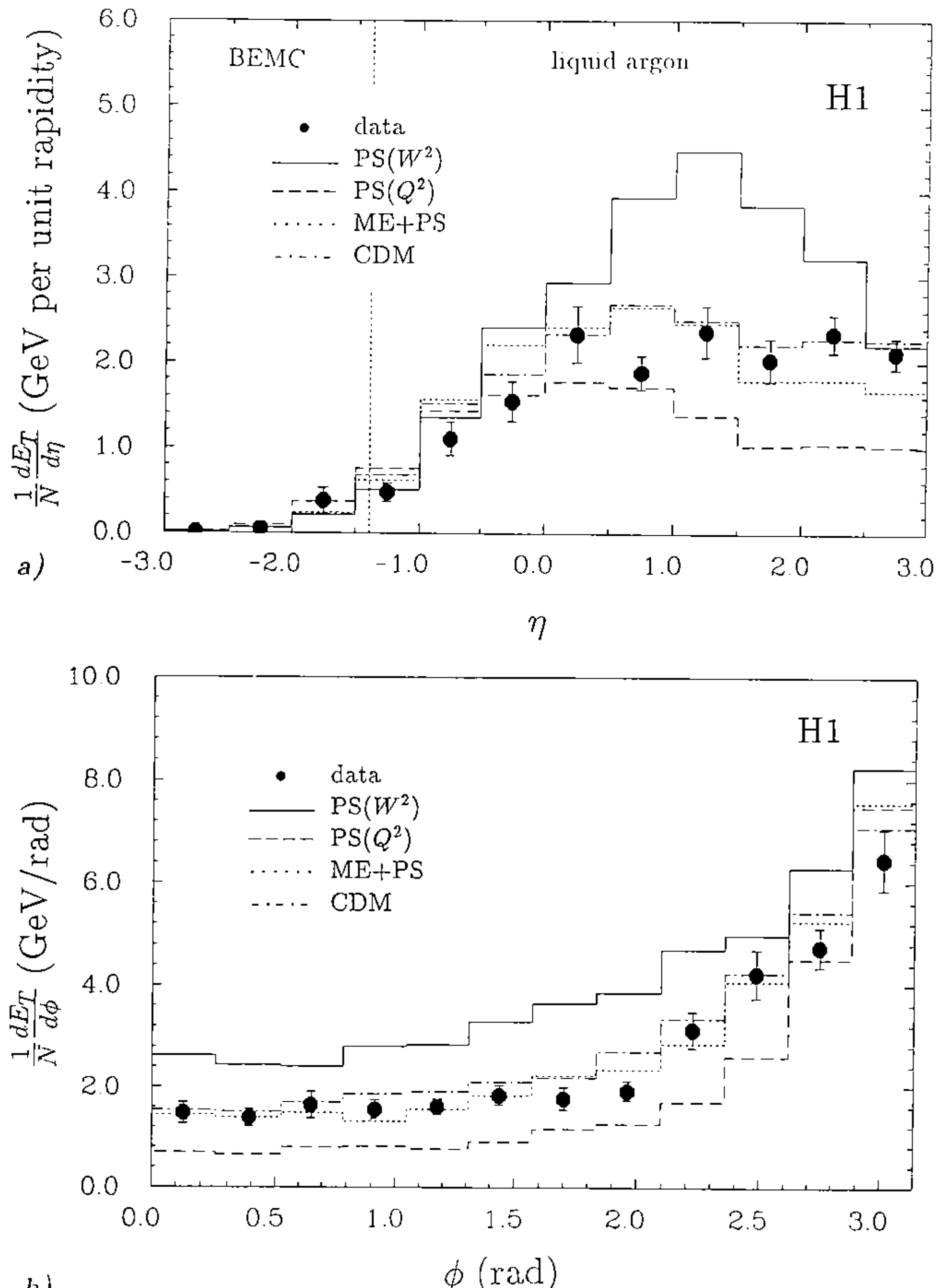
Run 26644 Event 8945 Run date 92/07/24
HAC
EMC
BPC
BEMC
TOF
FT
CT
liquid argon calorimeter
a)
R
Z
E(GeV)
30
15
0
-4
e⁻
current jet
η
0
4
0
π
2π
φ
b)
X
1
10
10²
Q²(GeV²)
W² ≈3000 GeV²
θₑ = 173°
θₑ = 157°
Eₑ ≈14GeV
y = 1
c)

Fig. 1



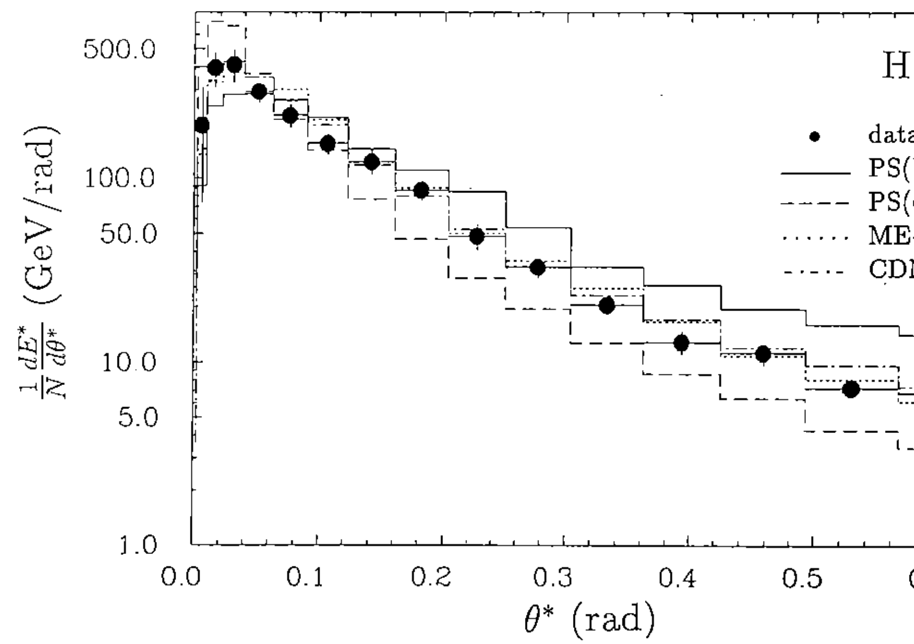
data
PS(W²)
PS(Q²)
ME+PS
CDM
H
10
1
0
0.5
1.5
2
2.5
3
3.5
4
4.5
p_T (GeV)

Fi



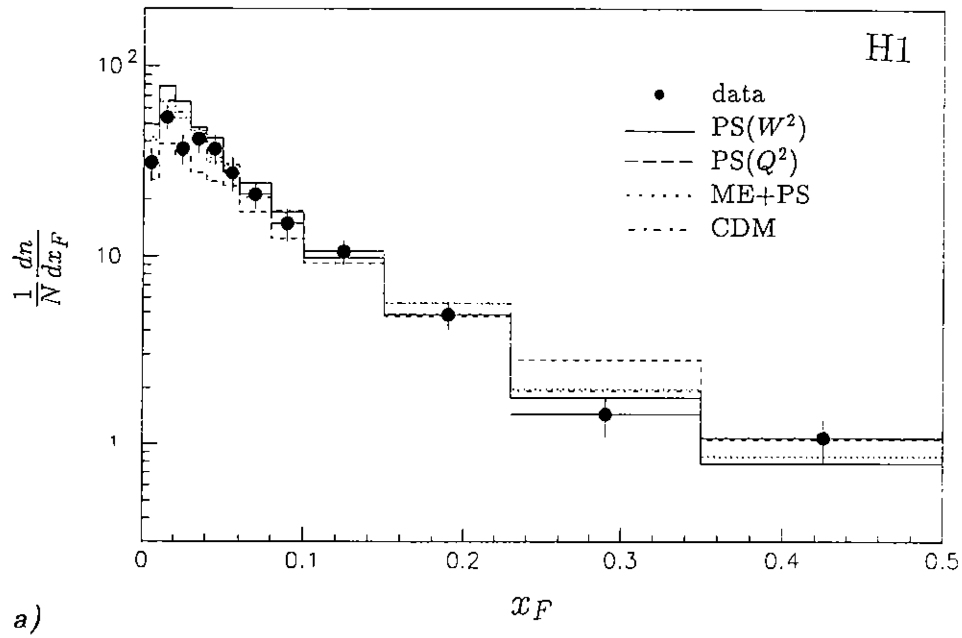
BEMC
liquid argon
H1
data
PS(W^2)
PS(Q^2)
ME+PS
CDM
$\frac{1}{N}\frac{dE_T}{d\eta}$ (GeV per unit rapidity)
η
a)
H1
data
PS(W^2)
PS(Q^2)
ME+PS
CDM
$\frac{1}{N}\frac{dE_T}{d\phi}$ (GeV/rad)
ϕ (rad)
b)

Fig. 3

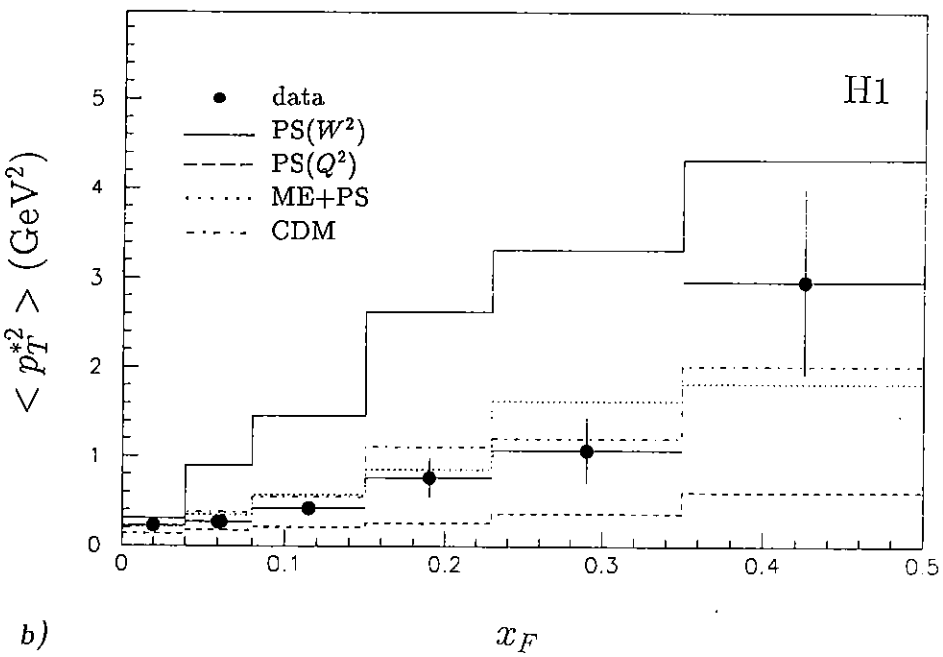


$\frac{1}{N}\frac{dE^*}{d\theta^*}$ (GeV/rad)
θ^* (rad)

Fig. 4


H1
data
PS(W^2)
PS(Q^2)
ME+PS
CDM
$\frac{1}{N}\frac{dn}{dx_F}$
10^2
10
1
0
0.1
0.2
0.3
0.4
0.5
x_F

a)


H1
data
PS(W^2)
PS(Q^2)
ME+PS
CDM
$< p_T^{*2} >$ (GeV^2)
5
4
3
2
1
0
0.1
0.2
0.3
0.4
0.5
x_F

b)

Fig. 5