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WA59 + E180 Collaborations

Paper submitted to the 14th International Conference on Neutrino Physics and Astrophysics, CERN, Geneva, Switzerland, 10-15 June, 1990

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L. VERLUYTEN[3,a,b], T. COGHEN[5], E. DE WOLF[3,a,c], O. ERRIQUEZ[1],
G.S. GAPIENKO[9],J. GUY[13], G.T. JONES[2], V.A. KOROTKOV[9], P. MARAGE[3],
D.R.O. MORRISON[4], M. NEVEU[14], N. SCHMITZ[11], K. VARVELL[2],
W. VENUS[13], W. WITTEK[11], V.G. ZAETZ[9]

1 Dipartimento di Fisica dell'Università e Sezione INFN, I–70126 Bari, Italy.

2 University of Birmingham, Birmingham, B15 2TT, UK.

3 Inter–University Institute for High Energies, ULB–VUB, B–1050 Brussels, Belgium.

4 CERN, CH–1211 Geneva 23, Switzerland.

5 Institute of Nuclear Physics, PL–30055 Cracow, Poland.

6 Nuclear Research Centre Demokritos, GR Athens, Greece.

7 LPNHE, Ecole Polytechnique, F–91128 Palaiseau, France.

8 Imperial College of Science and Technology, London, SW7 2AZ, UK.

9 Institute of High Energy Physics, Serpukhov, USSR.

10 Institute of Theoretical and Experimental Physics, Moscow, USSR.

11 Max–Planck–Institut für Physik und Astrophysik, D–8000 München 40, Federal Republic of Germany.

12 Department of Nuclear Physics, Oxford, OX1 3RH, UK.

13 Rutherford Appleton Laboratory, Chilton, Didcot, OX11 0QX, UK.

14 DPhPE, Centre d'Etudes Nucléaires, Saclay, F–91191 Gif sur Yvette, France.

15 Institute of Physics, University of Stockholm, S–11346 Stockholm, Sweden.

16 Department of Physics and Astronomy, University College London, London WC1E 6BT, UK.

a Also at Universitaire Instelling Antwerpen, B–2610 Wilrijk, Belgium.

b Researcher IIKW, Belgium.

c Research Associate NFWO, Belgium.

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Abstract

Preliminary results are presented on the behaviour of the scaled factorial moments of order 2, 3 and 4 in ν_μNe, ν_μD$_2$ and $\overline{\nu}_\mu$Ne charged current interactions observed with the bubble chamber BEBC exposed to the CERN wide band beam. Comparison of the data with a Monte Carlo simulation based on the Lund programs LEPTO 4.3 and JETSET 6.3 and including smearing due to measurement errors and nuclear reinteractions, are presented. The results are also interpreted in the framework of conventional short–range two–particle rapidity correlations. Predictions from the assumption of an underlying negative binomial multiplicity distribution for the moments of order 3 and 4 are compared with data.

1 Introduction

The study of particle density fluctuations in multiparticle production has recently attracted much attention. The structure and size of such fluctuations could be the clues to a further understanding of hadronization mechanisms.

Until a few years ago, an efficient method to separate the statistical from the dynamical fluctuations was missing, making this kind of research extremely difficult. In 1986, A. Bialas and R. Peschanski[1] proposed a systematic method for these studies, based on the use of scaled factorial moments. These are free of statistical fluctuations and are equal to the scaled moments of the underlying particle density distribution. They are thus a useful tool in the study of reaction dynamics.

The behaviour of scaled factorial moments as a function of the (pseudo)rapidity bin size has been studied in e^+e^-[2] [3], hadron–hadron[4],hadron–nucleus[5], nucleus–nucleus[6] and muon–hadron[7] reactions. All these experiments find evidence for intermittent behaviour (i.e. non–statistical self–similar particle density fluctuations at all (pseudo)rapidity intervals) down to the experimental resolution.

The comparison of the data (for hh, hA, AA and μp) with Monte Carlo simulation showed a persistent disagreement. This deviation triggered a series of discussions whether new physics is the origin of this effect or whether an adaptation of the existing hadronization models can explain the disagreement.

We have studied the behaviour of the scaled factorial moments for ν_μ–nucleus (Ne) and ν_μ–nucleon (D_2) reactions (average hadronic mass $< W > = 6.5$ GeV) and for $\overline{\nu}_\mu$–nucleus (Ne) ($< W > = 5.2$ GeV) reactions.

2 Experimental layout and event selection

The data come from exposures of BEBC to the CERN–SPS wide band neutrino and antineutrino beams produced by 400 GeV protons. The chamber was filled with deuterium, for the experiment WA25, and with a 75 mole per cent neon– hydrogen mixture, for the experiment WA59. The targets occupy the same volume and have identical spatial relationships to the beam and detectors. Beam conditions were carefully controlled throughout. This analysis is based on samples of ν_μNe, $\nu_\mu D_2$ and $\overline{\nu}_\mu$Ne events.

Event selection, energy correction method, as well as analysis and fitting programs are the same for the neon and deuterium data.

Charged Current events are identified using the same two–plane External Muon Identifier. To ensure high detection efficiencies and low background, muons are required to have momenta over 5 GeV/c.

Only events with at least 4 charged tracks in the hadronic final state are used, eliminating elastic, quasi–elastic and coherently produced events. Identified protons with momenta less than 320 MeV/c, mainly coming from nuclear evaporation, are removed from the sample. Identified muons and electrons at the interaction vertex are also eliminated.

The cuts reduce the sample to 5127 ν_μNe, 5538 $\nu_\mu D_2$ and 6359 $\overline{\nu}_\mu$Ne CC events.

The visible neutrino energy, calculated from the outgoing muon and the visible hadronic shower, is corrected for missing neutrals using a method based on transverse momentum balance.

For each observed particle, the rapidity is calculated in the exchanged boson – nucleon center-of-mass frame. The rapidity axis is taken along the momentum vector $\vec{q}$ of the exchanged weak boson:

$$\vec{q} = \vec{p}_\nu - \vec{p}_\mu$$

with $\vec{p}_\nu$ the corrected neutrino momentum and $\vec{p}_\mu$ the muon momentum in the laboratory system.

3 Factorial moments, correlations and the negative binomial distribution

Factorial moments are calculated by subdividing the total rapidity region of interest Y into M smaller intervals of equal length δy = Y/M. The normalized factorial moment of order i is then calculated as

$$< \overline{F}_i >= M^{i-1} \frac{< \sum_{m=1}^{M} n_m(n_m - 1)...(n_m - i + 1) >}{< \sum_{m=1}^{M} n_m >^i} \tag{1}$$

where n_m is the number of particles in bin m and <> denotes the average over all events. In formula (1) the factorial moments are calculated by averaging over all events and all bins.

If intermittent behaviour or self–similar fluctuations exist at all scales in rapidity, then the factorial moments are characterized by a power law

$$< \overline{F}_i > \propto (\delta y)^{-f_i}, 0 < f_i \leq i - 1, \tag{2}$$

showing a singular behaviour for δy → 0. The intermittency strength is given by the exponents f_i. These are related to the generalized dimensions (or Renyi dimensions)[8] D_i, describing fractals and multifractals, by

$$D_i = 1 - \frac{f_i}{i-1}, i \geq 2 \tag{3}$$

For a non–flat rapidity distribution, varying with the bin size δy, intermittency is shown more directly by studying the reduced scaled factorial moments [9], defined as

$$F_i^R = \frac{F_i}{R_i} \tag{4}$$

with

$$R_i = \frac{\frac{1}{M} \sum_{m=1}^{M} < n_m >^i}{(\frac{1}{M} \sum_{m=1}^{M} < n_m >)^i} \tag{5}$$

If the dynamical fluctuations have a typical correlation length δy_o, the factorial moments are expected to rise with decreasing bin size for δy larger than δy_o and to saturate to some constant value for δy below δy_o. Saturation of the moments is also expected when δy becomes smaller than the experimental resolution in δy.

There exists a strictly mathematical relation between factorial moments and correlation functions[10]. The second order normalized factorial moment satisfies the relation:

$$F_2 = 1 + \frac{\int_0^{\delta y} dy_1 \int_0^{\delta y} dy_2 C_2(y_1, y_2)}{[\int_0^{\delta y} dy I_1(y)]^2}, \tag{6}$$

where $C_2(y_1, y_2)$ is the two–particle correlation function, which can be expressed as:

$$C_2(y_1, y_2) = I_2(y_1, y_2) - I_1(y_1) I_1(y_2) \tag{7}$$

with $I_r(y_1, ..., y_r)$ the inclusive probability density for producing r indistinguishable particles with rapidities $y_1, ..., y_r$.

Recently it has been suggested that the behaviour of F_2 can also be explained by short–range two–particle rapidity correlations [11], which lead to the parametrization:

$$< \overline{F}_2 >= 1 + \gamma \xi (1 - e^{-\delta y/\xi})/\delta y \tag{8}$$

where γ represents the correlation strength and ξ the correlation length. Using the linked–pair approximation for higher–order correlations, the higher–order factorial moments are expressed in terms of two–particle correlation functions. This would suggest that little additional information is gained from investigating the behaviour of higher–order factorial moments. In the limit $\delta y/\xi \rightarrow 0$, $< \overline{F}_2 >$ saturates at the value $1+\gamma$.

It is also well known that the charged multiplicity distributions are of approximate negative binomial (NB) type in various central rapidity windows. If this is assumed to remain valid down to the smallest bin sizes in rapidity, then it can be shown that all higher–order factorial moments can be derived from F_2 by the recursion formula[10]:

$$< \overline{F}_i >=< \overline{F}_{i-1} > [1 + (i-1)(< \overline{F}_2 > -1)], i \geq 3 \tag{9}$$

In the following discussion the notation F_i will be used instead of $< \overline{F}_i >$.

4 Experimental results and discussion

We have studied the behaviour of the normal and reduced scaled factorial moments in the rapidity region $-2 \leq y \leq 2$ (Y = 4).

The resolution in δy ($\sigma_{\delta y}$) was determined by a Monte Carlo simulation taking into account the smearing of the momentum and angle of the final state particles due to measurement errors and the systematic error on the neutrino energy estimate due to the loss of neutral particles. It was found to be 0.17 for ν_μNe, 0.12 for $\nu_\mu D_2$ and 0.16 for $\overline{\nu}_\mu$Ne charged current interactions.

Figure 1 shows the factorial moments (ln F_i) as a function of the bin size (ln δy) for charged hadrons. For the neon data, the moments are observed to increase with decreasing bin size. The increase is consistent with being linear up to the resolution $\sigma_{\delta y}$; the increase is stronger for higher order moments. On the other hand, the deuterium data display a systematically smaller increase of the factorial moments with decreasing bin size than the neon data. Although the kinematical properties of the ν_μNe and $\nu_\mu D_2$ are identical, the factorial moments appear thus to behave quite differently. Tables 1 to 3 give the results f_i of a linear fit in the range $1 > \delta y > \sigma_{\delta y}$ for ν_μNe, $\nu_\mu D_2$ and $\overline{\nu}_\mu$Ne interactions. The corresponding slopes f_i^R for the reduced moments are also given. The regions $\delta y > 1$ are excluded from the fits to decrease the influence of particles from the decay of softly produced resonances.

Figure 2 contains the predictions from Monte Carlo, using the LEPTO 4.3 event generator and the JETSET 6.3 hadronization and fragmentation model[12], and including the smearing due to measurement errors and nuclear reinteractions. The factorial moments, predicted by the LUND program, are systematically smaller than the ones determined from the data, but the values for the slopes, also given in tables 1 to 3, are in reasonable agreement with the measured ones. The difference observed between Ne and D_2 data is qualitatively reproduced by the simulation.

Values for the correlation strength γ and length ξ are obtained by fitting the moments F_2 to equation (8) with 2 free parameters γ and ξ in the range $1.3 > \delta y > \sigma_{\delta y}$. The results of the fit to the measured and simulated values for F_2 are displayed in table 4. The negative correlation ρ between the fit parameters γ and ξ is also given in table 4, and has to be taken into account for comparison among different samples. Within the errors, the correlation length ξ is found to be independent of the kind of target nucleus, while the correlation strength γ is lower for the D_2 data than for the Ne data. The correlation length ξ for the Ne is underestimated by the Monte Carlo, whereas the simulated values for F_2 in D_2 saturate around 1 and could not be fitted to equation (8).

Strong correlations among the factorial moments for different bin sizes δy are present. The quoted errors on the intermittency strenghts $f_i^{(R)}$, the correlation strength γ and the correlation length ξ were therefore checked by subdividing the total ν_μ Ne data sample into 10 smaller, but different subsamples. The standard deviation for the fit parameters, obtained from these 10 subsamples, is close to the quoted error, except for the error on the correlation strength, which could be 1.7 times larger.

The difference in the intermittency strenghts $f_2^{(R)}$ and $f_3^{(R)}$ between the Ne and D_2 data, observed by comparing tables 1 and 2, seems to be mainly due to nuclear reinteractions, as can be deduced from table 5, which presents the results of the Monte Carlo simulation for the true values of the moments F_2, for the values obtained when considering only the effects of the measurement smearing ("no reinteractions") and when considering both the effects of the measurement smearing and of nuclear reinteractions ("observed"). Indeed, the measurement smearing alone does not affect the true values of f_2 and f_3. On the other hand, both the measurement smearing and the nuclear reinteractions influence strongly the absolute value for the factorial moments, as can be seen in figure 3. The correlation length ξ does not seem to be affected by the presence of nuclear reinteractions, since its measured value is the same for Ne and D_2 data (see table 4).

We have calculated the moments F_3 and F_4 from the measured moment F_2 according to equation (9) which holds in the case that the underlying multiplicity distribution is of the NB–type. The results are displayed in figure 4 for ν_μNe, $\nu_\mu D_2$ and $\overline{\nu}_\mu$Ne. The agreement with the measured moment F_3 and F_4 is quite good for $\overline{\nu}_\mu$Ne and $\nu_\mu D_2$ data. In case of the ν_μNe data the predicted values are smaller than the measured values.

5 Conclusions

The following preliminary results on the behaviour of the scaled factorial moments in (anti)neutrino–Ne and neutrino–D_2 interactions are obtained:

- F_2,F_3 and F_4 for neon are observed to be above their values for deuterium for the same beam. Nuclear reinteractions contribute to the effect commonly called intermittency. Such a nuclear contribution should be present in all data with targets or beams with more than 2 nucleons.

- The intermittency strengths f_2 and f_3 in Ne events, obtained by fitting the factorial moments F_2 and F_3 as a function of δy in the range $1 > \delta y > 0.17$ for ν_μNe CC interactions and in the range $1 > \delta y > 0.16$ for $\overline{\nu}_\mu$Ne CC interactions, are determined to be non–zero. The obtained values are displayed in tables 1 and 3 respectively.

- The intermittency strengths f_2 and f_3 for $\nu_\mu D_2$ CC interactions as obtained by fitting the factorial moments in the range $1 > \delta y > 0.12$ are compatible with 0 (table 2).

- The results on intermittency strengths f_2 and f_3 are in agreement with predictions from our Monte Carlo simulation, based on the Lund programs (LEPTO 4.3 and JETSET 6.3) and including the effects of smearing due to measurement errors and of nuclear reinteractions.

- The behaviour of the factorial moment F_2 can be explained by conventional short–range two–particle rapidity correlations, as suggested by P. Carruthers and I. Sarcevic. The values for the correlation strength and length are underestimated by our Monte Carlo, as shown in table 4.

- Nuclear reinteractions introduce a systematic bias on the determination of intermittency strenghts. Smearing effects, due to measurement errors, do not affect the intermittency strenghts, but increase the moments F_2. The correlation length ξ is not affected by nuclear reinteractions.

- The factorial moments up to 4th order are in reasonable agreement with the assumption of an underlying negative binomial multiplicity distribution.

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Table 1. Fitted intermittency strengths (f_i and f_i^R) obtained for the measured (data) and simulated (MC) normal and reduced scaled factorial moments for charged hadrons with -2 $\leq$ y $\leq$ 2, produced in ν_μNe Charged Current interactions.

	WA59 ν_μ data	WA59 ν_μ MC
f_2	0.029 ± 0.009	0.023 ± 0.007
f_3	0.133 ± 0.030	0.091 ± 0.021
f_2^R	0.022 ± 0.009	0.017 ± 0.006
f_3^R	0.118 ± 0.031	0.076 ± 0.021

Table 2. Fitted intermittency strengths (f_i and f_i^R) obtained from the measured (data) and simulated (MC) normal and reduced scaled factorial moments for charged hadrons with -2 $\leq$ y $\leq$ 2, produced in $\nu_\mu D_2$ Charged Current interactions.

	WA25 ν_μ data	WA25 ν_μ MC
f_2	0.011 ± 0.006	0.007 ± 0.004
f_3	-0.028 ± 0.023	0.031 ± 0.014
f_2^R	0.002 ± 0.006	0.001 ± 0.004
f_3^R	-0.048 ± 0.020	0.013 ± 0.015

Table 3. Fitted intermittency strenghts (f_i and f_i^R) obtained from the measured (data) and simulated (MC) normal and reduced scaled factorial moments for charged hadrons with -2 $\leq$ y $\leq$ 2, produced in $\overline{\nu}_\mu$Ne Charged Current interactions.

	WA59 $\overline{\nu}_\mu$ data	WA59 $\overline{\nu}_\mu$ MC
f_2	0.024 ± 0.008	0.026 ± 0.006
f_3	0.075 ± 0.024	0.110 ± 0.021
f_2^R	0.014 ± 0.008	0.018 ± 0.006
f_3^R	0.053 ± 0.024	0.091 ± 0.021

Table 4. Fitted values for the correlation strength γ and the correlation length ξ for the measured (data) and simulated (MC) factorial moment F_2 for charged hadrons with -2 $\leq$ y $\leq$ 2, produced in ν_μNe, $\overline{\nu}_\mu$Ne and $\nu_\mu D_2$ CC interactions. ρ is the absolute value of the negative correlation among the 2 fitted parameters.

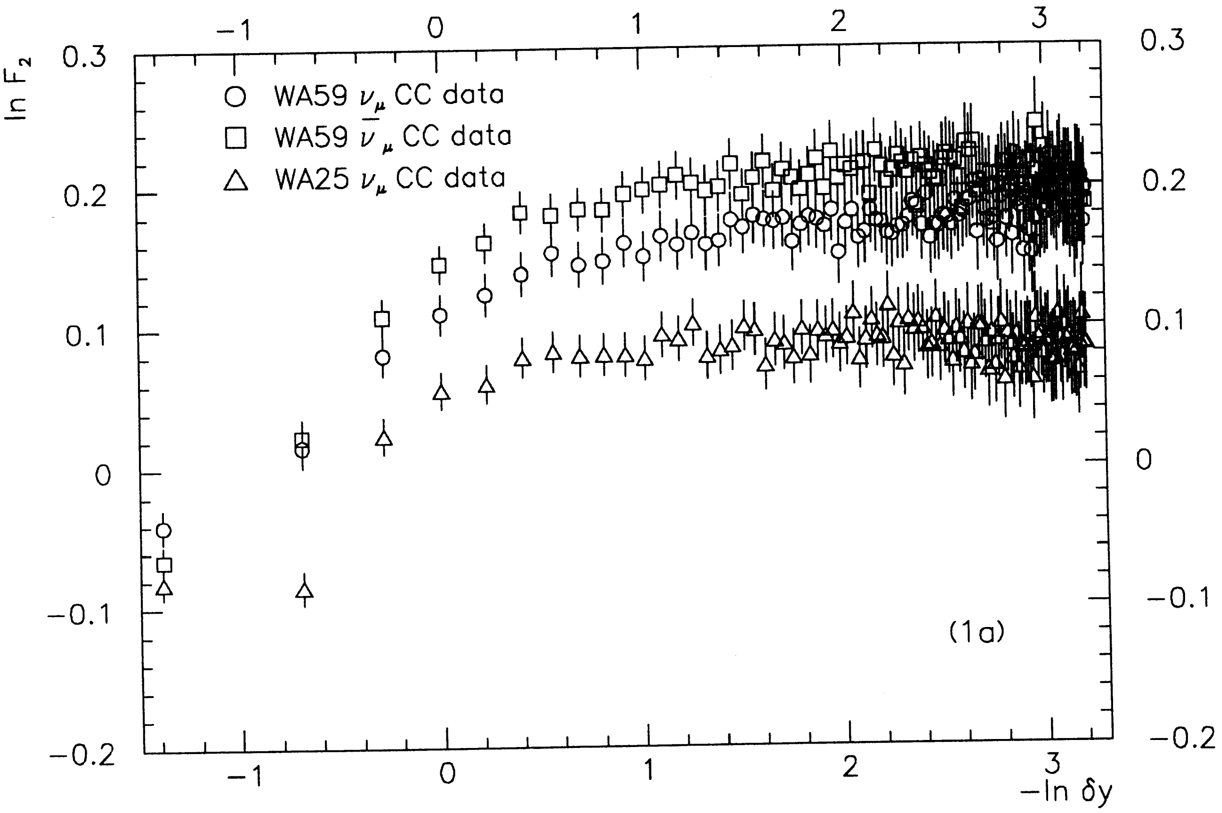
	γ	ξ	ρ
WA59 ν_μ data	$0.218^{+0.013}_{-0.012}$	$0.70^{+0.17}_{-0.12}$	0.76
WA59 $\overline{\nu}_\mu$ data	0.260 ± 0.010	$0.89^{+0.18}_{-0.12}$	0.73
WA25 ν_μ data	0.110 ± 0.008	0.65 ± 0.17	0.68
WA59 ν_μ MC	$0.118^{+0.012}_{-0.010}$	$0.39^{+0.09}_{-0.08}$	0.82
WA59 $\overline{\nu}_\mu$ MC	$0.133^{+0.015}_{-0.012}$	$0.29^{+0.07}_{-0.06}$	0.84

Table 5a. Fitted values for the intermittency strenghts for the simulated factorial moments for charged hadrons with -2 $\leq$ y $\leq$ 2, produced in ν_μNe (a) and in $\nu_\mu D_2$ (b) interactions. Results are displayed for 3 samples: the "observed" sample (column 2), the sample in which nuclear reinteraction is eliminated (column 3) and the sample with nuclear reinteractions and smearing removed (column 4), displaying the true physical results.

	"observed"	no reinteractions	true
f_2	0.023 ± 0.007	0.013 ± 0.007	0.014 ± 0.006
f_3	0.091 ± 0.021	0.043 ± 0.023	0.048 ± 0.020
f_2^R	0.017 ± 0.006	0.003 ± 0.007	0.005 ± 0.006
f_3^R	0.076 ± 0.021	0.019 ± 0.023	0.027 ± 0.021

Table 5b.

	"observed"	no reinteractions	true
f_2	0.007 ± 0.004	0.005 ± 0.004	0.006 ± 0.004
f_3	0.031 ± 0.014	0.033 ± 0.015	0.022 ± 0.015
f_2^R	0.001 ± 0.004	-0.003 ± 0.004	-0.002 ± 0.004
f_3^R	0.013 ± 0.015	0.013 ± 0.015	0.005 ± 0.015


ln F_2
○ WA59 ν_μ CC data
□ WA59 $\bar{\nu}_\mu$ CC data
△ WA25 ν_μ CC data
−ln δy
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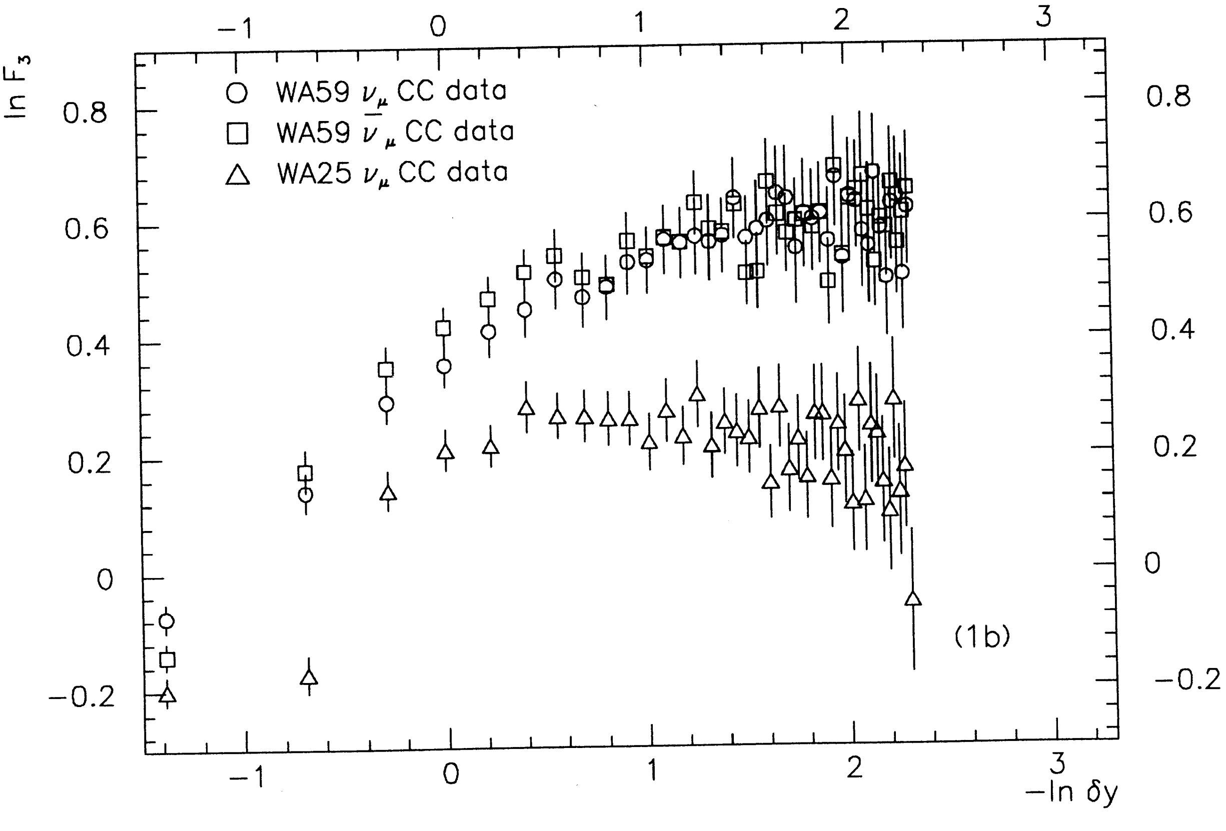
0
1
2
3
0.3
0.2
0.1
0
−0.1
−0.2

(1a)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△ WA25 ν_μ CC data
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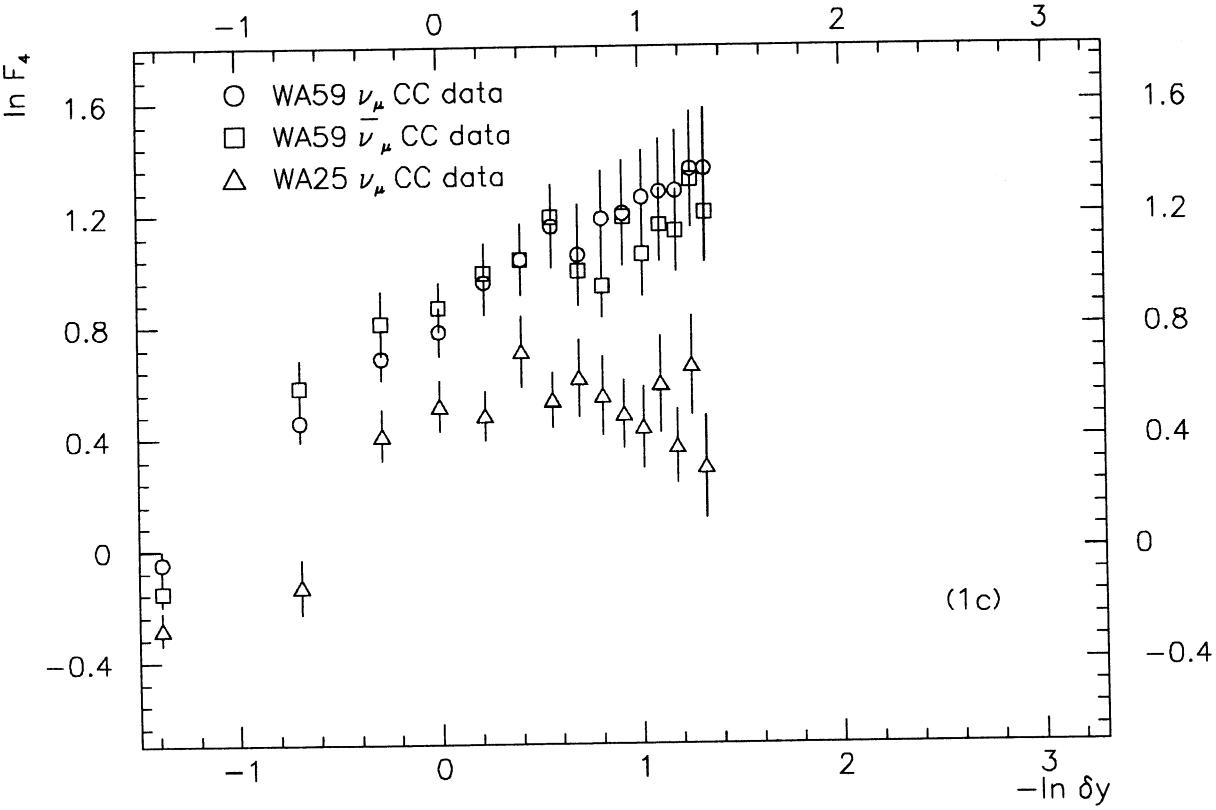
2
3
0.8
0.6
0.4
0.2
0
−0.2

(1b)


ln F$_4$
−In δy
○ WA59 ν_μ CC data
□ WA59 $\bar{\nu}_\mu$ CC data
△ WA25 ν_μ CC data
(1c)
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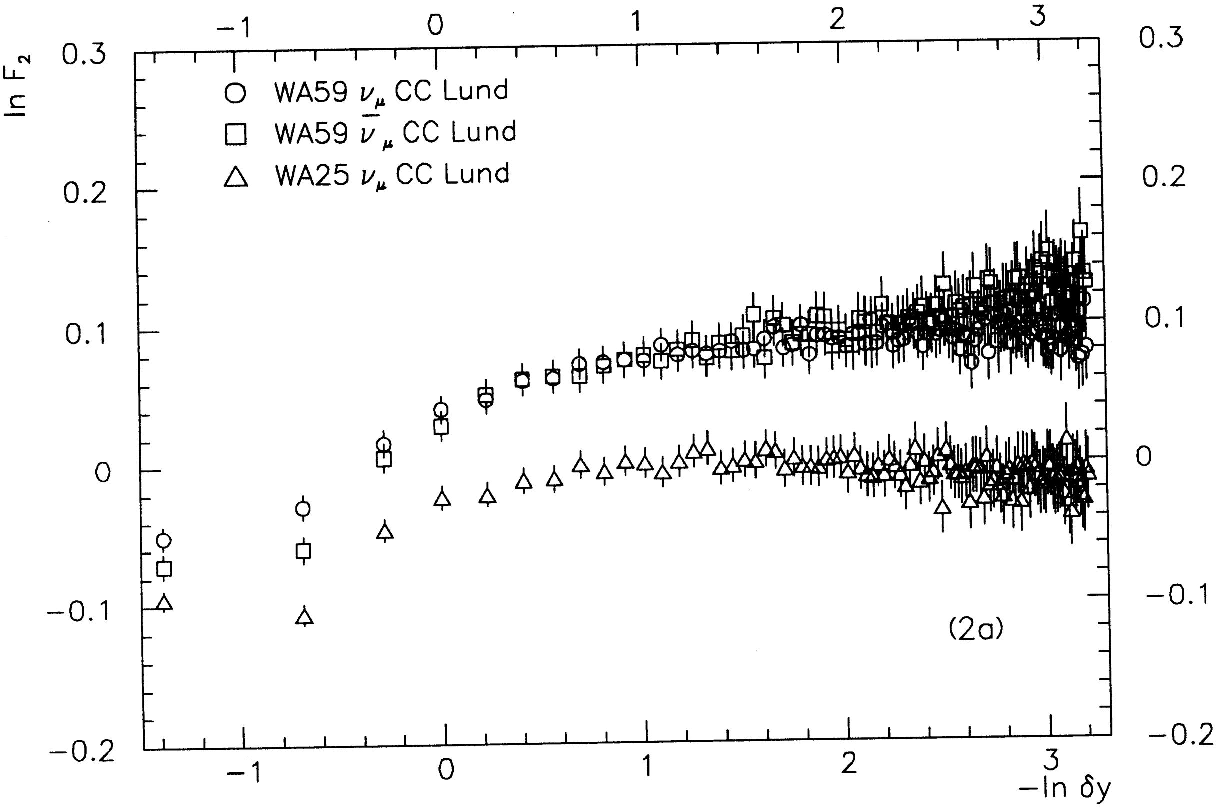
0
1
2
3
1.6
1.2
0.8
0.4
0
−0.4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WA59 ν_μ CC Lund
WA59 $\bar{\nu}_\mu$ CC Lund
WA25 ν_μ CC Lund
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3
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0.2
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0
−0.1
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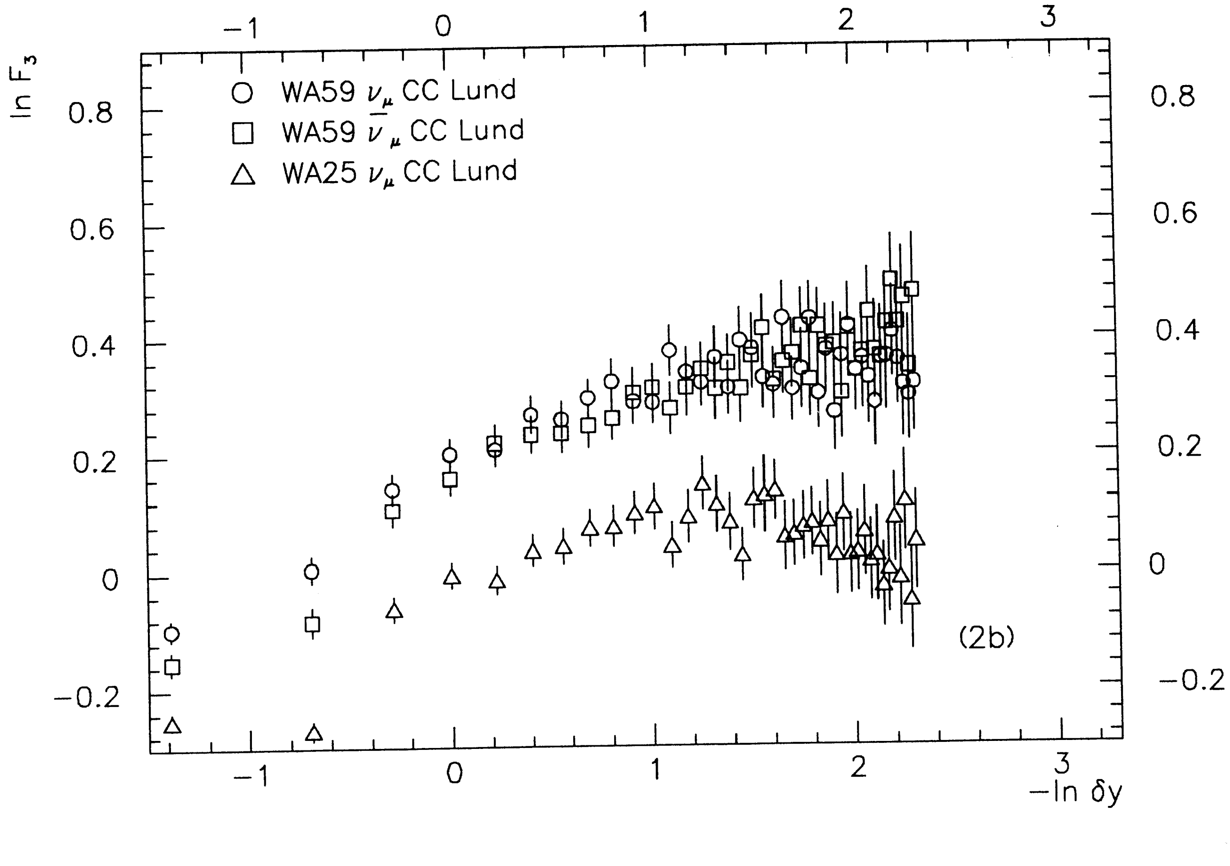
ln F_3
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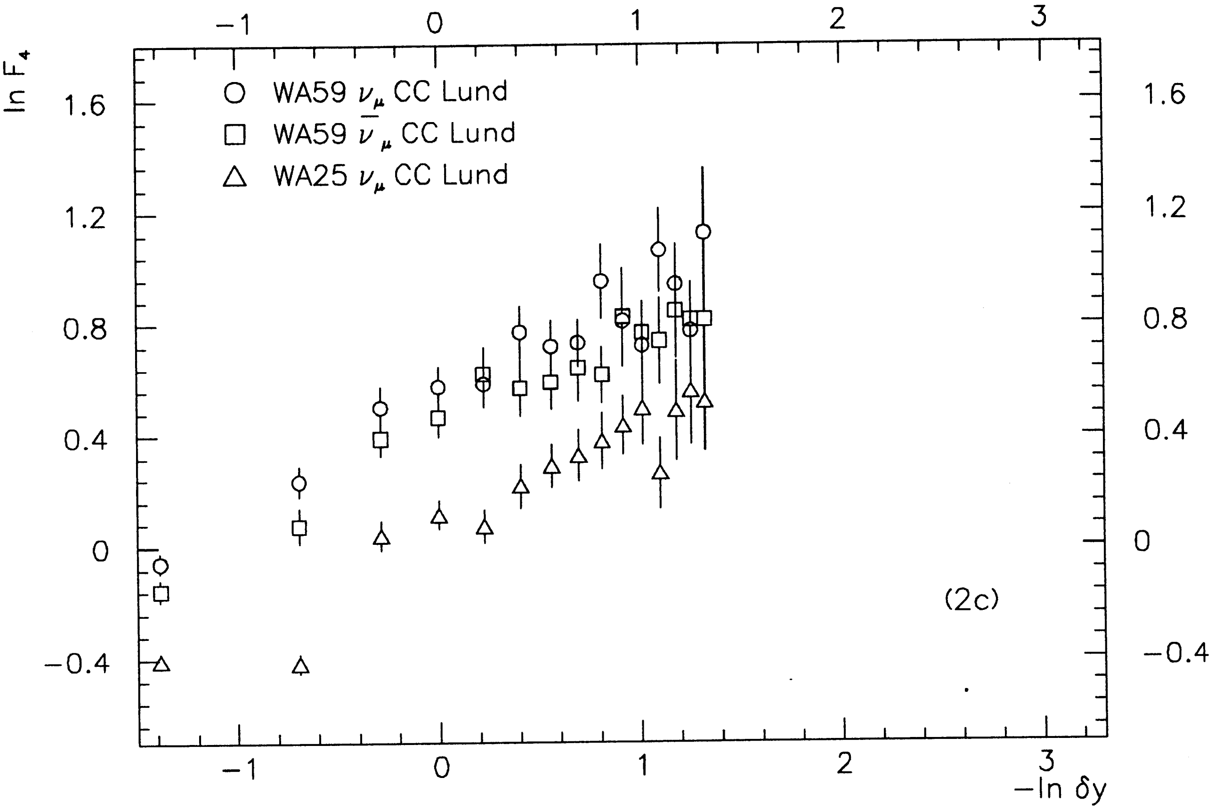
ln F_4
-ln δy
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□ WA59 $\bar{\nu}_\mu$ CC Lund
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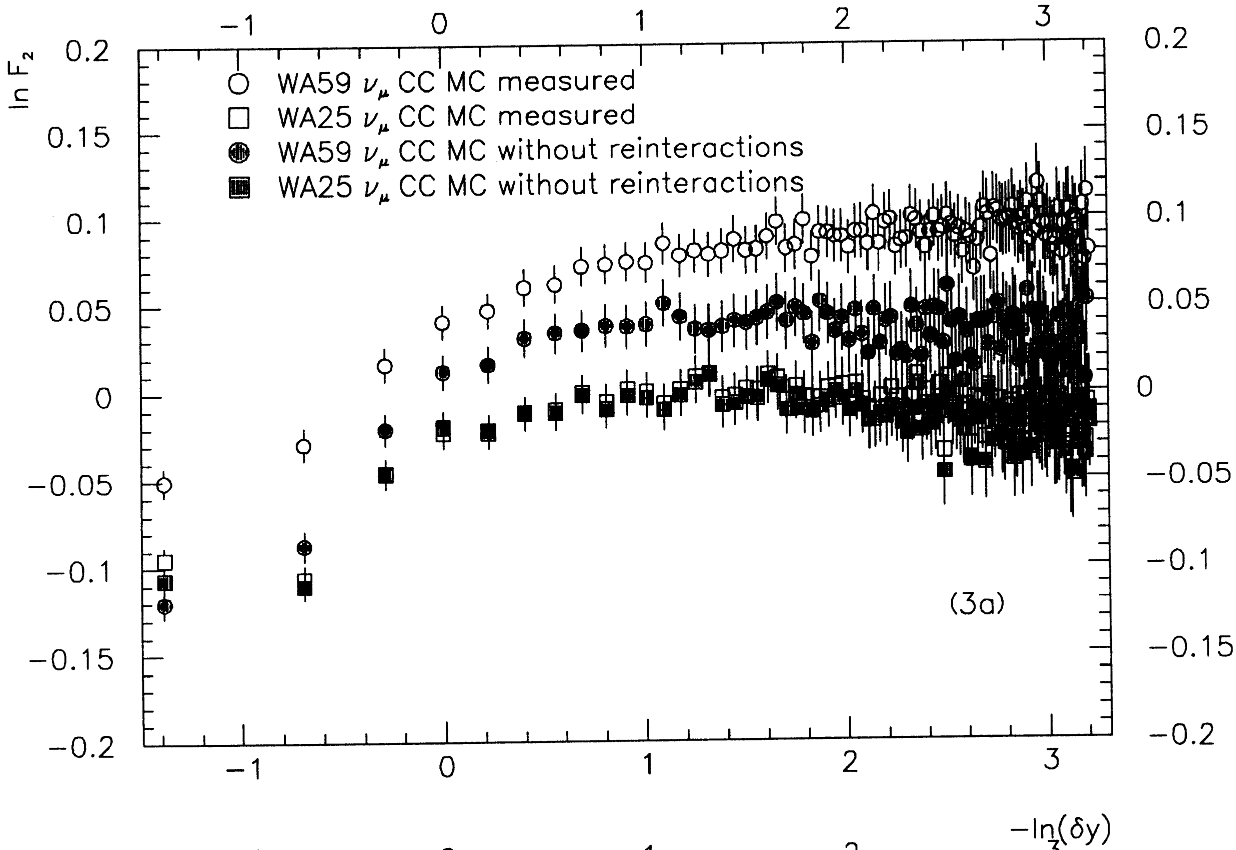
ln F₂
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1
2
3
0.2
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
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WA25 ν_μ CC MC measured
WA59 ν_μ CC MC without reinteractions
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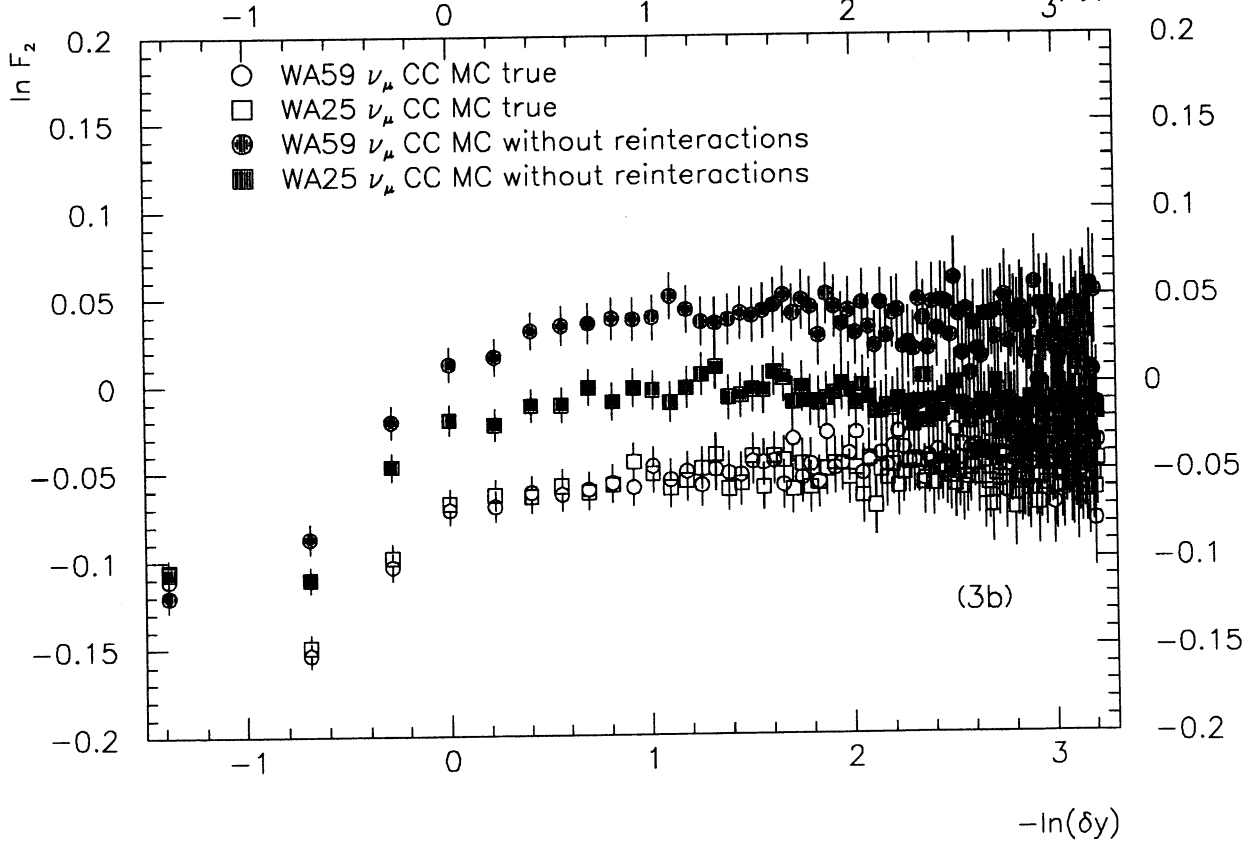
(3a)


ln F₂
−ln(δy)
−1
0
1
2
3
0.2
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
WA59 ν_μ CC MC true
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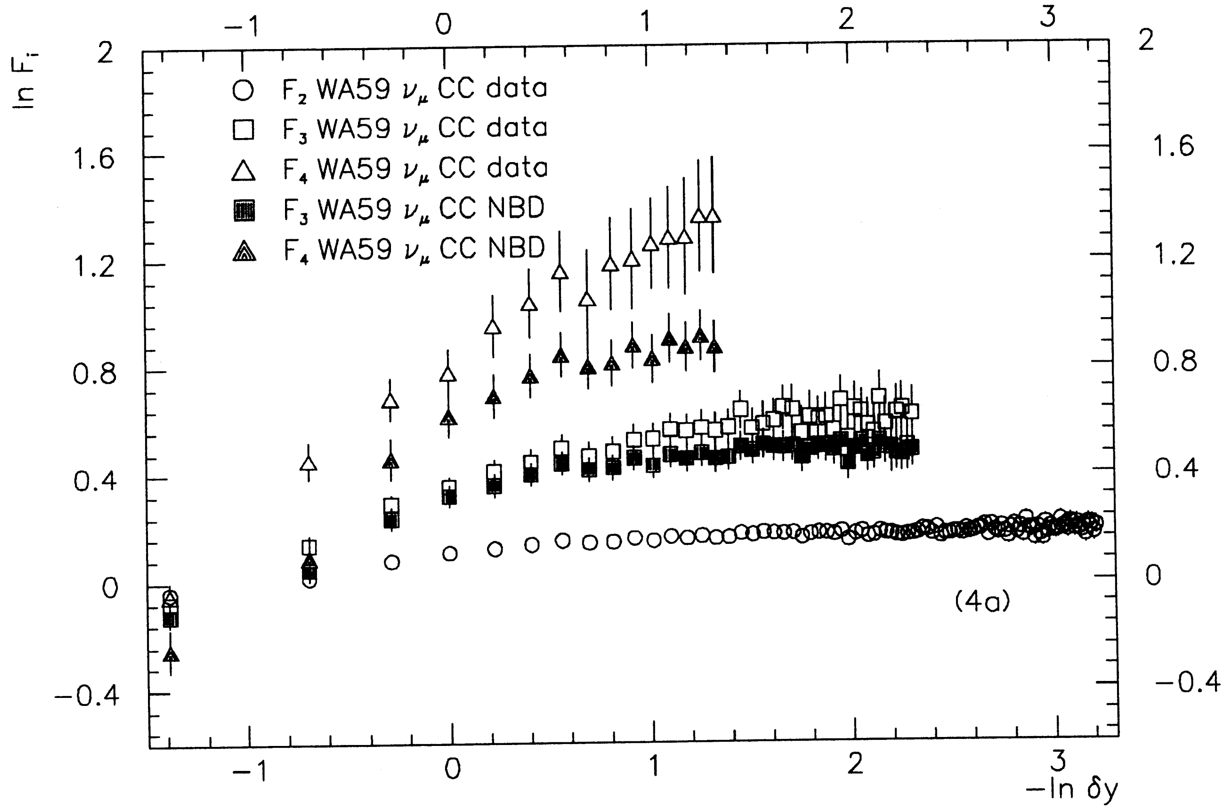
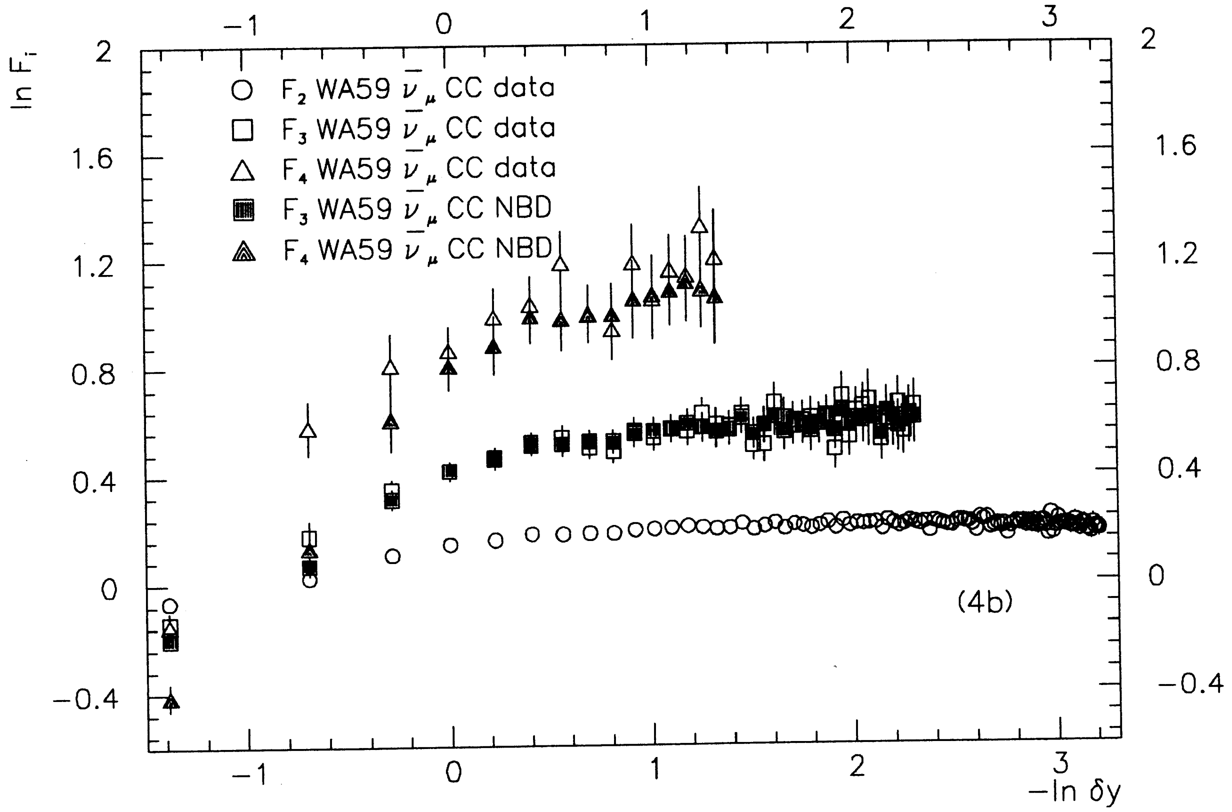
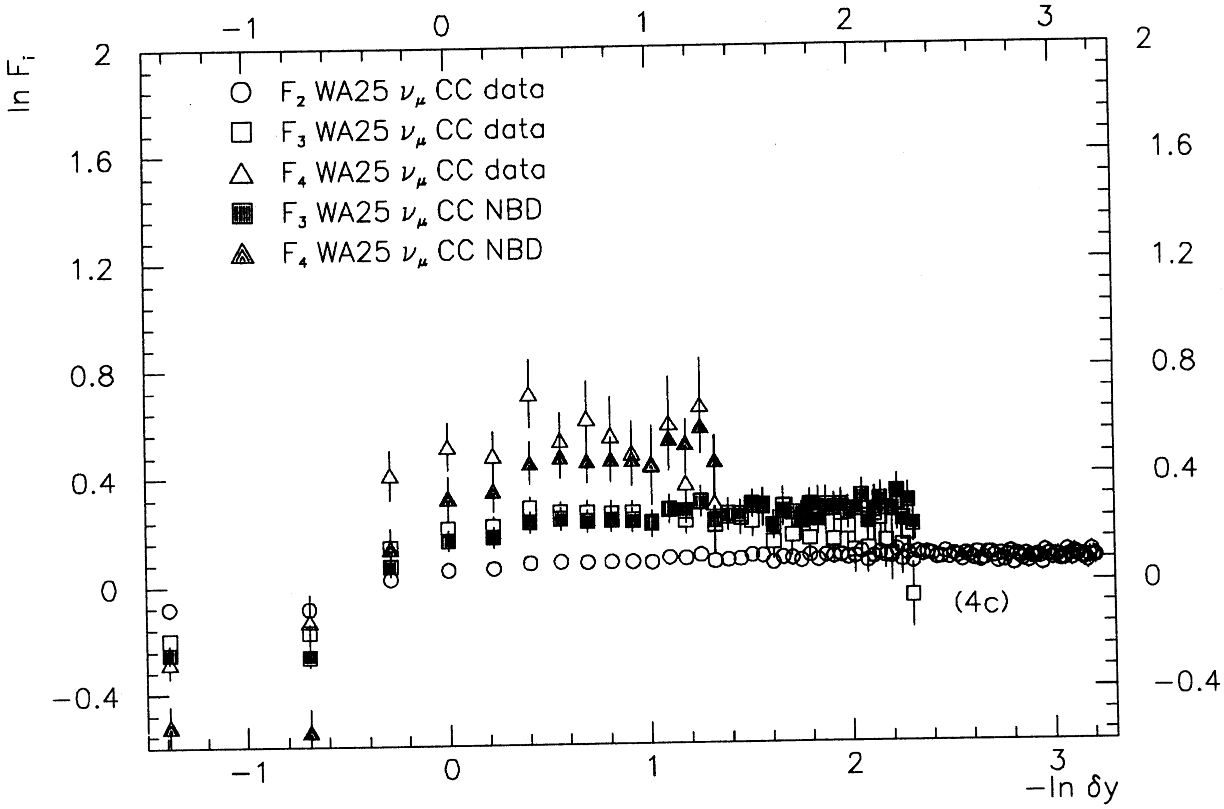
WA25 ν_μ CC MC without reinteractions
(3b)


ln F_i
F_2 WA59 ν_μ CC data
F_3 WA59 ν_μ CC data
F_4 WA59 ν_μ CC data
F_3 WA59 ν_μ CC NBD
F_4 WA59 ν_μ CC NBD
(4a)
−ln δy
−1
0
1
2
3
2
1.6
1.2
0.8
0.4
0
−0.4


ln F_i
F_2 WA59 $\bar{\nu}_\mu$ CC data
F_3 WA59 $\bar{\nu}_\mu$ CC data
F_4 WA59 $\bar{\nu}_\mu$ CC data
F_3 WA59 $\bar{\nu}_\mu$ CC NBD
F_4 WA59 $\bar{\nu}_\mu$ CC NBD
(4b)
−ln δy
−1
0
1
2
3
2
1.6
1.2
0.8
0.4
0
−0.4



ln F_i
−ln δy
−1
0
1
2
3
2
1.6
1.2
0.8
0.4
0
−0.4
○ F₂ WA25 ν_μ CC data
□ F₃ WA25 ν_μ CC data
△ F₄ WA25 ν_μ CC data
■ F₃ WA25 ν_μ CC NBD
▲ F₄ WA25 ν_μ CC NBD
(4c)