Neutrino induced meson production and Parity Violating Electron Scattering

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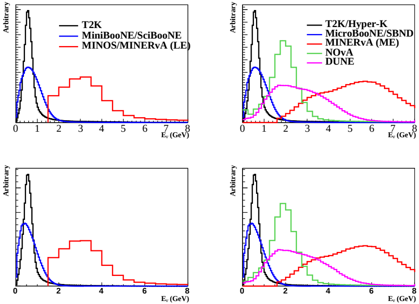
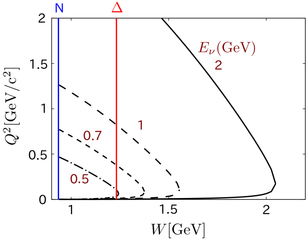
GeV neutrino in current and future accelerator neutrino experiments.



Neutrino

Anti-Neutrino



T. Katori and M. Martini arXiv 1611.07770

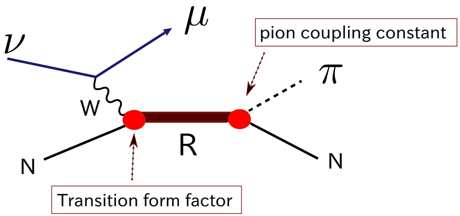
- Description of neutrino reactions in the resonance region is important.
- Reaction model should be constrained as much as possible from available pion, photon, and electron induced meson production data.
- Resonance region $(W < 2GeV)$ and DIS$(W > 2GeV, Q^2 \geq 1GeV^2)$

$$\boxed{< MB|J^\mu_\alpha|N >}$$

$$\begin{aligned} J^\mu_{em} &= V^\mu_3 + V^\mu_{IS} \\ J^\mu_{CC} &= V^\mu_{1+i2} - A^\mu_{1+i2} \quad (\Delta S = 0 \text{ current without CKM}) \\ J^\mu_{NC} &= V^\mu_3 - A^\mu_3 - 2\sin^2\theta_W J^\mu_{em} - \frac{1}{2}\bar{s}\gamma^\mu(1-\gamma_5)s \end{aligned}$$

- Isobar model and ANL-Osaka coupled channel model
- Neutrino induced single and double pion production
- Inclusive cross section and parity violating asymmetry
- Summary

Isobar Models



For each partial wave amplitude $(J^\pi I)$

$$\mathcal{F}^{J^\pi I} = \frac{g_{\pi NR} \;\; g_{JNR}}{W - M_R + i\Gamma_R/2}$$

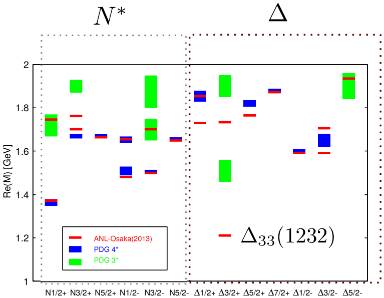
- Mass(M_R), Width(Γ_R) of resonance R from PDG.
- Coupling constants$g_{\pi NR}, g_{VNR}$ can be estimated from branching ratio(B_α), g_{ANR}: use quark model estimation or use $g_{\pi NR}$ assuming PCAC.

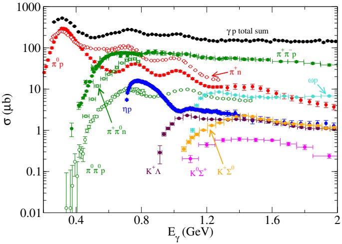
  $$g_{\pi NR} = \sqrt{\frac{\Gamma}{2} B_\pi}, \quad g_{VNR} = \sqrt{\frac{\Gamma}{2} B_\gamma}$$
- No control of non-resonant mechanism, relative phases between non-res $\leftrightarrow$ res, (J^π, I) channels.
- model implemented in neutrino generators.(Rein-Sehgal model)

ANL-Osaka Coupled channel model

new feature beyond $\Delta_{33}(1232)$

- many N^* and Δ resonances $M_R < 2GeV$



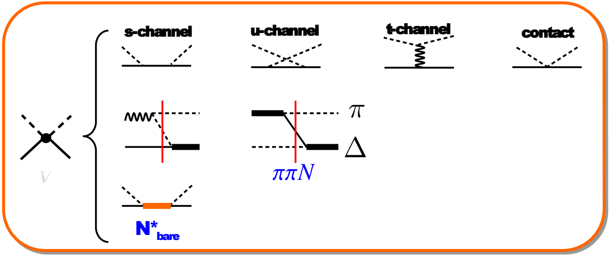


- opening of $\eta N, \pi\pi N, K\Lambda, K\Sigma, , ,$ channels

  $\rightarrow$ needs multi-channel unitarity including three-body($\pi\pi N$).

(ANL-Osaka model)

- Meson exchange picture of meson-baryon interaction.



- Included Meson-baryon channels:
  $\pi N, \eta N, \pi\pi N(\sigma N, \rho N, \pi\Delta), K\Lambda, K\Sigma$
- Satisfy three body($\pi\pi N$) unitarity

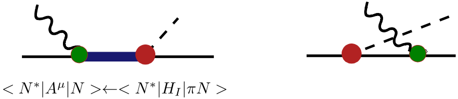
$$T = V + VG_0T$$

Step 1: πN reactions. [fix strong interaction part of model]

Step 2:Analysis of $\gamma, \gamma^*(\sigma/d\Omega, P, \Sigma, ..)$.[fix model of Vector current]

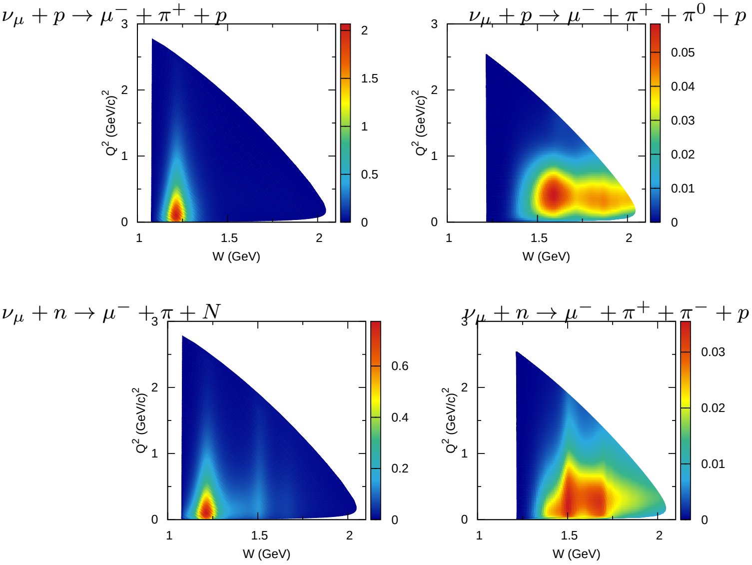
validity of reaction mechanisms(non-resonant, resonant) are tested through the analysis of extensive data.

Step 3 Axial vector coupling of N to N^*, Δ(only parameters left undetermined.):



PCAC(not all coupling constants are determined.), Q^2 dependence: assume dipole

Overview of neutrino induced reaction (ANL-Osaka Model) $d\sigma/dW/dQ^2$ at $E_\nu = 2GeV$



S. X. Nakamura et al. PRD 92, 074024 (2015)

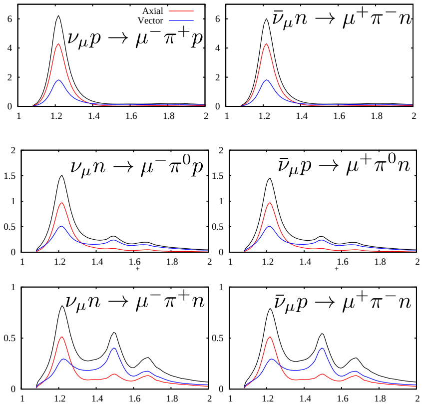
Single pion production data

Data on Neutrino induced Single pion production
(http://hepdata.cedar.ac.uk/review/neutrino/)

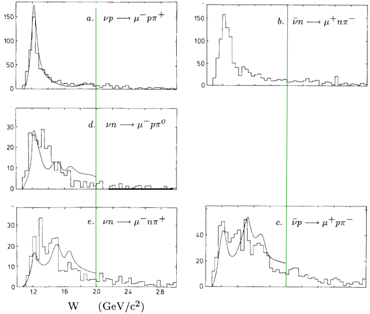
				1π	2π
GGM	Lerche 1978	ν	Propane	1-10	
	Bolognese 1979	$\bar{\nu}$	Propane-Freon	1-7.5	
BEBC	Allen 1986	ν	p	10-80	
	Allasia 1990	$\nu, \bar{\nu}$	d	5-150	
BNL	Kitagaki 1986	ν	d	0.5 - 3	0.5 - 3
ANL	Barish 1979	ν	p,d	0.4 - 6	
	Radecky 1982	ν	d	0.5 - 1.5	
	Day 1983	ν	d		0.75-5.55
FNAL	Bell 1978	ν	p	15-40	
SKAT	Ammosov 1988	ν	Freon(CF_3Br)	4-18	
	Grabosch 1989	$\nu, \bar{\nu}$	Freon(CF_3Br)	3.5-6	

- Reanalysis of ANL/BNL data
  (C. Wilkinson et al. PRD90 (2014), Rodrigues et al. arXiv:1601.01888)

$d\sigma/dW$ of single pion production $E_\nu = 40GeV$



Neutrino anti-neutrino



BEBC NP343,285(1990)

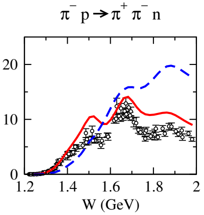
Only qualitative comparison can be made for higher W region.

pi N → pi pi N reaction

Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC79 025206 (2009)

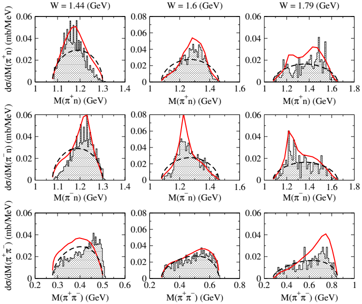
Parameters used in the calculation are from πN → πN analysis.

$$\pi^- p \to \pi^+ \pi^- n$$



Full result

C.C. effect off



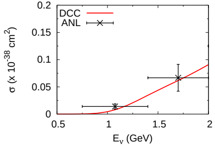
Full result **Phase space**

Data handled with the help of R. Arndt

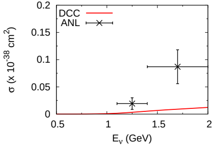
H. Kamano@BARYON10

Neutrino induced two pion production

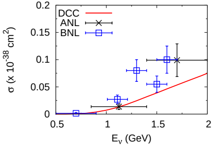
$\nu_\mu p \to \mu^- \pi^+ \pi^- p$



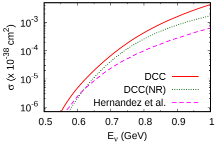
$\nu_\mu p \to \mu^- \pi^+ \pi^+ n$

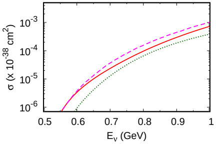


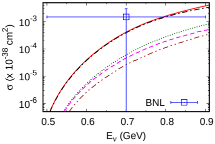
$\nu_\mu n \to \mu^- \pi^+ \pi^- n$



Near threshold(compare with Hernandez et al.(D(1232)+N(1440))





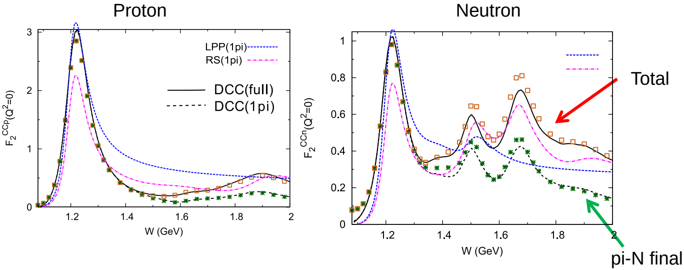


Inclusive cross section and parity violating asymmetry

How well our model accounts total strength of reaction?

- $Q^2 = 0$ PCAC (compare with πN total and elastic cross sections)
- Large Q^2
  vector current : data and parton model
  axial vector current : parton model, PV electron scattering

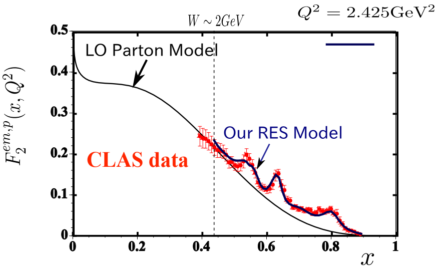
Axial Vector current F_2^{CC} at $Q^2 = 0$

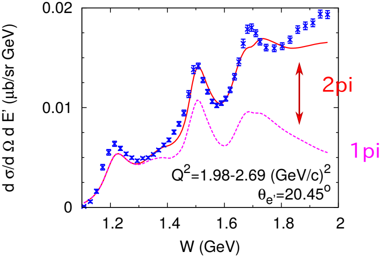


Using PCAC, $F_2^{CC}(Q^2 = 0) = \frac{2f_\pi^2}{\pi}\sigma(virtual\pi + N)$

open box, green cross are data.

Vector current at large Q^2

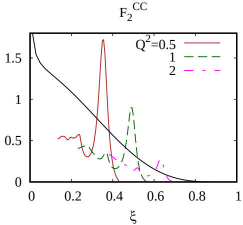


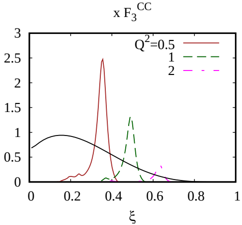


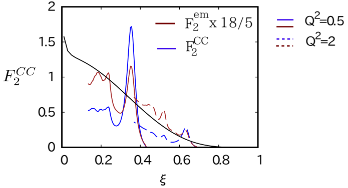
description of ep in RES, smoothly connected to DIS

Axial vector current at large Q^2

strength of axial vector current at large W, Q^2 in DCC model may be too weak.







$F_2^{CC} \sim |V|^2 + |A|^2$ $\quad$ $F_3^{CC} \sim Re(VA^*)$ $\quad$ F_2^{CC}

$$
\begin{aligned}
F_2^{CC} &\propto |V_{IV}|^2 + |A_{IV}|^2, \quad F_2^{em} \propto |V_{em}|^2 && \text{DCC} \\
F_2^{CC} &\approx \frac{18}{5} F_2^{em} \sim x(u + \bar{u} + d + \bar{d}) && \text{PDF}
\end{aligned}
$$

$$F_i^\alpha = \frac{F_{ip}^\alpha + F_{in}^\alpha}{2}$$

Approximate relation between structure functions

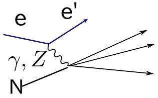
F_3^{CC} and $F_3^{\gamma Z}$ $(F_i^\alpha = (F_{ip}^\alpha + F_{in}^\alpha)/2)$

$$
\begin{aligned}
2F_3^{\gamma Z} &= F_3^{CC} \propto V_{IV}(A_{IV})^* && \text{DCC} \\
2F_3^{\gamma Z} &\approx F_3^{CC} \sim u - \bar{u} + d - \bar{d} && \text{PDF}
\end{aligned}
$$

* $W_3^{\gamma N}$ can be used to test F_3^{CC} for neutrino reaction.

Parity violating electron scattering

Parity violating asymmetry of $N(\vec{e},e')X$ reaction $< \vec{\sigma}\cdot\vec{p}_e >$



$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = -\frac{Q^2 G_F}{\sqrt{2}4\pi\alpha}\frac{N}{D}$$

$$N = \cos^2\frac{\theta}{2}W_2^{\gamma Z} + \sin^2\frac{\theta}{2}[2W_1^{\gamma Z} + (1-4\sin^2\theta_W)\frac{E_e + E'_e}{M_N}W_3^{\gamma Z}]$$

$$D = \cos^2\frac{\theta}{2}W_2^{em} + \sin^2\frac{\theta}{2}W_1^{em}$$

Here

$$W_i^{em} \propto \sum_f \delta(p_i + q - p_f) < f|J^\mu_{em}|N >< f|J^\nu_{em}|N >^*$$

$$W_i^{\gamma Z} \propto \sum_f \delta(p_i + q - p_f)[< f|J^\mu_{em}|N >< f|J^\nu_{NC}|N >^* + < f|J^\mu_{NC}|N >< f|J^\nu_{em}|N >^*]$$

Parity Violating Asymmetries

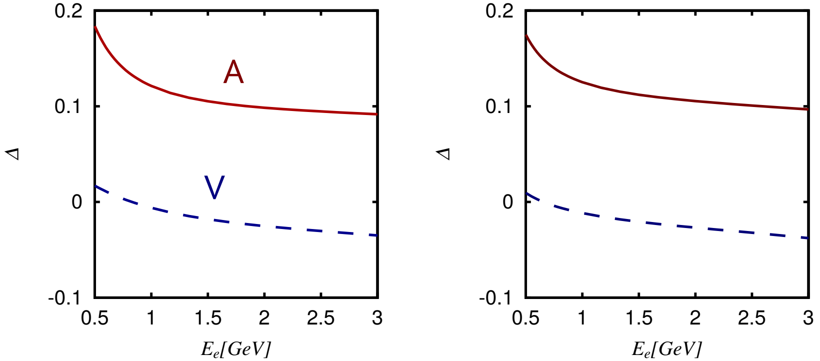
Using $V^\mu_{NC} = (1 - 2\sin^2\theta_W) J^\mu_{em} - V^\mu_{IS}$

$$
\begin{aligned}
Q^2 A_{PV} &= \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = -\frac{G_F}{\sqrt{2}4\pi\alpha}[2 - 4\sin^2\theta_W + \Delta_V + \Delta_A] \\
&= -8.99 \times 10^{-5}[1.075 + \Delta_V + \Delta_A]
\end{aligned}
$$

$$
\begin{aligned}
\Delta_V &= -[\cos^2\frac{\theta}{2} W_2^{em-is} + 2\sin^2\frac{\theta}{2} W_1^{em-is}]/D \\
\Delta_A &= \sin^2\frac{\theta}{2}(1 - 4\sin^2\theta_W)\frac{E_e + E'_e}{M_N} W_3^{\gamma Z}/D
\end{aligned}
$$

- Δ_V : only isospin 1/2 final state contributes. expected to be small in the Delta region
- $W_3^{\gamma Z}$ might be seen in backward electron scattering

Estimation of Δ_V, Δ_A

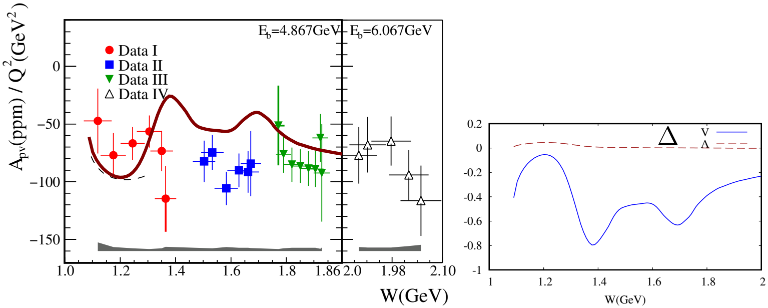


$p(\vec{e}, e')$,$W = 1.232GeV$,$\theta = 60^o(left)$ $110^o(right)$

Parity Violating Asymmetries

Parity violating asymmetry of $d(\vec{e}, e')$ reaction in DCC model with simple estimation for deuteron reaction

$$Q^2 A_{PV} = -\frac{G_F}{\sqrt{2}4\pi\alpha}\frac{N_p + N_n}{D_p + D_n} = -8.99 \times 10^{-5}[1.075 + \Delta_V + \Delta_A]$$



The PVDIS Collaboration PRC91 045506 (2015) ($E_e = 4.867GeV, \theta = 12.9^o$)

Summary

- Current status of DCC model on neutrino-nucleon reaction in the resonance region is discussed.
- In $\nu - p(\bar{\nu} - n)$ reaction, $\Delta_{33}(1232)$ plays dominant role.For other channels, N^* resonances contribute appreciably.
- One can obtain hint on the validity of the model comparing with parton model, suggesting missing strength of axial vector current at non-zero Q^2 in DCC model.
- PV asymmetry, in principle, give us information on W_3^{CC}.
- To disentangle nuclear effects from model dependence of nucleon reaction, benchmark test will be necessary. (Rein-Sehgal, Hernandez-Nieves, Leitner-Lalakulich-Mosel, Aligah,Kabirnezhad,Nakamura et al.)
  not only $\sigma(E_\nu)$,

$$\frac{d\sigma}{dWdQ^2}, \quad \frac{d\sigma}{dWdQ^2d\Omega^*_\pi}$$

$$L^{\mu\nu}W_{\mu\nu}=\frac{1}{2}\sum_{s'_N,s_N}[R_T+R_L+R_{LT}\cos\phi_\pi+R_{TT}\cos 2\phi_\pi + R_{LT'}\sin\phi_\pi+R_{TT'}\sin 2\phi_\pi]. \quad (28)$$

Acknowledgments KAKENHI JP25105010,JP16K053454.

NPB62 (1973) 61, C. Wilkin et al. $\bar{\sigma} = [\sigma_{\pi^-} + \sigma_{\pi^+}]/2, \quad \Delta\sigma = [\sigma_{\pi^-} - \sigma_{\pi^+}]/2$

Table 1

Average cross section $\bar{\sigma}$ and cross-section differences $\Delta\sigma$ for $\pi^{\pm}$ on ^{4}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{12}C and ^{32}S. Only statistical errors are quoted. In column 4 the relative real part ρ of the forward scattering amplitude used for the extraction of the cross-section difference is listed. Column 6 gives the increase of the cross-section difference for a decrease of ρ by 0.1

Nucleus	Momentum (MeV/c)	Average cross section $\bar{\sigma}$ (mb)	Cross-section difference $\Delta\sigma$ (mb)	Relative real part ρ	$-\frac{\partial(\Delta\sigma)}{\partial\rho} \times 0.1$ (mb)
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
^{12}C	167	473 ± 3	70 ± 6	0.84	10
	202	627 ± 2	68 ± 4	0.43	12
	243	693 ± 2	29 ± 4	0.15	13
	293	661 ± 2	6 ± 4	− 0.09	12
	332	596 ± 2	9 ± 3	− 0.23	10
	372	528 ± 2	9 ± 3	− 0.34	8
^{32}S	170	1235 ± 6	213 ± 11	0.50	43
	203	1334 ± 6	97 ± 11	0.30	45
	244	1351 ± 5	76 ± 10	0.07	48
	294	1280 ± 4	59 ± 8	− 0.09	42
	333	1200 ± 3	37 ± 6	− 0.17	38
	373	1090 ± 3	21 ± 6	− 0.23	35

NPA209 (1973)1, B.W.Allardyce et al.

TABLE 2

π^- reaction cross sections
(values in mb)

Momentum (GeV/c)	C	Al	Ca	Ni	Sn	^{120}Sn	Ho	Pb	^{208}Pb
0.71	243±3		608±5	764±6	1221±11			1806±15	
0.84	250±2	433±6	607±5	764±6	1230± 9	1241±10	1583±14	1814±12	1759±40
1.00	264±1	454±3	624±5	772±3	1249± 6	1260±11	1607±13	1808± 6	1810± 9
1.36	254±2	444±3	611±4	771±5	1249± 7	1258±10	1594±10	1817± 9	1806±16
1.58	246±2	444±4	598±5	758±4	1233± 5			1802± 7	
2.00	224±2		550±3	710±4	1164±11			1703±16	

An additional systematic error of ±1 % should be applied to the values for each momentum at 0.71, 0.84 and 1.00 GeV/c. (See text for a discussion of errors.)

TABLE 3

π^+ reaction cross sections
(values in mb)

Momentum (GeV/c)	C	Al	Ca	Ni	Sn	^{120}Sn	Ho	Pb	^{208}Pb
0.71	263±3		587±7	741±8	1187±17			1754±16	
0.84	246±3	429±11	594±9	742±9	1190±10	1221±14	1543±28	1752±16	1764±21
1.00	257±2	451±3	609±5	749±5	1231± 8	1254±10	1606±15	1772± 9	1762±26
1.36	248±3	437±4	599±4	752±5	1217± 9	1223±14	1544±26	1743±13	1742±24
1.58	243±3	435±3	601±5	750±6	1208±11			1736±16	
2.00	224±2		555±5	707±8	1154±10			1670±13	

An additional systematic error of ±1 % should be applied to the values for each momentum at 0.71, 0.84 and 1.00 GeV/c. (See text for a discussion of errors.)