Spin, Mass and 3D Imaging:
"What can Lattice QCD teach us?"

Martha Constantinou

Temple University

EIC Users Group Meeting

July 31, 2018

OUTLINE OF TALK

A. **Motivation - Introduction**

C. **Proton Mass**

D. **Proton Spin**

E. **PDFs**

F. **TMDs**

G. **Discussion**

A

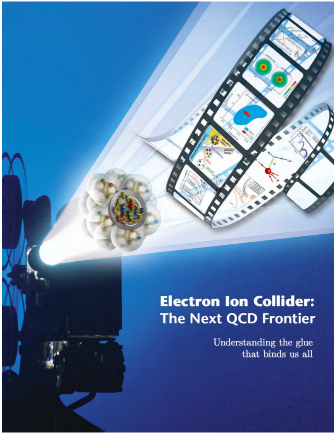
Motivation

&

Introduction

Synergy of the EIC and Lattice QCD

★ **4-D discretization, *ab initio* formulation of QCD**



"... EIC and lattice calculations will have a high degree of complementarity. For some quantities ... a precise determination will be possible both in experiment and on the lattice.

... to validate methods used in lattice calculations, one will gain confidence in computing quantities whose experimental determination is very hard...

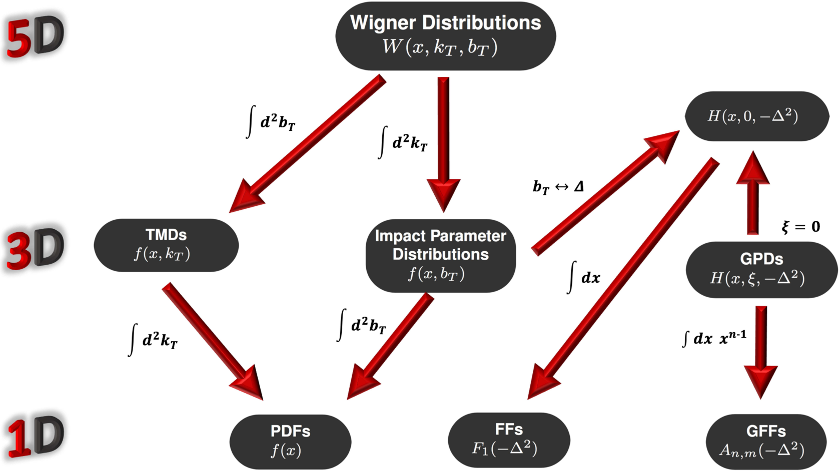
... gain insight into the underlying dynamics by computing the same quantities with values of the quark masses that are not realized in nature, so as to reveal the importance of these masses for specific properties of the nucleon."

[A. Accardi et al., arXiv:1212.1701]

★ **Also: Guide New Physics searches**

See also talk by Ross Young, this meeting

Nucleon Characterization



[X. Ji, D. Mueller, A. Radyushkin]

What can we learn from Lattice QCD?

★ **Long history of calculating moments of PDFs and GPDs:**

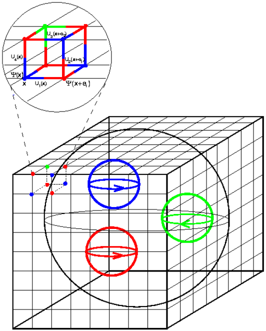
- Addressing open questions: proton mass, spin, charged radii
- FFs and GFF vs momentum transfer
- Investigation of sea quark and gluon contributions

★ **Exploration of novel approaches to access PDFs and TMDs directly from the lattice**

- x-dependence of unpolarized, polarized and transversity quark distributions
- Sivers function, Boer-Mulders function, generalized tensor charge, Worm Gear function
- Quark Orbital Angular Momentum in different decompositions

Lattice formulation of QCD

- Space-time discretization on a finite-sized 4-D lattice
  - Quark fields on lattice points
  - Gluons on links
- Serves as a regulator
  - UV cut-off: inverse lat. spacing
  - IR cut-off: inverse lattice size



courtesy: USQCD

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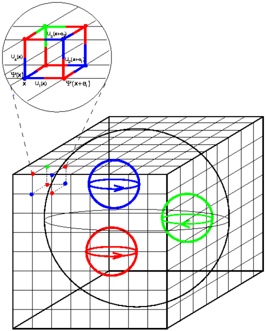

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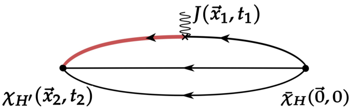
Technical Aspects

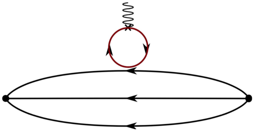
★ Parameters (define cost of simulations):
- quark masses (aim at physical values)
- lattice spacing (ideally fine lattices)
- lattice size (need large volumes)

★ Discretization not unique:
- Wilson, Clover, Twisted Mass, Staggered, Overlap, Domain Wall
- Mixed actions

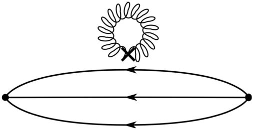
Nucleon on the Lattice



Connected

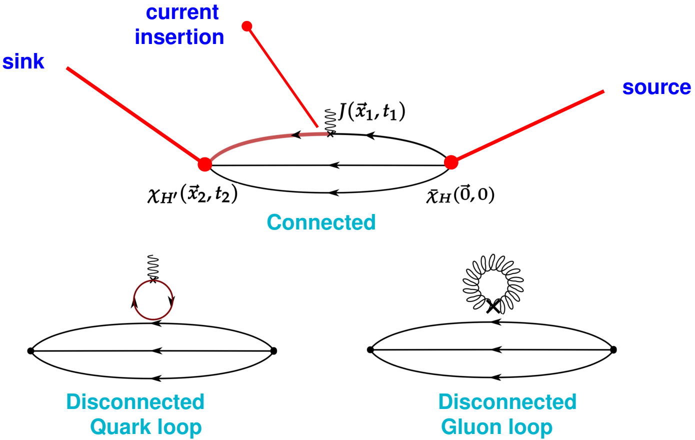


Disconnected
Quark loop



Disconnected
Gluon loop

Nucleon on the Lattice



Separation between source & sink (T_{sink}): excited states investigation

Current insertion: ultra-local, cov. derivatives, Wilson line(straight, stables)

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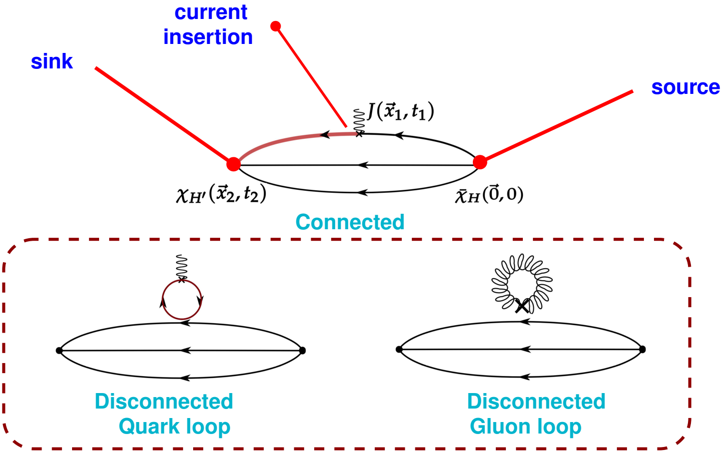

Particularly interesting for EIC physics

Separation between source & sink (T_{sink}): excited states investigation

Current insertion: ultra-local, cov. derivatives, Wilson line(straight, stables)

Inherited Uncertainties

Laborious effort to eliminate uncertainties

Statistical errors significantly increase with:

- ★ decrease of pion mass
- ★ increase of momentum transfer Q^2 between source-sink
- ★ increase of source-sink separation ($T_{\rm sink}$)

Systematic

- ★ Cut-off Effects due to finite lattice spacing
- ★ Finite Volume Effects
- ★ Contamination from other hadron states
- ★ Chiral extrapolation for unphysical pion mass
- ★ Renormalization and mixing

B

Proton Mass

Origin of Proton Mass

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- ★ **Mass is a complicated mechanism:**

Energy-Momentum Tensor [Ji, Phys. Rev. Lett. 74 (1995)]

$$T^{\mu\nu}=\frac{1}{2}\bar{\psi}i\overleftrightarrow{D}^{(\mu}\gamma^{\nu)}\psi+\frac{1}{4}g^{\mu\nu}F^2-F^{\mu\alpha}F_{\alpha}^{\nu}$$

$$m=\frac{\langle N|\int d^3xT^{44}|N\rangle}{\langle N|N\rangle}$$

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- ★ **Very important to compute from first principles and test it against planned measurements**

[https://www.jlab.org/exp_prog/proposals/12/PR12-12-006.pdf", "Near Threshold Electro- production of J/Ψ at 11 GeV."]

See also talk by Ian Cloët, this meeting

Proton Mass Decomposition

Results @ physical point of connected & disconnected contributions:

[C. Alexandrou et al., PRL 116, 252001 (2016), arXiv:1601.01624] [C. Alexandrou et al., PRL 119, 142002 (2017), arXiv:1706.02973]

- ★ **nucleon σ-terms** $\sum_{q=u,d,s,c} \sigma_q$
- ★ **quark momentum fraction** $\sum_{q=u,d,s,c} \langle x \rangle_q$
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$$M_q = \frac{3}{4}\left(M_p \sum_q \langle x \rangle_q - \sum_q \sigma_q\right)$$

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- ★ **Gluon energy**

$$M_g = \frac{3}{4} M_p \langle x \rangle_g$$

- ★ **Trace anomaly**

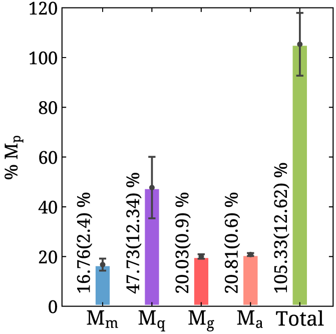
$$M_a = \frac{1}{4} \left(M_p - \sum_q \sigma_q \right), \quad M_p = -4 \langle \hat{T}_{44} \rangle$$

Proton Mass Budget

Approach A

$$M_a = \frac{M_p}{4} - \sum_q \frac{\sigma_q}{4} \sim \textbf{20.81(0.6)\%}$$

$$M_p = M_m + M_q + M_g + M_a = \textbf{105.33(12.62)\%}$$



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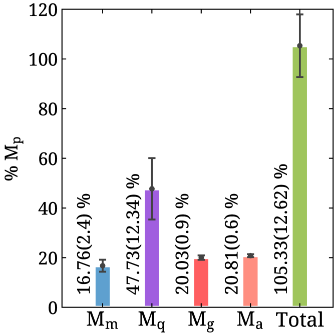
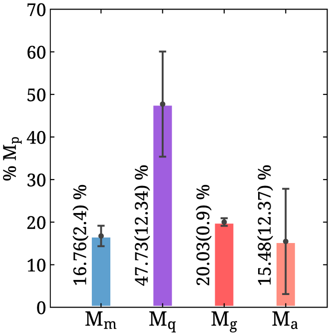


Approach B

$$M_a = M_p - \sum_{i=m,q,g} M_i \sim \boxed{15.48(12.37)\%}$$

M_p: **constrained**



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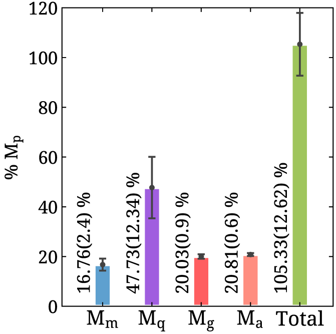

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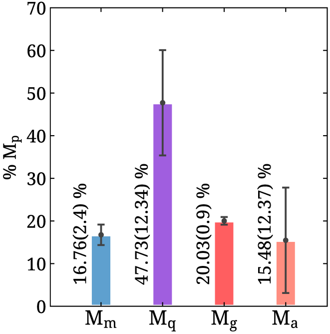

- ★ M_a in Approach A and B compatible, but different systematics
- ★ Thus, sum rules should be avoided if possible
- ★ Crucial to compute $\langle \hat{T}_{44} \rangle$ directly to control uncertainties

B

Proton Spin

Spin Structure from First Principles

DIS experiment (1988) show 20-30% of spin carried by valence quarks

"... $g_1(x)$ for the proton has been determined and its integral over x found to be $0.114 \pm 0.012 \pm 0.026$, in disagreement with the Ellis-Jaffe sum rule. ... These values for the integrals of g_1 lead to the conclusion that the total quark spin constitutes a rather small fraction of the spin of the nucleon." [J. Ashman et al., Phys. Lett., vol. B206 (1988) 364]

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We need a theoretical formulation to address the proton spin puzzle
Lattice QCD

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Spin Sum Rule (Ji):

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

L_q: **Quark orbital angular momentum**
$\Delta\Sigma_q$: **intrinsic spin**
J^G: **Gluon part**

- **naive non-relativistic SU(6) quark model:** $\Delta\Sigma = 1,\ L_q = 0,\ J_g = 0$

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Extraction from Lattice QCD:

$$\boxed{J^q = \frac{1}{2}\left(A^q_{20} + B^q_{20}\right), \quad L^q = J^q - \Sigma^q, \quad \Sigma^q = g^q_A}$$

Necessary computations:

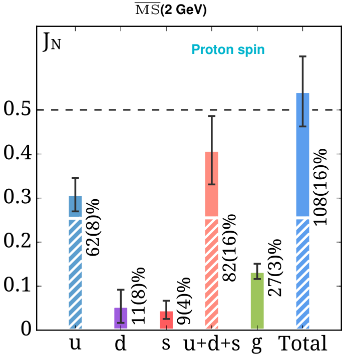
- ★ **Axial Charge**
- ★ **Quark Momentum Fraction**
- ★ **Gluon Momentum Fraction**

See also talk by Andrea Bressan, this meeting

The proton spin puzzle from Lattice QCD

C. Alexandrou et al., Phys. Rev. Lett. 119, 142002 (2017), [arXiv:1706.02973]

★ **ETM Collaboration: simulations at the physical point**



Striped segments: valence quark contributions (connected)
Solid segments: sea quark & gluon contributions (disconnected)

★ **Satisfaction of spin and momentum sum rule is not forced**

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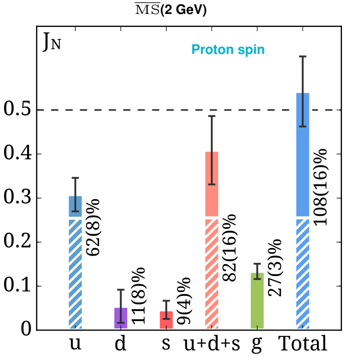
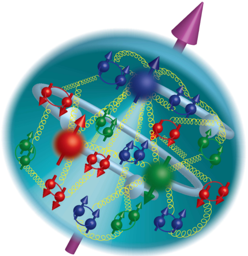


Better understanding of the spin distribution



Designed by Z.-E. Meziani

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D

1-D Structure:

Direct Access to PDFs

PDFs on the Lattice

★ **Moments of PDFs easily accessible in lattice QCD**

- one relies on OPE to reconstruct the PDFs
- reconstruction difficult task:

  $\Rightarrow$ signal-to-noise is bad for higher moments
  $\Rightarrow$ n $>$ 3: operator mixing (unavoidable!)

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★ **Alternative approaches to access PDFs**

- Hadronic Tensor [K.F. Liu, Dong, PRL 72 (1994) 1790, K.F. Liu, PoS(LATTICE 2015) 115]
- Compton amplitude and OPE [A. Chambers et al. (QCDSF), [arXiv:1703.01153]

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★ **Direct access to PDFs**

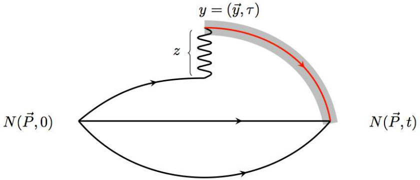
- quasi-PDFs [X. Ji, arXiv:1305.1539]
- pseudo-PDFs [A. Radyushkin, arXiv:1705.01488]
- good lattice cross-sections [Y-Q Ma&J. Qiu, arXiv:1709.03018]

Access of PDFs on a Euclidean Lattice

Novel direct approach:

[X.Ji, Phys. Rev. Lett. 110 (2013) 262002, arXiv:1305.1539]

- ★ **Matrix elements of spatial operators with a Wilson line (length z)**
- ★ **Nucleon is boosted with momentum in spatial direction (e.g. z)**
- ★ **Renormalization more complicated than other nucleon quantities**

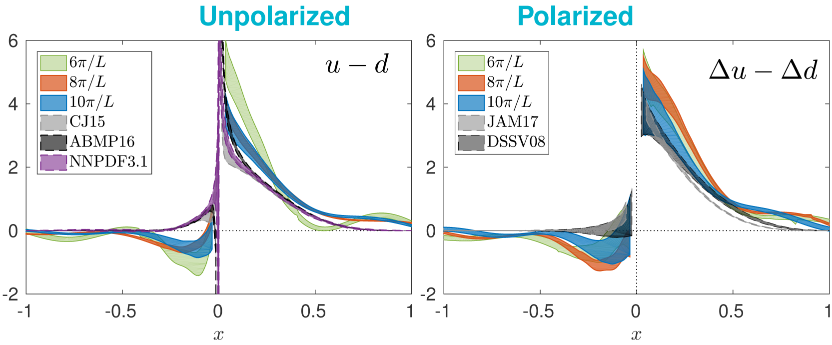


Contact with light-cone PDFs:

- ★ **Difference between quasi-PDFs and light-cone PDFs:**
  $\mathcal{O}\left(\frac{\Lambda^2_{QCD}}{P_3^2}, \frac{m_N^2}{P_3^2}\right)$
- ★ **Matching procedure (in LaMET) necessary**
  (provided that momenta are finite but feasibly large for lattice)

Towards light-cone PDFs

[C. Alexandrou et al. (ETMC), arXiv:1803.02685]

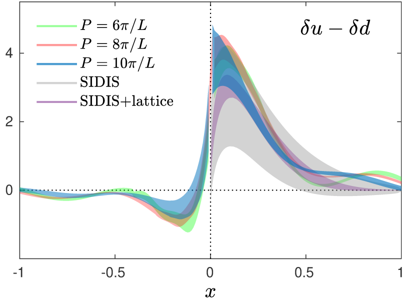


- ★ **Increasing momentum approaches the phenomenological fits**
- ★ **Saturation for** $p = 8\pi/L$ **and** $p = 10\pi/L$
- ★ $0 < x < 0.5$: **Lattice polarized PDF overlap with phenomenology**
- ★ **Negative** x **region: anti-quark contribution**

Towards light-cone PDFs

[C. Alexandrou et al. (ETMC), arXiv:1807.00232]

Transversity



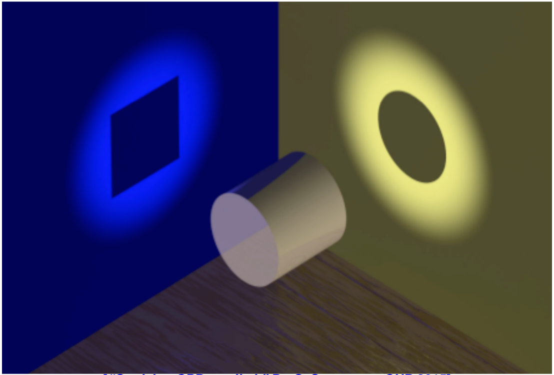
- ★ **Transversity PDFs poorly constrained from phenomenology**
- ★ **Lattice results on g_T reduces SIDIS uncertainties**
- ★ **Smaller uncertainties in *ab* initio lattice calculation (quasi-PDFs)**
- ★ **Precise data are expected from SoLID**

E

3-D Structure:

TMDs

Why 3-D structure important?



[*"Studying GPDs at JLab"* Dr. S. Stepanyan, GHP 2015]

- ★ **Hadron structure is extremely complicated**
- ★ **Variety of functions are needed for a better understanding: PDFs, GPDs, TMDs**
- ★ **A need to study 3-D imaging *ab initio***

DoE funded Topical Collaboration for theory

Slide from J.-W. Qiu, Transversity 2018

TMD Collaboration

18 institutions
Theory, phenomenology, lattice QCD
Several postdoc positions.
2 tenure track positions: Temple, NMSU
Support of undergraduates.

The TMD Collaboration
Spokespersons: William Detmold (MIT) and Jianwei Qiu (BNL)

Co-Investigators - (in alphabetical order of institutions):
Jianwei Qiu and Raju Venugopalan (Brookhaven National Laboratory)
Thomas Mehen (Duke University)
Ted Rogers (Jefferson Laboratory and Old Dominion University)
Alexei Prokudin (Jefferson Laboratory and Penn State University at Berks)
Feng Yuan (Lawrence Berkeley National Laboratory)
Christopher Lee and Ivan Vitev (Los Alamos National Laboratory)
William Detmold, John Negele and Iain Stewart (MIT)
Matthias Burkardt and Michael Engelhardt (New Mexico State University)
Leonard Gamberg (Penn State University at Berks)
Andreas Metz (Temple University)
Sean Fleming (University of Arizona)
Keh-Fei Liu (University of Kentucky)
Xiangdong Ji (University of Maryland)
Simonetta Liuti (University of Virginia)

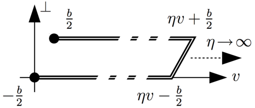
- 5 years of funding
- 18 institutions
- Theory, phenomenology, lattice QCD
- Several postdoc and tenure track positions are created
- "To address the challenges of extracting novel quantitative information about the nucleon's internal landscape"
- "To provide compelling research, training, and career opportunities for young nuclear theorists"

TMDs from Lattice QCD

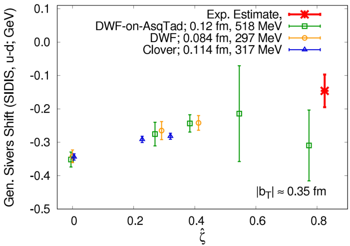
[B. Yoon et al., Phys. Rev. D 96, 094508 (2017), and earlier works of M. Engelhardt]

Correlator studied on the lattice:

$$\tilde{\Phi}^{[\Gamma]}_{\text{unsubtr.}}(b, P, S) \equiv \langle P, S|\bar{\psi}(-b/2)\Gamma\mathcal{U}[-b/2, b/2]\psi(b/2)|P, S\rangle$$



- ★ $\mathcal{U}$: **Staple of gauge links**
- ★ $\tilde{\Phi}^{[\Gamma]}_{\text{unsubtr.}}$ **includes ultraviolet and soft divergences**
- ★ $n = 0$ **may also be studied (straight wilson line)**
- ★ $|n| \to \infty$: **gluon exchange in SIDIS and DY**
- ★ b: **transverse to proton momentum (**P**)**
- ★ **different structures for** Γ **give access to: Sivers ratio, Boer-Mulders ratio,** h_1 **,** g_{1T}



Plot:
Collins-Soper parameter: $\hat{\zeta} \equiv \frac{u \cdot P}{|u|\,|P|}$**, light cone:** $\hat{\zeta} \to \infty$
Exp. value: global fit to HERMES, COMPASS and JLab data [M. Echevarria et al., Phys. Rev. D 89 (2014)]

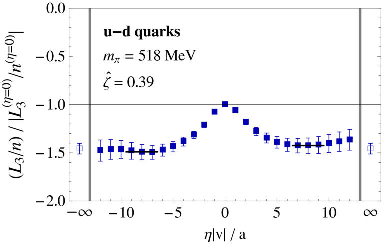
TMDs and Orbital Angular momentum

[Abha et al., Phys. Rev. D 94, 034041 (2016), M. Engelhardt, Phys. Rev. D 95, 094505 (2017)]

$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta_q + \boxed{\textstyle\sum_q L_q} + J_g \qquad \text{(Ji)}$$

$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta_q + \boxed{\textstyle\sum_q \mathcal{L}_q} + \Delta_g + \mathcal{L}_g \qquad \text{(Jaffe} - \text{Manohar)}$$

- ★ L_q **extracted indirectly in Lattice QCD:** $L_q = J_q - \frac{1}{2}\Delta_q$
- ★ $\mathcal{L}_q$ **not accessible in Lattice QCD**
- ★ **straight link operators related to** L_q
- ★ **staple-link operators related to** $\mathcal{L}_q$
- ★ **operator same as in TMD studies (off-forward matrix element)**
- ★ **Difference is torque accumulated due to final state interaction**



Plot: $\mathcal{L}_q$ **vs staple length parameter, in units of** L_q

See also talk by Simonetta Liuti, this meeting

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Discussion

Discussion

Lattice QCD important for understanding nucleon structure

- ★ **Simulations at the physical point**
- ★ **Addressing open questions: proton mas and spin**
- ★ **More complicated calculations**
  (quasi-PDfs, pseudo-PDFs, good LCSs, hadronic tensor)
- ★ **First calculation on 3-D structure are here (TMDs)**
- ★ **Can provide valuable input for the EIC**

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Many more “mountain peaks” to conquer

- ★ Quantify systematic uncertainties
  (excited states, volume effects, discretization effects...)
- ★ Direct access to important quantities (OAM, trace anomaly)
- ★ Explore other baryons and mesons

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Significant progress also in:

- ★ Spectroscopy
- ★ Nuclear effects

THANK YOU

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