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MEASUREMENT OF THE RATIO OF NEUTRAL TO CHARGED CURRENT CROSS SECTIONS OF NEUTRINO INTERACTIONS IN HYDROGEN

Aachen-Bonn-CERN-Munich-Oxford Collaboration

J. Blietschau, H. Grässler, W. Krenz, D. Lanske, R. Schulte and H.H. Seyfert
III. Physikalisches Institut der Technischen Hochschule, Aachen, Germany

K. Böckmann, P. Checchia, C. Geich-Gimbel, H.G. Heilmann, T. Kokott,
B. Nellen and R. Pech
Physikalisches Institut der Universität Bonn, Bonn, Germany

P. Bosetti[1], D.C. Cundy, A. Grant, D. Haidt[2], P.O. Hulth, G. Kellner,
H. Klein, D.R.O. Morrison, L. Pape, Ch. Peyrou, P. Schmid, W.G. Scott,
H. Wachsmuth and E. de Wolf[3]
CERN, European Organization for Nuclear Research, Geneva, Switzerland

M. Aderholz, N. Schmitz, R. Settles, K.L. Wernhard and W. Wittek
Max-Planck-Institut für Physik und Astrophysik, Munich, Germany

P. Cartwright, R. Giles, P. Grossmann, R. McGow, G. Myatt,
D. Radojicic, P. Renton and B. Saitta
Department of Nuclear Physics, University of Oxford, Oxford U.K.

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1 CERN Fellow from III. Physik. Inst. Aachen.

2 Now at DESY, Hamburg.

3 From Inst. Kernphys. Onderzoek, Amsterdam.

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ABSTRACT

The ratio R_p of the neutral current to charged current cross sections has been measured in the BEBC bubble chamber filled with hydrogen and exposed to the CERN SPS Wideband Neutrino Beam. It is found that an event selection in terms of the transverse momentum of the hadronic system is very effective in reducing backgrounds and enables R_p to be determined with an error of less than 10%. Combining the results from hydrogen and isoscalar targets, the individual values of the coupling constants u_L^2 and d_L^2 are determined separately to be $u_L^2 = 0.15 \pm 0.05$ and $d_L^2 = 0.17 \pm 0.07$. The results are compatible with the standard SU(2) × U(1) model. The value of $\sin^2\theta_W$ determined from this experiment is 0.19 ± 0.03.

We report on a measurement of the ratio R_p of neutral current (NC) to charged current (CC) cross sections for neutrino interactions on protons. Using this ratio and the values of σ_{NC}/σ_{CC} for ν and $\bar{\nu}$ interactions on isoscalar targets [1,2], the magnitude of the neutral current couplings to u and d quarks can be determined [3]. The only published measurement of R_p, namely 0.48 ± 0.17, [4] does not reach the precision required to put significant constraints on the couplings. In the present experiment, R_p is determined to better than 10%.

The experiment was carried out in the CERN SPS Wideband Neutrino Beam, obtained from 350 GeV protons. A total of about 285 000 pictures were taken in the bubble chamber BEBC filled with hydrogen. The pictures were double-scanned for events with at least three charged tracks. The chamber was equipped with a two-plane External Muon Identifier (EMI) [5]. The subsample used for this analysis consists of 2750 events with an EMI identified muon with momentum $p^{\mu} > 3$ GeV/c (CC events) and 3900 events were no muon was detected (NC candidates), both with measured hadronic energy $E^{H} \geqslant 5$ GeV, and in a fiducial volume of 18 m^3 corresponding to $\sim$ 1 t of H_2. The average measured event energy in the CC sample is $\sim$ 37 GeV.

Corrections have to be applied to the raw number of events both because the NC sample contains background events and because, for the CC events, the muon is not always identified. The main sources contributing to the contamination in the NC sample are: (a) CC events where the muon is not identified, mainly because of the limited EMI geometrical acceptance. From a Monte-Carlo simulation it is estimated that the geometrical acceptance is 98% for $p^{\mu} > 10$ GeV/c, but that it decreases rapidly for smaller p^{μ} and is essentially zero below 3 GeV/c. The corresponding contamination in the NC candidates is approximately 70% of the number of genuine NC events; (b) interactions in the liquid produced by incoming neutral hadrons (K^0's and neutrons) originating from neutrino interactions in the material in front of the chamber. A Monte-Carlo program was used to simulate the production of the neutral hadrons in the material surrounding the bubble chamber, to follow their cascade and to determine the number of neutral hadron interactions in the bubble chamber. This computation was checked using the observed rate of secondary interactions due to neutral hadrons produced in neutrino interactions in the bubble chamber. The contamination from neutral hadron interactions was found to be approximately 40% of the number of genuine NC events.

The uncertainties in these corrections are large; they can, however, be reduced drastically using the method explained below. In neutrino nucleon scattering, the momenta, transverse to the ν-direction, of both the outgoing lepton and the outgoing observed hadronic system p_T^H are in general large and in the opposite direction, as seen in fig. 1(a). Any CC event, which is misclassified as NC will give an apparent p_T^H which is on the average small, as the muon is included with the hadrons, and would be zero if all neutral particles were detected (fig. 1(b)). In addition, because of the limited transverse momentum of hadrons relative to the direction of the hadronic shower, the transverse momentum of individual hadrons is much smaller than that of the total hadronic system. Thus, events induced by neutral hadrons will also have small values of p_T^H (fig. 1(c)). Hence, a selection of events with p_T^H above a suitable value will substantially reduce the contamination of the NC candidates. It was found that the selection $p_T^H \geq 1$ GeV/c is about ten times more efficient in rejecting the CC contamination in the sample of NC candidates than a cut on the hadronic energy $E^H > 15$ GeV, which retains a comparable fraction of events. The rejection of the hadronic background is as efficient with this cut in p_T^H as with the cut in E^H.

The raw ratio R_p for events with p_T^H greater than a given value p_T^{min} is shown as a function of p_T^{min} in fig. 2. The fast drop of the ratio as p_T^{min} increases reflects the presence of contaminations in the NC sample, together with the loss of CC events due to inefficiencies in muon identification. In addition to the two dominant corrections discussed above, corrections have been applied for:

(a) The "electronic" inefficiency of the EMI, estimated to be $(1.0 \pm 0.5)\%$ for muon momenta $p^{\mu} \geq 3$ GeV/c.

(b) Accidental associations of hadrons to hits on the EMI due to background ($\sim$ 1% of the charged current sample), which simulate a μ.

(c) Associations due to decay in flight of hadrons into muons, simulating muon hits on the EMI (0,25% of the genuine NC events).

(d) Anti-neutrino background leading to CC events with a μ^+ (which are rejected from the CC sample) and to a corresponding number of NC events, indistinguishable from the NC events due to neutrinos (1% of the number of genuine NC events).

(e) ν_e and $\bar{\nu}_e$ interactions which lead to background in the NC sample, because the electrons are usually not identified in the hydrogen. This effect is estimated to be 3% of the ν_μ flux. The correction was applied assuming μ-e universality.

(f) Scanning biases: only events with $\geqslant$ 3 charged tracks have been recorded at the scanning, and so one-prong NC final states are missed. Using a Monte-Carlo, which reproduces the observed features of the CC and NC samples, the loss due to this effect is estimated to be (4 ± 2)% of the genuine NC events.

(g) The value of the hadronic p_T^H is determined from the measured particles only, hence the contribution due to neutral hadrons is in general missing. A calibration of the measured p_T^H was obtained from CC events by comparing p_T^H to the p_T^μ of the muon. It was found that the measured p_T^H corresponds on average to 0.8 of p_T^μ, with a spread of 0.3. The calibration of p_T^H in NC events could be different if the p_T carried by neutral hadrons were different in NC and CC events. From a Monte-Carlo calculation, differences in the π^0 and neutron production are estimated to lead to a systematic loss of NC compared to CC events, amounting to $\sim$ 4% for p_T^{min} = 1.5 GeV/c.

The NC to CC ratio R_p, after all corrections have been applied, is shown in fig. 2 as a function of p_T^{min}. The value of p_T^{min} which makes the systematic errors due to uncertainties in the correction procedure about equal to the statistical errors corresponds to 1.5 GeV/c (measured transverse momentum). The values of all corrections for this selection of p_T^{min} are listed in table 1. It can be clearly seen that the corrections are drastically reduced by the cut in p_T. The best value of R_p is therefore

$$R_p = 0.51 \pm 0.04 \text{ for } p_T^H > 1.5 \text{ GeV/c}, \qquad (1)$$

where the statistical and the systematic errors each contribute ± 0.03. The cut $p_T^H > 1.5$ GeV/c on the measured p_T (only charged hadrons and seen neutrals) corresponds to a cut on the true p_T (all hadrons) of 1.9 GeV/c. As seen from fig. 2, the value of R_p is not very sensitive to the exact value of p_T^{min} used.

The analysis of the inclusive scattering of ν and $\bar{\nu}$ on isoscalar targets has given accurate determinations of the total left- and right-handed couplings of neutral currents. The chiral couplings, using the notation of Sehgal [3], are called u_L, u_R, d_L, d_R, where u and d refer to the up and down quarks, and L and R refer to left- and right-handed couplings, respectively. The ABCLOS Collaboration [2] used the ratios of total cross sections to determine the combinations $(u_L^2 + d_L^2)$ and $(u_R^2 + d_R^2)$ in a model independent way and obtained

$$u_L^2 + d_L^2 = 0.32 \pm 0.03, \qquad u_R^2 + d_R^2 = 0.04 \pm 0.03. \qquad (2)$$

If the above result is combined with the NC to CC cross section ratio on protons, u_L^2 and d_L^2 can be determined separately.

In the quark parton model the inclusive differential cross sections for ν-proton inclusive scattering are

$$\frac{d^2\sigma}{dxdy}(CC) = \frac{2G^2ME}{\pi} x \left[(d_V + d_S + s_S) + (u_S + c_S)(1-y)^2\right]$$

$$\frac{d^2\sigma}{dxdy}(NC) = \frac{2G^2ME}{\pi} x \left\{u_V\left[u_L^2 + u_R^2(1-y)^2\right] + d_V\left[d_L^2 + d_R^2(1-y)^2\right]\right. \qquad (3)$$

$$\left. + \left[(u_S + c_S)(u_L^2 + u_R^2) + (d_S + s_S)(d_L^2 + d_R^2)\right]\left[1 + (1-y)^2\right]\right\}$$

where u_V, u_S, d_V and d_S are the quark density distributions for u and d valence and sea quarks, s_S and c_S are the density distribution of strange and charmed quarks. All quark densities are functions of x and Q^2 [6]. In the eq. (3) it has been assumed that the sea quark and anti-quark density distributions are identical and that the couplings are the same for quarks of the same charge.

Integrating the differential cross sections over x and y gives for the ratio R_p of NC and CC total cross sections

$$R_p = f_1 u_L^2 + f_2 d_L^2 + f_3 u_R^2 + f_4 d_R^2 , \qquad (4)$$

where the f_i are ratios of integrals over the quark density distributions.

For the evaluation of the integrals f_i we have used the Q^2 dependent parametrization of the quark density distributions proposed by Buras and Gaemers [7], with a non-SU(3) symmetric contribution of strange quarks as suggested by the di-muon data in ν and $\bar{\nu}$ interactions [8]. This parametrization describes well the charged current interactions of ν and $\bar{\nu}$ on isoscalar targets [2]. We have also checked that they reproduce the p_T distribution of muons in this experiment. The quark density distributions were then evaluated taking into account the energy distribution of the neutrino wideband beam and the effect of the cuts. For $E^H > 5$ GeV and $p_T^H > 1.5$ GeV/c, the values obtained for the integrals are

$$f_1 = 2.1 \qquad f_2 = 1.0 \qquad f_3 = 0.70 \qquad f_4 = 0.36. \qquad (5)$$

These values(*) are not sensitive to the detailed shape of the beam, as the neutrino energy enters only via the Q^2-dependence of the quark density functions. This dependence is known to be small and it is partially absorbed because the f_i are ratios of quark densities.

(*) The uncertainty on f_1 is due to uncertainties on the ratios of quark density distribution for large x. They are estimated to be ∿ 10% on f_1 using ep and en scattering data [9]. Uncertainties on f_2 are negligible. In total, they produce uncertainties on u_L^2, d_L^2 and $\sin^2\theta$ of about 15%, which is smaller than our estimated errors.

Using the value of $u_R^2 + d_R^2$ of eq. (2) and the values for f_3 and f_4 of eq. (5), the right-handed contribution R_p^{RH} to the NC/CC ratio R_p is bound to lie inside the limits $R_p^{RH} = 0.03 \pm 0.02$ and $R_p^{RH} = 0.02 \pm 0.01$ corresponding to $d_R = 0$ and $u_R = 0$, respectively. As the difference between these two values of R_p^{RH} is small compared to the errors of this experiment, we have assumed that $R_p^{RH} = 0.025 \pm 0.02$. Taking the value of $u_L^2 + d_L^2$ from eq. (2) and the result of eq. (1) for R_p, we obtain

$$u_L^2 = 0.15 \pm 0.05$$

$$d_L^2 = 0.17 \pm 0.07 \; .$$

Fig. 3 displays the constraints on u_L^2 and d_L^2 coming from measurements on an isoscalar target and from this experiment. It also shows that the results agree with the standard SU(2) × U(1) model [10]. The value of $\sin^2\theta_w$ determined from the R_p value obtained in this experiment is

$$\sin^2\theta_w = 0.19 \pm 0.03,$$

in reasonable agreement with other determinations.

In conclusion, it has been found that a cut on the momentum, transverse to the neutrino direction, of the hadronic system is an efficient way of reducing backgrounds in the NC sample. With the selection $p_T^H > 1.5$ GeV/c, the value of NC/CC cross section ratio on protons obtained is $R_p = 0.51 \pm 0.04$. When combined with measurements of the NC/CC ratio on isoscalar targets this measurement of R_p allows for the first time using inclusive data alone, a determination of u_L^2 and d_L^2 separately. The values obtained, namely $u_L^2 = 0.15 \pm 0.05$ and $d_L^2 = 0.17 \pm 0.07$, are in good agreement with the standard SU(2) × U(1) model. From this experiment alone $\sin^2\theta_w = 0.19 \pm 0.03$.

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TABLE 1

Corrections to the CC and NC samples
with $E^H \geqslant 5$ GeV and $p_T^H \geqslant 1.5$ GeV/c

	CC events	NC events
Raw numbers	1029	651
Accidental associations of hadrons	− 4	+ 7
CC events with $p_\mu > 3$ GeV/c	+ 9	− 4
EMI geometrical acceptance for $p_\mu > 3$ GeV/c	+ 90	− 41
EMI electronics inefficiency + badly measured tracks	+ 20	− 2
Neutral hadronic background	−	− 50
Loss of one-prong topology in NC	−	+ 23
Excess of neutrals in NC events	−	+ 23
$\bar{\nu}_\mu$ background in NC events	−	− 5
ν_e background from CC + NC events	−	− 21
Corrected event numbers	1144	581

FIGURE CAPTIONS

Fig. 1 Event distributions as functions of the transverse momentum p_T with respect to the ν-direction:

(a) the p_T of the detected hadronic system p_T^H in CC events;

(b) the p_T of all tracks, including the muons, in CC events;

(c) the p_T of neutral hadrons, obtained from V^0's associated to neutrino interactions;

(d) the p_T of the detected hadrons p_T^H in NC candidates, including background.

Fig. 2 Ratio R_p of NC to CC events with p_T^H above a given p_T^{min}, plotted as a function of p_T^{min}. Only events with $E^H \geq 5$ GeV are included. The values of R_p are displayed before corrections (Δ) and after all corrections have been applied (●).

Fig. 3 Relations between the coupling constants u_L^2 and d_L^2 obtained from isoscalar data (line (b)) [2] and from νp interactions in this experiment (line (a)). The errors indicated by the dotted lines correspond to one-standard deviation. Also shown is the prediction of the standard SU(2) × U(1) model as a function of the single parameter $\sin^2\theta_W$.

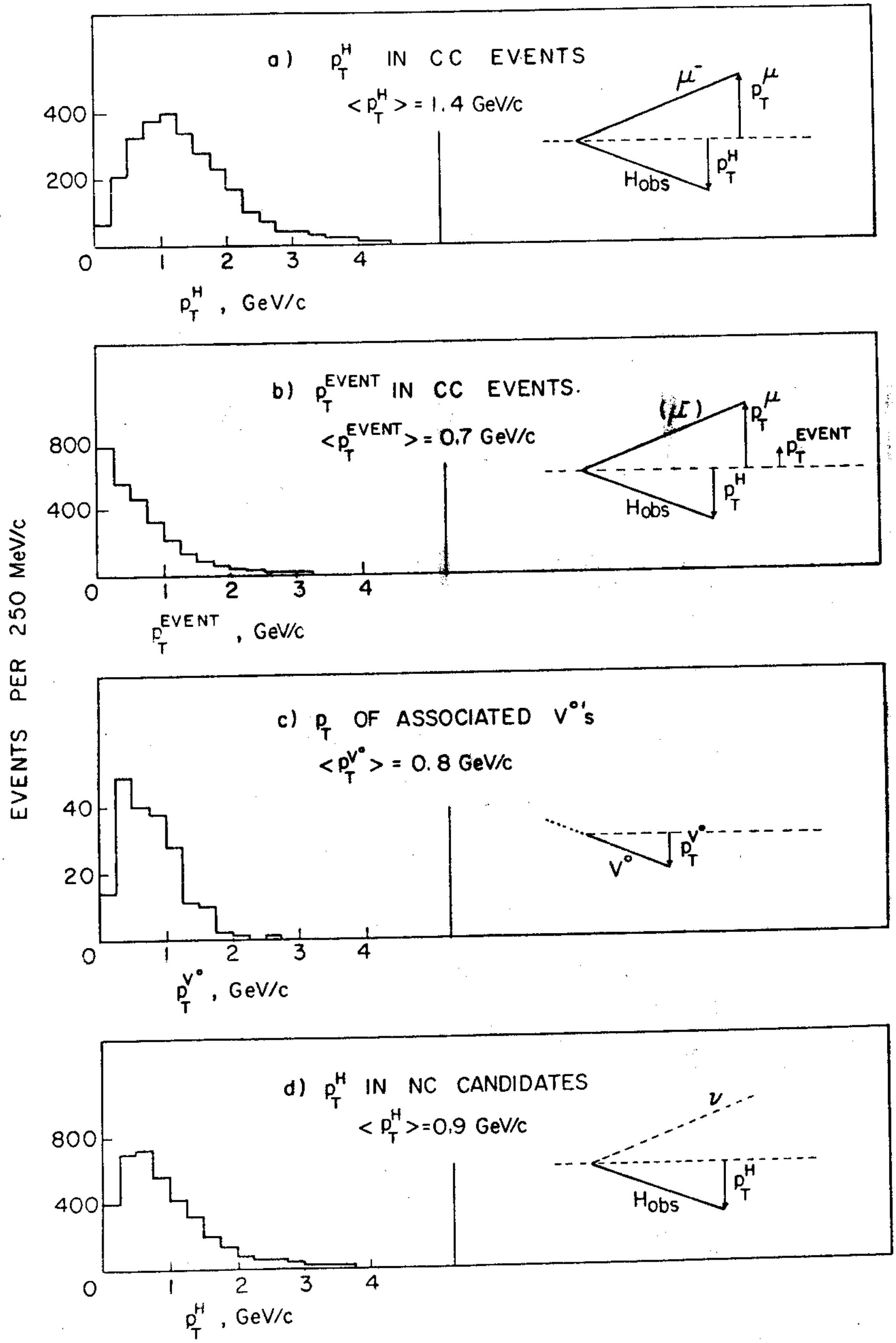

a) p_T^H IN CC EVENTS
$< p_T^H > = 1.4$ GeV/c
μ^-
p_T^μ
p_T^H
Hobs
p_T^H , GeV/c
b) p_T^{EVENT} IN CC EVENTS.
$< p_T^{EVENT} > = 0.7$ GeV/c
(μ^-)
p_T^μ
p_T^{EVENT}
p_T^H
Hobs
p_T^{EVENT} , GeV/c
EVENTS PER 250 MeV/c
c) p_T OF ASSOCIATED V°'s
$< p_T^{V°} > = 0.8$ GeV/c
V°
$p_T^{V°}$
$p_T^{V°}$, GeV/c
d) p_T^H IN NC CANDIDATES
$< p_T^H > = 0.9$ GeV/c
ν
p_T^H
Hobs
p_T^H , GeV/c

Fig. 1

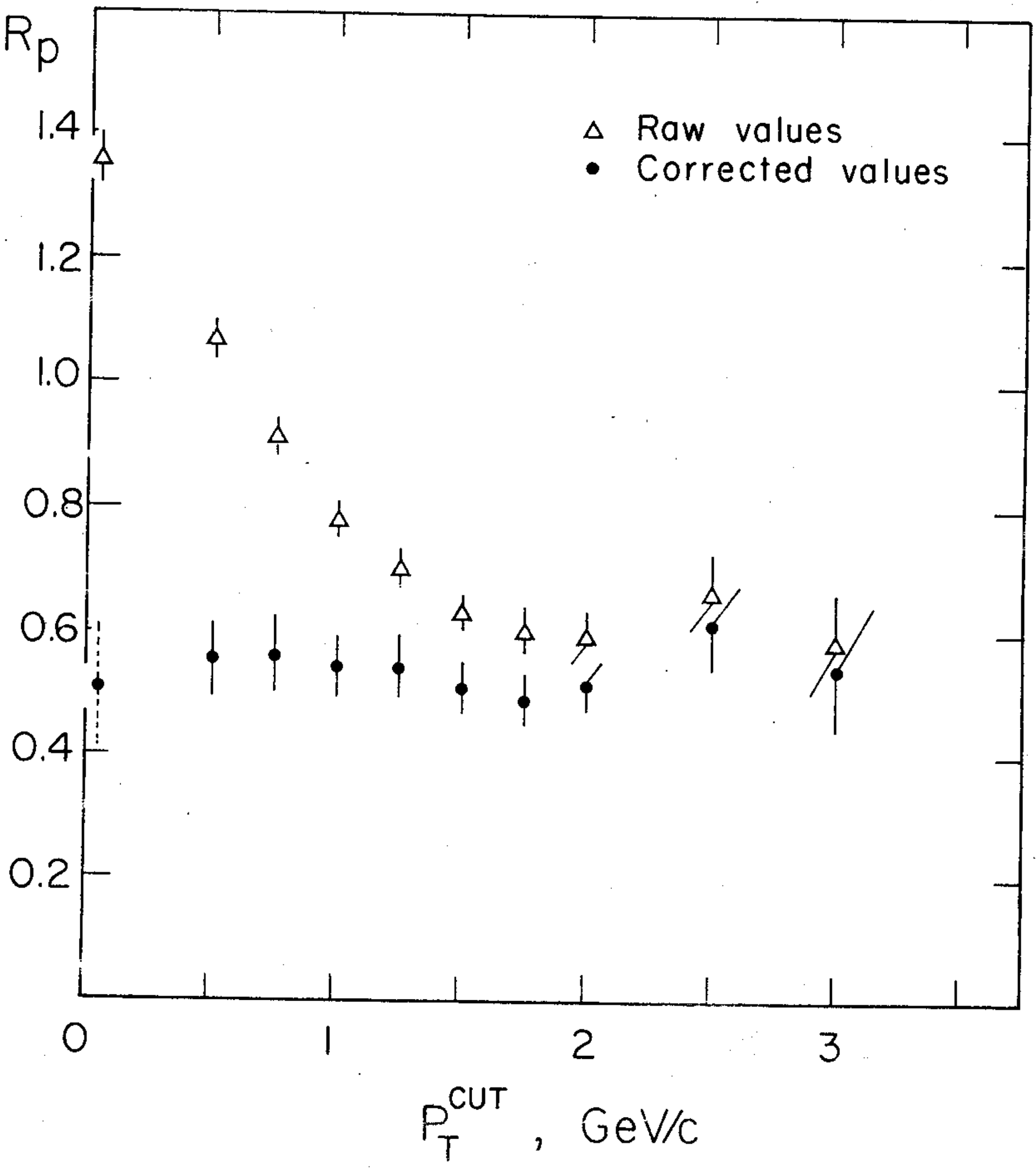
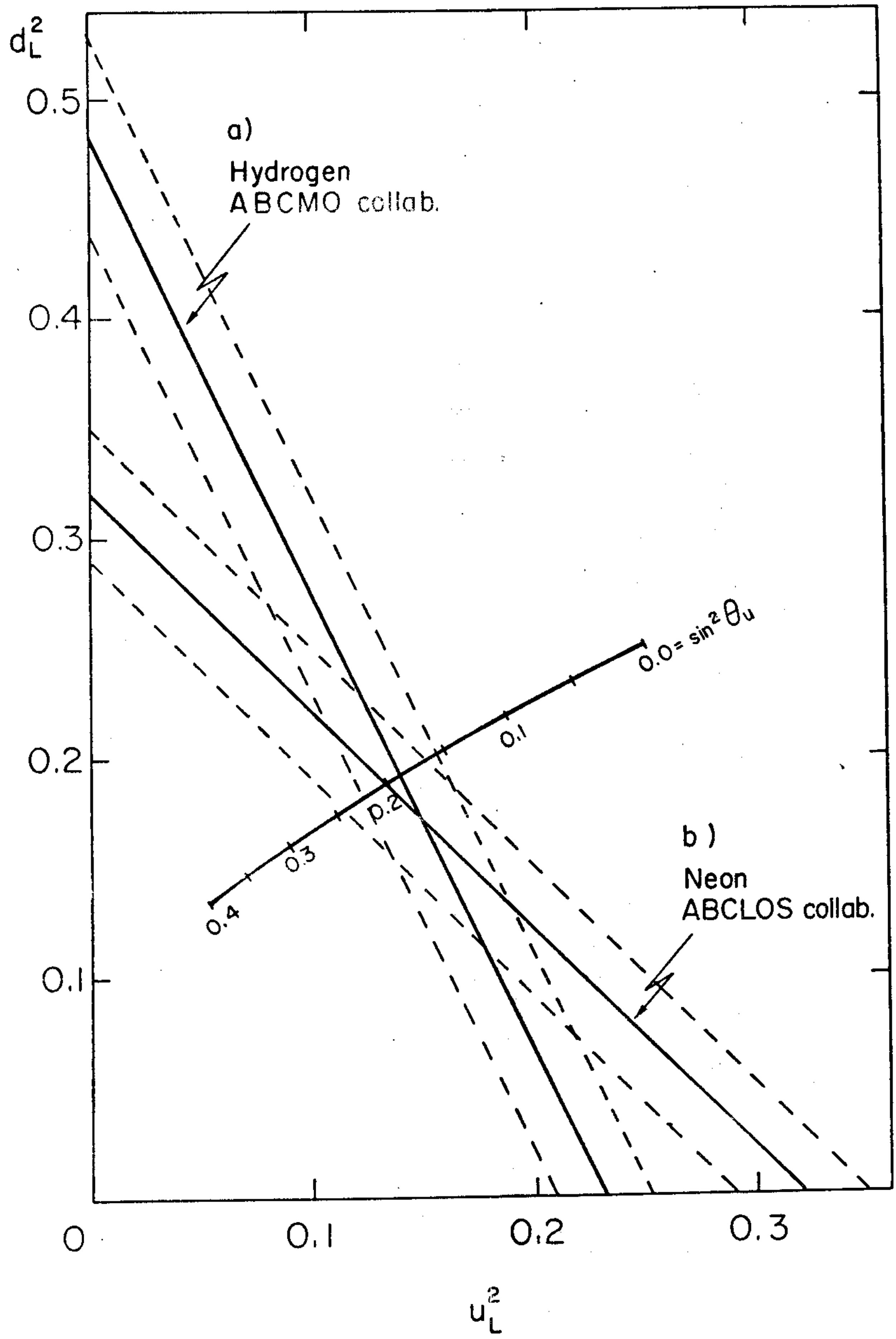

Rp
1.4
1.2
1.0
0.8
0.6
0.4
0.2
△ Raw values
● Corrected values
0
1
2
3
P_T^{CUT} , GeV/c

Fig. 2



d_L^2
0.5
0.4
0.3
0.2
0.1
a)
Hydrogen
ABCMO collab.
b)
Neon
ABCLOS collab.
0.0 = $\sin^2\theta_u$
0.1
0.2
0.3
0.4
0
0.1
0.2
0.3
u_L^2

Fig. 3