Language: 英語/English

KEK 物理セミナー Physics Seminar

10月29日 (水) October 29 (Wed)
15:00 ~ 16:00

4号館 346号室 Room 346 in the 4th Building

Neutrino Production of the Delta Resonance

Ji Young Yu
(Univ. of Dortmund)

- Abstract:
We take a fresh look at the analysis of resonance production by neutrinos. We consider three resonances P_{33}, P_{11} and S_{11} with a detailed discussion of their form factors. The article presents results for free proton and neutron targets and discusses the corrections which appear on nuclear targets. The Pauli suppression factor is derived in the Fermi gas model and shown to apply to resonance production. The importance of the various resonances is demonstrated with numerical calculations. The Δ-resonance is described by two formfactors and its differential cross sections are compared with experimental data. The article is self-contained and could be helpful to readers who wish to reproduce and use these cross sections.

After finishing this topics, I may discuss on the muon spectrum in the neutrino experiment in a few GeV region.

Past presentations are archived at our home page, http://seminar.kek.jp/physics/ .

Organizers: T. Komatsubara and I. Adachi

2003.10.14

KEK, Japan, ~~27-31~~ 29/10/2003

Neutrino Interactions at Low Energies

Ji-Young Yu
(Dortmund University)

in collaboration with: E. A. Paschos, M. Sakuda [1]
~~I. Schienbein, F. von Horsten~~ ~~[2]~~

Outline

- Overview and Motivation
- Neutrino Interactions
  - Single pion (resonance) production (RES)
  - Quasi-elastic scattering (QE)
  - Deep inelastic scattering (DIS)
- Conclusions and Outlook

Neutrino Production of Resonances:
[1] E. A. Paschos, M. Sakuda, J.Y. Yu, PRD /hep-ph 0308130

~~χ^2 analysis of QE data:~~
~~[2] F. von Horsten, I. Schienbein, J.Y. Yu, in preparation~~

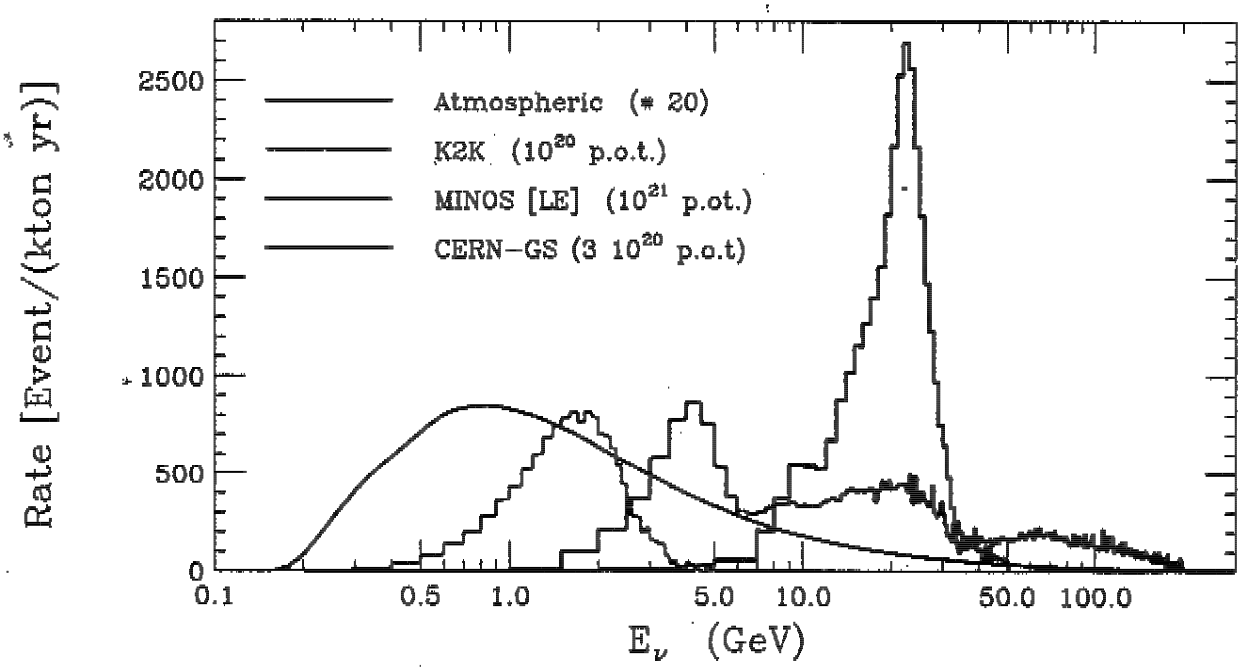
Overview and Motivation

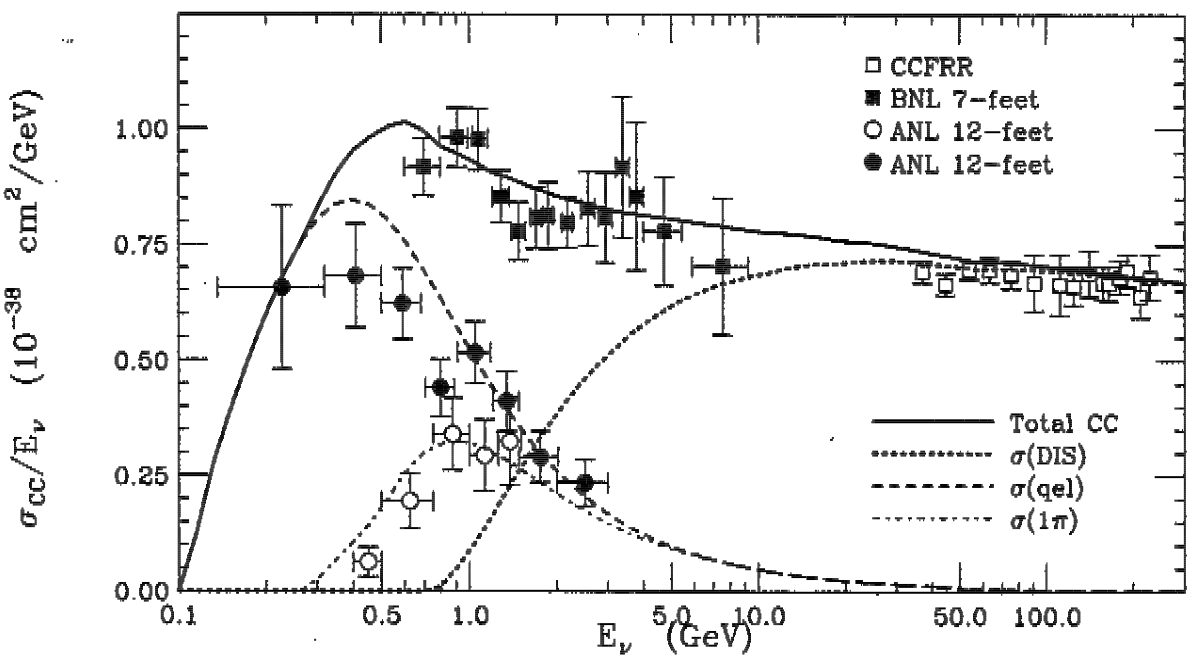
Title quite general: 'Neutrino Interactions at Low Energies'

This Talk: Neutrino Hadron Interactions @ $E_\nu \simeq \mathcal{O}(1\ \mathrm{GeV})$
['atmospheric neutrino energies']

→ current/future LBL experiments: K2K, MINOS, CERN-GS, ...
⇝ determine neutrino properties: main underlying motivation

Neutrino cross sections at atmospheric ν energies

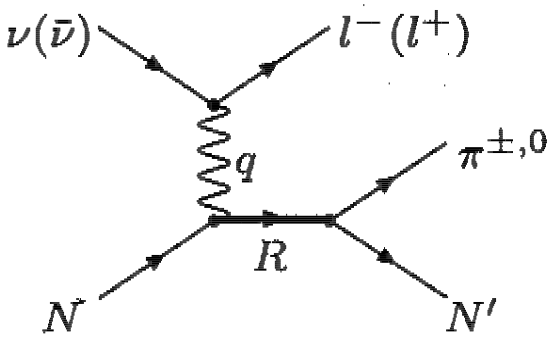




- Figure from P. Lipari, hep-ph/0207172

Neutrino nucleon interactions: Overview

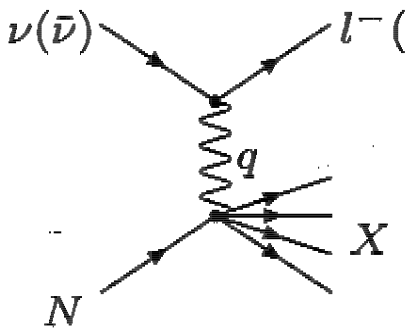
- Resonance production (RES)



Charged Current (CC):
$\nu(\bar{\nu}) + N \rightarrow l^-(l^+) + N + \pi^{\pm,0}$

Neutral Current (NC):
$\nu(\bar{\nu}) + N \rightarrow \nu(\bar{\nu}) + N + \pi^{\pm,0}$

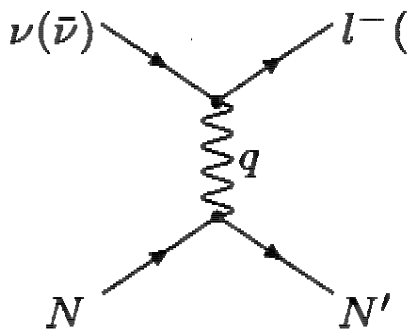
- Deep inelastic scattering (DIS)



CC: $\nu(\bar{\nu}) + N \rightarrow l^-(l^+) + X$

NC: $\nu(\bar{\nu}) + N \rightarrow \nu(\bar{\nu}) + X$

- Quasi-elastic scattering (QE)



CC: $\nu(\bar{\nu}) + N \rightarrow l^-(l^+) + N'$

NC: $\nu(\bar{\nu}) + N \rightarrow \nu(\bar{\nu}) + N'$

- Need these cross sections on free nucleons and nuclear targets

Nuclear Effects: Overview

- Pauli Priciple

  $\rightsquigarrow$ reduction at small momentum transfer Q^2 [→ Figure]

- Fermi Motion

  $\rightsquigarrow$ Broadening, area almost unchanged

- Multiple Scattering: [1,2,3,4]
  - Charge Exchange
  - Absorption

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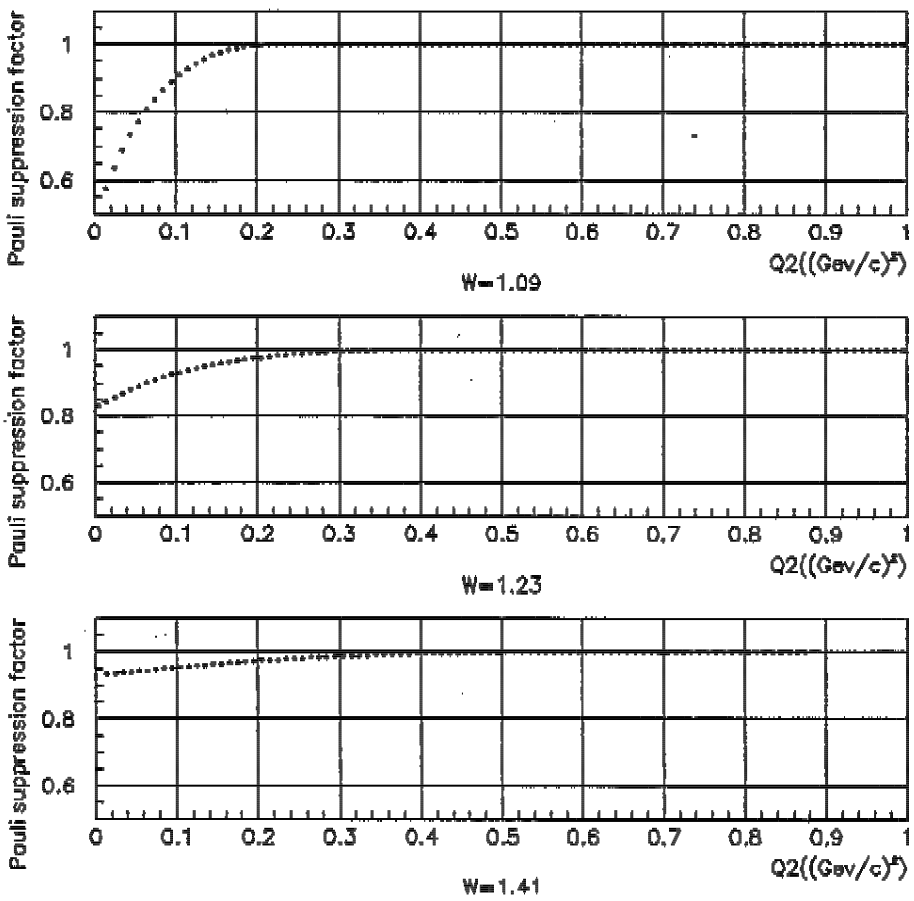
[1] S. L. Adler, S. Nussinov, E. A. Paschos, PRD9(1974)2125

[2] E. A. Paschos, L. Pasquali, J. Y. Yu, NPB588(2000)263

[3] E. A. Paschos, J. Y. Yu, PRD65(2002)033002

[4] I. Schienbein, J. Y. Yu, Proceedings of NUINT'02

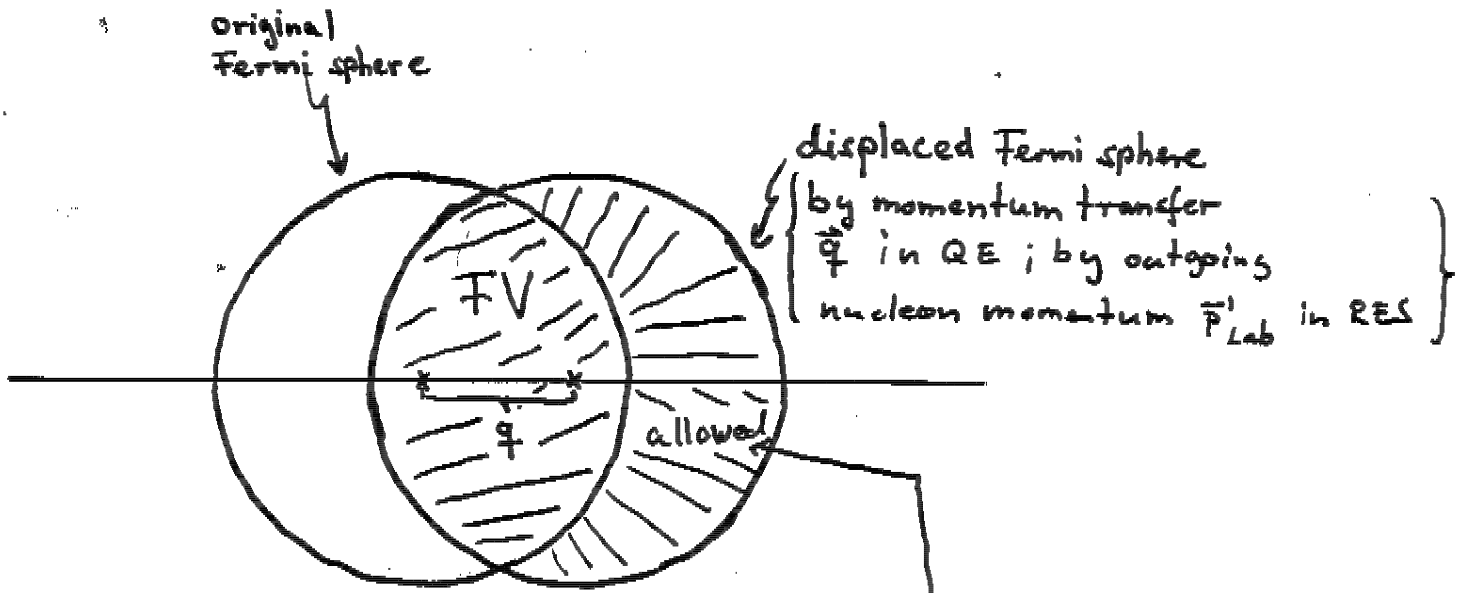
Pauli Suppression Factors in the simple FGM as function of Q^2 for various W



- simple Fermi Gas Model (FGM) with $p_F = 0.226$ GeV
- isoscalar target $Z = N$
- the suppression appears for $Q^2 \lesssim 0.2\ \mathrm{GeV}^2$

The <u>Pauli suppression factor</u> has a simple geometrical interpretation

S. Berman ('61)



FV: forbidden Volume

Suppression factor :

$$S(|\vec{q}|) = \frac{\text{allowed Volume}}{\frac{4\pi}{3} R_F^3} = 1 - \frac{\text{forbidden Volume}}{\frac{4\pi}{3} R_F^3}$$

[depends on the kinematics]

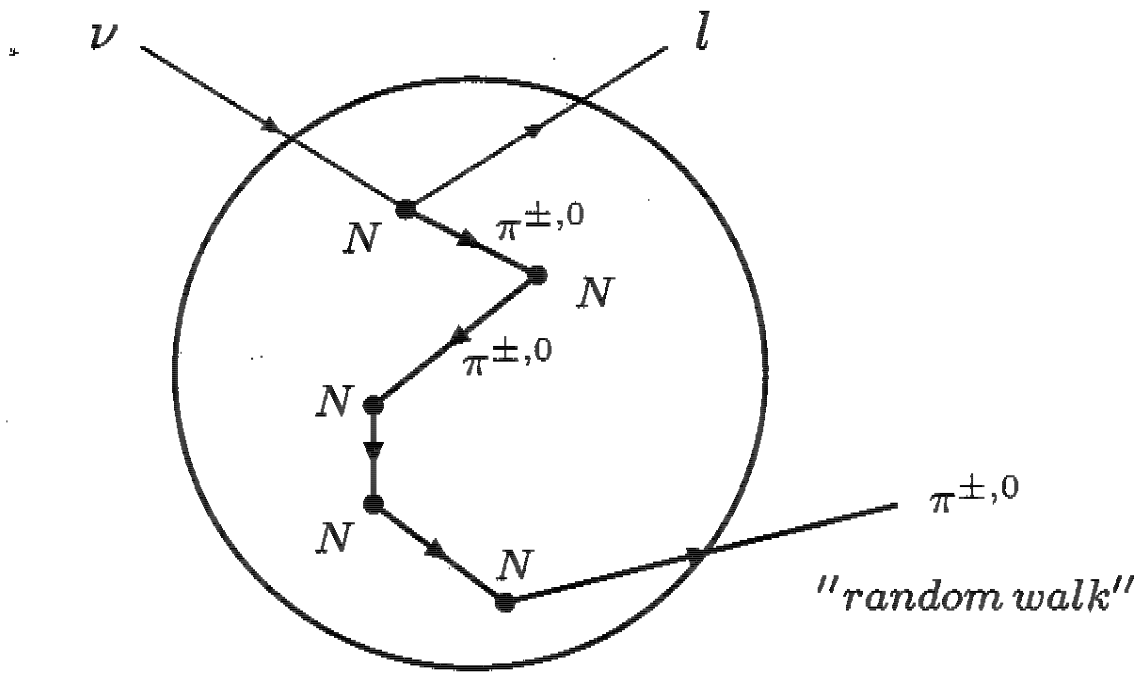
Factorization

- Reactions

$$\nu + T \rightarrow l + T' + \pi^{\pm,0}$$

  - T: nuclear target ($_8O^{16}$, $_{18}Ar^{40}$, $_{26}Fe^{56}$)
  - T': final nuclear state

- Two step process



1. single pion production in νN scattering
   → Pauli Principle, Fermi motion
2. multiple scattering of pions
   → Charge exchange, absorption, Pauli Principle

- step 2 is described by the charge exchange matrix M
  - only depends on properties of the target
    → charge density profile $\rho(r)$
- basic assumption: two steps independent → predictive power

Single pion resonance production (RES)

- RES on free nucleons
  - $\exists$ several calculations in the literature [1-4]
  - Our calculation uses [4] $\oplus$ modified form factors [5] as input
  - calculations differ by about 20 %
- Nuclear corrections
  - Our approach: ANP model [6,7,8]
  - $\exists$ other approaches from 'nucl-th side'

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[1] Adler, Ann. Phys. 50(1968)189;

[2] Fogli, Nardulli, NPB160(79)116; NPB165(80)162

[3] Rein, Schgal, Ann. Phys. 133(81)79

[4] Zucker, PRD4(71)3350; Schreiner, von Hippel, NPB58(73)333

[5] Paschos, Sakuda, Yu, PRD(2003)

[6] Adler, Nussinov, Paschos, PRD9(1974)2125

[7] Paschos, Pasquali, Yu, NPB588(2000)263

[8] Paschos, I.S., Yu, work in progress; I.S., J.-Y. Yu, talk at NuInt'02

Δ–resonance production

The triple-differential cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2\mathrm{d}W\mathrm{d}E_\pi} = \frac{1}{\beta\gamma|p_\pi^{CMS}|}\frac{WG_F^2}{16\pi M_N^2}\times \sum_{i=1}^{3}\left[K_i\widetilde{W}_i - \frac{1}{2}K_iD_i(3\cos^2\theta_\pi - 1)\right]$$

- G_F: Fermi constant, $M_N (N = n, p)$: Nucleon mass
  $\beta\gamma$: Boost from LAB $\rightarrow \pi N$-CMS
- Kinematic factors:
  $K_1(Q^2, E_\nu)$, $K_2(Q^2, E_\nu, W)$, $K_3(Q^2, E_\nu, W)$
- Structure functions:
  - $\widetilde{W}_1$, $\widetilde{W}_2$, $\widetilde{W}_3$, D_1, D_2, D_3: can be expressed in terms of helicity amplitudes
- Helicity amplitudes:
  - $T_{3/2,1/2}$, T_C, $U_{3/2,1/2}$, U_C, U_D
  - depend on $f(W)$ and form factors ~~(*)~~ $(C_i^V, C_i^A, i = 1, ..., 6)$
- Breit – Wigner factor $f(W)$

$$f(W) = \frac{\sqrt{\frac{\Gamma_\Delta(W)}{2\pi}}}{(W - M_\Delta) - 1/2i\Gamma_\Delta(W)}$$

Schreiner von Hippel, Nucl. Phys. **B58**, 333 (1973)

~~(*) Alvarez-Ruso et al., Phys. Rev. C57, 2693 (1998)~~

- Form Factors from Paschos et al. [1]
  - Vector Form Factors:

Dipol ↙ ↘ Modification

$$C_3^V(Q^2) = \frac{C_3^V(0)}{\left[1+\frac{Q^2}{M_V^2}\right]^2}\left(\frac{1}{1+\frac{Q^2}{4\,M_V^2}}\right)$$

$$C_4^V(Q^2) = -\frac{M_N}{W}C_3^V(Q^2)$$

$$C_5^V(Q^2) = 0$$

$$C_6^V(Q^2) = 0 \quad \text{(CVC)}$$

  - Axial Form Factors:

$$C_5^A(Q^2) = \frac{C_5^A(0)}{\left[1+\frac{Q^2}{M_A^2}\right]^2}\left(\frac{1}{1+\frac{Q^2}{3\,M_A^2}}\right), \quad 3M_A^2 \sim 4M_V^2$$

$$C_4^A(Q^2) = -\frac{1}{4}\,C_5^A(Q^2) \quad [2]$$

$$C_3^A(Q^2) = 0$$

$$C_3^V(0) = 1.95\,, \quad C_5^A(0) = 1.2\,\text{(PCAC)}$$

$$M_V = 0.84\,\text{GeV}\,, \quad M_A = 1.05\,\text{GeV}$$

Note:

- $d\sigma|_{C_6^A} \propto m_l^2 \rightarrow$ neglected
- $C_3^V(Q^2)$ and $C_5^A(Q^2)$ give dominant contribution to cross section
- All the form factors need to be multiplied by $\sqrt{3}$ due to $< \Delta^{++}|V_\alpha|p > = \sqrt{3} < \Delta^{+}|V_\alpha^{em}|p >$.

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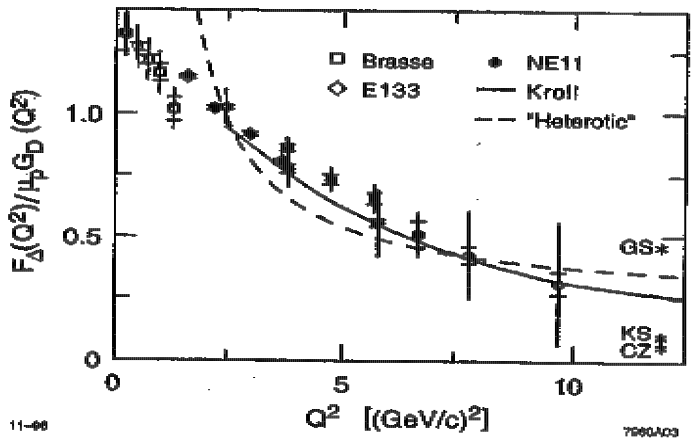
[1] Paschos, Sakuda, Yu, PRD(2003)
[2] Schreiner, von Hippel, NPB58(1973)23

NΔ FF falls more rapidly than Nucleon FF (M_V)

- Size of Δ is larger
  = Q^2 distribution small

$$G_D \equiv \frac{1}{\left(1+\frac{Q^2}{M_V^2}\right)^2}$$

New



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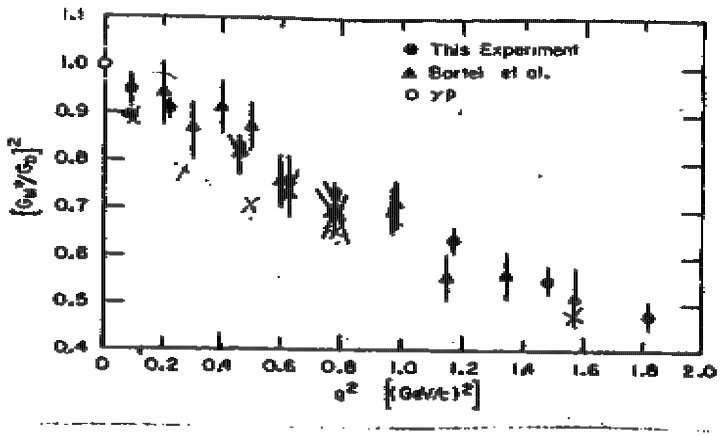

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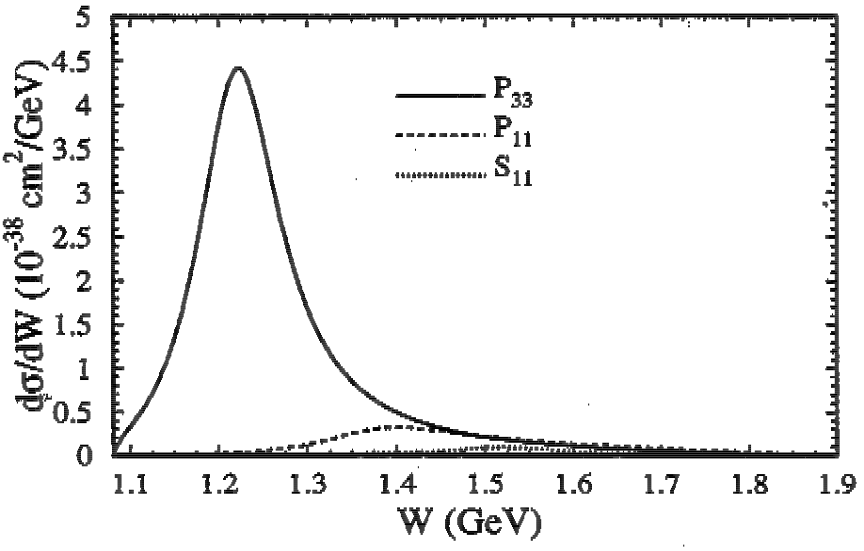
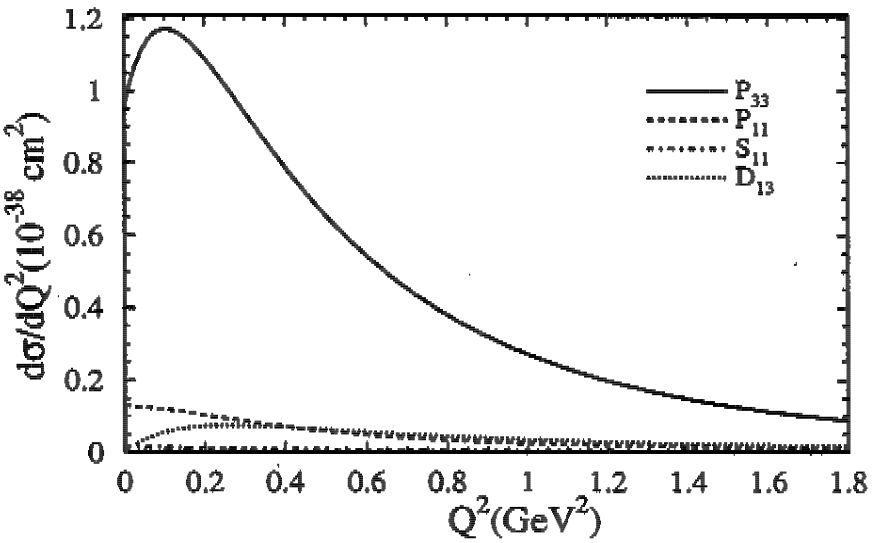
Spectra for P_{33}, P_{11} and S_{11} resonances

Spectra of invariant mass W:



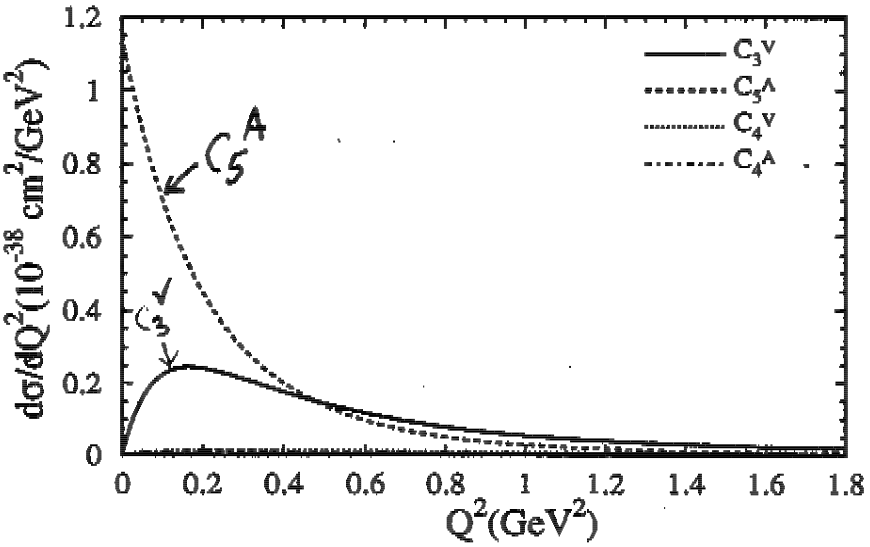
- $E_\nu = 1.5$ GeV (analogous results for $E_\nu = 2.0$ GeV)
- $W < 1.4$ GeV: Δ-resonance (P_{33}) dominant

Spectra of momentum transfer Q^2:



- 1.08 GeV $< W <$ 1.6 GeV
- S_{11} resonance negligible
- $D_{13}(1520)$ resonance contribution also shown

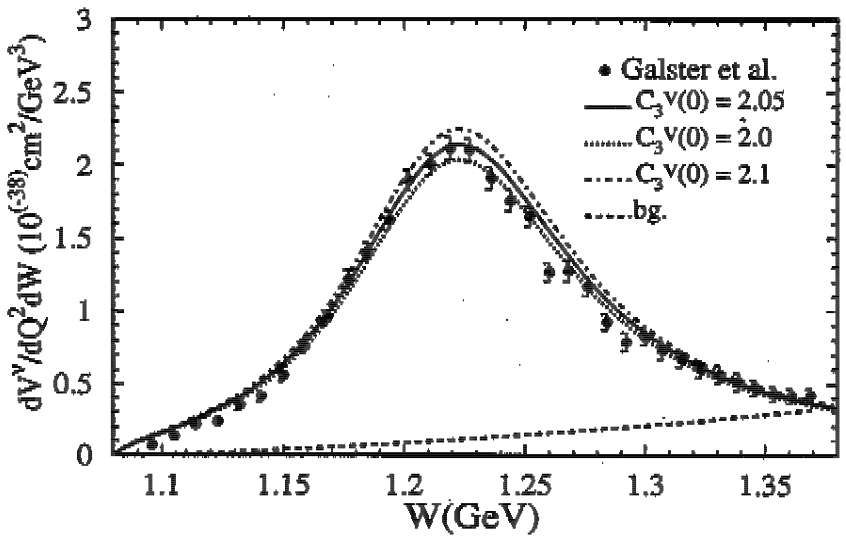
Contribution of Form Factors to the Cross Section



- C_3^V and C_5^A dominate the cross section
- The contributions from C_4^V and C_4^A are very small

$\Rightarrow$ The excitation of the Δ-resonance is well described by <u>two form factors</u>

Comparison of the Vector Contribution to $\nu + p \to \mu^- + p + \pi^+$ with renormalized Electroproduction Data



$$\frac{dV^\nu}{dQ^2 dW} = \frac{G^2}{\pi}\ \frac{3}{8}\ \frac{Q^4}{\pi\alpha^2}\ \frac{d\sigma^{\mathrm{em},\,I=1}}{dQ^2 dW}$$

- Electroproduction data for the reactions $e + p \to e + \begin{cases} p\,\pi^0 \\ n\,\pi^+ \end{cases}$ [1]
- Subtraction of the $I = 1/2$ background (dashed line)
- Renormalize to the reaction $\nu + p \to \mu^- + p + \pi^+$

→ Comparison with the vector contribution to $\nu + p \to \mu^- + p + \pi^+$ denoted by $V^\nu \leftrightarrow C_3^V(Q^2)$ part

- find good agreement using $C_3^V(0) = 2.05 \pm 0.05$

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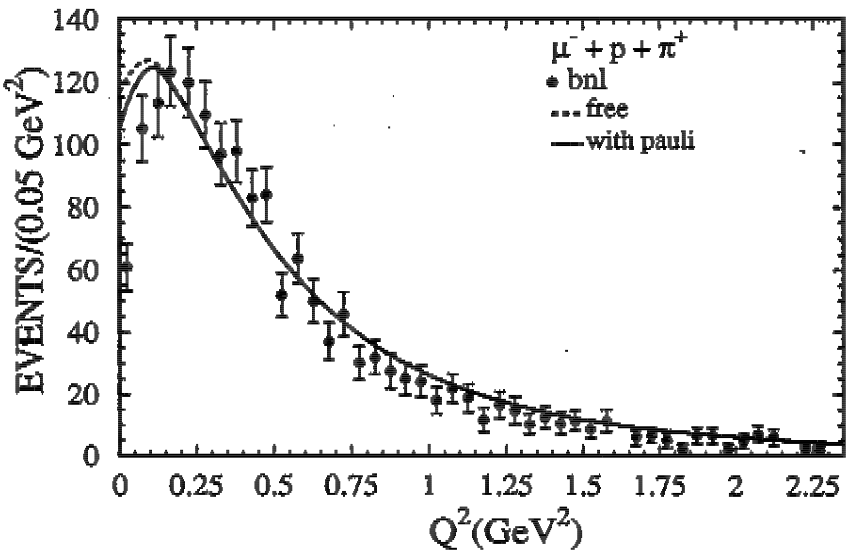
[1] Galster et al., PRD5(1972)519

Q^2-spectrum of the process $\nu p \to \mu^- p \pi^+$ in comparison with BNL data [1]



- BNL data as histograms, averaged over neutrino flux, and with unspecified normalization

$\to$ fix normalization such that area under theoretical curve and histogram is the same for $Q^2 \geq 0.2\ \mathrm{GeV}^2$

- Reduce nuclear effects: fit to all data with $Q^2 > 0.2\ \mathrm{GeV}^2$
- best fit result: $\chi^2/\mathrm{d.o.f.} = 1.04 \quad [Q^2 \geq 0.2\ \mathrm{GeV}^2]$

paramters:

$$C_3^V(0) = 1.95\,, \quad C_5^A(0) = 1.2$$
$$M_V = 0.84\,\mathrm{GeV}\,, \quad M_A = 1.05\,\mathrm{GeV}$$

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[1] Kitagaki et al., PRD34(1986)2554

Conclusions

- Single pion neutrino production at low energies important to measure properties of neutrino oscillations
  - exist several more complicated calculations (more parameters, more complicated functional form of form factors)
    $O(20\%)$ theoretical uncertainty
  - our approach particularly simple (self-contained) $\rightarrow$ helpful for physical interpretation
- We have analysed the differential cross section $\frac{d\sigma}{dQ^2}$ in terms of two form factors
  - four free parameters M_V, M_A, $C_3^V(0)$, $C_5^A(0)$
  - Good fit to BNL data for $Q^2 \geq 0.2\ \mathrm{GeV}^2$ $(\chi^2/d.o.f = 1.04)$
  - $Q^2 \leq 0.2\ \mathrm{GeV}^2$: theory is too high
    * Pauli correction is small
    * possible other medium effect?

$\Rightarrow$ The neutrino production of Δ-resonance can be described by two form factors: C_3^V, C_5^A

- C_3^V consistency check from electroproduction data
- C_5^A only from neutrino data

- Furthermore: included higher resonances (P_{11}, S_{11}, D_{13}):
  - At $E_\nu < 2$ GeV and $W < 1.4$ GeV Δ-resonance dominant
  - S_{11}, P_{11}: isospin $I = 1/2$ background
    $\Rightarrow$ contribute only to $p\pi^0$ and $n\pi^+$ final states

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Outlook:

- include higher resonances
- waiting new data

KEK, October, 2003

Muon Spectra of Quasi-Elastic and 1-Pion Production Events in LBL Neutrino Oscillation Experiments

I. Schienbein
(DESY)

in collaboration with: E. A. Paschos, D. P. Roy and J. Y. Yu [1,2]

Outline

- Motivation
- Muon spectra at LBL experiments $\Rightarrow$ Information on ν-oscillation
- Conclusions

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[1] E. A. Paschos, D. P. Roy, I. S., J. Y. Yu, hep-ph/0307223 (PLB)
[2] J. Y. Yu, talk at ICFP03

Motivation

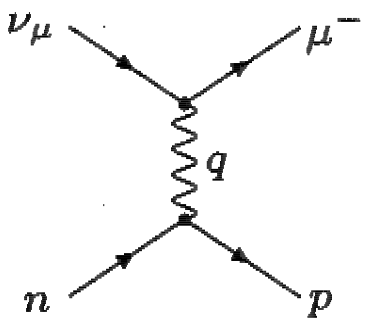
ν_μ-oscillation at LBL experiments:

- Muon neutrino oscillation probability:
  $P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E_\nu}$
- Main goal: precision measurement of $\Delta m^2, \sin^2 2\theta$
- Standard approach:
  1. Reconstruction of E_ν
  2. Plot $P_{\mu\mu}$ as function of E_ν:

     at Minimum: $P_{\mu\mu} \stackrel{!}{=} 1 - \sin^2 2\theta \Rightarrow \sin^2 2\theta$
     $\frac{\Delta m^2 L}{4E_{\nu,\min}} \stackrel{!}{=} \frac{\pi}{2} \Rightarrow \Delta m^2$

Reconstruction of E_ν from QE scattering events:

simple kinematics



- measure energy and polar angle of muon: $(E_\mu, \cos\theta_\mu) \Rightarrow E_\nu$

$$E_\nu = E_\nu[E_\mu, \cos\theta_\mu] = \frac{M_p E_\mu - m_\mu^2/2}{M_p - E_\mu + |\vec{k}_\mu| \cos\theta_\mu}$$

Difficulties: about 30% of 1Rμ events are 1-π events!

- 'Contamination' of QE event samples by 1-pion production events with unidentified/absorbed pions
- Reconstruction of E_ν more complicated including binding energy ϵ_B and Fermi motion of nucleons:

$$\begin{aligned} E_\nu &= E_\nu[E_\mu, \cos\theta_\mu, \vec{p}, \epsilon_B] \\ &= \frac{(E_p + \epsilon_B)E_\mu - (2E_p\epsilon_B + \epsilon_B^2 + m_\mu^2)/2 - \vec{p}\cdot\vec{k}_\mu}{E_p + \epsilon_B - E_\mu + |\vec{k}_\mu|\cos\theta_\mu - |\vec{p}|\cos\theta_p} \end{aligned}$$

→ Uncertainty of the reconstructed energy at given $(E_\mu, \cos\theta_\mu, \epsilon_B)$ about -9% to $+6\%$ (for a single event)

⇒ Look for alternative/complementary approach using E_μ spectra: directly measurable Paschos, Roy, Schienbein, Yu, hep-ph/0307223

Flux averaged muon energy spectra

Calculated flux averaged muon energy spectra for QE and 1-pion events

- Neutrino fluxes at K2K:
  - Near detector: $f(E_\nu)$ [→ Figure]
  - Far detector: $f_{SK}(E_\nu) = f(E_\nu) \cdot P_{\mu\mu}(E_\nu)$
- Flux-averaged E_μ spectra: 'R = QE, 1-π' [→ Figure]

$$\langle \frac{\mathrm{d}\sigma^R}{\mathrm{d}E_\mu} \rangle \equiv \int f(E_\nu) \frac{\mathrm{d}\sigma^R}{\mathrm{d}E_\mu} \, \mathrm{d}E_\nu$$

- Main observation/result:

$$\langle \frac{\mathrm{d}\sigma^R}{\mathrm{d}E_\mu} \rangle \simeq \sigma^R_{\mathrm{tot}}(\overline{E_R}) \, f(\overline{E_R}) \underset{E_\mu > E_0}{\longrightarrow} \text{const.} \times f(\overline{E_R})$$

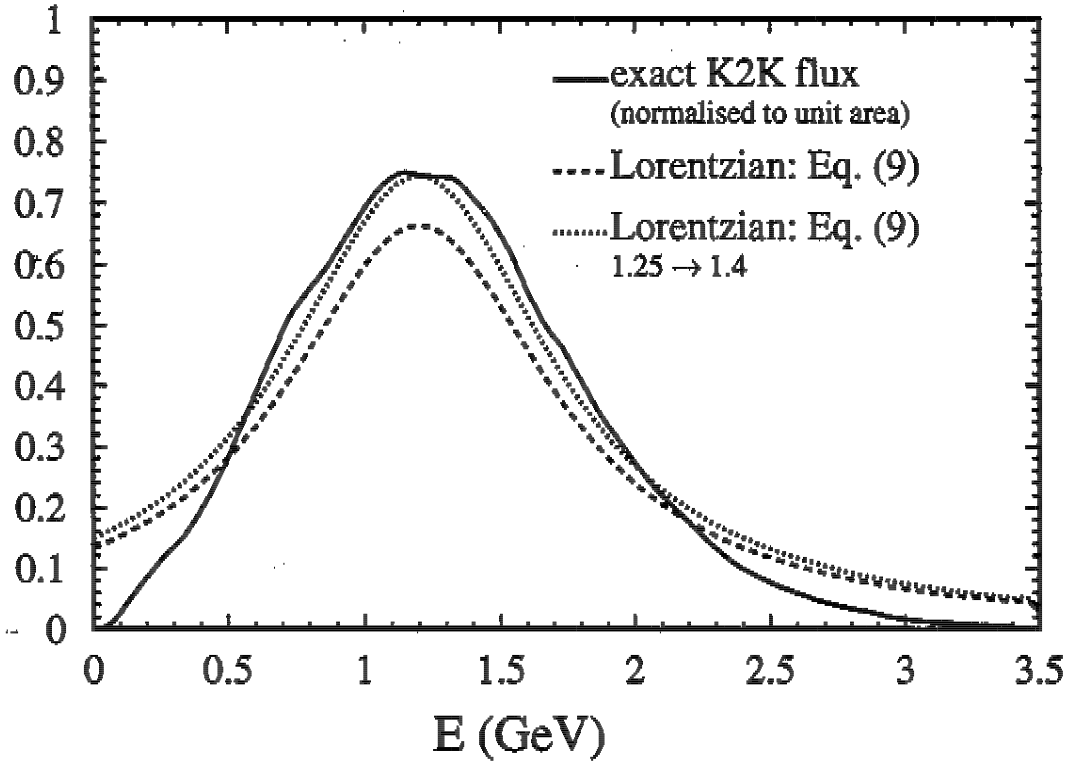
$$\overline{E_R} = E_\mu + \begin{cases} 0.15\ \mathrm{GeV} & \text{for QE} \\ 0.4\ \mathrm{GeV} & \text{for 1-pion} \end{cases}$$

⇒ At large muon energies [$E_0 = \mathcal{O}(1\ \mathrm{GeV})$] the flux-av. cross section $\langle \frac{\mathrm{d}\sigma^R}{\mathrm{d}E_\mu} \rangle$ is directly proportional to the neutrino flux, shifted in energy

[→ Figure]

- Remarks:
  - holds true for near and far detector with flux at far detector: $f_{SK}(\overline{E_R}) = f(\overline{E_R}) \cdot P_{\mu\mu}(\overline{E_R})$
  - normalization constants N and shifts ΔE:
    - are different for QE and 1-pion events
    - follow from theoretical calculation
    - experimentally from near detector data (?): $E_\mu > E_0$: $\langle \frac{\mathrm{d}\sigma}{\mathrm{d}E_\mu} \rangle = N \cdot f(E_\mu + \Delta E)$

K2K neutrino energy spectrum



Lorentzian:

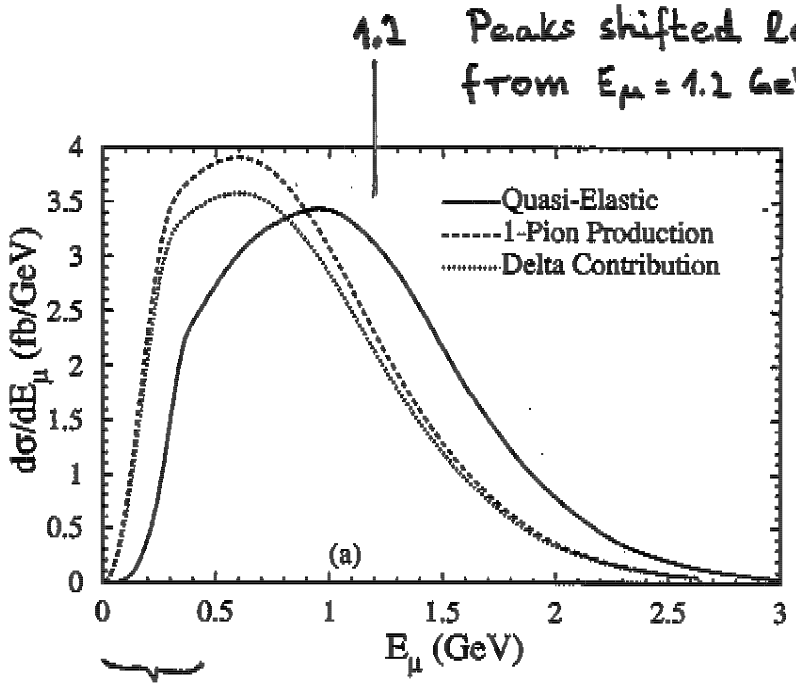
$$f(E) = \frac{\text{Norm}}{\pi} \frac{\gamma}{(E - E_0)^2 + \gamma^2}$$

$$(E_0 = 1.2\ \text{GeV},\ \gamma = 0.6\ \text{GeV})$$

K2K muon energy spectra: Flux-averaged, Exact

$\left\langle \frac{d\sigma}{dE_\mu} \right\rangle$: cross section/nucleon for H_2O

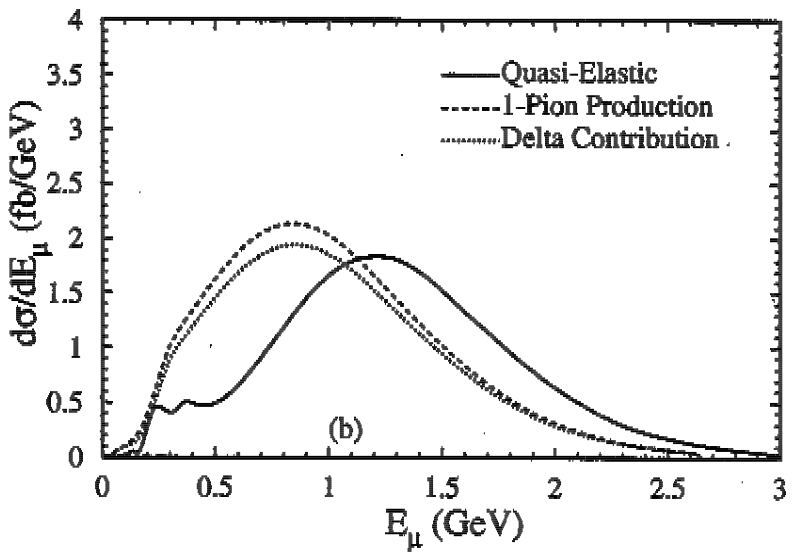
Near Detector



- Right to the peak: shapes closely follow ν-spectrum

Far Detector

Spectrum distorted due to ν-oscillation

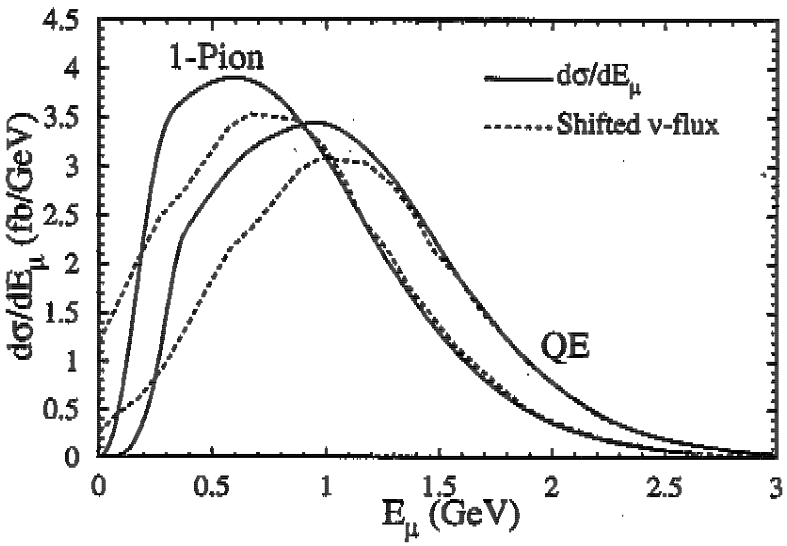


$\sin^2 2\theta = 1$

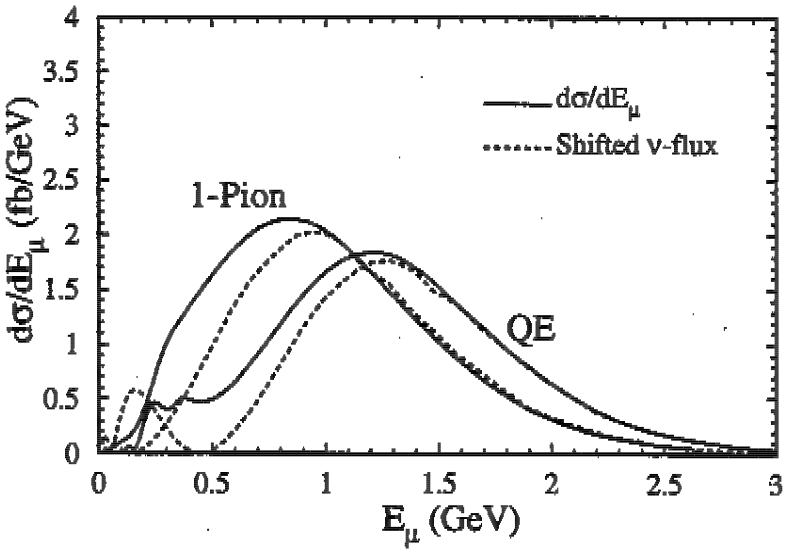
$\Delta m^2 = 3 \cdot 10^{-3}\ eV^2$

Comparison: $\langle d\sigma/dE_\mu \rangle \leftrightarrow N \cdot f(E_\mu + \Delta E)$ (shifted ν-flux)

Near Detector: 'shifted flux' = $N \cdot f(\overline{E_R})$



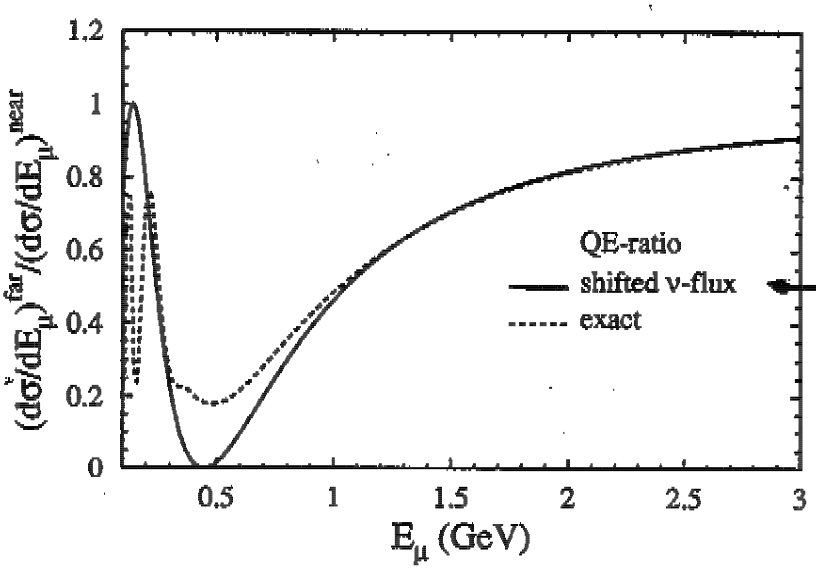
Far Detector: 'shifted flux' = $N \cdot f(\overline{E_R}) \cdot P_{\mu\mu}(\overline{E_R})$



- Good agreement at: $E_\mu \geq E_0 = 1$ GeV (1-pion)
  $E_\mu \geq E_0 = 1.2$ GeV (QE)

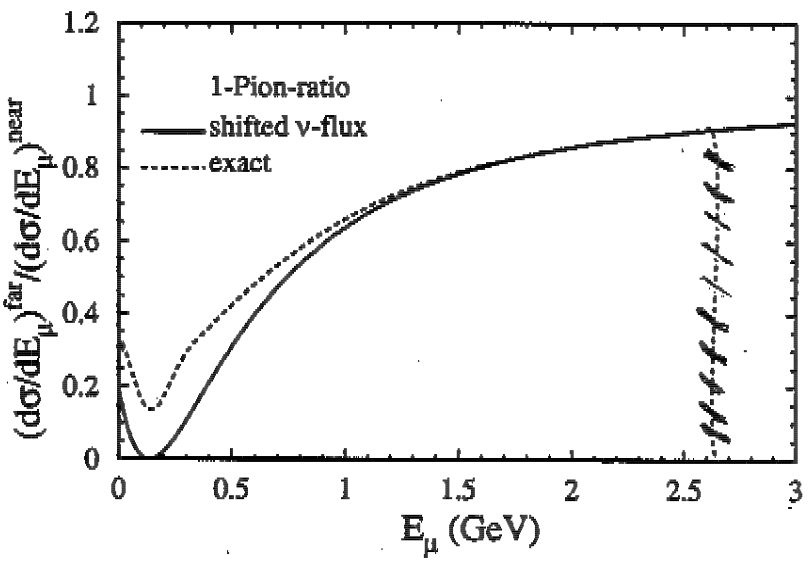
Far-Near-Ratio $\langle \frac{d\sigma}{dE_\mu} \rangle^{far} / \langle \frac{d\sigma}{dE_\mu} \rangle^{near} \leftrightarrow P_{\mu\mu}(\overline{E_R})$

QE: $\overline{E_R} = E_\mu + 0.15\ \mathrm{GeV}$ ($\Delta m^2 = 3 \cdot 10^{-3}\ eV^2$, $\sin^2 2\theta = 1$)



← $P_{\mu\mu}(\overline{E_R})$

1-Pion Production: $\overline{E_R} = E_\mu + 0.4\ \mathrm{GeV}$



← numerical artefact

$\langle \frac{d\sigma}{dE_\mu} \rangle \to 0$

Discussion

Shown Results:

- exact calculation (no theor. approximations)
- exact K2K flux (not the Lorentzian)
- cross sections / nucleon for H_2O
- $\Delta m^2 = 3 \cdot 10^{-3}\ eV^2$, $\sin^2 2\theta = 1$

Idealized case:

- clean QE / clean 1-π samples

  experimentally 1-Ring (2-Ring) muon events:

  CC $1R\mu \simeq$ QE + 30% 1-π

  CC $1R_\mu + 2R_\mu \gtrsim$ QE + 1-π [multi-π : $\approx$ 15%]

- perfect detector : 100% efficiency , no cuts
- did not consider Fermi motion :
  → effect should be small
- sensitivity of method to Δm^2, $\sin^2 2\theta$?

Further aspects in our paper not discussed here/so far :

- Derivation/Motivation of $\left\langle \frac{d\sigma}{dE_\mu} \right\rangle \simeq \sigma_{tot}(\overline{E}_R) f(\overline{E}_R)$

  → $\overline{E}_R = E + \Delta E$; $\Delta E = \frac{\langle Q^2 \rangle + \Delta M^2}{2M}$; $\Delta M^2 = \begin{cases} 0 & : QE \\ M_\Delta^2 - M_p^2 & : 1\text{-}\pi \end{cases}$

  $\langle Q^2 \rangle \simeq 0.3\ GeV^2$

  Norm: $\sigma_{tot}^R \xrightarrow[E \to \infty]{} const = N$

- Simple analytic expression with help of:
  - param. of $\sigma_{tot}^R(E)$
  - Lorentzian form for the flux
- qualitative comparison with spectra of the K2K ND

Conclusions

- Muon Spectra of QE and 1-Pion Events provide an alternative/complementary approach to experimental extractions of atmospheric muon oscillation parameters at K2K

- Method can be useful for other LBL experiments