Strange Quark Contribution to the Nucleon Spin from Electroweak Elastic Scattering Data

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Overview

- Strange quark contribution to nucleon spin is not uniquely determined by DIS data
- The full contribution may be determined by a measurement of the nucleon axial form factor in neutrino neutral-current elastic scattering
- A global fit of existing electroweak data has been performed; need more neutrino scattering data at low Q^2
- Prospects for MicroBooNE to complete this dataset

$\Delta s(x)$ from **inclusive** deep inelastic scattering combined with hyperon β-decay data

HERMES [Phys. Rev. D75 (2007) 012007]

Precise determination of the spin structure function g_1 of the proton, deuteron, and neutron

Longitudinal spin asymmetries in **inclusive** positron-proton and positron-deuteron deep-inelastic scattering determine g_1 of the proton, deuteron and neutron.

$0.0041 < x < 0.9$ $\quad$ $0.18\ \text{GeV}^2 < Q^2 < 20\ \text{GeV}^2$ -- evolved to $Q^2 = 5\ \text{GeV}^2$

Using **SU(3) flavor symmetry**, these data are combined with triplet and octet axial charges (F and D from hyperon β-decay data) in a NNLO analysis to obtain the singlet axial charge and the quark contributions to the proton spin.

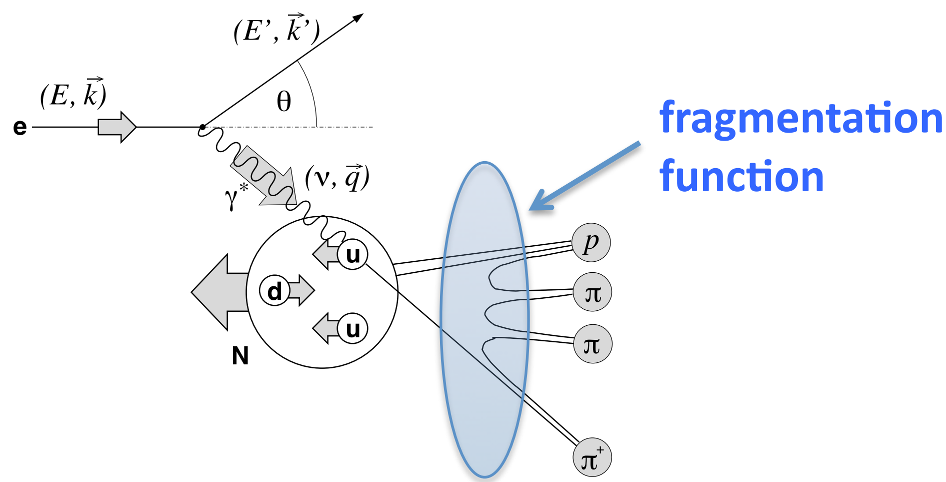
$$\begin{aligned}
a_0 &= +0.330 \pm 0.011\ (\text{th}) \pm 0.025\ (\text{ex}) \pm 0.028\ (\text{ev}) \\
\Delta u + \Delta\bar{u} &= +0.842 \pm 0.004\ (\text{th}) \pm 0.008\ (\text{ex}) \pm 0.009\ (\text{ev}) \\
\Delta d + \Delta\bar{d} &= -0.427 \pm 0.004\ (\text{th}) \pm 0.008\ (\text{ex}) \pm 0.009\ (\text{ev}) \\
\Delta s + \Delta\bar{s} &= -0.085 \pm 0.013\ (\text{th}) \pm 0.008\ (\text{ex}) \pm 0.009\ (\text{ev})
\end{aligned}$$

strange contribution to proton spin strongly inconsistent with 0

$\Delta s(x)$ from **semi-inclusive** deep inelastic scattering

HERMES [Phys. Rev. D71 (2005) 012003]

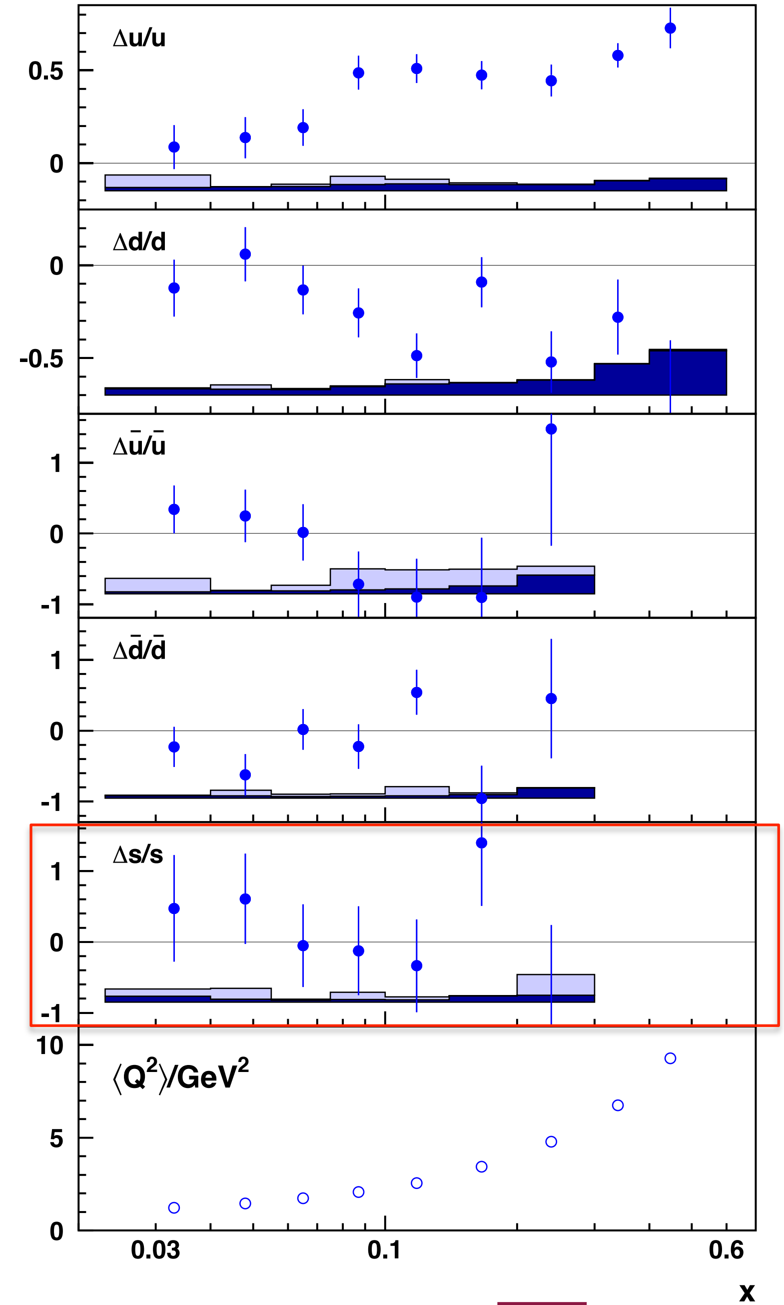
Quark helicity distributions in the nucleon for up, down, and strange quarks from semi-inclusive deep-inelastic scattering



Observed asymmetries in production of charged pions from protons, and in production of charged pions and kaons from deuterons

$$\int_{0.023}^{0.30} \Delta s(x)\, dx = +0.028 \pm 0.033(\text{stat}) \pm 0.009(\text{sys})$$

$\Delta s(x)$ and its integral both consistent with 0 in measured x-range



$\Delta s(x)$ from de Florian, Sassot, Stratmann, Vogelsang global QCD fit [PRD80 (2009) 034030]

Assumes strange and anti-strange polarized distributions are equal; this is supported by recent COMPASS results

Allows for node in distributions

Allows for SU(2) and SU(3) symmetry violation, but best fit does not support any significant deviation from these symmetries

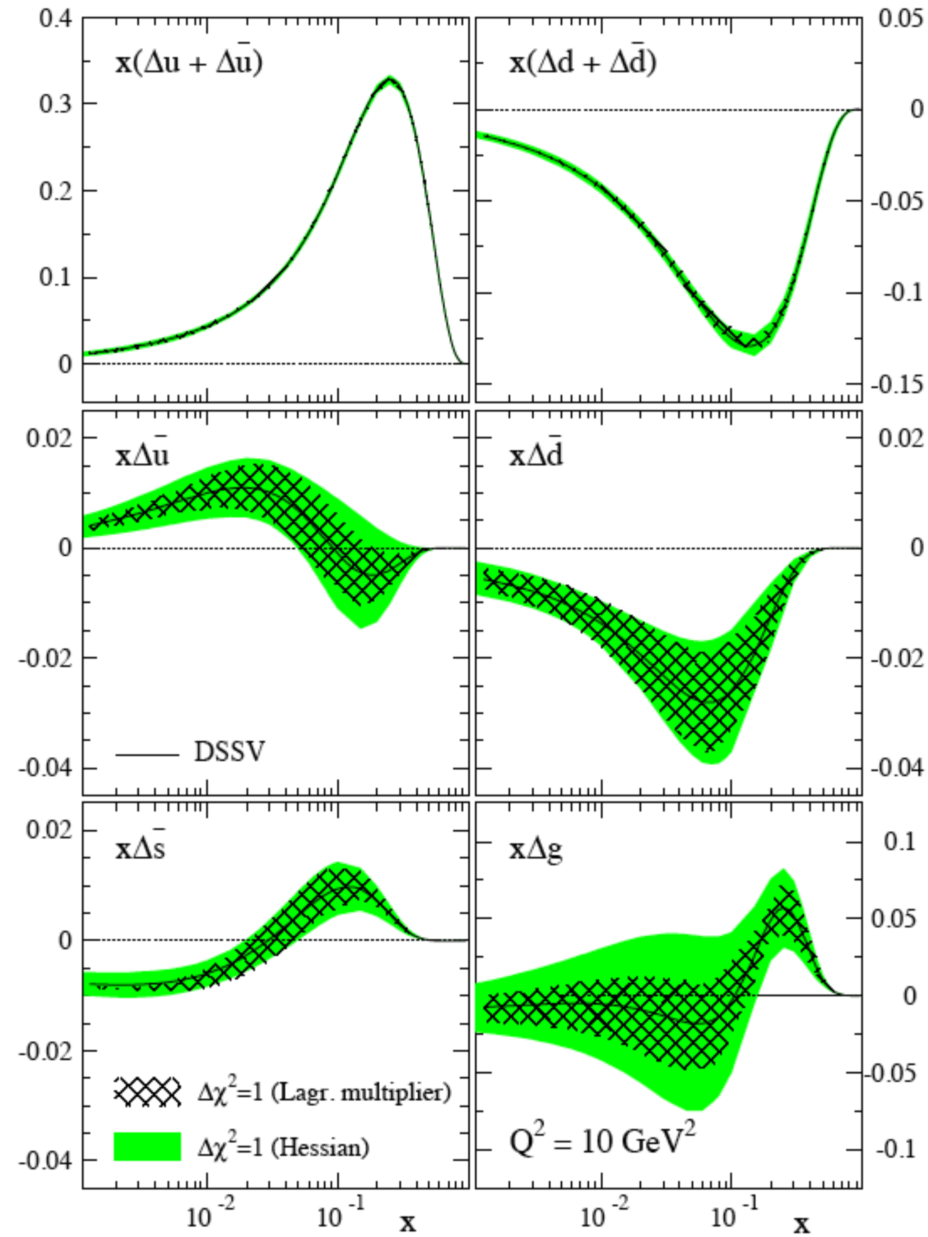
Truncated first moment

$$\int_{0.001}^{1.0} \Delta\bar{s}(x)dx = -0.006^{+0.028}_{-0.031} \quad \left(\Delta\chi^2/\chi^2 = 2\%\right)$$

Full integral – the effect of SU(3) symmetry and hyperon β-decay data is seen

$$\int_{0}^{1.0} \Delta\bar{s}(x)dx = -0.057$$

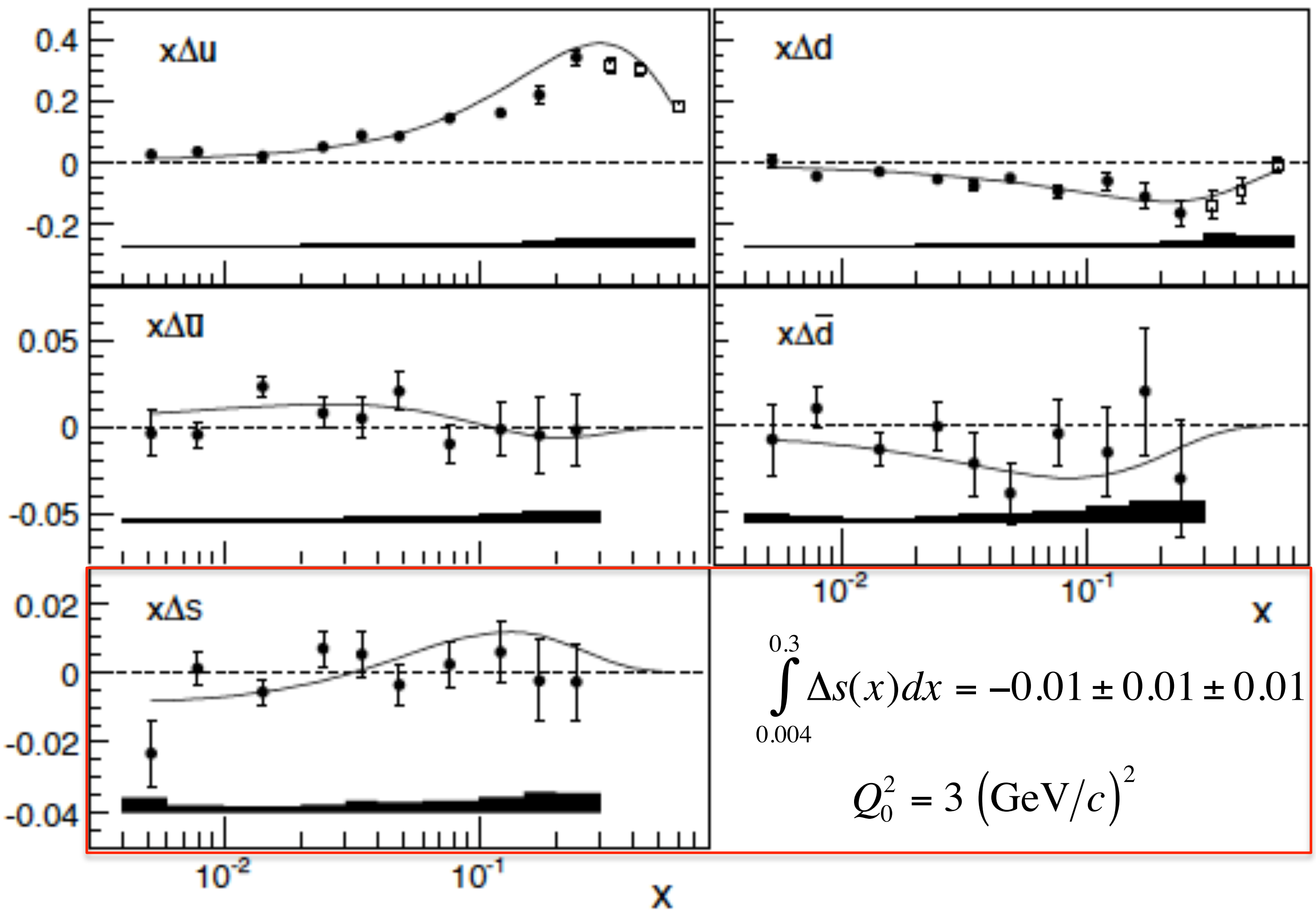
$$\Rightarrow \Delta s + \Delta\bar{s} = -0.114$$



$\Delta s(x)$ from **semi-inclusive** deep inelastic scattering

COMPASS [Phys. Lett. B693 (2010) 227]

Quark helicity distributions from longitudinal spin asymmetries in muon–proton and muon–deuteron scattering



$$\int_{0.004}^{0.3} \Delta s(x)dx = -0.01 \pm 0.01 \pm 0.01$$

$$Q_0^2 = 3\ (\mathrm{GeV}/c)^2$$

Data points from COMPASS

Curve is DSSV global QCD fit

$\Delta s(x)$ and its integral both consistent with 0 in measured x-range

It is clearly of interest to examine Δs in a way that is independent of SU(3) symmetry and fragmentation functions.

The full strange quark contribution to the proton spin can be directly determined by a measurement of the strange contribution to the proton elastic axial form factor in low energy electroweak elastic scattering.

$$\Delta S \equiv \Delta s + \Delta \bar{s} = G_A^s(Q^2 = 0)$$

By combining cross sections for νp and $\bar{\nu} p$ elastic scattering with parity - violating asymmetries observed in $\vec{e}N$ elastic scattering, the strange quark contributions to the nucleon electromagnetic and axial form form factors (G_E^s, G_M^s, and G_A^s) may be determined simultaneously.

[S.P., PRL 92 (2004) 082002]

Elastic Form Factors in Electroweak Interactions

Hadronic electromagnetic current:

$$J_\mu^{EM} = {}_N\langle p' | \mathbf{J}_\mu^{EM} | p \rangle_N = \bar{u}(p') \left[\gamma_\mu F_1^{\gamma,N}(q^2) + i \frac{\sigma_{\mu\nu} q^\nu}{2M} F_2^{\gamma,N}(q^2) \right] u(p)$$

for two nucleon states of momentum p and p'. $\left[q^2 = (p' - p)^2 \right]$

F_1 and F_2 (Dirac and Pauli) form factors may also be expressed in the Sachs formulation:

$$G_E^{p,n} = F_1^{p,n} - \tau F_2^{p,n} \qquad G_M^{p,n} = F_1^{p,n} + F_2^{p,n} \qquad \tau = Q^2 / 4M^2$$

These are now well-measured from many years of elastic electron-scattering experiments at many laboratories.

Elastic Form Factors in Electroweak Interactions

Hadronic weak neutral current:

$$J_\mu^{NC} = {}_N\langle p' | \mathbf{J}_\mu^{NC} | p \rangle_N = \bar{u}(p') \Big[\gamma_\mu F_1^{Z,N}(q^2) + i \frac{\sigma_{\mu\nu} q^\nu}{2M} F_2^{Z,N}(q^2)$$

$$+ \gamma_\mu \gamma_5 G_A^{Z,N}(q^2) + \frac{q_\mu}{M} \gamma_5 G_P^{Z,N}(q^2) \Big] u(p)$$

Z-exchange versions of F_1 and F_2 are analogous to γ-exchange versions, but with weak couplings.

Axial form factor G_A -- parity-violation in weak interaction.

(The pseudo-scalar form factor G_P does not contribute to either PVeN scattering or to neutral-current elastic scattering, so we will ignore it hence.)

Flavor Decomposition of Form Factors

Lepton-quark interactions are point-like, so we may write the nucleon form factors in terms of contributions from individual quarks, with appropriate couplings.

For example, the electric form factors due to single photon- and *Z*-exchange:

$$G_E^{\gamma,p} = \frac{2}{3}G_E^u - \frac{1}{3}G_E^d - \frac{1}{3}G_E^s$$

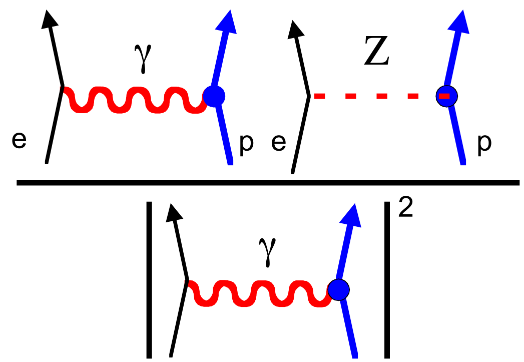
$$G_E^{Z,p} = \left(1 - \tfrac{8}{3}\sin^2\theta_W\right)G_E^u + \left(-1 + \tfrac{4}{3}\sin^2\theta_W\right)G_E^d + \left(-1 + \tfrac{4}{3}\sin^2\theta_W\right)G_E^s$$

Similarly for the axial form factor: $G_A^{Z,p} = \frac{1}{2}\left(\boxed{-G_A^u + G_A^d} + G_A^s\right)$

This part of axial form factored measured in charged-current neutrino reactions.

Parity Violating Electron Scattering

polarized electrons
unpolarized target



$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$$\tau = \frac{Q^2}{4M^2}$$

$$\varepsilon = \left[1 + 2(1+\tau)\tan^2(\theta/2)\right]^{-1}$$

$$\varepsilon' = \sqrt{(1-\varepsilon^2)\tau(1+\tau)}$$

for a nucleon:

$$= \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{\varepsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1 - 4\sin^2\theta_W)\varepsilon' G_M^\gamma G_A^e}{\varepsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2}$$

Forward-scattering sensitive to

G_E^s and G_M^s

Backward-scattering sensitive to

G_M^s and G_A^e

effective axial-vector
e-N form factor

Elastic NC neutrino-proton cross sections

$$\frac{d\sigma}{dQ^2}(\nu p \to \nu p) = \frac{G_F^2}{2\pi}\frac{Q^2}{E_\nu^2}\left(A \pm BW + CW^2\right) \qquad \begin{array}{ll} + & \nu \\ - & \bar{\nu} \end{array}$$

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

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

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

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

Dependence on strange form factors is buried in the weak (Z) form factors.

Combined analysis of electroweak data

Use vector form factors measured in elastic electron-nucleon scattering in parametrized form; many parametrizations are available.

$$G_E^p(Q^2) \quad G_M^p(Q^2)$$
$$G_E^n(Q^2) \quad G_M^n(Q^2)$$

Use charged-current portion of axial form factor measured in *W*-exchange processes, also in parametrized form.

$$G_A^{CC}(Q^2) \equiv G_A^u - G_A^d$$

Use neutrino-proton elastic scattering cross section data from BNL E734 (MiniBooNE data to be included also, in the near term).

$$\frac{d\sigma}{dQ^2}(\nu p \to \nu p)$$
$$\frac{d\sigma}{dQ^2}(\bar{\nu} p \to \bar{\nu} p)$$

Use parity-violating asymmetries in elastic (or quasi-elastic) scattering of polarized electrons from unpolarized nucleon (or nuclear) targets. [SAMPLE, PVA4, G0, HAPPEx]

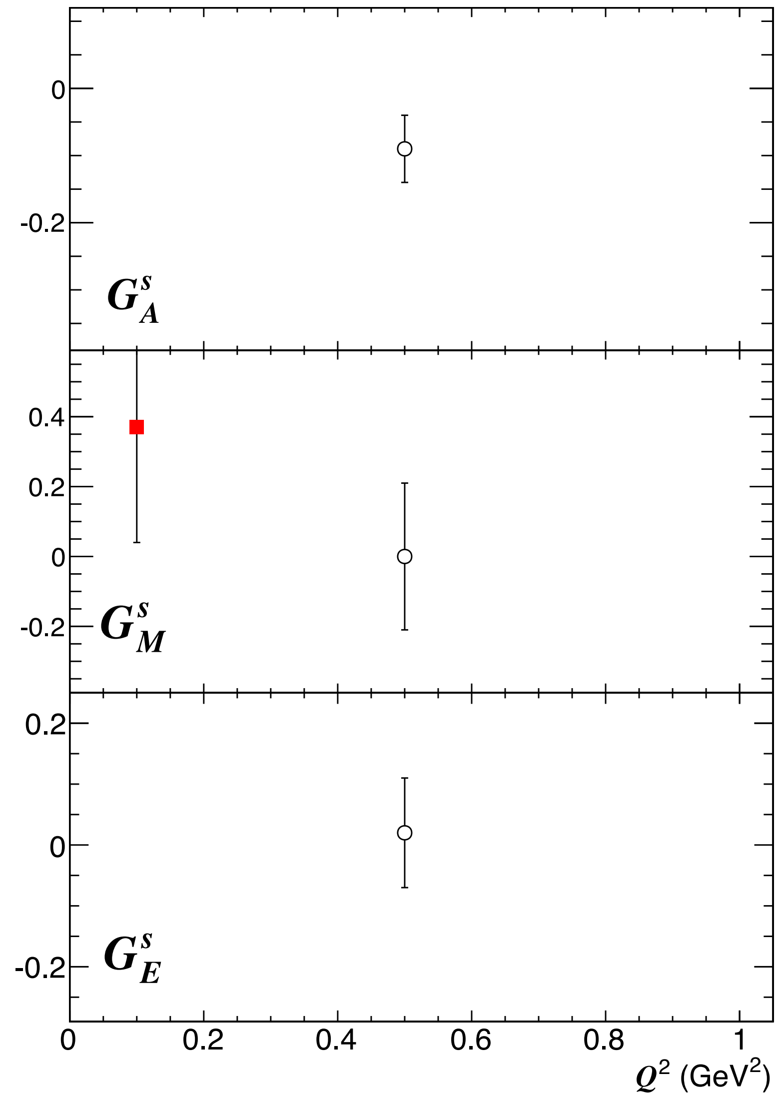
$$A_L^{PV} \text{ in } \vec{e}p, \quad \vec{e}d, \text{ and } \vec{e}\text{-}^4\text{He}$$

Extract strange contribution to electric, magnetic and axial form factors.

$$\boxed{\Rightarrow G_E^s(Q^2) \quad G_M^s(Q^2) \quad G_A^s(Q^2)}$$

Strangeness Form Factors vs. Q^2 (2004)

- HAPPEx (forward ep) + E734 (νp and $\bar{\nu} p$)
  Pate, PRL 92 (2004) 082002
- SAMPLE (backward ep)
  Spayde et al., PLB 583 (2004) 79



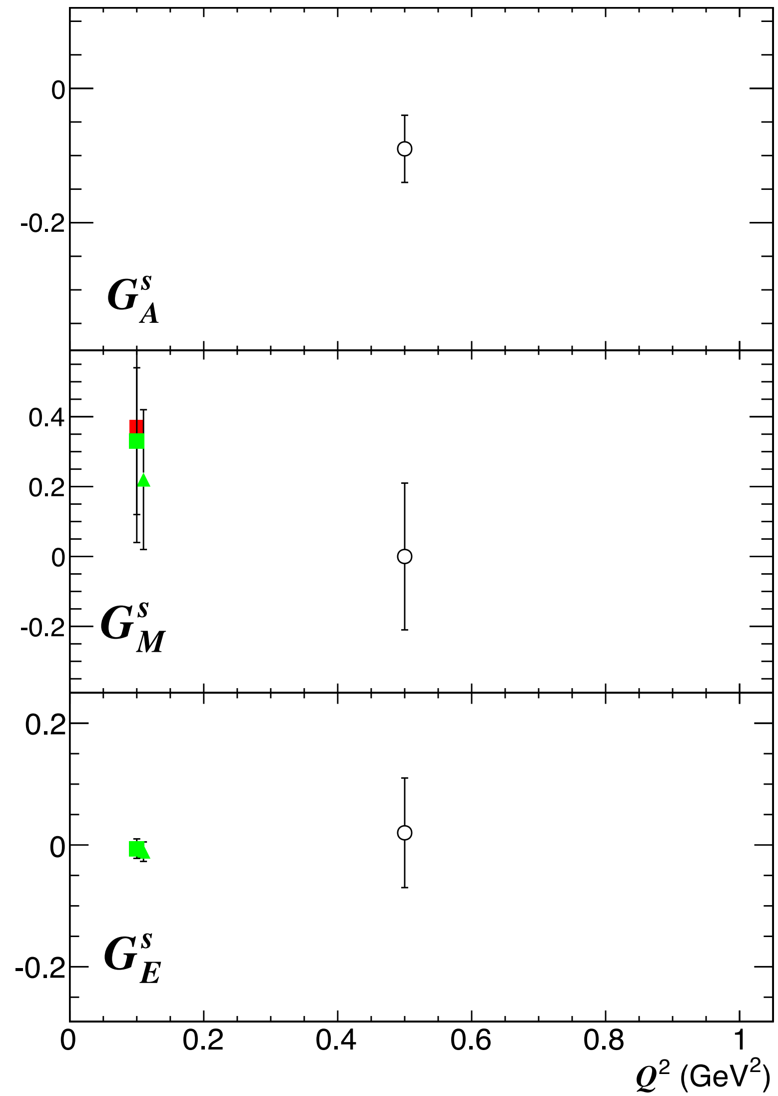
Strangeness Form Factors vs. Q^2 (2007)

- ○ HAPPEx (forward ep) + E734 (νp and $\bar{\nu} p$)
  Pate, PRL 92 (2004) 082002

- ■ SAMPLE (backward ep)
  Spayde et al., PLB 583 (2004) 79

- ▲ HAPPEx (forward ep and e^4He) + G0 (forward ep)
  + SAMPLE (backward ep and ed) + PVA4 (forward ep)
  near $Q^2 = 0.1\ \mathrm{GeV}^2$
  Young et al., PRL 99 (2007) 122003

- ■ HAPPEx (forward ep and e^4He) + G0 (forward ep)
  + SAMPLE (backward ep and ed) + PVA4 (forward ep)
  near $Q^2 = 0.1\ \mathrm{GeV}^2$
  Liu, McKeown & Ramsey-Musolf, PRC 76 (2007) 02520!



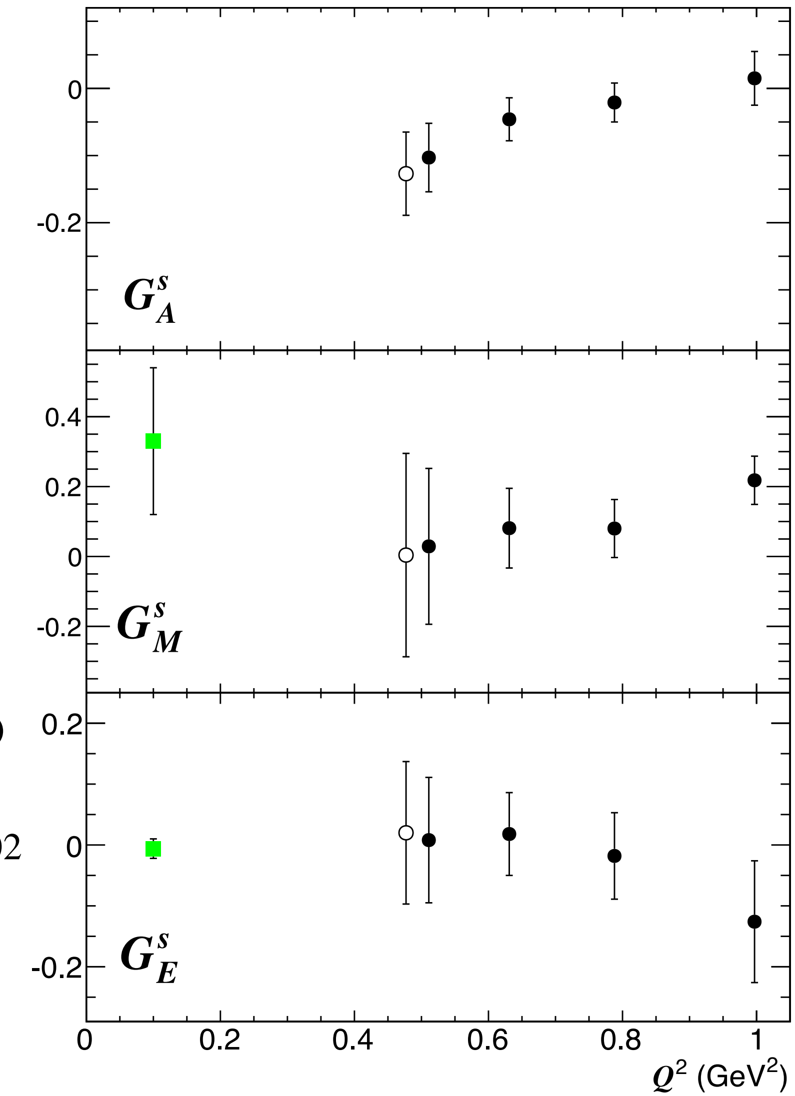
Strangeness Form Factors vs. Q^2 (2008)

- ● 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

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

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



Strangeness Form Factors vs. Q^2 (2009)

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

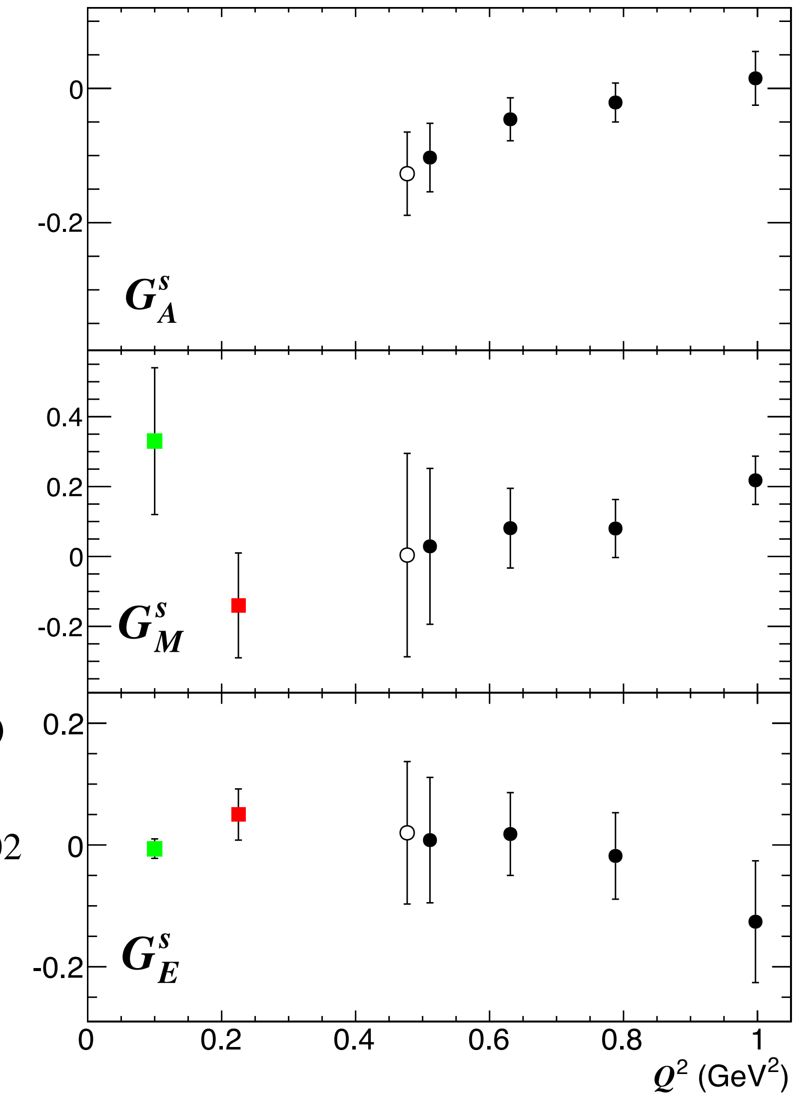
  Pate, Papavassiliou & McKee, PRC 78 (2008) 015207

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

  Baunack et al., PRL 102 (2009) 151803

- ■ (green) HAPPEx (forward ep and e^4He) + 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



Strangeness Form Factors vs. Q^2 (2010)

- ● 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*)

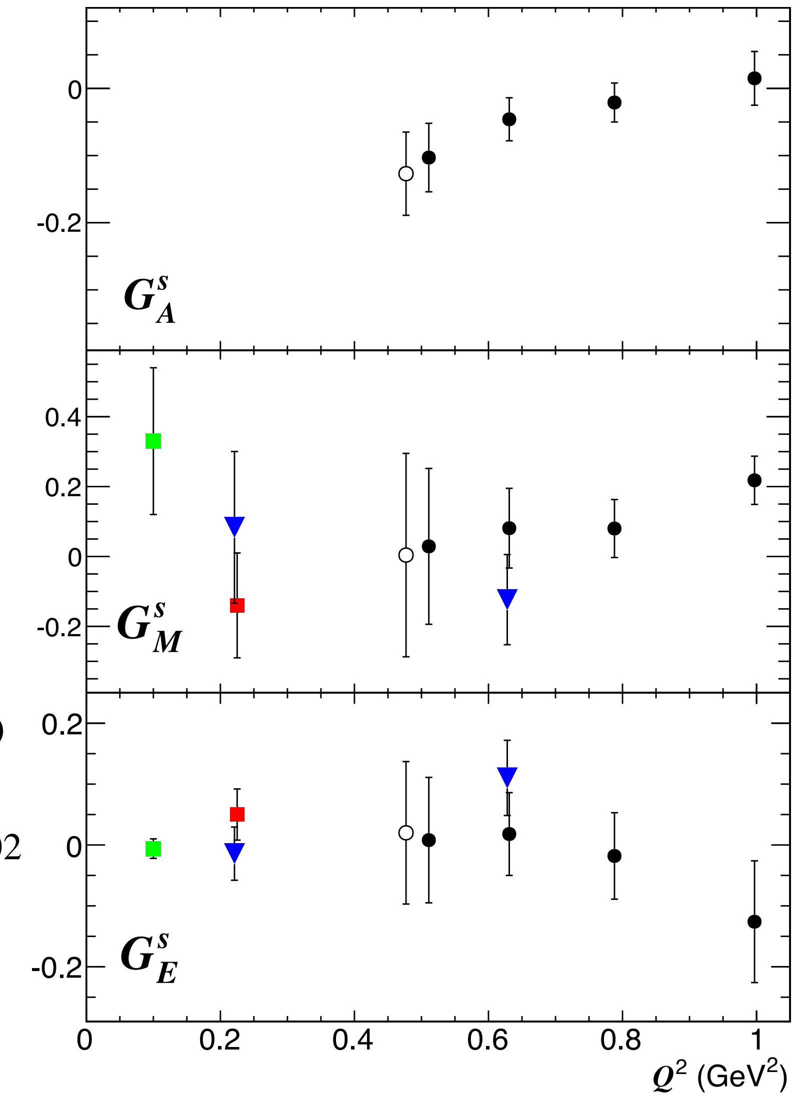
  D. Androic et al., PRL 104 (2010) 012001

- ■ HAPPEx (forward *ep* and $e\,{}^4$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



Parameters for a Global Fit

$$G_E^s = \rho_s \tau \qquad \rho_s \equiv \left.\frac{dG_E^s}{d\tau}\right|_{\tau=0} \qquad \tau = \frac{Q^2}{4M_N^2}$$

ρ_s = "strangeness radius"

$$G_M^s = \mu_s$$

μ_s = strangeness contribution to the magnetic moment

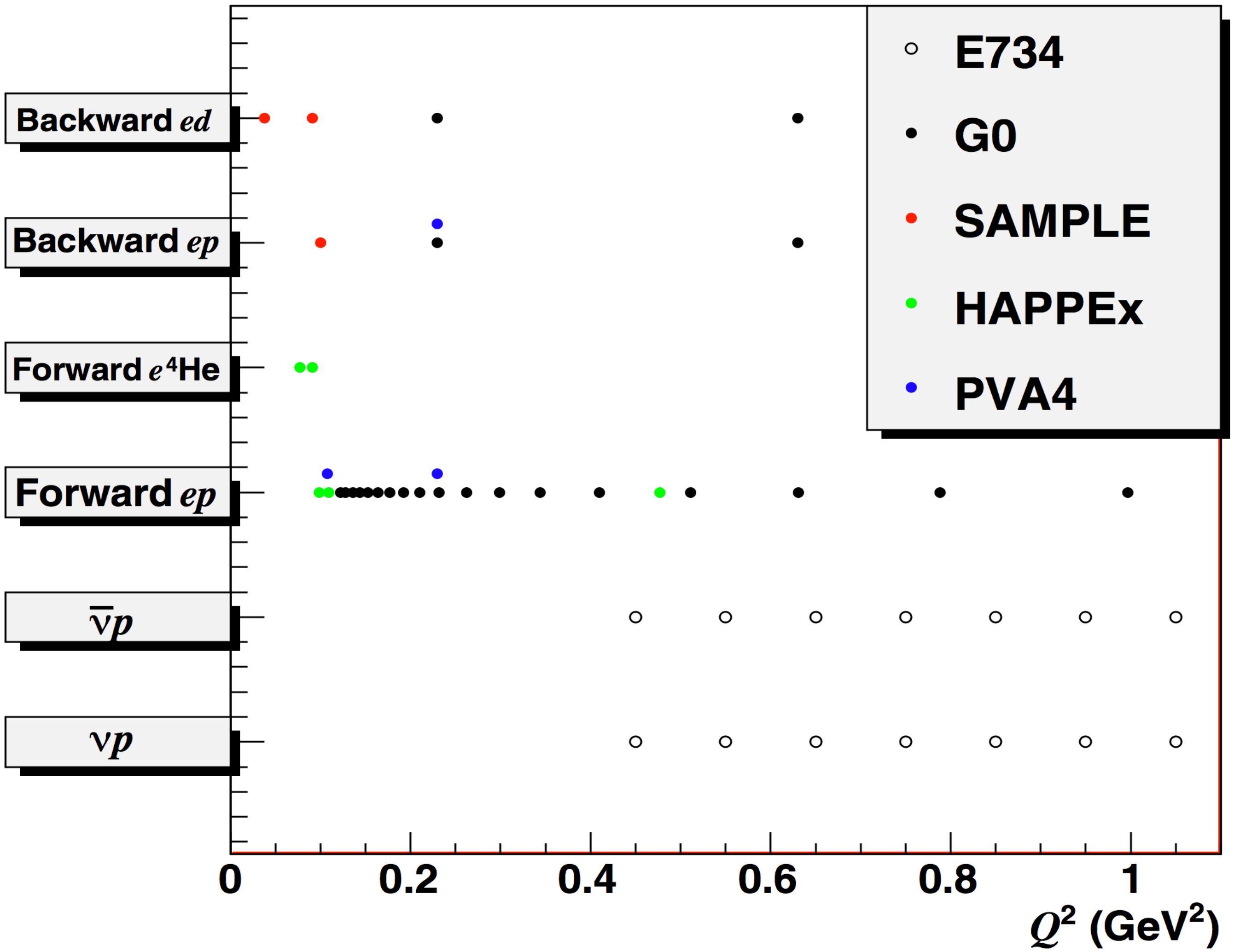
$$G_A^s = \frac{\Delta S + S_A Q^2}{\left(1 + Q^2/\Lambda_A^2\right)^2}$$

ΔS = strangeness contribution to the nucleon spin

Using S_A allowed fit to agree with existing determinations and to avoid large negative ΔS.

$\rho_s \quad \mu_s \quad \Delta S \quad \Lambda_A \quad S_A$ 5 fit parameters

Elastic and quasi-elastic electroweak scattering data used to determine the strangeness form factors of the nucleon in our global fit (47 points)

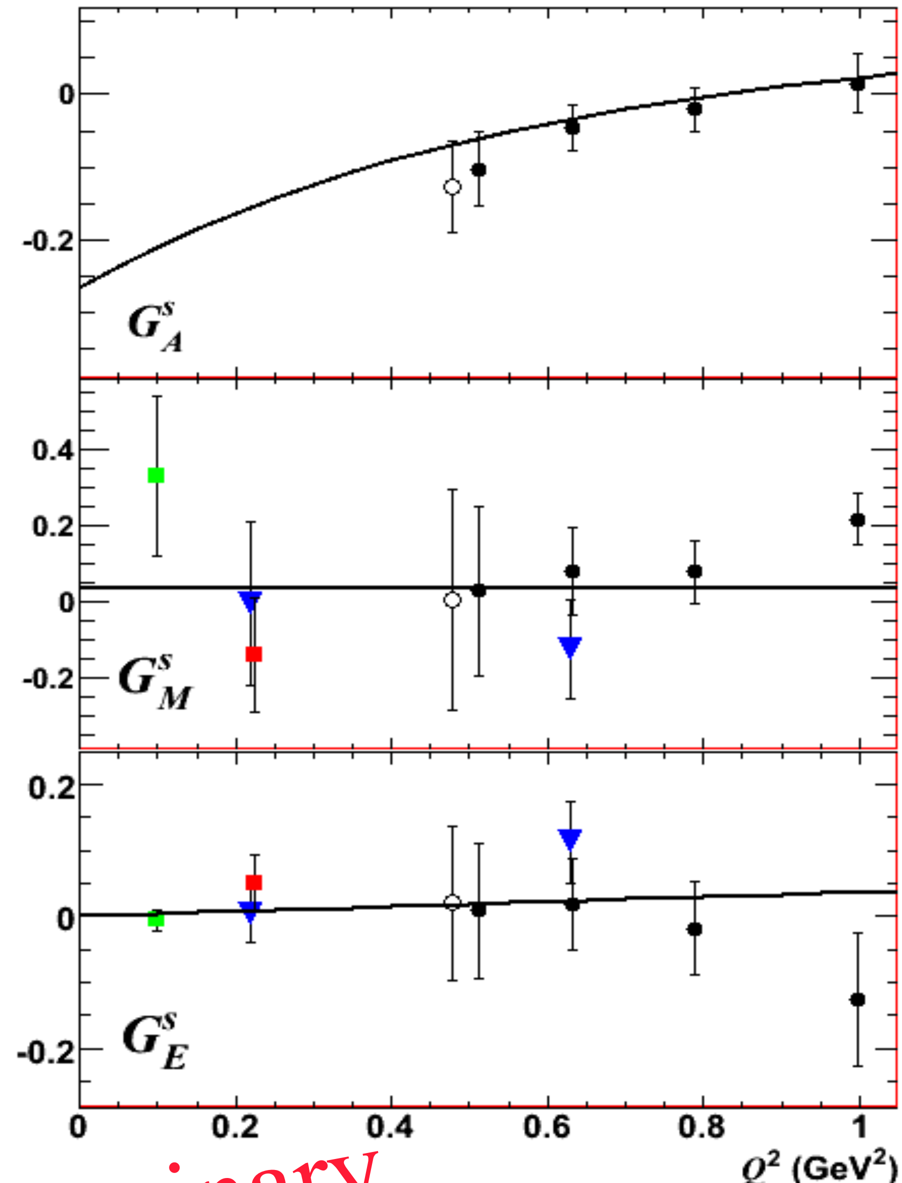


Comparison of Global Fit to Determinations at Individual Q^2 Values

- ● G0 (forward ep) + E734 (νp and $\bar{\nu}p$)
- ○ HAPPEx (forward ep) + E734 (νp and $\bar{\nu}p$)
- ■ PVA4 (forward and backward ep)
- ▼ G0 (forward and backward ep, and backward ed)
- ■ HAPPEx + PVA4 + SAMPLE + G0 (0.1 GeV^2)

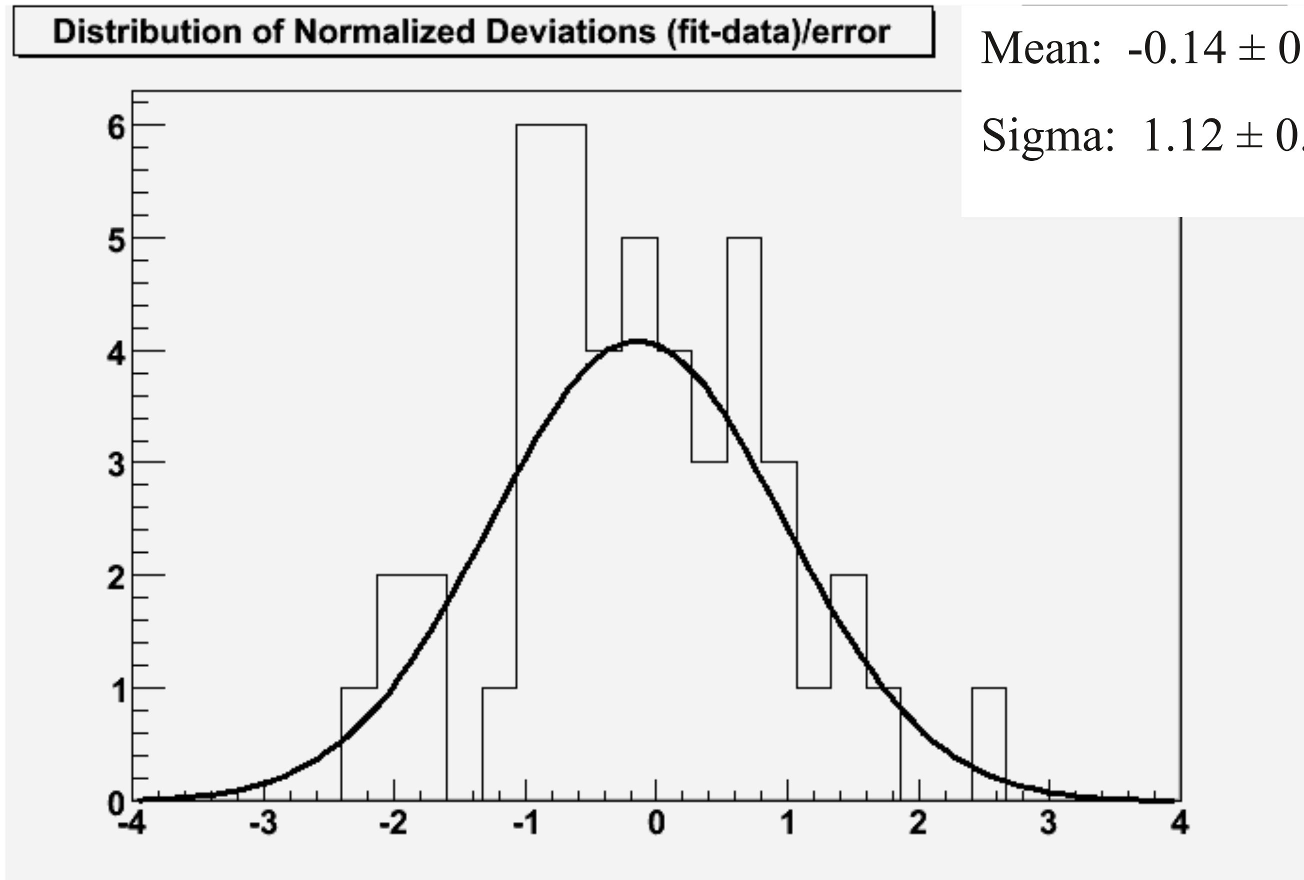
——— 5 parameter fit

Parameter	Fit to Existing Data
ρ_s	0.13 ± 0.21
μ_s	0.035 ± 0.053
ΔS	−0.27 ± 0.41
Λ_A	1.3 ± 1.9
S_A	0.32 ± 0.48



Preliminary

Distribution of Normalized Deviations of the Fit from the Data



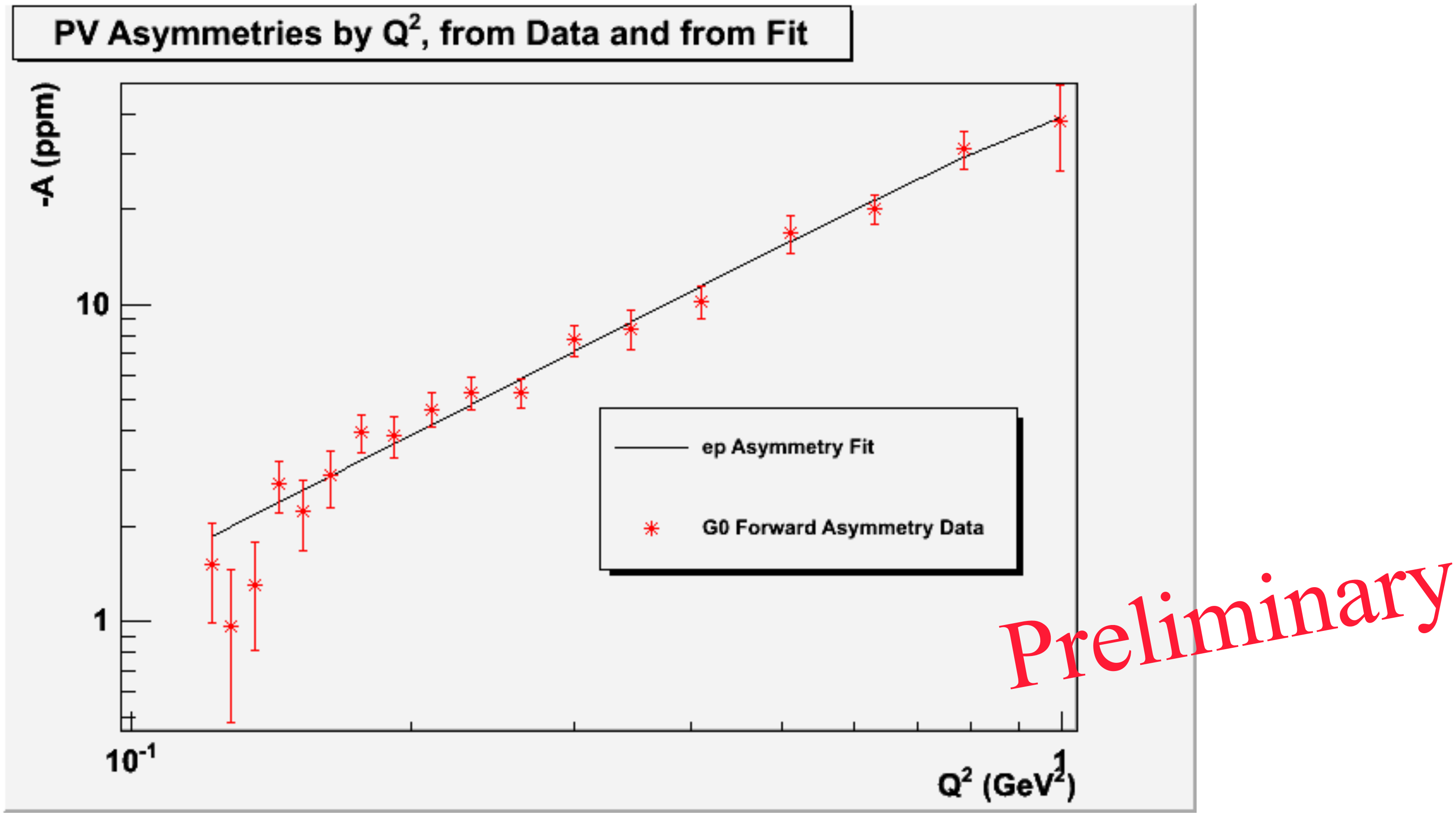
Mean: -0.14 ± 0.21

Sigma: 1.12 ± 0.29

Data normally distributed with respect to fit

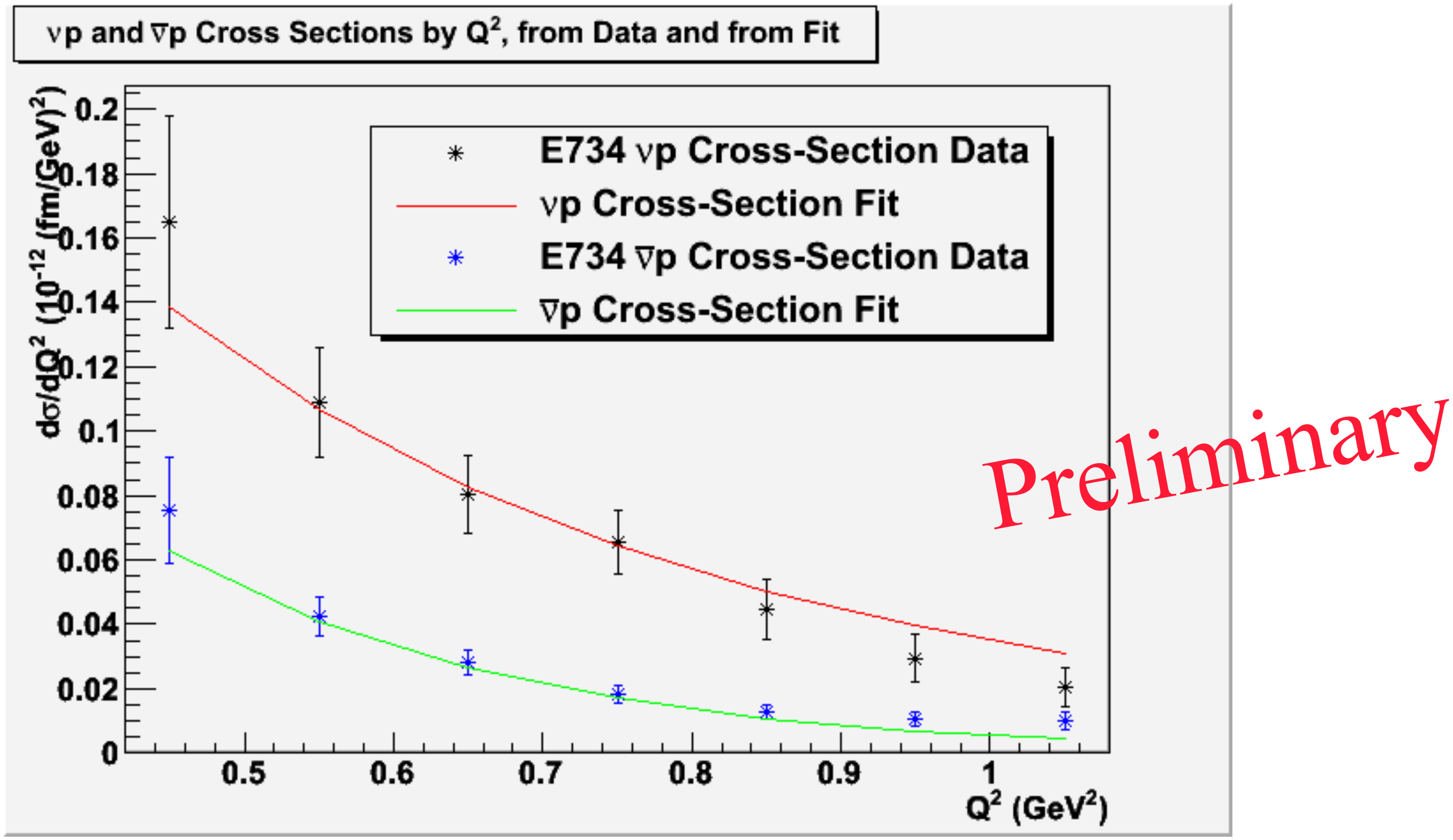
Preliminary

Asymmetry Fit and G0 Forward Asymmetries



Fit within 2 sigma of all points

Cross Section Fits and E734 Cross Sections



Fit within 2 sigma of all points

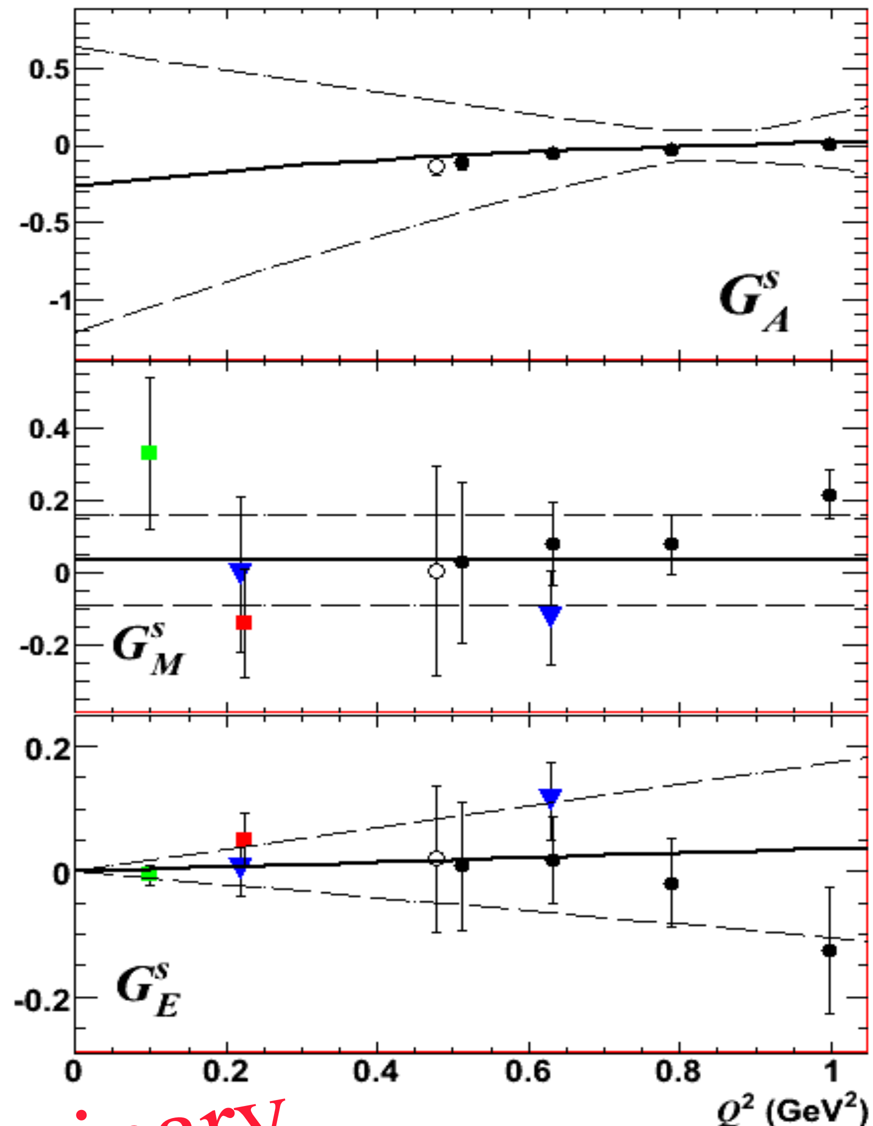
Fit Uncertainty Limit Curves

- ● G0 (forward *ep*) + E734 (νp and $\bar{\nu} p$)
- ○ HAPPEx (forward *ep*) + E734 (νp and $\bar{\nu} p$)
- ■ PVA4 (forward and backward *ep*)
- ▼ G0 (forward and backward *ep*, and backward *ed*)
- ■ HAPPEx + PVA4 + SAMPLE + G0 (0.1 GeV^2)

——— 5 parameter fit

— — — 70% confidence level

Parameter	Fit to Existing Data
ρ_s	0.13 ± 0.21
μ_s	0.035 ± 0.053
ΔS	−0.27 ± 0.41
Λ_A	1.3 ± 1.9
S_A	0.32 ± 0.48



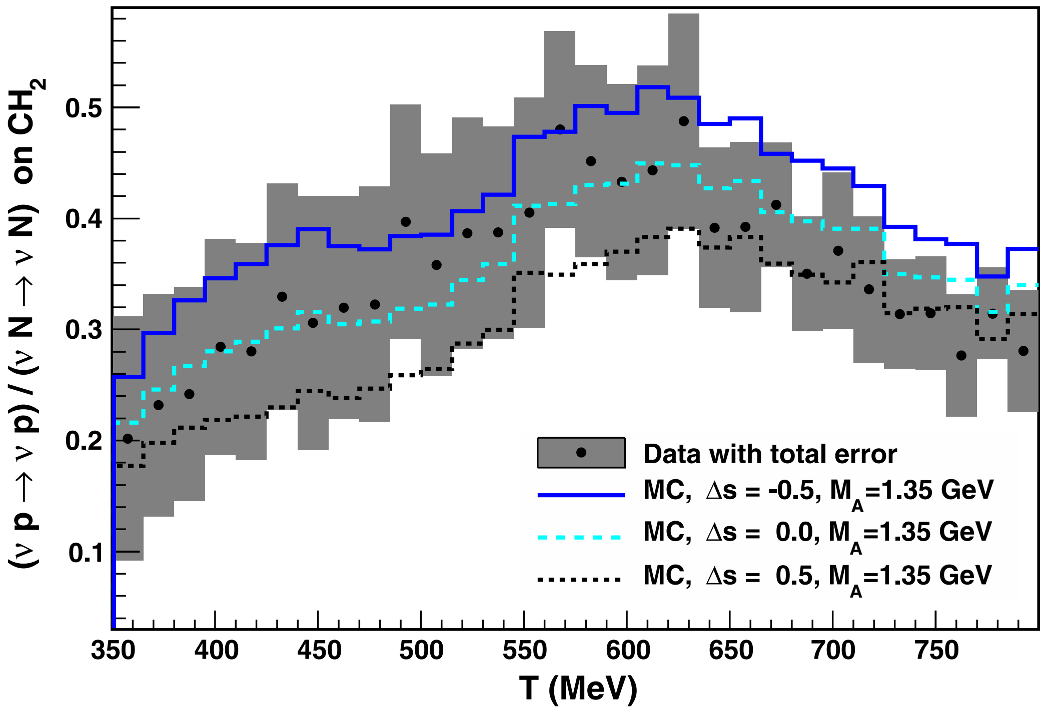
Preliminary

New MiniBooNE Data (2010)

Measured the yield ratio of NC elastic scattering events:

$$\frac{\nu p \rightarrow \nu p}{\nu N \rightarrow \nu N} \qquad \frac{\text{Numerator is very sensitive to } G_A^s}{\text{Denominator is insensitive to } G_A^s\text{; mixing of proton and neutron yields cancels its contribution}}$$

Aguilar-Arevalo *et al.*, PRD 82 (2010) 092005



$$\Delta s = -0.08 \pm 0.26$$

The MiniBooNE analysis assumes the Q^2-dependence of G_A^s is the same as G_A^{CC}. We have seen in our global fit that this is not a good assumption. There is also no physics motivation for this assumption.

We will include the MiniBooNE yield ratio into our fit in the next few months, reducing our uncertainty band for G_A^s.

New HAPPEx Datum (2012)

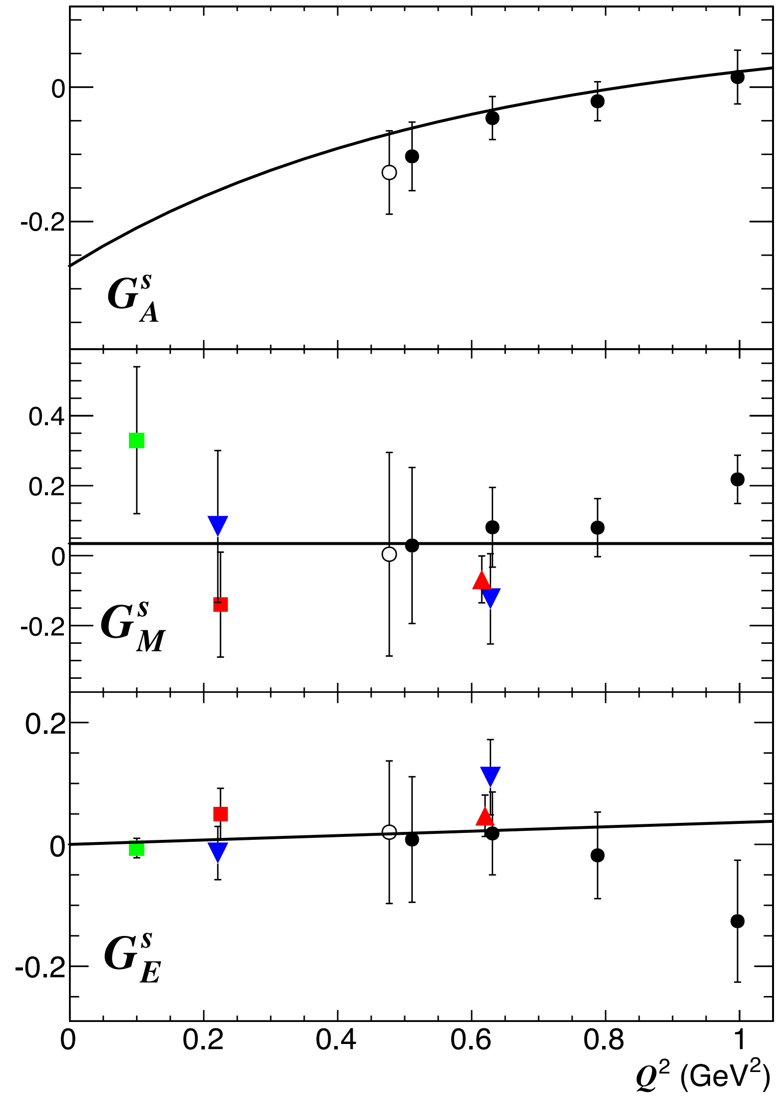
- ● G0 (forward *ep*) + E734 (νp and $\bar{\nu} p$)
- ○ HAPPEx (forward *ep*) + E734 (νp and $\bar{\nu} p$)
- ■ PVA4 (forward and backward *ep*)
- ▼ G0 (forward and backward *ep*, and backward *ed*)
- ■ HAPPEx + PVA4 + SAMPLE + G0 (0.1 GeV^2)

- ▲ HAPPEx (forward *ep*)

  + G0 (forward and backward *ep*) 0.624 GeV^2

  Ahmed *et al*., PRL 108 (2012) 102001

This new HAPPEx datum is consistent with previous data sets and with our fit. Including it into our fit will reduce the uncertainty bands for G_E^s and G_M^s, but will not significantly affect the G_A^s fit.



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The M_A Issue

The NC elastic νp cross section is sensitive to the total NC axial form factor.

$$G_A^Z = \frac{1}{2}\left(-G_A^{CC} + G_A^s\right)$$ Determination of G_A^s requires a knowledge of G_A^{CC}.

For many years, the charged-current portion of the axial form factor was nicely parametrized by a value of the "axial mass" near 1.0.

$$G_A^{CC} = G_A^u - G_A^d = \frac{g_A}{\left(1+Q^2/M_A^2\right)^2}$$

$g_A = 1.2695 \pm 0.0029$ [PDG]

$M_A = 1.001 \pm 0.020$ GeV [Budd, Bodek, and Arrington]

But recent high-statistics measurements of the CCQE channel seemed to indicate a higher value for M_A.

$M_A = 1.39 \pm 0.11$ GeV MiniBooNE, Carbon Aguilar - Arevalo et al., PRL 100 (2008) 032301

$M_A = 1.20 \pm 0.12$ GeV K2K, Oxygen Gran et al., PRD 74 (2006) 052002

Those analyses used a simple relativistic Fermi gas model to account for nuclear effects. Recently, a number of more sophisticated calculations have demonstrated that the charged-current results from MiniBooNE and K2K can be understood without any need to increase the value of M_A above 1.0.

The M_A Issue

Bodek, Budd, Christy [EPJ C (2011) 71:1726] – Transverse Enhancement model; observed enhancement in the transverse electron quasielastic response function for bound nucleons is used for the transverse cross section in neutrino scattering; this resolves much of the discrepancy without any modification in M_A; easily applied to existing simulation codes as a correction to the magnetic form factors of bound nucleons

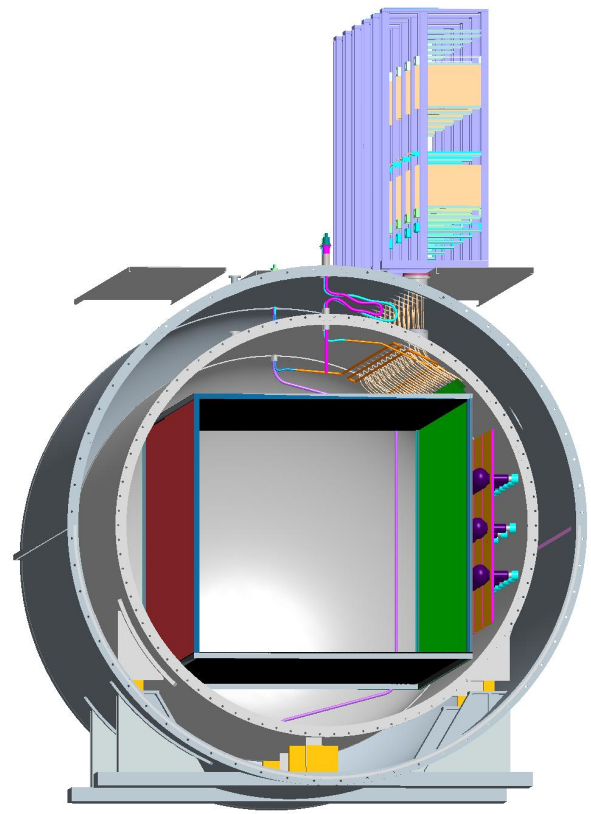
Meucci, Giusti, and Pacati [PRD 84 (2011) 113003] – fully relativistic treatment, based on techniques used in electron-nucleus scattering; final state interactions can significantly enhance the cross section, eliminating the need to increase M_A

Martini, Ericson, Chanfray [PRC 84 (2011) 055502] – no need for modification in M_A if multi-nucleon processes are taken into consideration

Other good reading:
Nieves, Ruiz Simo, Vicente Vacas [PRC 83 (2011) 045501]
Amaro, Barbaro, Caballero, Donnelly, Williamson [PLB 696 (2011) 151]
Martinez, Meloni [PLB 697 (2011) 477]
Gallagher, Garvey, Zeller [Ann. Rev. Nucl. Part. Sci. 61 (2011) 355]

A successful determination of Δs will require reliable measurements of NC scattering at $Q^2 \sim 0.1$ GeV^2.

MicroBooNE: an approved experiment at Fermilab to build a large liquid Argon Time Projection Chamber (LArTPC) to be exposed to the Booster neutrino beam and the NuMI beam at Fermilab. The experiment will address the low energy excess observed by the MiniBooNE experiment, measure low energy neutrino cross sections, and serve as the necessary next step in a phased program towards massive Liquid Argon TPC detectors.



Liquid argon is very well-suited to observe low energy protons from low-Q^2 neutral-current and charged-current scattering; may be an ideal place to move towards a successful determination of Δs.

Rough Estimation of MicroBooNE Capability

- Simulated 2×10^{20} protons-on-target (about one running year) with reasonable event selection cuts
- Estimated statistical uncertainty NC/CC yield ratio:

$$R_{NC/CC} = \frac{N(\nu p \to \nu p)}{N(\nu n \to \mu^- p)}$$

- Many experimental uncertainties cancel in this ratio (flux, efficiencies, …), and some theoretical ones may also (nuclear corrections)

→Ratio a more attractive observable than NC cross section

Thanks to B. Fleming, J. Spitz, and V. Papavassiliou for providing this simulation.

Estimation of Fit Improvement Due to MicroBooNE Data

• Used our fit for $R_{NC/CC}$ values, MicroBooNE simulation for uncertainties
• Didn't include estimate of systematic errors, but also didn't use full statistics
→Only a crude indicator
• Fed simulated data back into our fit to see effects on parameter uncertainties size of uncertainty bands

Q^2	$R_{NC/CC}$	$dR_{NC/CC}$
0.08-0.2	0.206	0.005
0.2-0.4	0.181	0.005
0.4-0.6	0.156	0.007
0.6-0.8	0.136	0.009
0.8-1.0	0.118	0.012
1.0-1.2	0.101	0.015

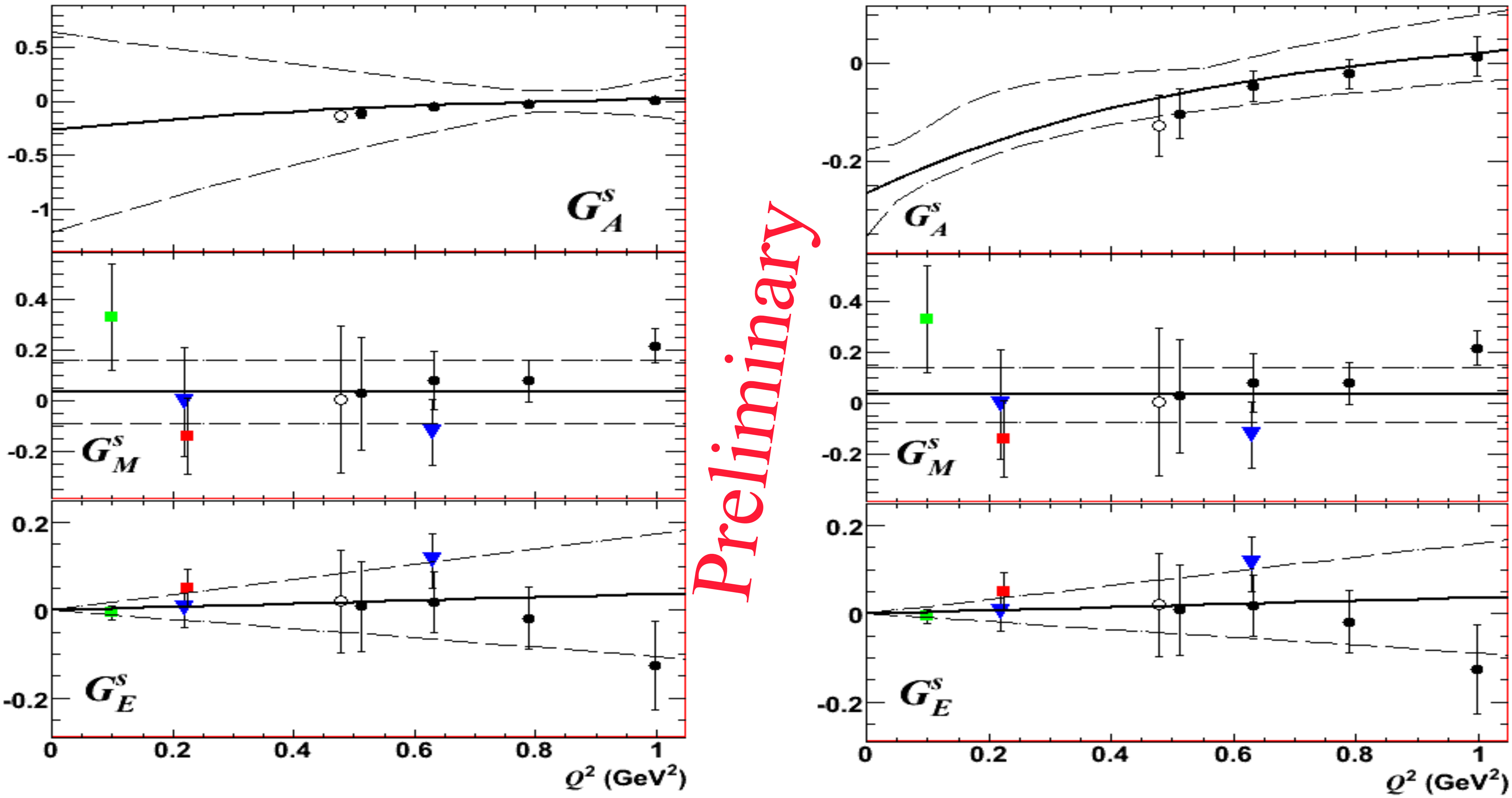
Parameter	Fit to Existing Data	Including μBooNE
ρ_s	0.13 ± 0.21	0.13 ± 0.19
μ_s	0.035 ± 0.053	0.034 ± 0.046
ΔS	-0.27 ± 0.41	-0.265 ± 0.038
Λ_A	1.3 ± 1.9	1.34 ± 0.38
S_A	0.32 ± 0.48	0.322 ± 0.071

Minor improvement in vector form factor fits

Major improvement in axial form factor fit!

Preliminary

Fit Uncertainty Limit Curves Including Simulated MicroBooNE Data



fit uncertainty limits much tighter with MicroBooNE data

Summary

The strangeness contribution to the nucleon spin may be determined from a combined analysis of low-energy electron-nucleon and neutrino-nucleon elastic scattering data.

However, existing neutral-current neutrino data (from BNL E734 and MiniBooNE) lack sufficient precision and Q^2-range to make possible a definitive determination of Δs.

New experiments (e.g. MicroBooNE) can provide the datasets needed for a consistent treatment of the electroweak nuclear response and extraction of the strange axial form factor.