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SAME-SIGN DILEPTON PRODUCTION BY NEUTRINOS

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ABSTRACT

Experiment results on same-sign dilepton production by neutrinos are reviewed.

1. INTRODUCTION

The first observation of same-sign dileptons in neutrino interactions was reported by the Fermilab ElA collaboration[1)] in 1975. They observed 7 $\mu^-\mu^-$ events and concluded that it was unlikely that the $\mu^-\mu^-$ events could be explained as (π^-,K^-) decay background. Since then, many neutrino experiments have searched for same-sign dilepton events. While most experiments have an excess of candidates compared to their expected backgrounds few claim that their excess is statistically significant.

An obvious source for same sign dileptons within the Standard Model is associated charm production (the $\bar{c}$-quark decays semi-leptonically to an ℓ^-). The rate for $\mu^-\mu^-$ production from this source calculated in 1st order QCD[2)] is significantly ($\lesssim$ 30 times) lower than the reported experimental rates. Furthermore, bubble chamber experiments have no excess of strange particles as would be expected from $c\bar{c}$ production. It is unclear at present how to accommodate either the lack of strange particles or a high rate for same-sign dileptons within the Standard Model.

Only neutrino results will be discussed. Similar conclusions, with poorer statistics, can be drawn from anti-neutrino data.

2. EXPERIMENTAL RESULTS

The measured experimental rates for $\nu_\mu N \to \mu^- \ell^-$ production relative to the total charged current rates are shown in Fig. 1. The number of candidates and expected backgrounds are given in Table I. Apart from a recent high statistics bubble chamber measurement only counter experiment results are shown. Of the previously published[3-7] results, the HPWFOR[6] and CHARM[7] results are the most significant.

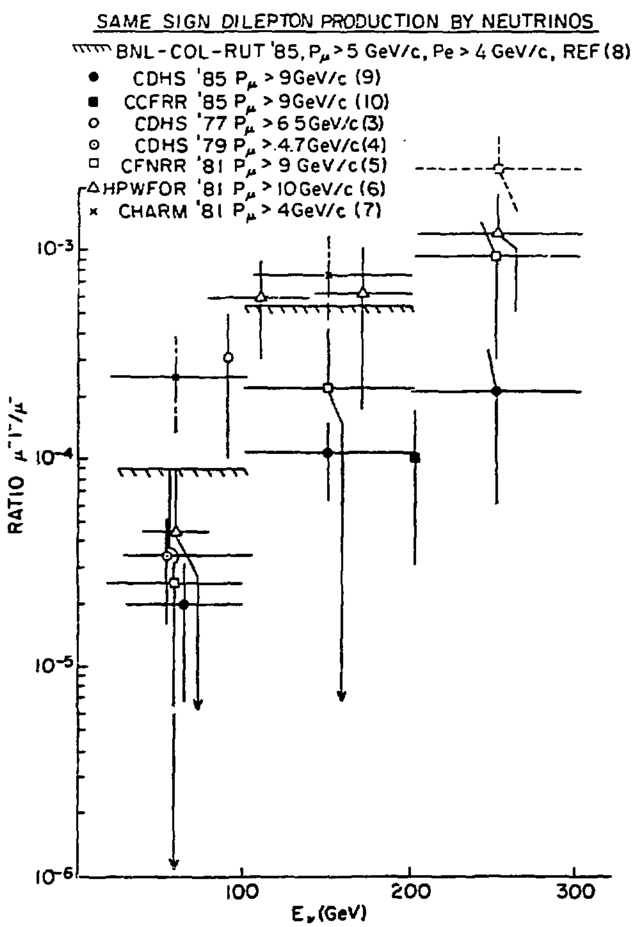


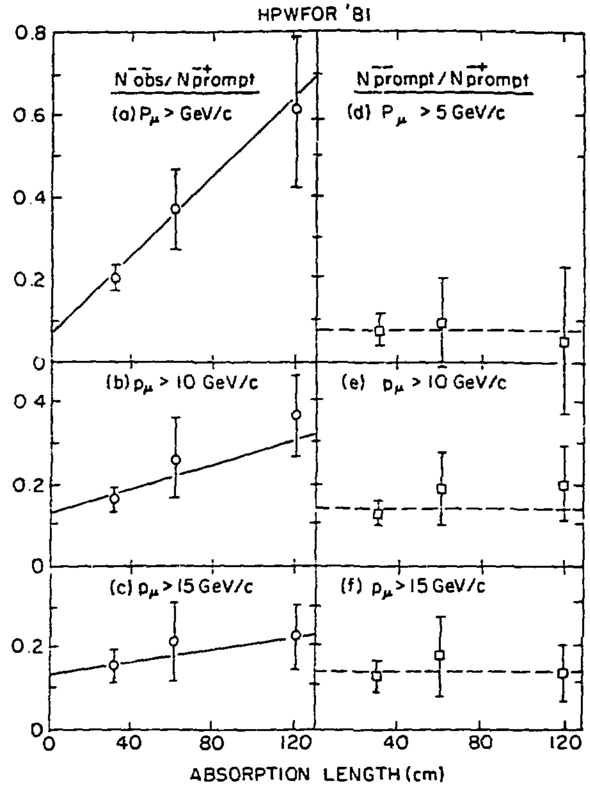
Fig. 1. Measured rates for same-sign dilepton production by neutrinos relative to the charged current rate.

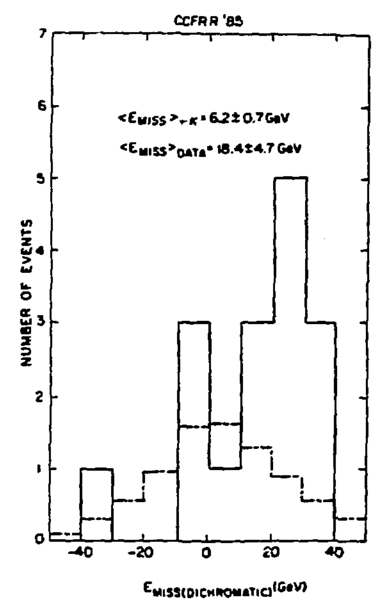
Two recent changes are reflected in Fig. 1. A new analysis of the CFNRR[5] experiment gave a much less significant result and a reduction in the measured rate. The CHARM data points now include systematic errors. This does not affect the result quoted in their paper which is for the rate of same-sign dileptons relative to opposite-sign dileptons.[7]

The major difficulty with $\mu^-\ell^-$ counter experiments is that the dominant background (π/K decays) is comparable to the total observed rate so the estimate of this background and the uncertainty in this estimate are very important. Most experiments use a Monte Carlo calculation where the hadron production details are constrained by available bubble chamber data and the probability that a given hadron is identified as a μ^- is determined by a shower calculation coupled with test beam π/K measurements. The uncertainties in these procedures are such that the large errors quoted on the background estimates are not unexpected. It is also difficult to foresee how this procedure can be significantly improved in the future.

The HPWFOR[6] detector had three distinct target sections with quite different effective collision lengths so, in principle, one could measure the dilepton rate for each target region and extrapolate to infinite density to obtain the true prompt signal. This method was not used directly for the $\mu^-\mu^-$ events because the statistics were limited. It was used for the more abundant opposite-sign ($\mu^-\mu^+$ events) and in this case served as a check on the calculation of the π/K background for the various targets. The straight lines shown in Fig. 2(a–c) for the $\mu^-\mu^-$ data are single parameter fits with the slopes fixed by the same background calculation used for the $\mu^-\mu^+$ events applied to the production and decay of negative hadrons. Given this calculated slope, the intercepts are systematically non-zero and for $P_\mu > 10$ GeV the probability is $< 10^{-4}$ that all the $\mu^-\mu^-$ events are due to π/K background.

A number of new results on same-sign dilepton production are now available.[8-11] The BCR[8] bubble chamber experiment has no candidates with $P_{\mu^-} > 5$ GeV and $P_{e^-} > 4$ GeV. This experiment is a





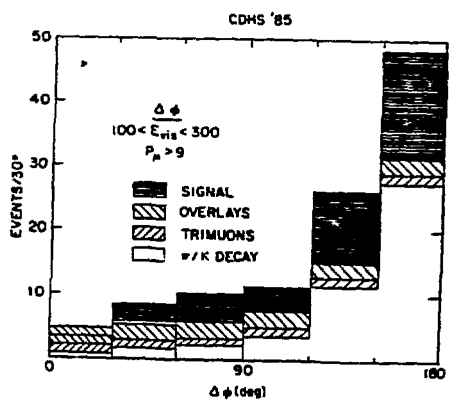


Fig. 2. (a)-(c) Ratio of $N^{obs}(\mu^-\mu^-)/N^{pr}$ $\mu^-\mu^+)$ as a function of absorption length. The solid lines are fits to the data with the slope fixed by the decay calculation. (d)-(f) Ratio of $N^{pr}(\mu^-\mu^-)/N^{pr}(\mu^-\mu^+)$ as a function of absorption length. The errors on the points include the uncertainty in the background calculation. The dashed line represents the weighted average.

Fig. 3. Missing energy for $\mu^-\mu^-$ data and π/K decays in μ^- events.

Fig. 4. Angle ($\Delta\theta$) between μ_1 and μ_2 in the plane normal to ν_μ- direction.

high statistics ($\approx$50,000 $\nu_\mu \to \mu^-$ events) experiment in the Fermilab 15' Bubble Chamber filled with a heavy Ne/H_2 mixture. The External Muon Identifier (EMI) was used to select muon candidates. A total of 91 events with a leaving negative track of momentum $P_{L^-} > 5$ GeV/c and an electron of momentum $P_{e^-} > 1$ GeV/c were observed. Of these events 25 were rejected as being δ-rays, Dalitz pairs or K^- decays. One event was rejected as a trilepton event. Only 12 of the remaining 65 events had an identified muon in the EMI. The expected background due to asymmetric Dalitz pairs or Compton electrons was (9.5 ± 1.7) events so there is no evidence for a signal. None of the 12 events had $P_{e^-} > 4$ GeV/c. The resultant 90% CL upper limits for $P_{\mu^-} > 5$ GeV/c and $P_{e^-} > 4$ GeV/c are shown in Fig. 1, Table II.

A CERN SPS experiment[12)] (WA59) using BEBC filled with a Ne/H_2 mixture has recently reported on a search for μ^-e^- events. No excess of μ^-e^- events over the expected background was observed in a sample of $\approx$25,000 charged current events and the resultant limits are also given in Table II.

The CDHS collaboration[9)] has completed the analysis of new narrow and wide band beam exposures at the CERN SPS. The neutrino wide band beam data set contains $\approx$ 1.5 million $\nu_\mu \to \mu^-$ events with $P_{\mu^-} > 9$ GeV, a significant increase over previous experiments. The major concern in this effort was to improve the systematics of the background subtraction.

The π/K background was determined by a Monte Carlo calculation. The dominant uncertainty comes from the hadron shower fragmentation and the overall uncertainty in the π/K decay subtractions were estimated to be $\lesssim$ 15%. Smaller and less uncertain corrections arise from trimuon events and overlap events where two independent charged current events overlap both in space and time to the extent that the reconstruction program cannot resolve them. The results (Table I,II) from this analysis are in agreement with earlier work by the same collaboration. There is an indication of a prompt likesign signal. However, even in the optimum region it is less than 3 standard deviations.

There is also a recent result from the CCFRR collaboration using a narrow band beam at Fermilab.[10] Since the incident neutrino energy is reasonably well known for a narrow band beam one can, as an alternative to a π/K background subtraction, look for kinematic differences between the $\mu^-\mu^-$ candidates and π/K decay events. The missing energy distributions for the two event classes (Fig. 3) are different and indicate a possible real signal.

3. DISCUSSION OF RESULTS

The measured $\nu_\mu N \to \mu^- \ell^-$ rates are summarized in Table II. The experiments listed in Table IIa used wideband beams with similar energy spectra so the overall rates can be directly compared. The BCR[8] upper limit is significantly below the rate for the CHARM experiment. From the CHARM rate one would expect 7.6 events in the BCR exposure and no events are observed. Taking into account all the appropriate errors the probability for this is $< 10^{-3}$.

The experiments listed in Table IIb have different energy spectra so the energy dependence is relevant. Here the BCR limit of $< 0.76 \times 10^{-4}$ is much less than the overall HPWFOR rate of $(3.4 \pm 0.9) \times 10^{-4}$. It is not possible to directly compare the rates as a function of energy in a meaningful way since the HPWFOR energy dependence is given only for a date set with much less statistical significance than that used for the overall rate.

The more recent experiments do not yield significant new evidence for same-sign dileptons. However, most of them still do have an excess of events over the expected background. It is also worth noting that these new measurements give lower rates than those of earlier measurements but even these are still significantly higher than the rates calculated in 1st order QCD.

There is general agreement that the evidence for a real signal increases as the neutrino energy increases ($E_\nu > 100$ GeV) and as the muon momentum cut increases. Consequently, the present Tevatron experiments at Fermilab could yield new insights into this problem.

4. ORIGIN OF SAME-SIGN DILEPTON EVENTS

There is good agreement among the various experiment on the charactristics of the same-sign dilepton candidates. The angle between the two muons in the plane normal to the neutrino direction peaks at ≈180° as one would expect if the second lepton (μ_2) is associated with the hadron vertex (Fig. 4). The second muon has limited transverse momentum with respect to the hadron direction $\langle P_T \rangle_\mu \approx \langle P_T \rangle_{\pi K}$ (Fig. 5). Likewise the momentum component out of the ν-μ_1 production plane is, on average, very similar for μ_2 and for π/K's. The energy dependence of the same-sign events is less clear. The rate relative to the total charged current rate is complicated by the requirement of a second high momentum track in the numerator which introduces an artificial threshold. A better measure, perhaps, is the rate relative to same-sign dileptons. In Fig. 6 the ratio $(\nu_\mu \to \mu^-\mu^-)/(\nu_\mu \to \mu^-\mu^+)$ for the HPWFOR[6)] and the new CDHS[9)] experiments is shown. The data areconsistent with similar energy dependences for both event classes although the HPWFOR data could be consistent with a high energy threshold effect.

Overall the characteristics of same-sign dilepton events are not inconsistent with the production and semi-leptonic decay of a relatively light hadron such as one would expect from $c\bar{c}$ production.

5. CONCLUSION

There has been considerable experimental work on same-sign dilepton production in neutrino interactions over the past 10 years. However, the situation is still unclear. Most experiments do have evidence for an excess of candidates but there is a lack of independent statistically significant results. Present experiments at the Tevatron may provide important new information. However the recent revision of older results and the lower rates from recent experiments indicate that real progress will be difficult. Furthermore, the problems encountered with π/K background subtractions argue for a multi-target experiment. Also, given the conflict with present $c\bar{c}$

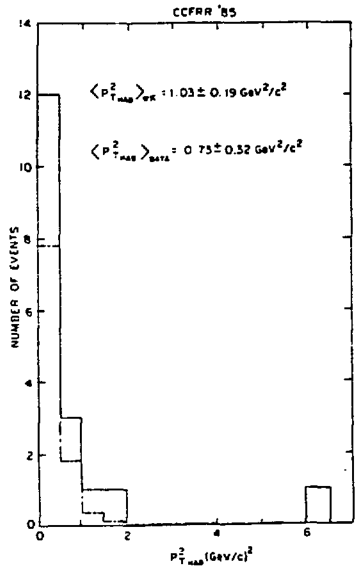


Fig. 5. Transverse momentum of μ_2 in $\mu^-\mu^-$ events and of μ from π/K decay relative to the hadron direction.

Fig. 6. Relative rates of $\mu^-\mu^-$ and $\mu^-\mu^+$ events as a function of neutrino energy.

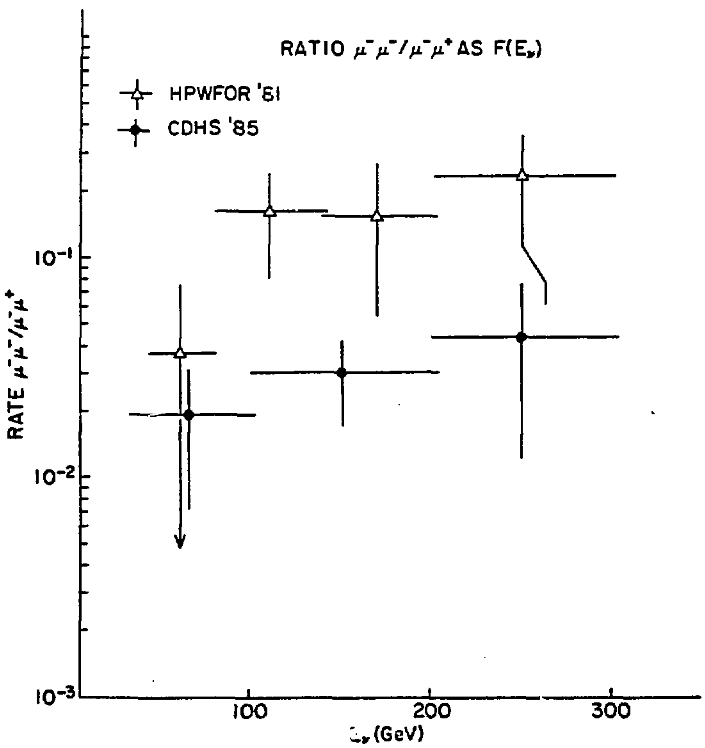


TABLE IIb. Experiments with Narrow Band (NB) or Quad Triplet (QT) Beam.

	EXPERIMENT BEAM	BCR[8] WB	CDHS[3] NB	NCFRR[5] QT	HPWFOR[6]* QT	CDHS[9] NB&WB	CCFRR[10] NB	BFHWW[13] QT
	P_μ cut (GeV/c)	5	4.7	9	10	9	9	4
	P_ℓ cut (GeV/c)	4	4.7	9	10	9	9	0.8
$\frac{\mu^-\ell^-}{\mu^-}\times 10^4$	all E_ν	$\leq$0.76	3±2	2.0±1.1	3.4±.9	-	1.4±0.8	-
	E_ν<100	$\leq$0.88	-	0.25±0.64	0.45±0.45	.20±.13	0.1±0.5	-
	100$\leq E_\nu \leq$200	$\leq$5.4	-	2.2±2.4	6.0±3.0	1.05±.43	3.6±2.1	-
	200$\leq E_\nu \leq$300	-	-	9.5±6.5	10.0±7.0	2.1±1.5	2.5±3.1	-
$\frac{\mu^-\ell^-}{\mu^-\ell^+}\times 10^2$	all E_ν	$\leq$5.3	5±3	-	-	1.9±1.2	-	<7
	$E_\nu \leq$100	$\leq$7.2	-	-	-	2.9±1.2	-	<15
	100$\leq E_\nu \leq$200	$\leq$23.0	-	-	-	4.2±3.0	-	<12

*In this experiment the division between the two lower energy bins is at 80 GeV. The overall rate is for events originating in the iron target while the energy dependence is taken from Fig. 4(a) of Ref. 15 which is for events originating in the liquid scintillator and iron calorimeters.