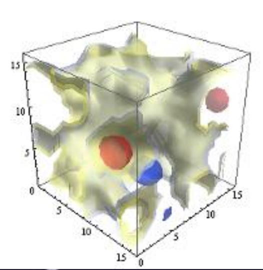
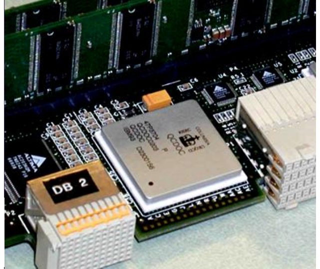
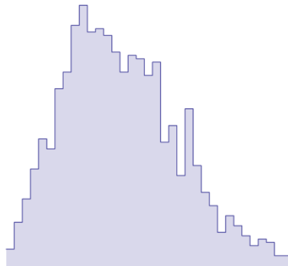
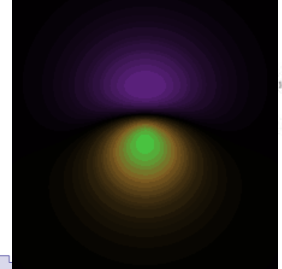
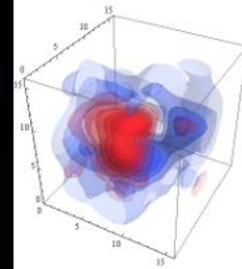
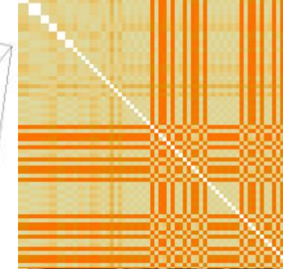
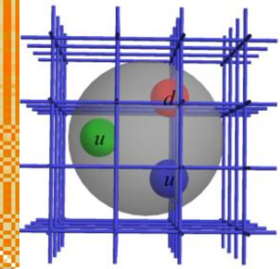



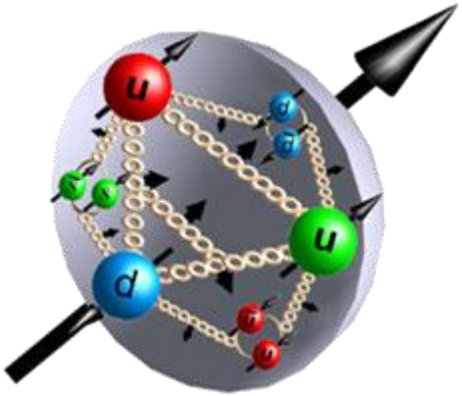
Lattice Hadron Structure: QCD and Beyond

Huey-Wen Lin
University of Washington

Selected Topics

Apologies in advance to those I cannot fit in today…

Outline



§ The Old: Hadron Structure

- Selected latest updates

§ The New: Applications to BSM Physics

- Neutron electric dipole moment
- New tensor and scalar interactions in neutron β decay

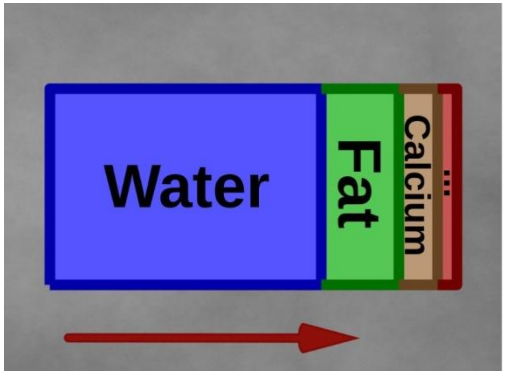
§ The Ugly: Nucleon Axial Charge

- Are we facing a new crisis?

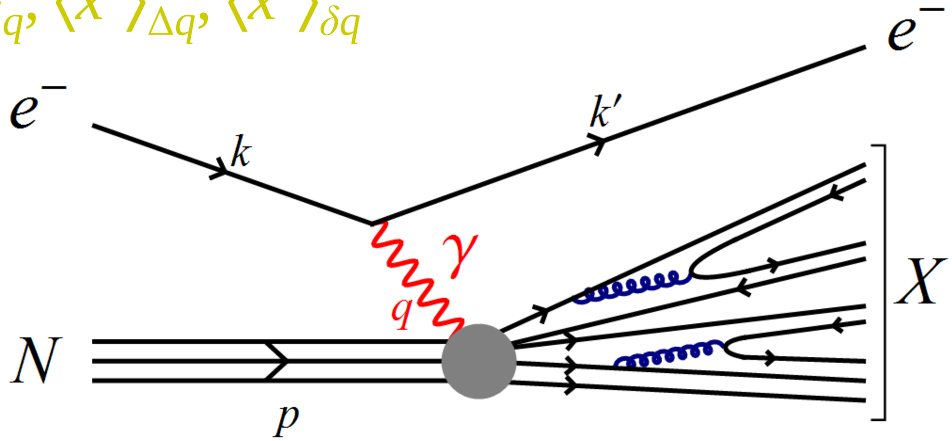
Building a Picture of Hadrons

Hadron Structure

§ Structure function/distribution functions



- Deep inelastic scattering (DIS)
- $\langle x^n \rangle_q$, $\langle x^n \rangle_{\Delta q}$, $\langle x^n \rangle_{\delta q}$



- For example, OPE for unpolarized contribution

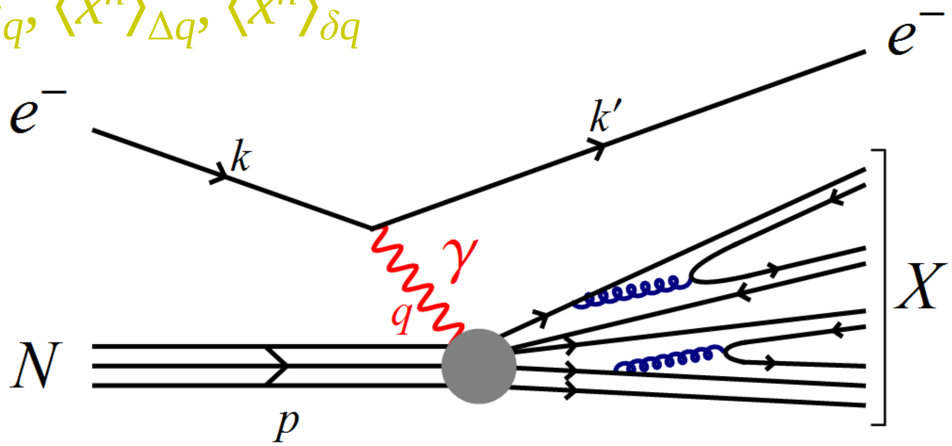
$$2\int dx\, x^{n-1} F_1(x,Q^2) = \sum_{q=u,d} c_{1,n}^{(q)}(\mu^2/Q^2, g(\mu))\langle x^n \rangle_q$$

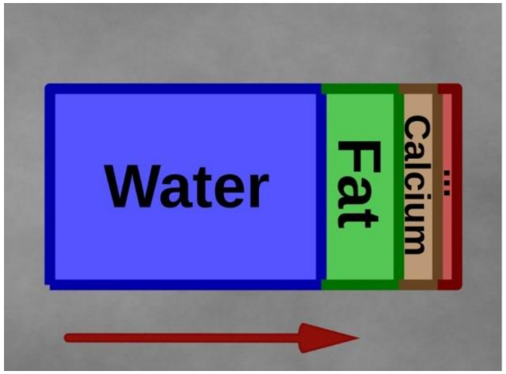
$$\int dx\, x^{n-2} F_2(x,Q^2) = \sum_{q=u,d} c_{2,n}^{(q)}(\mu^2/Q^2, g(\mu))\langle x^n \rangle_q$$

Hadron Structure

§ Structure function/distribution functions

- Deep inelastic scattering (DIS)
- $\langle x^n\rangle_q$, $\langle x^n\rangle_{\Delta q}$, $\langle x^n\rangle_{\delta q}$





- TMDs (M. Engelhard)
- Disconnected $\langle x^n\rangle$ (M. Sun)

Gluonic Momentum Fraction

§ Exploratory stage: quenched results

$$O_{\mu\nu} = -\mathrm{tr}_c F_{\mu\alpha} F_{\nu\alpha}$$

- Quenched, heavy pion masses, linear chiral extrapolation

§ QCDSF ('97) and LHPC ('07)

- Direct matrix-element calculation: $\langle x \rangle_g = 0.53(23)$ QCDSF
- HYP-smearing, study pion: $\langle x \rangle_g = 0.6(2)(1)$

§ χQCD K.F. Liu et al., 1203.6388

- Rewrite gluonic observables with massless overlap kernel

$$\mathrm{tr}_s(\sigma_{\mu\nu} D_{\mathrm{ov}}) \propto a^2 F_{\mu\nu}$$

§ QCDSF R. Horseley et al., 1205.6410

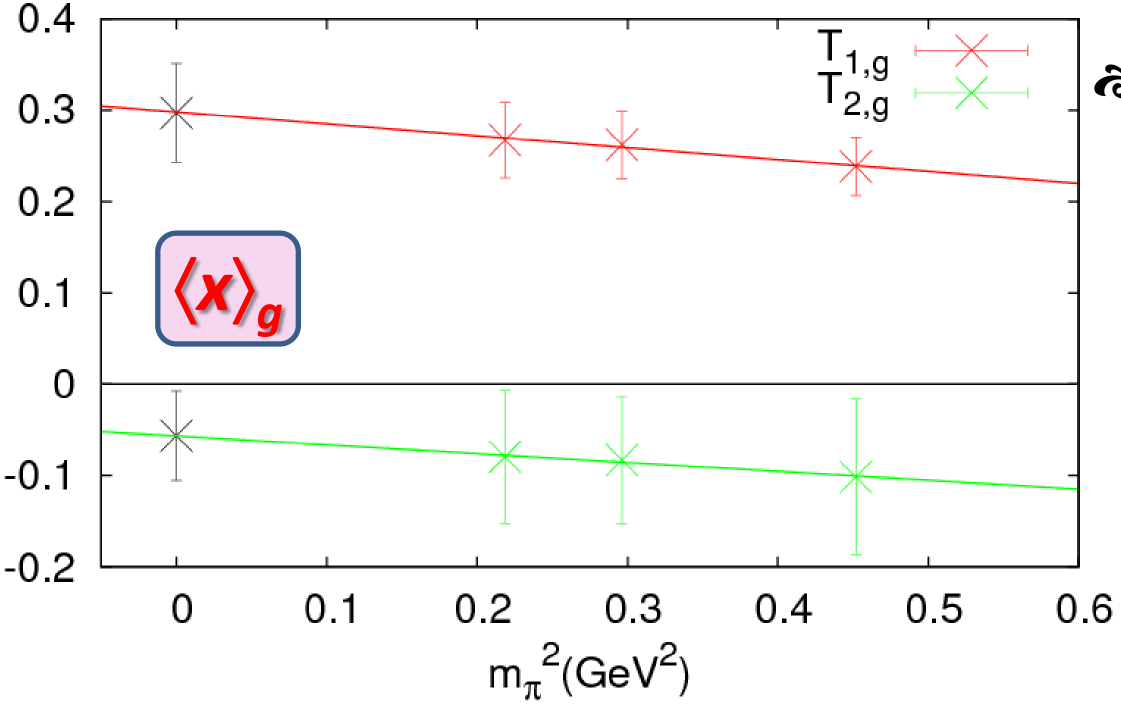
- Feynman-Hellmann theorem with modification of the action

$$S \to S + \lambda S_{\mathcal{O}} \longrightarrow \beta\lambda \frac{1}{3}\left(\sum_{\vec{x},i} \mathrm{Re\,tr}_c\left[1 - P_{i4}(\vec{x})\right] - \sum_{\vec{x},i<j} \mathrm{Re\,tr}_c\left[1 - P_{ij}(\vec{x})\right]\right)$$

Gluonic Momentum Fraction

§ χQCD   K.F. Liu et al., 1203.6388 & private communication

- Rewrite gluonic observables $\mathrm{tr}_s(\sigma_{\mu\nu} D_{\mathrm{ov}}) \propto a^2 F_{\mu\nu}$
- Use $\mathbf{Z}_4$ noise sources to estimate D_{ov} stochastically
- $a \approx 0.1$ fm, 16^3 Wilson + Wilson, $M_\pi \approx 480$–650 MeV, 500 confs, $\langle x \rangle_g = 0.313(56)$

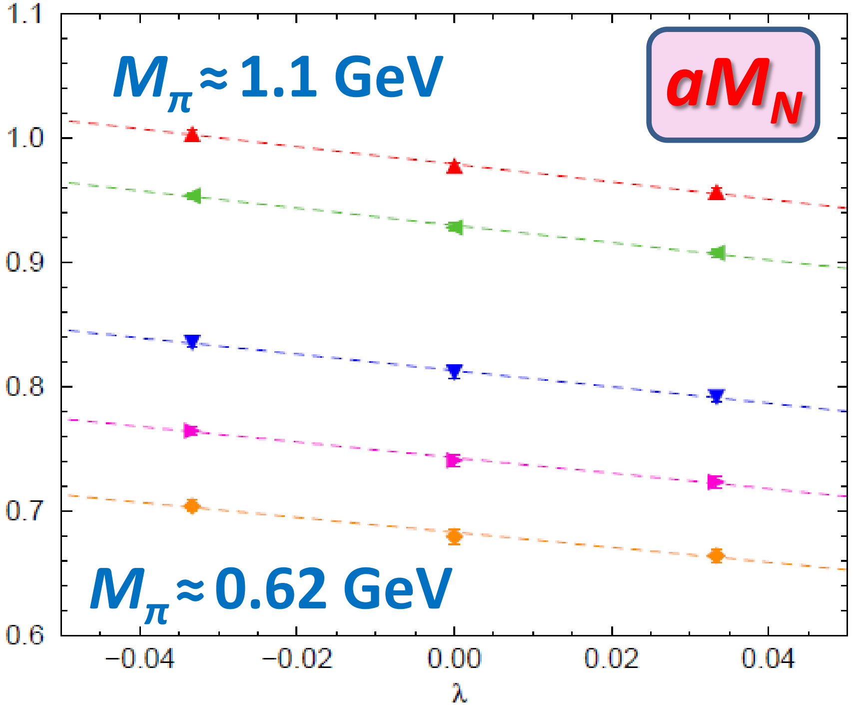


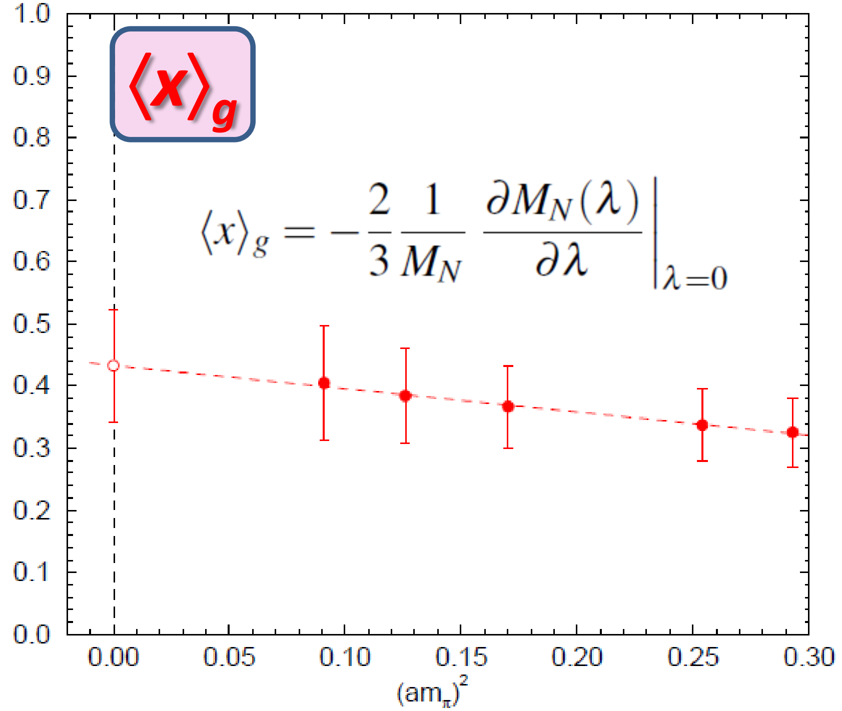
- Expensive!
(but D_{ov} reusable for disconnected contribution?)

Gluonic Momentum Fraction

§ QCDSF R. Horseley et al., 1205.6410

- Feynman-Hellmann theorem (absorbed operators in the action)
- $a \approx 0.1$ fm, 24^3 Wilson + NP clover, $M_\pi \approx 1100$–600 MeV
  O(500) confs, $\langle x \rangle_g = 0.43(7)$
- Cheap, operator by operator; reweighting for dynamical lattices

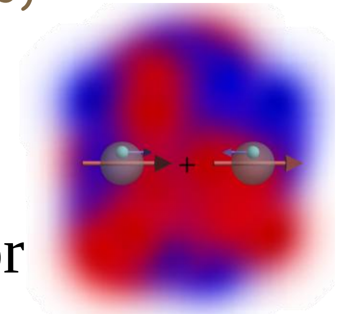




Medium Modification

§ The EMC effects

J. J. Aubert et al. Phys. Lett. 123, 275 (1983)



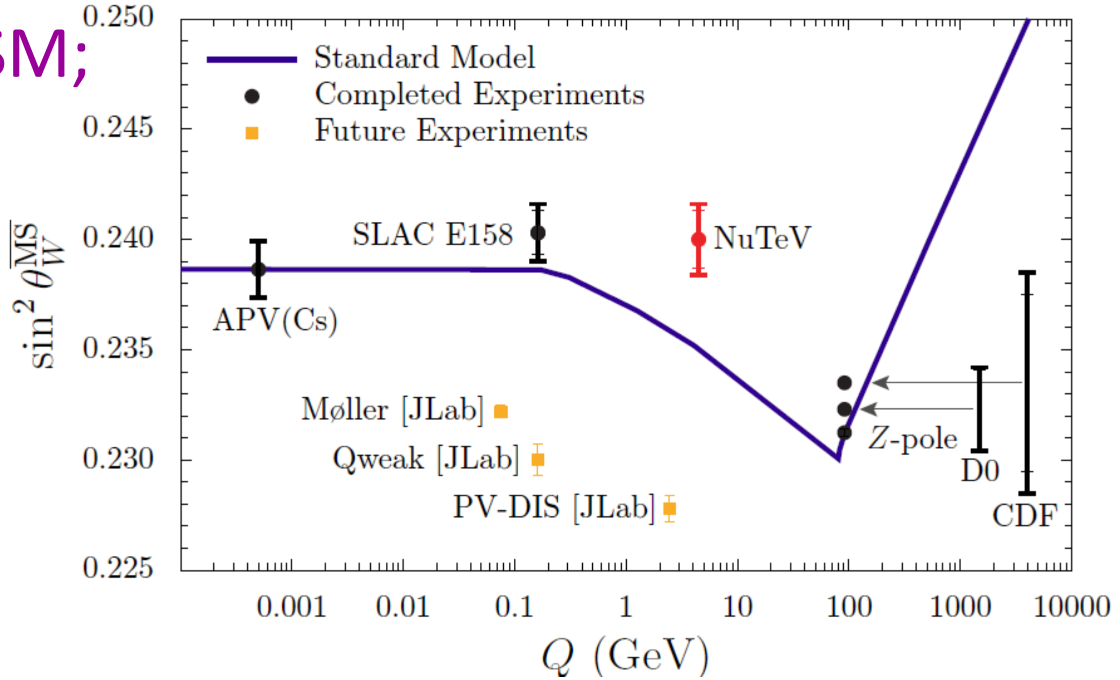
- Structure function changes significantly between heavy nuclei and deuterium
- Not only significant for heavy nuclei, also important for light-nuclear systems

J. Seely et al., Phys. Rev. Lett. 103, 202301 (2009)

§ Important for tests of SM; e.g. NuTeV anomaly

- Weak mixing angle expt. 3 sigma away from SM

G. P. Zeller et al. Phys. Rev. Lett. 88, 091802 (2002)



Medium Modification

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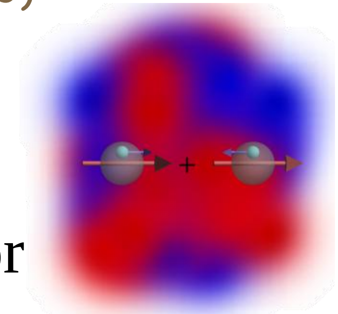


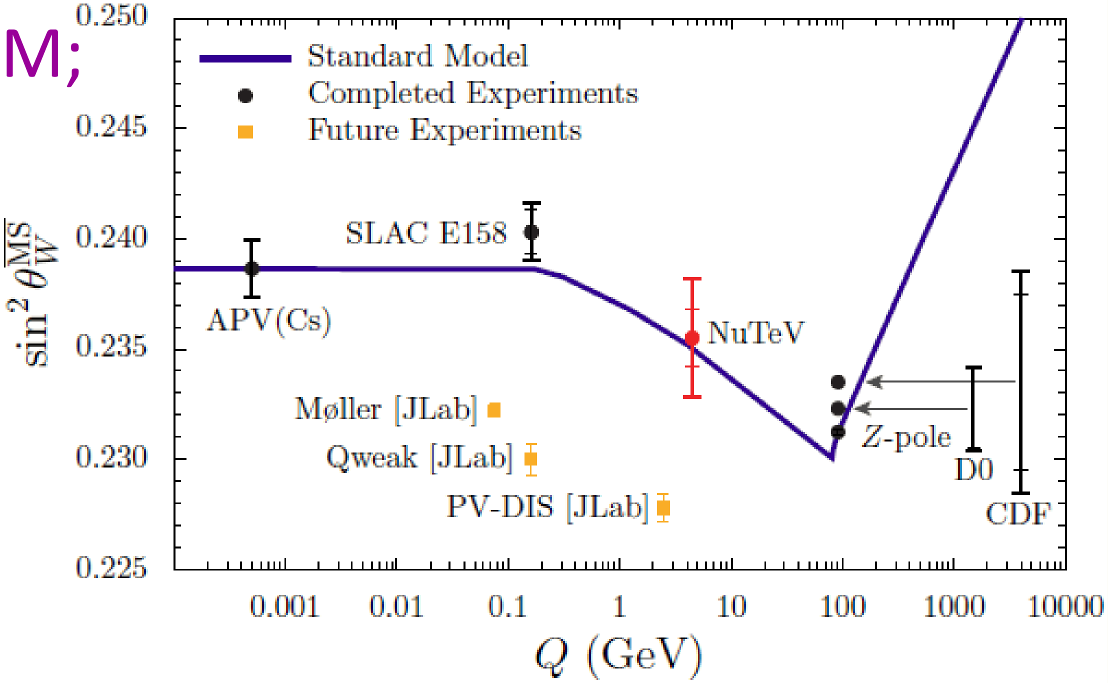
- Structure function changes significantly between heavy nuclei and deuterium
- Not only significant for heavy nuclei, also important for light-nuclear systems

J. Seely et al., Phys. Rev. Lett. 103, 202301 (2009)

§ Important for tests of SM; e.g. NuTeV anomaly

- Evidence for medium modification effects?

I. Cloët, W. Bentz, A. Thomas, Phys. Lett. B693, 462 (2010)



Medium Modification

§ First lattice-QCD attempt to measure EMC effects

- Pion momentum fraction in pion medium

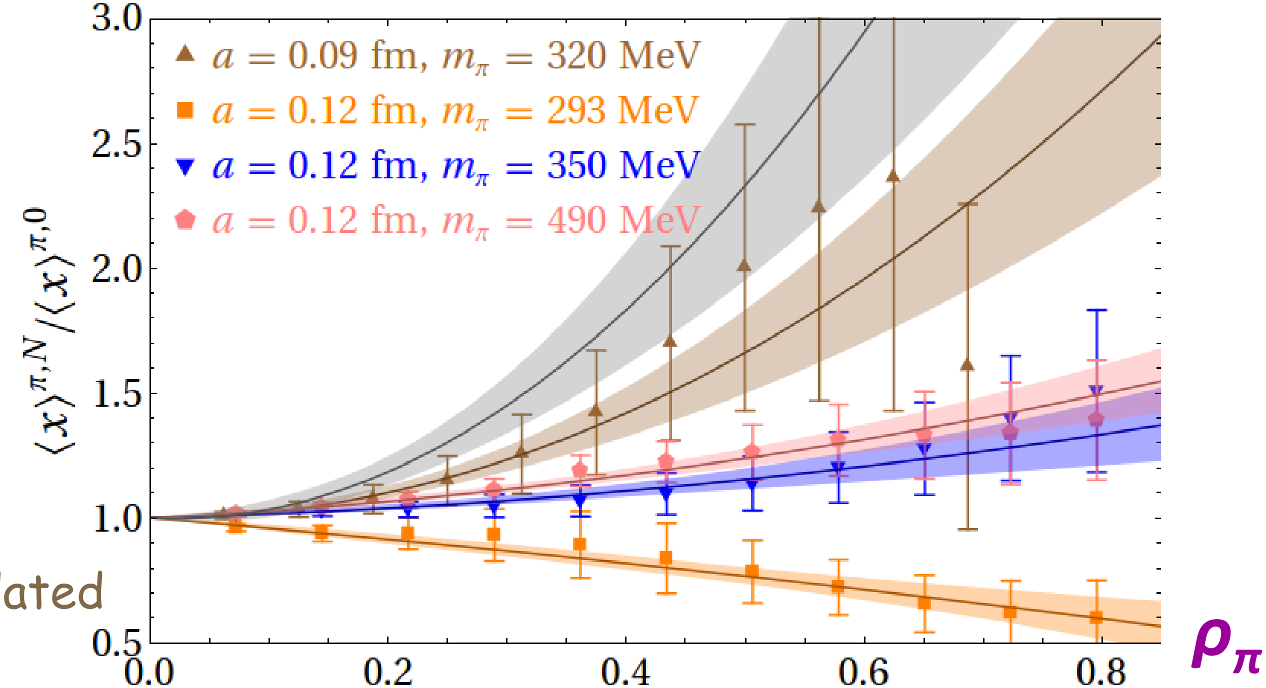
$$\mathcal{O} = \mathcal{O}_{\{44\}} - \frac{1}{3}\left(\mathcal{O}_{\{11\}} + \mathcal{O}_{\{22\}} + \mathcal{O}_{\{33\}}\right)$$

- With $m_\pi \approx 290$–490 MeV, 2 lattice spacings

§ $\langle x\rangle^{\pi,N}/\langle x\rangle^{\pi,0}$ with thermal-state degrees of freedom

multiple t_{sep} used

Preliminary

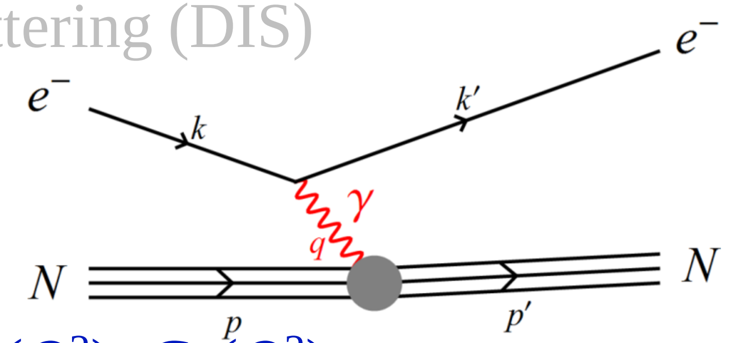


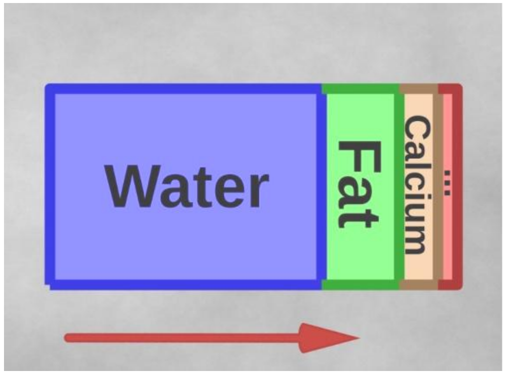
W. Detmold + HWL; and updated

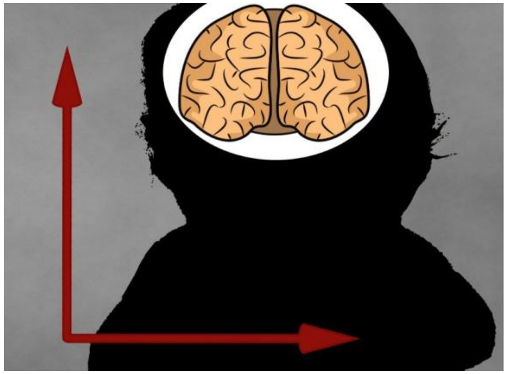
Form Factors

§ Structure function/distribution functions

- Deep inelastic scattering (DIS)
- $\langle x^n \rangle_q$, $\langle x^n \rangle_{\Delta q}$, $\langle x^n \rangle_{\delta q}$







§ Form factors

- Elastic scattering
- $F_1(Q^2)$, $F_2(Q^2)$, $G_A(Q^2)$, $G_P(Q^2)$
- For example, octet baryons

$$\langle B\,|V_\mu|\,B\rangle(q) \;=\; \overline{u}_B(p')\left[\gamma_\mu F_1(q^2) + \sigma_{\mu\nu} q_\nu \frac{F_2(q^2)}{2M_B}\right] u_B(p)$$

Dirac Pauli

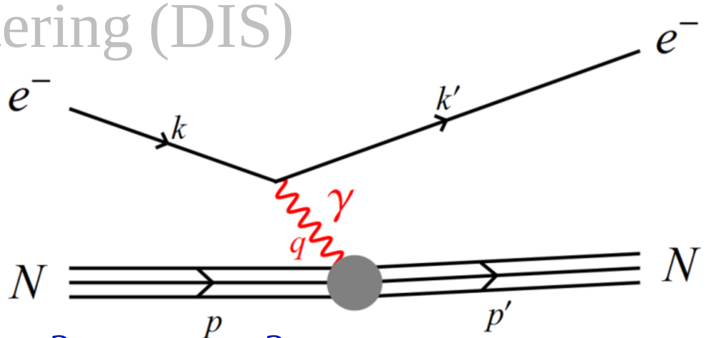
$$\langle B\,|A_\mu(q)|\,B\rangle \;=\; \overline{u}_B(p')\left[\gamma_\mu \gamma_5 G_A(q^2) + \gamma_5 q_\nu \frac{G_P(q^2)}{2M_B}\right] u_B(p)$$

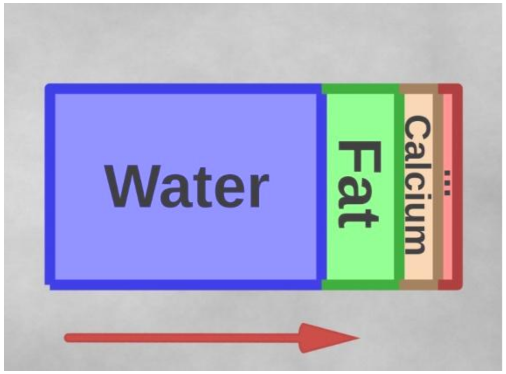
Axial Induced Pseudoscalar

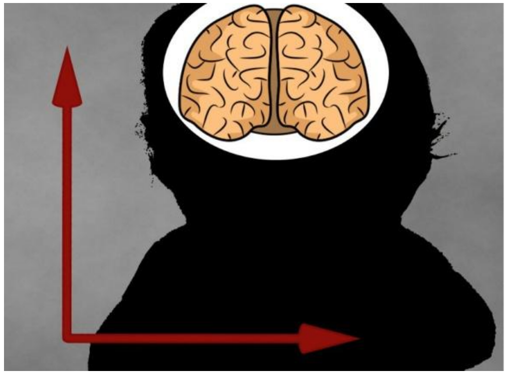
Form Factors

§ Structure function/distribution functions

- Deep inelastic scattering (DIS)
- $\langle x^n \rangle_q$, $\langle x^n \rangle_{\Delta q}$, $\langle x^n \rangle_{\delta q}$







§ Form factors

- Elastic scattering
- $F_1(Q^2)$, $F_2(Q^2)$, $G_A(Q^2)$, $G_P(Q^2)$

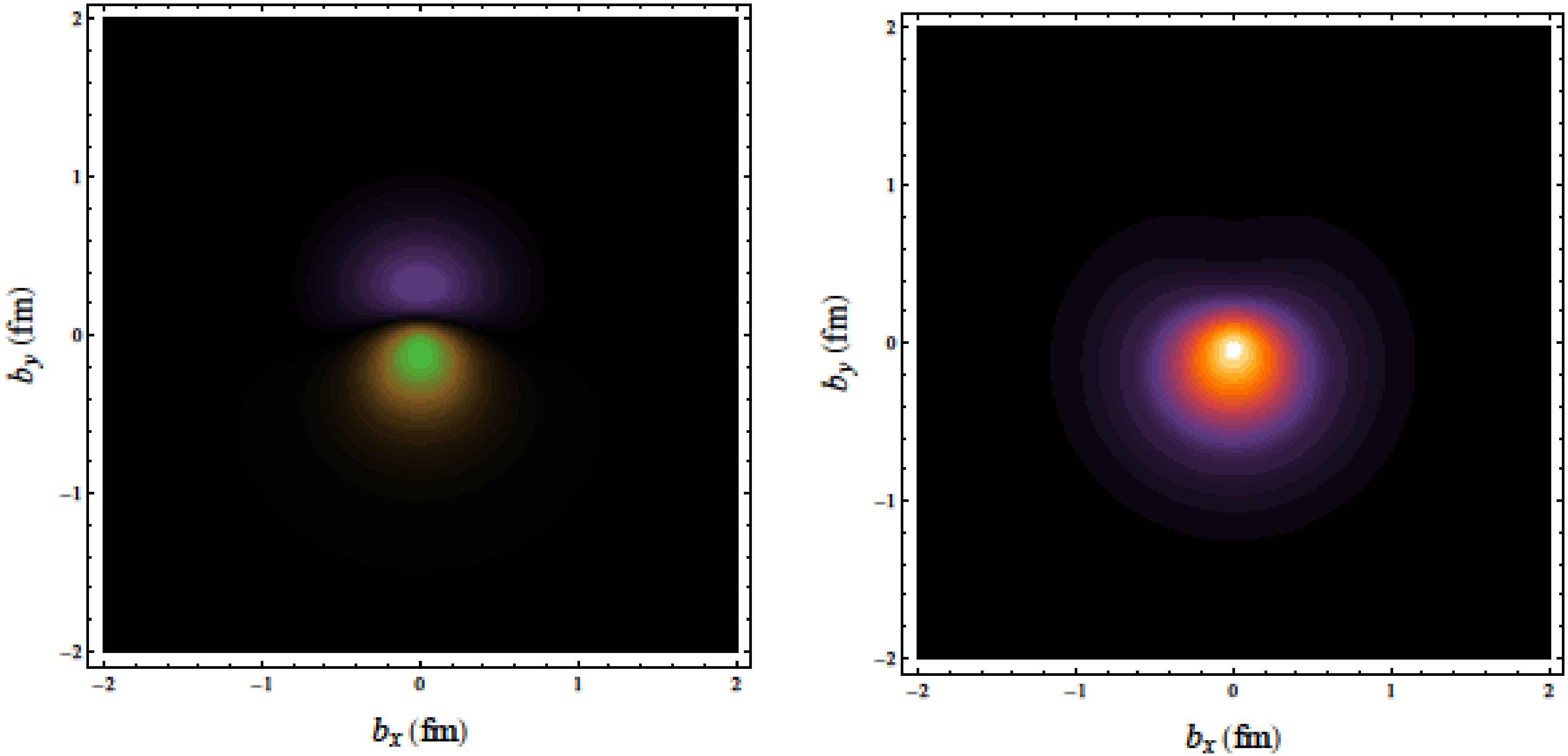
Lattice 2012

- Charges and radii (J. Green, S. Ohta, M. Lin, B. Owen, T. Rae, B. Menadue, V. Guelpers; C. Alexandrou, J. Zanotti)
- Transition form factors (X. Feng; B. Menadue; C. Alexandrou, S. Sasaki)

Large Q^2 Form Factor

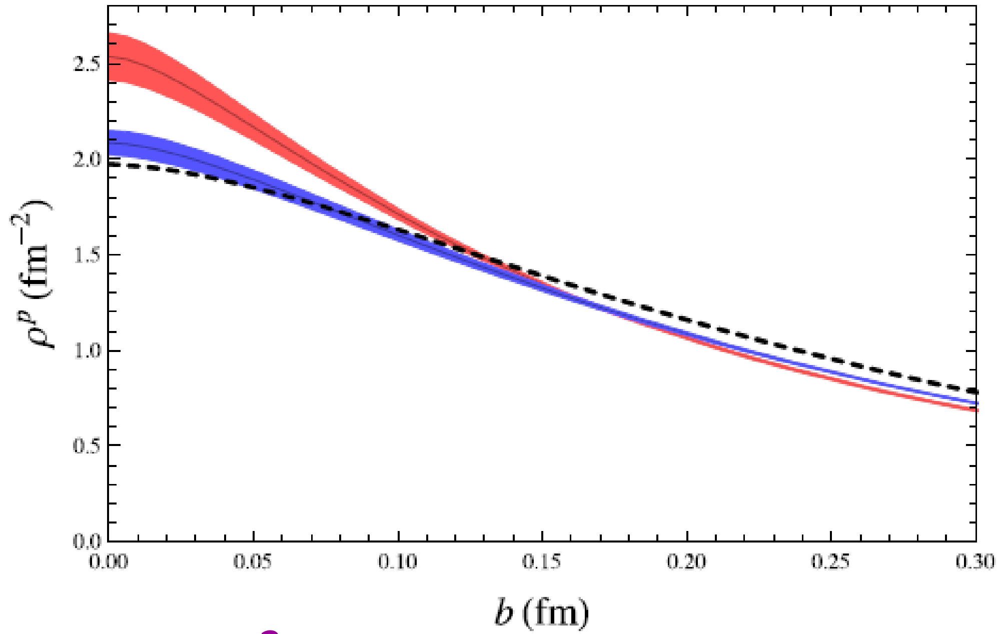
- Fourier transform using large-Q^2 form factors to reveal transverse charge densities in a polarized nucleon

National Academies Press



Transverse Charge Density

§ How does high-Q^2 data affect the charge density?



- Red band uses lattice data $\leq 2.0\ \text{GeV}^2$
- Blue band uses lattice data $\leq 4.0\ \text{GeV}^2$

HWL et al., arXiv: 1005.0799

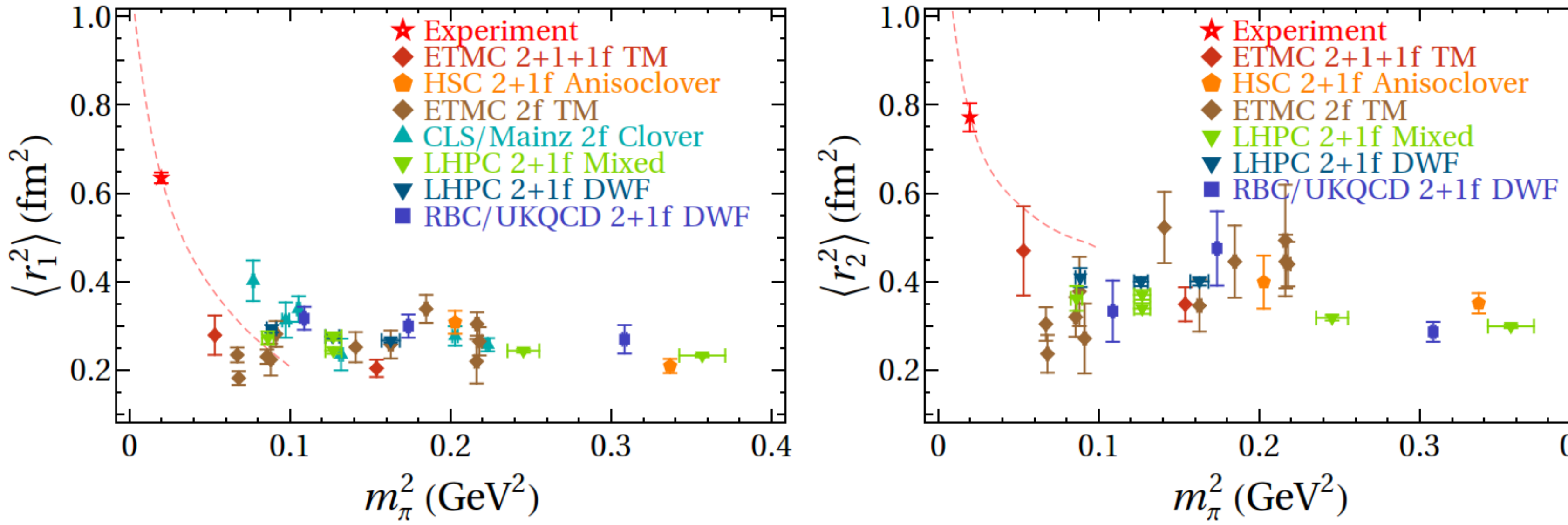
§ Large-Q^2 Caveats

- Essential to get coordinate-space distribution in central region
- Further studies needed for discretization effects
- Possible improvement: step-scaling method, …
- Important for pion form factor

Form Factors

§ Charge radii

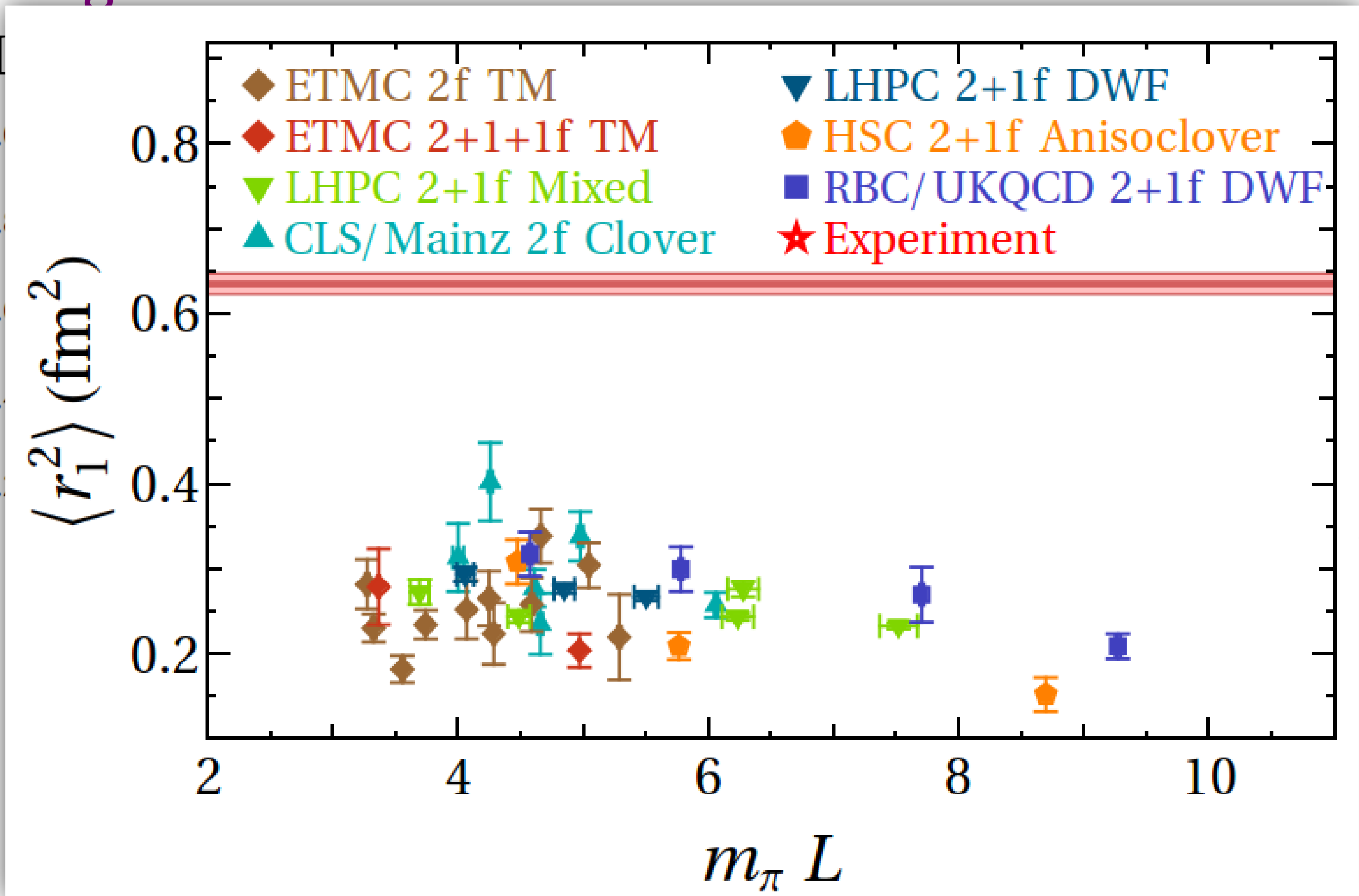
- Lattice data way too low; no help for the proton-radius puzzle



Form Factors

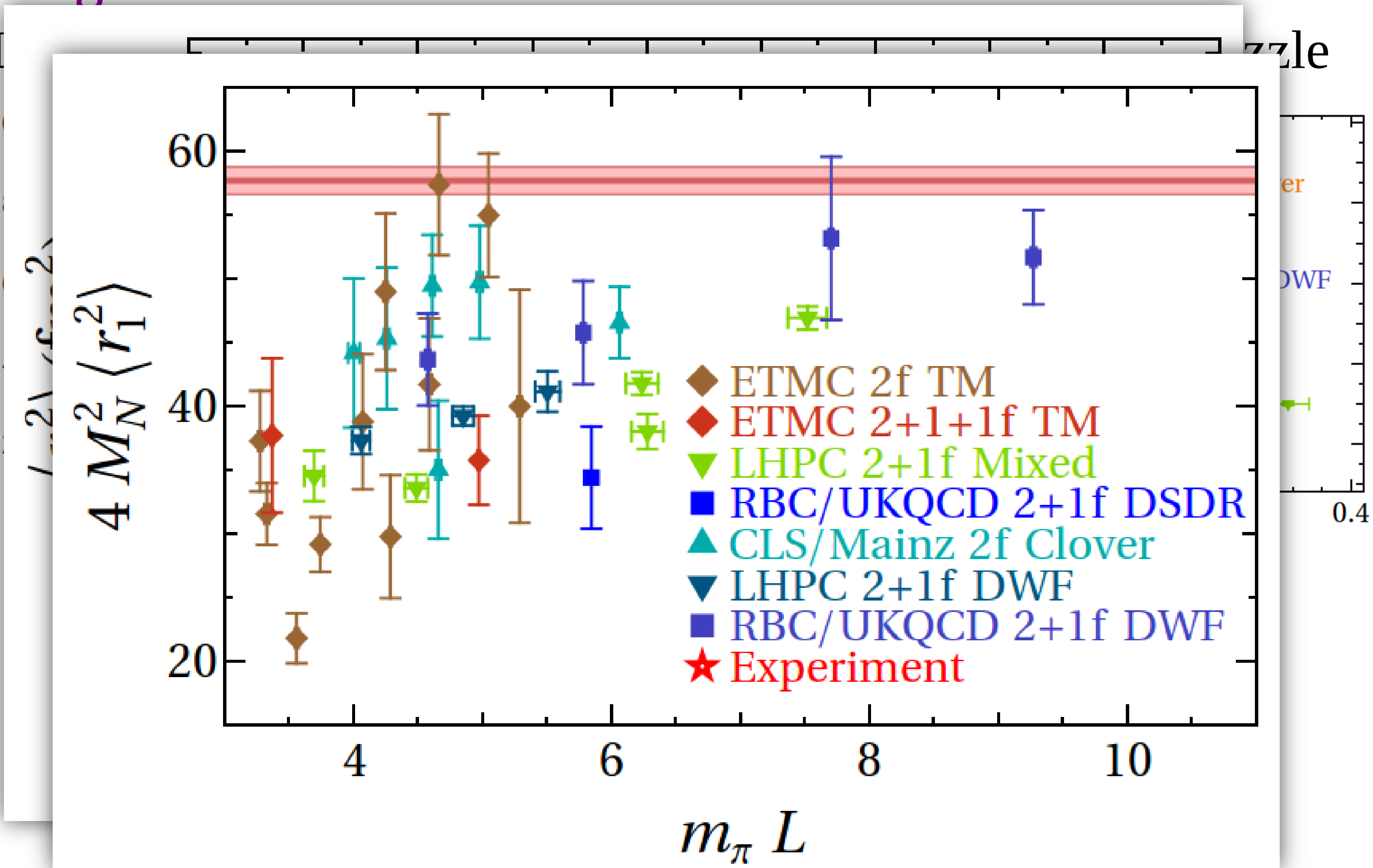
§ Charge radii

- I … zzle



Form Factors

§ Charge radii



Form Factors

§ Charge radii

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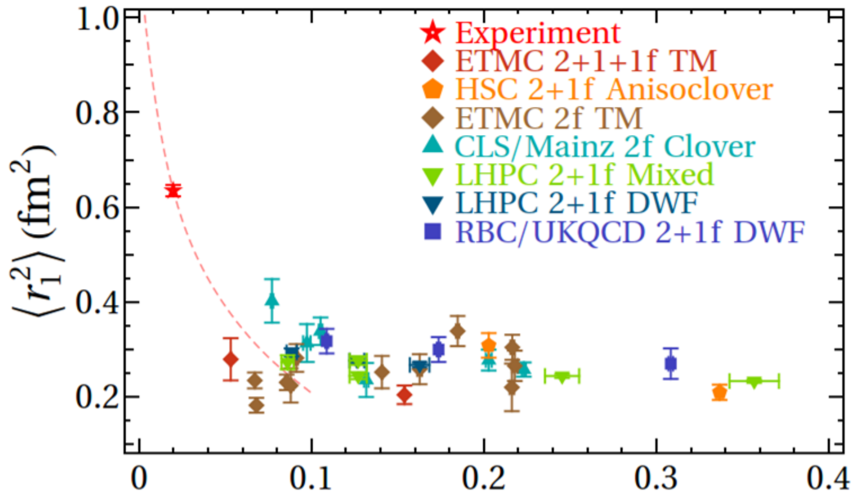
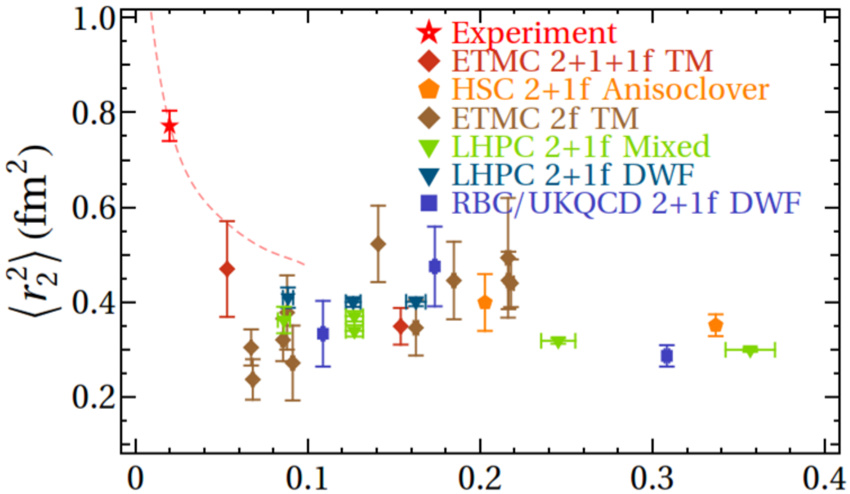
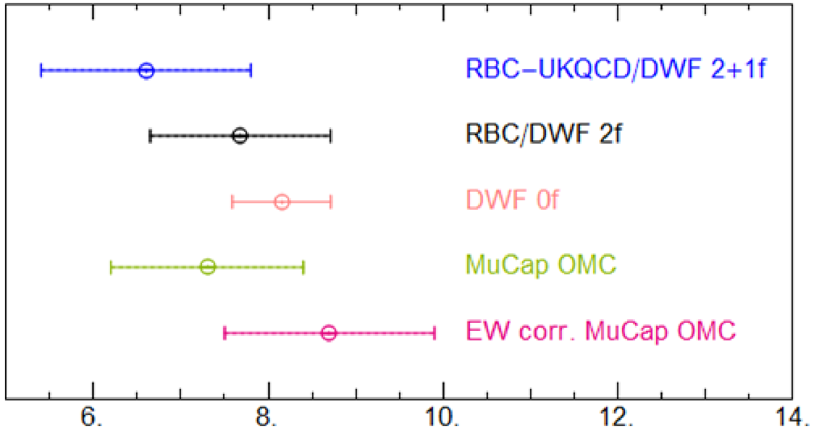




§ Induced-pseudoscalar

$$g_P = [m_\mu G_P(0.88\, m_\mu^2) / 2\, m_N]$$

- Poor constraints (DWF numbers so far)
- Important for muon physics



Generalized Parton Distribution

§ Structure function/distribution functions

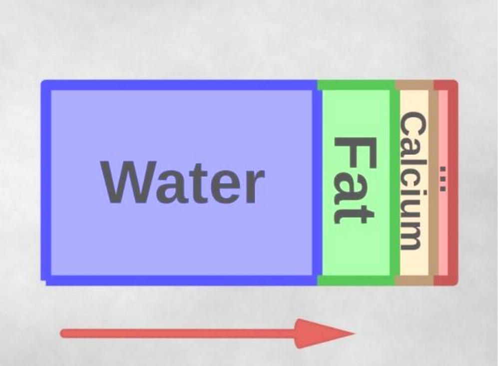
- Deep inelastic scattering (DIS)
- $\langle x^n \rangle_q$, $\langle x^n \rangle_{\Delta q}$, $\langle x^n \rangle_{\delta q}$

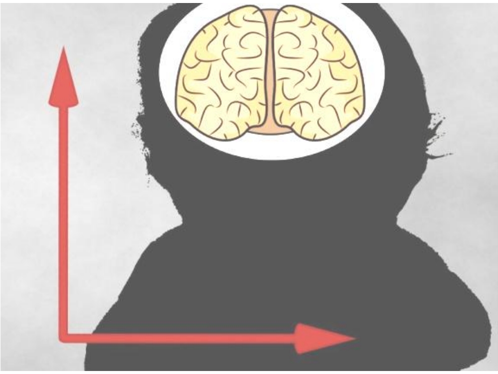
§ Form factors

- Elastic scattering
- $F_1(Q^2)$, $F_2(Q^2)$, $G_A(Q^2)$, $G_P(Q^2)$

§ Generalized Parton Distribution

- Deeply virtual Compton scattering (DVCS)
- $\langle x^{n-1} \rangle_q = A_{n0}(0)$, $\langle x^{n-1} \rangle_{\Delta q} = \tilde{A}_{n0}(0)$, $\langle x^n \rangle_{\delta q} = A_{Tn0}(0)$
- $F_1(Q^2) = A_{10}(Q^2)$, $F_2(Q^2) = B_{10}(Q^2)$, $G_A(Q^2) = \tilde{A}_{10}(Q^2)$, $G_P(Q^2) = \tilde{B}_{10}(Q^2)$
- Nucleon spin $A_{20}(0)$, $B_{20}(0)$





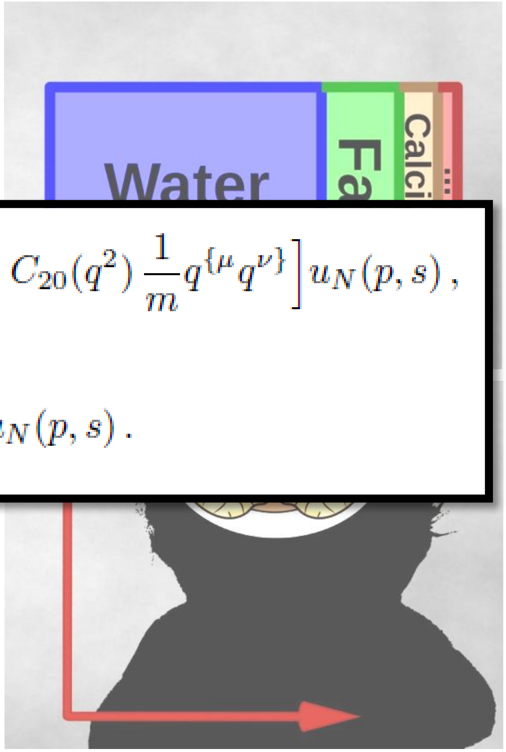
Generalized Parton Distribution

$$
\begin{aligned}
\mathcal{O}_V^{\mu_1\ldots\mu_n} &= \bar{\psi}\gamma^{\{\mu_1} i\overleftrightarrow{D}^{\mu_2}\ldots i\overleftrightarrow{D}^{\mu_n\}}\psi \\
\mathcal{O}_A^{\mu_1\ldots\mu_n} &= \bar{\psi}\gamma^{\{\mu_1} i\overleftrightarrow{D}^{\mu_2}\ldots i\overleftrightarrow{D}^{\mu_n\}}\gamma_5\psi
\end{aligned}
$$

$$
\begin{aligned}
\langle N(p',s')|\mathcal{O}^{\mu\nu}_{\not{q}}|N(p,s)\rangle &= \bar{u}_N(p',s')\left[A_{20}(q^2)\,\gamma^{\{\mu}P^{\nu\}} + B_{20}(q^2)\,\frac{i\sigma^{\{\mu\alpha}q_\alpha P^{\nu\}}}{2m} + C_{20}(q^2)\,\frac{1}{m}q^{\{\mu}q^{\nu\}}\right]u_N(p,s)\,, \\
\langle N(p',s')|\mathcal{O}^{\mu\nu}_{\not{q}\gamma_5}|N(p,s)\rangle &= \bar{u}_N(p',s')\left[\tilde{A}_{20}(q^2)\,\gamma^{\{\mu}P^{\nu\}}\gamma^5 + \tilde{B}_{20}(q^2)\,\frac{q^{\{\mu}P^{\nu\}}}{2m}\gamma^5\right]u_N(p,s)\,.
\end{aligned}
$$

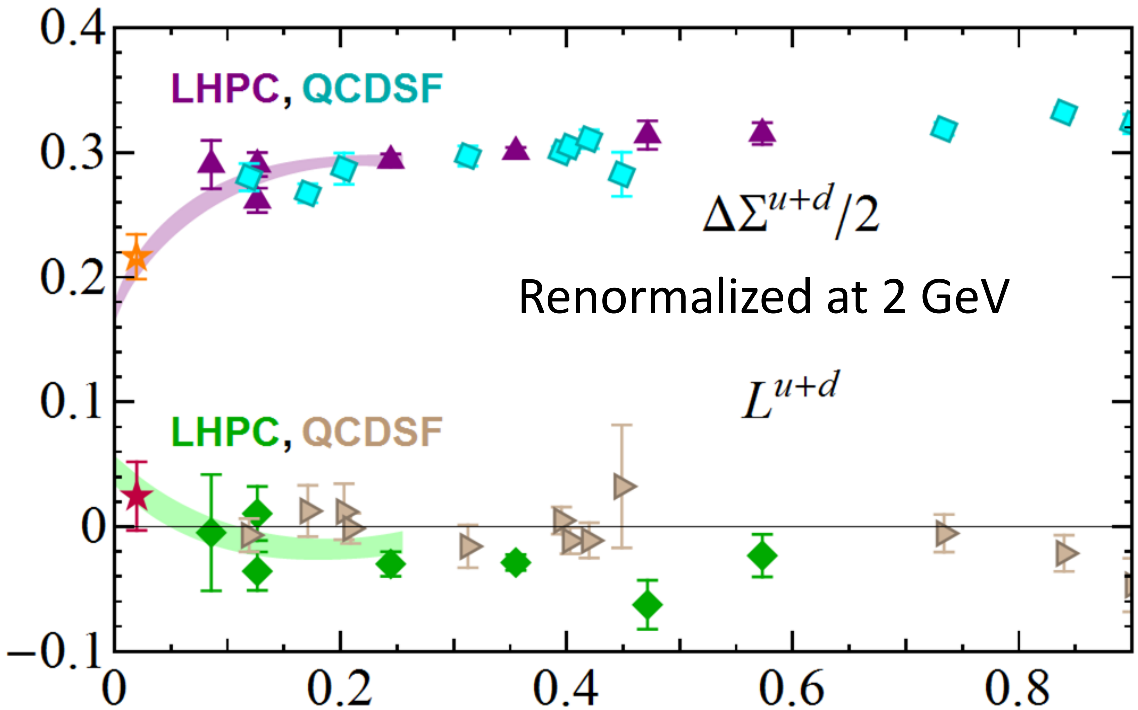
§ Generalized Parton Distribution

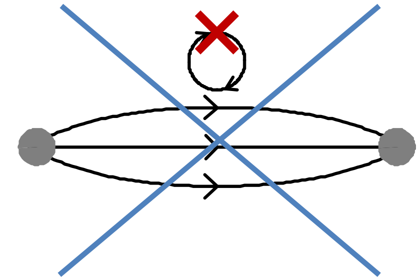
- Deeply virtual Compton scattering (DVCS)
- $\langle x^{n-1}\rangle_q = A_{n0}(0)$, $\langle x^{n-1}\rangle_{\Delta q} = \tilde{A}_{n0}(0)$, $\langle x^{n}\rangle_{\delta q} = A_{Tn0}(0)$
- $F_1(Q^2) = A_{10}(Q^2)$, $F_2(Q^2) = B_{10}(Q^2)$, $G_A(Q^2) = \tilde{A}_{10}(Q^2)$, $G_P(Q^2) = \tilde{B}_{10}(Q^2)$
- Nucleon spin $A_{20}(0)$, $B_{20}(0)$



Origin of Proton Spin

- What is the makeup of the nucleon?
  - The origin of the nucleon's spin (the "spin crisis")
  - For example, LHPC + QCDSF dynamical results





$\Delta\Sigma$: spin

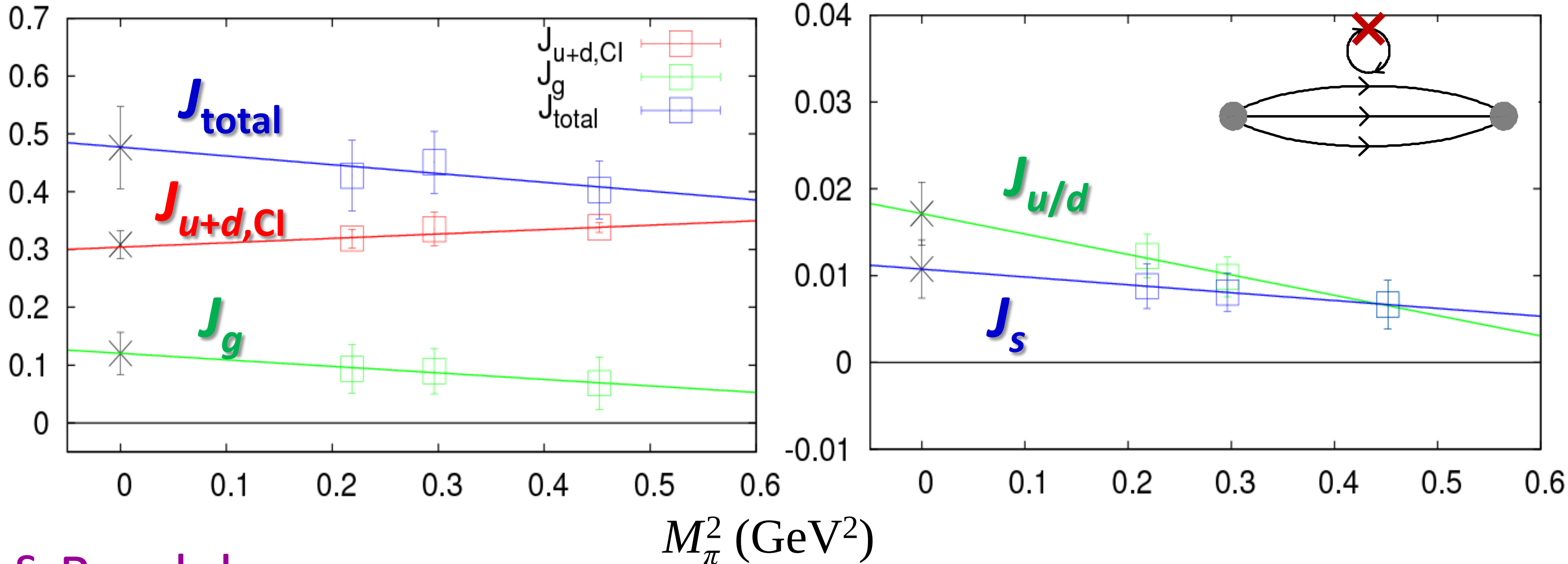
L: orbital angular momentum

- Ignore disconnected diagram
- Gluon contribution estimated from sum rule

Origin of Proton Spin

§ What is the makeup of the nucleon?

χQCD, 1203.6388 [hep-ph] and private communication w/ Y. Yang

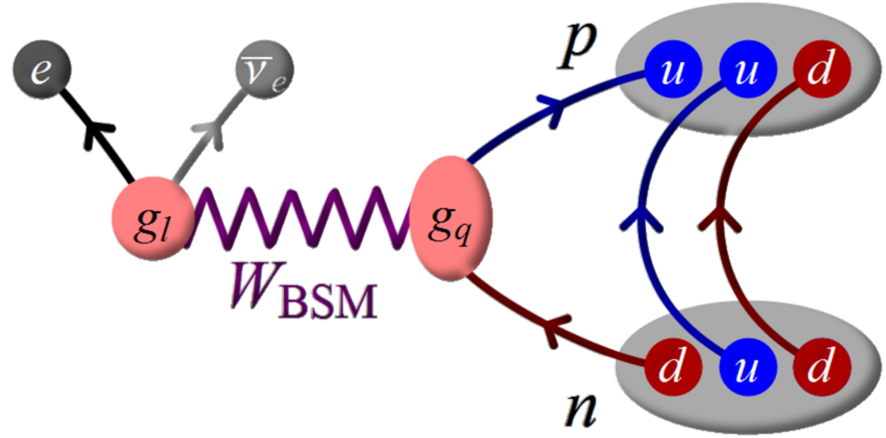


§ Breakdown:

- $\Delta\Sigma_q = 50(2)\%$, $L_q = 25(12)\%$ (mostly DI), $J_g = 25(8)\%$

§ Looking forward to χQCD (overlap/DWF), QCDSF (clover)

Applications beyond QCD



Nucleons and BSM

Many opportunities to probe BSM with LQCD

- Muon *g*−2

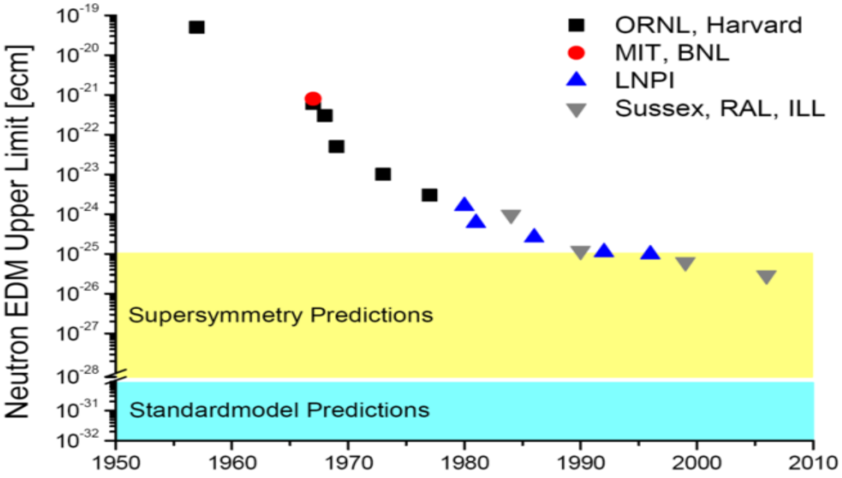
Tom Blum, Friday

- Strangeness and dark matter

Ross Young, Thursday

- Electric dipole moment
  - CP-violating effect
  - Extremely small in SM: $\approx 10^{-30}$ *e*-cm
  - Best SUSY model killer

(T. Bhattacharya; E. Shintani)



- Nucleon beta decay
  - Non-*V*−*A* (e.g. scalar and tensor) interactions
  - Scalar and tensor charges R. Gupta (PNDME), J. Green (LHPC)

nEDM

§ Lagrangian

$$\mathcal{S} = \mathcal{S}_{\text{QCD}}^{\text{CP Even}} - i\,\Theta\,\frac{g^2}{16\,\pi^2}\int d^4x\, G^{\mu\nu}\,\tilde{G}_{\mu\nu}$$

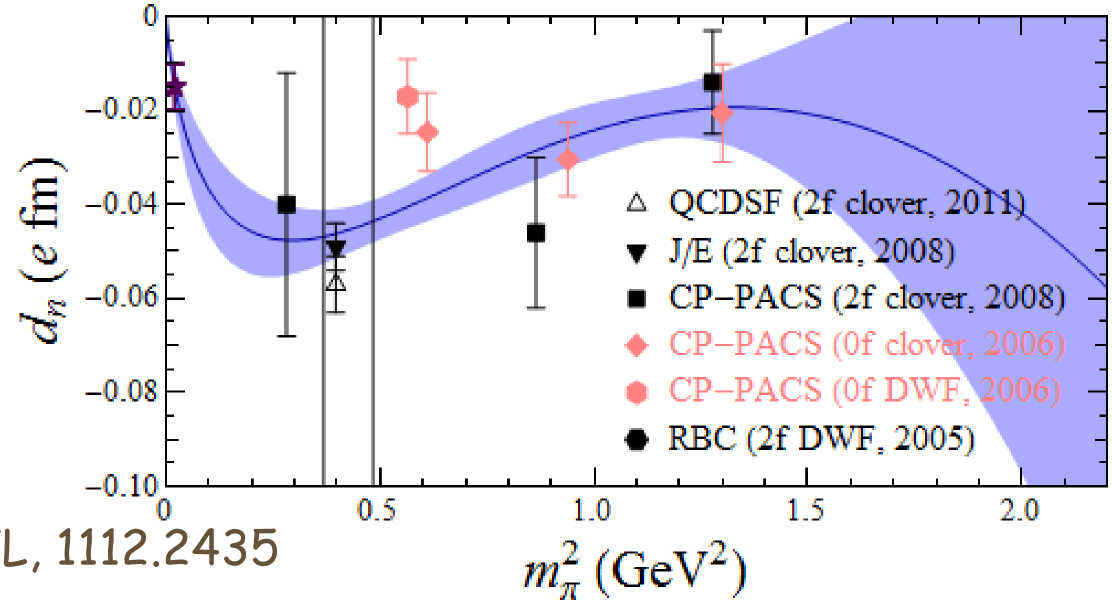
§ Leading contribution

- Nucleon EM form factor $eF_3(0)/2M_N$ RBC, J/E, CP-PACS(2005), …
  E. Shintani (Improved algorithm to increase statistics)
- Energy shift in nucleon mass with external $\vec{E}$ CP-PACS(2006, 2010),
- Calculate $\tan[2\alpha(\theta)]\,F_2(0)$ QCDSF(2011), …

$nEDM$

- Lagrangian $\mathcal{S} = \mathcal{S}_{\text{QCD}}^{\text{CP Even}} - i\,\Theta\,\frac{g^2}{16\,\pi^2}\int d^4x\, G^{\mu\nu}\,\tilde{G}_{\mu\nu}$

- Leading contribution



HWL, 1112.2435

Chiral extrapolation
K. Ottnad et al., 2010

−0.015(5) θ e·fm

- Plenty of room to make improvement

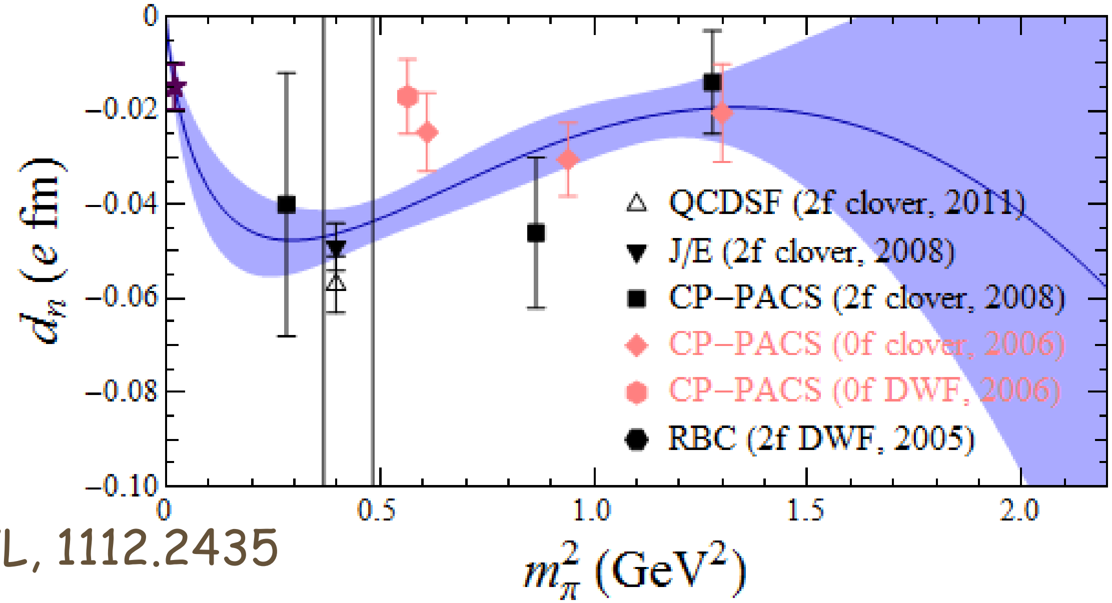
nEDM

§ Lagrangian $\mathcal{S} = \mathcal{S}_{\rm QCD}^{\rm CP\ Even} - i\,\Theta\,\frac{g^2}{16\,\pi^2}\int d^4x\, G^{\mu\nu}\,\tilde{G}_{\mu\nu} +$

$$\frac{i\,e\,d_u^\gamma}{\Lambda_{\rm BSM}^2}\,\overline{Q}\,\sigma_{\mu\nu}\,\gamma_5\,F^{\mu\nu}\,\tilde{H}\,U + \frac{i\,e\,d_d^\gamma}{\Lambda_{\rm BSM}^2}\,\overline{Q}\,\sigma_{\mu\nu}\,\gamma_5\,F^{\mu\nu}\,H\,D +$$

$$\frac{i\,g_3\,d_u^G}{\Lambda_{\rm BSM}^2}\,\overline{Q}\,\sigma_{\mu\nu}\,\gamma_5\,\lambda^A\,G^{\mu\nu\,A}\,\tilde{H}\,U + \frac{i\,g_3\,d_d^G}{\Lambda_{\rm BSM}^2}\,\overline{Q}\,\sigma_{\mu\nu}\,\gamma_5\,\lambda^A\,G^{\mu\nu\,A}\,H\,D$$

§ Leading contribution



HWL, 1112.2435

§ Higher-order operators

T. Bhattacharya (this conference)

Effective field theory and proposed LQCD calculations

BSM Interactions

§ Neutron beta decay could be related to new interactions: the scalar and tensor

R. Gupta (PNDME), Tue.

$$H_{\text{eff}} = G_F \left(J^{\text{lept}}_{V-A} \times J^{\text{quark}}_{V-A} + \sum_i \varepsilon_i^{\text{BSM}} \hat{O}_i^{\text{lept}} \times \hat{O}_i^{\text{quark}} \right)$$

$$\hat{O}_S = \overline{u}d \times \overline{e}(1-\gamma_5)\nu_e \quad \rightarrow \quad g_S = \langle n|\overline{u}d|p\rangle$$

$$\hat{O}_T = \overline{u}\sigma_{\mu\nu}d \times \overline{e}\sigma^{\mu\nu}(1-\gamma_5)\nu_e \quad \rightarrow \quad g_T = \langle n|\overline{u}\sigma_{\mu\nu}d|p\rangle$$

- ε_S and ε_T are related to the masses of the new TeV-scale particles
- … but the unknown coupling constants $g_{S,T}$ are needed

§ Given precision $g_{S,T}$ and O_{BSM}, predict new-physics scales

Experiment → $\boxed{O_{\text{BSM}} = f_O(\varepsilon_{S,T}\, g_{S,T})}$ ← Precision LQCD input ($m_\pi \approx 140$ MeV, $a \rightarrow 0$)

$$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$$

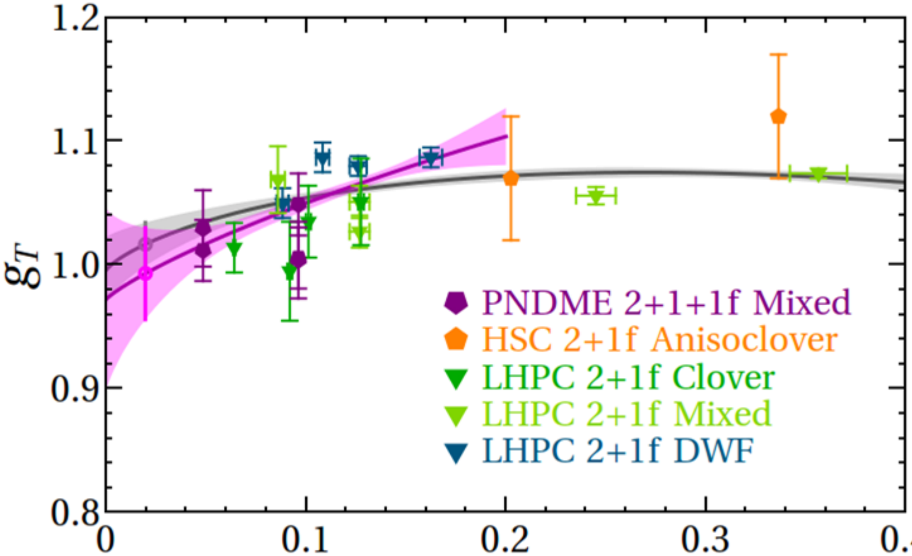
Tensor and Scalar Charges

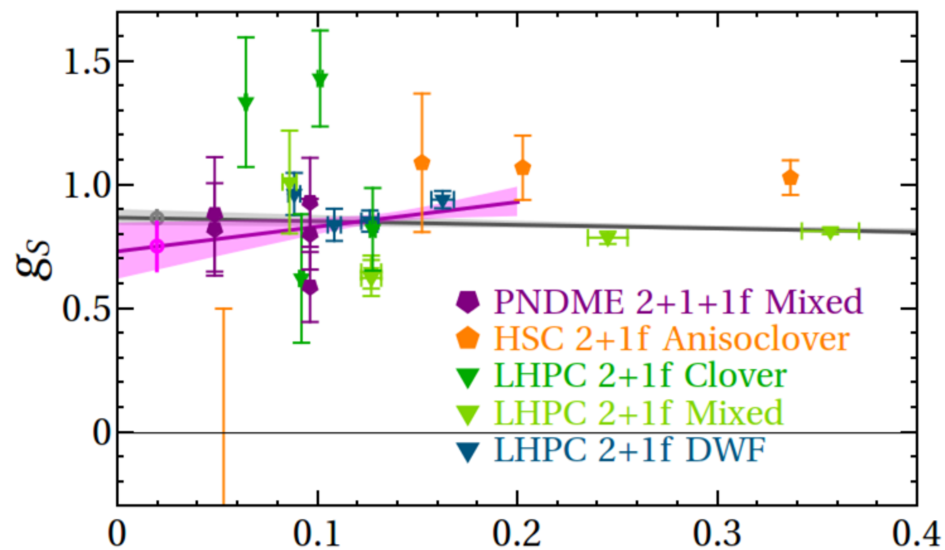
§ Tensor charge: the zeroth moment of the transversity

$$g_T = \delta u - \delta d$$

- Experimentally, probed through SIDIS: $g_T(Q^2{=}0.8\ \mathrm{GeV}^2) = 0.77^{+0.18}_{-0.24}$
- Model estimate: 0.8(4)

§ Scalar charge $\langle n|\bar{u}d|p\rangle$ Prior model estimate: $1 \gtrsim g_S \gtrsim 0.25$



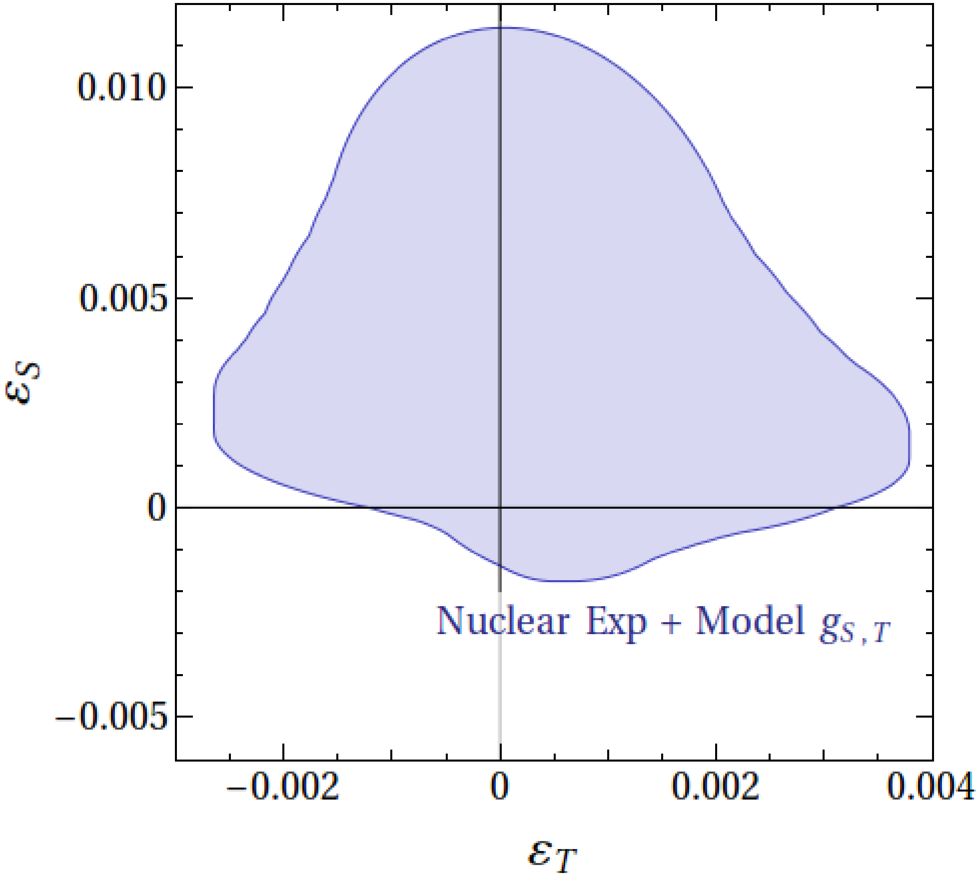


$g_T^{\mathrm{LQCD}} = 0.988(42)(?)$ $m_\pi^2\ (\mathrm{GeV}^2)$ $g_S^{\mathrm{LQCD}} = 0.761(88)(?)$

Combined with Experiments

§ Given precision $g_{S,T}$ and O_{BSM}, predict new-physics scales

Nuclear Exp. → $\boxed{O_{\mathrm{BSM}} = f_O(\varepsilon_{S,T}\, g_{S,T})}$ ← Model input



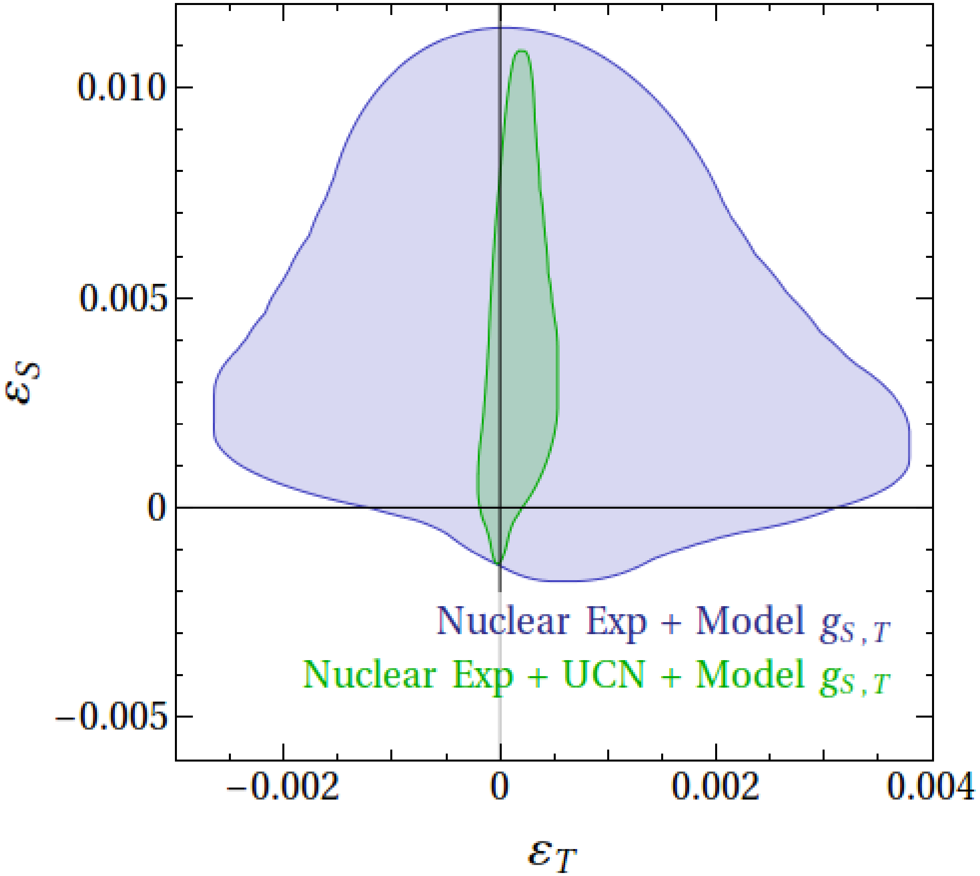
$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$

- Nuclear beta decays
  - $0^+ \longrightarrow 0^+$ transitions
  - β asym in Gamow-Teller ^{60}Co
  - polarization ratio between Fermi and GT in ^{114}In
  - positron polarization in polarized ^{107}In
  - β-ν correlation parameter a

Combined with Experiments

§ Given precision $g_{S,T}$ and O_{BSM}, predict new-physics scales

New UCN Exp. → $\boxed{O_{\mathrm{BSM}} = f_O(\varepsilon_{S,T}\, g_{S,T})}$ ← Model input



$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$

LANL UCN neutron decay exp't

$$d\Gamma \propto F(E_e)\left[1 + \boxed{b\frac{m_e}{E_e}} + \left(B_0 + \boxed{B_1\frac{m_e}{E_e}}\right)\frac{\vec{\sigma}_n \cdot \vec{p}_\nu}{E_\nu} + \cdots\right]$$

Expect by 2013:

$|B_1 - b|_{\mathrm{BSM}} < 10^{-3}$

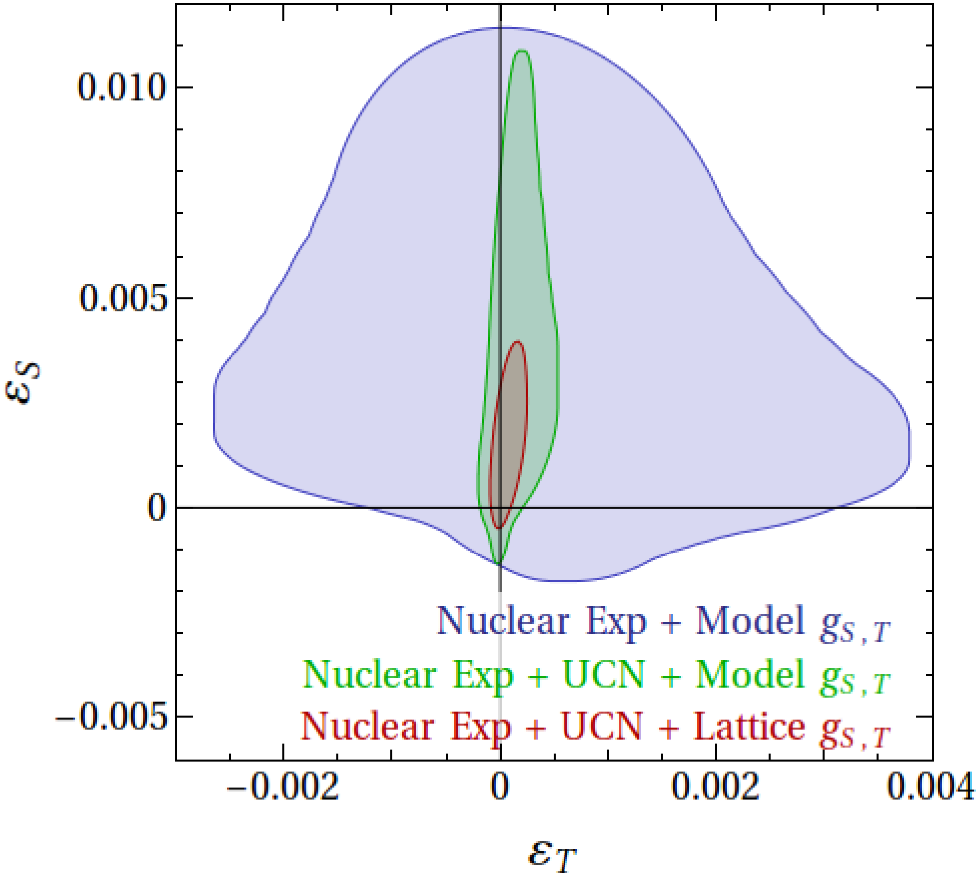
$|b|_{\mathrm{BSM}} < 10^{-3}$

Similar proposal at ORNL by 2015

Combined with Experiments

§ Given precision $g_{S,T}$ and $O_{\rm BSM}$, predict new-physics scales

New UCN Exp. → $O_{\rm BSM} = f_O(\varepsilon_{S,T}\, g_{S,T})$ ← Precision LQCD input ($m_\pi \to 140$ MeV, $a \to 0$)



$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$

LANL UCN neutron decay exp't

$$d\Gamma \propto F(E_e)\left[1 + \boxed{b\frac{m_e}{E_e}} + \left(B_0 + \boxed{B_1\frac{m_e}{E_e}}\right)\frac{\vec{\sigma}_n\cdot\vec{p}_\nu}{E_\nu} + \cdots\right]$$

Expect by 2013:

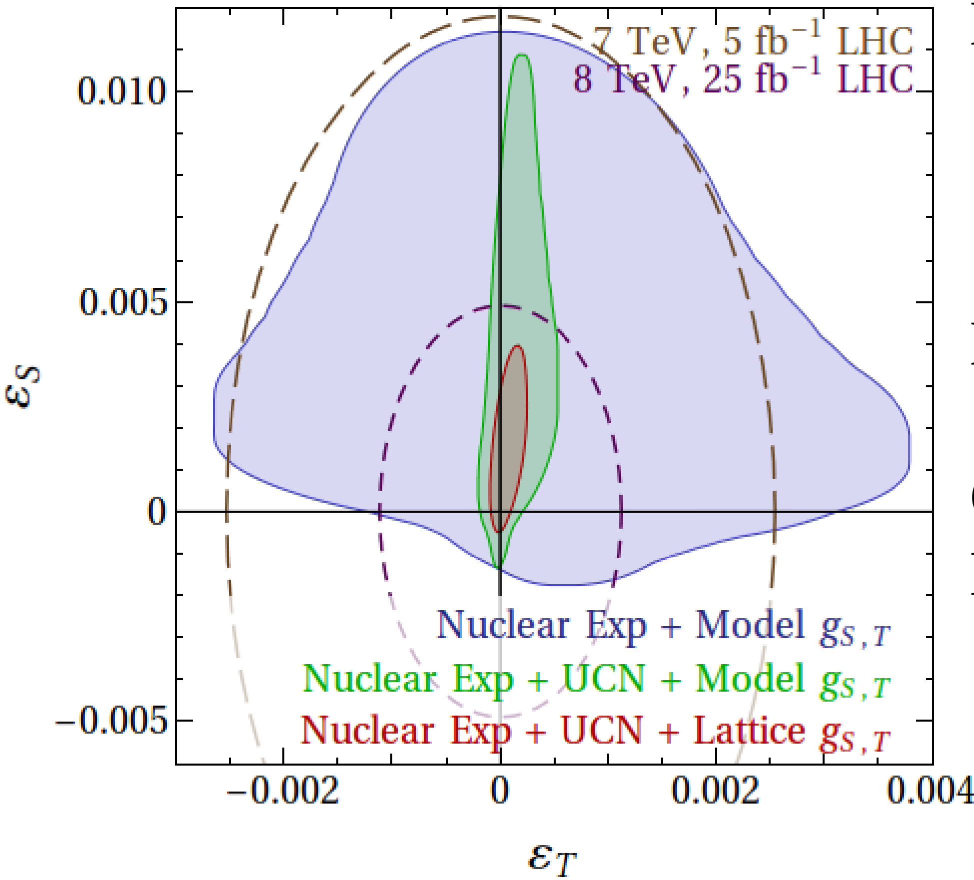
$$|B_1 - b|_{\rm BSM} < 10^{-3}$$
$$|b|_{\rm BSM} < 10^{-3}$$

Similar proposal at ORNL by 2015

High-Energy Constraints

§ Constraints from high-energy experiments?

LHC current bounds and near-term expectation



Estimated though effective L

$$\mathcal{L} = -\frac{\eta_S}{\Lambda_S^2} V_{ud}(\overline{u}d)(\overline{e}P_L\nu_e) - \frac{\eta_T}{\Lambda_T^2} V_{ud}(\overline{u}\sigma^{\mu\nu}P_L d)(\overline{e}\sigma_{\mu\nu}P_L\nu_e)$$

Looking at high transverse mass in $e\,\nu + X$ channel

Compare with W background

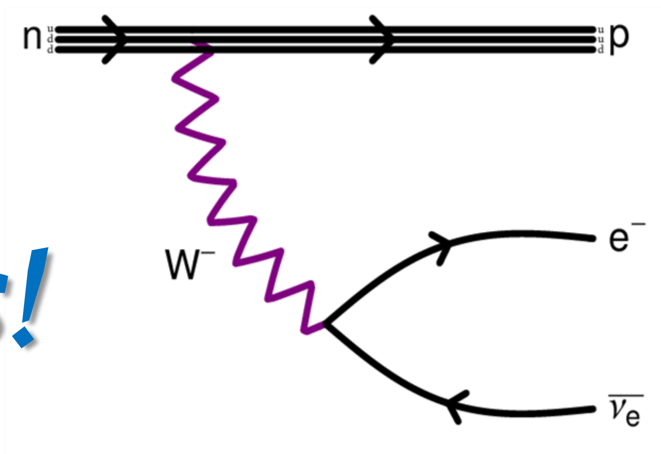
Estimated 90% C.L. constraints on

$$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$$

HWL, 1112.2435; 1109.2542

T. Bhattacharya et al, 1110.6448

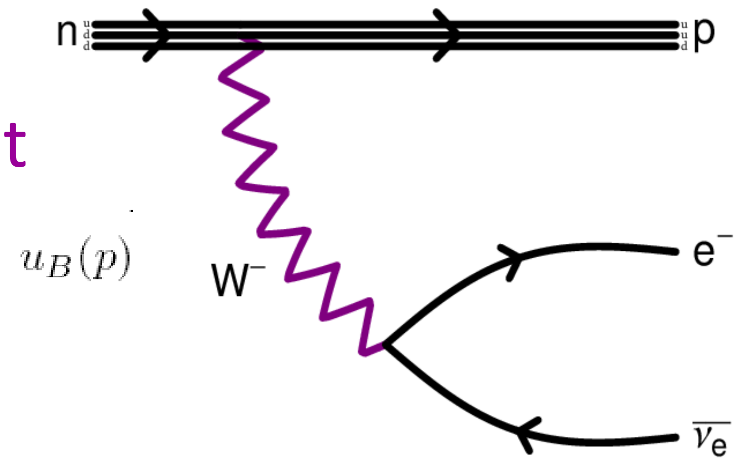
g_A Crisis!

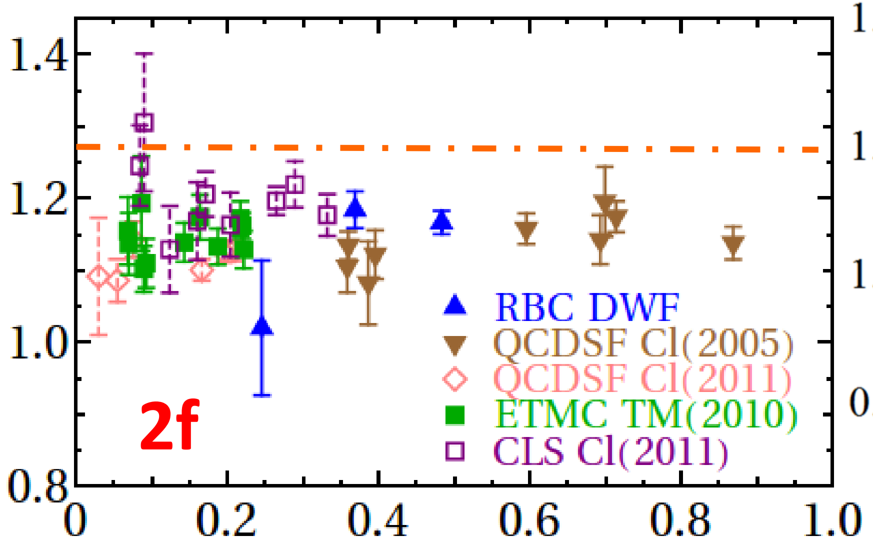


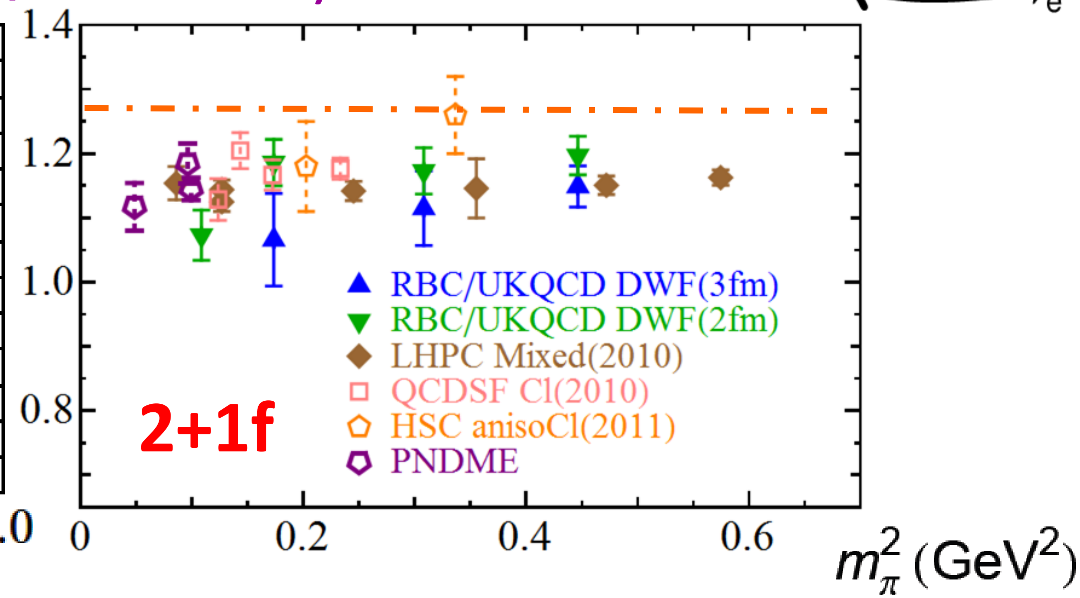
The ugly: when should we panic about it?

Nucleon Axial Charge

- A fundamental measure of nucleon structure
- Important to the rate of *pp* fusion
- Axial-vector–current matrix element
  and $g_A = G_A^{u-d}(Q^2{=}0)$
- Benchmark for nucleon structure
- Survey of lattice studies (2011 Nov)





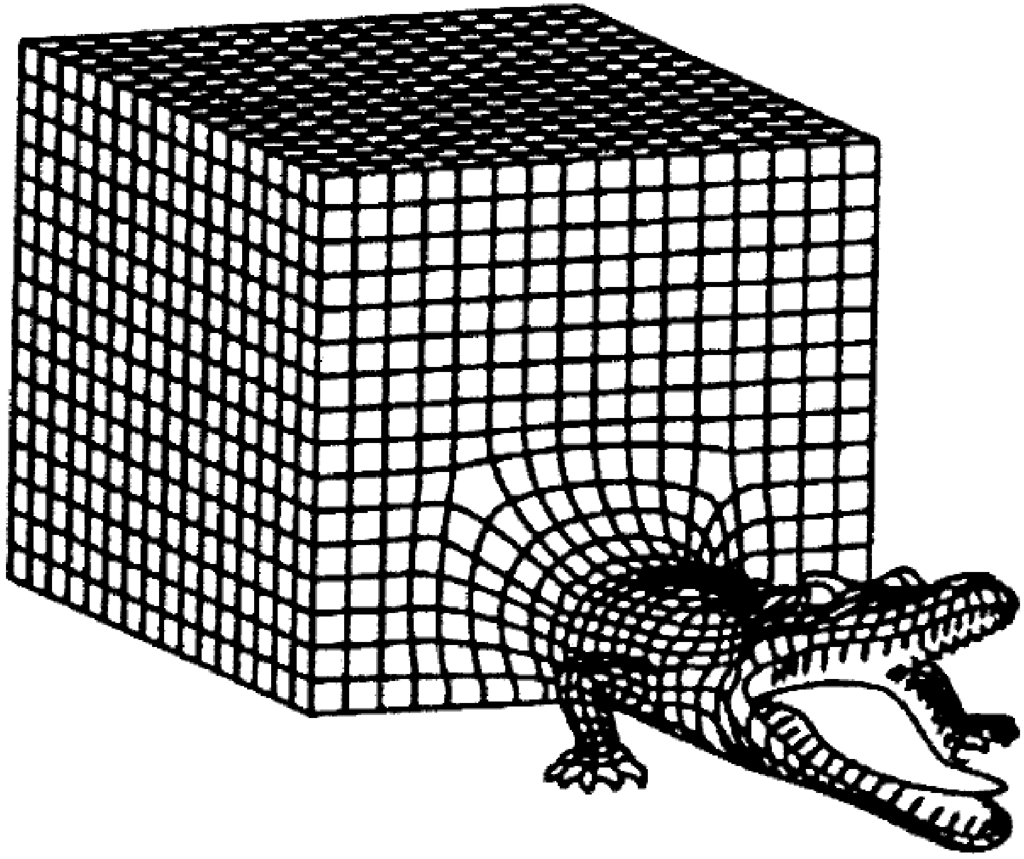


What's the Deal with g_A?

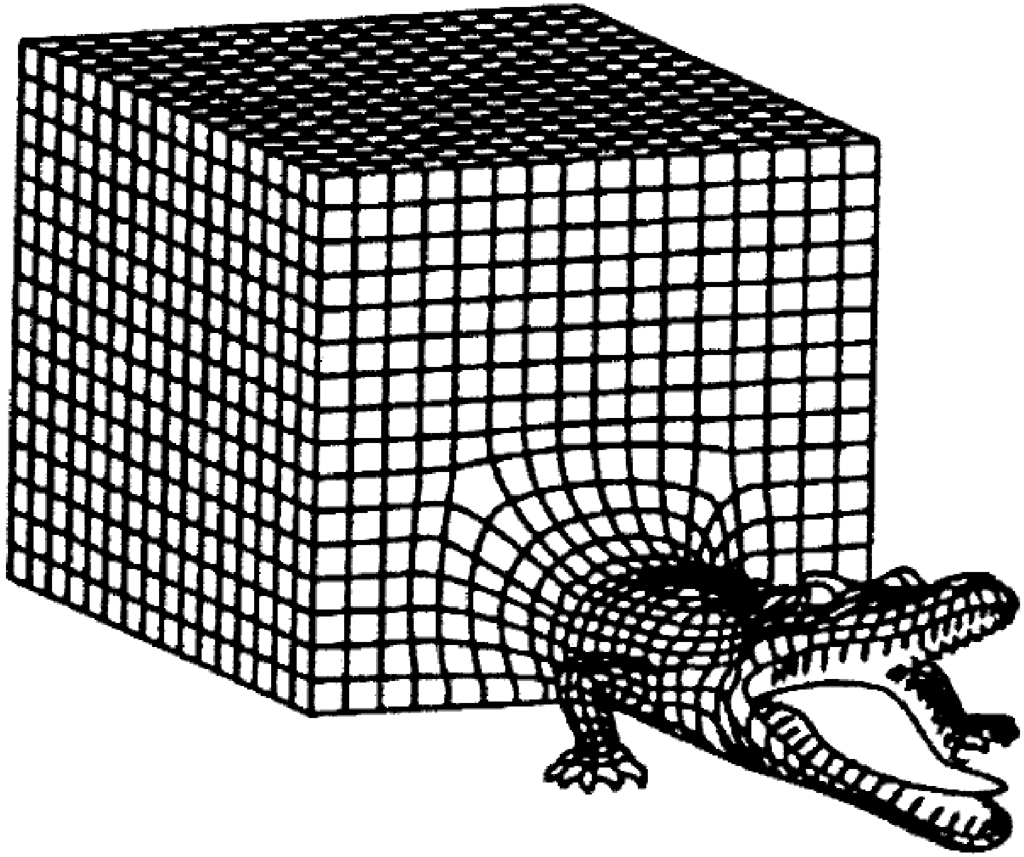
§ No longer gold-plated?

"Welcome to the lattice and its dangerous animals."

Karl Jansen



PROCEED WITH CAUTION



- § Re-examine all the systematics

The Trouble with Nucleons

Nucleons are more complicated than mesons because…

- Noise issue
  - Large t_{sep} loses signal
- Excited-state contamination
  - Nearby excited-state Roper(1440)
- Hard to extrapolate
  - Δ resonance nearby; multiple expansions, poor convergence…
  - May not be an issue in the physical pion-mass era
- Requires large volume and statistics
  - Ensembles are not always generated with nucleons in mind

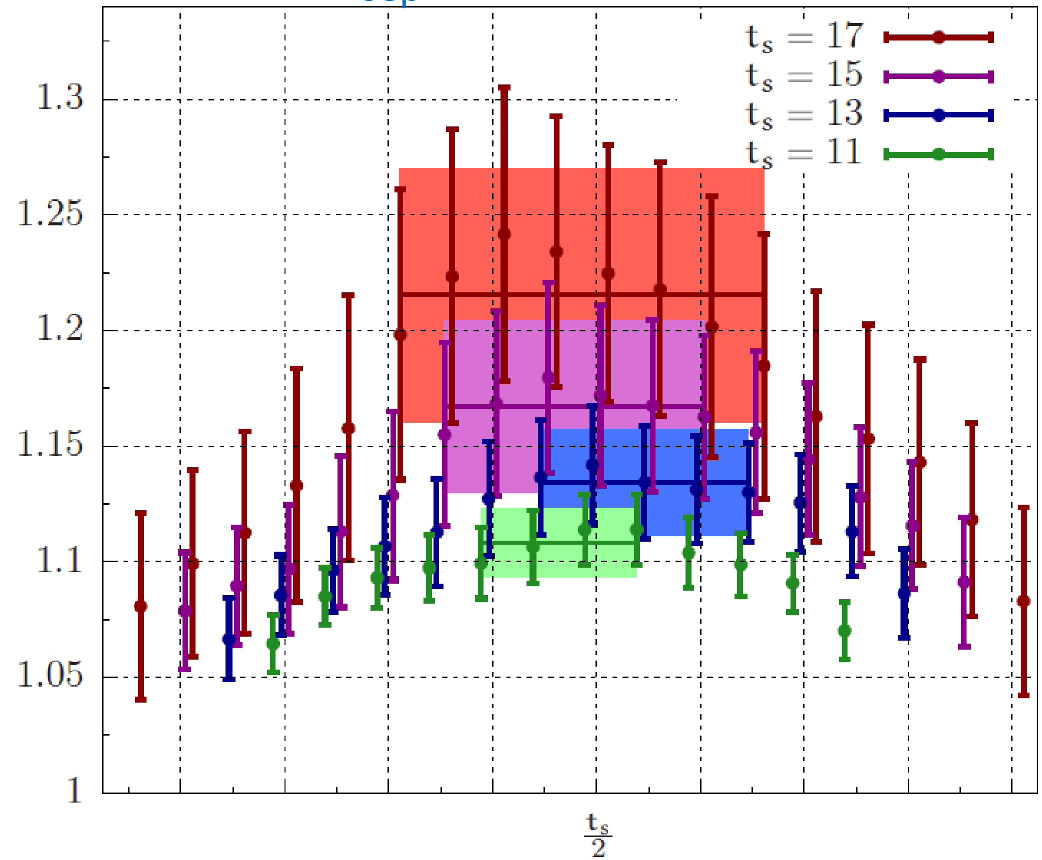
Excited-State Contamination

§ Trade off: signal-to-noise versus contamination

- Noise issue (P. Lepage; D. Kaplan 2011)
- For example, CLS/Mainz
  2f NP clover,
  $M_\pi \approx 320$ MeV
  $a \approx 0.063$ fm
  Fix $N_{\text{meas}} = 200$

1205.0180 &
private communication

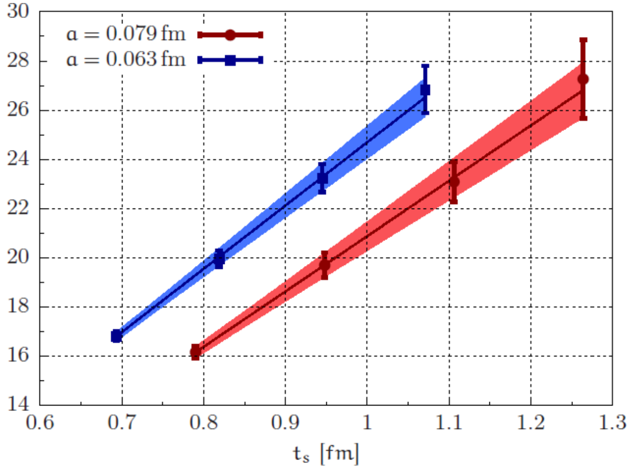
t_{sep} 0.69–1.07 fm



Excited-State Contamination

- § Trade off: signal-to-noise versus contamination
  - Noise issue (P. Lepage; D. Kaplan 2011)
- § Options
  - Stay at large t_{sink}: RBC/UKQCD (need to check smaller pion mass)
  - Include excited-state degrees of freedom
    - Multistate fitting or variational method from 3pt correlator matrix
    - HWL (Lat 2008); ETMC/LHPC/Mainz-CLS (2011); CSSM 2012 (mesons)
  - Extend to small t_{sink} to pick up better signal and apply "summation" method

$$S(t_s) := \sum_{t=0}^{t_s} R(t, t_s) \xrightarrow{t_s \gg 0} c + t_s \left\{ g_A^{\text{bare}} + \mathrm{O}(e^{-\Delta t_s}) \right\}$$

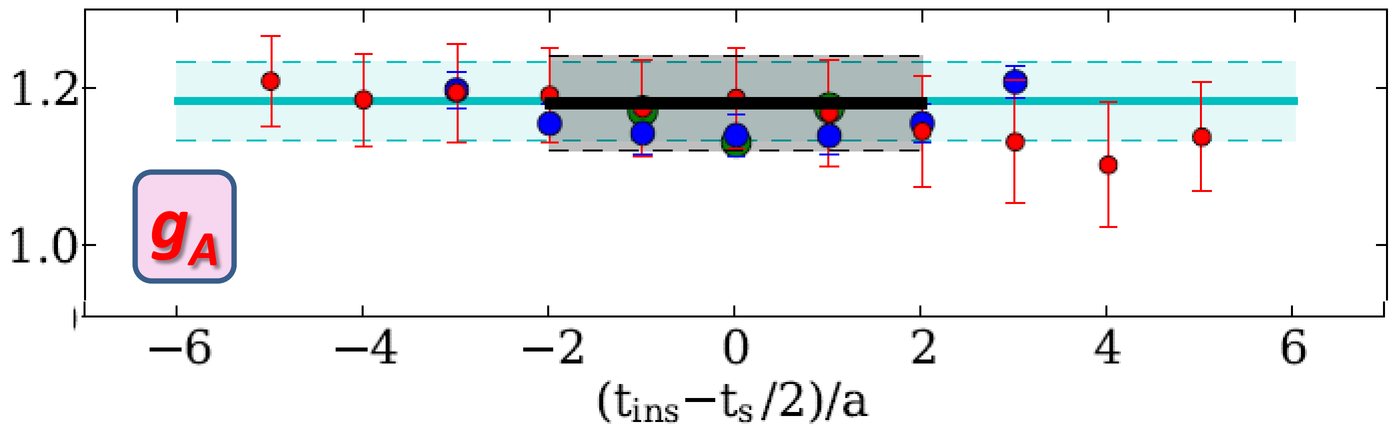


- g_A obtained from slope

Excited-State Contamination

§ ETMC C. Alexandrou et al. & private communication

- 2+1+1f, $M_\pi \approx 380$ MeV, APE + Gaussian
  increase $N_{\rm meas}$ to O(3000) at largest $t_{\rm sep}$,
- No effect due to $t_{\rm sep}$ from 0.31–1.01 fm
- Summation [5,13] is consistent with $t = 12a$ plateau fit



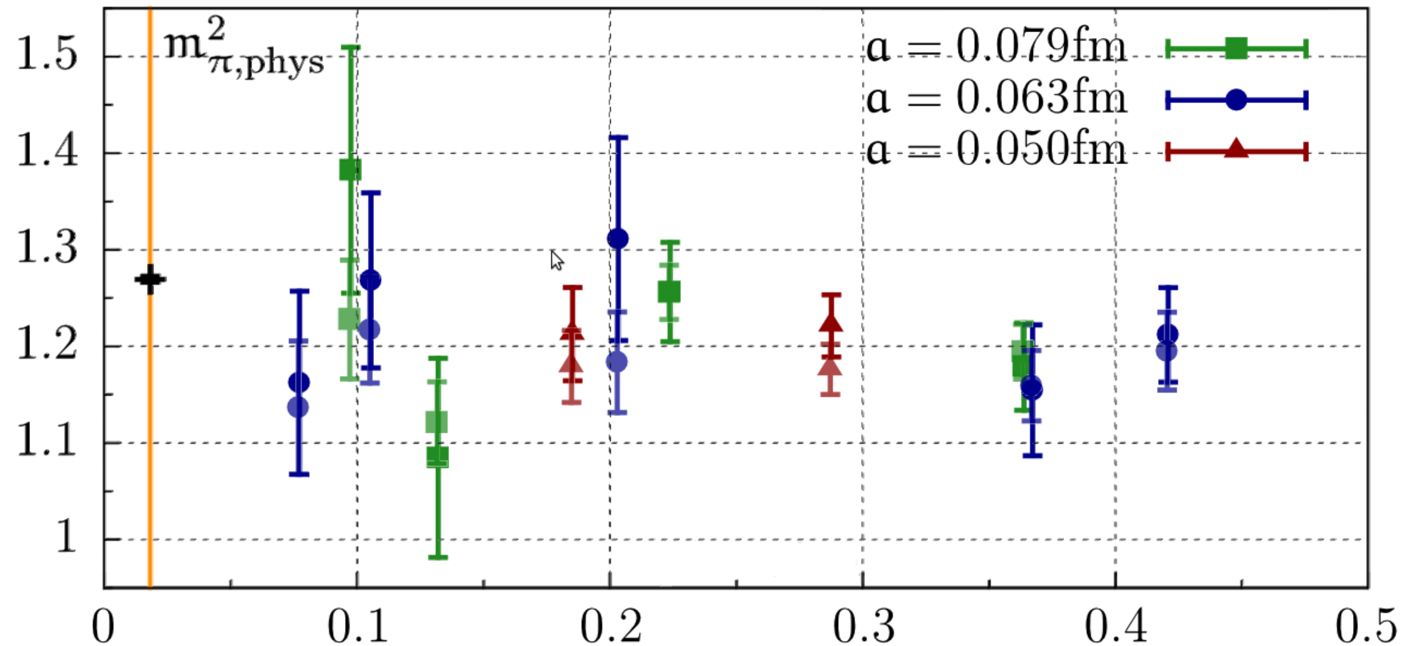
§ 0.31 fm, really? Would be interested to see other works

§ Check on lighter pion mass

Excited-State Contamination

§ CLS/Mainz S. Capitani et al. 1205.0180

- 2f, NP Clover ("summation" vs "plateau" t_{sep} =1.1 fm)



§ LHPC (J. Green):

consistent results using largest t_{sep} and summation

§ My two cents: Not clearly superior

Excited-State Contamination

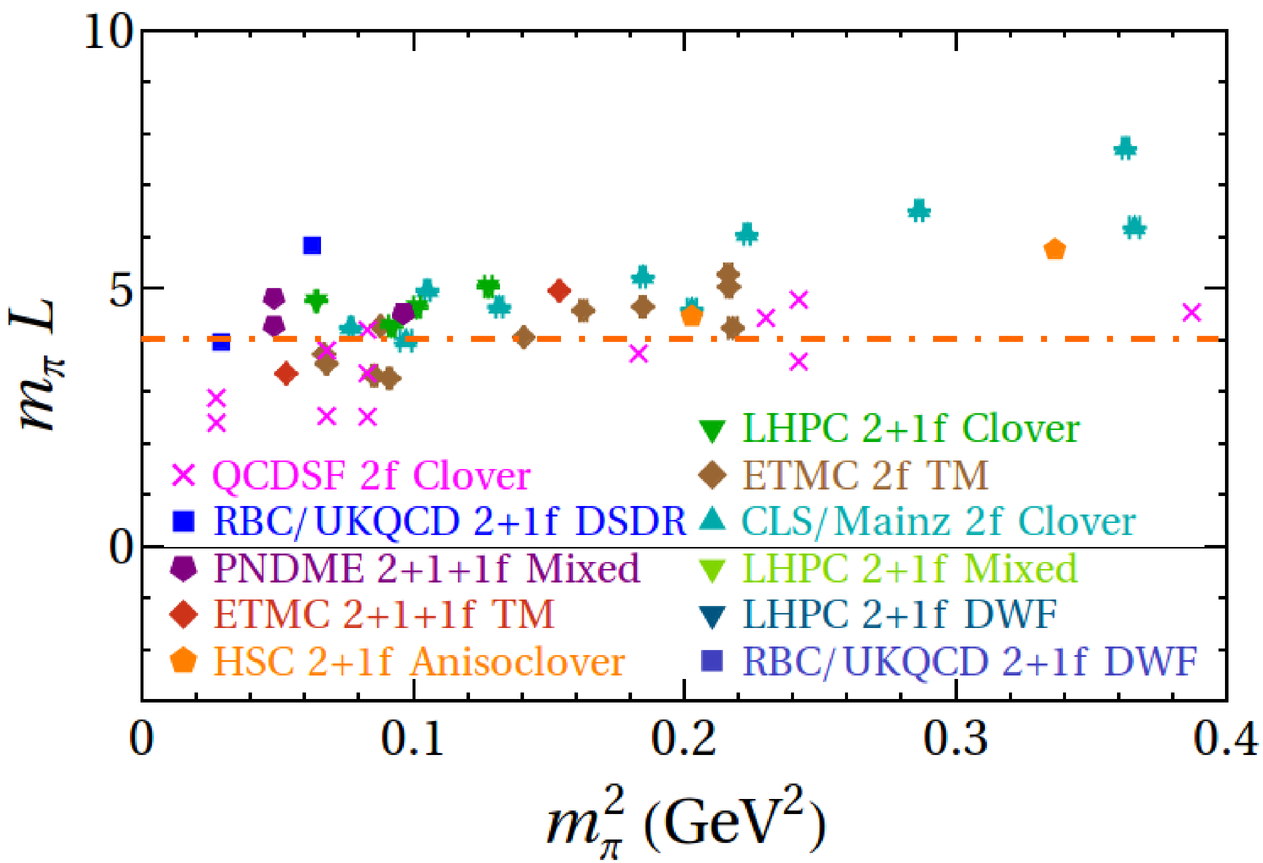
Including excited-states in the analysis is the way to go

- HWL (2008): simultaneous fit and 3pt correlator matrix
- PNDME — R. Gupta (Tuesday)
  - 2+1+1f, clover/HISQ; $t_{\mathrm{sep}} = 0.96$–1.44 fm
  - Sim. fit gives consistent results with largest t_{sep} at each ensemble
  - Will be more aggressive to try our smaller t_{sep}
- ETMC: variational method
  - 2f, 300 MeV pion, $t_{\mathrm{sep}} = 1.07$ fm
- CSSM: successful in meson cases — B. Owen (Wednesday)
  nucleon next

May still have an optimal t_{sep} but won't lose as much signal

Finite-Volume Effects

§ How big $M_\pi L$ is required?

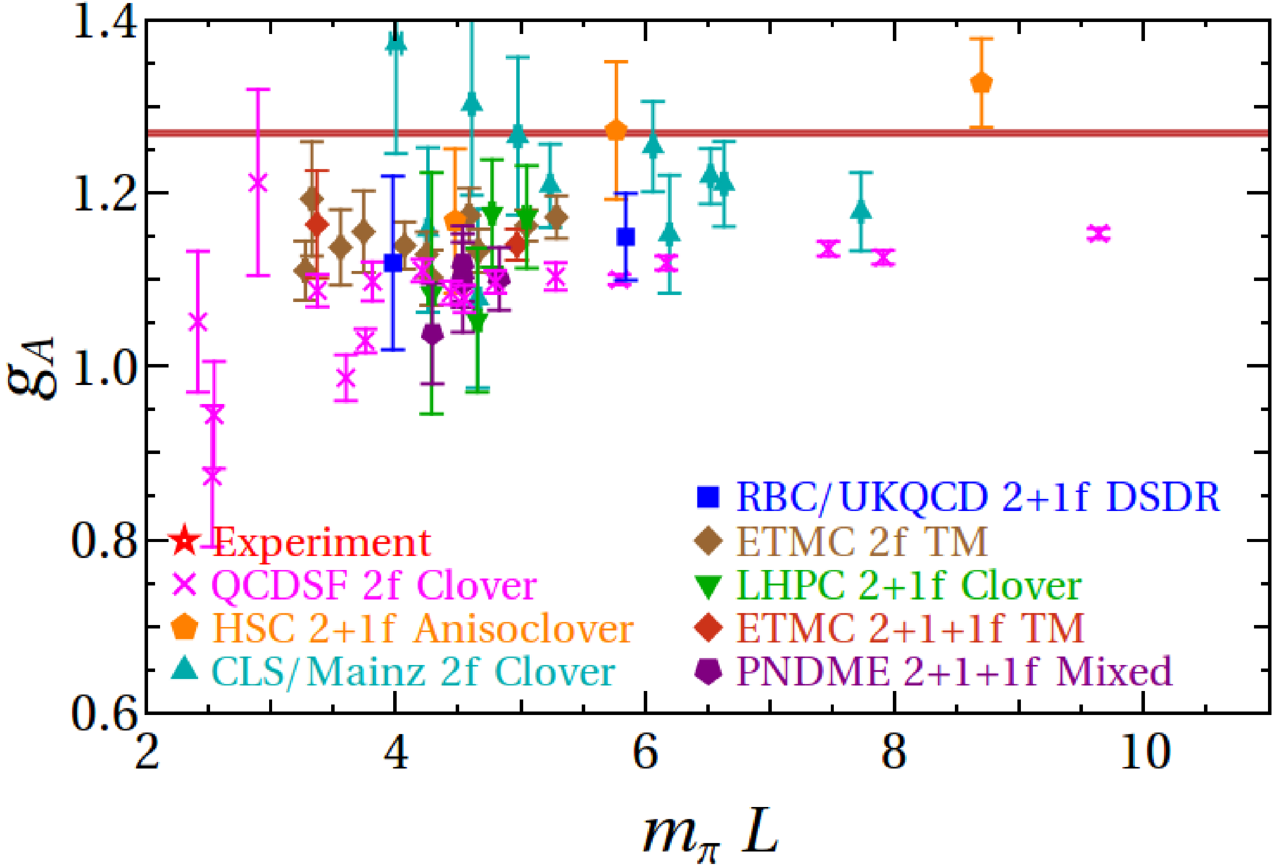


Finite-Volume Effects

§ How big $M_\pi L$ is required?

§ ChPT volume correction/used to estimate systematics

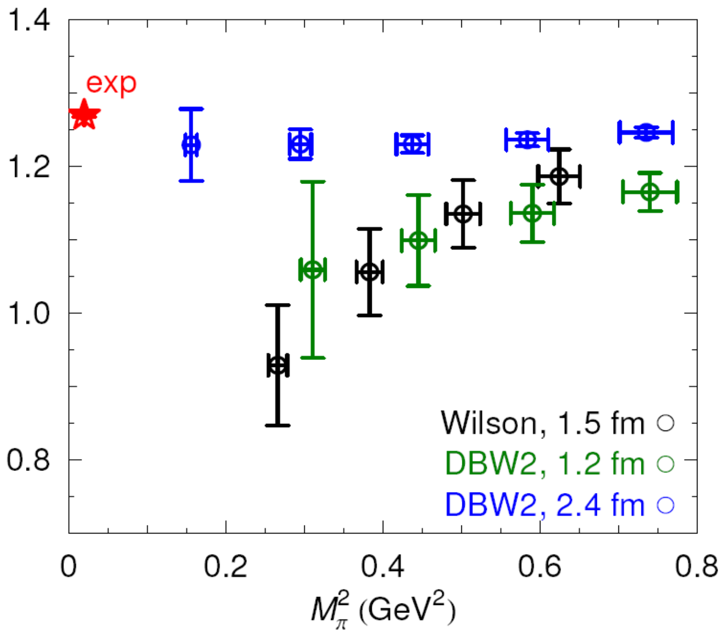
- ETMC, QCDSF, CLS/Mainz: possibly underestimated?



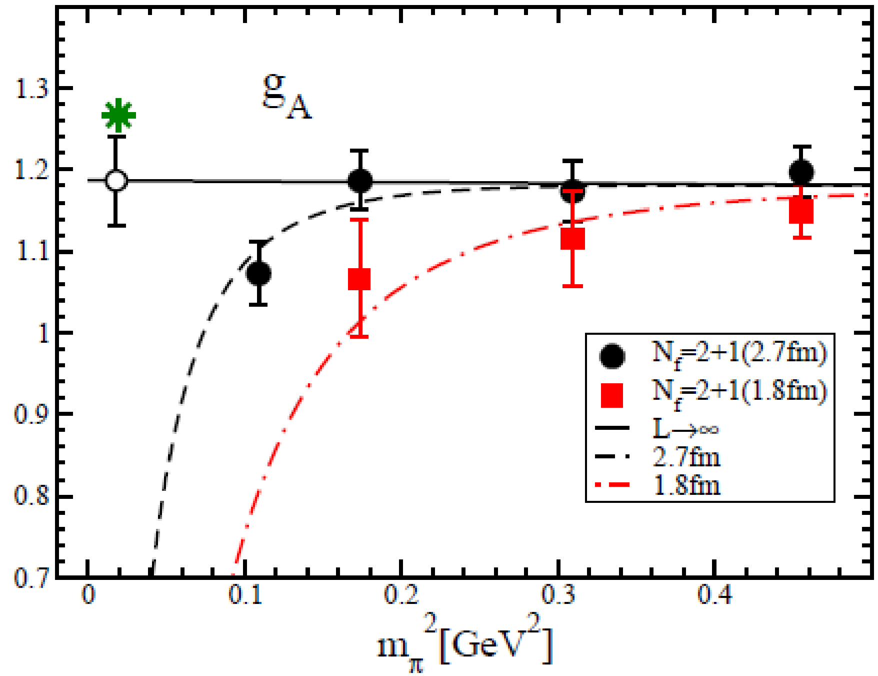
Finite-Volume Effects

- How big $M_\pi L$ is required?
- ChPT volume correction/used to estimate systematics
  - ETMC, QCDSF, CLS/Mainz: possibly underestimated?
- Example study (RBC/UKQCD)

$$A + B m_\pi^2 + C f_V(m_\pi L)$$



RBC, Phys.Rev.D68:054509 (2003)



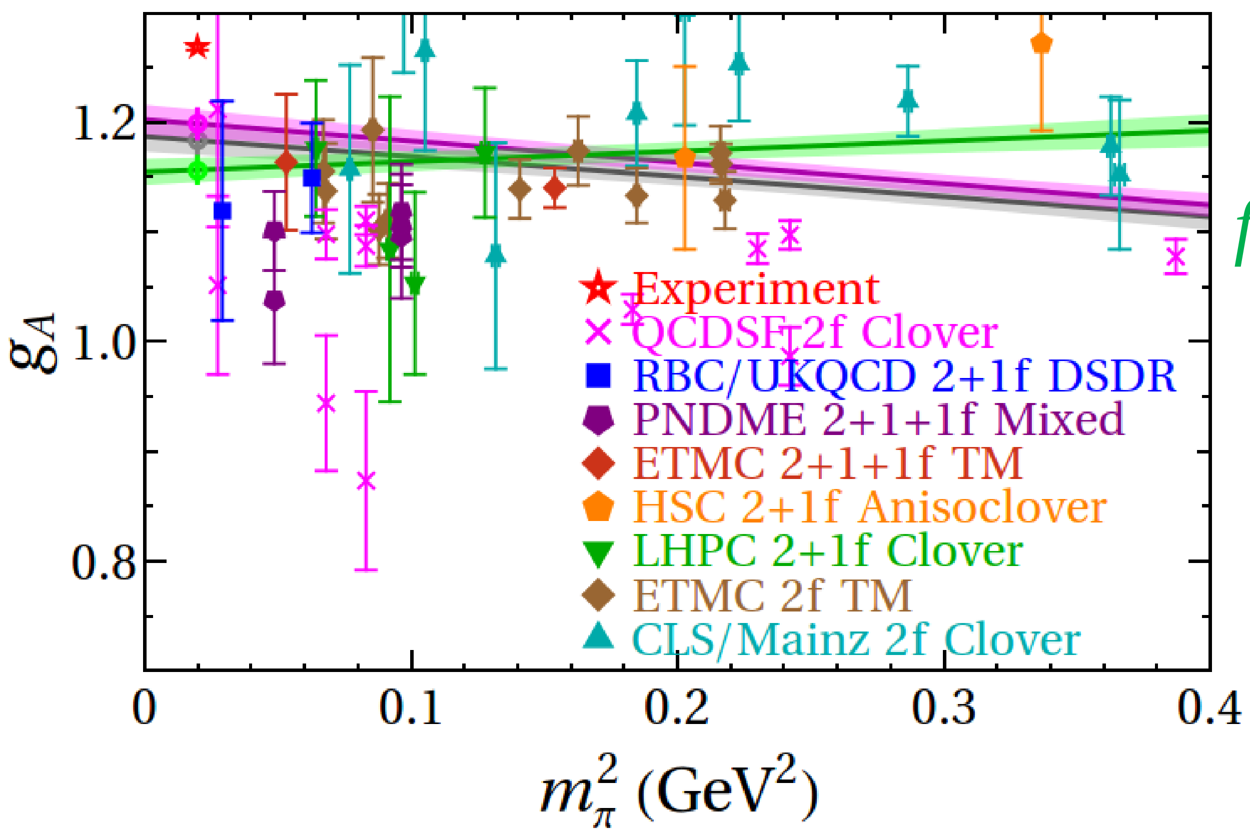
RBC/UKQCD, Phys. Rev. Lett. 100:171602 (2008)

Finite-Volume Effects

- How big $M_\pi L$ is required?
- How global data changes with a cut

$A + B m_\pi^2 + C f_V(m_\pi L)$

No cut



$f_V \sim e^{-m_\pi L}$

$f_V \sim (m_\pi L)^{-3}$

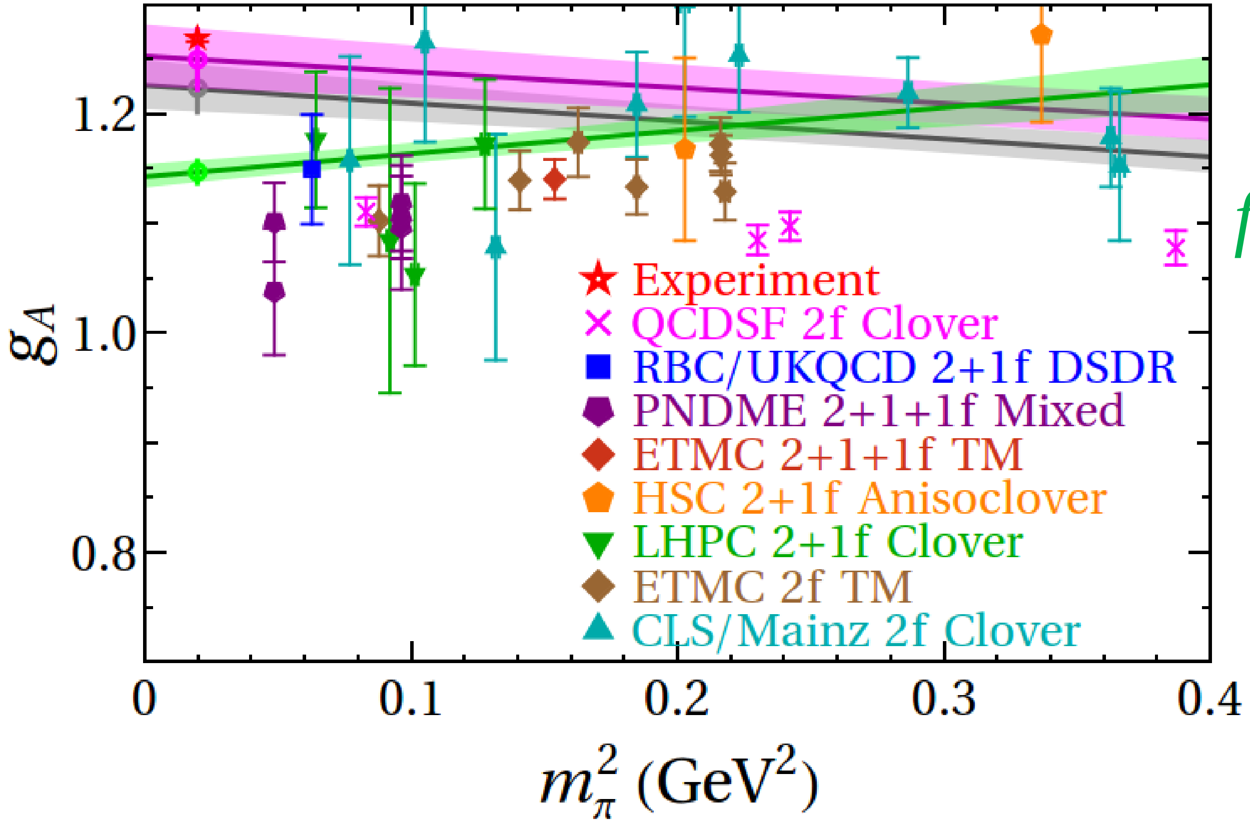
$f_V \sim m_\pi^2 e^{-m_\pi L} (m_\pi L)^{-0.5}$

Finite-Volume Effects

- How big $M_\pi L$ is required?
- How global data changes with a cut

$$A + B\,m_\pi^2 + C\,f_V(m_\pi L)$$

Cut by $m_\pi L > 4$



$f_V \sim e^{-m_\pi L}$

$f_V \sim (m_\pi L)^{-3}$

$f_V \sim m_\pi^2\, e^{-m_\pi L} (m_\pi L)^{-0.5}$

Finite-Volume Effects

- How big $M_\pi L$ is required?
- How global data changes with a cut

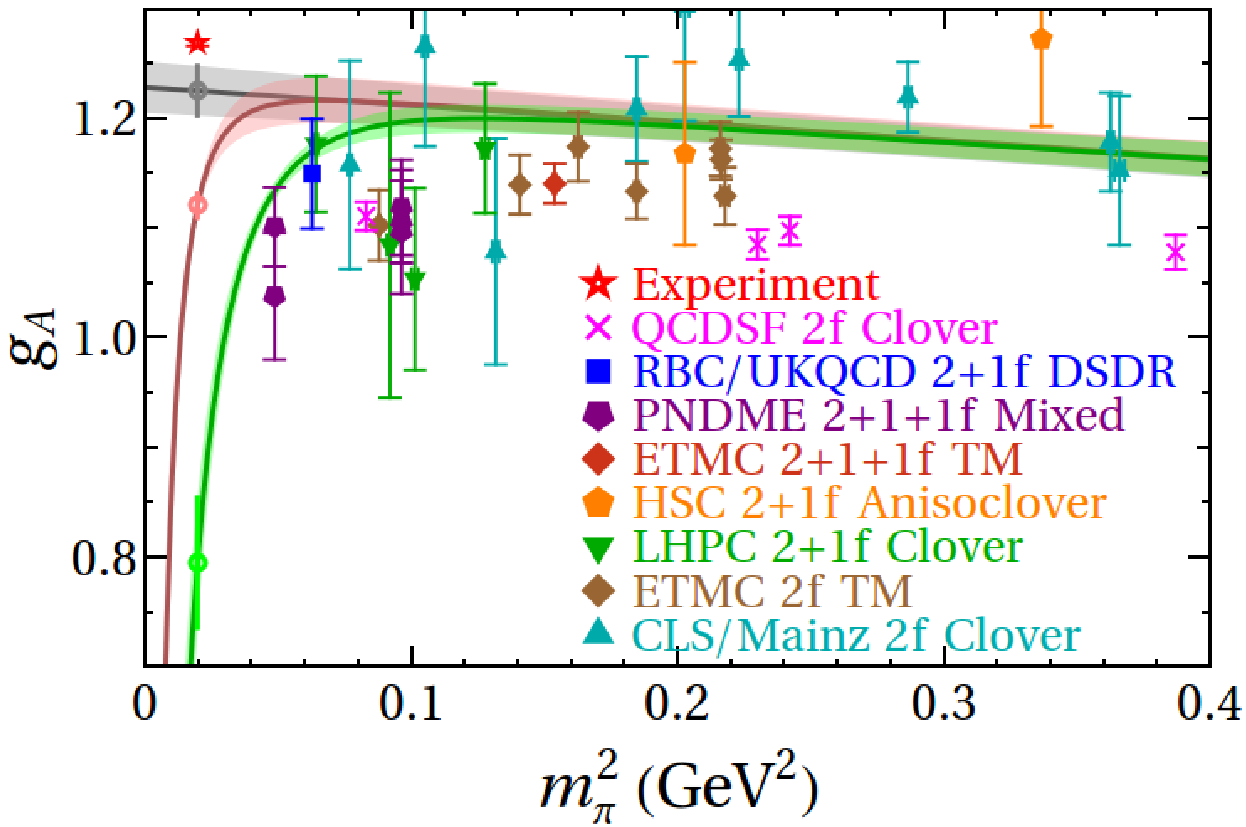
$A + B\, m_\pi^2 + C\, f_V(m_\pi L)$

$f_V \sim e^{-m_\pi L}$

6-fm box

4-fm box

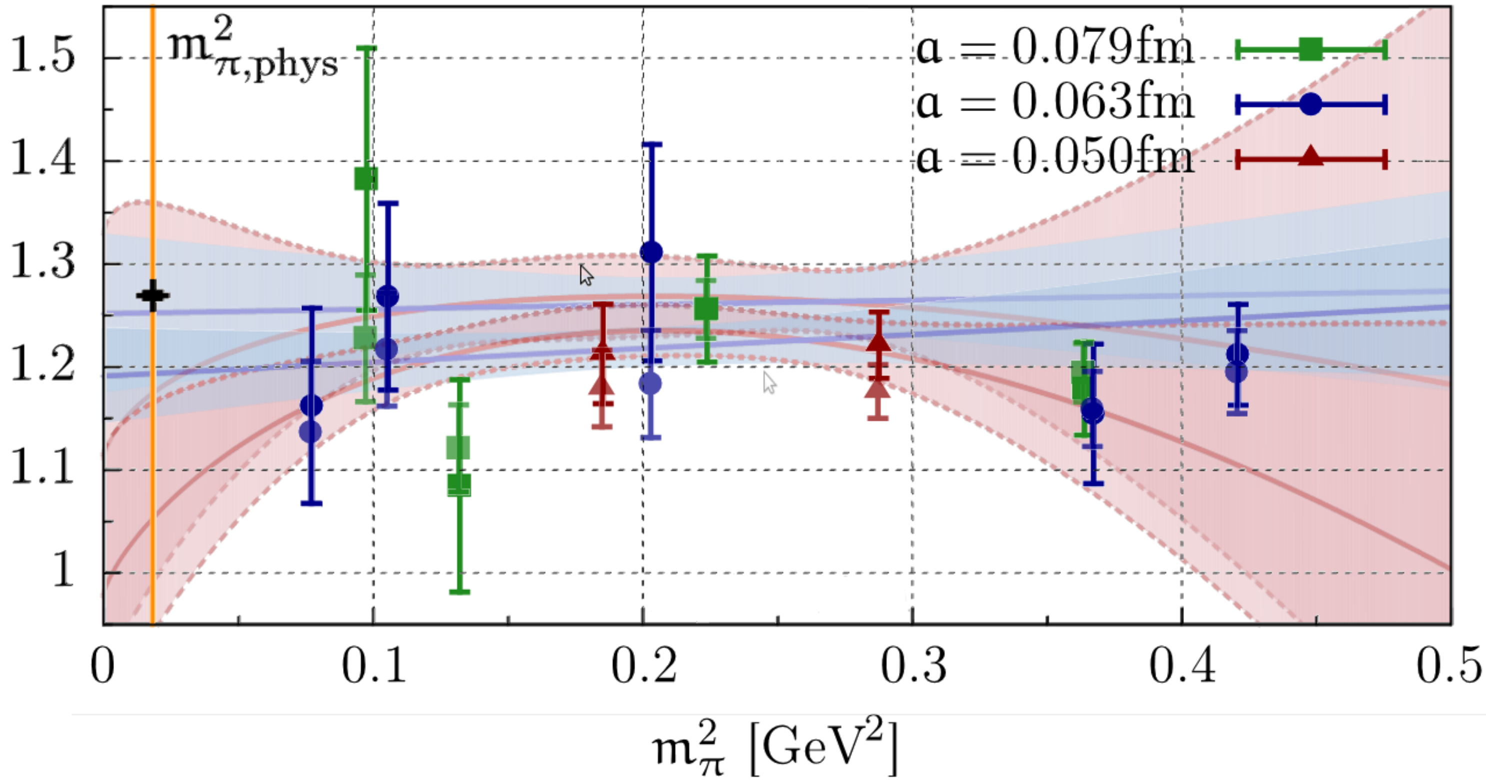
Cut by $m_\pi L > 4$



Chiral Extrapolation

§ Small shift matters?

CLS/Mainz, 1205.0180



§ Blind analysis?

§ More precise studies are needed

Systematics

- Answers?
  - I have more questions than when I started the review:

    Q: Is large t_{sep} needed for summation method?

    Do we gain anything? ETMC: "no", CLS/Mainz: "yes"

    Q: Can we get reliable ground-state signal from small t_{sep}?

    Current excited-state analysis (PNDME/LHPC) performed at larger t_{sep}, O(1) fm and larger errorbar too big to tell
- More VM basis analyses (all-to-all, AMA)
- High-statistics studies are needed!
- Disappointment?
  - Certainly not.

    We are just entering into the precision era to explore these issues…
- Difficulties = opportunities
- Affects the whole community! When we fail at g_A...

Summary

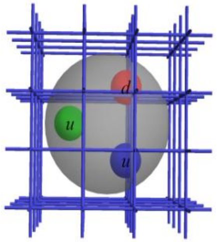
Exciting time to explore

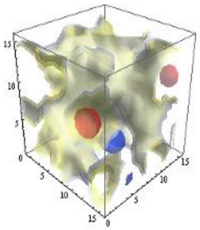
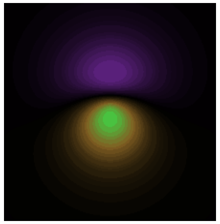
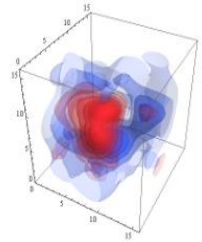
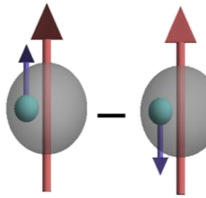
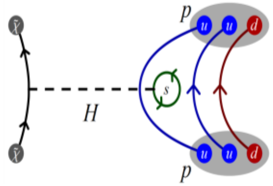
§ LQCD is building a picture of hadrons

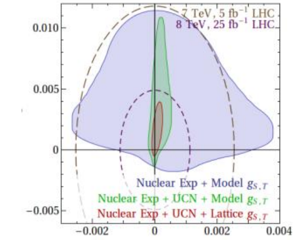
- Revealed proton spin components, hadron impact-space distribution
- New techniques for gluonic, disconnected and in-medium quantities shine new light for more calculations

§ Application of LQCD input to probe BSM

- Opportunities combining high- (TeV) and low- (GeV) energies
- Vital input when experiment is limited (e.g. g_S)



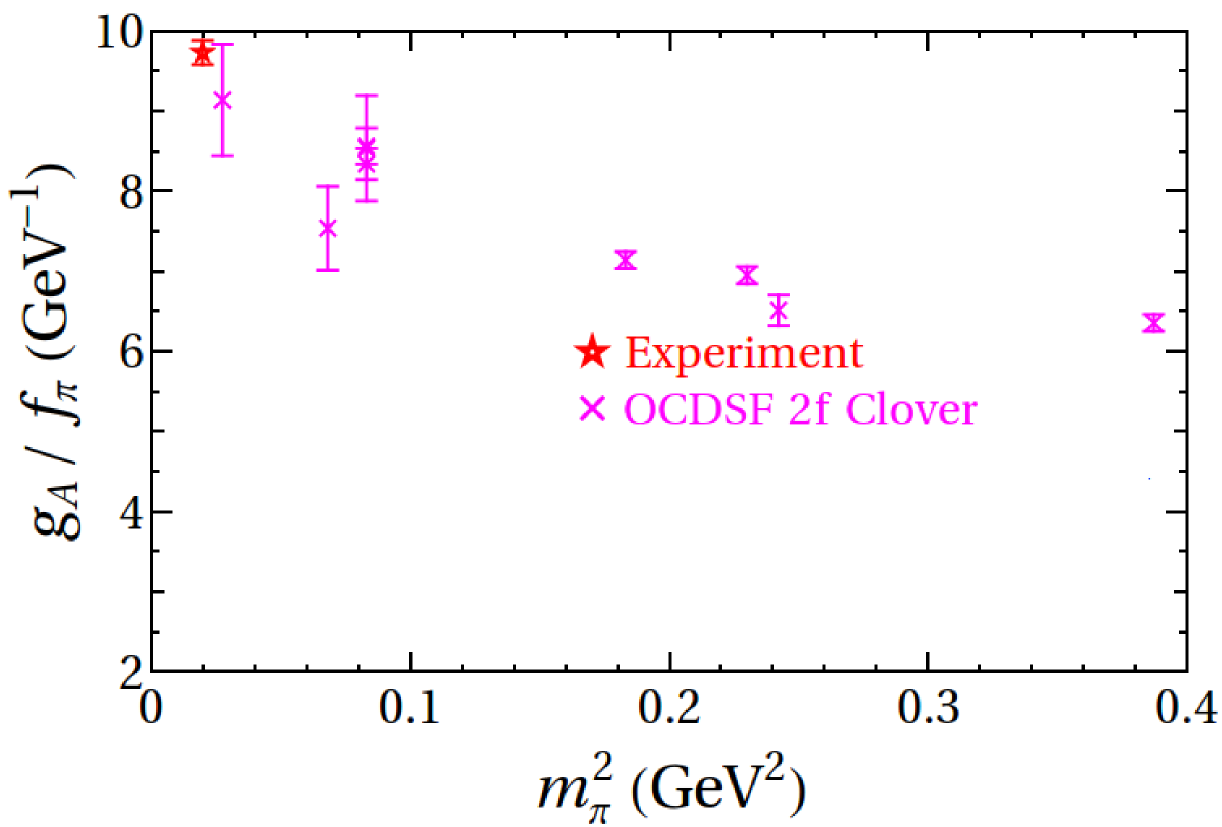


§ Aim at high precision and understand/quote systematics!

Backup Slides

Renormalization

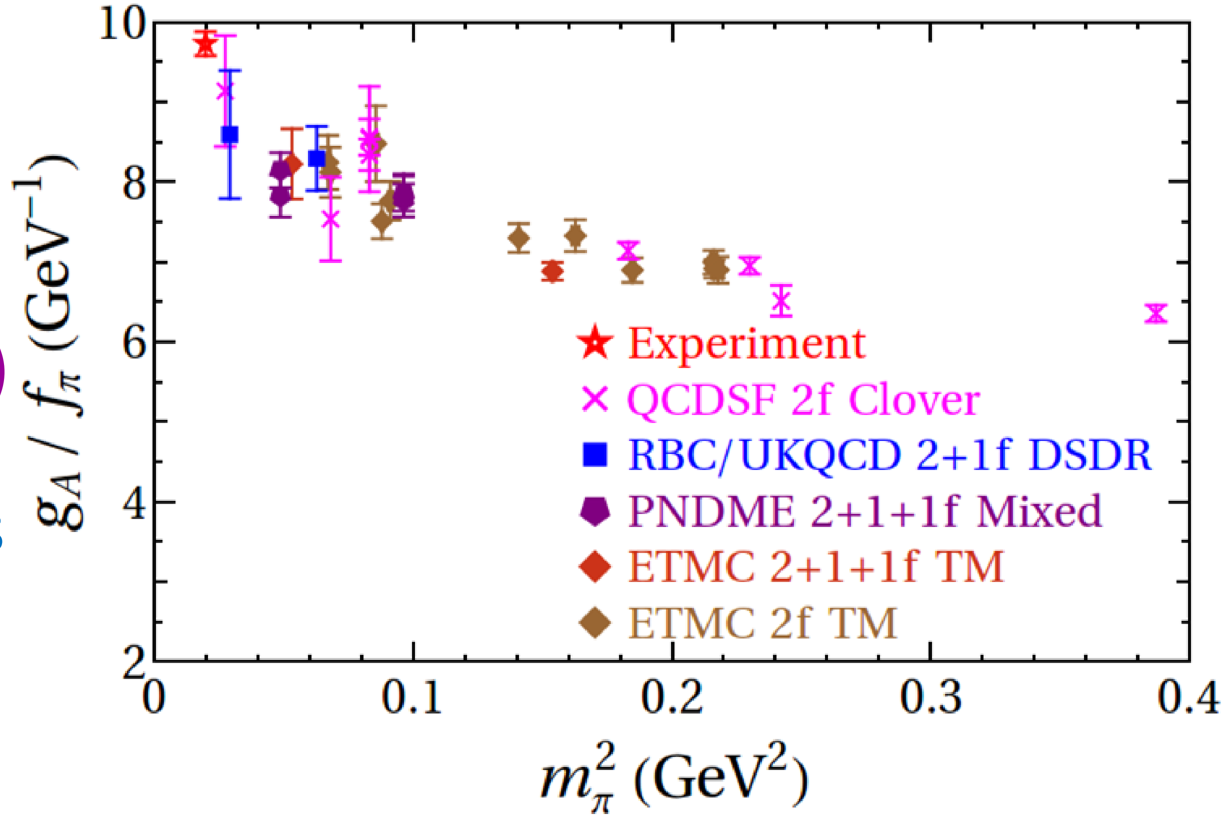
§ QCDSF hypothesis: Z_A might be a problem?



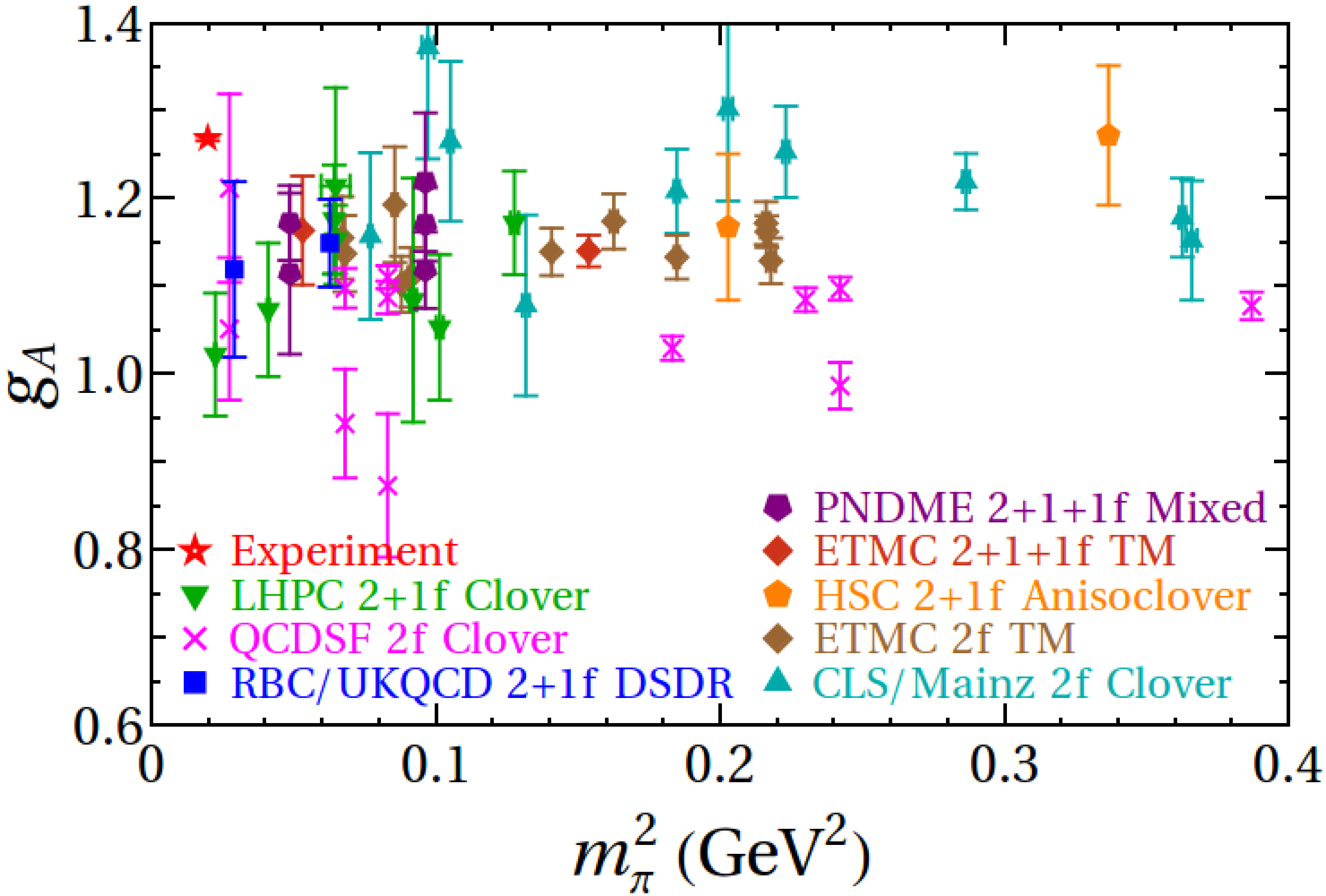
Renormalization

- § QCDSF hypothesis: Z_A might be a problem?
- § Residual O(a) artifacts in
  - Clover: $A_\mu^R = Z_A(1+b_A am_q)(A_\mu + ac_A\partial_\mu P)$
  - Chiral fermions: m_{res}
- § Other systematic cancellations (such as volume, …)

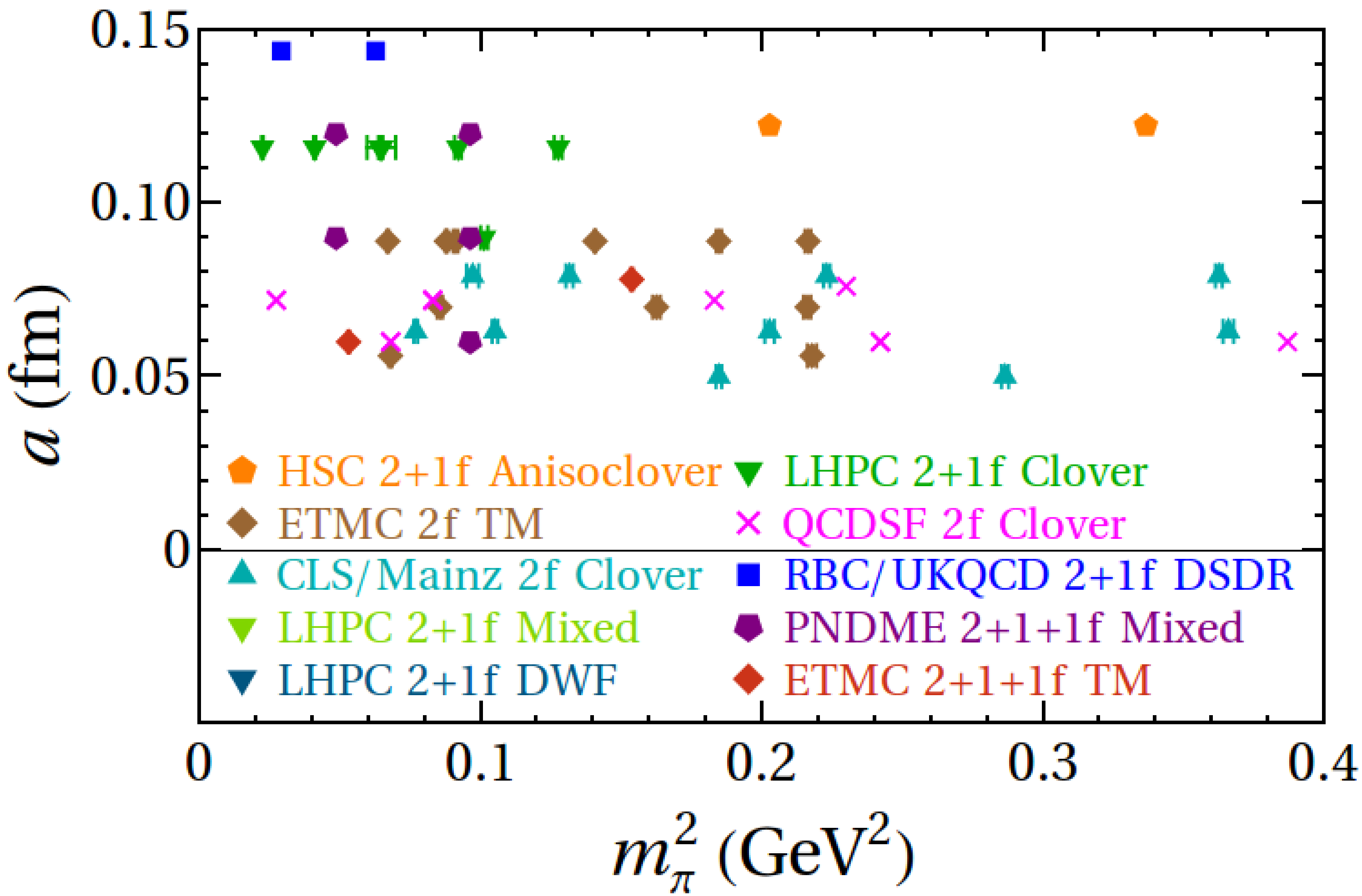
Need higher statistics to be conclusive



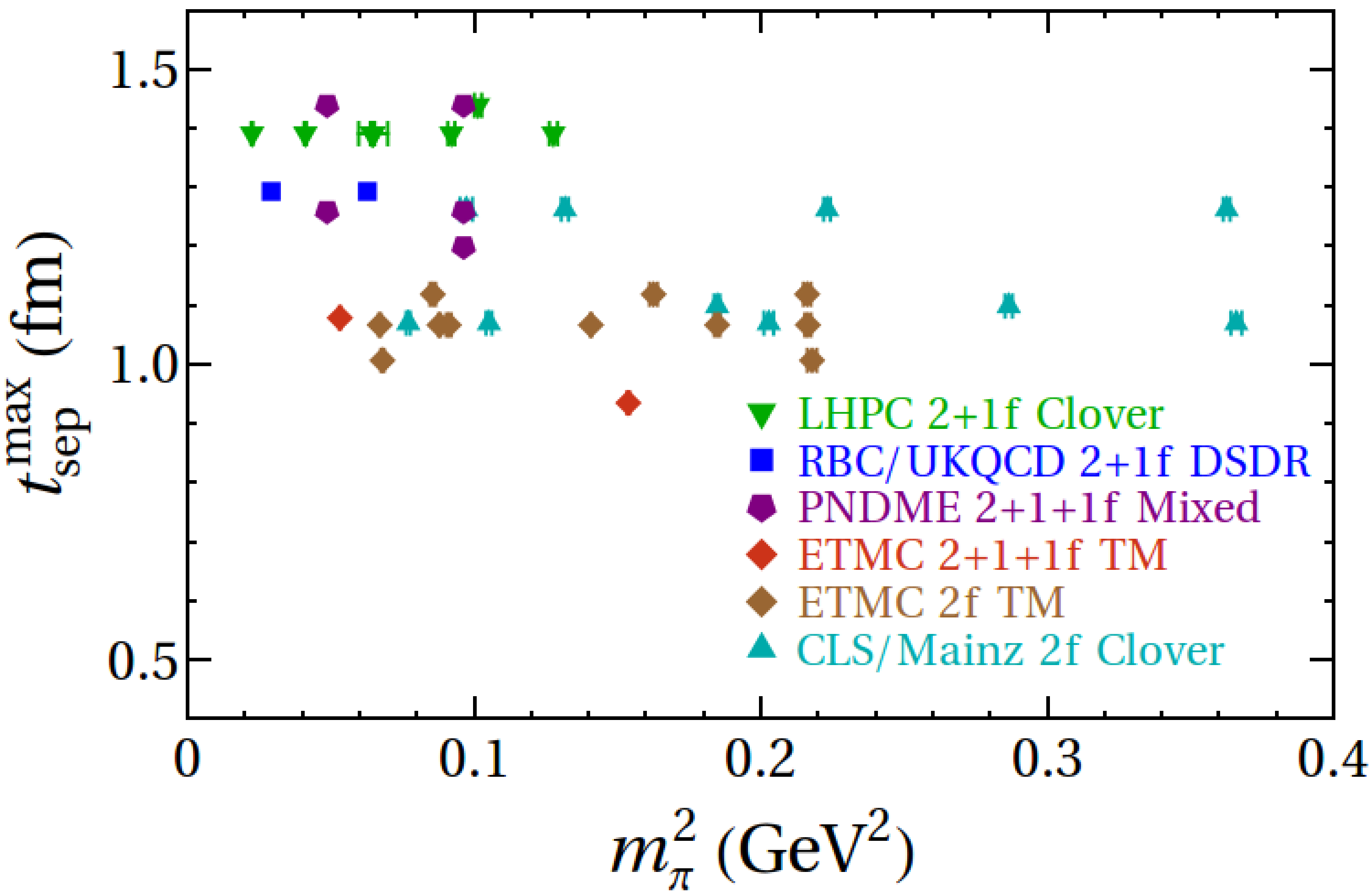
Nucleon Axial Charge



Nucleon Axial Charge



Nucleon Axial Charge



§ Structure

- TMDs (M. Engelhardt); disconnected $\langle x^n \rangle$ (M. Sun)

§ Form Factors

- Charges and radii (J. Green, S. Ohta, M. Lin, B. Owen, T. Rae, B. Menadue, V. Guelpers; C. Alexandrou)
- Transition form factors (X. Feng; B. Menadue; C. Alexandrou, S. Sasaki)

§ Generalized Parton Distribution

- χQCD (private communication)

§ Electric Dipole Moments

- T. Bhattacharya; E. Shintani

§ Scalar and Tensor Charges

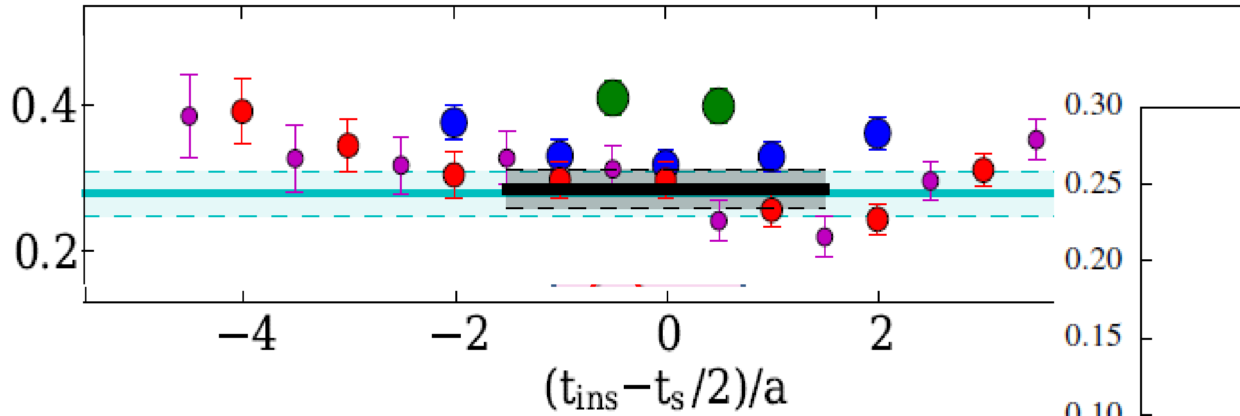
- R. Gupta (PNDME), J. Green (LHPC)

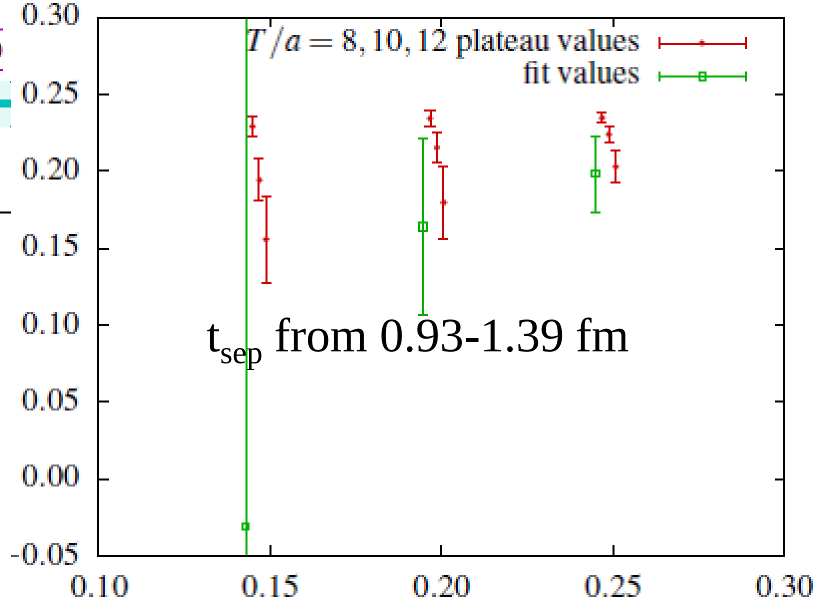
Systematics

§ Excited-State Contamination

§ ETMC *C. Alexandrou et al. & private communication*

- 2+1+1, $M_\pi \approx 380$ MeV, N_{meas} increase to O(3K), APE+Gaussian,
- Dramatic effects, t_{sep} from 0.39-1.01 fm for <x>
- Summation [6,13] , t=13a plat. Fit



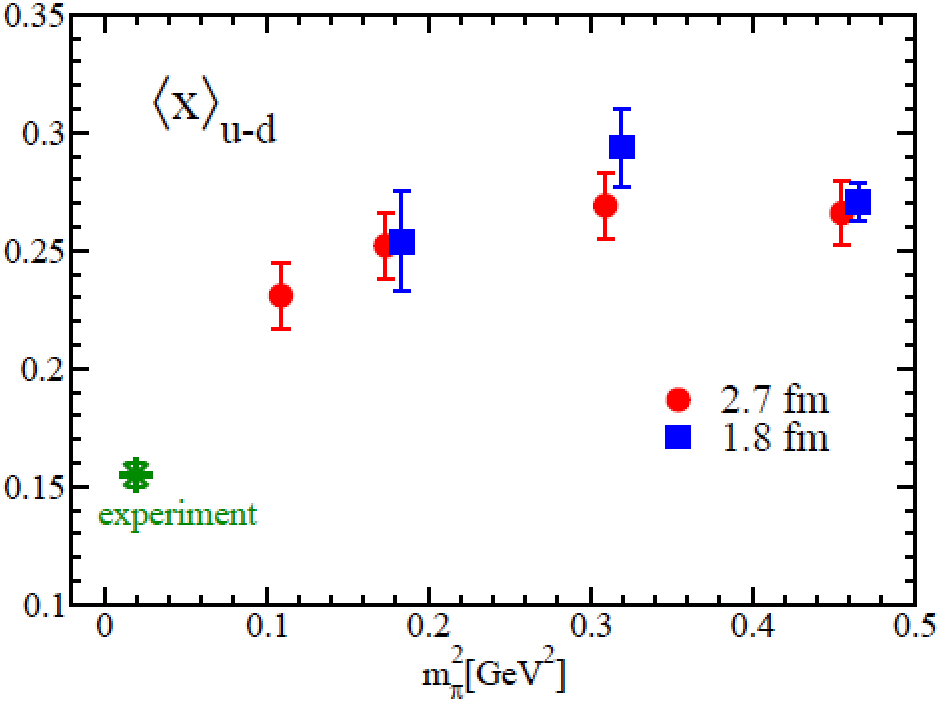


§ Similar results with LHPC

Finite-Volume Effects

§ How big $M_\pi L$ is required?

§ Example study (RBC/UKQCD)

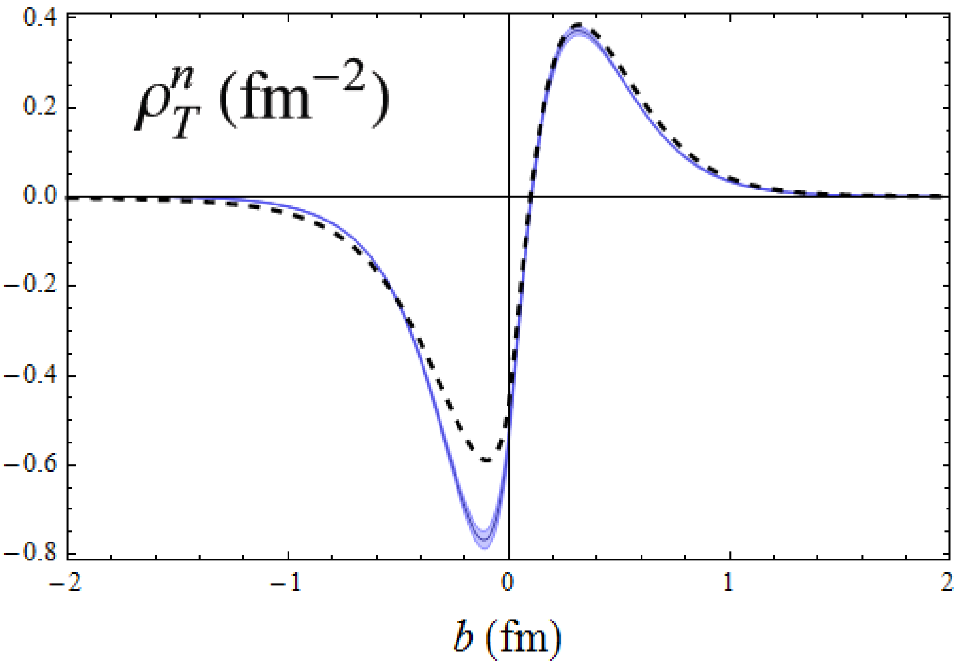


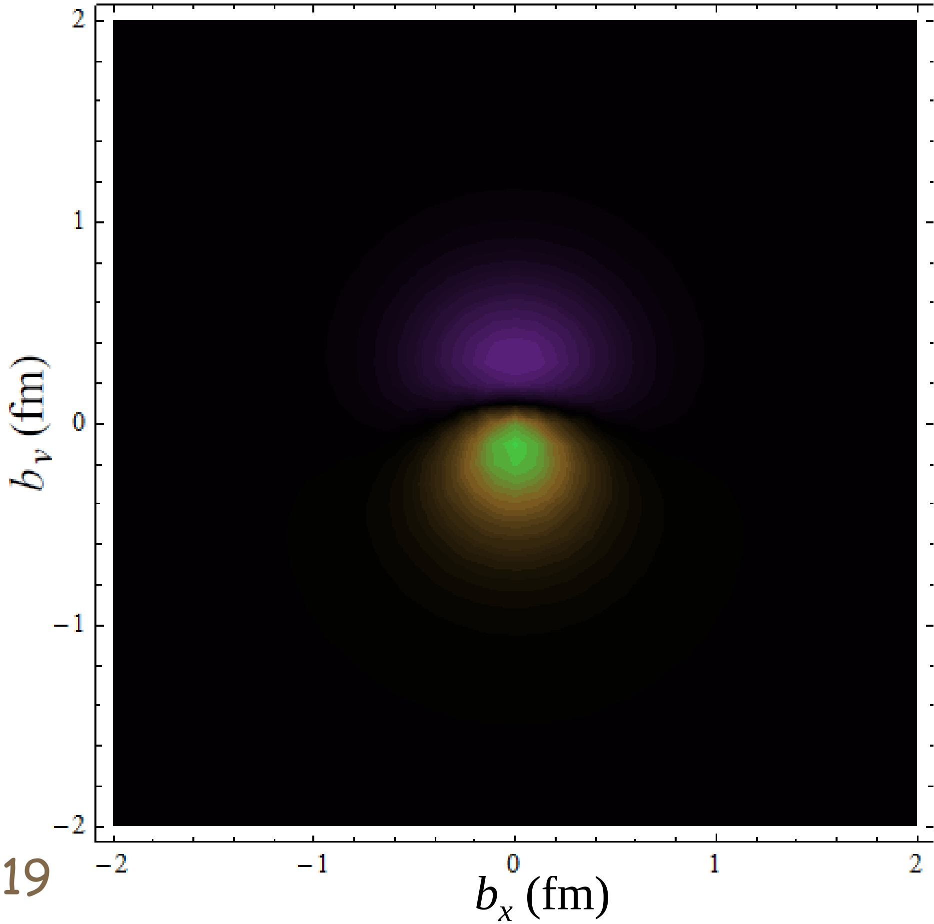
RBC/UKQCD arXiv:1003.3387[hep-lat]

Transversely Polarized Neutron

§ Fourier transform using large-Q^2 form factors to reveal transverse charge densities in a polarized nucleon

$$\rho_T^N(\vec{b}) = \rho_0^N(b) - \sin(\phi_b - \phi_S) \int_0^\infty \frac{dQ}{2\pi} \frac{Q^2}{2M_N} J_1(bQ) F_2(Q^2)$$





HWL and S. D. Cohen, LAT2010, 1104.4319

A Tale of Two Scales

§ LHC strikes out onto the high-energy frontier (8 TeV)

- Direct measurement of Higgs and BSM particles

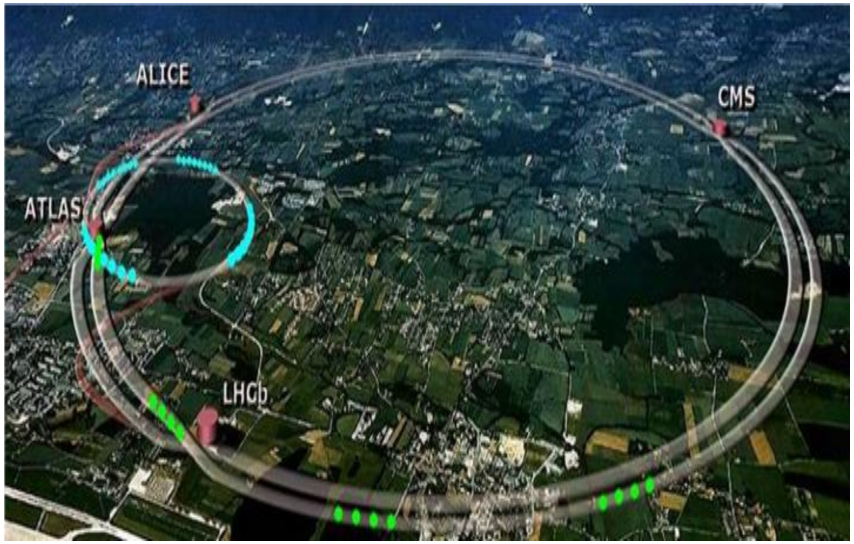
§ Many experiments refine low-energy measurements

- Discern small discrepancies from the Standard Model

  Muon $g-2$, Q_{weak}, CKM matrix…

- Probe small signals that are suppressed in the SM

  $0\nu\beta\beta$, nEDM, dark matter, non-$V-A$ interactions in β decay…



Ultra-Cold Neutrons

§ Worldwide UCN sources

- A rapidly expanding resource for nuclear physics
- Many facilities available and under construction

LANSCE

PAUL SCHERRER INSTITUT PSI UCN Ultra Cold Neutron Source

LENS The Low Energy Neutron Source

Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRM II)

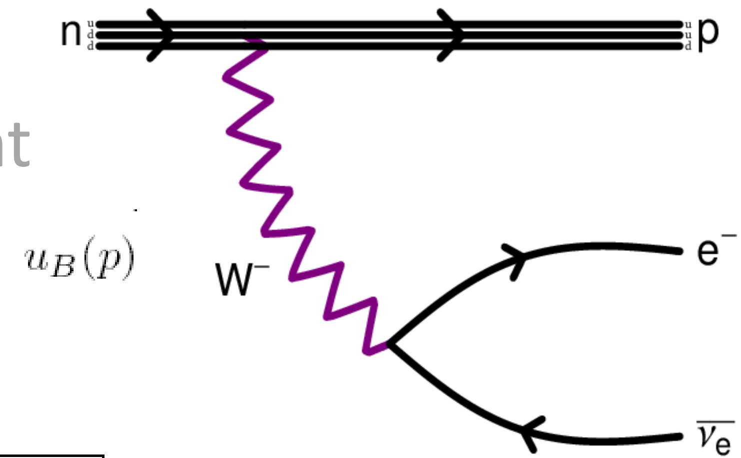
ill NEUTRONS FOR SCIENCE® Institut Laue-Langevin

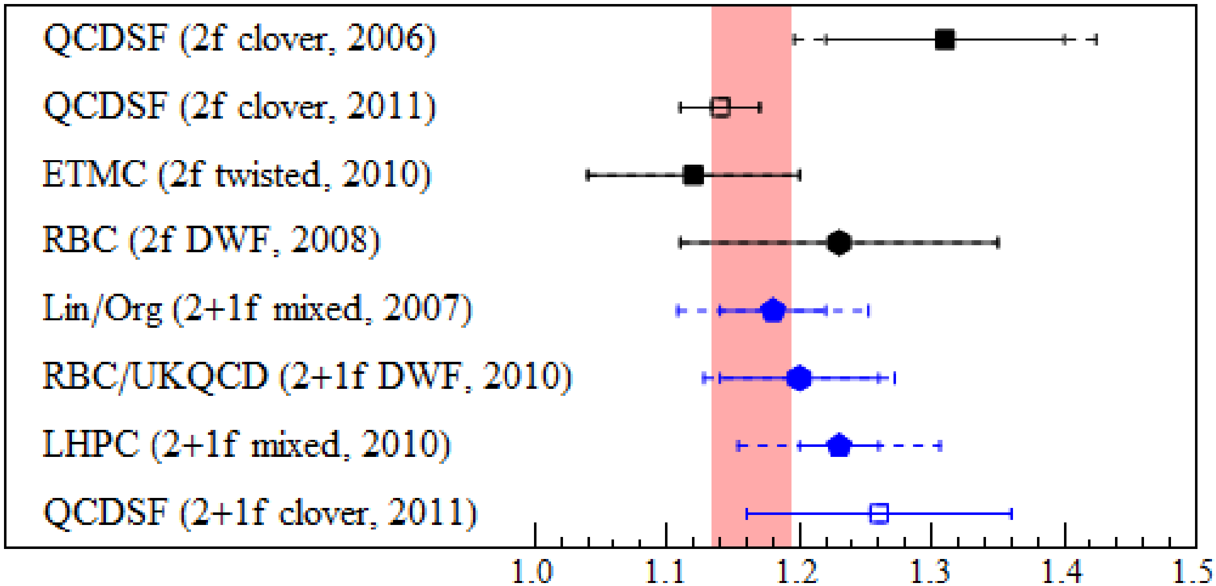
TRIUMF

§ Stay tuned for exciting low-energy precision data

Nucleon Axial Charge

- A fundamental measure of nucleon structure
- Important to the rate of *pp* fusion
- Axial-vector–current matrix element
  and $g_A = G_A^{u-d}(Q^2=0)$
- Benchmark for nucleon structure
- Survey of lattice studies (2011 Nov)



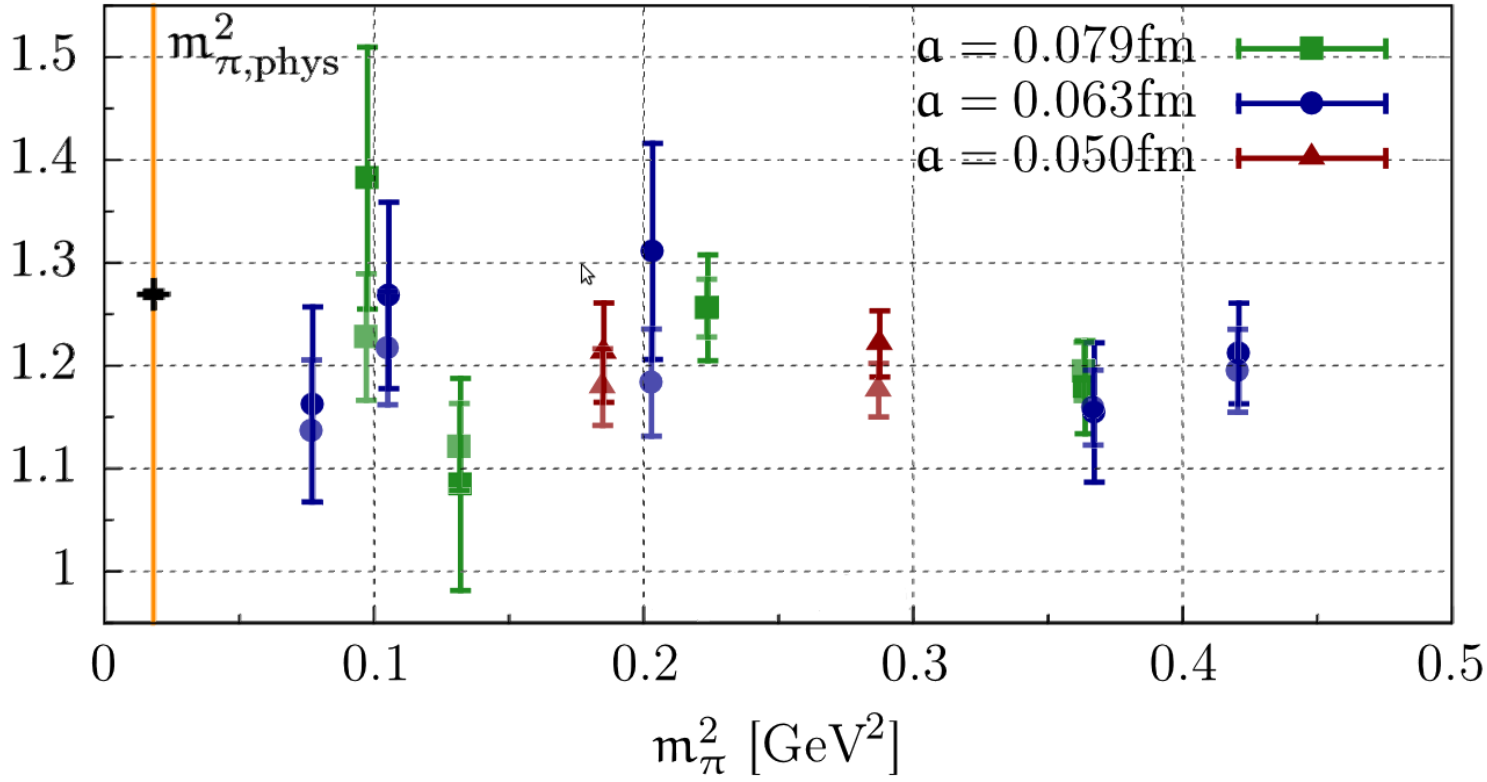


$g_A^{\mathrm{LQCD}} = 1.16(3)$

Chiral Extrapolation

- § Chiral extrapolation
- § Small shift matters?

CLS/Mainz, 1205.0180



Systematics Checklist

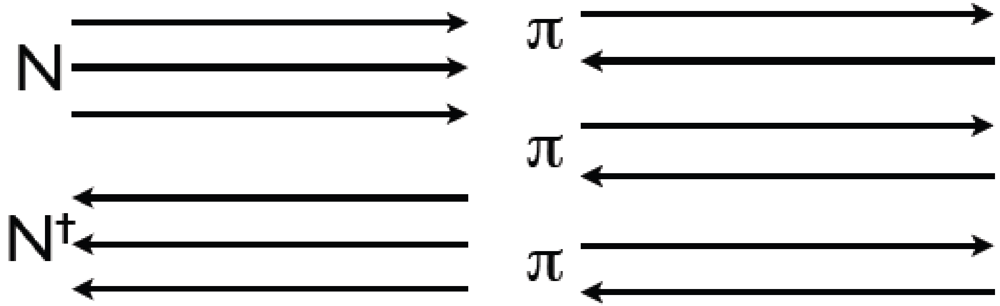
- § Focus on N_f = 2, 2+1, 2+1+1
  - Those who sent me the numbers to establish a database
- § Excited-state contamination
  - Lots of studies in the past few years
- § Finite-volume effects
- § Lattice actions, renormalization and O(a)-improved operators
- § Chiral extrapolation

Excited-State Contamination

§ Trade off: signal-to-noise versus contamination

- Noise issue (P. Lepage; D. Kaplan 2011)

What you want: What you get:



- Signal falls exponentially as $e^{-m_N t}$
- Noise falls as $e^{-(3/2)m_\pi t}$
- Problem worsens with decreasing quark (pion) mass