Strange Nucleon Form Factors from *ep* and *νp* Elastic Scattering

A combined analysis of HAPPEx, G^0, and BNL E734 data

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Outline

- Parity-violating electron-nucleon (PVeN) elastic scattering
- Neutrino-proton elastic scattering
- How the use of neutrino-proton elastic scattering data with PVeN data permits the extraction of the strange vector and axial form factors
- The results of a combined analysis of BNL E734 νp data with the HAPPEX and G^0 forward PVeN data begin to show the Q^2-dependence of the strange axial form factor for $Q^2 = 0.45$ -- $1.0\ \mathrm{GeV}^2$.
- **These results greatly restrict the possible configurations of strange quarks in the nucleon.**
- **How these results will aid the determination of the Q^2-dependence of the strange vector form factors**

Features of parity-violating forward-scattering *ep* data

- measures linear combination of form factors of interest
- axial terms are doubly suppressed

  $\rightarrow (1 - 4\sin^2\theta_W) \sim 0.075$

  $\rightarrow$ kinematic factor $\varepsilon' \sim 0$ at forward angles
- significant radiative corrections exist, especially in the axial term

➠ parity-violating data at forward angles are mostly sensitive to the strange electric and magnetic form factors

Full Expression for the PV *ep* Asymmetry

For a hydrogen target, the asymmetry as a linear combination of G_E^s, G_M^s, G_A^{CC} and G_A^s is:

$$A^p = A_0^p + A_E^p G_E^s + A_M^p G_M^s + A_{AIV}^p G_A^{CC} + A_A^p G_A^s$$

where
$$A_0^p = -K^p \left\{ \begin{array}{l} \left(1-4\sin^2\theta_W\right)\left(1+R_V^p\right)\left(\varepsilon {G_E^p}^2 + \tau {G_M^p}^2\right) \\ \quad -\left(1+R_V^n\right)\left(\varepsilon G_E^p G_E^n + \tau G_M^p G_M^n\right) \\ \quad -\varepsilon' G_M^p \left(1-4\sin^2\theta_W\right)\left[\sqrt{3} R_A^{T=0} G_A^8\right] \end{array} \right\}$$

$$A_E^p = K^p \left\{\varepsilon G_E^p \left(1+R_V^0\right)\right\}$$

$$A_M^p = K^p \left\{\tau G_M^p \left(1+R_V^0\right)\right\}$$

$$A_{AIV}^p = K^p \left\{\varepsilon' G_M^p \left(1-4\sin^2\theta_W\right)\left(1+R_A^{T=1}\right)\right\}$$

$$A_A^p = K^p \left\{\varepsilon' G_M^p \left(1-4\sin^2\theta_W\right)\left(1+R_A^0\right)\right\}$$

$$K^p = \frac{G_F Q^2}{4\pi\sqrt{2}\alpha}\frac{1}{\varepsilon {G_E^p}^2 + \tau {G_M^p}^2}$$

$$\tau = \frac{Q^2}{4M^2}$$
$$\varepsilon = \left[1 + 2(1+\tau)\tan^2(\theta/2)\right]^{-1}$$
$$\varepsilon' = \sqrt{(1-\varepsilon^2)\tau(1+\tau)}$$

Note suppression of axial terms by $(1 - 4\sin^2\theta_W)$ and ε'.

Things known and unknown in the PV *ep* Asymmetry

$G_{E,M}^{p,n}$ = Kelly parametrization [PRC 70 (2004) 068202]

with G^0 uncertainties [http://www.npl.uiuc.edu/exp/G0/Forward]

$$G_A^{CC} = \frac{g_A}{\left(1+Q^2/M_A^2\right)^2} \qquad G_A^8 = \frac{1}{2\sqrt{3}}\frac{\left(3F-D\right)}{\left(1+Q^2/M_A^2\right)^2}$$

$M_A = 1.001 \pm 0.020$ GeV [Budd, Bodek and Arrington: hep-ex/0308005 and 0410055]

$g_A = 1.2695 \pm 0.0029$ [Particle Data Group 2005]

$3F - D = 0.585 \pm 0.025$ [Goto *et al.* PRD 62 (2000) 034017]

[use of $3F-D$ implies use of flavor-SU(3), but G_A^8 is suppressed by ε' and $\left(1-4\sin^2\theta_W\right)$]

The R's are radiative corrections calculated at $Q^2 = 0$ in the formalism of Zhu et al. [PRD 62 (2000) 033008]. The Q^2-dependence is unknown, and so we have assigned a 100% uncertainty to the values.

$$R_V^p = -0.045 \qquad R_V^n = -0.012 \qquad R_V^0 = -0.012$$

$$R_A^{T=1} = -0.173 \qquad R_A^{T=0} = -0.253 \qquad R_A^0 = -0.552$$

[from evaluation of Arvieux *et al.*, to be published]

Features of elastic *νp* data

• measures quadratic combination of form factors of interest

• axial terms are dominant at low Q^2

$$\frac{d\sigma}{dQ^2}(\nu p \to \nu p) \xrightarrow[Q^2 \to 0]{} \frac{G_F^2}{128\pi} \frac{M_p^2}{E_\nu^2} \left[\left(-G_A^u + G_A^d + G_A^s \right)^2 + \left(1 - 4\sin^2\theta_W \right)^2 \right]$$

• radiative corrections are insignificant

[Marciano and Sirlin, PRD 22 (1980) 2695]

➠ neutrino data are mostly sensitive to the strange axial form factor

Elastic NC neutrino-proton cross sections

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

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

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

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

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

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

The BNL E734 Experiment

- performed in mid-1980's
- measured neutrino- and antineutrino-proton elastic scattering
- used wide band neutrino and anti-neutrino beams of $<E_\nu>$=1.25 GeV
- covered the range $0.45 < Q^2 < 1.05$ GeV^2
- large liquid-scintillator target-detector system
- still the **only** elastic neutrino-proton cross section data available

E734 Results

Uncertainties shown are total (stat and sys).

Correlation coefficient arises from systematic errors.

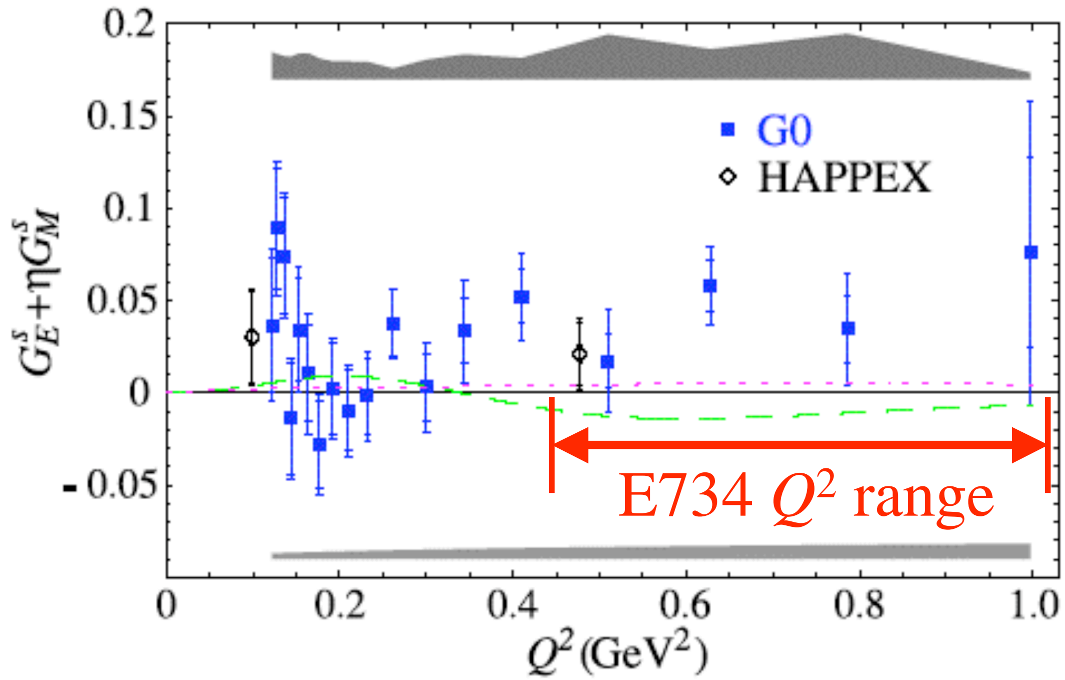
Q^2 $(\text{GeV})^2$	$d\sigma/dQ^2(\nu p)$ $(\text{fm/GeV})^2$	$d\sigma/dQ^2(\bar{\nu}p)$ $(\text{fm/GeV})^2$	correlation coefficient
0.45	0.165 ± 0.033	0.0756 ± 0.0164	0.134
0.55	0.109 ± 0.017	0.0426 ± 0.0062	0.256
0.65	0.0803 ± 0.0120	0.0283 ± 0.0037	0.294
0.75	0.0657 ± 0.0098	0.0184 ± 0.0027	0.261
0.85	0.0447 ± 0.0092	0.0129 ± 0.0022	0.163
0.95	0.0294 ± 0.0074	0.0108 ± 0.0022	0.116
1.05	0.0205 ± 0.0062	0.0101 ± 0.0027	0.071

Combination of the *ep* and *νp* data sets

We use PV *ep* data in the same range of Q^2 as the E734 experiment.

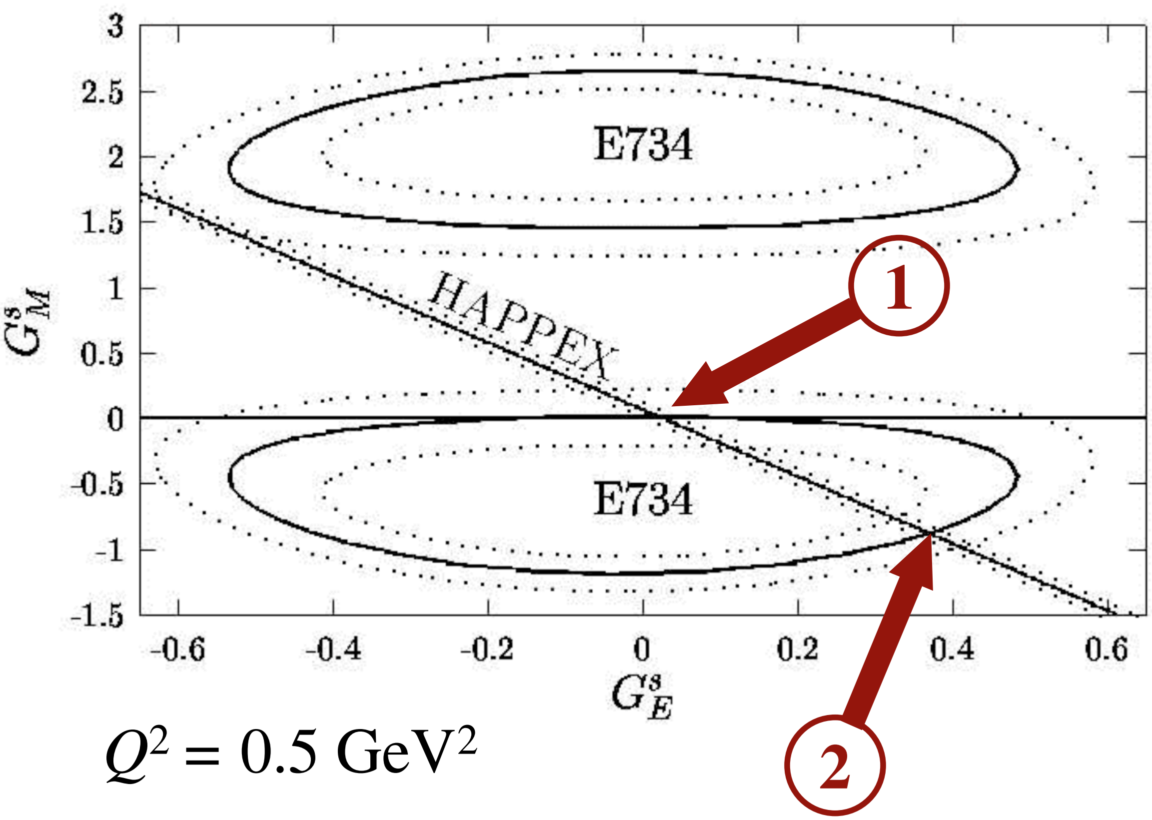
• The original HAPPEx measurement: $Q^2 = 0.477$ GeV^2
[PLB 509 (2001) 211 and PRC 69 (2004) 065501]

• The recent G^0 data covering the range $0.1 < Q^2 < 1.0$ GeV^2
[PRL 95 (2005) 092001]



Combination of the *ep* and *νp* data sets

Since the neutrino data are quadratic in the form factors, then there will be in general <u>two solutions</u> when these data sets are combined.



$Q^2 = 0.5\ \mathrm{GeV}^2$

Here are the advertised intersections between electron and neutrino data.

Fortunately, the two solutions are very distinct from each other, and other available data can select the correct physical solution.

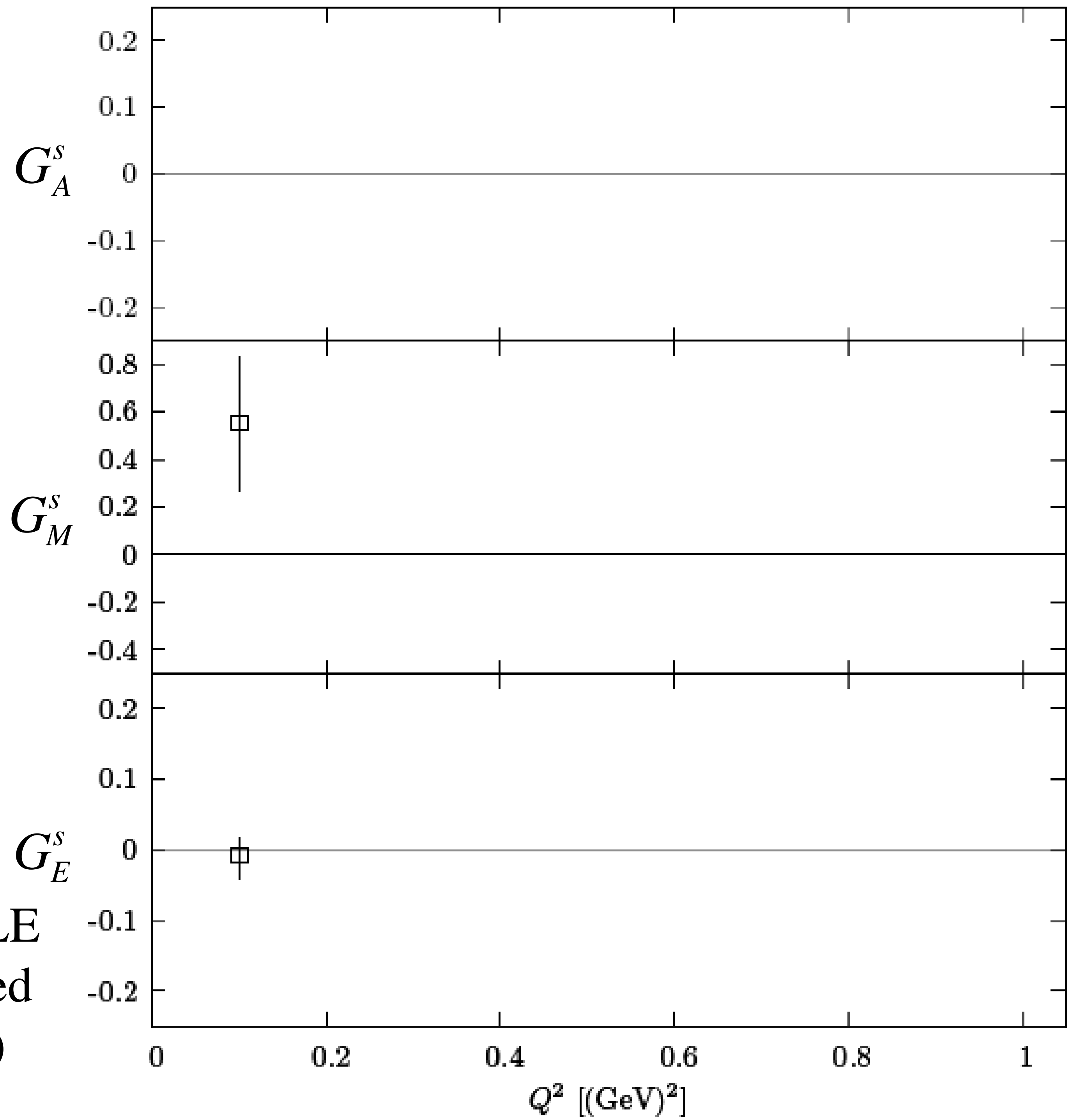
General Features of the two Solutions

	Solution 1	Solution 2
G_E^s	Consistent with zero (with large uncertainty)	Large and positive
G_M^s	Consistent with zero (with large uncertainty)	Large and negative
G_A^s	Small and negative	Large and positive

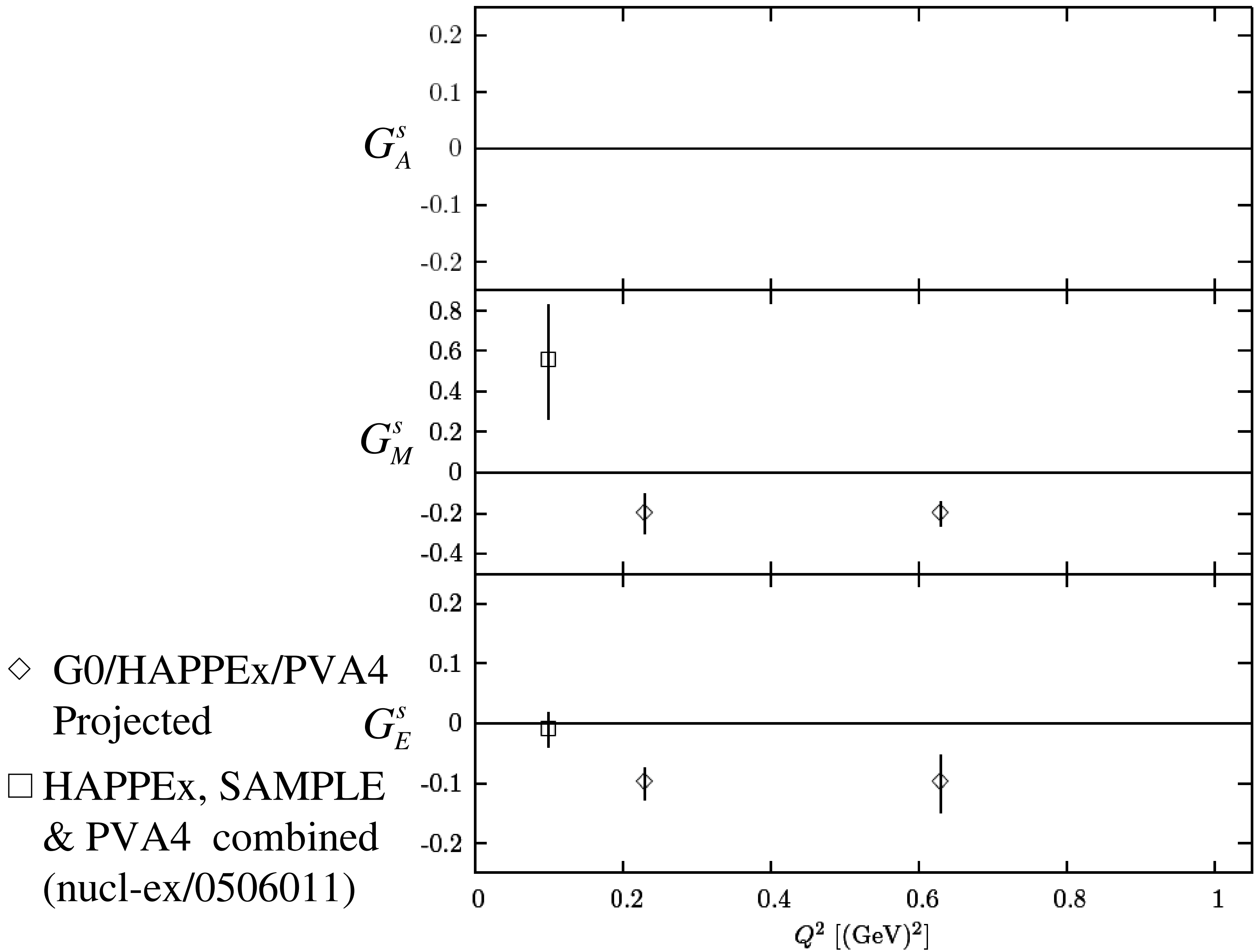
There are three strong reasons to prefer **Solution 1**:

- G_A^s in Solution 2 is inconsistent with DIS estimates for Δs
- G_M^s in Solution 2 is inconsistent with the combined SAMPLE/PVA4/HAPPEx result of G_M^s = ~+0.6 at $Q^2 = 0.1$ GeV^2
- G_E^s in Solution 2 is inconsistent with the idea that G_E^s should be small, and conflicts with expectation from recent G^0 data that G_E^s may be negative near $Q^2 = 0.3$ GeV^2

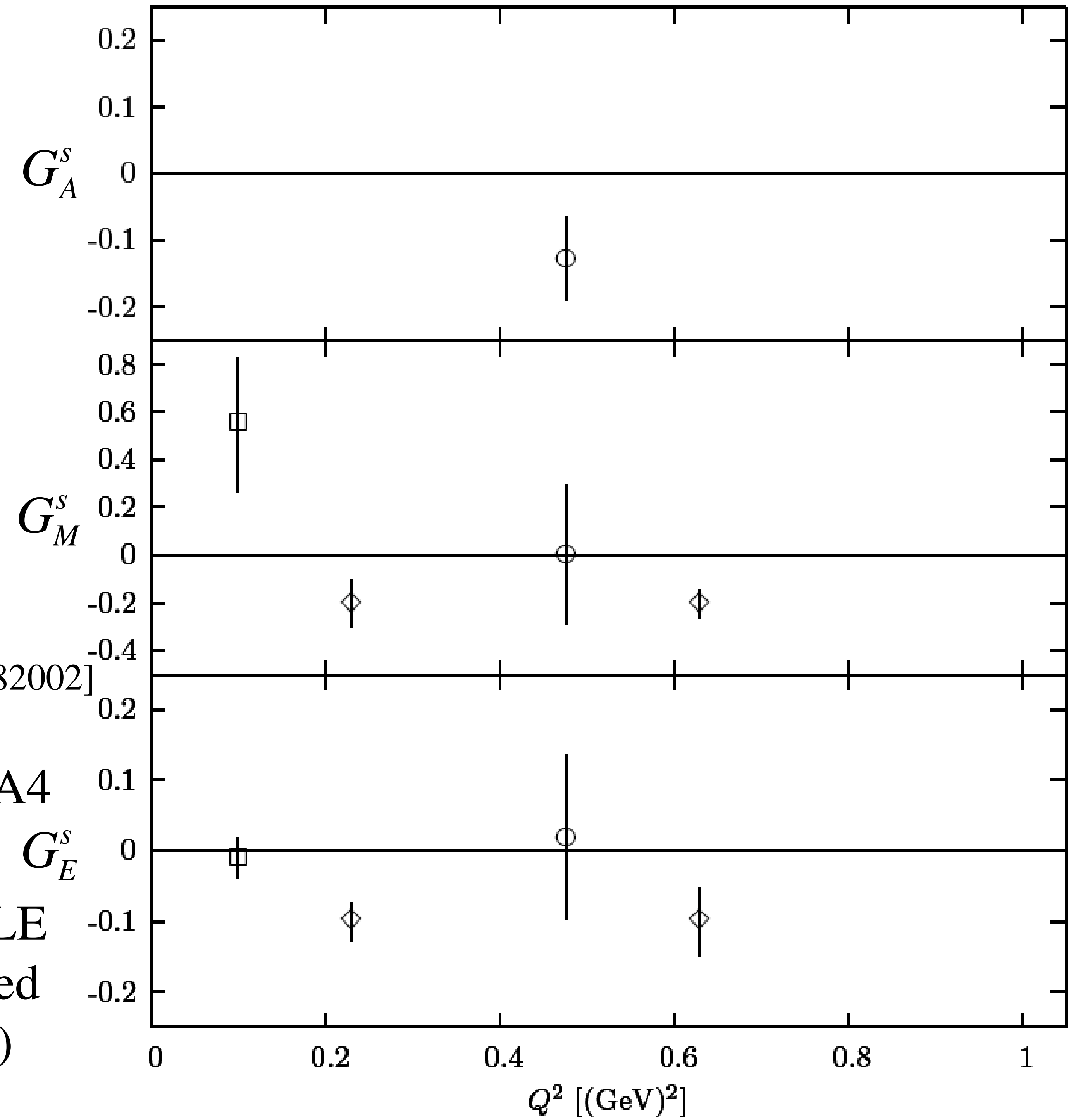
I only present Solution 1 in what follows.



□ HAPPEx, SAMPLE & PVA4 combined (nucl-ex/0506011)



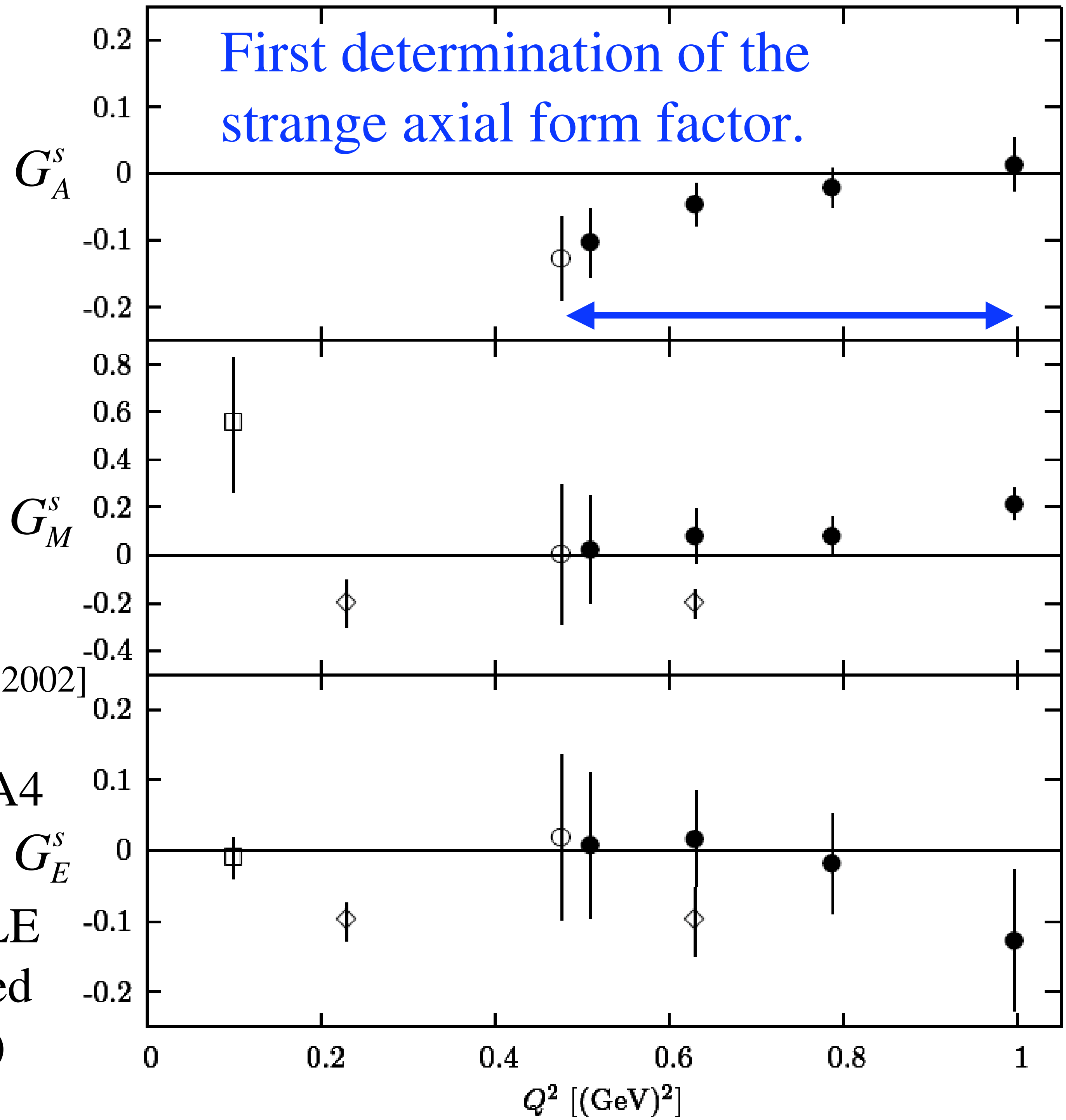
◇ G0/HAPPEx/PVA4
Projected
□ HAPPEx, SAMPLE
& PVA4 combined
(nucl-ex/0506011)
G_A^s
G_M^s
G_E^s
0.2
0.1
0
-0.1
-0.2
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0.2
0.1
0
-0.1
-0.2
0
0.2
0.4
0.6
0.8
1
Q^2 [(GeV)^2]



○ HAPPEx & E734
[Pate, PRL 92 (2004) 082002]

◇ G0/HAPPEx/PVA4
Projected

□ HAPPEx, SAMPLE
& PVA4 combined
(nucl-ex/0506011)

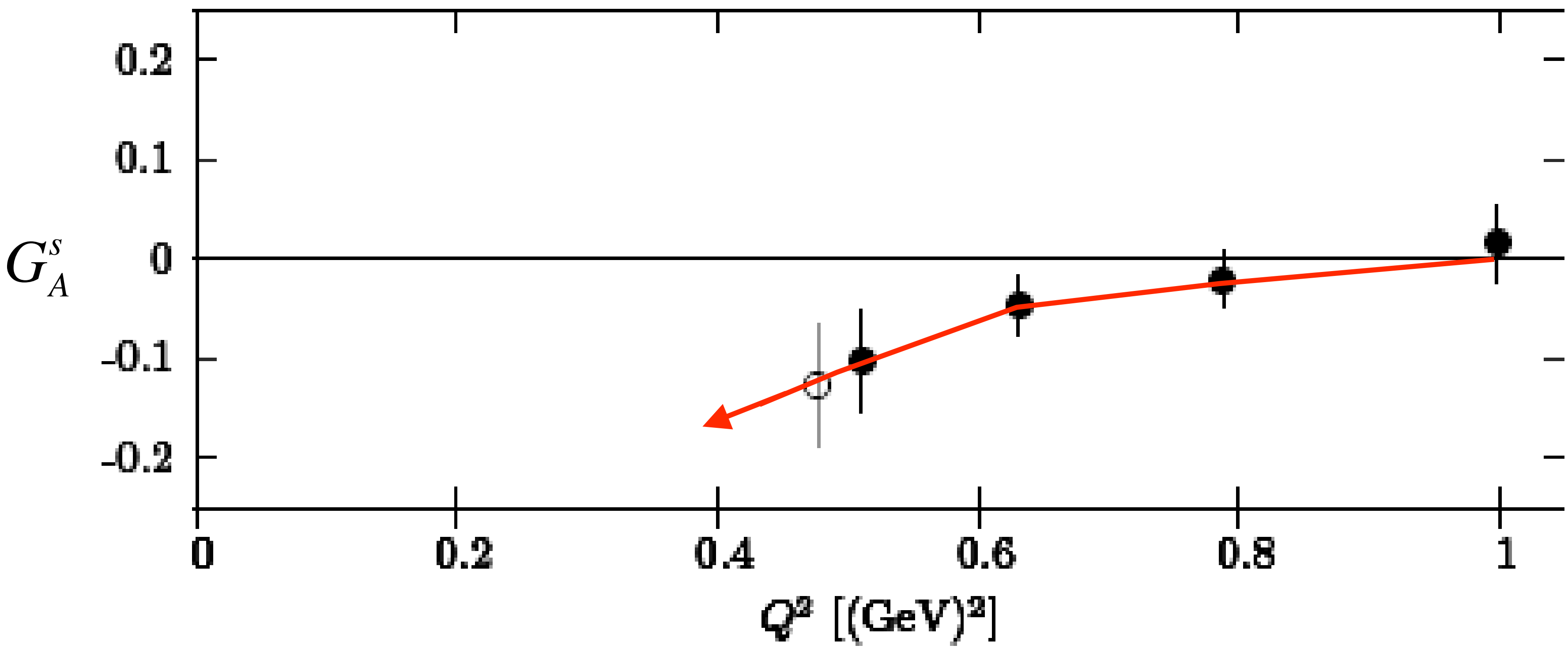


● G0 & E734
[to be published]

○ HAPPEx & E734
[Pate, PRL 92 (2004) 082002]

◇ G0/HAPPEx/PVA4
Projected

□ HAPPEx, SAMPLE
& PVA4 combined
(nucl-ex/0506011)



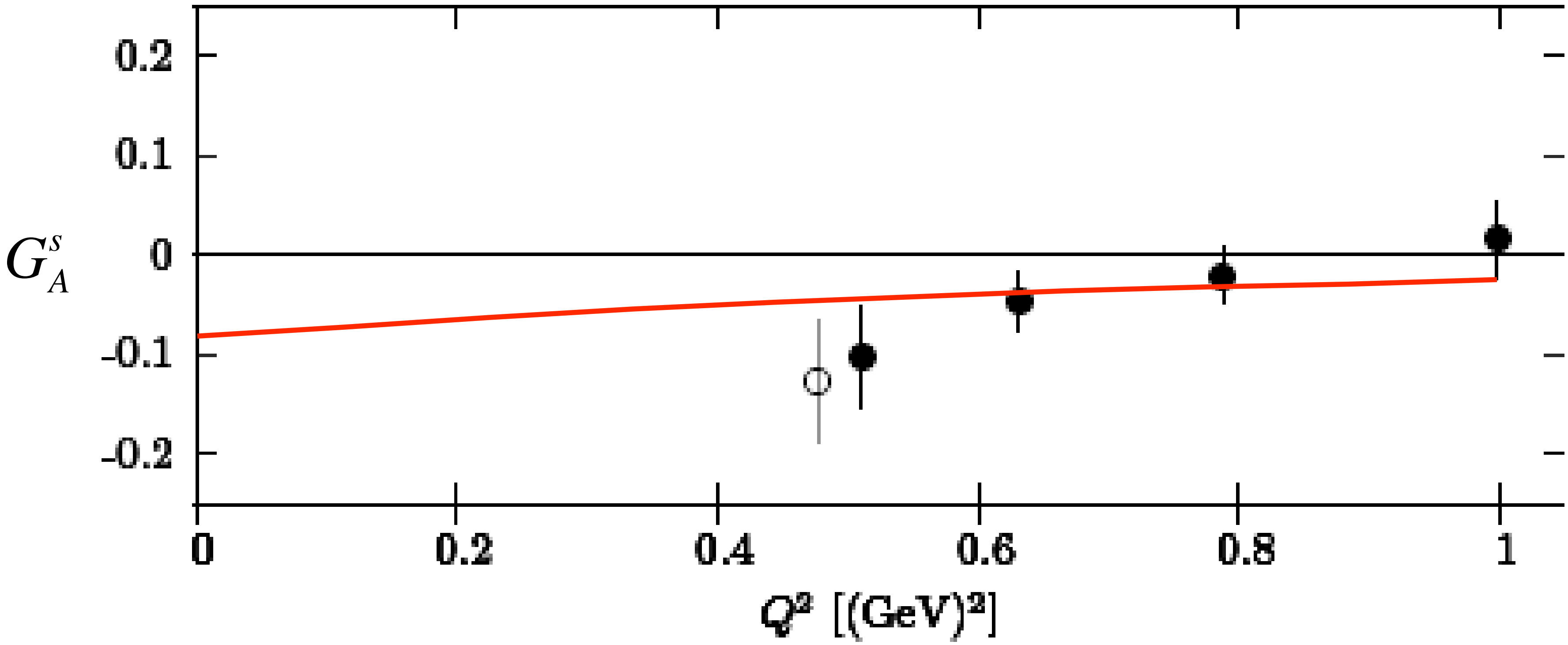
● G0 & E734

[to be published]

○ HAPPEx & E734

[Pate, PRL 92 (2004) 082002]

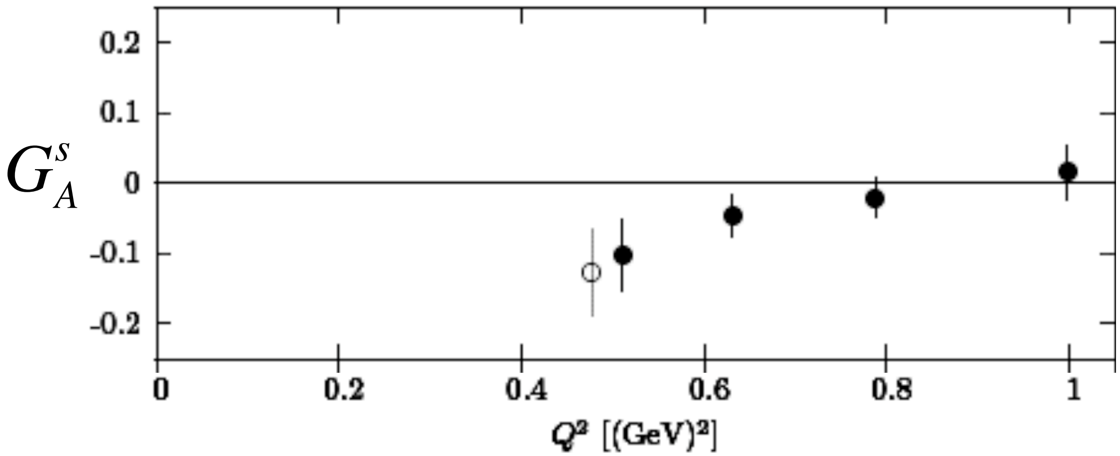
Q^2-dependence suggests $\Delta s < 0$!



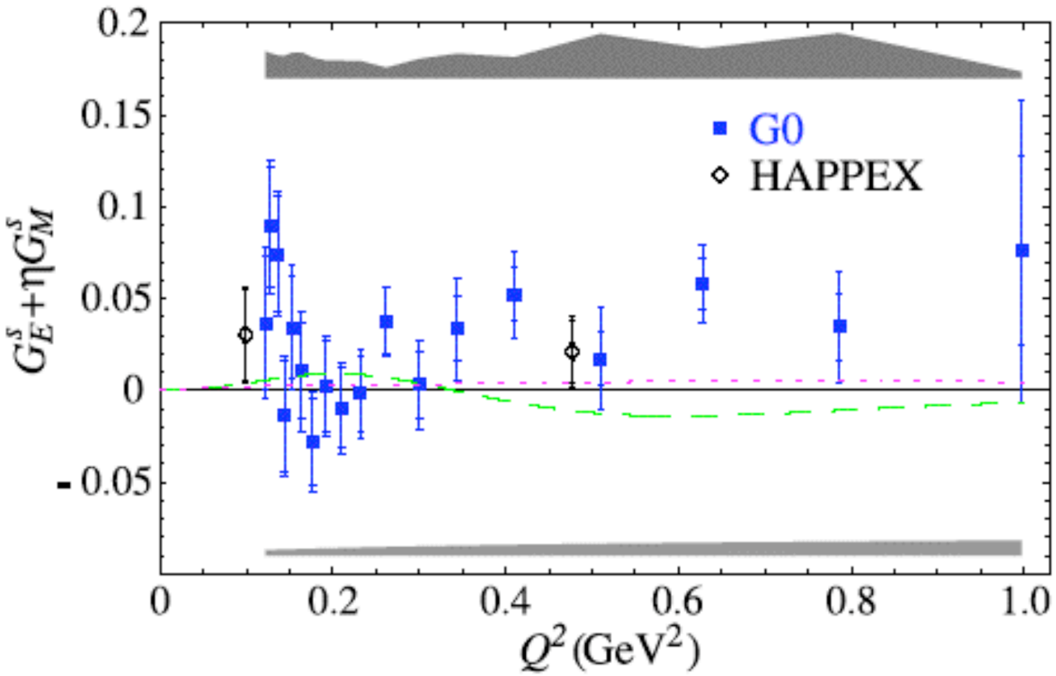
● G0 & E734
[to be published]

○ HAPPEx & E734
[Pate, PRL 92 (2004) 082002]

Recent calculation by Silva, Kim, Urbano, and Goeke (hep-ph/0509281 and Phys. Rev. D 72 (2005) 094011) based on chiral quark-soliton model is in rough agreement with the data.



These results on G_A^s...



combined with world data on $G_E^s + \eta G_M^s$...

determine a unique $uuds\bar{s}$ configuration, in which the *uuds* system is radially excited and the $\bar{s}$ is in the ground state.

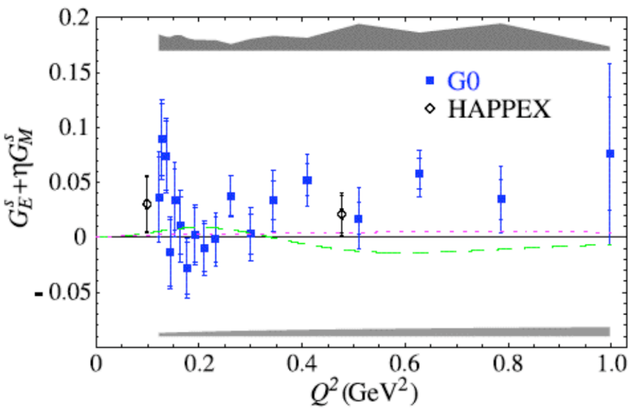
An, Riska and Zou, hep-ph/0511223; Riska and Zou, nucl-th/0512102.

Strange Vector Form Factors:
Using *ep* and *νp* data

The international program of PV *ep* measurements will completely resolve the strange vector form factors at only three Q^2 points: 0.1, 0.23 and 0.63 GeV^2.

At many other points in the range $0.038 < Q^2 < 1.0$ GeV^2, we have PV physics asymmetries that represent linear combinations of the vector, axial and anapole form factors. These can be used to constrain fits that seek to understand the Q^2-dependence of these form factors.

As has just been demonstrated, a combination of the forward-scattering PV *ep* data with elastic *νp* data provides several more points where the vector form factors are resolved, and with reasonable error bars: 0.63, 0.79, and 0.99 GeV^2. **These can already provide powerful constraints on global fits.**



Global fits will use these five resolved points,

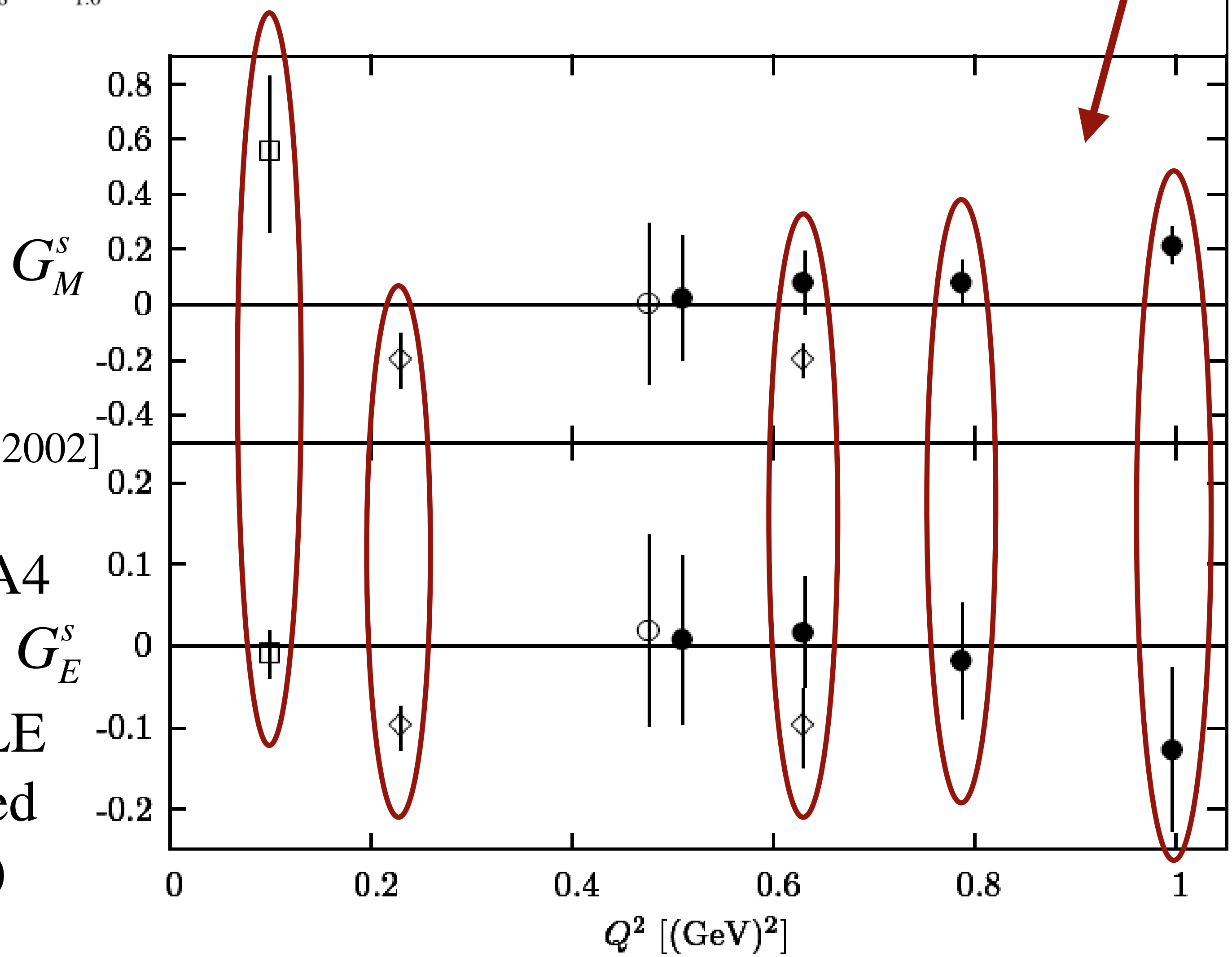
and also the linear combination constraints.

● G0 & E734
[to be published]

○ HAPPEx & E734
[Pate, PRL 92 (2004) 082002]

◇ G0/HAPPEx/PVA4
Projected

□ HAPPEx, SAMPLE
& PVA4 combined
(nucl-ex/0506011)



But better νp data are needed!

The E734 data have insufficient precision and too narrow a Q^2 range to achieve the full potential of this physics program. Better neutrino data is needed, with smaller uncertainties and points nearer $Q^2 = 0$, to fulfill the potential of this analysis method.

A detailed understanding of the Q^2-dependence of these form factors will not be possible until a more dense set of resolved data points are available. FINeSSE can provide these additional data points.

△ FINeSSE (& G0)
[exp. proposal:
no nuclear initial or
final state effects
included in errors]

● G0 & E734
[to be published]

○ HAPPEx & E734
[Pate, PRL 92 (2004) 082002]

◇ G0/HAPPEx/PVA4
Projected

□ HAPPEx, SAMPLE
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