Fermi National Accelerator Laboratory

FERMILAB-Conf-83/57-EXP
7410.701

A SEARCH FOR INCLUSIVE OSCILLATIONS OF MUON NEUTRINOS IN THE MASS RANGE, $20 < \Delta m^2 < 900$ eV^2*

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July 1983

*Presented by Wesley Smith at the Meeting of the European Physical Society, Brighton, England, July 20-27, 1983, and contributed to the 1983 International Symposium on Lepton and Photon Interactions at High Energies, Cornell University, Ithaca, New York, August 4-9, 1983.

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Nevis Preprint 1290

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Abstract

A sensitive search for inclusive neutrino oscillations has been performed using two similar detectors running simultaneously at different locations in the Fermilab dichromatic muon-neutrino beam. The preliminary results show no significant oscillation signal and rule out inclusive oscillations of muon neutrinos into any other type of neutrinos for $20<\Delta m^2<900$ eV^2 and $\sin^2(2\theta)>0.03-0.10$.

Introduction

We report preliminary results of a search for oscillation of muon neutrinos into any other type of neutrino for $20<\Delta m^2<900$ eV^2. This search (Fermilab experiment 701) is based on the analysis of 300,000 charged current events in two detectors running simultaneously at different locations. The Fermilab dichromatic neutrino beam produces neutrinos with energies from 40 to 230 GeV.

There are many theoretical suggestions[1] that a neutrino of one type, such as ν_μ, may oscillate into a neutrino of a different type such as ν_e, ν_τ, $\bar{\nu}_\mu$, or some presently unknown neutrino type. If two of the neutrino eigenstates of the weak interaction, $|\nu_\mu\rangle$ and $|\nu_x\rangle$, are quantum mechanical mixtures of the neutrino mass eigenstates $|\nu_1\rangle$ and $|\nu_2\rangle$ with M_1 and M_2 respectively, then:

$$|\nu_\mu\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle \ ,$$
$$|\nu_x\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle \ ,$$

where θ is the mixing angle. The probability P of the appearance of a neutrino of type x at a distance L from the source of a pure ν_μ beam is $P(\nu_\mu \rightarrow \nu_x) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 \frac{L}{E})$, where $\Delta m^2 = M_1^2 - M_2^2$ is the mass difference in eV^2, L is the distance from the source in kilometers and E_ν is the energy of the neutrino in GeV.

Oscillations can be detected from an initially pure beam of ν_μ either by exclusively searching for ν_e and ν_τ downstream of the source or by measuring a change of the ν_μ flux as a function of distance from the source. Oscillations in the channels $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ have been ruled out by exclusive experiments[2,3] for $\Delta m^2 > 1-3$ eV^2 and $\sin^2(2\theta) > 0.006-0.02$. However, recent results from a β-decay experiment[4] indicate an electron neutrino mass of 14 to 46 eV. The existence of neutrino masses in this range is also suggested by astrophysical measurements indicating an abundance of dark matter in the universe.[5,10,11]

Exclusive measurements are insensitive to the neutrino oscillations of the type $\nu_\mu \rightarrow \nu_x$, where ν_x is not necessarily ν_e or ν_τ. This ν_x could be a neutrino associated with a fourth flavor of charged lepton with a mass too high to be produced in present neutrino experiments. Results from e^+e^- experiments[6] indicate that the mass of such a charged lepton must be greater than 16 GeV/c^2. The ν_x could also be a left-handed muon antineutrino which might not be observed because its interactions would be highly suppressed by the V-A structure of the weak interaction. An inclusive or disappearance experiment is sensitive to oscillations into any neutrino type.

The interpretation of disappearance experiments with only a single detector is difficult because conclusions depend critically on the precision of the flux measurements and on assumptions about the energy dependence of total neutrino cross-sections. The uncertainty in the flux as a function of time complicates any comparison of data taken at different distances by moving a single detector with respect to the neutrino source. These systematic uncertainties are minimized for this experiment by the use of two similar detectors simultaneously measuring the interaction rate at two different distances from the neutrino source. We present preliminary results from the first two-detector experiment searching for neutrino oscillations in the mass range 20 $eV^2 < \Delta m^2 < 900$ eV^2.

Experiment

An overview of the Fermilab neutrino line and the two detectors is shown in Fig. 1. Monoenergetic pions and kaons, momentum and sign selected by the Fermilab narrow band beam ($\Delta E_{\pi,K}/E_{\pi,K}$=11%), decay in a 352 m evacuated pipe. Hadrons and muons are absorbed by steel and earth shielding. The detector target centers are located 715 m (Wonder Building) and 1116 m (Lab E) from the center of the decay pipe. Figure 2 shows the neutrino detectors in Lab E and the Wonder Building. Both detectors consist of a target calorimeter, instrumented with spark chambers, which is followed by a toroidal muon spectrometer.

The Lab E target calorimeter consists of 690 tons of 3m x 3m x5 cm thick steel plates. Spark chambers are located after every 20 cm of steel and liquid scintillation counters are located after every 10 cm of steel. The downstream 2/3 of this target, including 444 tons of steel (112 plates), 26 spark chambers and 56 scintillation counters, was used for the oscillation measurement. The Wonder Building 108 ton target calorimeter was made of 1.5 m x 1.5 m x 5 cm thick steel plates. Fifty-six 1.5m x 1.5m doped acrylic scintillation counters were located after every 10 cm of steel and 17 1.5 x 3 m spark chambers were located after every 30 cm of steel. All spark chambers in both detectors were read out magnetostrictively in two dimensions with a resolution of 0.5 mm. Minimum ionizing muons were used to calibrate the scintillation counters of both detectors. The Lab E target had also been calibrated with a hadron beam. Both detectors have a hadron energy resolution of $\Delta E= 0.9 \sqrt{E_h}$(GeV).

The Lab E muon spectrometer consists of three 1.6 m long toroidal iron magnets with a 1.8 m outer radius and a 12.7 cm radius central hole for the excitation coils. Each toroid is followed by five 3 m x 3 m spark chambers. The total P_t kick of the toroids is 2.4 GeV/c and the momentum resolution is 11%. The Wonder Building muon spectrometer consists of a single 2.4 m long iron toroid 1.5 m in outer radius with a 12.7 cm radius central hole. The toroid is followed by six planes of spark chambers. The total P_t kick is 1.2 GeV/c and the momentum resolution is 15%.

The trigger employed in the oscillation measurement required a particle to penetrate the downstream part of the calorimeter and one toroid. To achieve this, the trigger required a signal in counters T0 and T2 (cf. Fig. 2), no signal in a charged particle veto counter preceding the target, and at least one minimum ionizing signal in the target calorimeter. The T2 requirement assured that the muon could be momentum analyzed. The detectors and their triggers are described in greater detail in Refs. 7, 8, and 9.

The initial charged current trigger sample contains 160,000 events in Lab E and 140,000 events in the Wonder Building. These were obtained from an integrated flux of 3.4×10^{18} protons on target at several selected secondary energies of 100, 140, 165, 200 and 250 GeV/c, yielding a large range of neutrino energies. The requirement that data come from running when both detectors are operating at the same time and that the secondary hadron beam is correctly steered reduced the sample to 110,000 Lab E events and 94,000 Wonder Building events. The analysis is then restricted to events in a 1.3 m x 1.3 m square in the Wonder Building. This fiducial cut is scaled to the Lab E detector by the ratio of the two detector's distances to the decay pipe center (1.56). The analysis in each detector also requires that the event vertex is found between scintillators 55 and 18. These cuts prevent hadron shower leakage outside of the fiducial volume. After these fiducial volume cuts there are 49,000 events in Lab E and 48,000 events in the Wonder Building.

The events are required to pass a series of geometrical cuts which are applied twice to each event. First the cut is applied in the detector in which the event is found. Second, the event is translated along a straight line (assuming that the neutrino had come from the decay pipe center) to the same relative vertex point in the target of the other detector. Here the cut is again applied. This ensures that each event passes analysis cuts in both detectors. The first analysis cut is a 200 mr limit on the angle of the muon. The muon target track is then extrapolated on a straight line through the toroid to the T2 counter (c.f. Fig. 2) where it must lie within a square 2.95 m on a side. (The actual T2 counter is 3.25 m on a side and the effect of the toroid is to bend the muon toward the center of the counter.) The event track must stay within the 1.5 m x 3.0 m spark chamber area in the Wonder Building detector until it has passed six chambers, to ensure track identification. Finally, the extrapolated straight track must go through the toroid steel for 80% of its length, avoiding escape outside the toroid or in the center hole. These cuts assure that each accepted event satisfies the trigger requirements and can be fully reconstructed in both detectors. Those events which pass these cuts are then required to have a muon with momentum greater than 7.5 GeV/c. The final data sample consisted of 36,100 Lab E and 35,500 Wonder Building events of which about one third are kaon neutrino events and two thirds are pion neutrino events.

The oscillation measurement is performed by comparing the number of events in the two detectors as a function of neutrino energy. The source of the neutrinos is a distribution of pions and kaons in the decay pipe. The kinematics of the parent pion/kaon decay determine a correlation between the neutrino angle (which translates into a particular interaction radius in each detector) and the neutrino energy. There are, at a given radius, neutrinos of two distinct energies arising from the decay of either pions or kaons. Neutrinos from kaon decay have energies near the hadron beam energy and neutrinos from pion decay cover a range below 0.45 of the secondary hadron beam energy setting.

The measured total neutrino energy is the sum of the hadron energy measured in the calorimeter and the muon energy measured in the spectrometer. Figure 3 shows a scatter plot of the measured energy vs. radius of events in the Lab E detector at a secondary hadron beam energy setting of 165 GeV. The beam centers used in this analysis are determined to better than 1 cm using the vertex distribution of high energy pion events. Two bands are seen in Fig. 3 corresponding to neutrinos from pion and kaon decay. Most of the events in the region between the two bands are attributed to neutrinos from the three-body decay of kaons. The band structure is used to separate events into the two types of neutrinos. Events at larger radii have lower neutrino energy than those near the beam center.

A comparison of the total energy distributions in the two detectors is shown in Fig. 4 for a secondary hadron beam energy setting of 165 GeV. This comparison shows that the two detectors are similar in calibration and resolution. The relative difference in average total energy for pion and kaon decay neutrino events between the two detectors at each energy setting is always less than 2.5%. The measured total energy of the neutrino events is only used in determining whether the events are due to neutrinos from pion or kaon decay. A change of 2.5% in the relative energy calibration of the two detectors changes the ratio of pion decay neutrino events in the two detectors by 0.3% and the ratio of kaon decay neutrino events by 0.6%.

Results

To compare the number of neutrino events in the two detectors as a function of energy, the events are separated into those originating from neutrinos from the decay of pions (ν_π) and kaons (ν_K) by using the radius and visible energy correlation. The radius information and the neutrino type are used to determine the mean energy. The ν_π events are further separated into those with radius of 0-50 cm and those with radius 50-100 cm in Lab E. These bins are scaled to the Wonder Building detector as if all neutrinos originated at the decay pipe center. The number of events in these three bins for the Lab E detector is divided by the corresponding number for the Wonder Building detector at each energy setting. These ratios are plotted versus the average neutrino energy of each bin in Fig. 5. The ratios of events in Fig. 5 are corrected for the ratio of the detector livetimes. These corrections range between 0.1% and 15%. There are also corrections of order 1% for the relative reconstruction efficiencies of the two detectors as determined by hand-scanning reconstruction failures and a correction of 3.7% for the greater mass of the Lab E fiducial target volume.

In the data of Fig. 5 all binning and software cuts are made assuming that all the neutrinos originated from the center of the decay pipe. This assumption leads to additional corrections which need to be applied to the data in Fig. 5. They arise mainly from the exponential decay distribution in the decay pipe, solid angle effects for the two detectors, and the secondary hadron beam angular divergence, which is measured by a profile monitor of the secondary beam in the decay pipe. The angular divergence is also measured by a monitor of the muons from pion and kaon decays, which is placed after the hadron dump. These monitors yield an rms angular divergence of θ_x=0.15 mr and θ_y=0.2 mr with an error of 0.05 mr. Further studies of angular divergence are in progress. These studies use beam distributions in the profile monitors taken while a 1.3 cm x 1.3 cm collimator mapped out the beam area directly upstream of the decay pipe. The effect of the angular divergence is to make the neutrinos appear to come from upstream of the decay pipe center. Corrections for these effects are calculated from full reconstruction of Monte Carlo events generated from a neutrino flux determined by modeling the production and transport of the secondary hadron beam. In addition, neutrinos from π and K decay before the momentum and sign selection that precedes the decay pipe (wideband background) result in small corrections of 1% to the ν_π ratio and 0.5% to the ν_K ratio. These corrections, which differ for ν_π and ν_K events at the various energy settings, are shown in Fig. 6.

Application of the corrections to the data gives the preliminary event ratios shown in Fig. 7. Neutrino oscillations would appear as an energy dependent ratio which is different from unity. No apparent difference from 1.0 is indicated by the data and a fit with no oscillations gives a χ^2 of 17 for 15 degrees of freedom (C.L.=70%).

There are several sources of systematic error in the overall event ratios. The principle source is the uncertainty of ±0.05 mr in the angular divergence of the secondary hadron beam. A change of ±.05 mr in the angular divergence causes changes of up to 1.5% in the event ratios for low radius ν_π events, 0.5% for high radius ν_π events, and 0.5% for ν_k events. The changes are correlated and different at the various energy settings. The errors in the determination of the beam centers in the detectors and the amount of wide band background cause changes of up to 0.3% in the overall event ratios. Additional systematic errors come from the uncertainty in the relative target masses

(0.3%); the relative live flux in the two detectors (1%); the front counter veto deadtime (0.3%); the reconstruction ine^ffi^ciencies (0.6%); and the relative locations along the beamline of the decay pipe and detectors (0.1%). The total systematic normalization error in the Lab E to Wonder Building event ratio is 1.5%.

The 90% confidence level limits shown in figure 8 have been extracted from the data (cf. fig. 7). The limits include the effects of systematic errors. All oscillations with Δm^2 and $\sin^2(2\theta)$ to the right of the curve are excluded. This limit is obtained by finding the $\sin^2(2\theta)$ for each Δm^2 where the χ^2 for the data of figure 7 relative to an oscillation prediction (including the finite decay pipe length and energy resolution) becomes greater than 22.3, which is the 90% confidence level value for 15 degrees of freedom. For these calculations, an independent normalization uncertainty of ±1.5% is assumed for each secondary momentum setting and the correlated changes induced by an error of ±0.5 mr in the angular divergence are included.

In the mass region of Δm^2 between 20-900 eV^2 no significant signal was observed down to mixing angles with $\sin^2(2\theta)$= 0.03-0.10 (θ=5-18^o). If $\sin^2 2\theta >$ (0.03-0.10) and only one neutrino has a mass, then its mass must be outside the range 4-30 eV; or if two neutrinos have mass then the range $20<2m\Delta m<900$ eV^2 is excluded, where m is the average neutrino mass. Depending on the neutrino mixing angle, the above result restricts the possible neutrino masses commonly used to account for the dark matter in the universe[10] ($3<m_\nu<100$ eV). These results are preliminary. An analysis is in progress in order to reduce the systematic errors and increase the statistics by a factor of 1.5.

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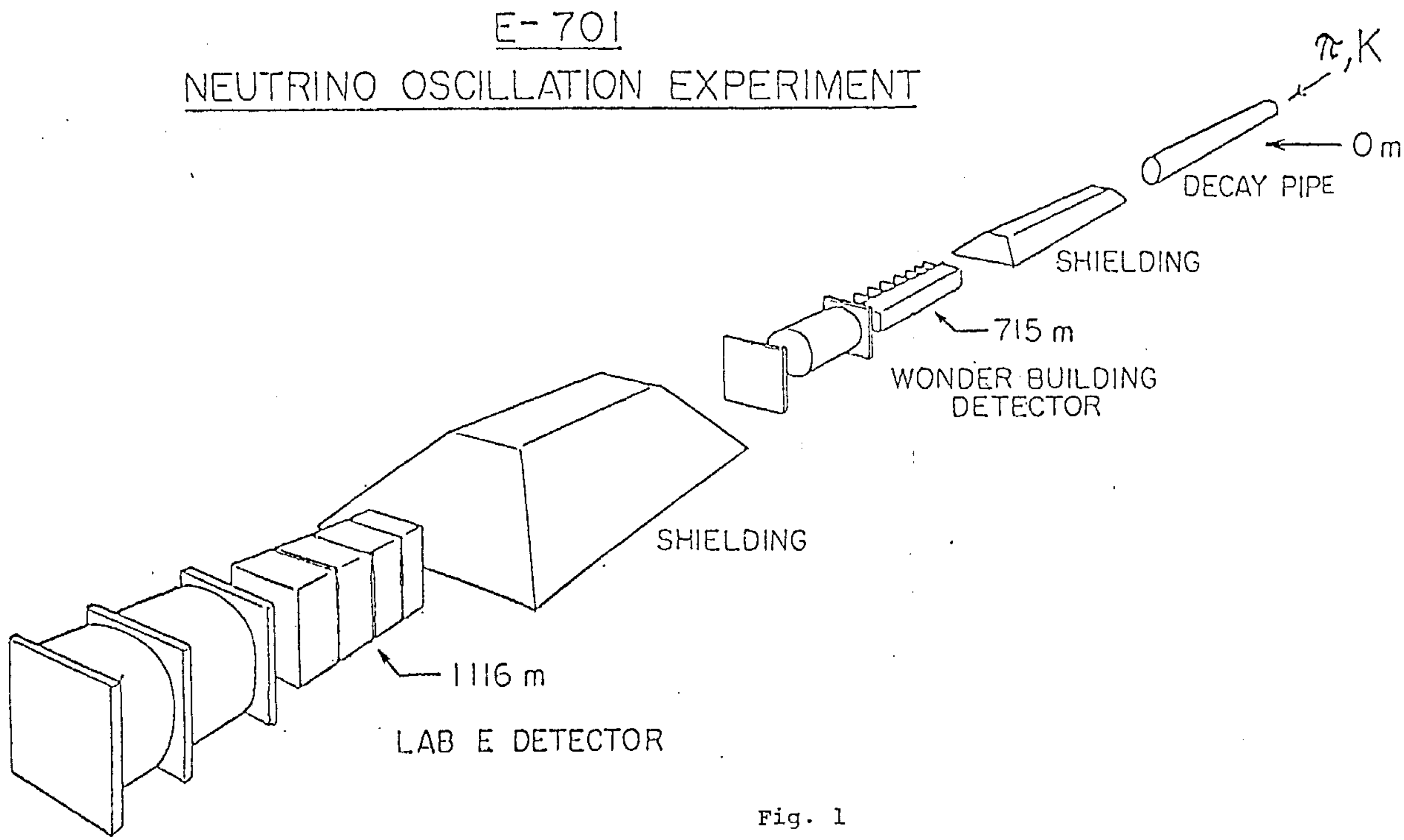
E- 701
NEUTRINO OSCILLATION EXPERIMENT
π,K
0 m
DECAY PIPE
SHIELDING
715 m
WONDER BUILDING
DETECTOR
SHIELDING
1116 m
LAB E DETECTOR

Fig. 1

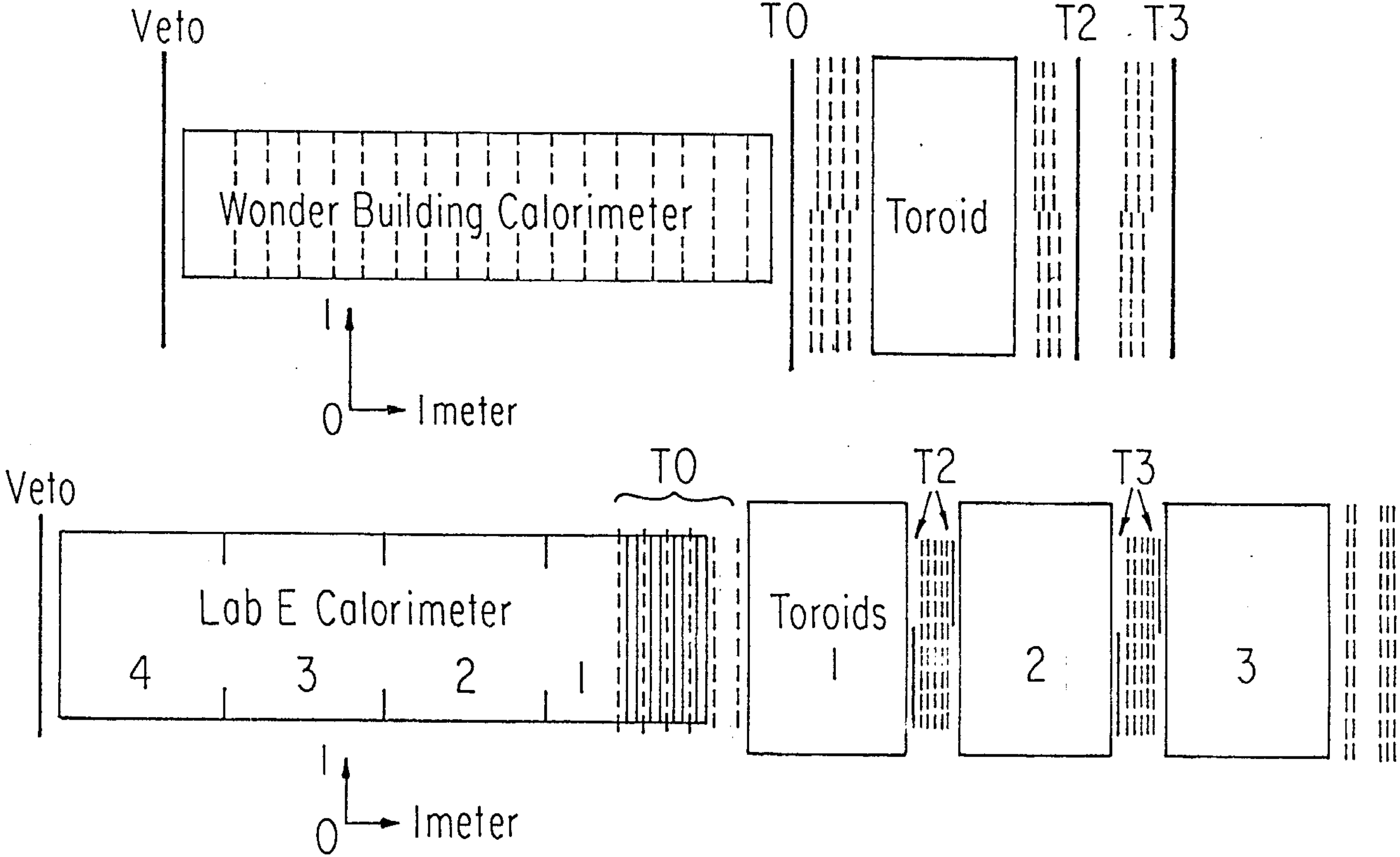

Fig. 2: Layout of the Two Detectors

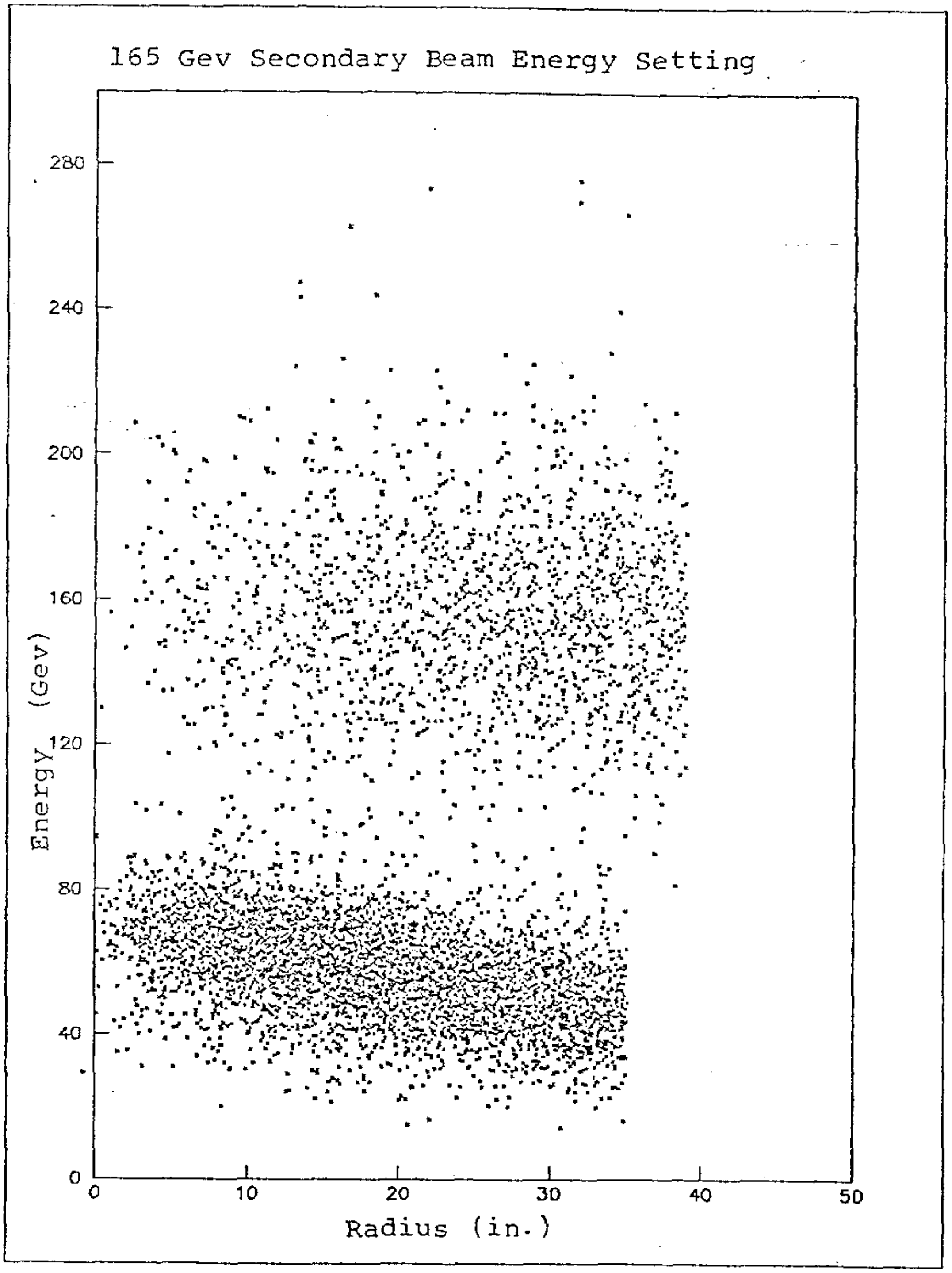

Fig. 3: Energy vs. Radius for Lab E events.

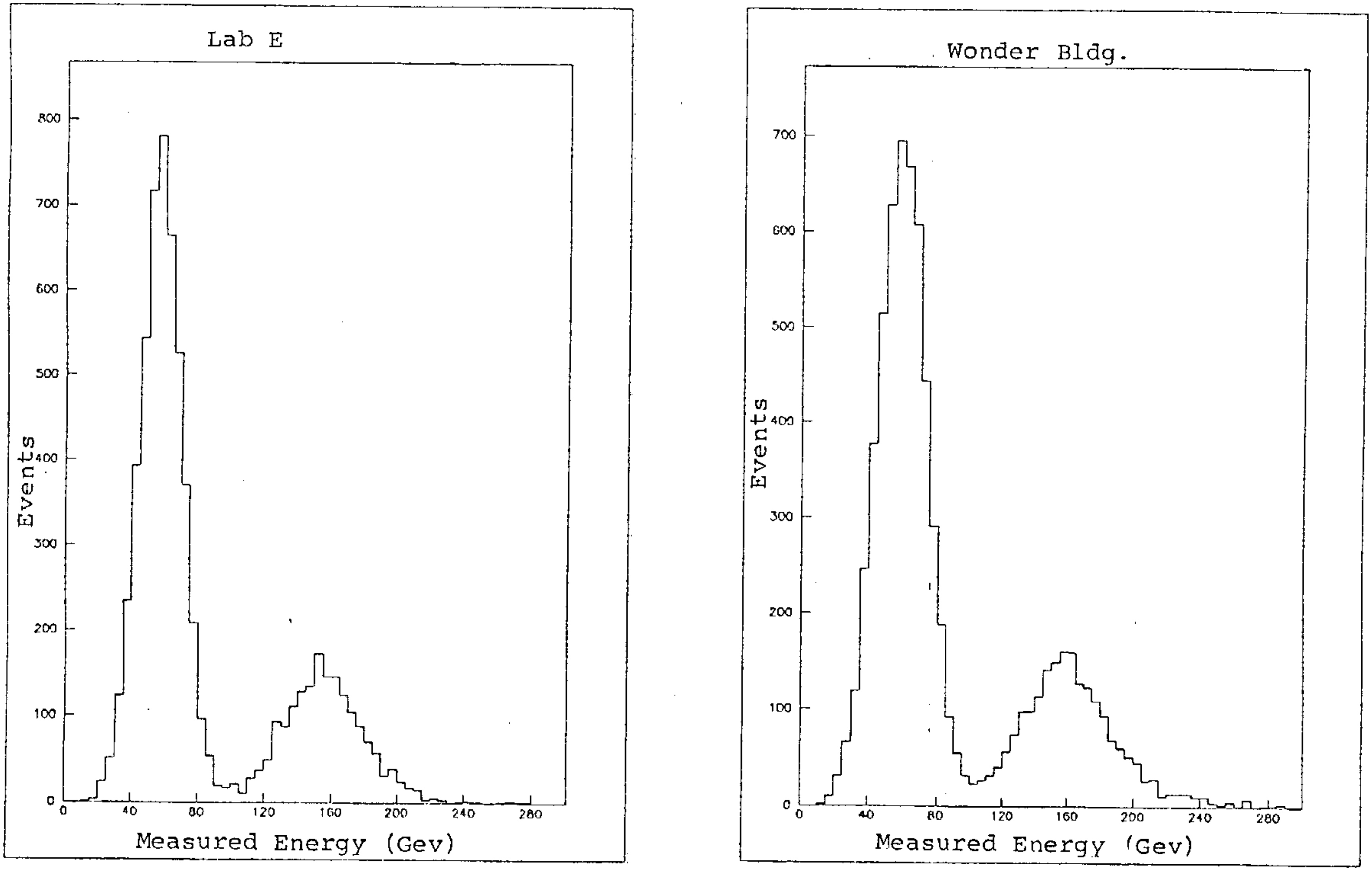

Fig. 4: Total Measured Energy vs. Number of Events for 165 Gev Secondary Beam Energy Setting

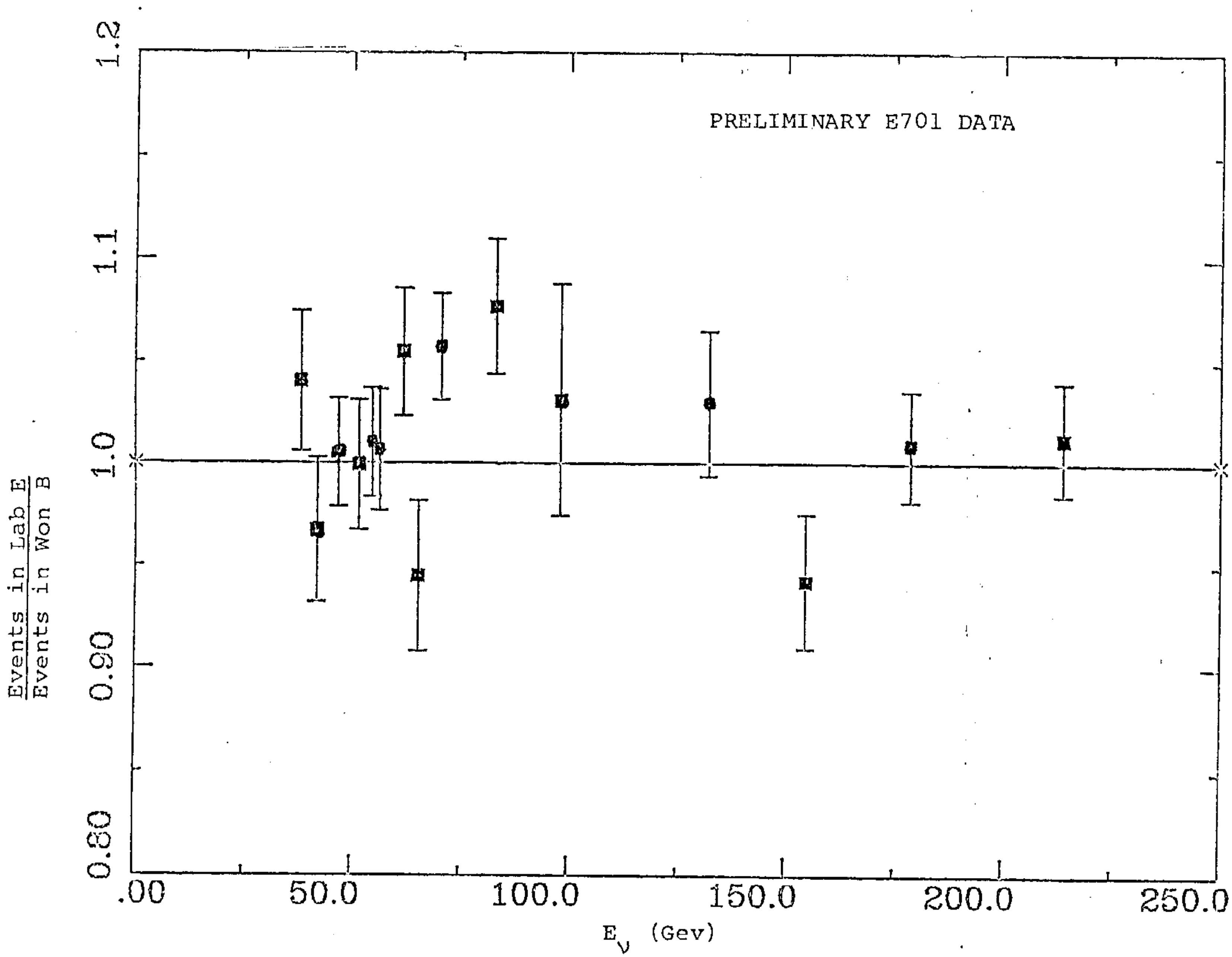

Fig. 5: Raw Event Ratio vs. Energy

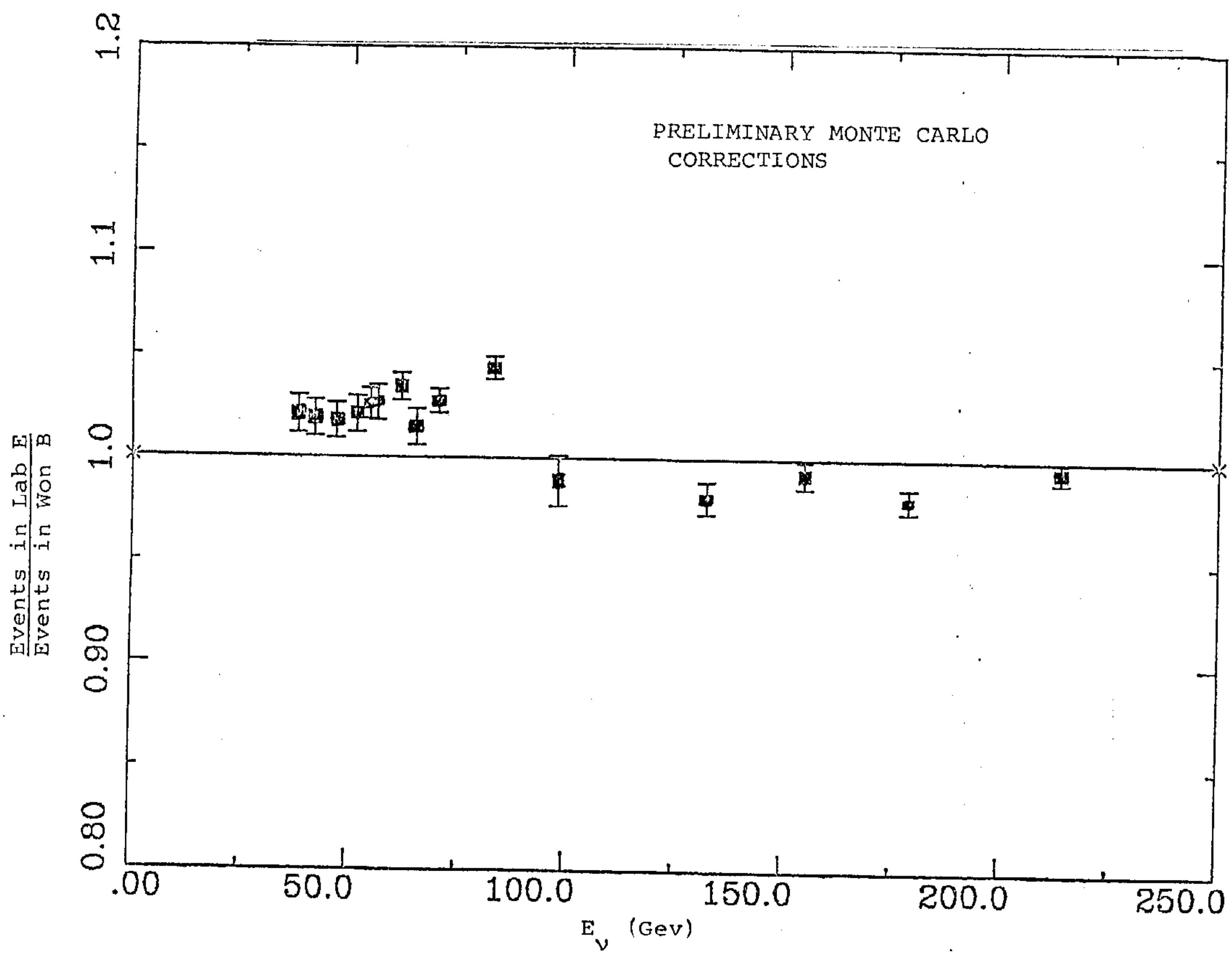

Fig. 6: Calculated corrections to the data in Fig. 5

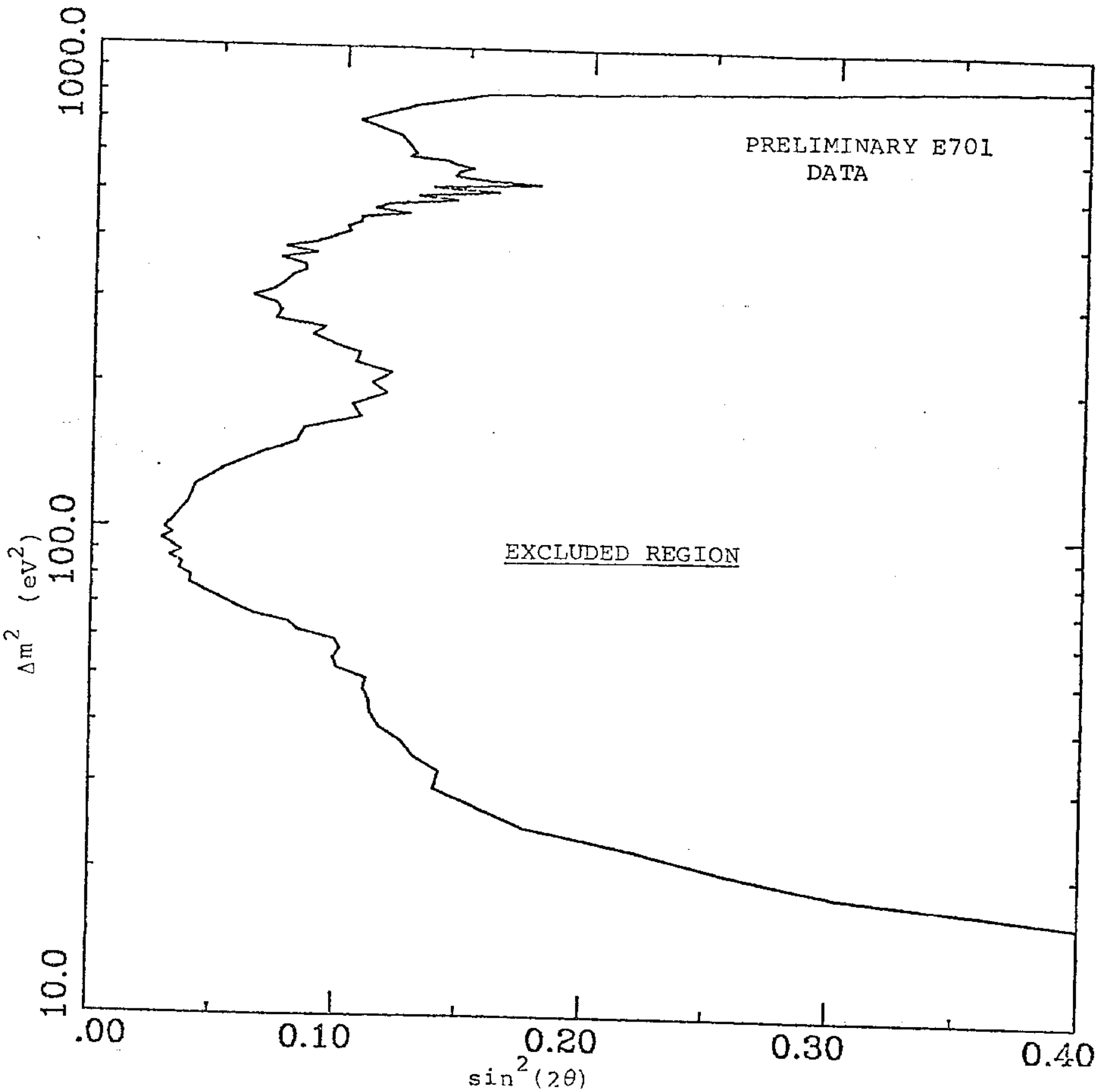

Fig. 8: Δm^2-$\sin^2(2\theta)$ Region Excluded by E701 Data

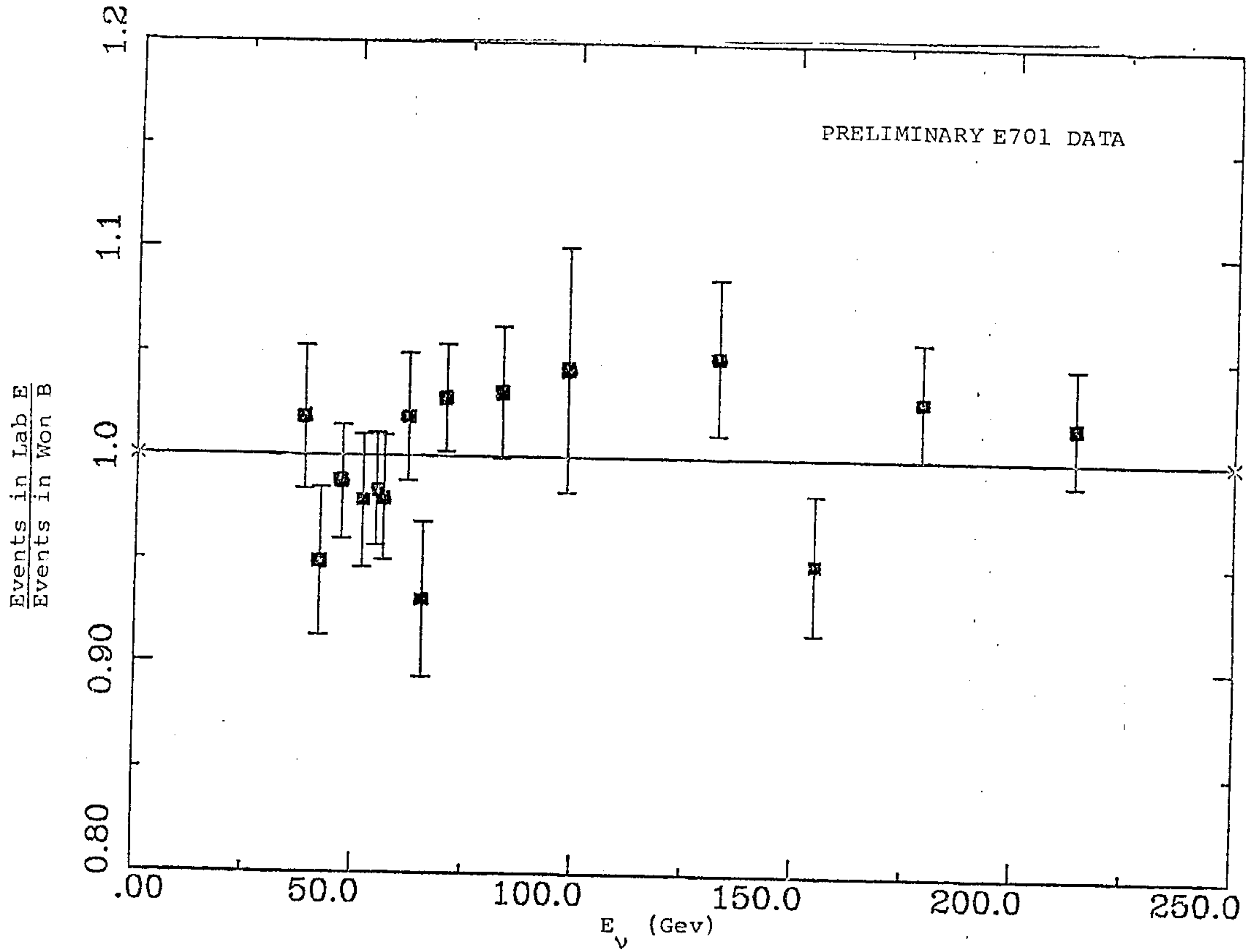

Fig 7: Final Event Ratio After Corrections