FERMILAB-CONF-76-151-E

NEUTRINO-PROTON INTERACTIONS IN THE 15-FOOT BUBBLE CHAMBER AND PROPERTIES OF HADRON JETS*†

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ABSTRACT

An analysis is made on about 600 charged-current neutrino events from the Fermilab 15-foot hydrogen bubble chamber. Properties of the inclusive reaction $\nu p \to \mu^- + h^\pm +$ anything, where $h^\pm$ represents a charged hadron, are studied. Longitudinal and transverse properties of hadron jets are described. An analysis is made to see whether the hadrons carry with them the charges of their parent elementary quarks. Distributions are presented for the number of tracks, average charge, and average P_T vs. rapidity in the lab, c.m., "hole", and "quark" reference frames.

* Supported in part by the U.S. Energy Research and Development Agency.

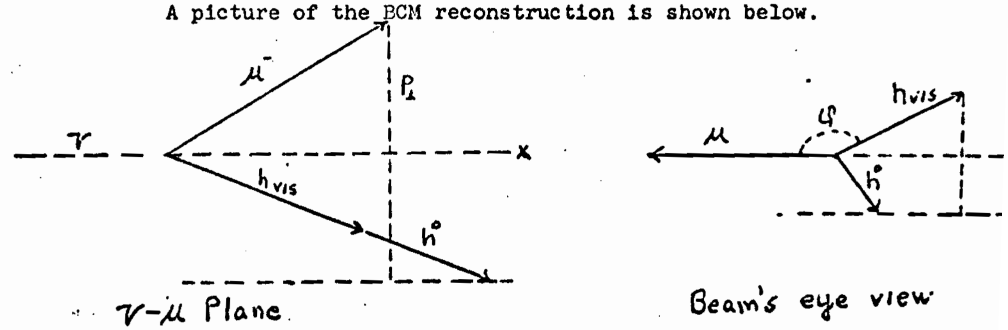
** A. Barbaro-Galtieri, G.R. Lynch, J.P. Marriner, F.T. Solmitz, M.L. Stevenson, Lawrence Berkeley Laboratory; J.P. Berge, D.V. Bogert, D.C. Cundy, F.A. DiBianca, V. Efremenko, P. Ermolov, R. Hanft, F.A. Nezrick, Y. Rjabov, W.G. Scott, W. Smart, Fermilab; M.W. Peters, R.J. Cence, F.A. Harris, S.I. Parker, V.Z. Peterson, V.J. Stenger, U. of Hawaii; C.T. Coffin, R.N. Diamond, H.T. French, W. Louis, B.P. Roe, A.A. Seidl, J. Vander Velde, U. of Michigan.

† Talk presented at the IVth International Winter Meeting on Fundamental Physics, Salardú, Spain (1976).

I will report on certain features of νp charged-current interactions from about 700 events found in an exposure of 70,000 pictures in the Fermilab 15-foot hydrogen chamber exposed to a wide-band horn-focused neutrino beam. Several results from this same set of data have already been presented(1) and published(2-6) elsewhere. We must begin by expressing our appreciation to the large number of colleagues listed on page 1 who are responsible for the collection and analyses of these data. (They cannot be held responsible for what I will say about it however.)

We use the so-called BCM method(7,8) to extract the deep-inelastic parameters E_ν, Q^2, and invariant mass W in the reaction $\nu p \to \mu^- + W$. The neutrino direction is accurately known as the μ^- momentum measured for each event. The unseen neutral particles, if there are any, we assign a momentum whose component in the μ-ν plane is assumed to lie in the same direction as that of the visible hadrons. One then balances transverse momentum in and perpendicular to the plane and thereby obtains the deep-inelastic parameters. The BCM assumption seems entirely justified since, as we'll see, the individual hadrons have typically small transverse momentum compared to their longitudinal momentum along the overall hadron direction.

A picture of the BCM reconstruction is shown below.



The angle φ will be used to select an enriched sample of charged current events which is about 85% pure[1]. For our present analysis we will define the μ^- as the highest $P_\perp$ non-interacting negative. The additional information provided by the External Muon Identifier has only recently been incorporated and will not be used in the present analysis.

The distribution in angle φ is shown in Figure 1. The uniquely large transverse momentum of the μ^- reflects itself in the sharply peaked φ distribution. We will henceforth consider only the 585 events in the charged-current sample which we define by $\varphi > 90°$. If we take the events in this sample and, neglecting the μ^-, plot the φ' opposite the next highest $P_\perp$ hadron, we get the dotted curve. This presumably shows the shape of the misinterpreted φ that neutral current events will give and gives a picture of the background from this source. (Neutral current events are about 1/4 of the total events).

We turn now to the properties of the individual hadrons produced in the inclusive reaction

$$\nu\, p \rightarrow \mu^- + h^\pm + x$$

Figure 2 shows how the $h^\pm$ from a sample of high mass events distribute themselves, their charge, and their average $P_\perp$ vs. their rapidity in the overall hadronic c.m. Note that 208 out of 585 events survive the cut $S = W^2 > 25\ \text{GeV}^2$. The open circles have the same size error bars as the solid circles above them, and the area under the open circles represents the net charge (+2) of the hadronic system. We expect an average of about 0.5 protons per event, or 104 protons, in these high-s events whereas we see only 33. The rest we assume escaped identification because they went out of the bubble chamber and were too fast to be identified by ionization. These particles were thus misidentified as π^+, which means they have been assigned a rapidity which is ~ 1.0 units too large on the average. The identified protons are shown separately so that the reader can use their position to approximately correct for the misidentified ones. An interesting feature of Figure 2b is the dotted curve, which comes from 102 GeV/c pp data[9]. There appears to be a remarkable similarity between the kinematic properties of the hadrons produced in these completely different reactions if one takes in both cases the rapidity axis along the direction of the total hadronic momentum in the target rest frame.

Figure 3a shows the particle and charge distribution vs. the variable $Z_\parallel$. We define $Z_\parallel$ as the fraction of total longitudinal momentum in the $\nu\,\mu$ plane carried by the individual charged hadrons. For $Z_\parallel \gtrsim 0.2$ this corresponds to the hadronic scaling parameter X of Feynman. We see no evidence here of a leading charge effect which might arise in the collision of the virtual W^+ (intermediate boson) with the proton. The selection $Q^2 > 8\ \text{GeV}^2$ was made in order to separate the effects of the fragmenting target proton into the small Z region. Plotting $< P_\perp >$ vs. $Z_\parallel$ (Figure 3b) we see the fall-off near $Z_\parallel = 0$, which is similar to that in Figure 2b, and is no doubt due to the proximity of the kinematic boundary. There appears to be no evidence for any abnormal behavior in the large Z "current fragmentation" region. (See also Figure 11b concerning this point).

It seems apparent from Figures 2 and 3 that we are dealing with high mass states of hadronic matter given a sudden impulse by the weak interaction. The asymptotic particles produced have transverse momenta which are generally small compared to their longitudinal momenta along their total direction in the target rest frame. We can define these states as single "jets" whose charge, baryon number, 4-momentum, etc., are known and see if similar states are produced in electroproduction, e^+e^- annihilation and high P_T hadron-hadron collisions.

The way in which the particles in the jet share the longitudinal lab momentum is shown in Figure 4. It appears that the highest $P_\parallel$ particle takes(50 ± 20)%of the total, the next highest(25 ± 10)%,etc. (The peak at $Z_\parallel^\pm = 1$ in the "1st plus 2nd" curve is due to events with only two visible hadrons). These data may be of interest to people designing and doing experiments with jets produced in other types of reactions.

We turn now to a subject which could be dubbed "virtual quark hunting". According to standard ideas the virtual intermediate boson W^+ of the weak $\Delta S = 0$ interaction changes a down-quark in the proton into an up-quark, i.e. $W^+ + d \to u$. The quarks don't actually materialize, but recombine in such a way so as to produce the particles we see. This process is shown schematically in Figure 5 where we show the various momentum vectors in the Breit frame in which the u and d quarks have equal but opposite momentum. (This is also the frame in which the virtual W^+, whose 4-momentum squared is Q^2, has zero energy).

The questions is: Do the particles we see carry with them any of the quantum numbers of the elemental quarks? Are the characteristics of the current fragments, such as the height of the rapidity plateau or the average P_T, any different than those of the target fragments? The theoretical aspects of such questions have been discussed in the literature.[10] The shape of the rapidity distribution might be expected to look like the limousine shown in Figure 6. If the rapidity intervals $\ln(S/Q^2)$ and $\ln(Q^2/M^2)$ (M is the target mass) are large enough, and the hadrons retain the charge or isospin of their parent quarks, then we would expect the +2 units of charge in each event to accumulate, on the average, in the three areas shown. There seems to be unanimity in the literature that the charge of the W^+ should be split evenly between the "Hole" and "Quark" regions rather than 1/3 and 2/3 as expected from the elementary quark charges. This is a refinement which cannot be illuminated by our present data. In any case we expect the 1/2, 1/2 split when $S/Q^2 = 1/x + M^2/Q^2 - 1 \approx 1/x$ becomes large, since at $x = 0$ there should be equal amounts of the two reactions $W^+ + d \to u$ and $W^+ + \bar{u} \to \bar{d}$.

Since the events cover a wide range of the variables S and Q^2 we will plot the data in such a way that we line up only one of these areas of charge accumulation at a time. Figure 7 gives the distribution of particles and net charge $\langle q_\cdot \rangle$ vs. laboratory rapidity. We have made the selection $S/Q^2 > 8$ in order to keep the Hole region more than two rapidity units away. The accumulations in the Hole and Quark regions will be smeared out on this plot but the Lab (proton) region should show an accumulation of +1 unit of charge below $Y_{Lab} \lesssim 1.0$. That is, half of the area under the open circles should be in a peak with $Y_{Lab} \lesssim 1.0$, with a long tail extending out to large Y values containing the other half. The data are in reasonable agreement with this expectation provided we take account of the unidentified protons. Assuming an average of .5 protons per event we expect about 214/2 - 59 = 48 misidentified protons lying about $\Delta Y = 1$ unit to the right of the identified ones. Transferring these back by $\Delta Y = -1$ unit makes the resulting $< q >$ distributions look as expected. This can be seen more qualitatively in Figure 8a where corrections to each point have been made based on the above assumptions about missing protons. For $S/Q^2 > 8$, we see reasonable agreement with the expectation $< q > = 1.0$.

We next move to plotting the tracks, charge, and $<P_T>$ vs. the rapidity in the Hole frame (Figure 9), where $Y_{Hole} = Y_{Lab} - \ell n\ (S/Q^2)$. We have made the cuts $Q^2 > 4$ GeV^2 and $S/Q^2 > 4$ in order to remove the effects of the Lab and Quark regions. Unfortunately the data become very sparse if we make both $Q^2 > 8$ GeV^2 and $S/Q^2 > 8$. This can be seen in Figure 8b where we've required $Q^2 > 8$ GeV^2 and plotted the net charge in the Hole region vs. S/Q^2, and in Figure 10a where we've required $S/Q^2 > 8$ and plot vs. Q^2. In each case the dotted curves represent our simplest expectations of what the data should look like if the particles we see reflect the charge of their quark parentage.

Continuing on to the Quark frame, we plot in Figure 11 these same quantities vs. $Y_{Quark} = Y_{Lab} - \ell n\ (S/M^2)$. It is of interest to note in Figure 11b that $< P_T >$ in the current fragmentation region ($Y_{Quark} > -1.0$) behaves much as it does in the target fragmentation region (Figure 7b) for $Y_{Lab} < 1.0$. Apparently a fragmenting W^+ behaves much like a fragmenting proton in terms of rapidity, charge, and $< P_T >$ distributions.

In Figure 10b we plot, for $S/Q^2 > 8$, the average charge to the right of $Y_{Quark} = -1.0$ vs. Q^2. The data are in reasonable agreement with our simplest expectations, at least neglecting the somewhat contrary downward trend of the three points with $Q^2 > 8$ GeV^2.

It is expected that more definitive answers to these questions can be obtained with the ten-fold increase in data which will eventually come in this experiment. Maybe then we'll be able to trade in our present "limousine" (Figure 12) for one of those deluxe models shown in Figure 6.

I am indebted to R. Cahn for an illuminating discussion about limousines, etc. I want to express my appreciation to A. Ferrando and the organizers of the conference for an interesting and enjoyable meeting.

References

(1) Study of Charged Current Neutrino Interactions in Hydrogen at Fermilab Energies, paper presented by F.A. Nezrick at the 1975 Neutrino Conference, Balatonfüred, Hungary. Neutrino Interactions on Protons at Fermilab Energies, paper presented by B.P. Roe at the 1975 Meeting of the European Physical Society, Palermo, Sicily. Neutrino-Proton Interactions in the Fermilab 15-foot Bubble Chamber, paper presented by B.P. Roe at the 1975 International Symposium on Lepton and Photon Interactions, Stanford, California. Neutrino-Proton Interactions in the Fermilab 15-foot Bubble Chamber, paper presented by F.A. DiBianca at the 1975 D.P.F. Meeting of the American Physical Society, Seattle, Washington. (To be published in A.I.P. Conference Proceedings).

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(4) J.P. Berge et al., Phys. Rev. Letters 36, 127 (1976)

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(8) G. Myatt, ECFA 300 GeV Working Group Proceedings, Vol. II, p. 117.

(9) Inclusive and Semi-Inclusive Pion Production in PP Collisions at 102 GeV/c and 400 GeV/c, C. Bromberg et al., University of Rochester Report UR-563, University of Michigan Report UMBC-76-2 (1976) (to be published in Nuclear Physics).

(10) R.P. Feynman, Neutrino Conference, Balatonfüred, Hungary (1972); J.D. Bjorken, Phys. Rev. D7, 282 (1973); G.R. Farrar and J.L. Rosner, Phys. Rev. D7 2747 (1973); R.N. Cahn and E.W. Colglazier, Phys. Rev. D9 2658 (1974); G.R. Farrar and J.L. Rosner, Phys. Rev. D10 2226 (1974).

Figure Captions

Figure 1. The φ and φ' distributions (see text) for all events with $\Sigma P_x > 5$ GeV/c. The charged-current sample is defined by $\varphi > 90°$.

Figure 2. Distribution of (a) charged tracks (solid circles) and net charge (open circles), and (b) $< P_T >$ vs. rapidity in the c.m. frame of the recoiling hadrons. The dotted curve in (b) comes from 102 GeV/c pp collisions. The neutrino data has the selection S (invariant hadronic mass-squared) > 25 GeV^2.

Figure 3. Distribution of (a) charged tracks and net charge, and (b) $< P_T >$ vs. $Z_\parallel$ in the lab. $Z_\parallel$ is the longitudinal momentum of a hadron divided by the total hadronic momentum.

Figure 4. Distribution of $Z_\parallel^\pm$ for the charged hadron with the largest longitudinal momentum, 2nd largest, and their sum. In $Z_\parallel^\pm$ the denominator is the sum of the longitudinal (ν-μ plane) charged hadron momentum components.

Figure 5. Momentum components of various real and virtual particles in the Breit frame. (See text).

Figure 6. The shape of the rapidity distribution as envisioned by various people riding therein. (See references 10).

Figure 7. Distribution of (a) charged tracks and net charge, and (b) $< P_T >$ vs. rapidity in the laboratory frame. The dotted curves are simply to guide the eye, and must be corrected for misidentified protons. (See text).

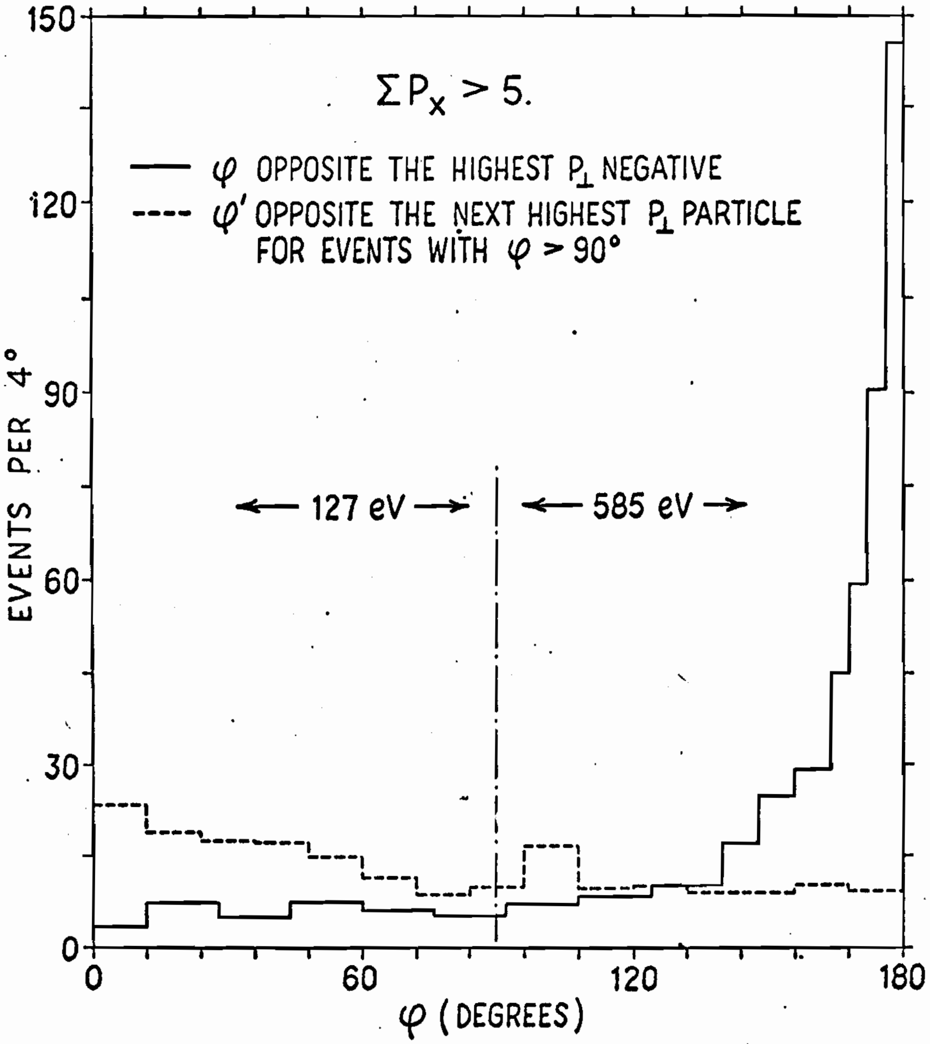
Figure 8. (a). Average charge per event which lies within $Y_{Lab} < 1.0$. The solid circles are the raw data and the open circles after correcting for misidentified protons (see text). The dotted curves in this and Figure 10 represent the simplest expectations of the quark model. (b) Similar to (a) but in the Hole frame.

Figure 9. Distribution of (a) charged tracks and net charge, and (b) $< P_T >$ vs. rapidity in the Hole frame.

Figure 10. Captions are self explanatory. Dotted curves and open circles are explained in Figure 8.

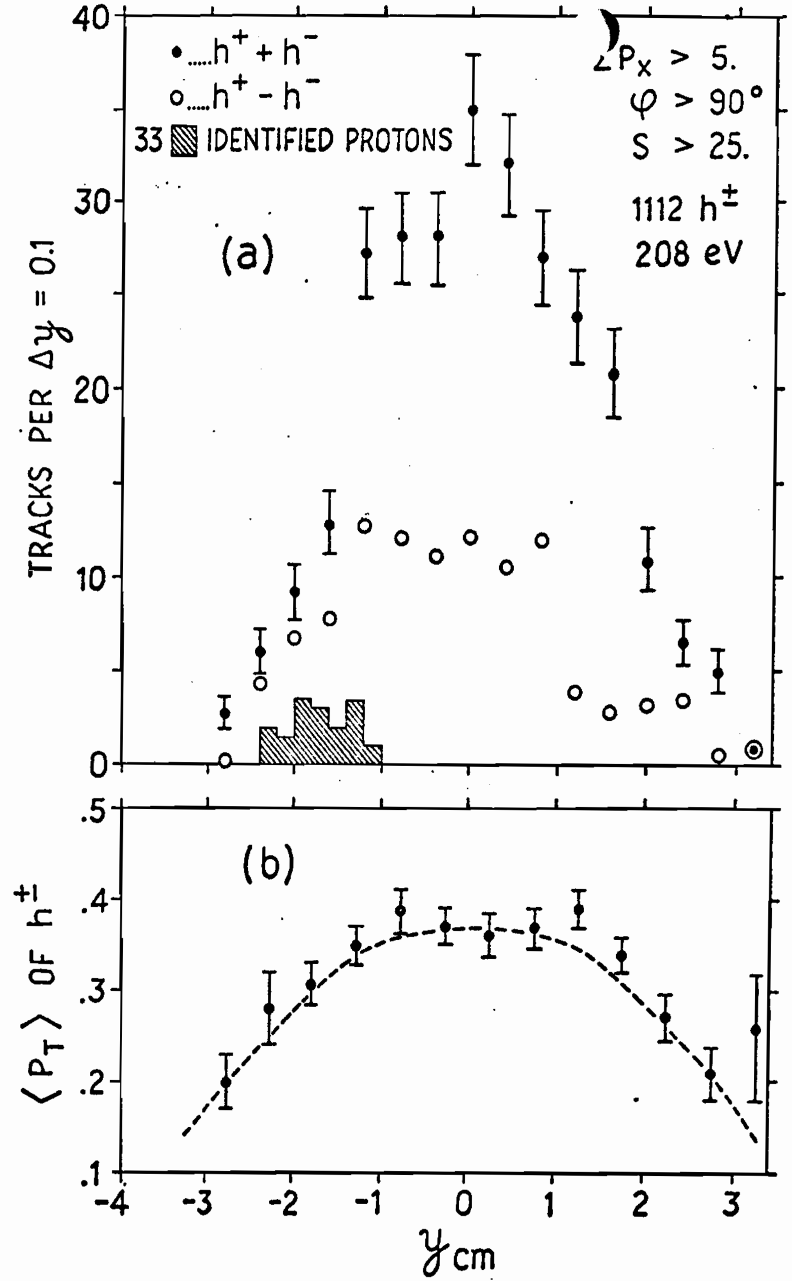
Figure 11. Distribution of (a) charged tracks and net charge, and (b) $< P_T >$ vs. rapidity in the Quark frame.

Figure 12. What Figure 6 looks like to an experimentalist.



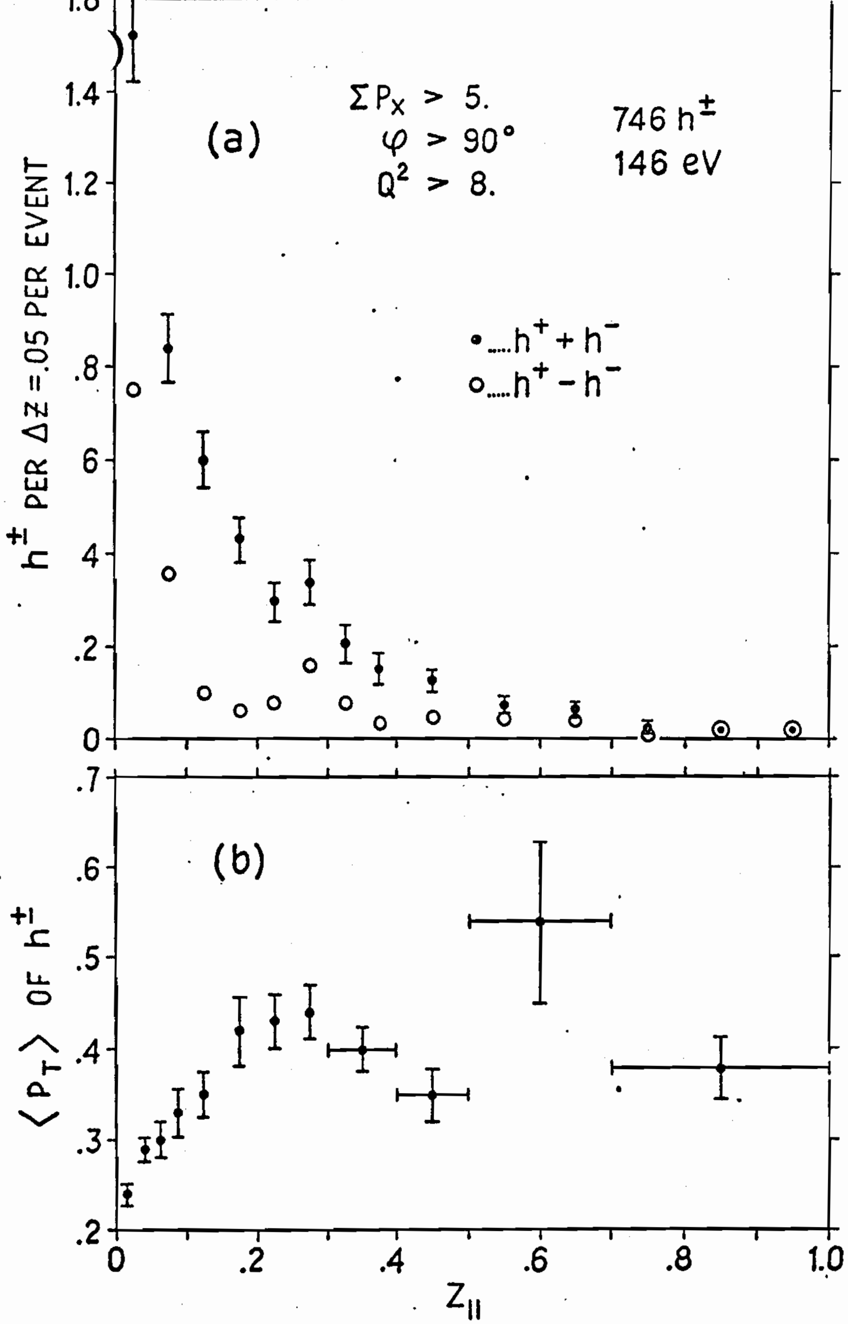
$\Sigma P_x > 5.$
φ OPPOSITE THE HIGHEST $P_\perp$ NEGATIVE
φ' OPPOSITE THE NEXT HIGHEST $P_\perp$ PARTICLE FOR EVENTS WITH φ > 90°
← 127 eV →
← 585 eV →
EVENTS PER 4°
φ (DEGREES)

Fig. 1



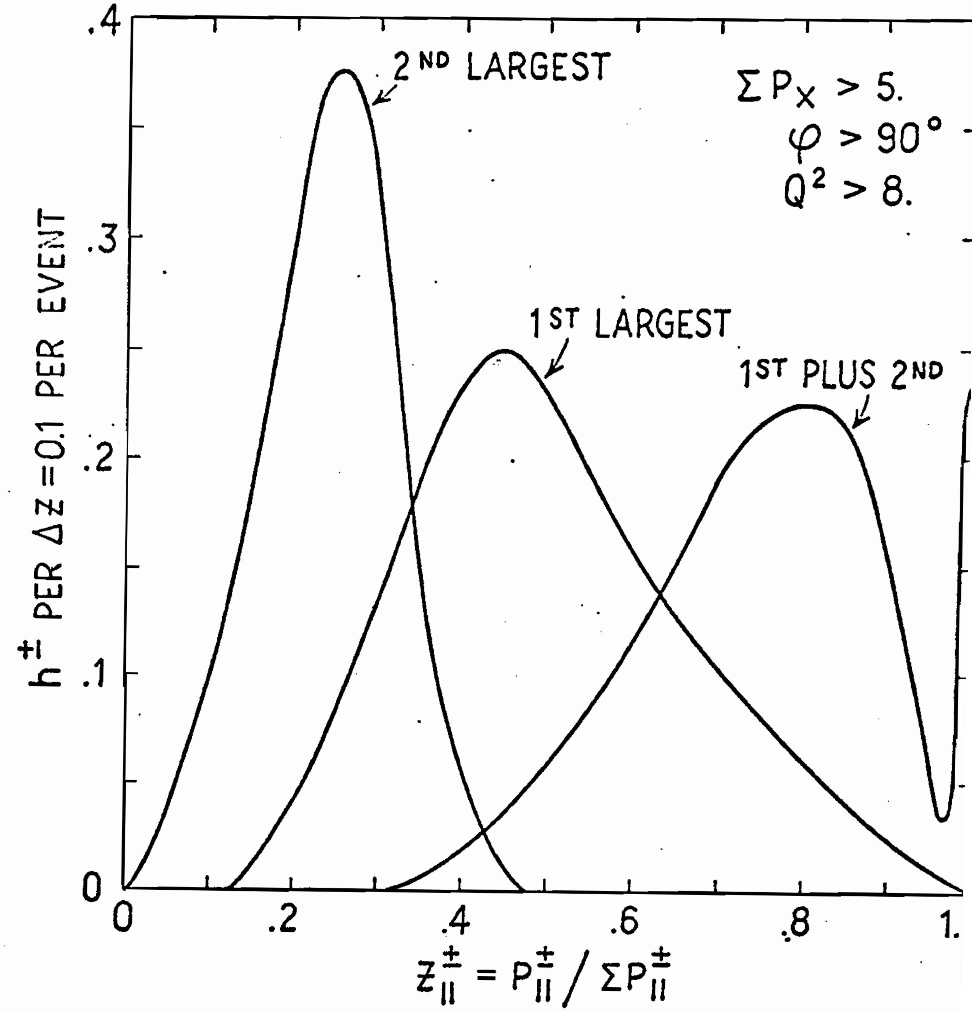
• $h^+ + h^-$
○ $h^+ - h^-$
33 IDENTIFIED PROTONS
$\Sigma P_x > 5.$
φ > 90°
S > 25.
1112 $h^\pm$
208 eV
(a)
TRACKS PER Δy = 0.1
(b)
$\langle P_T \rangle$ OF $h^\pm$
y_{cm}

Fig. 2



(a)
ΣPx > 5.
φ > 90°
Q2 > 8.
746 h±
146 eV
•....h+ + h−
○....h+ − h−
h± PER Δz = .05 PER EVENT
(b)
⟨PT⟩ OF h±
Z∥

Fig. 3



2ND LARGEST
1ST LARGEST
1ST PLUS 2ND
ΣPx > 5.
φ > 90°
Q2 > 8.
h± PER Δz = 0.1 PER EVENT
z∥± = P∥± / ΣP∥±

Fig. 4

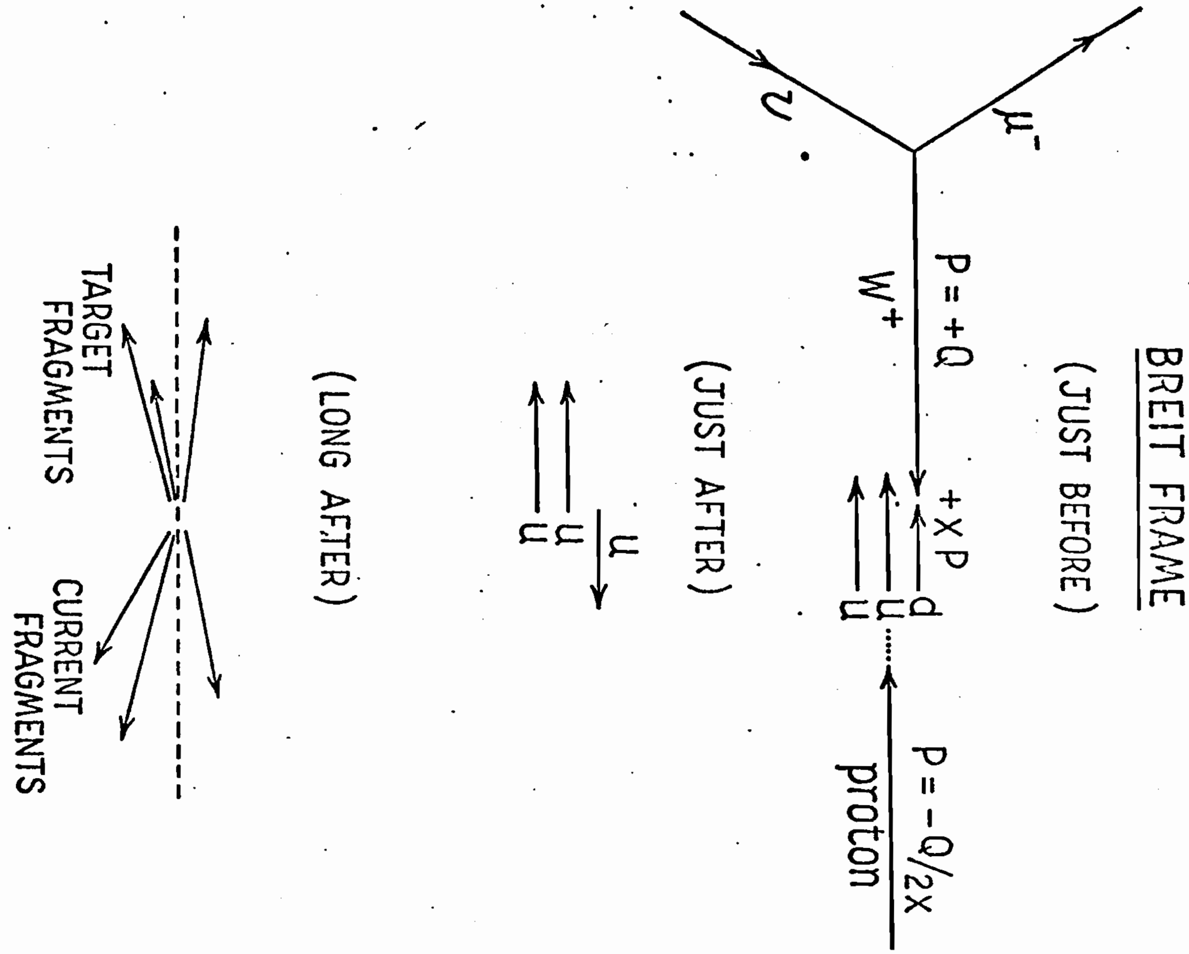

BREIT FRAME
(JUST BEFORE)
ν
μ⁻
P = +Q
W⁺
+xP
d
u
u
P = −Q/2x
proton
(JUST AFTER)
u
u
u
(LONG AFTER)
TARGET FRAGMENTS
CURRENT FRAGMENTS

Fig. 5

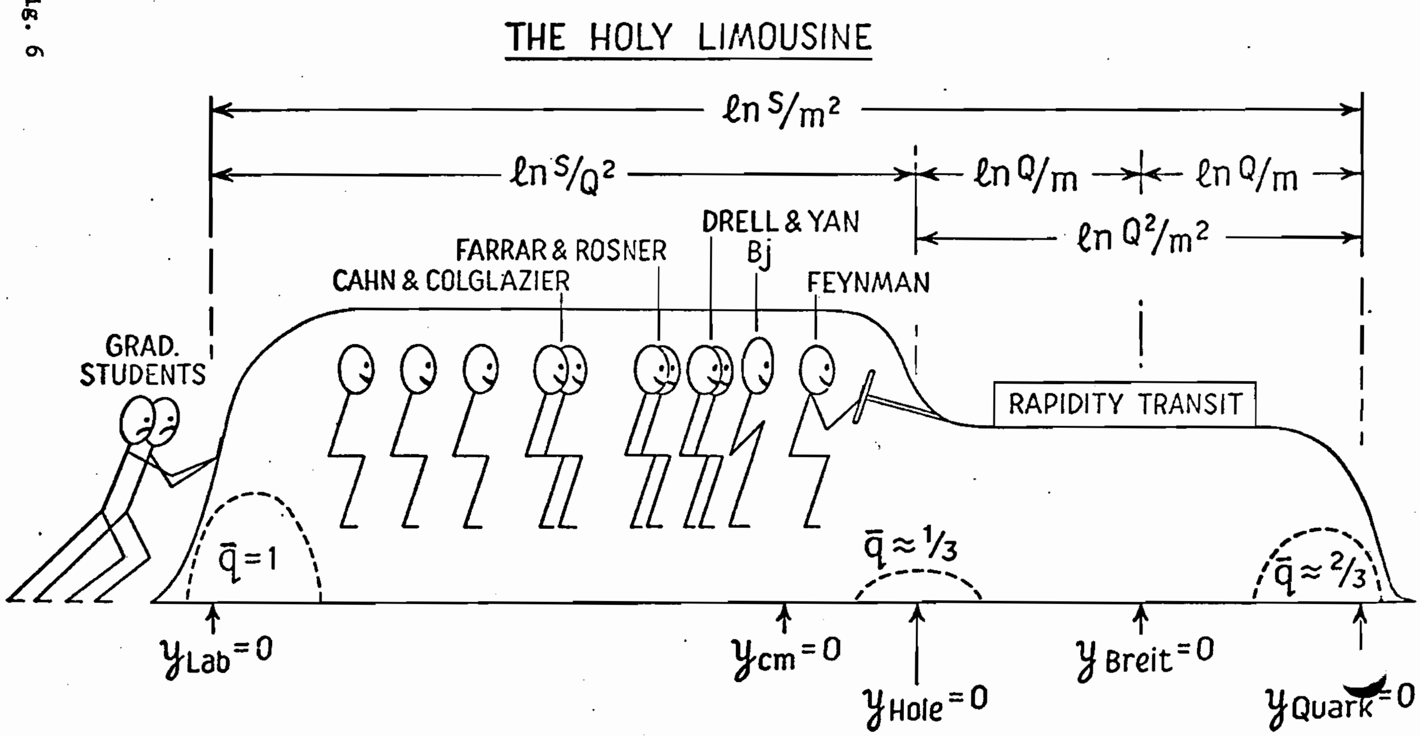
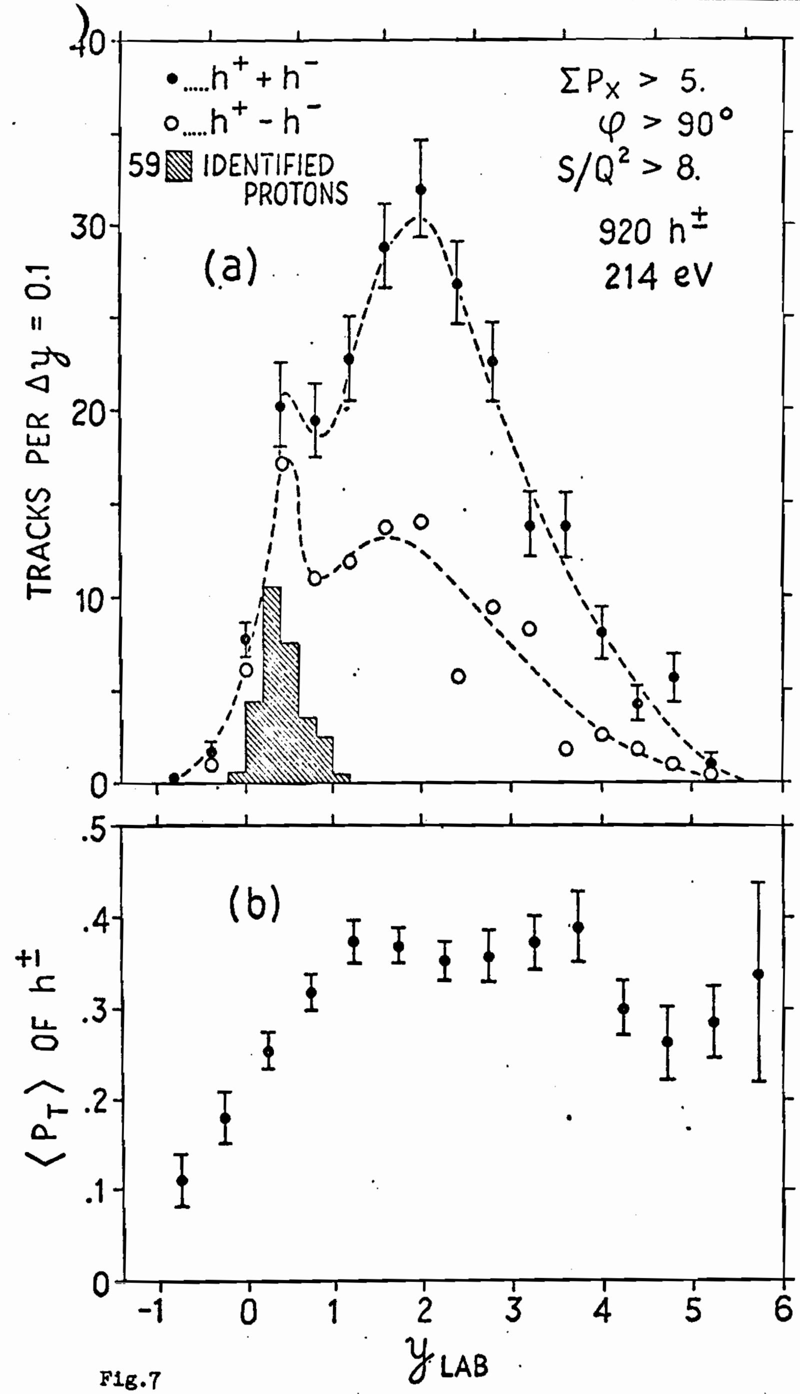
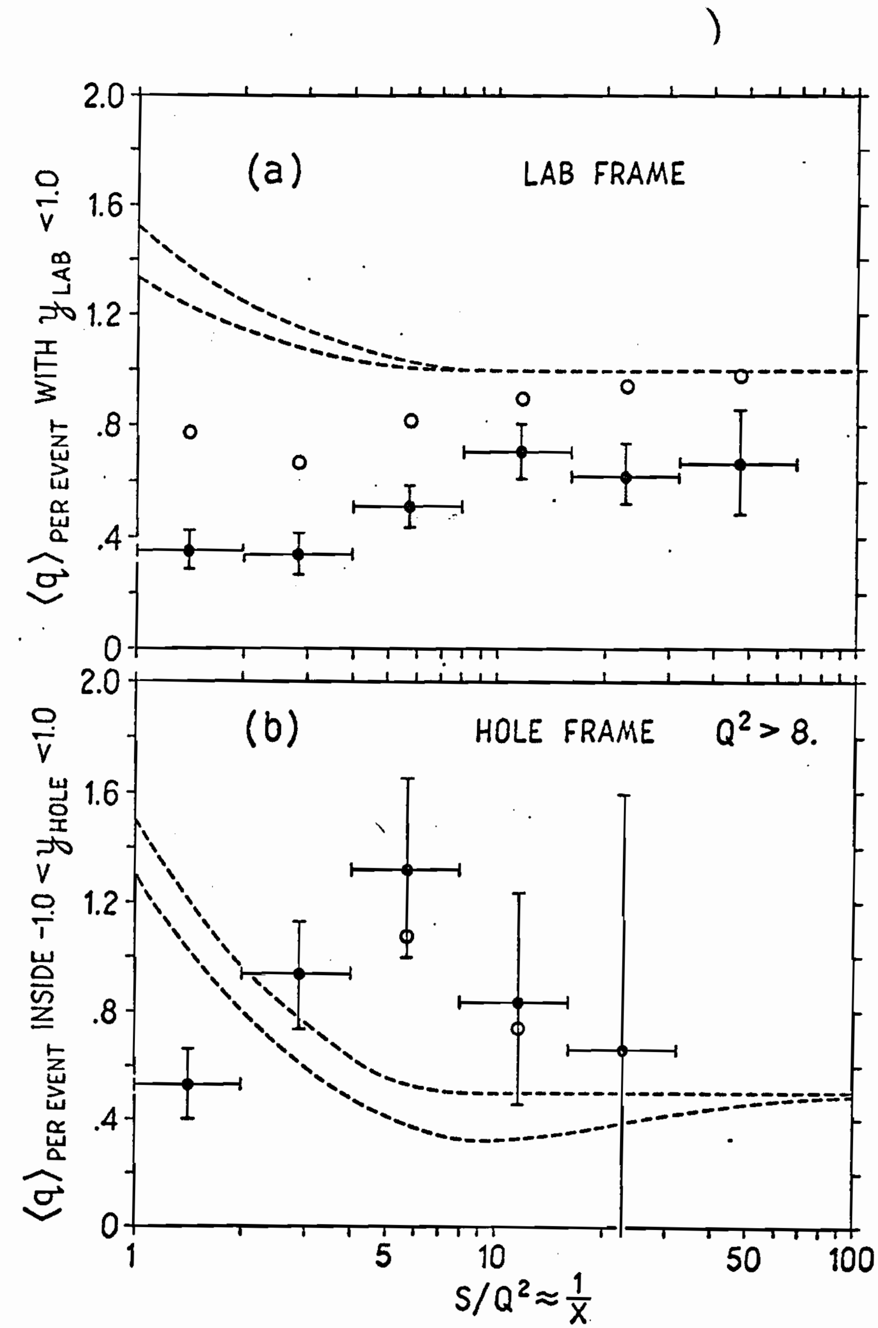

THE HOLY LIMOUSINE
ℓn s/m²
ℓn s/Q²
ℓn Q/m
ℓn Q/m
ℓn Q²/m²
DRELL & YAN
Bj
FARRAR & ROSNER
CAHN & COLGLAZIER
FEYNMAN
GRAD. STUDENTS
RAPIDITY TRANSIT
q̄ = 1
q̄ ≈ 1/3
q̄ ≈ 2/3
y_Lab = 0
y_cm = 0
y_Hole = 0
y_Breit = 0
y_Quark = 0

Fig. 6



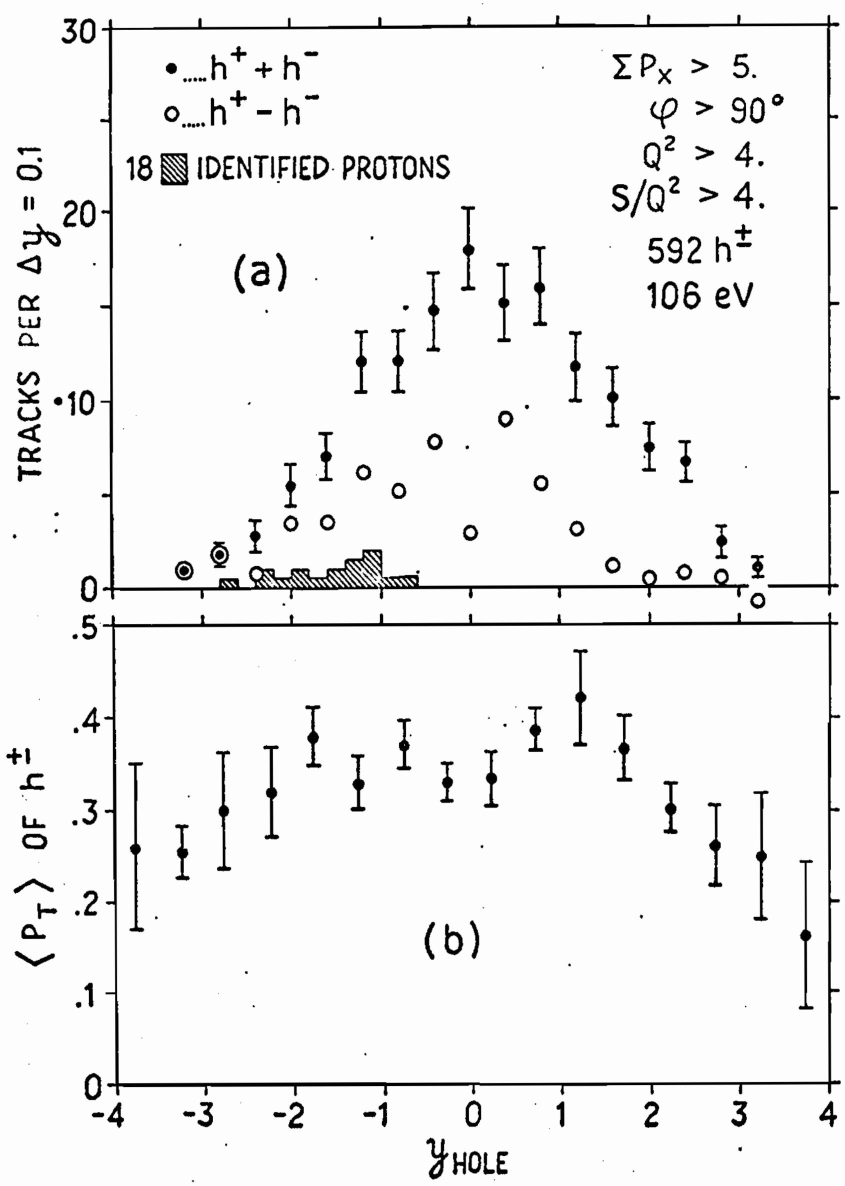
•.....h⁺ + h⁻
○.....h⁺ - h⁻
59 IDENTIFIED PROTONS
ΣP_X > 5.
φ > 90°
S/Q² > 8.
920 h±
214 eV
(a)
TRACKS PER Δy = 0.1
(b)
⟨P_T⟩ OF h±
y LAB

Fig.7



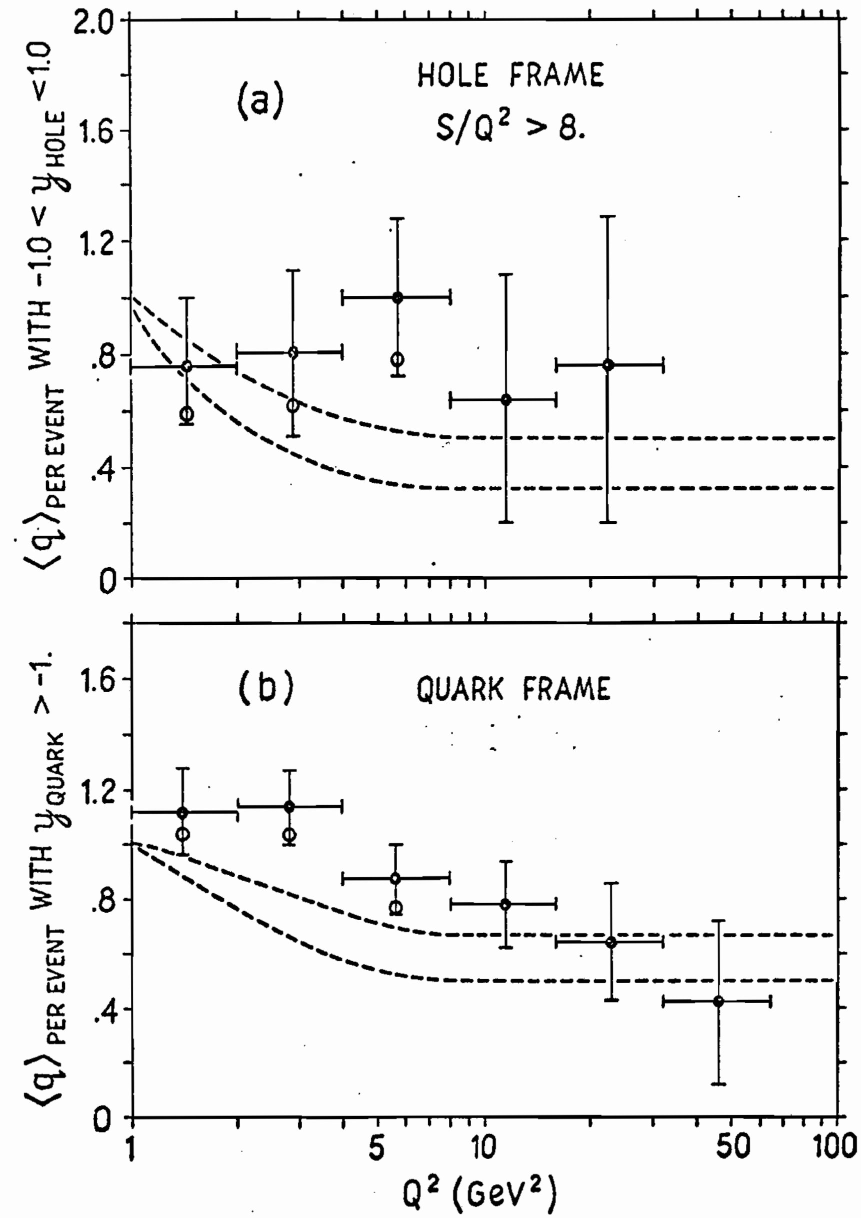
(a)
LAB FRAME
⟨q⟩ PER EVENT WITH y LAB <1.0
(b)
HOLE FRAME
Q² > 8.
⟨q⟩ PER EVENT INSIDE -1.0 < y HOLE <1.0
S/Q² ≈ 1/X

Fig. 8



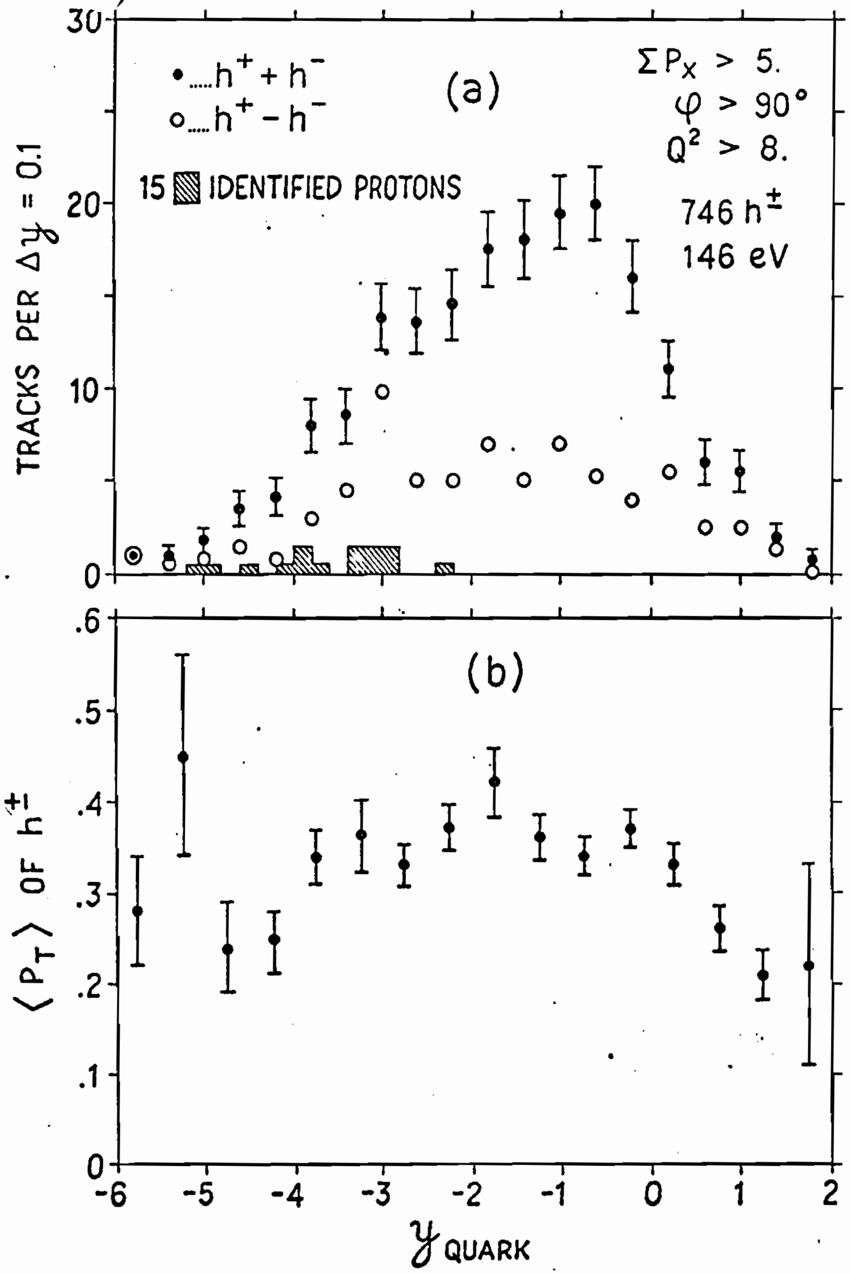
•.....h⁺ + h⁻
○.....h⁺ − h⁻
18 IDENTIFIED PROTONS
ΣPx > 5.
φ > 90°
Q² > 4.
S/Q² > 4.
592 h±
106 eV
(a)
(b)
TRACKS PER Δy = 0.1
⟨PT⟩ OF h±
yHOLE

Fig. 9



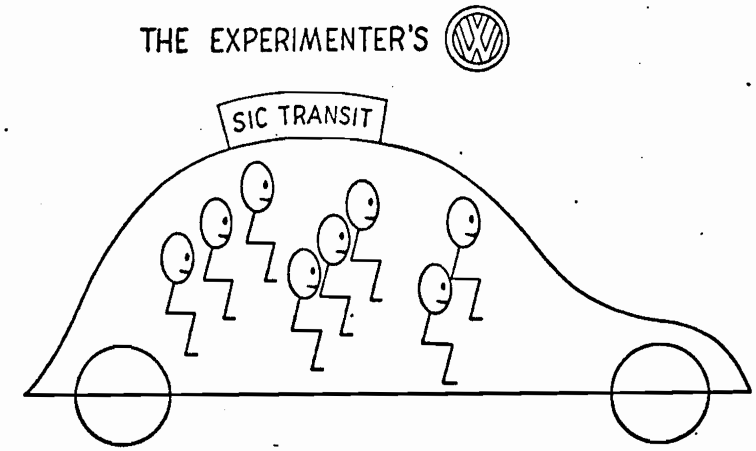
(a)
HOLE FRAME
S/Q² > 8.
⟨q⟩ PER EVENT WITH −1.0 < yHOLE < 1.0
(b)
QUARK FRAME
⟨q⟩ PER EVENT WITH yQUARK > −1.
Q² (GeV²)

Fig.10



30
20
10
0
TRACKS PER Δy = 0.1
•.....h⁺ + h⁻
o.....h⁺ − h⁻
(a)
ΣPx > 5.
φ > 90°
Q² > 8.
15 IDENTIFIED PROTONS
746 h±
146 eV
.6
.5
.4
.3
.2
.1
0
⟨PT⟩ OF h±
(b)
-6 -5 -4 -3 -2 -1 0 1 2
y QUARK

Fig. 11



THE EXPERIMENTER'S
SIC TRANSIT

Fig. 12