Hadronic Structure from Lattice QCD

James Zanotti
University of Edinburgh

Lattice 2008, College of William & Mary, July 14-19, 2008

A Mass of Work to Cover

Worst pun contender, Lattice 2008!

- 32 parallel talks
- 2 posters

Lattice 2007: 26 talks, 1 poster

Lattice 2006: 19 talks 4 posters

Thanks to those who provided material

- >120 pages of material
- >200 figures!

Sorry if I've left out your favourite result

Jefferson Lab Research Program

http://www.jlab.org/highlights/phys.html

- Precision Test of the Standard Model
- Quark-Hadron Duality
- Strange Quarks in the Proton
- Generalized Parton Distributions
- Electric and Magnetic Proton Form Factors
- Neutron Charge Distribution
- Nucleon-Delta Transition
- Pion Form Factor
- Short-Range Correlations
- Deuteron Photodisintegration
- Spin Sum Rules
- Nucleon Spin Asymmetries
- Deuteron Form Factors
- Pentaquark Search
- Neutron Magnetic Structure

Jefferson Lab Research Program

http://www.jlab.org/highlights/phys.html

- Precision Test of the Standard Model
- Quark-Hadron Duality
- Strange Quarks in the Proton
- Generalized Parton Distributions
- Electric and Magnetic Proton Form Factors
- Neutron Charge Distribution
- Nucleon-Delta Transition
- Pion Form Factor
- Short-Range Correlations
- Deuteron Photodisintegration
- Spin Sum Rules
- Nucleon Spin Asymmetries
- Deuteron Form Factors
- Pentaquark Search
- Neutron Magnetic Structure

Jefferson Lab Research Program

http://www.jlab.org/highlights/phys.html

- Electric and Magnetic Proton Form Factors
- Neutron Charge Density
- Neutron Magnetic Structure
- Strange Quarks in the Proton
- Nucleon-Delta Transition
- Pion Form Factor
- Generalized Parton Distributions
- Spin Sum Rules
- Nucleon Spin Asymmetries

Topics to Cover

- Form Factors (pi, N, Delta, transition,...)
  - Provide information on size, shape and internal (charge) densities
  - eg. Neutron has charge zero, but charge density? +/-?
- Nucleon Axial Charge, g_A
  - Neutron beta decay, chiral symmetry breaking
- Generalised Parton Distributions
  - "Spin crisis": quarks carry only 30% of proton's spin
    - gluons? quark orbital angular momentum?
  - "3D" picture of nucleon
- $\langle x \rangle$: Is this thing ever going to bend down?
- Distribution Amplitudes:
  - exclusive processes; hadron wave function
- Strange quark+ other disconnected contributions
  - Strangeness/gluonic content of nucleon

Jefferson Lab Research Program

http://www.jlab.org/highlights/phys.html

- **Electric and Magnetic Proton Form Factors**
- **Neutron Charge Density**
- **Neutron Magnetic Structure**
- Nucleon-Delta Transition
- Pion Form Factor
- Generalized Parton Distributions
- Spin Sum Rules
- Nucleon Spin Asymmetries
- Strange Quarks in the Proton

Form Factors

Nucleon

Q^2 Scaling

$$\langle p',\, s'|J^\mu(\vec{q})|p,\, s\rangle \;=\bar{u}(p',\, s')\left[\gamma^\mu F_1(q^2)+i\sigma^{\mu\nu}\frac{q_\nu}{2m}F_2(q^2)\right]u(p,\, s)$$

$$G^{BJ^\mu B}(t,\tau)=\sum_{s,s'}e^{-E_{p'}(t-\tau)}e^{-E_p\tau}\langle\Omega|\chi|p',s'\rangle\langle p',s'|J^\mu|p,s\rangle\langle p,s|\overline{\chi}|\Omega\rangle$$

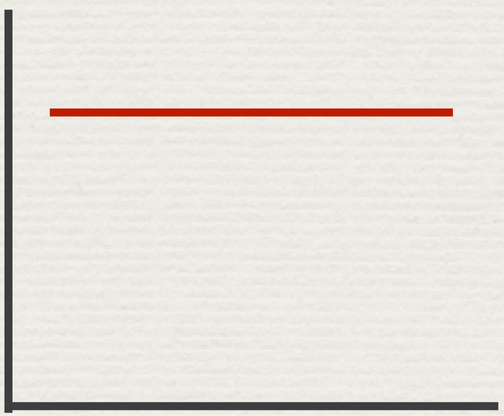
Naive expectation from dimensional counting *[Brodsky & Farrar, 1973]*

$$F_1 \quad\propto\quad \frac{1}{Q^4} \qquad \text{(dipole?)}$$

$$F_2 \quad\propto\quad \frac{1}{Q^6} \qquad \text{(tripole?)}$$

$$\frac{F(0)}{(1+Q^2/M^2)^p}$$

Pre JLab



Form Factors

Nucleon

Q^2 Scaling

$$\langle p',\, s'|J^\mu(\vec{q})|p,\, s\rangle = \bar{u}(p',\, s')\left[\gamma^\mu F_1(q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{2m}F_2(q^2)\right]u(p,\, s)$$

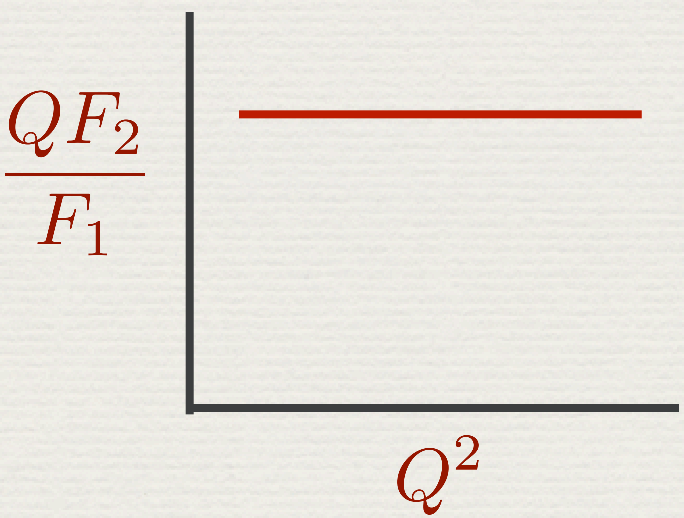
$$G^{BJ^\mu B}(t,\tau) = \sum_{s,s'} e^{-E_{p'}(t-\tau)}e^{-E_p\tau}\langle\Omega|\chi|p',s'\rangle\langle p',s'|J^\mu|p,s\rangle\langle p,s|\overline{\chi}|\Omega\rangle$$

Naive expectation from dimensional counting *[Brodsky & Farrar, 1973]*

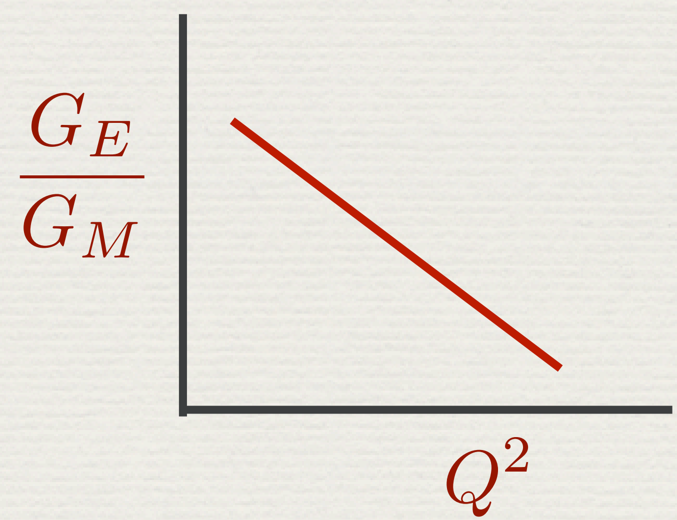
$$F_1 \propto \frac{1}{Q^4} \quad \text{(dipole?)}$$

$$F_2 \propto \frac{1}{Q^6} \quad \text{(tripole?)}$$

$$\frac{F(0)}{(1+Q^2/M^2)^p}$$



JLab



Form Factors

Nucleon

Q^2 Scaling

$$\langle p',\, s'|J^\mu(\vec{q})|p,\, s\rangle \;=\bar{u}(p',\, s')\left[\gamma^\mu F_1(q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{2m}F_2(q^2)\right]u(p,\, s)$$

$$G^{BJ^\mu B}(t,\tau) = \sum_{s,s'} e^{-E_{p'}(t-\tau)}e^{-E_p\tau}\langle\Omega|\chi|p',s'\rangle\langle p',s'|J^\mu|p,s\rangle\langle p,s|\overline{\chi}|\Omega\rangle$$

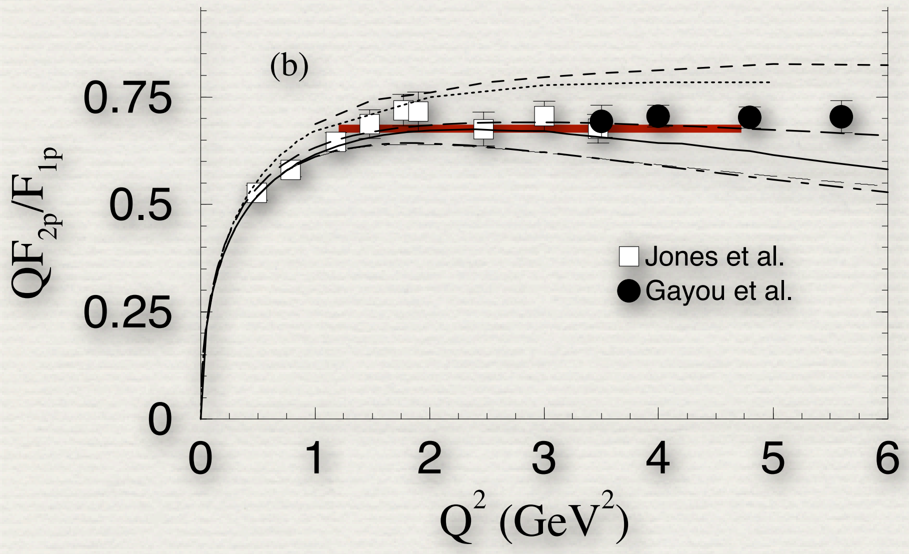
Naive expectation from dimensional counting *[Brodsky & Farrar, 1973]*

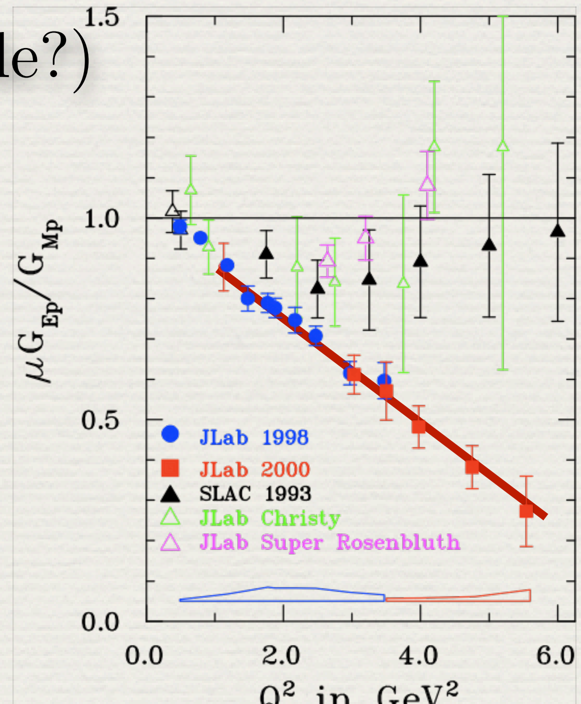
$$F_1 \quad\propto\quad \frac{1}{Q^4} \qquad \text{(dipole?)}$$

$$F_2 \quad\propto\quad \frac{1}{Q^6} \qquad \text{(tripole?)}$$

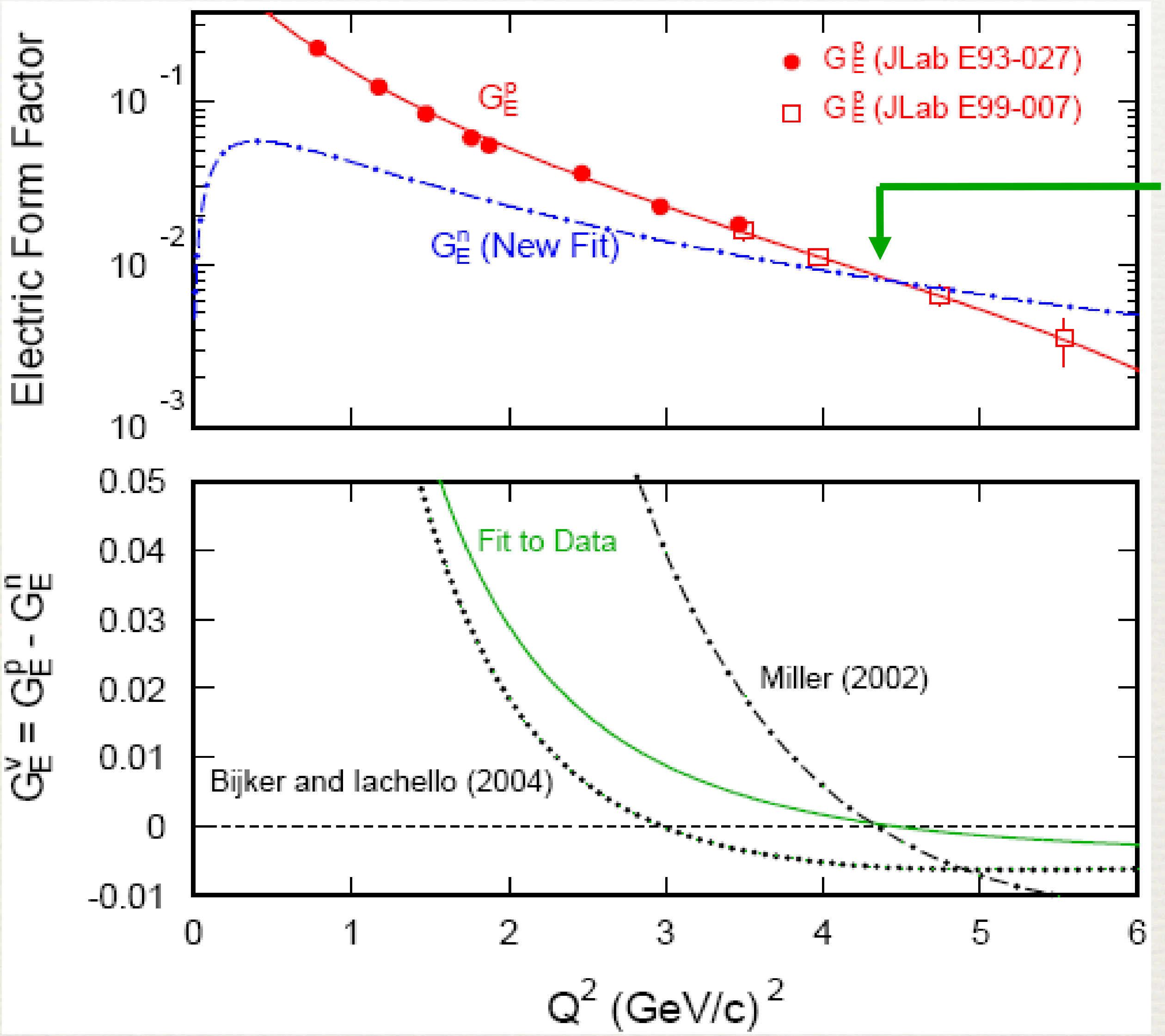
$$\frac{F(0)}{(1+Q^2/M^2)^p}$$

JLab





Zero Crossing?

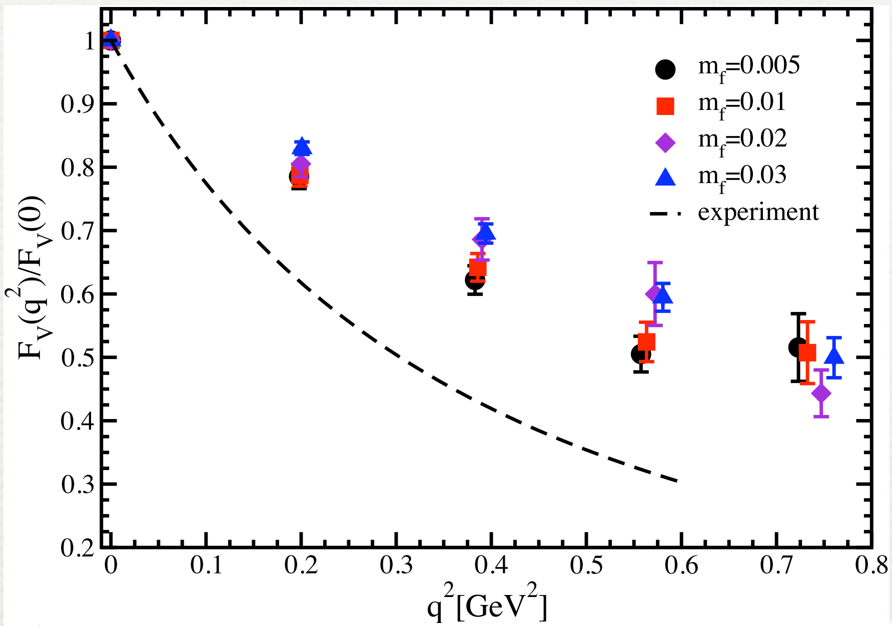


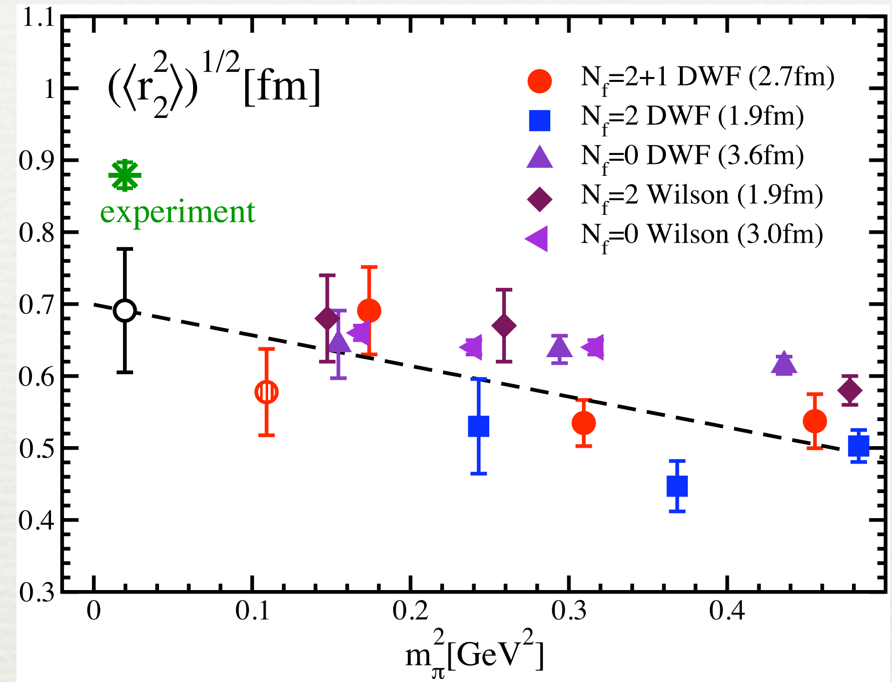
Possible zero crossing in isovector electric form factor G_E^V at $Q^2 \sim 4.5$ (GeV/c)^2

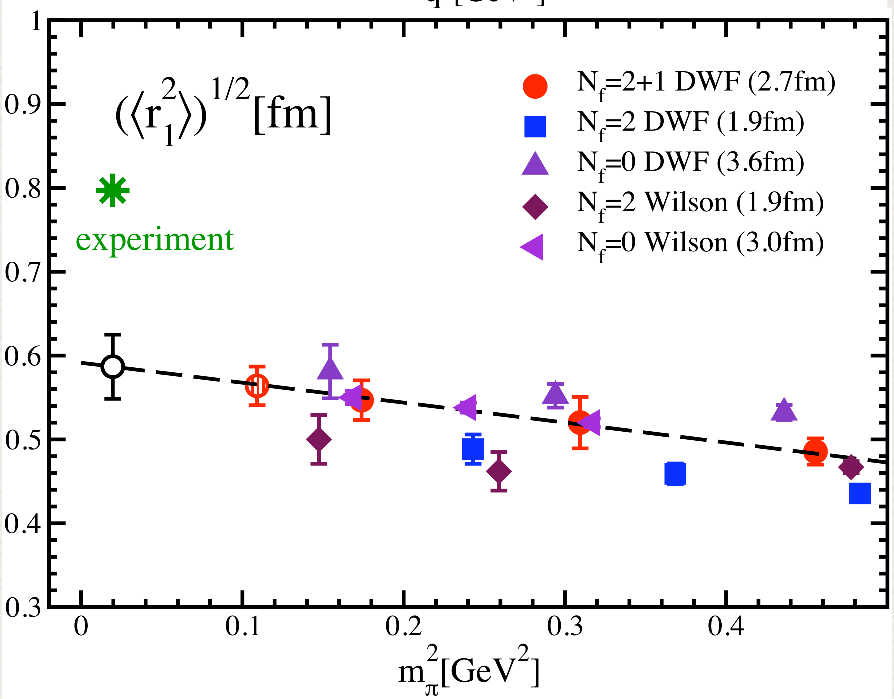
[P. Anderson, Trento 2008]

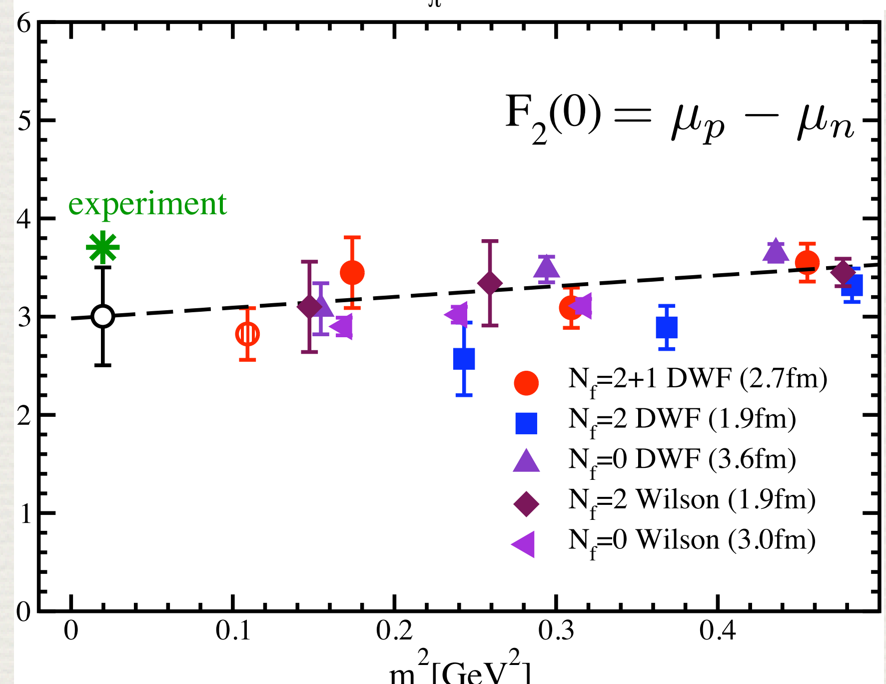
RBC/UKQCD *[Takeshi Yamazaki]* Monday 4:10

N_f=2+1 Domain Wall Fermions $24^3 \times 64 \ \ a^{-1} = 1.729$ GeV









LHPC on RBC/UKQCD Configurations

N_f=2+1 Domain Wall Fermions

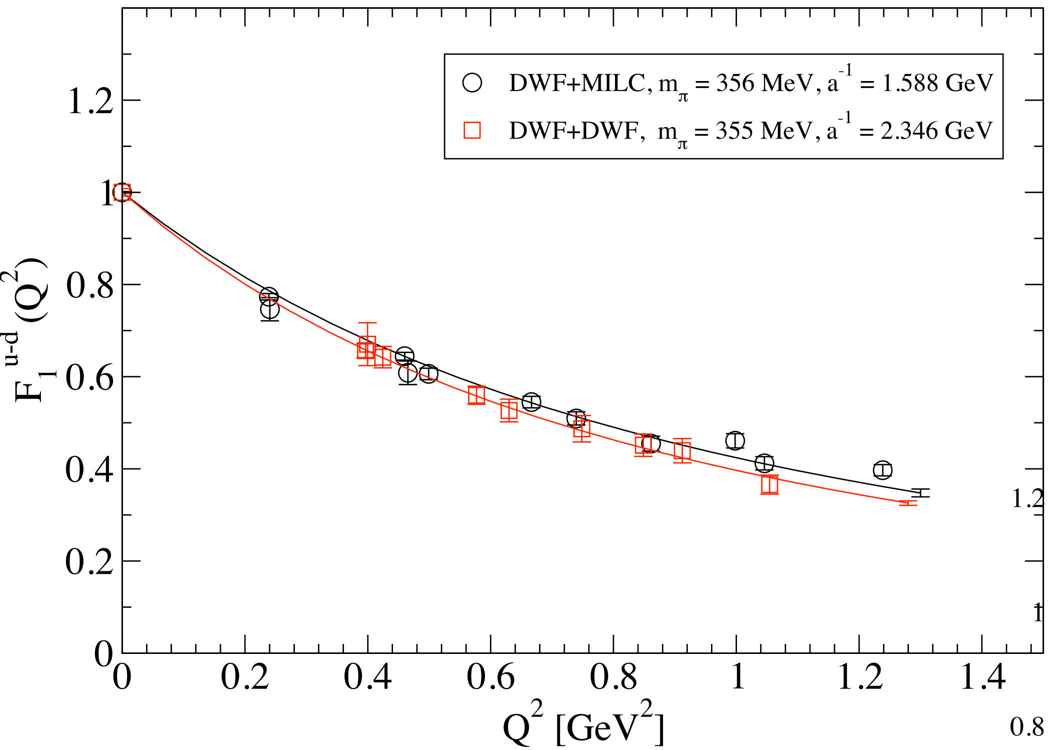
S. Syritsyn Friday 5:40

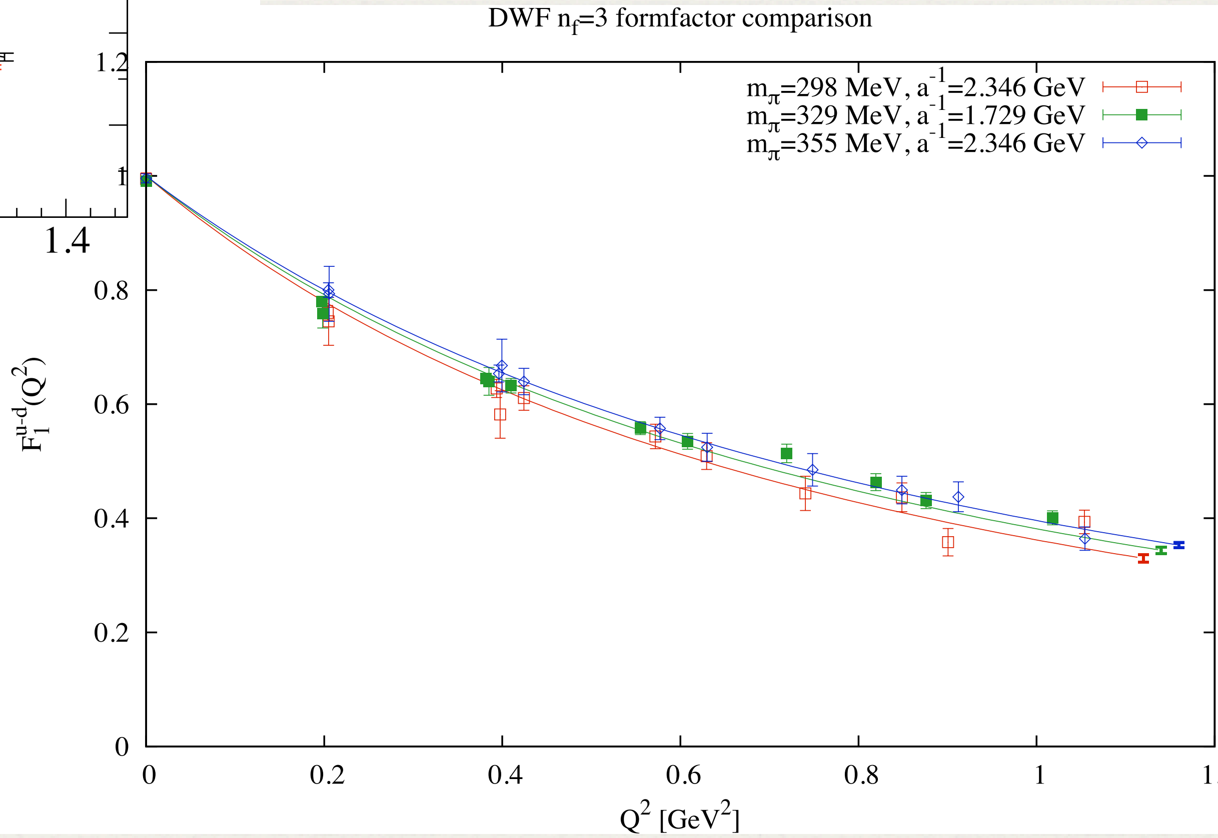
$$24^3 \times 64 \quad a^{-1} = 1.729 \text{ GeV}$$

$$m_\pi \approx 330\text{MeV}$$

$$32^3 \times 64 \quad a^{-1} = 2.35 \text{ GeV}$$

$$m_\pi \approx 355,\ 298\text{MeV}$$





Also see Monday 3:30

M. Lin, DWF + asqtad

New results at m_{pi}=293 MeV

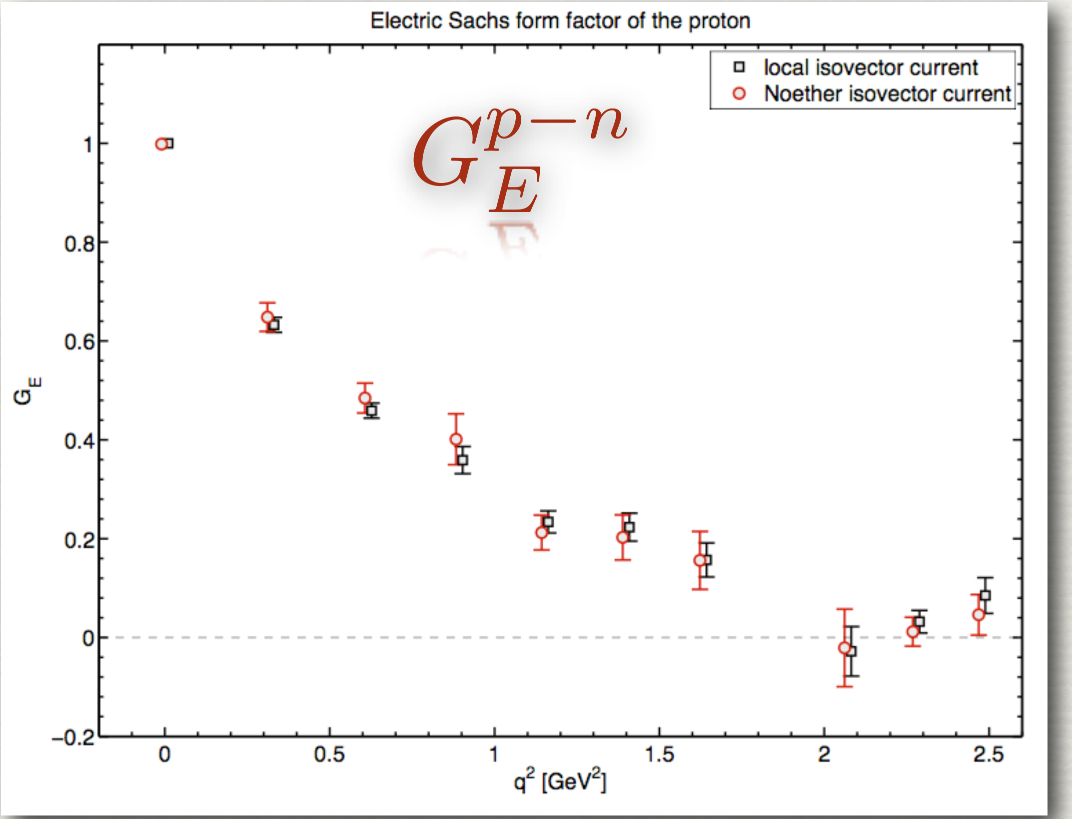
T. Korzec [ETMC] Monday 2:50

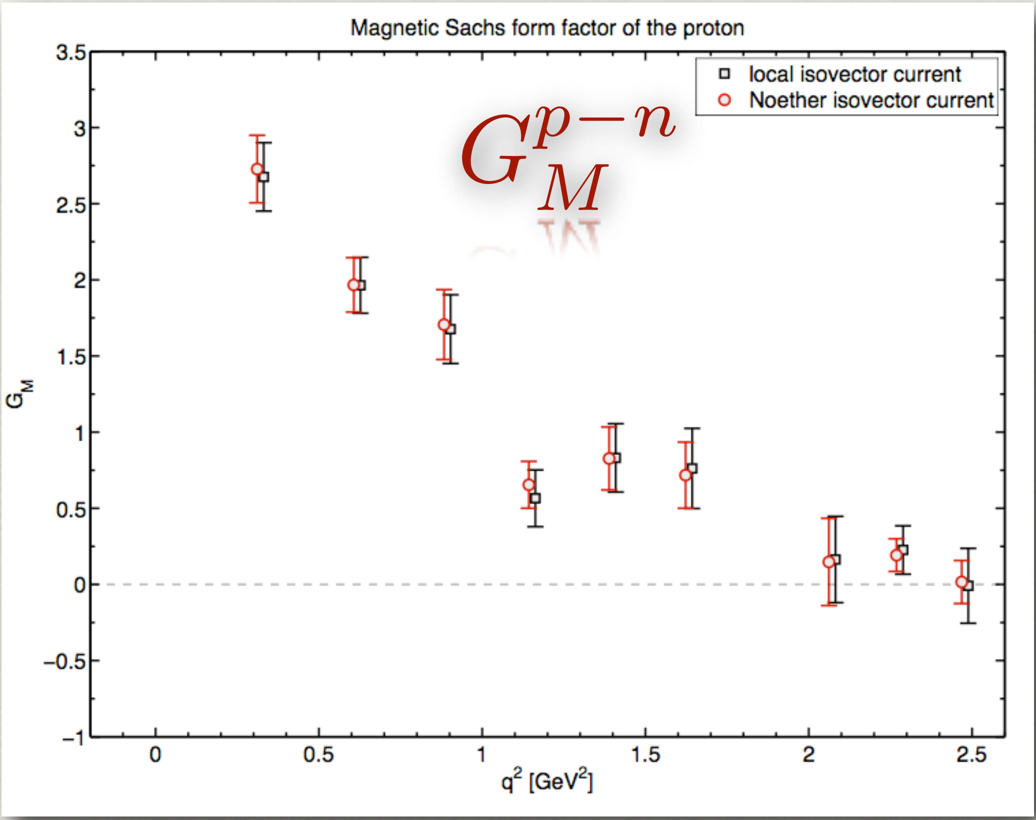
N_f=2 Twisted Mass Fermions

$a = 0.089(1)$ fm

$L = 2.13$ fm

$m_\pi = 447,\ 313$ MeV





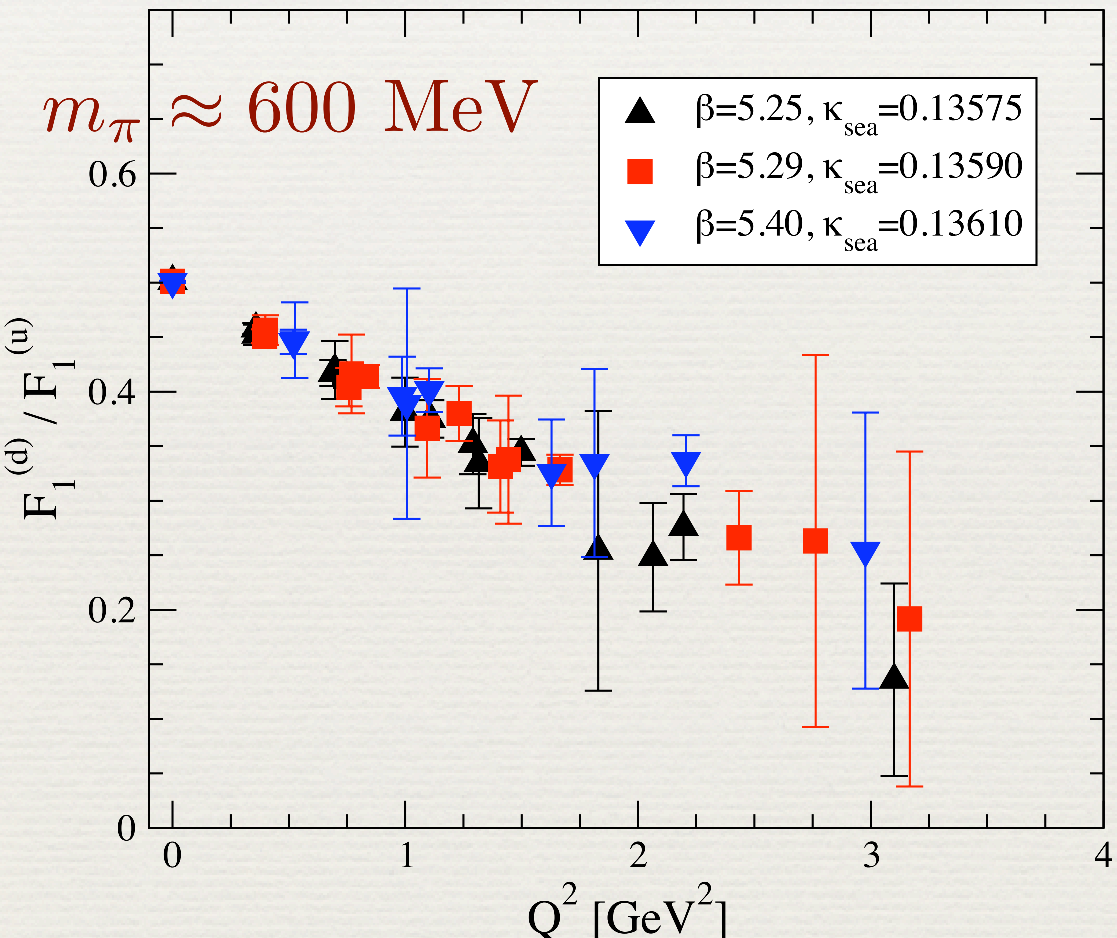
Flavour Distribution

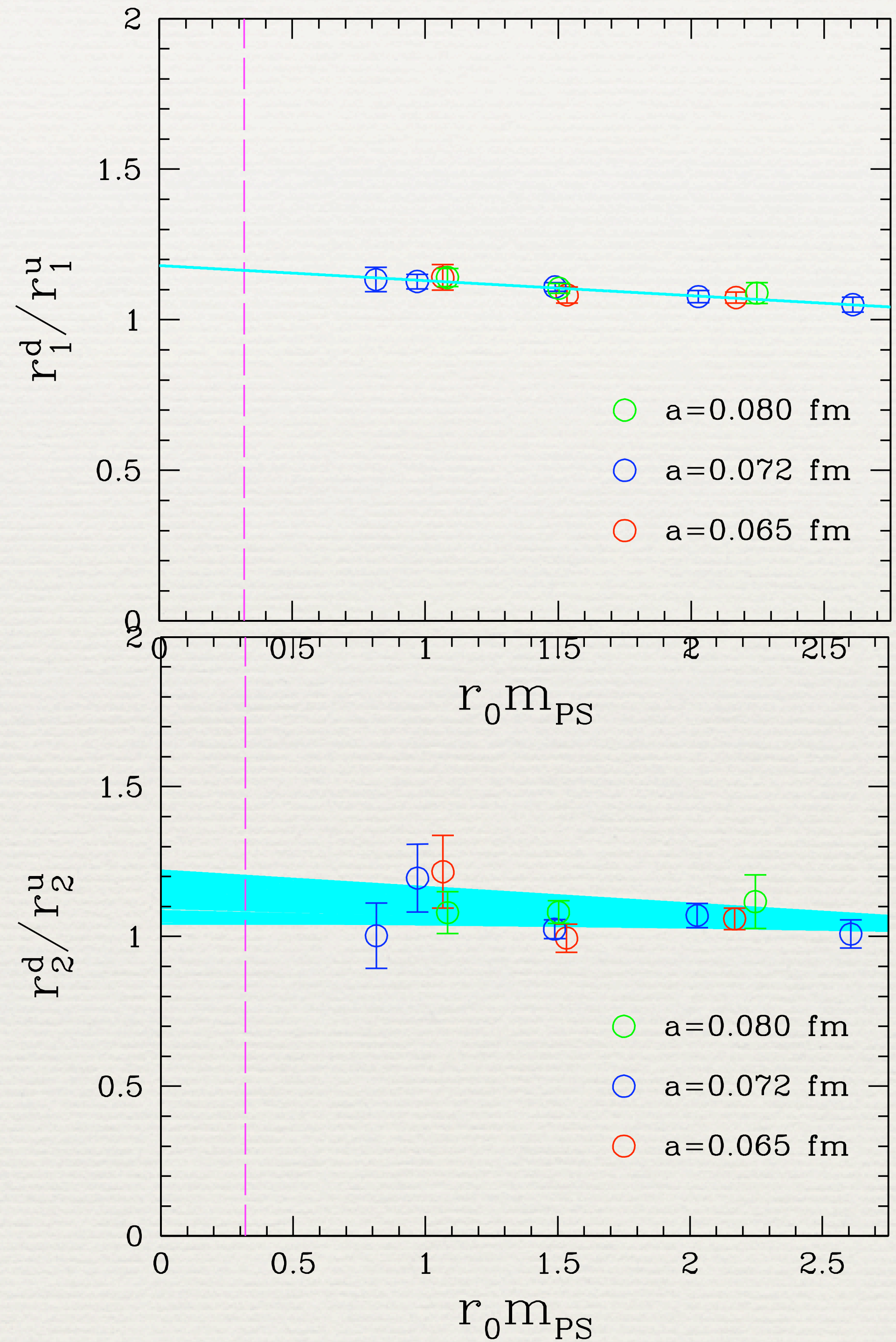
[QCDSF, N_f=2 Clover]

$$F^p = \frac{2}{3}F^u - \frac{1}{3}F^d$$

$$F^n = -\frac{1}{3}F^u + \frac{2}{3}F^d$$

$m_\pi \approx 600$ MeV

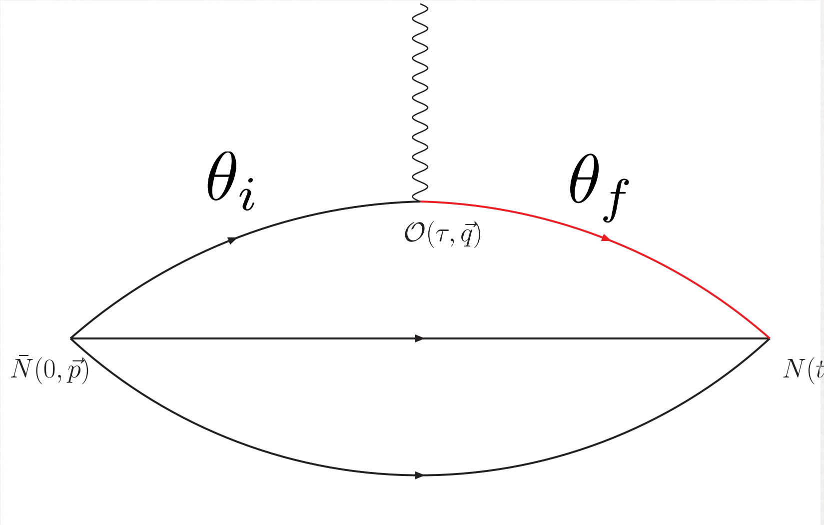




$$r^d_{1,2} > r^u_{1,2}$$

Accessing Small Q^2: Partially Twisted Boundary Conditions

Bedaque hep-lat/0411033
Sachrajda & Villadoro hep-lat/0703005



- Modify boundary conditions on the valence quarks

$$\psi(x_k + L) = e^{i\theta_k}\psi(x_k), \qquad (k = 1, 2, 3)$$

- allows to tune the momenta continuously $\vec{p}_{\mathrm{FT}} + \vec{\theta}/L$

$$q^2 = (p_f - p_i)^2 = \left\{ [E_f(\vec{p}_f) - E_i(\vec{p}_i)]^2 - \left[(\vec{p}_{\mathrm{FT},f} + \vec{\theta}_f/L) - (\vec{p}_{\mathrm{FT},i} + \vec{\theta}_i/L) \right]^2 \right\}$$

- Introduces additional finite volume effect $\sim e^{-m_\pi L}$

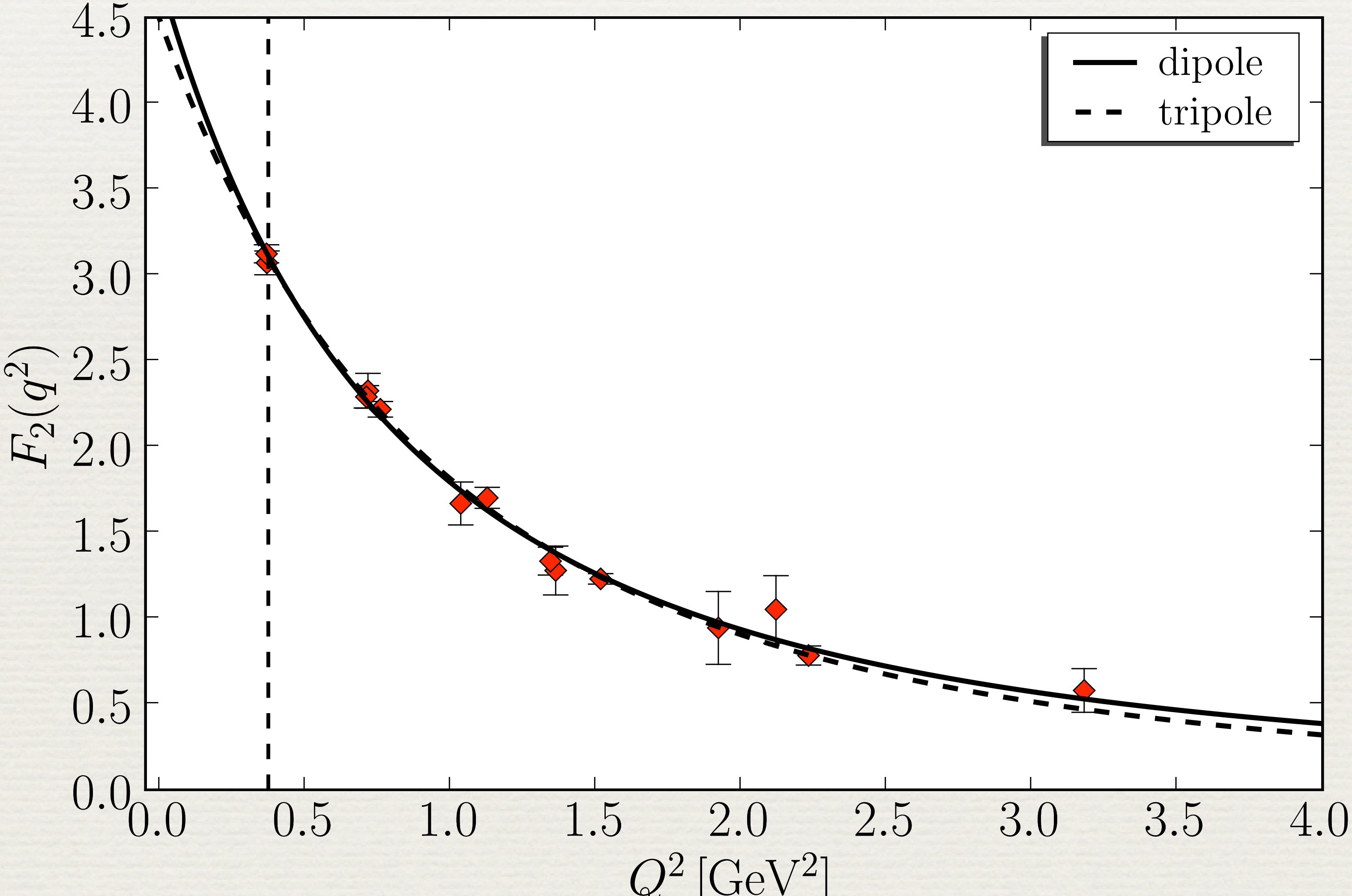
Jiang & Tiburzi, arXiv:0806.4371: Finite Volume effects for partially twisted b.c. small for pion form factor in the Breit frame

Nucleon form factors??

Accessing Small Q^2: Partially Twisted Boundary Conditions

Ph. Hägler [QCDSF]: N_f=2 Clover Monday 2:30

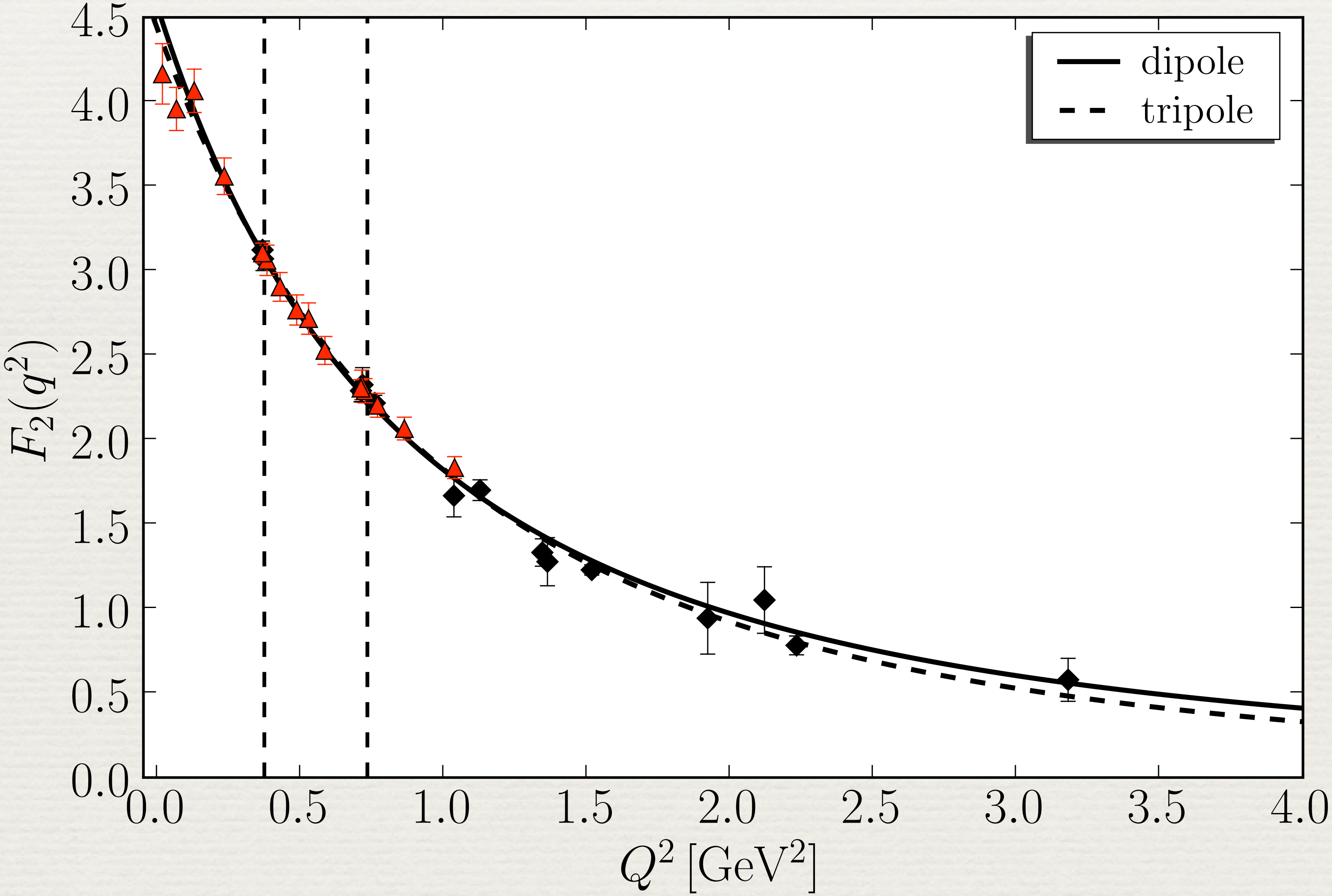
We need to extrapolate $F_2(q^2)$ to q^2=0 → **Model dependence**



Accessing Small Q^2: Partially Twisted Boundary Conditions

Ph. Hägler [QCDSF]: N_f=2 Clover Monday 2:30

We need to extrapolate $F_2(q^2)$ to q^2=0 → **Model dependence**

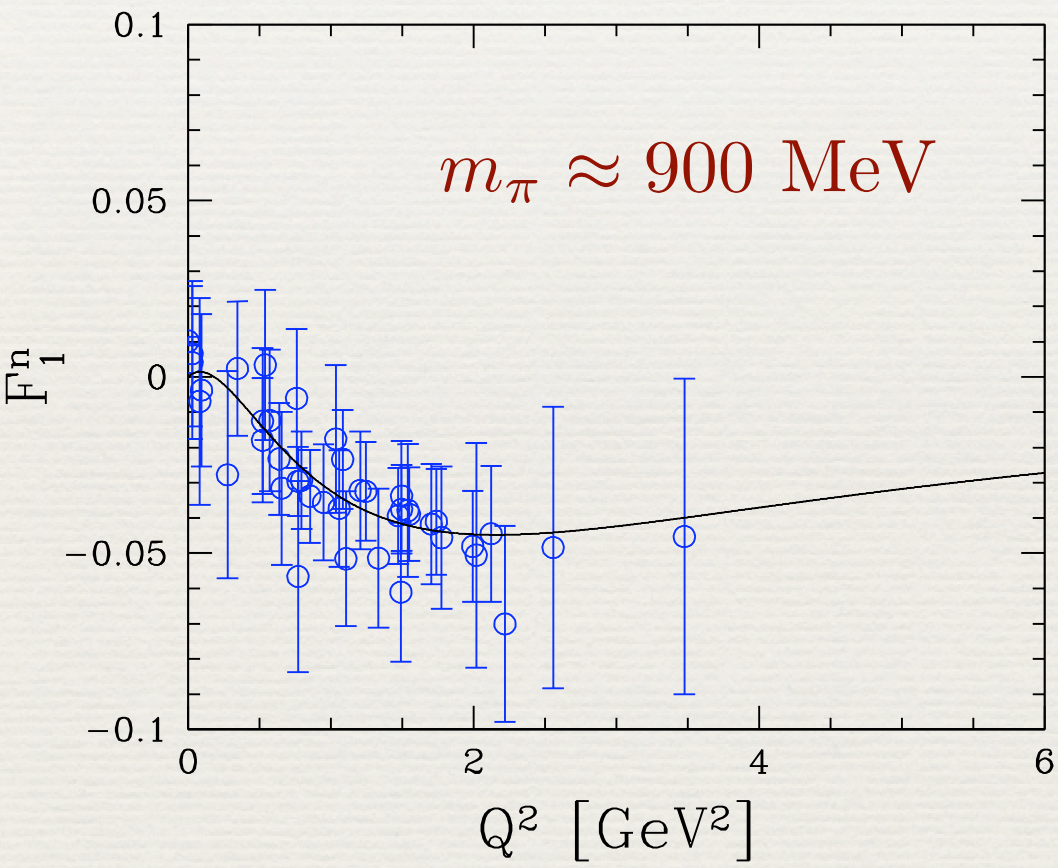


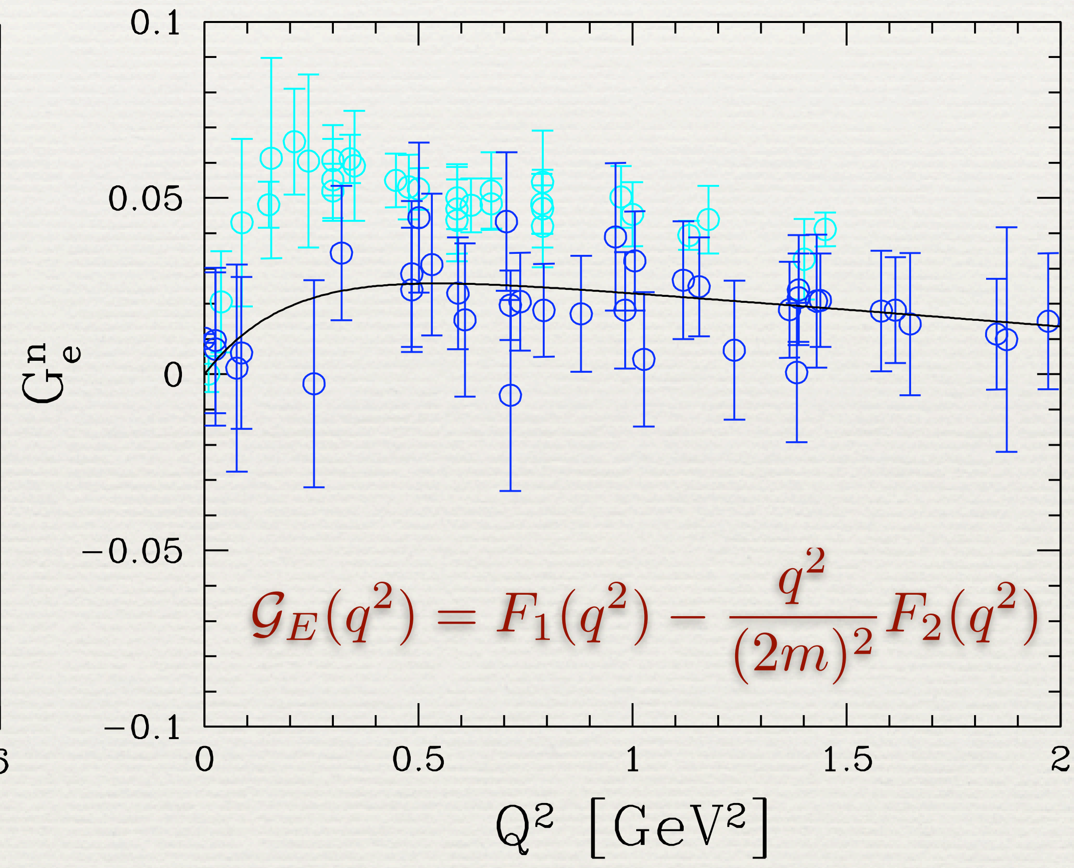
Neutron Form Factors

QCDSF: N_f=2 Clover

Phenomenological multipole fit (a la Kelly)

$$F(Q^2) = F(0)(1 + c_1 Q^2 + c_n Q^{2n})^{-1}$$





F_1 neutron negative at small Q^2

How does "hump" change with quark mass?

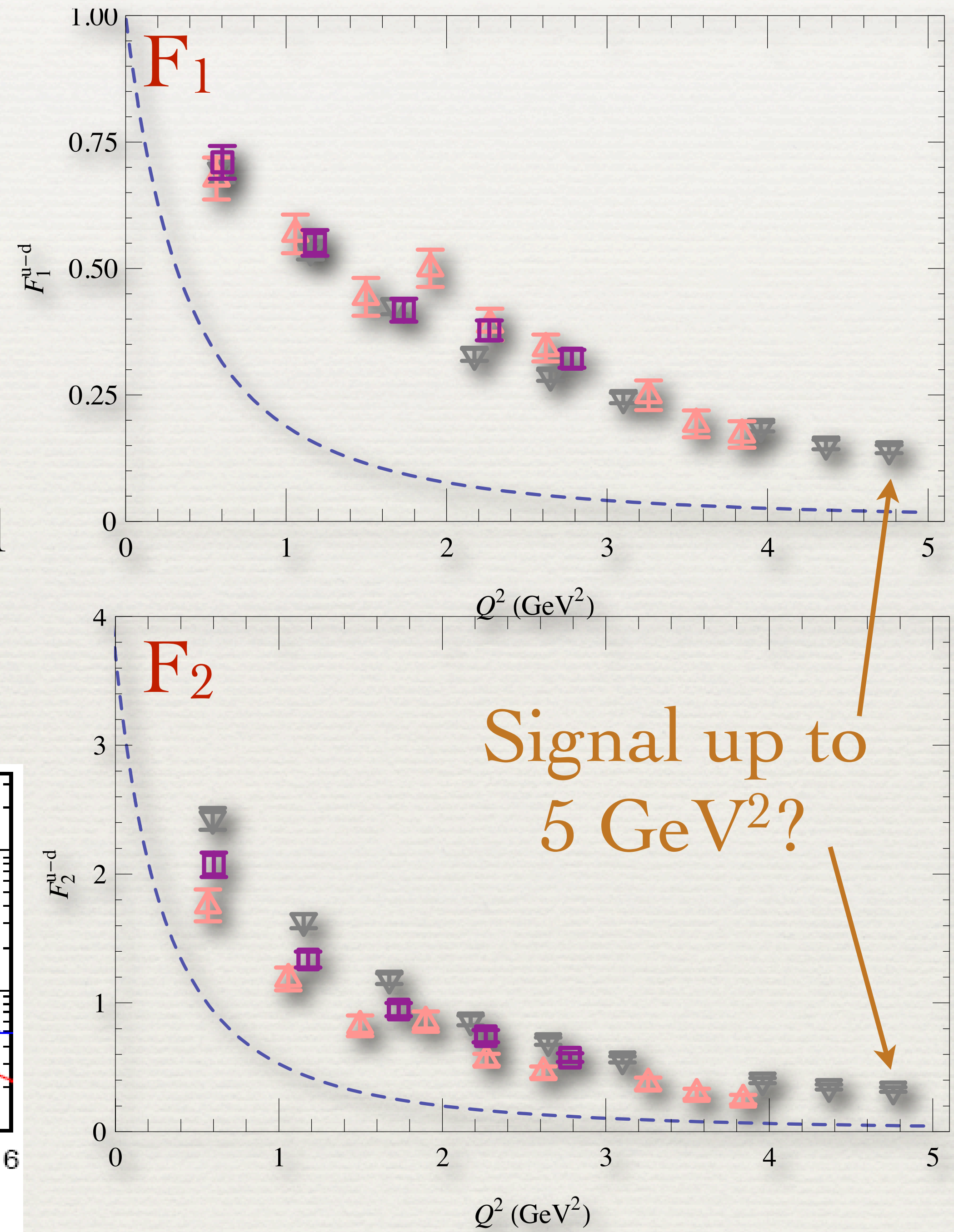
Large Q^2

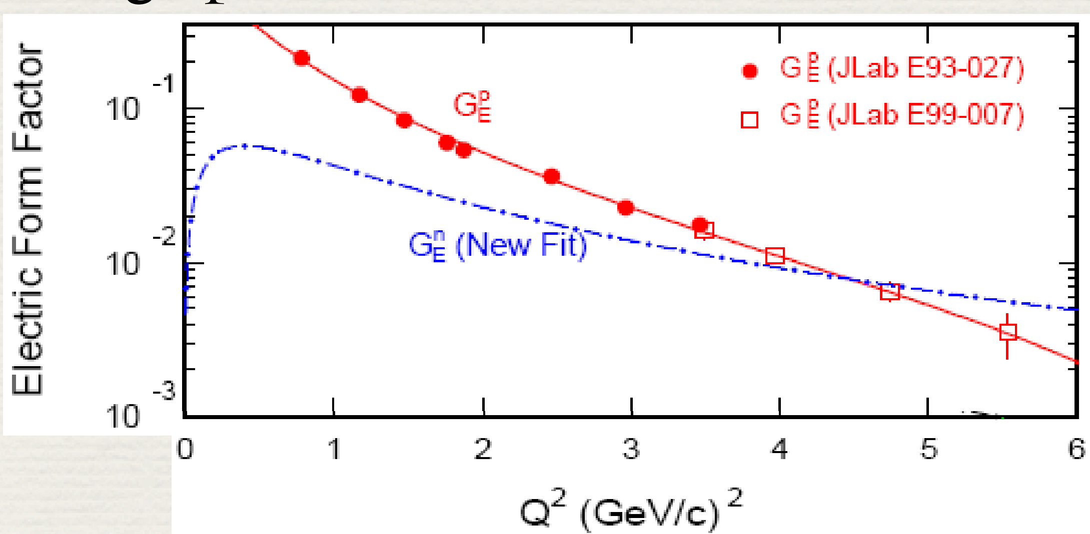
H.-W. Lin, S. Cohen, R. Edwards, D. Richards

Monday 3:10

m_{pi} = 480, 720, 1100 MeV

- Quenched
- Variational methods
- Three gaussian smearings
- Solve generalised eigenvalue problem to obtain Z's and m's
- Use Z's and m's in 3pt correlator and solve for form factors
- Smearing tuned for p=0 not ideal at large p





Nucleon-Roper Form Factors Monday 3:10

H.-W. Lin, S. Cohen, R. Edwards, D. Richards [arXiv:0803.3020]

Quenched study with variational methods at m_{pi} = 480, 720, 1100 MeV

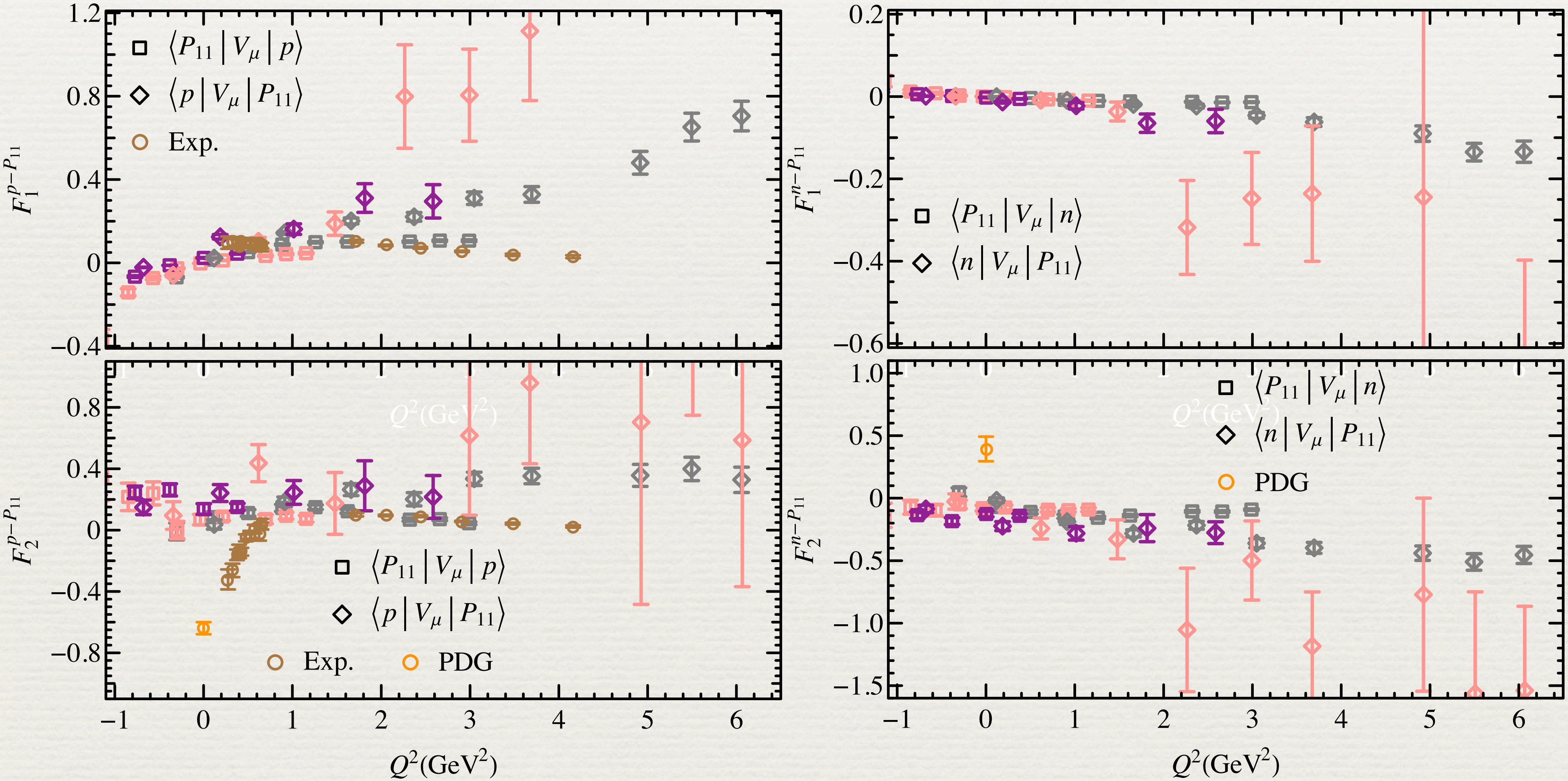
$$\langle N_2 | j_\mu(\vec{q}) | N_1 \rangle = \bar{u}_{N_2}(p') \left[F_1(q^2) \left(\gamma_\mu - \frac{q_\mu}{q^2} \not{q} \right) + \sigma_{\mu\nu} q_\nu \frac{F_2(q^2)}{M_{N_1} + M_{N_2}} \right] u_{N_1}(p)$$

Nucleon-Roper Form Factors Monday 3:10

H.-W. Lin, S. Cohen, R. Edwards, D. Richards [arXiv:0803.3020]

Quenched study with variational methods at m_{pi} = 480, 720, 1100 MeV

$$\langle N_2|j_\mu(\vec{q})|N_1\rangle = \bar{u}_{N_2}(p')\left[F_1(q^2)\left(\gamma_\mu - \frac{q_\mu}{q^2}\not{q}\right) + \sigma_{\mu\nu}q_\nu\frac{F_2(q^2)}{M_{N_1}+M_{N_2}}\right]u_{N_1}(p)$$



Jefferson Lab Research Program

http://www.jlab.org/highlights/phys.html

- Electric and Magnetic Proton Form Factors
- Neutron Charge Density
- Neutron Magnetic Structure
- Nucleon-Delta Transition
- **Pion Form Factor**
- Generalized Parton Distributions
- Spin Sum Rules
- Nucleon Spin Asymmetries
- Strange Quarks in the Proton

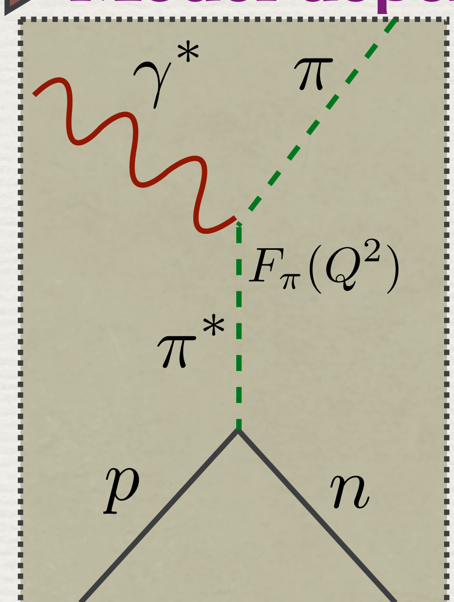
Pion Form Factor

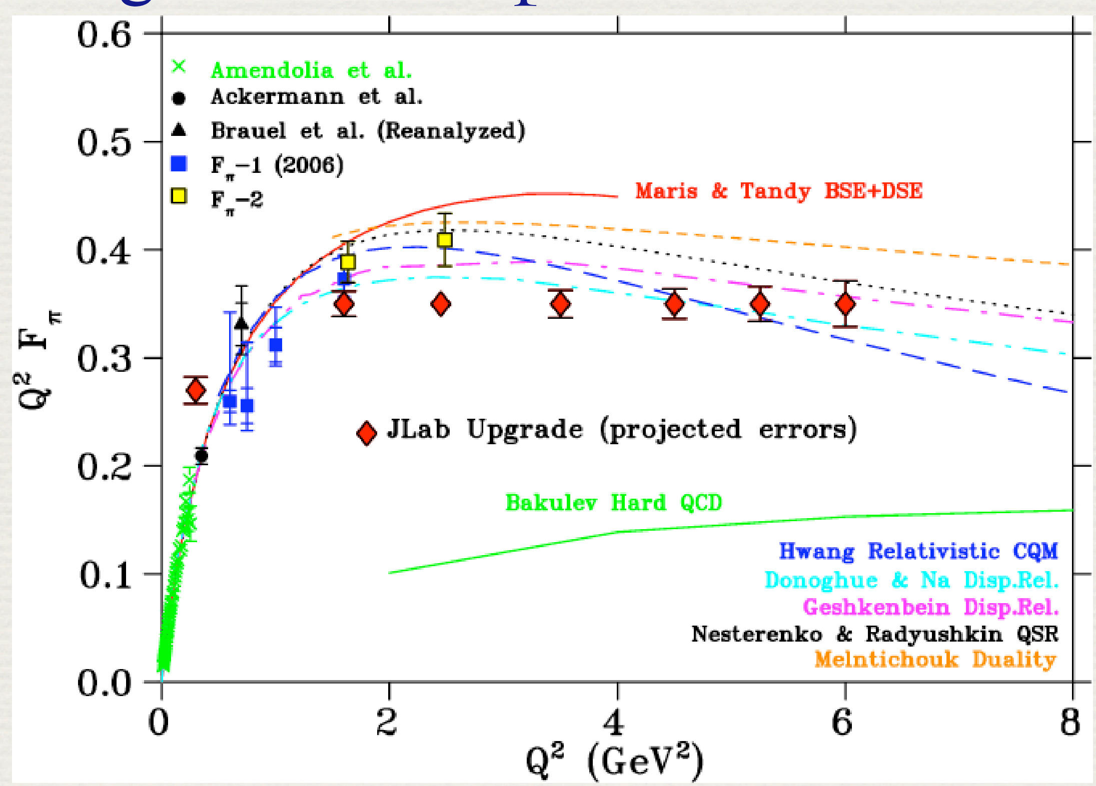
- Asymptotic normalisation known from $\pi \to \mu + \nu$ decay

$$F_\pi(Q^2 \to \infty) = \frac{16\pi\alpha_s(Q^2) f_\pi^2}{Q^2}$$

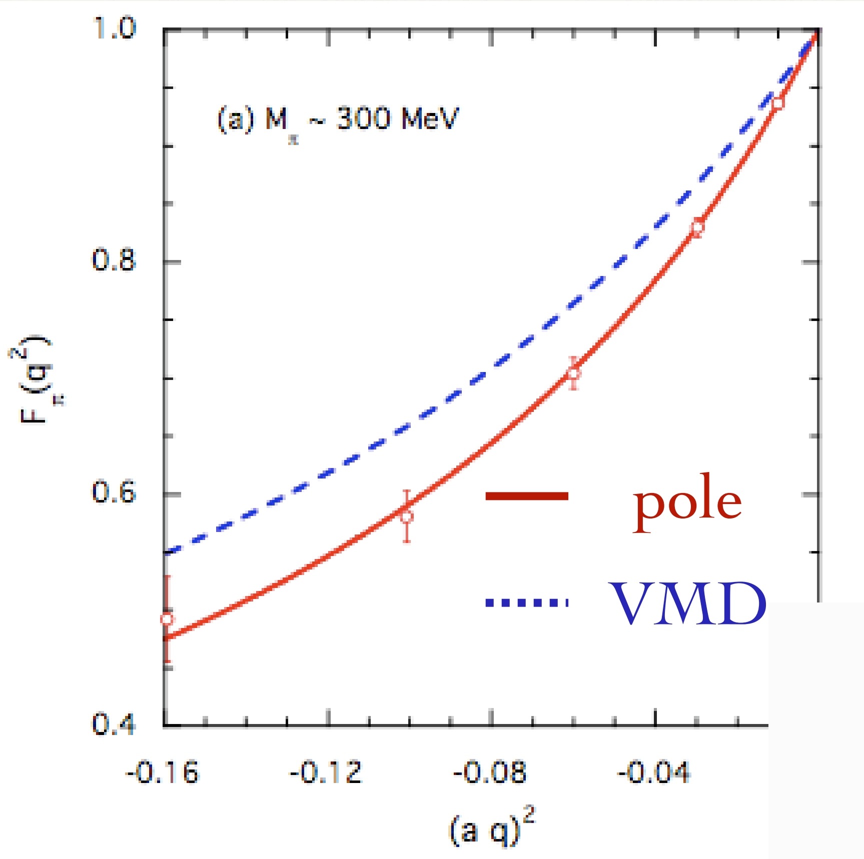
- Allows to study the transistion from the soft regime (quark-gluon correlations) to the hard regime (perturbative QCD)
- Low Q^2: F_π measured directly by scattering high energy π^+ from atomic elections [CERN] $r_\pi = 0.657 \pm 0.006$ fm
- High Q^2: quasi-elastic scattering off virtual pions [DESY & JLab]

Model dependence



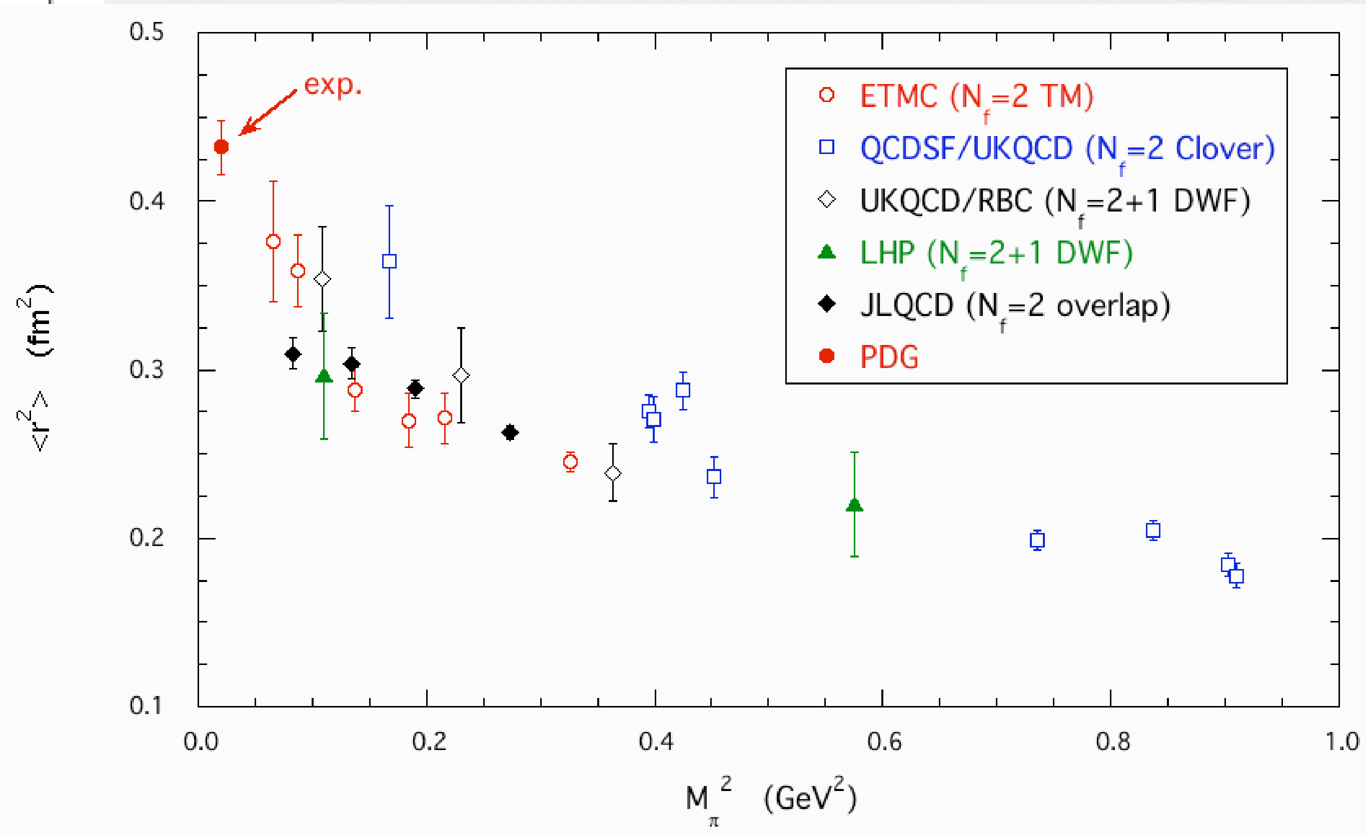


Pion Charge Radius



S.Simula et al., [ETMC]

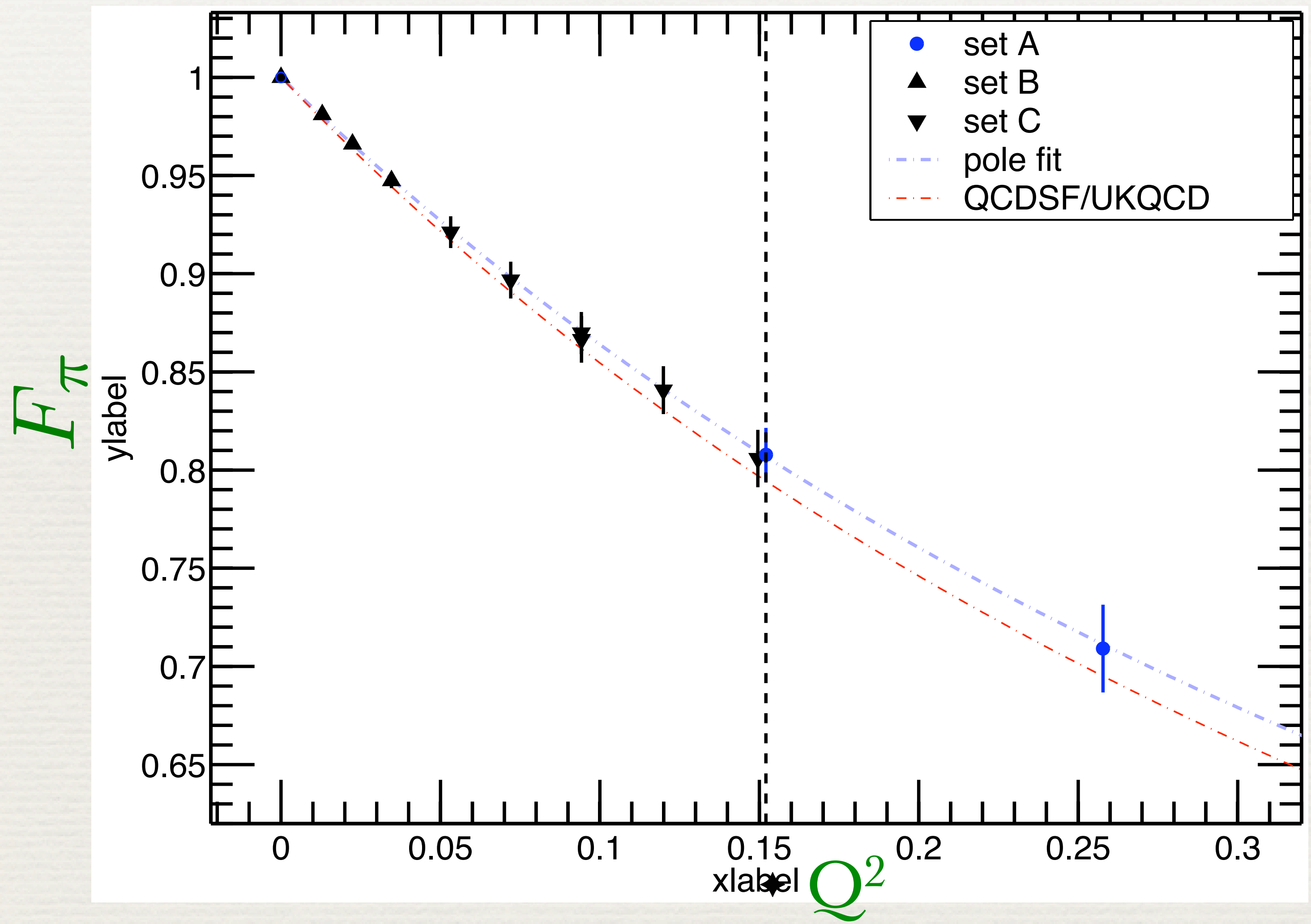
- N_f=2 Twisted Mass fermions
- Stochastic prop (one-end trick)
- Twisted boundary conditions



Finite Volume?
Discretisation?

Pion Charge Radius

[Boyle et al. [UKQCD/RBC], DWF N_f=2+1, arXiv: 0804.3971]



- Stochastic prop (one-end trick)
- Twisted boundary conditions

$m_\pi \approx 330\text{MeV}$

$24^3 \times 64$

$a \approx 0.114$ fm

[0.418(28)]

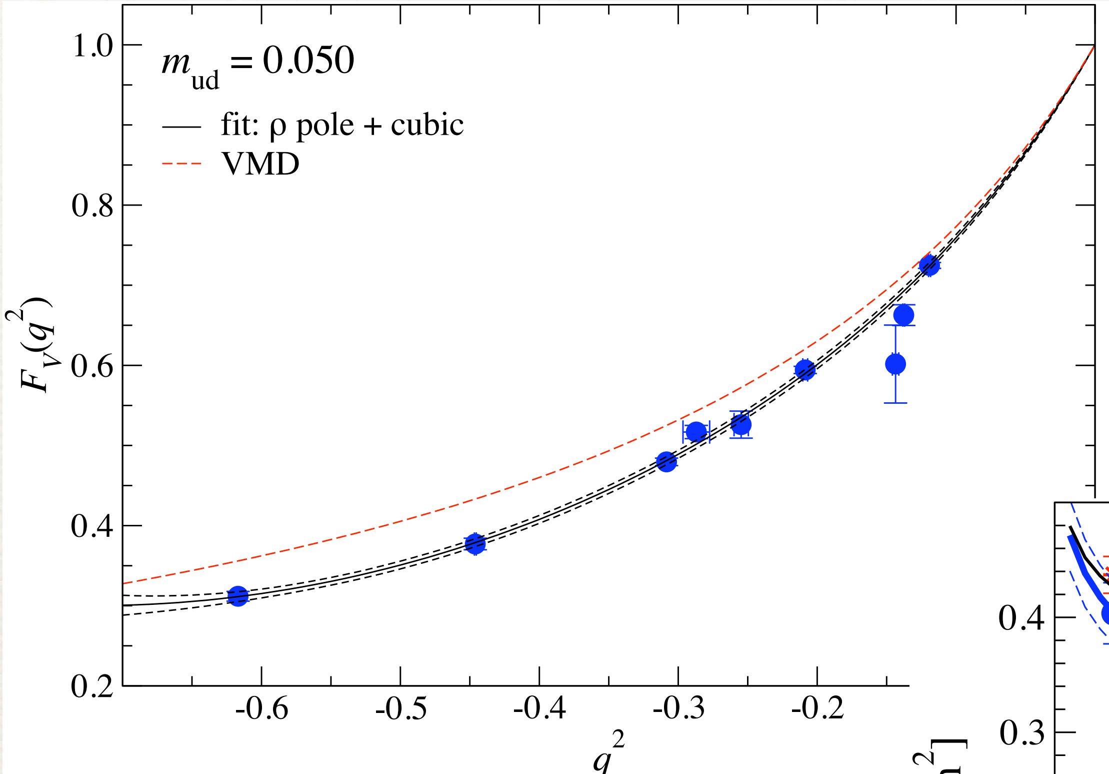
[0.452(11)]exp

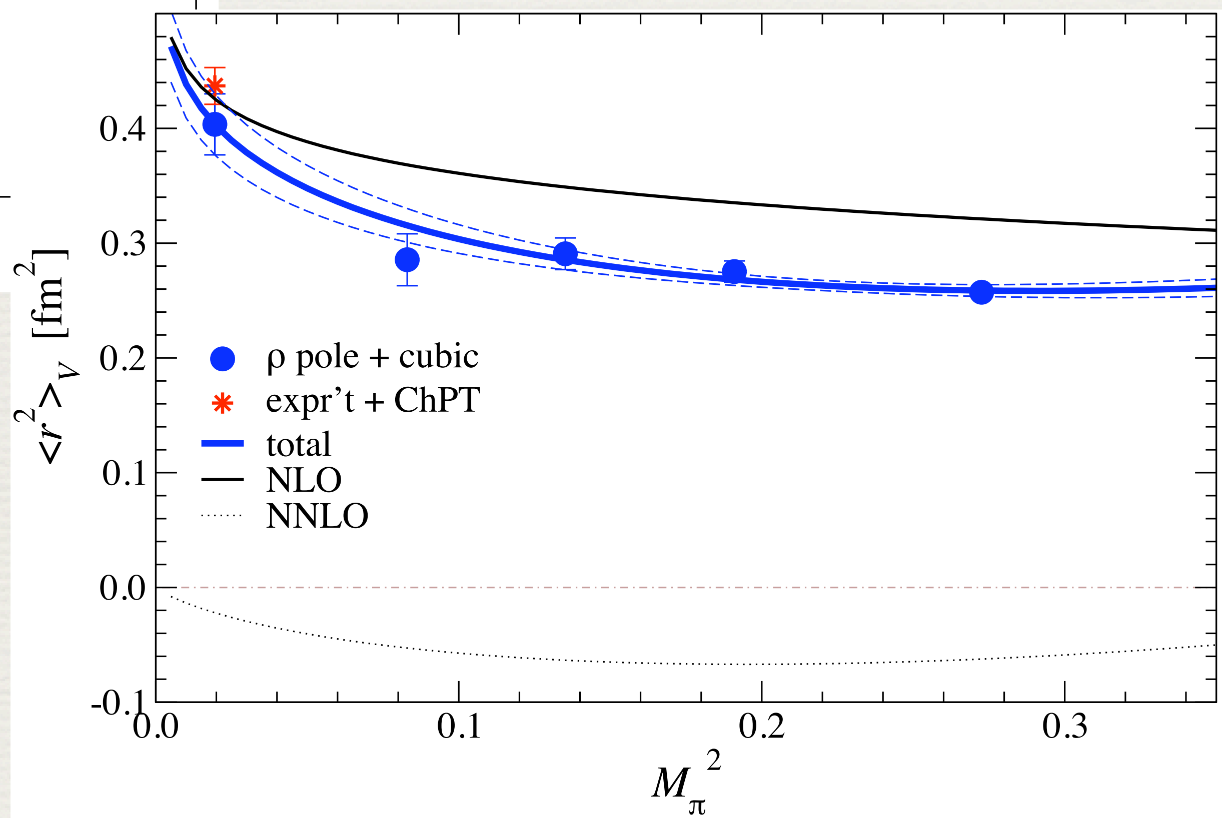
$$\langle r_\pi^2 \rangle_{(2),\mathrm{NLO}} = -\frac{12 l_6^r}{f^2} - \frac{1}{8\pi^2 f^2}\left(\log\frac{m_\pi^2}{\mu^2} + 1\right)$$

Pion Form Factor

Thursday 9:10

T. Kaneko [JLQCD]: Nf=2 Overlap, all-to-all propagators





Pion Charge Radius

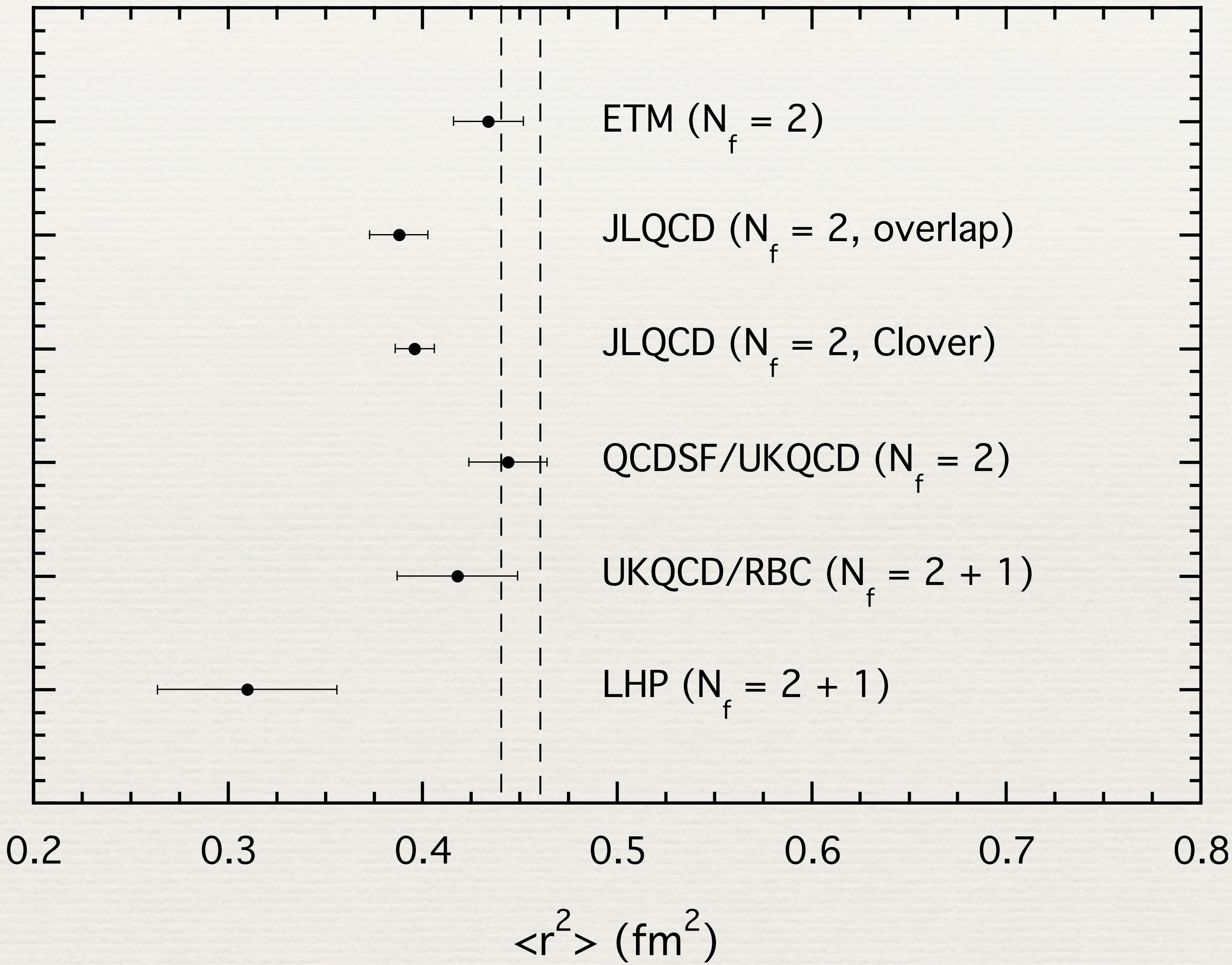


Figure by S.Simula

Jefferson Lab Research Program

http://www.jlab.org/highlights/phys.html

- Electric and Magnetic Proton Form Factors
- Neutron Charge Density
- Neutron Magnetic Structure
- Nucleon-Delta Transition
- Pion Form Factor
- **Generalized Parton Distributions**
- **Spin Sum Rules**
- Nucleon Spin Asymmetries
- Strange Quarks in the Proton

Spin Sum Rule

- Spin decomposed in terms of quark and gluon angular momentum

$$\frac{1}{2} = \sum_q J_q(\mu^2) + J_g(\mu^2)$$

- Further decomposition into spin and orbital angular momentum

$$\frac{1}{2} = \sum_q \frac{1}{2}\Delta\Sigma_q + \sum_q L_q + \Delta G + L_g$$

- Also expressed in terms of moments of GPDs

$$J_{q/g} = \frac{1}{2}[A_{20}^{q/g}(\Delta^2 = 0) + B_{20}^{q/g}(\Delta^2 = 0)]$$

- Matrix elements of the energy momentum tensor

$$\langle P'|T^{\mu\nu}|P\rangle = \overline{U}(P')\left\{\gamma^\mu \overline{P}^\nu A_{20}(\Delta^2) + \frac{i\sigma^{\mu\rho}\Delta_\rho \overline{P}^\nu}{2m_N} B_{20}(\Delta^2) + \frac{\Delta^\mu \Delta^\nu}{m_N} C_{20}(\Delta^2)\right\} U(P)$$

Momentum conservation:

$$\begin{aligned} 1 &= \sum_q A_{20}^q(0) + A_{20}^g(0) \\ &= \sum_q \langle x \rangle_q + \langle x \rangle_g \end{aligned}$$

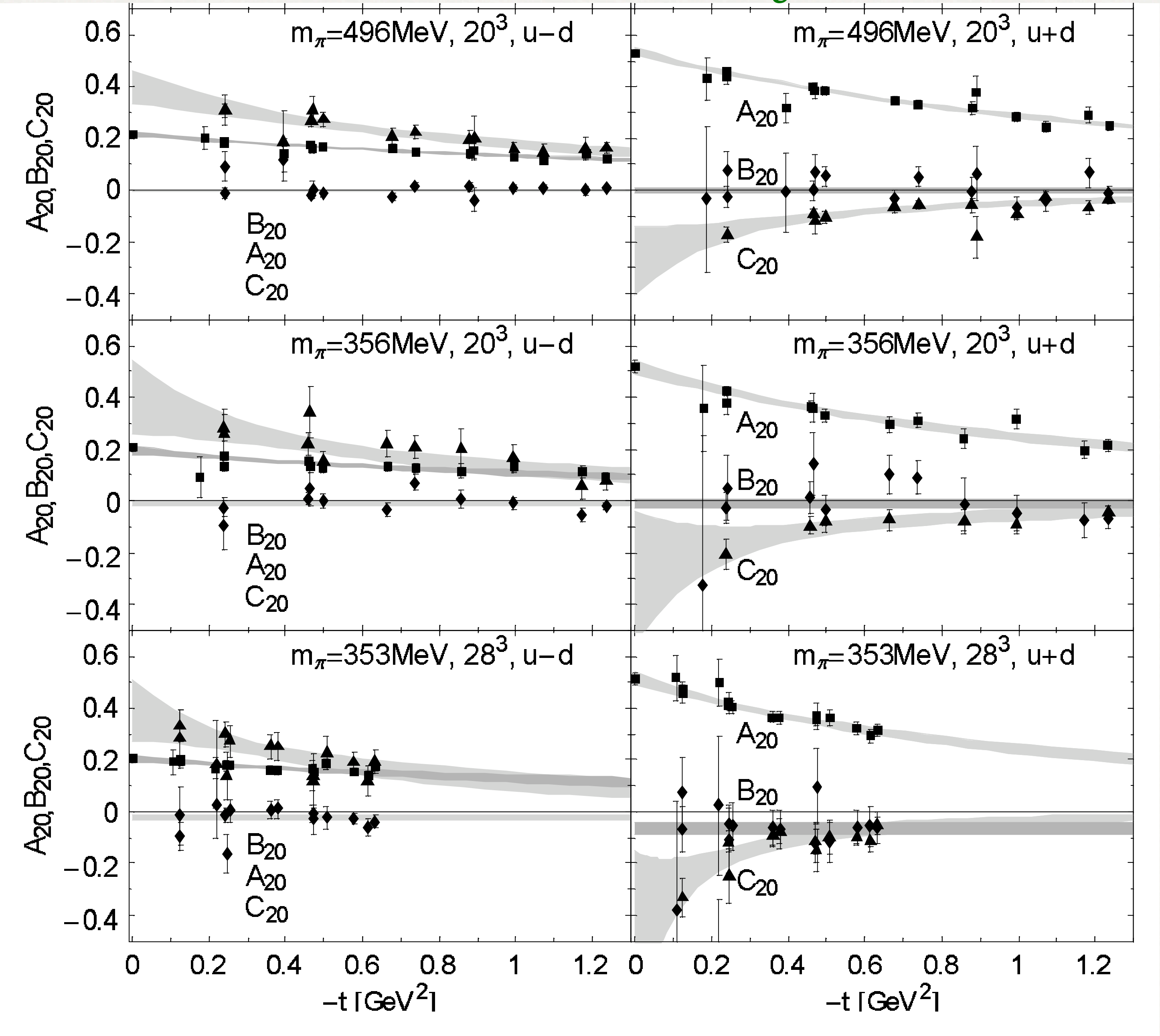
Anomalous gravitomagnetic moment

$$0 = \sum_q B_{20}^q(0) + B_{20}^g(0)$$

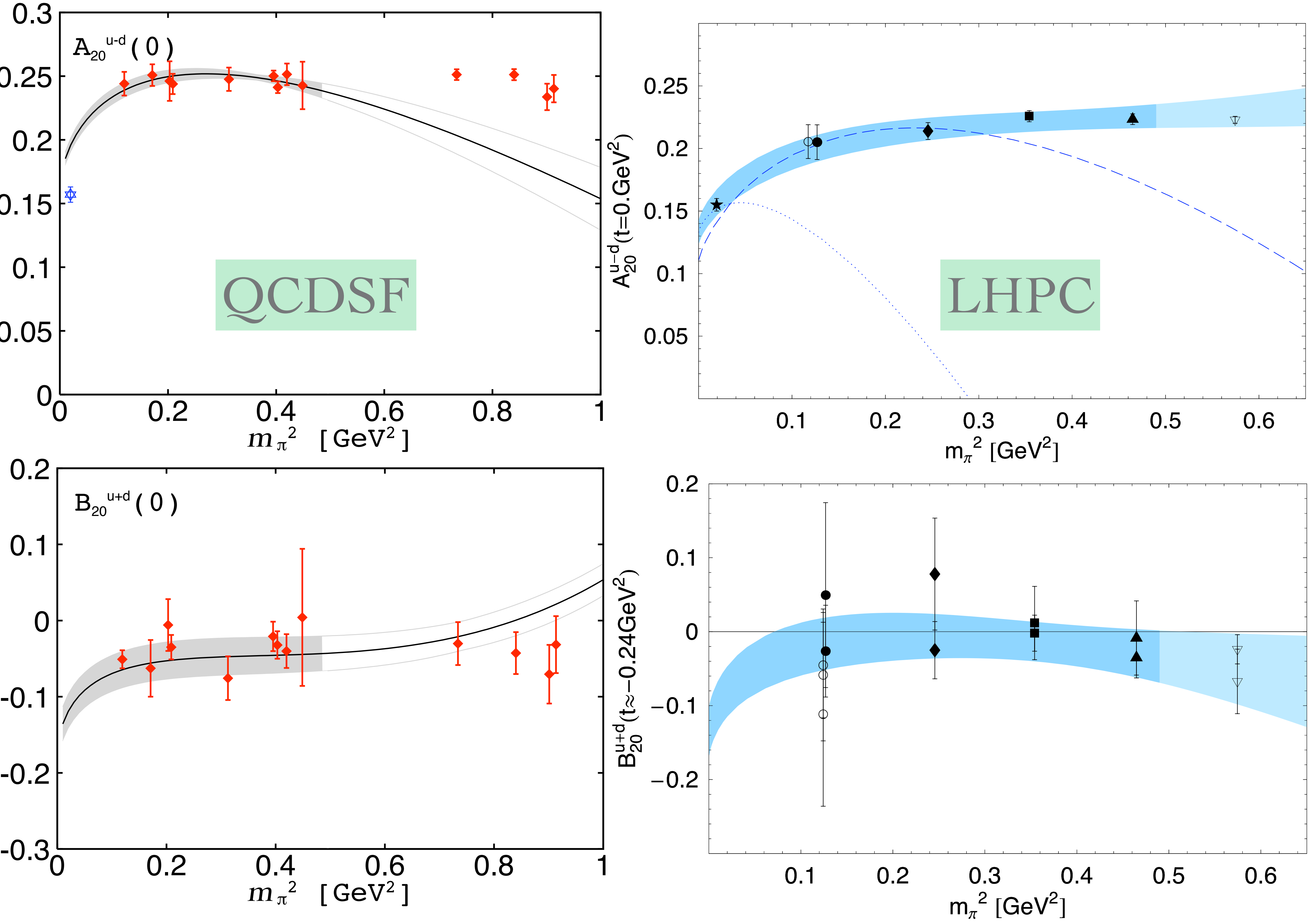
Generalised Form Factors A_2, B_2, C_2

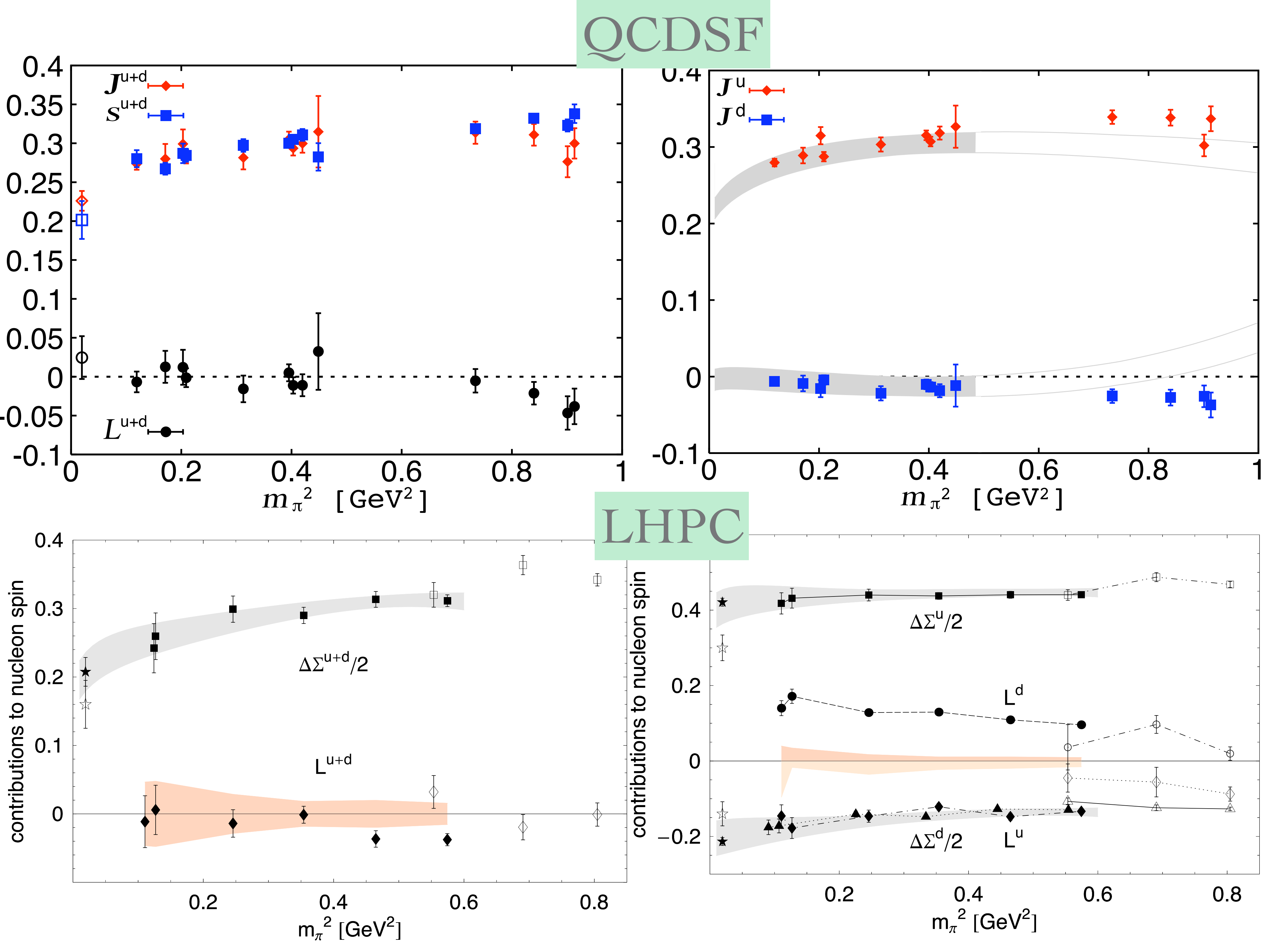
LHPC: PRD 77, 094502(2008), 0705.4295

J. Negele Friday 5:00

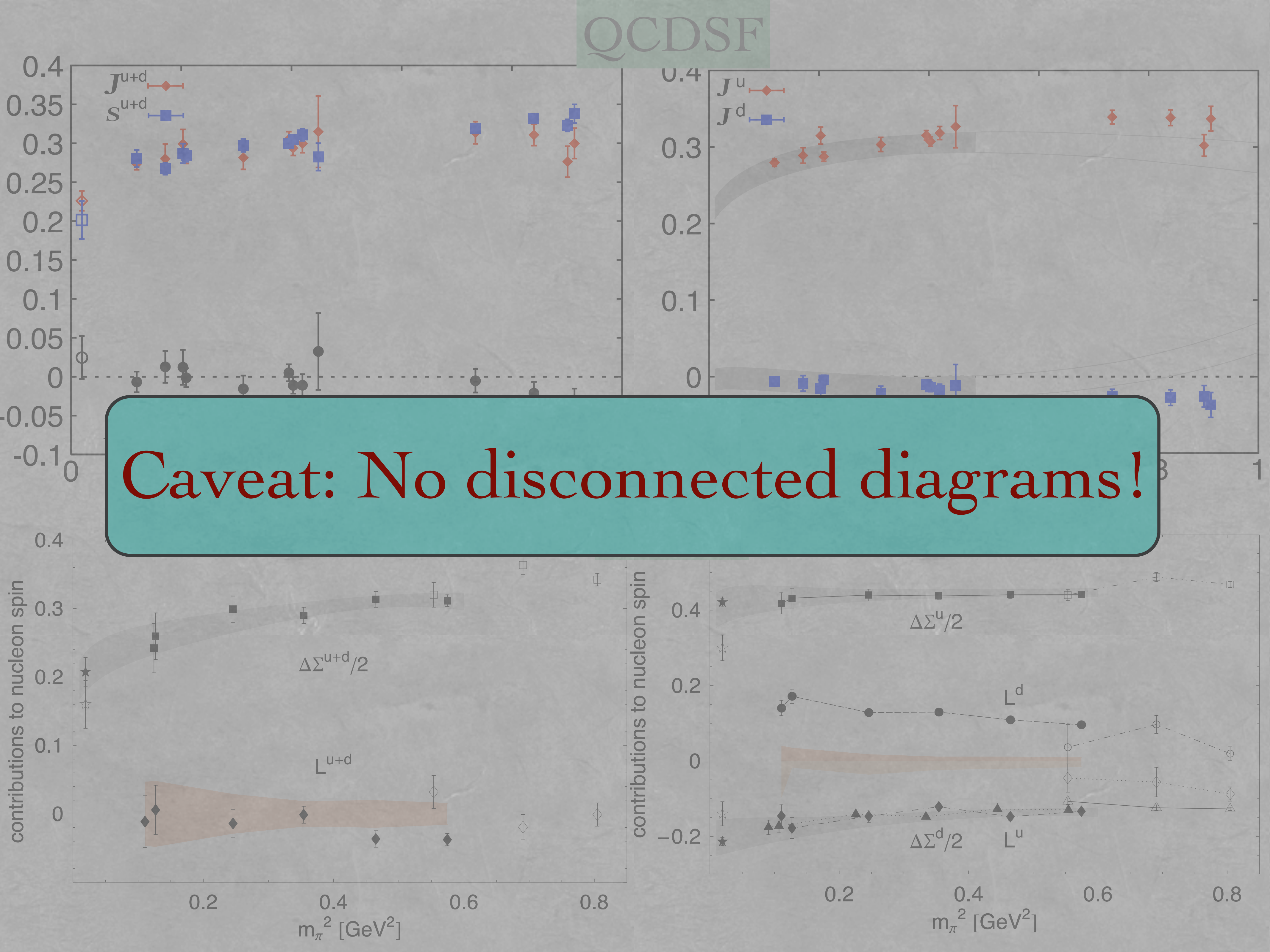


Lattice 2007: 0710.1534 PRD 77, 094502(2008), 0705.4295



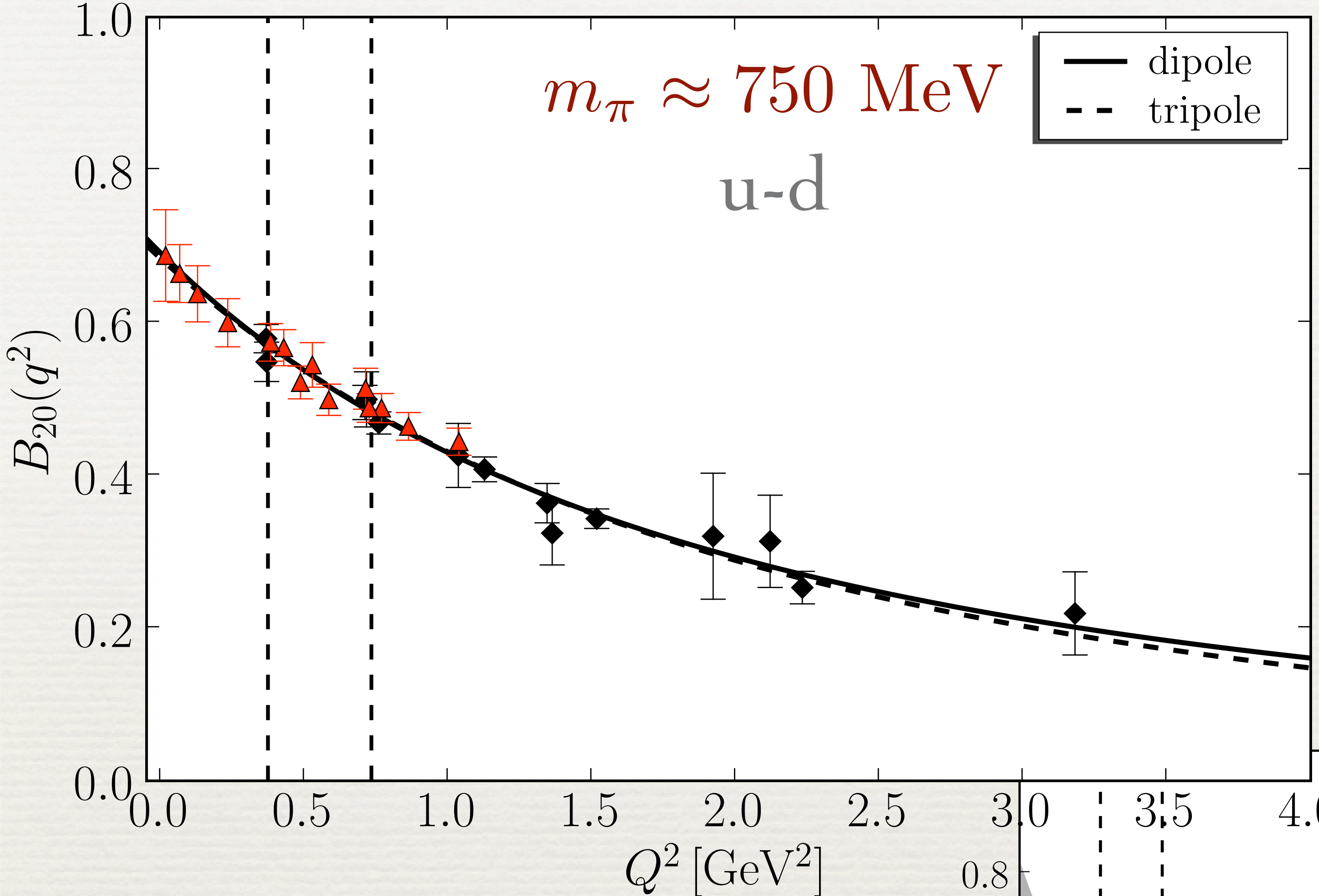


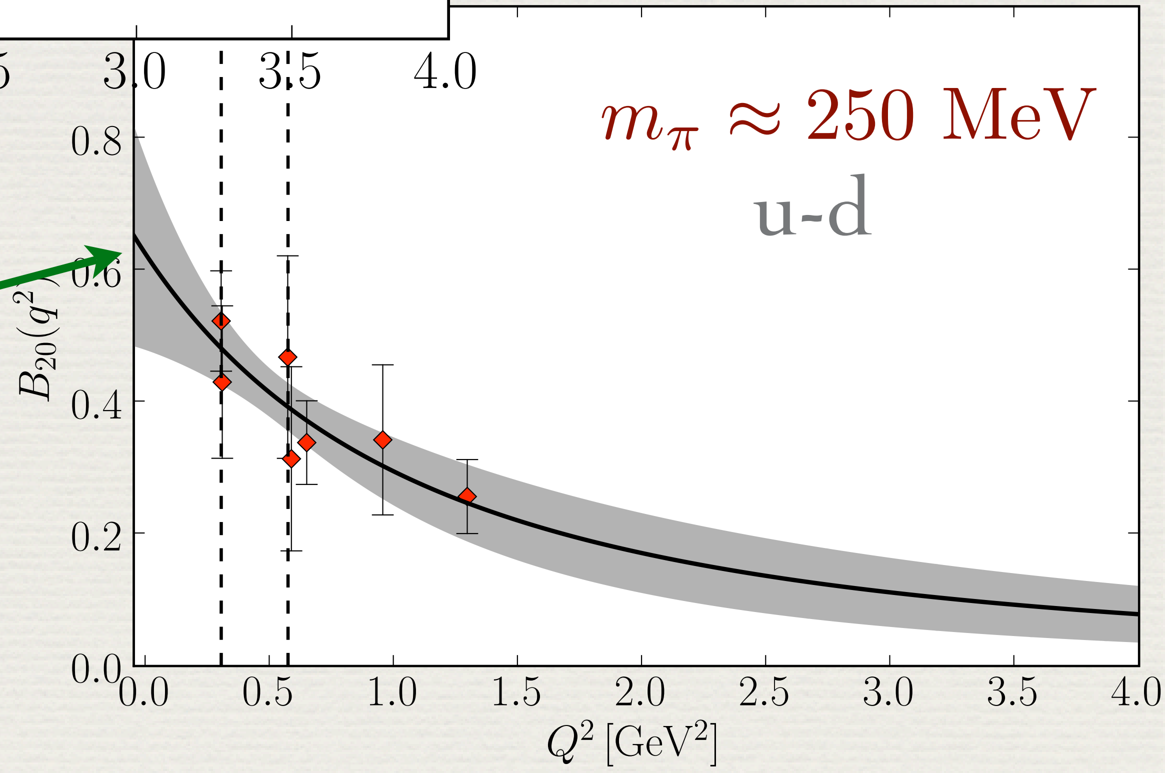
QCDSF
LHPC
J u+d
s u+d
L u+d
J u
J d
m π 2 [GeV 2]
contributions to nucleon spin
ΔΣ u+d /2
L u+d
ΔΣ u /2
L d
ΔΣ d /2
L u
m π 2 [GeV 2]



Caveat: No disconnected diagrams!

Accessing Small Q^2: Partially Twisted Boundary Conditions





TBC to help?

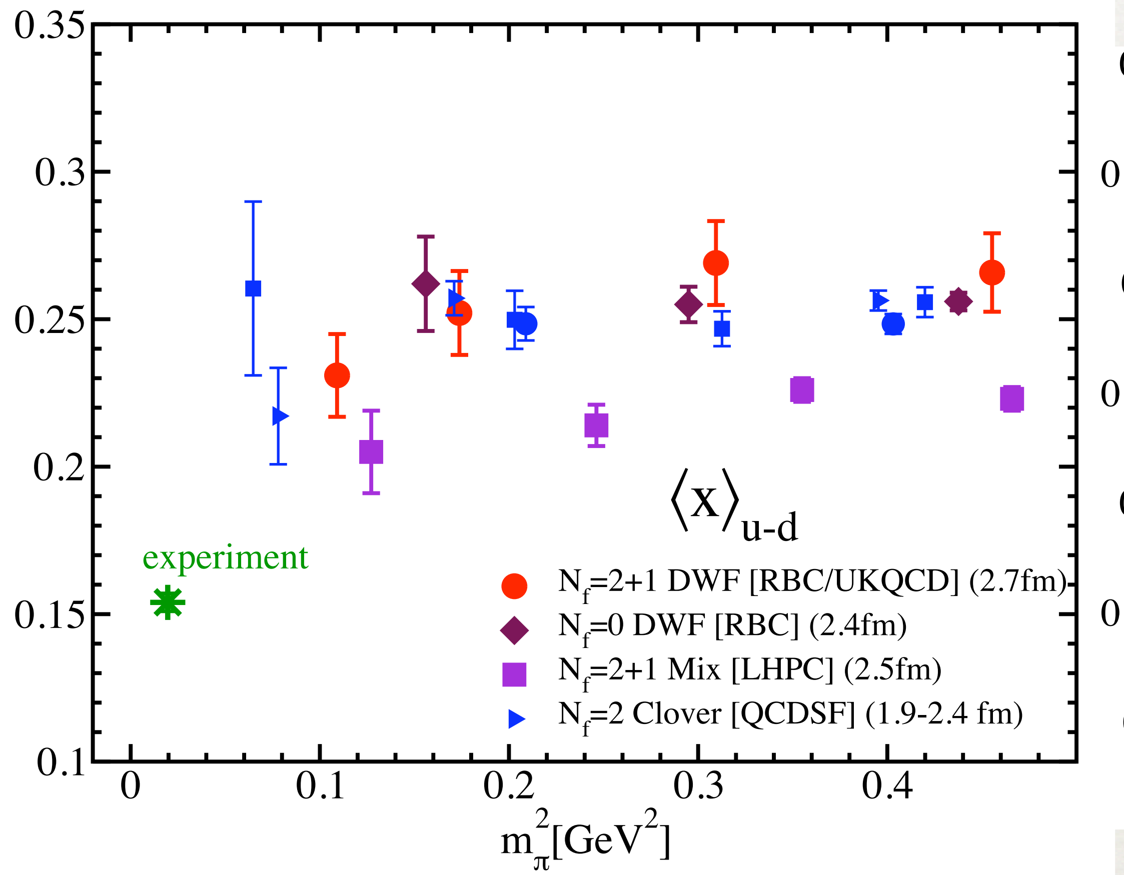
Ph. Hägler [QCDSF]:
N_f=2 Clover

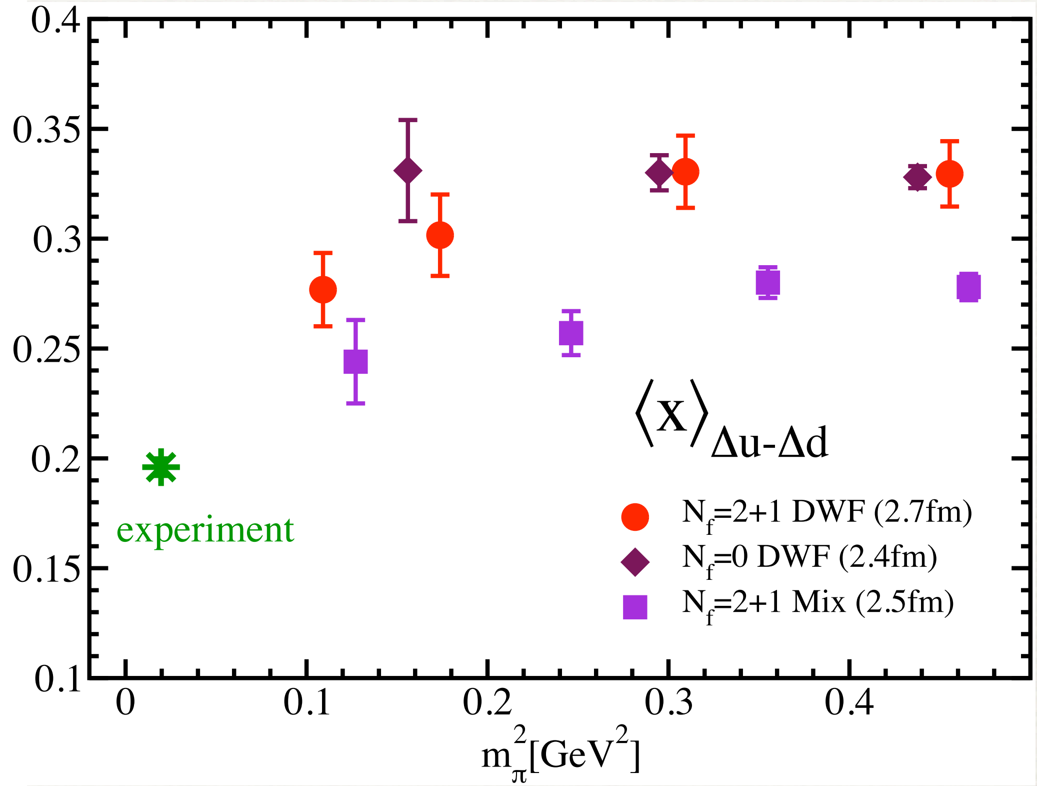
Monday 2:30

$\langle x \rangle_{u-d}, \ \langle x \rangle_{\Delta u - \Delta d}$

S. Ohta [RBC/UKQCD]
2+1 DWF

Friday 5:20





Also see *D. Mankame [Kentucky] N_f=2+1 Clover (CP-PACS/JLQCD)*

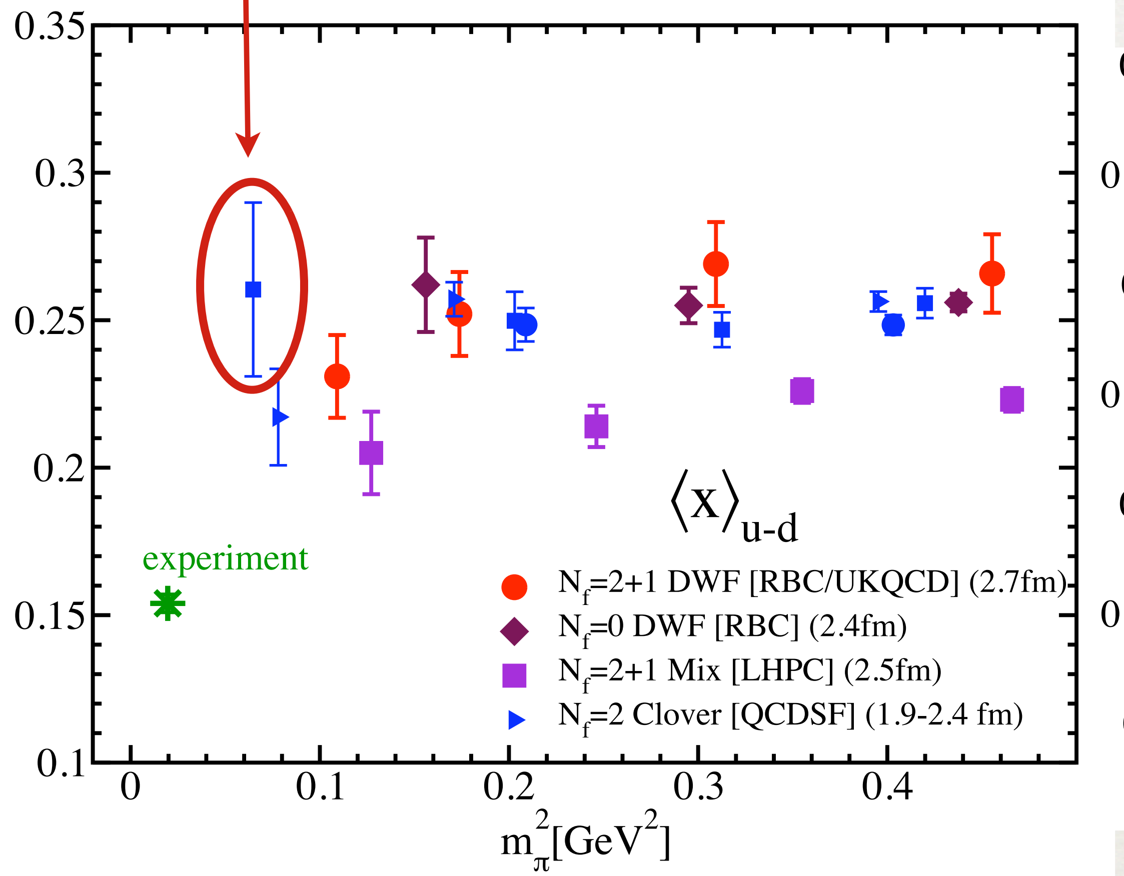
Monday 3:50

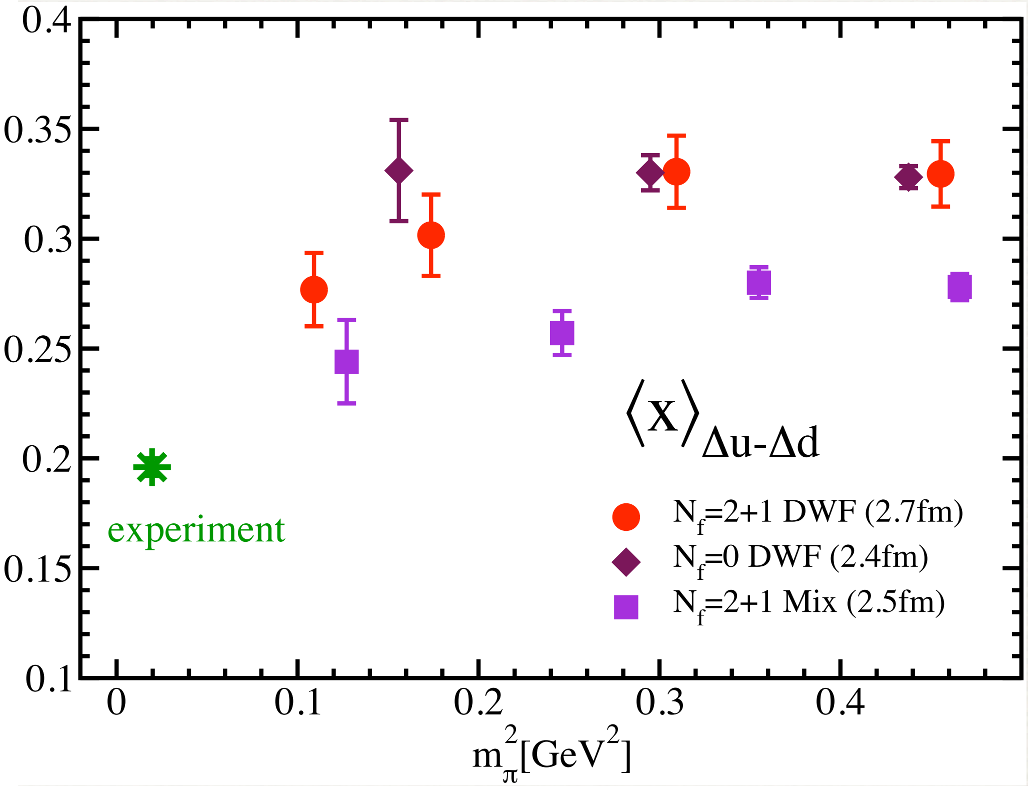
$\langle x \rangle_{u-d}$, $\langle x \rangle_{\Delta u - \Delta d}$

Finite size effect? $(m_\pi L = 2.78)$

S. Ohta [RBC/UKQCD]
2+1 DWF

Friday 5:20





Also see *D. Mankame [Kentucky] N_f=2+1 Clover (CP-PACS/JLQCD)*

Monday 3:50

Nucleon Axial Charge g_A

[RBC/UKQCD] 2+1 DWF PRL 100, 171602 (2008)

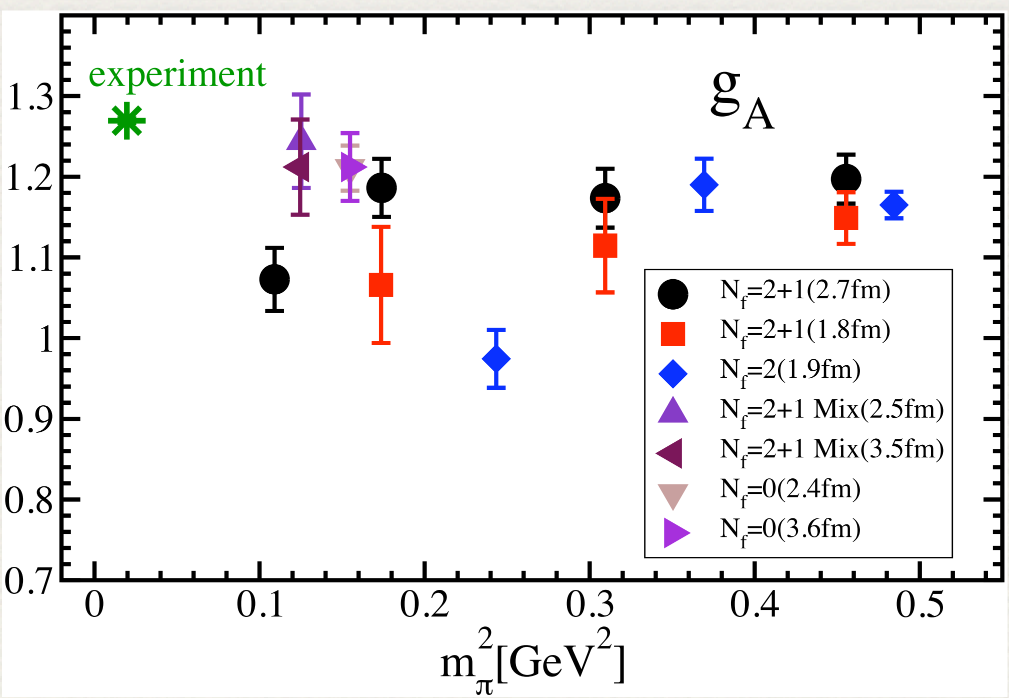
T.Yamazaki Monday 4:10

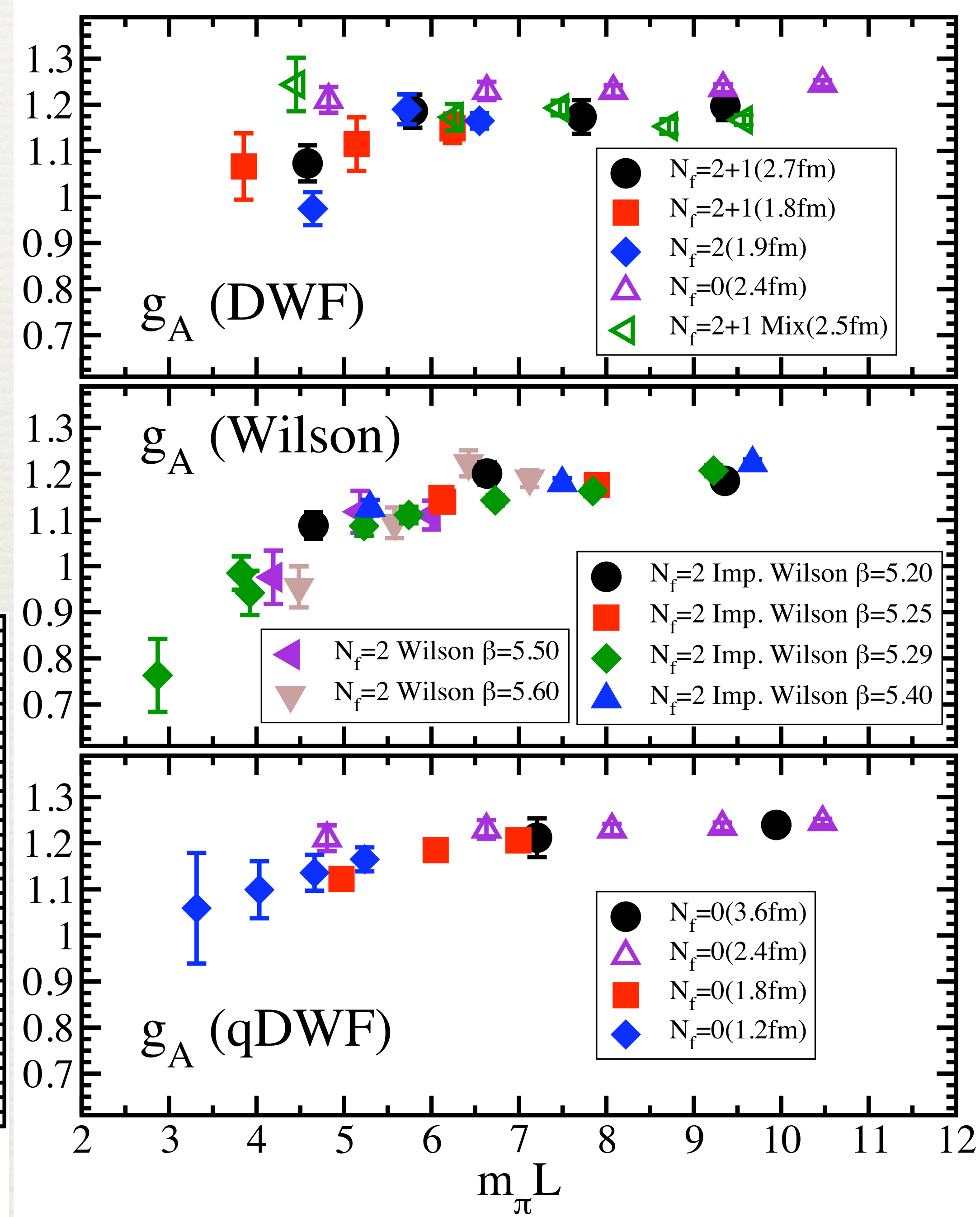
$$\langle p,\ s|A^{\mu}_{u-d}|p,\ s\rangle\ = 2g_A s^{\mu}$$

Also see

R. Baron N_f=2 Twisted Mass

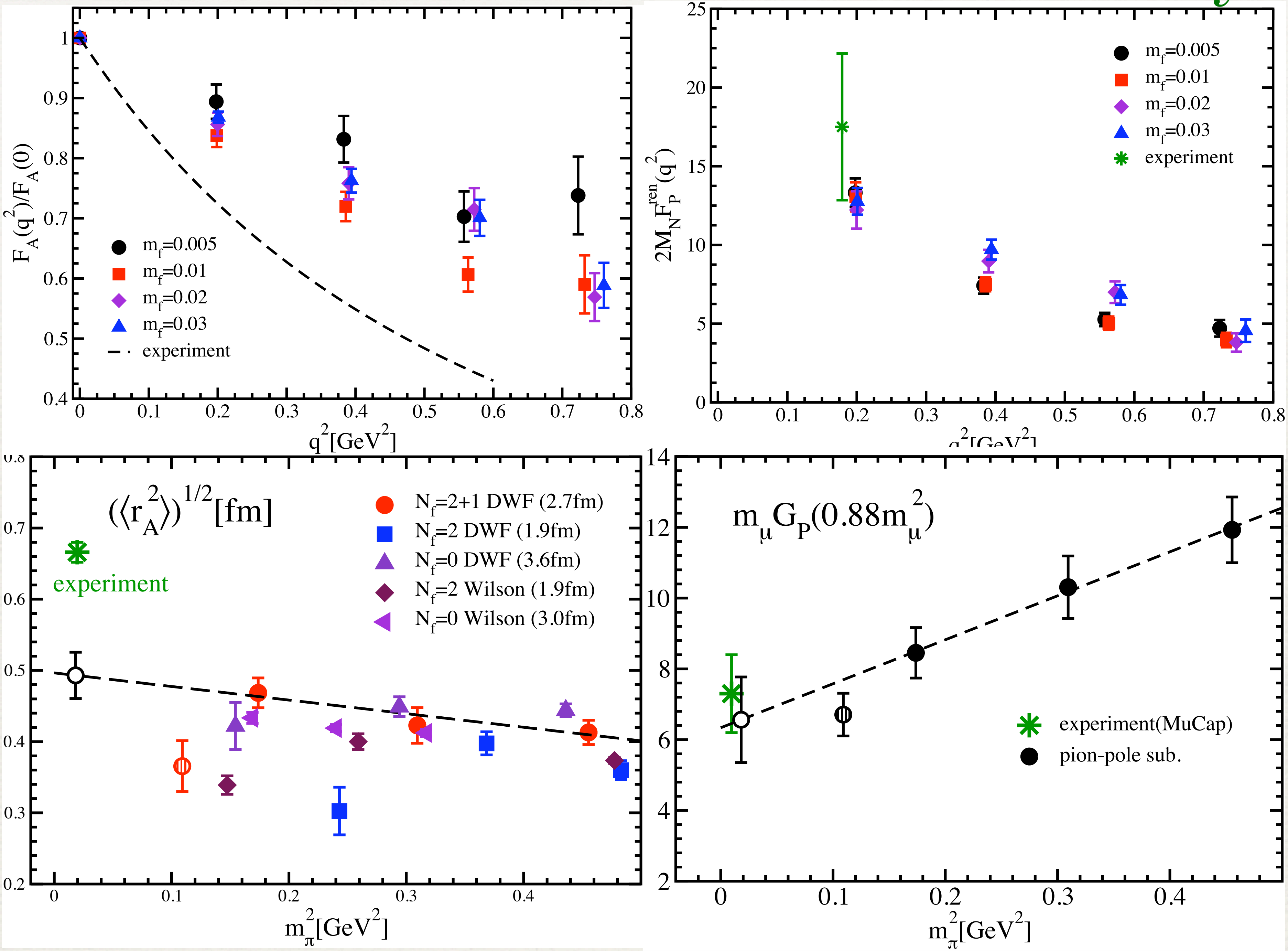
Thursday 11:20





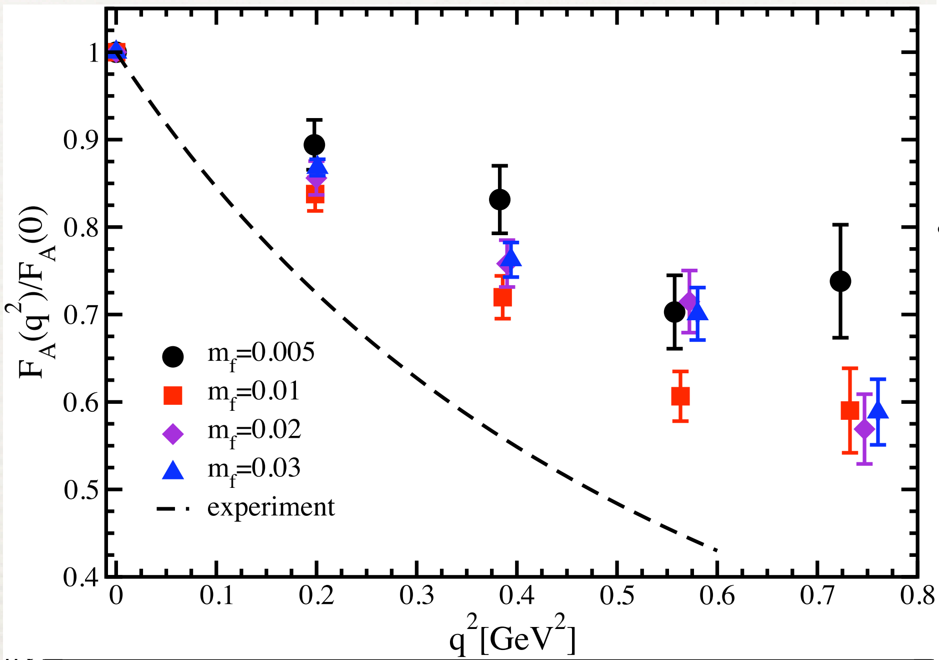
Axial & Induced Psuedoscalar Form Factor

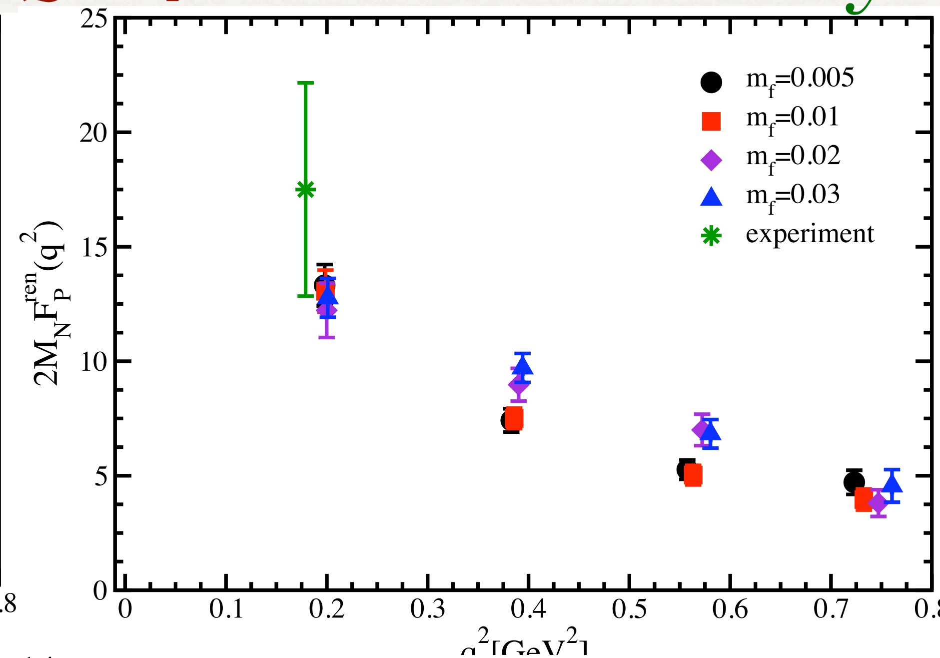
T.Yamazaki [RBC/UKQCD] 2+1 DWF Monday 4:10

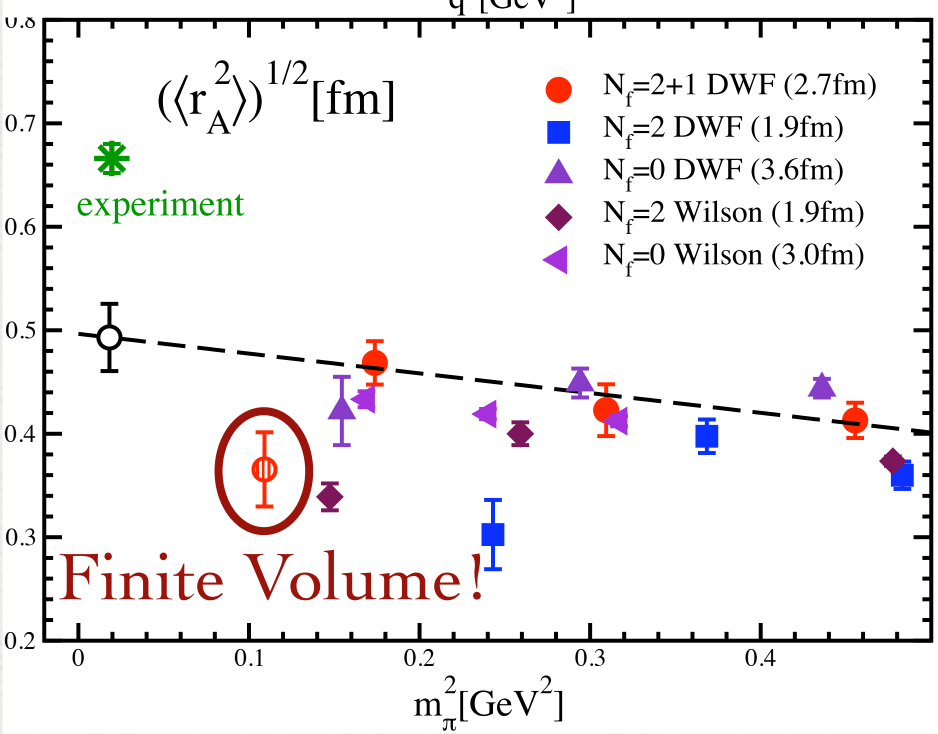


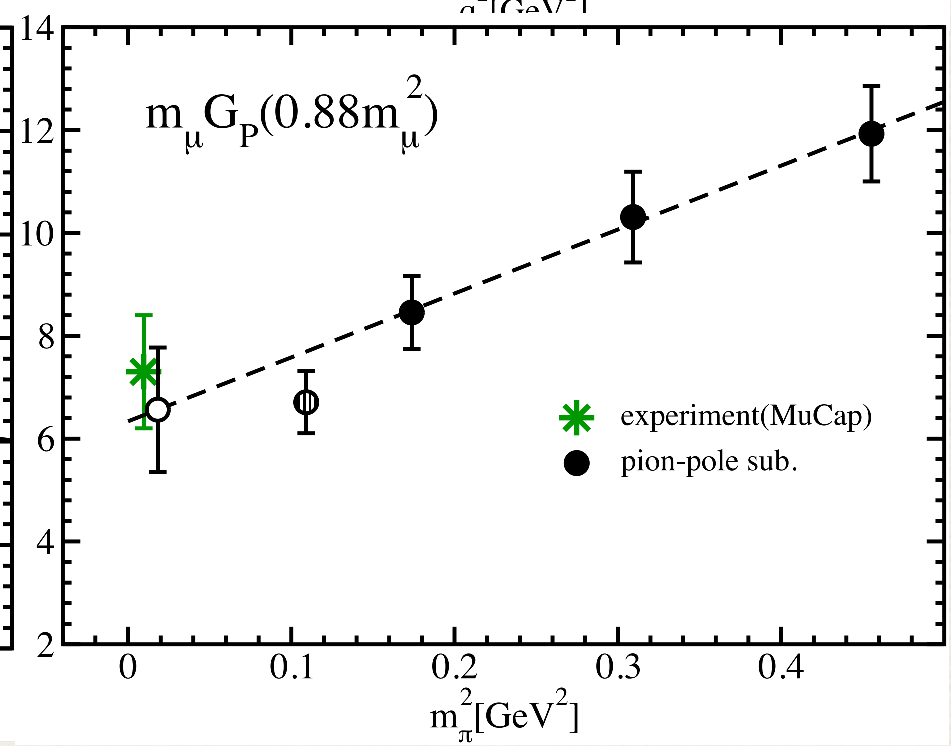
Axial & Induced Psuedoscalar Form Factor

T.Yamazaki [RBC/UKQCD] 2+1 DWF Monday 4:10









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

H.-W. Lin, K. Orginos [arXiv:0712.1214]

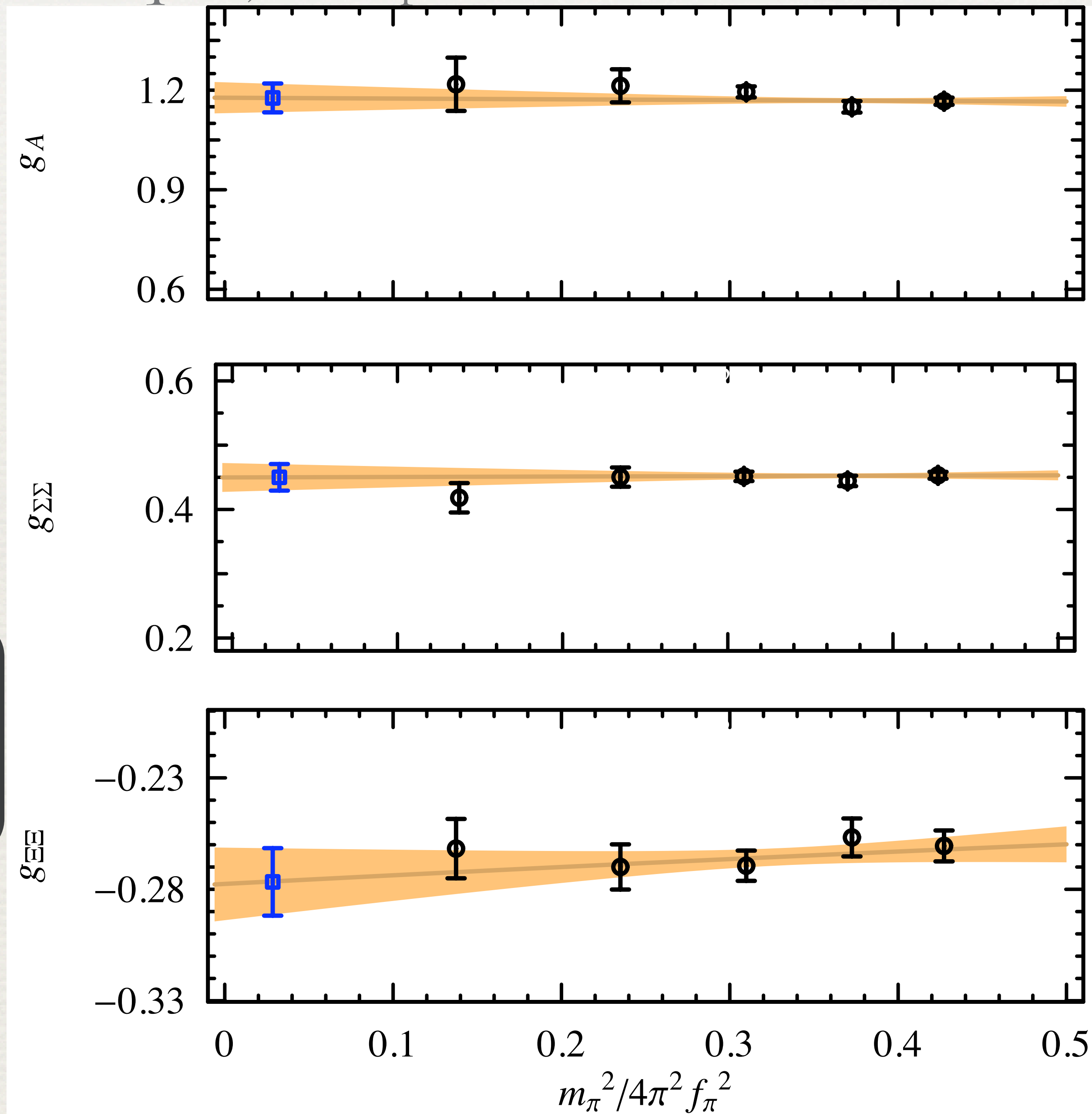
Mixed action (DWF+asqtad) at m_{pi} = 350-750 MeV

$$g_A = D + F + \sum_n C_N^{(n)} x^n$$

$$g_{\Xi\Xi} = F - D + \sum_n C_\Xi^{(n)} x^n$$

$$g_{\Sigma\Sigma} = F + \sum_n C_\Sigma^{(n)} x^n$$

$$x = (m_K^2 - m_\pi^2)/(4\pi f_\pi^2)$$



$$g_A = 1.18(4)_{\text{stat}}(6)_{\text{sys}}$$

$$g_{\Xi\Xi} = 0.450(21)_{\text{stat}}(27)_{\text{sys}}$$

$$g_{\Sigma\Sigma} = -0.277(15)_{\text{stat}}(19)_{\text{sys}}$$

D=0.715(6)(29) F=0.453(5)(19)

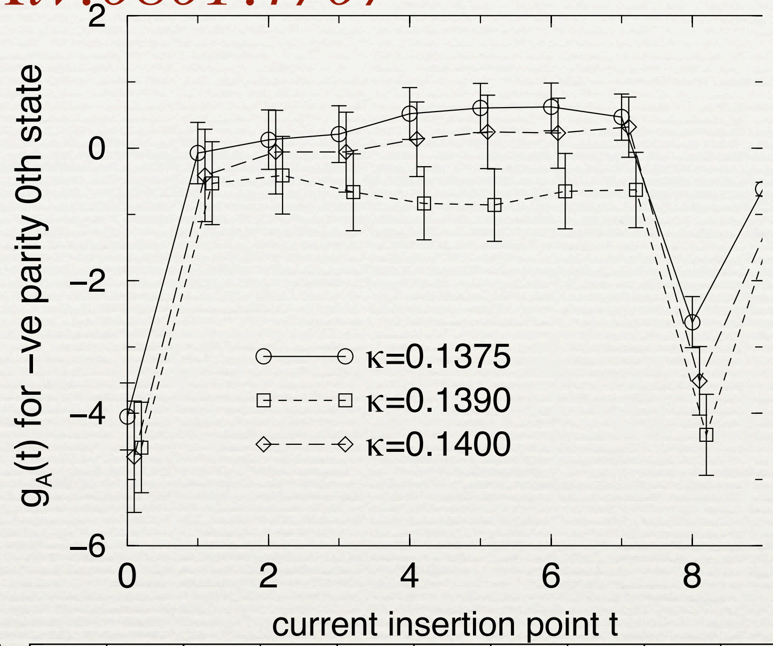
N* Axial Charges

T. Takahashi and T. Kunihiro, arXiv:0801.4707

- N_f=2 clover (CP-PACS)
- 16^3x32, a=0.1555(17) fm
- m_{ps}/m_v = 0.804(1), 0.752(1), 0.690(1)
- Construct optimised sources/sinks from a combination of

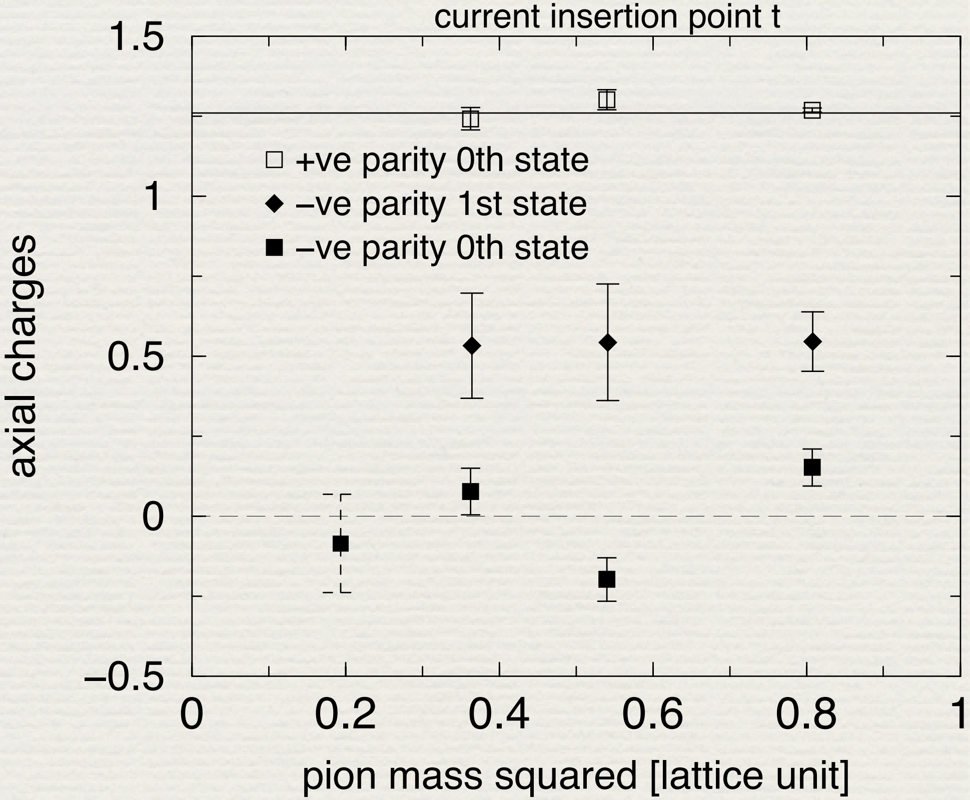
$$N_1(x) \equiv \epsilon_{abc} u^a(x)(u^b(x) C\gamma_5 d^c(x))$$

$$N_2(x) \equiv \epsilon_{abc} \gamma_5 u^a(x)(u^b(x) C d^c(x))$$



$$\begin{aligned} g_A^{0-} &< 0.2 \\ g_A^{1-} &\approx 0.55 \end{aligned}$$

Consistent with NR quark model



Jefferson Lab Research Program

http://www.jlab.org/highlights/phys.html

- Electric and Magnetic Proton Form Factors
- Neutron Charge Density
- Neutron Magnetic Structure
- **Nucleon-Delta Transition**
- Pion Form Factor
- Generalized Parton Distributions
- Spin Sum Rules
- Nucleon Spin Asymmetries
- Strange Quarks in the Proton

$N \longrightarrow \Delta$

$$\langle \Delta(\vec{p}\,', s')|j_\mu|N(\vec{p}, s)\rangle = \mathrm{i}\sqrt{\frac{2}{3}\left(\frac{m_\Delta m_N}{E_\Delta(\vec{p}\,')E_N(\vec{p})}\right)^{1/2}}\bar{u}^\sigma(\vec{p}\,', s')O_{\sigma\mu}u(\vec{p}, s)$$

$$O_{\sigma\mu} = G_{M1}(q^2)K^{M1}_{\sigma\mu} + G_{E2}(q^2)K^{E2}_{\sigma\mu} + G_{C2}(q^2)K^{C2}_{\sigma\mu}$$

Magnetic dipole: dominant

Electric quadrupole

Coulomb quadrupole

C. Alexandrou, G. Koutsou, H. Neff, J. W. Negele, W. Schroers and A. Tsapalis, Phys. Rev. D77, 085012, 2008

$$N \longrightarrow \Delta$$

$$\langle\Delta(\vec{p}\,', s')|j_\mu|N(\vec{p}, s)\rangle = \mathrm{i}\sqrt{\frac{2}{3}\left(\frac{m_\Delta m_N}{E_\Delta(\vec{p}\,')E_N(\vec{p})}\right)^{1/2}}\bar{u}^\sigma(\vec{p}\,', s')O_{\sigma\mu}u(\vec{p}, s)$$

$$O_{\sigma\mu} = G_{M1}(q^2)K^{M1}_{\sigma\mu} + G_{E2}(q^2)K^{E2}_{\sigma\mu} + G_{C2}(q^2)K^{C2}_{\sigma\mu}$$

Magnetic dipole: dominant

Electric quadrupole

Coulomb quadrupole

N, Δ deformed?

Nonzero Quadrupole moments

C. Alexandrou, G. Koutsou, H. Neff, J. W. Negele, W. Schroers and A. Tsapalis, Phys. Rev. D77, 085012, 2008

$N \longrightarrow \Delta$

$$\langle \Delta(\vec{p}', s')|j_\mu|N(\vec{p}, s)\rangle = \mathrm{i}\sqrt{\frac{2}{3}\left(\frac{m_\Delta m_N}{E_\Delta(\vec{p}')E_N(\vec{p})}\right)^{1/2}}\bar{u}^\sigma(\vec{p}', s')O_{\sigma\mu}u(\vec{p}, s)$$

$$O_{\sigma\mu} = G_{M1}(q^2)K^{M1}_{\sigma\mu} + G_{E2}(q^2)K^{E2}_{\sigma\mu} + G_{C2}(q^2)K^{C2}_{\sigma\mu}$$

Magnetic dipole: dominant

Electric quadrupole

Coulomb quadrupole

N, Δ deformed?

Nonzero Quadrupole moments

Quantities measured in the lab frame of the Δ are the ratios

$$R_{EM}(EMR) = -\frac{G_{E2}(Q^2)}{G_{M1}(Q^2)} \qquad R_{SM}(CMR) = -\frac{|\vec{q}|}{2m_\Delta}\frac{G_{C2}(Q^2)}{G_{M1}(Q^2)}$$

- Precise experimental data strongly suggest deformation of N/D
- First confirmation of non-zero EMR and CMR in full QCD

C. Alexandrou, G. Koutsou, H. Neff, J. W. Negele, W. Schroers and A. Tsapalis, Phys. Rev. D77, 085012, 2008

$N \longrightarrow \Delta$

$$\langle \Delta(\vec{p}', s')|j_\mu|N(\vec{p}, s)\rangle = \mathrm{i}\sqrt{\frac{2}{3}\left(\frac{m_\Delta m_N}{E_\Delta(\vec{p}')E_N(\vec{p})}\right)^{1/2}}\bar{u}^\sigma(\vec{p}', s')O_{\sigma\mu}u(\vec{p}, s)$$

$$O_{\sigma\mu} = G_{M1}(q^2)K^{M1}_{\sigma\mu} + G_{E2}(q^2)K^{E2}_{\sigma\mu} + G_{C2}(q^2)K^{C2}_{\sigma\mu}$$

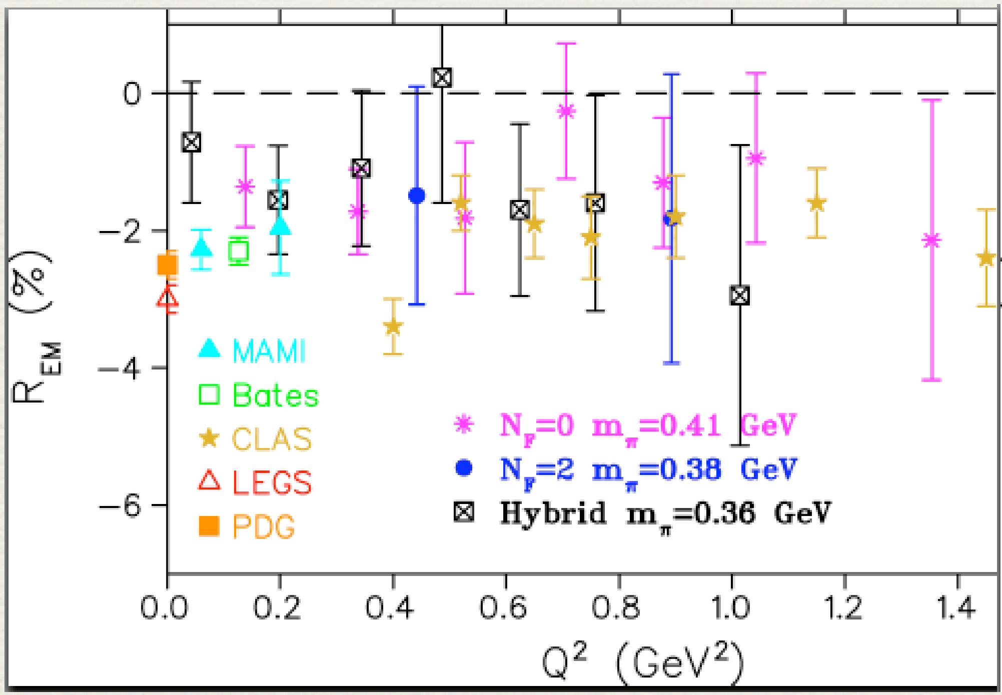
Magnetic dipole: dominant — Electric quadrupole — Coulomb quadrupole

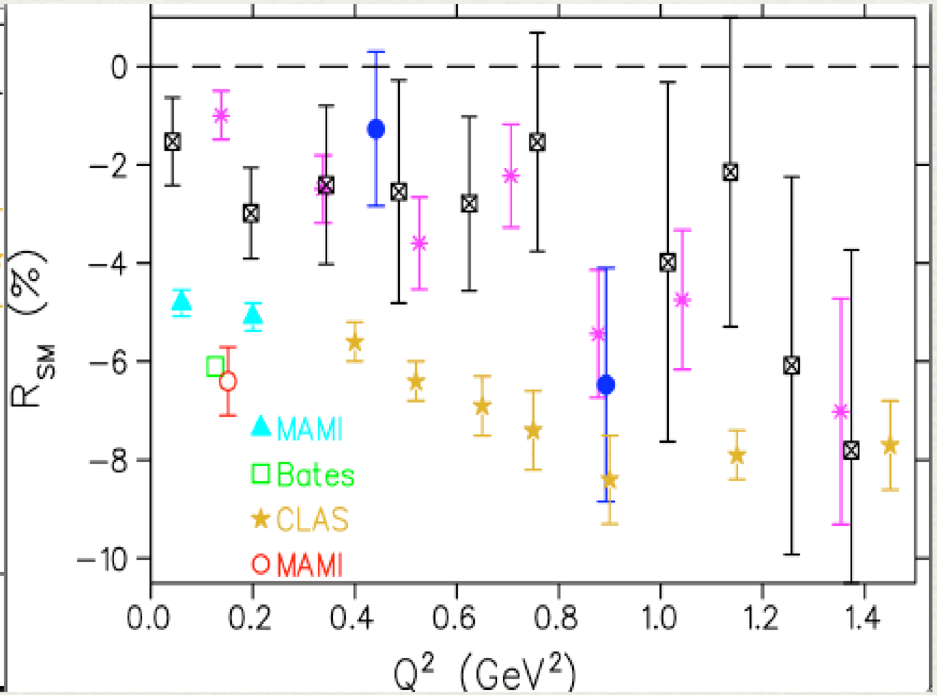
N, Δ deformed?
Nonzero Quadrupole moments

Quantities measured in the lab frame of the Δ are the ratios

$$R_{EM}(EMR) = -\frac{G_{E2}(Q^2)}{G_{M1}(Q^2)} \qquad R_{SM}(CMR) = -\frac{|\vec{q}|}{2m_\Delta}\frac{G_{C2}(Q^2)}{G_{M1}(Q^2)}$$

- Precise experimental data strongly suggest deformation of N/D
- First confirmation of non-zero EMR and CMR in full QCD





C. Alexandrou, G. Koutsou, H. Neff, J. W. Negele, W. Schroers and A. Tsapalis, Phys. Rev. D77, 085012, 2008

Axial N to Δ

C. Alexandrou, G. Koutsou, Th. Leontiou, J. W. Negele and A. Tsapalis PRD76, 094511,2007.

$$\langle\Delta(\vec{p}\,')|A_\mu|N(\vec{p})\rangle = \bar{u}^\sigma\left(\frac{C_3^A}{m_N}\gamma^\nu + \frac{C_4^A}{m_N^2}p'^\nu\right)(g_{\sigma\mu}g_{\rho\nu} - g_{\sigma\rho}g_{\mu\nu})q^\rho u + \bar{u}^\sigma C_5^A g_{\sigma\mu}u + \bar{u}^\sigma\frac{C_6^A}{m_N^2}q_\sigma q_\mu u$$

Axial vector $N \to \Delta$: four addition form factors $C_3^A(Q^2),\ C_4^A(Q^2),\ C_5^A(Q^2), C_6^A(Q^2)$

Dominant axial form factors C_5, C_6 correspond to the nucleon axial G_A, G_P

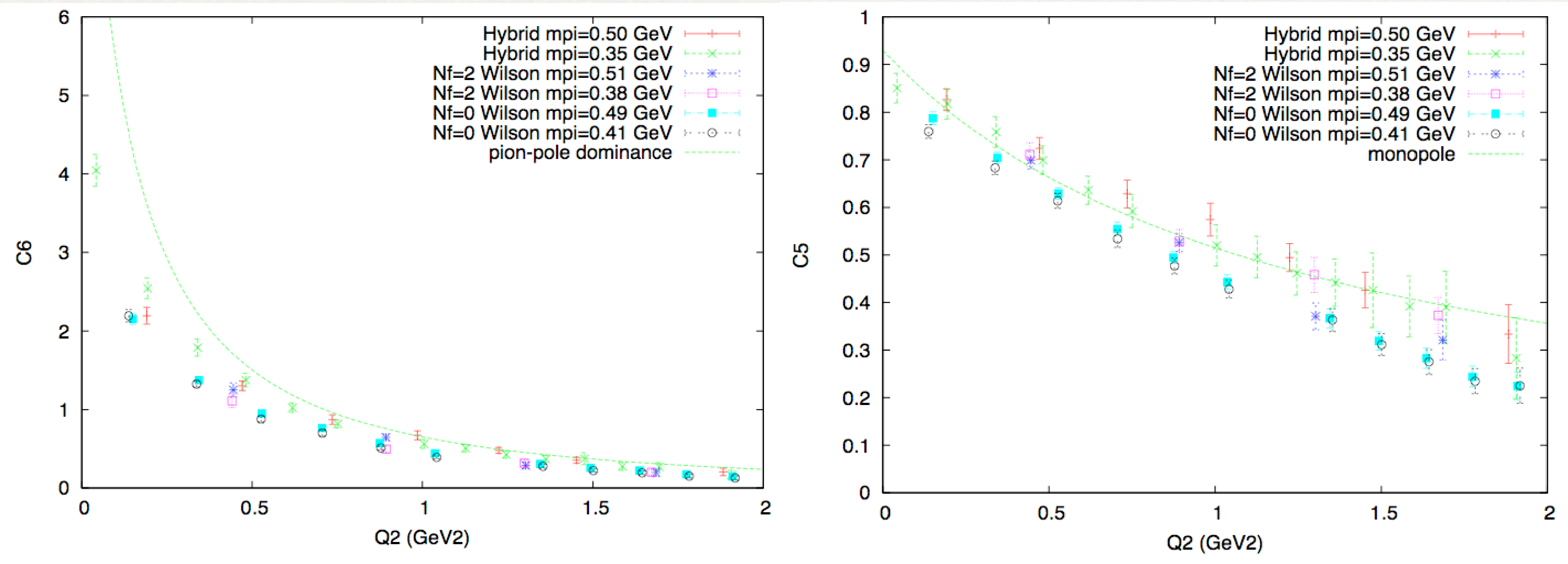
Axial N to Δ

C. Alexandrou, G. Koutsou, Th. Leontiou, J. W. Negele and A. Tsapalis PRD76, 094511,2007.

$$\langle\Delta(\vec{p}\,')|A_\mu|N(\vec{p})\rangle = \bar{u}^\sigma\left(\frac{C_3^A}{m_N}\gamma^\nu + \frac{C_4^A}{m_N^2}p'^\nu\right)(g_{\sigma\mu}g_{\rho\nu} - g_{\sigma\rho}g_{\mu\nu})q^\rho u + \bar{u}^\sigma C_5^A g_{\sigma\mu}u + \bar{u}^\sigma\frac{C_6^A}{m_N^2}q_\sigma q_\mu u$$

Axial vector $N \to \Delta$: four addition form factors $C_3^A(Q^2),\ C_4^A(Q^2),\ C_5^A(Q^2), C_6^A(Q^2)$

Dominant axial form factors C_5, C_6 correspond to the nucleon axial G_A, G_P



Unquenching effects at small Q^2??

Pion-pole dominance for C_6

$$\longrightarrow \frac{C_6^A}{m_N^2} = \frac{1}{m_\pi^2 + Q^2}C_5^A$$

Δ electromagnetic form factors *P. Moran et al. [Adelaide]*

$$\langle \Delta(\vec{p}\,', s')|j_\mu|\Delta(\vec{p}, s)\rangle = \mathrm{i}\sqrt{\frac{m_\Delta^2}{E_\Delta(\vec{p}\,')E_\Delta(\vec{p})}}\,\bar{u}^\sigma(\vec{p}\,', s')O_{\sigma\mu\tau}u_\tau(\vec{p}, s)$$

$$O_{\sigma\mu\tau} = \delta^{\sigma\tau}\left[a_1(q^2)\mathrm{i}\gamma^\mu + \frac{a_2(q^2)}{2m_\Delta}(p'^\mu + p^\mu)\right] - \frac{q^\sigma q^\tau}{2m_\Delta^2}\left[c_1(q^2)\mathrm{i}\gamma^\mu + \frac{c_2(q^2)}{2m_\Delta}(p'^\mu + p^\mu)\right]$$

Four form factors: G_{E0}, G_{E2}, G_{M1}, G_{M3} given in terms of a_1, a_2, c_1, c_2

Δ electromagnetic form factors

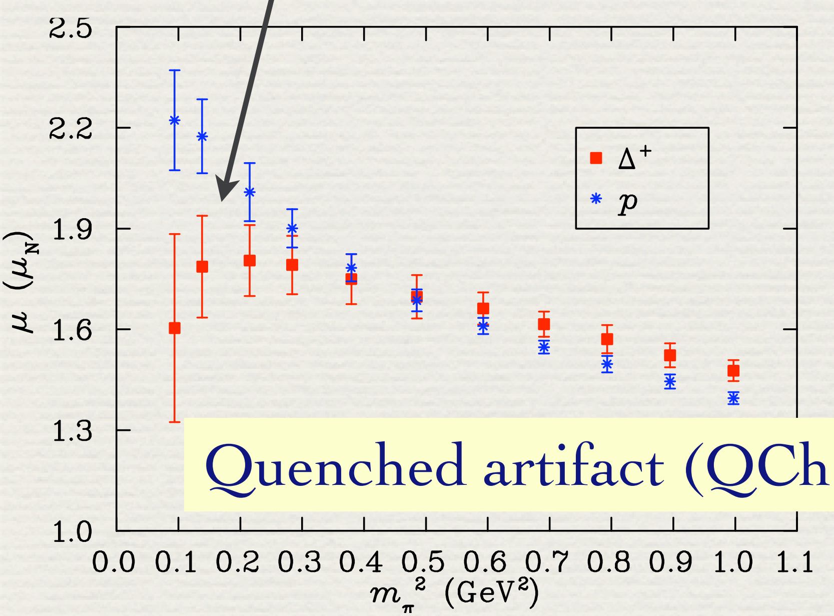
P. Moran et al. [Adelaide]

$$\langle \Delta(\vec{p}\,', s')|j_\mu|\Delta(\vec{p}, s)\rangle = \mathrm{i}\sqrt{\frac{m_\Delta^2}{E_\Delta(\vec{p}\,')E_\Delta(\vec{p})}}\,\bar{u}^\sigma(\vec{p}\,', s')O_{\sigma\mu\tau}u_\tau(\vec{p}, s)$$

$$O_{\sigma\mu\tau} = \delta^{\sigma\tau}\left[a_1(q^2)\mathrm{i}\gamma^\mu + \frac{a_2(q^2)}{2m_\Delta}(p'^\mu + p^\mu)\right] - \frac{q^\sigma q^\tau}{2m_\Delta^2}\left[c_1(q^2)\mathrm{i}\gamma^\mu + \frac{c_2(q^2)}{2m_\Delta}(p'^\mu + p^\mu)\right]$$

Four form factors: G_{E0}, G_{E2}, G_{M1}, G_{M3} given in terms of a_1, a_2, c_1, c_2

Should go away with dynamical fermions



Quenched artifact (QChPT)

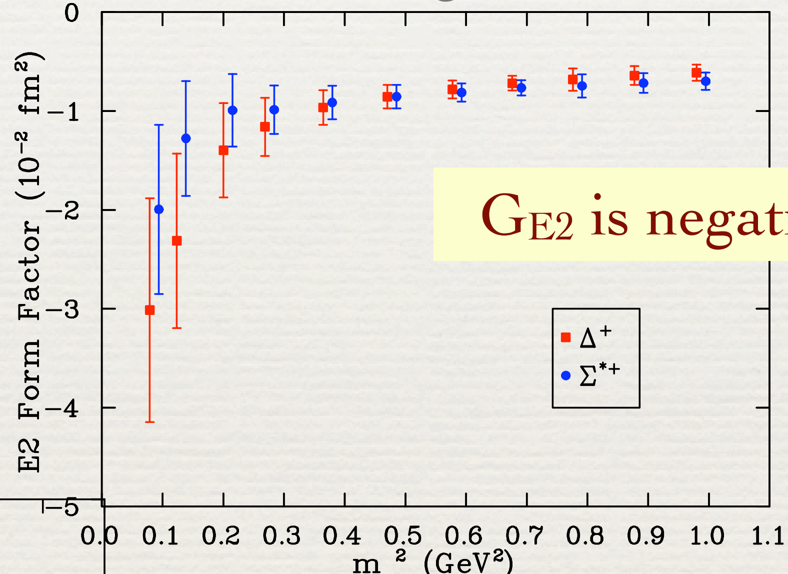
Δ electromagnetic form factors

P. Moran et al. [Adelaide]

$$\langle \Delta(\vec{p}', s')|j_\mu|\Delta(\vec{p}, s)\rangle = \mathrm{i}\sqrt{\frac{m_\Delta^2}{E_\Delta(\vec{p}')E_\Delta(\vec{p})}}\,\bar{u}^\sigma(\vec{p}', s')O_{\sigma\mu\tau}u_\tau(\vec{p}, s)$$

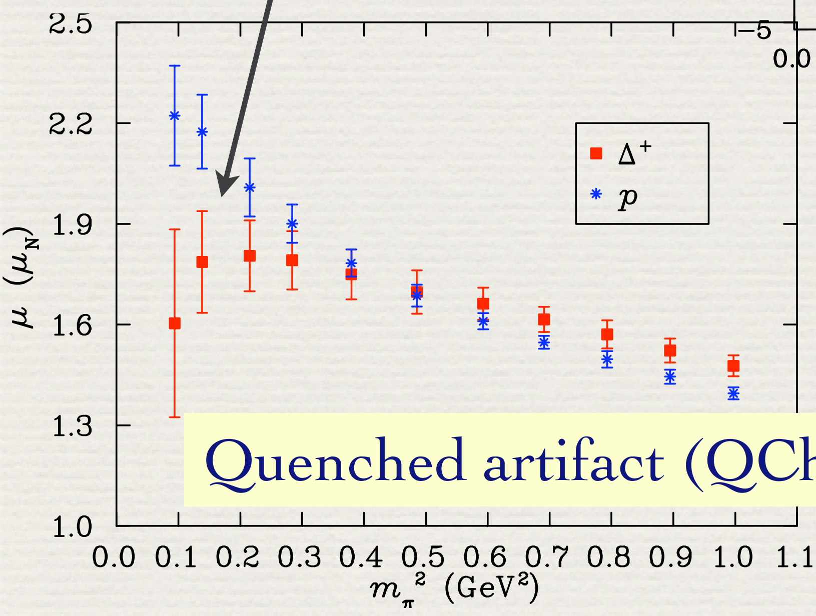
$$O_{\sigma\mu\tau} = \delta^{\sigma\tau}\left[a_1(q^2)\mathrm{i}\gamma^\mu + \frac{a_2(q^2)}{2m_\Delta}(p'^\mu + p^\mu)\right] - \frac{q^\sigma q^\tau}{2m_\Delta^2}\left[c_1(q^2)\mathrm{i}\gamma^\mu + \frac{c_2(q^2)}{2m_\Delta}(p'^\mu + p^\mu)\right]$$

Four form factors: G_{E0}, G_{E2}, G_{M1}, G_{M3} given in terms of a_1, a_2, c_1, c_2



G_{E2} is negative ⟹ Delta oblate

Should go away with dynamical fermions



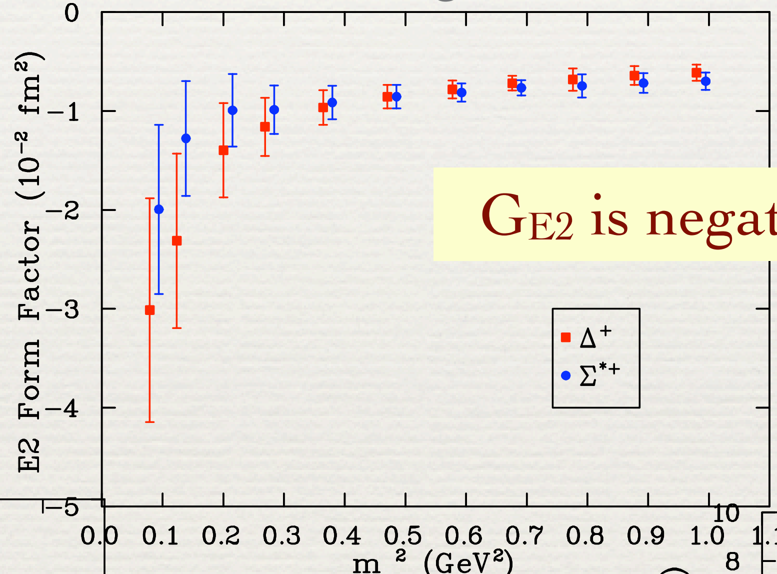
Quenched artifact (QChPT)

Δ electromagnetic form factors *P. Moran et al. [Adelaide]*

$$\langle \Delta(\vec{p}\,', s')|j_\mu|\Delta(\vec{p}, s)\rangle = \mathrm{i}\sqrt{\frac{m_\Delta^2}{E_\Delta(\vec{p}\,')E_\Delta(\vec{p})}}\,\bar{u}^\sigma(\vec{p}\,', s')O_{\sigma\mu\tau}u_\tau(\vec{p}, s)$$

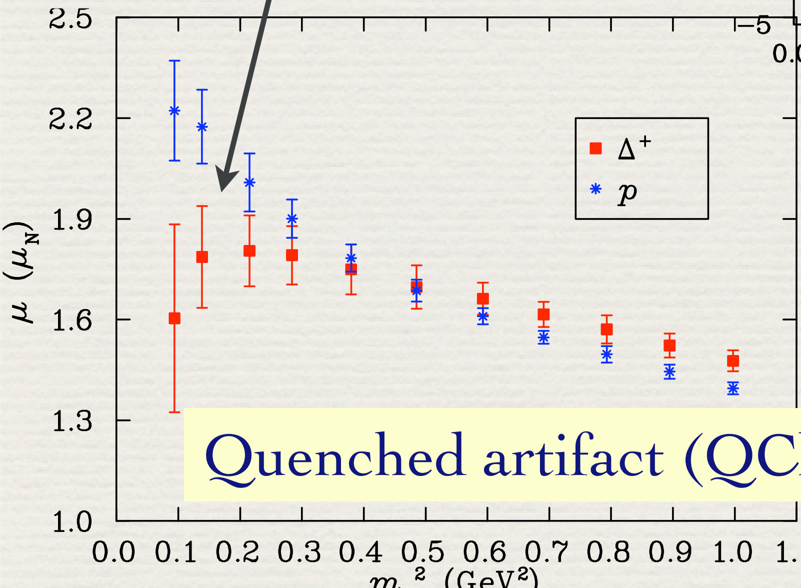
$$O_{\sigma\mu\tau} = \delta^{\sigma\tau}\left[a_1(q^2)\mathrm{i}\gamma^\mu + \frac{a_2(q^2)}{2m_\Delta}(p'^\mu + p^\mu)\right] - \frac{q^\sigma q^\tau}{2m_\Delta^2}\left[c_1(q^2)\mathrm{i}\gamma^\mu + \frac{c_2(q^2)}{2m_\Delta}(p'^\mu + p^\mu)\right]$$

Four form factors: G_{E0}, G_{E2}, G_{M1}, G_{M3} given in terms of a_1, a_2, c_1, c_2



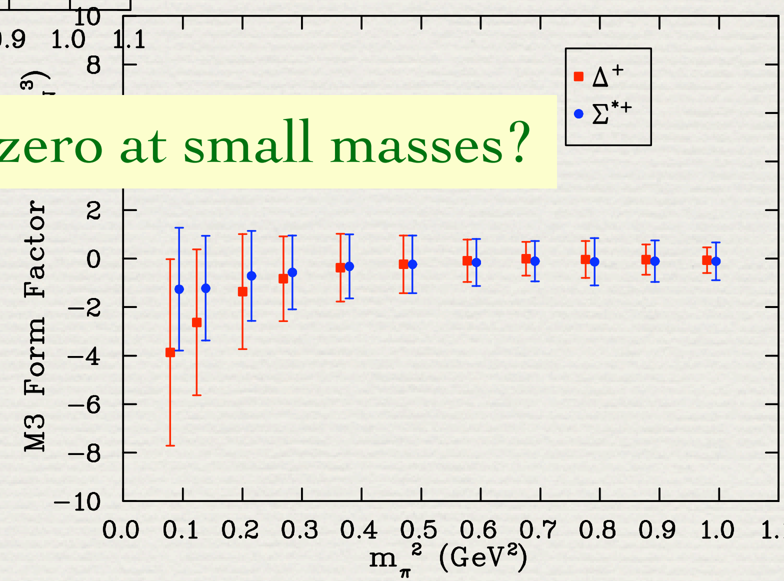
G_{E2} is negative ⇒ Delta oblate

Should go away with dynamical fermions



Quenched artifact (QChPT)

G_{M3} deviates from zero at small masses?



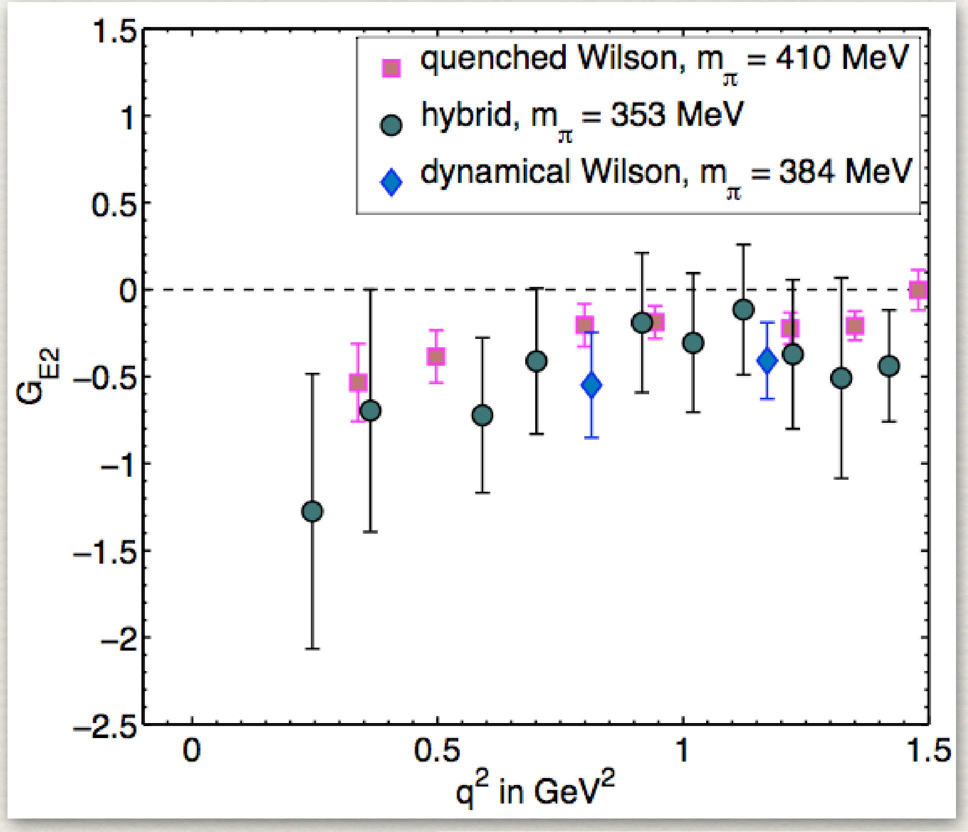
Δ electromagnetic form factors

[C. Alexandrou , Th. Korzec, Th. Leontiou J. W. Negele, A. Tsapalis]

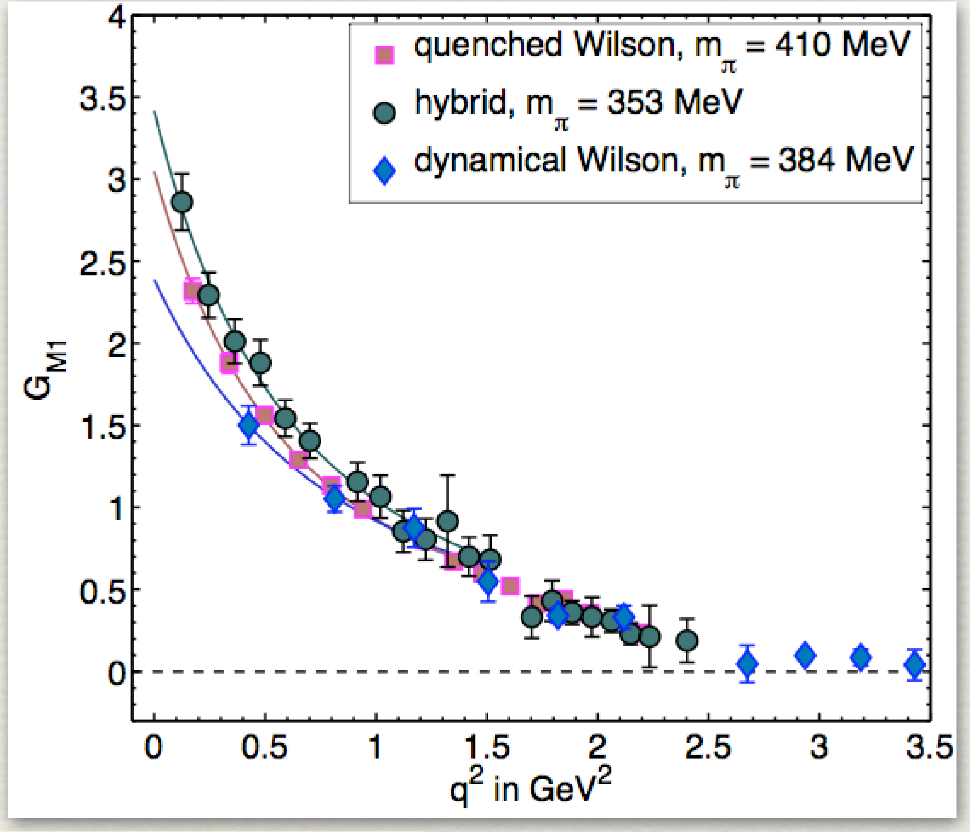
Δ electromagnetic form factors

[C. Alexandrou , Th. Korzec, Th. Leontiou J. W. Negele, A. Tsapalis]

G_{E2} is negative ⟹ Delta oblate



Entering area to look for "bending down"



G_{M3} consistent with zero.
Deviate from zero at small masses?

Rho Form Factor

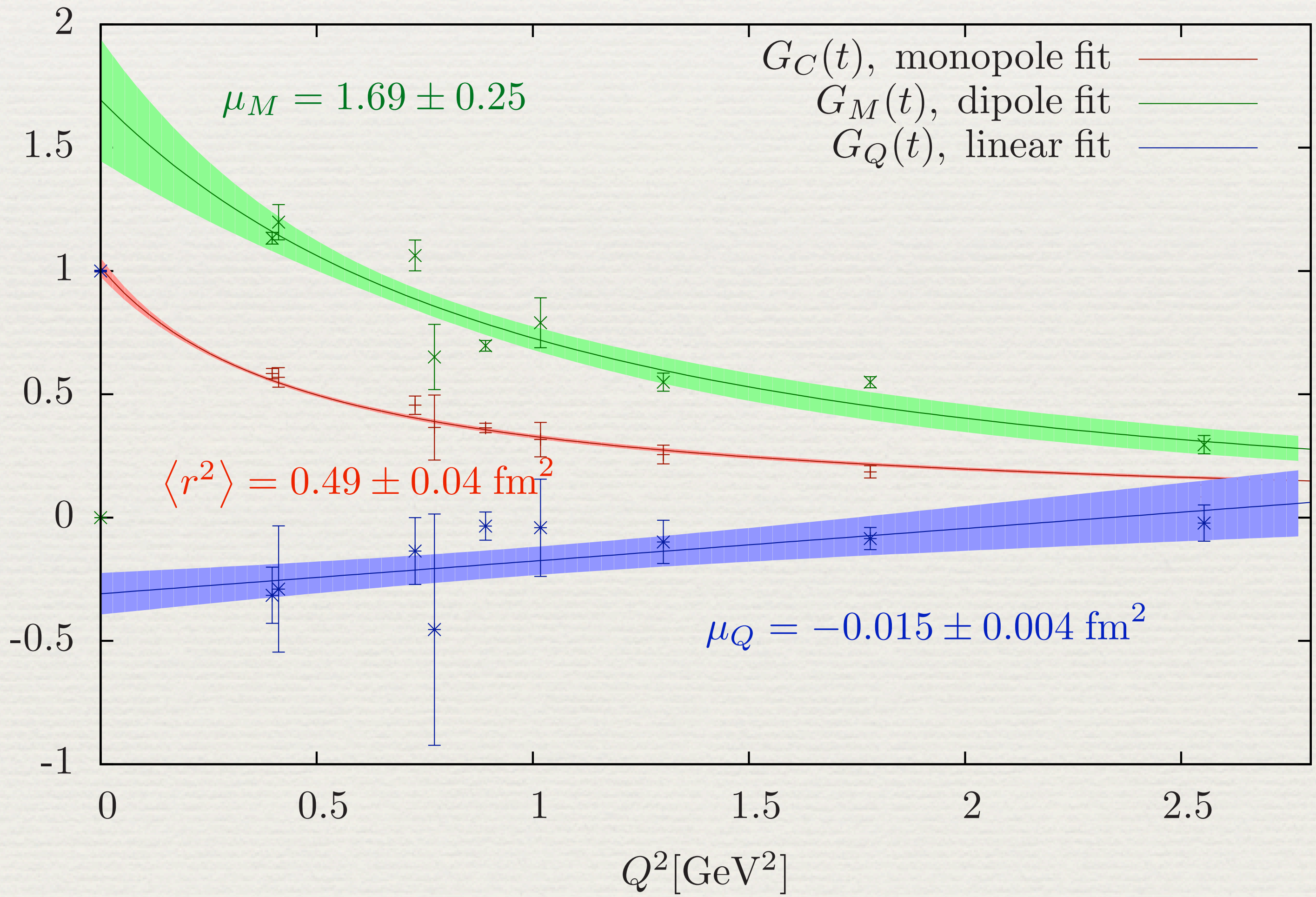
M. Gürtler [QCDSF] Thursday 9:40

$$\langle \rho(\vec{p}', s')|J^\alpha|\rho(\vec{p}, s)\rangle \propto G_E(Q^2),\ G_M(Q^2),\ G_Q(Q^2)$$

$G_Q(Q^2 = 0)$ → Quadrupole moment

$\neq 0$ → Spatial deformation

$\beta = 5.29 \quad \kappa = .13620 \quad \mathrm{Vol}24^3 48 \quad m_\pi = 406\mathrm{MeV}$



Jefferson Lab Research Program

http://www.jlab.org/highlights/phys.html

- Electric and Magnetic Proton Form Factors
- Neutron Charge Density
- Neutron Magnetic Structure
- Nucleon-Delta Transition
- Pion Form Factor
- Generalized Parton Distributions
- Spin Sum Rules
- **Nucleon Spin Asymmetries**
- Strange Quarks in the Proton

Transverse Spin Structure of the Nucleon

Ph. Hägler (QCDSF) [PRL 98, 222001 (2007)]

Transverse densities:

$$\rho^n(b_\perp, s_\perp, S_\perp) = \int_{-1}^{1} dx\, x^{n-1} \rho(x, b_\perp, s_\perp, S_\perp) = \frac{1}{2}\Big\{ A_{n0}(b_\perp^2) + s_\perp^i S_\perp^i \left(A_{Tn0}(b_\perp^2) - \frac{1}{4m^2} \Delta_{b_\perp} \widetilde{A}_{Tn0}(b_\perp^2) \right)$$

$$+ \frac{b_\perp^j \epsilon^{ji}}{m} \left(S_\perp^i B'_{n0}(b_\perp^2) + s_\perp^i \overline{B}'_{Tn0}(b_\perp^2) \right) + s_\perp^i (2 b_\perp^i b_\perp^j - b_\perp^2 \delta^{ij}) S_\perp^j \frac{1}{m^2} \widetilde{A}''_{Tn0}(b_\perp^2) \Big\}$$

[Diehl & Haegler, 2005] [Burkardt, 2005]

$$F(b_\perp^2) = \int d^2\Delta_\perp\, \mathrm{e}^{-i\vec{b}_\perp \cdot \Delta_\perp} F(\Delta_\perp^2) = \int d^2\Delta_\perp\, \mathrm{e}^{-i\vec{b}_\perp \cdot \Delta_\perp} \frac{F(0)}{(1 - \Delta_\perp^2 / M^2)^p}$$

Transverse Spin Structure of the ~~Nucleon~~ Pion

Transverse densities:

$$\rho^n(b_\perp, s_\perp, S_\perp) = \int_{-1}^{1} dx\, x^{n-1} \rho(x, b_\perp, s_\perp, S_\perp) = \frac{1}{2}\Big\{ A_{n0}(b_\perp^2) + s_\perp^i S_\perp^i \left(A_{Tn0}(b_\perp^2) - \frac{1}{4m^2} \Delta_{b_\perp} \widetilde{A}_{Tn0}(b_\perp^2) \right)$$
$$+ \frac{b_\perp^j \epsilon^{ji}}{m} \left(S_\perp^i B'_{n0}(b_\perp^2) + s_\perp^i \overline{B}'_{Tn0}(b_\perp^2) \right) + s_\perp^i (2 b_\perp^i b_\perp^j - b_\perp^2 \delta^{ij}) S_\perp^j \frac{1}{m^2} \widetilde{A}''_{Tn0}(b_\perp^2) \Big\}$$

[Diehl & Haegler, 2005] [Burkardt, 2005]

$$F(b_\perp^2) = \int d^2\Delta_\perp\, \mathrm{e}^{-i\vec{b}_\perp \cdot \Delta_\perp} F(\Delta_\perp^2) = \int d^2\Delta_\perp\, \mathrm{e}^{-i\vec{b}_\perp \cdot \Delta_\perp} \frac{F(0)}{(1 - \Delta_\perp^2/M^2)^p}$$

Transverse Spin Structure of the ~~Nucleon~~ Pion

Transverse densities:

$$\rho^n(b_\perp, s_\perp, S_\perp) = \int_{-1}^{1} dx\, x^{n-1} \rho(x, b_\perp, s_\perp, S_\perp) = \frac{1}{2}\Big\{ A_{n0}(b_\perp^2) + s_\perp^i S_\perp^i \Big(A_{Tn0}(b_\perp^2) - \frac{1}{4m^2} \Delta_{b_\perp} \widetilde{A}_{Tn0}(b_\perp^2) \Big)$$

$$+ \frac{b_\perp^j \epsilon^{ji}}{m} \Big(S_\perp^i B'_{n0}(b_\perp^2) + s_\perp^i \overline{B}'_{Tn0}(b_\perp^2) \Big) + s_\perp^i (2 b_\perp^i b_\perp^j - b_\perp^2 \delta^{ij}) S_\perp^j \frac{1}{m^2} \widetilde{A}''_{Tn0}(b_\perp^2) \Big\}$$

[Diehl & Haegler, 2005] [Burkardt, 2005]

$$F(b_\perp^2) = \int d^2\Delta_\perp\, \mathrm{e}^{-i\vec{b}_\perp \cdot \Delta_\perp} F(\Delta_\perp^2) = \int d^2\Delta_\perp\, \mathrm{e}^{-i\vec{b}_\perp \cdot \Delta_\perp} \frac{F(0)}{(1 - \Delta_\perp^2/M^2)^p}$$

Transverse Spin Structure of the ~~Nucleon~~ Pion

D. Brömmel (QCDSF) [arXiv:0708.2249]

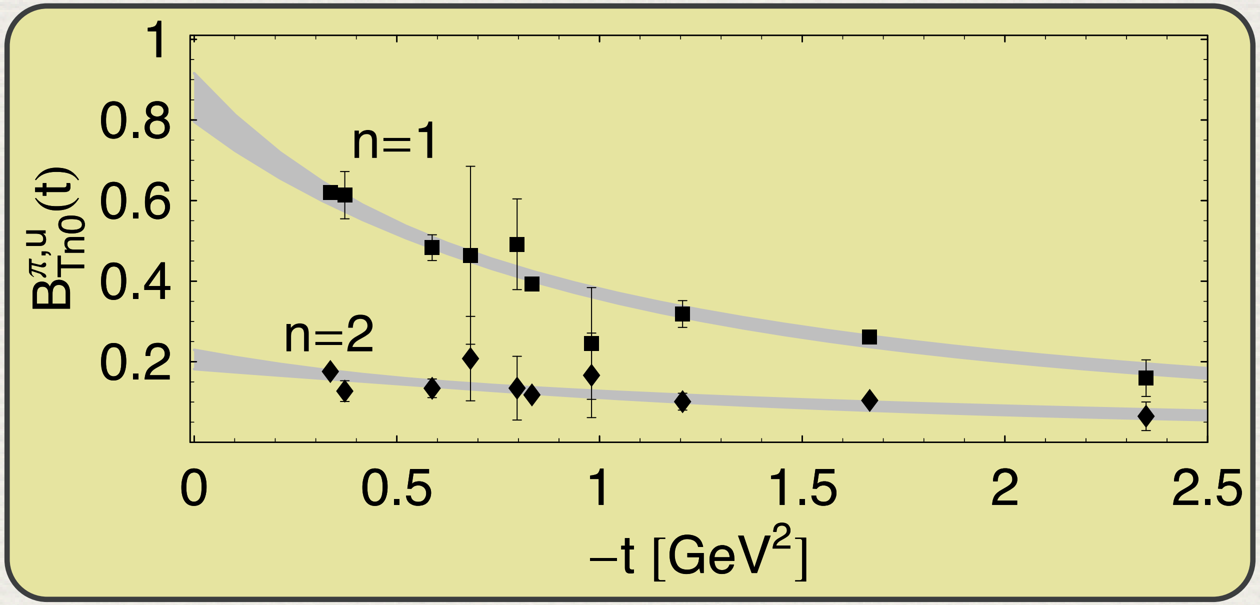
Transverse densities:

$$\rho^n(b_\perp, s_\perp, S_\perp) = \int_{-1}^{1} dx\, x^{n-1} \rho(x, b_\perp, s_\perp, S_\perp) = \frac{1}{2}\Big\{ A_{n0}(b_\perp^2) + s_\perp^i S_\perp^i \Big(A_{Tn0}(b_\perp^2) - \frac{1}{4m^2} \Delta_{b_\perp} \widetilde{A}_{Tn0}(b_\perp^2) \Big)$$

$$+ \frac{b_\perp^j \epsilon^{ji}}{m} \Big(S_\perp^i B'_{n0}(b_\perp^2) + s_\perp^i \overline{B}'_{Tn0}(b_\perp^2) \Big) + s_\perp^i (2 b_\perp^i b_\perp^j - b_\perp^2 \delta^{ij}) S_\perp^j \frac{1}{m^2} \widetilde{A}''_{Tn0}(b_\perp^2) \Big\}$$

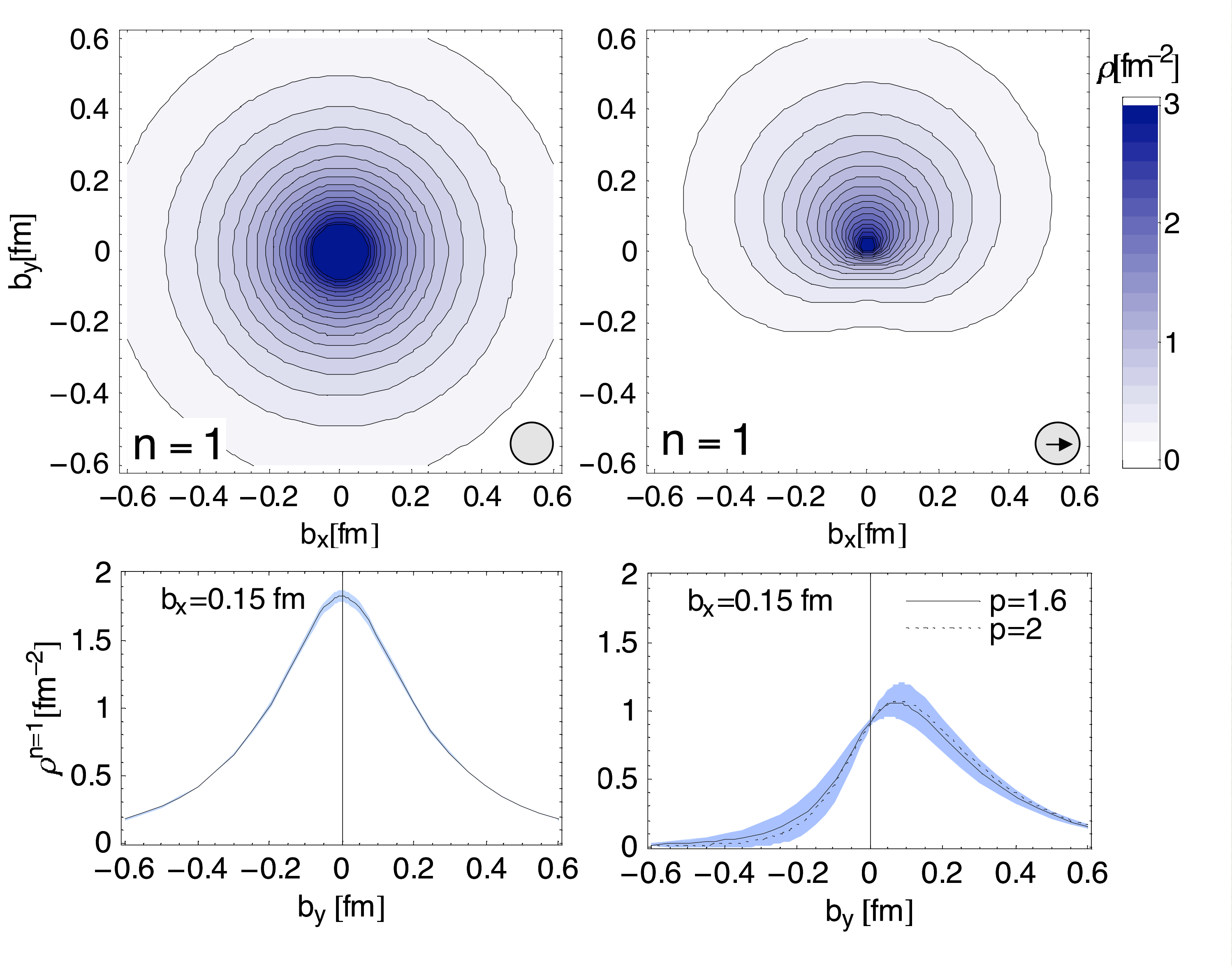
[Diehl & Haegler, 2005] [Burkardt, 2005]

$$F(b_\perp^2) = \int d^2\Delta_\perp\, \mathrm{e}^{-i\vec{b}_\perp \cdot \Delta_\perp} F(\Delta_\perp^2) = \int d^2\Delta_\perp\, \mathrm{e}^{-i\vec{b}_\perp \cdot \Delta_\perp} \frac{F(0)}{(1 - \Delta_\perp^2/M^2)^p}$$



Deformed Spin Densities
Pion

D. Brömmel (QCDSF) [arXiv:0708.2249]

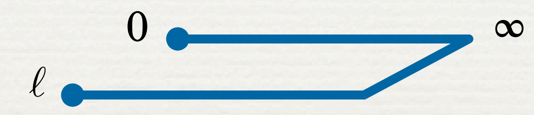


Transverse Momentum Dependent PDFs

***B. Musch** [LHPC], arXiv:0710.4423 (Lattice 2007)* [DWF + asqtad]

$f_1(x, k_\perp)$ Information on distribution of quarks with longitudinal momentum fraction, x, and transverse momentum, $k_\perp$

Factorisation in SIDIS $\langle P|\bar{q}(l)\,\Gamma\,\mathcal{U}\,q(0)|P\rangle$

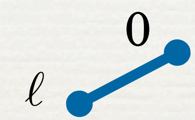


Transverse Momentum Dependent PDFs

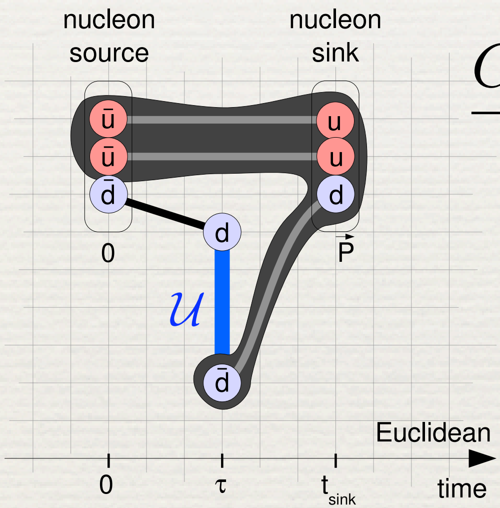
***B. Musch** [LHPC], arXiv:0710.4423 (Lattice 2007)* [DWF + asqtad]

$f_1(x, k_\perp)$ Information on distribution of quarks with longitudinal momentum fraction, x, and transverse momentum, $k_\perp$

Factorisation in SIDIS $\langle P|\bar{q}(l)\,\Gamma\,\mathcal{U}\,q(0)|P\rangle$



(Lattice)



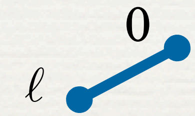
$$\frac{C_{3\mathrm{pt}}(\tau, t_{\mathrm{sink}}, P, \Gamma)}{C_{2\mathrm{pt}}(t_{\mathrm{sink}}, P)} \xrightarrow{0 \ll \tau \ll t_{\mathrm{sink}}} \langle P|\bar{q}(l)\,\Gamma\,\mathcal{U}\,q(0)|P\rangle \propto \tilde{A}_i(l^2, l\cdot P)$$

Transverse Momentum Dependent PDFs

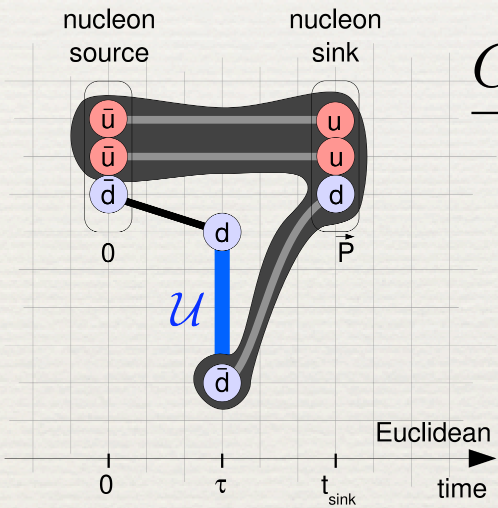
***B. Musch** [LHPC], arXiv:0710.4423 (Lattice 2007)* [DWF + asqtad]

$f_1(x, k_\perp)$ Information on distribution of quarks with longitudinal momentum fraction, x, and transverse momentum, $k_\perp$

Factorisation in SIDIS $\langle P|\bar{q}(l)\,\Gamma\,\mathcal{U}\,q(0)|P\rangle$



(Lattice)



$$\frac{C_{3\mathrm{pt}}(\tau, t_{\mathrm{sink}}, P, \Gamma)}{C_{2\mathrm{pt}}(t_{\mathrm{sink}}, P)} \xrightarrow{0 \ll \tau \ll t_{\mathrm{sink}}} \langle P|\bar{q}(l)\,\Gamma\,\mathcal{U}\,q(0)|P\rangle \propto \tilde{A}_i(l^2, l\cdot P)$$

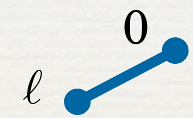
Γ	$\tilde{A}_i$
γ_μ	$\tilde{A}_2,\ \tilde{A}_3$
$\gamma_\mu\gamma_5$	$\tilde{A}_6,\ \tilde{A}_7,\ \tilde{A}_8$

Transverse Momentum Dependent PDFs

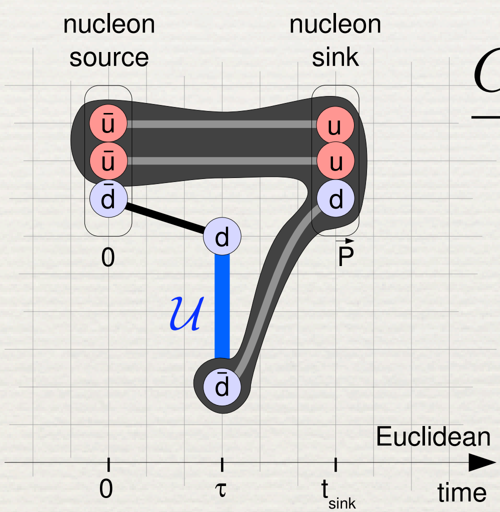
***B. Musch** [LHPC], arXiv:0710.4423 (Lattice 2007)* [DWF + asqtad]

$f_1(x, k_\perp)$ Information on distribution of quarks with longitudinal momentum fraction, x , and transverse momentum, $k_\perp$

Factorisation in SIDIS $\langle P|\bar{q}(l)\,\Gamma\,\mathcal{U}\,q(0)|P\rangle$



(Lattice)



$$\frac{C_{3\mathrm{pt}}(\tau, t_{\mathrm{sink}}, P, \Gamma)}{C_{2\mathrm{pt}}(t_{\mathrm{sink}}, P)} \xrightarrow{0 \ll \tau \ll t_{\mathrm{sink}}} \langle P|\bar{q}(l)\,\Gamma\,\mathcal{U}\,q(0)|P\rangle \propto \tilde{A}_i(l^2, l\cdot P)$$

Γ	$\tilde{A}_i$
γ_μ	$\tilde{A}_2,\ \tilde{A}_3$
$\gamma_\mu\gamma_5$	$\tilde{A}_6,\ \tilde{A}_7,\ \tilde{A}_8$

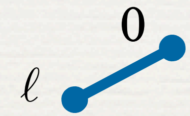
$$f_{1,\mathrm{lat}}^{n=1}(\vec{k}_T) = \int dx\, f_1(x, \vec{k}_\perp) = \int \frac{d^2\vec{\ell}_\perp}{(2\pi)^2} e^{i\,\vec{k}_\perp\cdot\vec{\ell}_\perp} 2\tilde{A}_2(|\vec{\ell}_\perp|, 0)$$

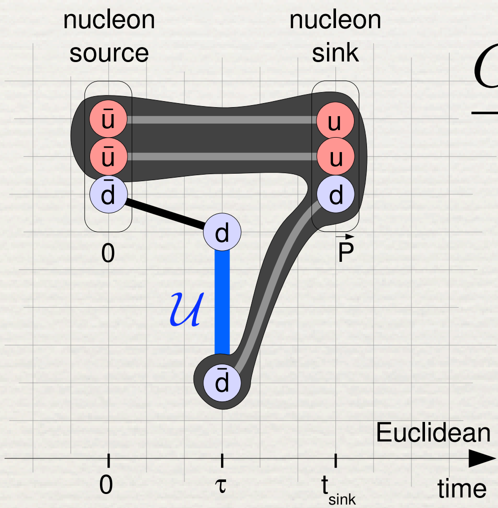
Transverse Momentum Dependent PDFs

***B. Musch** [LHPC], arXiv:0710.4423 (Lattice 2007)* [DWF + asqtad]

$f_1(x, k_\perp)$ Information on distribution of quarks with longitudinal momentum fraction, x, and transverse momentum, $k_\perp$

Factorisation in SIDIS $\langle P|\bar{q}(l)\,\Gamma\,\mathcal{U}\,q(0)|P\rangle$ (Lattice)





$$\frac{C_{3\mathrm{pt}}(\tau, t_{\mathrm{sink}}, P, \Gamma)}{C_{2\mathrm{pt}}(t_{\mathrm{sink}}, P)} \xrightarrow{0\ll\tau\ll t_{\mathrm{sink}}} \langle P|\bar{q}(l)\,\Gamma\,\mathcal{U}\,q(0)|P\rangle \propto \tilde{A}_i(l^2, l\cdot P)$$

Γ	$\tilde{A}_i$
γ_μ	$\tilde{A}_2,\ \tilde{A}_3$
$\gamma_\mu\gamma_5$	$\tilde{A}_6,\ \tilde{A}_7,\ \tilde{A}_8$

$$f_{1,\mathrm{lat}}^{n=1}(\vec{k}_T) = \int dx\, f_1(x, \vec{k}_\perp) = \int \frac{d^2\vec{\ell}_\perp}{(2\pi)^2} e^{i\,\vec{k}_\perp\cdot\vec{\ell}_\perp} 2\tilde{A}_2(|\vec{\ell}_\perp|, 0)$$

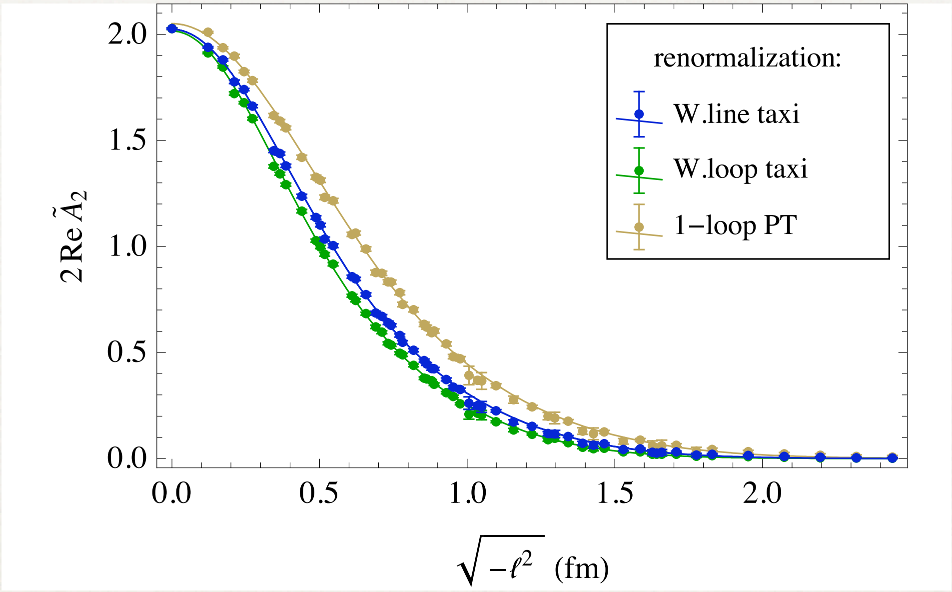
In a transversely polarised nulcleon:

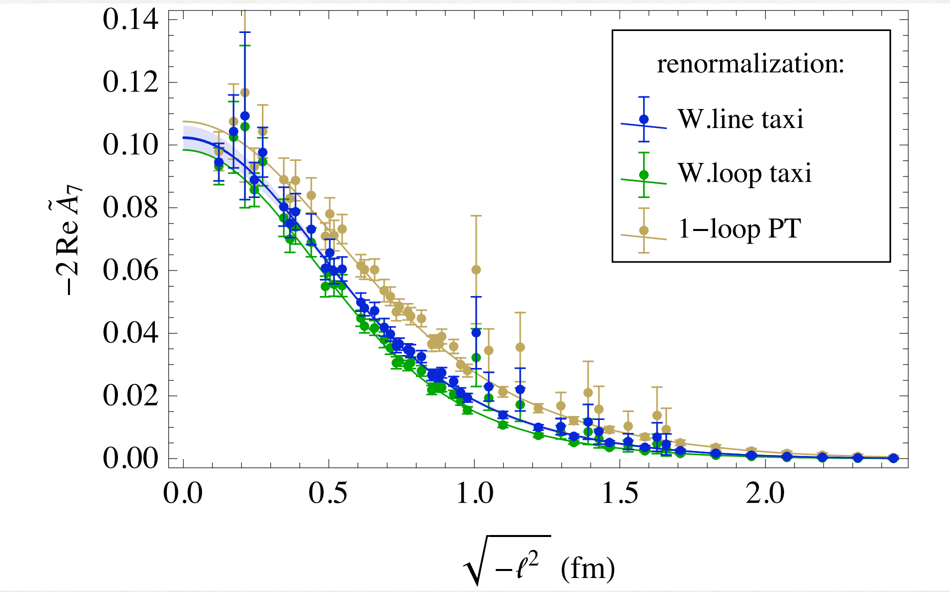
from $\tilde{A}_7$

$$\frac{1}{2}\left(f_1^{(1)\mathrm{lat}}(k_\perp) + \frac{k_\perp\cdot S_\perp}{m_N} g_{1T}^{(1)\mathrm{lat}}(k_\perp)\right)$$

Transverse Momentum Dependent PDFs

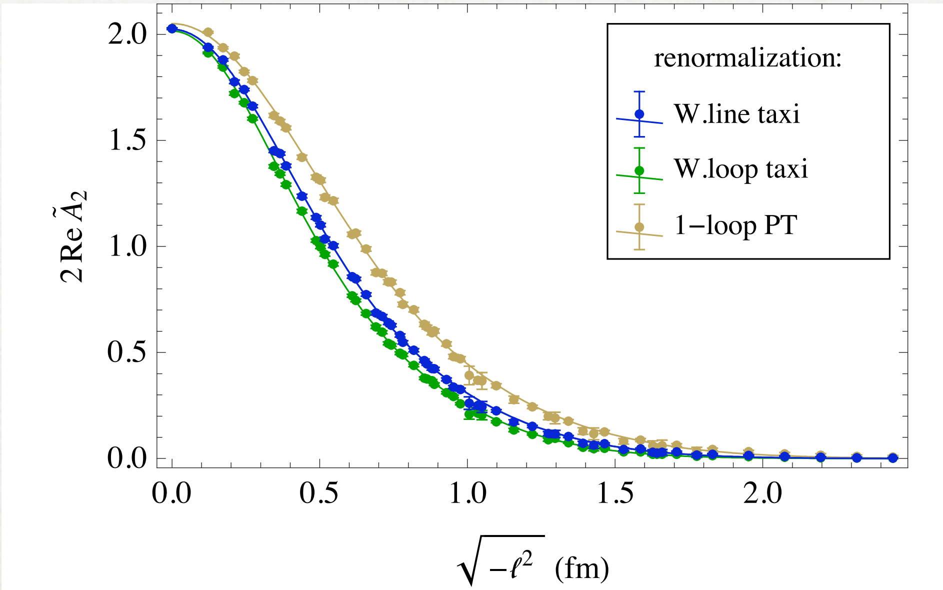
***B. Musch** [LHPC], arXiv:0710.4423 (Lattice 2007)* Friday 3:30

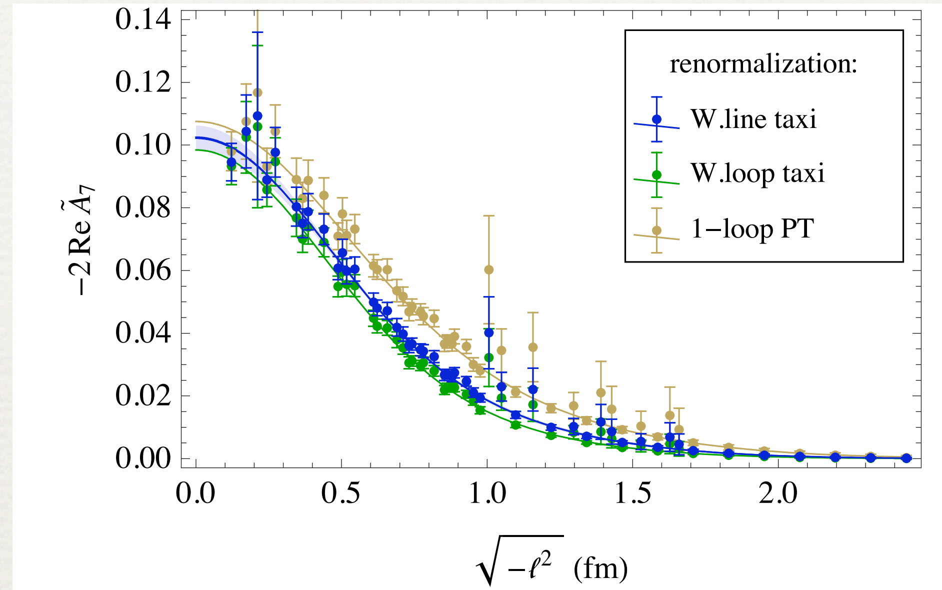


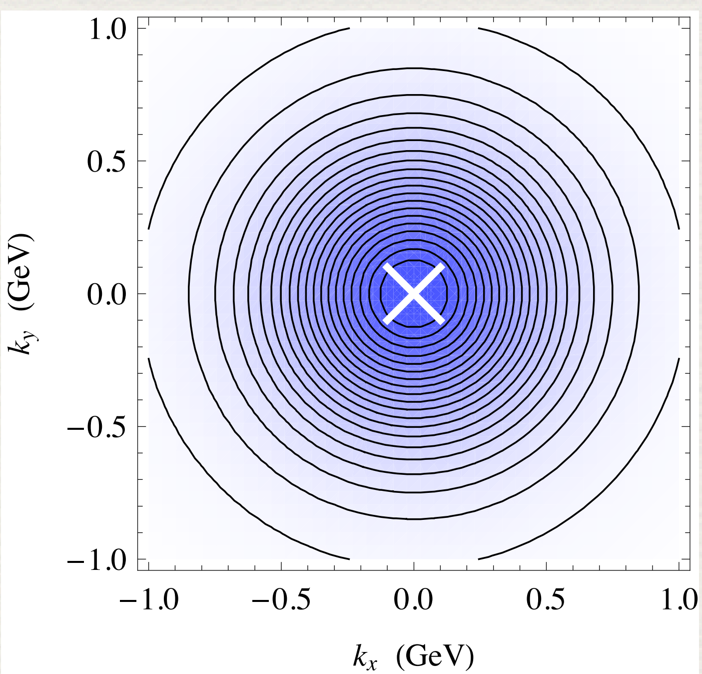


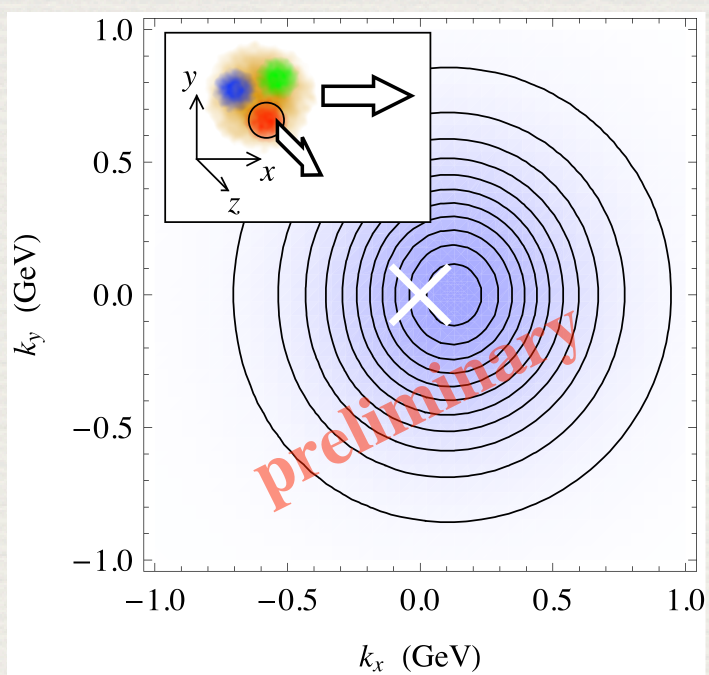
Transverse Momentum Dependent PDFs

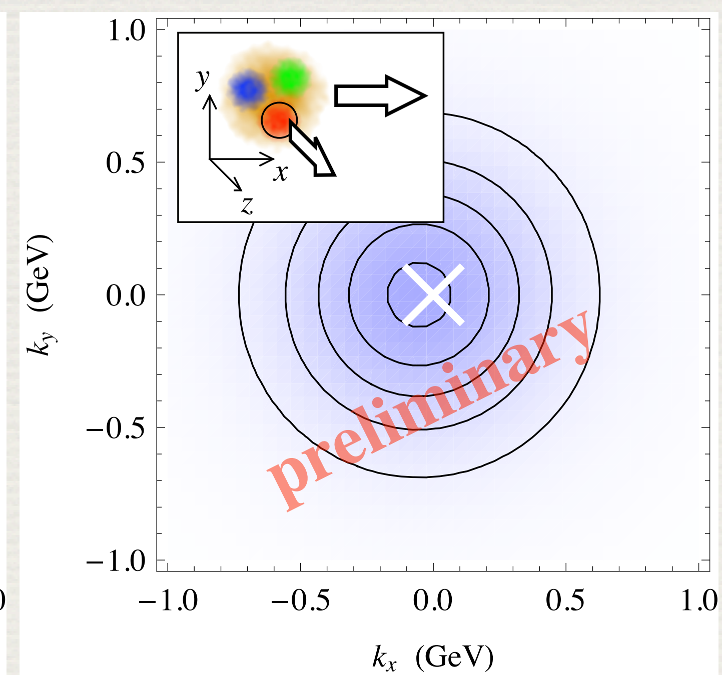
***B. Musch** [LHPC], arXiv:0710.4423 (Lattice 2007)* Friday 3:30











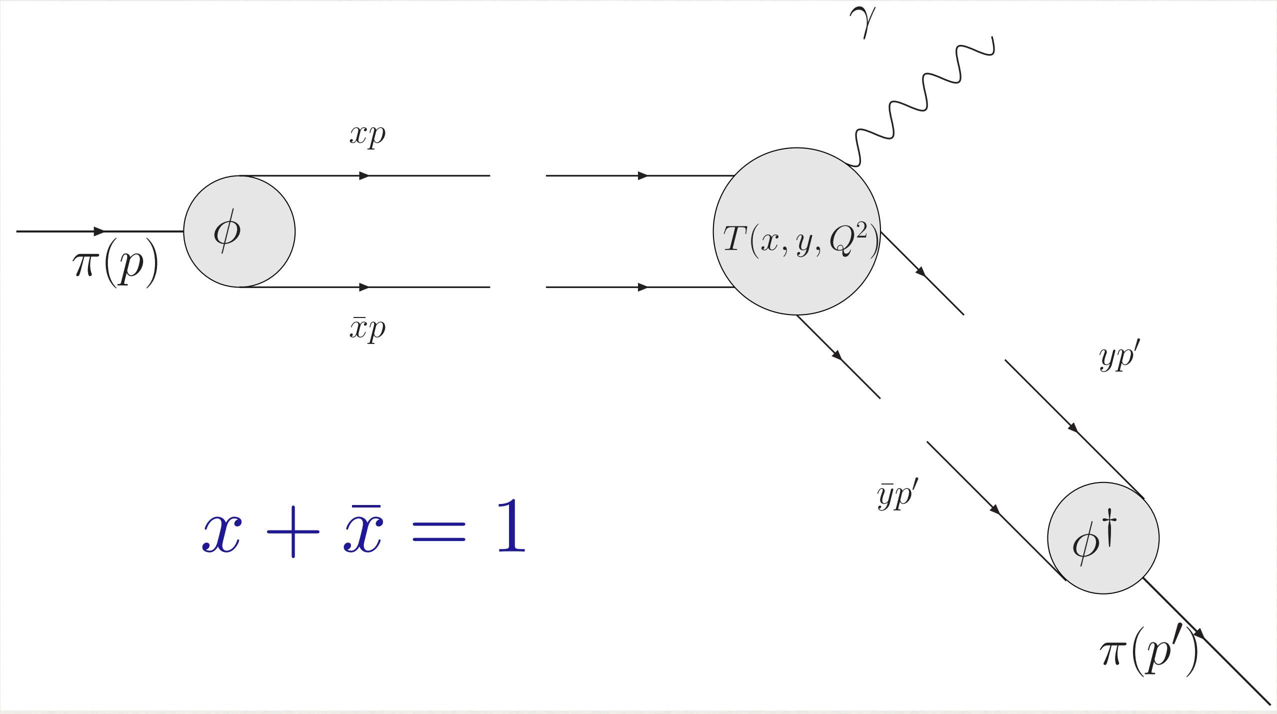
Distribution Amplitudes

Exclusive processes at large $Q^2 \to \infty$ can be factorised into:

- perturbative hard scattering amplitude (process dependent)
- nonperturbative wave functions describing the hadron's overlap with lowest Fock state (process independent)

$$F(Q^2) = \int_0^1 dx \int_0^1 dy \phi^\dagger(y, Q^2) T(x, y, Q^2) \phi(x, Q^2) [1 + \mathcal{O}(m^2/Q^2)]$$

$$\langle 0 | \bar{q}(-z) \gamma_\mu \gamma_5 [-z, z] u(z) | \Pi^+(p) \rangle = i f_\Pi p_\mu \int_{-1}^1 d\xi \, e^{-i\xi p\cdot z} \phi_\Pi(\xi, \mu^2)$$



$$\xi = x - \bar{x}$$

$$\int_{-1}^1 d\xi \, \phi_\Pi(\xi, \mu^2) = 1$$

- For spin 1 mesons:

$$\phi^\parallel(\xi), \; \phi^\perp(\xi)$$

Meson Distribution Amplitudes

D. Brömmel [UKQCD/RBC] 2+1 DWF Friday 3:10

Meson Distribution Amplitudes

D. Brömmel [UKQCD/RBC] 2+1 DWF Friday 3:10

π, K *QCDSF: PRD 74, 074501 (2006)*

UKQCD/RBC: PLB 641, 67 (2006)

arXiv:0710.0869 (Lattice 2007)

Meson Distribution Amplitudes

D. Brömmel [UKQCD/RBC] 2+1 DWF Friday 3:10

π, K *QCDSF: PRD 74, 074501 (2006)*

UKQCD/RBC: PLB 641, 67 (2006)

arXiv:0710.0869 (Lattice 2007)

ρ, K^*

QCDSF: PoS, Lattice 2007

UKQCD/RBC: in preparation

$$\langle 0|\bar{q}(0)\gamma_{\{\rho}\overleftrightarrow{D}_{\mu\}}\, s(0)|K^*(p,\lambda)\rangle = m_{K^*} f_{K^*} p_{\{\rho}\epsilon^{(\lambda)}_{\mu\}} \langle \xi^1 \rangle^{\parallel}_{K^*}$$

$$\langle 0|\bar{q}(0)\gamma_{\{\rho}\overleftrightarrow{D}_{\mu}\overleftrightarrow{D}_{\nu\}}\, q(0)|\rho(p,\lambda)\rangle = -i m_{\rho} f_{\rho} p_{\{\rho} p_{\mu}\epsilon^{(\lambda)}_{\nu\}} \langle \xi^2 \rangle^{\parallel}_{\rho}$$

Meson Distribution Amplitudes

D. Brömmel [UKQCD/RBC] 2+1 DWF Friday 3:10

π, K *QCDSF: PRD 74, 074501 (2006)*

UKQCD/RBC: PLB 641, 67 (2006)

arXiv:0710.0869 (Lattice 2007)

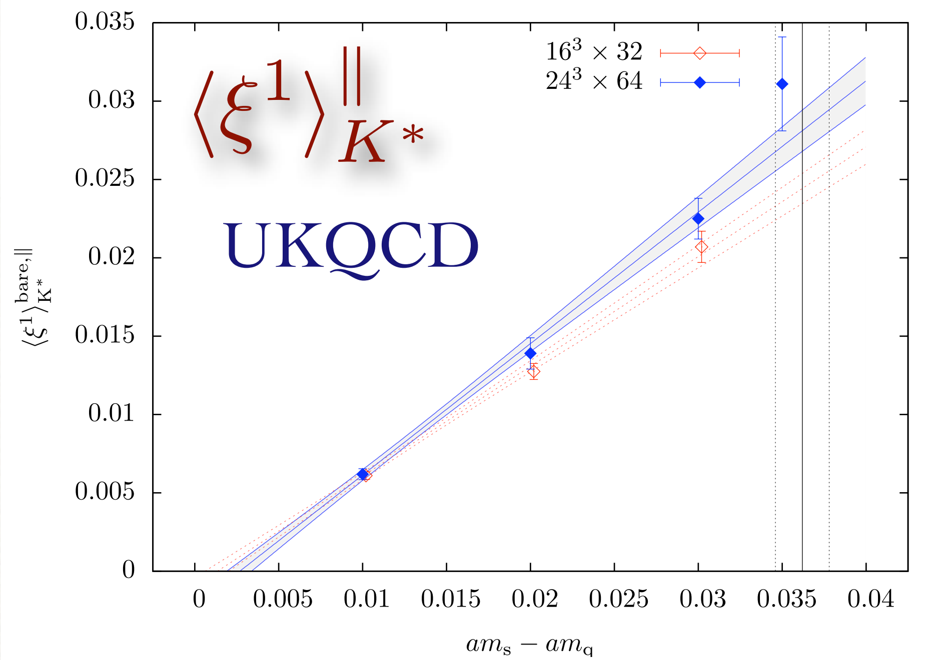
ρ, K^*

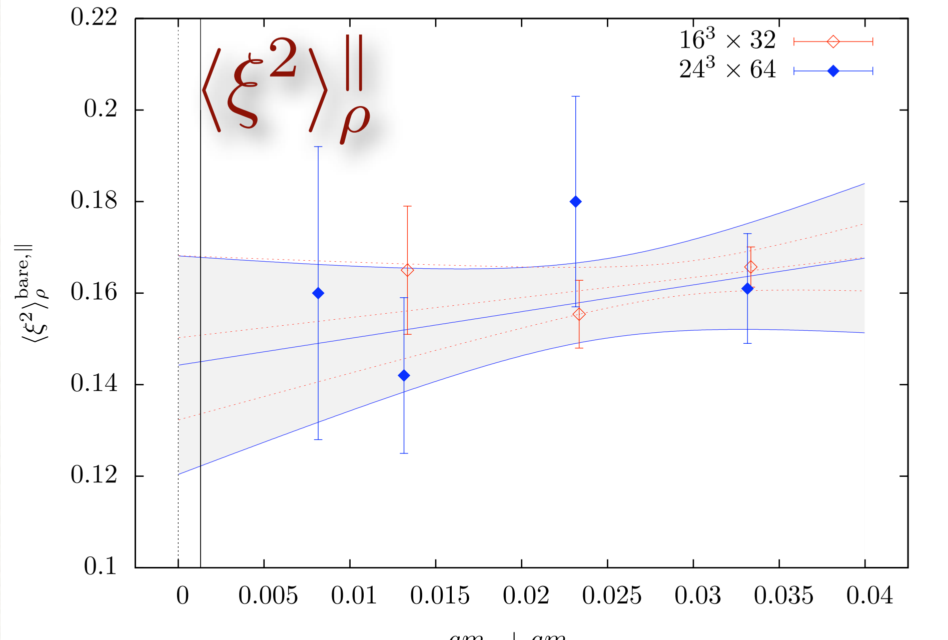
QCDSF: PoS, Lattice 2007

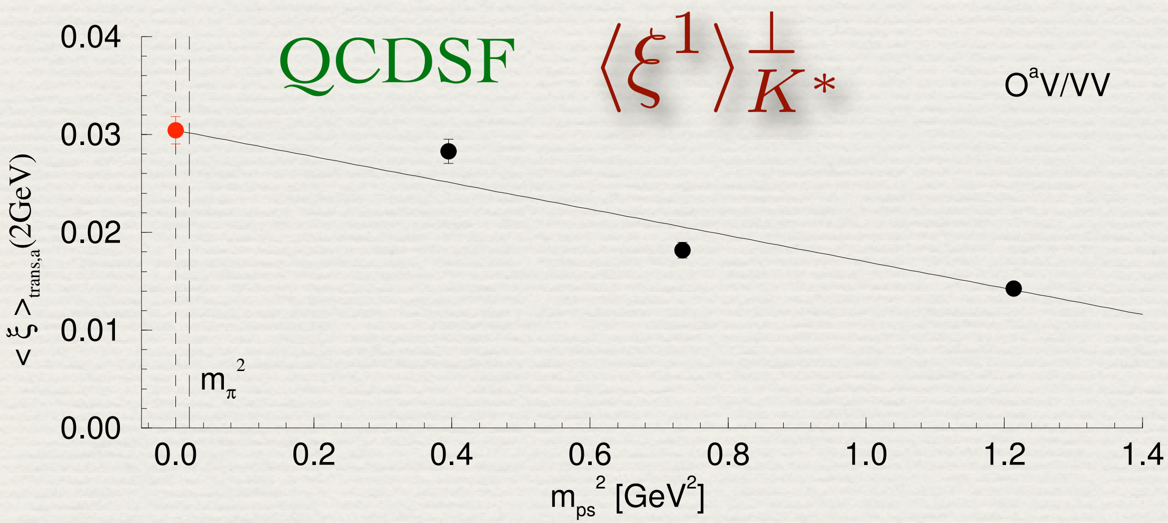
UKQCD/RBC: in preparation

$$\langle 0|\bar{q}(0)\gamma_{\{\rho}\overleftrightarrow{D}_{\mu\}}\, s(0)|K^*(p,\lambda)\rangle = m_{K^*} f_{K^*} p_{\{\rho}\epsilon^{(\lambda)}_{\mu\}} \langle\xi^1\rangle^{\parallel}_{K^*}$$

$$\langle 0|\bar{q}(0)\gamma_{\{\rho}\overleftrightarrow{D}_{\mu}\overleftrightarrow{D}_{\nu\}}\, q(0)|\rho(p,\lambda)\rangle = -i m_\rho f_\rho p_{\{\rho} p_\mu \epsilon^{(\lambda)}_{\nu\}} \langle\xi^2\rangle^{\parallel}_{\rho}$$







Vector Meson Distribution Amplitudes

ρ, K^* $\quad \overline{\mathrm{MS}},\ \mu^2 = 4\,\mathrm{GeV}^2$

QCDSF:

$$\langle \xi \rangle^{\parallel}_{K^*} \approx 0.036(3)$$

$$\langle \xi \rangle^{\perp}_{K^*} \approx 0.030(2)$$

UKQCD:

$$\langle \xi \rangle^{\parallel}_{K^*} \approx 0.0359(17)(22)$$

$$\langle \xi^2 \rangle^{\parallel}_{\rho} \approx 0.240(36)(12)$$

$$\langle \xi^2 \rangle^{\parallel}_{K^*} \approx 0.252(17)(12)$$

Sum Rules

$$\langle \xi \rangle^{\parallel}_{K^*} \sim 0.02(2)$$

$$\langle \xi \rangle^{\perp}_{K^*} \sim 0.03(3)$$

$$\langle \xi^2 \rangle^{\parallel}_{K^*,\rho} \sim 0.24(2)$$

Asymptotic

$$\langle \xi \rangle^{\parallel}_{K^*} = 0$$

$$\langle \xi \rangle^{\perp}_{K^*} = 0$$

$$\langle \xi^2 \rangle^{\parallel}_{K^*,\rho} = 0.2$$

Nucleon Distribution Amplitudes

N. Warkentin (QCDSF) [arXiv:0804.1877] Wednesday 3:30

- Three distribution amplitudes for the proton: V, A, T

- Expansion in local matrix elements give **moments**

$$\epsilon^{abc}\langle 0|[i^l D^{\lambda_1}\dots D^{\lambda_l} u^a_\alpha(0)](C\gamma^\rho)_{\alpha\beta}[i^m D^{\mu_1}\dots D^{\mu_m} u^b_\beta(0)][i^n D^{\mu_1}\dots D^{\nu_n}(\gamma_5 d^c_\gamma(0))_\gamma]|p\rangle$$
$$= \quad -f_N V^{lmn} p^\rho p^{\lambda_1}\dots p^{\lambda_l} p^{\mu_1}\dots p^{\mu_m} p^{\nu_1}\dots p^{\nu_n} N_\gamma(p)$$

Useful combination:

$$\phi^{lmn} = \frac{1}{3}(V^{lmn} - A^{lmn} + 2T^{lnm})$$

Momentum conservation: $\phi^{lmn} = \phi^{(l+1)mn} + \phi^{l(m+1)n} + \phi^{lm(n+1)}$

DA normalisation

$$\phi^{000} \equiv 1$$

$$\begin{aligned} 1 &= \phi^{100} + \phi^{010} + \phi^{001} \\ &= \phi^{200} + \phi^{020} + \phi^{002} + 2(\phi^{011} + \phi^{101} + \phi^{110}) \end{aligned}$$

Asymptotic behaviour $\varphi(x_i, Q^2 \to \infty) = 120 x_1 x_2 x_3$

$$\phi^{100} = \phi^{010} = \phi^{001} = \frac{1}{3}$$

$$\phi^{110} = \phi^{101} = \phi^{011} = \frac{2}{21}$$

$$\phi^{200} = \phi^{020} = \phi^{002} = \frac{1}{7}$$

Asymmetries important

$$\phi^{100} - \phi^{010}$$

Constrained Analysis

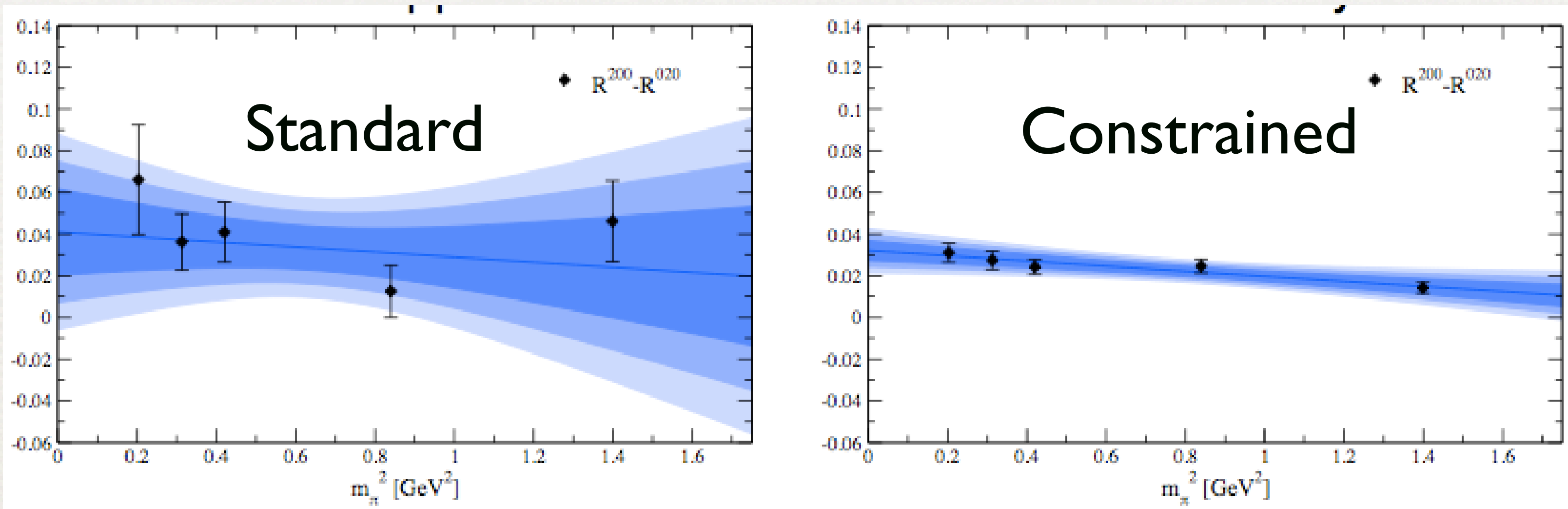
N. Warkentin (QCDSF) [arXiv:0804.1877]

Wednesday 3:30

DA correlator ratios

$$R^{lmn} = \frac{\phi^{lmn}}{S_{(l+m+n)}}$$

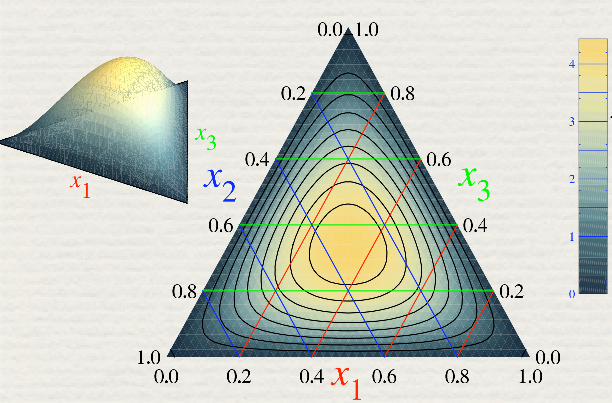
$$S_1 = \phi^{100} + \phi^{010} + \phi^{001}$$
$$S_2 = \phi^{200} + \phi^{020} + \phi^{002} + 2(\phi^{110} + \phi^{101} + \phi^{011})$$



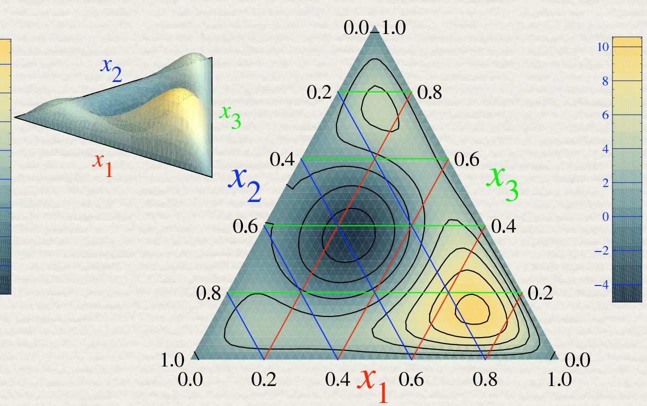
u-quark with spin aligned with proton spin has largest momentum fraction

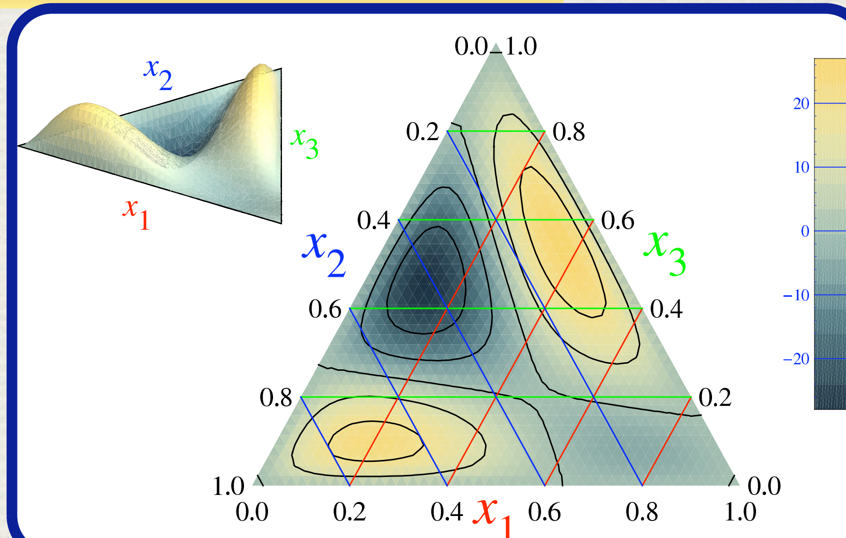
Asymmetries less pronounced than for QCD-SR!

Asymptotic case:



Sum Rules





Jefferson Lab Research Program

http://www.jlab.org/highlights/phys.html

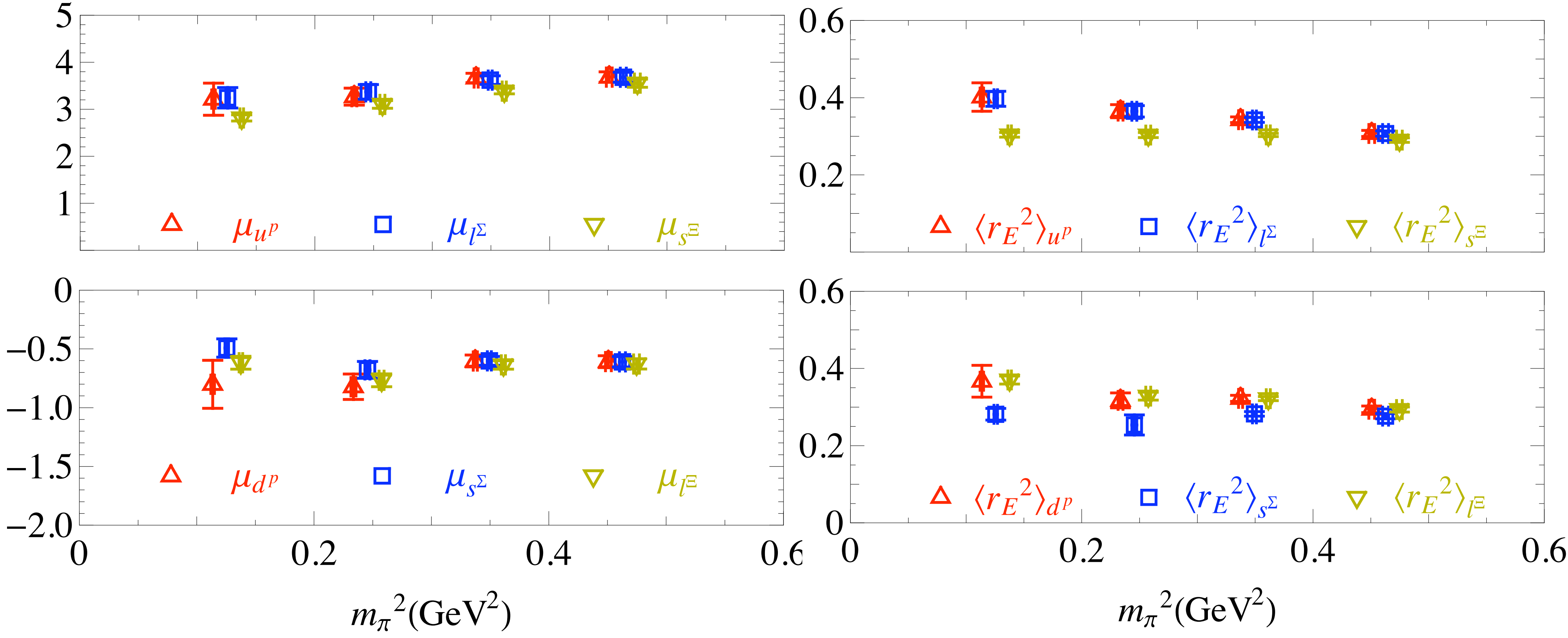
- Electric and Magnetic Proton Form Factors
- Neutron Charge Density
- Neutron Magnetic Structure
- Nucleon-Delta Transition
- Pion Form Factor
- Generalized Parton Distributions
- Spin Sum Rules
- Nucleon Spin Asymmetries
- **Strange Quarks in the Proton**

Octet Baryon Form Factors

H.-W. Lin, K. Orginos

Mixed action (DWF+asqtad) at m_{pi} = 350-750 MeV

- Smaller strange contribution to charge radii
- Similar behaviour to quenched (Adelaide)



Strangeness

H.-W. Lin, K. Orginos

Mixed action (DWF+asqtad) at m_{pi} = 350-750 MeV

Indirect: Charge symmetry + chiral extrapolations

[D.Leinweber et al., PRL 94, 212001 (2005); 97, 022001(2006)]

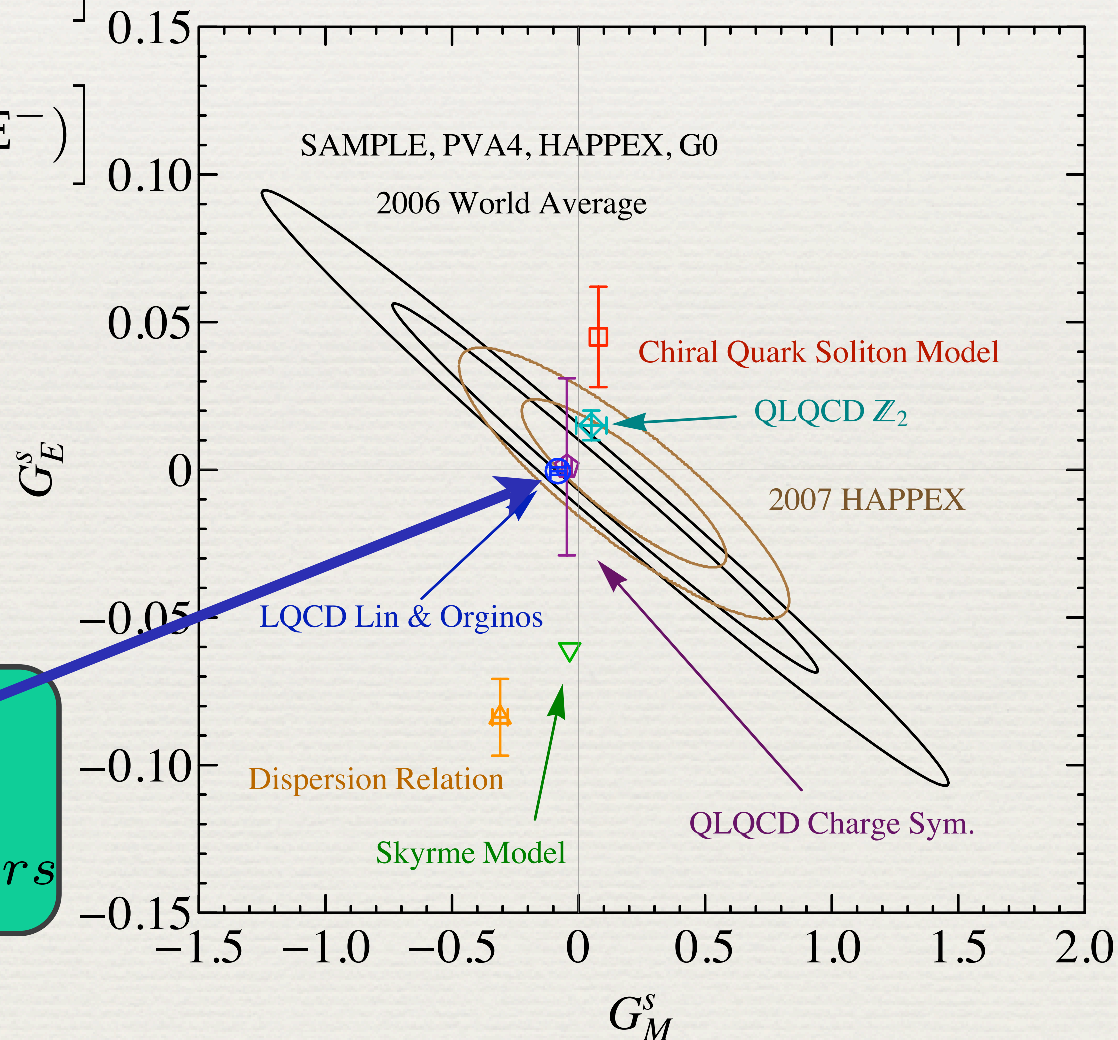
$$G_M^s = \left(\frac{{}^lR_d^s}{1-{}^lR_d^s}\right)\left[2p + n - \frac{u^p}{u^\Sigma}(\Sigma^+ - \Sigma^-)\right]$$

$$G_M^s = \left(\frac{{}^lR_d^s}{1-{}^lR_d^s}\right)\left[p + 2n - \frac{u^n}{u^\Xi}(\Xi^0 - \Xi^-)\right]$$

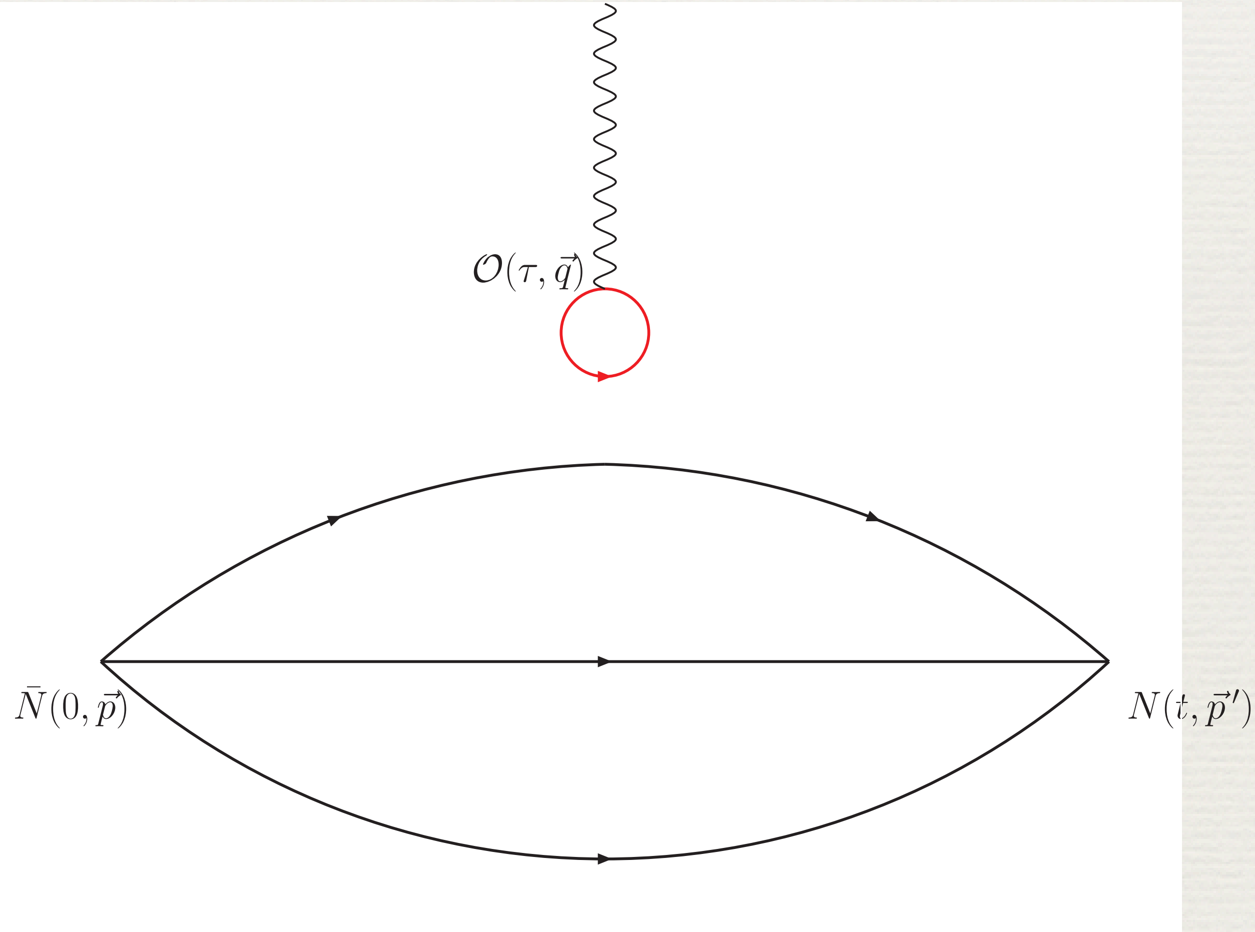
ChPT Exp Lattice

$Q^2 \sim 0.1\ \mathrm{GeV}^2$

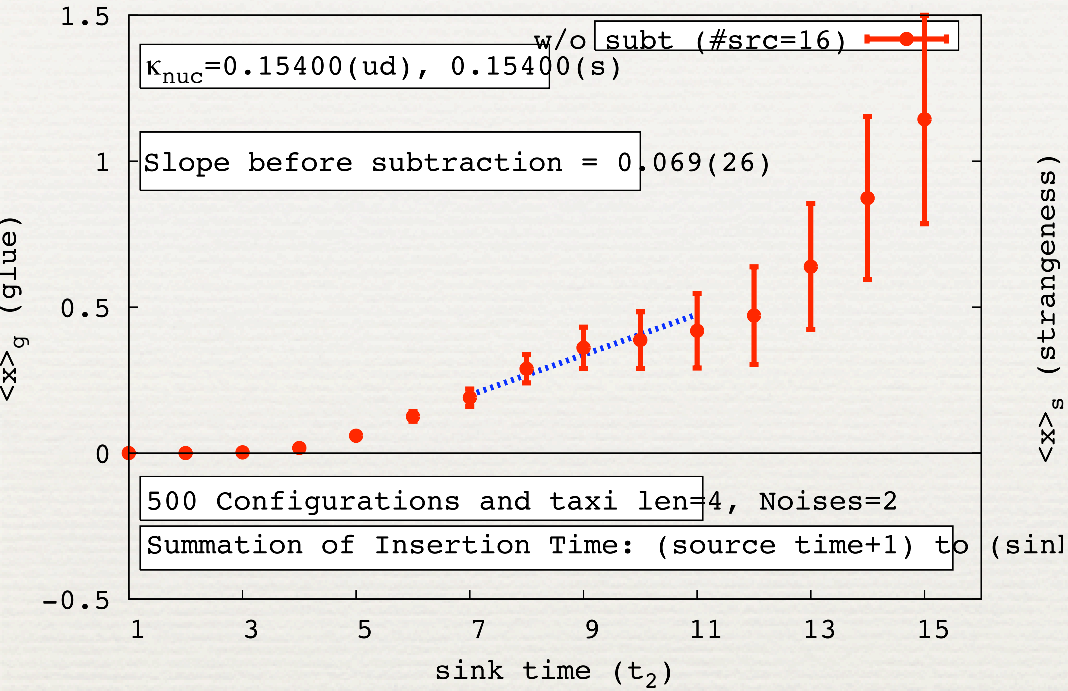
$$G_M^s = -0.082(8)_{\mathrm{stat}}(25)_R$$
$$G_E^s = -0.00044(1)_{\mathrm{stat}}(130)_{rs}$$

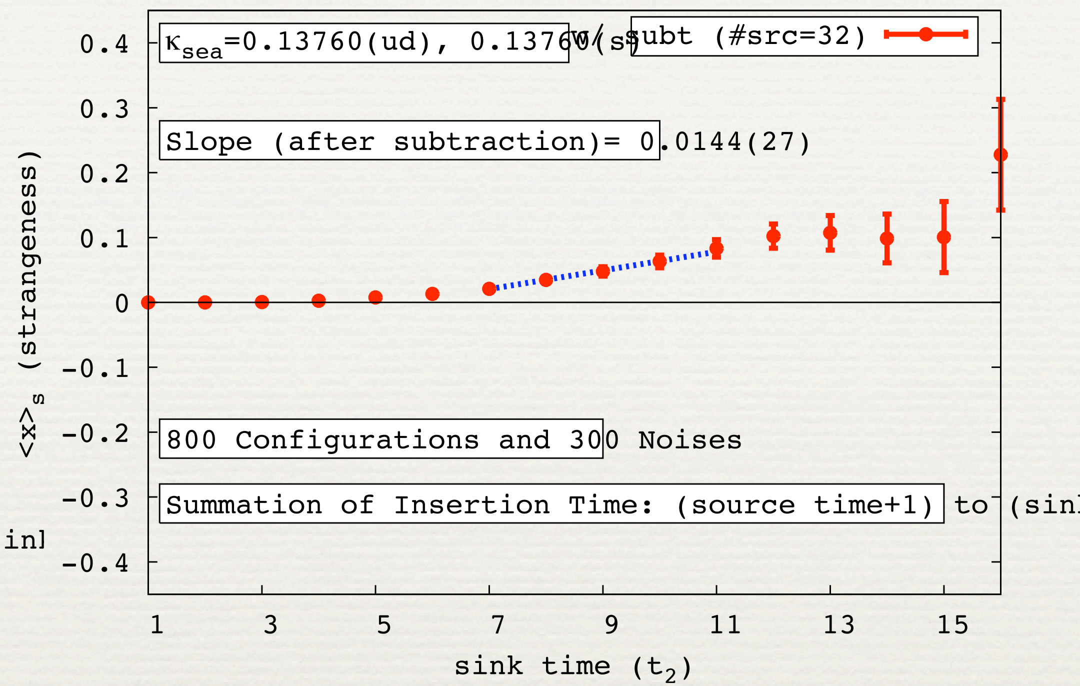


Disconnected



$\langle x \rangle_g, \ \langle x \rangle_s$ ***T. Doi [Kentucky]*** Thursday 11:40





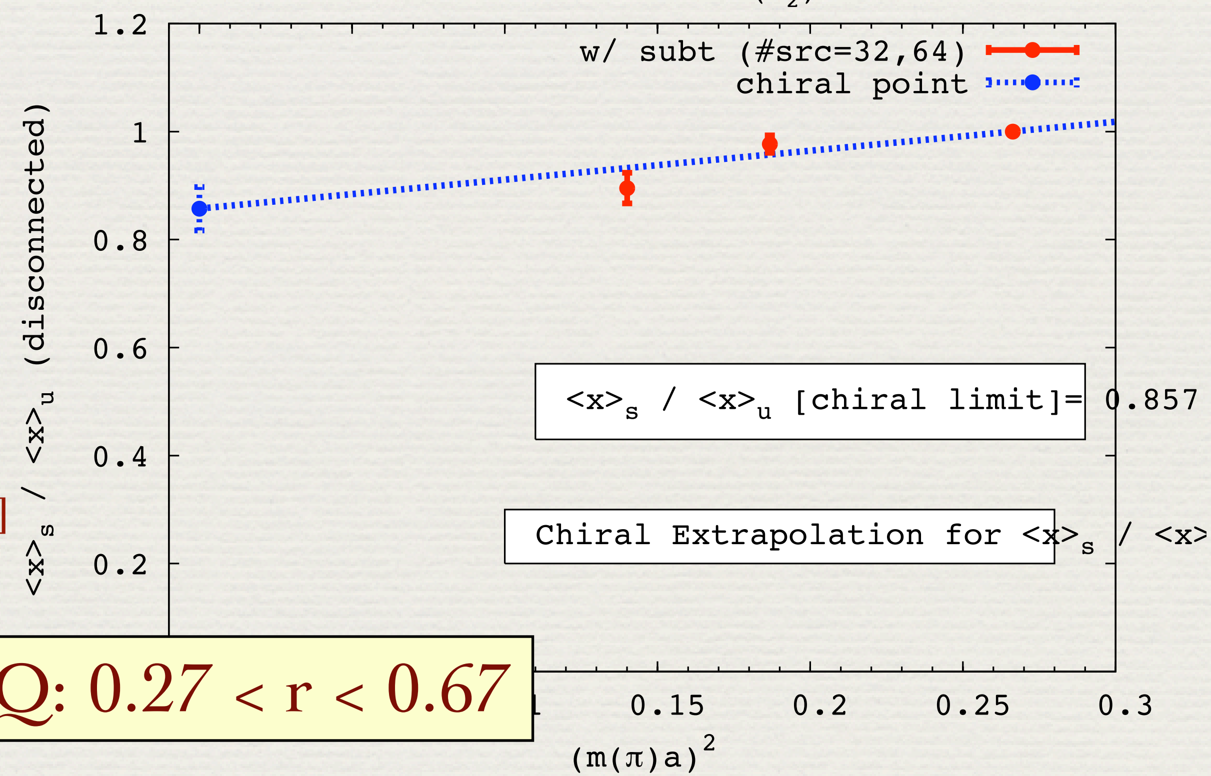
- N_f=2+1 clover (CP-PACS/JLQCD)
- Z(4) noise sources (300)
- Multiple source locations
- Sum over operator insertion times

→ fit to slope

[PLB 659, 773 (2008)]

- Overlap operator for $F_{\mu\nu}$

$$\frac{< x >_{\bar{s}}}{\frac{1}{2}(< x >_{\bar{u}} + < x >_{\bar{d}})} \approx 85\%$$



CTEQ: 0.27 < r < 0.67

$G_S^s(q^2=0)$, $G_A^s(q^2=0) = \Delta s$ Thursday 10:40

$24^3 \times 64$ anisotropic N_f=2 Wilson

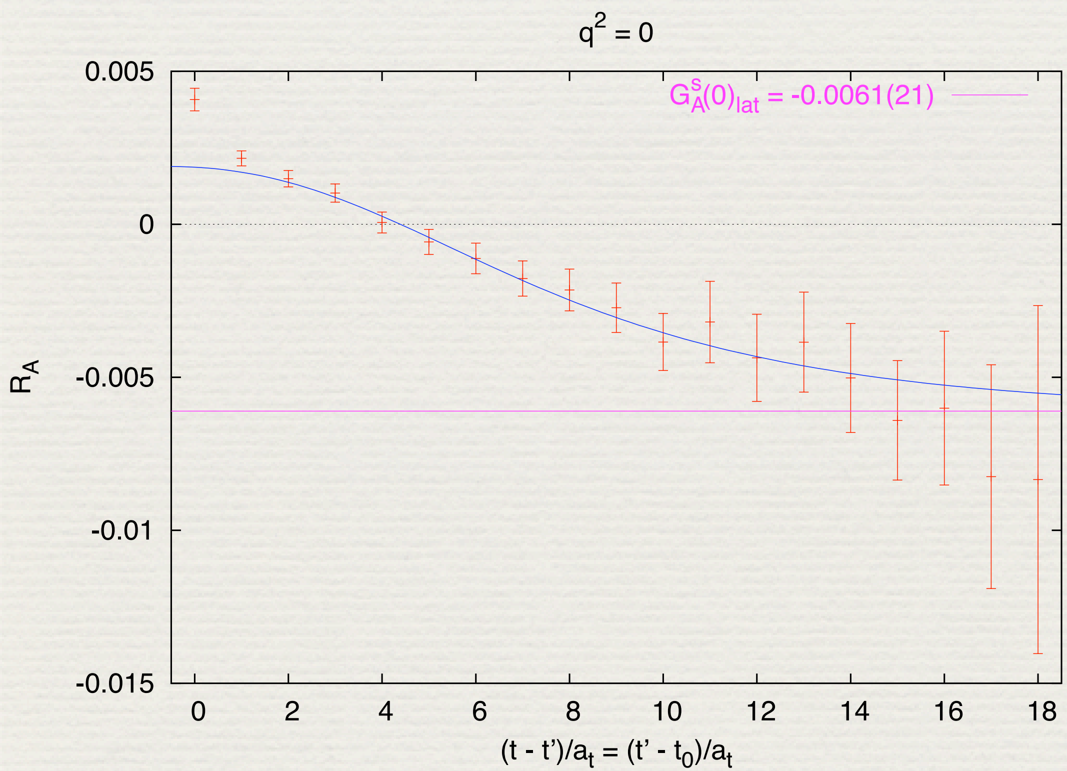
Stochastic sources with maximum dilution

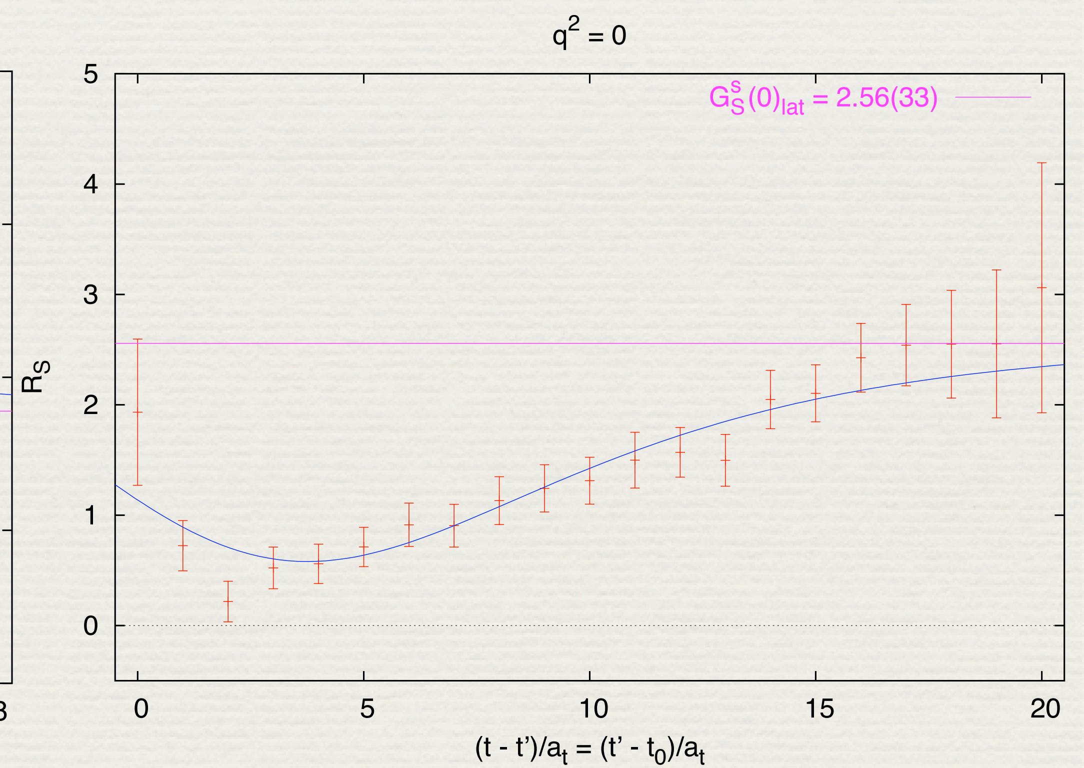
R. Babich [Boston]

G_M^s Consistent with zero

Δs can be obtained with 30% errors

$$f_{Ts} = \frac{m_s \langle N|\bar{s}s|N\rangle}{M_N} = 0.48(7)(3)$$



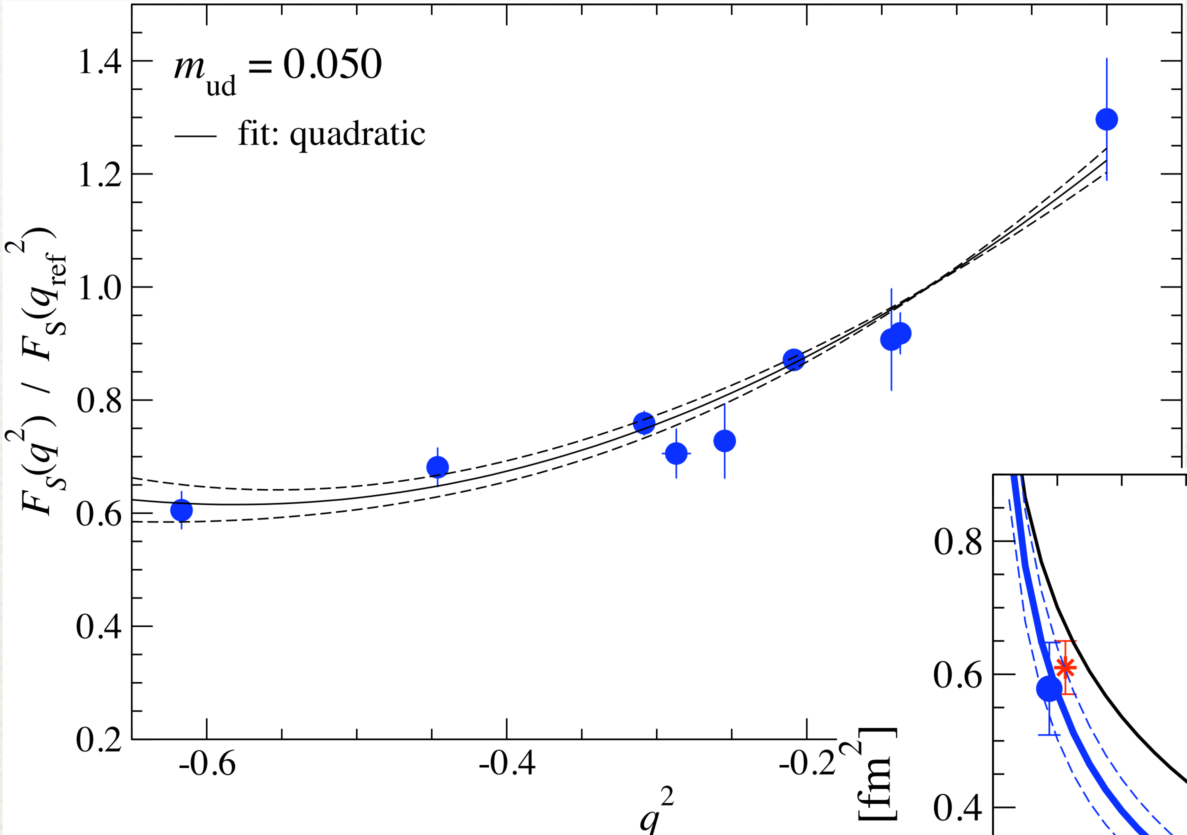


Scalar Form Factor

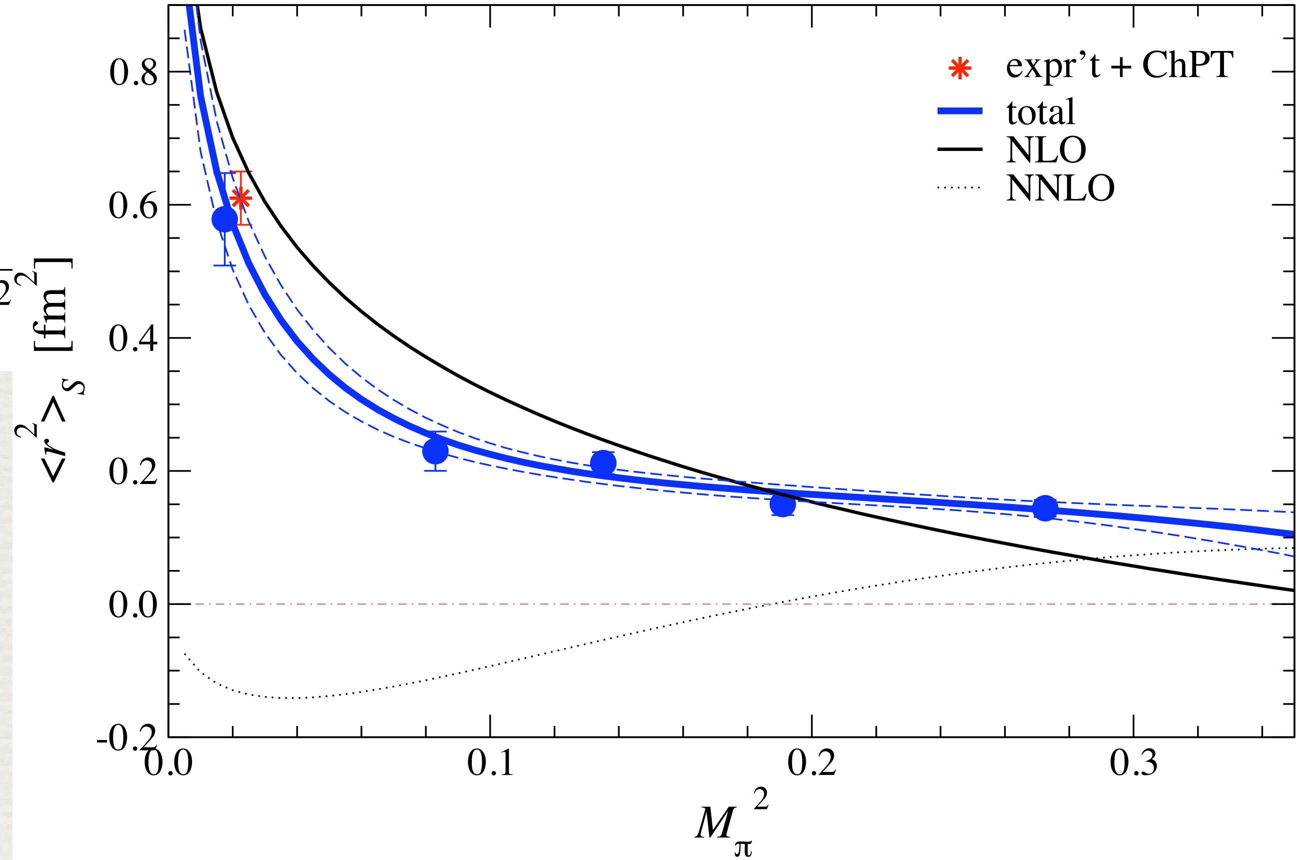
T. Kaneko [JLQCD]: Nf=2 Overlap, all-to-all propagators

Thursday 9:10

Include disconnected contribution



$$\langle r^2 \rangle_\pi^S = 0.578(69)(46)\ \mathrm{fm}^2$$



Other Disconnected/ Strangeness Talks

- Gunnar Bali Thursday 11:00
  - *"Hunting for the strangeness content of the nucleon"*

Δs using variance-reduced all-to-all propagators

Background Field & Polarizabilities

- Andrei Alexandru   Monday 5:20 α_E^n
  - *"The background field method on the lattice"*
- Christopher Aubin   Monday 5:40 $\mu_{\Delta^+},\ \mu_{\Delta^{++}},\ \mu_{\Omega^-}$
  - *"Finite volume study of the Delta magnetic moments using dynamical clover fermions"*
- Brian Tiburzi   Monday 6:00 α_E both neutral and charge hadrons (Clover on DWF)
  - *"Polarizabilities from Lattice QCD"*
- Scott Moerschbacher   Monday 6:20 $\beta_M^{p,n}$ (CP-PACS configs)
  - *"Magnetic polarizability of hadrons from dynamical configurations"*

Conclusion & Outlook

- Calculations of hadronic quantities becoming available at $m_\pi \approx 250$ MeV **(beware finite size effects)**
- q^2 scaling of hadronic form factors
  - **Twisted b.c.s give access to small q^2 (charge radii, F_1^n negative)**
  - **Large q^2 > 4 GeV^2?**(JLab)
- Moments of Generalised Parton Distributions
  - **Quark contribution to nucleon spin and angular momentum**
  - **Non-trivial transverse spin densities in pion and nucleon**

$$J_u \approx 46\%$$
$$J_d \approx 0$$
$$L_{u+d} \approx 0$$

- Moments of Ordinary Parton Distribution Functions
  - **Finite sized effects severe for g_A**
  - **Results for $\langle x \rangle_{u-d}$ appear to be "bending down"**
- Moments of Distribution Amplitudes
  - **Proton: Asymmetries are less pronounced as in QCD-SR**

Conclusions and Outlook

Also important to develop new techniques/ideas

- Moments of Transverse Momentum Dependent PDFs $f_1^{(1)}(\vec{k}_\perp),\ g_1^{(1)}(\vec{k}_\perp)$
  - **Densities of longitudinally polarised quarks in a transversely polarised nucleon are deformed**
- Disconnected contributions
  - **Strangeness/gluonic content of nucleon**
  - **Contribution to nucleon spin**
- Background field methods
  - **Magnetic moments**
  - **Polarisabilities**