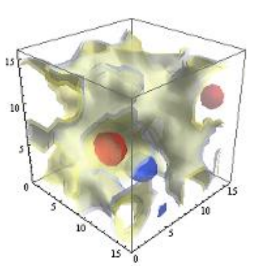
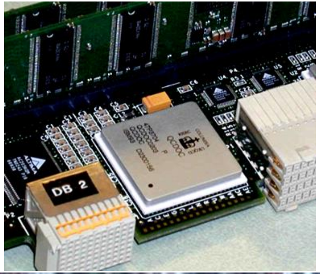
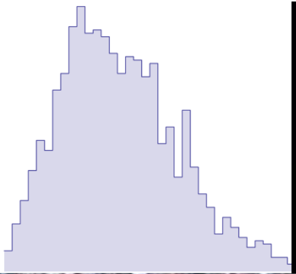
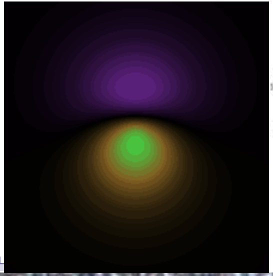
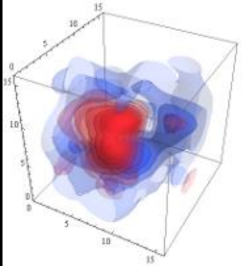
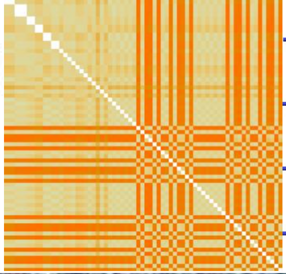
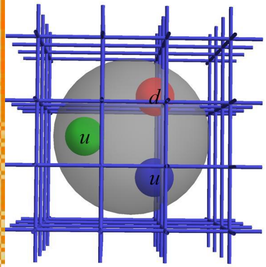
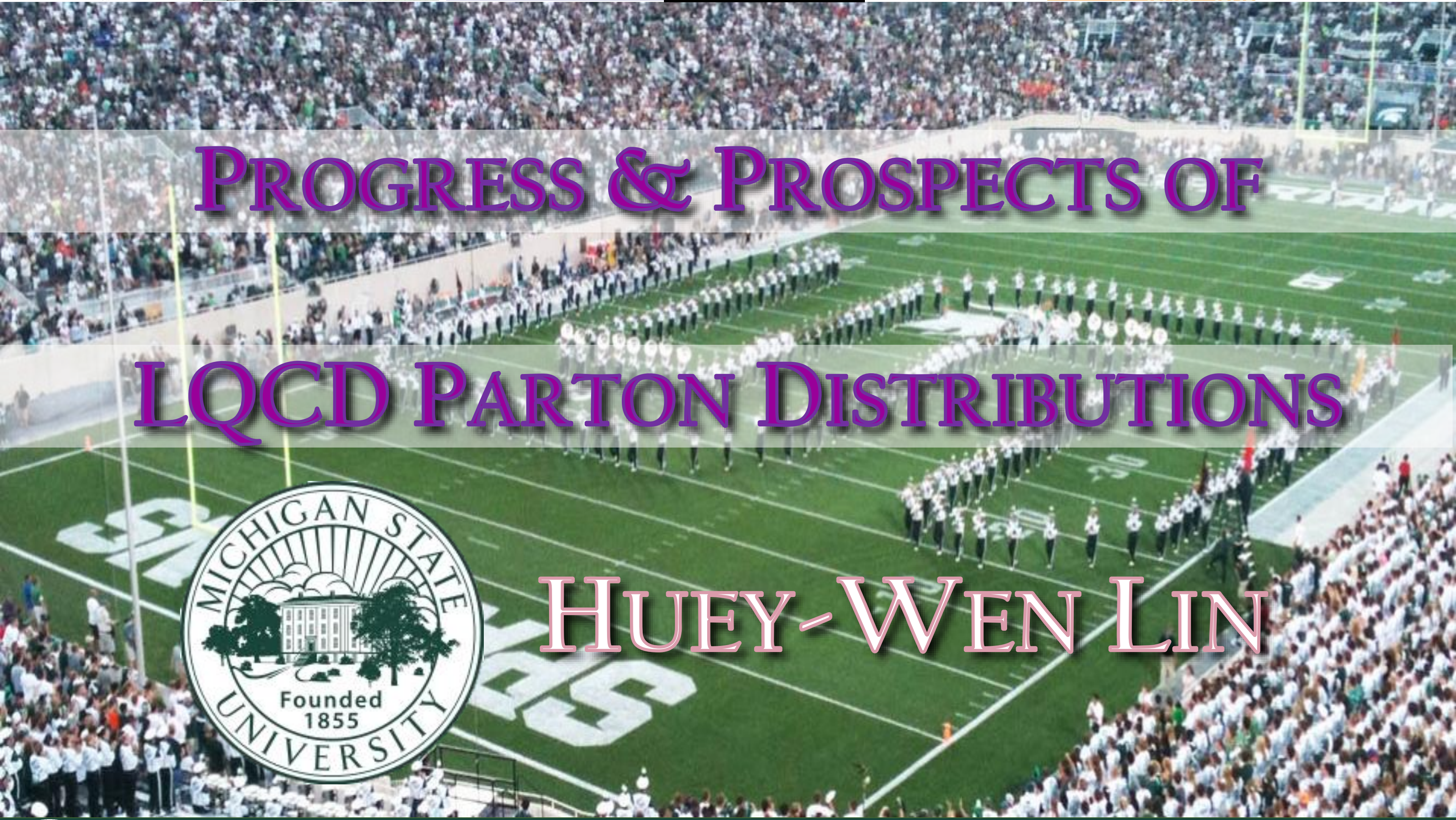








Progress & Prospects of LQCD Parton Distributions



Huey-Wen Lin

Parton Distribution Functions

§ PDFs are universal quark/gluon distributions of nucleon

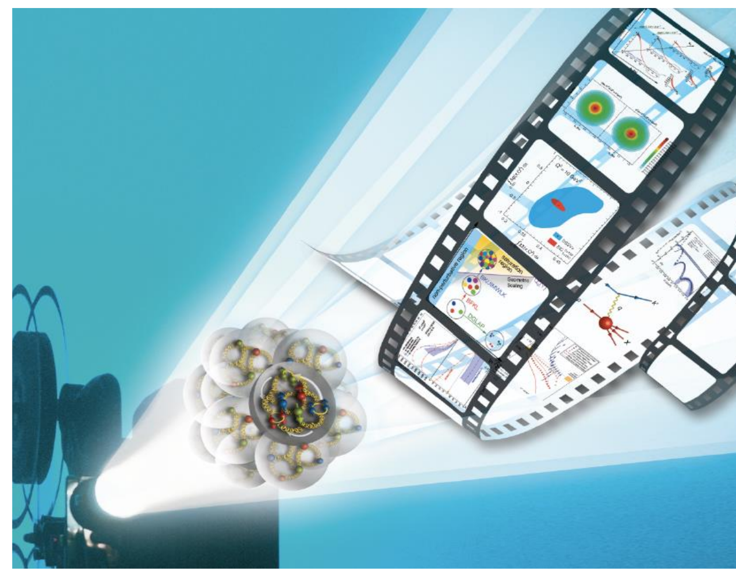
- Many ongoing/planned experiments (BNL, JLab, J-PARC, COMPASS, GSI, EIC, LHeC, …)

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



Global Analysis

§ Experiments cover diverse kinematics of parton variables

- Global analysis takes advantage of all data sets

Theory Input → **Global Analysis of PDFs** ← **Exp't Input**

§ 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

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

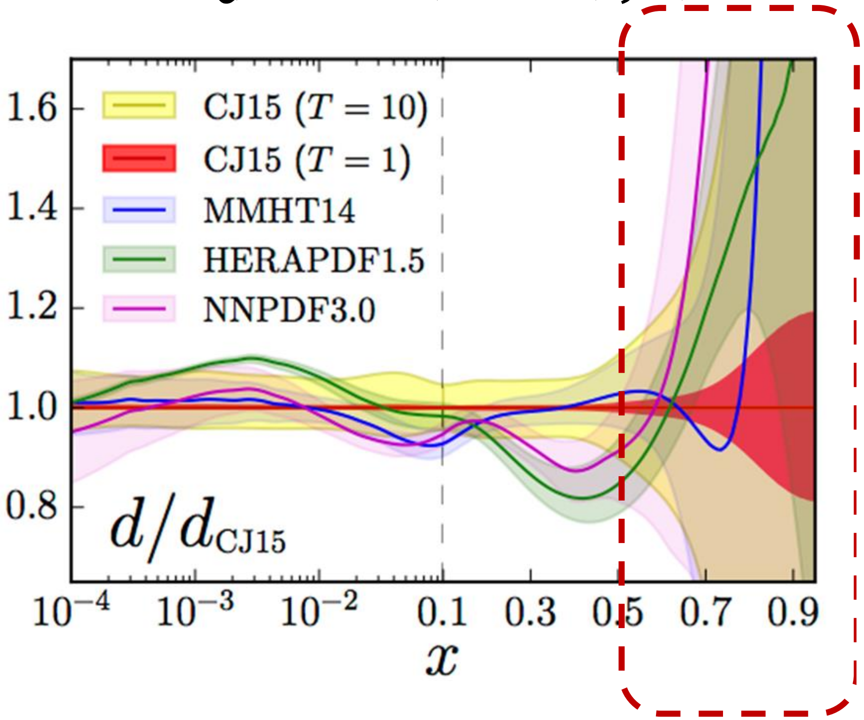
- Assumptions imposed

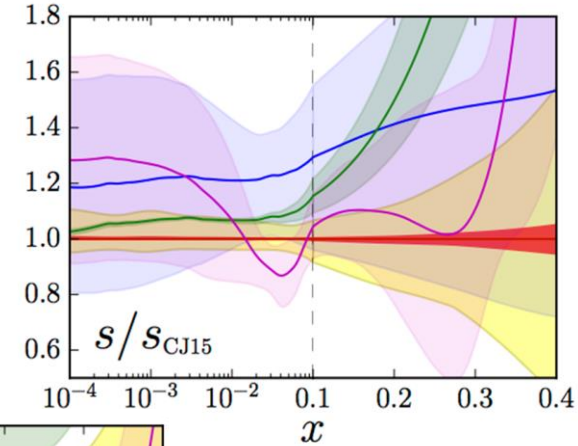
  SU(3) flavor symmetry, charge symmetry, strange and sea distributions

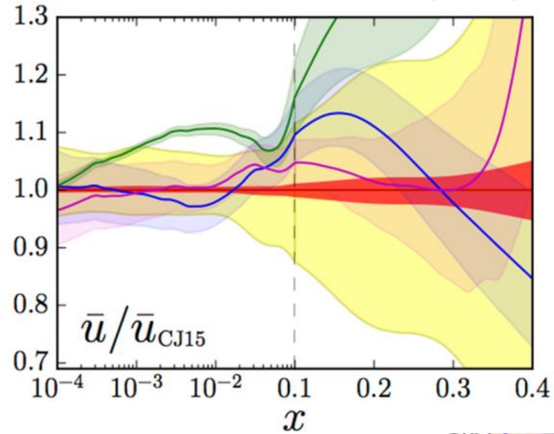
$$s = \bar{s} = \kappa(\bar{u} + \bar{d})$$

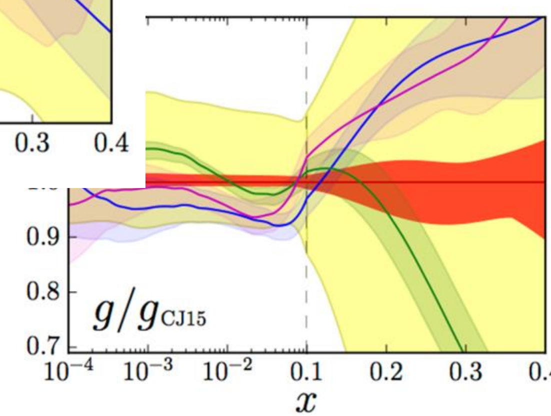
Global Analysis

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









CTEQ-JLAB
https://www.jlab.org/theory/cj/

What can we do on the lattice?

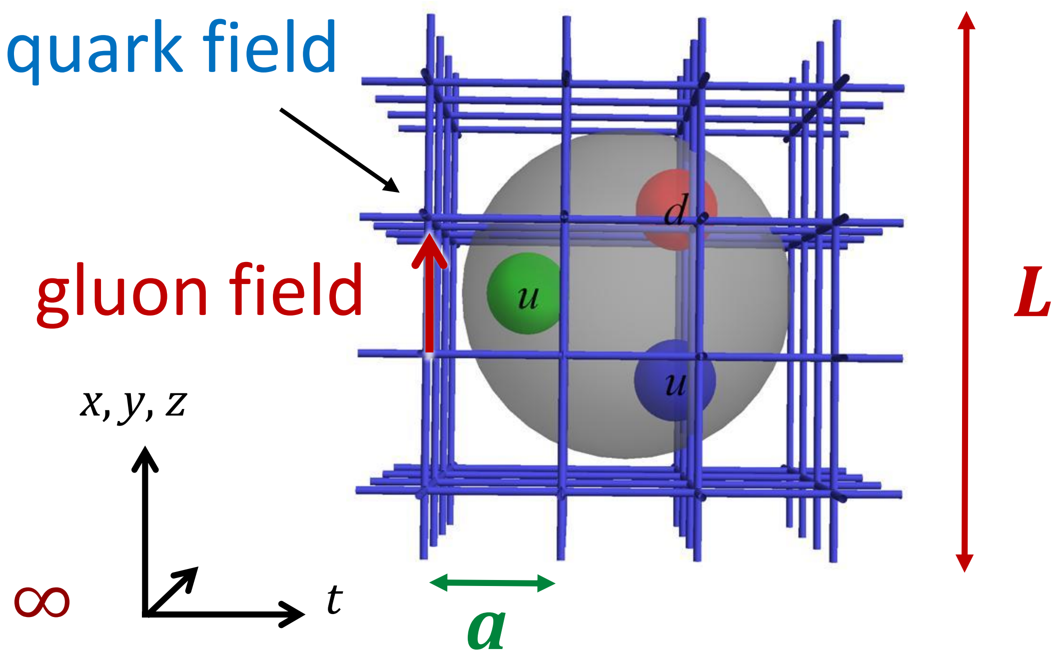
Lattice QCD 101

- § Lattice QCD is an ideal theoretical tool for investigating strong-coupling regime of quantum field theories
- § Physical observables are calculated from the path integral

$$\langle 0|O(\bar{\psi},\psi,A)|0\rangle = \frac{1}{Z}\int \mathcal{D}A\,\mathcal{D}\bar{\psi}\,\mathcal{D}\psi\, e^{iS(\bar{\psi},\psi,A)}O(\bar{\psi},\psi,A)$$

in **Euclidian** space

- Quark mass parameter (described by m_π)
- Impose a UV cutoff
  discretize spacetime
- Impose an infrared cutoff
  finite volume



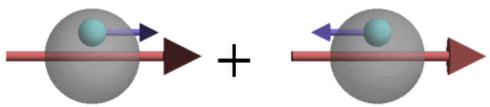
- § Recover physical limit

$$m_\pi \to m_\pi^{\text{phys}},\ a \to 0,\ L \to \infty$$

PDFs on the Lattice

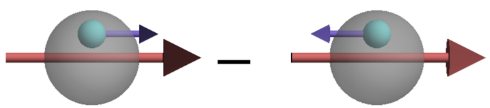
§ Lattice calculations rely on operator product expansion, only provide moments

most well known



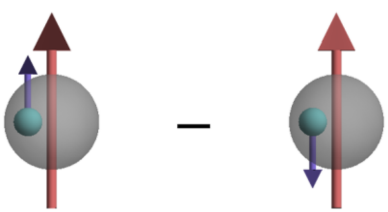
Quark density/unpolarized

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



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

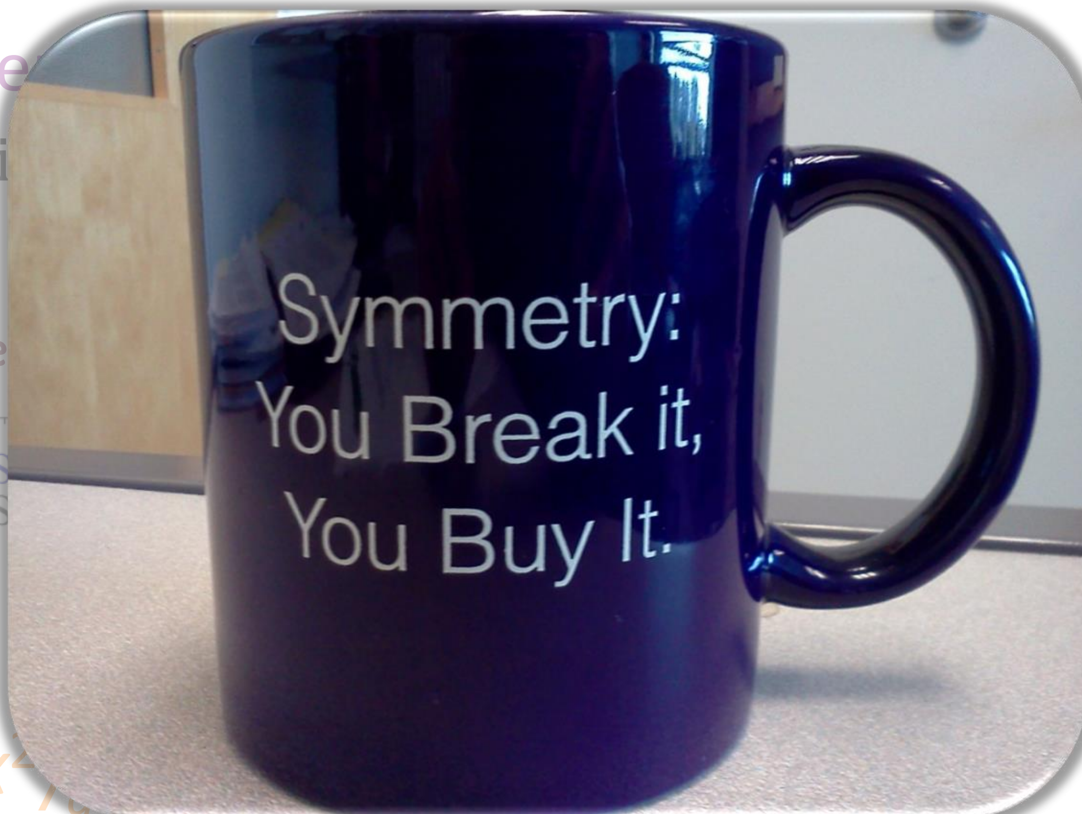
§ True distribution can only be recovered with all moments

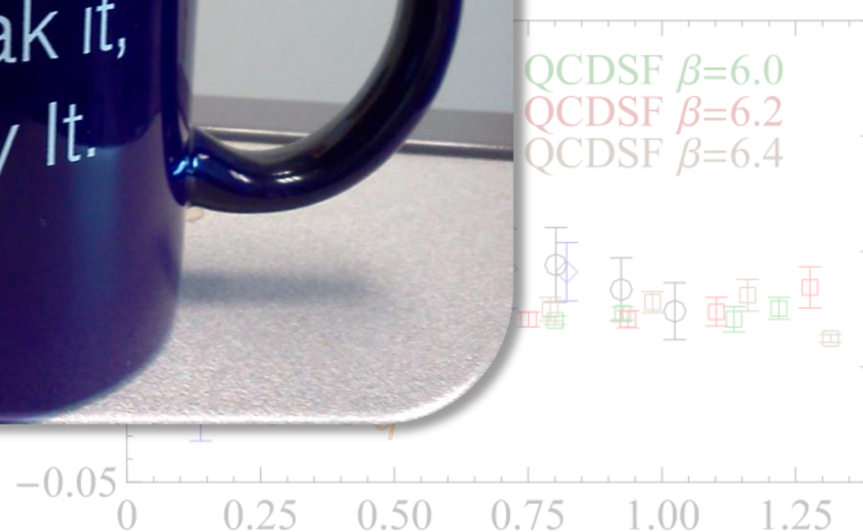
Problem with Moments

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

Dolgov et
Göckeler e

SAM):
clover





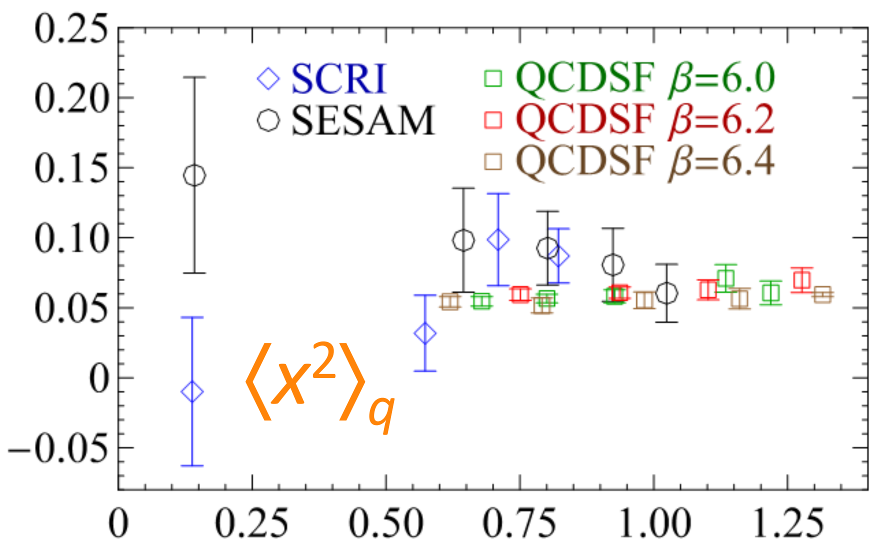
Problem with Moments

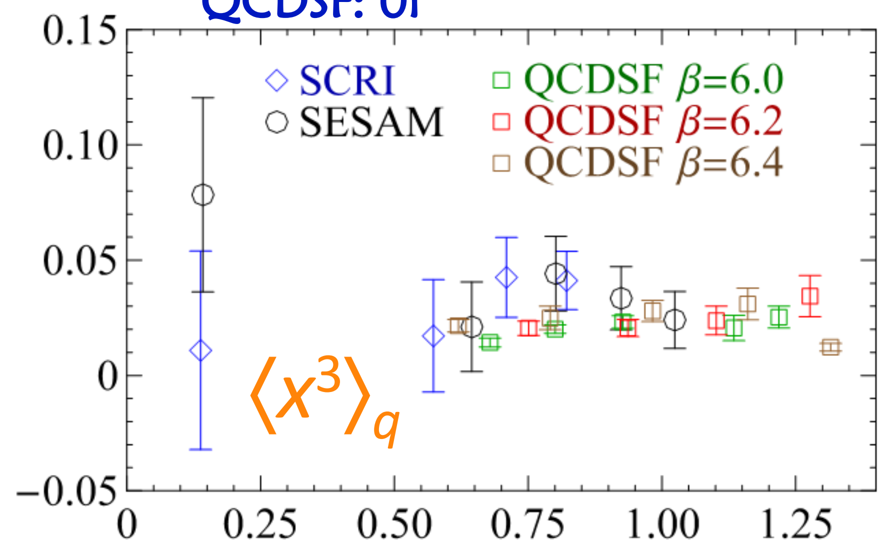
- § For higher moments, ops mix with lower-dimension ops
  - Renormalization is difficult too
- § Relative error grows in higher moments
  - Calculation would be costly and difficult

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

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

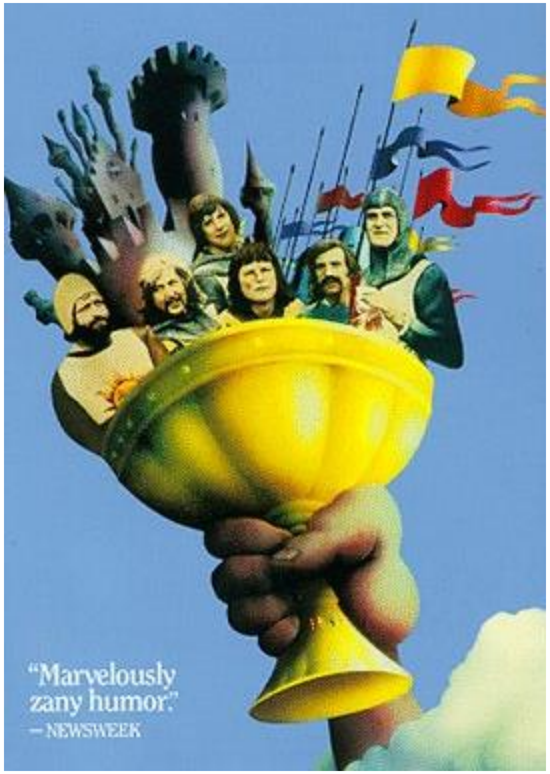
QCDSF: 0f





Beyond Traditional Moments?

- Longstanding obstacle!
- Holy grail of structure calculations
- Applies to many structure quantities:
  - Generalized parton distributions (GPDs)
  - Transverse-momentum distributions (TMD)
  - Meson distribution amplitudes…
  - Wigner distribution



Beyond Traditional Moments?

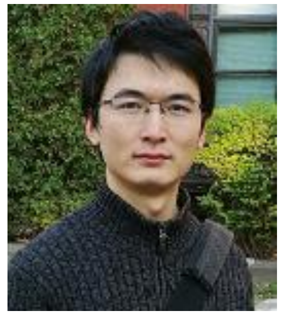
- **Reaching for higher moments**
  - Fictitious heavy quarks (Detmold and Lin, hep-lat/0507007)
  - Smeared lat. ops (Davoudi et al. 1204.4146)
- **Direct calculation of *x* dependence**
  - Hadronic tensor currents (Liu et al., hep-ph/9806491, ... 1603.07352)
  - Inversion method/OPE without OPE (QCDSF, hep-lat/9809171, …1703.01153)
  - Euclidean correlation functions (RQCD, 1709.04325)
  - Lattice cross-section method (Y.-Q. Ma and J. Qiu, 2014, 2017)
  - Large-momentum effective theory (LaMET) and variations
    - Original LaMET ("quasi-PDF" method) This talk
    - Pseudo-PDF method: differs in FT (A. Radyushkin, 2017)
    - Smeared quasi-PDF (C. Monahan and K. Orginos, 2017)

Lattice Parton Physics Project (LP^3)

https://www.pa.msu.edu/~hwlin/LP3/

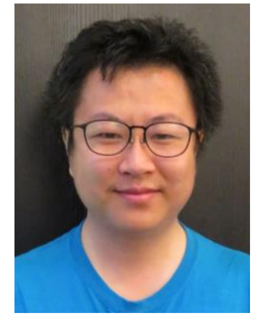
HL
(MSU)

Xiangdong Ji
(UMD)



Luchang Jin
(Conn)

Ruizi Li
(MSU)



Yi-Bo Yang
(MSU)

Yong Zhao
(MIT)

International collaborators

Jiunn-Wei Chen
(NTU)

Yu-Sheng Liu
(SJTU)

Andreas Schäfer
(Regensburg)

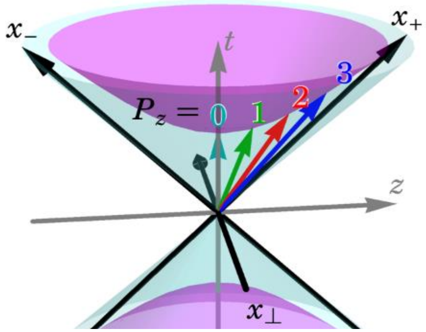
Jian-Hui Zhang
(Regensburg)

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)

§ 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

hadron momentum $P_\mu = \{P_t, 0, 0, P_z\}$

Product of lattice gauge links

§ Take the infinite-P_z limit to recover lightcone functions

- Just another limit to take, like taking $a \to 0$ or $V \to \infty$

Progress in the theoretical development of LaMET

- **Renormalization:**

Ji and Zhang, 2015; Ishikawa et al., 2016, 2017; Chen, Ji and Zhang, 2016;

Xiong, Luu and Meiβner, 2017; Constantinou and Panagopoulos, 2017; Ji, Zhang, and Y.Z., 2017; J. Green et al., 2017; Ishikawa et al. (LP3), 2017; Wang, Zhao and Zhu, 2017; Spanoudes and Panagopoulos, 2018.

- **Factorization:**

Ma and Qiu, 2014, 2015, 2017; Izubuchi, Ji, Jin, Stewart and Y.Z., 2018.

- **One-loop matching:**

Xiong, Ji, Zhang and Y.Z., 2014; Ji, Schaefer, Xiong and Zhang, 2015; Xiong and Zhang, 2015; Constantinou and Panagopoulos, 2017; I. Stewart and Y. Z., 2017; Wang, Zhao and Zhu, 2017; Izubuchi, Ji, Jin, Stewart and Y.Z., 2018.

- **Power corrections:**

J.-W. Chen et al., 2016; A. Radyushkin, 2017.

- **Transvers momentum dependent parton distribution function:**

Ji, Xiong, Sun, Yuan, 2015; Ji, Jin, Yuan, Zhang and Y.Z., 2018; Ebert, Stewart and Y.Z., in progress.

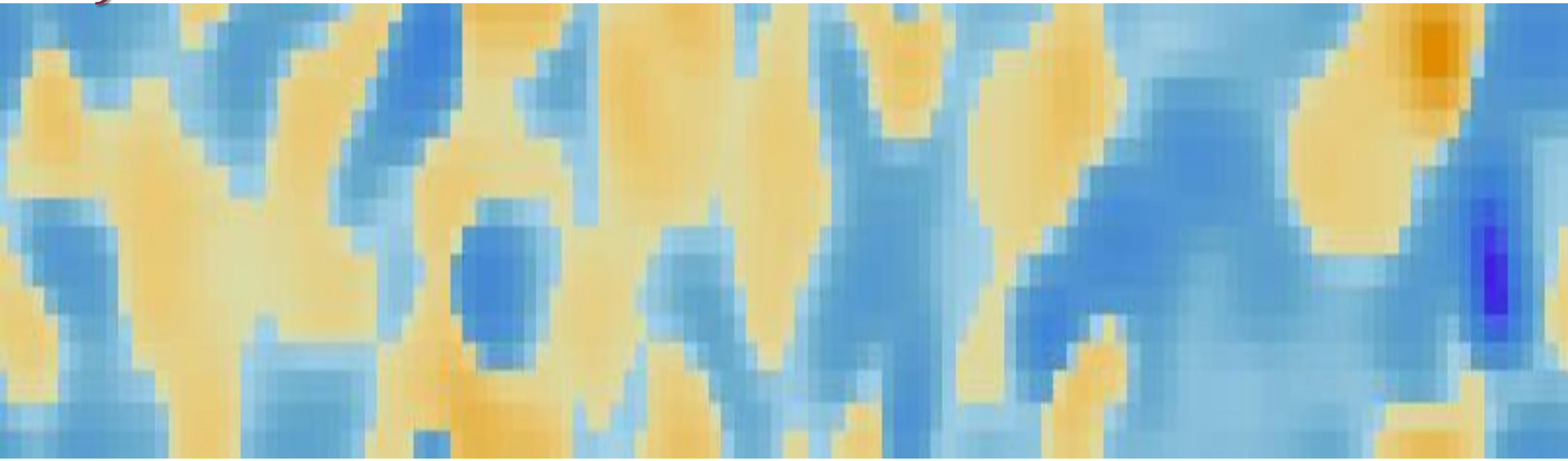
Slide credit: Yong Zhao, CIPANP 2018 Plenary talk

LaMET: Step-by-Step

Large-Momentum Effective Theory for PDFs

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

1) Calculate nucleon matrix elements on the lattice



Thanks to MILC collaboration for sharing their 2+1+1 HISQ lattices

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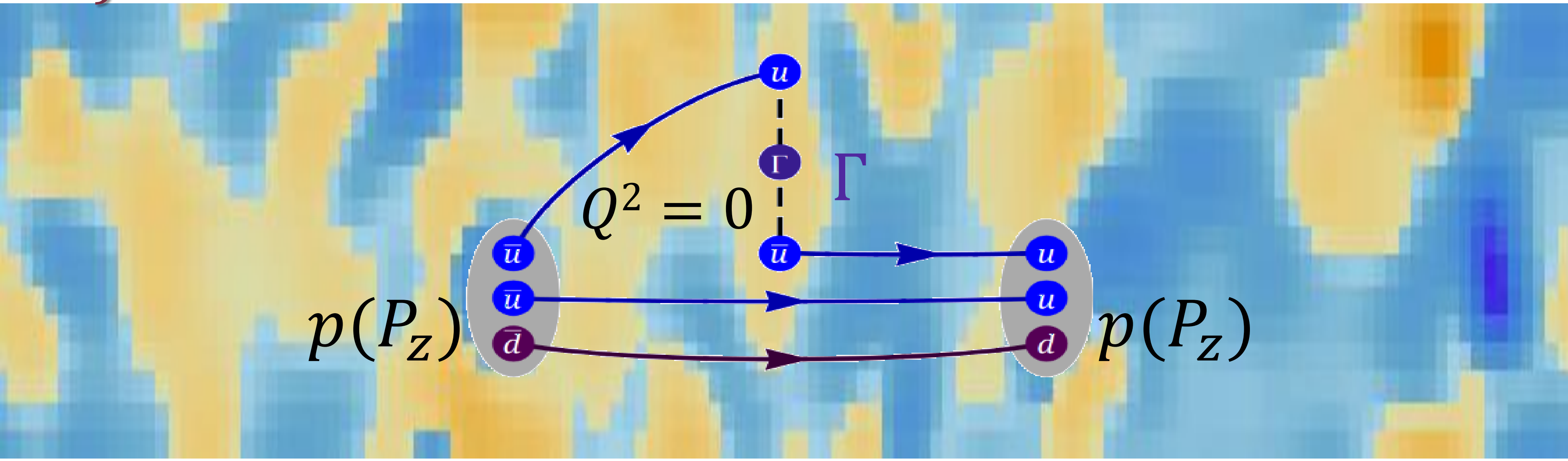

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LaMET: Step-by-Step

Large-Momentum Effective Theory for PDFs

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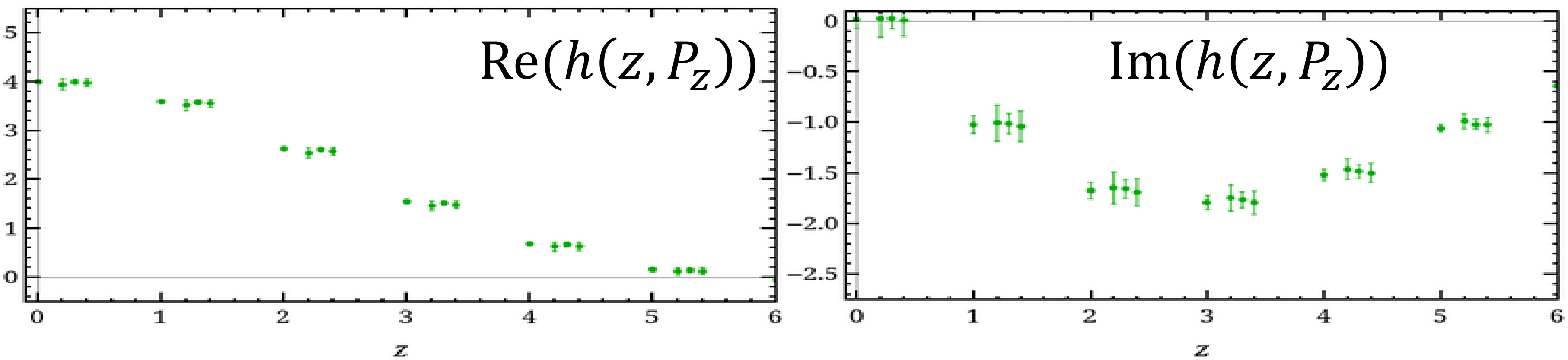
1) Calculate nucleon matrix elements on the lattice

$$h(z,Pz) = \left\langle P \left| \overline{\psi}(z)\,\gamma_z \exp\left(-ig\int_0^z dz'\,A_z(z')\right)\psi(0)\right| P\right\rangle$$



$P_z =$ 2.6 GeV

$M_\pi \approx$ **135 MeV**, $a \approx 0.09$ fm

LP[3] 1804.01483

Ruizi Li

Blinded 3-state fits produced consistent results

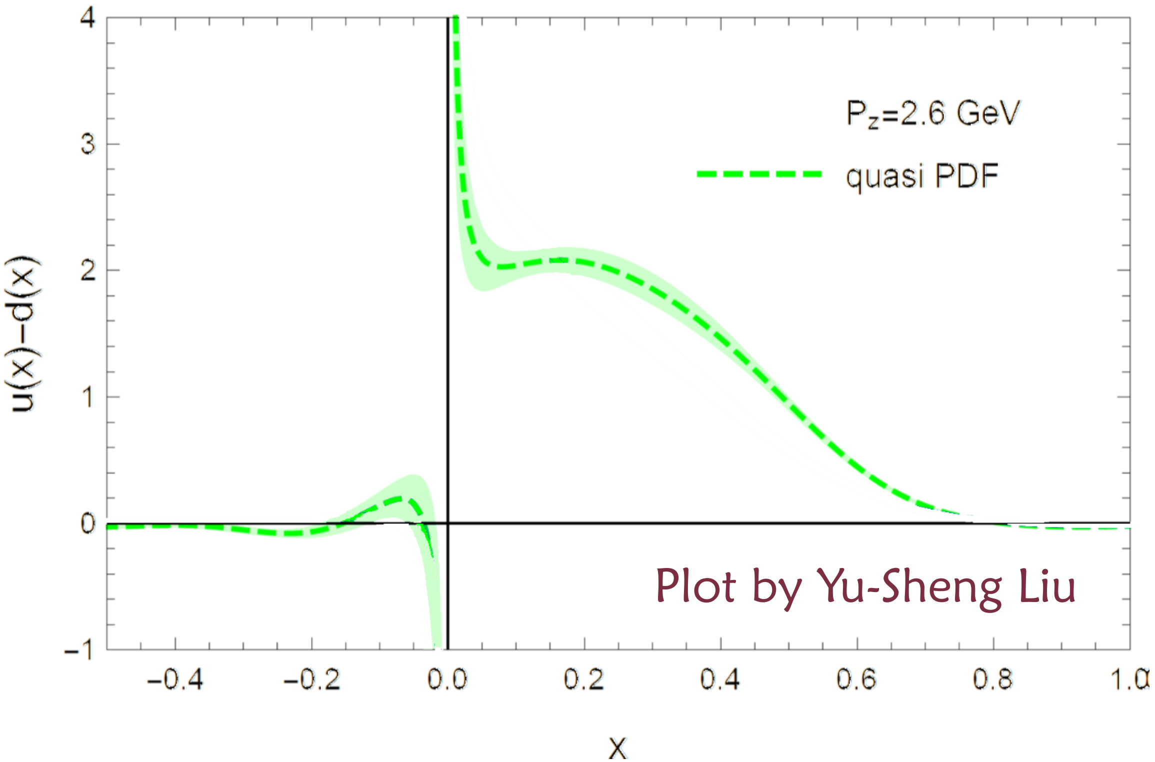
LaMET: Step-by-Step

Large-Momentum Effective Theory for PDFs

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

2) Compute "quasi-distribution" via

$$\tilde{q}(x,\mu,P_z) = \int \frac{dz}{4\pi} e^{-i\,x\,zP_z}\, h_R(z,\mu,P_z)$$



Yu-Sheng Liu

LaMET: Step-by-Step

Large-Momentum Effective Theory for PDFs

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

3) Recover true distribution (take $P_z \to \infty$ limit)

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

Finite $P_z \leftrightarrow \infty$ perturbative matching

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

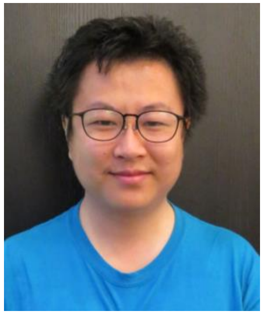
Non-singlet case only

Stewart, Zhao: 1709.04933

LP[3], 1807.06566, 1810.05043

Yong Zhao

Yu-Sheng Liu



Yi-Bo Yang

LaMET: Step-by-Step

Large-Momentum Effective Theory for PDFs

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Dominant correction
(for nucleon);
known scaling form
LP³ , 1402.1462, 1603.06664

LaMET: Step-by-Step

Large-Momentum Effective Theory for PDFs

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complicated higher-twist operator;
smaller P_z correction for nucleon
LP[3] , 1603.06664 and references within
(extrapolate it away)

§ Some similarity to more broadly-studied HQET…

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

LaMET: Step-by-Step

Large-Momentum Effective Theory for PDFs

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

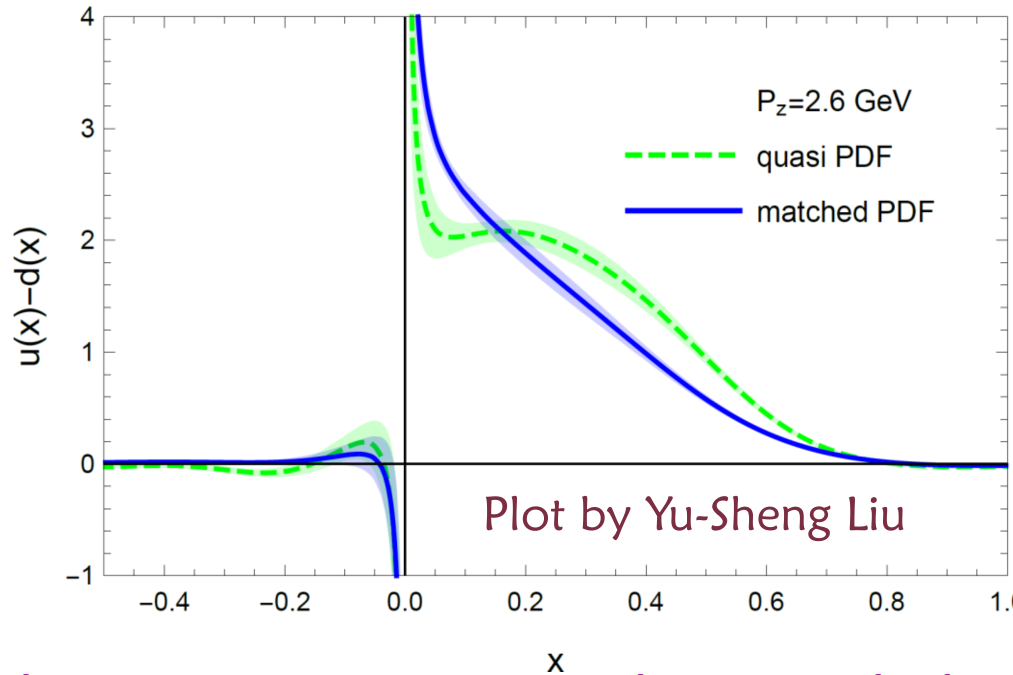
3) Recover true distribution (take $P_z \to \infty$ limit)

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

$M_\pi \approx$ **135 MeV**

$a \approx 0.09$ fm

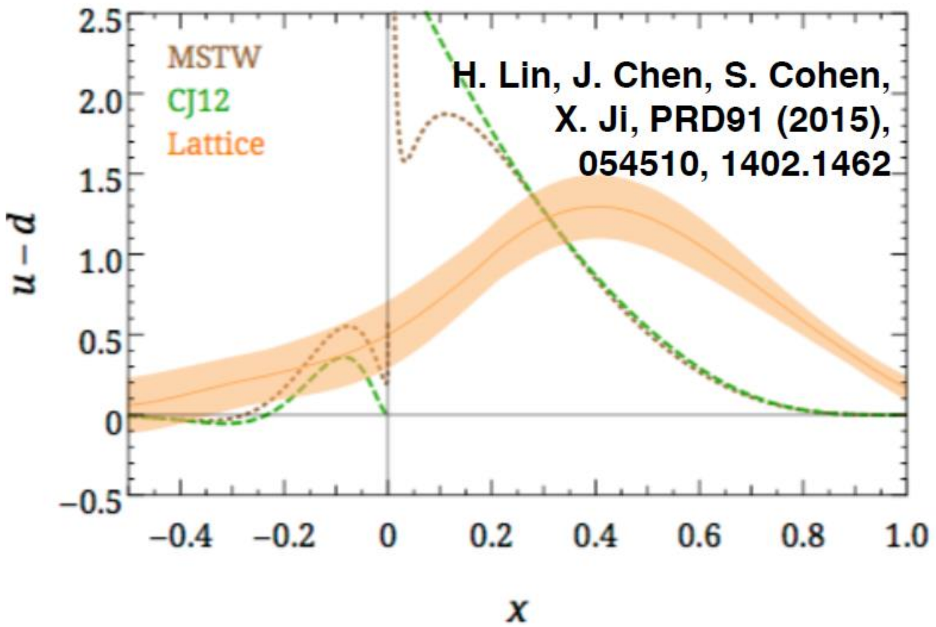
LP[3] 1804.01483



§ Matching is a crucial step in recovering the true lightcone distribution

Nucleon Unpolarized PDF

§ From 2014 to 2018

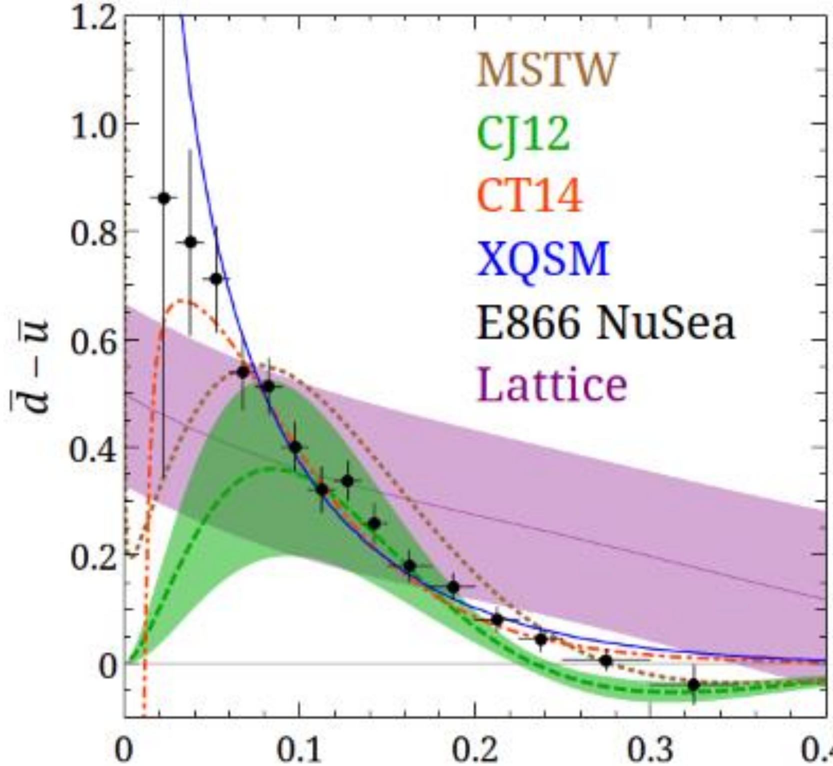


First result in 2014!

- $M_\pi \approx$ **310 MeV**, $a \approx 0.12$ fm ($M_\pi L \approx 4.5$)
- Largest $P_z \approx 1.3$ GeV
- 1-loop $\overline{\text{MS}}$ matching + target-mass correction

Nucleon Unpolarized PDF

§ From 2014 to 2018



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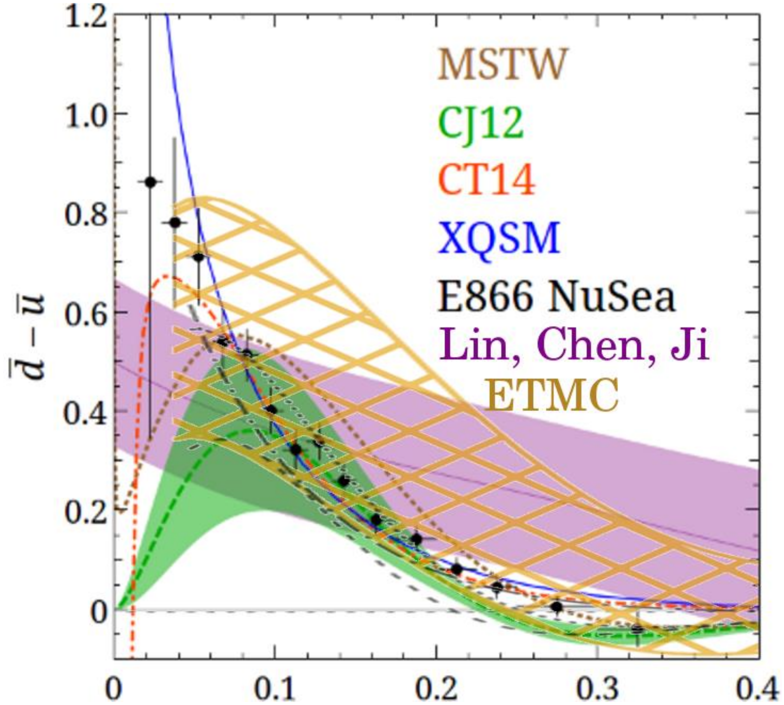
- Largest $P_z \approx 1.3$ GeV
- 1-loop $\overline{\text{MS}}$ matching + target-mass correction

First sea flavor asymmetry ever calculated!

Overcomes decades of obstacles in LQCD structure calculations

Nucleon Unpolarized PDF

§ From 2014 to 2018

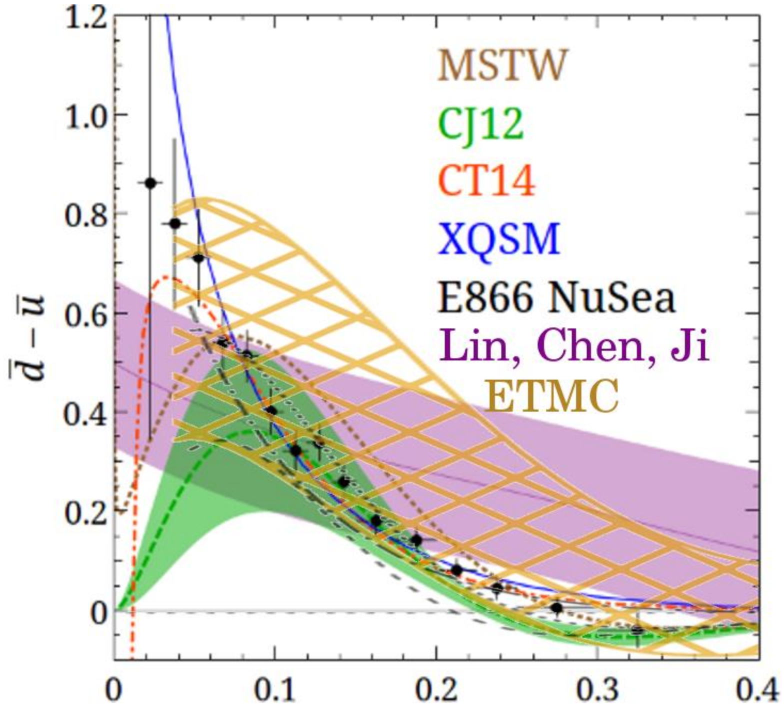


Similar results repeated by ETMC,
at $M_\pi \approx 373$ MeV, a$\approx 0.8 fm$
ETMC, 1504.07455

First helicity and transversity results: 1603.06664 (LP[3])

Nucleon Unpolarized PDF

§ From 2014 to 2018



Similar results repeated by ETMC,
at $M_\pi \approx 373$ MeV, a$\approx 0.8 fm$
ETMC, 1504.07455

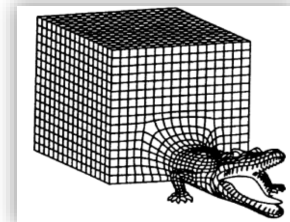
§ Updated results in 2017/18

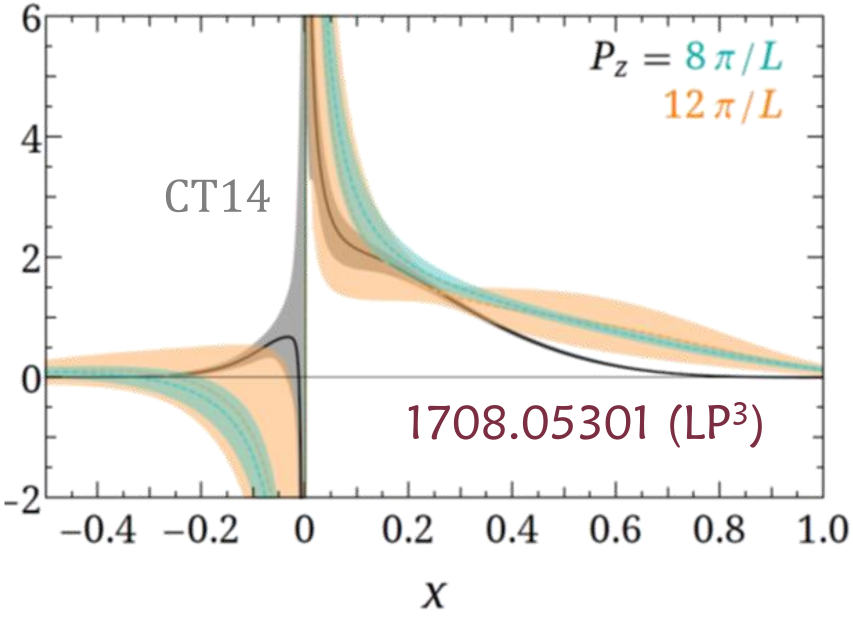
- RI/MOM nonperturbative renormalization and corresponding matching to lightcone distribution
- Improved quasi-distribution definition

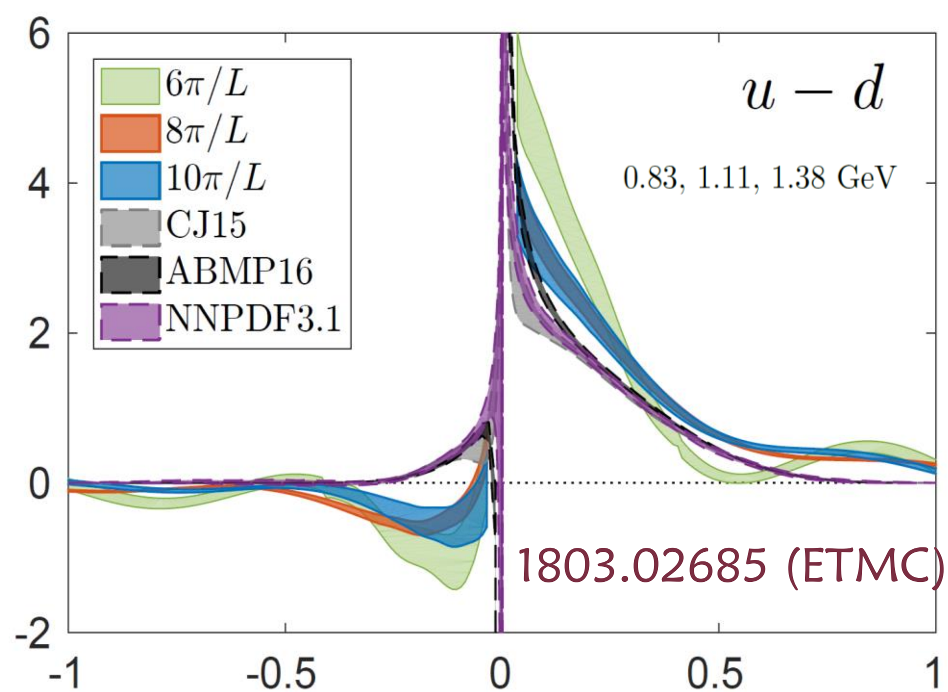
Physical Pion Mass Results

§ Exciting! Two collaborations' results at physical pion mass

- Boost momenta $P_z \leq 1.4$ GeV
- Study of systematics still needed





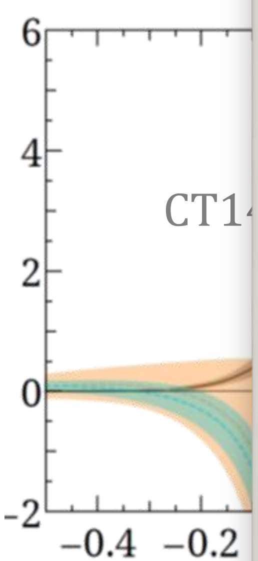


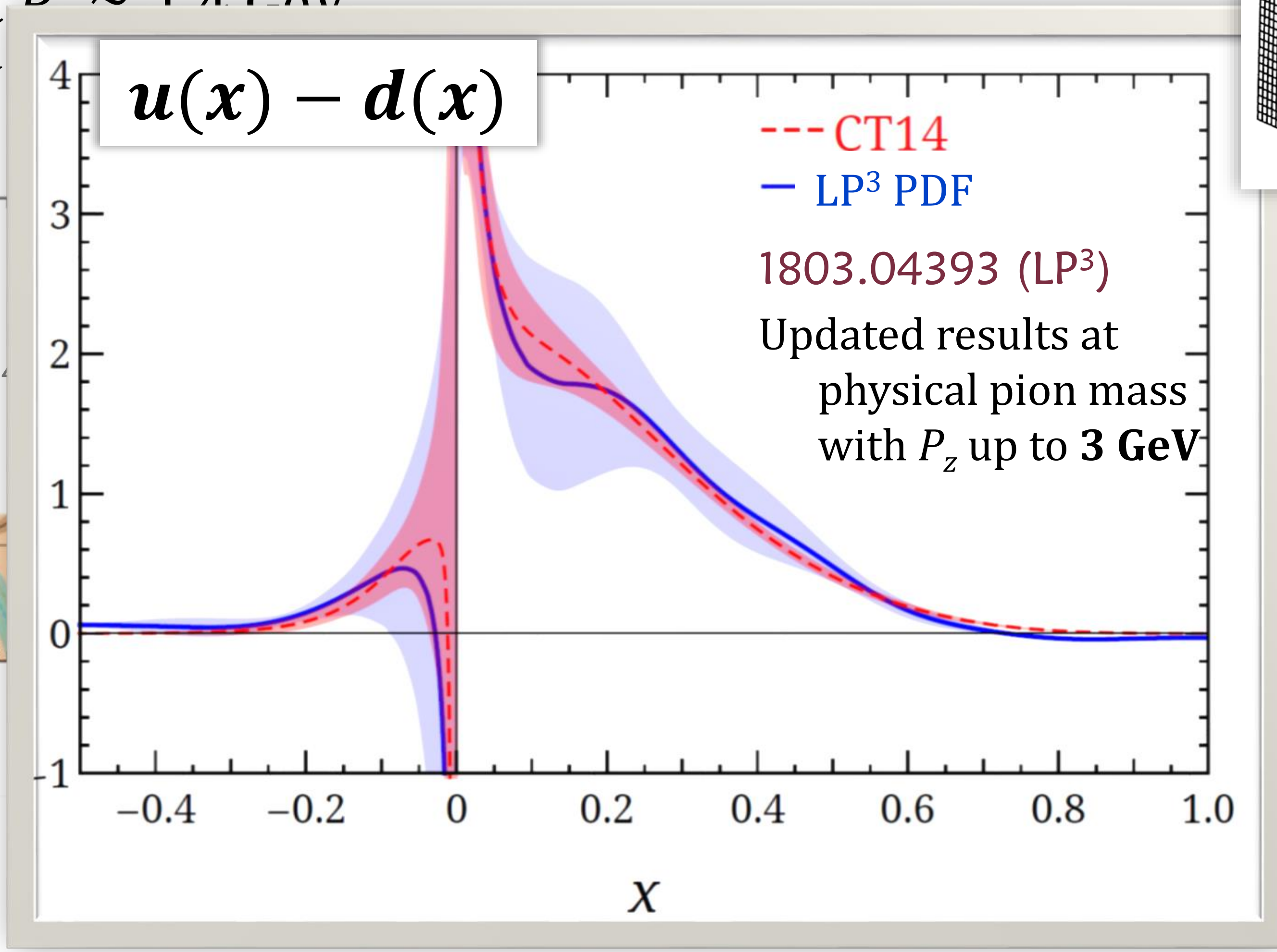
Not use any parametrization form like $xf(x,\mu_0) = a_0 x^{a_1}(1-x)^{a_2}P(x)$

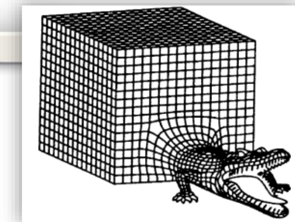
Physical Pion Mass Results

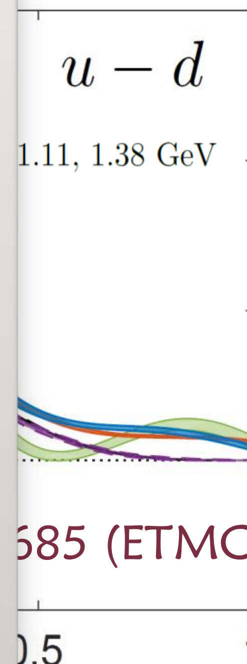
§ Exciting! Two collaborations' results at physical pion mass

- Boost $P_z \sim 1.4$ GeV
- Study





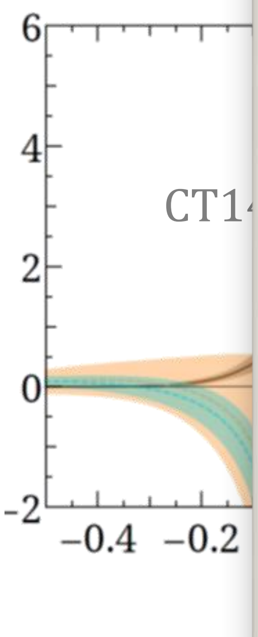


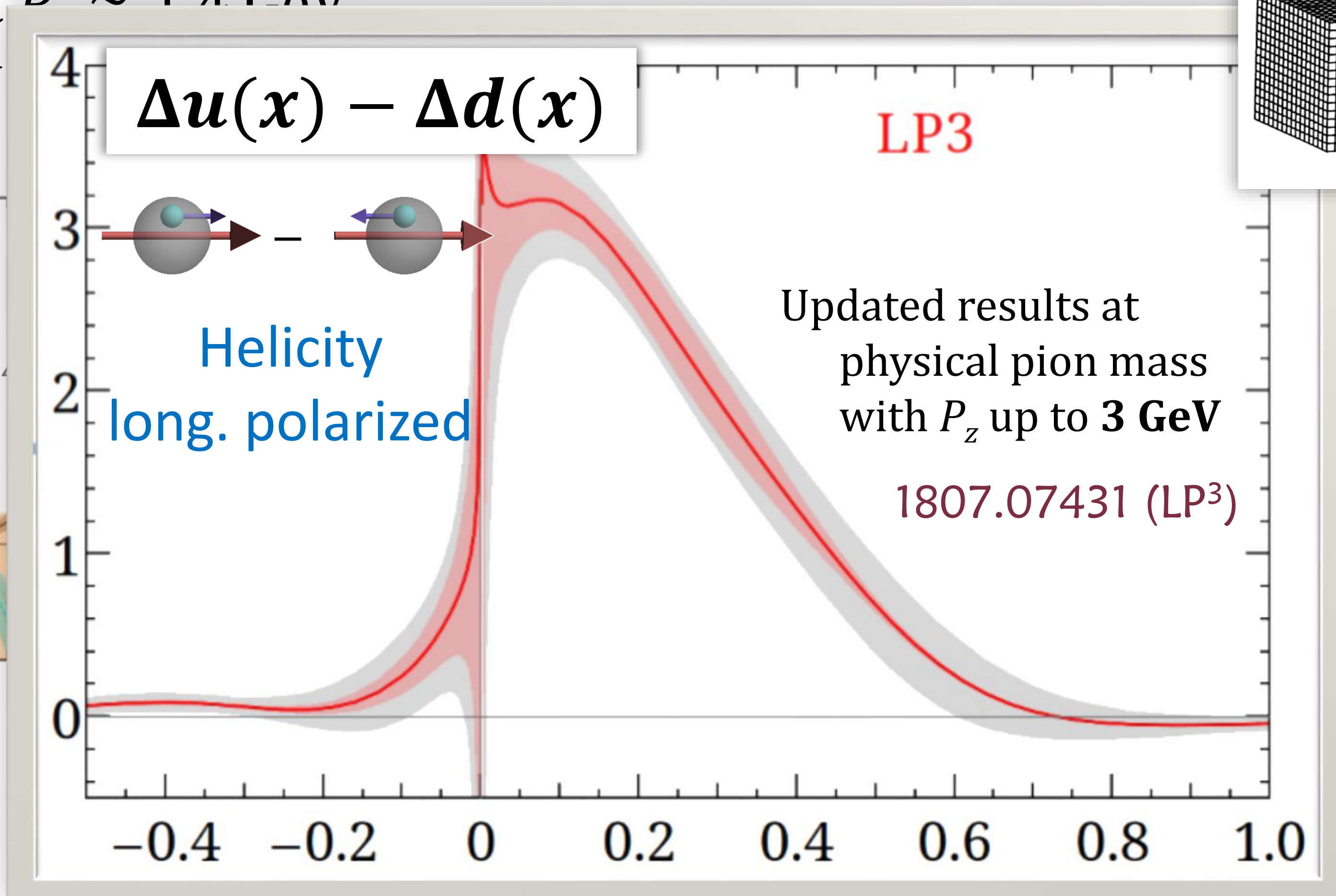


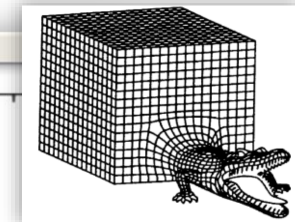
Physical Pion Mass Results

§ Exciting! Two collaborations' results at physical pion mass

- Boost $P_z \sim 1.4$ GeV
- Study







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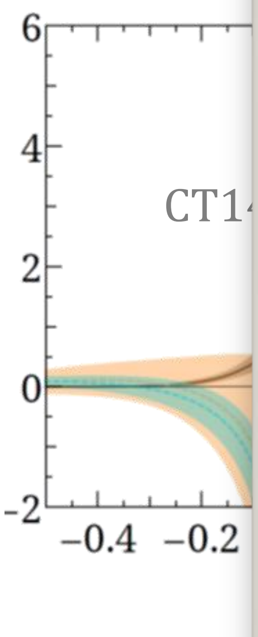

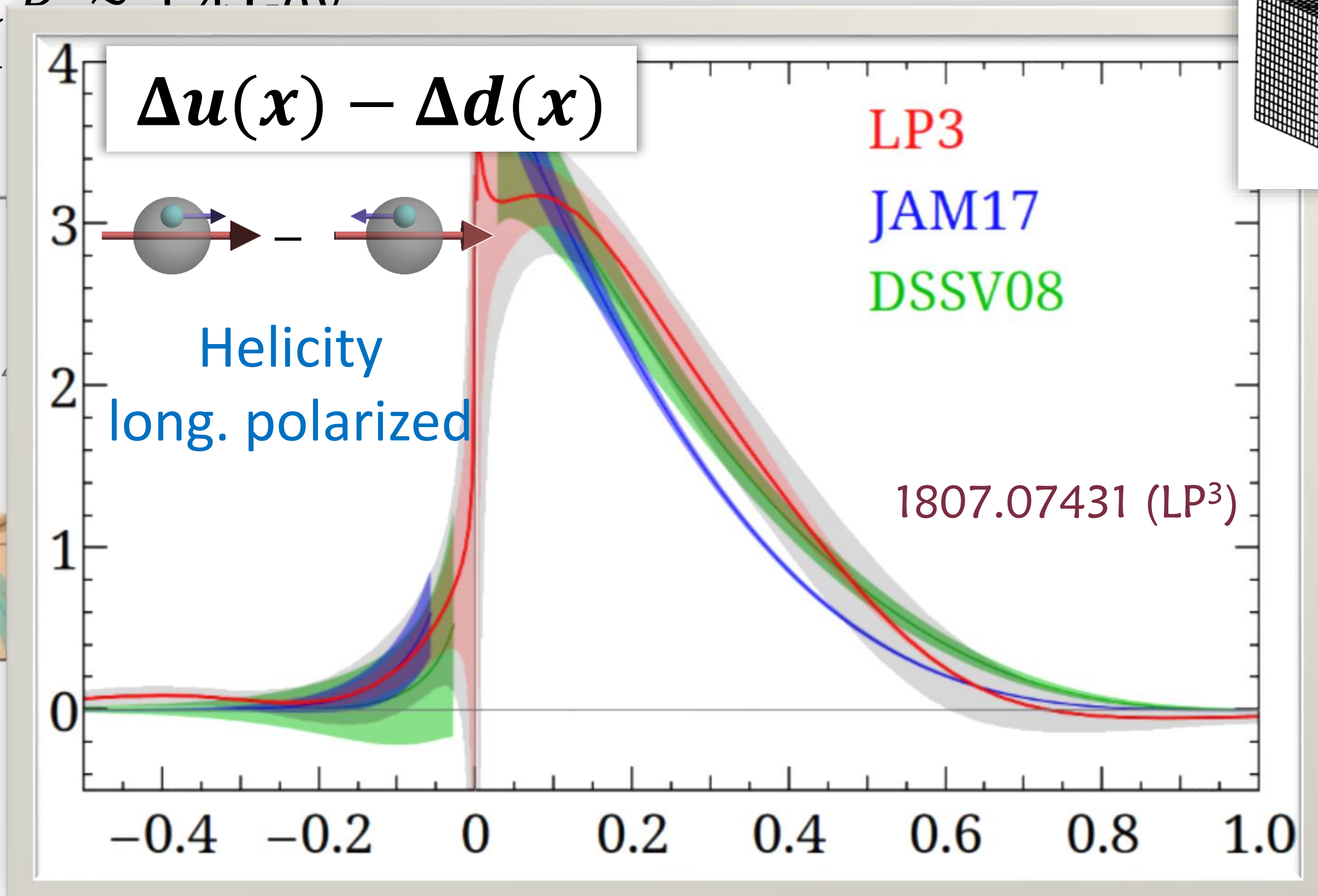

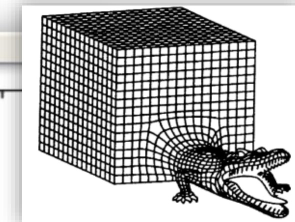

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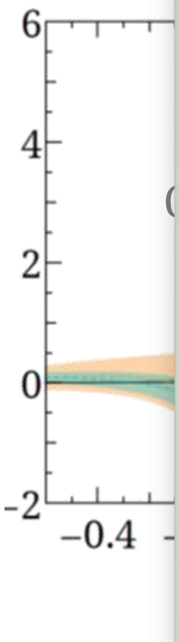
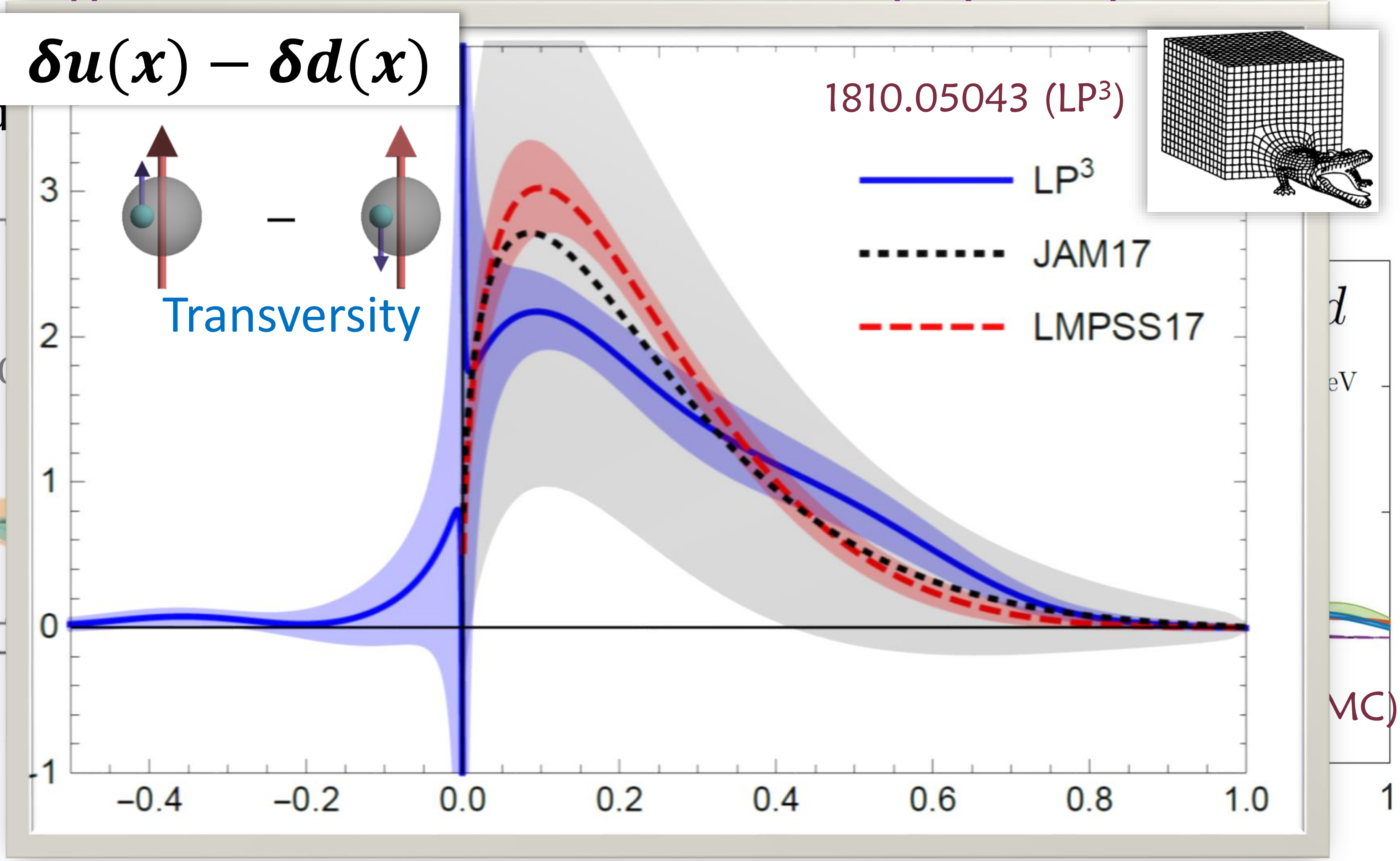
- Bo
- Stu





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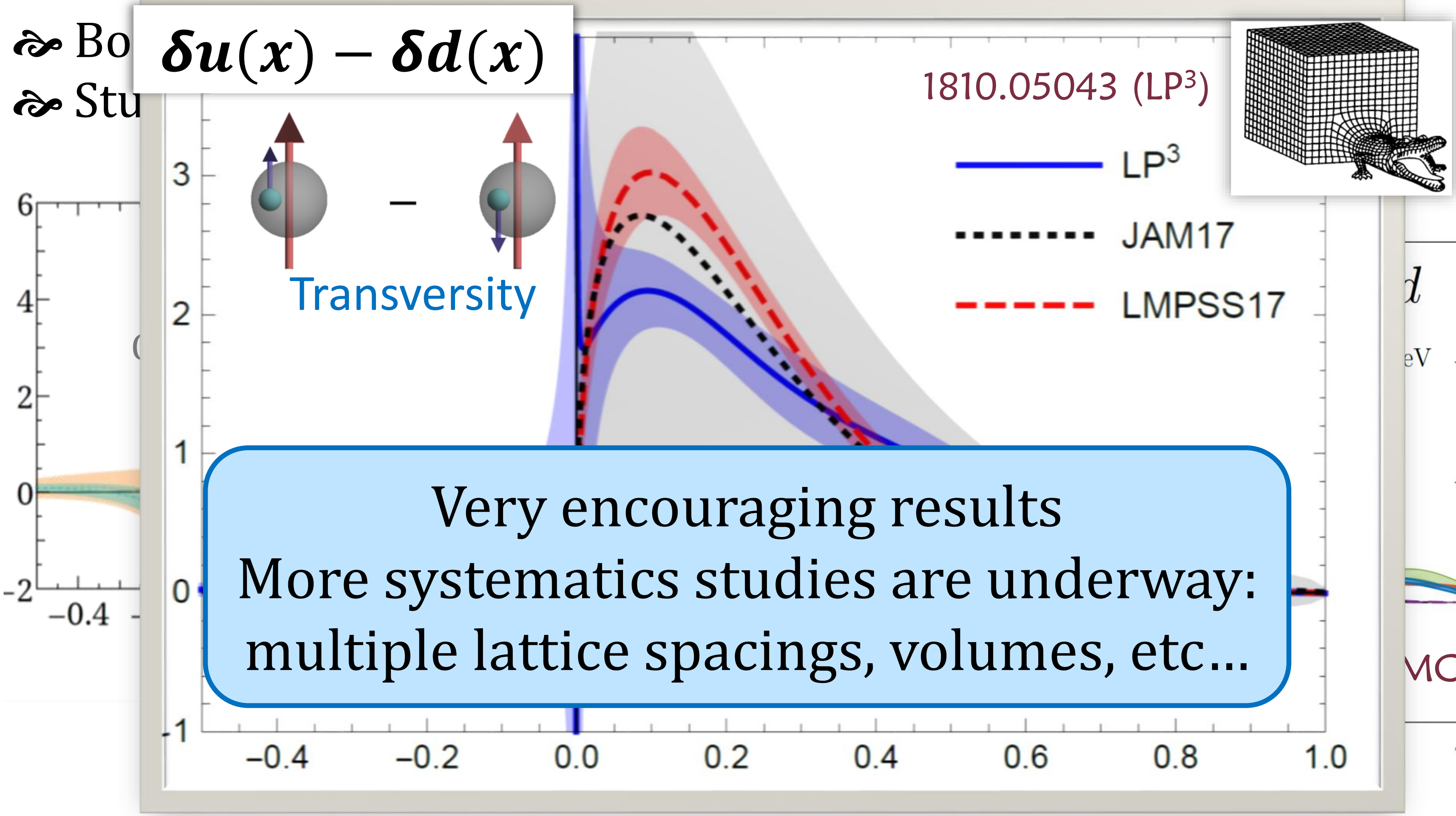


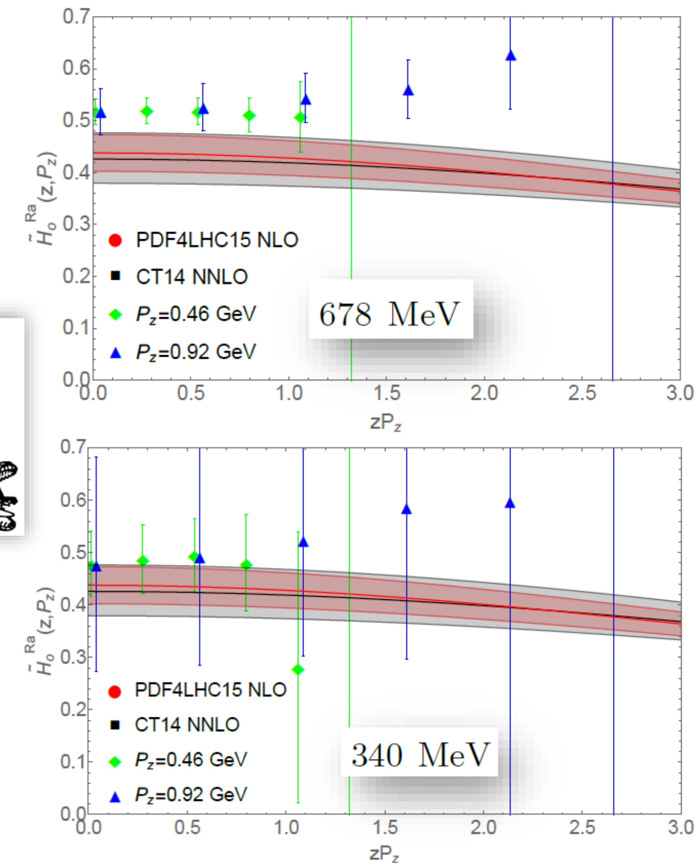
Very encouraging results
More systematics studies are underway:
multiple lattice spacings, volumes, etc…

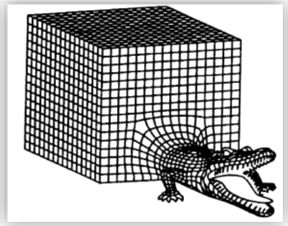
Gluon PDF

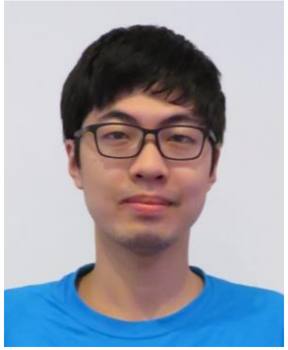
§ Pioneering first glimpse into gluon PDF using LaMET

- Lattice details: overlap/2+1DWF, 0.16fm, 340-MeV sea pion mass
- Study strange/light-quark
- Promising results using coordinate-space comparison, but signal does not go far in *z*
- Hard numerical problem to be solved

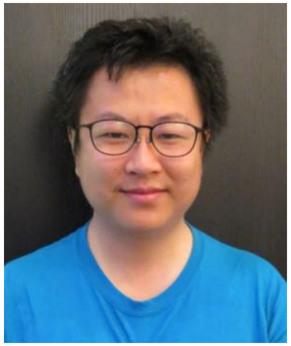
Fan. et al, 1808.02077



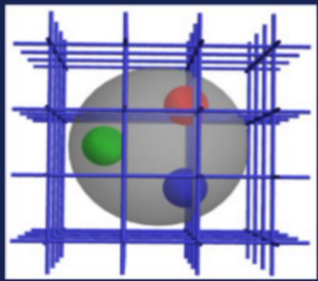


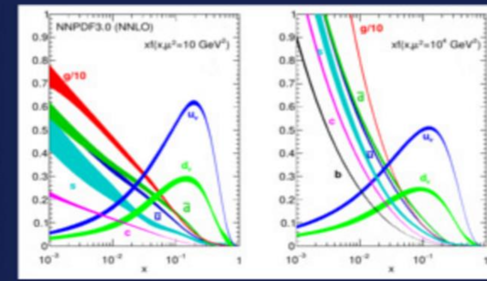


Zhouyou Fan



Yi-Bo Yang





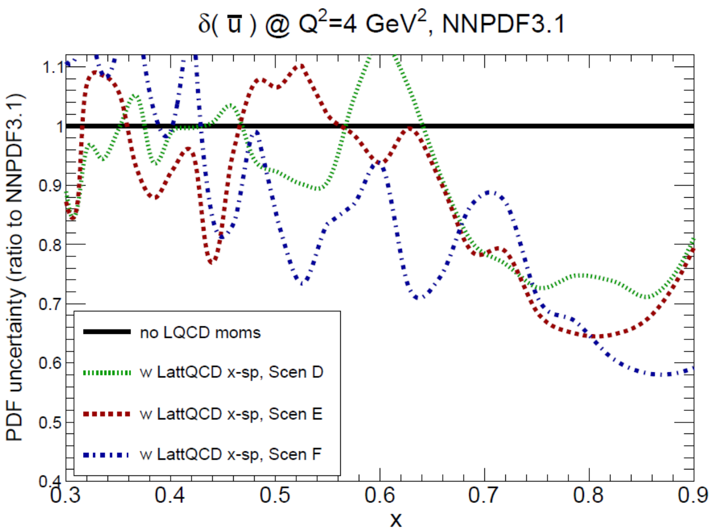
§ Implementing the pseudo-data from LQCD with $x = 0.7$–0.9

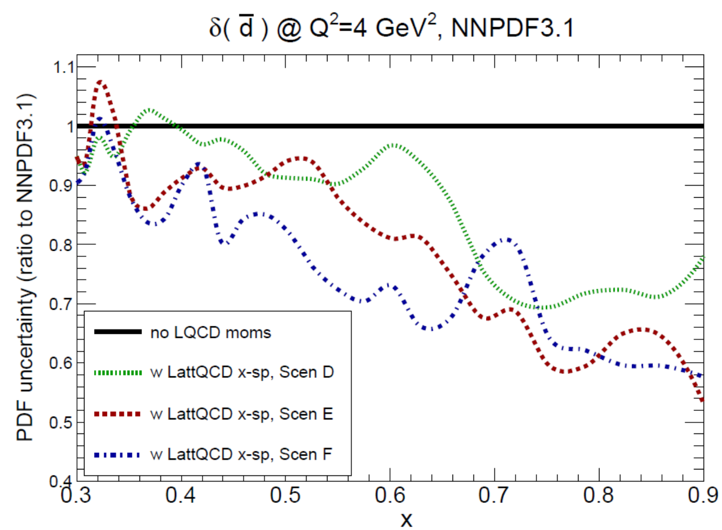
$$u(x_i, Q^2) - d(x_i, Q^2) \text{ and } \bar{u}(x_i, Q^2) - \bar{d}(x_i, Q^2)$$

D: 12%

E: 6%

F: 3%



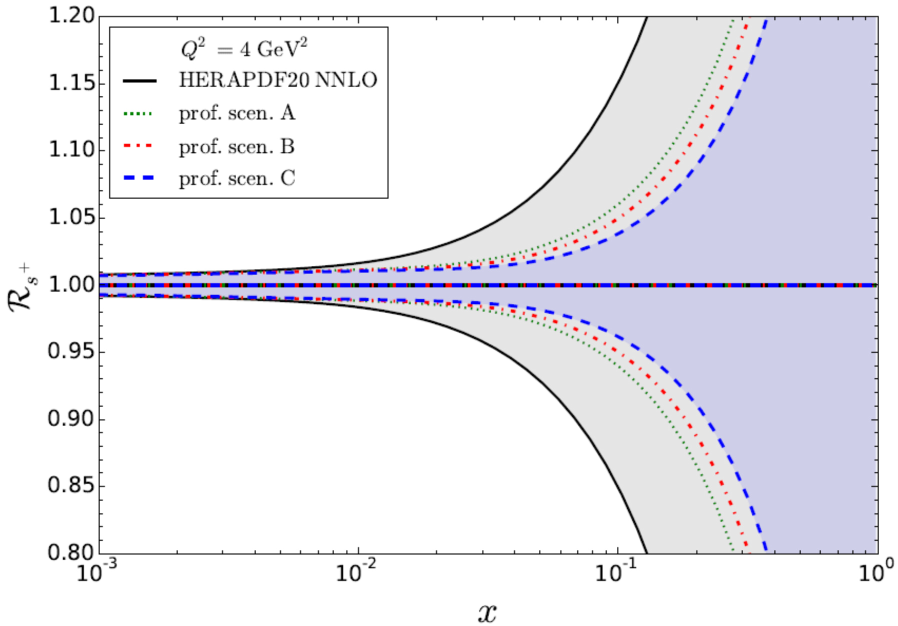


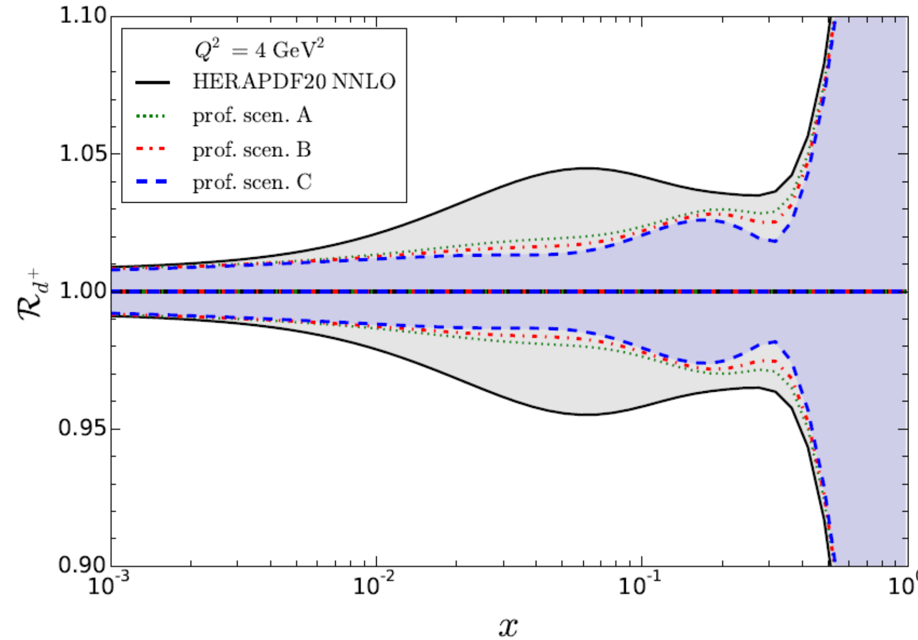
Lin et al, Progress in Particle and Nuclear Physics 100, 106 (2018)

LQCD Impacts

- Precision moments can be useful to improve PDFs!
- Case study on the impacts (example)

A: 5% B: 4% C: 3%



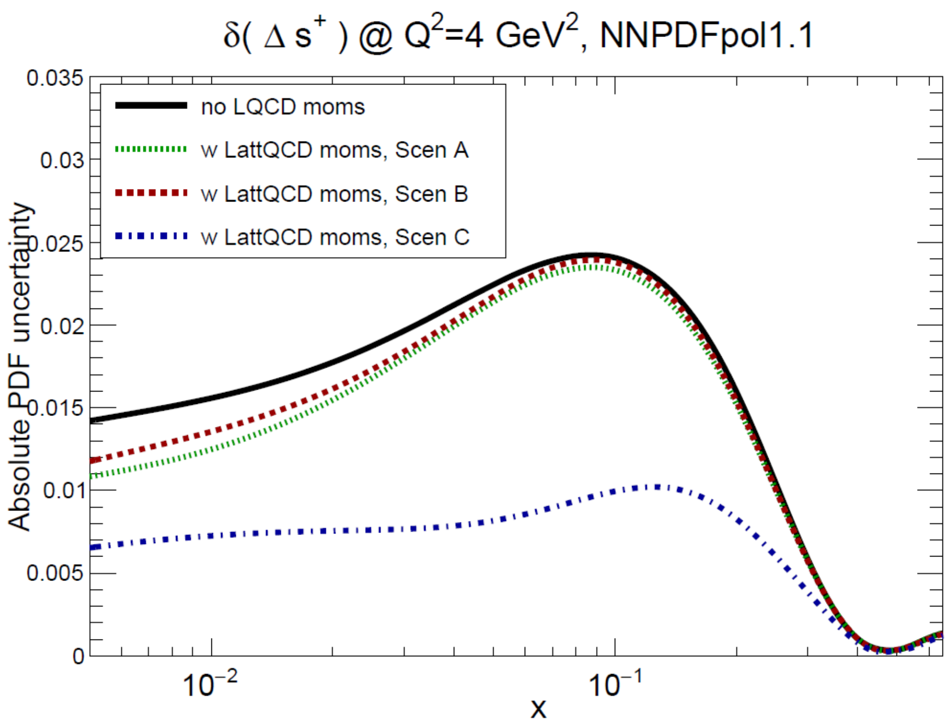


Lin et al, Progress in Particle and Nuclear Physics 100, 106 (2018)

LQCD Impacts

- Precision moments can be useful to improve PDFs!
- Case study on the impacts (one example)

A: 70% B: 50% C: 20%

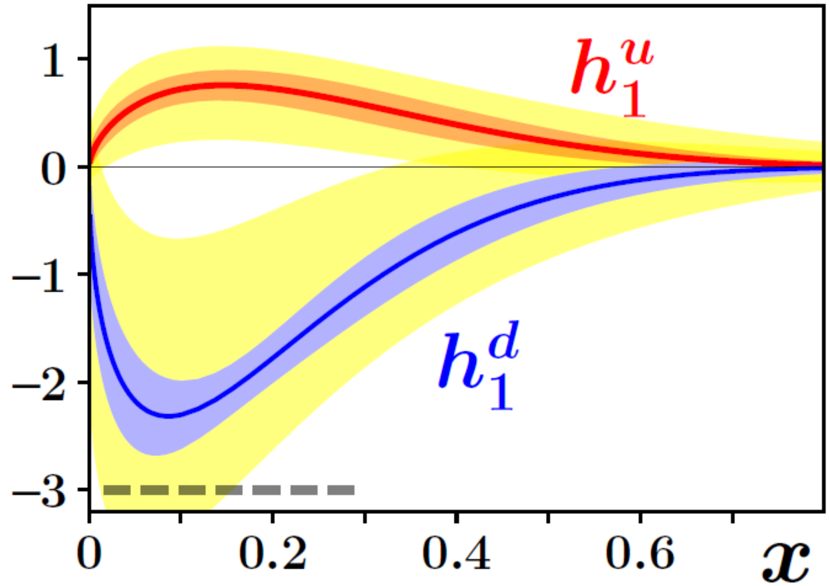


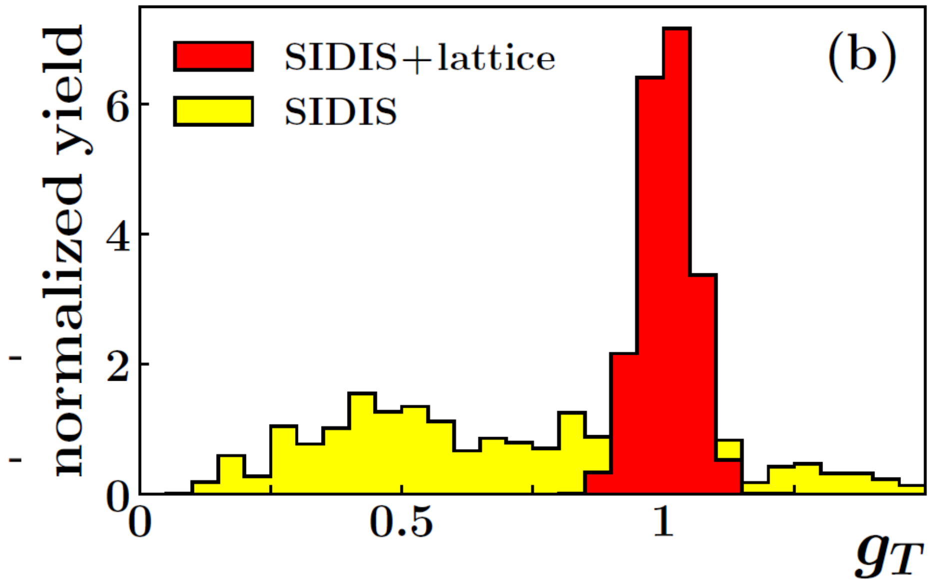
Lin et al, Progress in Particle and Nuclear Physics 100, 106 (2018)

LQCD Impacts

§ Improved transversity distribution with LQCD g_T

- Global analysis with 12 extrapolation forms: $g_T = 1.006(58)$
- Use to constrain the global analysis fits SIDIS $\pi^{\pm}$ production data from proton and deuteron targets





Lin, Melnitchouk, Prokudin, Sato, Phys. Rev. Lett. 120, 152502 (2018)

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.

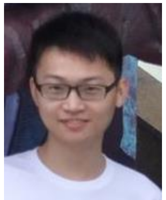
They carry secret plans to build the most powerful

Summary & Outlook

Exciting time for studying structure on the lattice

§ Overcoming longstanding obstacle to full *x*-distribution

- Progress made in first lattice pion PDF (1804.01483) & meson distribution amplitudes (1702.0008,1712.10025)

J. Zhang R. Zhang

§ Exciting/promising physical pion mass results

§ Further systematics study needed

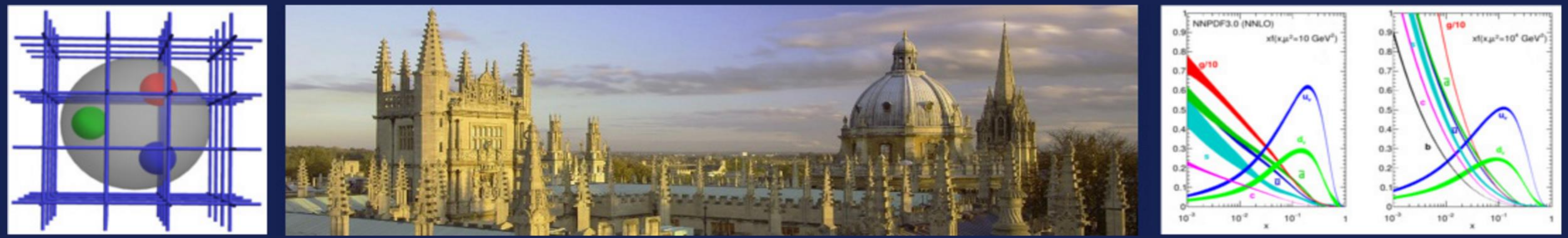
- Need further work on larger momentum boost with finer lattice spacing, higher statistics, higher-order matching, …

§ LQCD impacts for current PDFs in the next few years

- Large-*x* isovector PDFs and precision momrnts (examples shown)
- More work need to be done in small-*x* region

The work of HL is sponsored by NSF CAREER Award under grant PHY 1653405

Backup Slides



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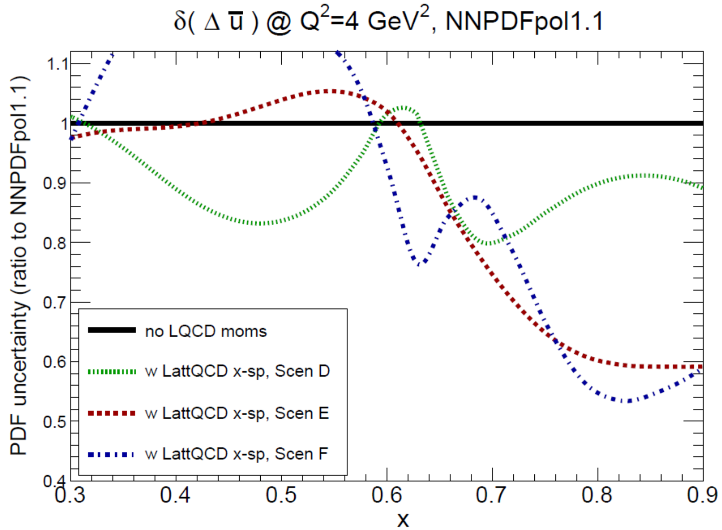
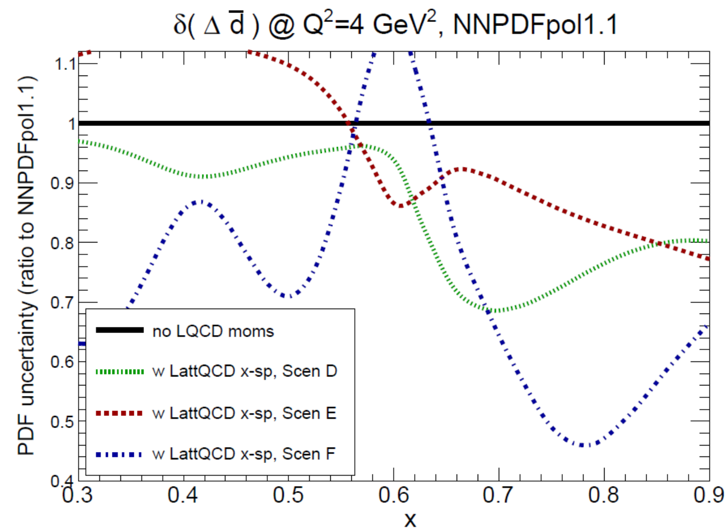




Lin et al, Progress in Particle and Nuclear Physics 100, 106 (2018)

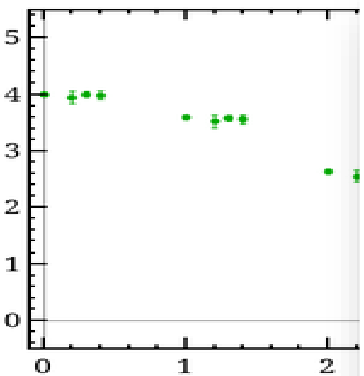
LaMET: Step-by-Step

Large-Momentum Effective Theory for PDFs

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

1) Calculate nucleon matrix elements on the lattice

$$h(z, Pz) = \left\langle P \,\middle|\, \overline{\psi}(z)\, \gamma_z \exp\left(-ig \int_0^z dz'\, A_z(z')\right) \psi(0) \,\middle|\, P \right\rangle$$



$P_z =$ 2.6 (

$M_\pi \approx$ **135 Me**

LP³ 1804.01483

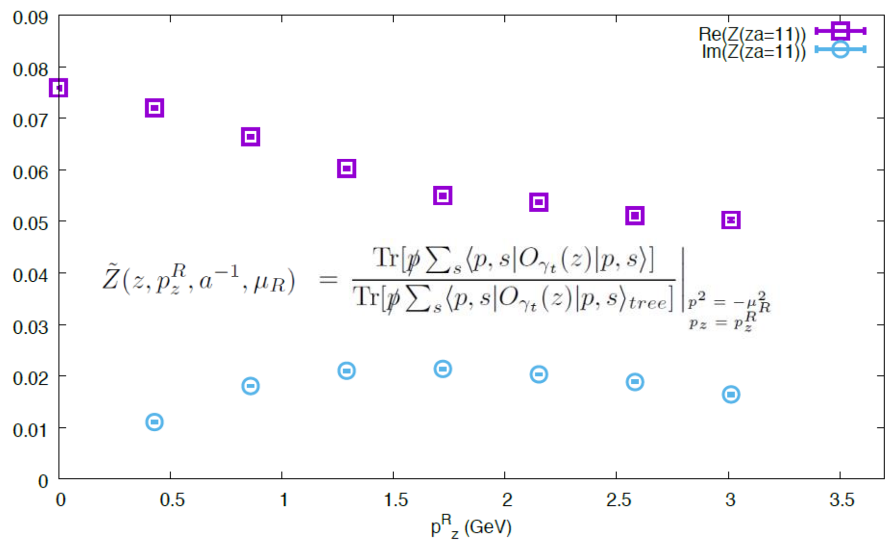
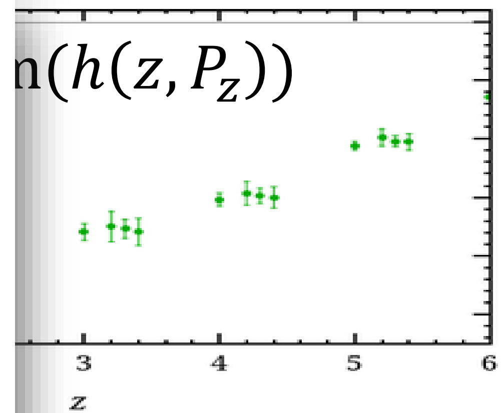


FIG. 1. The values of $Z(z)$ (the inverse of the renormalization constant) at $\mu_R = 3.7$ GeV and $z = 11a \approx 1.0$ fm as a function of p_z^R. Note that $Z(z)$ becomes stable at large p_z^R.



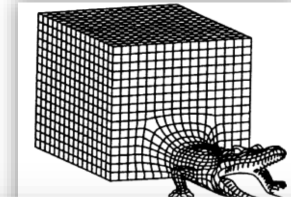
Blinded 3-state fits produced consistent results

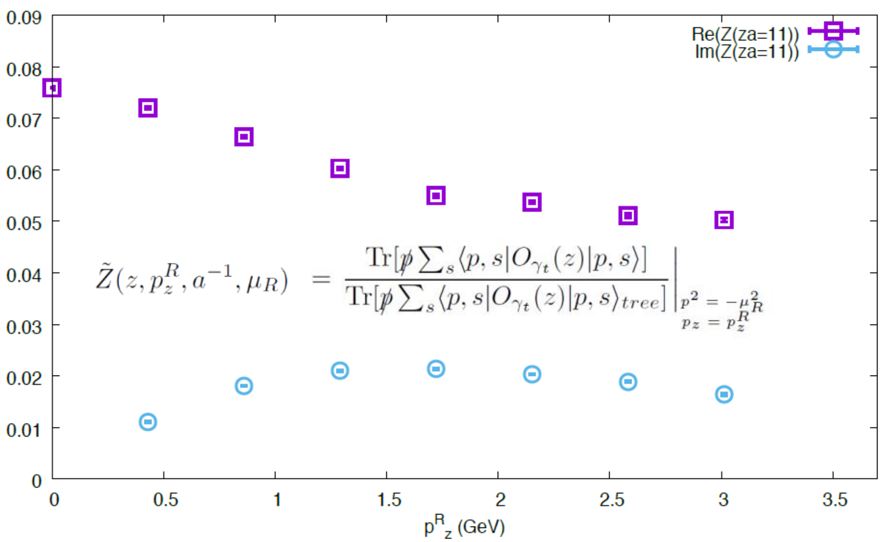
Ruizi Li

Physical Pion Mass Results

§ Exciting! Two collaborations' results at physical pion mass

- Boost $P_z \approx 1.4$ GeV
- Study of systematics still needed





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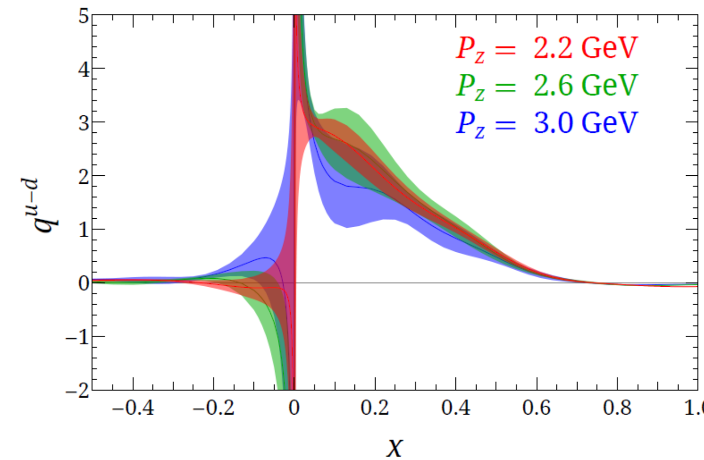

FIG. 3. Nucleon boost momentum dependence of the matched unpolarized isovector PDFs. The parameters of the central value of matched PDF is $(\mu_R, p_z^R) = (3.7, 2.2)$ GeV. For quark asymmetry, the shape is consistent throughout most x regions. However, in the antiquark region, there is a significant change in distribution as momentum increases.

Physical Pion Mass Results

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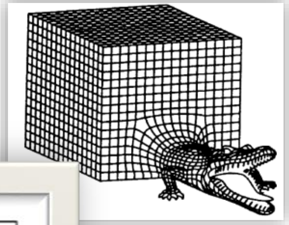

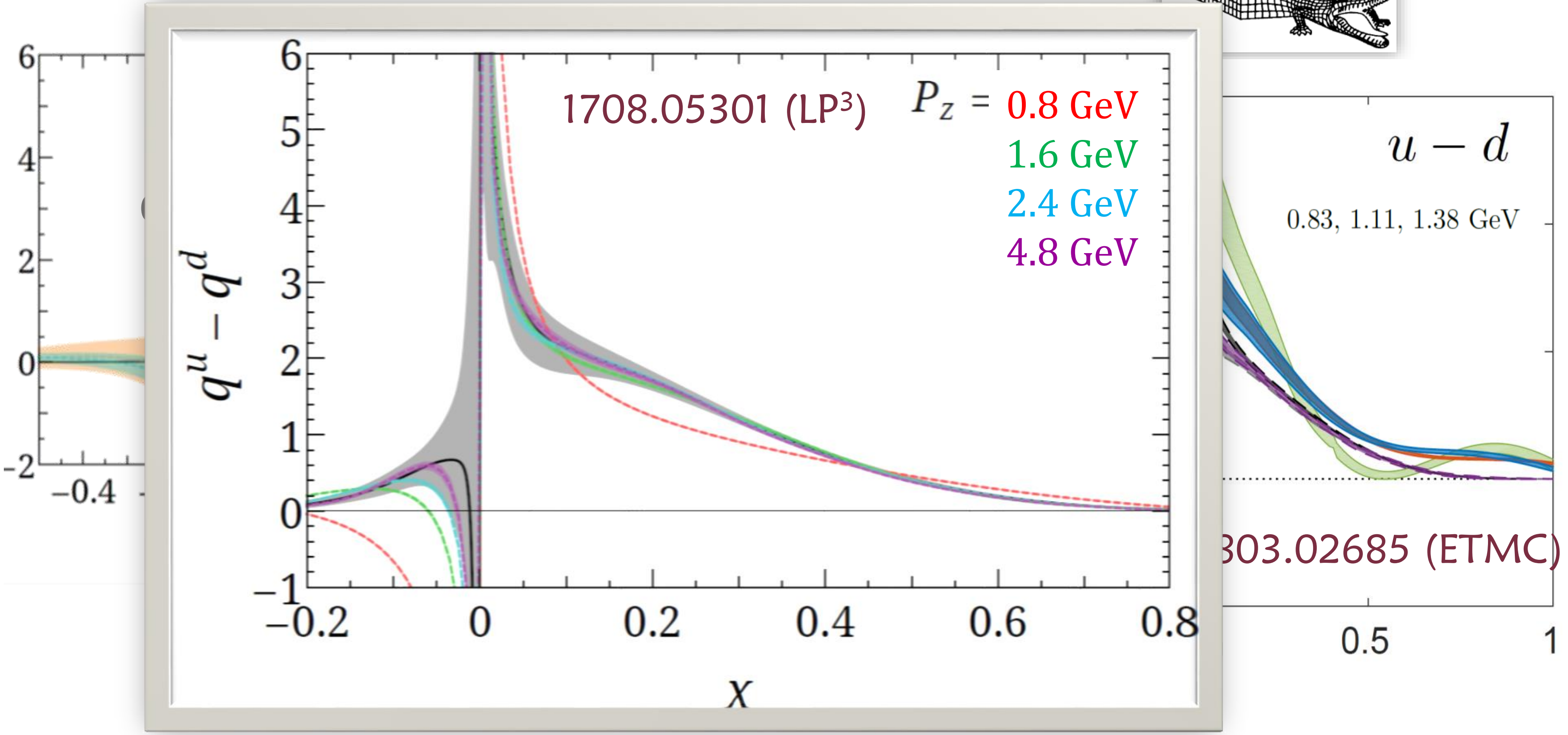

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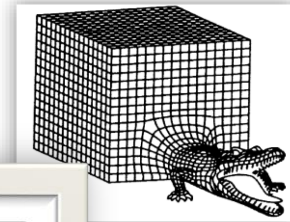
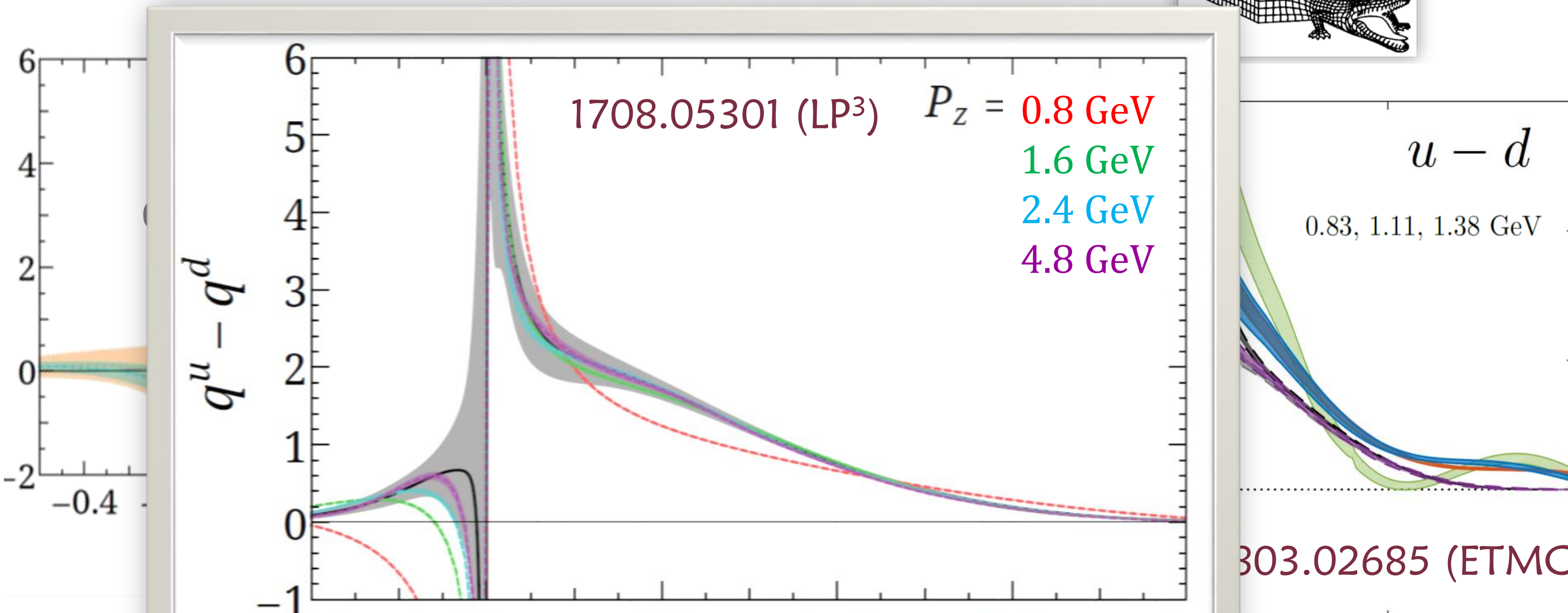


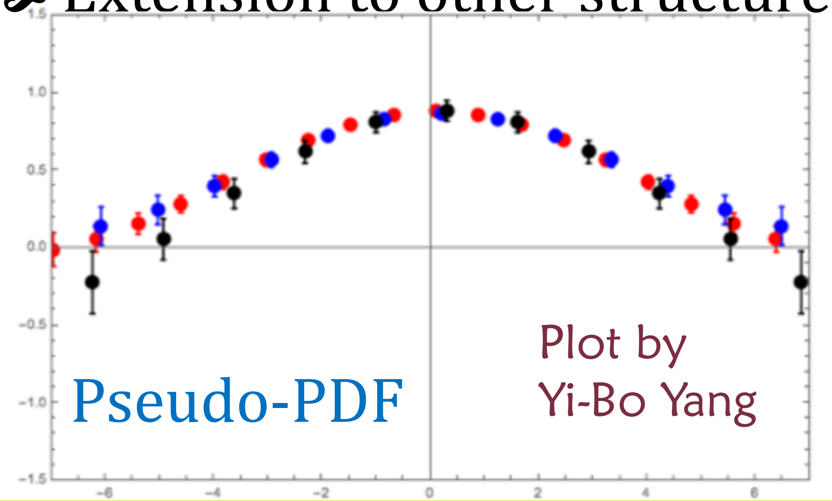


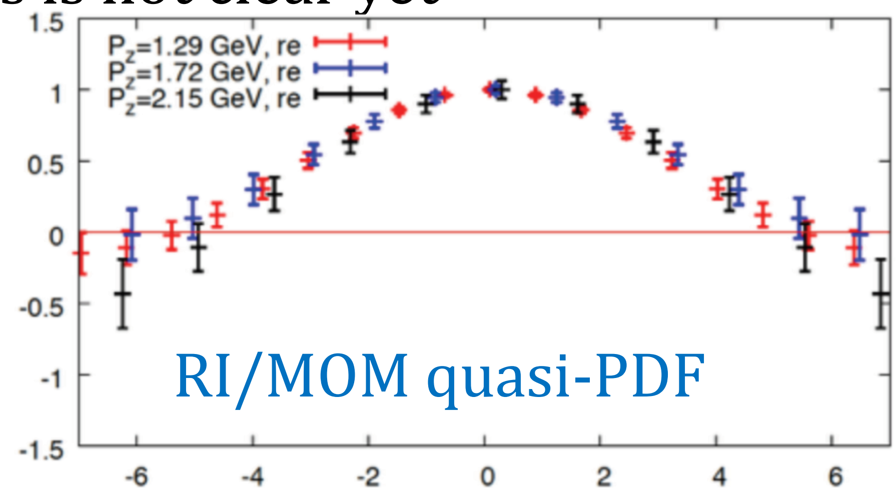
Reaching $x < 0.1$ for antiquark remains challenging

especially without replying on an assumed parametrization

Pseudo-PDF Comparison

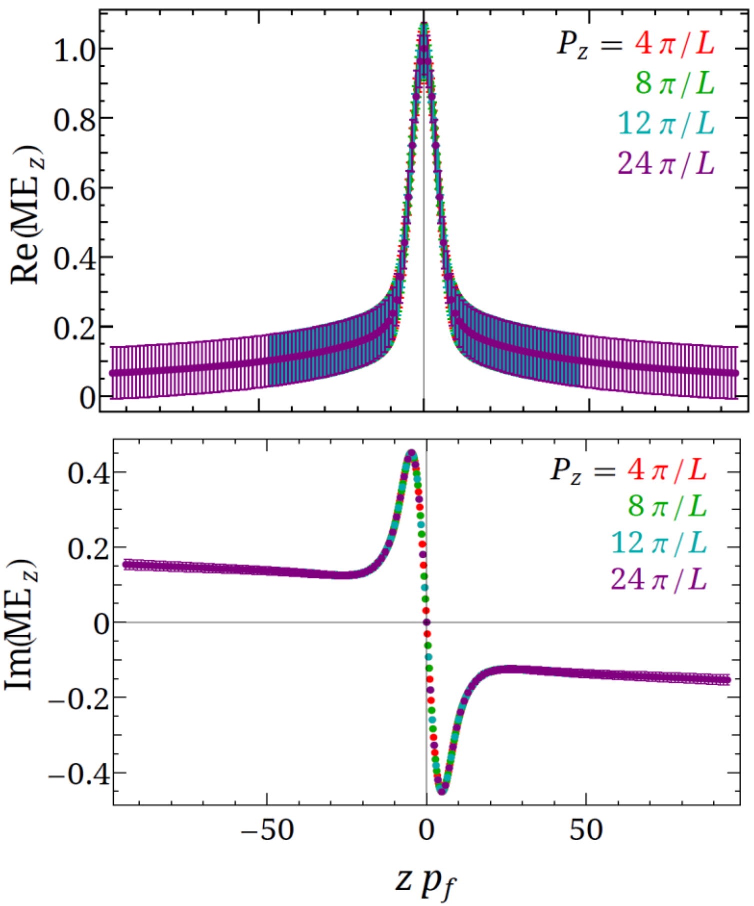
- § A variation of LaMET: A. Radyushki, 1705.01488
  - $\mathcal{P}(x, z^2, \mu, \epsilon) = \int dz (p_z/2\pi) e^{ix\cdot v} h(v, z^2, \mu, \epsilon)$
- § Versus quasi-PDF Ji, Zhang, Zhao 1706.07416
  - $\tilde{q}(x, p_z, \mu, \epsilon) = \int (dz/2\pi) e^{ix\cdot z\, p_z} h(zp_z, z^2, \mu, \epsilon)$
- § Similarity and issues: $h(v, z^2)/h(0, z^2) = M(v, z^2)$
- § One of the numerical attractions
  - Similar matrix elements; same problems we have
  - Extension to other structures is not clear yet

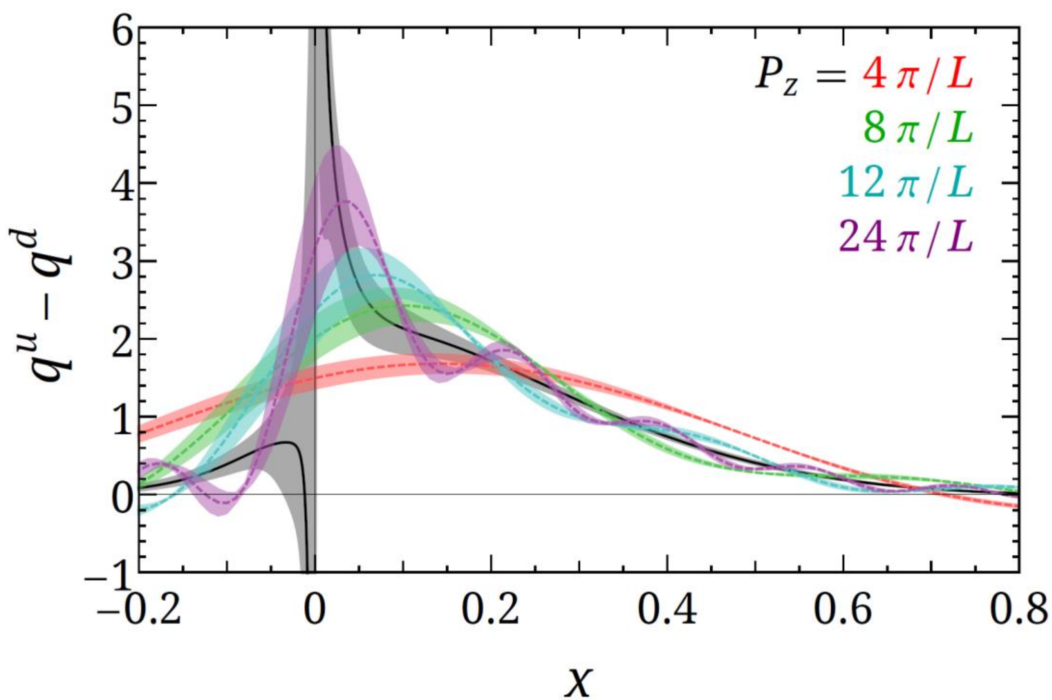




Physical Pion Mass

- Not a lattice problem but Fourier transform issue
- Simple exercise with CT14 PDF 1506.07443





1708.05301 (LP3)

Fixed $L_z = 32$

Physical Pion Mass

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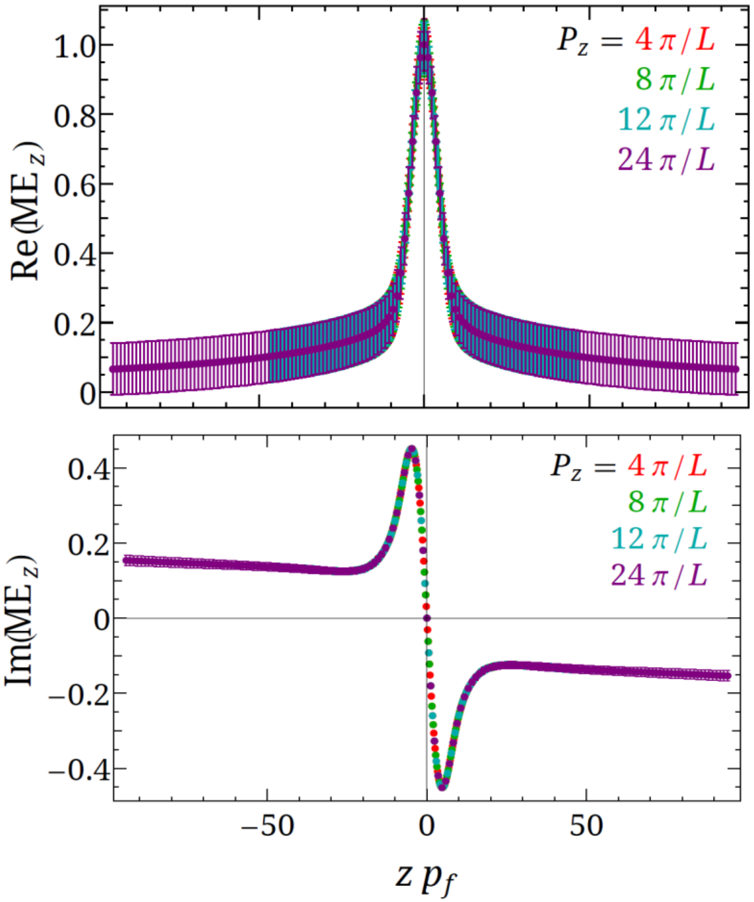
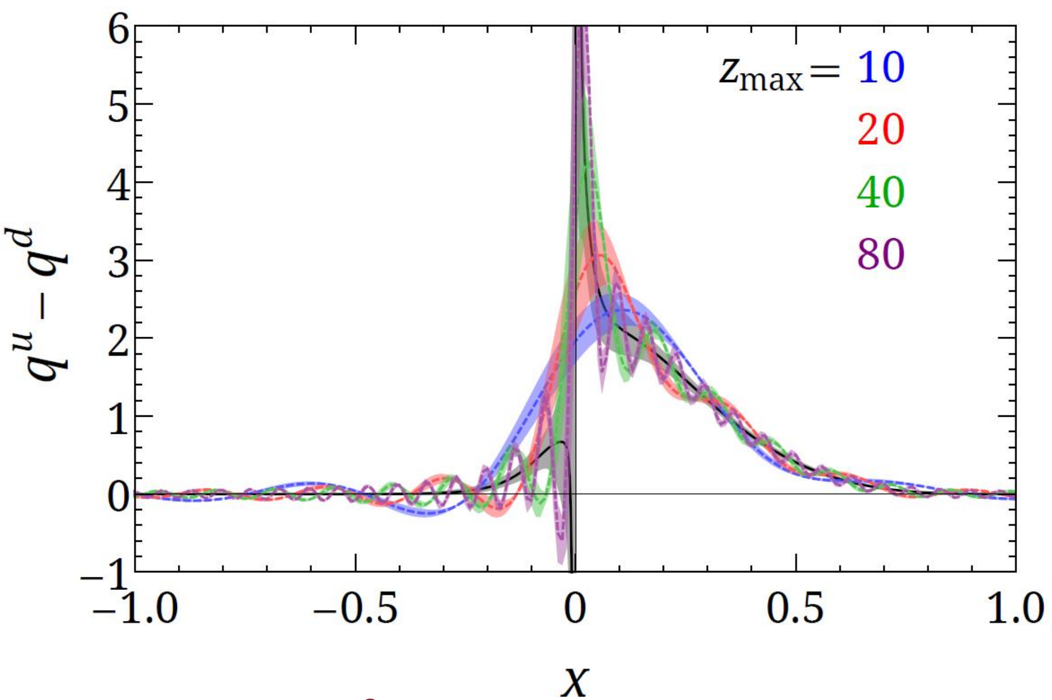
- Simple exercise with CT14 PDF 1506.07443





1708.05301 (LP[3])

Fixed $P_z = 24\pi/L$

Physical Pion Mass

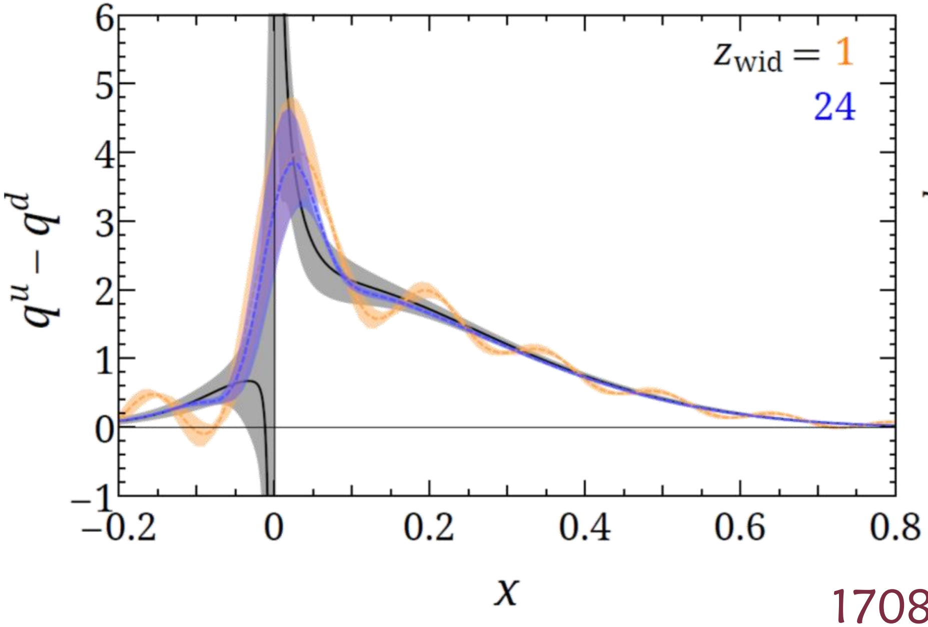
- Not a lattice problem but Fourier transform issue
- Two possible solutions proposed (likely more)

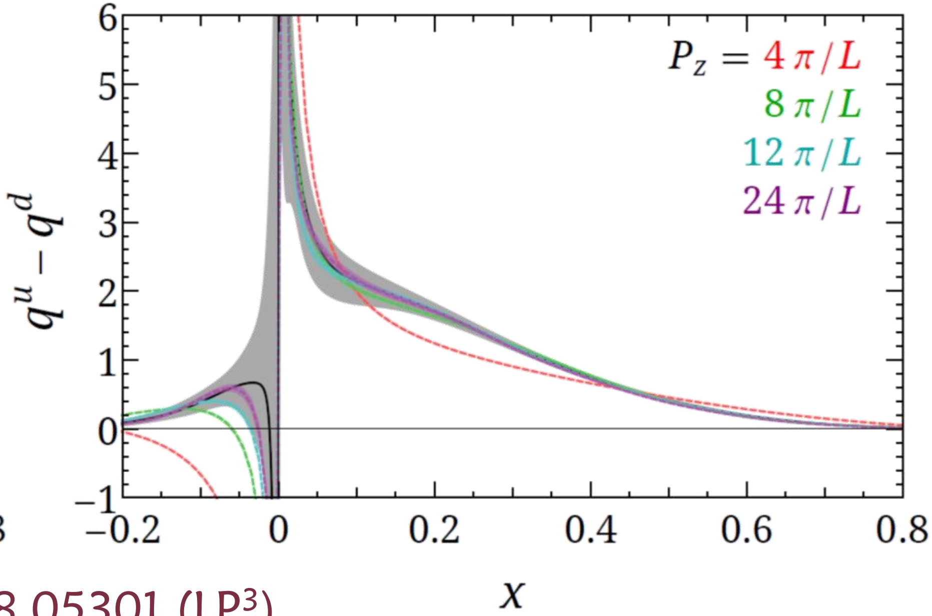
Filter approach

$$F(z_{\text{lim}}, z_{\text{wid}}) = \frac{1 + \text{erf}\left(\frac{z + z_{\text{lim}}}{z_{\text{wid}}}\right)}{2} \frac{1 - \text{erf}\left(\frac{z - z_{\text{lim}}}{z_{\text{wid}}}\right)}{2}$$

Derivative approach

$$q(x) = \int_{-z_{\max}}^{+z_{\max}} dz \frac{-P_z}{2\pi} \frac{e^{ixP_z z}}{iP_z x} h'(z)$$





1708.05301 (LP[3])

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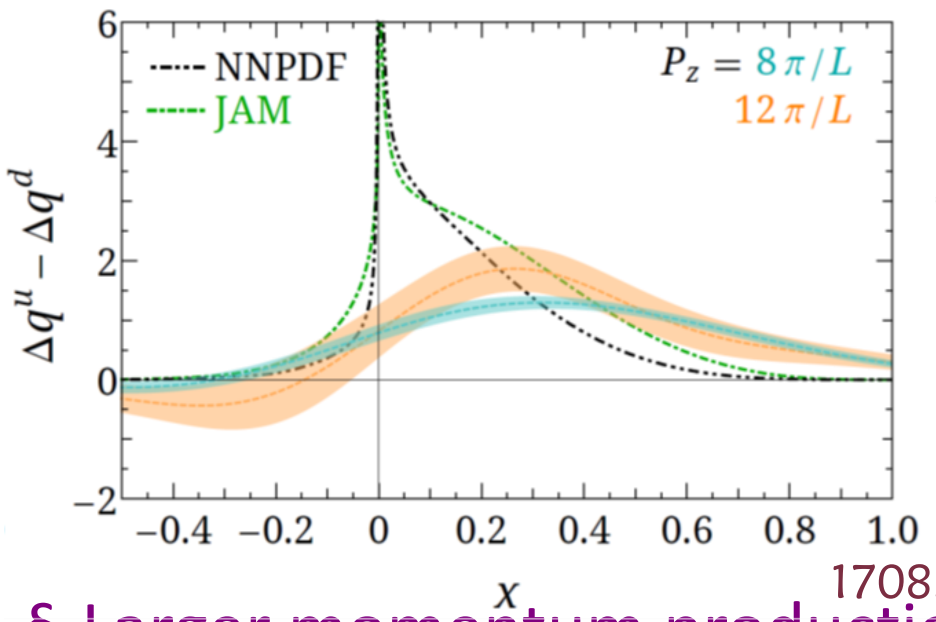
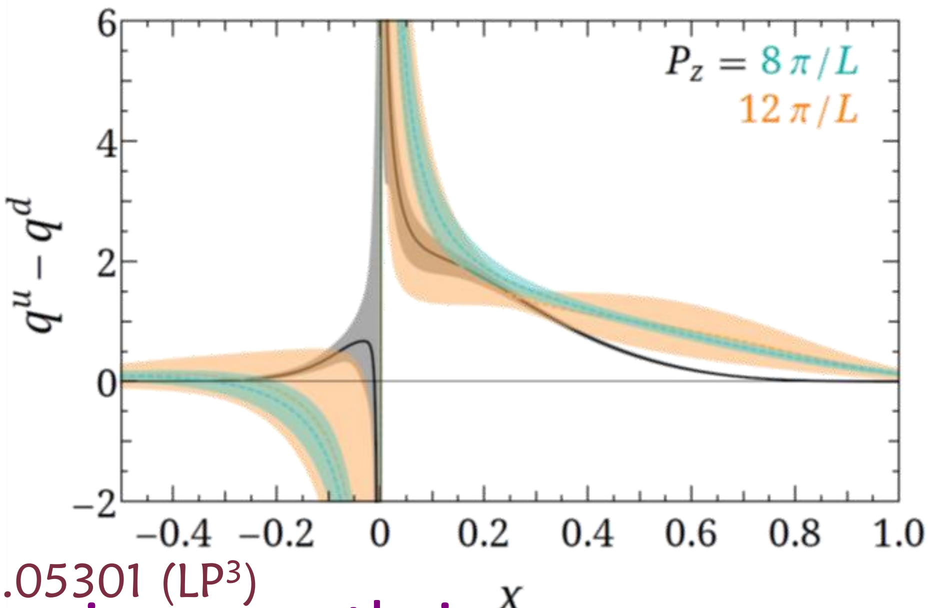




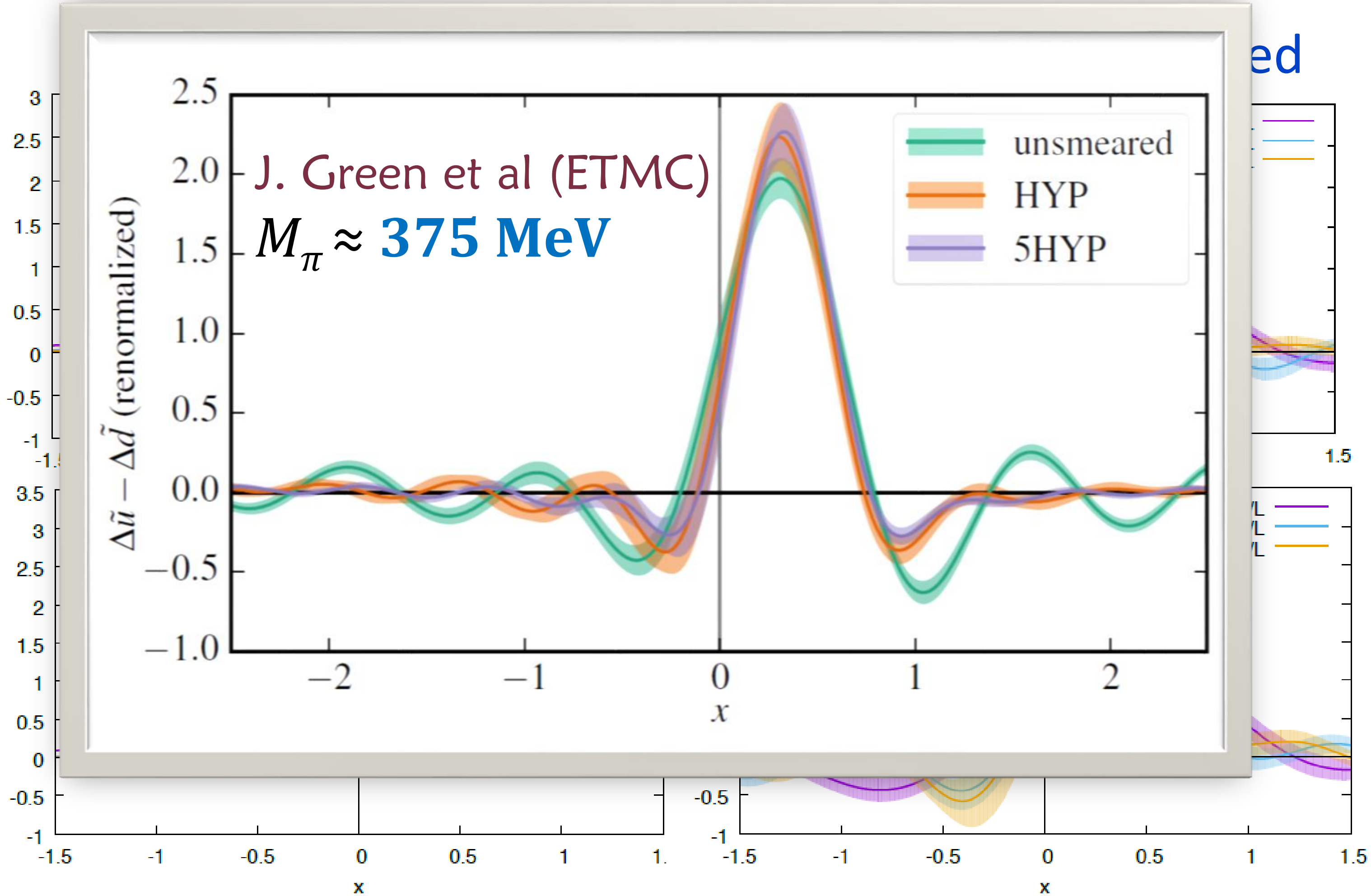
1708.05301 (LP[3])

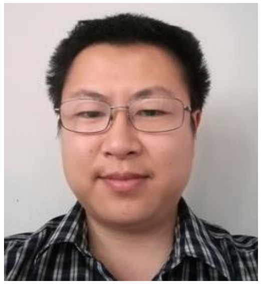
- Larger momentum production is currently in progress

Physical Pion Mass

§ The problem persists/worsens at physical pion mass

$M_\pi \approx$ **135 MeV**, $a \approx$ **0.09 fm** , $L \approx$ **5.6 fm**





Yi-Bo Yang
(MSU)