What are possible origins of prompt $\mu^-\mu^-$ events? Only $\mu^-\mu^+$ are expected if charmed particles are produced *singly* by neutrinos. Any mechanism to explain the $\mu^-\mu^-$ events that invokes new physics beyond charm[9] must be measured against the following alternatives: (a) radiative or direct muon-pair production in deep-inelastic charmed-current interactions,[10,11] (b) associated production of charmed particles.[12] However, $\mu^-\mu^-$ events could result from the mechanisms in (a) only if the μ^+ escapes experimental detection. Calculations[11] for mechanisms (a) lead to $R(\mu^-\mu^-)/R(\mu^-\mu^-\mu^+) < 1$, contrary to the experimental observation.[13] Therefore mechanism (a) is not likely to be the dominant source of like-sign dimuon events. Both $\mu^-\mu^-$ and $\mu^-\mu^-\mu^+$ are expected from associated charm production. The ratio $R(\mu^-\mu^-\mu^+)/R(\mu^-\mu^-)$ is expected to be roughly $B(C \to \mu + \nu + X) \simeq 0.1$, which is compatible with our observed ratio. The distributions shown in Figs. 3 and 4 are also consistent with this mechanism. However, the calculated rate for associated charm production may be too low.[12]

In conclusion, we have presented evidence for the production of prompt like-sign dimuons ($\mu^-\mu^-$) by neutrinos. The rate of prompt $\mu^-\mu^-$ events relative to the prompt $\mu^-\mu^+$ events is measured to be 0.06 ± 0.05 for $p_\mu > 5$ GeV/c, and 0.12 ± 0.05 for $p_\mu > 10$ GeV/c. The properties of the $\mu^-\mu^-$ events are similar to those of the $\mu^-\mu^+$ events. We have no evidence for prompt $\mu^+\mu^+$ events produced by antineutrinos.

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Remarks on Single-Pion Production by the Weak Neutral Current

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I compare gauge-theory–model predictions for exclusive pion production by the weak neutral current, incorporating corrections for scattering off nuclear targets where appropriate, with all the available data. I find that, based on these data, no model should be completely ruled out.

Recently there has been much interest in extracting from data restrictions on the values of the neutral-current couplings of the u and d quarks. The restrictions imposed by neutrino elastic scattering have been investigated for various gauge-theory models by many authors.[1,2] Inclusive neutrino interactions have also been investigated,[3] and two sets of values for the neutral-current couplings, labeled A and B by Hung and Sakurai,[4] have been found to be consistent[2,4] with both the elastic and inclusive data. Values for the parameters of various gauge-theory models which best fit both elastic and inclusive data[2] have also been determined.

In this paper, I start with the Hung-Sakurai phenomenological solutions A and B and the elastic-inclusive-data best-fit parameters for the Weinberg-Salam[5] model (WS), a version of the Gürsey-Sikivie[6] $SU(2)\otimes U(1)$ model (GS B), a version of the Mohapatra-Sidhu[7] $SU(2)_L\otimes SU(2)_R\otimes U(1)$ model (MS I), the Langacker-Segrè[8] $SU(3)\otimes U(1)$ model (LS), and the Lee-Weinberg[9] $SU(3)\otimes U(1)$ model (LW), and calculate the ratios of various single-pion production total cross sections. An analysis of differential cross sections for some of these exclusive processes will appear elsewhere.[10]

The model of weak pion production in the $\Delta(1232)$ region that I use was developed by Adler.[11] In Adler's dispersion theoretic treatment, nonresonant multipoles are given in terms of the pseudovector Born approximation, while the $I=J=\frac{3}{2}$ resonant multipoles are enhanced over the basic Born-approximation values by resonant rescattering effects. In this calculation, all s- and p-wave multipoles have been included. The vector and axial-vector mass parameters used are $M_V=0.84$ GeV and $M_A=0.90$ GeV, respectively.

Most data for single-pion production in the first resonance region have been obtained using nuclear targets such as aluminum or freon and propane. Corrections due to nuclear charge-exchange scattering can be substantial, and the magnitude of these corrections differs significantly from model to model.[10] Whenever the data have not been corrected for this effect, my calculated values have been corrected following the prescription of Adler, Nussinov, and Paschos.[12]

Data and model predictions for the ratio of the cross sections for neutral-current π^0 production to charged-current π^0 production by neutrinos, R_0^{ν}, are presented in Table I. A glaring discrepancy exists between the data of Lee *et al.*[13] in the first column and those of Faissner *et al.*[14] in the third column, despite the fact that these are very similar experiments. The resolution of this conflict seems to lie in the very different cuts imposed on the pion momenta in the two experiments.[13,14] It is expected that the theory should not be sensitive to this experimental cut,[13,14] and so no cut is made on the pion momentum in the calculations. The appropriate model predictions are more generally in agreement with the data of Lee *et al.*[13] rather than those of Faissner *et al.*[14] General agreement between the appropriate model predictions and the old (Hasert *et al.*[15]) and new (Krenz *et al.*[16]) Gargemelle data is also good. In all cases (except for comparison of the data of Faissner *et al.*[14] with theory), the Hung-Sakurai solution A is closer to the data than solution B, although for the new Gargamelle data (Ref. 16) both solutions are acceptable, while for the old Gargamelle data (Ref. 15) and the data of Ref. 13, neither solution actually falls within the error limits. When we attempt to place restrictions on models as a result of these calculations, we find some inconsistencies. The new Gargamelle data (Ref. 16) tend to rule out $SU(3)\otimes U(1)$ models and favor the WS and MS I models. However, the situation is reversed when the data of Lee *et al.* (Ref. 13) and old Gargamelle data (Ref. 16) are considered. This discrepancy may be due to an

TABLE I. Data and model predictions for R_0^{ν}.

Data Theory	0.17 ± 0.04[a] (Predictions corrected)	0.45 ± 0.08[b] (Data corrected)	0.40 ± 0.06[c]; $0.10-0.20$[d] (Predictions corrected)
HS A	0.219	0.382	0.219
HS B	0.225	0.374	0.227
WS	0.233	0.407	0.233
GS B	0.232	0.388	0.234
MS I	0.260	0.455	0.260
LS	0.175	0.294	0.176
LW	0.201	0.342	0.201

[a] Data of Ref. 13; model predictions are Brookhaven National Laboratory–flux averaged and for an Al target.

[b] Data of Ref. 16; model predictions are Gargamelle-flux averaged and for single nucleon targets.

[c] Data of Ref. 14; model predictions are Gargamello-flux averaged and for an Al target.

[d] Data of Ref. 15; model predictions are as described in Footnote c.

TABLE II. Data and model predictions for $R_0^{\bar{\nu}}$.

Data Theory	0.39 ± 0.18[a] (Predictions corrected)	$0.57^{+0.11}_{-0.10}$[b] (Data corrected)	0.61 ± 0.10[c]; $0.26-0.44$[d] (Predictions corrected)
HS *A*	0.254	0.358	0.242
HS *B*	0.227	0.290	0.228
WS	0.296	0.409	0.278
GS *B*	0.227	0.297	0.229
MS I	0.297	0.420	0.283
LS	0.165	0.221	0.166
LW	0.181	0.253	0.182

[a] Data of Ref. 13; model predictions are Brookhaven National Laboratory–flux averaged and for an Al target.

[b] Data of Ref. 17; model predictions are Gargamelle-flux averaged and for single nuccleon targets.

[c] Data of Ref. 14; model predictions are Gargamelle-flux averaged and for an Al target.

[d] Data of Ref. 15; model predictions are as described in Footnote c.

inadequacy of the nuclear correction techniques in the two cases.

Table II presents data and model predictions for the antineutrino analog of R_0^{ν}: $R_0^{\bar{\nu}}$. The $R_0^{\bar{\nu}}$ data of Refs. 13 and 14 show the same sort of discrepancy as they did for R_0^{ν}. The data of Erriques *et al.*[17] taken at Gargamelle, in propane and freon and corrected for nuclear effects by the experimenters, are listed in the second column. Again, I find that solution *A* is preferred over solution *B*; however, for both the new (Ref. 17) and old (Ref. 15) Gargamelle data, neither *A* nor *B* falls within the error limits, while both *A* and *B* fall within 1 standard deviation of the data of Ref. 13. The data of Ref. 13 and old Gargamelle data (Ref. 15) indicate that the WS and MS I models are preferred and that the GS *B*, LS, and LW models are inadequate. Although all of the model predictions fall below the lower error limit of the new Gargamelle data of Erriques *et al.* (Ref. 17), they are in qualitative agreement with the results of the comparison between data of Ref. 13 and the old Gargamelle data (Ref. 15).

TABLE III. Cross-section ratios measured by Krenz *et al.* (Ref. 16) and compared to flux-averaged calculations in the five models.

	$\frac{\sigma(\nu p \to \nu n \pi^+)}{\sigma(\nu n \to \mu^- p \pi^0)}$ (Data corrected)	$\frac{\sigma(\nu n \to \nu p \pi^-)}{\sigma(\nu n \to \mu^- p \pi^0)}$ (Data corrected)
Data of Ref. 16	0.34 ± 0.10	0.45 ± 0.17
HS *A*	0.255	0.237
HS *B*	0.378	0.391
WS	0.273	0.268
GS *B*	0.354	0.393
MS I	0.292	0.285
LS	0.250	0.277
LW	0.277	0.261

Table III presents ratios of the total cross sections for $\pi^{\pm}$ production by the neutral-current to charged-current π^0 production measured by Krenz *et al.* (Ref. 16). In contrast to the previous discussion, we see here that the Hung-Sakurai solution *B* is closer to the data than solution *A* and that the GS *B* model predictions are better than the WS predictions which are low.

Table IV presents ratios measured by Barish *et al.*[18] at the Argonne National Laboratory zero-gradient synchrotron. All of the models make acceptable predictions for the ratio of neutral-current to charged-current π^+ production. No model compares well with the ratio $\sigma(\nu p \to \nu p \pi^0)/\sigma(\nu p \to \mu^- p \pi^+)$, all of them falling below the lower error limit; the MS I prediction comes closest to the data. All of the models make acceptable predictions for the ratio $\sigma(\nu n \to \nu p \pi^-)/\sigma(\nu n \to n \pi^+)$.

A recent analysis[19] of neutral-current data, including only the new Gargamelle data for exclusive pion production,[16,17] has reached the conclusion that solution *A* is preferred to solution *B*. In order to reach this conclusion, agreement between theory and experiment for the exclusive-pion-production reactions has been required only to within 2 standard deviations. With this requirement, both *A* and *B* are again acceptable for π^0 production by neutrinos (see Table I), and now both are also acceptable for $\pi^{\pm}$ production (see Table III). However, only solution *A* becomes acceptable (within the error limits allowed for

TABLE IV. Cross-section ratios measured by Barish *et al.* (Ref. 18) and compared to flux-averaged calculations in the five models.

	$\frac{\sigma(\nu p\to\nu n\pi^+)}{\sigma(\nu p\to\mu^- p\pi^+)}$	$\frac{\sigma(\nu p\to\nu p\pi^0)}{\sigma(\nu p\to\mu^- p\pi^+)}$	$\frac{\sigma(\nu n\to\nu p\pi^-)}{\sigma(\nu n\to\mu^- n\pi^+)}$
Data of Ref. 18	0.13 ± 0.06	0.40 ± 0.22	0.38 ± 0.11
WS	0.091	0.132	0.322
GS *B*	0.099	0.124	0.392
MS I	0.100	0.149	0.351
LS	0.072	0.094	0.285
LW	0.083	0.115	0.291

solution *A*) for π^0 production by antinueutrinos (see Table II). Thus, the antineutrino production of π^0's is the determining factor in this analysis.[20]

In summary, I see that no model is in agreement with all of the available data to within 1 standard deviation. This indicates the need for further experimentation and also for decreasing the uncertainties in and discrepancies between the various methods of handling the problem of corrections for the use of nuclear targets. In view of these problems, both experimental and theoretical, I feel that, at this time, none of the models of the weak neutral current considered in this paper should be conclusively ruled out by consideration of exclusive-pion-production data.

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