Neutral Current Weak Form Factors & Neutrino Scattering

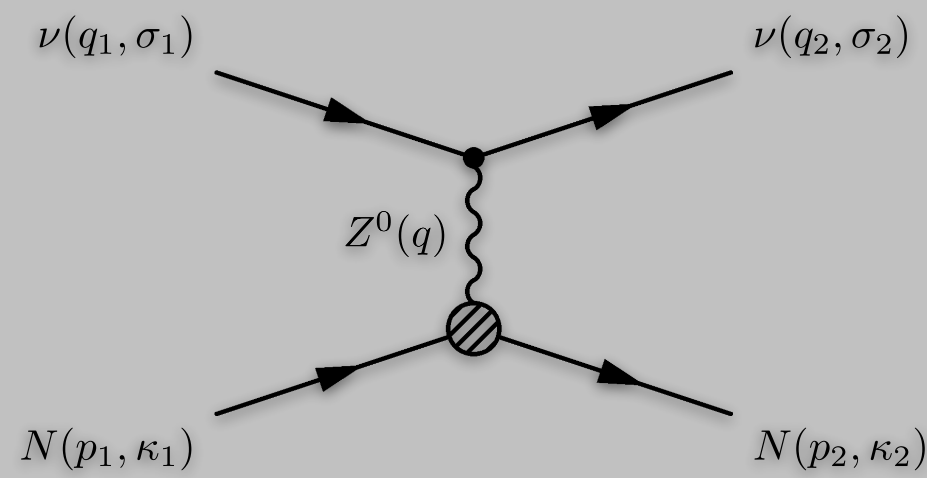
Raza Sabbir Sufian

USQCD All Hands' Meeting 2018

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Neutrino-Nucleon Neutral Current Elastic Scattering

$$\boxed{\begin{array}{ccc} \nu + p & \longrightarrow & \nu + p \\ \bar{\nu} + p & \longrightarrow & \bar{\nu} + p \end{array}}$$



Matrix element in V-A structure of leptonic current

$$M = \frac{i}{2\sqrt{2}} G_F \underbrace{\bar{\nu}(q_2)\gamma_\mu(1-\gamma_5)\nu(q_1)}_{\text{leptonic current}} \underbrace{\langle N(p_2)|J_Z^\mu|N(p_1)\rangle}_{\text{hadronic current}} .$$

$$\boxed{\langle N(p_2)|\, J_Z^\mu \,|N(p_1)\rangle = \bar{u}(p_2)[F_1^Z(Q^2) + F_2^Z(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M_N} + F_A^Z(Q^2)\gamma^\mu\gamma_5]u(p_1)}$$

(Anti)Neutrino-Nucleon Scattering Differential Cross Section

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

$$W = 4(E_\nu/M_p - \tau)$$

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

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

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

Neutral Weak Dirac & Pauli FFs

Weak axial FF

Calculation of F_1^Z and F_2^Z

$$\boxed{F^{Z,p}_{1,2} = \left(\frac{1}{2} - \sin^2\theta_W\right)(F^p_{1,2}(Q^2) - F^n_{1,2}(Q^2)) - \sin^2\theta_W(F^p_{1,2} + F^n_{1,2}) - \frac{F^s_{1,2}}{2}}$$

Nucleon EMFF from Model Independent z-expansion

PL B 777 (2018) 8-15

Ye, Arrington, Hill, Lee

Strange EMFF from Lattice QCD

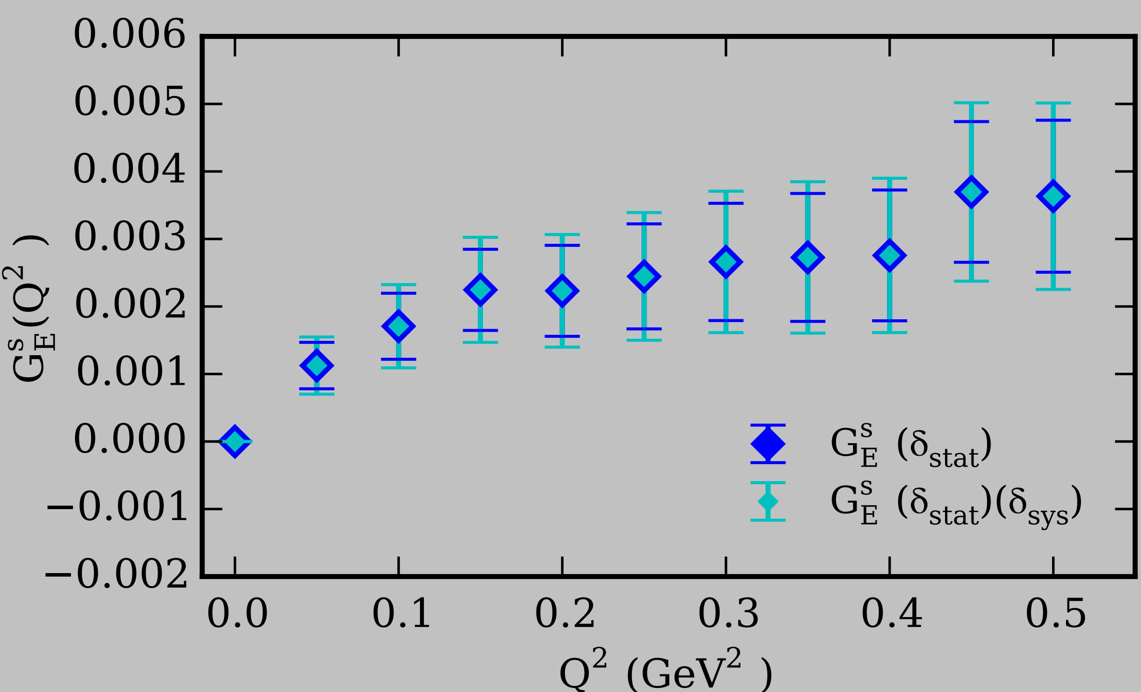
PRL 118, 042001 (2017)

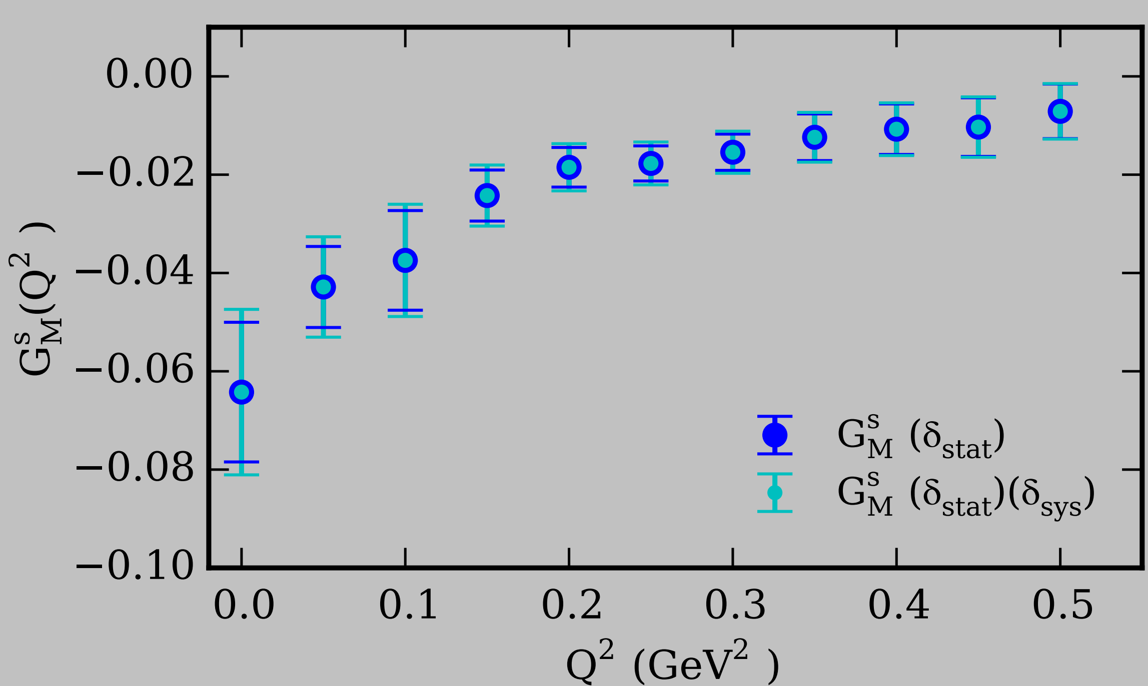
RSS, Yang, Alexandru, Draper, Liang, Liu

Physical point
4 lattice spacings
3 volumes

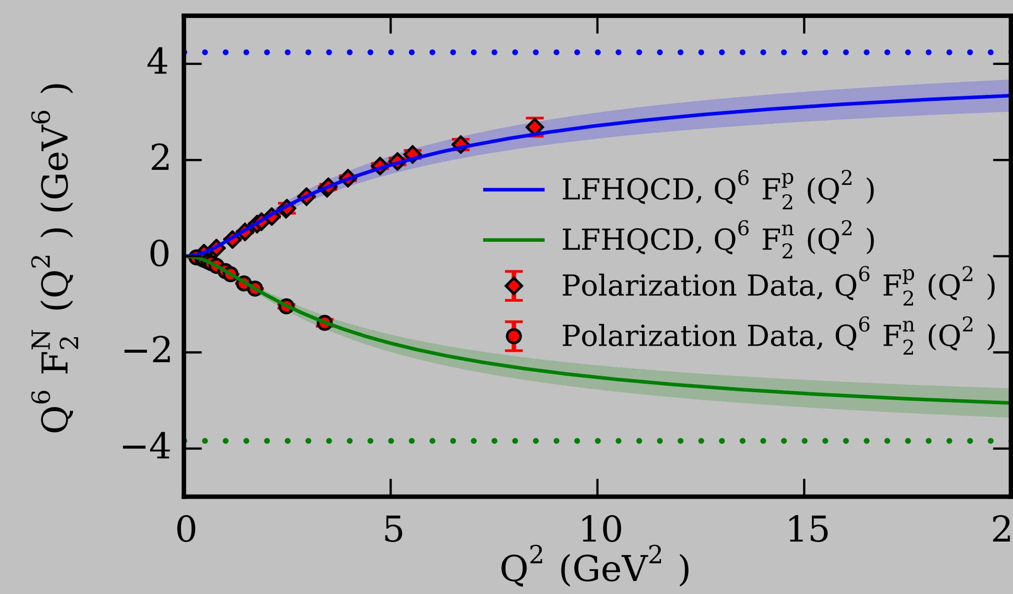
Inputs for Previous Neutral Weak EMFFs

Strange EMFF

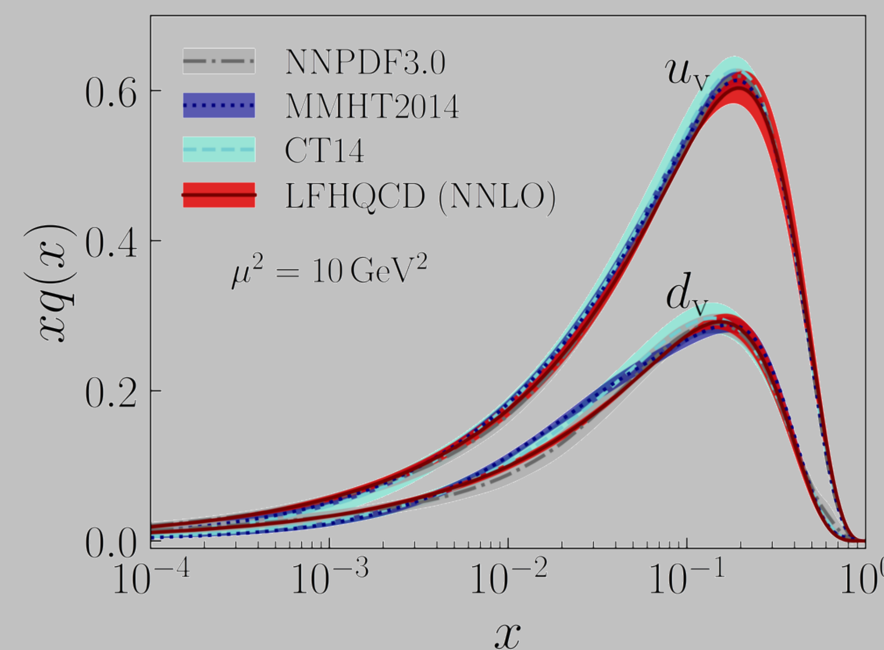




Nucleon EMFF (total)



PRD 95, 014011(2017)
RSS, de Teramond, Brodsky, Dosch, Deur

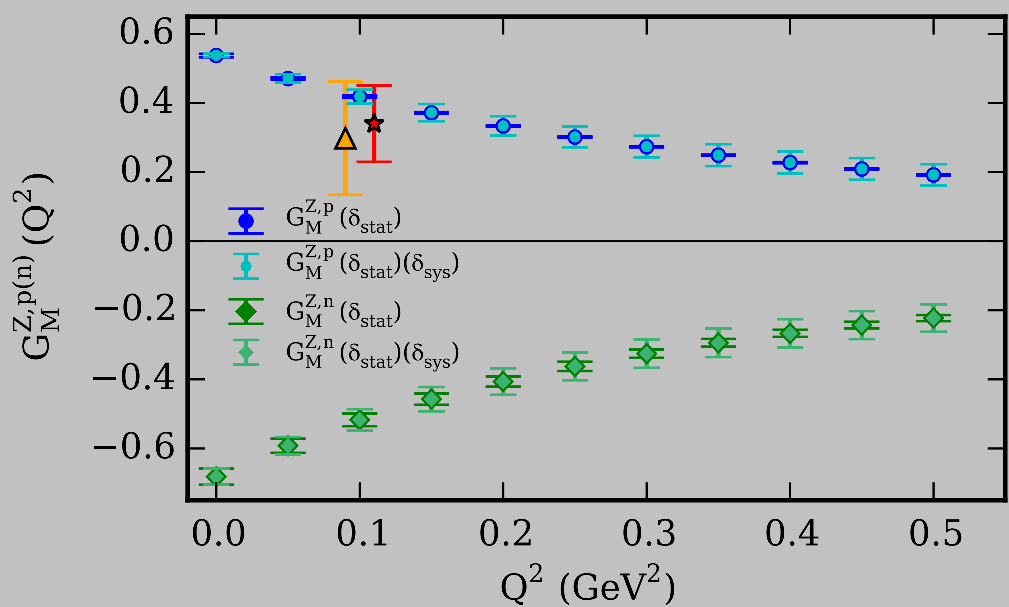


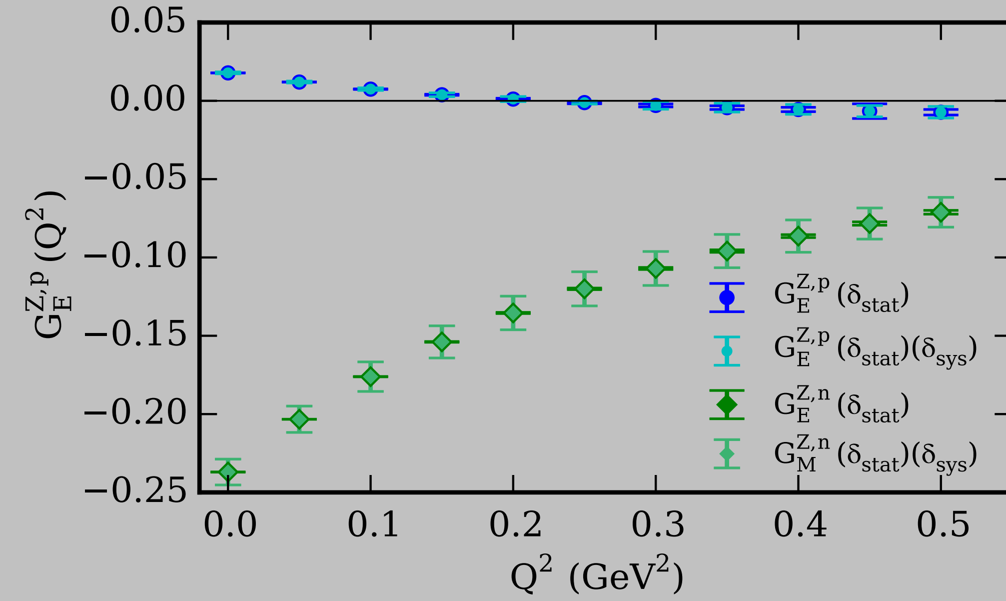
PRL 2018
de Teramond, Liu, RSS, Brodsky, Dosch, Deur

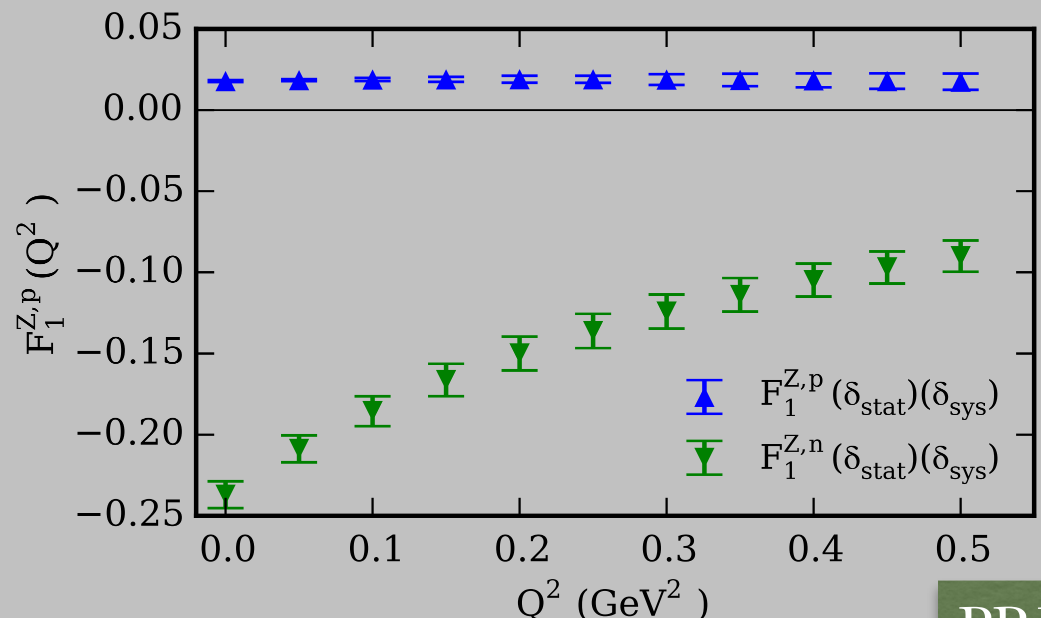
Calculation of Neutral Weak EMFFs

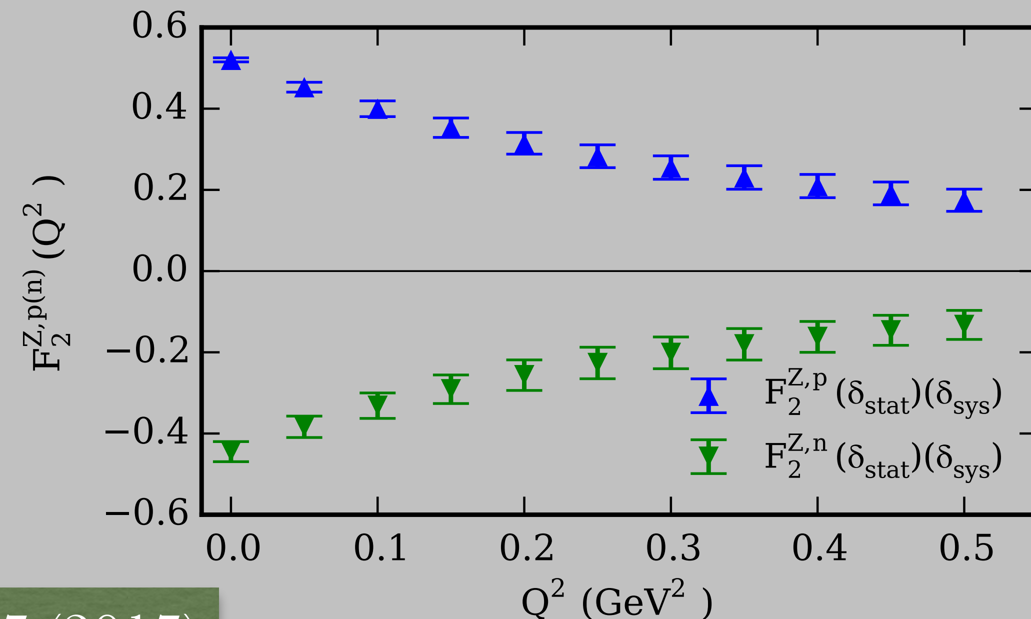
$$G^{Z,p(n)}_{E,M}(Q^2) = \frac{1}{4}\Big[(1-4\sin^2\theta_W)(1+R_V^{p(n)})G^{\gamma,p(n)}_{E,M}(Q^2) - (1+R_V^{n(p)})G^{\gamma,n(p)}_{E,M}(Q^2) - G^{s}_{E,M}(Q^2)\Big]$$

Radiative corrections for e-p scattering









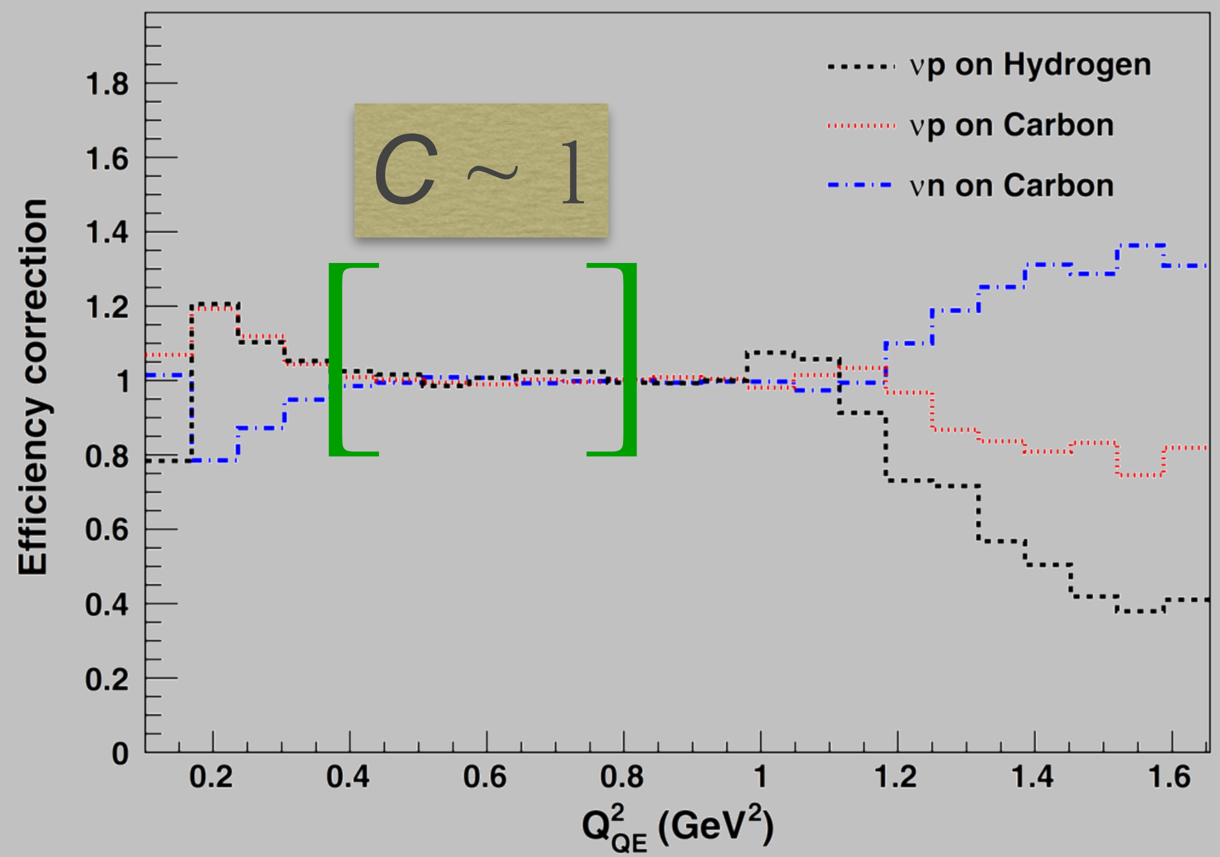
PRD 96, 093007 (2017)
RSS

Determination of Neutral Current Weak Axial FF

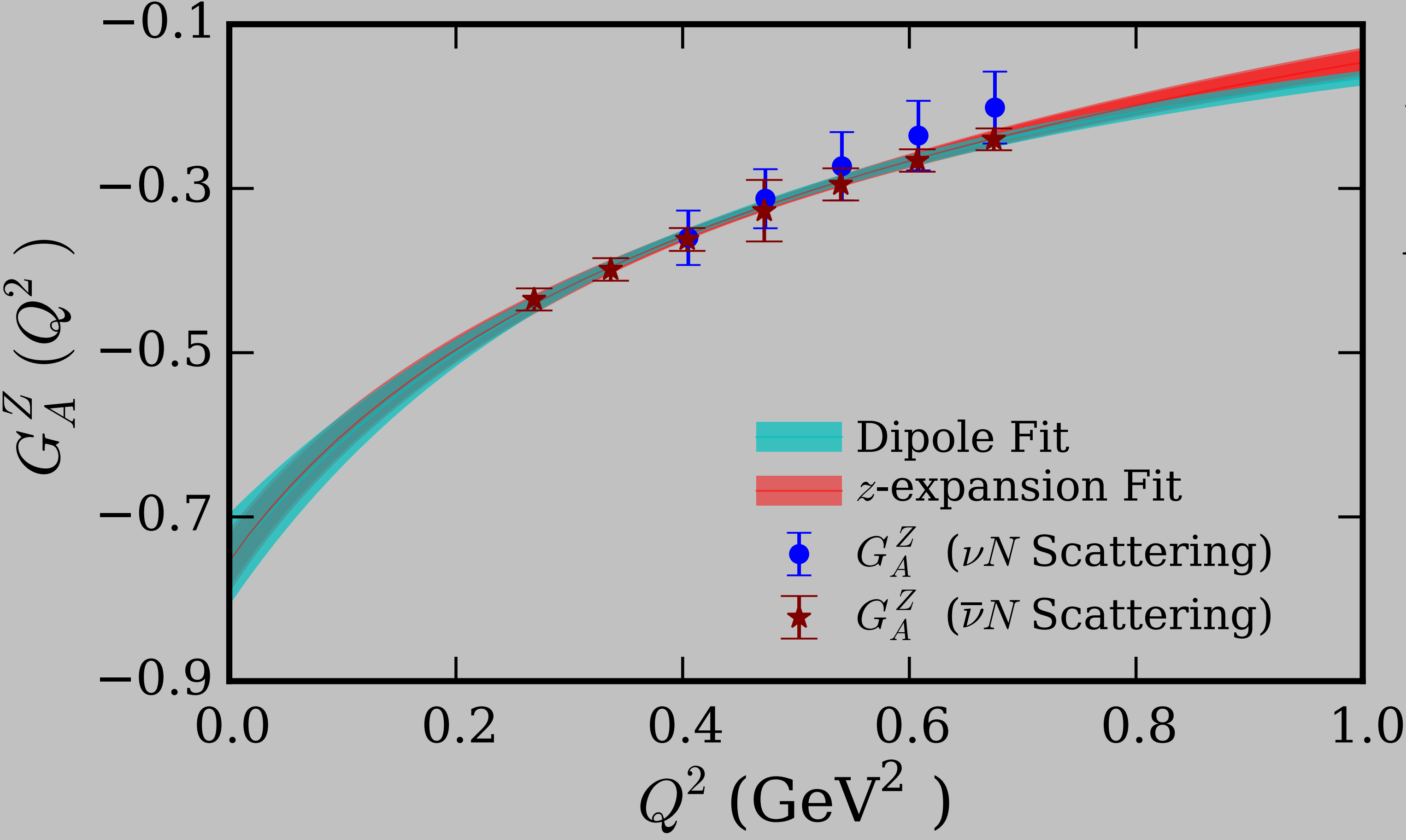
*Use MiniBooNE data ($0.27 < Q^2 < 0.65$ GeV^2)

Reason 1: Uncertainty in $G^s_{E,M}$ becomes very large and values consistent with zero

Reason 2: Nuclear effect can be large for at low Q^2



Determination of Neutral Current Weak Axial FF



$\frac{d\sigma}{dQ^2}$ From MiniBooNE Experiment

$\left.\begin{matrix} F^p_{1,2} \\ F^n_{1,2} \end{matrix}\right\}$ From Experiment

$F^s_{1,2}$ From Lattice QCD

$G^Z_A(0) = -0.751(56)$

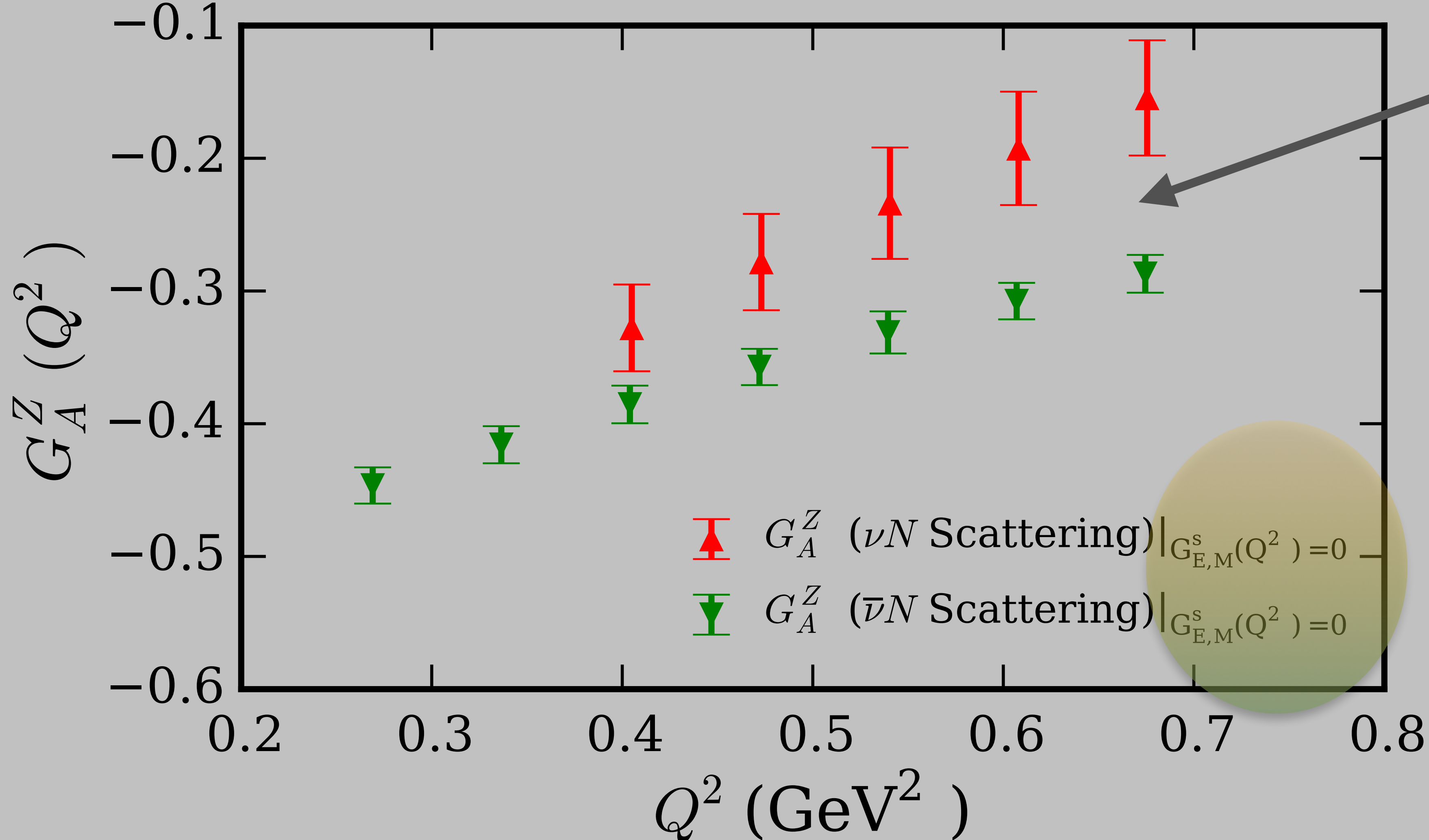
$M_{dipole} = 0.95(6)$ GeV

In preparation with
Keh-Fei Liu & David Richards

Impact of Lattice QCD Strange EMFF

Possibility: Since strange quark contribution is small

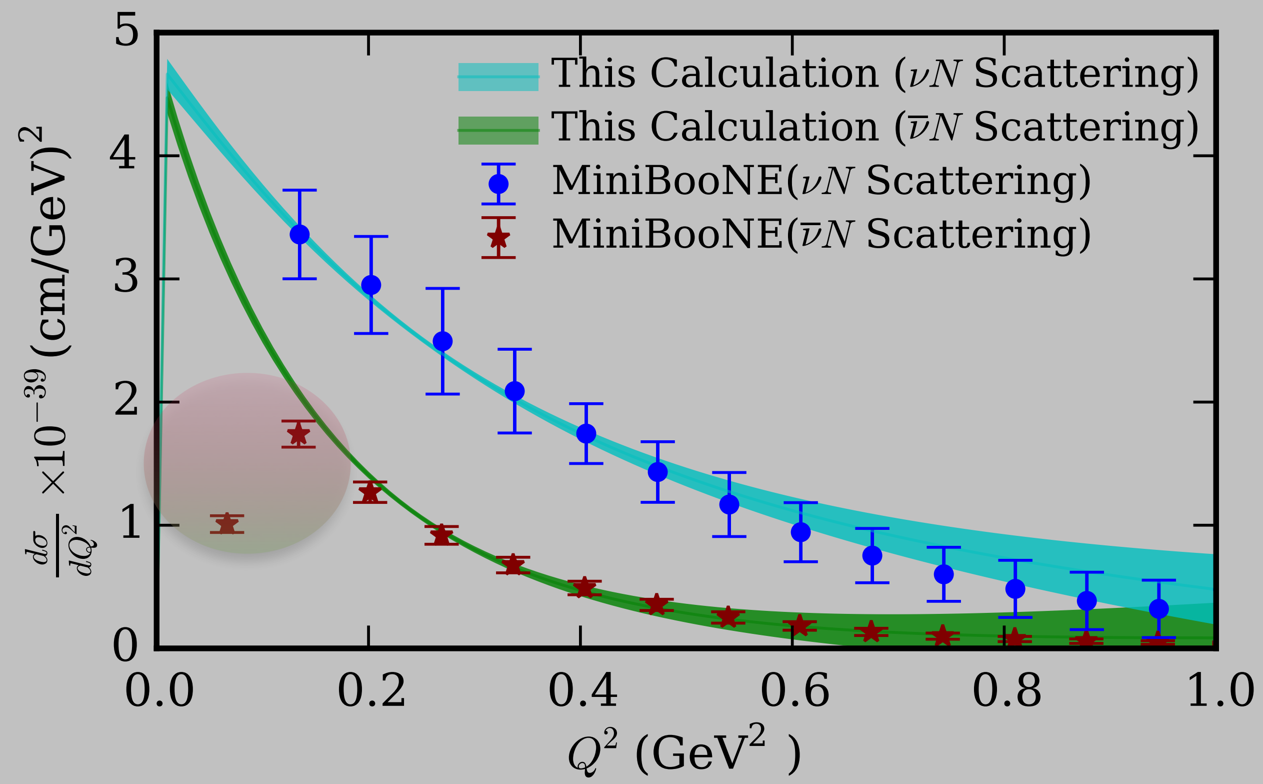
set $G^s_{E,M}$ =0 (??)



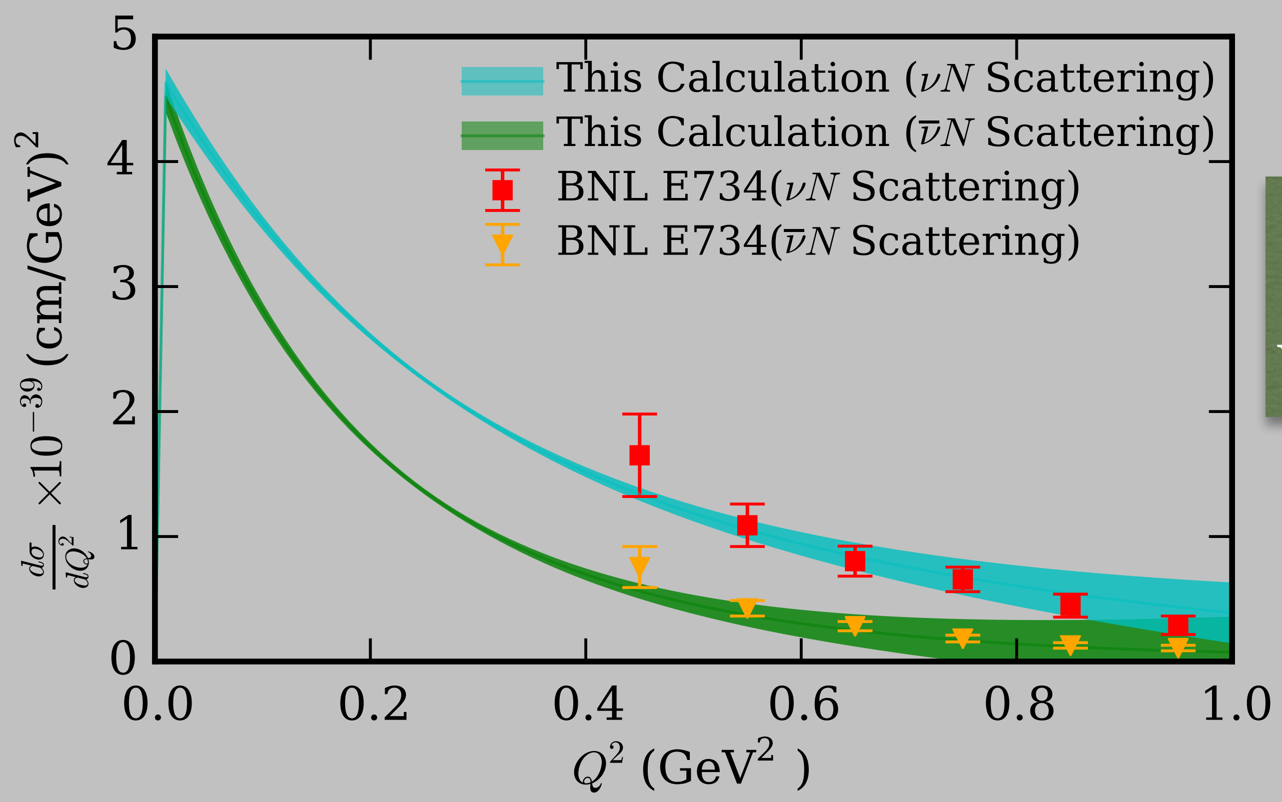
Discrepancy !!

$G^s_{E,M}=0$

Reconstruction of Differential Cross Sections



Nuclear effects
Pauli blocking &
nuclear shadowing
at $Q^2 < 0.15$ GeV^2



BNL E734 data
was NOT used in the analysis

Estimate of $G^s_A(0)$

This Calculation

$$G^Z_A = \frac{1}{2}(-G^{CC}_A + G^s_A)$$

$$G^Z_A(0) = -0.751(56)$$

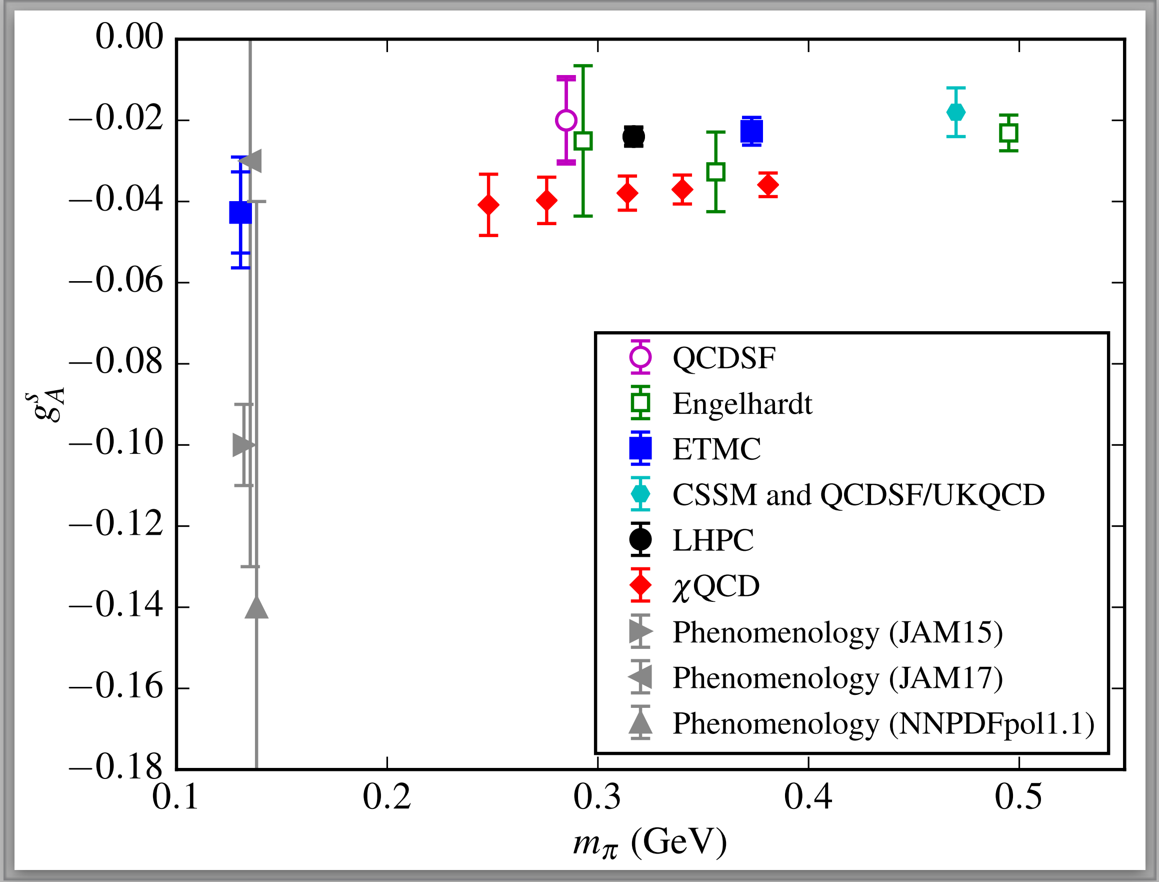
$$G^{CC}_A(0) = 1.2723(23)$$

$$G^s_A(0) = -0.23(11)$$

Other Calculations

MiniBooNE, PRD 82 (2010) $G^s_A(0) = 0.08(26)$

BNL E734, PRC 48 (1993) $G^s_A(0) = -0.21(10)$



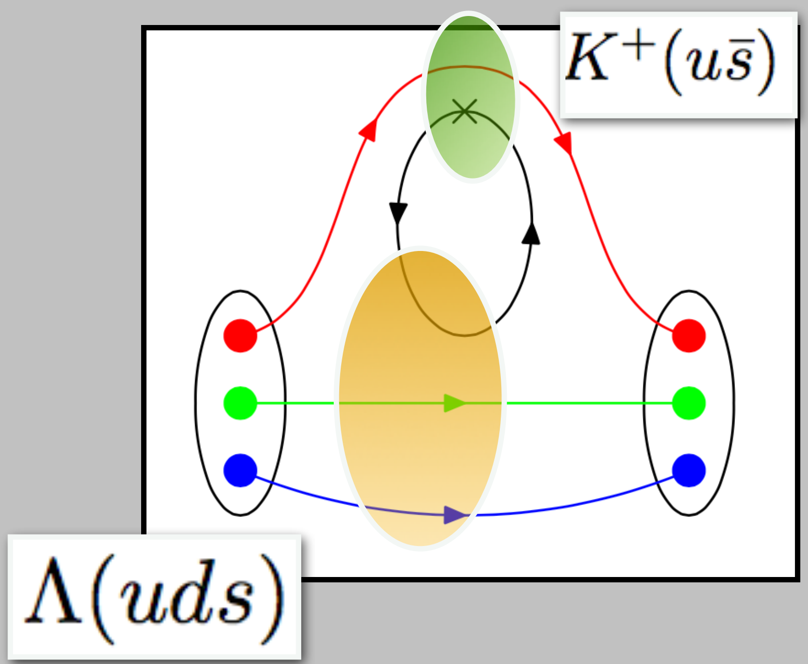
From Jeremy Green's Talk

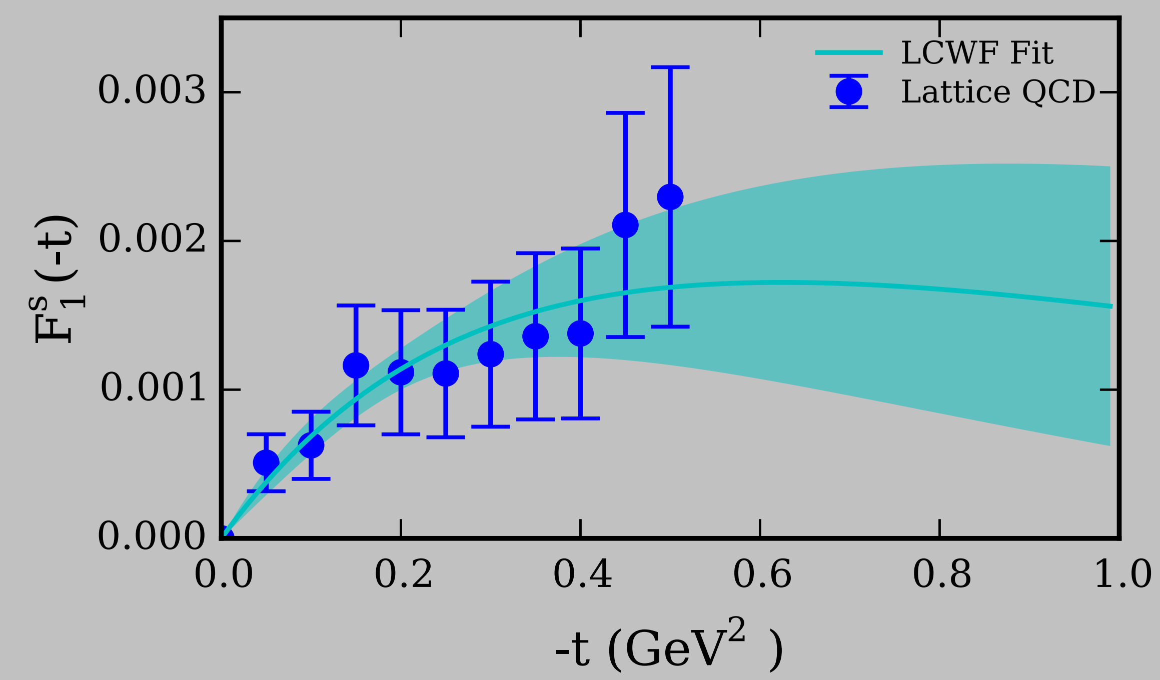
Summary

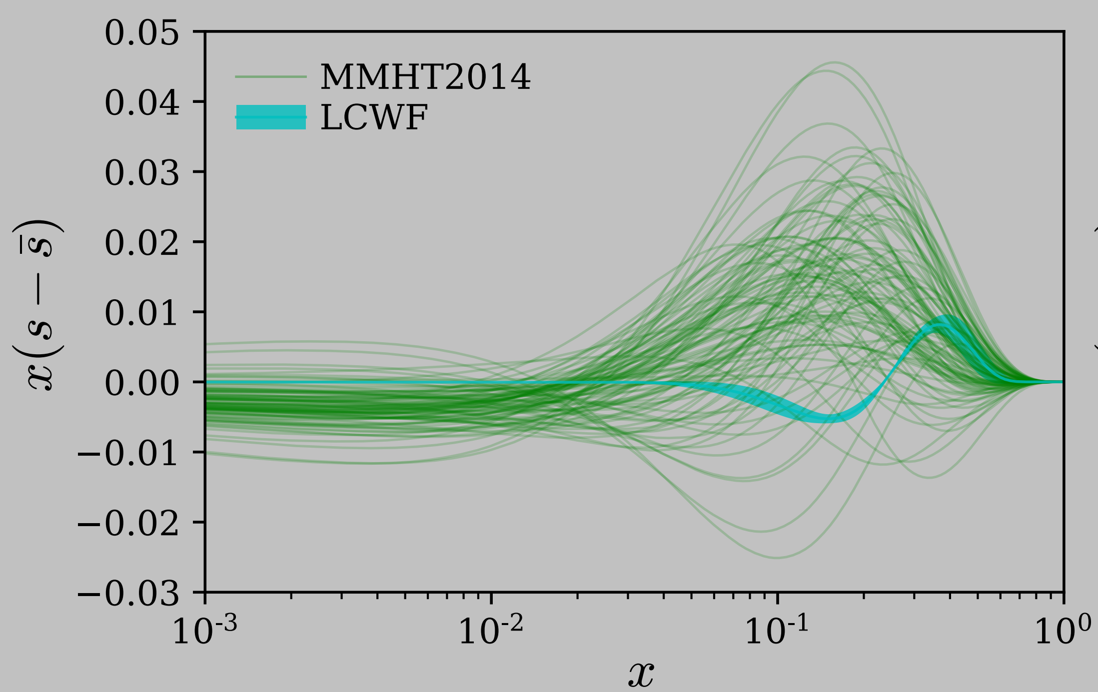
- Precise estimate of NC weak axial form factor G^Z_A
- Strange quark contribution cannot be ignored
- Reconstruction of (anti)neutrino- nucleon diff. cross sections with correct prediction of G^Z_A and lattice input of $G^s_{E,M}$
- Lattice QCD calculation of G^s_A in the continuum and infinite volume limit with controlled systematic uncertainties required

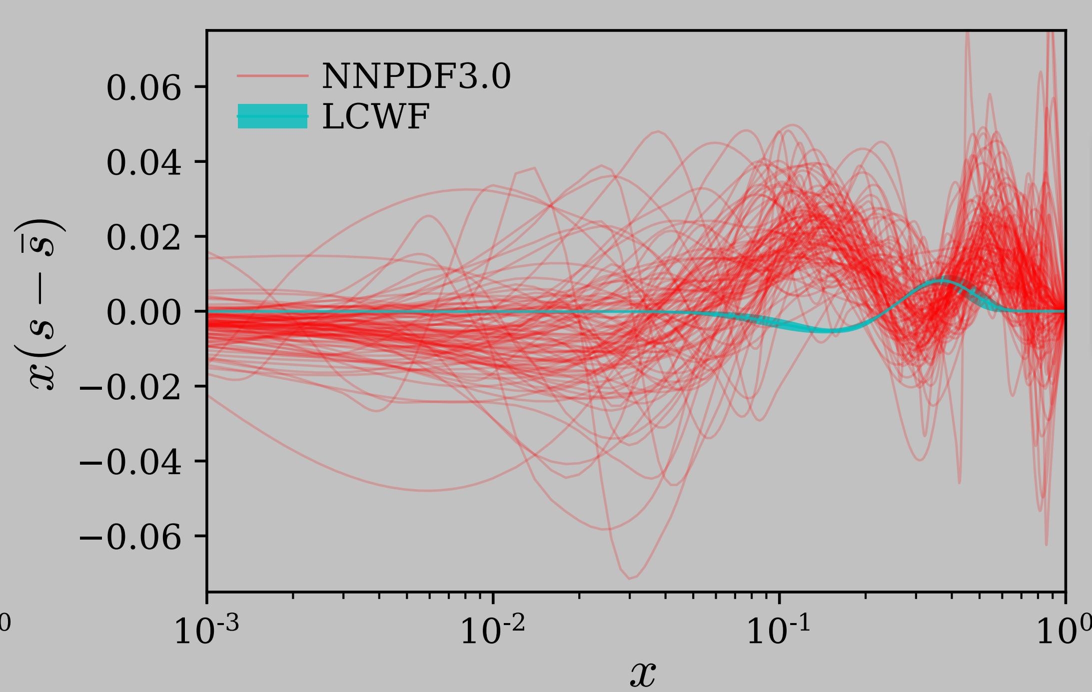
An Example: LQCD Constraint on Models

Many models of meson-baryon fluctuations to study *s(x)-$\bar{s}$(x) asymmetry*









In Preparation

S.F. Pate, Phys. Rev. Lett. **92**, 082002 (2004)

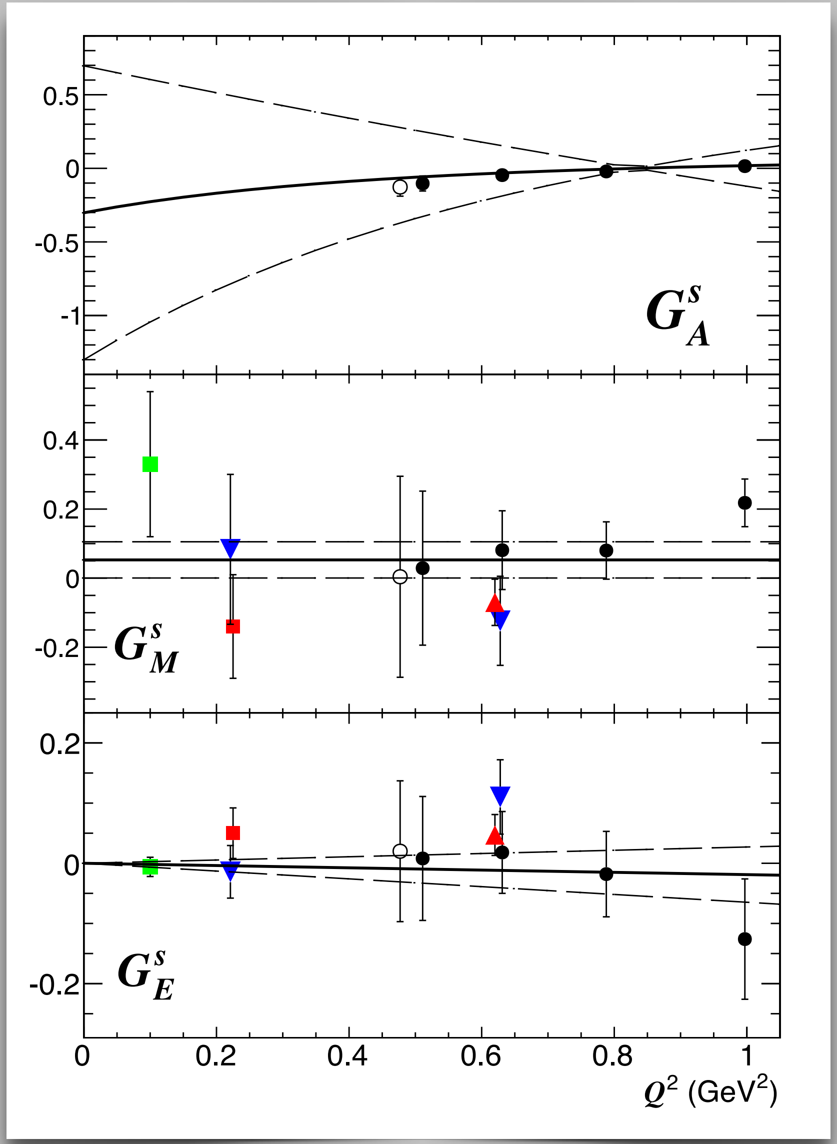
TABLE II. Two solutions for the strange form factors at $Q^2 = 0.5\ \text{GeV}^2$ produced from the E734 and HAPPEX data.

	Solution 1	Solution 2
G_E^s	0.02 ± 0.09	0.37 ± 0.04
G_M^s	0.00 ± 0.21	-0.87 ± 0.11
G_A^s	-0.09 ± 0.05	0.28 ± 0.10

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

Pate, et al

EPJ Web Conf. 66 (2014) 06018



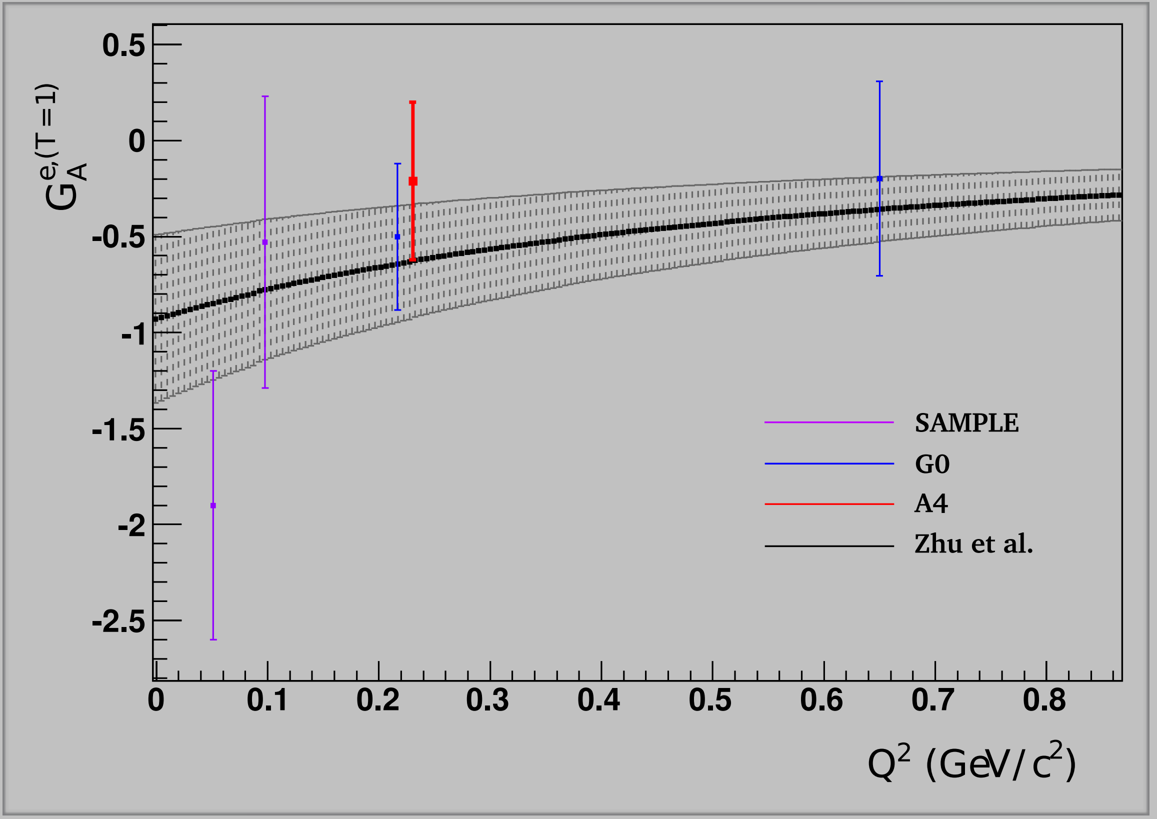
Weak Axial FF form e-p scattering

$$
\begin{aligned}
A^p_{PV} = &-\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\frac{1}{[\epsilon(G^p_E)^2+\tau(G^p_M)^2]}\\
&\times\{(\epsilon(G^p_E)^2+\tau(G^p_M)^2)(1-4\sin^2\theta_W)(1+R^p_V)\\
&-(\epsilon G^p_E G^n_E+\tau G^p_M G^n_M)(1+R^n_V)\\
&-(\epsilon G^p_E G^s_E+\tau G^p_M G^s_M)(1+R^{(0)}_V)\\
&-\epsilon'(1-4\sin^2\theta_W)G^p_M G^e_A\},
\end{aligned}
$$

with

$$
\tau=\frac{Q^2}{4M_p^2},\quad \epsilon=\left(1+2(1+\tau)\tan^2\frac{\theta}{2}\right)^{-1},
$$

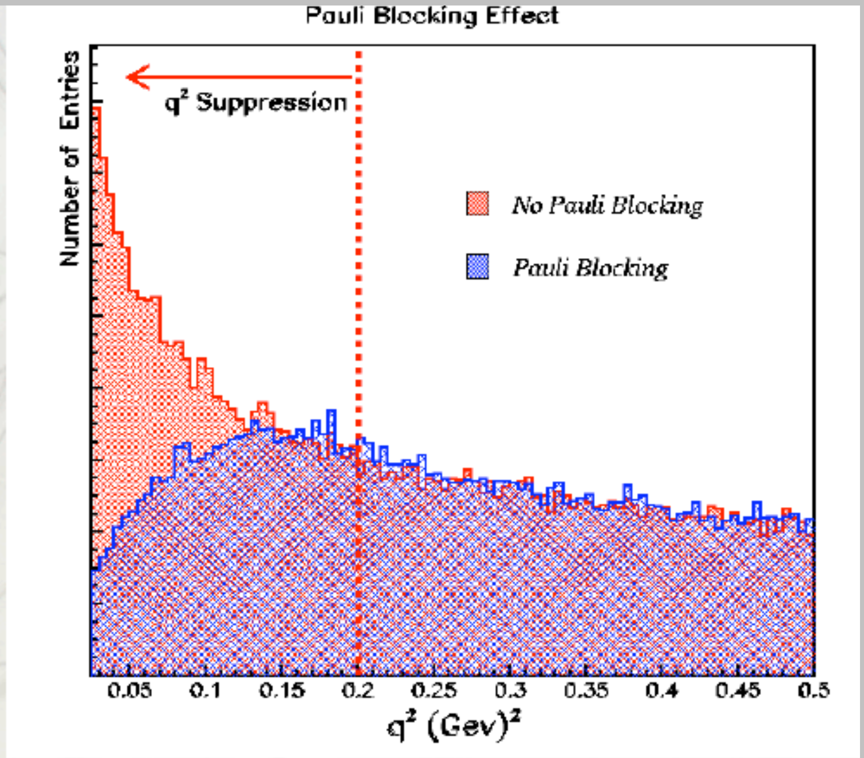
$$
\epsilon'=\sqrt{\tau(1+\tau)(1-\epsilon^2)},
$$



	$R_A^{T=1}$	$R_A^{T=0}$	$R_A^{(0)}$
one-quark	-0.172	-0.253	-0.551
many-quark	$-0.086(0.34)$	$0.014(0.19)$	N/A
total	$-0.258(0.34)$	$-0.239(0.20)$	$-0.55(0.55)$

$$\nu_\mu + n \to \mu^- + p \quad , \quad \bar{\nu}_\mu + p \to \mu^+ + n \ ,$$
$$\nu_e + n \to e^- + p \quad , \quad \bar{\nu}_e + p \to e^+ + n \ .$$

Particle	Lifetime (ns)	Decay mode	Branching ratio (%)
π^+	26.03	$\mu^+ + \nu_\mu$	99.9877
		$e^+ + \nu_e$	0.0123
K^+	12.385	$\mu^+ + \nu_\mu$	63.44
		$\pi^0 + e^+ + \nu_e$	4.98
		$\pi^0 + \mu^+ + \nu_\mu$	3.32
K_L^0	51.6	$\pi^- + e^+ + \nu_e$	20.333
		$\pi^+ + e^- + \overline{\nu}_e$	20.197
		$\pi^- + \mu^+ + \nu_\mu$	13.551
		$\pi^+ + \mu^- + \overline{\nu}_\mu$	13.469
μ^+	2197.03	$e^+ + \nu_e + \overline{\nu}_\mu$	100.0


Pauli Blocking Effect
Number of Entries
q² Suppression
No Pauli Blocking
Pauli Blocking
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
q² (Gev)²