Progress on Constraining the Strange Quark Contribution to the Proton Axial Form Factor

Stephen Pate
with V. Papavassiliou , J.P. Schaub, D.P. Trujillo (NMSU)
M.V. Ivanov (Institute for Nuclear Research and Nuclear Energy, Sofia)
M.B. Barbaro (Universita' degli Studi di Torino & INFN Torino)
C. Giusti (INFN Pavia)

https://arxiv.org/abs/2402.10854 now in **Phys. Rev. D 109, 093001**

NuFact 2024   20-Sept-2024   Argonne National Lab

Axial form factor of the proton

$$G_A^{Z,p} = \frac{1}{2}\left(-G_A^u + G_A^d + G_A^s\right)$$

Critical to understanding neutral-current and charged-current interaction of neutrinos with matter.

$$G_A^{CC} = G_A^u - G_A^d$$

The up-down part is very well-known from decades of study of CC interactions.

$$\nu_\mu + n \rightarrow \mu + p \qquad n \rightarrow p + e + \bar{\nu}_e$$

$$G_A^s$$

The strange part is only directly accessible via NC scattering.

$$\nu + p \rightarrow \nu + p$$

Still only very limited information available on G_A^s!

Traditional models of G_A^s

Due to limited available information, most modeling of G_A^s is based on two ingredients:

- The Q^2-dependence is assumed to be the same as $G_A^{CC} = G_A^u - G_A^d$
  - But there is no physics to support this assumption.
- The value of G_A^s at $Q^2 = 0$ is the strange quark contribution to the proton spin, Δs. A value for Δs is taken from a polarized deep-inelastic scattering measurement.
  - But there is no agreed-upon value for Δs from pDIS; could be anything from 0 to -0.2. Big uncertainty!

Our goal is to determine the Q^2-dependence of G_A^s and the value of Δs directly from elastic electron and neutrino scattering data.

Strange Quark Contribution to Nucleon Spin Δs

Broad Physics Interest

- **Searches for heavy dark matter particles [Ellis, Olive, & Savage, Phys Rev D 77 (2008) 065026]**

- **Lattice QCD calculates a small value:**

$\Delta s = -0.031(17)$ [M. Engelhardt, Phys. Rev. D 86 (2012) 114510];
$\Delta s = -0.024(15)$ [Babich et al., Phys. Rev. D 85 (2012) 054510];
requires experimental verification

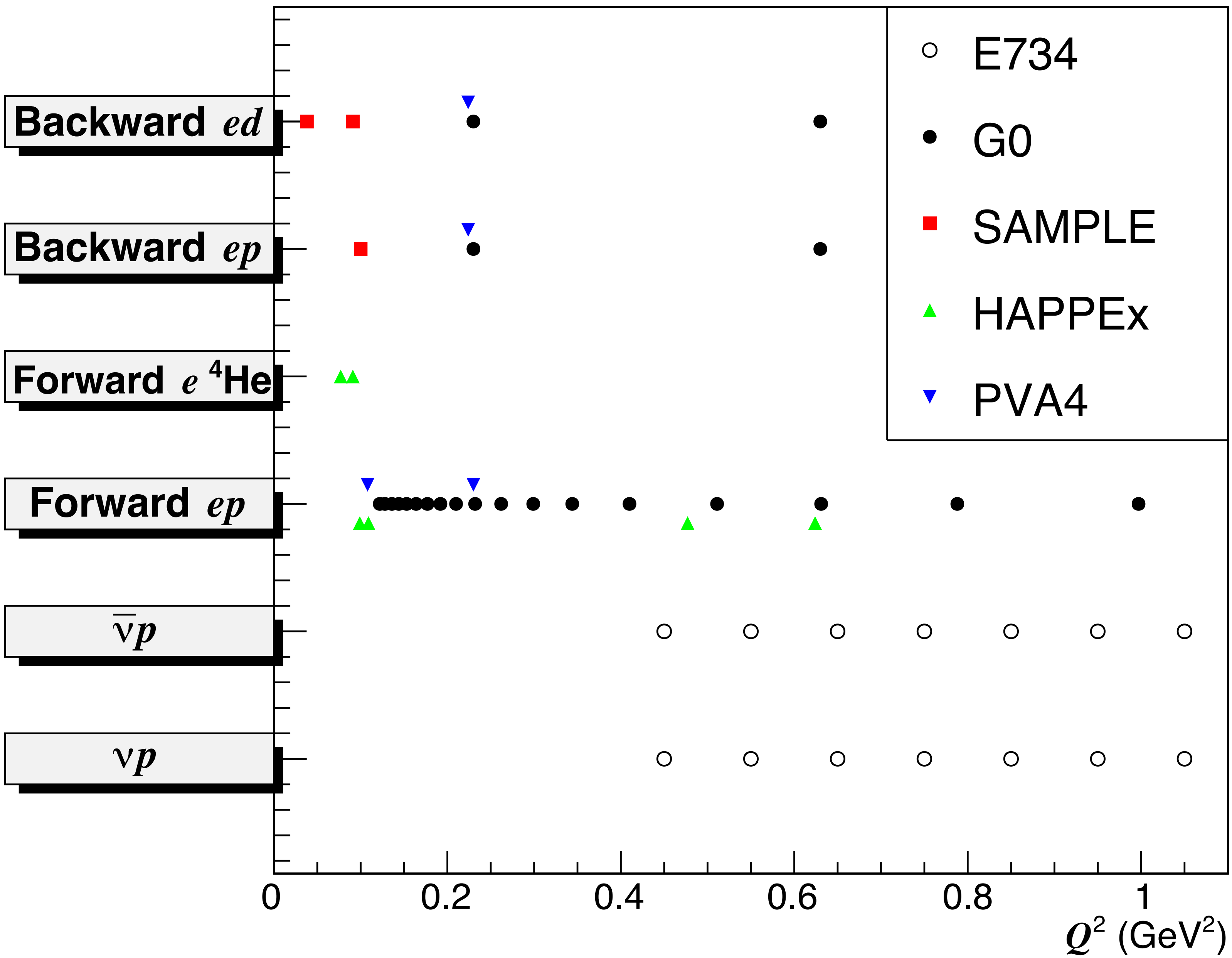
- **Simulations of supernovae are sensitive to the value of Δs [Melson, Janka, Bollig, Hanke, Marek, Mueller, Astro. J. Lett. 808 (2015) L42]**

- **Atomic PV experiments on hydrogen are sensitive to Δs [Gasenzer, Nachtmann, Trappe, EPJ D (2012) 66:113]**

Simultaneous determination of strange quark contribution to vector and axial form factors

- Our approach will be to determine G_E^s, G_M^s, and G_A^s together, by combining data from neutrino neutral-current elastic scattering (NCES) and parity-violating electron scattering (PVES)
- This was first done in PRL 92 082002 (2004) by combining BNL E734 NCES data with HAPPEx PVES data at $Q^2 = 0.477$ GeV^2.
- This analysis was expanded [PRC 78 015207 (2008)] to include points in the range $0.55 < Q^2 < 1.05$ GeV^2 when the G0 PVES data became available.

NCES and PVES data available for this analysis technique, not including MiniBooNE; 49 data points in total.



Determinations of G_E^s, G_M^s, and G_A^s using subsets of the E734, G0, HAPPEx, PVA4 and SAMPLE data.

● G0 (forward *ep*) + E734 (νp and $\bar{\nu} p$)

○ HAPPEx (forward *ep*) + E734 (νp and $\bar{\nu} p$)

Pate, Papavassiliou & McKee, PRC 78 (2008) 015207

■ (red) PVA4 (forward and backward *ep*)

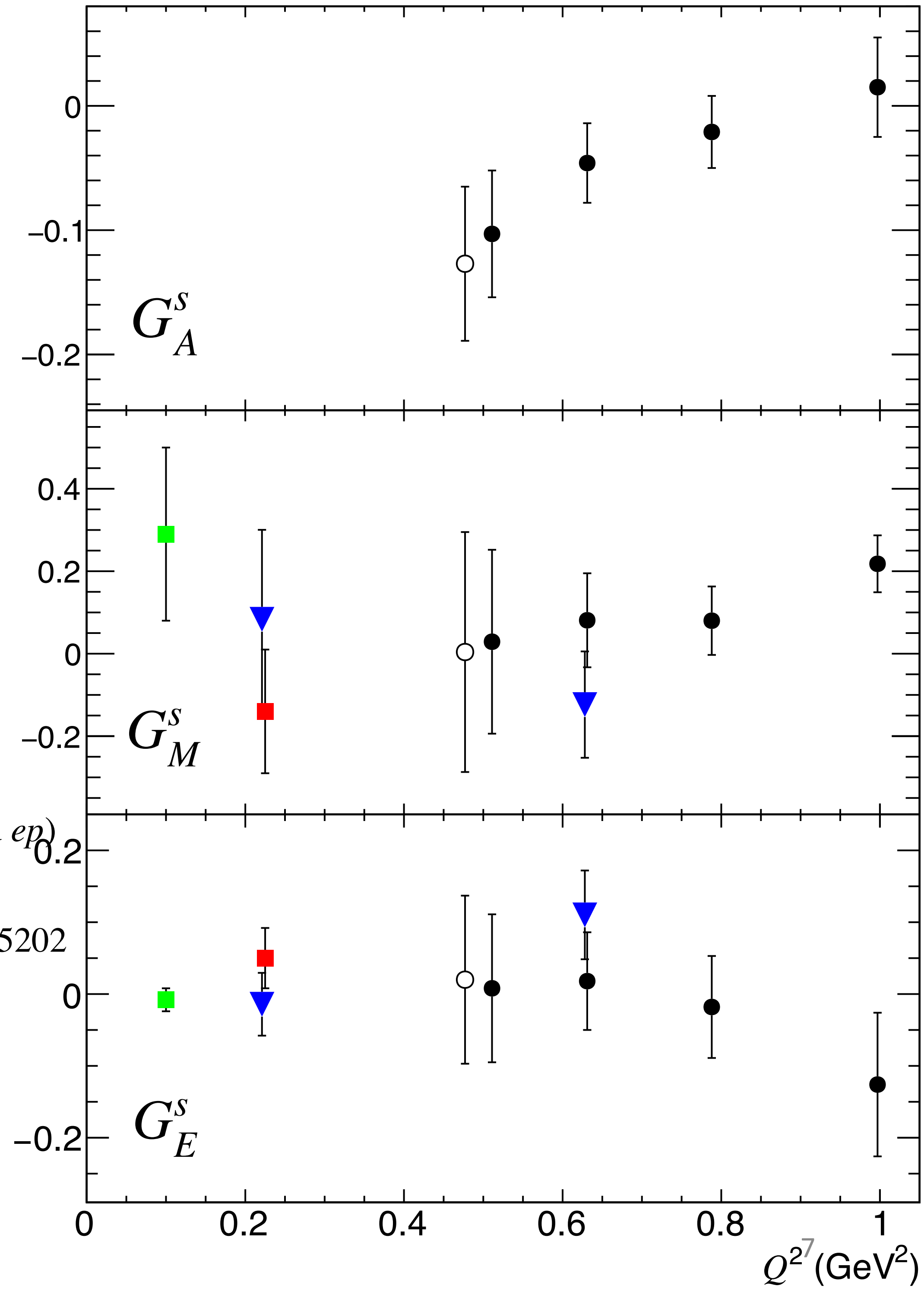
Baunack et al., PRL 102 (2009) 151803

▼ (blue) G0 (forward and backward *ep*, and backward *ed*)

D. Androic et al., PRL 104 (2010) 012001

■ (green) HAPPEx (forward *ep* and $e\,^4$He) + G0 (forward *ep*) + SAMPLE (backward *ep* and *ed*) + PVA4 (forward *ep*) near $Q^2 = 0.1$ GeV^2

Liu, McKeown & Ramsey-Musolf, PRC 76 (2007) 025202



⇒ G_E^s and G_M^s are flat and consistent with zero.

⇒ G_A^s has a definite Q^2-dependence, trending negative with decreasing Q^2.

Instead of calculating the form factors at individual points using subsets of the data, **use all the data in a fitting procedure.**

Each kind of data is most sensitive to a different form factor.

Need all three kinds of data in our approach.

Neutral Current Elastic Scattering

G_E^s G_M^s G_A^s

Parity-Violating Electron Scattering

(forward $\vec{e}p$)

G_E^s G_M^s G_A^s

Parity-Violating Electron Scattering

(backward $\vec{e}p$ & $\vec{e}d$)

G_E^s G_M^s G_A^s

Models for the Strangeness Form Factors

- G_E^s and G_M^s are consistent with zero and featureless; use simple zeroth-order model.

$$G_E^s = \rho_s \tau \qquad G_M^s = \mu_s \qquad [\tau = Q^2/4M^2]$$

- G_A^s appears to have a definite Q^2-dependence. We consider two different models for G_A^s.

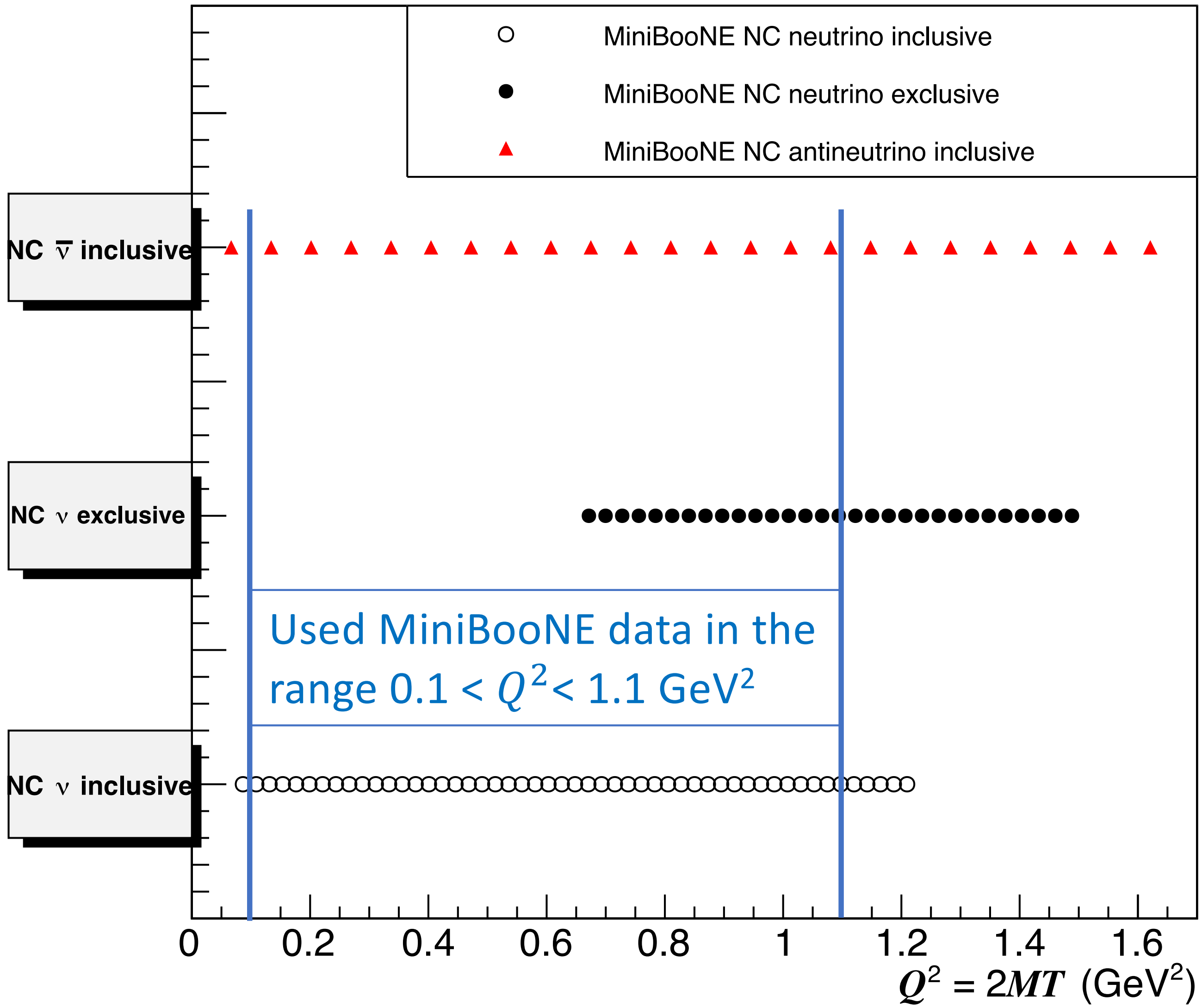
--- "Modified-dipole model"

$$G_A^s = \frac{\Delta s + S_A Q^2}{(1 + Q^2/\Lambda_A^2)^2}$$

--- "z-Expansion Model"

$$G_A^s = \sum_{k=0}^{6} a_k [z(Q^2)]^k \qquad z(Q^2) = \frac{\sqrt{(4m_\pi)^2 + Q^2} - \sqrt{(4m_\pi)^2}}{\sqrt{(4m_\pi)^2 + Q^2} + \sqrt{(4m_\pi)^2}}$$

NCES data from MiniBooNE available for this analysis. We use the data in the range $0.1 < Q^2 < 1.1$ GeV^2, bringing the total number of data points to 128.



Models for the ν–Carbon interaction; needed for the use of the MiniBooNE data

- Relativistic Fermi Gas (RFG): Carbon nucleus is described by a Fermi momentum k_F based on electron scattering data; nucleons are plane waves constrained by the Pauli principle.
- SuperScaling Approximation (SuSA): Scaling behavior of (e, e') data used to predict NC and CC neutrino-scattering cross sections
- Spectral Function (SF): a spectral function $S(p, \mathcal{E})$ based on (e, e') data has been used to better describe single-nucleon removal

$G_E^s = \rho_s \tau$

$G_M^s = \mu_s$

Modified-dipole model

$$G_A^s = \frac{\Delta s + S_A Q^2}{(1 + Q^2/\Lambda_A^2)^2}$$

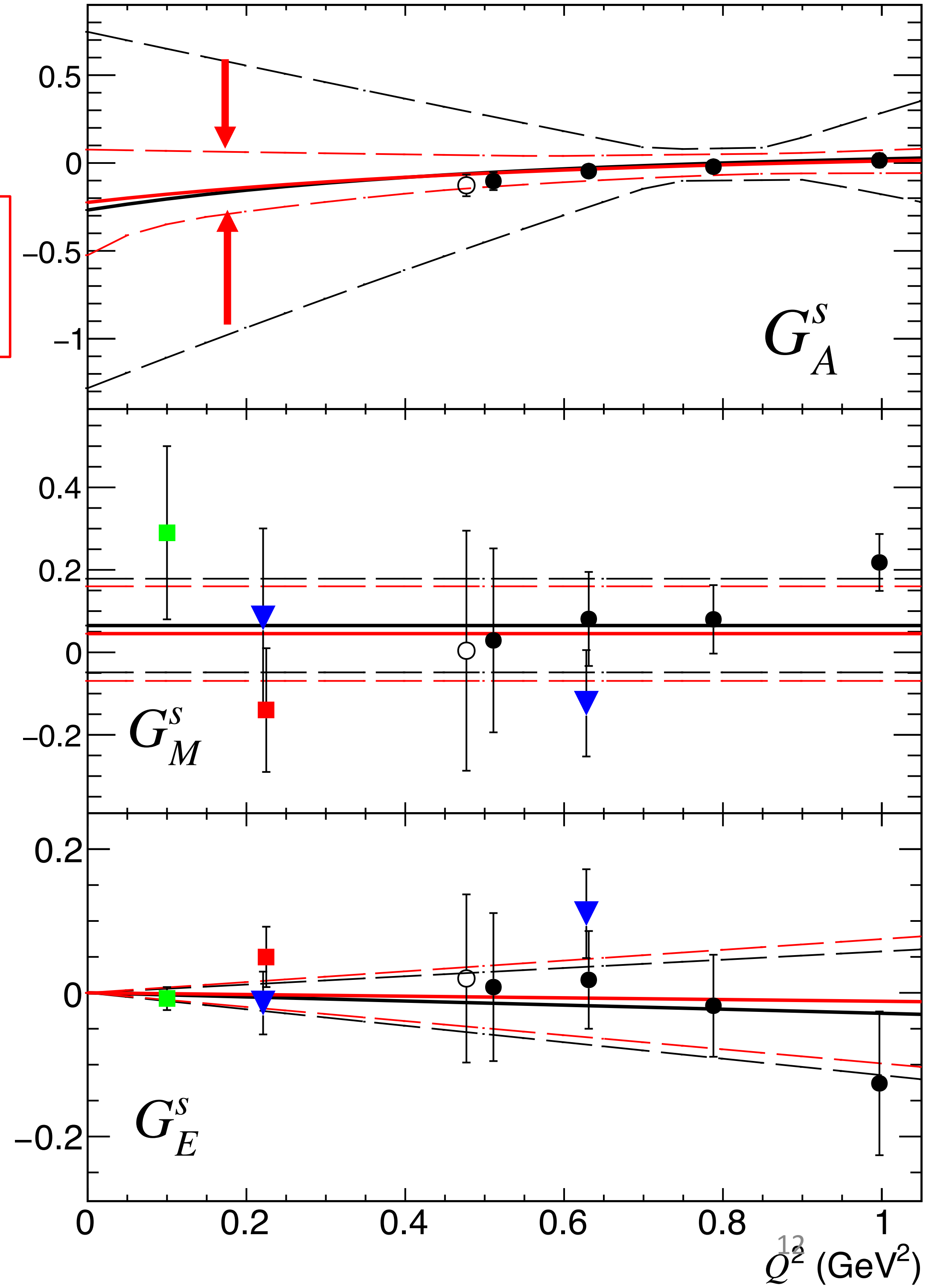
Improved constraint on G_A^s via inclusion of MiniBooNE data

Fit not including any MiniBooNE data. Uses data from BNL E734, HAPPEx, PVA4, G0 and SAMPLE. (49 data points)

Fit including also MiniBooNE data from NC neutrino and antineutrino scattering, using spectral function model. (128 data points)

Dashed lines show 70% confidence level.

$$\frac{\chi^2}{\text{ndf}} = 1.1 - 1.2$$



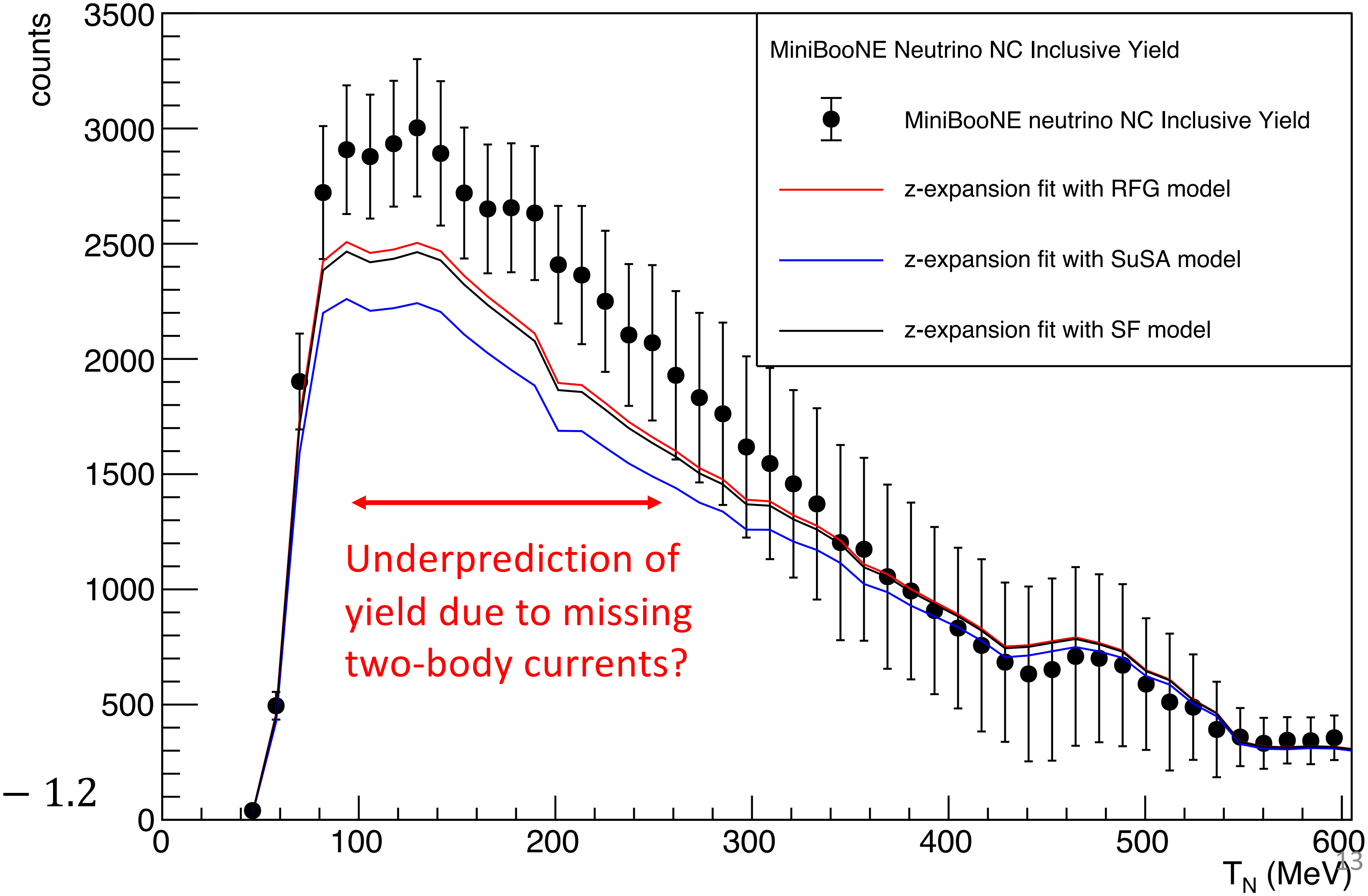
MiniBooNE NCES neutrino inclusive yield

RFG

SuSA

SF

All three fits use the z-expansion model for G_A^s.



$$\frac{\chi^2}{\mathrm{ndf}} = 1.1 - 1.2$$

MiniBooNE NCES neutrino

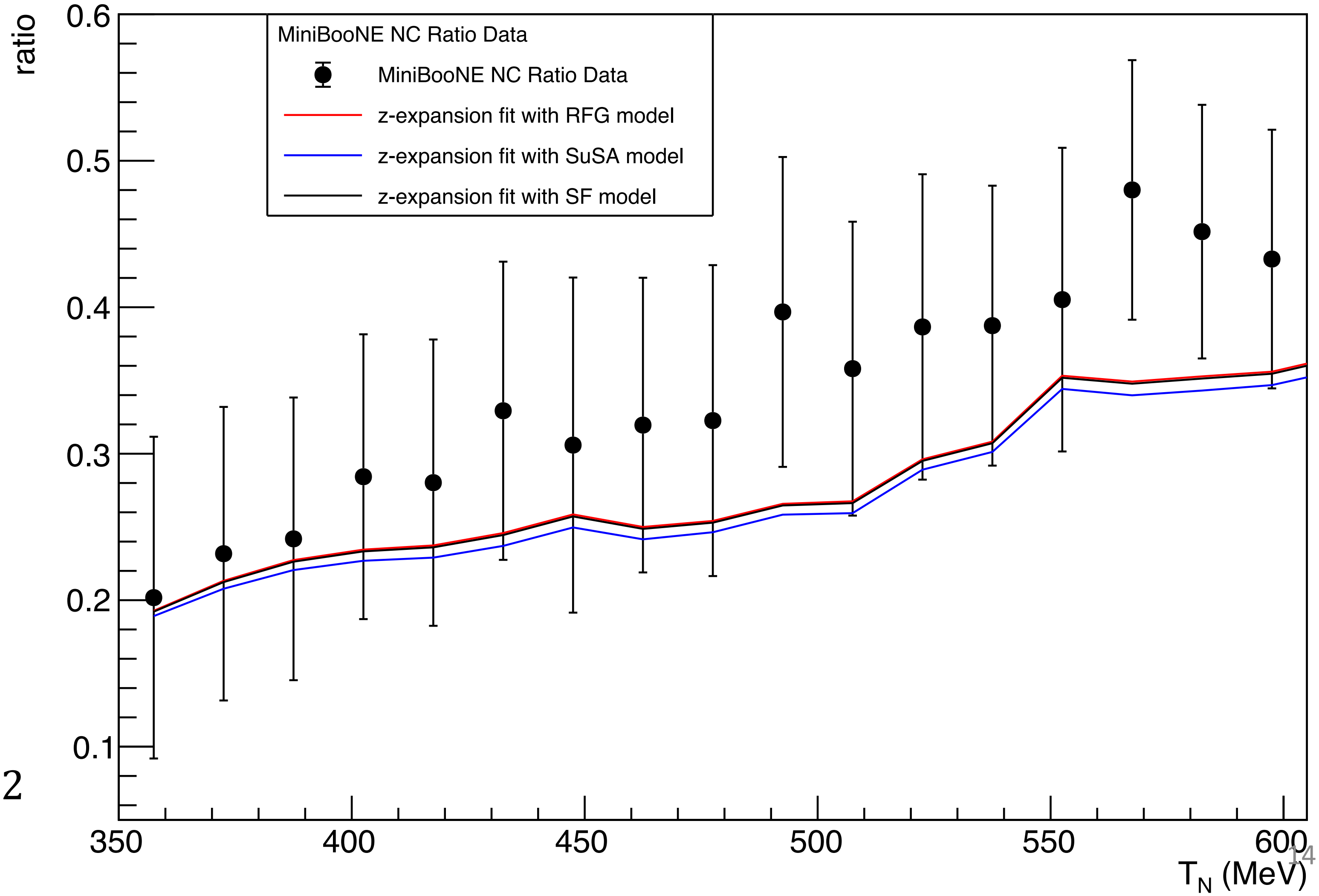
Exclusive/inclusive $p/(p+n)$ yield ratio

All three fits use the z-expansion model for G_A^s.

RFG

SuSA

SF



$$\frac{\chi^2}{\text{ndf}} = 1.1 - 1.2$$

MiniBooNE NC inclusive cross sections on mineral oil

○ ν

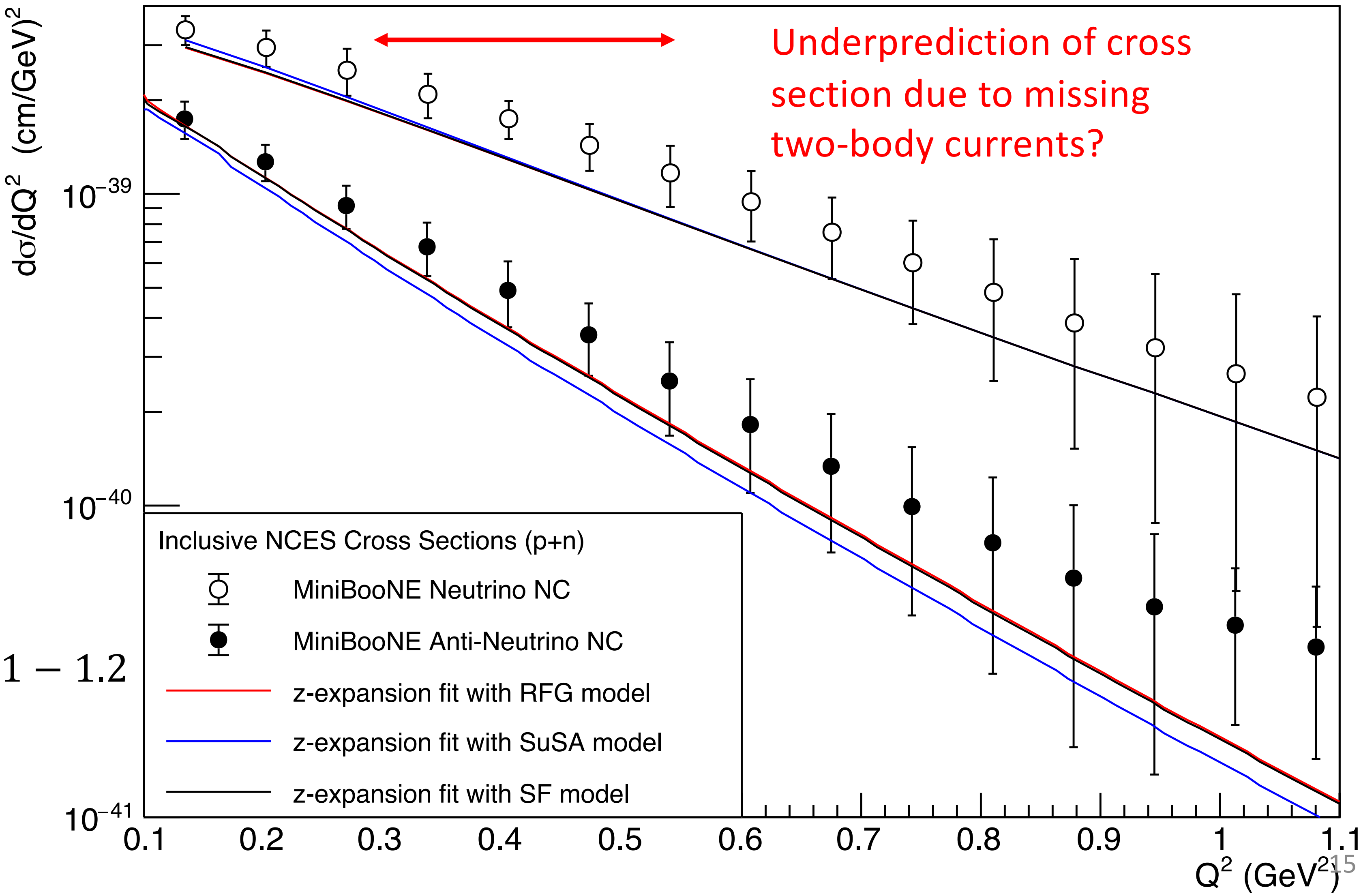
● $\bar{\nu}$

RFG

SuSA

SF

All three fits use the z-expansion model for G_A^s.



$$\frac{\chi^2}{\text{ndf}} = 1.1 - 1.2$$

$$G_E^s = \rho_s \tau$$

$$G_M^s = \mu_s$$

Need exclusive NC data in low-Q^2 region to finalize this work

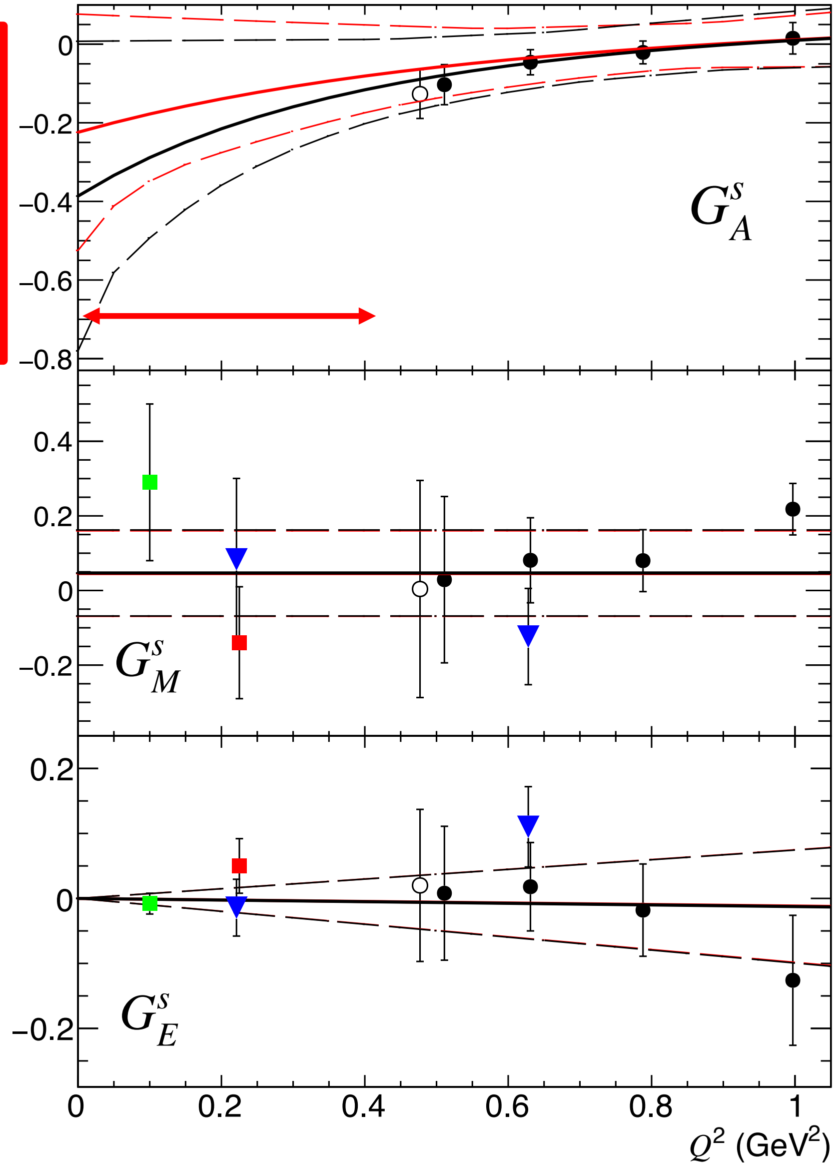
SuSA

SF

$$\frac{\chi^2}{\text{ndf}} = 1.1 - 1.2$$

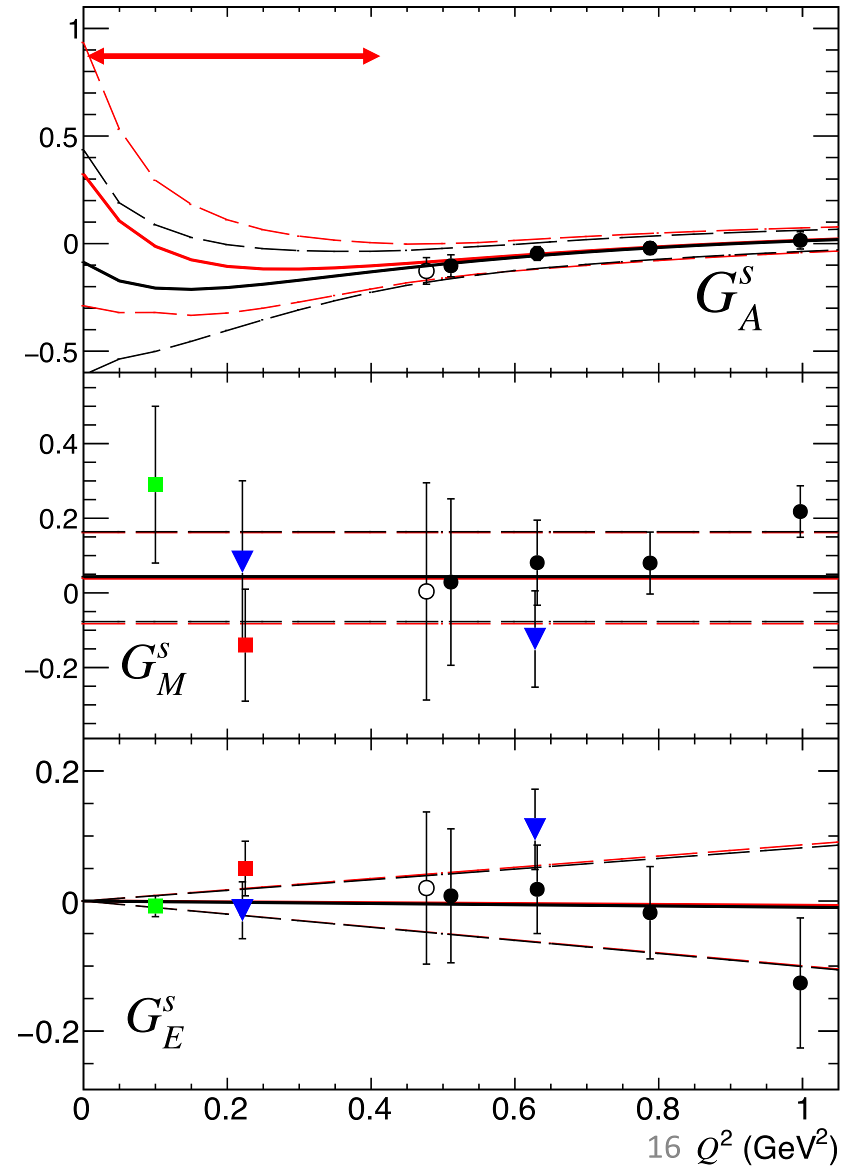
Modified-dipole model

$$G_A^s = \frac{\Delta s + S_A Q^2}{(1 + Q^2/\Lambda_A^2)^2}$$



z-expansion model

$$G_A^s = \sum_{k=0}^{6} a_k [z(Q^2)]^k$$



Next Steps

- Inclusion of the MiniBooNE neutral-current data is a big step forward in advancing our knowledge of the strange quark contribution to the axial form factor.

  https://arxiv.org/abs/2402.10854

  now in **Phys. Rev. D 109, 093001**

- Modeling of NC scattering needs improvements (two-body currents, final-state interactions, …)

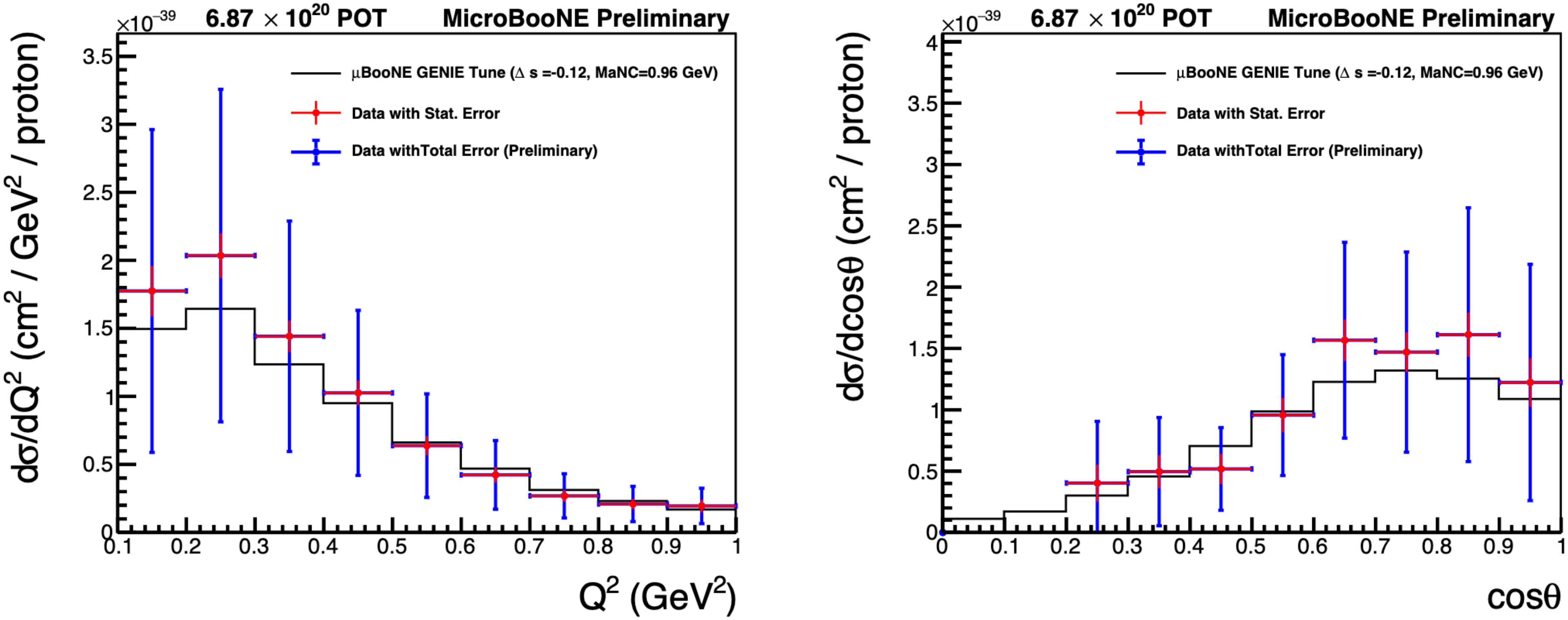
- Still need low-Q^2 exclusive neutral-current scattering data, with a single proton in the final state, such as will be available from MicroBooNE very soon.

  L. Ren, JPS Conf. Proc. 37, 020309 (2022)

  https://journals.jps.jp/doi/10.7566/JPSCP.37.020309

- Other experiments should look for their NC1p events – more data is needed!

Preliminary MicroBooNE Data (2022)

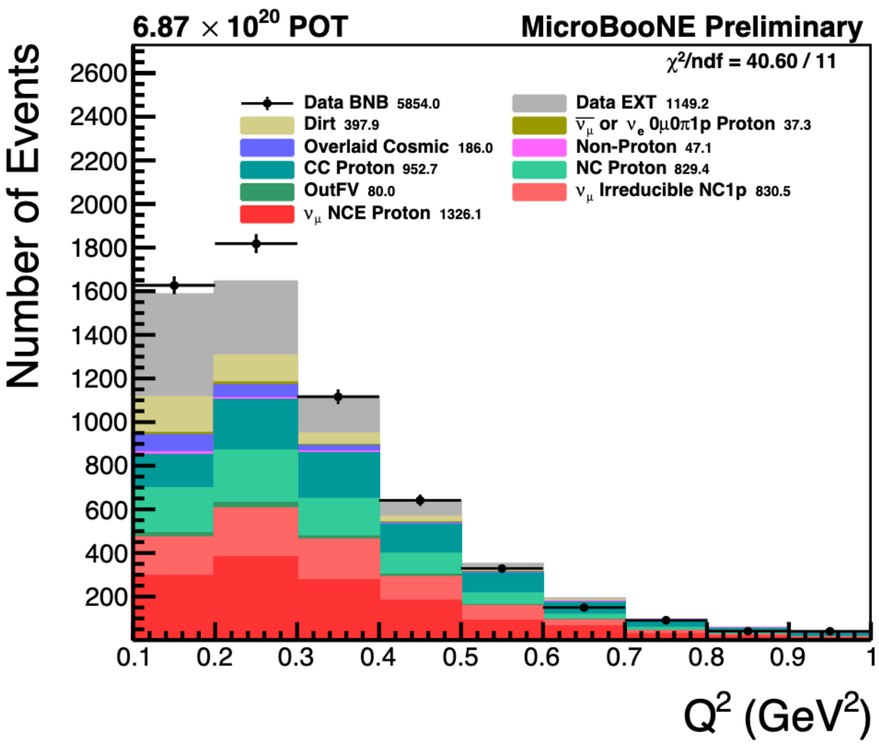


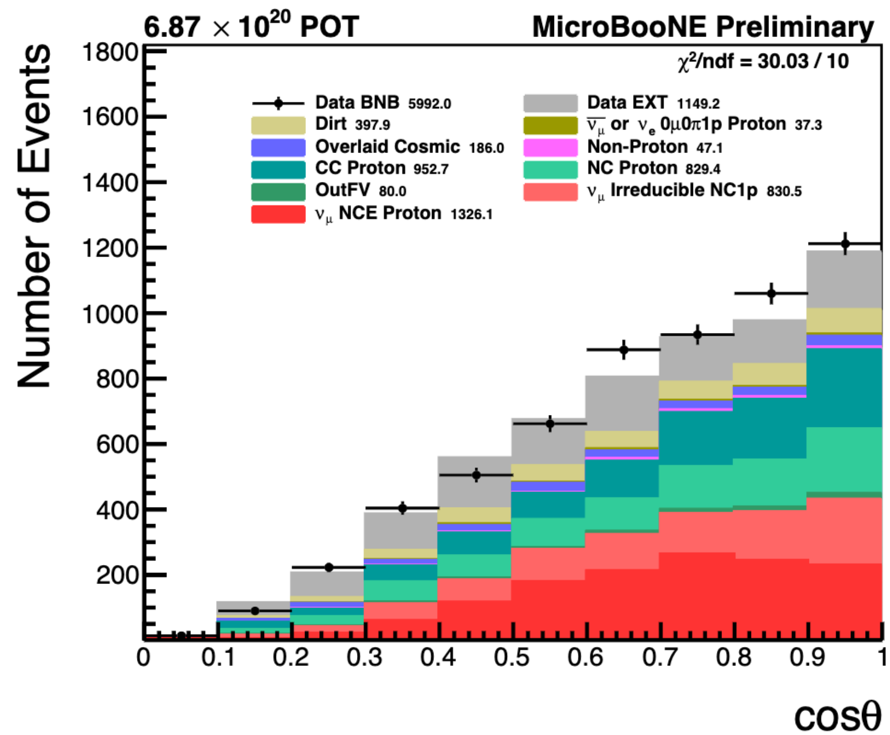
We have significantly reduced the systematic errors in the subsequent two years.

Solid line is a GENIE calculation using a dipole model for G_A^s with $\Delta s = -0.12$ and $M_A^{NC} = 0.96$ GeV.

L. Ren, JPS Conf. Proc. 37, 020309 (2022)
https://journals.jps.jp/doi/10.7566/JPSCP.37.020309

Preliminary MicroBooNE Data (2022)





Breakdown of the yield into signal and background components, as a function of Q^2 and $\cos\theta$. Some backgrounds have been significantly reduced in the meantime.

L. Ren, JPS Conf. Proc. 37, 020309 (2022)
https://journals.jps.jp/doi/10.7566/JPSCP.37.020309

Theoretical effort to reproduce these NC1p data…

… will need all neutrino-argon interactions that can contribute to the signal:

- Quasi-elastic NC on proton
- NC Δ-production, with FSI to absorb the pion/kaon
- NC DIS, with FSI to absorb the pion/kaon
- Quasi-elastic MEC and/or 2p2h and/or SRC, with FSI to absorb the 2nd nucleon

This work is in progress, and we welcome others to join the effort.

Thank you!

Backup Slides

z-Expansion Model for G_A^s

$$G_A^s = \sum_{k=0}^{6} a_k [z(Q^2)]^k$$

$$z(Q^2) = \frac{\sqrt{t_{cut} + Q^2} - \sqrt{t_{cut} - t_0}}{\sqrt{t_{cut} + Q^2} + \sqrt{t_{cut} - t_0}}$$

$$t_{cut} = (4m_\pi)^2 \qquad t_0 = 0$$

Four constraints: $\left(\frac{d^n}{dz^n} G_A^s\right)_{z=1} = 0 \qquad n = 0,1,2,3$

$\Rightarrow$ only three parameters a_0, a_1, a_2

Richard J. Hill and Gil Paz Phys. Rev. D 82, 113005

Gabriel Lee, John R. Arrington, and Richard J. Hill Phys. Rev. D 92, 013013

Elastic NC neutrino-proton cross section

$$\frac{d\sigma}{dQ^2} = \frac{G_F^2}{2\pi}\frac{Q^2}{E_\nu^2}\left(A \pm BW + CW^2\right) \qquad +(-) \Rightarrow \nu(\bar{\nu})$$

$$W = 4\left(E_\nu/M_p - \tau\right) \qquad \tau = Q^2/4M_p^2$$

$$\begin{aligned} A &= \frac{1}{4}\left[\left(G_A^Z\right)^2(1+\tau) - \left(\left(F_1^Z\right)^2 - \tau\left(F_2^Z\right)^2\right)(1-\tau) + 4\tau F_1^Z F_2^Z\right] \\ B &= -\frac{1}{4}G_A^Z\left(F_1^Z + F_2^Z\right) \\ C &= \frac{1}{64\tau}\left[\left(G_A^Z\right)^2 + \left(F_1^Z\right)^2 + \tau\left(F_2^Z\right)^2\right] \end{aligned}$$

G_A^{CC}

The best data on the *CC* axial form factor is from deuterium bubble chamber data from the 70s and 80s.

No background. $\nu_\mu + n \rightarrow \mu + p$

No significant nuclear corrections.

Unambiguous event selection.

The results of these experiments still form the basis for our understanding of G_A^{CC} and continue to be used in fits and comparisons to model calculations.

$$G_A^{CC} = \frac{g_A}{(1 + Q^2/M_A^2)^2}$$

$g_A = 1.2670 \pm 0.0030$ Cabibbo et al., Ann. Rev. Nucl. Part. Sci. 53, 39-75, 2003

$M_A = 1.014 \pm 0.014$ Bodek et al., Eur. Phys. J. C 53, 349-354, 2008

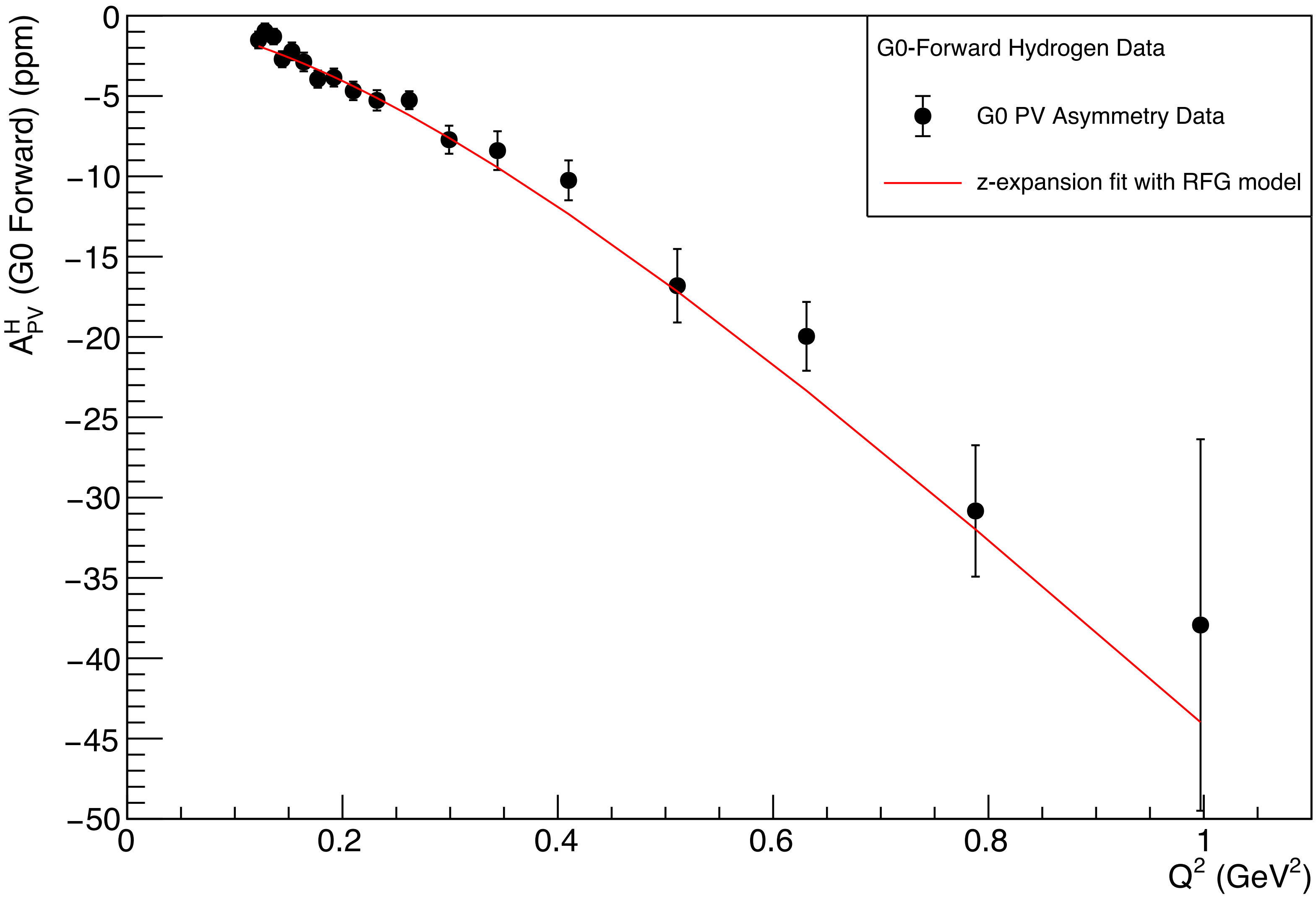
TABLE III. Summary of the results of the fits performed with three nuclear models (RFG, SuSA, and SF) and two strangeness axial form factor models (modified-dipole and z-expansion); also shown are the results when no MiniBooNE data are included. The central value and uncertainty is given for each fit parameter, and also the χ^2 per number of degrees of freedom at the optimal fit point. The first uncertainty is that arising from the fit itself, and the second uncertainty is a systematic due to the uncertainties in the quantities in Table I as described in the text.

		RFG	SuSA	SF	w/o MiniBooNE Data
Modified-Dipole	ρ_s	$-0.043 \pm 0.120 \pm 0.063$	$-0.047 \pm 0.120 \pm 0.064$	$-0.044 \pm 0.120 \pm 0.063$	$-0.107 \pm 0.121 \pm 0.058$
	μ_s	$0.045 \pm 0.036 \pm 0.032$	$0.047 \pm 0.036 \pm 0.032$	$0.045 \pm 0.036 \pm 0.032$	$0.065 \pm 0.036 \pm 0.030$
	Δs	$-0.203 \pm 0.115 \pm 0.030$	$-0.386 \pm 0.155 \pm 0.055$	$-0.224 \pm 0.121 \pm 0.033$	$-0.267 \pm 0.393 \pm 0.156$
	Λ_A	$1.37 \pm 0.73 \pm 0.13$	$1.04 \pm 0.33 \pm 0.08$	$1.31 \pm 0.64 \pm 0.12$	$1.20 \pm 1.36 \pm 1.69$
	S_A	$0.230 \pm 0.133 \pm 0.037$	$0.422 \pm 0.178 \pm 0.070$	$0.253 \pm 0.139 \pm 0.041$	$0.335 \pm 0.491 \pm 0.195$
	χ^2/ndf	133/123	144/123	134/123	55/44
z-Expansion	ρ_s	$-0.022 \pm 0.128 \pm 0.071$	$-0.036 \pm 0.125 \pm 0.070$	$-0.025 \pm 0.127 \pm 0.070$	$-0.080 \pm 0.126 \pm 0.045$
	μ_s	$0.038 \pm 0.038 \pm 0.034$	$0.044 \pm 0.037 \pm 0.034$	$0.040 \pm 0.038 \pm 0.034$	$0.055 \pm 0.038 \pm 0.024$
	a_0	$0.403 \pm 0.222 \pm 0.183$	$-0.087 \pm 0.199 \pm 0.150$	$0.323 \pm 0.220 \pm 0.191$	$1.07 \pm 0.33 \pm 1.39$
	a_1	$-8.09 \pm 2.44 \pm 1.98$	$-3.18 \pm 2.27 \pm 1.58$	$-7.25 \pm 2.42 \pm 2.07$	$-14.8 \pm 3.4 \pm 15.1$
	a_2	$44.5 \pm 11.3 \pm 8.2$	$25.1 \pm 10.8 \pm 6.4$	$41.1 \pm 11.3 \pm 8.6$	$71.4 \pm 14.8 \pm 62.7$
	χ^2/ndf	130/123	143/123	131/123	53/44

from https://arxiv.org/abs/2402.10854

G0 PVES forward-scattering A_{PV} data on hydrogen.

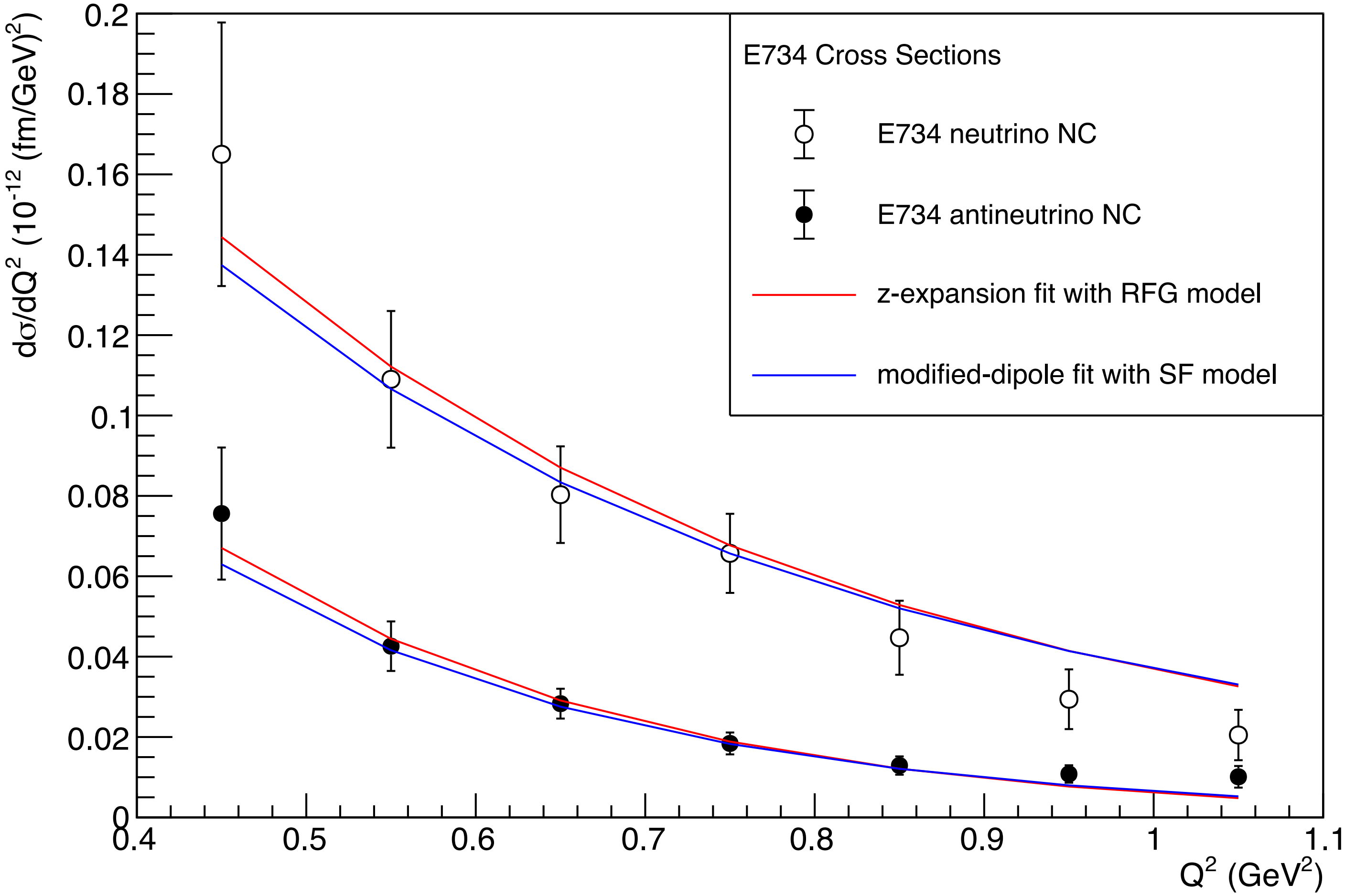
Fit uses z-expansion model for G_A^S and RFG nuclear model.



BNL E734 NC neutrino and antineutrino data.

Fit uses z-expansion model for G_A^S and RFG nuclear model.

Fit uses modified-dipole model for G_A^S and SF nuclear model.



A Brief History of Δs

First experimental data came from measurements of the ***inclusive*** deep-inelastic scattering of polarized muons from polarized hydrogen (EMC). ➔ $\Delta s < 0$
This has been confirmed in all subsequent ***inclusive*** measurements (SMC, SLAC, HERMES, COMPASS, JLab).
N.B. This analysis always assumes SU(3) flavor symmetry, combining the extrapolated integral of the DIS measurements with the triplet and octet axial charges determined from hyperon β-decay.

Later, it became possible to observe ***semi-inclusive*** deep-inelastic scattering, where the leading hadron (pion or kaon) served to "tag" the struck quark. ➔ $\Delta s \sim 0$
(SMC, HERMES, COMPASS).
N.B. This analysis does not use SU(3) flavor symmetry, but does rely on an understanding of quark→hadron fragmentation functions.

This dichotomy exists today: Analyses of leptonic DIS and polarized *pp* collision data still show a discrepancy in the determination of Δs.

de Florian, Sassot, Stratmann, and Vogelsang [PRD 80 (2009) 034030]
Nocera, Ball, Forte, Ridolfi, and Rojo [NPB 887 (2014) 276-308]
Leader, Sidorov, and Stamenov [PRD 91 (2015) 054017]
Hirai and Kumano (AAC) [Nucl. Phys. B 813 (2009) 106]
Blumlein and Böttcher [Nucl. Phys. B 841 (2010) 205]