Q^2 DEPENDENCE OF CHARGED CURRENT π^+ PRODUCTION DATA VS. THEORY

JAROSLAW NOWAK
For the MiniBooNE Collaboration
LOUISIANA STATE UNIVERSITY

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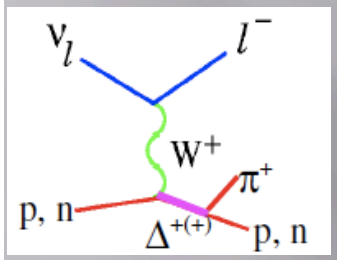
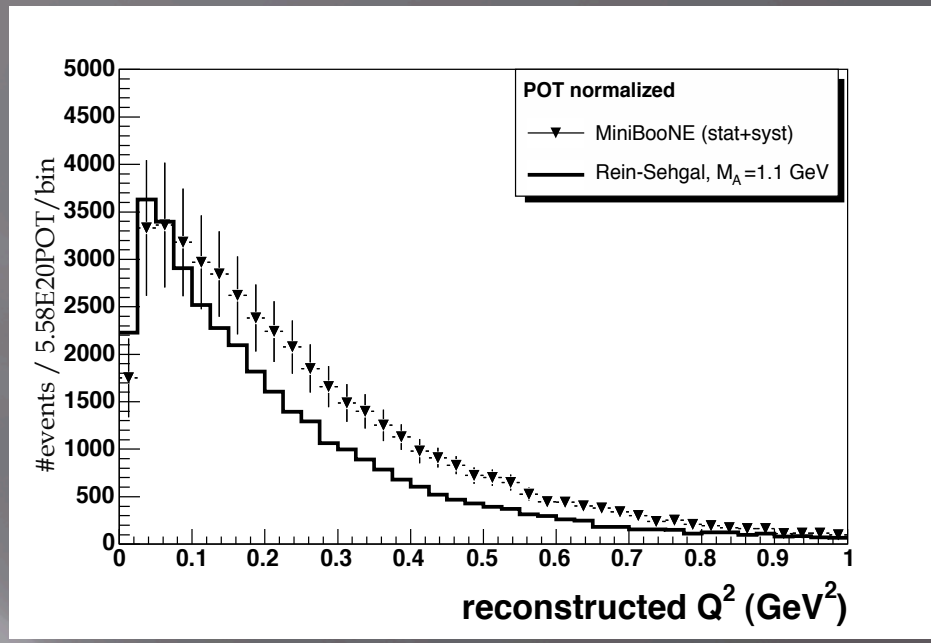
CC π^+ sample

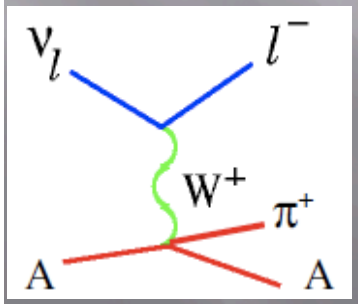


Rein-Sehgal model of resonance excitations with M_A=1.1GeV [Annals of Physics, 133, 79 (1981)]



The Q^2 distribution has been presented by Bonnie Fleming at NuInt 07

No muon mass in dynamics in CC π^+

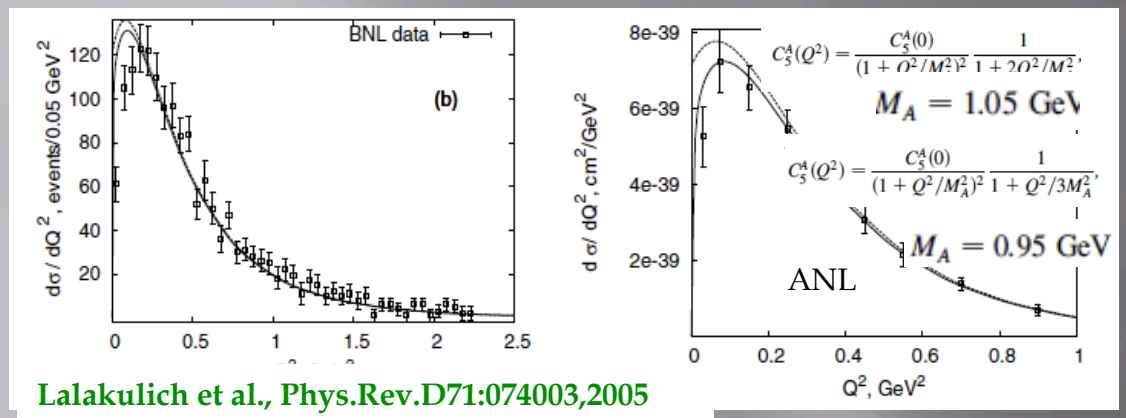


Rein-Sehgal model for coherent π^+ production with M_A=1.03 GeV [Nucl. Phys. B223, 29, (1983)]

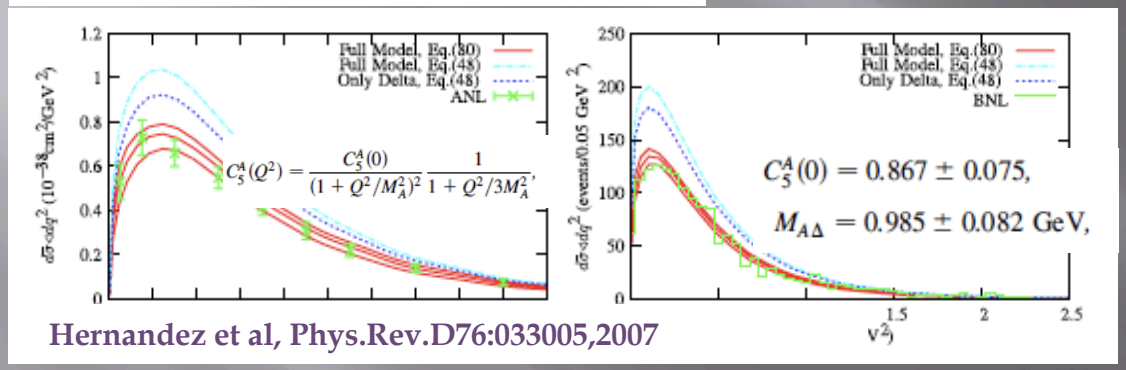
Rescale to reproduce MiniBooNE NC π^0 results (PLB 664, 1, 2008)

Process	Fraction of reconstructed CC1 π^+ events
CC1 π^+ Resonant	81
CC1 π^+ Coherent	5.9
CCQE	5.3
Multi-pion	3.8
CC1 π^0	1.5

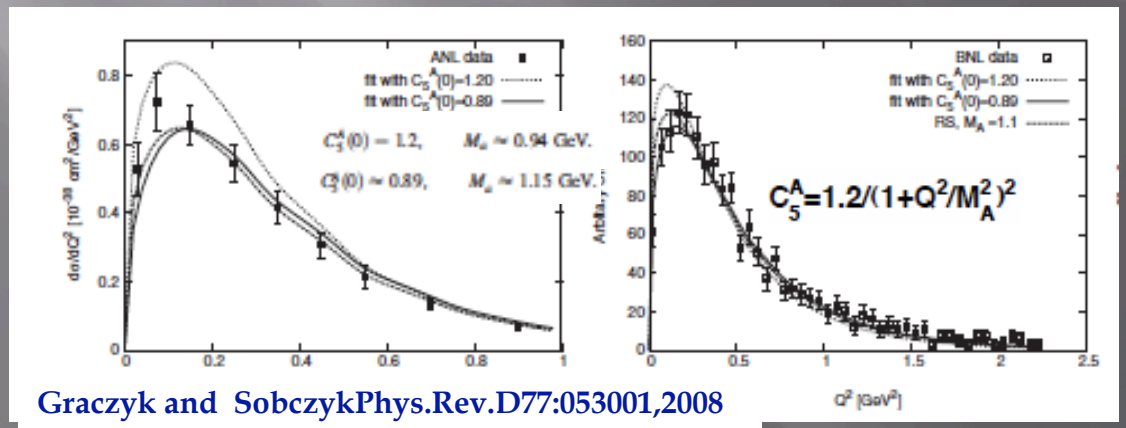
Recent theoretical predictions



Lalakulich et al., Phys.Rev.D71:074003,2005



Hernandez et al, Phys.Rev.D76:033005,2007



Graczyk and SobczykPhys.Rev.D77:053001,2008

All models are described by the Rarita-Schwinger formalism

Vector form factors from Lalakulich et al. **Phys.Rev.D74:014009,2006**

$$C_3^V = \frac{2.13}{(1-q^2/M_V^2)^2} \times \frac{1}{1-\frac{q^2}{4M_V^2}},$$

$$C_4^V = \frac{-1.51}{(1-q^2/M_V^2)^2} \times \frac{1}{1-\frac{q^2}{4M_V^2}}, \quad M_V = 0.84 \text{ GeV}$$

$$C_5^V = \frac{0.48}{(1-q^2/M_V^2)^2} \times \frac{1}{1-\frac{q^2}{0.776M_V^2}},$$

Axial-vector form factors: Adler model – used also in The analyses for ANL and BNL

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

With the biggest contribution From $C_5^A(Q^2)$

Necessary improvement – muon mass

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)]
- Similar prediction by Graczyk & Sobczyk
  [**Phys.Rev.D77:053003,2008**]

With muon mass partial cross sections depend on the helicity

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

Only three Functions Modified

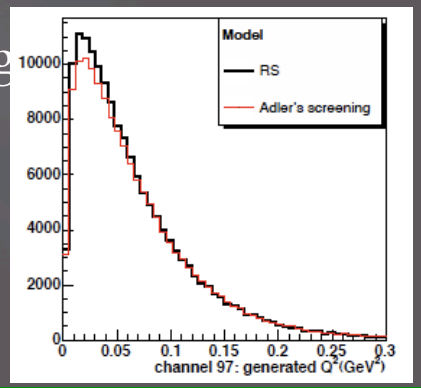
$$\begin{aligned}
T^V &= \frac{1}{3W}\sqrt{\frac{\Omega}{2}}G^V(Q^2)\\
R^V &= \sqrt{2}\frac{M_N}{W}\frac{(W+M_N)|\mathbf{q}|}{(W+M_N)^2+Q^2}G^V(Q^2) = R\\
S &= \frac{Q^2}{|\mathbf{q}|^2}\frac{3WM_N - Q^2 - M_N^2}{6M_N^2}G^V(Q^2)\\
T^A &= \frac{2}{3}\sqrt{\frac{\Omega}{2}}\frac{M_N}{W}\frac{|\mathbf{q}|}{(W+M_N)^2+Q^2}ZG^A(Q^2)\\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

Muon mass in coherent π^+ production is introduced by applying 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

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



Improvements – form factors

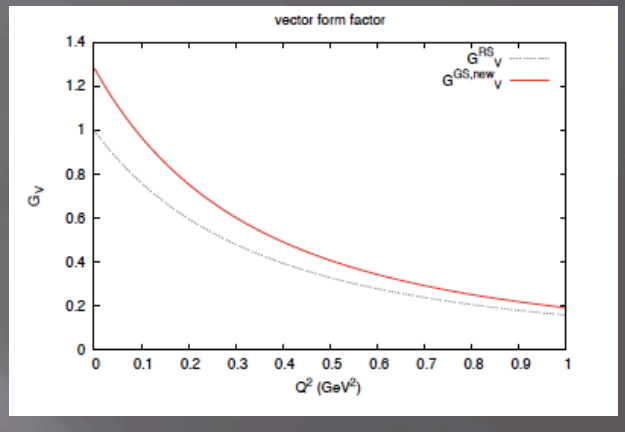
The relationship between vector form factor in the Rein-Sehgal model and the Rarita-Schwinger form factors taken from Graczyk and Sobczyk, Phys.Rev.D77:053001,2008

Vector form factor

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

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

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



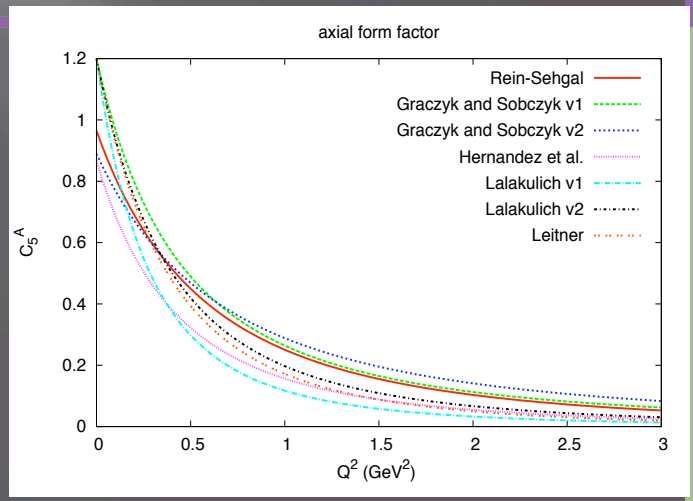
Axial vector form factor

$$G_A(Q^2) = 1.267\left(1+\frac{Q^2}{M_A^2}\right)^{-2}.$$

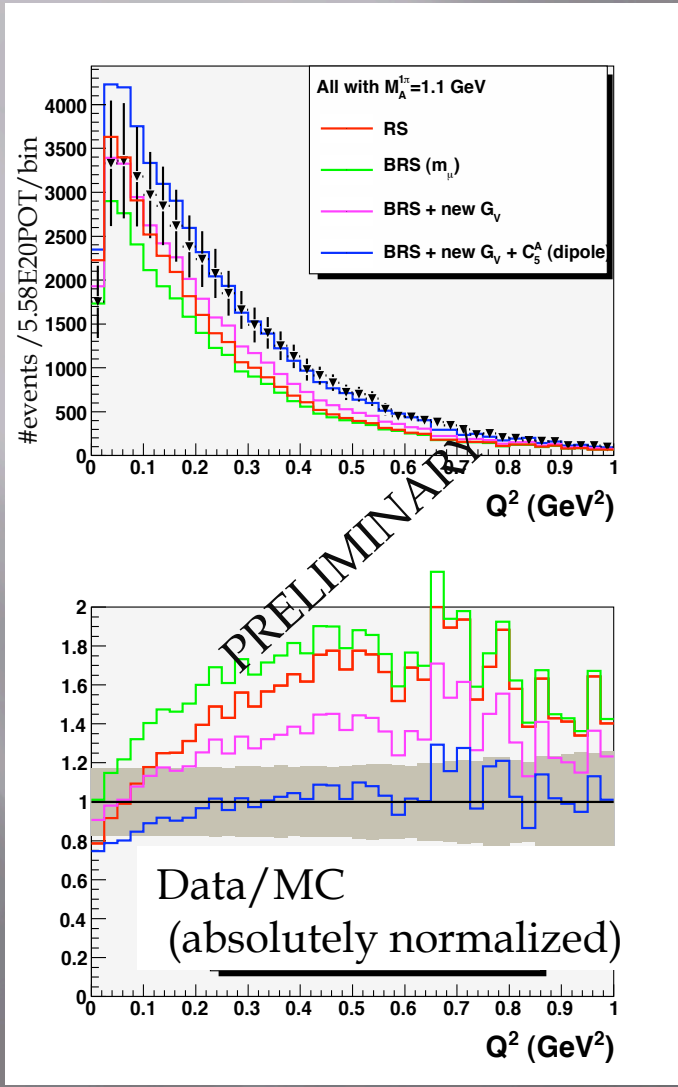
$$\tilde{G}_A^{RS} = ZG_A^{RS}(Q^2) = \frac{3}{5}\left(1+\frac{Q^2}{4M^2}\right)^{1/2}G_A(Q^2).$$

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

$$\tilde{G}_A^{RS,new}(W,Q^2) = \frac{\sqrt{3}}{2}\left(1+\frac{Q^2}{(M+W)^2}\right)^{1/2} \times\left[1-\frac{W^2-Q^2-M^2}{8M^2}\right]C_5^A(Q^2).$$

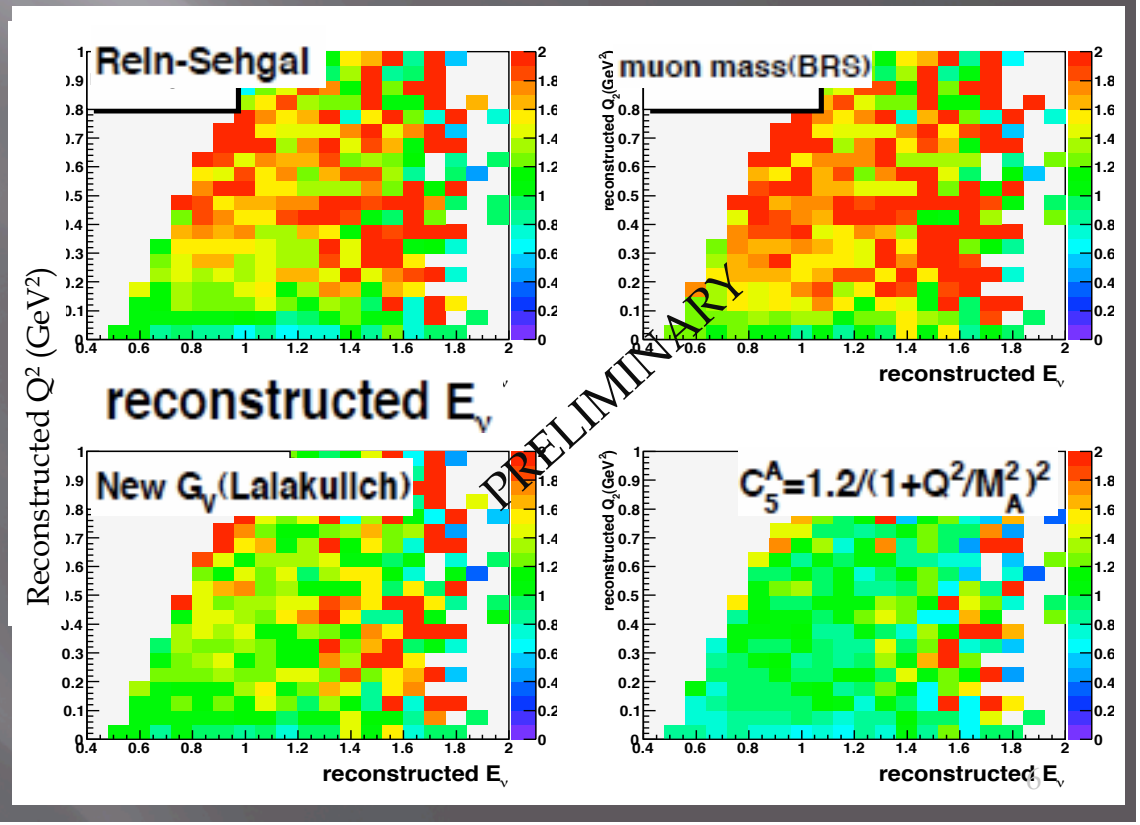


Improvement of the model of pion production



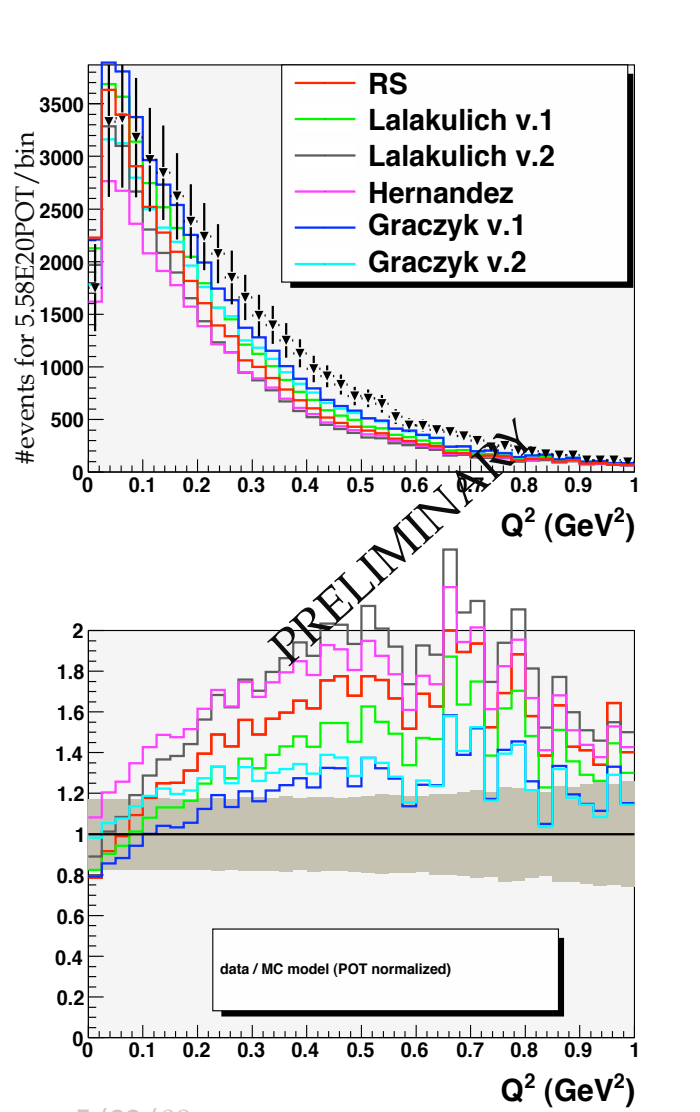
Model (M_A=1.1GeV)	χ^2/ndf
Rein-Sehgal	280/39
BRS(m_μ)	341/39
+ new G_V	138/39
+C_5^A (dipole)	24.7/39

Improvement
In the agreement
With data for Q^2
And for E_ν vs. Q^2

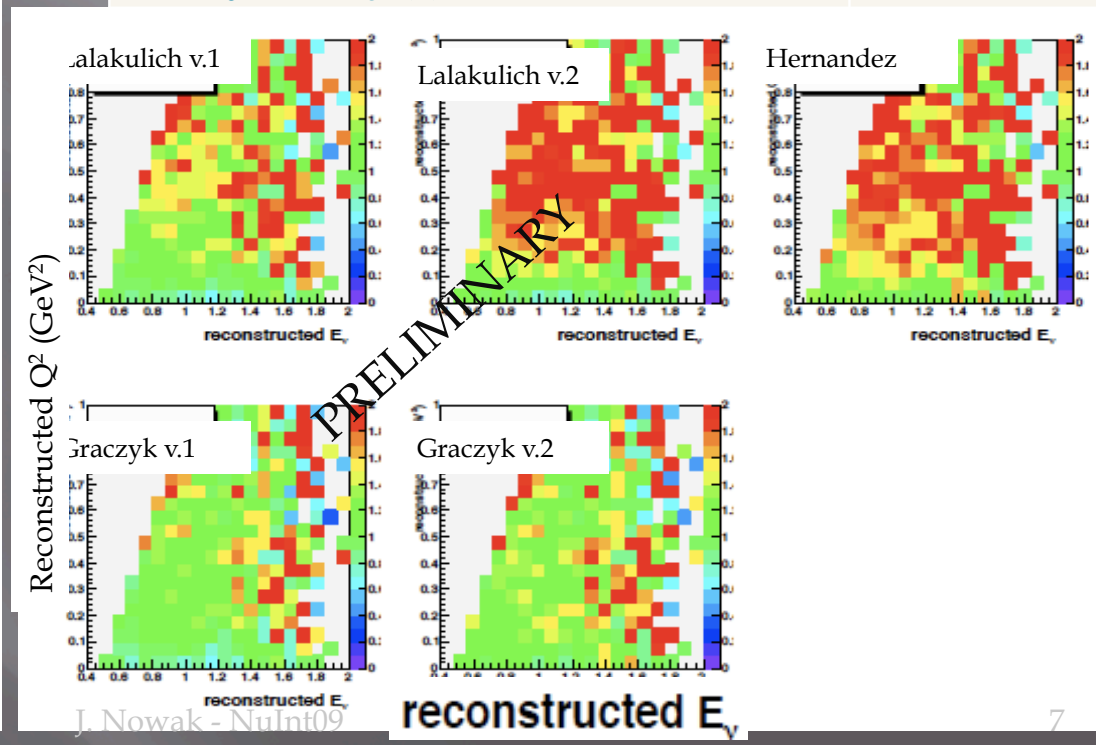


Comparison to other models

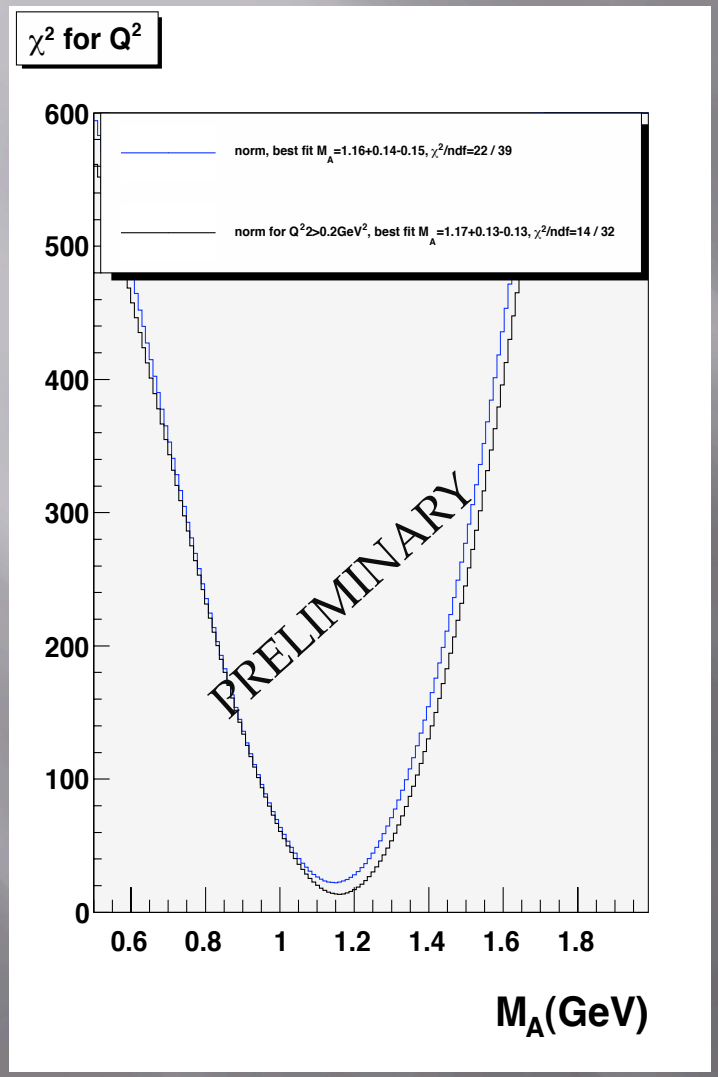
All models but the Rein-Sehgal are with muon mass effect and new vector form factor



Model	χ^2/ndf
Rein-Sehgal	280/39
Lalakulich v1, $C_5^A(0)$=1.2, M_A =0.95	188/39
Lalakulich v2, $C_5^A(0)$=1.2, M_A =1.05	391/39
Hernandez, $C_5^A(0)$=0.867, M_A =0.985	353/39
Graczyk v1, $C_5^A(0)$=1.2, M_A =0.94	90/39
Graczyk v2, $C_5^A(0)$=0.98, M_A =1.15	109/39



MiniBooNE results for the $M_A^{1\pi}$ fit

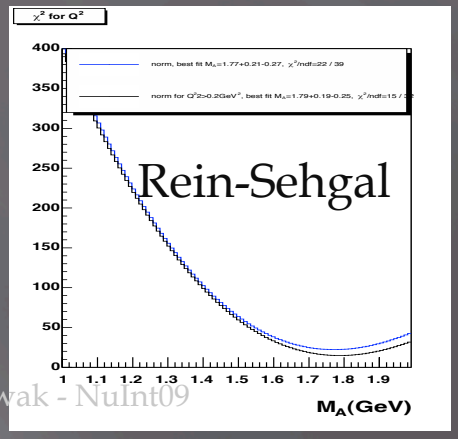


The fit for the $M_A^{1\pi}$ has been performed for the improved Rein-Sehgal model:

- Absolutely normalized distributions
- Fit for entire range of Q^2 and without the coherent π^+ production

$M_A^{1\pi}$=1.16±0.15 GeV with χ^2/ndf =22/39
For $0.0<Q^2/GeV^2<1.0$

$M_A^{1\pi}$=1.17±0.13 GeV with χ^2/ndf =14/32
For $Q^2>0.2$ GeV^2



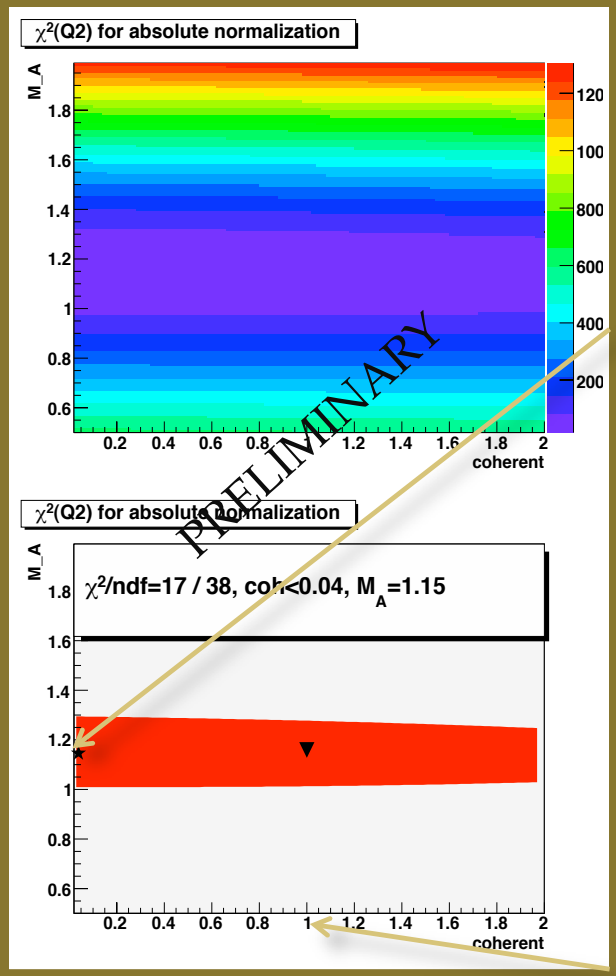
The same analysis for the default model In Nuance gives

$M_A^{1\pi}$=1.77±0.27 GeV with χ^2/ndf =22/39

Two-parameter fit

Keeping the dipole form of the C_5^A we performed two-parameter fits

$M_A^{1\pi}$ and coherent contribution

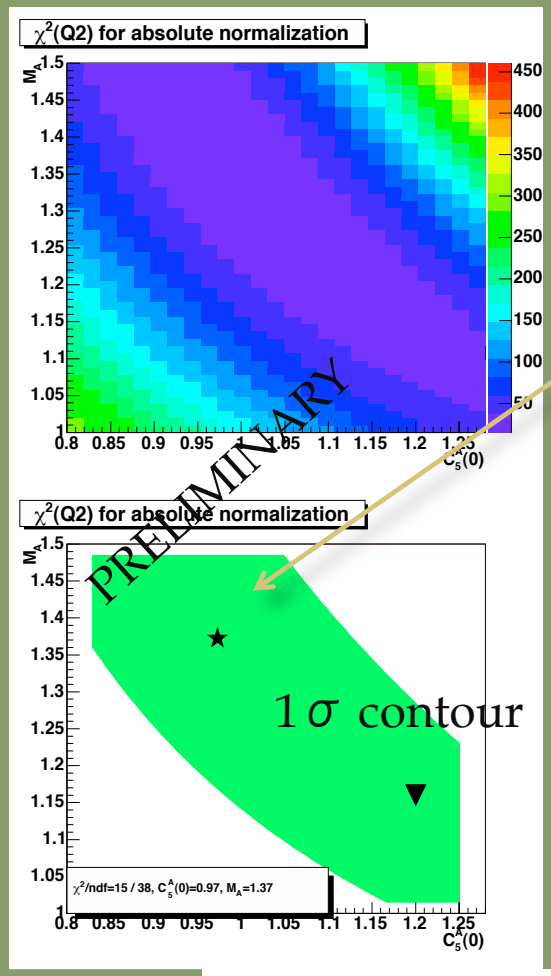


Best fit
$M_A^{1\pi}$=1.15 GeV
Coherent<0.04

▼ M_A only fit

Default contribution to CC π^+ events

$M_A^{1\pi}$ and $C_5^A(0)$

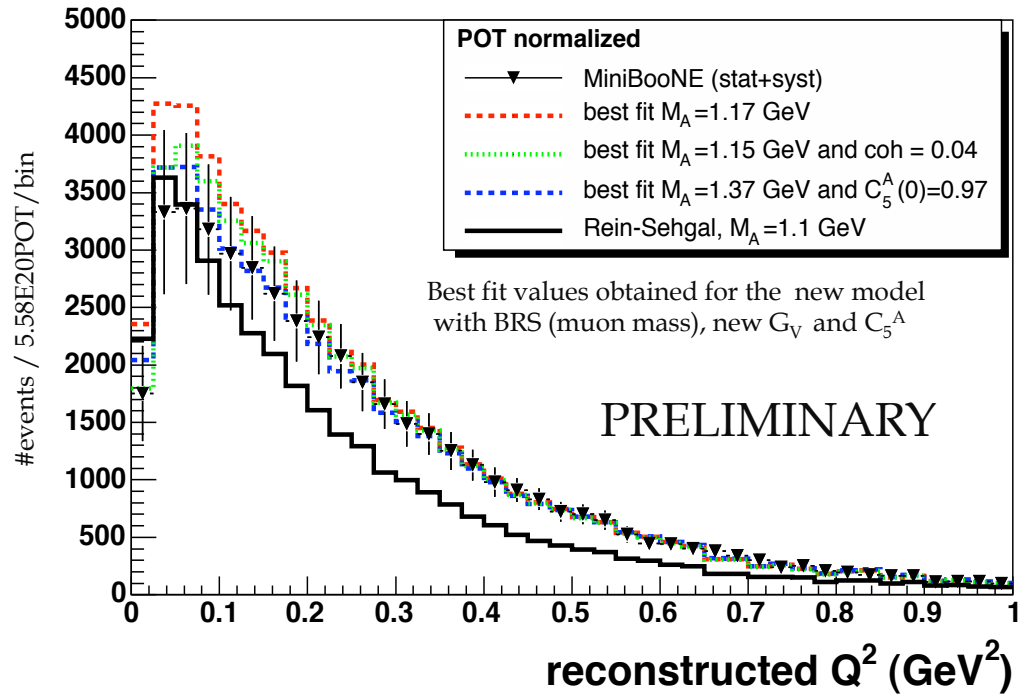


Best fit
$M_A^{1\pi}$=1.37 GeV
$C_5^A(0)$=0.97

$G_A^{RS}(0)$=0.764

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

Conclusions



- The new model of charged Current pion production Improved agreement with data
- We performed fits for three models

1. The fit result for $M_A^{1\pi}$ for Q^2>0.2GeV^2

$M_A^{1\pi$=1.17±0.13 GeV.

2a. Coherent contribution and $M_A^{1\pi}$

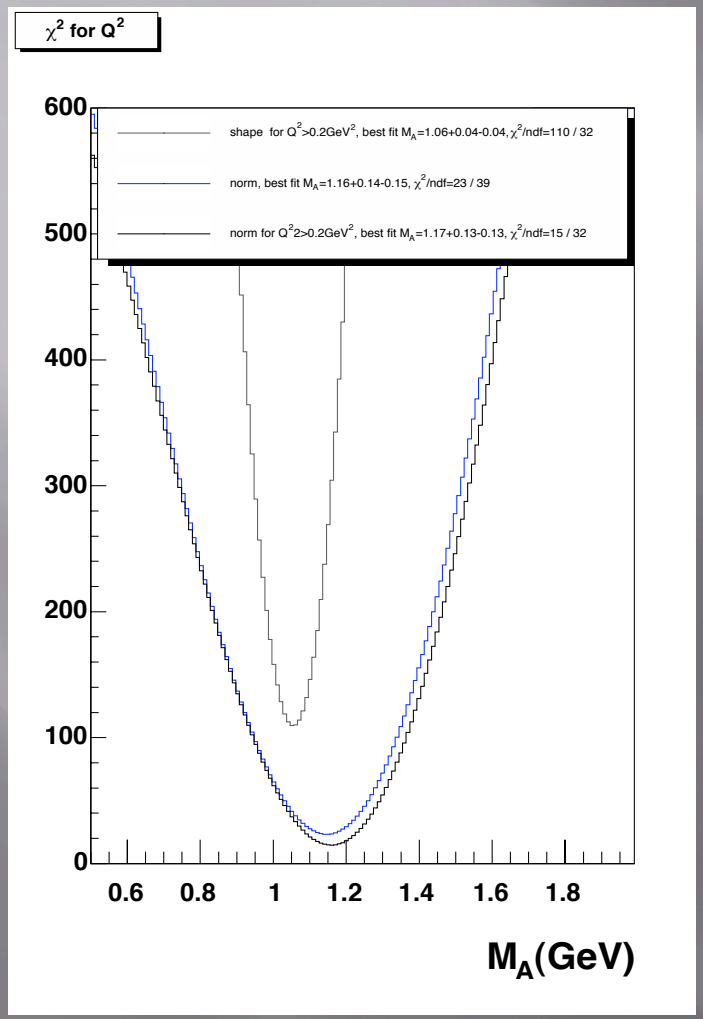
$M_A^{1\pi}$=1.15 GeV
Coherent<0.04

2b. $M_A^{1\pi}$ and $C_5^A(0)$

$M_A^{1\pi}$=1.37 GeV
$C_5^A(0)$=0.97

Backup slides

$M_A^{1\pi}$ for the shape



$M_A^{1\pi}$=1.16±0.15 GeV with χ^2/ndf =22/39
For $0.0<Q^2/GeV^2<1.0$

$M_A^{1\pi}$=1.17±0.13 GeV with χ^2/ndf =14/39
For $Q^2>0.2$ GeV^2

$M_A^{1\pi}$=1.06±0.1 GeV
For shape $Q^2>0.2$ GeV^2

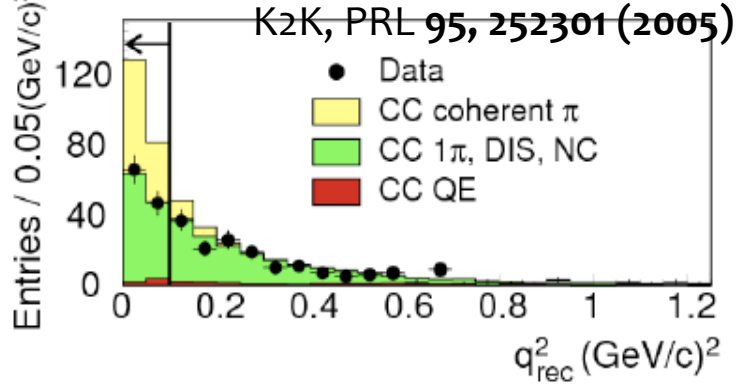
with χ^2/ndf =110/39
(absolutely normalized)

Recent experimental results

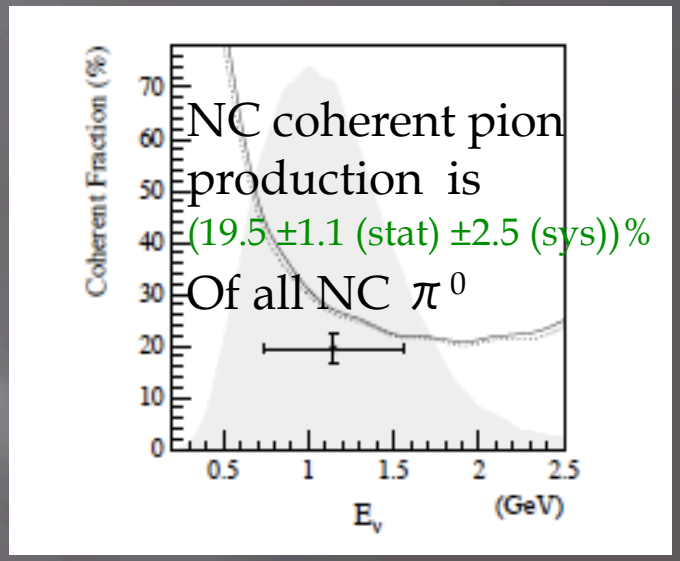
$\sigma(\text{CC coherent } \pi)/\sigma(\nu_\mu \text{CC}) < 0.60 \times 10^{-2}$.

1.3 GeV

K2K, PRL **95, 252301 (2005)**



MiniBooNE, PHLTA,B664,41



NC coherent pion production is

(19.5 ±1.1 (stat) ±2.5 (sys))%

Of all NC π^0

- SciBooNE

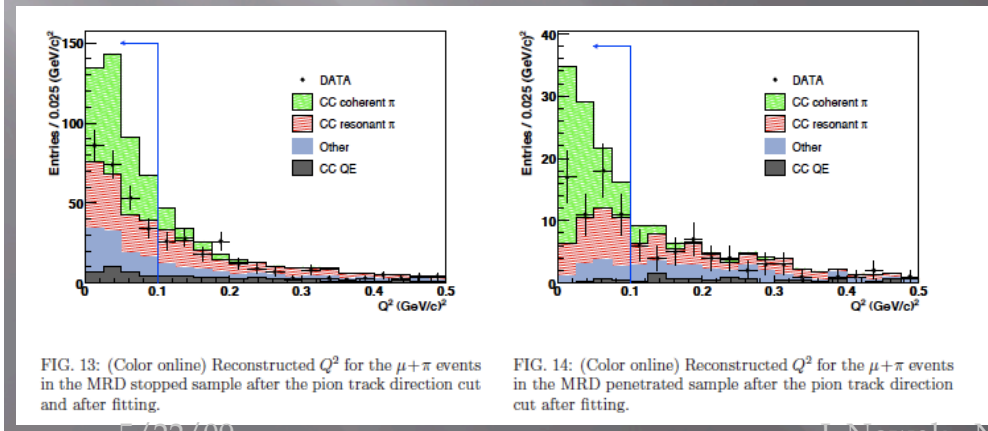


FIG. 13: (Color online) Reconstructed Q^2 for the $\mu+\pi$ events in the MRD stopped sample after the pion track direction cut and after fitting.

FIG. 14: (Color online) Reconstructed Q^2 for the $\mu+\pi$ events in the MRD penetrated sample after the pion track direction cut after fitting.

$$\frac{\sigma(\text{CC coherent } \pi)}{\sigma(\text{CC})} < 0.67 \times 10^{-2}$$

1.1 GeV

$$\frac{\sigma(\text{CC coherent } \pi)}{\sigma(\text{CC})} < 1.36 \times 10^{-2}$$

2.2 GeV