Progress in Hadron Structure from Lattice QCD

Martha Constantinou

Chiral Dynamics 2015

Pisa, Italy

July 3rd, 2015

OUTLINE

A **Motivation**

B **QCD on the Lattice**

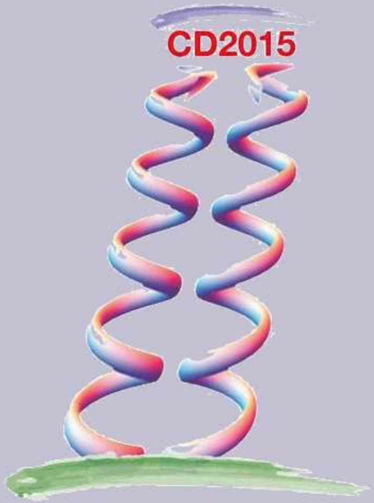
C **Nucleon Sector**

- Charges
- Electromagnetic form factors
- Parton distribution functions
- Nucleon Spin
- Neutron Electric Dipole Moment

D **Other Particles** Backup slides

- Electromagnetic form factors
- Axial charges of Hyperons
- Pion Quark distribution function

E **Conclusions & Perspectives**

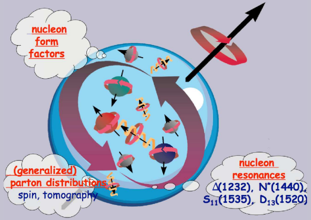


A

MOTIVATION

LQCD meets Nature

LQCD:
- estimates for experimentally well known quantities
- input for not well known quantities



Rich experimental activities in major facilities: JLab, MAMI, MESA, etc

- **Investigation of baryon and meson structure**
- **Origin of mass and spin**
- **New physics searches: scalar/tensor interactions, $(g-2)_\mu$, dark photon searches**
- **proton radius puzzle**
- **the list is long...**

Proton Radius Puzzle

$< r_p^2 >$ from muonic hydrogen μp 7.7σ smaller than hydrogen spectroscopy

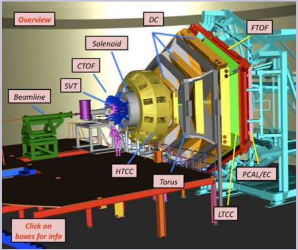
[R. Pohl et al. Nature 466, 213-217 (2010)]

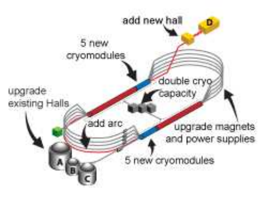
Talk by C. Carlson
Mon @ 14:30

- measured energy difference between the 2P and 2S states of muonic hydrogen
- μp: 10 times more accurate than other measurements
- very sensitive to the proton size
- no obvious way to connect with other measurements (4$\%$ diff)

[I. Lorenz et al., (2014), arXiv:1405.6582]
[J. Bernauer et al. (2010), arXiv:007.5076]

12GeV Upgrade at JLab





Physics Program for CLAS12 (Selected Hadron Experiments)

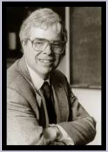
- The Longitudinal Spin Structure of the Nucleon
- Nucleon Resonance Studies with CLAS12
- Meson spectroscopy with low Q^2 electron scattering
- High Precision Measurement of the Proton Charge Radius
- Scalar and Tensor interactions
- Transversity related measurements
- and many more....

Talk by K. Allada
Thu @ 09:25

B

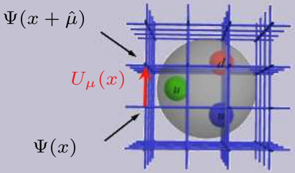
QCD ON THE LATTICE

Lattice formulation of QCD



K. Wilson

formulation (1974)



M. Creutz

1$^{\mathrm{st}}$ numerical computation

- Space-time discretization on a finite-sized 4-D lattice
  - $\Psi(x),\ \bar{\Psi}(x)$: Quark fields on lattice points
  - $U_\mu(x)$: Gauge fields (gluons) on links (Wilson lines)
- Finite degrees of freedom
- Construction of an action $\quad \mathcal{S} = \mathcal{S}_{\text{fermions}} + \mathcal{S}_{\text{gluons}}$

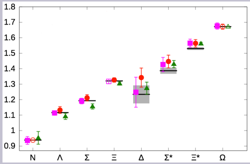
  (with correct continuum limit)
- Numerical simulations and perturbative lattice calculations

Computation of Observables

Configuration Generation

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int_U \mathcal{O}(D^{-1}, U)\, det(D[U]^{N_f})\, e^{-S[U]}$$

Physics!

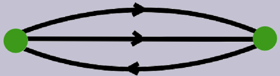


Quark Propagators

(CPUs, GPUs)

Data analysis

Contraction of propagators



Improved fermion action

- **Clover improved Wilson**
  - ✓ computationally fast
  - × broken chiral symmetry & requires operator improvement

  ★ Employed by: **ALPHA, BMW, CLS, LHPC, NPQCD, PACS-CS, QCDSF, RQCD**

- **Twisted Mass**
  - ✓ computationally fast & automatic improvement
  - × broken chiral symmetry & violation of isospin

  ★ Employed by: **ETMC**

- **Staggered**
  - ✓ computationally fast &
  - × 4 doublers & difficult contractions

  ★ Employed by: **MILC, LHPC**

- **Overlap**
  - ✓ exact chiral symmetry
  - × computationally expensive

  ★ Employed by: **JLQCD**

- **Domain Wall**
  - ✓ improved chiral symmetry
  - × computationally demanding & requires tuning

  ★ Employed by: **RBC-UKQCD**

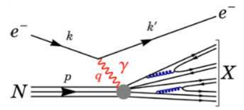
★ **Fermion actions: $\mathcal{O}(a)$-improved**
★ **Gluon actions: $\mathcal{O}(a^2)$-improved**

C

NUCLEON

SECTOR

Nucleon on the Lattice in a nutshell



Probing Nucleon Structure

- **Generalized Parton Distributions (GPDs)**

  Introduced late '90s

  Deep inelastic scattering (DIS)

  Comprehensive description of hadron structure from first principles

- **Parametrization of off-forward matrix of a bilocal quark operator (light-like)**

$$F_\Gamma(x,\xi,q^2) = \frac{1}{2}\int \frac{d\lambda}{2\pi} e^{ix\lambda} \langle p'|\bar\psi(-\lambda n/2)\, \mathcal{O}\, \underbrace{\mathcal{P}e^{ig\int_{-\lambda/2}^{\lambda/2} d\alpha n\cdot A(n\alpha)}}_{\text{gauge invariance}} \psi(\lambda n/2)|p\rangle$$

$q = p' - p$, $\bar P = (p'+p)/2$, n: **light-cone vector (**$\bar P.n = 1$**),** $\xi = -n\cdot\Delta/2$

- **Choices of operators in LQCD:** towers of local twist-2 operators
- **Rely on OPE to extract moments**

$$f^n = \int_{-1}^{1} dx\, x^{n-1} f(x)$$

Contain information of:

- ★ Form factors and parton distributions
- ★ quark orbital angular momentum
- ★ spin structure of the nucleon

A Unpolarized

$$\mathcal{O}^{\mu_1 \cdots \mu_n} = \bar{q}\, \gamma^{\{\mu}\, iD^{\mu_1} \ldots iD^{\mu_{n-1}\}} q$$

DIS, Drell-Yan, W-asymmetry, γ^+ jet, ...

B Helicity (polarized)

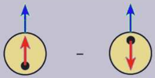
$$\tilde{\mathcal{O}}^{\mu_1 \cdots \mu_n} = \bar{q}\, \gamma_5 \gamma^{\{\mu}\, iD^{\mu_1} \ldots iD^{\mu_{n-1}\}} q$$

polarized DIS, SIDIS, pp collisions,photo/electro production, ...

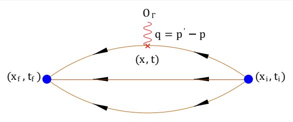
C Transversity

$$\mathcal{O}^{\mu_1 \cdots \mu_{n-1}} = \bar{q}\, \sigma^{\mu\,\{\nu}\, iD^{\mu_1} \ldots iD^{\mu_{n-1}\}} q$$

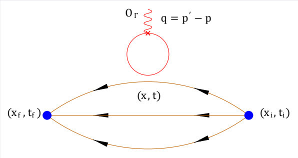
single-spin asymmetry in SIDIS, ...



1. Contributing diagrams:



Connected



Disconnected

2. Computation of 2pt- and 3pt-functions:

$$\text{2pt}: \quad G(\vec{q}, t) = \sum_{\vec{x}_f} e^{-i\vec{x}_f \cdot \vec{q}} \, \mathbf{\Gamma}^{\mathbf{0}}_{\beta\alpha} \, \langle J_\alpha(\vec{x}_f, t_f) \overline{J}_\beta(0) \rangle$$

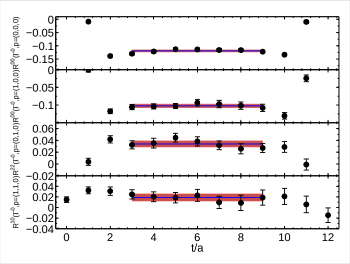
$$\text{3pt}: \quad G_{\mathcal{O}}(\mathbf{\Gamma}^\kappa, \vec{q}, t) = \sum_{\vec{x}_f, \vec{x}} e^{i\vec{x}\cdot\vec{q}} \, e^{-i\vec{x}_f \cdot \vec{p}'} \, \mathbf{\Gamma}^\kappa_{\beta\alpha} \, \langle J_\alpha(\vec{x}_f, t_f) \mathcal{O}(\tilde{\mathbf{x}}, \mathbf{t}) \overline{J}_\beta(0) \rangle$$

$\Gamma^0 \equiv \frac{1}{4}(1 + \gamma_0)$

$\Gamma^2 \equiv \Gamma^0 \cdot \gamma_5 \cdot \gamma_i$

and other variations

3. Construction of optimized ratio:



$$R_{\mathcal{O}}(\Gamma,\vec{q},t) \;=\; \frac{G_{\mathcal{O}}(\Gamma,\vec{q},t)}{G(\vec{0},t_f)} \times \sqrt{\frac{G(-\vec{q},t_f-t)G(\vec{0},t)G(\vec{0},t_f)}{G(\vec{0},t_f-t)G(-\vec{q},t)G(-\vec{q},t_f)}}$$

$$\xrightarrow[\substack{t_f-t\to\infty \\ t-t_i\to\infty}]{} \quad \Pi(\Gamma,\vec{q}) \quad \text{(Plateau Method)}$$

4. Renormalization: connection to experiments

$$\Pi^R(\Gamma,\vec{q}) = Z_{\mathcal{O}}\,\Pi(\Gamma,\vec{q})$$

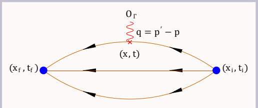
5. Extraction of form factors

e.g. Axial current:

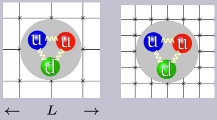
$$A^3_\mu \equiv \bar{\psi}\,\gamma_\mu\,\gamma_5\,\frac{\tau^3}{2}\,\psi \Rightarrow \bar{u}_N(p')\left[\mathbf{G_A(q^2)}\,\gamma_\mu\,\gamma_5 + \mathbf{G_p(q^2)}\,\frac{q_\mu\,\gamma_5}{2\,m_N}\right]u_N(p)$$

Isovector Combination: (u-d)

- ★ **disconnected contributions cancel out**
- ★ **Simpler renormalization**



Systematic uncertainties: Challenges & Progress



1 **Cut-off Effects: finite lattice spacing**

- Simulations with fine lattices ($a < 0.1$ fm)
- Improve actions, algorithmic improvements
- Continuum limit $a \to 0$

2 **Finite Volume Effects**

- Simulating hadrons in large volumes (Rule of thunb: $L\, m_\pi > 3.5$)
- Infinite volume limit $L \to \infty$

3 **Contamination from other hadron states**

- Various methods for extracting information from lattice data

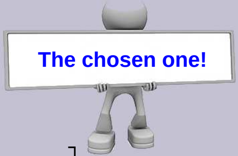
4 **Not simulating the physical world**

- Chiral extrapolation
- Simulations at physical parameters are now feasible

5 **Renormalization and mixing**

- Subtraction of lattice artifacts, utilize perturbation theory

AXIAL CHARGE

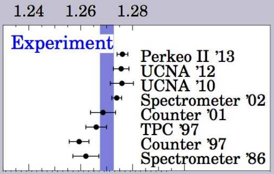


Nucleon Axial current: $A^3_\mu \equiv \bar{\psi}\,\gamma_\mu\,\gamma_5\,\frac{\tau^3}{2}\,\psi$

$$\langle N(\vec{p}')\mathcal{O}^a_A N(\vec{p})\rangle = \bar{u}_N(p')\left[\mathbf{G_A(q^2)}\,\gamma_\mu\,\gamma_5 + \mathbf{G_p(q^2)}\,\frac{q_\mu\,\gamma_5}{2\,m_N}\right]u_N(p)$$

$$g_A \equiv \langle N(\vec{p}')\mathcal{O}^a_A N(\vec{p})\rangle\Big|_{q^2=0} = G_A(0)$$

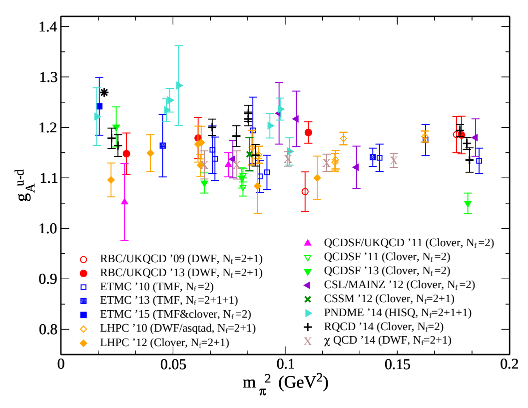
- **governs the rate of β-decay (Well-determined!)**

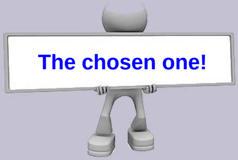


[T. Bhattacharya et al. (PNDME), arXiv:1306.5435]

- **related to the fraction of the nucleon spin carried by the quarks**
- **On the lattice: requires the lowest moment and zero momentum**
- **determined directly from lattice data (no fit necessary)**

AXIAL CHARGE





- $g_A^{exp} = 1.2701(25)$ [PDG'12]
- $m_\pi > 200$MeV: lattice results below exp.: $\sim$10-15%

★ Lattice data from 'plateau' methods

★ Latest achievement: lattice results at physical m_π

★ No necessity of chiral extrapolation

★ Different strategies for addressing systematic uncertainties

Selected Works:

- T. Yamazaki et al. (RBC/UKQCD,) [arXiv:0801.4016]
- T. Yamazaki(RBC/UKQCD), [arXiv:0904.2039]
- J.D. Bratt et at. (LHPC), [arXiv:1001.3620]
- C. Alexandrou et al. (ETMC), [arXiv:1012.0857]
- S. Collins et al. (QCDSF/UKQCD), [arXiv:1101.2326]
- B.B. Brandt et al. (CLS/MAINZ), [arXiv:1106.1554]
- G.S. Bali et al. (QCDSF), [arXiv:1112.3354]
- S. Capitani et al. (CLS/MAINZ), [arXiv:1205.0180]
- J.R. Green et al. (LHPC), [arXiv:1209.1687]
- J.R. Green et al. (LHPC), [arXiv:1211.0253]
- B.J. Owen et al. (CSSM), [arXiv:1212.4668]
- R. Horsley et al. (QCDSF), [arXiv:1302.2233]
- C. Alexandrou et al. (ETMC), [arXiv:1303.5979]
- T. Bhattacharya et al. (PNDME), [arXiv:1306.5435]
- S. Ohta et al. (RBC/UKQCD), [arXiv:1309.7942]
- G.S. Bali et al. (RQCD), [arXiv:1311.7041]
- A.J. Chambers et al. (QCDSF/UKQCD), [arXiv:1405.3019]

SCALAR & TENSOR CHARGES

- ★ Non $V - A$ structure of weak interaction
- ★ Small contributions of scalar/tensor interactions in SM (10^{-3})
- ★ ϵ_S, ϵ_T: low-energy couplings

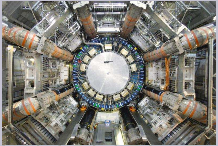
$$H_{eff} = G_F \left(J^l_{V_A} \times J^q_{V_A} + \sum_i \epsilon_i \mathcal{O}^l_i \times \mathcal{O}^q_i \right)$$

  - related to masses of new TeV-scale particles
  - require knowledge of g_S ($\langle p|\bar{u}d|n\rangle$), g_T ($\langle p|\bar{u}\sigma^{\mu\nu}d|n\rangle$)

- ★ scalar interactions: $0^+ \to 0^+$ nucleon decays
- ★ tensor interactions: radiative pion decay $\pi \to e\nu\gamma$
- ★ Upcoming experiments (TeV scale) that probe small signals:
  UCNB & UCNb at LANL, Nab at ORNL, ATLAS at LHC

UCN @ LANL

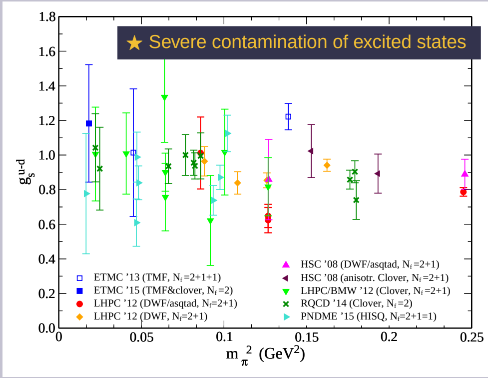
ATLAS @ LHC



Scalar Charge

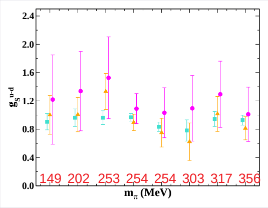
$g_S \equiv \langle N|\bar{u}u - \bar{d}d|N\rangle$

- related to nucleon σ-terms
- important for direct search of dark matter



LHPC: m_π=149−356MeV

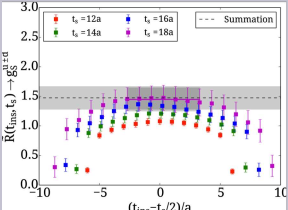
[J.R.Green et al. (LHPC), arXiv:1206.4527]



★ m_π=149MeV: 0.93 fm $\langle T_{\rm sink} \langle$ 1.39 fm

PNDME: m_π=310MeV

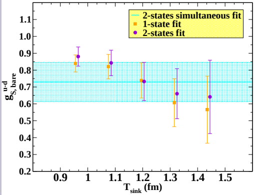
[T. Bhattacharya (PNDME), arXiv:1306.5435]



ETMC:: N_f=2+1+1, m_π=373MeV

[A.Abdel-Rehim et al. (ETMC), arXiv:1310.6339]

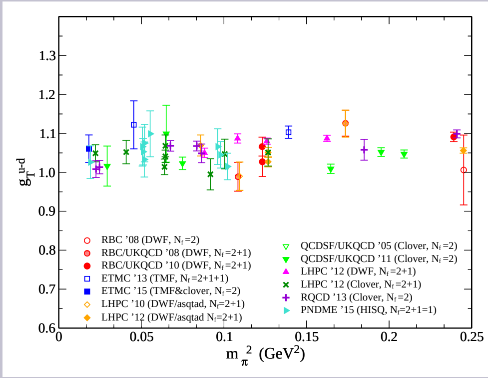
- **0.98 fm $\langle T_{\rm sink} \langle$ 1.48 fm**
- **$T_{\rm sink}$ $\leq$1.31 fm: agreement with SM**



Tensor Charge

$\langle N(p',s')|\,\sigma^{\mu\nu}\,|N(p,s)\rangle \;\Rightarrow\; \mathbf{A_{T10}(q^2)},\ \mathbf{B_{T10}(q^2)},\ \mathbf{C_{T10}(q^2)}$

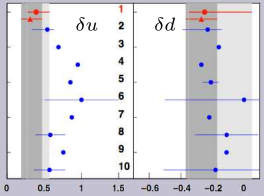
$g_T \equiv \langle 1 \rangle_{\delta q} = A_{T10}(0)$



SIDIS results (HERMES, COMPASS) and BELLE e+ e- analysis

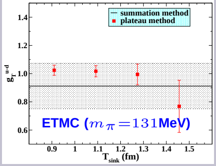
- $g_T^{\rm exp}(0.8\,{\rm GeV}^2) = 0.77^{+0.13}_{-0.27}$

[M.Anselmino et al., arXiv:0812.4366]



[M.Anselmino et al., arXiv:1303.3822]

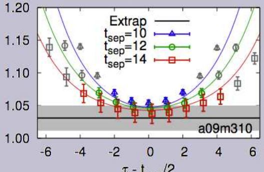
★ Agreement among most lattice points
★ Mild m_π dependence



ETMC ($m_\pi = 131$MeV)

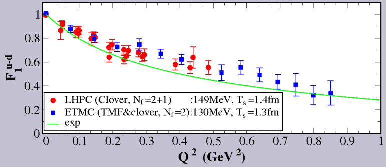
PNDME (m_π =310MeV) ⇒

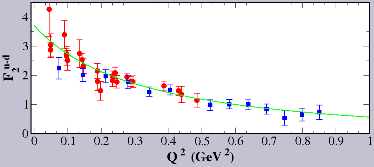
[T. Bhattacharya (PNDME), arXiv:1306.5435]



Nucleon EM form factors

$$\langle N(p',s')|\gamma_\mu|N(p,s)\rangle \sim \bar{u}_N(p',s')\left[\mathbf{F_1(q^2)}\gamma_\mu + \mathbf{F_2(q^2)}\frac{i\,\sigma^{\mu\rho}q_\rho}{2m_N}\right]u_N(p,s)$$



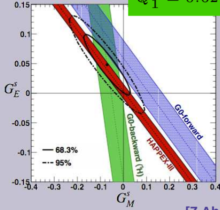


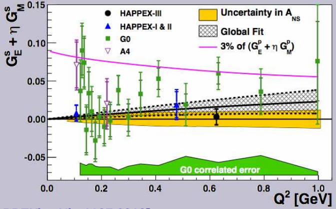
- the slope of lattice data leads to lower Dirac & Pauli radii than the experimental

Sachs FFs: $G_E(Q^2) = F_1(Q^2) - \frac{Q^2}{4m_N^2}F_2(Q^2), \quad G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$

Elastic scattering of polarized e from unpolarized p (Hall A @ JLab)

$Q_1^2 = 0.624\text{GeV}^2$

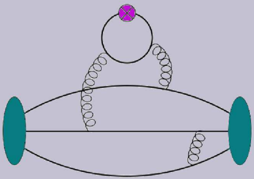




[Z.Ahmed et al. (HAPPEX) arXiv:1107.0913]

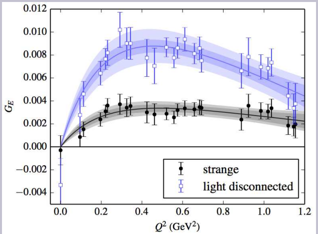
Fit: $G_E^s(Q_1) = 0.047(34) \qquad G_M^s(Q_1) = 0.070(67)$

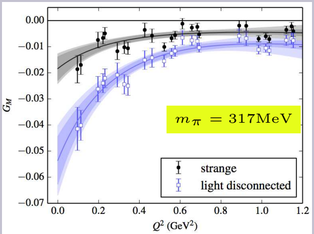
Disconnected contribution



$$\mathrm{Tr}\left[\mathcal{O}G(x;x)\right]$$

- ★ **We need to compute all-to-all propagator**
- ★ **extremely difficult to compute**
- ★ **very noisy and very expensive conputationally**
- ★ **We've come far in development of techniques:**
  - **Truncated Solver Method**
  - **One-end-trick**
  - **All-Mode-Averaging**
  - **Hierarchical probing**





[J.Green et al. (LHPC) arXiv:1505.01803]

- Clover ($N_f=2+1$), $L=3.58$ fm
- $\mathcal{O}(100\,000)$ statistics
- G_E^{dis} increases G_E^{tot}
- G_M^{dis} decreases G_M^{tot}

★ **Quark loops with hierarchical probing** [A.Stathopoulos et al., arXiv:1302.4018]

PDFs on the Lattice

- ★ characterize the dynamics of quarks and gluons inside hadrons
- ★ predictions for collision experiments
- ★ non-perturbative nature $\Rightarrow$ hard to compute
- ★ non-local light-cone correpators, time dependent and intrinsically Minkowskian, requires $t^2 + \vec{x}^2 \sim 0 \Rightarrow$ difficult on lattice

On the lattice we study Mellin moments of PDFs:

$$\langle x \rangle_q = \int_{-1}^{1} dx\, x^{n-1}\, q(x)\,, \qquad \langle x \rangle_{\Delta q} = \int_{-1}^{1} dx\, x^{n-1}\, \Delta q(x)\,, \qquad \langle x \rangle_{\delta q} = \int_{-1}^{1} dx\, x^{n-1}\, \delta q(x)$$

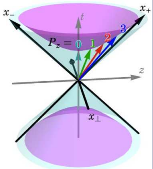
However, reconstruction of PDFs seems unfeasible:

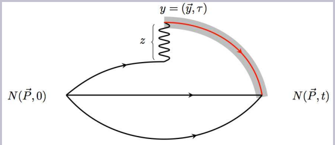
- ★ signal-to-noise is bad for higher moments
- ★ n $>$ 3: operator mixing (unavoidable!)
- ★ gluon moments: limited progress (discon. diagram, signal quality, operator mixing)

Nover direct approach [X.Ji, arXiv:1305.1539]

- ★ compute a P*quasi*-DF (accessible on the lattice)
- ★ contact with physical PDFs via a matching procedure

Access of PDFs on Euclidean lattice





★ **rest frame: parton physics correspond to light-cone correlation BUT:**

★ **same physics obtained from t-independent spatial correlation in the IMF**

★ **P*quasi*-DF ($\tilde{q}$) purely spatial for nucleons with finite momentum (e.g. in z-direction)**

$$\tilde{q}(x, \mu^2, P_3) = \int \frac{dz}{4\pi} e^{-i\, x\, P_3\, z} \langle N(P_3)|\bar{\Psi}(z)\, \gamma^z\, \mathcal{A}(z,0)\Psi(0)|N(P_3)\rangle_{\mu^2}$$

- $\mathcal{A}(z, 0)$: **Wilson line from $0 \to z$**
- z: **distance in any spatial direction (momentum boost in z direction)**

★ **At finite but feasibly large momenta on the lattice:**
a large momentum EFT can relate Euclidean $\tilde{q}$ to PDFs through a factorization theorem

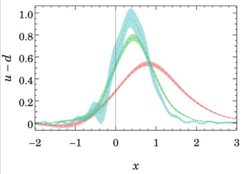
★ **use of Perturbation Theory for the matching**

Computation is difficult and costly

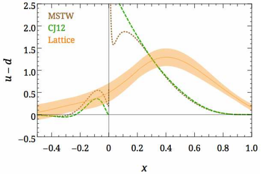
Lattice results on unpolarized PDFs

$$u(x) - d(x)$$

[H-W. Lin, arXiv:1402.1462]



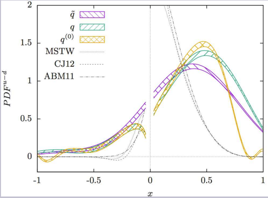
$P_3 = 2\pi/L * \{1, 2, 3\}$



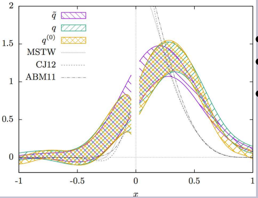
extrapolated in P_z

- $N_f = 2+1+1$
- Clover/HISQ
- m_π =310 MeV

[C. Alexandrou et al. (ETMC), arXiv:1504.07455]



$P_3 = 2\pi/L * 2$, 5 HYP steps



$P_3 = 2\pi/L * 3$, 5 HYP steps

- $N_f = 2+1+1$
- ETM
- m_π =375 Mev

Sea-quark distribution: $\tilde{q}(x) = -q(-x)$

Phenomenological data: MSDW: A. Martin, [arXiv:0901.0002] CTEQ-JLab: J. Owens, [arXiv:1212.1702]

★ **Renormalization of $\tilde{q}$: still in progress!**

Nucleon Spin

Where does the spin of the nucleon come from?

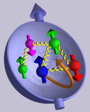
Understanding of proton spin has evolved:

Simple parton model

$\frac{1}{2}\left(\Delta u_v + \Delta d_v\right) = \frac{1}{2}$

Sea quarks & Gluons are polarized

$\frac{1}{2}\left(\Delta q + \bar{\Delta} q\right) + \Delta G = \frac{1}{2}$



Parton orbital angular momentum

$\frac{1}{2}\left(\Delta q + \bar{\Delta} q\right) + \Delta G + L_z = \frac{1}{2}$

Quark orbital angular momentum

Spin Sum Rule:

$$\frac{1}{2} = \sum_q J^q + J^G = \sum_q \left(L^q + \frac{1}{2}\Delta\Sigma^q\right) + J^G$$

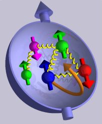
Quark Spin

Extraction from LQCD:

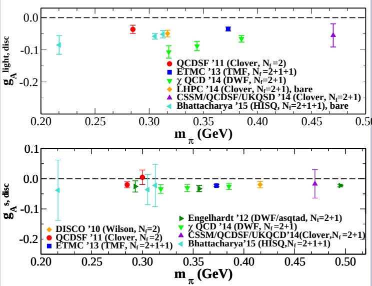
$$J^q = \frac{1}{2}\left(A_{20}^q + B_{20}^q\right)\,, \quad L^q = J^q - \Sigma^q\,, \quad \Sigma^q = g_A^q$$

★ **Individual quark contributions: disconnected insertion contributes**

Nucleon Spin



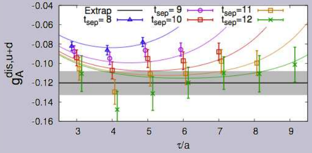
Disconnected Contributions



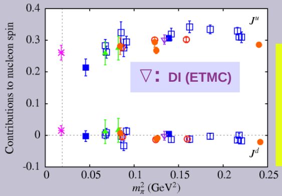
★ Agreement of various results

★ DI for g_A lower the total value

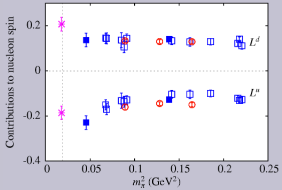
[T. Bhattacharya et al., arXiv:1503.05975]



Collected results



- ○ LHPC (DWF/asqtad, $N_f=2+1$)
- ● LHPC (DWF, $N_f=2+1$)
- ▲ QCDSF (Clover, $N_f=2$)
- □ ETMC (ETM, $N_f=2$)
- ■ ETMC (ETM, $N_f=2+1+1$)
- ✶ ETMC (ETM&$c_{\rm sw}$, $N_f=2$)



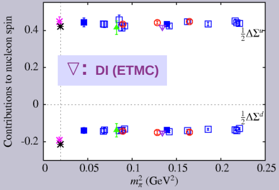
Most results: only CI

ETM: include $Z_A^s - Z_A^{ns}$

$m_\pi = 131$ MeV:

- $J^u \sim 0.25$, $J^d \sim 0$
- $\Delta\Sigma^u$, $\Delta\Sigma^d$ agrees with exp.

$L^{u+d} \sim 0$



Glue of the nucleon

Gluon helicity disctribution: very small (COMPASS, STAR)

[COMPASS Collaboration, Nucl.Phys.Proc.Suppl. 207-208, 53 (2010)] [P. Djawotho, (2013), arXiv:1303.0543]

glue orbital angular momentum $\sim$ 0

(single-spin asymmetry in unpolarized lepton scattering from transversely polarized nucleon)

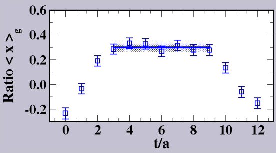
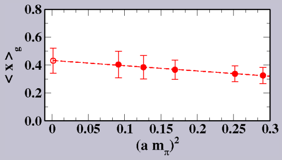
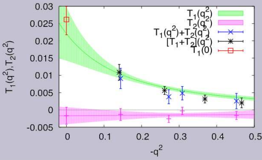
[S. Brodsky et al., hep-ph/0608219]

Gluon unpolarized disctribution

- $\mathcal{O}^g_{\mu\nu} = -\mathrm{Tr}\left[G_{\mu\rho}G_{\nu\rho}\right]$

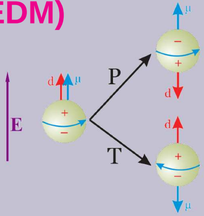
$$\langle N(p)|\mathcal{O}_{44} - \frac{1}{3}\sum_{j=1}^{3}\mathcal{O}_{jj}|N(p)\rangle = \left(m_N + \frac{2}{3\,E_N}\vec{p}^{\,2}\right)\langle x\rangle_g$$

- **Direct lattice computation of gluon moment $\langle x\rangle_g$: disconnected diagram**

Dynamical	Quenched	Quenched
		
[C. Alexandrou et al. (ETMC), 2015]	[R. Horsley (QCDSF), 2012, arXiv:1205.6410]	[M. Deka (χQCD), 2013, arXiv:1312.4816]
$N_f = 2+1+1$ ETM, $m_\pi = 375$ MeV	$N_f = 0$ Clover, $m_\pi = 314 - 555$ MeV	$N_f = 0$ Wilson, $m_\pi = 478 - 650$ MeV
$\langle x\rangle_g = 0.309(25)$	$\langle x\rangle_g = 0.43(7)(5)$	$\langle x\rangle_g = 0.313(56)$

Smearing: improves signal

Neutron Electric Dipole Moment (nEDM)



- ★ probe for BSM physics
- ★ nonzero EDM violates P, T symmetry (and also CP)
- ★ distribution of positive and negative charge in neutron
- ★ no finite nEDM has been reported
- ★ **Experiments:** change in spin presession frequency of UCN in weak B when a strong background E flips sign
- ★ first report in 1950 (ORNL)

THE NEWS — OAK RIDGE NATIONAL LABORATORY

A Publication by and for the ORNL Employees of Carbide and Carbon Chemicals Division, Union Carbide and Carbon Corporation

Vol. 3—No. 13 OAK RIDGE, TENNESSEE Friday, September 29, 1950

HARVARD UNIVERSITY SPONSORS PROGRAM HERE — James H. Smith, Harvard University graduate student in physics, is shown as he adjusts a neutron beam apparatus at the south face of the Oak Ridge Pile. Using the Pile as a source of neutrons, Mr. Smith is engaged in a project jointly sponsored by Harvard University and Oak Ridge National Laboratory for the purpose of determining if neutrons have permanent electric dipole moments.

Harvard University Conducts Important Research at ORNL

The growing importance of Oak Ridge National Laboratory as a research center is manifested particularly in its assistance to universities and technical schools on various projects in which nuclear research is involved. An example of such relationship is its present collaboration with Harvard University in an investigation to determine if neutrons have permanent electric dipole moments.

The work of the project is under the direction of Professors E. M. Purcell and Norman F. Ramsey of the Harvard University Physics Department and is being conducted on the Laboratory area by James H. Smith, a

DR. TAYLOR

ACS Lectureship Set For October 26, 27

The East Tennessee Section of the American Chemical Society will have its Annual East Tennessee Lectureship this year in two sessions, according to plans re-

Dr. Ellison Taylor Appointed Chem. Division Director

Effective October 1, Dr. Ellison H. Taylor will assume the duties of Director of the Chemistry Division. In this capacity he will succeed Dr. John A. Swartout, who was recently elevated to the position of Assistant Research Director of Oak Ridge National Laboratory.

Dr. Taylor's present connection with the Chemistry Division is that of Associate Director of the Division and Group Leader of the Radiation Chemistry Group, in which capacities he has served since June, 1948. Previously, he had been Assistant Director of the Division, from June, 1946, to February, 1948, and was Acting Di-

- current best exp. upper limit: $|d_n| < 2.9 \times 10^{-26}\, e\, cm$ (90 % C.L.)

(ILL Grenoble)

- EFT calculations: $|d_n| \sim \sum \theta \cdot \mathcal{O}(10^{-2} \sim 10^{-3})\, e \cdot \mathrm{fm} \Rightarrow \theta \lesssim \mathcal{O}(10^{-10} \sim 10^{-11})$

Recent Experimental Activity

PSI

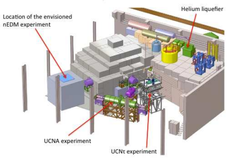
ILL

MLZ

RCNP

SNS

J-PARC



LANL

NIST

nEDM on the lattice

$$\mathcal{L}(x) \to \mathcal{L}_{QCD}(x) + \mathcal{L}_{CS}(x)\,, \qquad \mathcal{L}_{CS}(x) = \theta\, q(x)$$

does not modify the e.o.m.

- θ: **strength of the CP-breaking**
- $q(x)$: **topological charge density:** $\frac{i}{32\pi^2}\epsilon_{\mu\nu\rho\sigma}\mathrm{Tr}\left[F_{\mu\nu}(x)F_{\rho\sigma}(x)\right]$

★ **interaction between ψ_f and $F^{\mu\nu}$:**

$$i\theta\frac{F_3(q^2)}{2m_N}\bar{\psi}_f\sigma_{\mu\nu}\gamma_5\psi_f F^{\mu\nu}$$

F_3: **CP-odd form factor**

Talk by V. Cirigliano
Mon @ 11:50

$$|\vec{d}_N| = \lim_{\vec{q}\to 0}\theta\frac{F_3(q^2)}{2m_N}$$

Methods to extract nEDM:

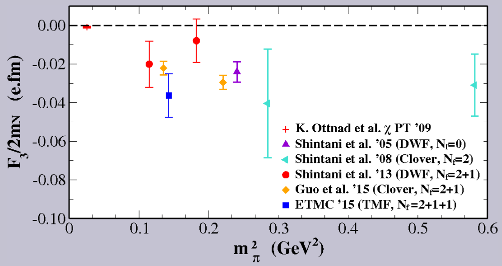
1. external electric field: ◀
2. imaginary θ: ◆
3. F_3 from $\mathcal{O}(\theta)$: ● ▲ ■

ETMC includes direct computation of $F_3(0)$!

$$|\theta_{\max}|^{\mathrm{Lat}} \sim \mathcal{O}(10^{-12} - 10^{-11})$$

(using $|d_n|^{exp}$)

[C. Alexandrou et al. (ETMC), 2015]



SUMMARY & CHALLENGES

Breakthrought: Simulating the physical world!

- **Dedication of human force and computational resources on:**
  - Control of statistical uncertainties $\Rightarrow$ noise reduction techniques crucial
  - comprehensive study of systematic uncertainties
  - study of DI at lower masses (Target: physical m_π!)
    - challenging task
    - exploid techniques: AMA, hierarchical probing, others
    - usage of GPUs
    - current computations of DI provide bounds
- **Nucleon spin: include dynamical simulations for gluon angular momentum**
  - Becoming feasible
  - Overcoming difficulties with renormalization and mixing
  - Rely on perturbation theory
- **PDFs on the lattice**
  - Now accessible!
  - Proper renormalization required
- **New physics BSM**
  - Lattice QCD provides predictions
- **Results emerging from other particles** (see Backup slides)

EINN2015

11th European Research Conference on
"Electromagnetic Interactions with Nucleons and Nuclei"
1-7 November 2015
Annabelle Hotel, Paphos, Cyprus

OVERVIEW

Pre-conference: 1-2 November 2015

- Frontiers and Careers in Photonuclear Physics - skill development and talks for students
- Introductory talks

Main conference: 3-7 November 2015

Conference Topics

- Nucleon form factors and low-energy hadron structure
- Partonic structure of nucleons and nuclei
- Precision electroweak physics and new physics searches
- Meson structure
- Baryon and light-meson spectroscopy
- Nuclear effects and few-body physics

Parallel Workshops

I. Spin structure of nucleons and nuclei from low to large energy scales
II. Spectroscopy – status and future prospects

Poster Session

We invite you to submit abstracts for talks at the workshops and for the poster session. Contributions not selected for talks will be given the option of a poster presentation.

INTERNATIONAL ADVISORY COMMITTEE

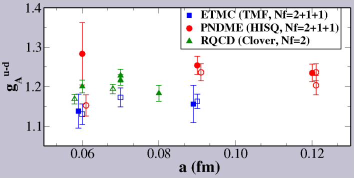
- Mauro Anselmino (University of Torino, Italy)
- Sinya Aoki (University of Kyoto, Japan)
- Reinhard Beck (University of Bonn, Germany)
- Andrea Bressan (CERN, Switzerland)
- Annalisa D'Angelo (University of Rome-II, Italy)
- Achim Denig (University of Mainz, Germany)
- Karl Jansen (DESY, NIC, Germany)
- Xiangdong Ji (University of Maryland, USA)
- Max Klein (DESY, Germany)
- Karlheinz Langanke (GSI, Germany)
- Gerhard Mallot (CERN, Switzerland)
- William Marciano (BNL, USA)

THANK YOU

Join us!

BACKUP SLIDES

1. Cut-off effects



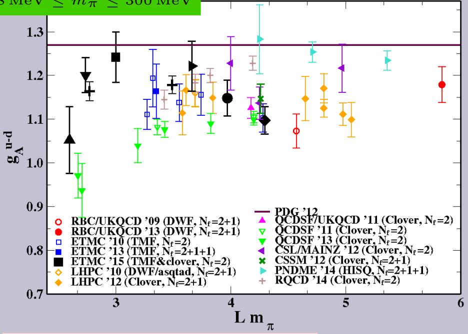
Continuum extrapolation requires 3 lattice spacings

[C. Alexandrou et al. (ETMC), arXiv:1012.0857]
[G. Bali et al. (RQCD), 2014]
[R. Gupta et al. (PNDME), 2014]

$a < 0.1$ fm is sufficient

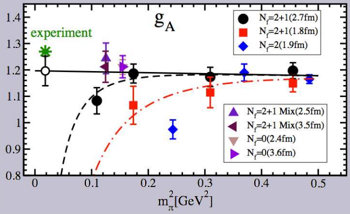
2. Finite Volume Effects

$128\ \text{MeV} \leq m_\pi \leq 300\ \text{MeV}$



Lattice data for plateau method
No volume corrections

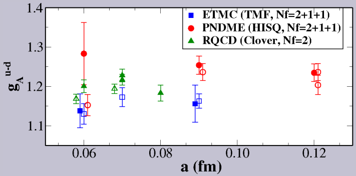
[T. Yamazaki et al. (RBC/UKQCD) arXiv:0801.4016]



FVE not fully understood:

Group	m_π (MeV)	Lm_π	g_A
QCDSF	158	2.7	1.052(76)
ETMC	131	3.0	1.242(57)
PNDME	125	3.7	1.222(57)
LHPC	149	4.0	1.097(32)

1. Cut-off effects



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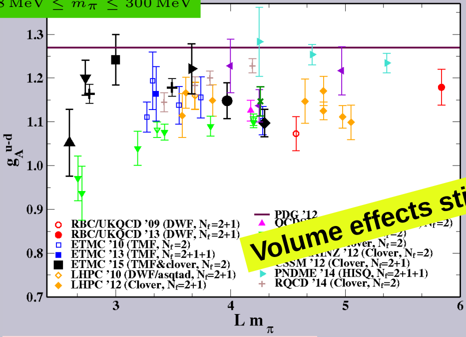
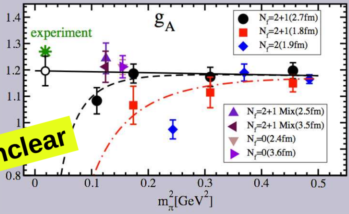


Volume effects still unclear

Lattice data for plateau method
No volume corrections

[T. Yamazaki et al. (RBC/UKQCD) arXiv:0801.4016]



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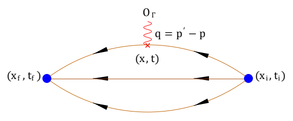
3. Excited State Analysis

Plateau Method: single-state fit

$$R(t_i, t, t_f) \xrightarrow[(t-t_i)\Delta >> 1]{(t_f - t)\Delta >> 1} \mathcal{M}\left[1 + \alpha\, e^{-((t_f - t)\Delta(p'))} + \beta\, e^{-((t - t_i)\Delta(p))} + \dots\right]$$

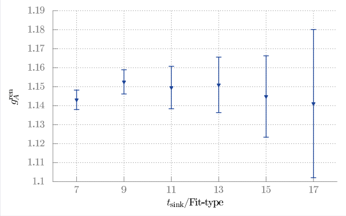


t_i : t_{source}
t : $t_{\text{insersion}}$
t : t_{sink}
$T_{\text{sink}} \equiv t_f - t_i$

Summation Method

$$\sum_{t=t_i}^{t_f} R(t_i, t, t_f) = \text{const.} + \mathcal{M}\, T_{\text{sink}} + \mathcal{O}\left(e^{-(T_{\text{sink}}\Delta(p'))}\right) + \mathcal{O}\left(e^{-(T_{\text{sink}}\Delta(p))}\right)$$

- **suppressed excited states (exponentials decaying with T_{sink})**
- **Matrix element extracted from the slope**
- **Alternatively: sum over $t_i + 1 \le t \le t_f - 1$**



❶ Plateau Method: single-state

⇐ **RQCD (2014):**

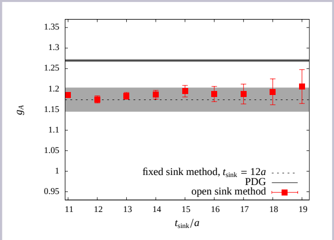
[G.Bali et al. (RQCD), 2014]

- $m_\pi = 285$MeV
- g_A not sensitive on T_{sink}: 0.49-1.19 fm

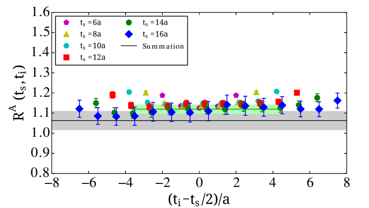
ETMC (2013): ⇒

[S.Dinter et al. (ETMC), arXiv:1108.1076]

- $m_\pi = 373$MeV
- g_A not sensitive on T_{sink}



$T_{\text{sink}} > 1$ fm appears safe

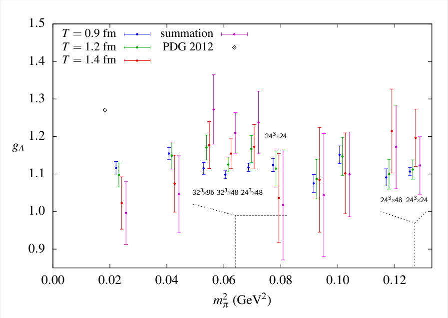


❷ Summation Method

⇐ **ETMC (2013):**

[S.Dinter et al. (ETMC), arXiv:1108.1076]

- $m_\pi = 373$MeV
- T_{sink}: 0.3 fm-1.3 fm
- No curvature is seen in slope
- No detectable excited states



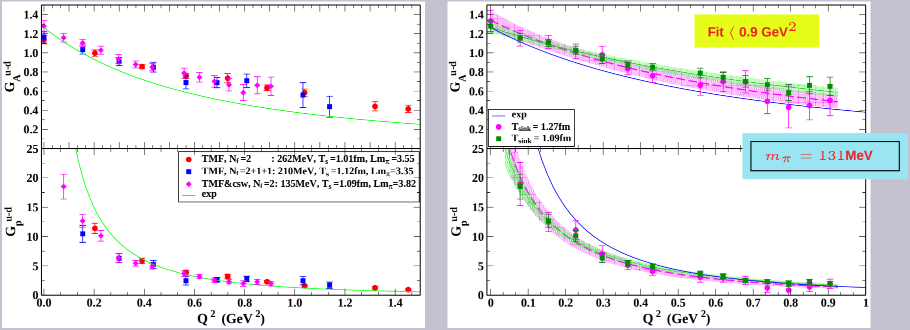
❶ Plateau Method: single-state fit

LHPC (2012): [J.R.Green et al. (LHPC), arXiv:1211.0253]

- $m_\pi \geq 149$MeV
- light m_π : g_A ↘ with T_s ↗
- $L_t/a \geq 48$: g_A ↗ with T_s ↗
- Indication of thermal pion states

B2. Nucleon Axial form factors

ETM, $N_f = 2$, $N_f = 2+1+1$ and ETM & clover , $N_f = 2$



★ **Dipole fits:**

$$G_A(Q^2) = \frac{g_A}{\left(1 + Q^2/m_A^2\right)^2}$$

$$G_p(Q^2) = \frac{G_A(Q^2)\,G_p(0)}{\left(Q^2 + m_p^2\right)}$$

$m_A^{exp} = 1.069\text{GeV}$ †

$1.2\text{GeV} \langle m_A^{lattice} \langle 1.45\text{GeV}$ ⋆

$0.3\text{GeV} \langle m_p^{lattice} \langle 0.5\text{GeV}$ ⋆

† [V.Bernard et al., hep-ph/0607200]

⋆ ETM, m_π=131MeV (ETMC 2014)

- G_p strongly dependent on the lowest values of Q^2

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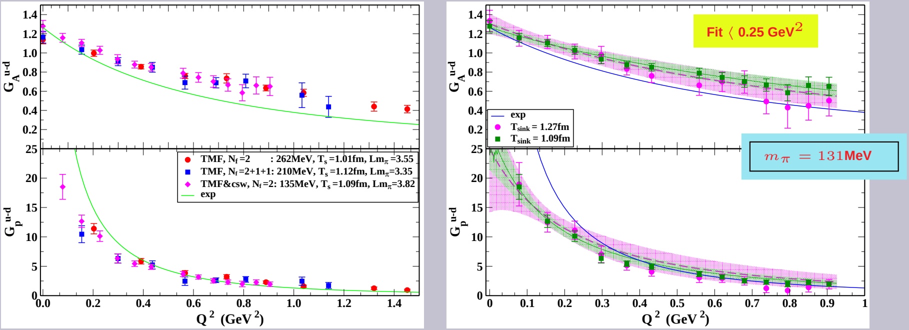

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Generalized pencil-of-function

- Better extraction of states contributing to a correlator
- Variational method using 3pt-functions with 3 equally spaced sink locations

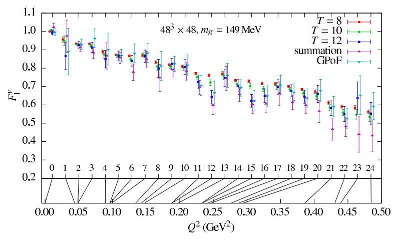
$$\mathbf{C}^{3-\mathrm{pt}}(t_i, t, t_f) = \begin{pmatrix} C^{3-\mathrm{pt}}(t_i, t, t_f) & C^{3-\mathrm{pt}}(t_i, t, t_f+\tau) \\ C^{3-\mathrm{pt}}(t_i, t+\tau, t_f+\tau) & C^{3-\mathrm{pt}}(t_i, t+\tau, t_f+2\tau) \end{pmatrix}$$

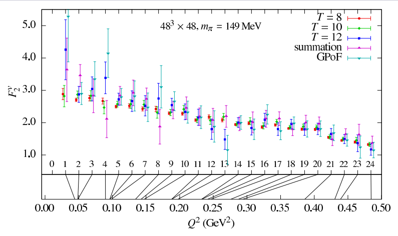
- Computational cost $\times 3$, but better ground signal

Nucleon EM form factors

$$\langle N(p', s')|\gamma_\mu|N(p,s)\rangle \sim \bar{u}_N(p', s')\left[\mathbf{F_1(q^2)}\gamma_\mu + \mathbf{F_2(q^2)}\frac{i\,\sigma^{\mu\rho}\,q_\rho}{2m_N}\right]u_N(p,s)$$

LHPC: $m_\pi = 149$MeV, $a = 0.116$fm, $\mathcal{O}(7\,800)$ stat.

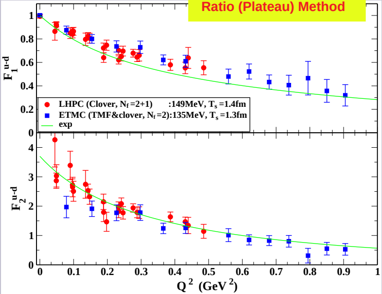




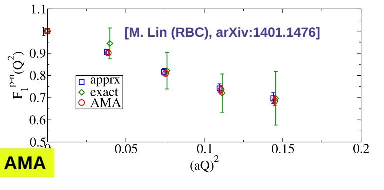
[J.R.Green et al. (LHPC), arXiv:1211.0253]

- **Summation method goes either direction**
- **errors are large**

Ratio (Plateau) Method



- **ETMC:** $a = 0.094$ fm, $L = 4.5$ fm, $L\,m_\pi = 3.1$
- **LHPC:** $a = 0.116$ fm, $L = 5.6$ fm, $L\,m_\pi = 4.2$



AMA

Quark Momentum Fraction

1-Derivative Vector current:

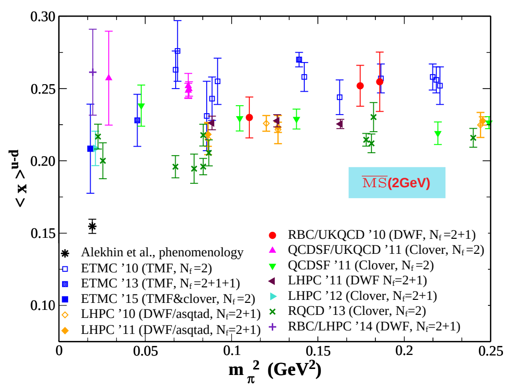
$$\mathcal{O}^{\mu\nu}_{\rm DV} \equiv \bar{\psi}\,\gamma^{\{\mu}\,\overleftrightarrow{D}^{\,\nu\}}\psi$$

$$\begin{aligned}\langle N(p',s')|\mathcal{O}^{\mu\nu}_{\rm DV}|N(p,s)\rangle \;&=\; \bar{u}_N(p',s')\Big[\mathbf{A_{20}(q^2)}\,\gamma^{\{\mu}P^{\nu\}} \\ &+\mathbf{B_{20}(q^2)}\,\frac{i\sigma^{\{\mu\alpha}q_\alpha P^{\nu\}}}{2m} + \mathbf{C_{20}(q^2)}\,\frac{1}{m}q^{\{\mu}q^{\nu\}}\Big]u_N(p,s)\end{aligned}$$

$$\langle x\rangle_q \equiv \langle N(\vec{p}')\mathcal{O}^{00}_{\rm DV}N(\vec{p})\rangle\Big|_{q^2=0} = A_{20}(0)$$

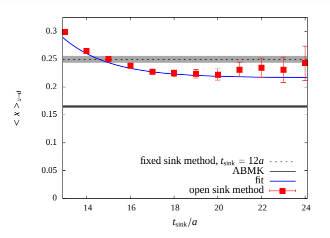
- ★ Important quantity to understand nucleon structure
- ★ Benchmark quantity for lattice QCD calculations

Quark Momentum Fraction



ETM, $m_\pi = 375$MeV

[S.Dinter et al. (ETMC), arXiv:1108.1076]



- $\mathcal{O}(23\,000)$ measurements
- $0.94\,\mathrm{fm} < T_{\mathrm{sink}} < 1.87\,\mathrm{fm}$

- Measured in DIS experiments. Value uses input from phen. models
- $\langle x \rangle^{\mathrm{phen}} = 0.1646(27)\ (\overline{\mathrm{MS}}(2\mathrm{GeV}))$

[S. Alekhin et al., arXiv:0908.2766]

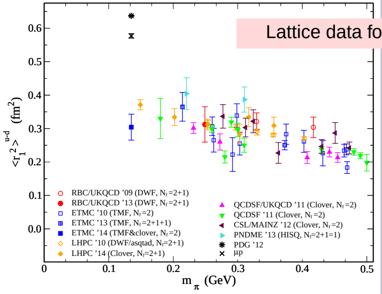
- Scheme and scale dependence
- All lattice results overestimate phen. value
- Chiral behavior: $m_\pi^2\ \log(m_\pi^2)$

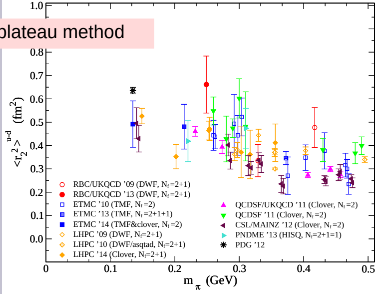
Dirac & Pauli radii

$$F_i(Q^2) \sim F_i(0)\left(1 - \frac{1}{6}Q^2\langle \mathbf{r_i^2}\rangle + \mathcal{O}(Q^4)\right) \qquad \langle \mathbf{r_i^2}\rangle = -\frac{6}{F_i(Q^2)}\frac{dF_i(Q^2)}{dQ^2}\Big|_{Q^2=0}$$

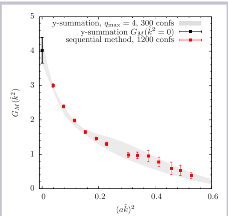
$$F_i(Q^2) \sim \frac{F_i(0)}{\left(1+\frac{Q^2}{m_i^2}\right)^2} \Rightarrow \langle \mathbf{r_i^2}\rangle = \frac{12}{m_i^2}$$

Lattice data for plateau method





- **Estimation of radii strongly depends on small Q^2**
- **Need access for momenta close to zero $\Rightarrow$**
- **larger volumes**



★ **Avoid model dependence-fits: Position space method**

$$\langle N(p',s')|\gamma_\mu|N(p,s)\rangle \sim \bar{u}_N(p',s') \sim q_\rho \sigma^{\mu\rho} F_2 + \cdots$$

[C. Alexandrou et al. (ETMC), arXiv:1410.8818]

Renormalization

RI' scheme:

$$Z_q = \frac{1}{12}\mathrm{Tr}\left[\left(S^L(p)\right)^{-1} S^{\mathrm{Born}}(p)\right]\Big|_{p^2=\bar\mu^2} \qquad Z_q^{-1}\, Z_{\mathcal{O}}\, \frac{1}{12}\mathrm{Tr}\left[\Gamma^L_{\mathcal{O}}(p)\, \left(\Gamma^{\mathrm{Born}}_{\mathcal{O}}(p)\right)^{-1}\right]\Big|_{p^2=\bar\mu^2} = 1$$

★ **Tension between** $Z_{\mathcal{O}}^{\mathrm{pert}}$ **and** $Z_{\mathcal{O}}^{\mathrm{non-pert}}$

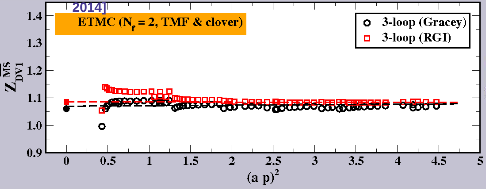
- up to 15%
- either direction

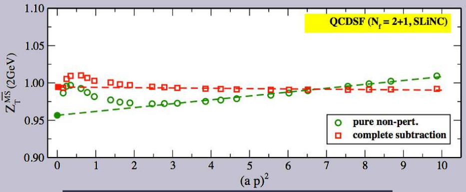
➥ **Non-perturbative renormalization**

★ **Conversion to** $\overline{\mathrm{MS}}(\mu = 2\mathrm{GeV})$

Control of lattice artifacts

[M. Constantinou et al. (QCDSF), 2014]

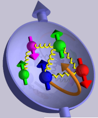




- Z_{DV1} : Z-factor of $\langle x\rangle_{u-d}$
- Systematic due to conversion insignificant

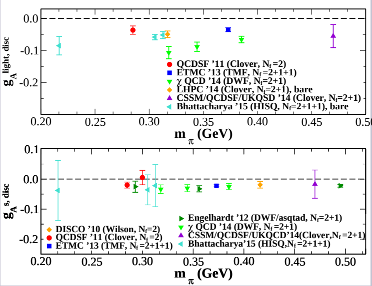
Synergy with P.T.:

- Lattice artifacts computed perturbatively
- Subtraction from non-perturbative estimates

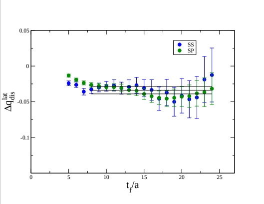


Nucleon Spin

Disconnected Contributions

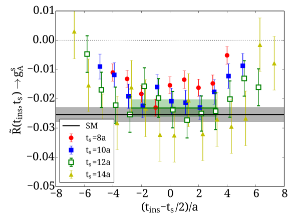


g_A^{light}



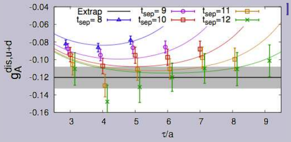
[G.S.Bali et al. (QCDSF), arXiv:1112.3354]

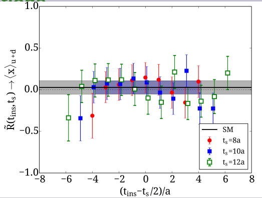
g_A^s



$$g_A^s \;:\; \langle N(p')|\bar{s}\,\gamma_\mu\,\gamma_5\,s|N(p)\rangle\Big|_{q^2=0}$$

- ★ **Agreement between different discretizations**
- ★ **DI for g_A lower the total value**





$\langle x \rangle_{u+d}$

Challenges with Renormalization of Gluon operator

- **Mixing with Quark singlet operator:** $\mathcal{O}^q \equiv \bar{\psi}\,\gamma^{\{\mu}\,\overleftrightarrow{D}^{\,\nu\}}\psi$

Unavoidable

- **Mixing with other Operators:**
  - Gauge invariant
  - BRS-variations
  - vanish by the e.o.m.

Vanish in physical matrix elements

Perturbative computation

[M. Constantinou et al. (Cyprus Group), 2015]

- **Multiplicative renormalization**
- **Identification of mixing**
- **General action parameters**
- **(wide applications)**
- **Stout smearing (action & operator)**

$$Z_{gg} = 1 + \frac{g^2}{16\pi^2}\left(1.0574\,N_f + \frac{-13.5627}{N_c} - \frac{2\,N_f}{3}\log(a^2\bar{\mu}^2)\right)$$

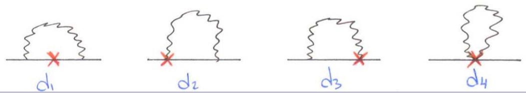
$$Z_{gq} = 0 + \frac{g^2\,C_f}{16\pi^2}\left(0.8114 + \frac{4}{3}\log(a^2\bar{\mu}^2)\right)$$

$$\langle x\rangle_g^R = Z_{gg}\langle x\rangle_g^B + Z_{gq}\langle x\rangle_q^B$$

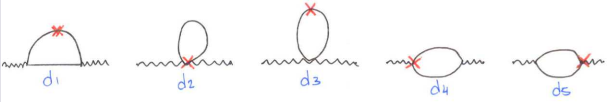
Challenges with Renormalization

Contributing Diagrams

$\times Z_{qq}$: $\Lambda_{qq} = \langle q|\mathcal{O}_q|q\rangle$



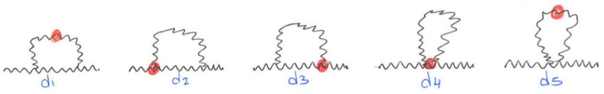
$\times Z_{qg}$: $\Lambda_{qg} = \langle g|\mathcal{O}_q|g\rangle$



$\bullet Z_{gq}$: $\Lambda_{gq} = \langle q|\mathcal{O}_g|q\rangle$

many millions of terms...

$\bullet Z_{gg}$: $\Lambda_{gg} = \langle g|\mathcal{O}_g|g\rangle$



D

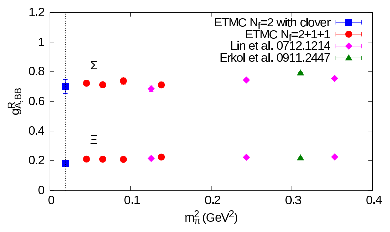
OTHER

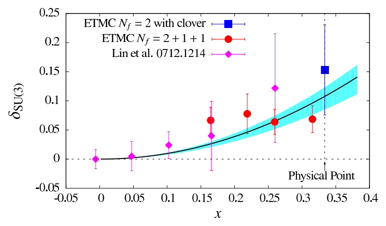
PARTICLES

D1. Axial charges of hyperons

Axial matrix element: $\langle B(p')|\bar{\psi}(x)\,\gamma_\mu\,\gamma_5\,\psi(x)|B(p)\rangle\Big|_{q^2=0}$

- **Connected part**





[C.Alexandrou et al. (ETMC), arXiv:1411.3494]

- **First promising results at the physical point**
- **SU(3) breaking** $\delta_{SU(3)} = g_A^N - g_A^\Sigma + g_A^\Xi$ **versus** $x = \left(m_K^2 - m_\pi^2\right)/(4\pi^2 f_\pi^2)$

D2. Pion Quark distribution function

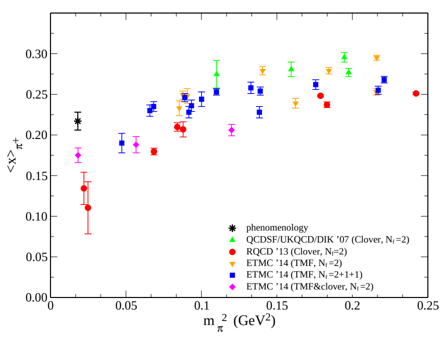
[C.Urbach et al. (ETMC), 2014]: $N_f=2$, $2+1+1$ ETM, $N_f=2$ ETM & clover

Lowest moment with H(4)-operator:

$$\mathcal{O}_{44}(x) = \frac{1}{2}\bar{u}(x)[\gamma_4 \overleftrightarrow{D}_4 - \frac{1}{3}\sum_{k=1}^{3}\gamma_k \overleftrightarrow{D}_k]u(x)$$

$$\langle x\rangle^{\text{bare}}_{\pi^+} = \frac{1}{2\,m_\pi^2}\langle \pi,\vec{0}|\mathcal{O}_{44}|\pi,\vec{0}\rangle$$

- No external momentum is needed in the calculation
- Stochastic time slice sources:
  - less inversions
  - statistical accuracy
- disconnected contributions not included



phenomenology: $\langle x\rangle^{u-d}_{\pi^\pm}(\mu = 2.28GeV) = 0.223(11) \rightarrow \langle x\rangle^{u-d}_{\pi^\pm}(\mu = 2GeV) = 0.229(11)$

[K. Wijesooriya et al., nucl-ex/0509012]

[R. Baron et al. (ETMC), arXiv:0710.1580]

[D. Brommel (QCDSF/UKQCD) Pos(LATTICE) 2007, 140]

[G. Bali et al. (RQCD), arXiv:1311.7639]

[C. Urbach et al. (ETMC), 2014]