Understanding the Forward Muon Deficit in Coherent Pion Production

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Nu Int 07

Fermilab

Outline

1. Evidence for Forward Deficit (Mini Boone, K2K)
2. PCAC and Forward Scattering Theorem
3. Screened – PCAC: Effect of Muon Mass
4. Explaining the Muon Angular Distribution
5. Explaining the Coherent π^+ "Extinction"
6. Lessons

PCAC and the Deficit of Forward Muons in π^+ Production by Neutrinos

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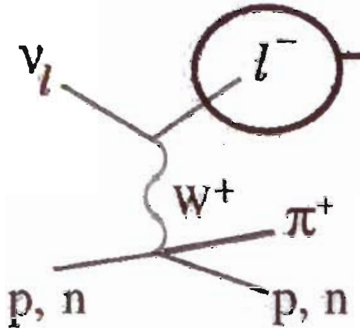
Abstract

The K2K experiment, using a fine-grained detector in a neutrino beam of energy $< E > \sim 1.3\,\text{GeV}$ has observed two-track events that can be interpreted as a coherent reaction $\nu_\mu + \mathcal{N} \to \mu^- + \mathcal{N} + \pi^+$ ($\mathcal{N} = \text{C}^{12}$) or an incoherent process $\nu_\mu + (p,n) \to \mu^- + \pi^+ + (p,n)$, the final nucleon being unobserved. The data show a significant deficit of forward-going muons in the interval $Q^2 \lesssim 0.1\text{GeV}^2$, where a sizeable coherent signal is expected. We provide an explanantion of this effect, using a PCAC formula that includes the effect of the non-vanishing muon mass. The deficit is caused by a destructive interference of the axial vector and pseudoscalar (pion-exchange) amplitudes. No such effect occurs in the neutral current channels such as $\nu_\mu + \mathcal{N} \to \nu_\mu + \pi^0 + \mathcal{N}$.

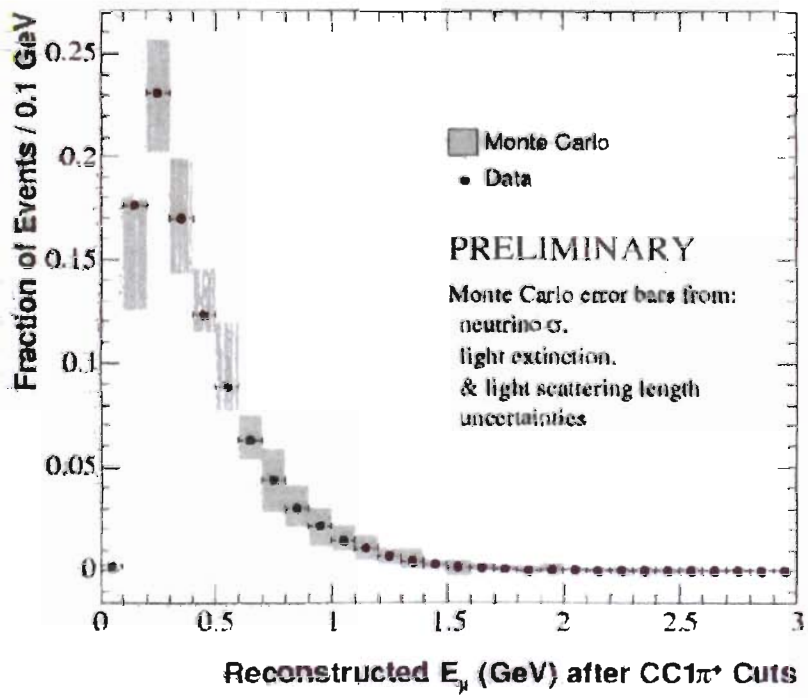
The K2K experiment has studied interactions of a low energy neutrino beam ($< E > \sim 1.3\,\text{GeV}$) in a fine-grained detector, designed as the "near detector" of a long-base-line neutrino oscillation experiment [1, 2, 3]. Evidence has been found for two-track events, which can be interpreted as either $\nu_\mu + \mathcal{N} \to \mu^- + \mathcal{N} + \pi^+$ (coherent π^+ production on a nuclear target) or incoherent π^+ production $\nu_\mu + (p,n) \to \mu^- + \pi^+ + (p,n)$, where the final nucleon is unobserved. The data have been compared with simulations based on a model for coherent π^0 production [4], and a model for incoherent single pion production via nuclear resonances [5]. It is stated that in comparison with the simulations, the two-track data show "a significant deficit of forward-going muons" in the kinematic interval $Q^2 \lesssim 0.1\text{GeV}^2$, in which a sizeable coherent contribution is expected. In this Letter, we suggest a possible explanation of this effect.

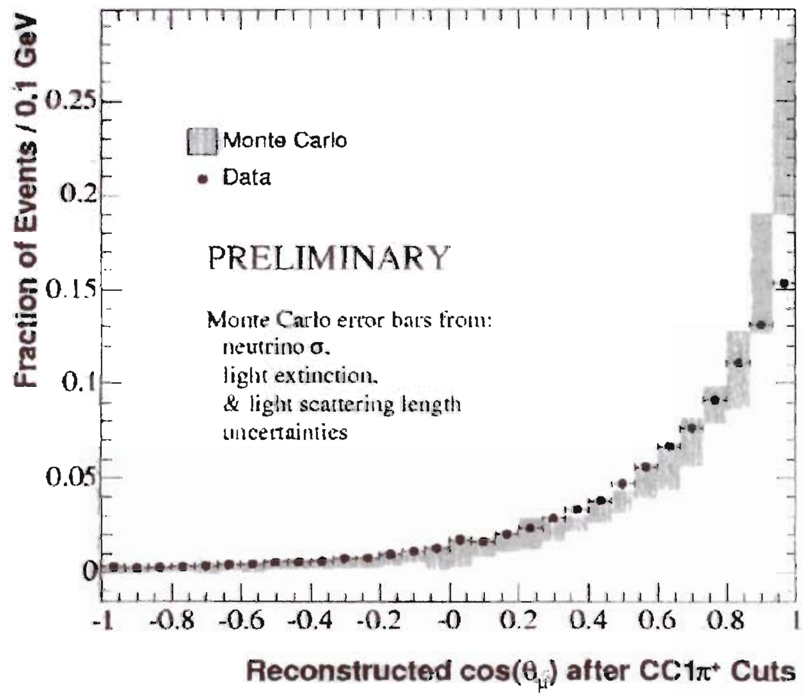
As is well-known, neutrino scattering in the forward-scattering configuration is described by Adlers PCAC theorem [6]. For any inelastic charged current reaction $\nu_\mu + N \to \mu^- + F$, where F denotes an inelastic channel, the cross section, neglecting the muon mass, is

$CC1\pi^+$ Data



measure visible energy from Cherenkov light only (to avoid light from π^+)





- Similar deficit of forward angle muons
- Deficit larger than CCQE sample: clue to interesting physics?
- Working on understanding this feature

Search for Coherent Charged Pion Production in Neutrino-Carbon Interactions

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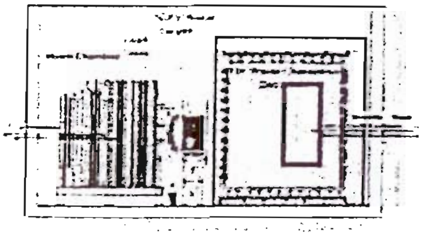
π^0 in K2K 1kt water Cherenkov Detector



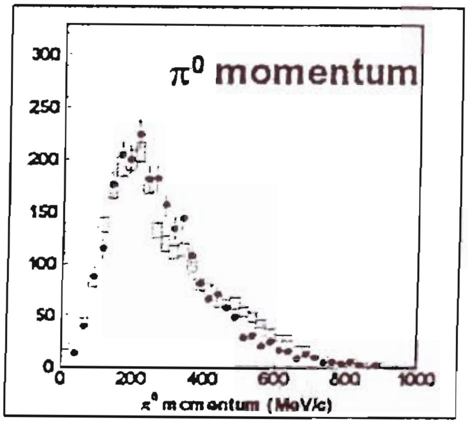
Single π^0 sample

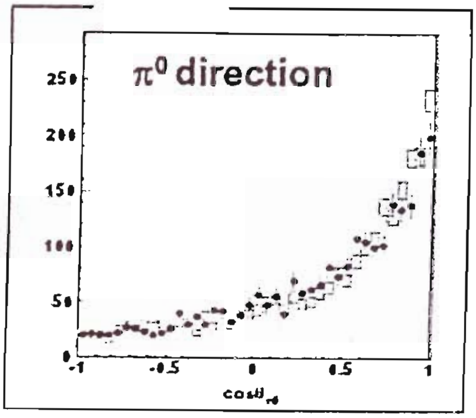
(2 ring e-like sample in 25t fiducial)

- Good NC sample
  - 86% from NC interaction
  - (54% from NC resonant prod.)
  - π^0 efficiency 49%
- Good measure of NC interaction at low energy
- Main background for ν_e search

MC

- M_V =0.81GeV
- M_A=1.1 GeV for QE and 1π prod.
- Rein-Sehgal model for 1π and coherent π prod.
- Fermi Gas
- Final state π absorption
  - photo-production data
  - π scattering data





K2K Data set : 3.2E19 POT

	Data	MC(*)
π^0	2496	2582.3
1-R FC μ	22612	22545.2
π^0/μ	0.110±2%±8% (stat) (sys)	0.115

Detector systematics
- Particle ID
- Ring counting, etc..

(*) normalized by number of total events in 25t fiducial

MC reproduces data in (rate, E_π θ_π) quite well !

K2K Results on Coherent π^+ Production

$$\sigma(\text{coh}\ \pi^+) \approx 0$$

$$\frac{\sigma(\text{coh}\ \pi^+)}{\sigma(CC,\mu^-)} < 0.6\,\% \quad (90\%\ CL)$$

Prediction of RS : 2.0 %

Reason for Concern

(1) "..... existing data agree with RS model for neutrino energies from 7 to 100 GeV ...."
However K2K energy is $\langle E \rangle = 1.3$ GeV

(2) K2K has evidence for coherent π^0 production; rate is compatible with RS ($\approx 1\%$); momentum and angle distribution also agree.

(3)

$$\frac{\pi^+}{\pi^0} = \begin{cases} 2 & (\text{PCAC} + \text{Isospin}) \\ \approx 0 & (\text{K2K}) \end{cases}$$

PCAC and Adler's Forward Scattering Theorem:

$$m_\ell = 0 \; ; \quad \partial_\mu V_\mu = 0 \quad (CVC)$$

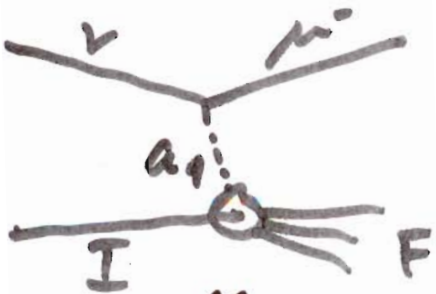
$$\partial_\mu A_\mu = f_\pi m_\pi^2 \phi_\pi \quad (PCAC)$$

$\Rightarrow$ Cross section for any inelastic reaction $\nu + I \to \mu^- + F \quad (I \neq F)$ for lepton in forward direction ($\theta = 0$, $Q^2 = 0$) is given by

$$\left(\frac{d\sigma}{dx\,dy}\right)_{Q^2=0} = \frac{G^2 M E}{\pi^2} f_\pi^2 (1-y)\, \sigma(\pi^+ + I \to F)$$

Correction for $Q^2 \neq 0$ are "gentle":

Reason: reaction mediated by spin-1 (1^{++}) mesons; spin-0 exchange forbidden due to $m_\ell = 0$



allowed

forbidden

Special Case: Coherent π^+ Production

I = Nucleus
F = Nucleus + π^+

Hence $\nu + N \to \mu^- + N + \pi^+$ proportional to $\sigma(\pi^+ + N \to \pi^+ + N)$.

∴ PCAC contribution $\sim A^2$ (coherence)
Corrections due to V, VA terms for $Q^2 \neq 0$ are only $\sim A$

$\Rightarrow$ Process dominated by PCAC

Rein-Sehgal model (1983):

$$\frac{d\sigma}{dx\,dy\,dt} = \frac{G^2 M E}{2\pi^2} f_\pi^2 (1-y) \frac{1}{16\pi} \left[\sigma_{\pi N}(Ey)\right]^2 \cdot (1+r^2)\left(\frac{m_A^2}{m_A^2+Q^2}\right)^2 e^{-b|t|} F_{abs} ,$$

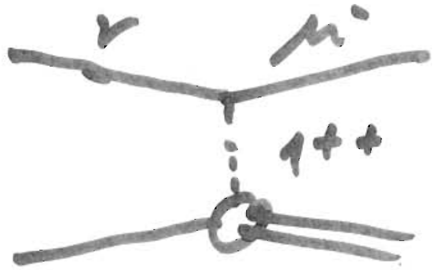
$$F_{abs} = \exp\left[-\langle x\rangle/\lambda\right]$$

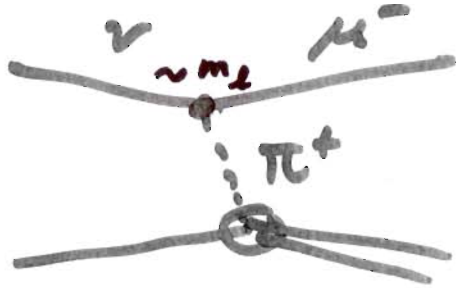
Consequence of symmetries: For $I=0$ nucleus:

$$\sigma_\nu = \sigma_{\bar{\nu}} \; ; \; \sigma_\nu(\pi^+) = 2\,\sigma_\nu(\pi^0).$$

Effect of $m_\ell \neq 0$:

Both spin-1 and spin-0 exchange possible





Correction to PCAC computed by Adler (1964, 2005). For small angles, leading term is a correction factor

$$C = \left(1 - \frac{1}{2}\frac{Q^2_{min}}{Q^2 + m_\pi^2}\right)^2 + \frac{1}{4}\, y\, \frac{Q^2_{min}\left(Q^2 - Q^2_{min}\right)}{\left(Q^2 + m_\pi^2\right)^2}$$

where

$$Q^2_{min} = m_\ell^2 \frac{y}{1-y}$$

(Written in this form by Rein & Sehgal, hep-ph / 0606185)

Physical Significance :

- Term $\left(1-\frac{1}{2}\frac{Q^2_{min}}{Q^2+m_\pi^2}\right)^2$ expresses

  the interference of spin-one and pion exchanges. This interference is **destructive**. (Screening!)

- In forward direction ($\theta = 0$), the correction factor is

$$C(\text{forward}) = \left(1-\frac{1}{2}\frac{Q^2_{min}}{Q^2_{min}+m_\pi^2}\right)^2$$

- Taking for y an average value $\langle y \rangle = 1/2$, $Q^2_{min} = m_\ell^2$, so that

$$C(\text{forward}) \sim \left(1-\frac{1}{2}\frac{m_\mu^2}{m_\mu^2+m_\pi^2}\right)^2$$

$$= \left(1-\frac{1}{2}\cdot\frac{0.01}{0.01+0.02}\right)^2$$

$$= \left(1-\frac{1}{2}\cdot\frac{1}{3}\right)^2 = \left(\frac{5}{6}\right)^2$$

- Effect determined by the ratio m_μ/m_π (<u>a constant of nature</u>).

- All inelastic CC cross-sections in forward direction are suppressed by the same factor

$$C(\text{forward}) = \left(1 - \frac{m_\mu^2 \frac{y}{1-y}}{m_\mu^2 \frac{y}{1-y} + m_\pi^2}\right)^2,$$

which depends on the inelasticity y.

- For general Q^2, y, the suppression factor is $C(Q^2, y)$.

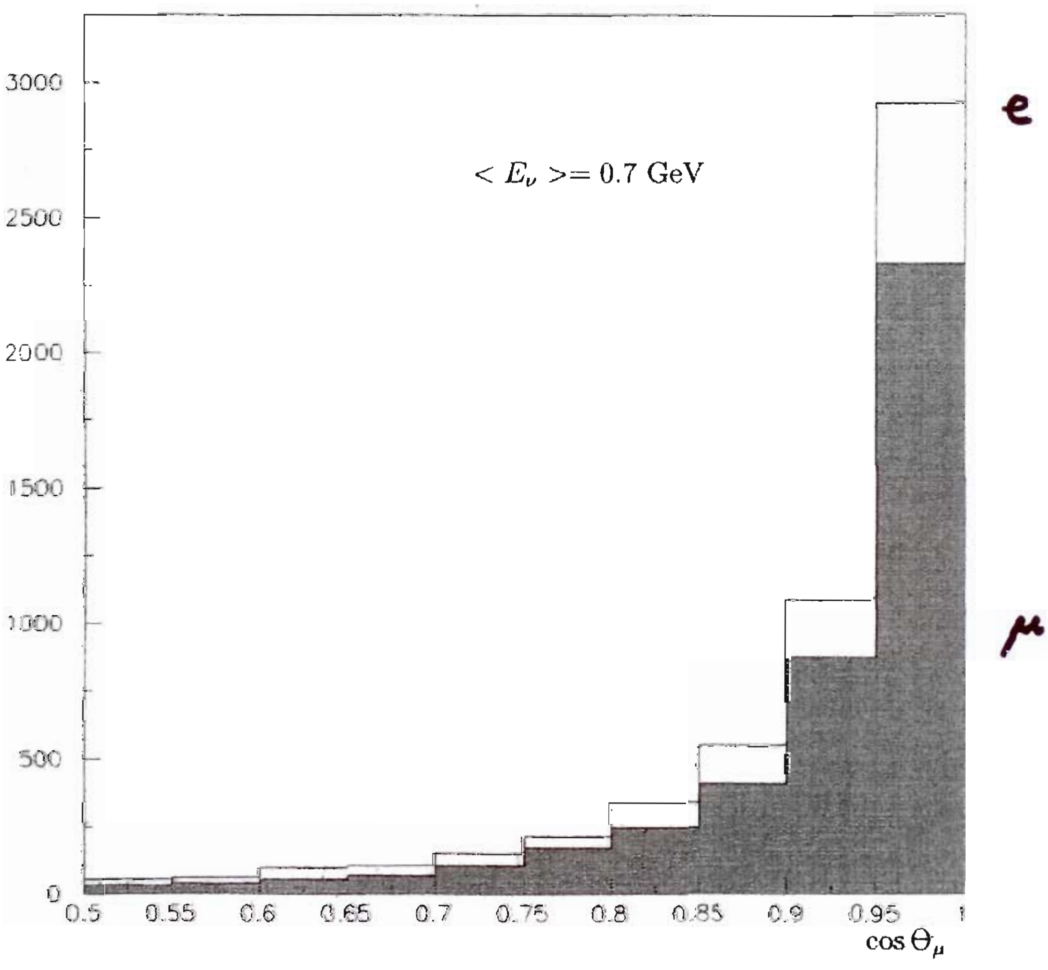
- <u>Conclusion</u>: all inelastic CC interactions will show a <u>forward muon deficit</u>!

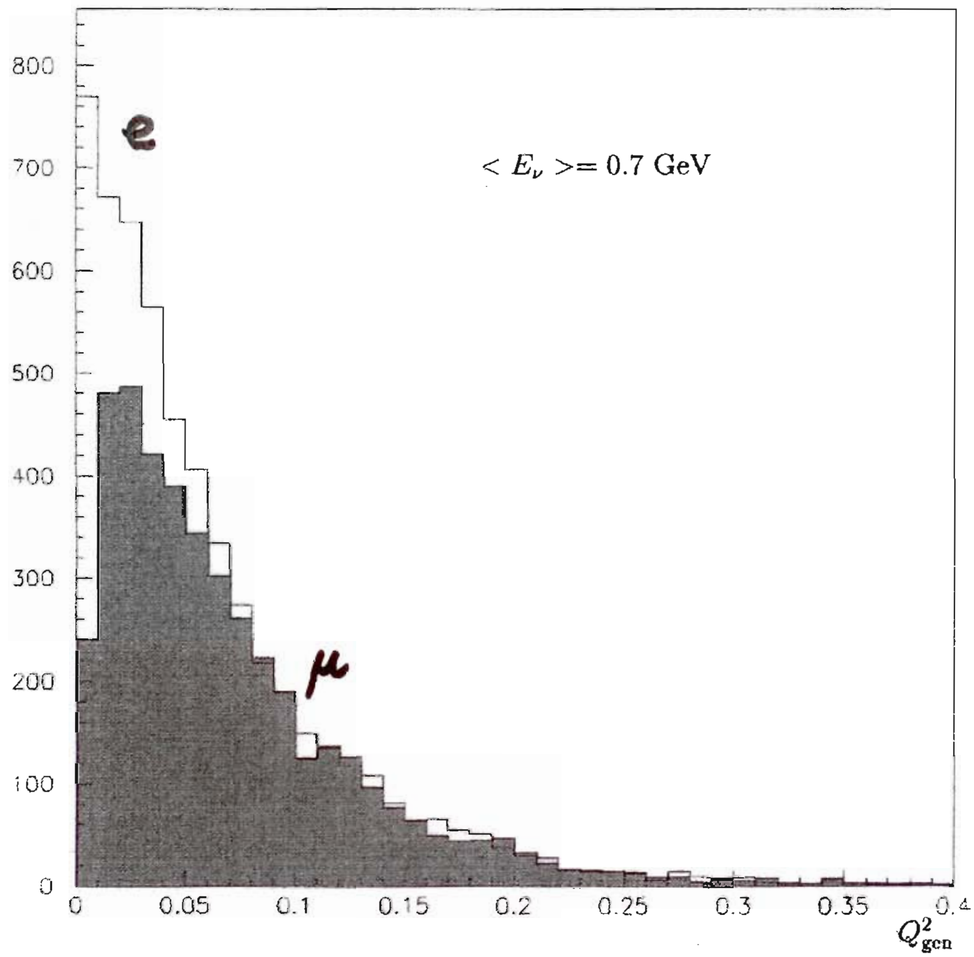
Caused by destructive interference.

Muon Deficit = <u>Muon Eclipse</u>!

Muon Eclipse in Coherent π^+ Prod.

(Mini Boone)





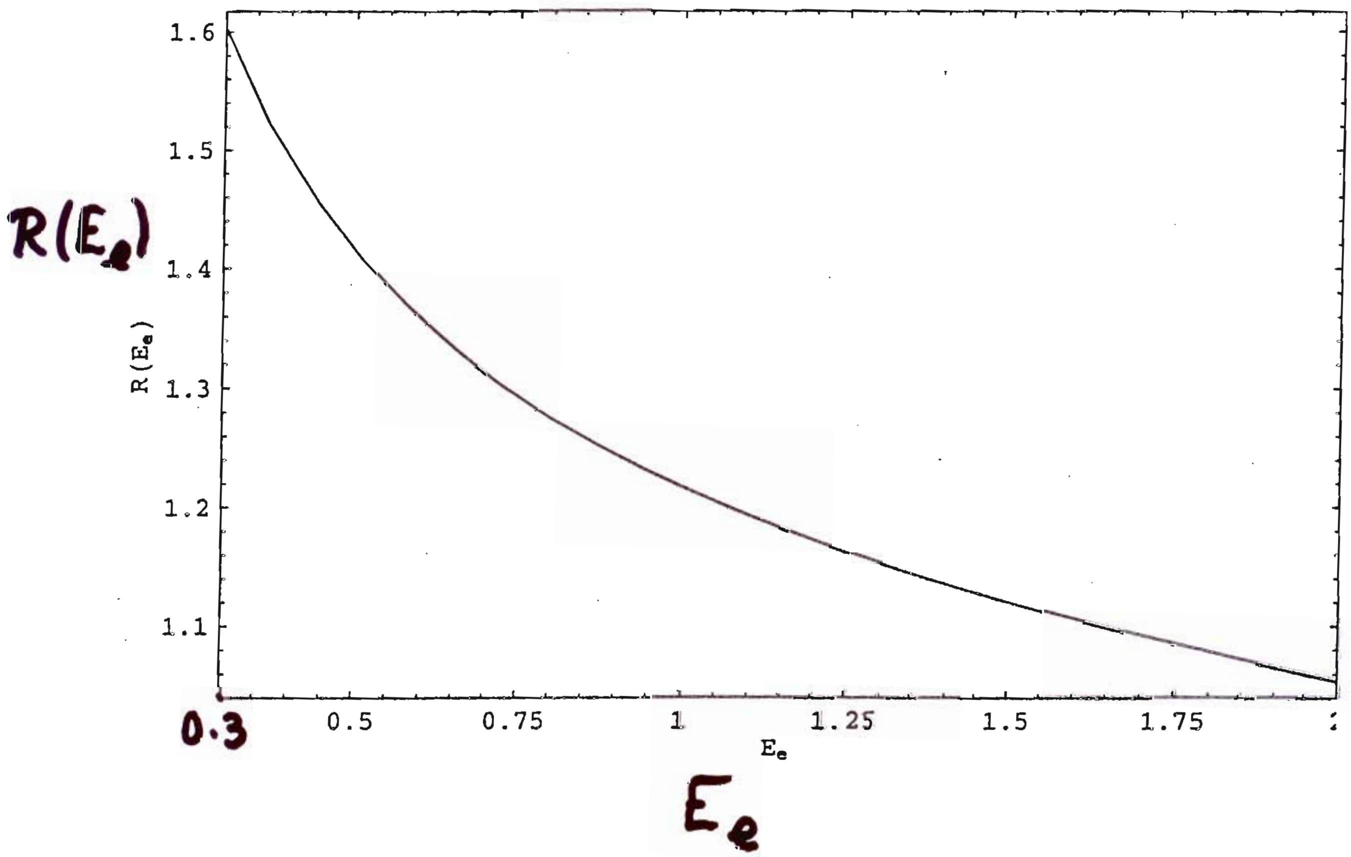
Figures courtesy of
Chris Berger

Question to Mini Boone:

Are the "Muon Deficit" and the "Electron Surplus" two sides of the same coin?

Apparent Enhancement of Low Energy Electrons due to "Muon Eclipse"

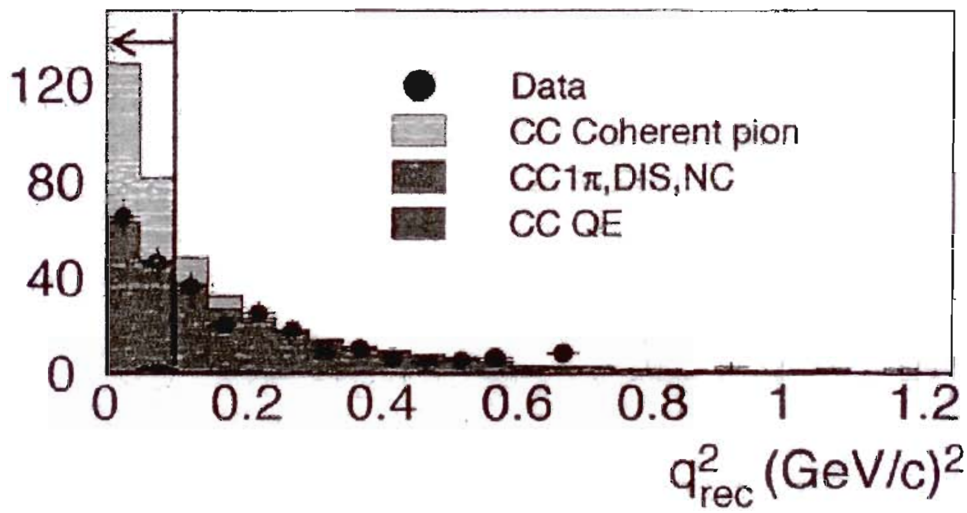
(Illustration only)



$$R(E_e) = \frac{\int dE_\nu \, Flux(E_\nu) \, [C(y)=1]}{\int dE_\nu \, Flux(E_\nu) \, C(y)}$$

$$y = 1 - E_e/E_\nu$$

CC coherent pion results



- **K2K Analysis**

$$\frac{d\sigma}{dq^2} = f_{coh}\left(\frac{d\sigma}{dq^2}\right)_{coh} + f_{res}\left(\frac{d\sigma}{dq^2}\right)_{res}$$

$$f_{coh} + f_{res} = 1$$

Conclude : $f_{coh} \approx 0$ $\quad f_{res} \approx 1.$

- **Analysis with Screening**

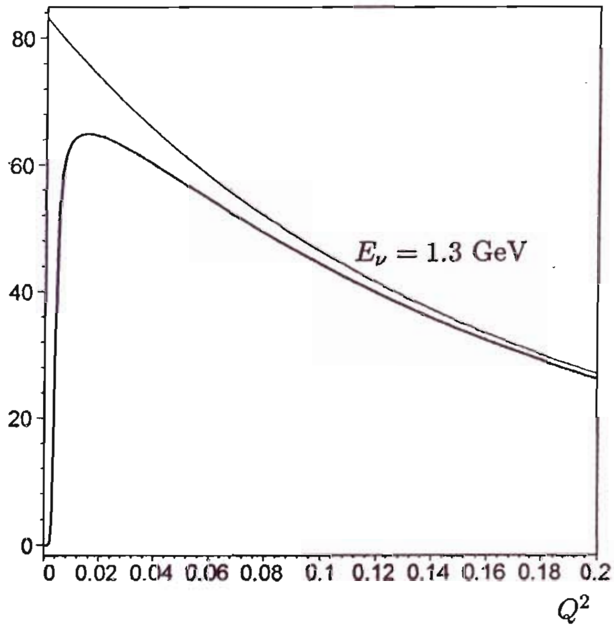
Screening suppresses coherent as well as resonant cross-section, affects shape

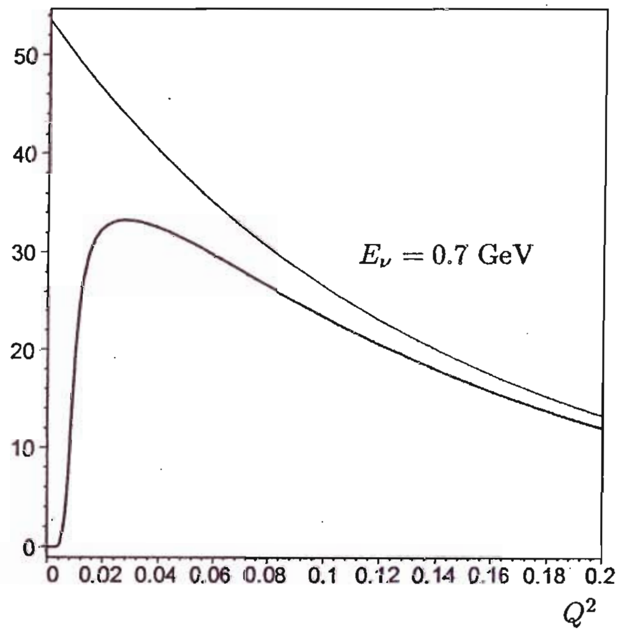
$$\left(\frac{d\sigma}{dq^2}\right)_{obs} = C(q^2, coh)\left(\frac{d\sigma}{dq^2}\right)_{coh} + C(q^2, res)\left(\frac{d\sigma}{dq^2}\right)_{res}$$

$$N_{obs} = C_{coh}\, N_{coh}(\text{expected}) + C_{res}\, N_{res}(\text{expected})$$

- Screening factors have to be det. by Monte Carlo

Effect of Screening (Resonant π^+)





$$\frac{d\sigma}{dQ^2} \sim \int_{y_{\min}}^{y_{\max}} G_D^2(Q^2) C_{\text{Adler}} \frac{1-y}{y} \frac{k^3_{\pi,\text{CM}}}{(W-M_R)^2 + k^6_{\pi,\text{CM}}\Gamma^2/4} dy$$

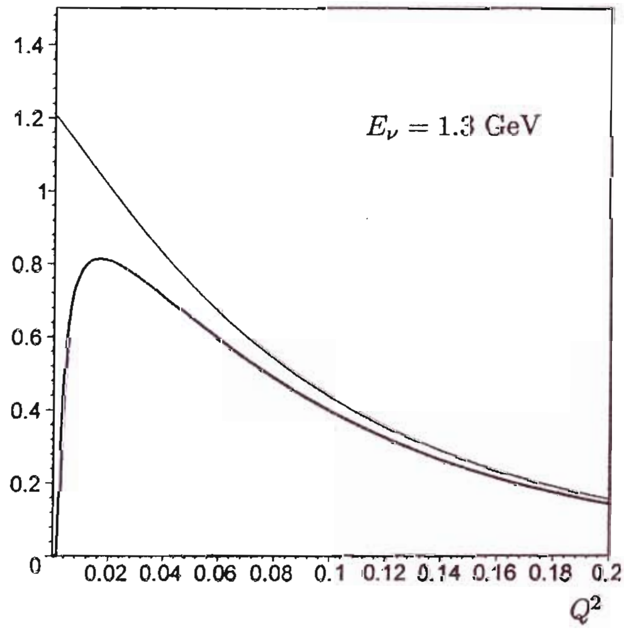
with $W = \sqrt{M_N^2 - Q^2 + 2EM_N y}$ and $k_{\pi,\text{CM}}$ in units of $k_{\pi,\text{CM}}(M_R)$

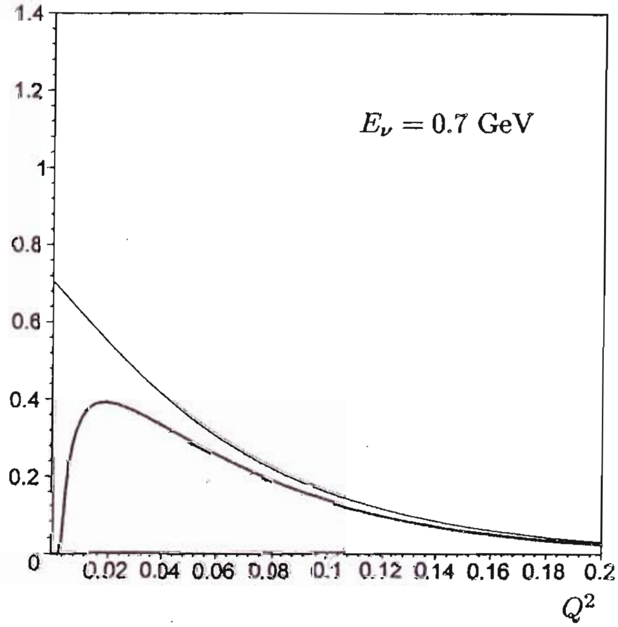
Comment : Only $\Delta(33)$ included

$\langle C \rangle_{\text{res}} \sim 0.86$ (K2K)

~ 0.73 (MB)

Effect of Screening (Coherent π^+)





$\langle C \rangle_{coh}$ ~ 0.77 (K2K)

~ 0.63 (MB)

(for $Q^2 < 0.1$)

Reanalysis of KZK with Screening

$$N_{obs} = 113$$

$$N_{coh} = 99 \text{ (expected without screening)}$$

$$N_{res} = 111 \text{ (")}$$

$$N_{obs} = \langle C \rangle_{coh} N_{coh} + \langle C \rangle_{res} N_{res}$$

$$113 = (0.77)(99) + (0.86)(111)$$

$$= 172 \pm 30 \text{ (my estimate)}$$

Discrepancy reduced (2σ) but not eliminated.

<u>N.B.</u> Proper analysis should be done by experimenters.

A value $\langle C \rangle_{coh} \sim \langle C \rangle_{res} \sim 0.7$ resolves the problem.

Lessons:

- Lepton masses are important
- Signs are important
- Physics of forward muon deficit is the physics of the negative sign between spin-zero (pion) and spin-one exchange
- Could be an interesting trail fo follow with the new generation of low energy neutrino beams and detectors
- PCAC-Screening affects $\nu_\mu + I \rightarrow \mu^- + F$, but not $\nu_e + I \rightarrow e^- + F$ $(F \neq I)$

  Thus ν_e cross sections are larger in forward direction:

$$\frac{\sigma(\nu_e; Q^2, y)}{\sigma(\nu_\mu; Q^2, y)} = \frac{1}{C(Q^2, y)}$$

Muon deficit $\xrightarrow{?}$ Electron Surplus