Nucleon and Hyperon Form Factors from Lattice QCD

Huey-Wen Lin

RIKEN BNL Research Center

Jefferson Lab
Thomas Jefferson National Accelerator Facility

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Outline

- Background on Lattice QCD
- Nucleon Properties
  - Axial coupling charge
  - Structure functions
  - Charge radius and Goldberger-Treiman relation ($N_f = 2$)
  - Summary/Outlook: I
- From Hyperon Analysis
  - Proton strangeness magnetic moment
  - Σ and Ξ axial coupling prediction
  - Summary/Outlook: II

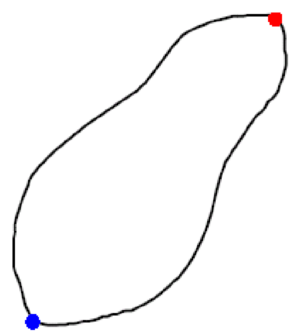
Background: Lattice 101

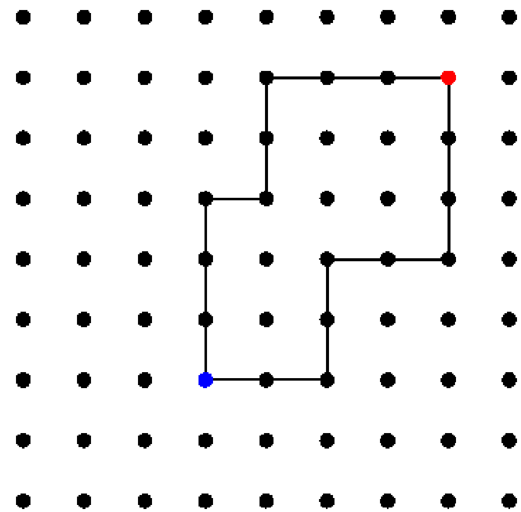
Lattice Gauge Theory

- Physical observables are calculated from the path integral

$$\langle\Omega|O|\Omega\rangle = \frac{1}{Z}\int [dU][d\overline{\psi}][d\psi]\,O(U,\overline{\psi},\psi)\,e^{i\int d^4x[S_F(U,\overline{\psi},\psi)+S_G(U)]}$$

- Lattice QCD is a discrete version of continuum QCD theory





- Use Monte Carlo integration combined with the "importance sampling" technique to calculate the path integral.

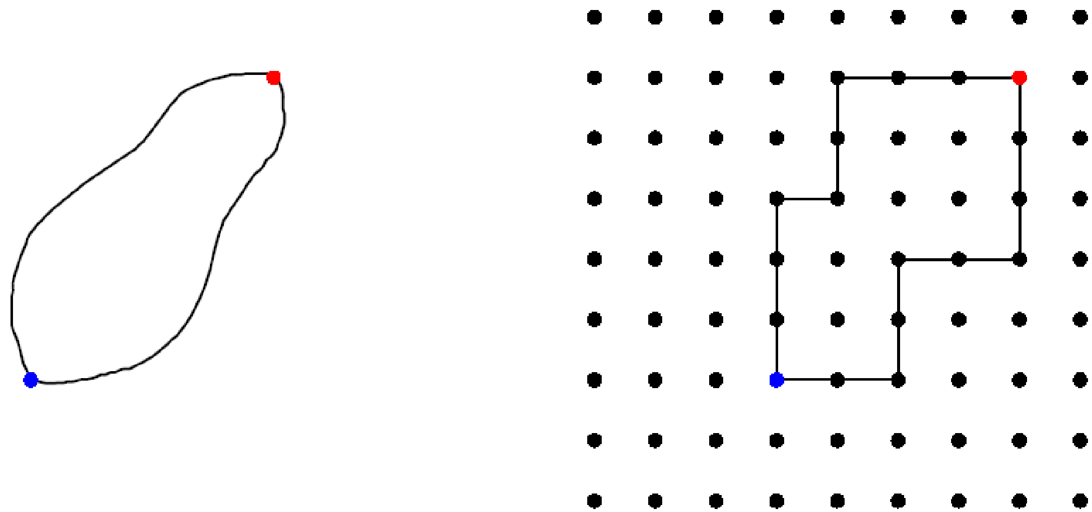
- Take $a \rightarrow 0$ and $V \rightarrow \infty$ for the "continuum limit"

Lattice Gauge Theory

- Physical observables are calculated from the path integral

$$\langle \Omega | O | \Omega \rangle = \frac{1}{Z} \int [dU][d\overline{\psi}][d\psi] O(U, \overline{\psi}, \psi) e^{i \int d^4x [S_F(U, \overline{\psi}, \psi) + S_G(U)]}$$

- Lattice QCD is a discrete version of continuum QCD theory



- Use Monte Carlo integration combined with the "importance sampling" technique to calculate the path integral.

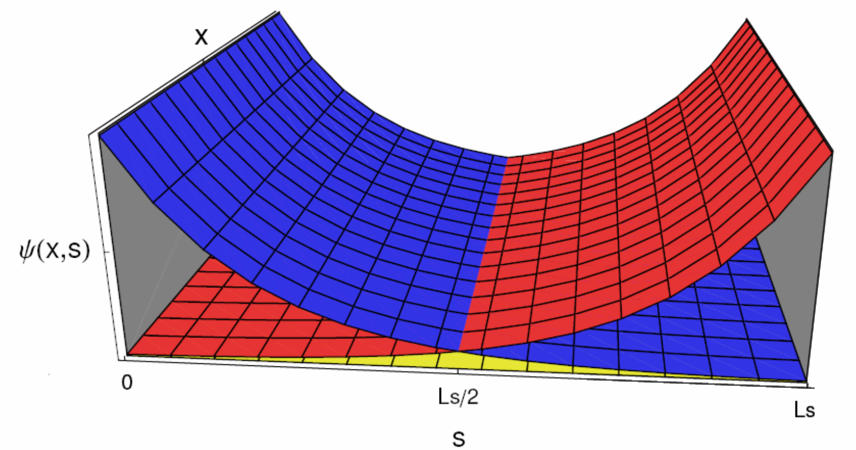
- Chiral extrapolation $m_\pi \rightarrow (m_\pi)_{\text{phys}}$

Lattice Fermion Actions

- **Chiral fermions (e.g., Domain-Wall/Overlap):**
  - Automatically $O(a)$ improved, suitable for spin physics and weak matrix elements
  - Expensive

$$D_{x,s;x',s'} = \delta_{x,x'} D^{\perp}_{s,s'} + \delta_{s,s'} D^{\|}_{x,x'}$$

$$\begin{aligned} D^{\perp}_{s,s'} &= \frac{1}{2}[(1-\gamma_5)\delta_{s+1,s'} + (1+\gamma_5)\delta_{s-1,s'} - 2\delta_{s,s'}] \\ &- \frac{m_f}{2}[(1-\gamma_5)\delta_{s,L_s-1}\delta_{0,s'} + (1+\gamma_5)\delta_{s,0}\delta_{L_s-1,} \end{aligned}$$



- **(Improved) Staggered fermions (asqtad):**
  - Relatively cheap for dynamical fermions (good)
  - Mixing among parities and flavours or "tastes"
  - Baryonic operators a nightmare — not suitable

- **Mixed actions:**
  - Staggered sea (cheap) with Domain-Wall valence (chiral)
  - Match the sea Goldstone pion mass to the DWF pion

Green Functions

- Interpolating field for a baryon

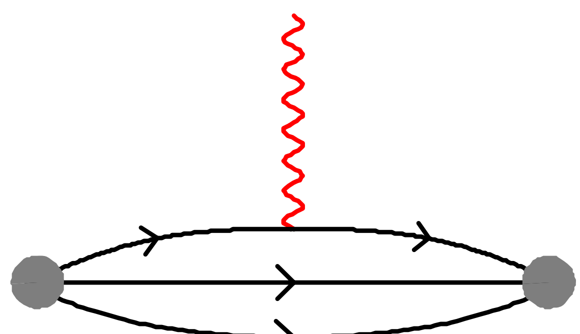
$$J_\alpha(\vec{p},t) = \sum_{\vec{x},a,b,c} e^{i\vec{p}\cdot\vec{x}}\epsilon^{abc}\left[u_a^T(y_1,t)C\gamma_5 d_b(y_2,t)\right]u_{c,\alpha}(y_3,t)\phi(y_1-x)\phi(y_2-x)\phi(y_3-x)$$

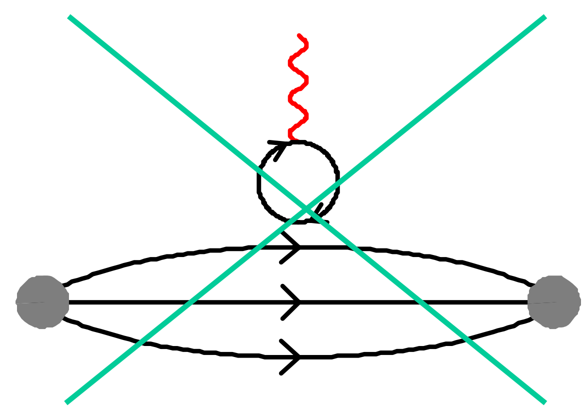
- Two-point function with projection

$$C_{\text{2pt}}(\vec{p},t) = \sum_{\alpha,\beta}\left(\frac{1+\gamma_4}{2}\right)_{\alpha\beta}\langle J_\beta(\vec{p},t)\overline{J}_\alpha(\vec{p},0)\rangle$$

- Three-point function with connected piece only

$$C_{\text{3pt}}^{\Gamma,\mathcal{O}}(\vec{p},t,\tau) = \sum_{\alpha,\beta}\Gamma^{\alpha,\beta}\langle J_\beta(\vec{p},t)\,\mathcal{O}(\tau)\overline{J}_\alpha(\vec{p},0)\rangle$$





Ratio Construction

- Two–point function

$$\Gamma^{NN}_{AB}(t_i,t_f,\vec{p}\,;\,T)\rightarrow a^6 Z^N_B(p)Z^N_A(p)\sum_s T_{\alpha\beta}\bar{u}_\alpha(\vec{p},s)u_\beta(\vec{p},s) \times \frac{m_N}{E_N(\vec{p})}e^{-(t_f-t_i)E_N(\vec{p})} = \left(\frac{E_N(\vec{p})+m_N}{2E_N(\vec{p})}\right)e^{-(t_f-t_i)E_N(\vec{p})}$$

- Three–point function

$$\Gamma^{NN}_{\mu,AB}(t_i,t,t_f,\vec{p}_i,\vec{p}_f;\,T)\rightarrow = \frac{m_N^2}{E_N(\vec{p}_f)E_N(\vec{p}_i)}e^{-(t_f-t)E_N(\vec{p}_f)}e^{-(t-t_i)E_N(\vec{p}_i)} \sum_{s,s'}T_{\alpha\beta}Z_B(p_f)u_\beta(\vec{p}_f,s') \langle N(\vec{p}_f,s')\,|j_\mu(0)|\,N(\vec{p}_i,s)\rangle\,\bar{u}_\alpha(\vec{p}_i,s)Z_A(p_i)$$

Ratio cancels out t and Z dependence

$$R_{j_\mu} = \frac{Z_V\Gamma^{(3),P}_{\mu,GG}(t_{\rm src},t,t_{\rm snk},\vec{p}_{\rm src},\vec{p}_{\rm snk})}{\Gamma^{(2),P_+}_{GG}(t_{\rm src},t_{\rm snk},\vec{p}_{\rm snk})}\sqrt{\frac{\Gamma^{(2),P_+}_{LG}(t_{\rm src},t_{\rm snk},\vec{p}_{\rm src})}{\Gamma^{(2),P_+}_{LG}(t_{\rm src},t_{\rm snk},\vec{p}_{\rm snk})}} \times\sqrt{\frac{\Gamma^{(2),P_+}_{LG}(t_{\rm src},t_{\rm snk},\vec{p}_{\rm snk})}{\Gamma^{(2),P_+}_{LG}(t_{\rm src},t_{\rm snk},\vec{p}_{\rm src})}}\sqrt{\frac{\Gamma^{(2),P_+}_{GG}(t_{\rm src},t,\vec{p}_{\rm snk})}{\Gamma^{(2),P_+}_{GG}(t_{\rm src},t,\vec{p}_{\rm src})}}$$

Nucleon Structure

(work in progress)

in collaboration with

Tom Blum, Shigemi Ohta, Kostas Orginos, Shoichi Sasaki and Takeshi Yamazaki

RIKEN BNL Research Center

2+1-flavor RBC/UKQCD Ensembles

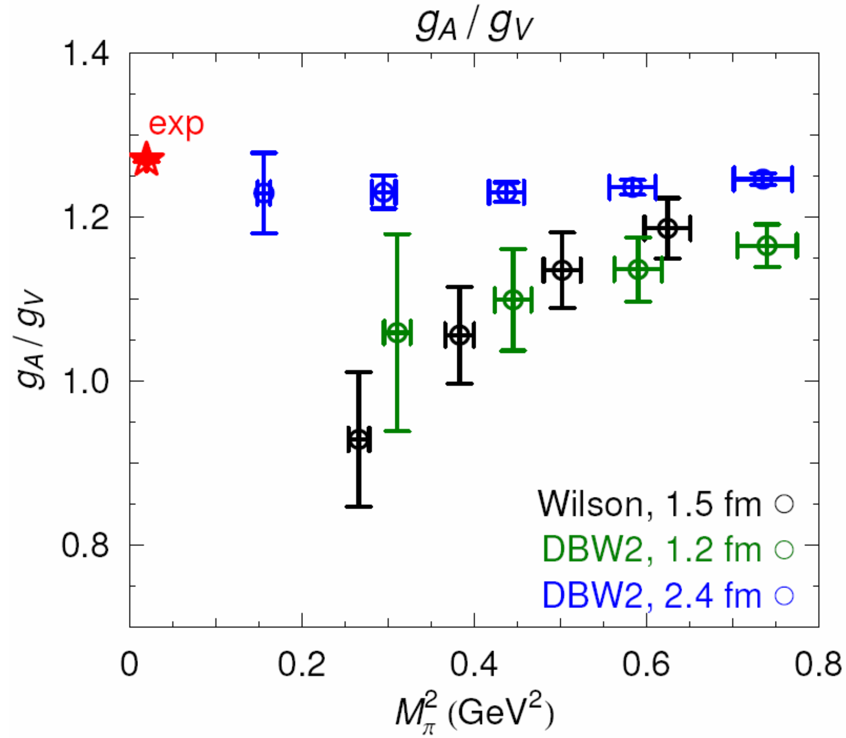
- Generated jointly by RBC and UKQCD
  - Iwasaki gauge action ($c_1 = -0.331$)
  - Pion mass range: 300–625 MeV
  - $V_{\rm lat} = 24^3 \times 64$, $a \approx 0.125$ fm, $L_s = 16$, $M_5 = 1.8$

TABLE I: Gaussian-smeared source parameters

$m_{\rm sea}$	0.01	0.02	0.03
$t_{\rm snk} - t_{\rm src}$	12	12	12
$t_{\rm src}$	0, 16, 32, 48	0, 16, 32, 48	0, 16, 32, 48
# of conf.	119	49	54
m_π (GeV)	0.399(3)	0.535(3)	0.625(3)
m_N (GeV)	1.169(19)	1.204(13)	1.474(18)

C. Allton, et al., RBC/UKQCD collaborations, coming soon

FSE (**RBCK** quenched study)



Axial Charge Coupling

- **Isovector** vector and axial-vector current

$$\langle p|V_\mu^\dagger(0)|n\rangle = \overline{u}_p[\gamma_\mu g_V(q^2) - q_\mu \sigma_{\mu\nu} g_T(q^2)]u_n$$

$$\langle p|A_\mu^\dagger(0)|n\rangle = \overline{u}_p[\gamma_\mu \gamma_5 g_A(q^2) - i q_\mu \gamma_5 g_P(q^2)]u_n$$

- Chiral symmetry gives $Z_A = Z_V = 1/g_V$
- Continuum χPT extrapolation (SSE scheme)

T. R. Hemmert et al., J. Phys. G24, 1831 (1998)

T. R. Hemmert et al., Phys. Rev. D68, 075009 (2003)

$$\begin{aligned} g_A^{\mathrm{SSE}}(m_\pi^2) \; = \; & g_A^0 + \left[4C_{\mathrm{SSE}}(\lambda) - \frac{(g_A^0)^3}{16\pi^2 f_\pi^2} - \frac{25c_A^2 g_1}{324\pi^2 f_\pi^2} + \frac{19c_A^2 g_A^0}{108\pi^2 f_\pi^2}\right] m_\pi^2 \\ & - \frac{m_\pi^2}{4\pi^2 f_\pi^2}\left[(g_A^0)^3 + \frac{1}{2} g_A^0\right] \ln\frac{m_\pi}{\lambda} + \frac{4c_A^2 g_A^0}{27\pi\Delta_0 f_\pi^2} m_\pi^3 \\ & + \left[25c_A^2 g_1 \Delta_0^2 - 57c_A^2 g_A^0 \Delta_0^2 - 24c_A^2 g_A^0 m_\pi^2\right] \frac{\sqrt{m_\pi^2 - \Delta_0^2}}{81\pi^2 f_\pi^2 \Delta_0} \arccos\frac{\Delta_0}{m_\pi} \\ & + \frac{25c_A^2 g_1 \left(2\Delta_0^2 - m_\pi^2\right)}{162\pi^2 f_\pi^2} \ln\frac{2\Delta_0}{m_\pi} + \frac{c_A^2 g_A^0 \left(3m_\pi^2 - 38\Delta_0^2\right)}{54\pi^2 f_\pi^2} \ln\frac{2\Delta_0}{m_\pi} + \mathcal{O}(\epsilon^4) \end{aligned}$$

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- Chiral symmetry gives $Z_A = Z_V = 1/g_V$
- Continuum χPT extrapolation (SSE scheme)

S. R. Beane et al., Phys. Rev. D70, 074029 (2004)

$$\delta_L(\Gamma_{NN}) \equiv \delta g_A = \frac{m_\pi^2}{3\pi^2 f^2}\left[\, g_A^3 \mathbf{F_1} + \left(g_{\Delta N}^2 g_A + \frac{25}{81} g_{\Delta N}^2 g_{\Delta\Delta}\right)\mathbf{F_2} + g_A \mathbf{F_3} + g_{\Delta N}^2 g_A \mathbf{F_4}\,\right]$$

$$\mathbf{F_2}(m,\Delta,L) = -\sum_{\mathbf{n}\neq 0}\left[\frac{K_1(mL|\mathbf{n}|)}{mL|\mathbf{n}|} + \frac{\Delta^2 - m^2}{m^2} K_0(mL|\mathbf{n}|) - \frac{\Delta}{m^2}\int_m^\infty d\beta \times \frac{2\beta\, K_0(\beta L|\mathbf{n}|) + (\Delta^2 - m^2)L|\mathbf{n}|\, K_1(\beta L|\mathbf{n}|)}{\sqrt{\beta^2 + \Delta^2 - m^2}}\right]$$

$$\mathbf{F_1}(m,L) = \sum_{\mathbf{n}\neq 0}\left[K_0(mL|\mathbf{n}|) - \frac{K_1(mL|\mathbf{n}|)}{mL|\mathbf{n}|}\right]$$

$$\mathbf{F_3}(m,L) = -\frac{3}{2}\sum_{\mathbf{n}\neq 0}\frac{K_1(mL|\mathbf{n}|)}{mL|\mathbf{n}|};$$

$$\mathbf{F_4}(m,\Delta,L) = \frac{8}{9}\sum_{\mathbf{n}\neq 0}\left[\frac{K_1(mL|\mathbf{n}|)}{mL|\mathbf{n}|} - \frac{\pi e^{-mL|\mathbf{n}|}}{2\Delta L|\mathbf{n}|} - \frac{\Delta^2 - m^2}{m^2\Delta}\int_m^\infty d\beta\, \frac{\beta\, K_0(\beta L|\mathbf{n}|)}{\sqrt{\beta^2 + \Delta^2 - m^2}}\right],$$

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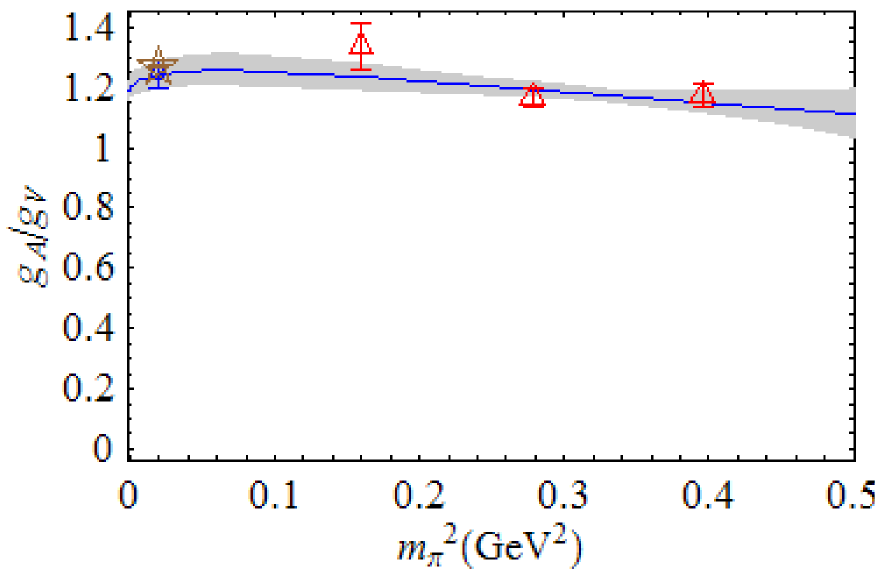
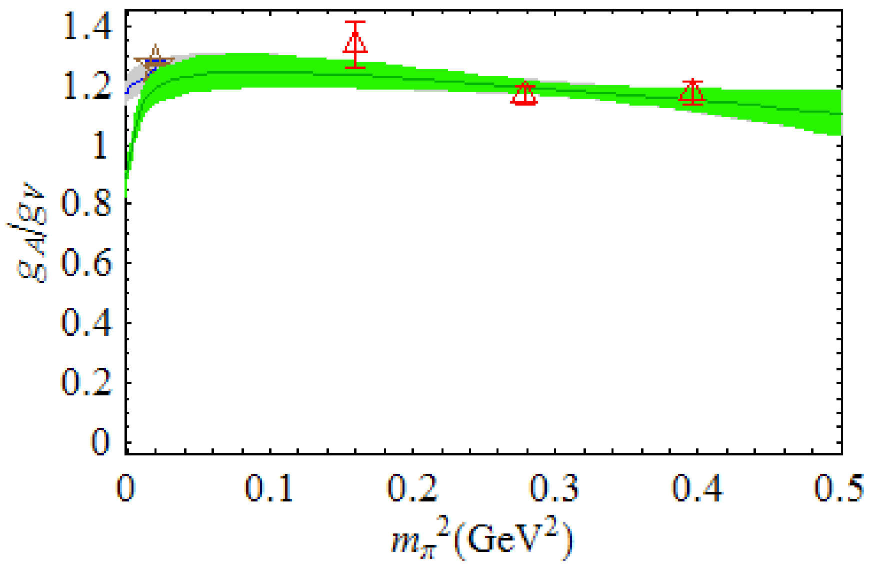
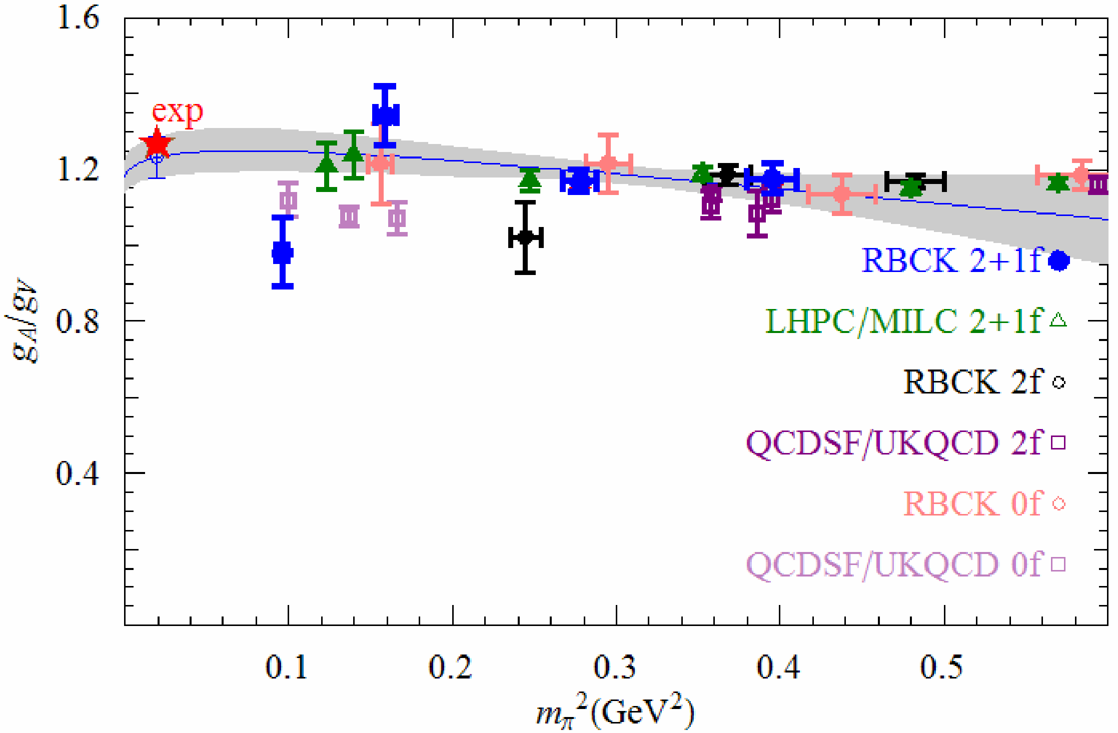




Axial Charge Coupling: Global View

- Comparison among various lattice results (Lattice 2006)
- Add in the lightest pion mass point (310 MeV)



K. Orginos et al., Phys.Rev.D73:094507, 2005; H.-W. Lin et al., coming soon

M. Guertler et al., PoS(LAT2006)107; D. Pleiter et al., PoS(LAT2006)120

D. Renner et al., PoS(LAT2006)121

Nucleon Structure Functions

- List of Operators: lowest moments only

$\langle x\rangle_q$	$\langle x\rangle_{\Delta q}$
momentum fraction	helicity distribution
$\mathcal{O}^q_{44} = \overline{q}\left[\gamma_4 \overleftrightarrow{D}_4 - \frac{1}{3}\sum_k \gamma_k \overleftrightarrow{D}_k\right] q$	$\mathcal{O}^{5q}_{\{34\}} = i\overline{q}\gamma_5\left[\gamma_3 \overleftrightarrow{D}_4 + \gamma_4 \overleftrightarrow{D}_3\right] q$
$\mathbf{3}^+_1$	$\mathbf{6}^-_3$
$R_{\langle x\rangle_q} = \frac{C_{\text{3pt}}^{\Gamma,\mathcal{O}^q_{44}}}{C_{\text{2pt}}} = m_N \langle x\rangle_q$	$R_{\langle x\rangle_{\Delta q}} = \frac{C_{\text{3pt}}^{\Gamma,\mathcal{O}^{5q}_{\{34\}}}}{C_{\text{2pt}}} = m_N \langle x\rangle_{\Delta q}$
${\mathcal{P}^q_{44}}^{-1} = \gamma_4 p_4 - \frac{1}{3}\sum_{i=1,3}\gamma_i p_i$	${\mathcal{P}^{5q}_{34}}^{-1} = i\gamma_5\left(\gamma_3 p_4 + \gamma_4 p_3\right)$

$\langle 1\rangle_{\delta q}$	d_1
transversity	twist-3 matrix element
$\mathcal{O}^{\sigma q}_{34} = \overline{q}\gamma_5\sigma_{34} q$	$\mathcal{O}^5 q_{[34]} = i\overline{q}\gamma_5\left[\gamma_3 \overleftrightarrow{D}_4 - \gamma_4 \overleftrightarrow{D}_3\right] q$
$\mathbf{6}^+_1$	$\mathbf{6}^+_1$
$R_{\langle 1\rangle_{\delta q}} = \frac{C_{\text{3pt}}^{\Gamma,\mathcal{O}^{\sigma q}_{\{34\}}}}{C_{\text{2pt}}} = \langle 1\rangle_{\delta q}$	$R_{d_1} = \frac{C_{\text{3pt}}^{\Gamma,\mathcal{O}^{5q}_{[34]}}}{C_{\text{2pt}}} = d_1$
${\mathcal{P}^{\sigma q}_{34}}^{-1} = \gamma_5\sigma_{34}$	${\mathcal{P}^{5q}_{[34]}}^{-1} = i\gamma_5\left(\gamma_3 p_4 - \gamma_4 p_3\right)$

Nucleon Structure Functions

- Chiral extrapolation formulae for each quantity

Chen et al., Nucl.Phys. A707, 452 (2002); Phys. Lett. B523, 107 (2001)

$$\langle x\rangle_{u-d} = C\left[1-\frac{3g_A^2+1}{(4\pi f_\pi)^2}m_\pi^2\ln\left(\frac{m_\pi^2}{\mu^2}\right)\right] + e(\mu^2)\frac{m_\pi^2}{(4\pi f_\pi)^2}$$

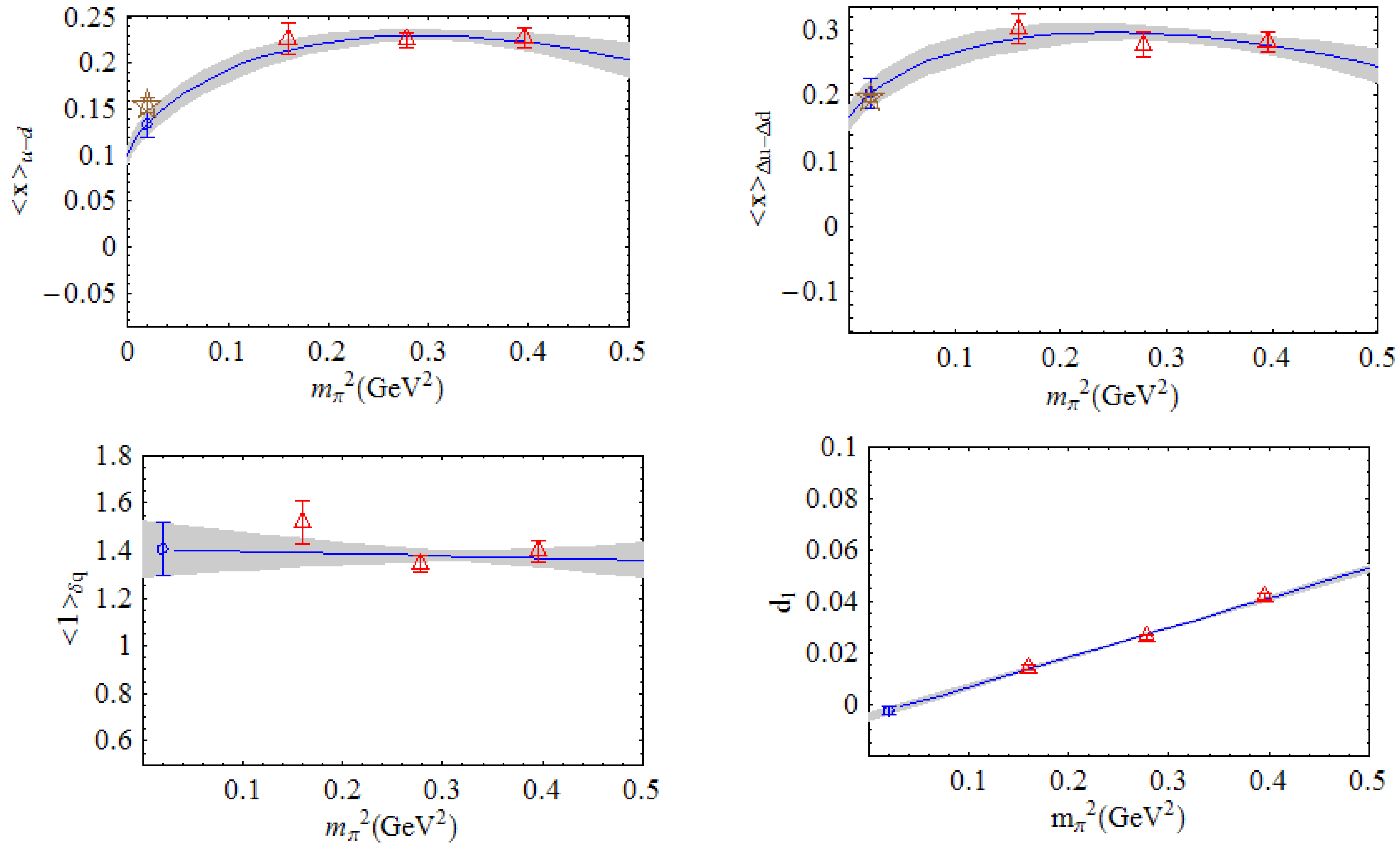
$$\langle x\rangle_{\Delta u-\Delta d} = \tilde{C}\left[1-\frac{2g_A^2+1}{(4\pi f_\pi)^2}m_\pi^2\ln\left(\frac{m_\pi^2}{\mu^2}\right)\right] + \tilde{e}(\mu^2)\frac{m_\pi^2}{(4\pi f_\pi)^2}.$$

Linear ansatz	Linear ansatz

- RI/MOM-scheme nonperturbative renormalization (except for d_1)

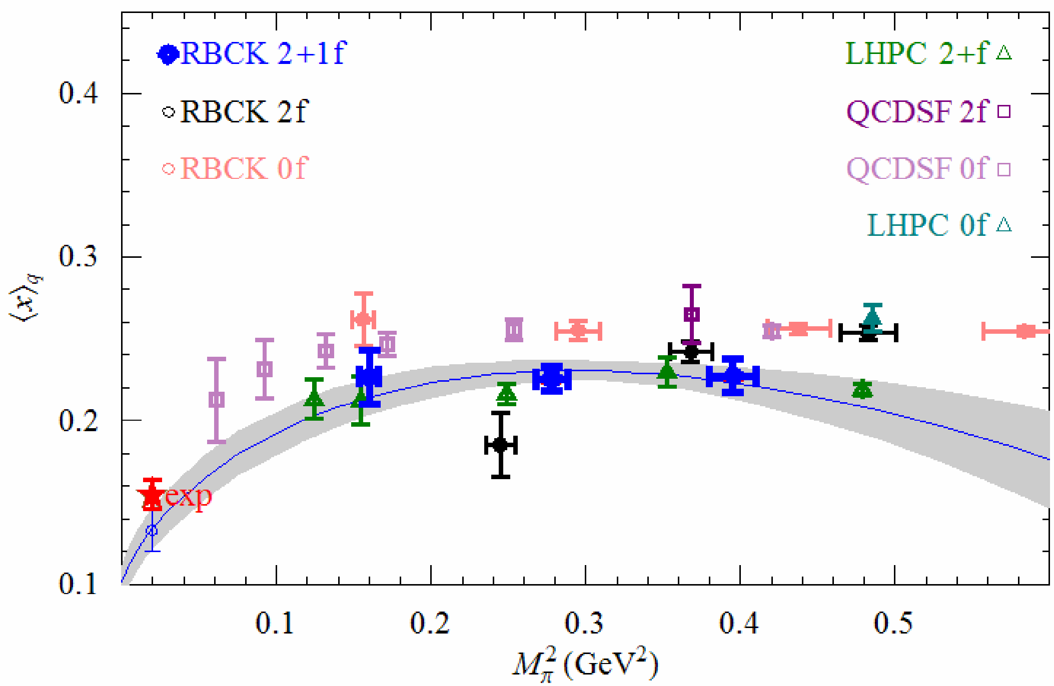
Nucleon Structure Functions

- Chiral extrapolations: lowest moments only



Nucleon Structure Functions

- Comparison among calculations of the first moment of the momentum fraction



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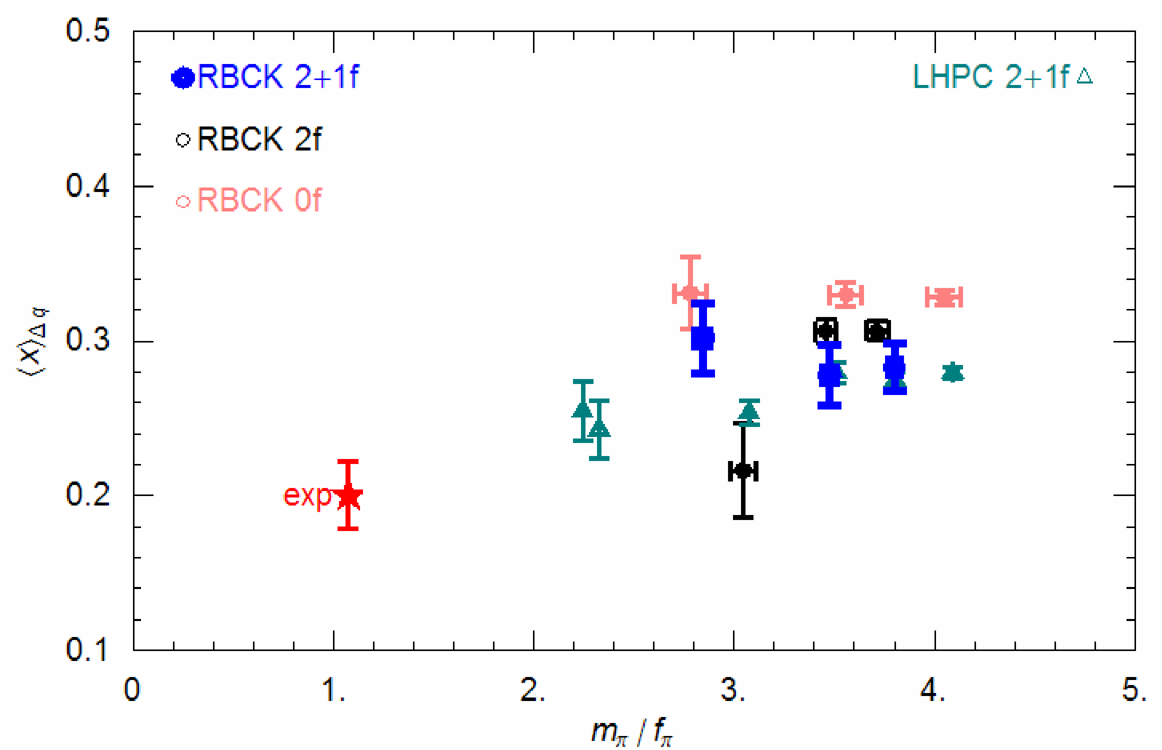
Nucleon Structure Functions

- Comparison among calculations of the first moment of the helicity distribution



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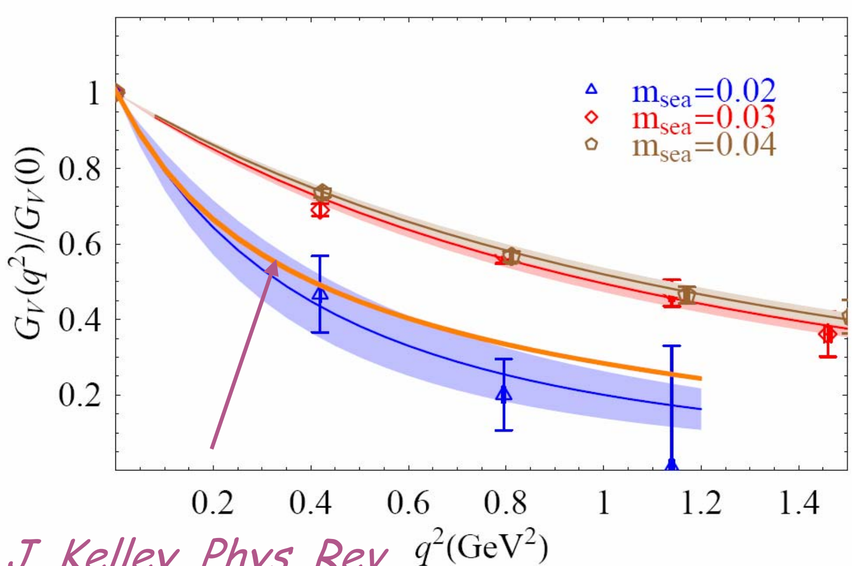
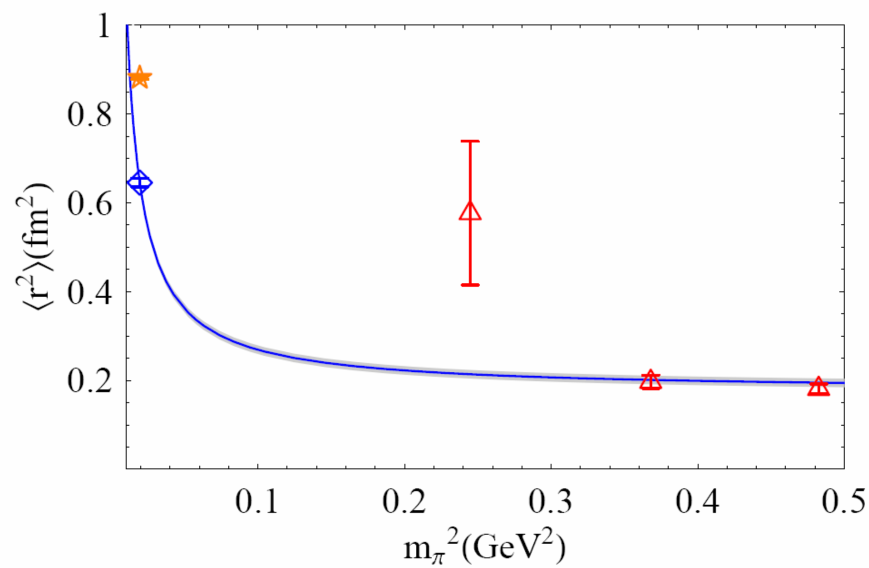
Nucleon Isovector Form Factor (F_1^{u-d})

- 2+1-flavor analysis not yet confirmed
- **2-flavor** DWF data with pion mass: 500–700 MeV





J. J. Kelley, Phys. Rev. C70, 068202 (2004)

Dipole-form extrapolation

$$\langle r^2 \rangle = c_1 - \frac{1+5g_A^2}{(4\pi f_\pi)^2} \log \frac{m_\pi^2}{m_\pi^2 + \Lambda^2}$$

G. V. Dunne et al., Phys. Lett. B531, 77 (2002)

Goldberger-Treiman Relation

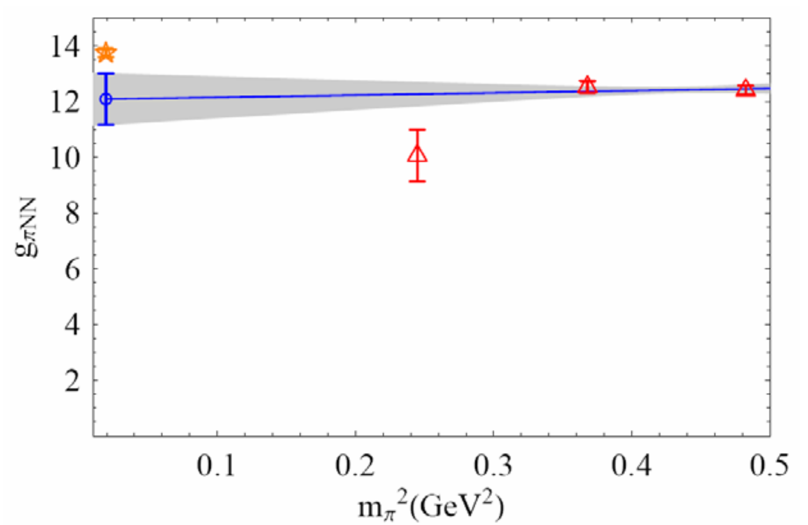
- The Goldberger-Treiman relation states:

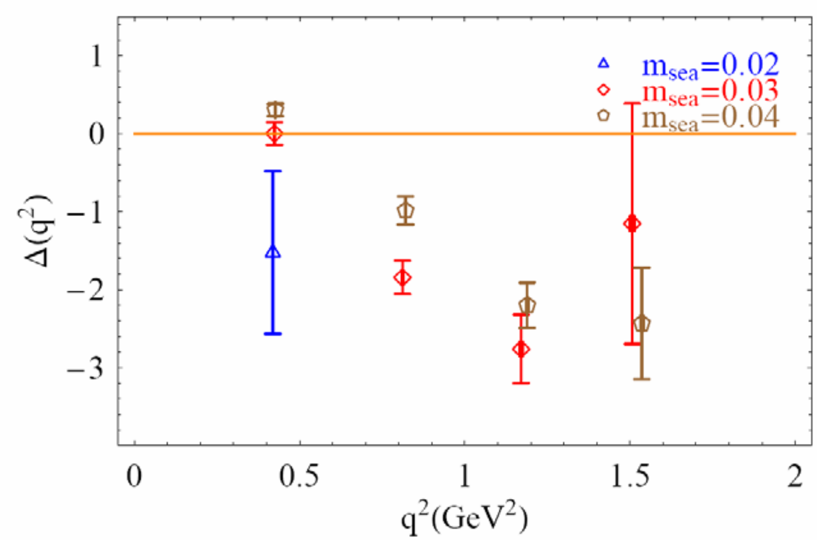
$$q^2 \frac{G_P(q^2)}{2m_N} - 2m_N G_A(q^2) = -\frac{g_{\pi NN} F_\pi m_\pi^2}{q^2 + m_\pi^2}$$

- A measure of the discrepancy

$$\Delta_{GT}(q^2) = 1 - \frac{q^2 + m_{\pi,\text{lat}}^2}{2m_{N,\text{lat}}} \frac{q^2 G_{P,\text{lat}}(q^2) - 4m_{N,\text{lat}}^2 G_{A,\text{lat}}(q^2)}{g_{\pi NN,\text{lat}} F_{\pi,\text{lat}} m_{\pi,\text{lat}}^2}$$

with $g_{\pi NN}^{\text{lat}} = \frac{2m_N^{\text{lat}} g_A^{\text{lat}}}{F_\pi^{\text{lat}}}$





Summary/Outlook: I

- Nucleon structure functions and form factors
  - Work in progress: Full-QCD calculation with pion masses 400–600 MeV
  - Preliminary study shows good agreement with experiment, even for notoriously difficult quantities, such as momentum fraction and helicity distribution
- In the near future
  - 300 MeV pion analysis is on the way (**Lattice 2007**)
  - Taking more statistics at each pion mass
  - Finite-volume studied (combined UKQCD $16^3{\times}32$ data)
  - Lattice discretization effects will be examined ($32^3{\times}64$, $a \sim 0.09$ fm lattices are on the way)
- Within a few years or so
  - < 200 MeV full-QCD gauge generation proposal

Hyperon Channel (preliminary)

in collaboration with

Kostas Orginos

Parameters

- This calculation:
  - Mixed action (staggered sea with DWF valence), 2+1-flavor
  - Pion mass range: 360–700 MeV
  - Strange-strange Goldstone fixed at 763(2) MeV
  - Volume fixed at 2.6 fm
  - $a \approx 0.125$ fm, $L_s = 16$, $M_5 = 1.7$
  - HYP-smeared gauge, box size of $20^3\times 32$

Label	m_π (MeV)	m_K (MeV)
m010	358(2)	605(2)
m020	503(2)	653(2)
m030	599(1)	688(2)
m040	689(2)	730(2)

Strangeness Magnetic Moment of Nucleon

- Disconnected diagrams are challenging
- Much effort has been put into resolving this difficulty
- Alternative approach:

D. B. Leinweber, Phys. Rev. D 53, 5115 (1996).

- Assume charge symmetry:

$$p = e_u u^p + e_d d^p + O_N; \qquad n = e_d u^p + e_u d^p + O_N,$$
$$\Sigma^+ = e_u u^\Sigma + e_s s^\Sigma + O_\Sigma; \qquad \Sigma^- = e_d u^\Sigma + e_s s^\Sigma + O_\Sigma,$$
$$\Xi^0 = e_s s^\Xi + e_u u^\Xi + O_\Xi; \qquad \Xi^- = e_s s^\Xi + e_d u^\Xi + O_\Xi.$$

- The disconnected piece for the proton is $O_N = \frac{2}{3}\,{}^lG_M^u - \frac{1}{3}\,{}^lG_M^d - \frac{1}{3}\,{}^lG_M^s$
- The strangeness contribution is

$$G_M^s = \left(\frac{{}^lR_d^s}{1 - {}^lR_d^s}\right)\left[\boxed{2p + n} - \frac{u^p}{u^\Sigma}\boxed{(\Sigma^+ - \Sigma^-)}\right]$$

$$G_M^s = \left(\frac{{}^lR_d^s}{1 - {}^lR_d^s}\right)\left[\boxed{p + 2n} - \frac{u^n}{u^\Xi}\boxed{(\Xi^0 - \Xi^-)}\right] \quad \text{with} \quad {}^lR_d^s \equiv {}^lG_M^s / {}^lG_M^d$$

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$$\Sigma^+ = e_u u^\Sigma + e_s s^\Sigma + O_\Sigma; \qquad \Sigma^- = e_d u^\Sigma + e_s s^\Sigma + O_\Sigma,$$
$$\Xi^0 = e_s s^\Xi + e_u u^\Xi + O_\Xi; \qquad \Xi^- = e_s s^\Xi + e_d u^\Xi + O_\Xi.$$

- The disconnected piece for the proton is $O_N = \frac{2}{3}\,{}^lG_M^u - \frac{1}{3}\,{}^lG_M^d - \frac{1}{3}\,{}^lG_M^s$
- The strangeness contribution is

$$G_M^s = \left(\frac{{}^lR_d^s}{1 - {}^lR_d^s}\right)\left[3.673 - \frac{u^p}{u^\Sigma}(3.618)\right]\mu_N$$

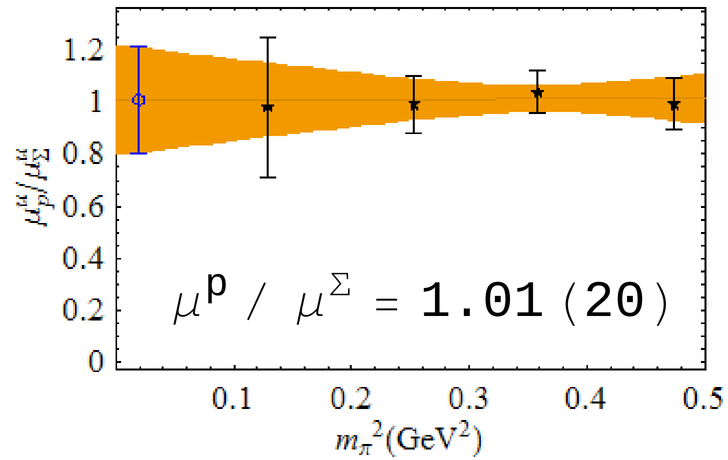
Need better statistics

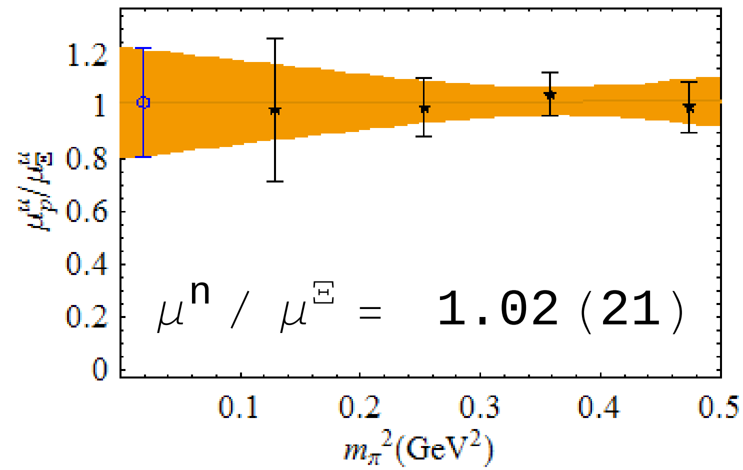
$$G_M^s = \left(\frac{{}^lR_d^s}{1 - {}^lR_d^s}\right)\left[-1.033 - \frac{u^n}{u^\Xi}(-0.599)\right]\mu_N$$

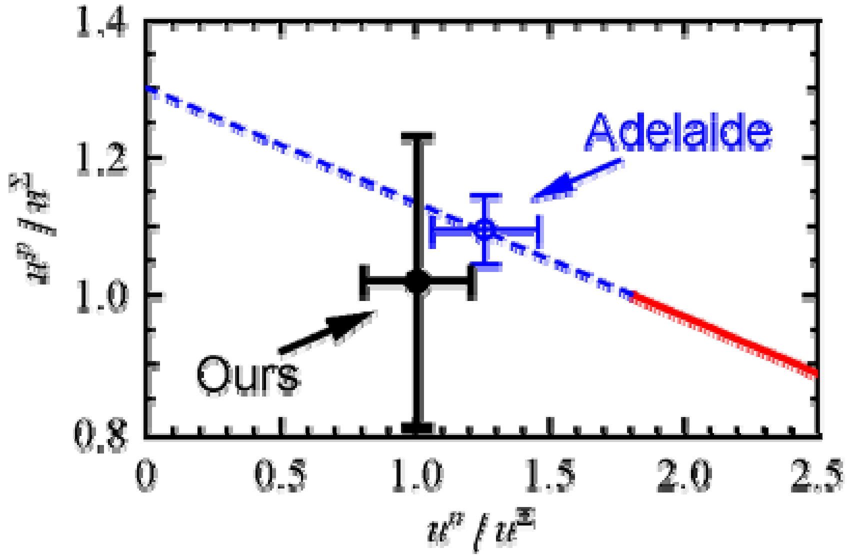
with $\quad {}^lR_d^s \equiv {}^lG_M^s / {}^lG_M^d$

Strangeness Magnetic Moment of Nucleon

- Dipole-form extrapolation to $q^2 = 0$
- Magnetic-moment ratios (linear extrapolation, for now)







D. B. Leinweber et al., Phys. Rev. Lett. 94, 212001 (2004).

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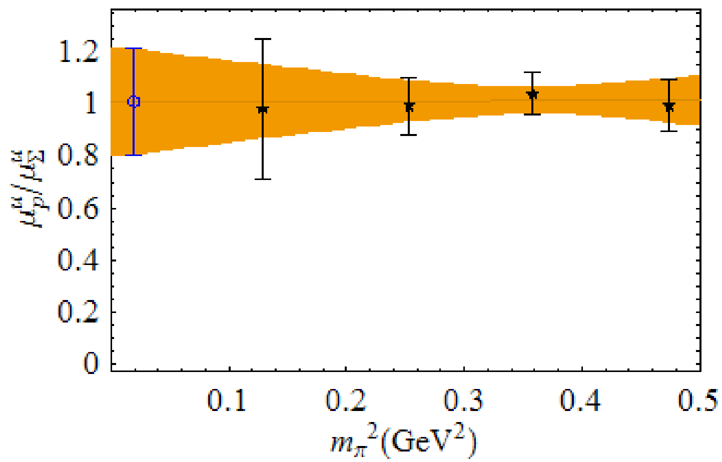
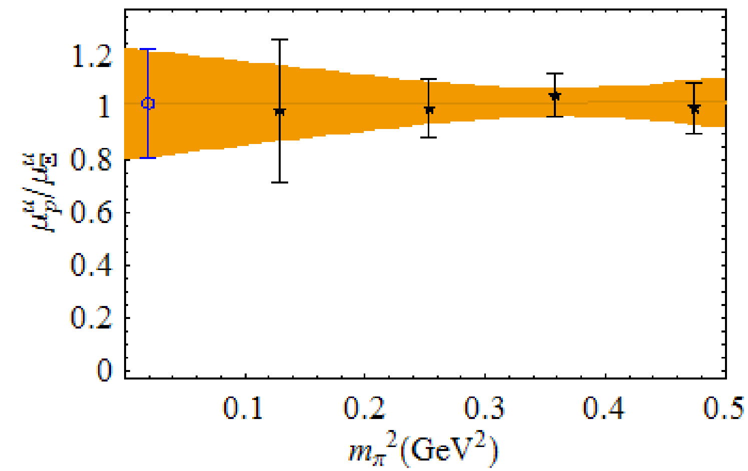
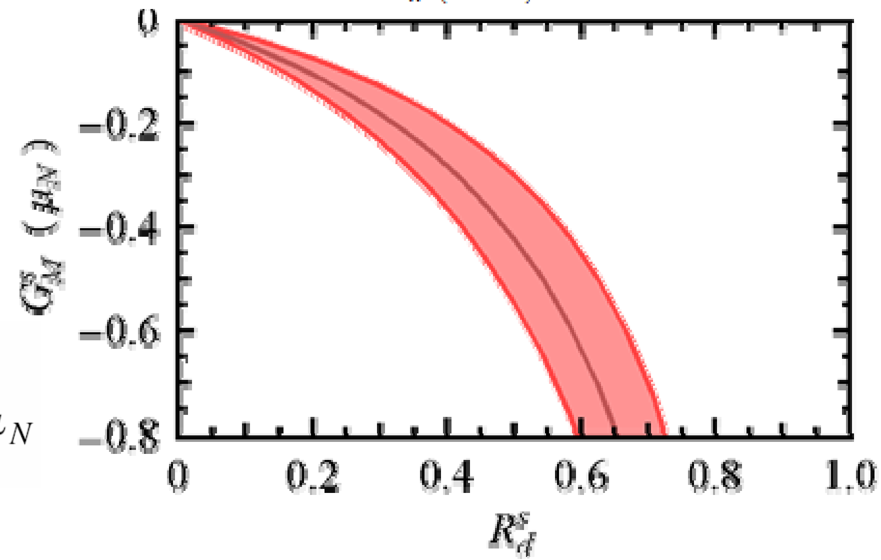




$$G_M^s = \left(\frac{{}^lR_d^s}{1 - {}^lR_d^s}\right)\left[-1.033 - \frac{u^n}{u^\Xi}(-0.599)\right]\mu_N$$



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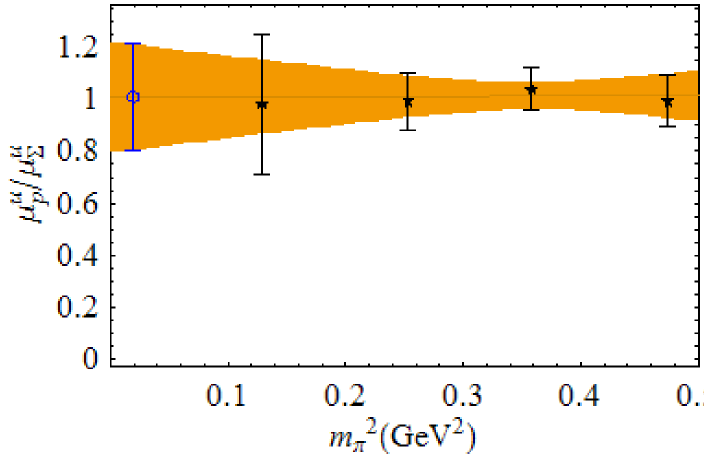
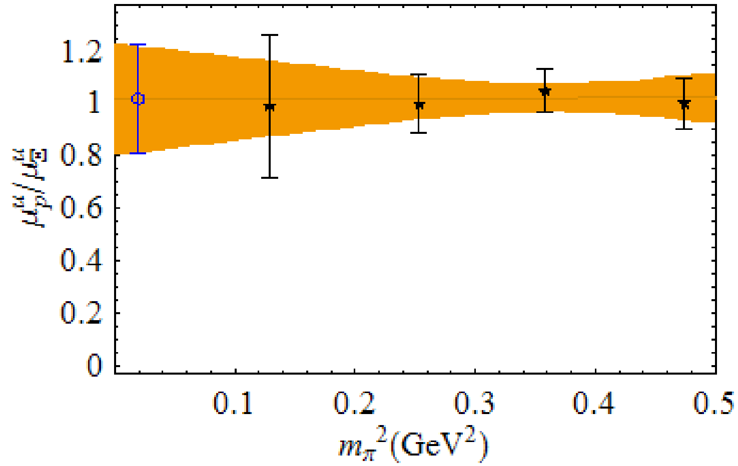


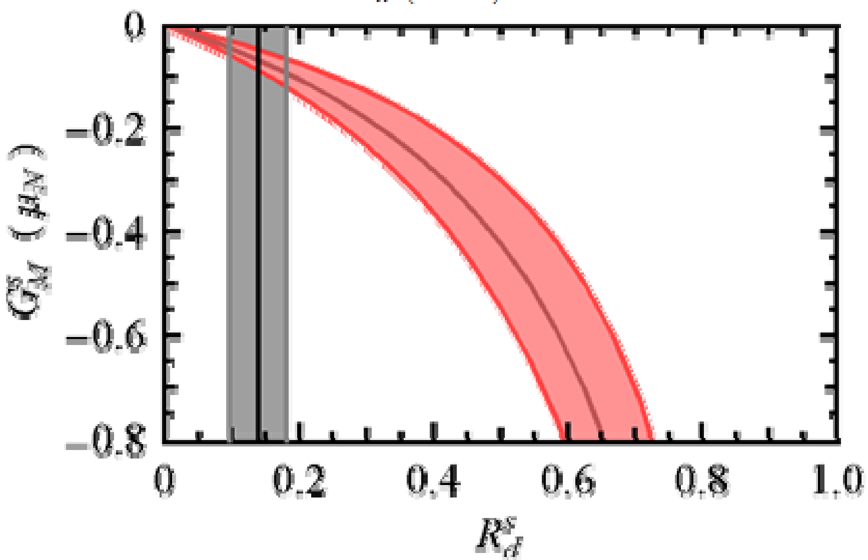


D. B. Leinweber et al., Phys. Rev. Lett. 94, 212001 (2004).

$$R_d^s = 0.139(42)$$

We find

$$G_M^s = -0.07(3)$$



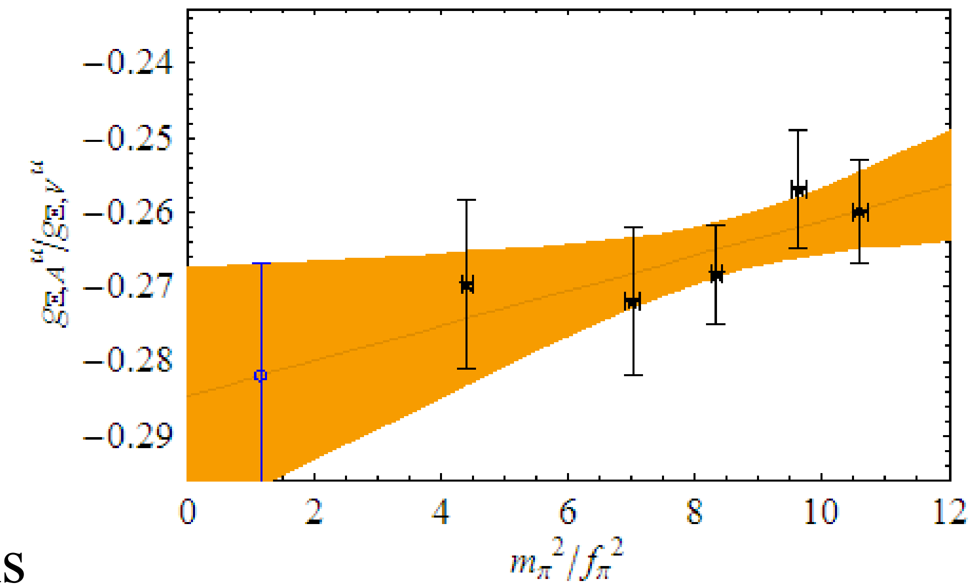
Axial Coupling Constants: $g_{\Xi\Xi}$ and $g_{\Sigma\Sigma}$

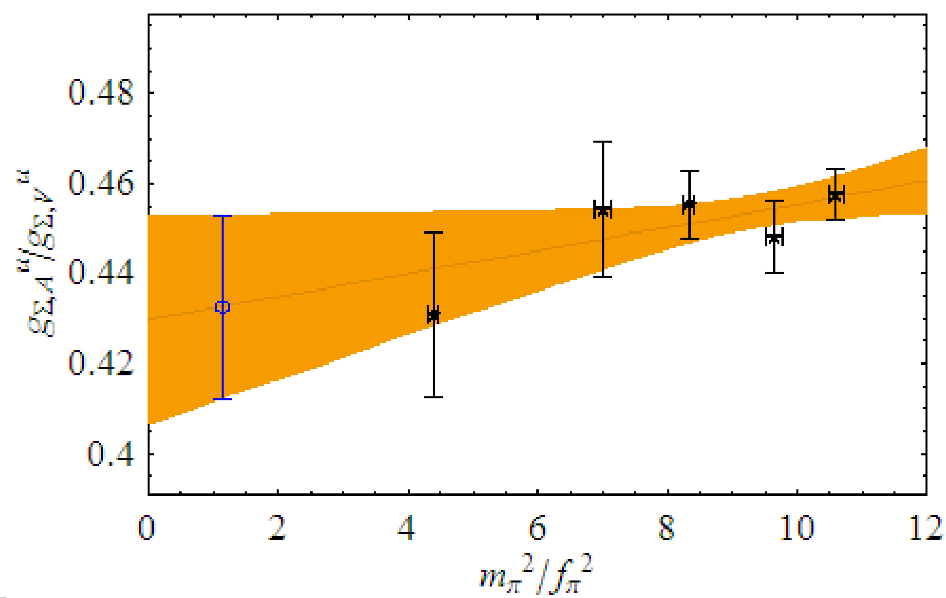
- Has applications such as hyperon scattering, non-leptonic decays, etc.
- Cannot be determined by experiment
- Existing predictions from χPT and large-N_c calculations

M. J. Savage et al., Phys. Rev. D55, 5376 (1997);
R. Flores-Mendieta et al., Phys. Rev. D58, 094028(1998);

$$0.18 < -g_{\Xi\Xi} < 0.36$$
$$0.30 < g_{\Sigma\Sigma} < 0.55$$

- We find consistent numbers with much smaller errors





Summary/Outlook: II

- From hyperon analysis
  - Preliminary estimate of the proton strange magnetic moment directly from full QCD: −0.07(3)
  - Predictions for $g_{\Sigma\Sigma} = 0.441(14)$ and $g_{\Xi\Xi} = -0.277(11)$
  - DWF are too expensive to get small errors with light pion masses, especially as the < 300 MeV era approaches
- In the future
  - Anisotropic 2+1-flavor clover lattices will be started soon
  - Proposed light pion mass < 200 MeV in a few years
  - Obvious cost benefit right away; share propagators
  - Anisotropic clover is good for separating excited contributions; thus cleaner ground-state signal for precision calculation