Structure Function/Electroweak Neutrino Beams

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Proton Driver Workshop
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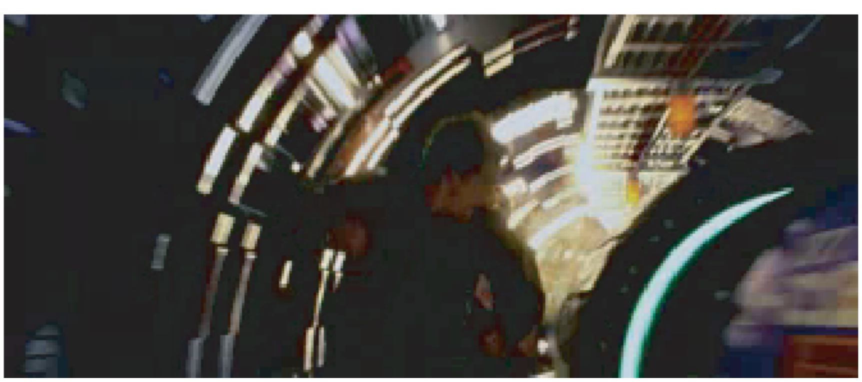
Outline

§1. Dichromatic Beams

§2. Quadrupole Triplets

§3. Sign-Selected Quadrupole Train

§4. Tagged Neutrino Beam



Overview of Neutrino Beams

Prior Beams

§1. Horn (MINOS)

- Low Energy Portion
- Separate $\nu, \bar{\nu}$

§2. Dichromatic (Cross-Section Measurements & Oscillations E616-701)

- Selects Mesons of Particular Momentum
- Low Flux

§3. Quadrupole Triplet (Structure Functions E744-770)

- Mixed $\nu, \bar{\nu}$
- High Energy, High Statistics

§4. Sign-Selected Quadrupole Train (E-815=NuTeV) (Electroweak, Strange Sea)

- Split $\nu, \bar{\nu}$
- Lower Statistics than QT
- ν_e Content Better Understood

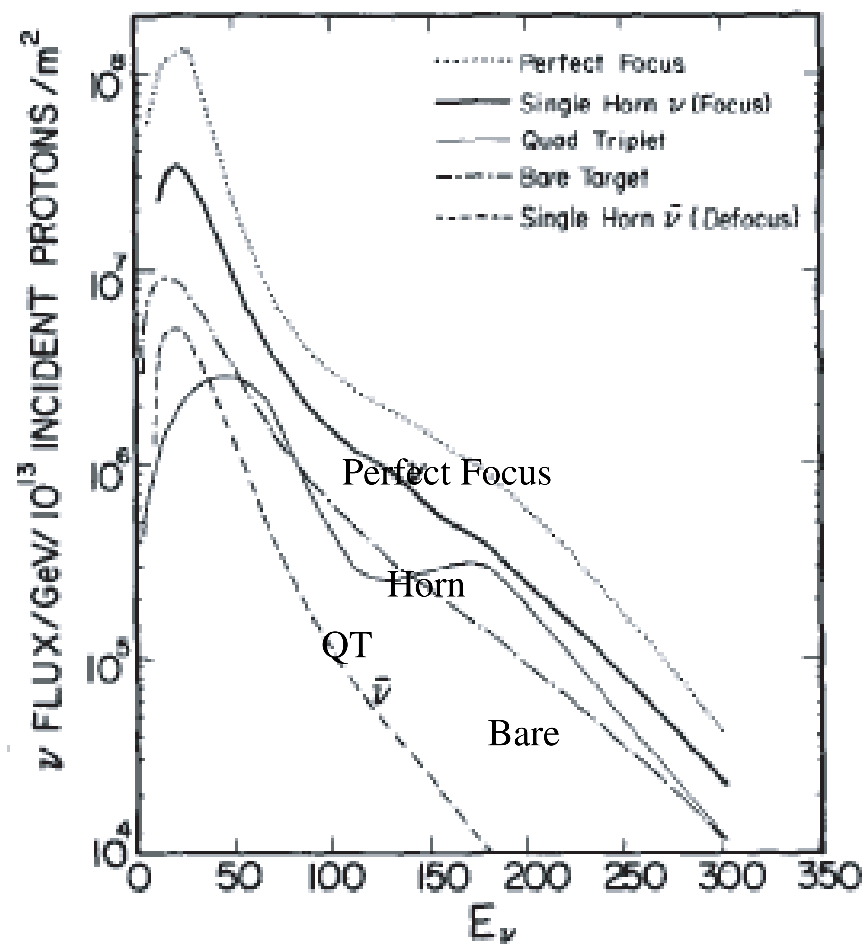


Figure 9 The calculated flux of neutrinos from various broad-band focusing devices used at Fermilab compared to that which would result from a perfect focusing device. The proton beam energy has been taken to be 400 GeV.

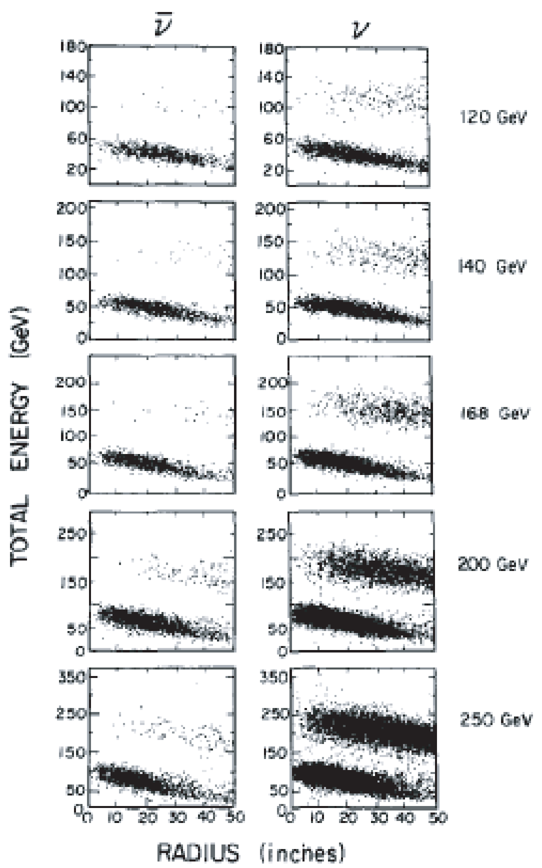
- Rule-of-Thumb:
  Horn (p_T focusing $\leq 1/2$ of Perfect Focusing)

Dichromatic Beams

- Momentum Select π, K Mesons:

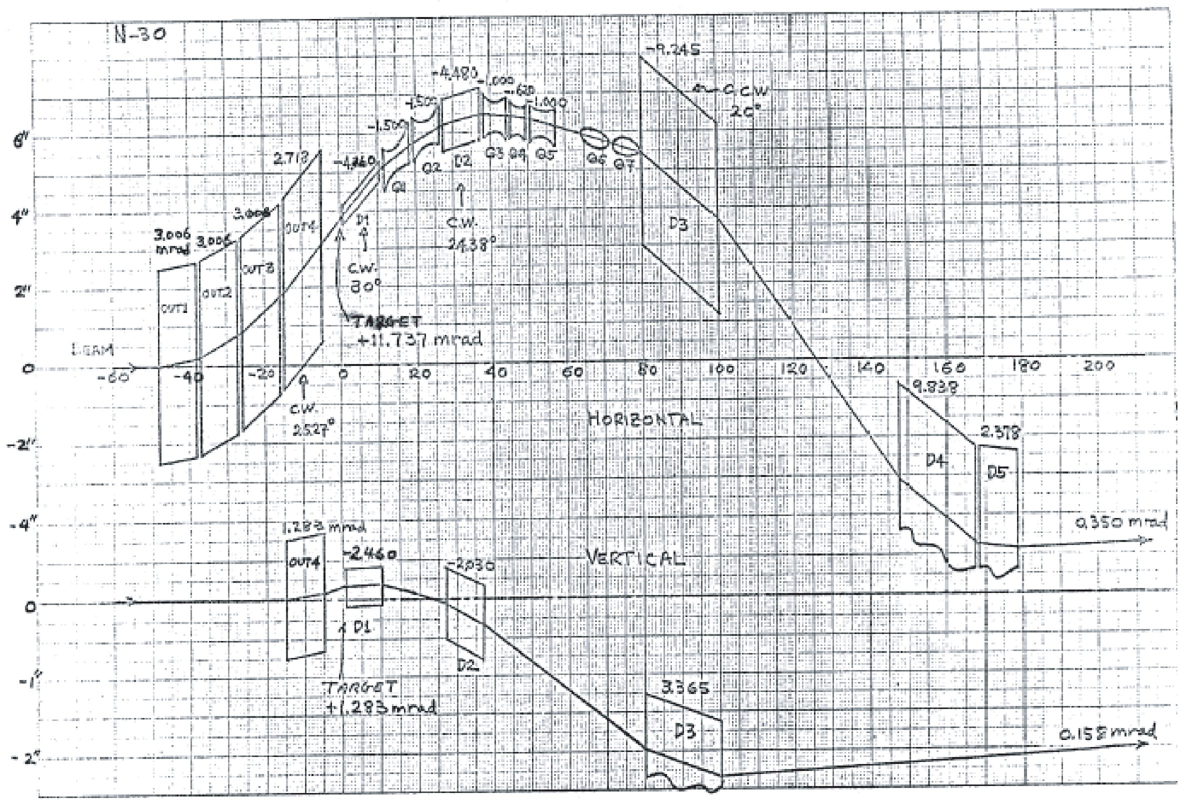
$$E_\nu = \frac{E_{\nu,\ \mathrm{max}}}{1+\gamma^2\theta^2}$$

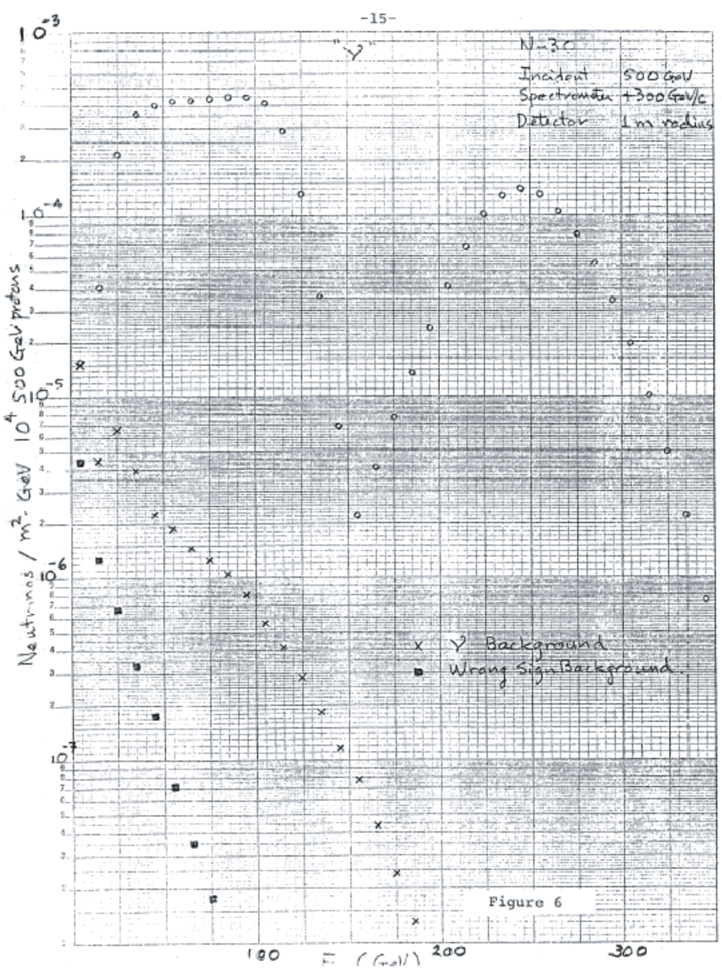
$$E_{\nu,\ \mathrm{max}} = E_{\pi,K}\left[1 - \frac{m_\mu^2}{m_{\pi,K}^2}\right]$$



Correlation between Position and E_ν: π-Band, K-band

(Fisk and Sciulli, Ann. Rev. Nucl. Sci. 1982: 32)





How things were done in
"the good old days"
--no PC's
--no PAW
--no NTUPLES

TM-0661 (Stutte et al.)

Flux Measurement

- Measure by Ion Chambers, Toroids, etc.
- Measure π/K fraction with Cerenkov

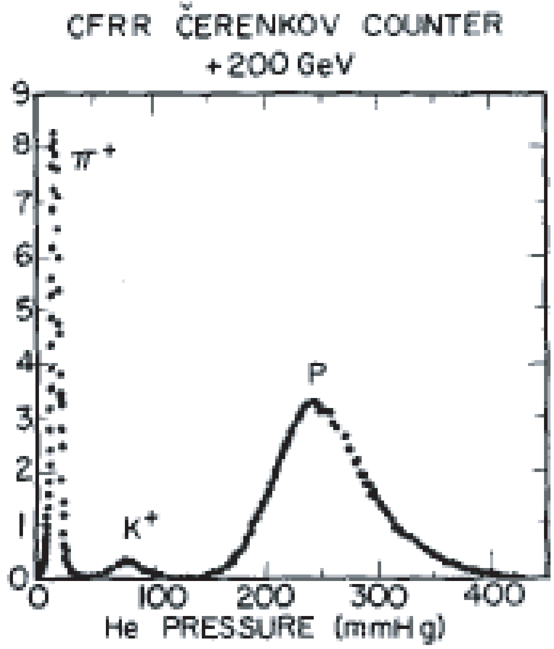
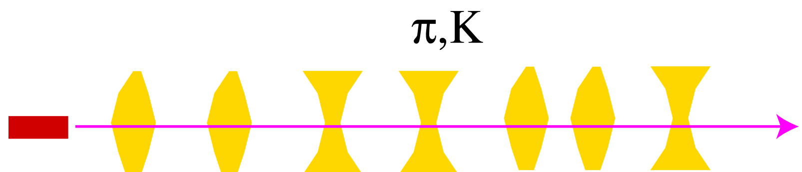


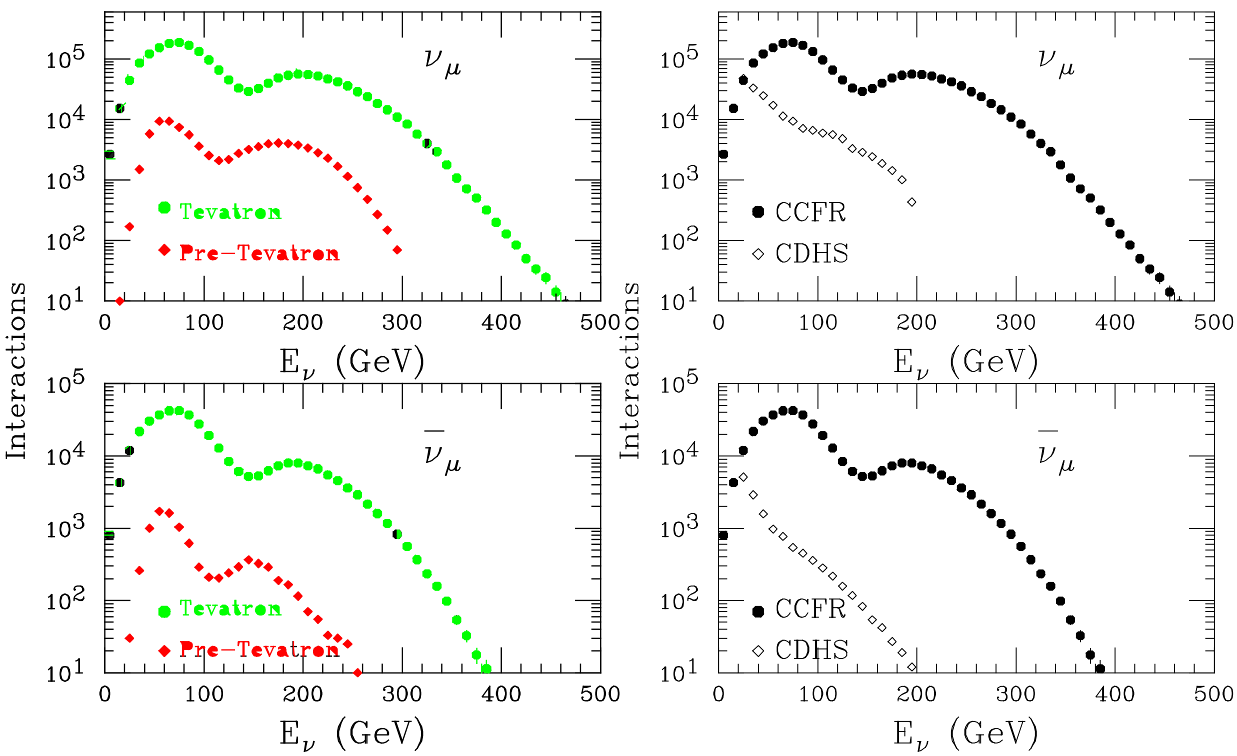
Figure 11 The net Čerenkov light per beam particle transmitted through a small (0.7–1 mrad) iris as a function of helium pressure. The peaks occur at the pressures expected for pions, kaons, and protons at this setting of the dichromatic beam (200 GeV). The areas under the peaks are directly proportional to the relative fractions of these particles in the beam.

- This beam used for Total Cross-Section (more later)
- Oscillation:

  Until NuTeV, best ν_μ Disappearance at High Δm^2

Quadrupole Triplet





- Highest Energy and Flux
- Structure Functions, Dimuons, Oscillations, WMA

Optics of Quad Triplet

- Thin Lenses
  - Quadrupoles are "Lenses"
  - Focusing or Defocusing in Transverse Plane
  - Can Calculate f in thin-lens approximation
  - Point-to-Parallel
- Typical QT:

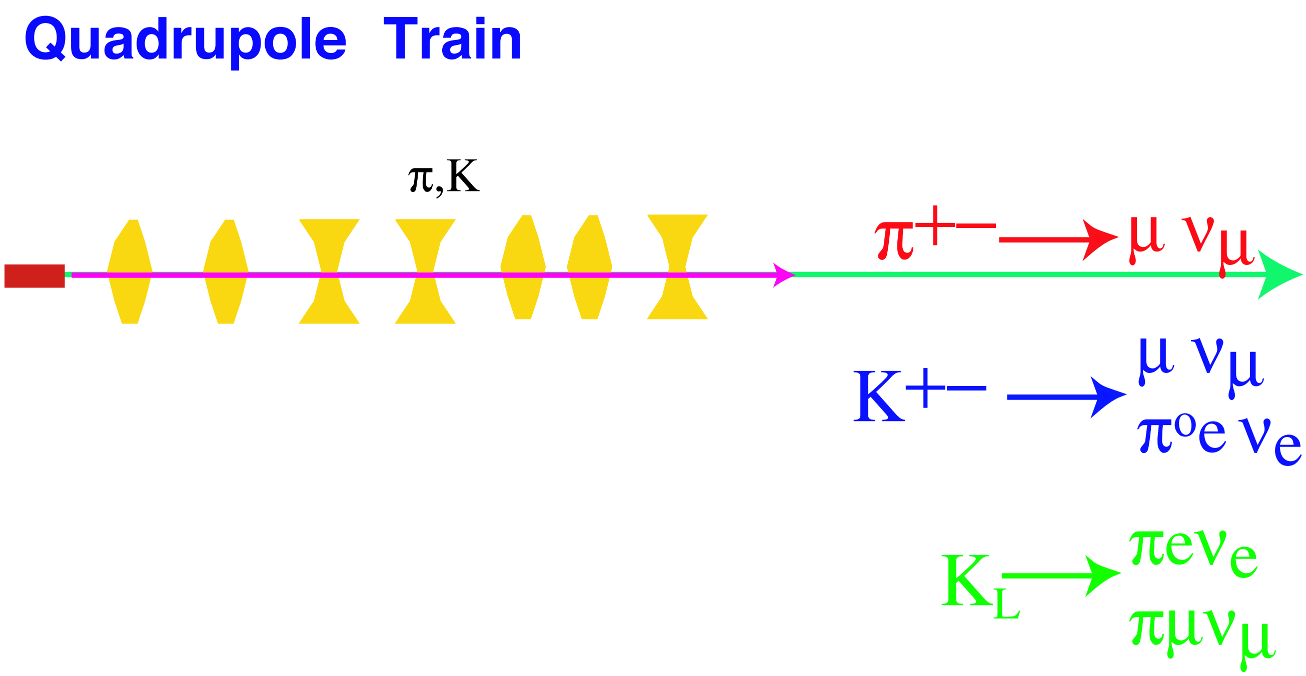
- Really Need Just a Doublet,
  But 3rd Quad Improves
  Behavior in Both Planes at Once

$$\frac{1}{f} = -\frac{qBL}{ap}$$

- And go back to "Image as Object" in Optics

Why Not More Quad Triplet?

Quadrupole Triplet Was Best, but Problems



§1. Mixed $\nu, \bar{\nu}$ Meant Can't
Experimentally Separate
neutral current $\nu, \bar{\nu}$
Measure Combination of $R_\nu, R_{\bar{\nu}} \Leftrightarrow \sin^2\theta_W, \rho$

§2. Also Have Charm Mass Problem:

- No Subtraction in $R_\nu = \sigma(\nu, \mathrm{NC})/\sigma(\nu, \mathrm{CC})$

§3. Allows $K_L \rightarrow \pi e \nu_e$

- Source of ν_e which can fake neutral currents
- Production not well known enough, big error!

Measuring the WMA with Neutrinos

Llewellyn Smith Relations:

$$R^{\nu} = \frac{\sigma^{\nu}_{NC}}{\sigma^{\nu}_{CC}} = \rho^2 \left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W (1 + r)\right)$$

$$R^{\overline{\nu}} = \frac{\sigma^{\overline{\nu}}_{NC}}{\sigma^{\overline{\nu}}_{CC}} = \rho^2 \left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W \left(1 + \frac{1}{r}\right)\right)$$

$$r = \frac{\sigma^{\overline{\nu}}_{CC}}{\sigma^{\nu}_{CC}} \text{ Measured From Data}$$

Isoscalar target composed of only u,d quarks at tree level

- Typically Have *Assumed* ρ from SM and fit $\sin^2\theta_W$
- Big Change With NuTeV:
  - Now Two Equations, Two Unknowns:

$$R^{\nu}, R^{\overline{\nu}} \Leftrightarrow \rho, \sin^2\theta_W$$

Measurement, continued

$$
\begin{aligned}
R^{\pm} &= \frac{\sigma^{\nu}_{NC} \pm \sigma^{\overline{\nu}}_{NC}}{\sigma^{\nu}_{CC} \pm \sigma^{\overline{\nu}}_{CC}} \\
R^{-} &= \rho^2 \left(\frac{1}{2} - \sin^2\theta_W\right) \\
R^{+} &= \rho^2 \left(\frac{1}{2} - \sin^2\theta_W + \frac{10}{9}\sin^4\theta_W\right)
\end{aligned}
$$

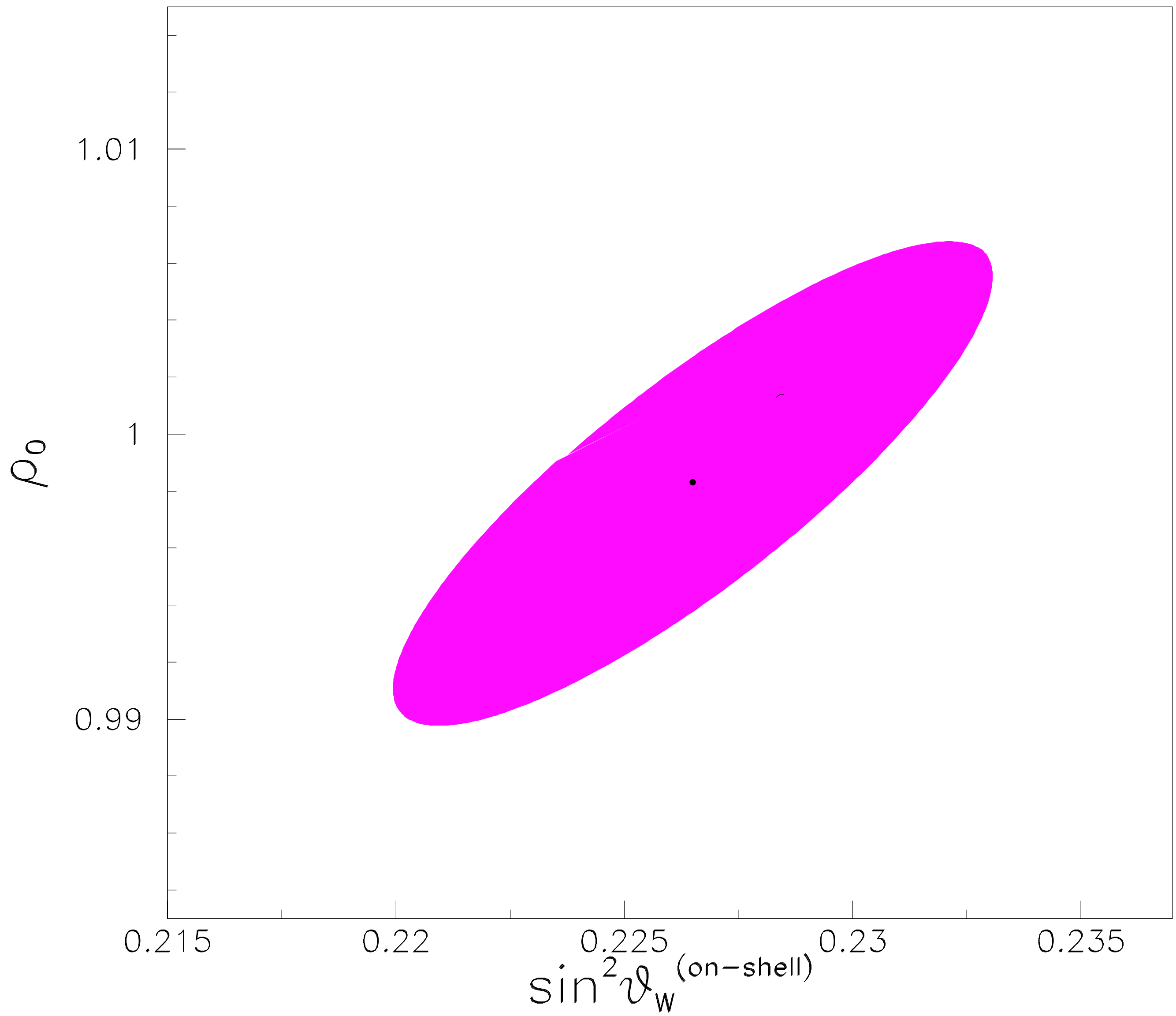
R^- Is Formed From Differences:

- R^- Contributions From Ocean Cancel in $\nu, \bar{\nu}$ Subtraction
  - Charm production error from d_V-quarks only (Cabibbo suppressed and at large x)

- Requires Separate ν and $\overline{\nu}$ Beams

$\Rightarrow$ NuTeV SSQT

Soundbite Version



- Fixing ρ and reporting R^-, R_ν is very close to

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

- This Is What We Usually Quote

The NuTeV Result

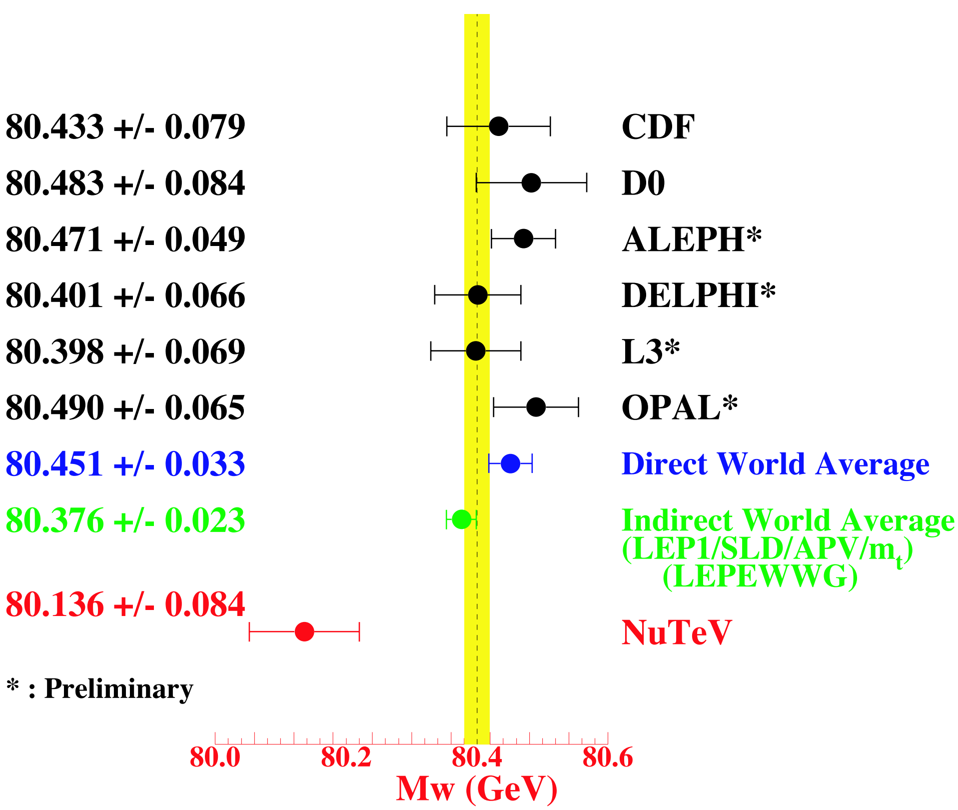
NuTeV Measures:

$$\sin^2\theta_W^{(\text{on-shell})} = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$$
$$- \quad 0.00022\times\left(\frac{M_{\text{top}}^2-(175\text{ GeV})^2}{(50\text{ GeV})^2}\right)$$
$$+ \quad 0.00032\times\ln\left(\frac{M_{\text{Higgs}}}{150\text{ GeV}}\right)$$

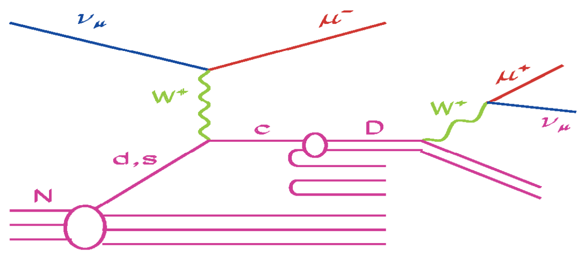
cf. standard model fit (LEPEWWG): 0.2227 ± 0.00037

A discrepancy of $3\sigma\ldots$

$$\sin^2\theta_W^{(\text{on-shell})} \equiv 1 - \frac{M_W^2}{M_Z^2}$$



And the Strange Sea



Don't know leading muon; make statistical guess in QT but SSQT tells you

FIG. 1. Dimuon production in ν-nucleon DIS from scattering off a strange or down quark (LO QCD charm production).

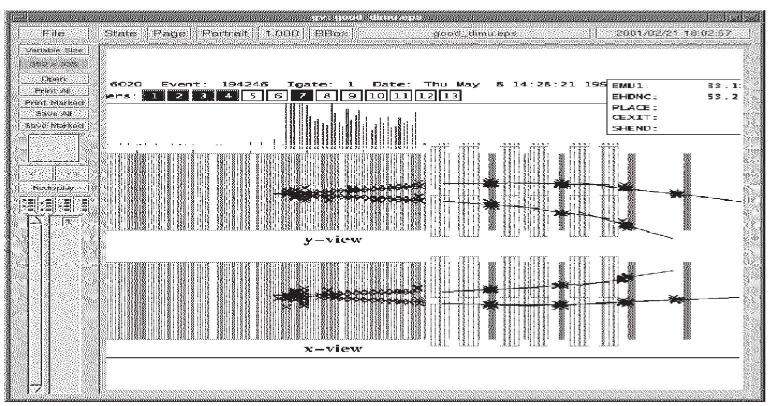
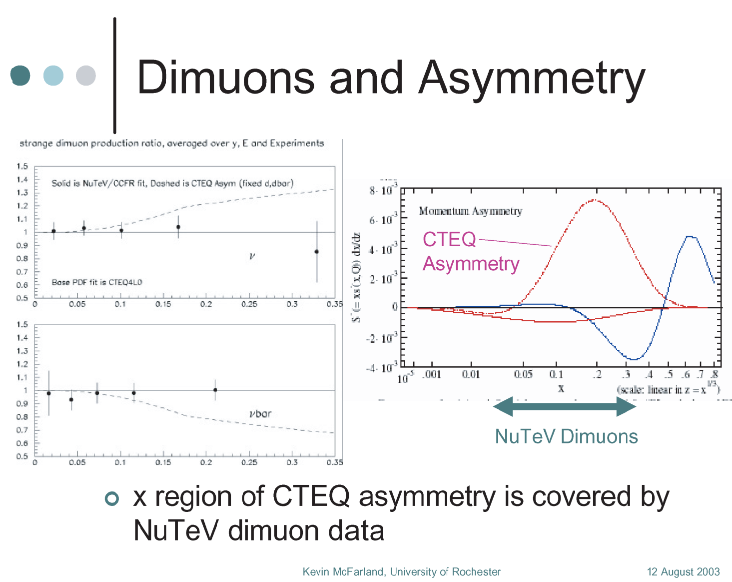
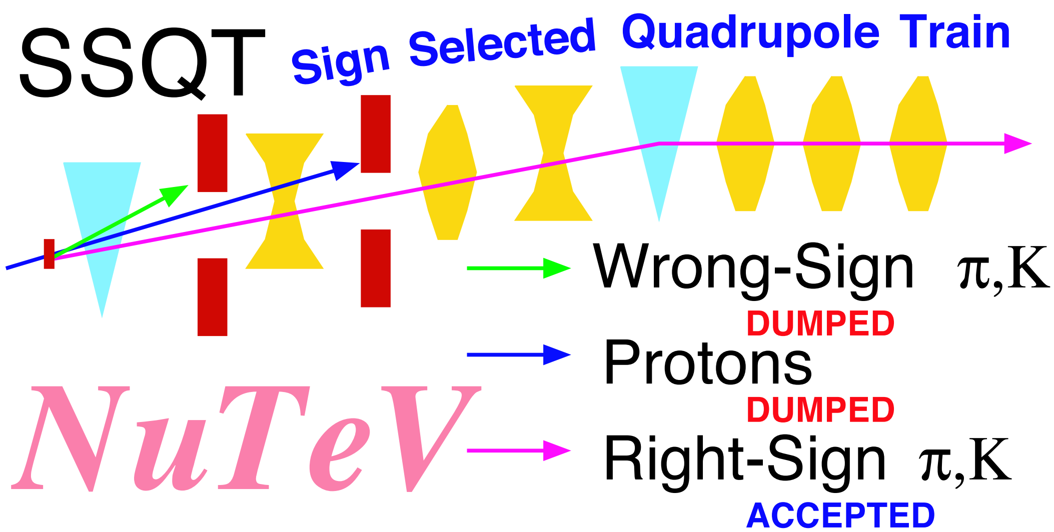


FIG. 3. Typical dimuon event.



Sign-Selected Quadrupole Train



- Basically Wedge QT between Dipoles:
- Resulting beam is almost purely ν or $\overline{\nu}$:
  ($\overline{\nu}$ in ν mode 3×10^{-4}, ν in $\overline{\nu}$ mode 4×10^{-3})
- Beam is $\sim$1.8% electron neutrinos
  - But Troublesome $K_L \to \nu_e$ Gone,
    Since K_L Head off Into Dumps,
    Away From Beam Direction
- About Half of QT flux/per proton
  - Switch All Polarities to Change
  - Move Dumps Transversely
- See FNAL TM-1884, -2040

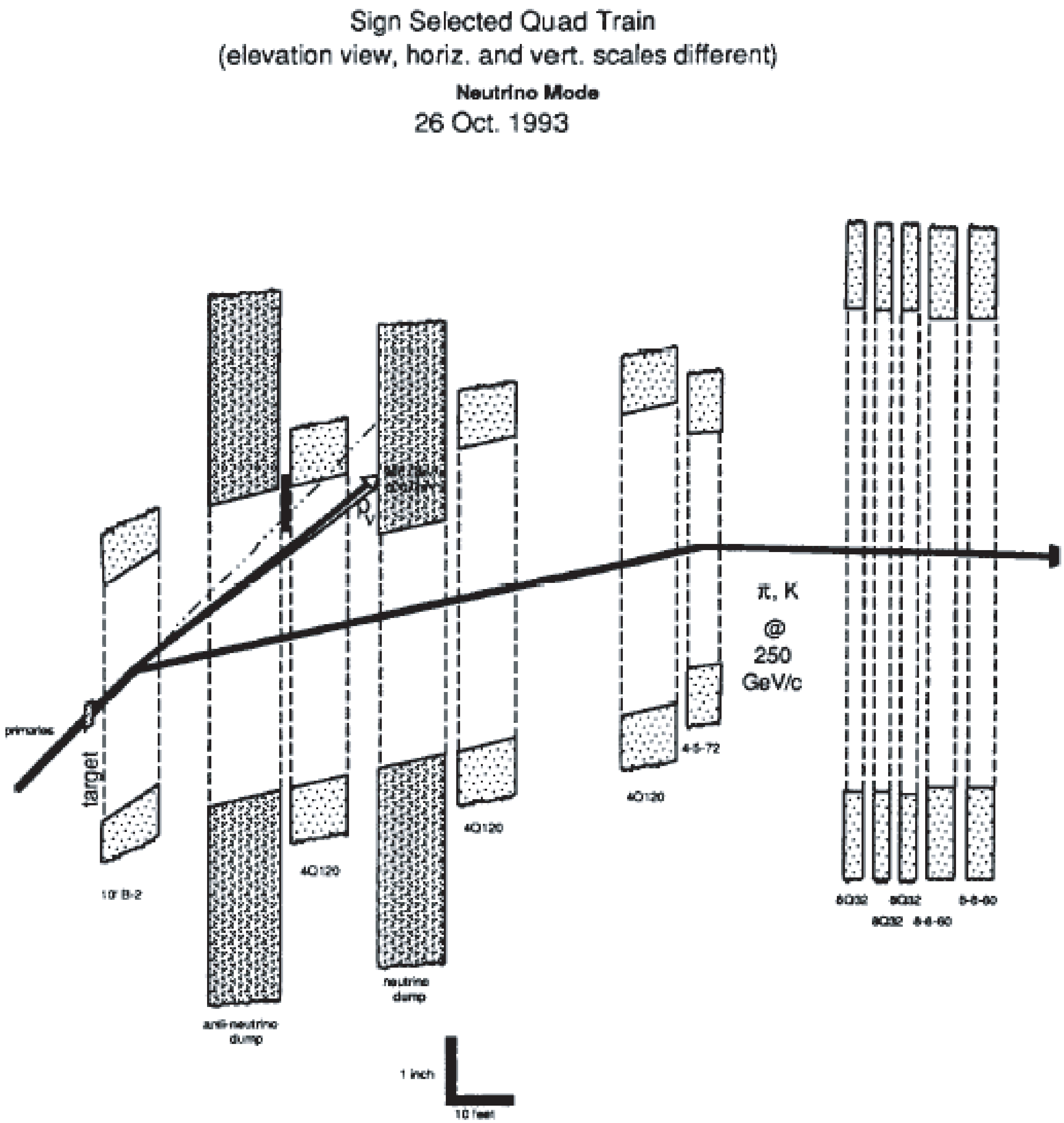


Figure 6: A schematic of the Sign-Selected Quadrupole Train in Neutrino Mode. Note the arrangement of the dumps, and that 900 GeV protons will still hit the dump.

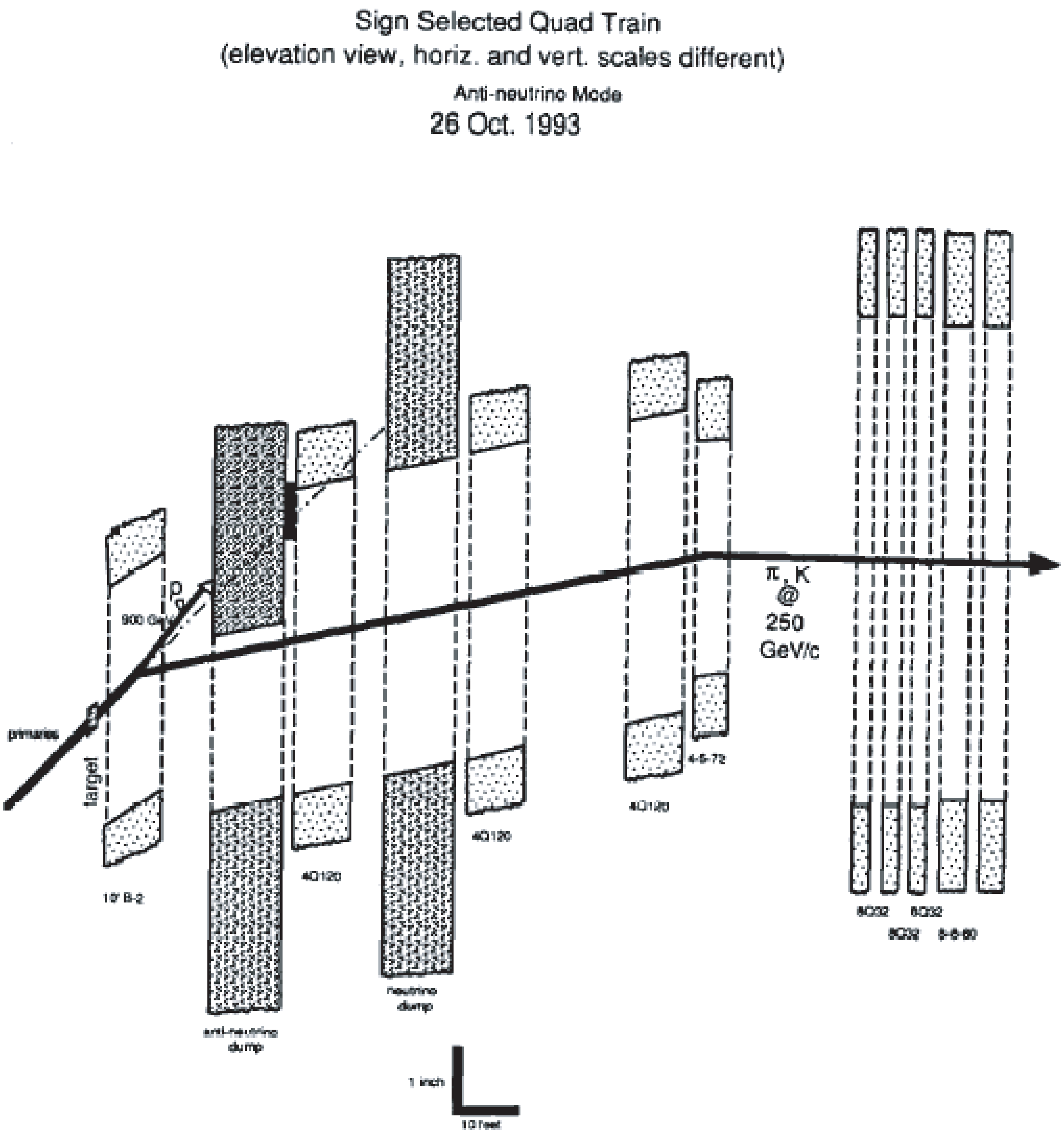
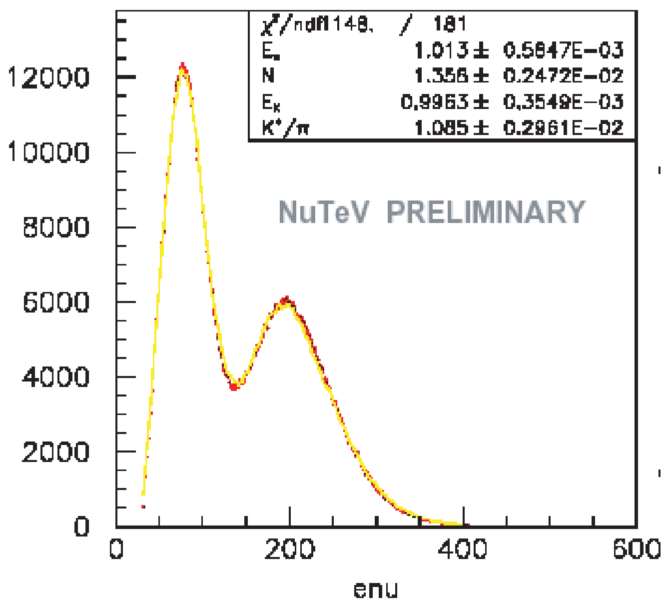
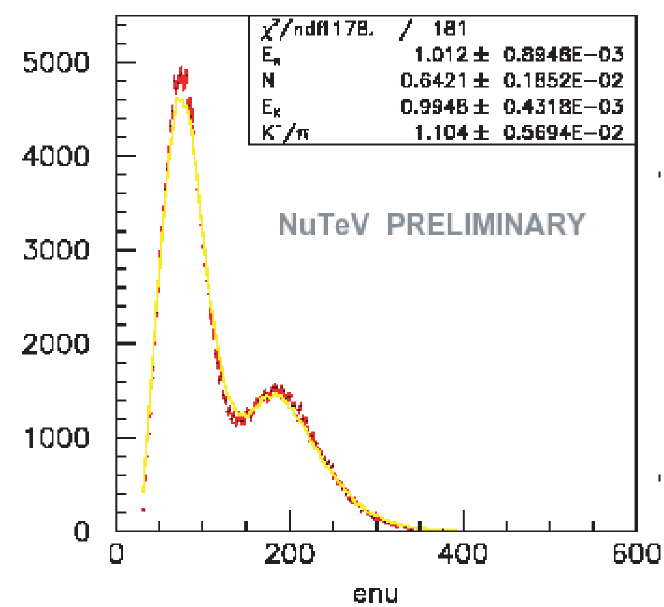


Figure 7: A schematic of the Sign-Selected Quadrupole Train in Antineutrino Mode. Note the first dump has been lowered, and that 900 GeV protons will still hit the dump.

- First Two Quads Maxed Out to capture phase-space
- Rest Bend Beam Parallel
- Predicted Rates and Backgrounds good to 5% before any tuning
  - Primarily π/K production ratio





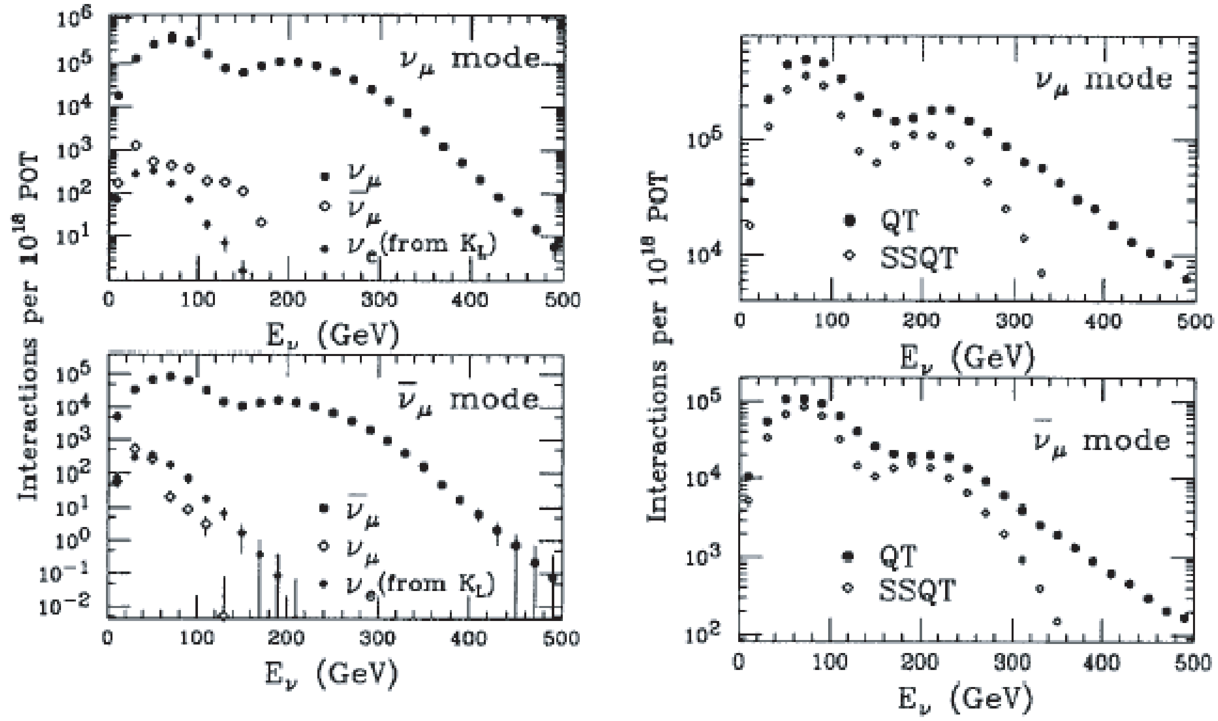
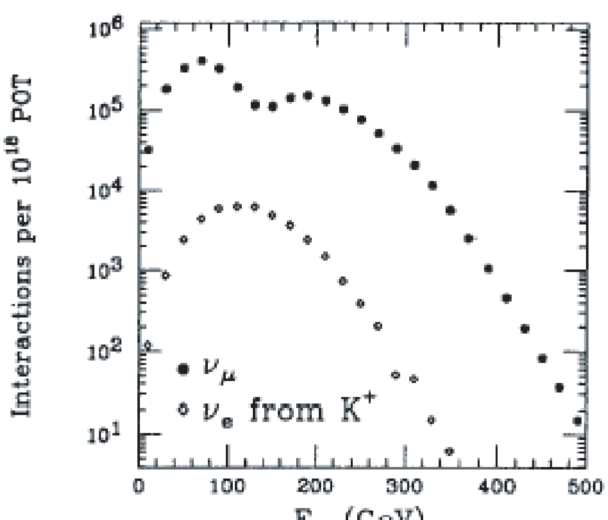


Figure 21: Rates and Backgrounds for ν_μ and $\bar{\nu}_\mu$ modes in the SSQT. All backgrounds have been included. The simulation has a radial cut of 50″.

- About $\times 5$ Reduction in K_L from QT
- $K^\pm \to \mu\nu_\mu$ Gives You $K^\pm \to \pi e \nu_e$
  - Fit to $K^\pm \to \mu\nu_\mu$, Get $K^\pm$ production



More Properties of SSQT

- Have Two Dumps Depending on Charge

  Temp Level Agreed

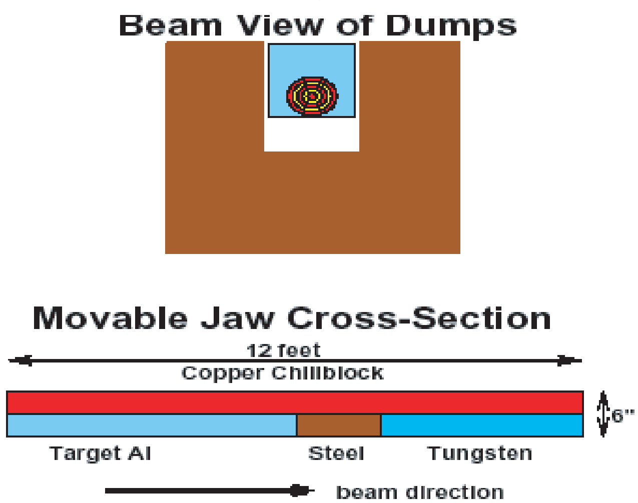
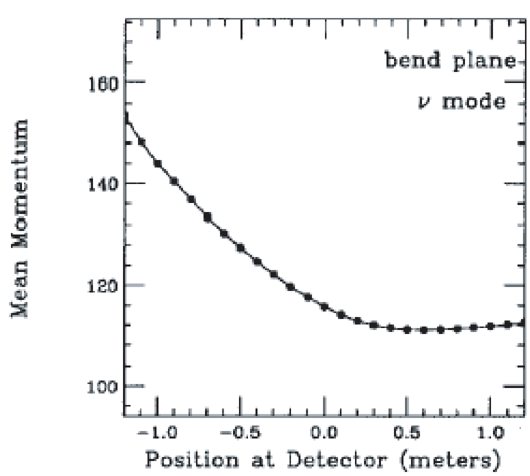


Figure 11: A schematic drawing of the proton dumps. The figure on the top shows the beam-view of the dump and the bottom shows the side view of the upper section of the dump.

- Dispersion Across Beam in Bend Plane



And Now for Something Completely Different... Tagged Neutrinos (*aka* P788)

- Make ν's from K_L beam
- Reconstruct $K_L \to \pi\mu\nu_\mu, \pi e\nu_e$ Event-By-Event
- Can Get Predicted Momentum Vector of ν
  Better than ν Detector!
- Cross-Sections, Dimuons, Structure Functions
- Low Statistics, Terrific Systematics

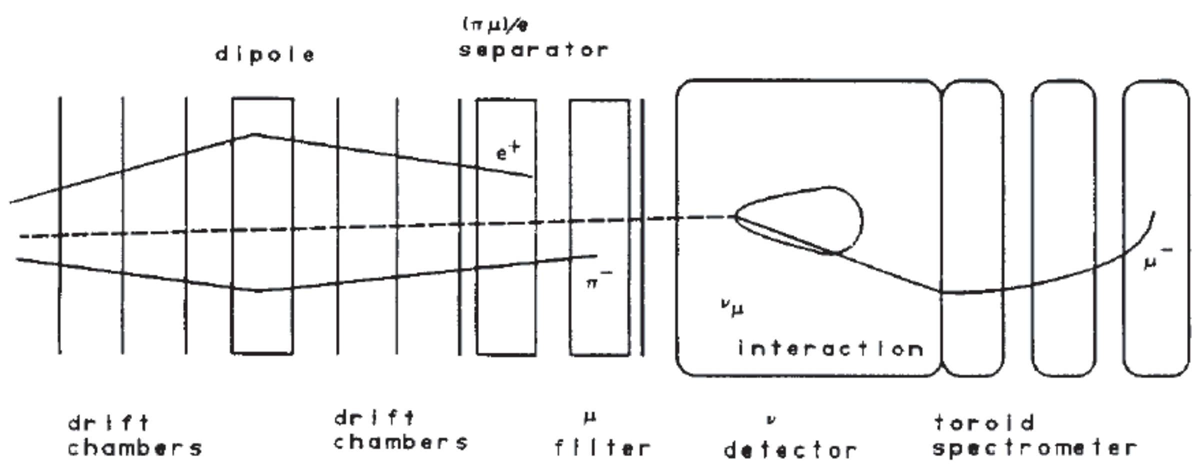


Figure 2: A schematic of a neutrino tagger. The beam direction is from the left; a $Ke3$ decay is pictured in the tagger, with the π and e identified and momentum analyzed. The neutrino detector downstream detected a ν_μ interaction, signaling an oscillation $\nu_e \to \nu_\mu$.

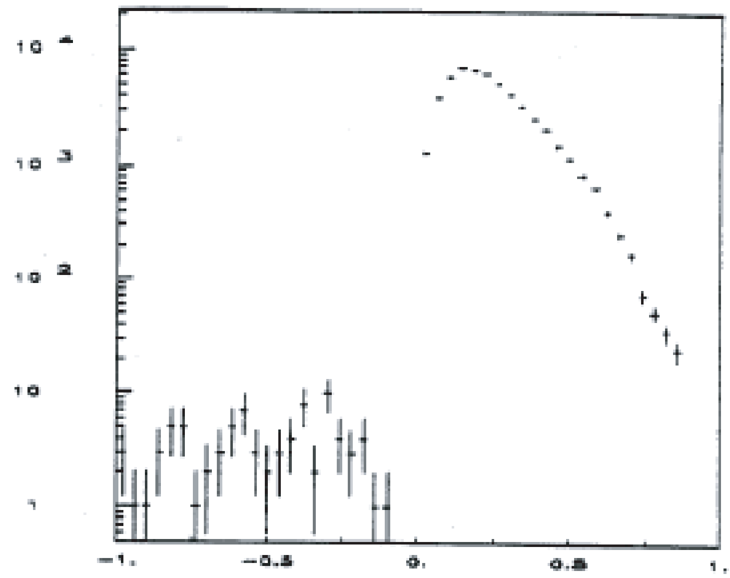


Fig. 19. The value of the K_L momentum is determined up to a two-fold ambiguity. Here we plot $(p_1 - p_2)/(p_1 + p_2)$; for physical events, we have chosen $p_1 > p_2$. The negative tail arises from resolution smearing.

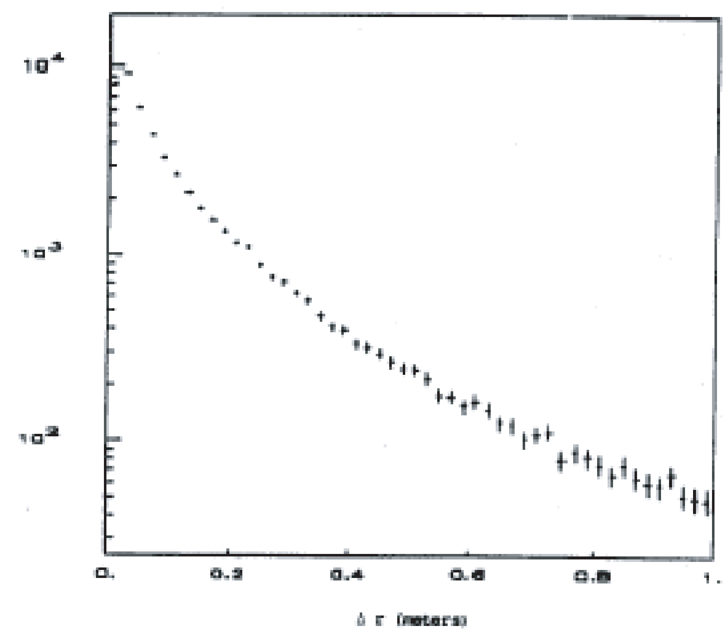


Fig. 20. The difference in distance from the reconstructed impact point in the neutrino detector to that predicted from the tagger. The distance is given in meters.

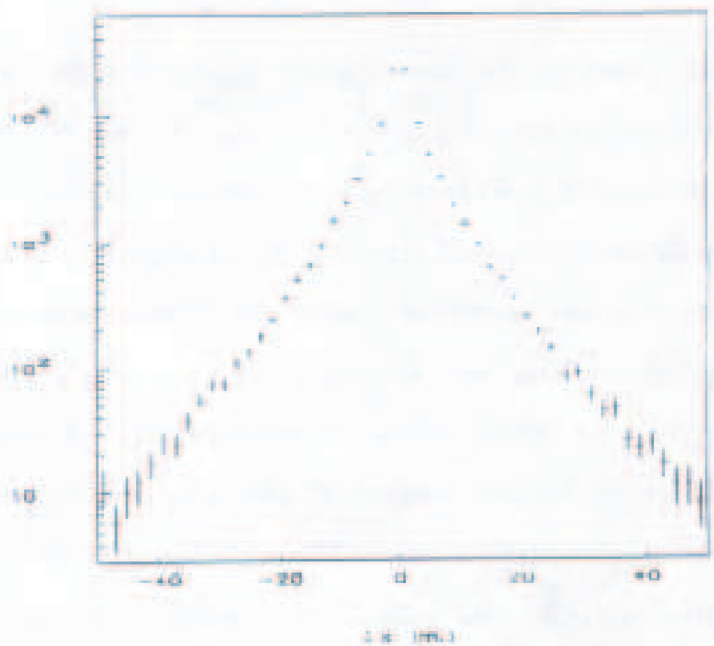


Fig. 17. The difference in the x-coordinate of the reconstructed vertex from the true value. The distance is given in mm.

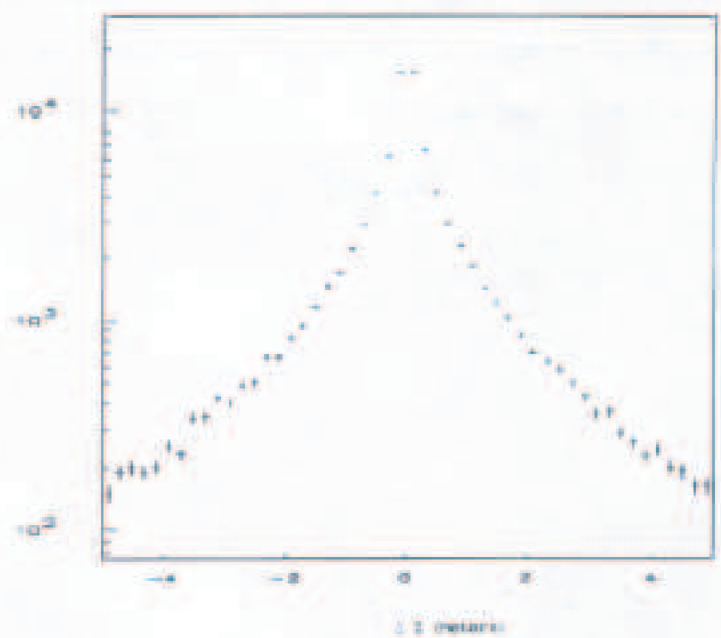


Fig. 18. The difference in the z-coordinate of the reconstruted vertex from the true value. The distance is given in meters.

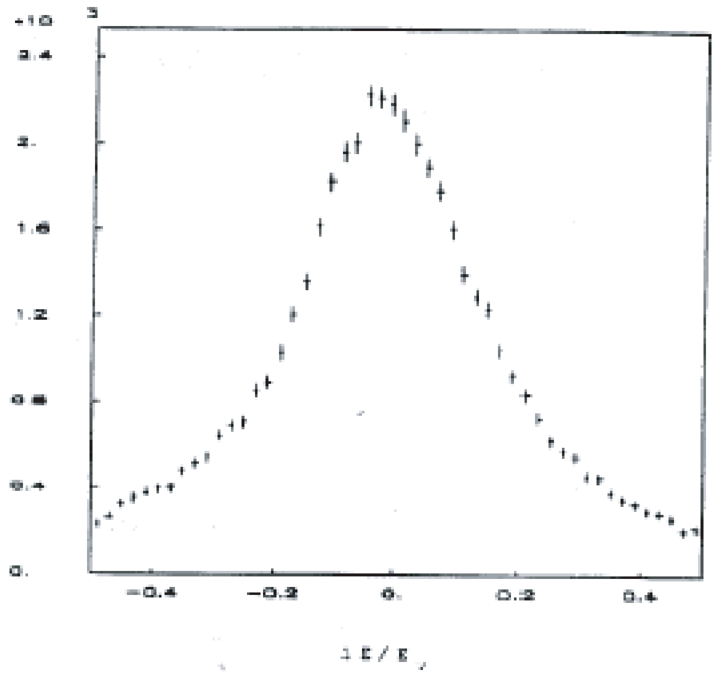
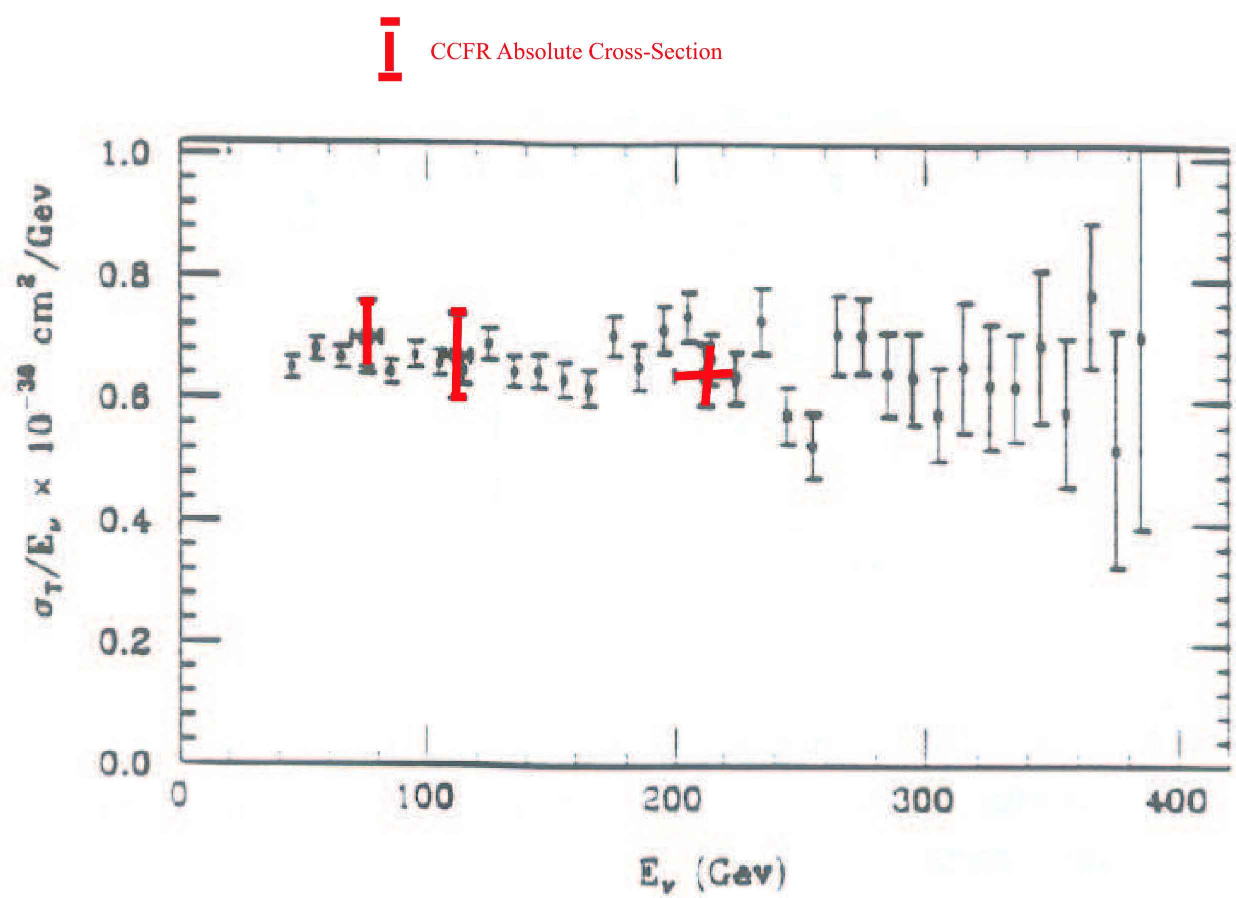


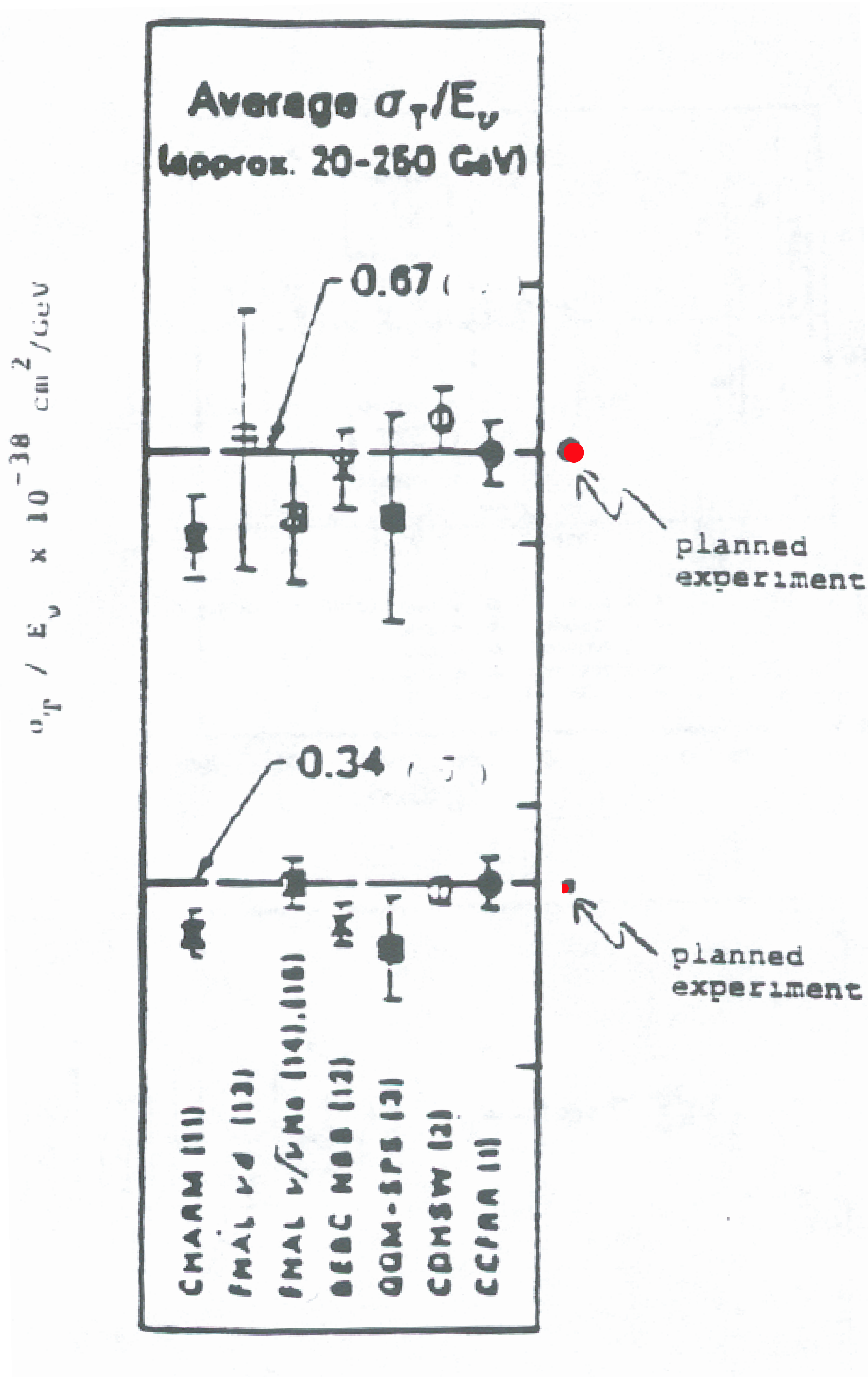
Fig. 21. **The difference in neutrino energy predicted from the tagger from the measured value, divided by the predicted value.**

- Demand Predicted E_ν and Impact Point Agree
- Primary Background is Multiples/Bucket
- Then cut on agreement
- $\Delta E/E \approx 10\%$ compared to 0.5–$0.8/\sqrt{E}$

Absolute Cross-Section

- Can Demand Neutrino Project to Detector
- Studied Systematics after Cuts
- Get <1%
- 20-30 K events easy
- Should be Able to get ≈ 500K




Average σ_T/E_ν
(approx. 20-260 GeV)
0.67
0.34
planned experiment
planned experiment
$\sigma_T / E_\nu \times 10^{-38}$ cm^2/GeV
CHARM (11)
FMAL νd (13)
FMAL ν/ν̄ Ne (14),(15)
BEBC NBB (12)
GGM-SPS (3)
CDMSW (2)
CCFRR (1)

Oscillations in Tagged Neutrino Beams: θ_{13}

- Originally Proposed to Check 17 KeV Neutrino
- Tag ν_e at Birth; look for muon in interaction
  - Same as Neutrino Factory
  - But Get ν and $\bar{\nu}$ Separated Event-by-Event
- Backgrounds Calculated $\leq 10^{-5}$
- Statistics Much Better than Needed for
  $\sin^2 2\theta_{13} < .01$
- *But* $\Delta m^2 > 1$ *Not* 10^{-3}
- *Probably Achievable, But Don't Know How*
- Needs Work