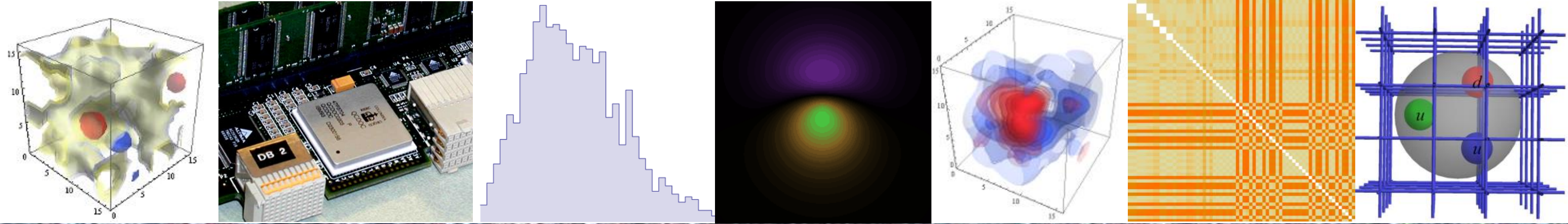
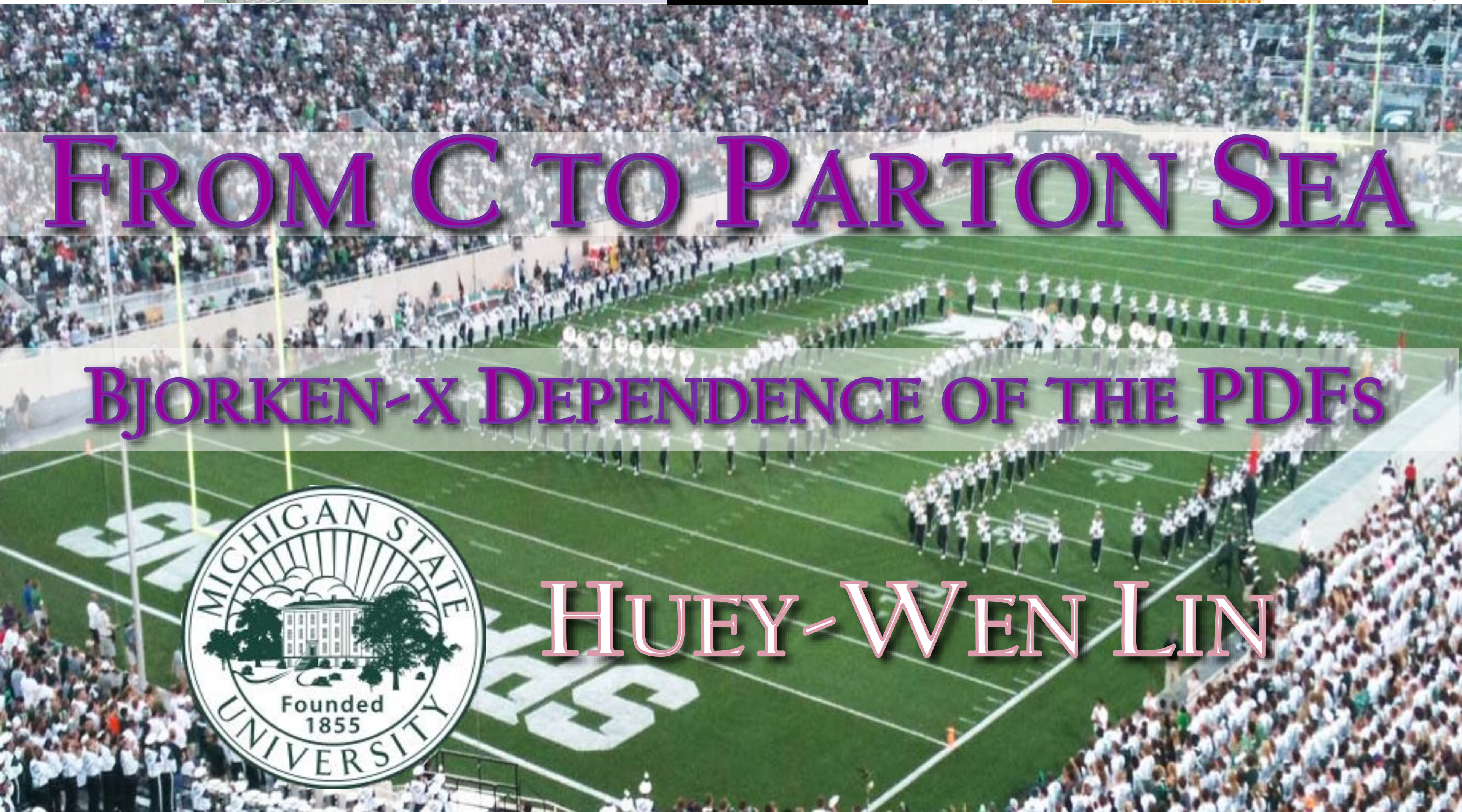




From C to Parton Sea

Bjorken-x Dependence of the PDFs

Huey-Wen Lin

Parton Distribution Functions

This talk is based on

"Flavor Structure of the Nucleon Sea from Lattice QCD", PRD 91, 054510 [arXiv:1402.1462]

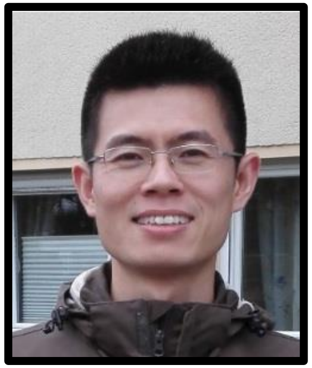
"Nucleon Helicity and Transversity Parton Distributions from Lattice QCD", to be appeared in Frontier Article in Nuclear Physics B, [arXiv:1603.06664]

in collaboration with

Jiunn-Wei Chen (NTU)

Saul Cohen (NVIDIA)

Xiangdong Ji (UMD/SJTU/INPAC)



Jian-Hui Zhang (Regensburg)

+ some recent developments

Parton Distribution Functions

§ PDFs are universal quark/gluon distributions inside nucleon

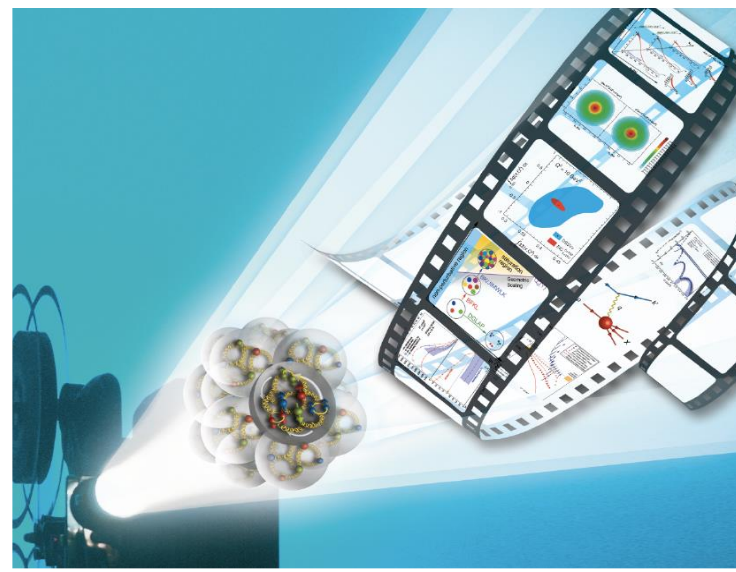
- Many ongoing/planned experiments
  (BNL, JLab, J-PARC, COMPASS, GSI, EIC, LHeC, …)

Electron Ion Collider:
The Next QCD Frontier

Imaging of the proton

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

EIC White Paper, 1212.1701



Parton Distribution Functions

§ PDFs are universal quark/gluon distributions inside nucleon

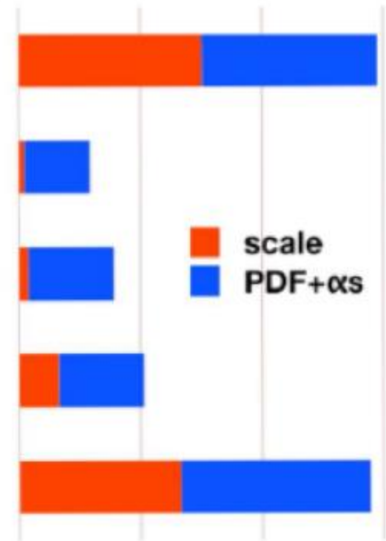
- Many ongoing/planned experiments (BNL, JLab, J-PARC, COMPASS, GSI, EIC, LHeC, …)

§ Important inputs to discern new physics at LHC

- Currently dominate errors in Higgs production

HIGGS PRODUCTION

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



(J. Campbell, HCP2012)

Global Analysis

§ Experiments cover diverse kinematics of parton variables

- Global analysis takes advantage of all data sets

Theory Input

Exp't Input

Global Analysis of PDFs

§ Some choices made for the analysis

- Choice of data sets and kinematic cuts
- Strong coupling constant $\alpha_s(M_Z)$
- How to parametrize the distribution

$$xf(x,\mu_0) = a_0 x^{a_1}(1-x)^{a_2} P(x)$$

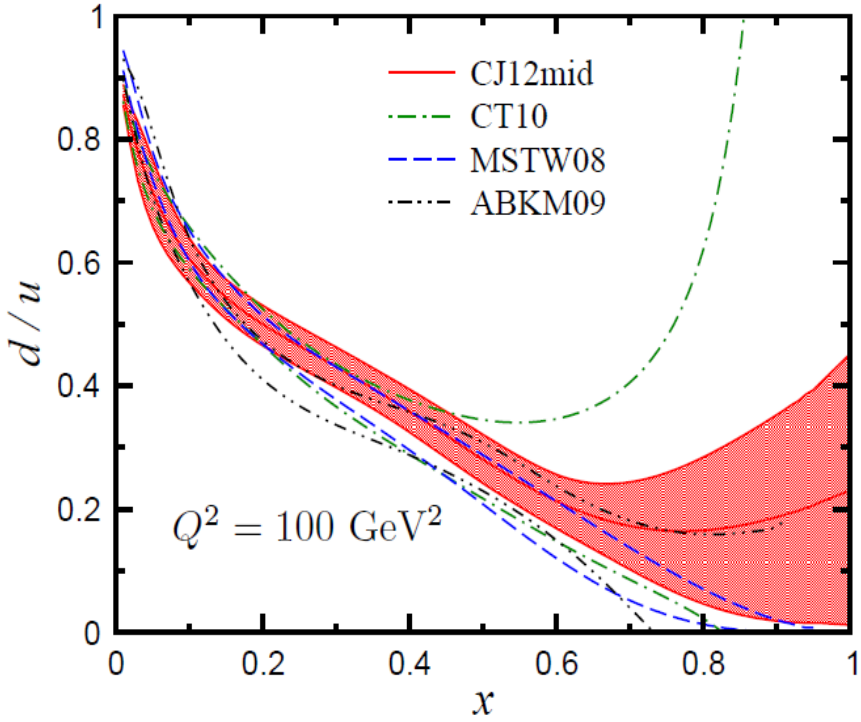
- Assumptions imposed

SU(3) flavor symmetry, charge symmetry, strange and sea distributions

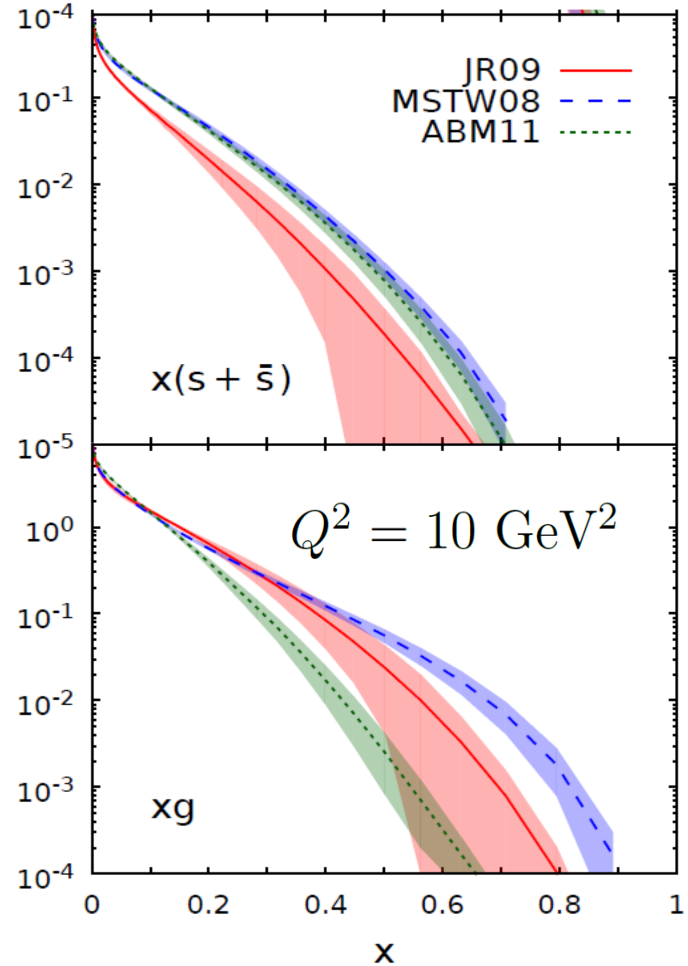
$$s = \bar{s} = \kappa(\bar{u} + \bar{d})$$

Global Analysis

- § Discrepancies appear when data is scarce
- § Many groups have tackled the analysis
  - CTEQ, MSTW, ABM, JR, NNPDF, etc.



Jimenez-Delgado, Melnitchouk, Owens, J.Phys. G40 (2013) 09310

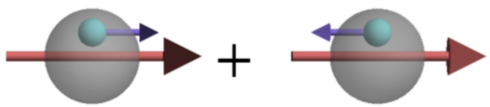


What can we do on the lattice?

PDFs on the Lattice

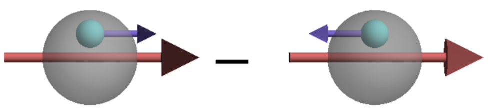
- Lattice calculations rely on operator product expansion, only provide moments

most well known



Quark density/unpolarized

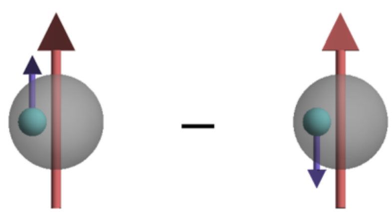
$$\langle x^n \rangle_q = \int_{-1}^{1} dx\, x^n q(x)$$



Helicity

longitudinally polarized

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



Transversity

transversely polarized

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

very poorly known

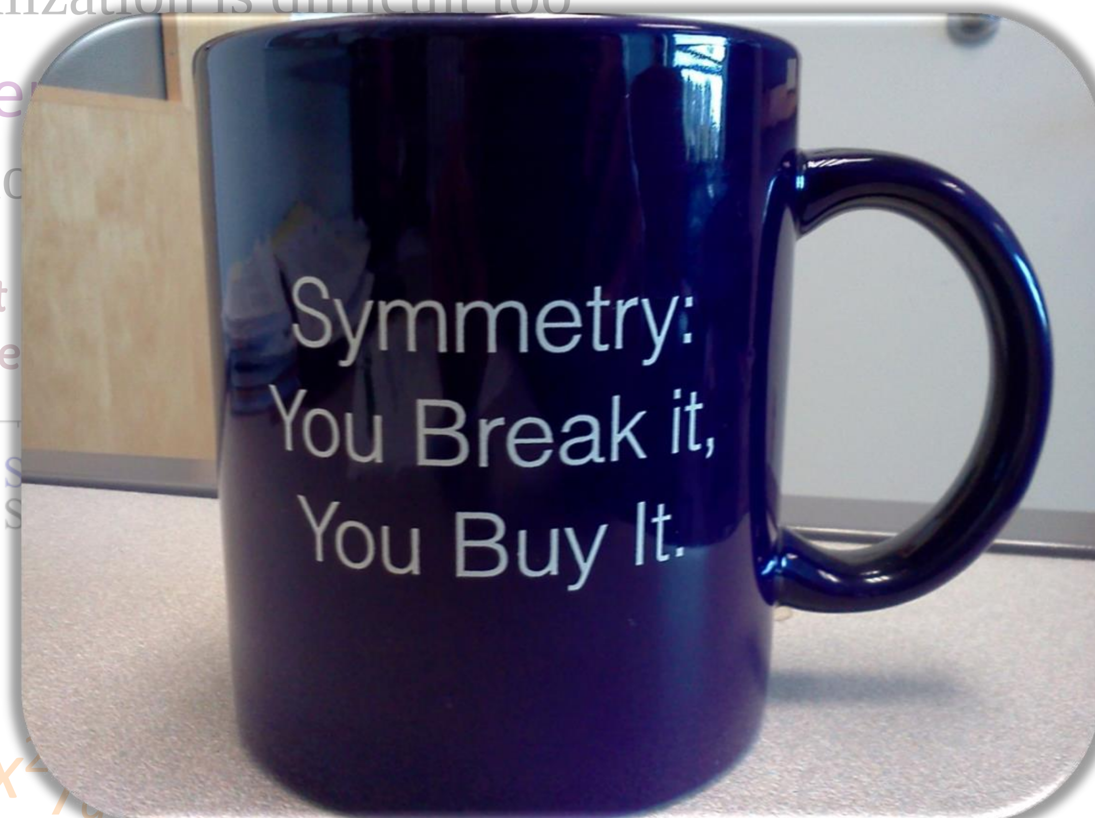
- True distribution can only be recovered with all moments

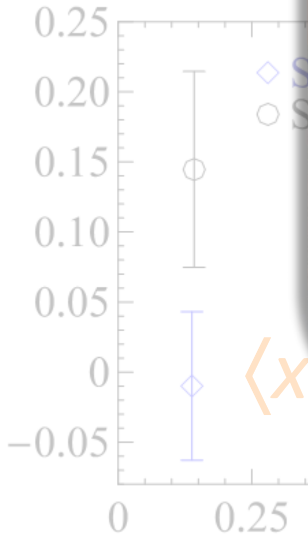
Problem with Moments

- For higher moments, ops mix with lower-dimension ops
  - Renormalization is difficult too
- Relative e
  - Calculatio

Dolgov et
Göckeler e

SAM):
clover






Problem with Moments

§ For higher moments, ops mix with lower-dimension ops

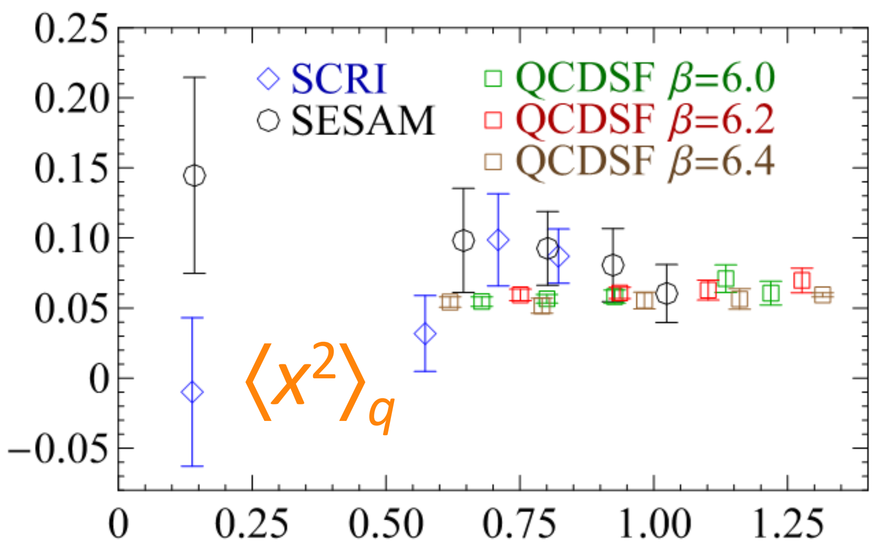
- Renormalization is difficult too

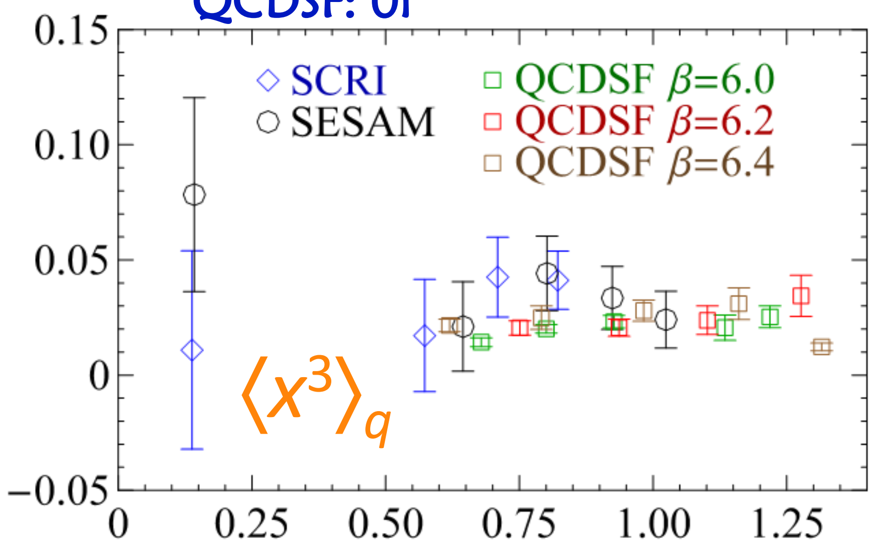
§ Relative error grows in higher moments

- Calculation would be costly and difficult

Dolgov et al. PRD66, 034506 (2002)
Göckeler et al. PRD71, 114511 (2005)

LHPC (SCRI, SESAM): 2f, Wilson and clover
QCDSF: 0f





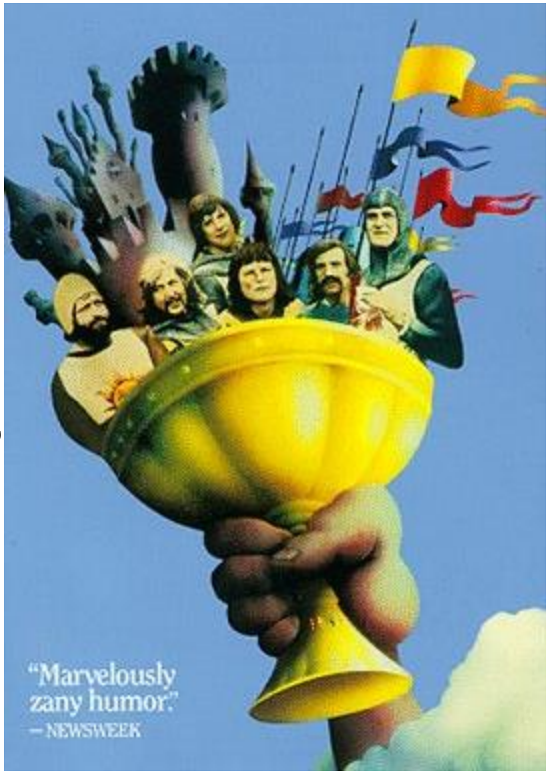
PDFs on the Lattice

Long existing obstacle!

§ Holy grail of structure calculations

§ Applies to many structure quantities:

Generalized parton distributions (GPDs),
Transverse-momentum distributions (TMD),
Meson distribution amplitudes, …



§ A few ideas try to solve this problem

- Hadronic tensor currents (Liu et al., hep-ph/9806491, … 1603.07352)
- OPE without OPE (QCDSF, hep-lat/9809171, … 1004.2100)
- Fictitious heavy quarks (Detmold et al. hep-lat/0507007)
- Smeared lattice operators (Davoudi et al. 1204.4146)

Looking forward to more developments here

A Promising New Direction

New Direction

Large-Momentum Effective Theory (LaMET)

X. Ji, PRL. 111, 262002 (2013)

- § Calculate the parton distributions through the infinite-momentum frame Feynman, Phys. Rev. Lett. 23, 1415 (1969)
- § Weinberg introduced a more convenient description using correlation functions along the lightcone

e.g. nucleon quark distribution

$$q(x,\mu) = \int \frac{d\xi_-}{4\pi} e^{-i\xi_- x P_+} \left\langle P \left| \overline{\psi}(\xi_-)\,\gamma_+ \exp\left(-ig\int_0^{\xi_-} d\eta_-\, A_+(\eta_-)\right)\psi(0) \right| P \right\rangle$$

Renormalization scale μ

Gluon potential A_+

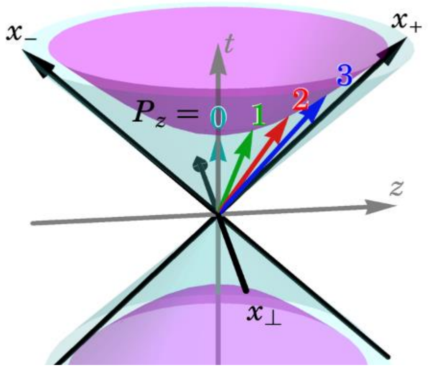
Lightcone coordinate $\xi_\pm = (t+z)/\sqrt{2}$

New Direction

Large-Momentum Effective Theory (LaMET)

X. Ji, PRL. 111, 262002 (2013)

- § Going back to the IMF concept
- § Finite-momentum quark distribution (quasi-distribution)
  - Suggested operator:



$$\tilde{q}(x, \mu, P_z) = \int \frac{dz}{4\pi} e^{-izk_z} \left\langle P \middle| \overline{\psi}(z)\, \gamma_z \exp\left(-ig \int_0^z dz'\, A_z(z')\right) \psi(0) \middle| P \right\rangle$$

$x = k_z / P_z$

Lattice z coordinate

Product of lattice gauge links

Nucleon momentum $P_\mu = \{P_0, 0, 0, P_z\}$

- § Take the infinite-P_z limit to recover lightcone functions
  - Just another limit to take, like taking $a \to 0$ or $V \to \infty$

New Direction

Large-Momentum Effective Theory (LaMET)

X. Ji, PRL. 111, 262002 (2013)

Finite-P_z corrections needed

- Neglect typical lattice corrections for now:

$$\tilde{q}(x,\mu,P_z) = \int_{-\infty}^{\infty} \frac{dy}{|y|} Z\left(\frac{x}{y}, \frac{\mu}{P_z}\right) q(y,\mu) + \mathcal{O}\left(M_N^2/P_z^2\right) + \mathcal{O}\left(\Lambda_{\text{QCD}}^2/P_z^2\right)$$

Finite $P_z \leftrightarrow \infty$ perturbative matching

$$Z(x,\mu/P_z) = C\delta(x-1) - \frac{\alpha_s}{2\pi} Z^{(1)}(x,\mu/P_z)$$

Non-singlet case only

X. Xiong, X. Ji, J. Zhang, Y. Zhao, 1310.7471;

Ma and Qiu, 1404.6860

Dominant correction (for nucleon); known scaling form

HWL et al. 1402.1462

J.-W. Chen et al, 1603.06664

§ Benefit from our pQCD colleagues

New Direction

Large-Momentum Effective Theory (LaMET)

X. Ji, PRL. 111, 262002 (2013)

Finite-P_z corrections needed

- Neglect typical lattice corrections for now:

$$\tilde{q}(x,\mu,P_z) = \int_{-\infty}^{\infty} \frac{dy}{|y|} Z\left(\frac{x}{y}, \frac{\mu}{P_z}\right) q(y,\mu) + \mathcal{O}\left(M_N^2/P_z^2\right) + \mathcal{O}\left(\Lambda_{\mathrm{QCD}}^2/P_z^2\right)$$

complicated higher-twist operator; smaller P_z correction for nucleon

J.-W. Chen et al, 1603.06664 and reference within

(extrapolate it away)

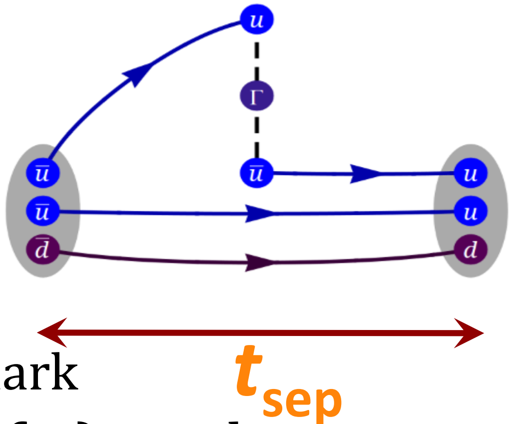
§ Some similarity in more broadly-studied HQET…

$$O\left(\frac{m_b}{\Lambda}\right) = Z\left(\frac{m_b}{\Lambda}, \frac{\Lambda}{\mu}\right) o(\mu) + \mathcal{O}\left(\frac{1}{m_b}\right) + \cdots$$

Some Lattice Details

§ Exploratory study

- $N_f = 2+1+1$ clover/HISQ lattices (MILC)
  $M_\pi \approx$ **310 MeV**, $a \approx$ **0.12 fm** ($L \approx 2.88$ fm)
- Isovector only ("disconnected" suppressed)
  gives us flavor asymmetry between up and down quark
- 2 source-sink separations ($t_{sep} \approx 0.96$ and 1.2 fm) used



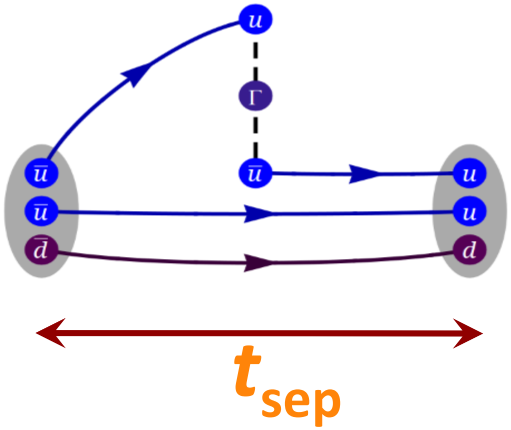
§ Properties known on these lattices

- Lattice Z_Γ for bilinear operator ~ 1
  (with HYP-smearing)
- $M_\pi L \approx 4.6$ large enough to avoid finite-volume effects

§ Feasible with today's resources!

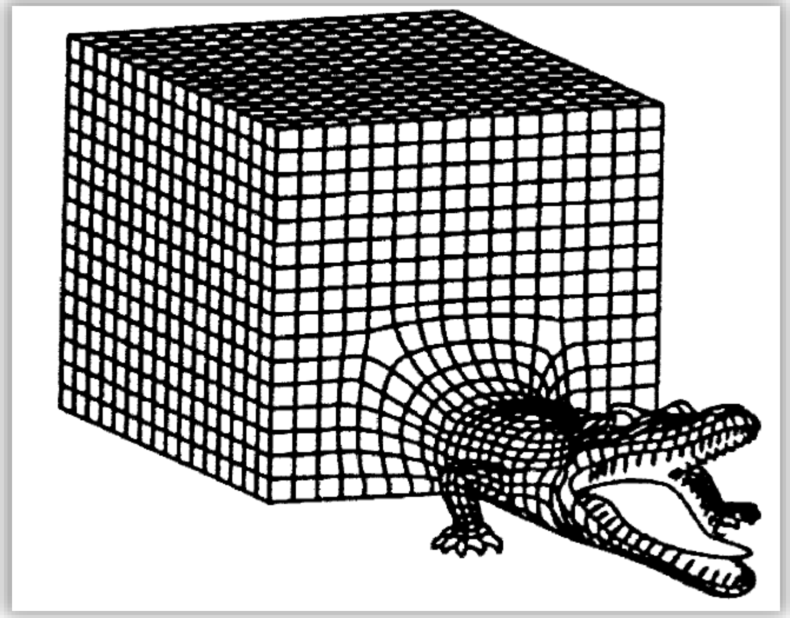
1402.1462 [hep-ph]; 1603.06664 [hep-ph]

Warning!



§ Exploratory study

- N_f = 2+1+1 clover/HISQ lattices (MILC)
  $M_\pi \approx$ **310 MeV**, $a \approx 0.12$ fm ($M_\pi L \approx 4.5$)



NO SYSTEMATICS YET!

§ Demonstration that the method works

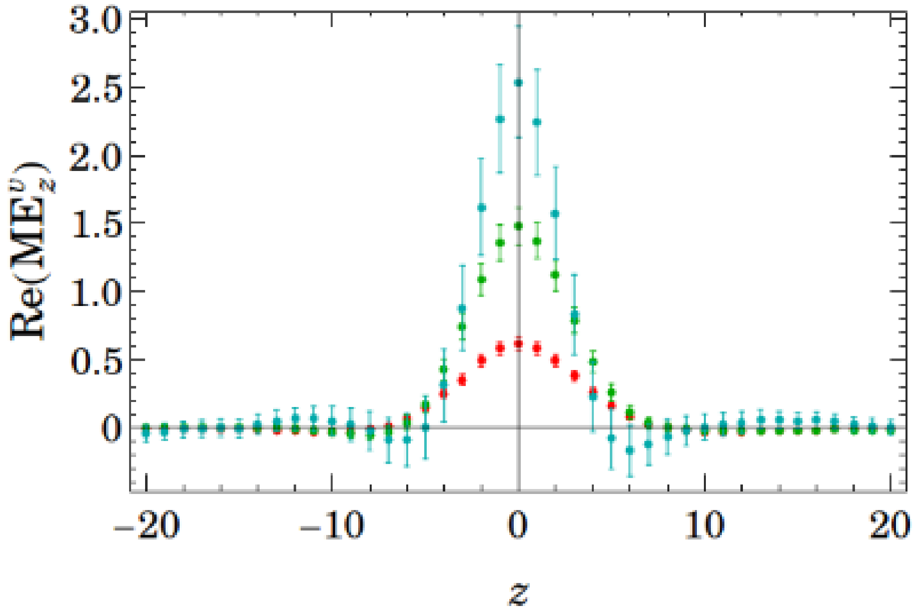
- Intend to motivate future LQCD work on many quantities

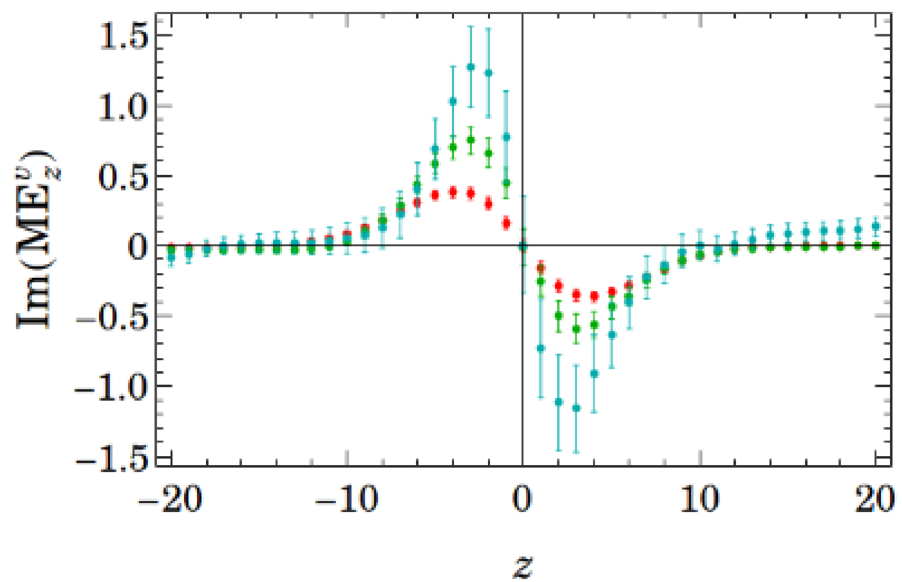
Step 1

§ Calculate nucleon matrix elements

$$\left\langle P \,\middle|\, \overline{\psi}(z)\,\gamma_z\,\exp\!\left(-i\,g\int_0^z dz'\,A_z(z')\right)\psi(0)\,\middle|\, P\right\rangle$$

- How many links are needed?





- Lattice momenta discretized by finite size of volume

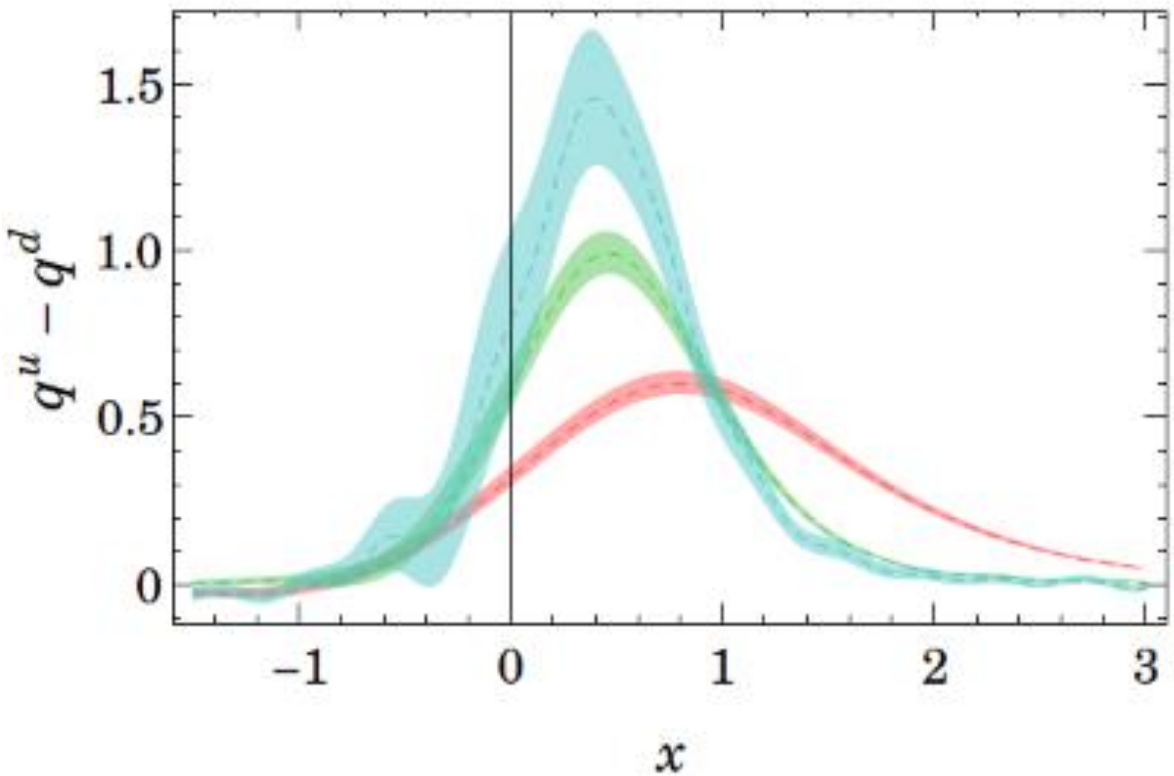
$P_z \in \{0.43, 0.86, 1.29\}$ GeV

Step 2

§ Do the integral

$$\int \frac{dz}{4\pi} e^{-izk_z} \left\langle P \left| \overline{\psi}(z)\, \gamma_z \exp\left(-ig \int_0^z dz'\, A_z(z')\right) \psi(0) \right| P \right\rangle$$

$P_z \in \{0.43, 0.86, 1.29\}$ GeV



Uncorrected bare lattice results

$x = k_z / P_z$

Distribution should sharper as P_z increases

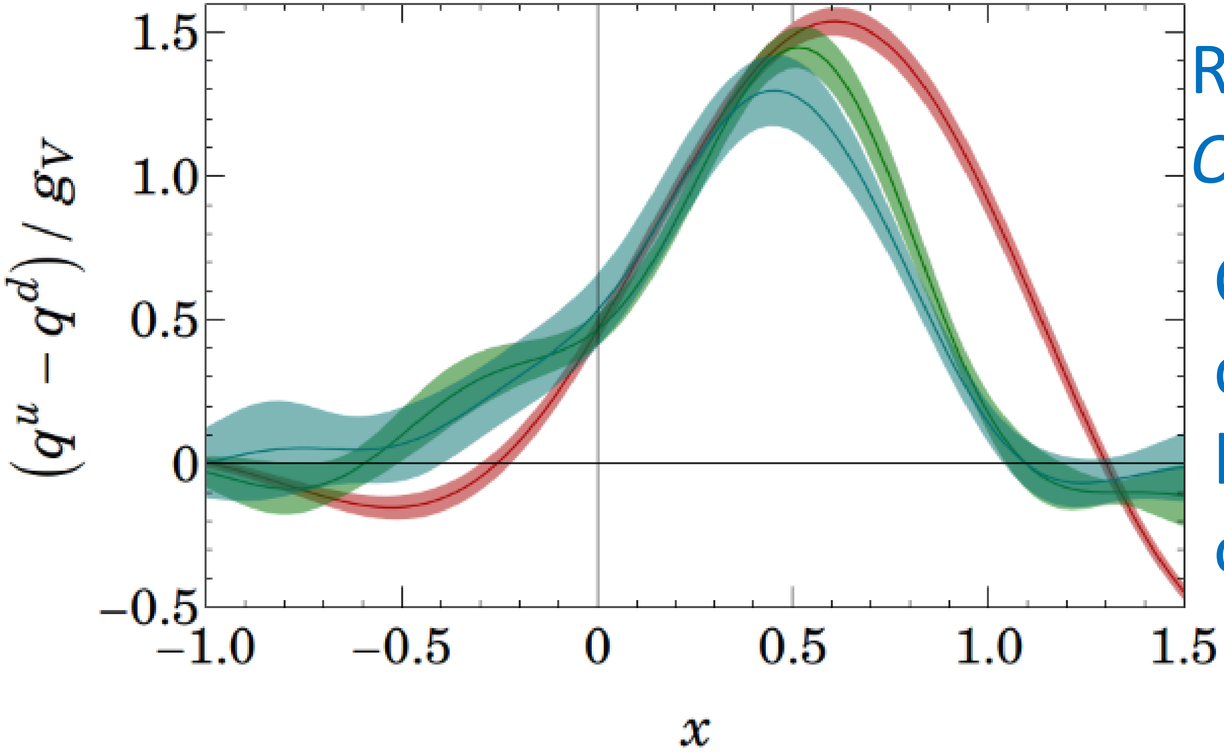
Artifacts due to finite P_z on the lattice

Step 3

§ Apply finite-P_z corrections

$$\tilde{q}(x, \mu, P_z) = \int_{-\infty}^{\infty} \frac{dy}{|y|} Z\left(\frac{x}{y}, \frac{\mu}{P_z}\right) q(y, \mu) + \mathcal{O}\left(M_N^2/P_z^2\right)$$

$P_z \in \{0.43, 0.86, 1.29\}$ GeV



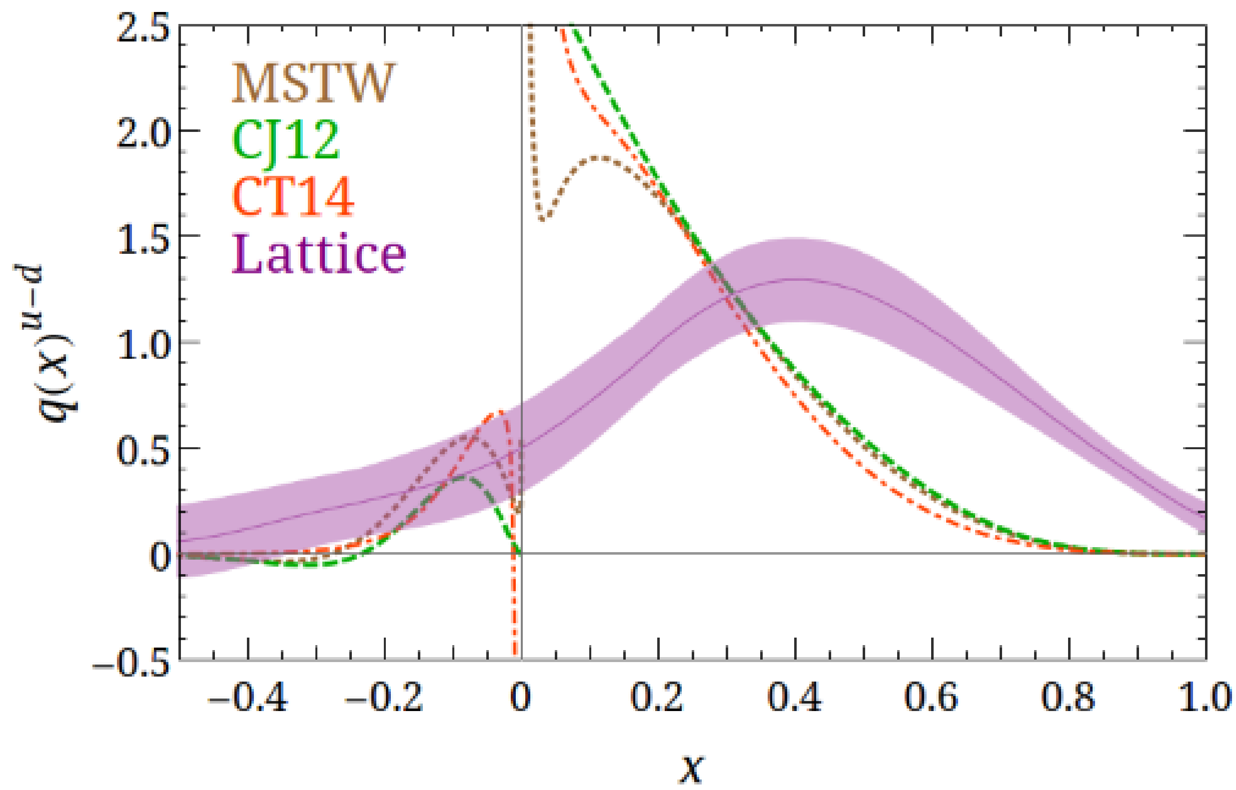
Removing $O(M_N^n/P_z^n)$ errors + $O(\alpha_s)$

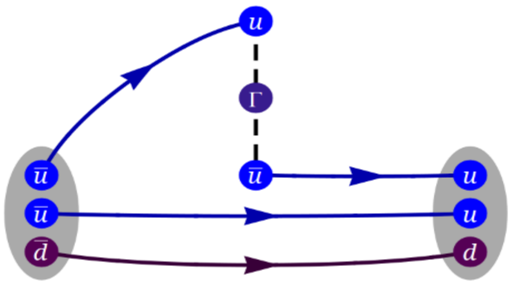
Corrected distributions from the largest 2 P_z show signs of convergence

Step 4

§ Extrapolate higher-twist effects $\mathcal{O}\left(\Lambda_{\mathrm{QCD}}^2/P_z^2\right)$

- N_f= 2+1+1 clover/HISQ lattices (MILC)
  $M_\pi \approx$ **310 MeV**, $a \approx 0.12$ fm ($M_\pi L \approx 4.5$), O(10^3) measurements





A.D. Martin et al. Eur.Phys.J. C63, 189 (2009)

J.F. Owens et al. PRD 87, 094012 (2012)

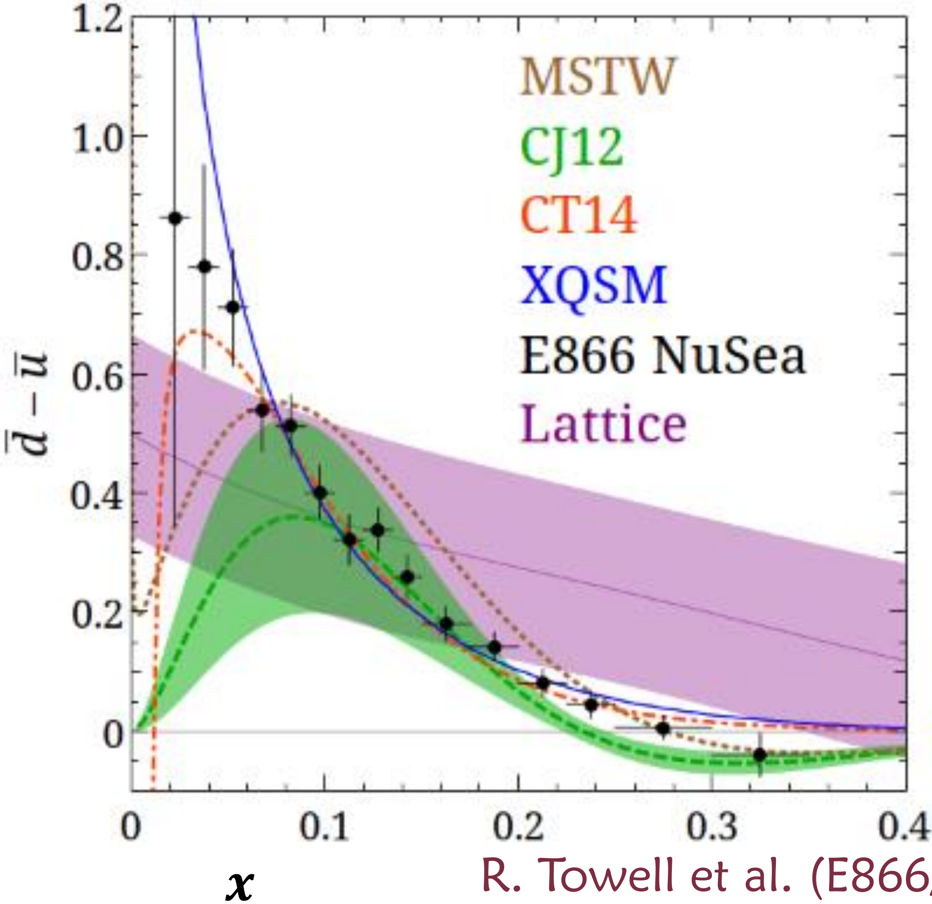
S. Dulat et al. arXiv:1506.07443

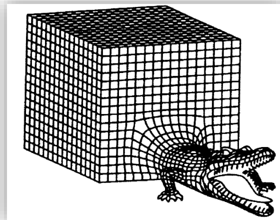
Sea Flavor Asymmetry

§ First time in LQCD history to study antiquark distribution!

- $M_\pi \approx 310$ MeV

HWL et al. 1402.1462





$\bar{q}(x) = -q(-x)$

Lost resolution in small-*x* region

Future improvement: larger lattice volume

$$\int dx\,\left(\bar{u}(x) - \bar{d}(x)\right) \approx -0.16(7)$$

Experiment	x range	$\int_0^1[\bar{d}(x)-\bar{u}(x)]dx$
E866	$0.015<x<0.35$	0.118 ± 0.012
NMC	$0.004<x<0.80$	0.148 ± 0.039
HERMES	$0.020<x<0.30$	0.16 ± 0.03

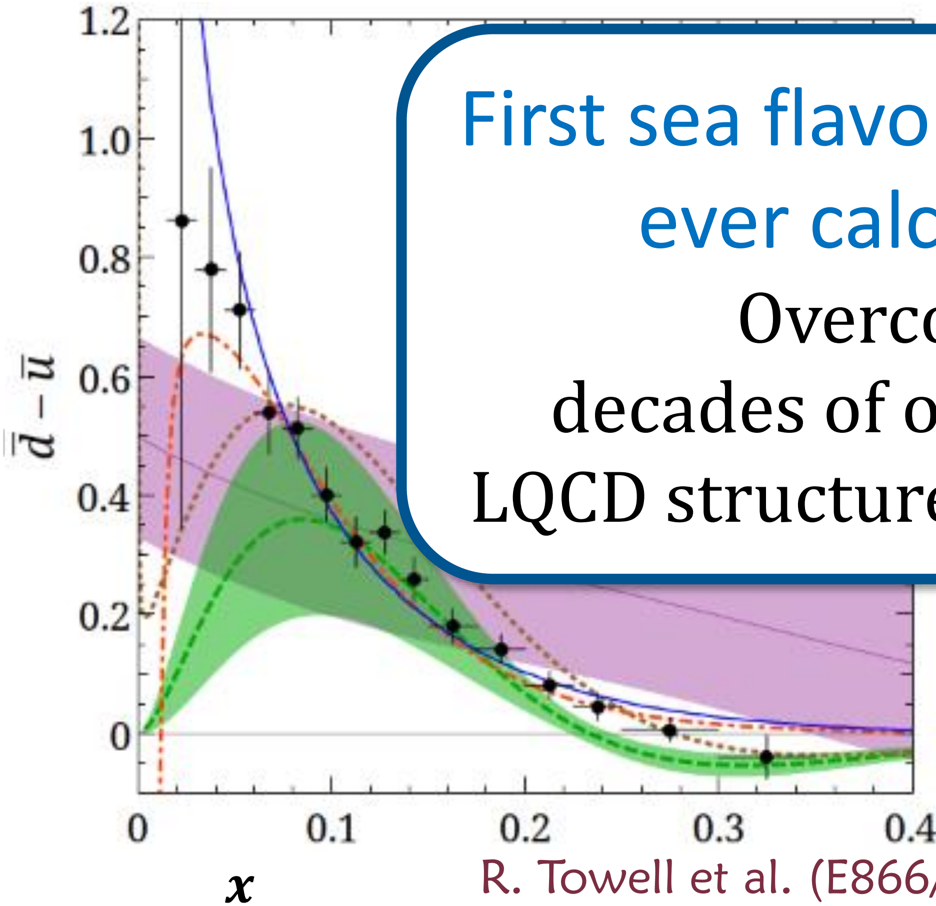
R. Towell et al. (E866/NuSea), Phys.Rev. D64, 052002 (2001)

Sea Flavor Asymmetry

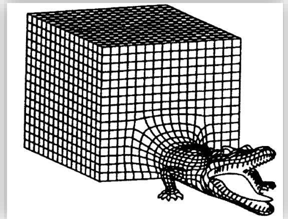
§ First time in LQCD history to study antiquark distribution!

- $M_\pi \approx 310$ MeV

HWL et al. 1402.1462



$\bar{q}(x) = -q(-x)$



First sea flavor asymmetry ever calculated!

Overcomes decades of obstacles in LQCD structure calculations

n in

n

ement:

volume

$x)) \approx -0.16(7)$

Experiment	x range	$\int_0^1[\bar{d}(x)-\bar{u}(x)]dx$
E866	$0.015<x<0.35$	0.118 ± 0.012
NMC	$0.004<x<0.80$	0.148 ± 0.039
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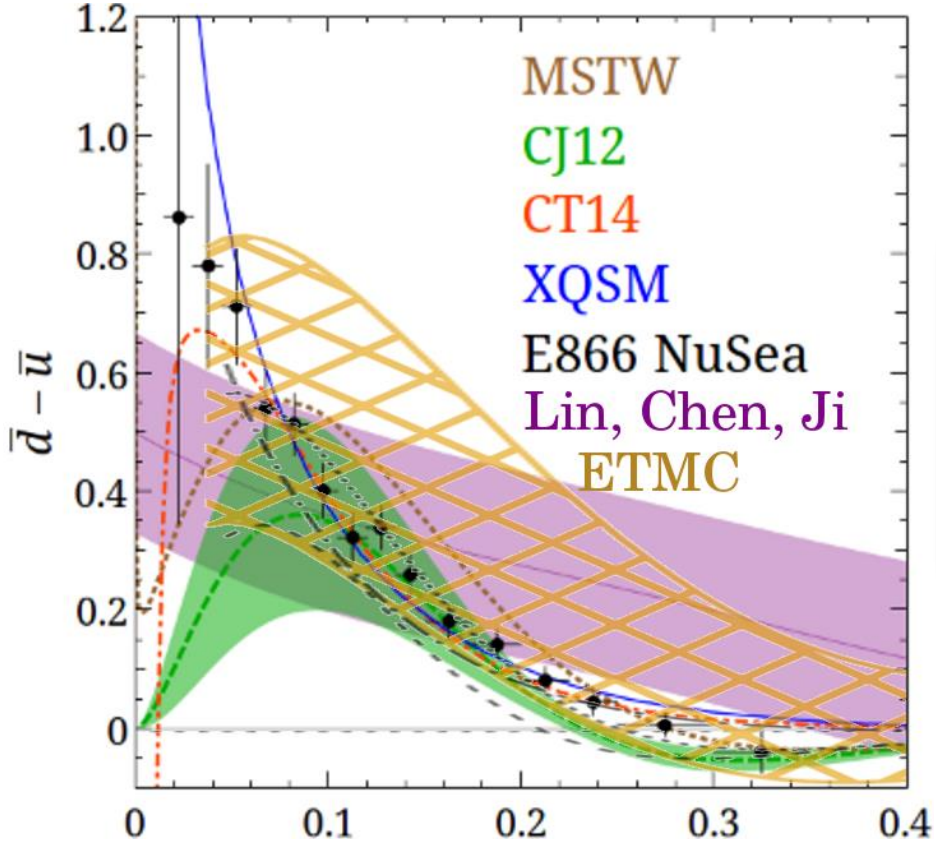
R. Towell et al. (E866/NuSea), Phys.Rev. D64, 052002 (2001)

Sea Flavor Asymmetry

§ Lattice exploratory study

- $M_\pi \approx 310$ MeV

HWL et al 1402.1462



Compared with E866

Too good to be true?

Lost resolution in small-x region

Similar results repeated by ETMC, at $M_\pi \approx 373$ MeV

ETMC, 1504.07455

C. WIESE, Mon. 14:15

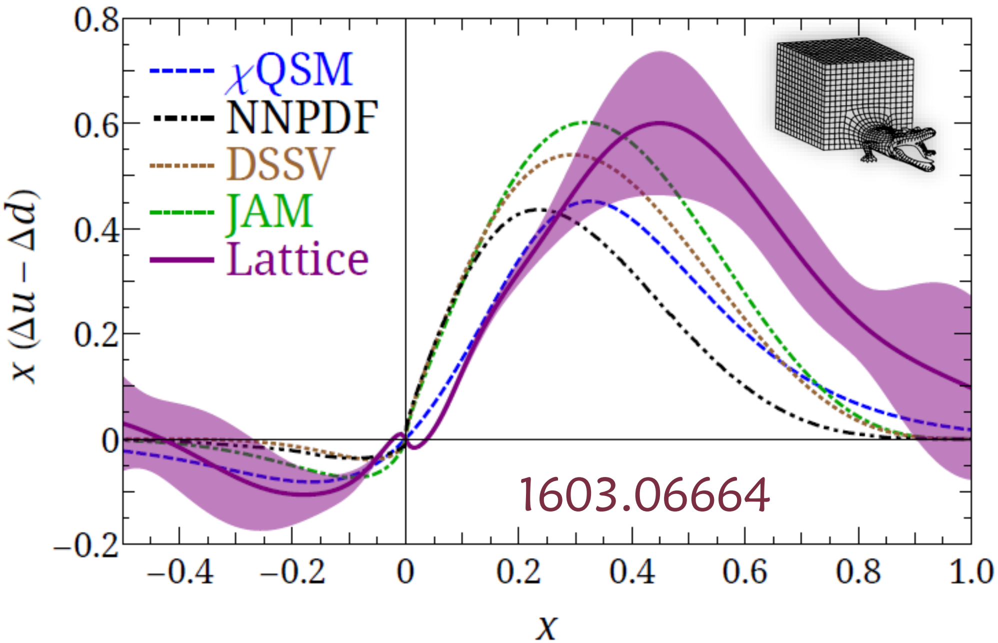
(7)

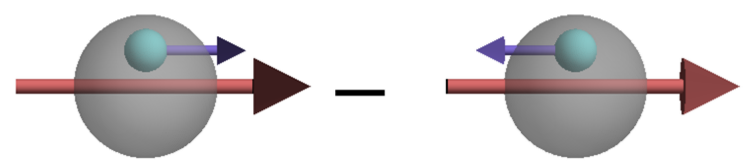
		$(x)]dx$
E866	$0.015<x<0.35$	0.118 ± 0.012
NMC	$0.004<x<0.80$	0.148 ± 0.039
HERMES	$0.020<x<0.30$	0.16 ± 0.03

R. Towell et al. (E866/NuSea), Phys.Rev. D64, 052002 (2001)

Helicity Distribution

§ Exploratory study ☙ $M_\pi \approx 310$ MeV





Removing
$O(M_N^n/P_z^n)$ errors + $O(\alpha_s)$
+ $O(\Lambda_{QCD}^2/P_z^2)$

☙ We see polarized sea asymmetry $\int dx\, \left(\Delta\bar{u}(x) - \Delta\bar{d}(x)\right) \approx 0.14(9)$

☙ Both STAR and PHENIX at RHIC see $\Delta\bar{u} > \Delta\bar{d}$

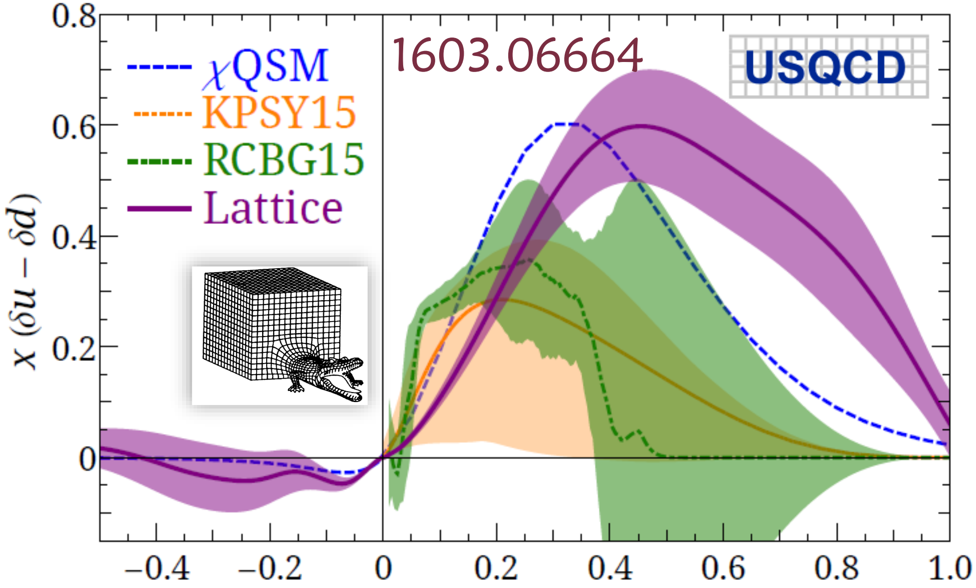
1404.6880 and 1504.07451

☙ Other experiments, Fermilab DY exp'ts (E1027/E1039), future EIC

Transversity Distribution

§ Exploratory study

$M_\pi \approx 310$ MeV



$$\int dx\,(\delta\bar{u}(x) - \delta\bar{d}(x)) \approx -0.10(8)$$

Removing

$O(M_N^n/P_z^n)$ errors + $O(\alpha_s)$

+ $O(\Lambda_{\mathrm{QCD}}^2/P_z^2)$

$$\delta\bar{q}(x) = -\delta q(-x)$$

1505.05589; 1503.03495

- We found sea asymmetry of $\int dx\,(\delta\bar{u}(x) - \delta\bar{d}(x)) \approx -0.10(8)$
- Chiral quark-soliton model $\int dx\,(\delta\bar{u}(x) - \delta\bar{d}(x)) \approx -0.082$

P. Schweitzer et al., PRD 64, 034013 (2001)

- SoLID at JLab, Drell-Yan exp't at FNAL (E1027+E1039), EIC, ...

Caveats

There are 2 key issues that need to be addressed

§ Large-momentum issues

- HWL, Lattice 2013

> § Need improvement for large-momentum sources
> - Better overlapping boosted hadron smearing (asymmetric source)
> - Applications: large-q form factors, hadronic and flavor physics, …

- Progress is being made:
  - RQCD, *Novel quark smearing for hadrons with high momenta in lattice QCD*, Phys. Rev. D 93, 094515 (2016)
  - *Momentum Smearing*, B. Lang, Tue. Poster
  - *The Calculation of Parton Distributions from Lattice QCD* C. WIESE, Mon. 14:15
- Systematics due to $(pa)^n$
  - Excited states get worse with larger $p \Rightarrow$ multiple t_{sep} + finer a
  - Moving frame action?

Caveats

There are 2 key issues that need to be addressed

§ Renormalization Issues

- Currently assume the renormalization is multiplicative

$$q_{\text{norm}}(x,\mu,P_z) = \frac{q(x,\mu,P_z)}{\int dx\, q(x,\mu,P_z)} \times g_V^{\overline{\text{MS}}}(2\text{ GeV})$$

- Progress is on its way:
  - *Matching issue in quasi parton distribution approach*
    T. ISHIKAWA, today 17:30
  - *Lattice study of Wilson line operators*
    H. PANAGOPOULOS, Wed 10:40
  - Gradient flow approach? K. Organos + C. Monahan
- Some lessons can be learned from static heavy-quark operators?

A NEW HOPE

It is a period of war and economic uncertainty.

Turmoil has engulfed the galactic republics.

Basic truths at foundation of the human civilization are disputed by the dark forces of the evil empire.

A small group of QCD Knights from United Federation of Physicists has gathered in a remote location on the third planet of a star called Sol on the inner edge of the Orion–Cygnus arm of the galaxy.

The QCD Knights are the only ones who can tame the power of the Strong Force, responsible for holding atomic nuclei together, for giving mass and shape to matter in the Universe.

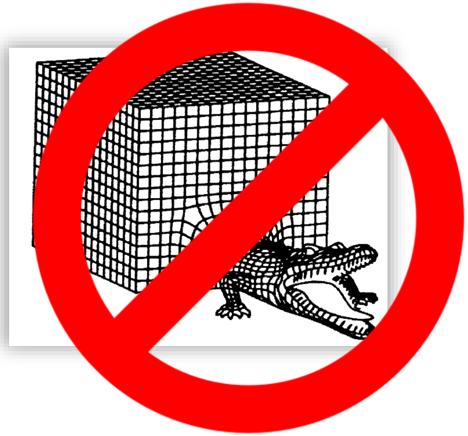
They carry secret plans to build the most powerful

Summary & Outlook

Exciting time for studying structure on the lattice

§ Overcoming longstanding obstacle to full x-distribution

- Most importantly, this can be done with today's computer
- First lattice approach to study sea asymmetry



§ Precision control

- Working on renormalization,
  statistics (all-mode averaging?),
  larger momentum boost,
  finer lattice-spacing ensembles, …

§ Closer collaboration with our heavy-quark colleagues

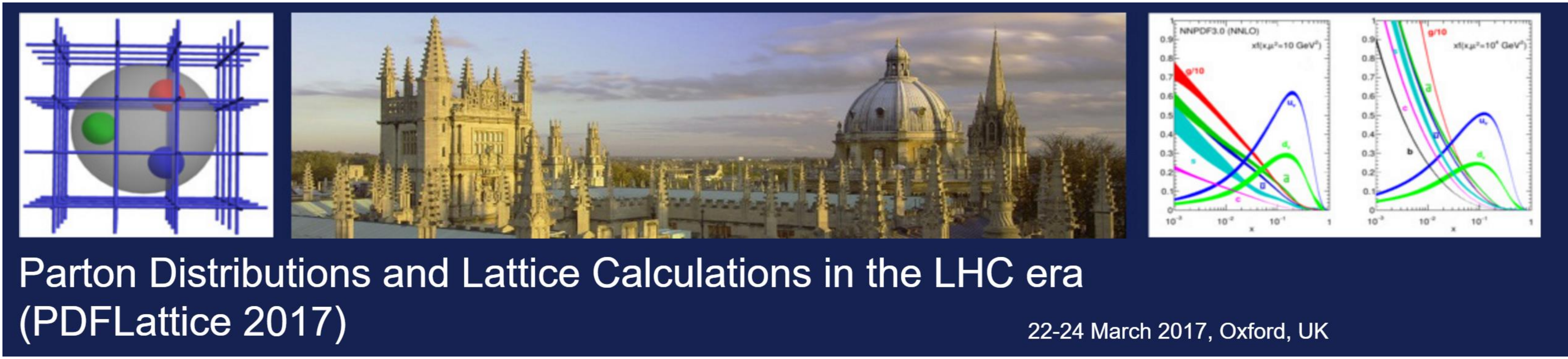
- Certain similar issues: large-q form factors, HQET, …

§ Opens doors to much future lattice-QCD structure work

- Many first calculations waiting to be done!

Future Prospects

- A first joint workshop with global-fitting community to address key LQCD inputs
  - http://www.physics.ox.ac.uk/confs/PDFlattice2017



"The goal of this workshop is to ***bring together the global PDF analysis and lattice-QCD communities*** *to explore ways to improve current PDF determinations. In particular, we plan to* ***set precision goals for lattice-QCD*** *calculations so that these calculations, together with experimental input, can achieve more reliable determinations of PDFs. In addition we will discuss what impact such improved determinations of PDFs will have on future new-physics searches."*

Backup Slides

This Conference

Various presentation addressing difference issues

§ Renormalization

- Matching issue in quasi parton distribution approach
  T. ISHIKAWA, today 17:30
- Lattice study of Wilson line operators,
  H. PANAGOPOU, Wed 10:40

§ Nucleon PDFs

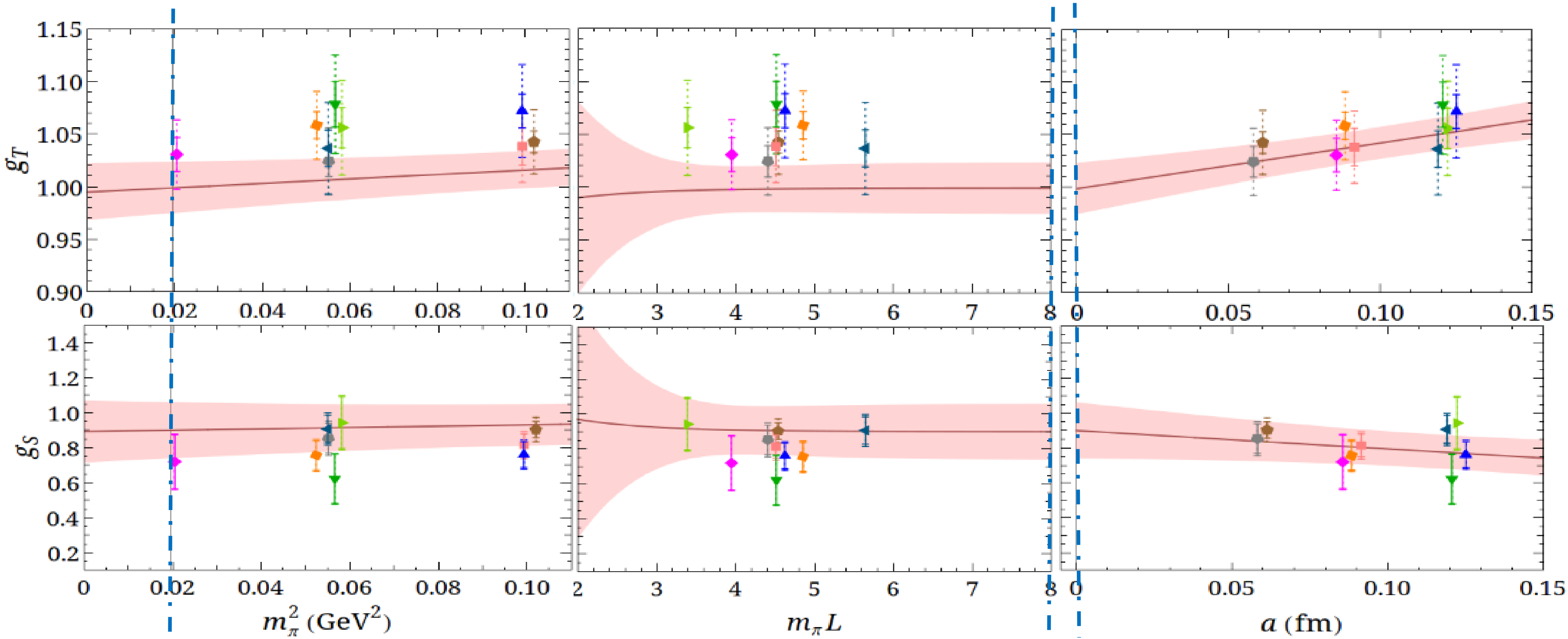
- The Calculation of Parton Distributions from Lattice QCD
  C. WIESE, Mon. 14:15

§ Pion distribution amplitude

- Momentum Smearing
  B. Lang, Tue. Poster

How Can LQCD Help?

- Lattice QCD is an ideal theoretical tool for investigating strong-coupling regime of quantum field theories
- We are beginning to do precision calculations in nucleons
- PNDME's $g_{T,S}$ calculations PNDME, 1506.06411; 1506.04196; in prep.
  - Extrapolate to the physical limit $m_\pi \to m_\pi^{\text{phys}}$, $a \to 0$, $L \to \infty$

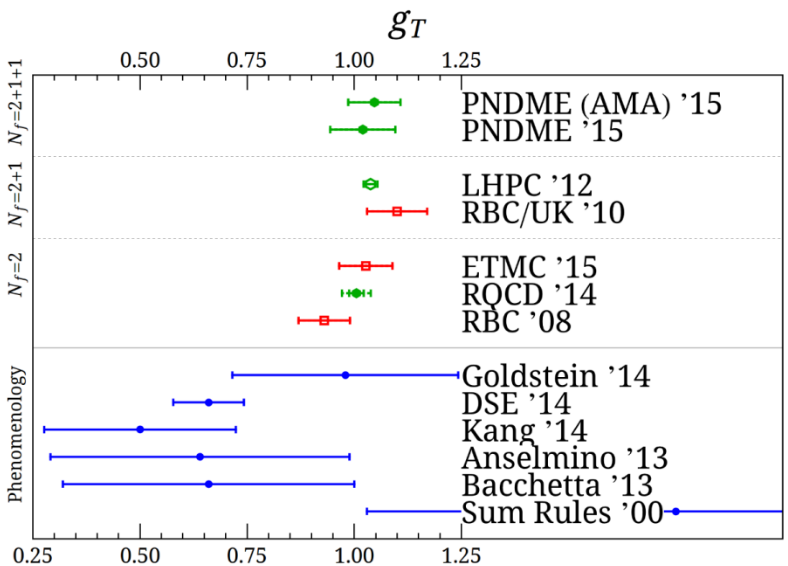


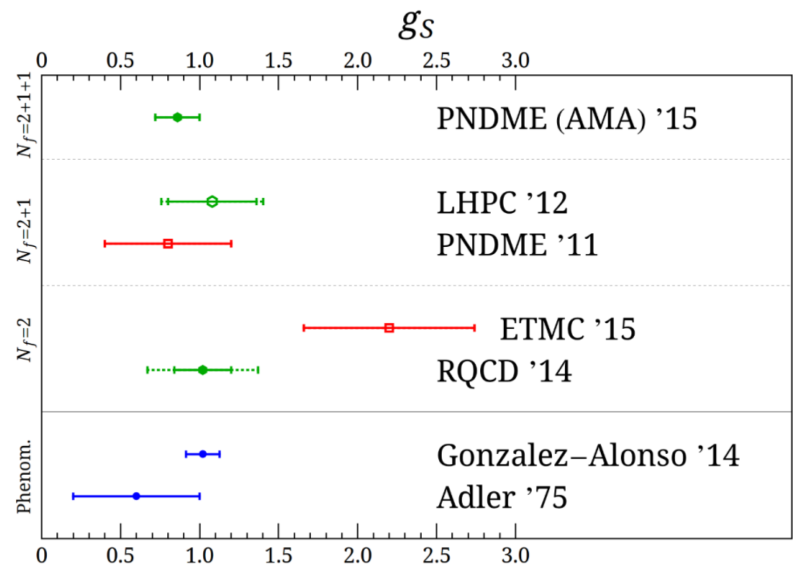
Tensor/Scalar Charges

FLAG rating system
New: excited-state rating

PNDME, 1506.06411; in preparation

Collaboration	Ref.	publication status	N_f	chiral extrapolation	continuum extrapolation	finite volume	excited state	renormalization	g_T
PNDME'15	This work	P	2+1+1	★	★	★	★	★	1.020(76)[a]
ETMC'13	[30]	C	2+1+1	■	○	○	■	★	1.11(3)[b]
LHPC'12	[28]	A	2+1	★	○	★	○	★	1.037(20)[c]
RBC/UKQCD'10	[29]	A	2+1	○	■	★	★	★	1.10(7)[d]
RQCD'14	[31]	P	2	★	★	★	○	★	1.005(17)(29))[e]
ETMC'13	[30]	C	2	★	■	○	■	○	1.114(46)[f]
RBC'08	[32]	P	2	■	■	★	■	★	0.93(6)[g]

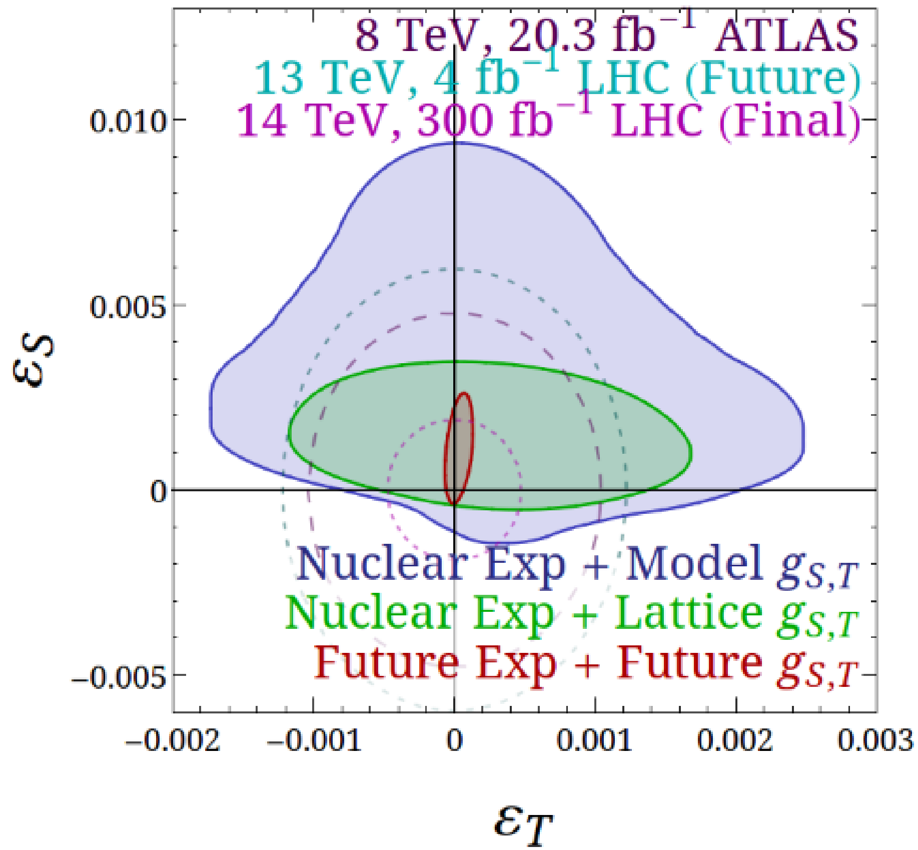




Beta Decays & BSM

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

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



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

Upcoming precision low-energy experiments

LANL/ ORNL UCN neutron decay exp't

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

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

CENPA: ^{6}He(b_{GT}) at 10^{-3}

PNDME, PRD85 054512 (2012); 1306.5435; in preparation