

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

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

Pacific Spin 2024 Hefei



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Axial form factor of the proton

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

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 charged-current (CC) interactions.



$$G_A^s$$

The strange part is only directly accessible via neutral-current (NC) scattering.



Still only very limited information available on G_A^s !

Physics Interest in G_A^S

- The interpretation of many future neutrino-scattering experiments (DUNE, Hyper-K) depends on accurate modelling of all neutrino-nucleus scattering process; we need a complete picture of the axial form factor.
- The $Q^2 = 0$ value of G_A^S is the strange quark contribution to the proton spin: $G_A^S(Q^2 = 0) = \Delta s$. This is of major interest in nuclear and particle physics and beyond.

Strange Quark Contribution to Proton Spin Δs

Broad Physics Interest

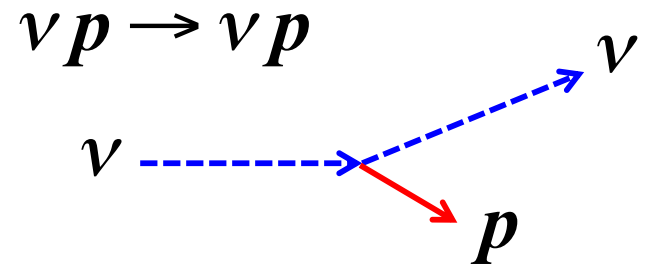
- Searches for heavy dark matter particles [Ellis, Olive, & Savage, Phys Rev D 77 (2008) 065026]
- **Lattice QCD calculates a small value:**
 $\Delta s = -0.031(17)$ [M. Engelhardt, Phys. Rev. D 86 (2012) 114510];
 $\Delta s = -0.024(15)$ [Babich et al., Phys. Rev. D 85 (2012) 054510];
requires experimental 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]

Measuring Low- Q^2 Neutral-Current Elastic Scattering

Not that simple, or someone would have done it already...

The observable part of the final state consists of a single isolated proton – that's all!

$$T = Q^2/2M_p$$



For $Q^2 = 0.1 \text{ GeV}^2$, this means $T \sim 50 \text{ MeV}$.

For a neutrino scattering experiment, you need a target/detector system composed of a solid or liquid material.

You will need to measure a track (direction and momentum) that will be only a few cm in length!

For this reason, there is very little data on this reaction.

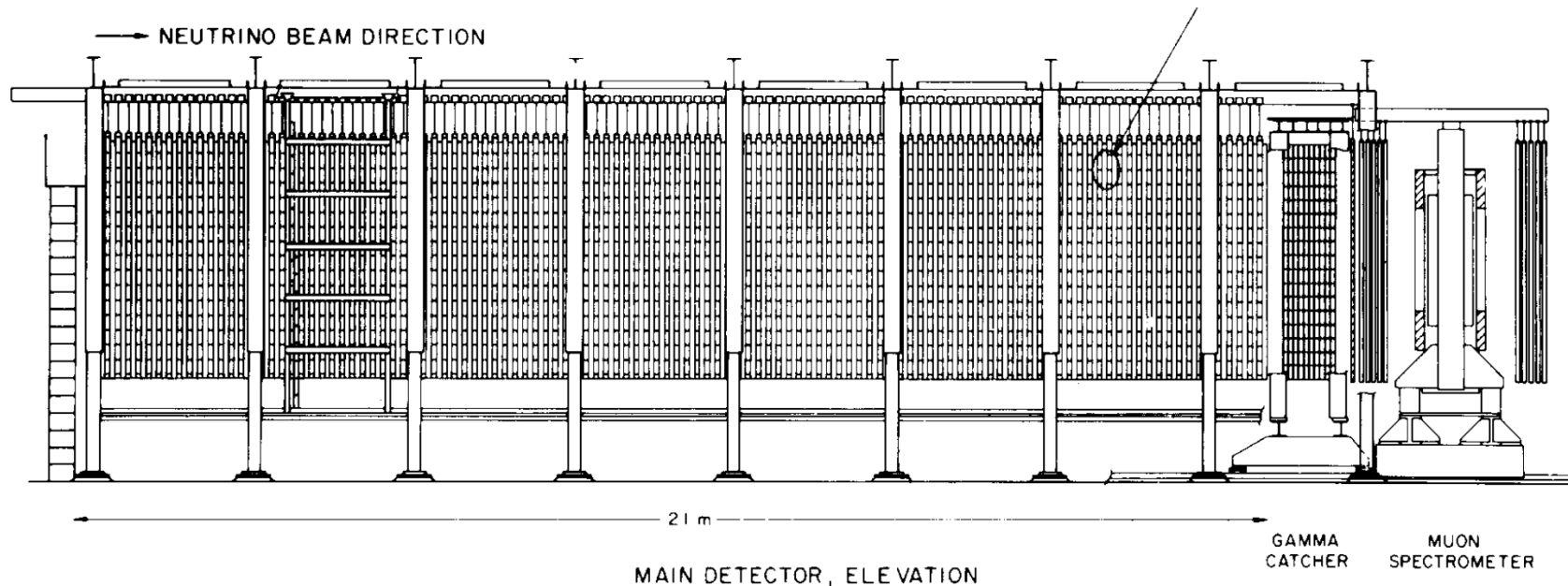
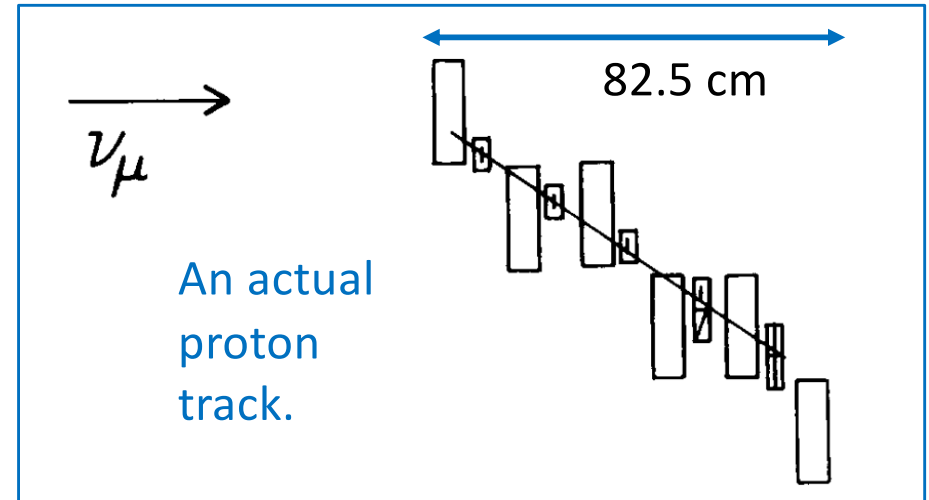
Neutral Current Elastic Neutrino Scattering

The E734 Experiment (Brookhaven)

Many alternating layers of scintillator (calorimetry) and drift tubes (tracking).

21 m in length!

NIMA, Volume 254, Issue 3, 1987, 515-528



Neutral Current Elastic Neutrino Scattering

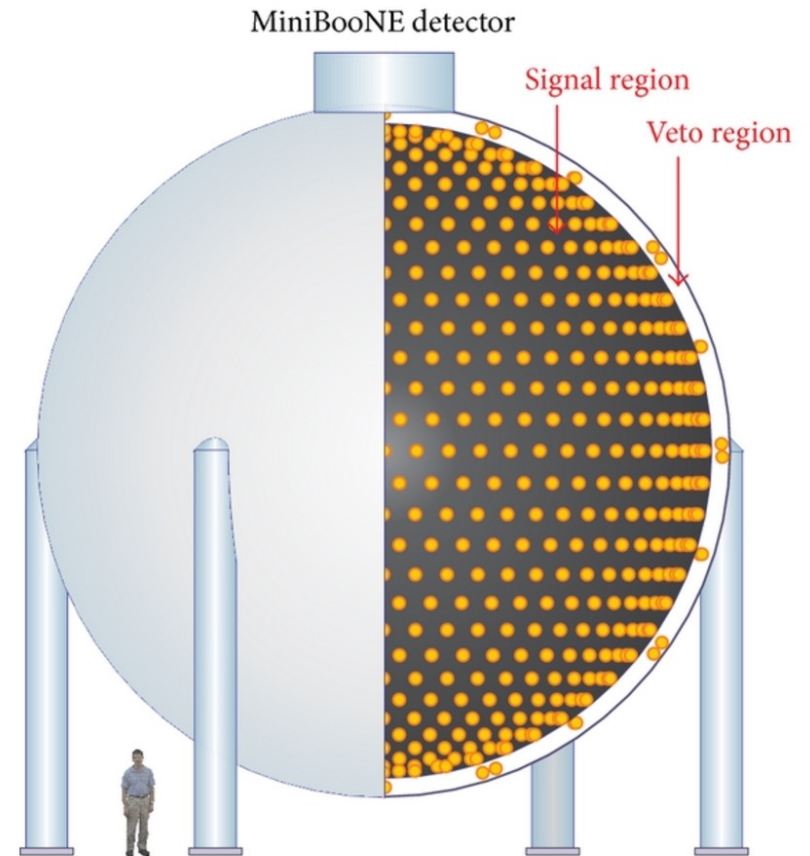
The MiniBooNE Experiment (Fermilab)

Large sphere containing mineral oil, lined with large phototubes.

Charged particles created in the mineral oil will produce:

- (1) Scintillation light (isotropic)
- (2) Cherenkov light (directional)

Analysis of these signals indicate the energy and momentum of the charged particle.



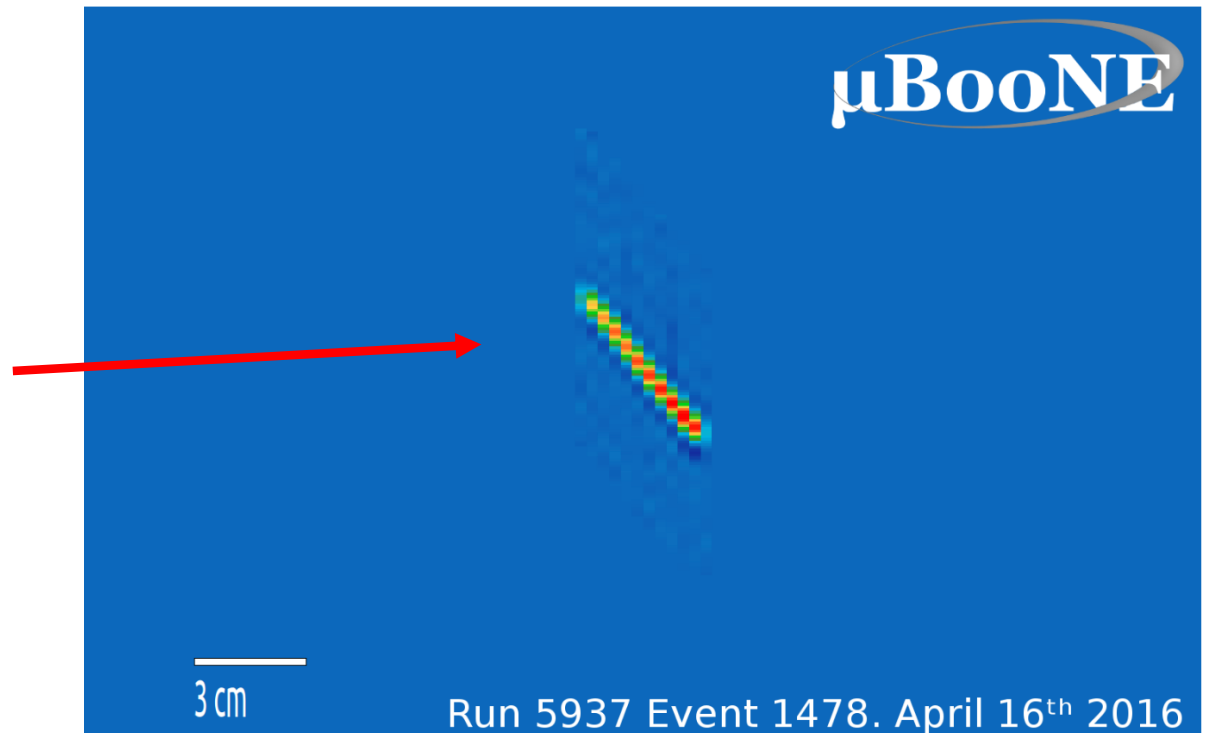
Neutral Current Elastic Neutrino Scattering

The MicroBooNE Experiment (Fermilab)

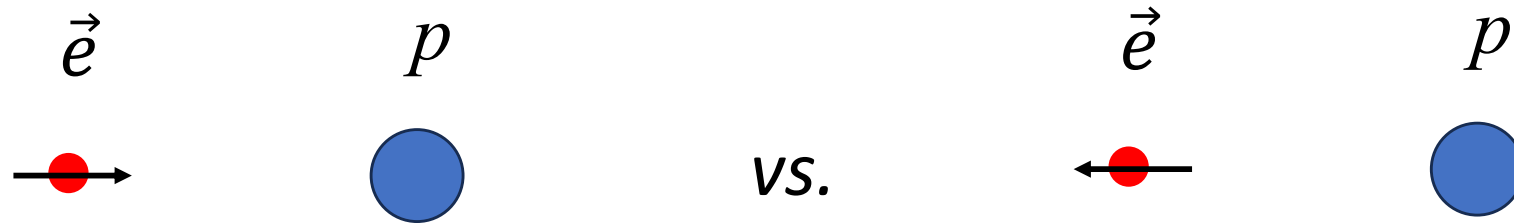
Liquid-argon time-projection-chamber (LArTPC).

Charged particles created in the liquid argon will produce an ionization trail, which is swept out by a large electric field to a set of sense wires.

An image of an isolated proton track from a neutrino interaction in the detector.



Parity-violating elastic electron scattering (PVES)



Compare count rates for parity-reversed elastic ep interactions.

Interference between γ -exchange and Z -exchange terms creates a small asymmetry in the count rates. Only $\sim 10^{-6}$!

This asymmetry is sensitive to the strange quark contributions to the electric, magnetic and axial form factors: G_E^S , G_M^S , and G_A^S .

Four experiments:

SAMPLE (MIT-Bates), HAPPEX and G0 (Jlab), PVA4 (Mainz)

Simultaneous determination of strange quark contribution to electromagnetic (G_E^S, G_M^S) and axial (G_A^S) 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 $Q^2 = 0.477 \text{ GeV}^2$.
- This analysis was expanded [PRC 78 015207 (2008)] to include points in the range $0.55 < Q^2 < 1.05 \text{ GeV}^2$ when the G0 PVES data became available.

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

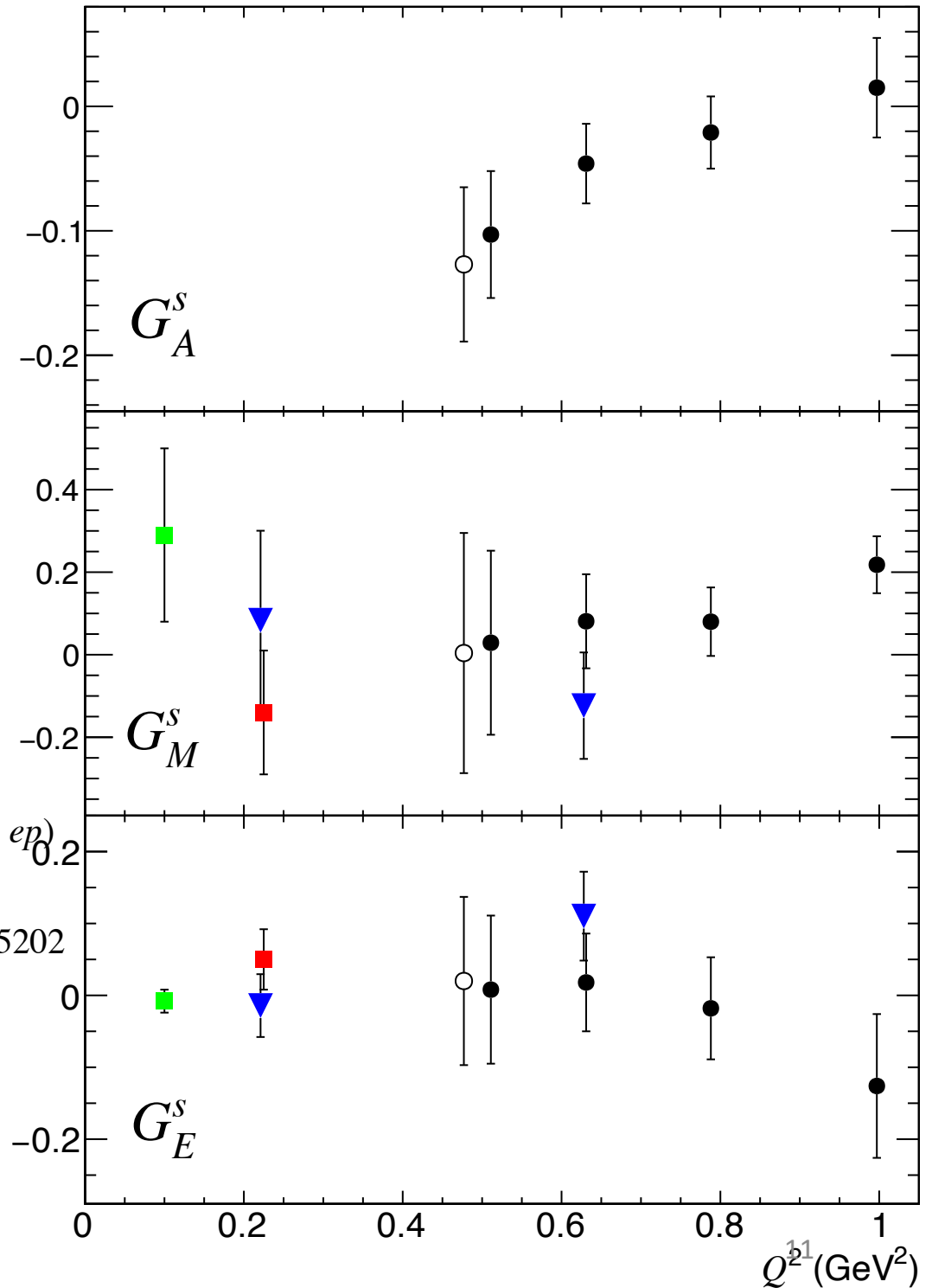
- PVA4 (forward and backward ep)
Baunack et al., PRL 102 (2009) 151803

- ▼ G0 (forward and backward ep , and backward ed)
D. Androic et al., PRL 104 (2010) 012001

- HAPPEX (forward ep and $e^4\text{He}$) + G0 (forward ep)
+ SAMPLE (backward ep and ed) + PVA4 (forward ep)
near $Q^2 = 0.1 \text{ GeV}^2$
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.

Neutral Current Elastic Scattering

$$G_E^S \quad G_M^S \quad G_A^S$$

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

Need all three kinds of data in our approach.

Parity-Violating Electron Scattering
(forward $\vec{e}p$)

$$G_E^S \quad G_M^S \quad G_A^S$$

Parity-Violating Electron Scattering
(backward $\vec{e}p$ & $\vec{e}d$)

$$G_E^S \quad G_M^S \quad G_A^S$$

Models for the Strangeness Form Factors

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

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

- 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”

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

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

$$G_E^S = \rho_s \tau \quad \text{Modified-dipole model}$$

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

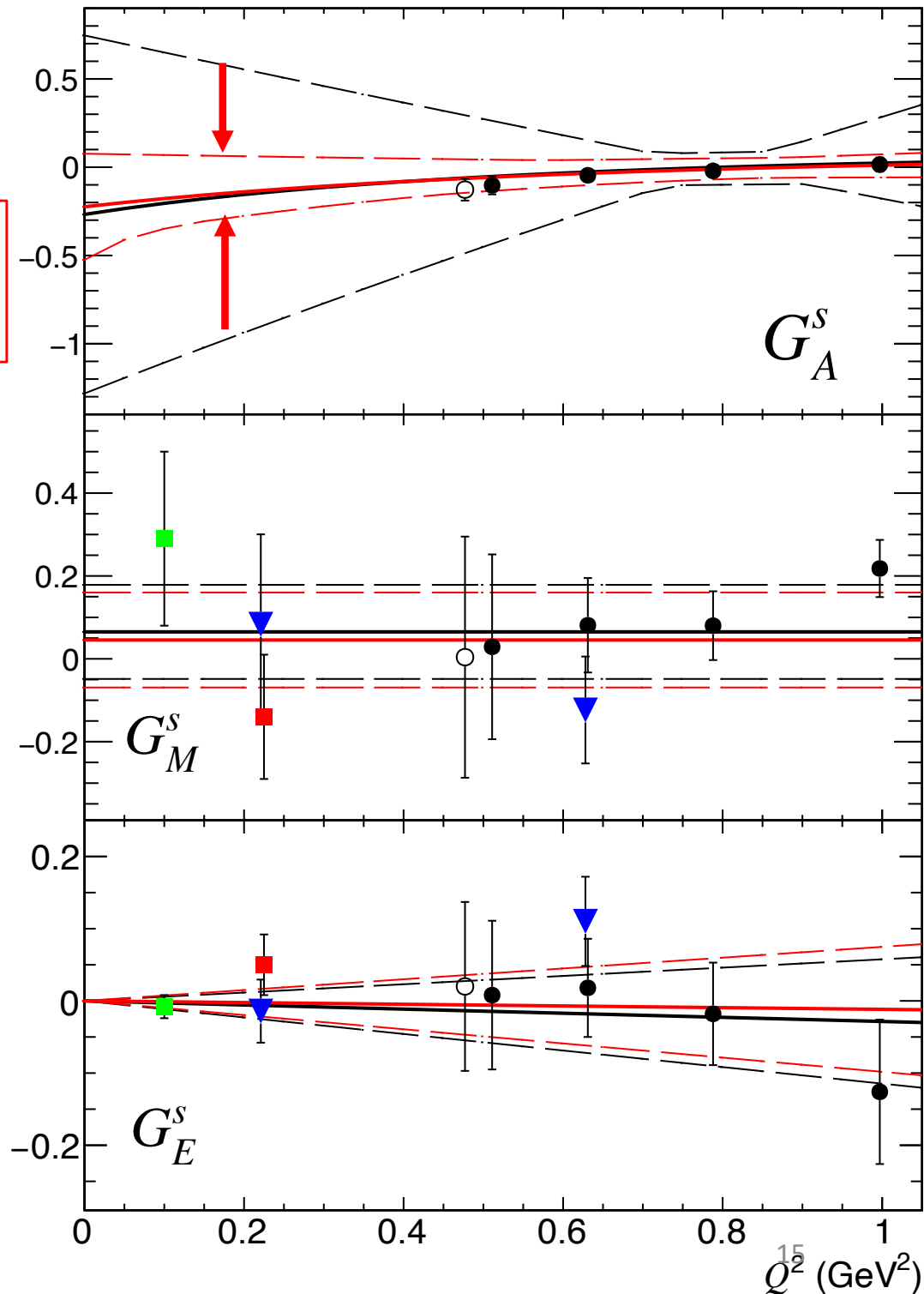
Improved constraint on G_A^S via inclusion of MiniBooNE data

— 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.

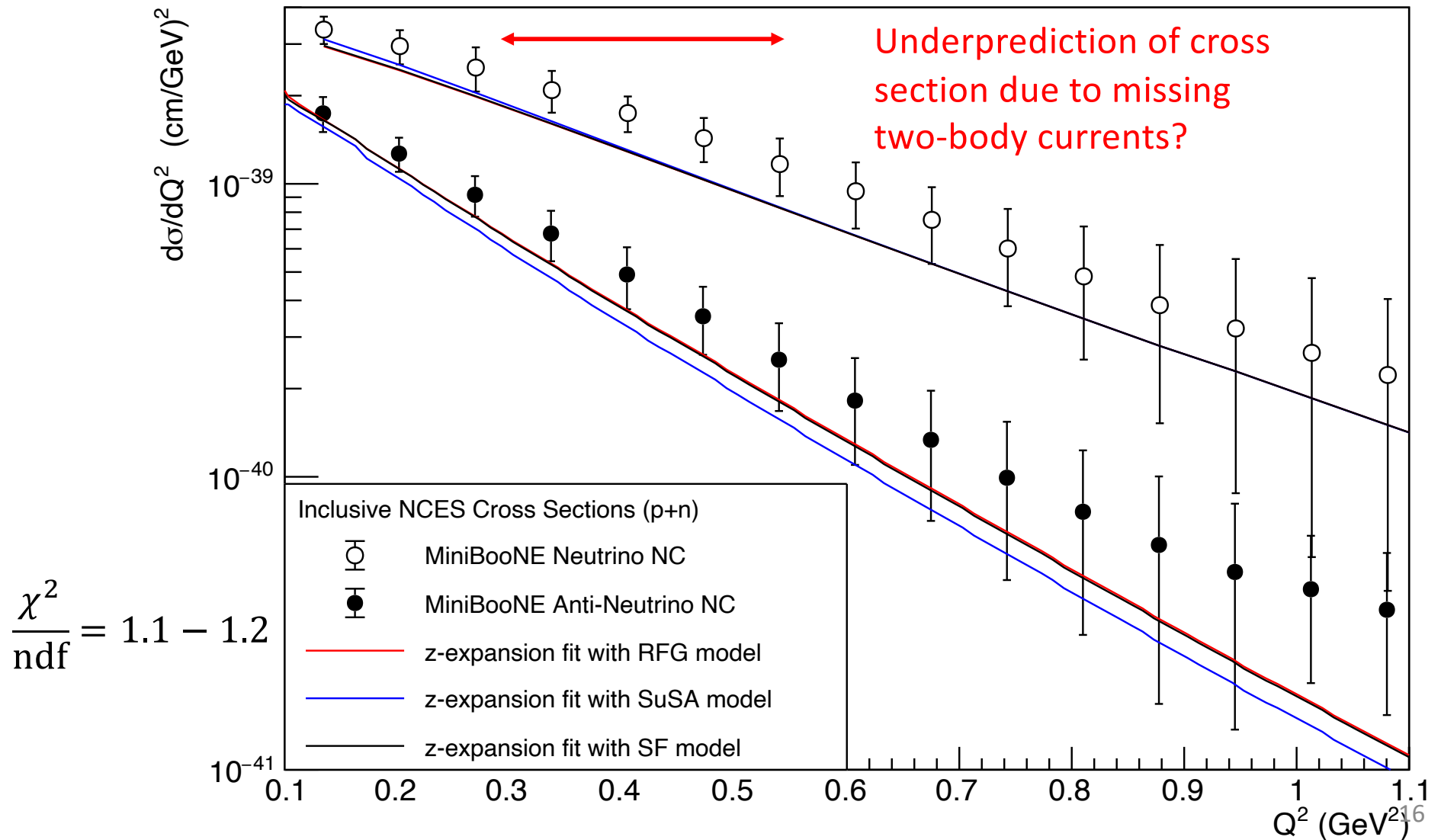
$$\frac{\chi^2}{\text{ndf}} = 1.1 - 1.2$$



MiniBooNE 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 .



$$G_E^S = \rho_s \tau$$

$$G_M^S = \mu_s$$

Modified-dipole model

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

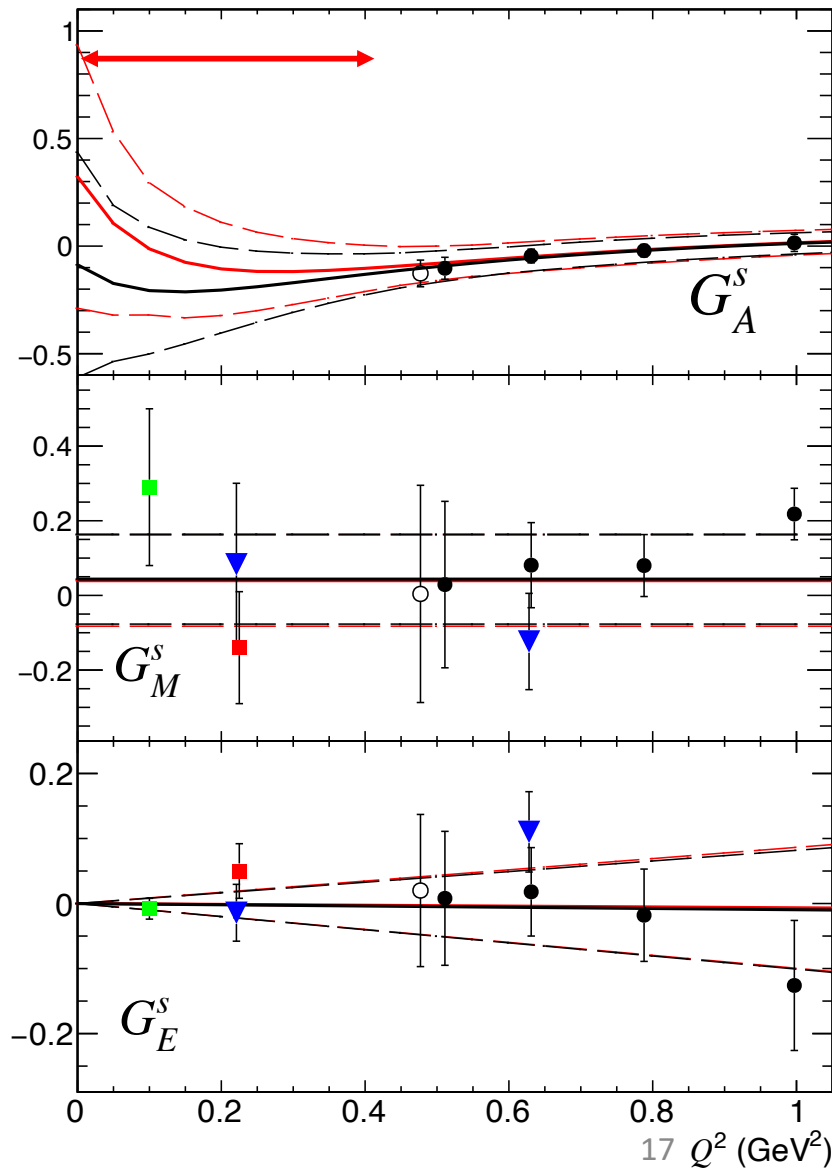
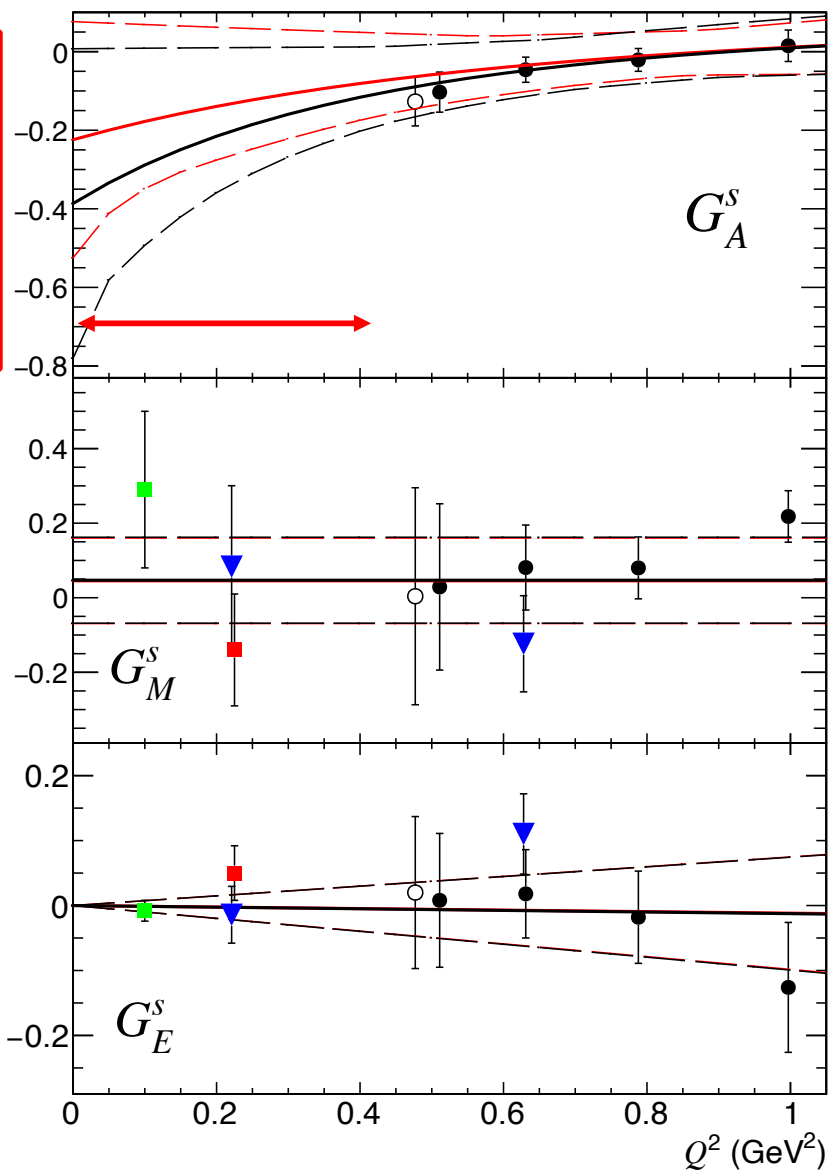
z-expansion model

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

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

— SuSA
— SF

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



Conclusions

- 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>

Backup Slides

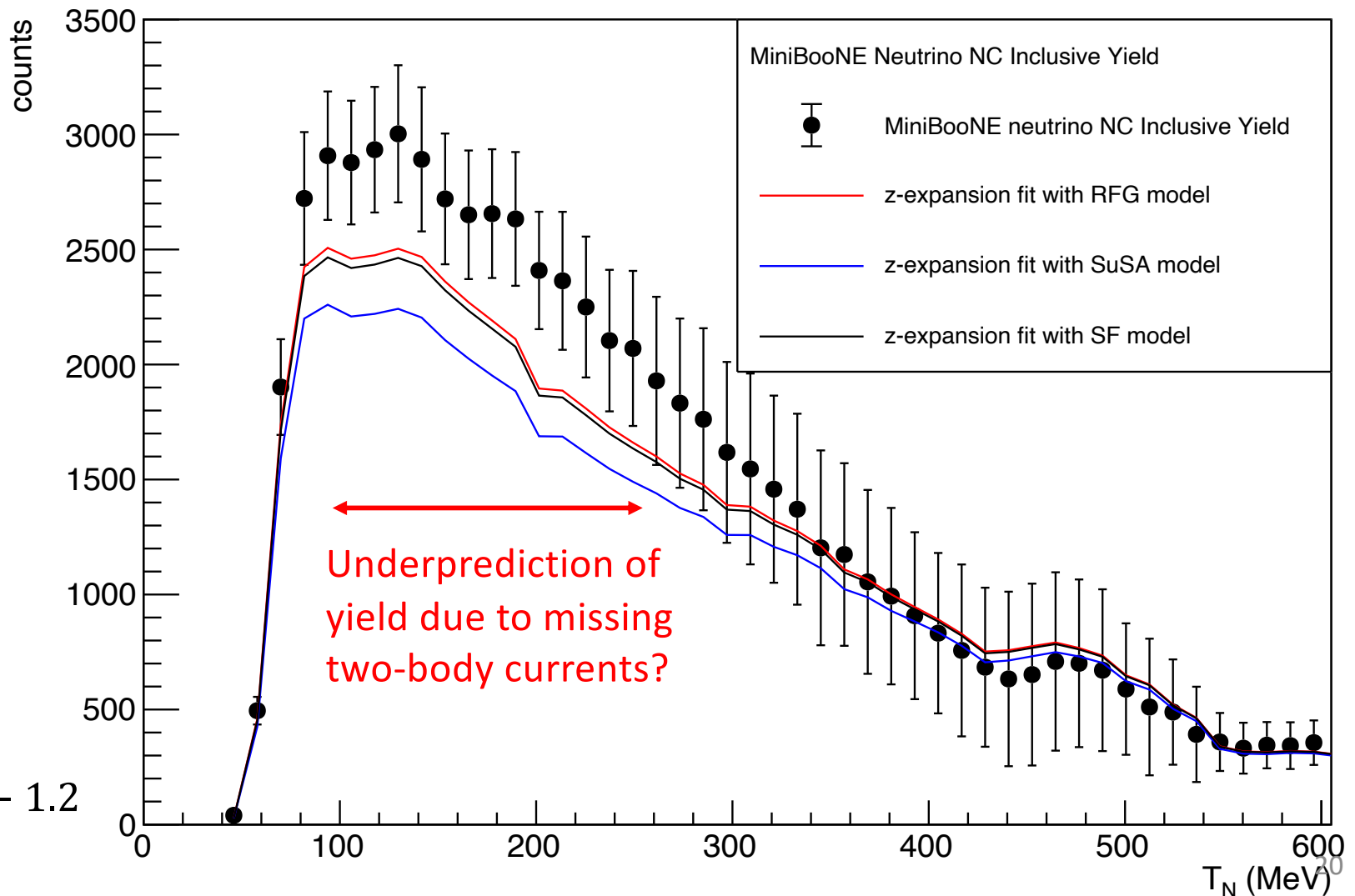
MiniBooNE NCES neutrino inclusive yield

— RFG

— SuSA

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

— SF

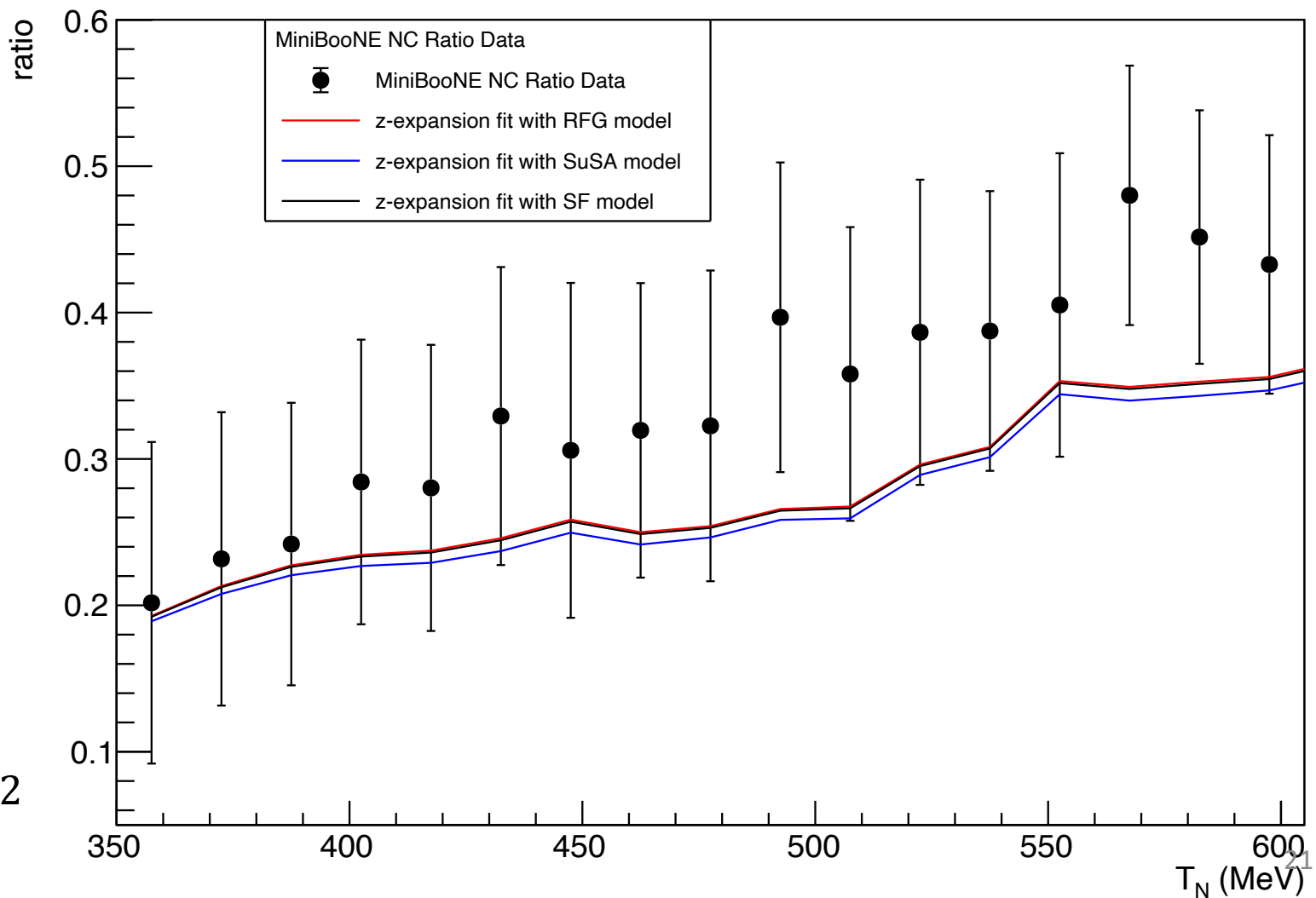
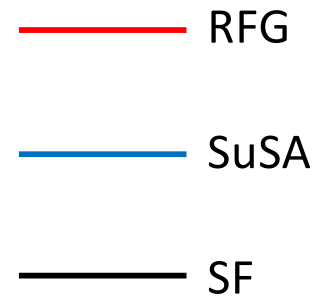


$$\frac{\chi^2}{\text{ndf}} = 1.1 - 1.2$$

MiniBooNE NCES neutrino

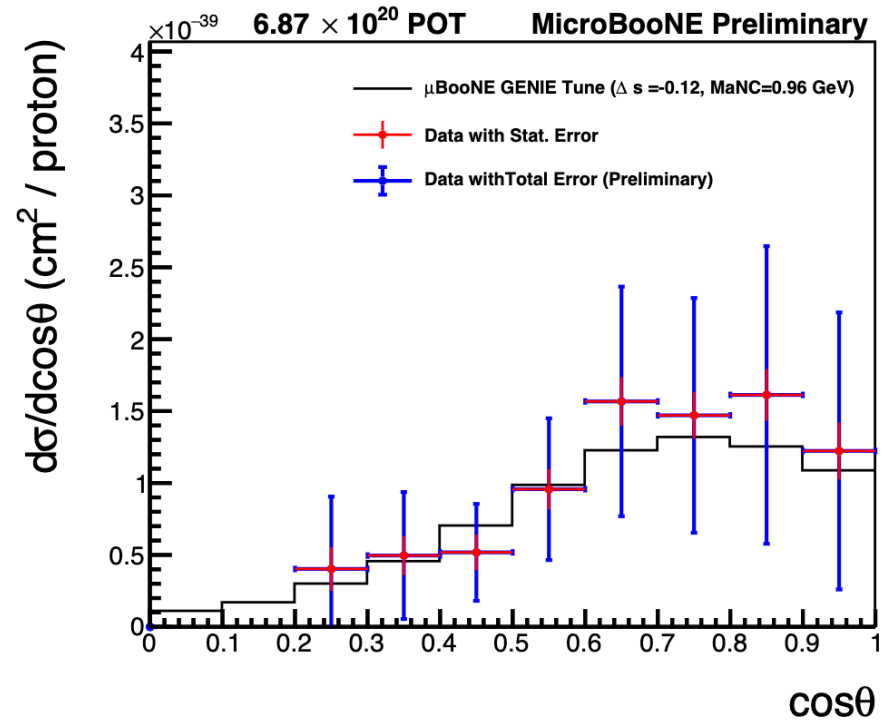
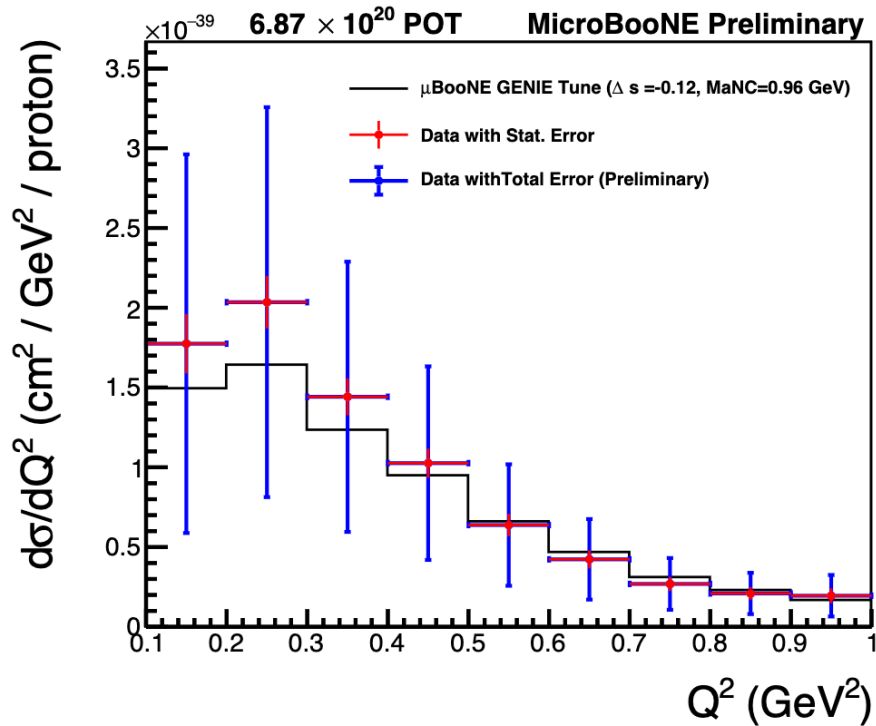
Exclusive/inclusive $p/(p + n)$ yield ratio

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



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

Preliminary MicroBooNE Data (2022)



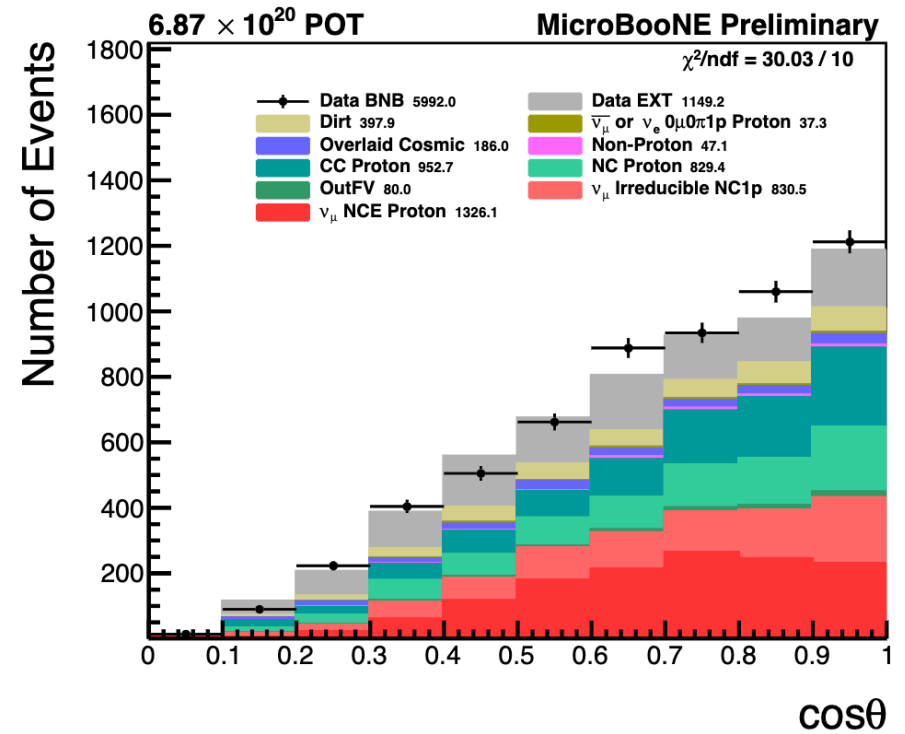
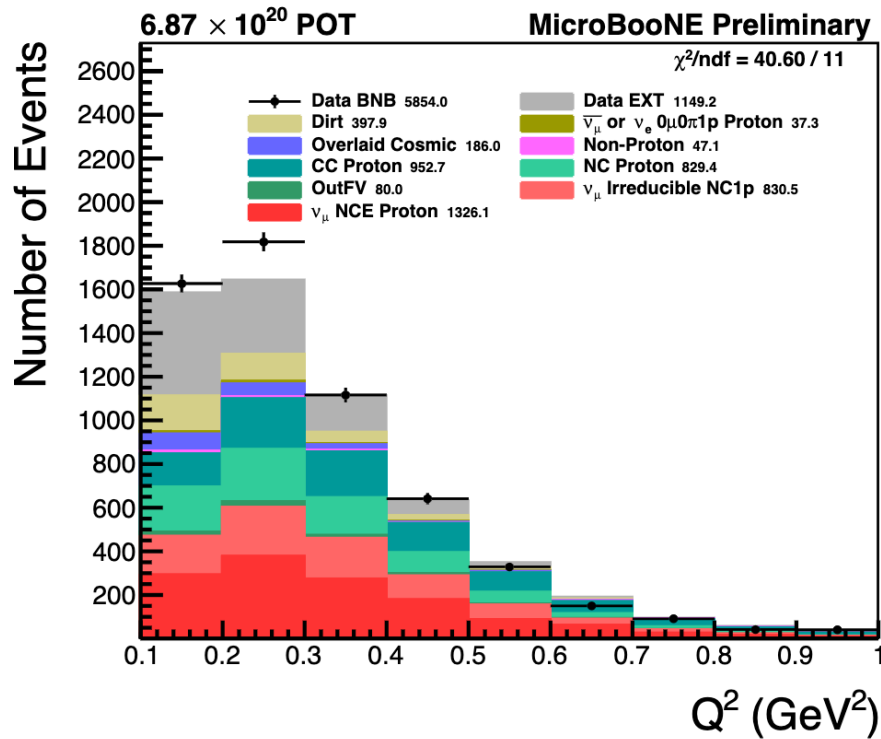
We have significantly reduced the systematic errors in the subsequent two years.

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...

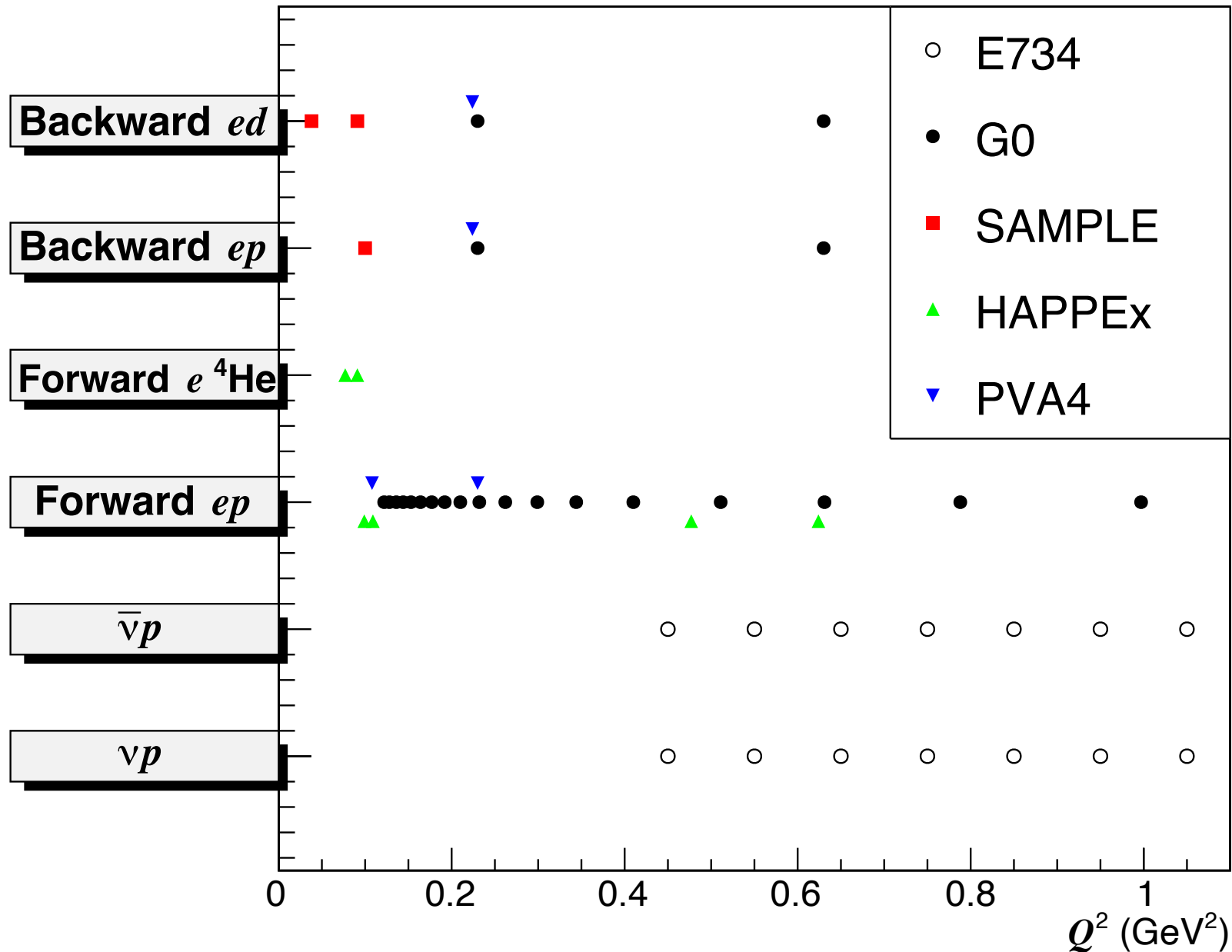
... will need all neutrino-argon interactions that can contribute to the signal:

- 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

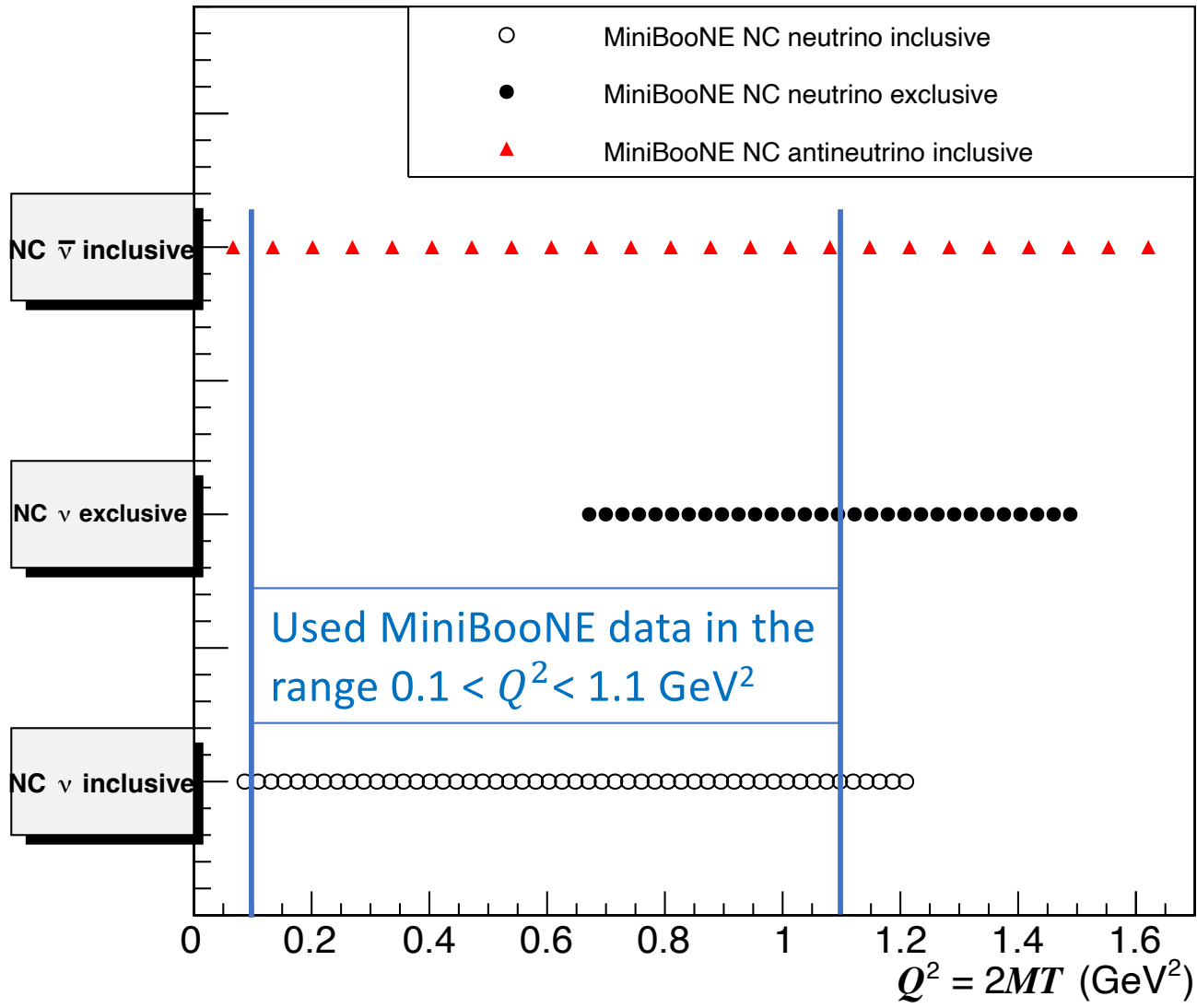
This work is in progress, and we welcome others to join the effort.

Thank you!

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



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



z-Expansion Model for G_A^S

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

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

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

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

\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

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

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

$$A = \frac{1}{4} \left[(G_A^Z)^2 (1 + \tau) - \left((F_1^Z)^2 - \tau (F_2^Z)^2 \right) (1 - \tau) + 4\tau F_1^Z F_2^Z \right]$$

$$B = -\frac{1}{4} G_A^Z (F_1^Z + F_2^Z)$$

$$C = \frac{1}{64\tau} \left[(G_A^Z)^2 + (F_1^Z)^2 + \tau (F_2^Z)^2 \right]$$

$$G_A^{CC}$$

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.

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

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

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

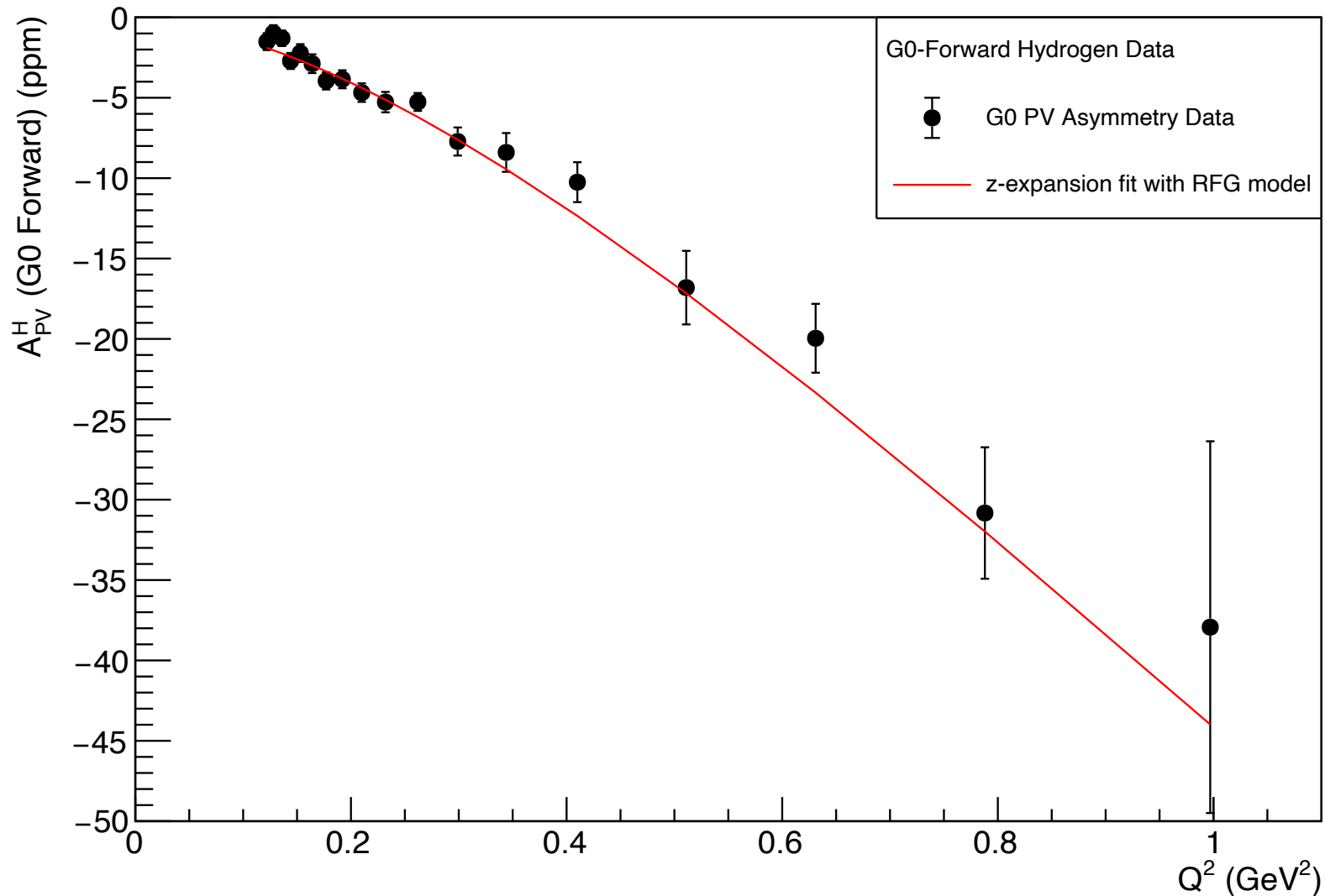
TABLE III. Summary of the results of the fits performed with three nuclear models (RFG, SuSA, and SF) and two strangeness axial form factor models (modified-dipole and z -expansion); also shown are the results when no MiniBooNE data are included. The central value and uncertainty is given for each fit 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.

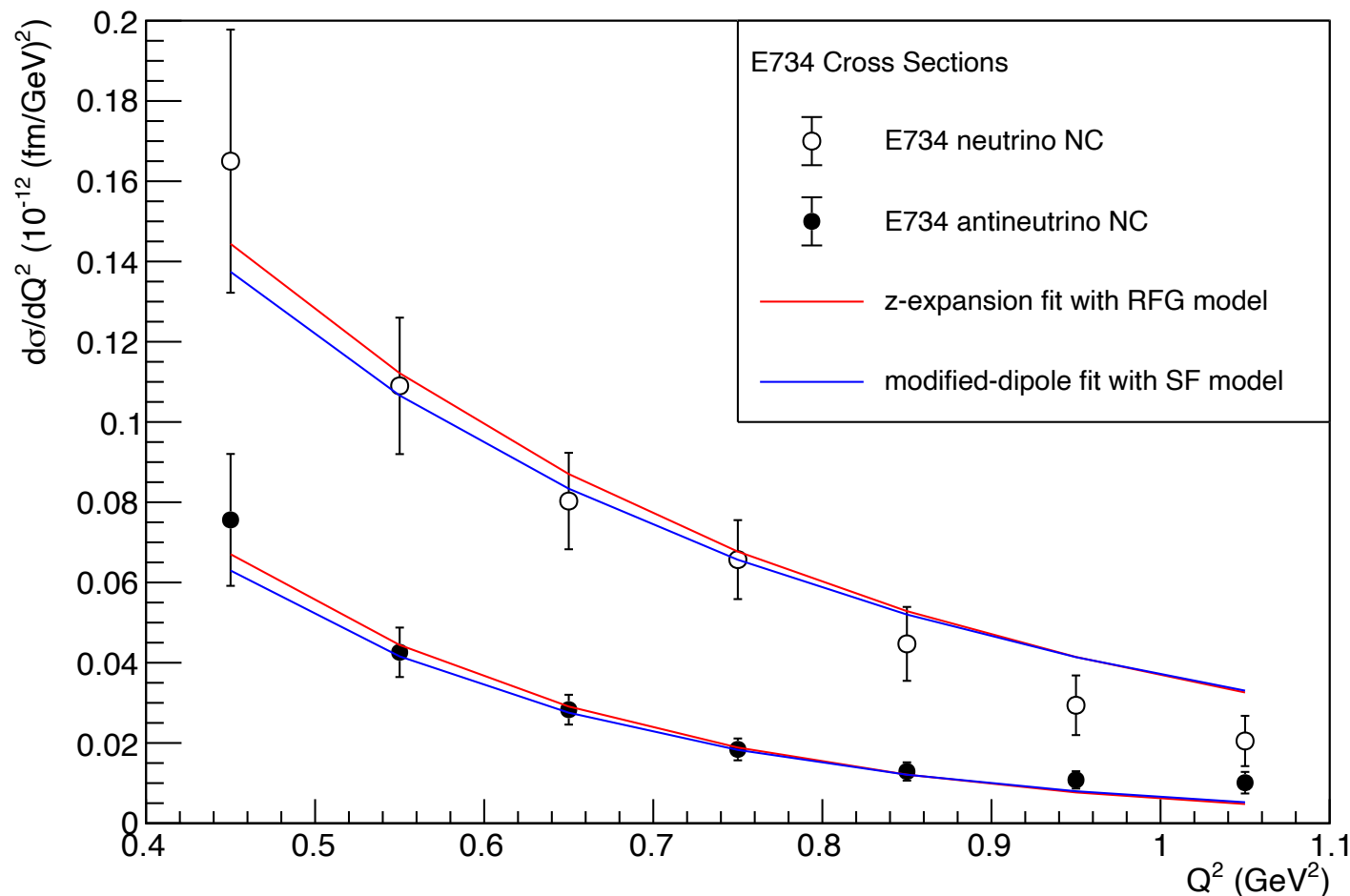
Fit uses z -expansion model for G_A^S and RFG nuclear model.



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.



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.

A Brief History of Δs

First experimental data came from measurements of the *inclusive* deep-inelastic scattering of polarized muons from polarized hydrogen (EMC). $\rightarrow \Delta s < 0$

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. $\rightarrow \Delta s \sim 0$
(SMC, HERMES, COMPASS).

N.B. This analysis does not use SU(3) flavor symmetry, but does rely on an understanding of quark \rightarrow 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]