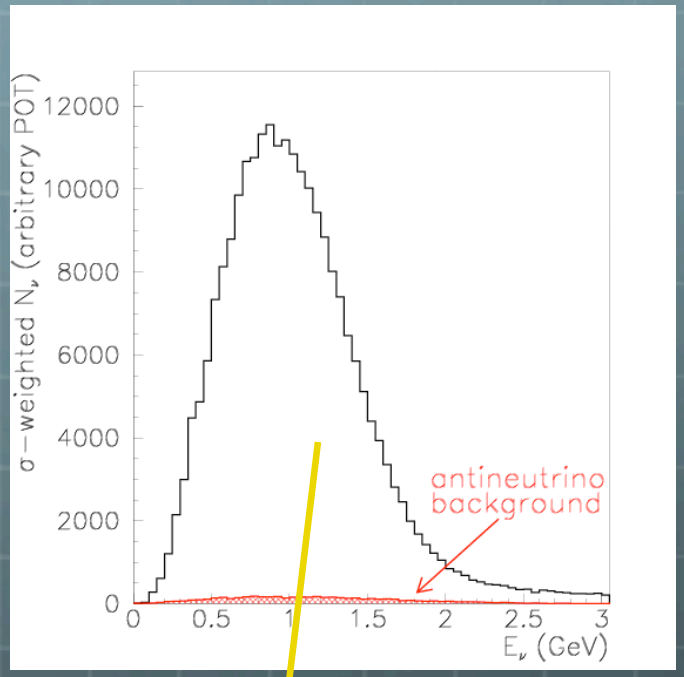
Improved description of Charged Current π^+ production in the MiniBooNE detector

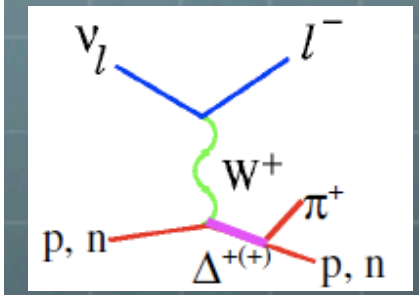
Jaroslaw Nowak
Louisiana State University
on behalf of MiniBooNE collaboration

2008 Annual Fall Meeting of the APS Division of Nuclear Physics
Oakland, California

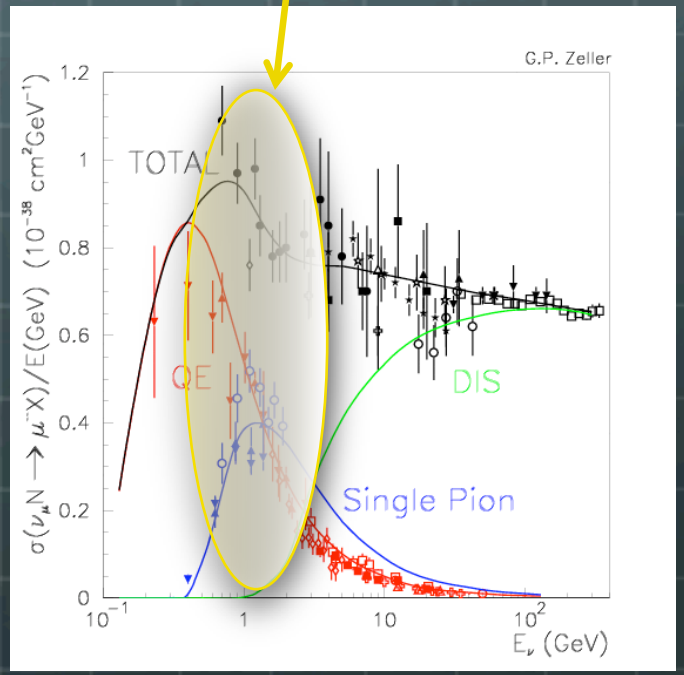
CC π^+ sample

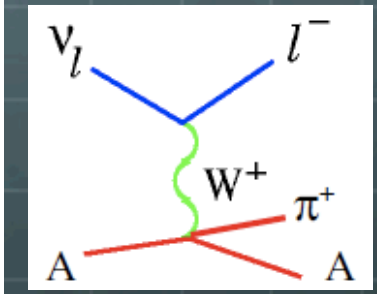
- Major background to the CCQE for the MiniBooNE experiment
- Resonant and coherent π^+ production





Rein-Sehgal model of resonance excitations with M_A=1.1GeV [Annals of Physics, 133, 79 (1981)]





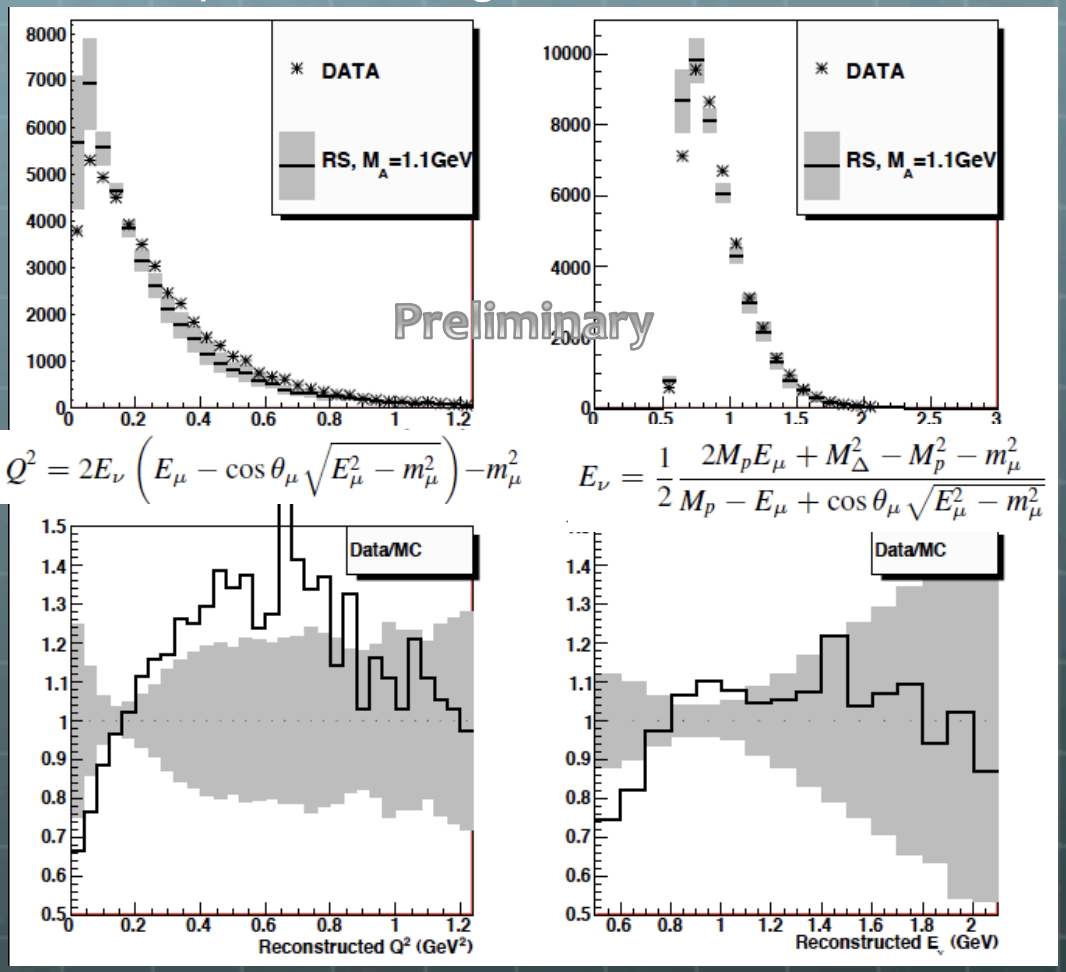
Rein-Sehgal model for coherent π^+ production with M_A=1.03 GeV [Nucl. Phys. B223, 29, (1983)]

Rescale to reproduce MiniBooNE NCπ^0 results (PLB 664, 1, 2008)

J. Nowak

MiniBooNE Results for CCπ^+

5.68E20 proton-on-target about 46k CCπ^+ events

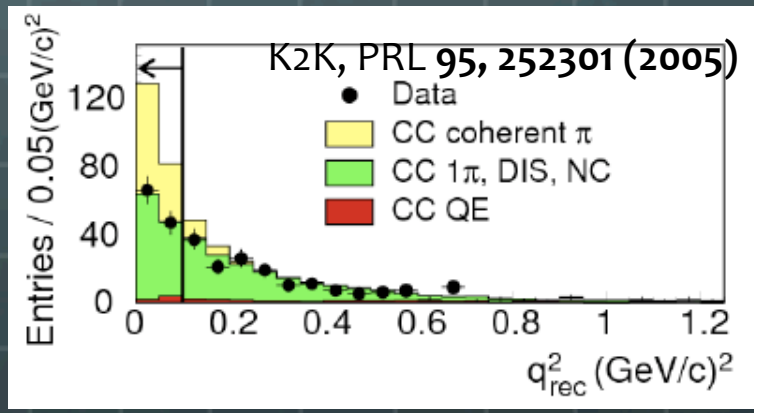


$$Q^2 = 2E_\nu\left(E_\mu - \cos\theta_\mu\sqrt{E_\mu^2 - m_\mu^2}\right) - m_\mu^2$$

$$E_\nu = \frac{1}{2}\frac{2M_pE_\mu + M_\Delta^2 - M_p^2 - m_\mu^2}{M_p - E_\mu + \cos\theta_\mu\sqrt{E_\mu^2 - m_\mu^2}}$$

In the CCπ^+ sample we see a discrepancy between data and predictions (presented at NuInt07 by B.Fleming)

The same phenomenon has been previously seen by the K2K



I will present our attempts to understand and fix the problem

List of necessary improvements

- Muon mass in resonace excitation model
  - Muon mass included only in the leptonic current –KLN model [Kuzmin, Lyubushkin and Naumov, Phys. Part. Nucl. 35, S133 (2004)]
  - Improving the KLN model by adding the pion-pole terms – BRS model [Berger and Sehgal, Phys. Rev. D 76, 113004 (2007)]
- Muon mass in coherent π^+ production is introduced by applying the Adler's screening factor [D. Rein and L. M. Sehgal, Phys. Lett. B 657, 207 (2007)]
- New vector form factor [O. Lalakulich and E. A. Paschos, Phys. Rev. D 71, 074003 (2005)]

List of possible improvements

- New axial vector form factor
  - Hernandez et al. [Phys. Rev. D 76, 033005 (2007)]
  - Lalakulich et al. [Phys. Rev. D 74, 014009 (2006)]
  - Graczyk and Sobczyk [Phys.Rev.D77:053001,2008]

Need to be determined
Form neutrino interaction

Muon mass effect in Rein-Sehgal Model

$$\frac{d\sigma}{dQ^2dW^2} = \frac{G_F^2}{8\pi^2 M_N}\kappa\frac{Q^2}{|\mathbf{q}|^2}\left[u^2\sigma_L + v^2\sigma_R + 2uv\sigma_S\right]$$

Three partial cross section corresponding to left-handed, right-handed and scalar polarization of intermediate boson

With muon mass partial cross sections depend on The helicity

Expressed by

$$\frac{d\sigma}{dQ^2dW^2} = \frac{G_F^2\cos\theta_C}{8\pi^2 M_N}\kappa\frac{Q^2}{|\mathbf{q}|^2}\sum_{\lambda=\pm}\left[\left(c_L^\lambda\right)^2\sigma_L^{(\lambda)} + \left(c_R^\lambda\right)^2\sigma_R^{(\lambda)} + \left(c_S^\lambda\right)^2\sigma_S^{(\lambda)}\right]$$

Dynamical form factors in the RS model

$$\begin{aligned}
T^V &= \frac{1}{3W}\sqrt{\frac{\Omega}{2}}G^V(Q^2)\\
R^V &= \sqrt{2}\frac{M_N}{W}\frac{(W+M_N)|\mathbf{q}|}{(W+M_N)^2+Q^2}G^V(Q^2) = R\\
S &= \frac{Q^2}{|\mathbf{q}|^2}\frac{3WM_N - Q^2 - M_N^2}{6M_N^2}G^V(Q^2)\\
T^A &= \frac{2}{3}\sqrt{\frac{\Omega}{2}}\frac{M_N}{W}\frac{|\mathbf{q}|}{(W+M_N)^2+Q^2}ZG^A(Q^2)\\
R^A &= \frac{\sqrt{2}}{6W}\left(W + M_N + \frac{2n\Omega W}{(W+M_N)^2+Q^2}\right)ZG^A(Q^2)\\
B &= \frac{1}{3W}\sqrt{\frac{\Omega}{2}}\left(1 + \frac{W^2 - M_N^2 - Q^2}{(W+M_N)^2+Q^2}\right)ZG^A(Q^2)\\
C &= \frac{1}{6M_N|\mathbf{q}|}\left(W^2 - M_N^2 + n\Omega\frac{W^2 - M_N^2 - Q^2}{(W+M_N)^2+Q^2}\right)
\end{aligned}$$

$$\begin{aligned}
S \to S_{KLN} &= \left(\nu^*_{(\lambda)}\nu^* - Q^*_{(\lambda)}|\mathbf{q}^*|\right)\left(1 + \frac{Q^2}{M_N^2} - \frac{3W}{M_N}\right)\frac{G^V(Q^2)}{6|\mathbf{q}|^2}\\
B \to B_{KLN} &= \sqrt{\frac{\Omega}{2}}\left(Q^*_{(\lambda)} + \nu^*_{(\lambda)}\frac{|\mathbf{q}^*|}{aM_N}\right)\frac{ZG^A(Q^2)}{3W|\mathbf{q}^*|}\\
C \to C_{KLN} &= \left[\left(Q^*_{(\lambda)}|\mathbf{q}^*| - \nu^*_{(\lambda)}\nu^*\right)\left(\frac{1}{3} + \frac{\nu^*}{aM_N}\right)\right.\\
&\quad \left. + \nu^*_{(\lambda)}\left(\frac{2}{3}W - \frac{Q^2}{aM_N} + \frac{n\Omega}{3aM_N}\right)\right]\frac{ZG^A(Q^2)}{2W|\mathbf{q}^*|}
\end{aligned}$$

Only three Functions Modified

$$\begin{aligned}
S^{(\lambda)}_{BRS} &= S^{(\lambda)}_{KLN}\\
B^{(\lambda)}_{BRS} &= B^{(\lambda)}_{KLN} + \frac{ZG^A(Q^2)}{2WQ^*}\left(Q^*_{(\lambda)}\nu^* - \nu^*_{(\lambda)}Q^*\right)\frac{\frac{2}{3}\sqrt{\frac{\Omega}{2}}\left(\nu^* + \frac{Q^{*2}}{M_N a}\right)}{m_\pi^2 + Q^2}\\
C^{(\lambda)}_{BRS} &= C^{(\lambda)}_{KLN} + \frac{ZG^A(Q^2)}{2WQ^*}\left(Q^*_{(\lambda)}\nu^* - \nu^*_{(\lambda)}Q^*\right)\frac{Q^*\left(\frac{2}{3}W - \frac{Q^2}{M_N a} + \frac{n\Omega}{3M_N a}\right)}{m_\pi^2 + Q^2}
\end{aligned}$$

Coherent production

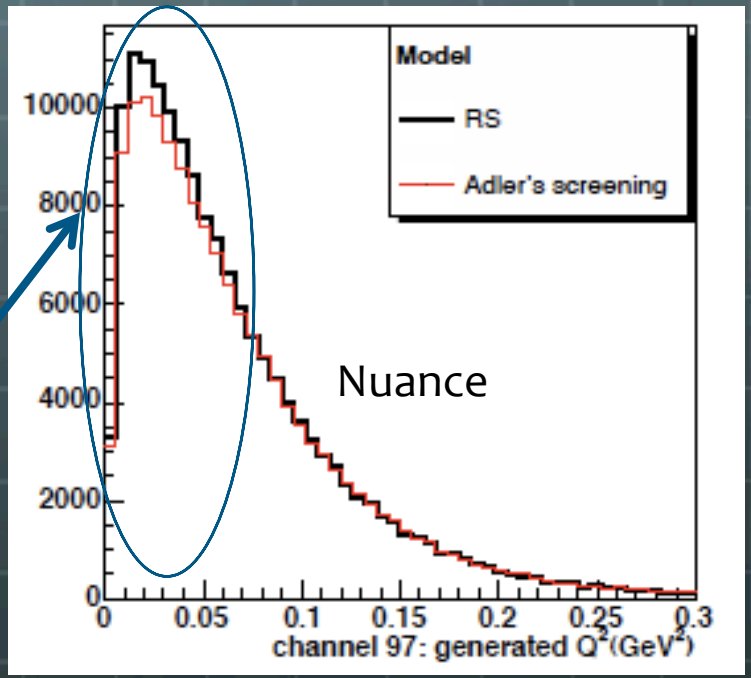
- The muon mass effect in coherent production is taken into account applying the Adler's screening factor

[D. Rein and L. M. Sehgal, Phys. Lett. B 657, 207 (2007)]

$$\frac{d\sigma}{dxdydt}$$

Multiply by Adler's screening factor

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



The change in overall CCπ^+ Production is small, but it is Included in all following results

Improvements – vector form factor

- The relationship between vector form factor in the Rein-Sehgal model and the Rarita-Schwinger form factors from Graczyk and Sobczyk, Phys.Rev.D77:053001,2008

$$G_V^{new} = \frac{1}{2}\left(1+\frac{Q^2}{(M+W)^2}\right)^{\frac{1}{2}-N}\sqrt{3(G_3^V)^2+(G_1^V)^2}$$

$$G_3^V = \frac{1}{2\sqrt{3}}\left[C_4V\frac{W^2-Q^2-M^2}{2M^2}+C_5^V\frac{W^2+Q^2-M^2}{2M^2}+C_3^V\frac{W+M}{M}\right]$$

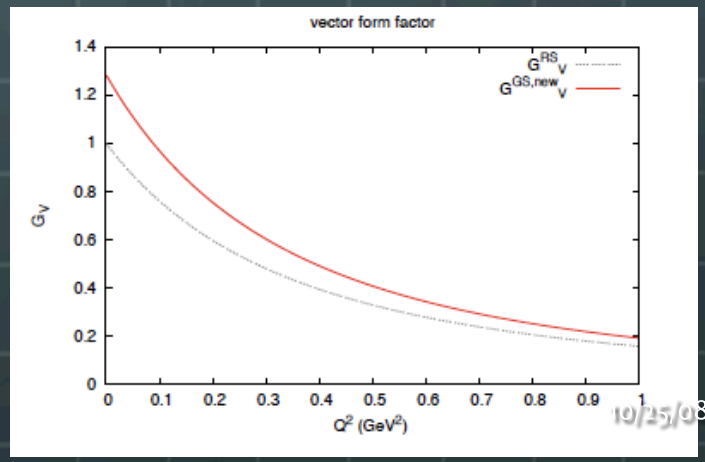
$$G_1^V = -\frac{1}{2\sqrt{3}}\left[C_4V\frac{W^2-Q^2-M^2}{2M^2}+C_5^V\frac{W^2+Q^2-M^2}{2M^2}-C_3^V\frac{M^2+Q^2+MW}{MW}\right]$$

- Form factor from O. Lalakulich et al., Phys. Rev. D 74, 014009 (2006)

$$C_3^V = 2.13\left(1+\frac{Q^2}{4M_V^2}\right)^{-1}\left(1+\frac{Q^2}{M_V^2}\right)^{-2}$$

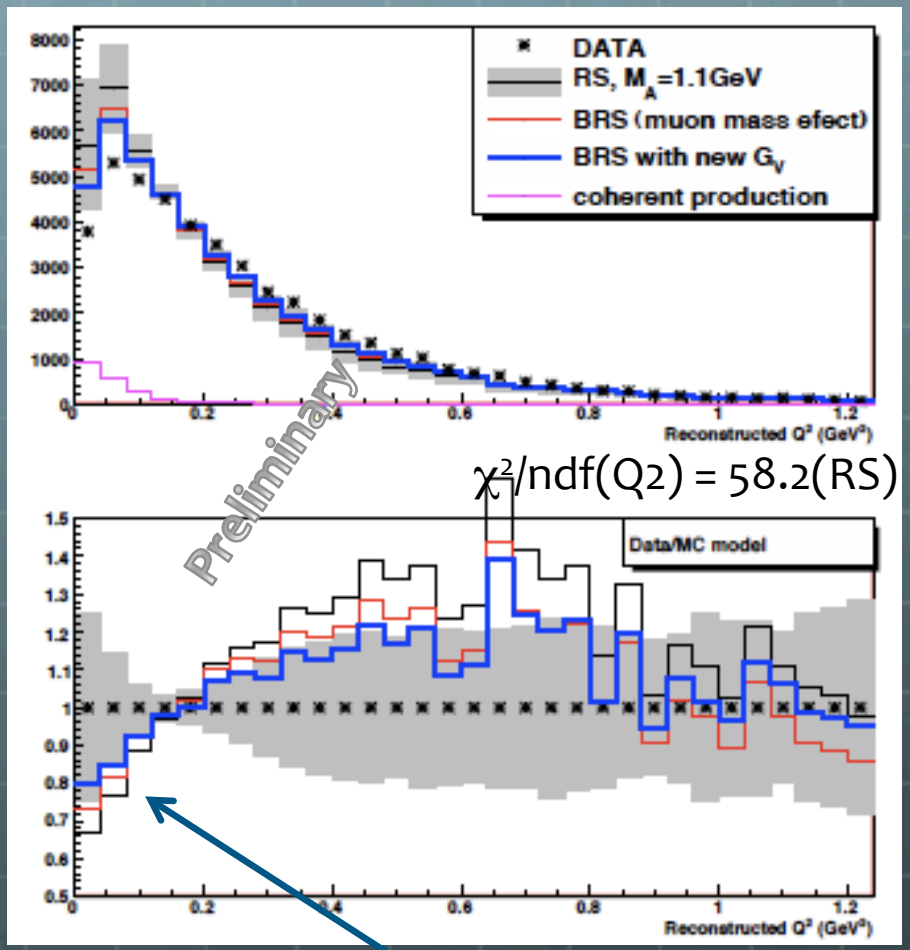
$$C_4^V = -1.51\left(1+\frac{Q^2}{4M_V^2}\right)^{-1}\left(1+\frac{Q^2}{M_V^2}\right)^{-2}$$

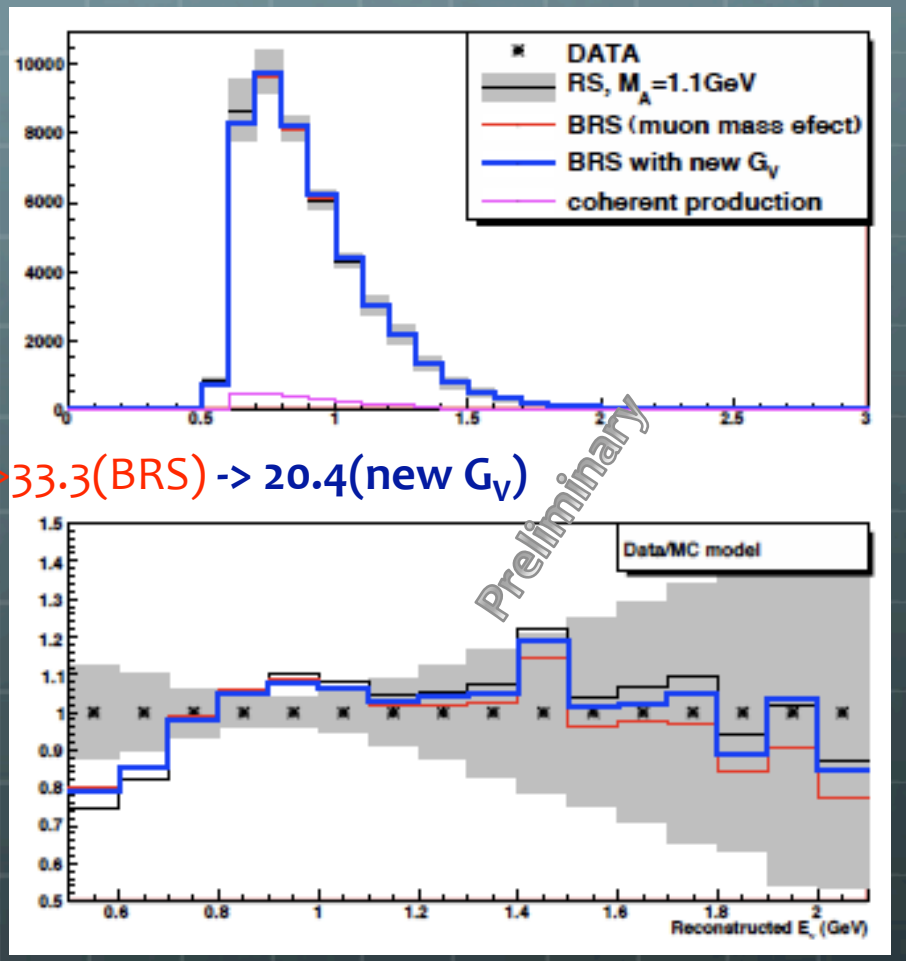
$$C_5^V = 0.48\left(1+\frac{Q^2}{4M_V^2}\right)^{-1}\left(1+\frac{Q^2}{0.766M_V^2}\right)^{-2}$$



Muon mass and new vector form factor

New models with Adler's screening factor for the coherent production





χ^2/ndf(Q2) = 58.2(RS) ->33.3(BRS) -> **20.4(new G_V)**

The best we can do using extension of RS models and data from electron scattering

- Dipole form of axial form factor in RS model

$$\bar{G}_A^{RS} = 0.76\left(1+\frac{Q^2}{M_A^2}\right)^{-2}\left(1+\frac{Q^2}{4M^2}\right)^{\frac{1}{2}-N}$$

- The Adler model assumed

$$C_3^A(Q^2) = 0, \qquad C_4^A(Q^2) = -\frac{C_5^A}{4}$$

Hernandez et al. $C_5^A(0) = 0.867, \quad M_A = 0.985GeV$:

$$C_5^A = C_5^A(0)\left(1+\frac{Q^2}{M_A^2}\right)^{-2}\left(1+\frac{Q^2}{3M_A^2}\right)^{-1}$$

Graczyk and Sobczyk v1 $C_5^A(0) = 1.2, \quad m_a = 0.54GeV^2$:

$$C_5^A = C_5^A(0)\left(1+\frac{Q^2}{m_a}\right)^{-2}$$

Graczyk and Sobczyk v2 $C_5^A(0) = 0.88, \quad m_a = 9,71GeV^2, \quad m_b = 0.35GeV^2$:

$$C_5^A = C_5^A(0)\left(1+\frac{Q^2}{m_a}\right)^{-2}\left(1+\frac{Q^2}{m_b}\right)^{-1}$$

Lalkulich et al. v1, $C_5^A(0) = 1.2, \quad M_A = 1.1GeV$:

$$C_5^A = C_5^A(0)\left(1+\frac{Q^2}{M_A^2}\right)^{-2}\left(1+2\frac{Q^2}{M_A^2}\right)^{-1}$$

Lalakulich et al., v2 $C_5^A(0) = 1.2, \quad M_A = 1.1GeV$:

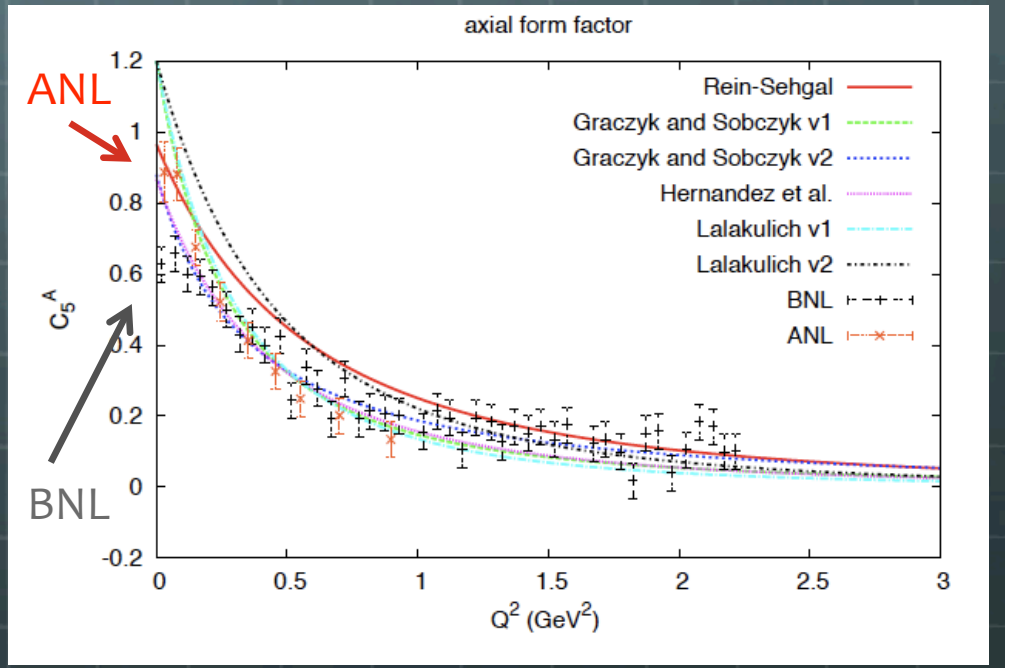
$$C_5^A = C_5^A(0)\left(1+\frac{Q^2}{M_A^2}\right)^{-2}\left(1+\frac{Q^2}{3M_A^2}\right)^{-1}$$

- From Graczyk and Sobczyk the for of the axial form factor

$$\bar{G}_A^{new} = \frac{\sqrt{3}}{2}\left(1+\frac{Q^2}{(M+W)^2}\right)^{\frac{1}{2}-N}\left[1-\frac{W^2-Q^2-M^2}{8M^2}\right]C_5^A$$

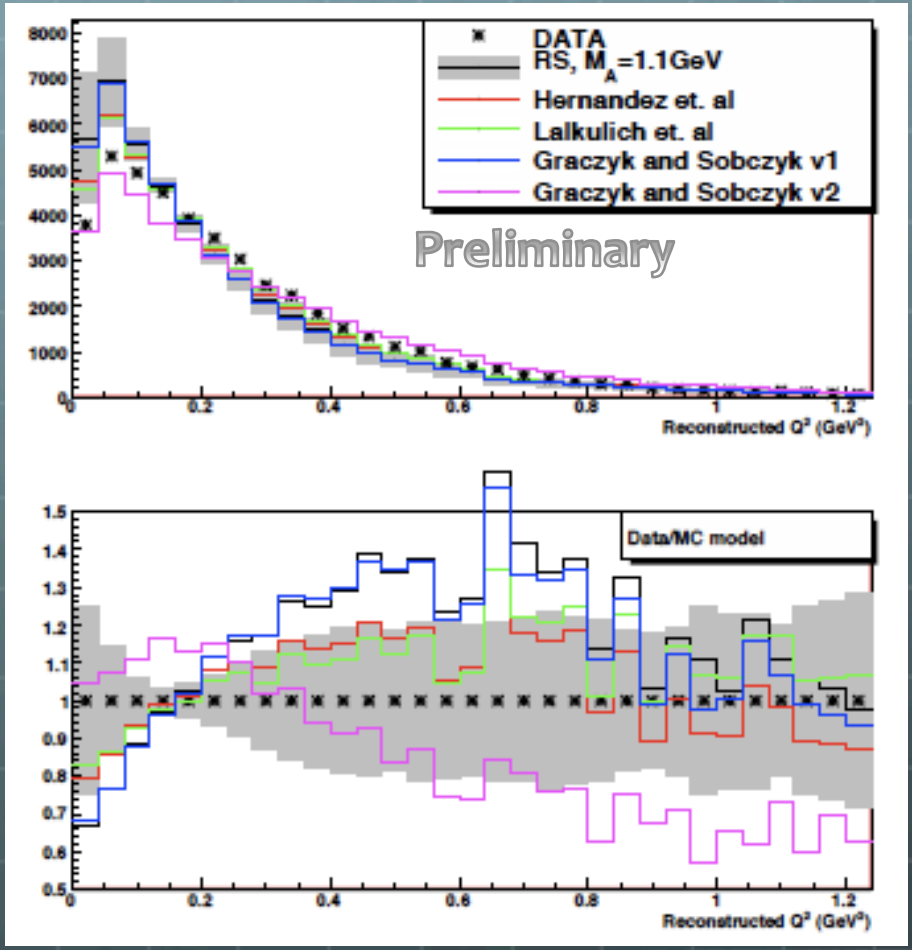
$$G_A(0) = \frac{\sqrt{3}}{2}\left(1-\frac{W^2-M^2}{8M^2}\right)C_5^A(0)$$

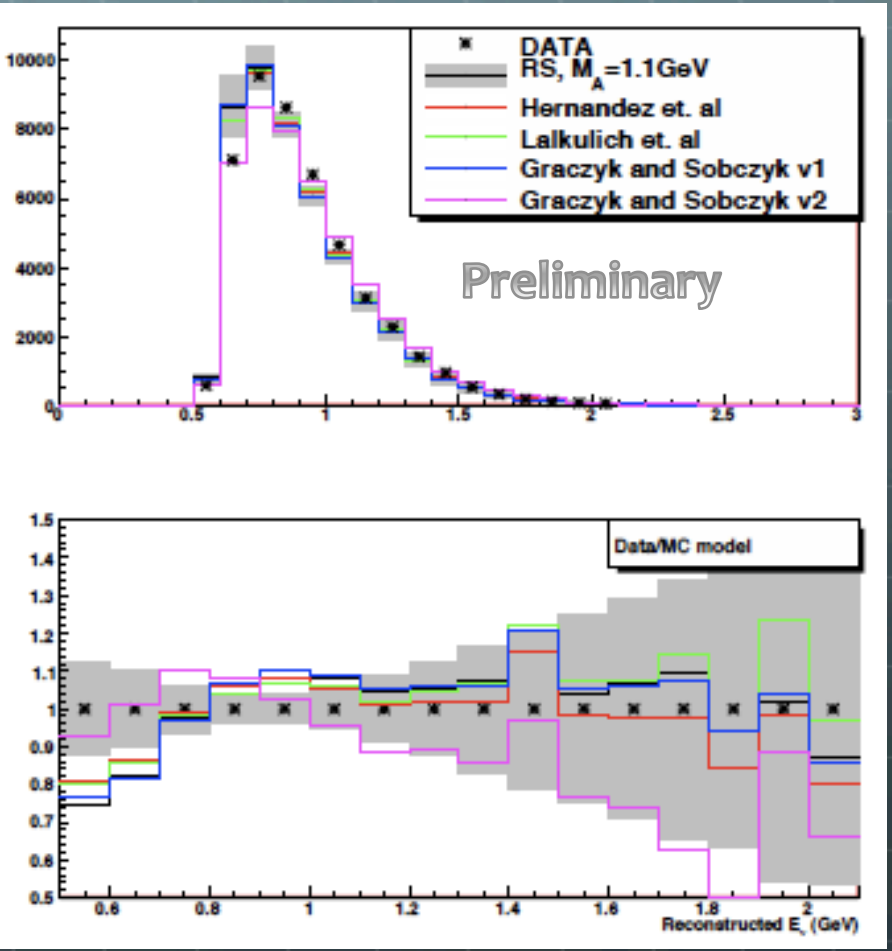
Two parameters: $C^A{}_5(0)$ and axial mass M_A



New axial vector form factor

All with BRS and new GV





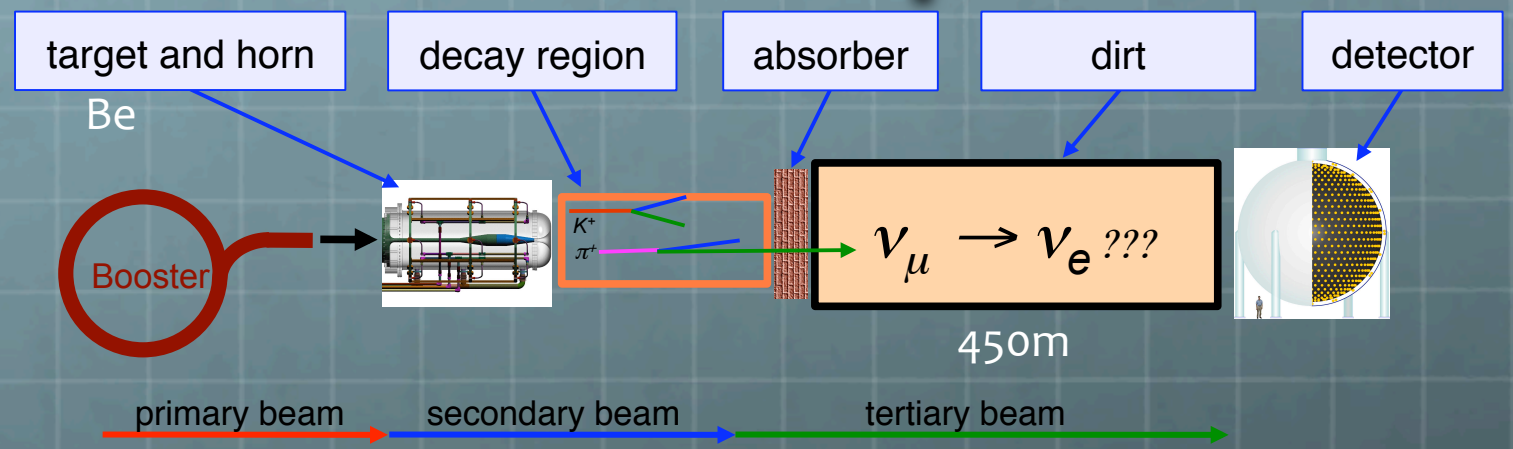
χ^2/ndf(Q2) = 19.5(Hernandez) , 14.9(Lalakulich), 55.1(G&S 1), 28.05(G&S 2)

Conclusions

- Charged current π^+ production models were extended to include the mass of charged lepton in final state.
- Vector form factor was updated using fit from electron scattering.
- All above changes improved our agreement with data.
- A number of the existing parameterizations of axial vector form factor were investigated but none of them is significantly better then our model with modifications.
- We will fit a general form of the the axial vector form factor to our high statistic data.

BACKUP SLIDES

MiniBooNE experiment



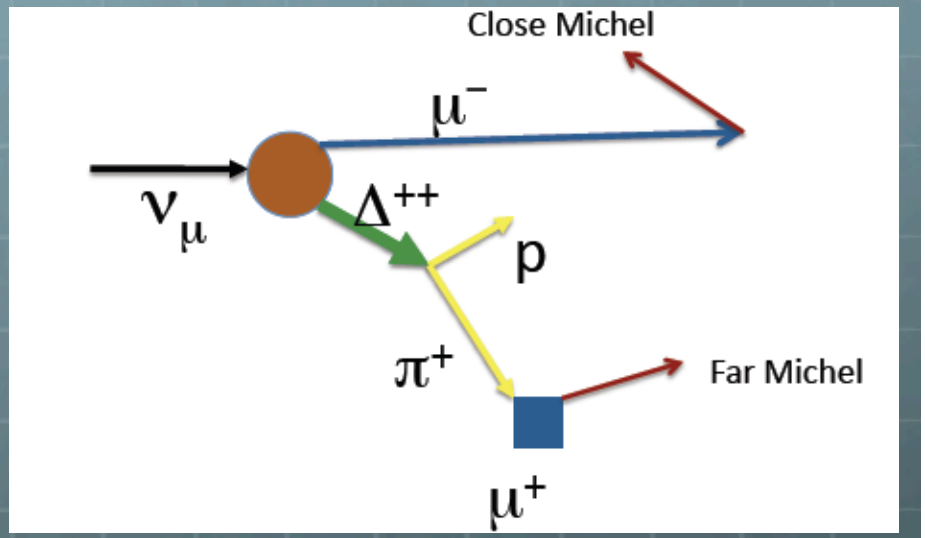
The MiniBooNE Collaboration

A. A. Aguilar-Arevalo[e], C. E. Anderson[p], L. M. Bartoszek[g], A. O. Bazarko[m], S. J. Brice[g], B. C. Brown[g], L. Bugel[e], J. Cao[ℓ], L. Coney[e], J. M. Conrad[e], D. C. Cox[i], A. Curioni[p], Z. Djurcic[e], D. A. Finley[g], B. T. Fleming[p], R. Ford[g], F. G. Garcia[g], G. T. Garvey[j], C. Green[j,g], J. A. Green[i,j], T. L. Hart[d], E. Hawker[j,c], R. Imlay[k], R. A. Johnson[c], G. Karagiorgi[e], P. Kasper[g], T. Katori[i], T. Kobilarcik[g], I. Kourbanis[g], S. Koutsoliotas[b], E. M. Laird[m], S. K. Linden[p], J. M. Link[o], Y. Liu[ℓ], Y. Liu[a], W. C. Louis[j], K. B. M. Mahn[e], W. Marsh[g], P. S. Martin[g], G. McGregor[j], W. Metcalf[k], H.-O. Meyer[i], P. D. Meyers[m], F. Mills[g], G. B. Mills[j], J. Monroe[e], C. D. Moore[g], R. H. Nelson[d], V. T. Nguyen[e], P. Nienaber[n], J. A. Nowak[k], S. Ouedraogo[k], R. B. Patterson[m], D. Perevalov[a], C. C. Polly[i], E. Prebys[g], J. L. Raaf[c], H. Ray[j,h], B. P. Roe[ℓ], A. D. Russell[g], V. Sandberg[j], W. Sands[m], R. Schirato[j], G. Schofield[k], D. Schmitz[e], M. H. Shaevitz[e], F. C. Shoemaker[m], D. Smith[f], M. Soderberg[p], M. Sorel[e1], P. Spentzouris[g], I. Stancu[a], R. J. Stefanski[g], M. Sung[k], H. A. Tanaka[m], R. Tayloe[i], M. Tzanov[d], R. Van de Water[j], M. O. Wascko[k2], D. H. White[j], M. J. Wilking[d], H. J. Yang[ℓ], G. P. Zeller[e,j], E. D. Zimmerman[d]

- Main goal: check LSND results for different systematic.
- The same L/E.
  - LSND: 30m/50MeV,
  - MB: about 540m / 800MeV.
- Detector: 12m diameter sphere filled with ~800 t of mineral oil. 1280 inner phototubes and 240 veto phototubes.
- MiniBooNE detector gives a opportunity of studying neutrino cross section with high statistics

Event selection

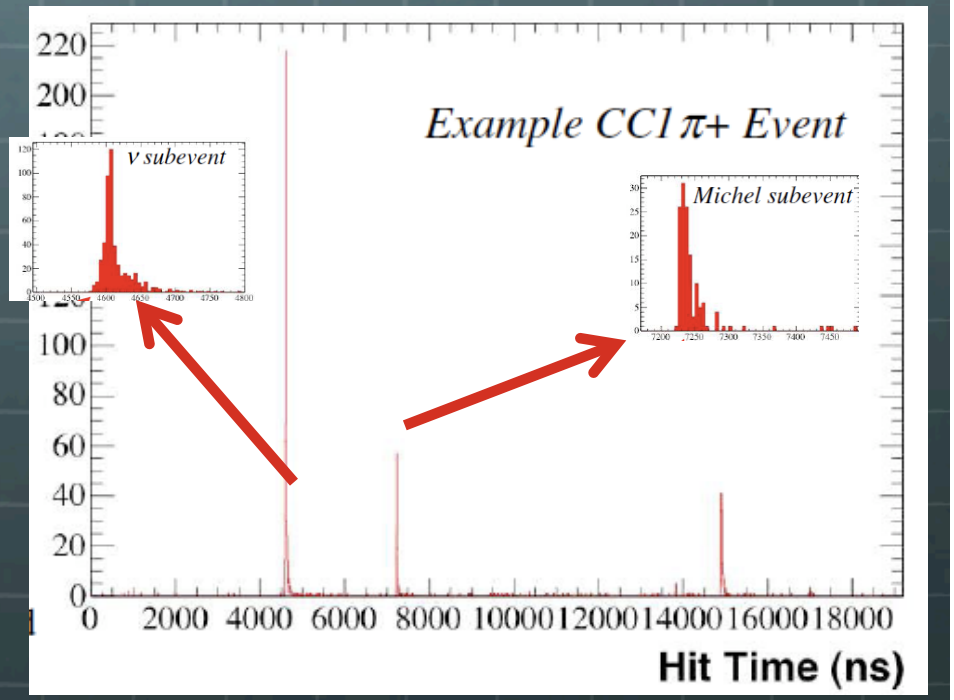
- 87% purity and 12% efficiency
- Veto hits < 6 (cosmic muons)
- Tank hits for 1st subevent> 200 – removes Michel electrons
- Three subevents cut, muon and 2 Michel electrons, reduces the background.



$\nu_\mu p \rightarrow \mu^- p \pi^+$	**68.88**
$\nu_\mu n \rightarrow \mu^- n \pi^+$	**11.98**
$\nu_\mu A \rightarrow \mu^- \pi^+ A$	**5.87**
$\nu_\mu n \rightarrow \mu^- p$	5.23
$\nu_\mu n \rightarrow \mu^- p \pi^0$	1.48
Else	6.56

SIGNAL

background



Muon mass effect

For model with introduced final lepton mass partial cross sections depend on the helicity λ

$$\frac{d\sigma}{dQ^2 dW^2} = \frac{G_F^2 \cos\theta_C}{8\pi^2 M_N}\kappa\frac{Q^2}{|\mathbf{q}|^2}\sum_{\lambda=\pm}\left[\left(c_L^\lambda\right)^2\sigma_L^{(\lambda)} + \left(c_R^\lambda\right)^2\sigma_R^{(\lambda)} + \left(c_S^\lambda\right)^2\sigma_S^{(\lambda)}\right] \quad (80)$$

where in the limit of massless lepton in the final state ($m_l \to 0$), $c_L^{(-)} \to u$, $c_R^{(-)} \to v$, $c_S^{(-)} \to 2uv$ and $c_{L,R,S}^{(+)} \to 0$.

$$\nu = \frac{E_\nu + E_l - |\mathbf{q}|}{2E_\nu}$$

$$\kappa = \frac{W^2 - M_N^2}{2M_N}$$

$$A_{(\lambda)} = \sqrt{E_\nu\left(E_l - \lambda P_l\right)}.$$

$$u = \frac{E_\nu + E_l + |\mathbf{q}|}{2E_\nu}$$

$$\begin{aligned}
j^*_{0(\lambda)} &= A_\lambda \frac{1}{W}\sqrt{1-\lambda\cos\theta}\,(M_N - E_l - \lambda P_l)\\
j^*_{x(\lambda)} &= A_\lambda \frac{1}{|\mathbf{q}|}\sqrt{1+\lambda\cos\theta}\,(P_l - \lambda E_\nu)\\
j^*_{y(\lambda)} &= i\lambda A_\lambda\sqrt{1+\lambda\cos\theta}\\
j^*_{z(\lambda)} &= A_\lambda \frac{1}{|\mathbf{q}|\mathbf{W}}\sqrt{1-\lambda\cos\theta}\,[(E_\nu + \lambda P_l)(M_N - E_l) + P_l(\lambda E_\nu + 2E_\nu\cos\theta - P_l)]
\end{aligned}$$

$$\begin{aligned}
Q^*_{(\lambda)} &= \sqrt{Q^2}\frac{j_0^{*(\lambda)}}{\sqrt{\left|\left(j_0^{*(\lambda)}\right)^2 - \left(j_z^{*(\lambda)}\right)^2\right|}}\\
\nu^*_{(\lambda)} &= \sqrt{Q^2}\frac{j_z^{*(\lambda)}}{\sqrt{\left|\left(j_0^{*(\lambda)}\right)^2 - \left(j_z^{*(\lambda)}\right)^2\right|}}
\end{aligned}$$

$$\begin{aligned}
\nu^* &= E_\nu^* - E_l^* = \frac{M_N\nu - Q^2}{W}\\
Q^* &= \sqrt{Q^2 + \nu^{*2}}\\
a &= 1 + \frac{W^2 + Q^2 + M_N^2}{2M_N W}
\end{aligned}$$

$$\begin{aligned}
c_L^{(\lambda)} &= \frac{K}{2}\left[j_x^{*(\lambda)} + i j_y^{*(\lambda)}\right]\\
c_R^{(\lambda)} &= \frac{K}{2}\left[j_x^{*(\lambda)} - i j_y^{*(\lambda)}\right]\\
c_S^{(\lambda)} &= K\sqrt{\left|\left(j_0^{*(\lambda)}\right)^2 - \left(j_z^{*(\lambda)}\right)^2\right|}
\end{aligned}$$

$$K = \frac{|\mathbf{q}|}{E_\nu\sqrt{2Q^2}}$$

$$\begin{aligned}
e_L^\mu &= \frac{1}{\sqrt{2}}(0, 1, -i, 0)\\
e_R^\mu &= \frac{1}{\sqrt{2}}(0, -1, -i, 0)\\
e_{(\lambda)}^\mu &= \frac{1}{\sqrt{Q^2}}(Q^*_{(\lambda)}, 0, 0, \nu^*_{(\lambda)})
\end{aligned}$$

The neutrino scattering in the forward direction is described by the Adler PCAC theorem [19]. The inelastic charged current reaction

$$\nu_\mu + A \to \mu^- + F \tag{112}$$

where A is a nucleus and F denotes an inelastic channel, the cross section, neglecting the muon mass, is

$$\left(\frac{d\sigma}{dxdy}\right)_{PCAC} = \frac{G^2 ME}{\pi^2} f_\pi^2 (1-y)\sigma(\pi^+ + A \to F)\Big|_{E_\pi = Ey} \tag{113}$$

where $x = Q^2/2m\nu$ and the $y = \nu/E$, and ν again is the energy transfer and E the neutrino energy. The pion decay constant has the value $f_\pi = 0.93 m_\pi$. The extrapolation of the PCAC formula to non-forward angles is given by a slowy varying form-factor $\left[\frac{M_A^2}{M_A^2+Q^2}\right]^2$ with $M_A \approx 1GeV$. So the cross section has a following form

$$\frac{d\sigma}{dxdydt} = \frac{G^2}{4\pi^2} f_\pi^2 \frac{1-y}{y} A^2 \frac{1}{16\pi} \left[\sigma_{tot}^{\pi^+\mathcal{N}}(E_\pi = Ey)\right]^2 (1+r^2) \left(\frac{M_A^2}{M_A^2+Q^2}\right)^2 e^{-b|t|} F_{abs}(E_\pi = Ey) \tag{114}$$

$|t| = |(p_\pi - q)^2| = (\mathbf{p} - \mathbf{q})^{\mathbf{2}}$, A is a number of nucleons in the nucleus, b is related to nuclear radius R by

$$b = \frac{1}{3}R^2, \quad (R = R_0 A^{1/3}), \tag{115}$$

and F_{abs} is a t-independent attenuation factor representing the pion absorption in the nucleus.

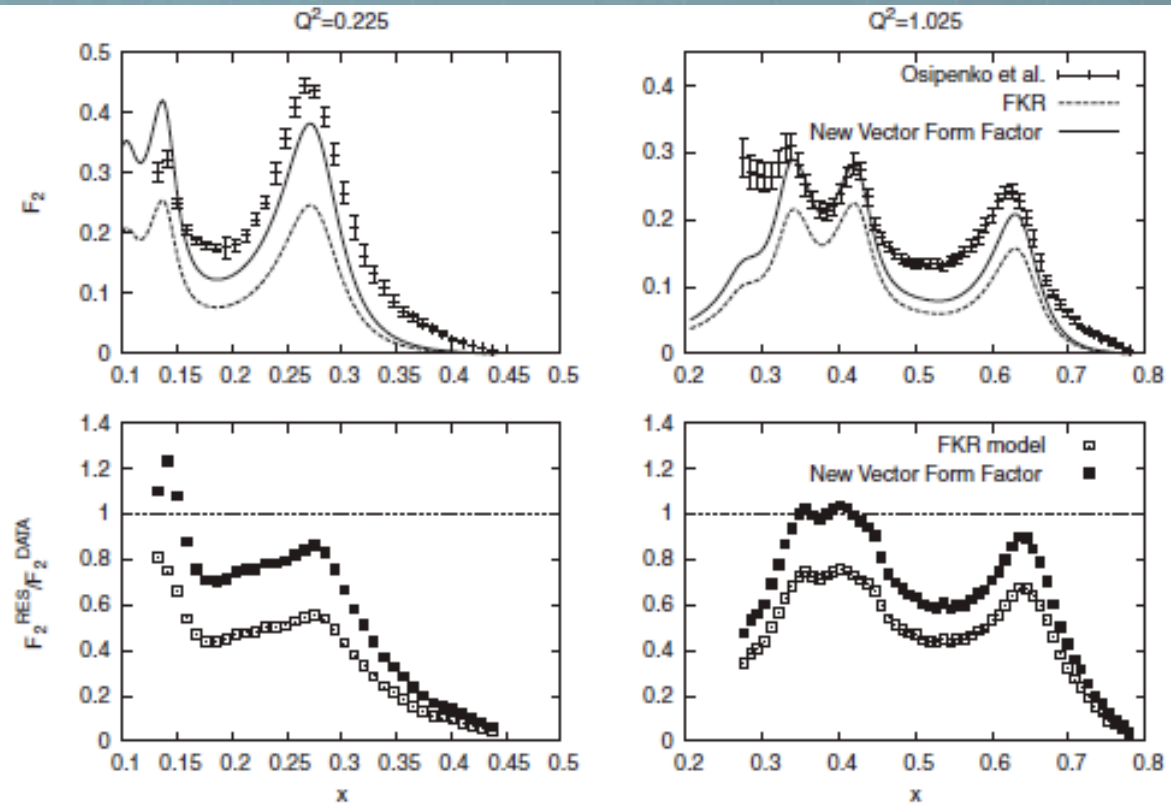


FIG. 2. In the top predictions for F_2 for ep scattering in the original FKR model and in the model of this paper for $Q^2 = 0.225$ GeV^2 and $Q^2 = 1.025$ GeV^2 are shown. The data is taken from [26]. In the bottom the fractions of the measured strength predicted by both models are presented.

Graczyk and Sobczyk, Phys.Rev.D77:053001,2008