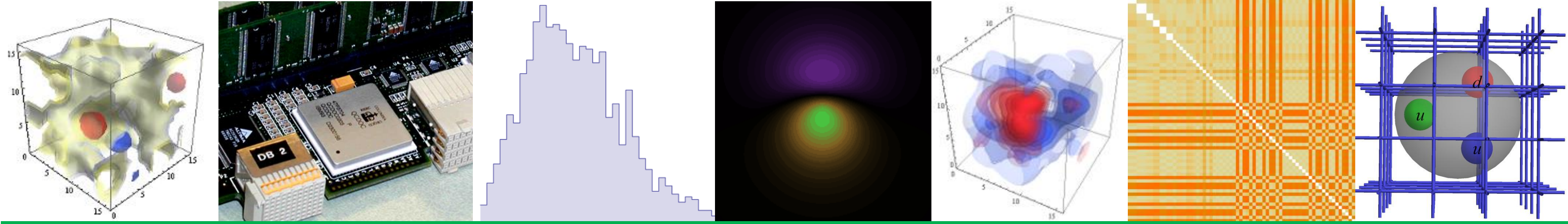


Lattice Computations of Parton Distributions

HUEY-WEN LIN

CTEQ

This work of HL is supported by the NSF under grant PHY 2209424 & 1653405, DOE under DE-SC0024053 and the Research Corporation for Science Advancement through the Cottrell Scholar Award

@LinQCD

U.S. DEPARTMENT OF ENERGY

RESEARCH CORPORATION for SCIENCE ADVANCEMENT

Learn QCD on Your Phone!

§ Learn QCD on your phone

[Google Play Store](#) [Apple Appstore](#)

Supported by the NSF under grant PHY 1653405

Outline

§ Lattice QCD in a Nutshell

§ Selected *x*-Dependent Parton Distributions

- Nucleon PDFs
- Pion/Kaon PDFs
- GPDs

§ Impact of Lattice-QCD PDFs on Global Fits

Biased selected results toward MSULat students and postdocs

What is Lattice QCD?

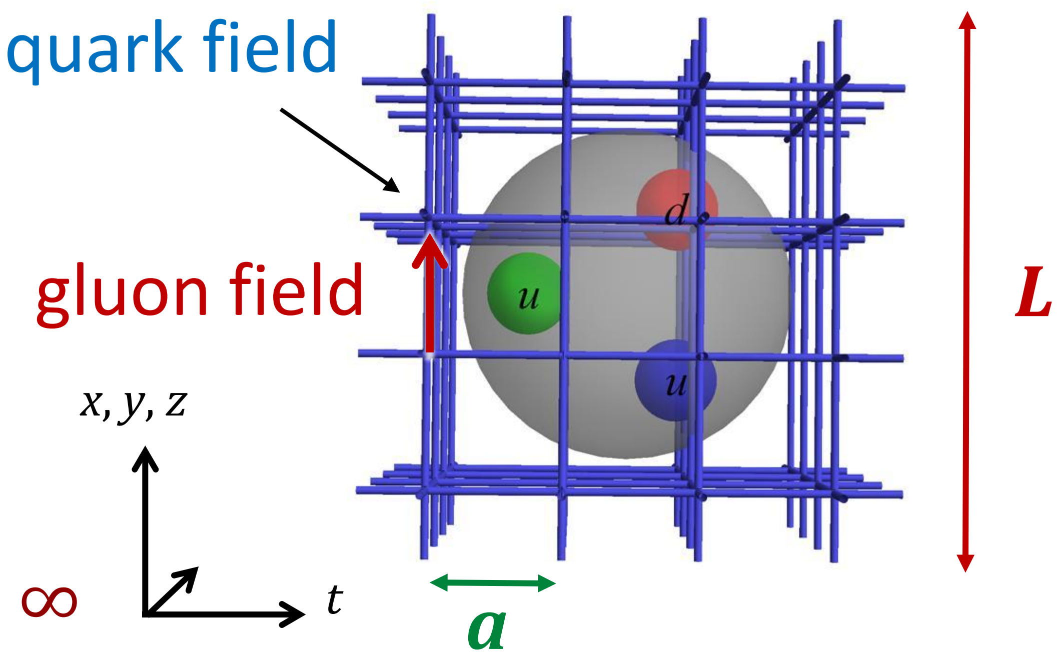
§ Lattice QCD is an ideal theoretical tool for investigating the strong-coupling regime of quantum field theories

§ 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 **Euclidean** space

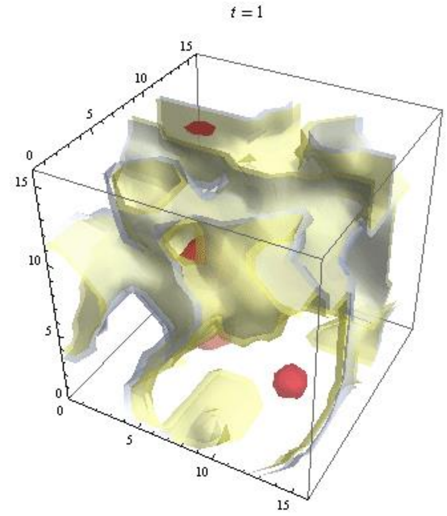
- Quark mass parameter (described by m_π)
- Impose a UV cutoff
  discretize spacetime
- Impose an infrared cutoff
  finite volume

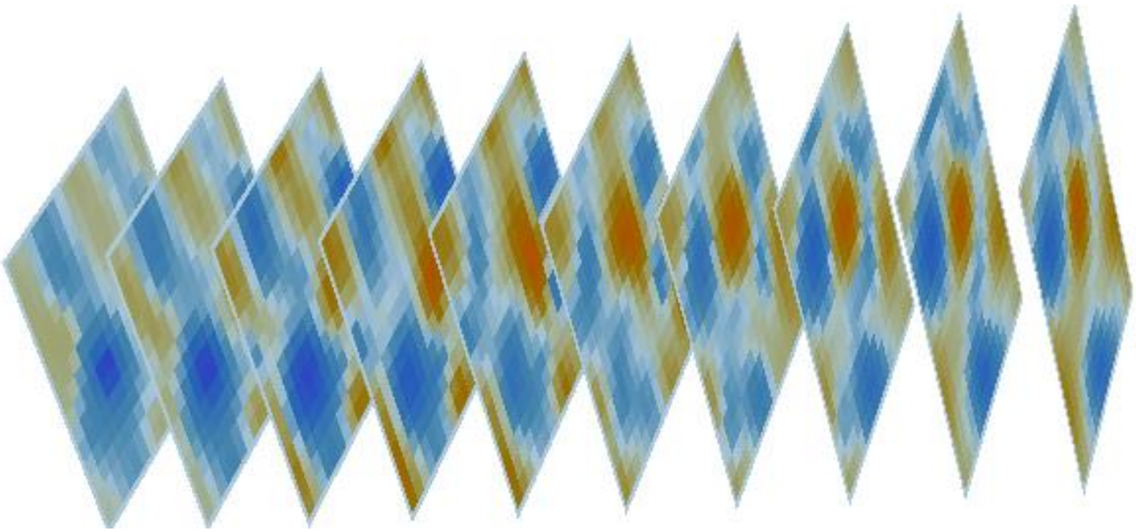


§ Recover physical limit

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

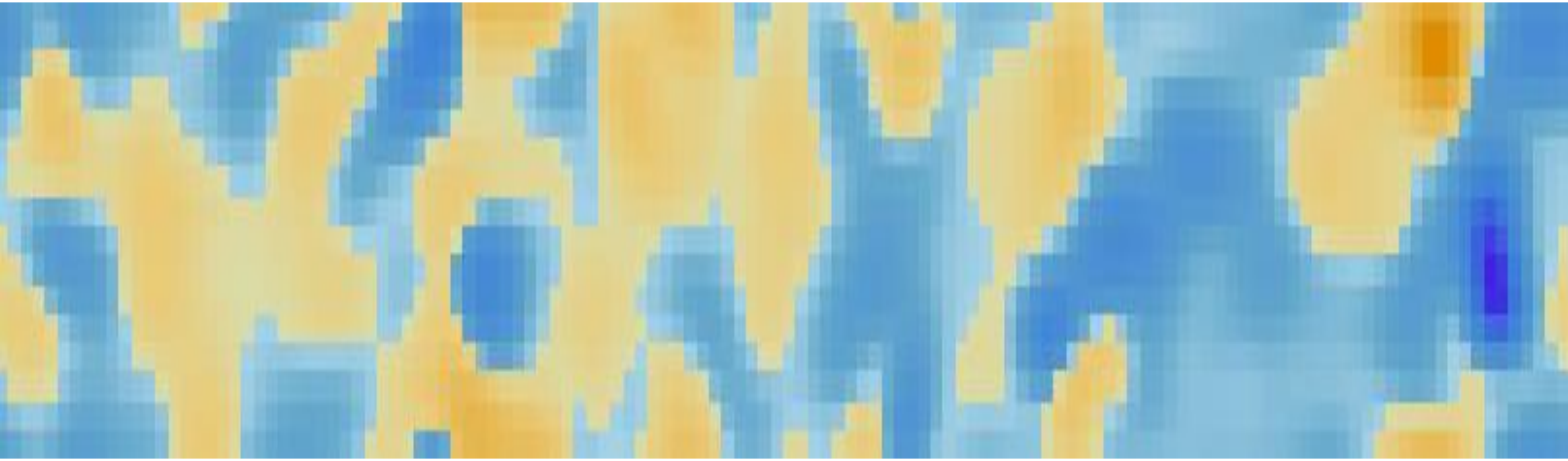
1. Start with QCD Vacuum (gauge configurations)





Anatomy of a Lattice Calculation

1. Start with QCD Vacuum (gauge configurations)

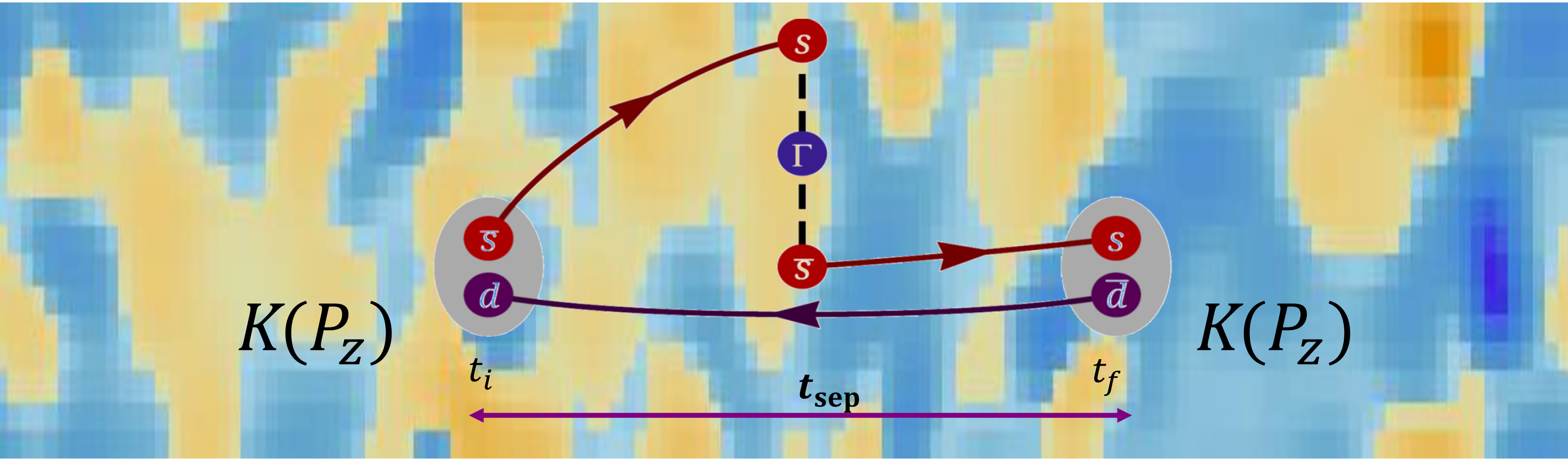


Thanks to MILC collaboration for sharing their 2+1+1 HISQ lattices

Anatomy of a Lattice Calculation

2. Correlators (hadronic observables)

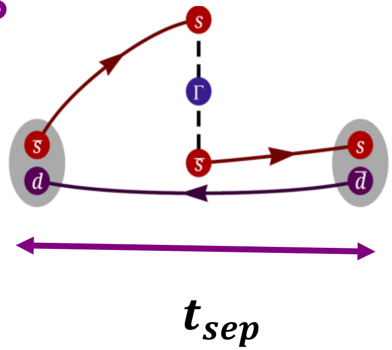
- Invert Dirac operator matrix (rank 10^{12})
- Combine using color, spin and momentum into hadrons



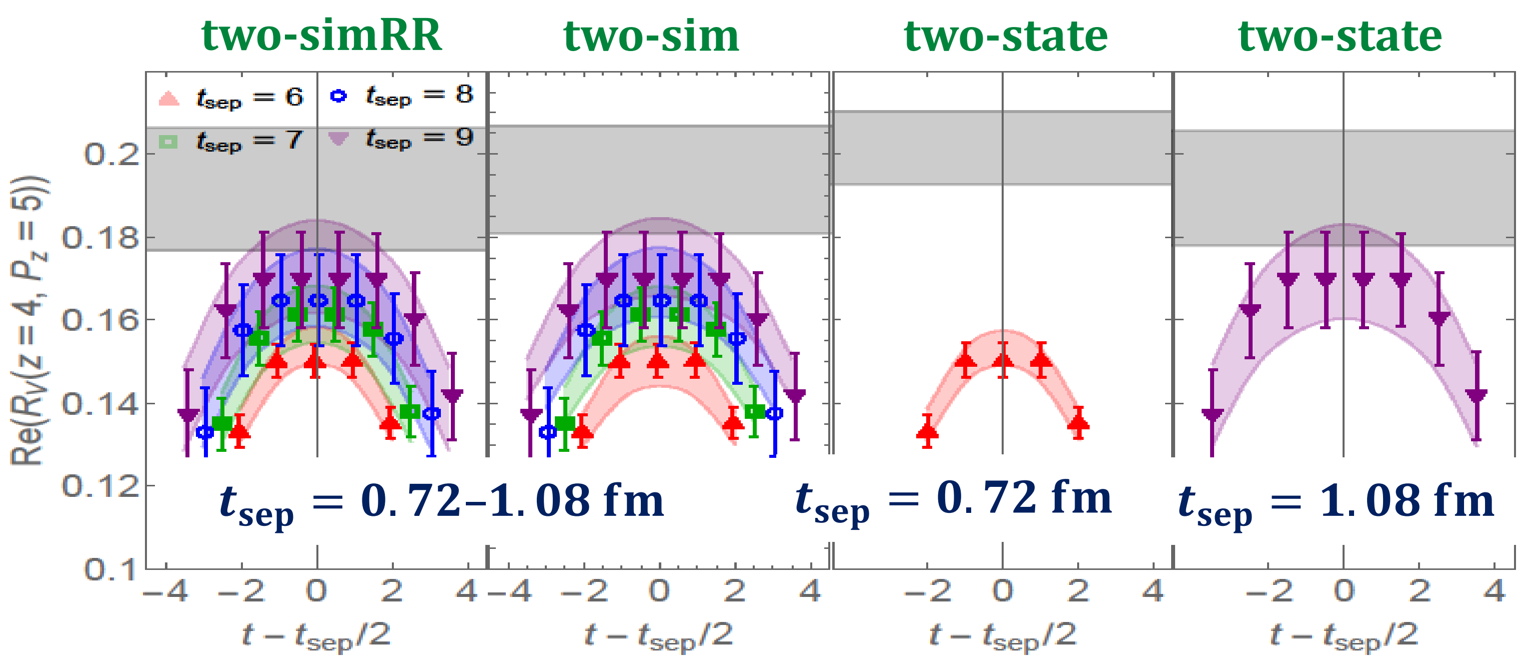
Thanks to MILC collaboration for sharing their 2+1+1 HISQ lattices

3. Extract reliable ground-state matrix elements

- Excited-state removal
  - For example, kaon matrix element at $M_\pi \approx 220$ MeV, $a \approx 0.12$ fm



HL et al. (MSULat), 2003.14128



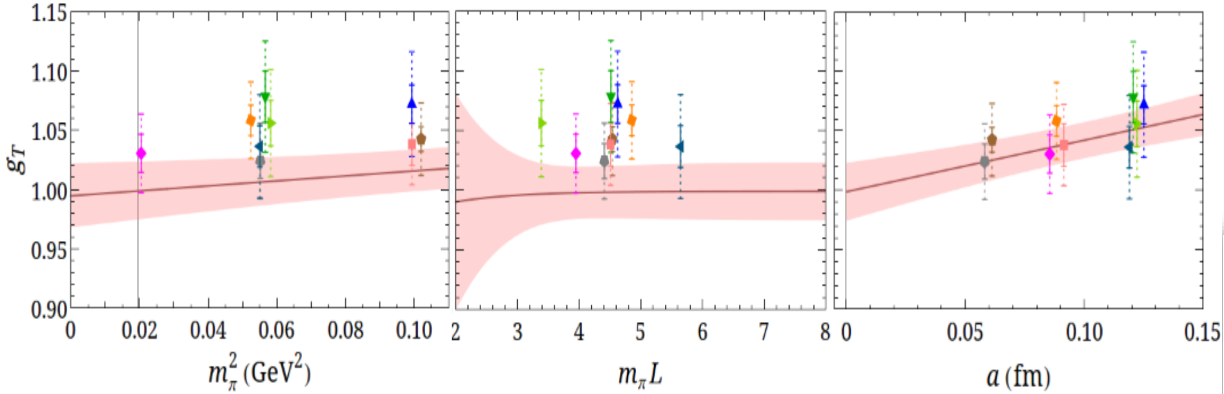
stability in extracting matrix elements

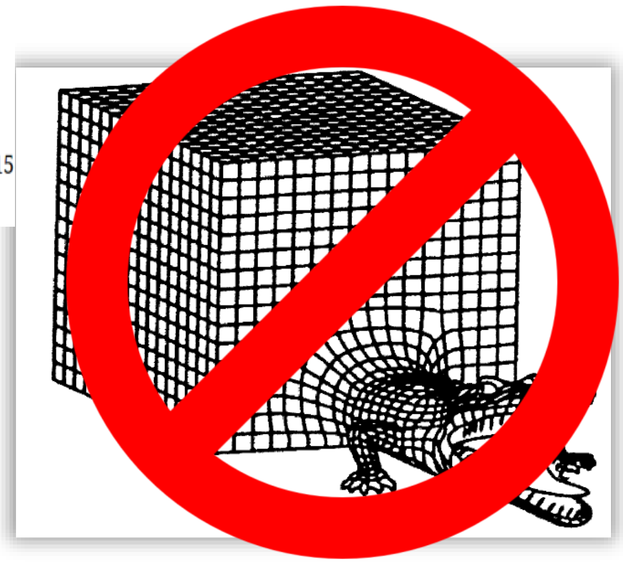
Anatomy of a Lattice Calculation

4. Systematic uncertainty (nonzero *a*, finite *L*, etc.)

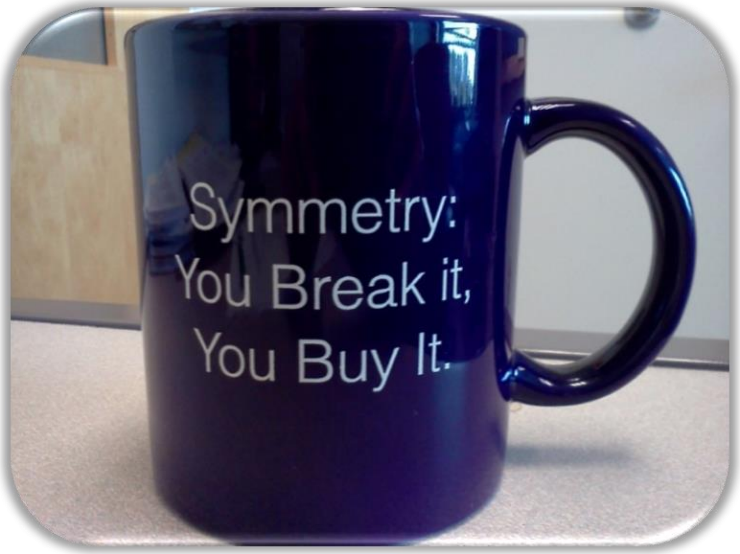
- Nonperturbative renormalization, etc
- Extrapolation to the continuum limit

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





Lattice Structure Limitation



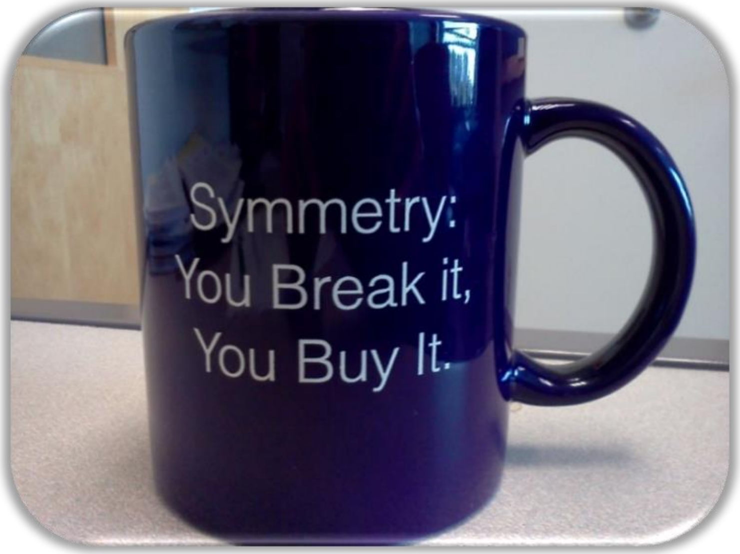
- Lattice calculations rely on operator product expansion, only provide moments

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

- Limited to the lowest few moments
  - For higher moments, all ops mix with lower-dimension ops
  - Novel proposals to overcome this problem

W. Detmold and C. Lin, Phys. Rev. D73 (2006) 014501
Z. Davoudi and M. J. Savage, Phys. Rev. D86 (2012) 054505
A. Shindler, arXiv:2311.18704

Lattice Structure Limitation



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

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

- Longstanding obstacle!
  - Holy grail of structure calculations
- Applies to many structure quantities:
  - Parton Distribution Functions (PDFs)
  - Generalized parton distributions (GPD)
  - Transverse-momentum distributions (TMD)

  ……..

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

Outline

§ Lattice QCD in a Nutshell

§ Selected *x*-Dependent Parton Distributions

- **Nucleon PDFs**
- Pion/Kaon PDFs
- GPDs

§ Impact of Lattice-QCD PDFs on Global Fits

Biased selected results toward MSULat students and postdocs

Direct x-Dependent Structure

§ Longstanding obstacle to lattice calculations!

Quantities that can be calculated on the lattice today $= \sum$ Wanted PDFs, GPDs, etc. $\times$ pQCD-calculated kernel

- **Quasi-PDF**/large-momentum effective theory (LaMET) (X. Ji, 2013; See 2004.03543 for review)
- **Pseudo-PDF** method: differs in FT (A. Radyushkin, 2017)
- Lattice cross-section method (**LCS**) (Y Ma and J. Qiu, 2014, 2017)
- Hadronic tensor currents (Liu et al., hep-ph/9806491, … 1603.07352)
- Euclidean correlation functions (RQCD, 1709.04325)
- …

Lattice Parton Calculations

§ Rapid developments!

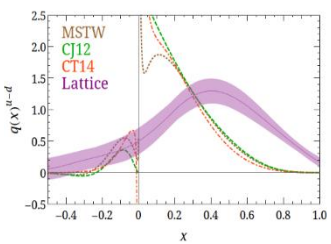
First unpol. PDF lattice calculation

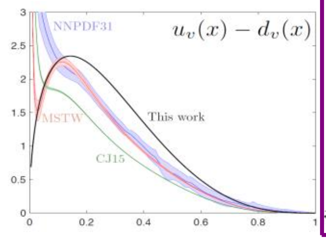
First lattice pseudo-PDFs

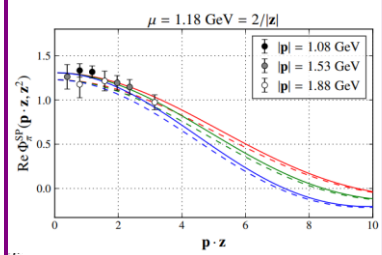
Euclidean correlation functions

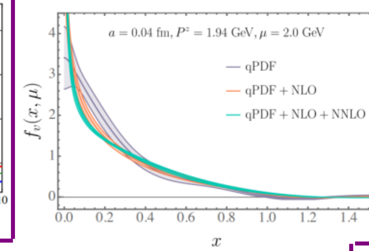
1st NNLO PDF

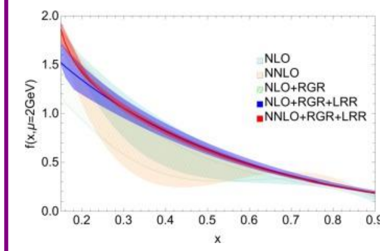
1stPDF w/ LRR+RGR











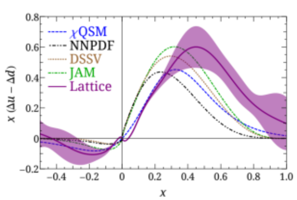
2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024

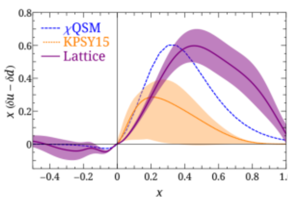
Pol. PDFs and mass corrections

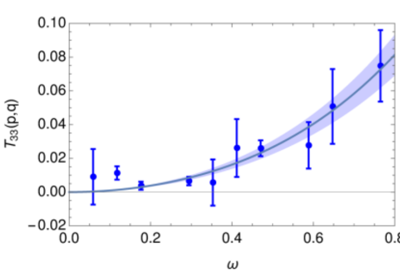
Compton amplitude

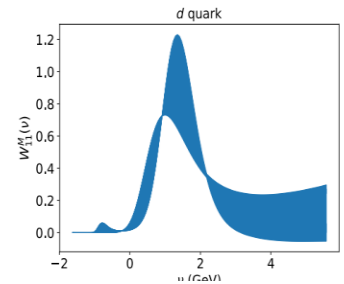
Hadronic tensor

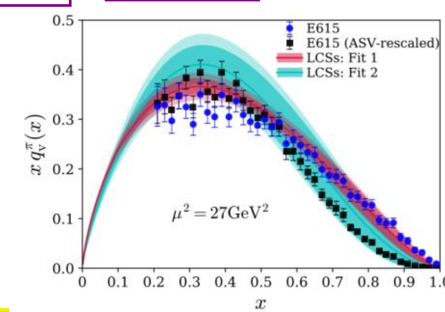
LCS









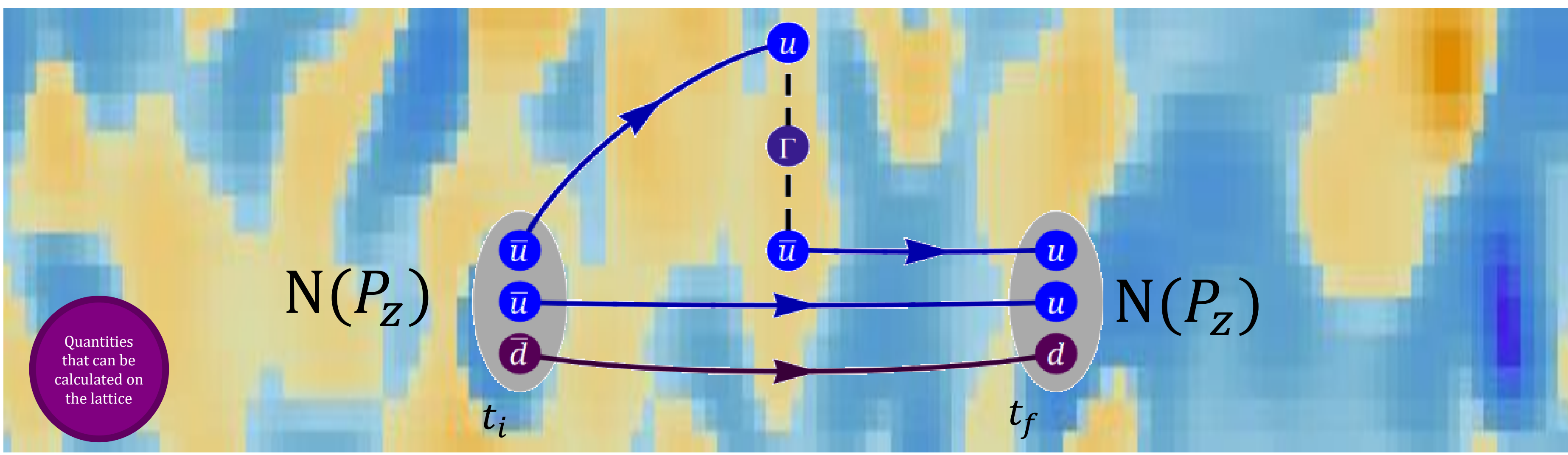


Direct x-Dependent Structure

- Longstanding obstacle to lattice calculations!

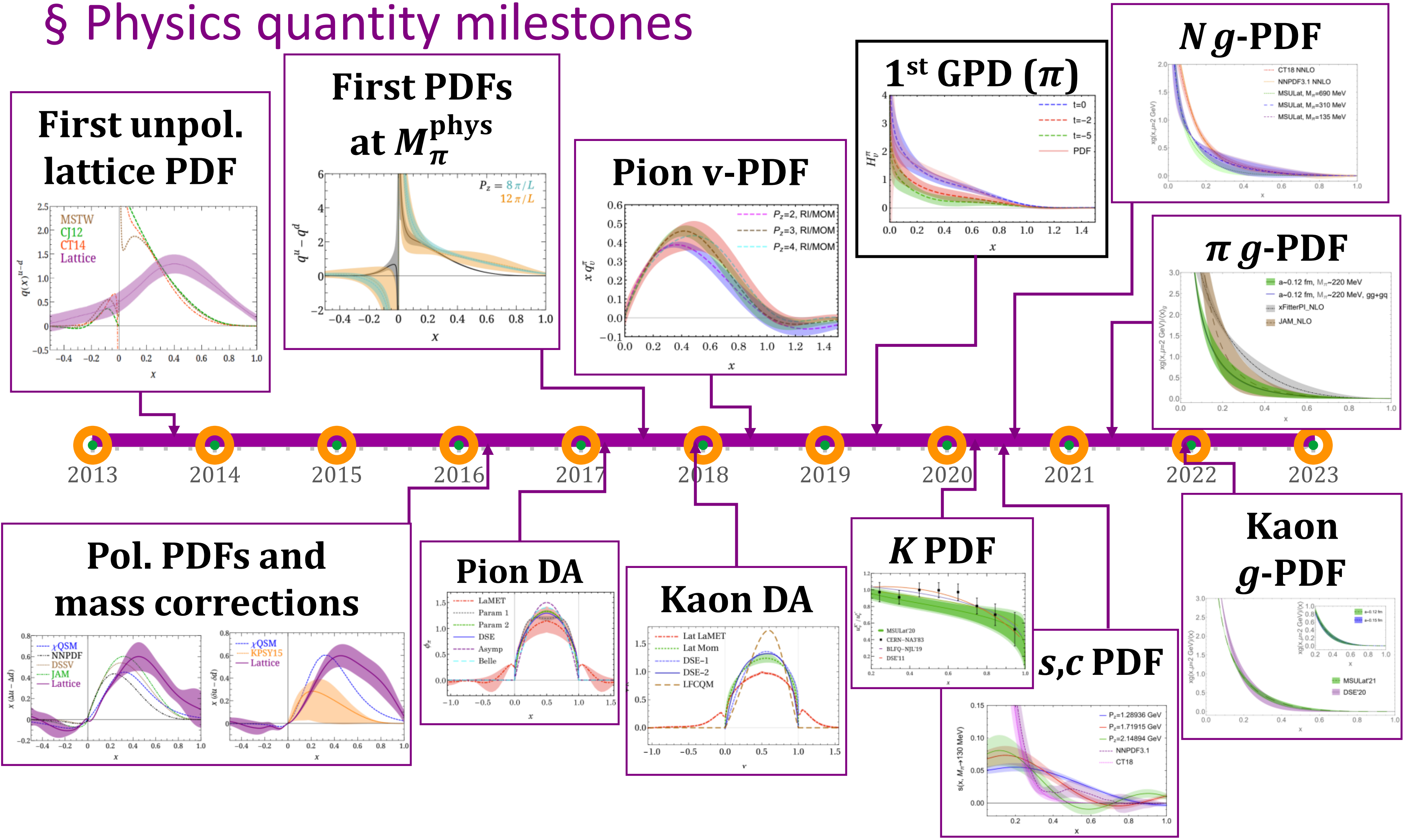
Quantities that can be calculated on the lattice today = $\sum$ Wanted PDFs, GPDs, etc. $\times$ pQCD-calculated kernel

Quasi-PDF & **Pseudo-PDF** method



Lattice Parton Calculations

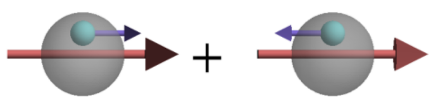
§ Physics quantity milestones



Lattice Example Results

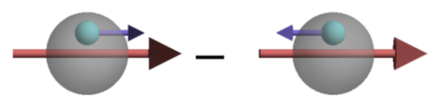
§ Summary of physical pion mass PDFs results

unpolarized



$u(x) - d(x)$

longitudinally polarized

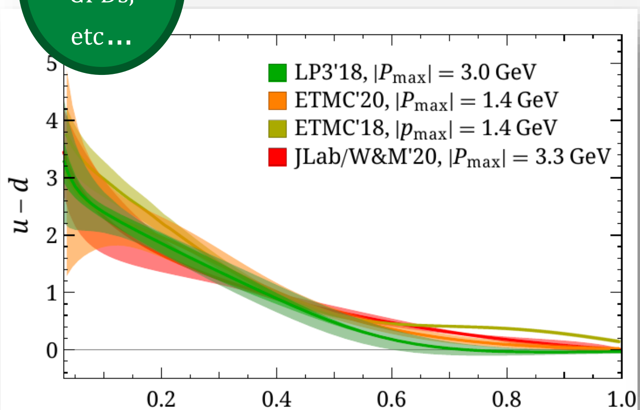


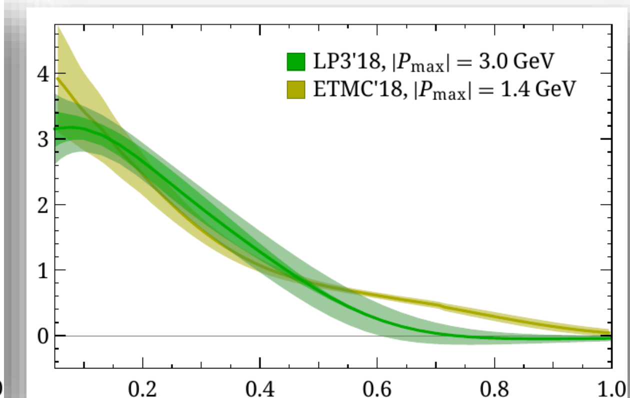
$\Delta u(x) - \Delta d(x)$

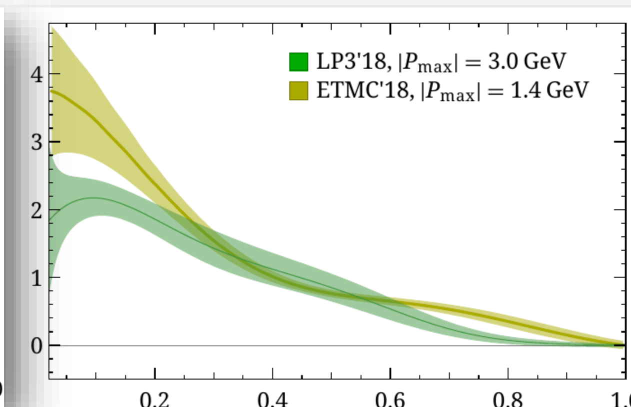
transversely polarized

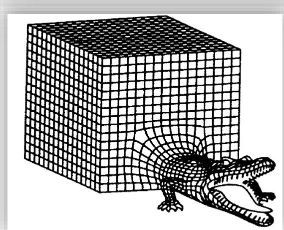
$\delta u(x) - \delta d(x)$

Wanted PDFs, GPDs, etc…









Finite volume,
Discretization,
…

2006.08636 (PDFLattice2019)

Lattice Example Results

§ Summary of physical pion mass PDFs results

unpolarized

longitudinally polarized

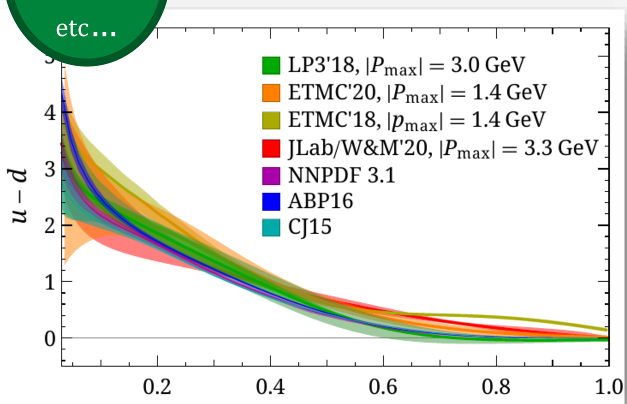
transversely polarized

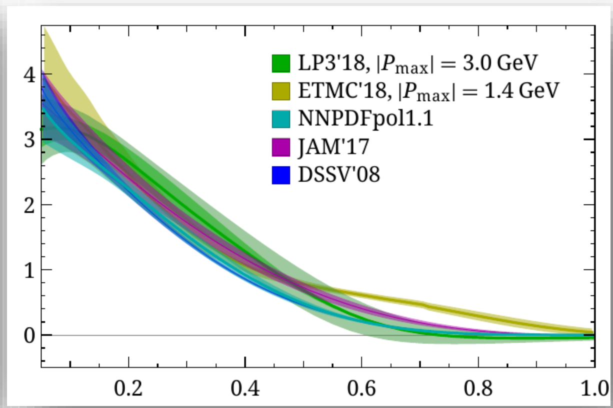
Wanted PDFs, GPDs, etc…

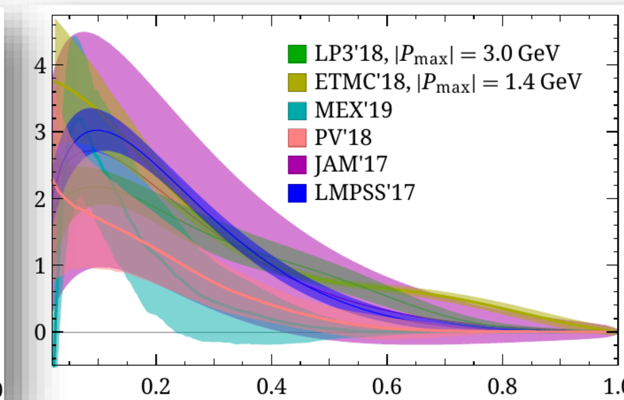
$u(x) - d(x)$

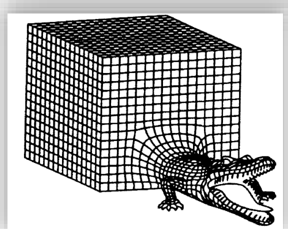
$\Delta u(x) - \Delta d(x)$

$\delta u(x) - \delta d(x)$









Finite volume,
Discretization,
…

2006.08636 (PDFLattice2019)

Isovector PDFs Update

§ Nucleon isovector PDF calculated directly at physical pion mass

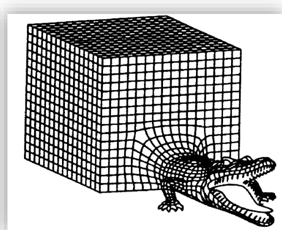
- NNLO matching & treat leading-renormalon effects
  - Leading-renormalon resummation (LRR)
  - Renormalization-group resummation (RGR)

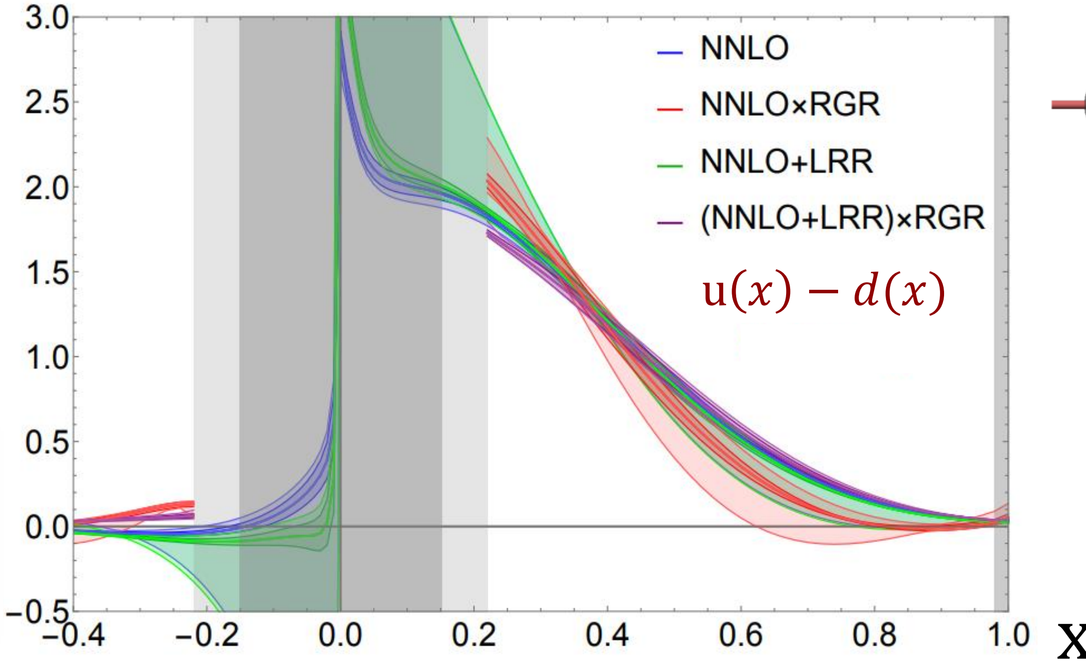
R. Zhang, et. al.
PLB 844, 138081 (2023)

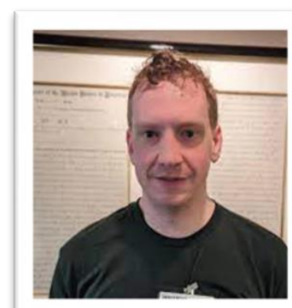
- N_f=2+1+1 clover/HISQ, a~0.09 fm

J. Holligan, HL (MSULat), 2312.10829 [hep-lat]

Wanted PDFs, GPDs, etc…







P: Jack Holligan

Isovector PDFs Update

§ Nucleon isovector PDF calculated directly at physical pion mass

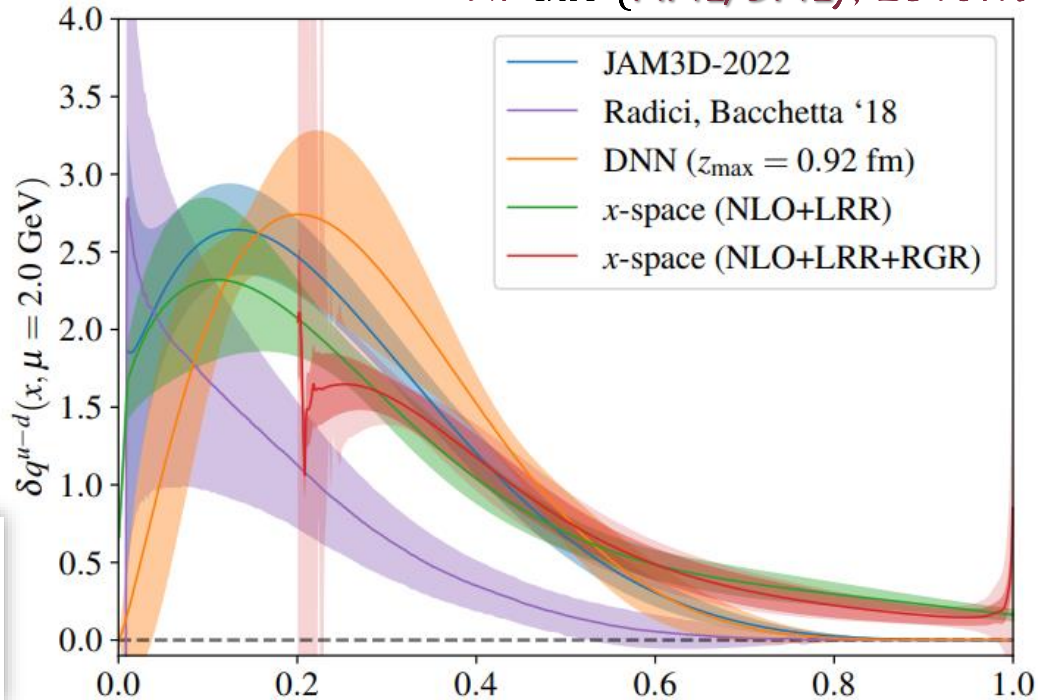
- NNLO matching & treat leading-renormalon effects
  - Leading-renormalon resummation (LRR)
  - Renormalization-group resummation (RGR)

R. Zhang, et. al.
PLB 844, 138081 (2023)

- N_f=2+1 clover/HISQ, a~0.076 fm

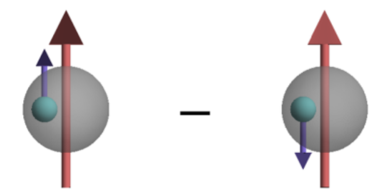
X. Gao (ANL/BNL), 2310.19047 [hep-lat]

Wanted PDFs, GPDs, etc…

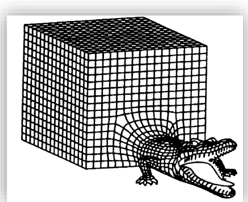


x

Transversity

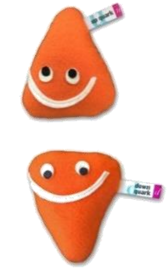


$\delta u(x) - \delta d(x)$

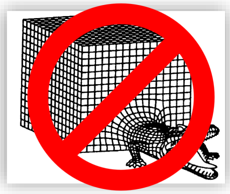


Continuum PDF

§ Nucleon PDFs using quasi-PDFs in the continuum limit

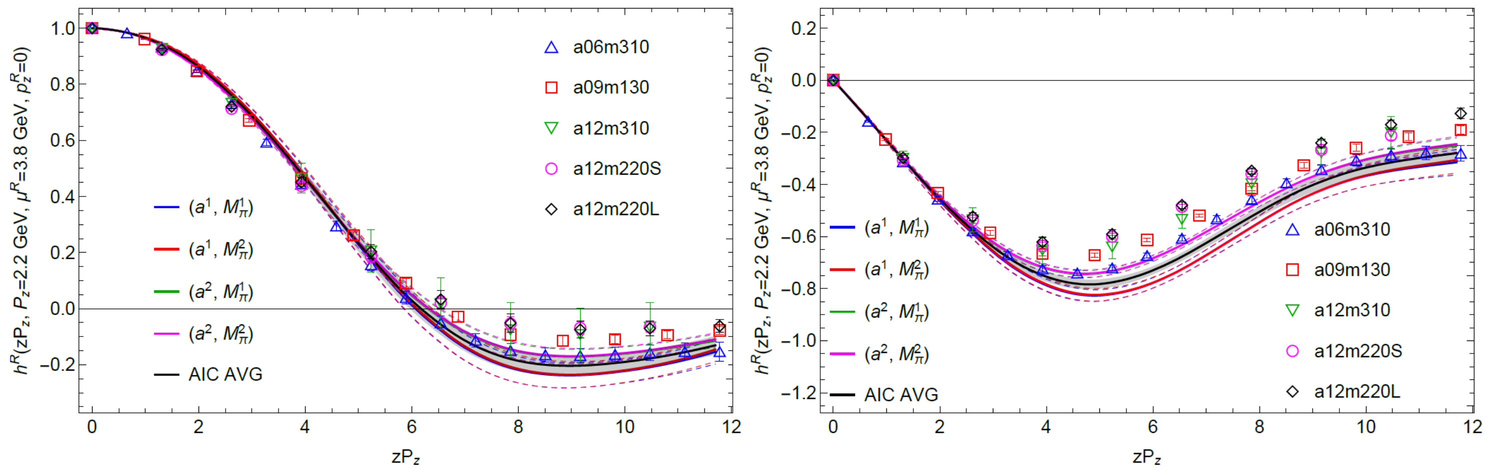


- Lattice details: clover/2+1+1 HISQ (MSULat)
  - $a \approx \{0.06, 0.09, 0.12\}$ fm,
  - $M_\pi \in \{\mathbf{135}, 220, 310\}$-MeV pion,
  - $M_\pi L \in \{3.3, 5.5\}$.
  - $P_z \approx 2$ GeV 2011.14971, HL et al (MSULat)



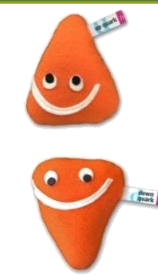
- Naïve extrapolation to physical-continuum limit

Quantities that can be calculated on the lattice

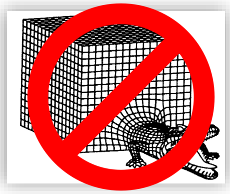


Continuum PDF

§ Nucleon PDFs using quasi-PDFs in the continuum limit



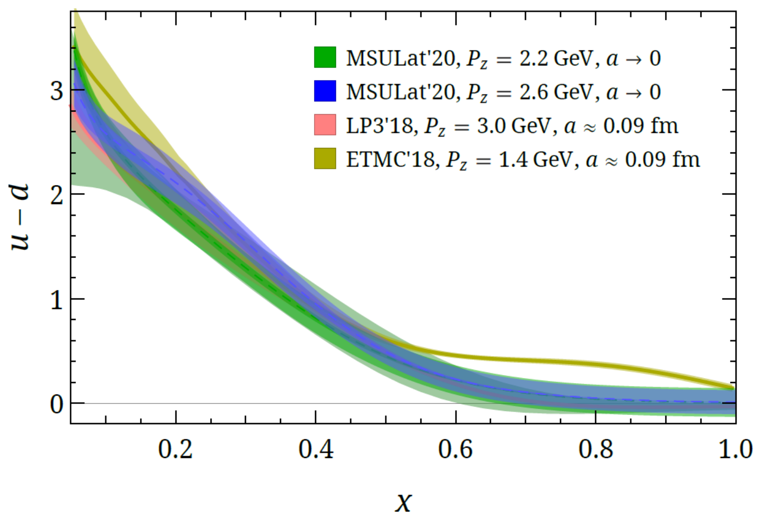
- Lattice details: clover/2+1+1 HISQ (MSULat)
  - $a \approx \{0.06, 0.09, 0.12\}$ fm,
  - $M_\pi \in \{135, 220, 310\}$-MeV pion,
  - $M_\pi L \in \{3.3, 5.5\}$.
  - $P_z \approx 2$ GeV 2011.14971, HL et al (MSULat)

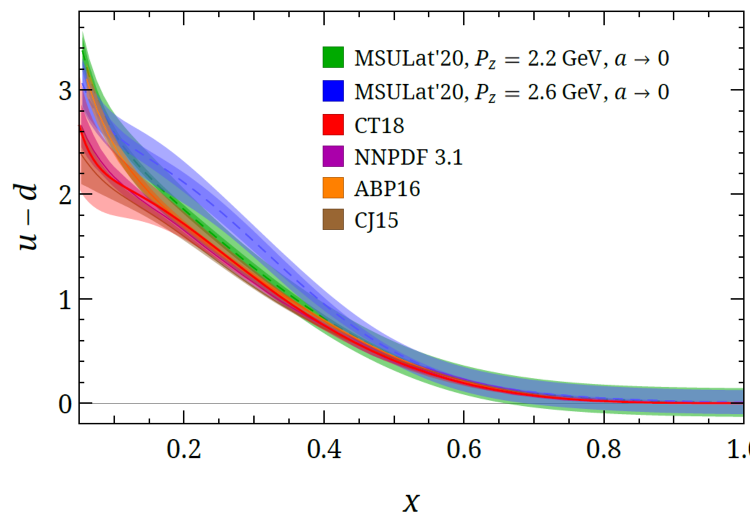


$u(x) - d(x)$

- Naïve extrapolation to physical-continuum limit

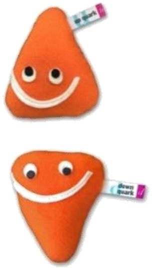
Wanted PDFs, GPDs, etc…

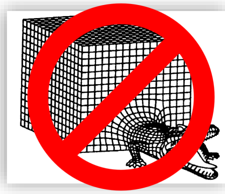




Continuum PDF

§ Nucleon PDFs using quasi-PDFs in the continuum limit

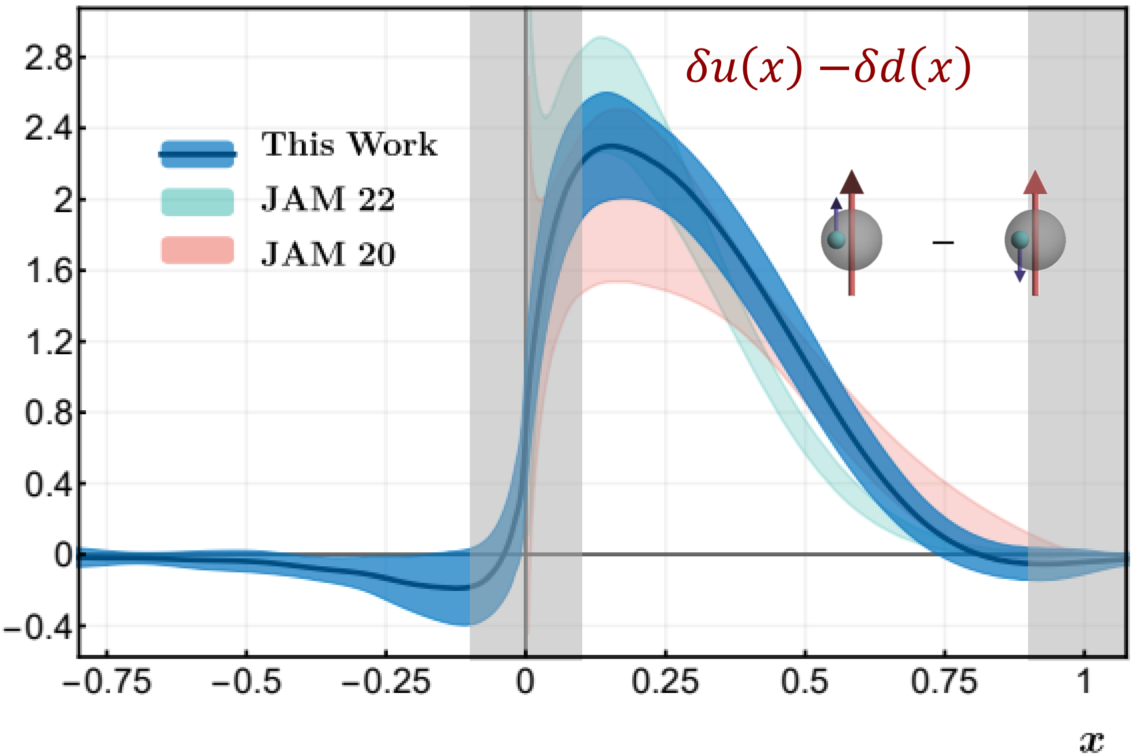




- Lattice details: clover/2+1 clover (LPC)
  - $a \approx \{0.49, 0.64, 0.85, 0.98\}$ fm,
  - $M_\pi \in [222, 354]$-MeV pion,
  - $M_\pi L \in [3.9, 8.1]$.
  - $P_z \approx \in [1.8, 2.8]$.

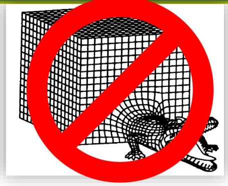
F. Yao et al (LPC), 2208.08008

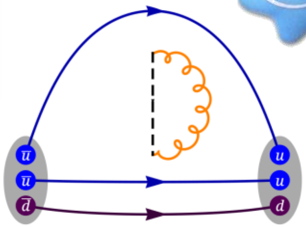
Wanted PDFs, GPDs, etc…



Gluon PDF in Nucleon

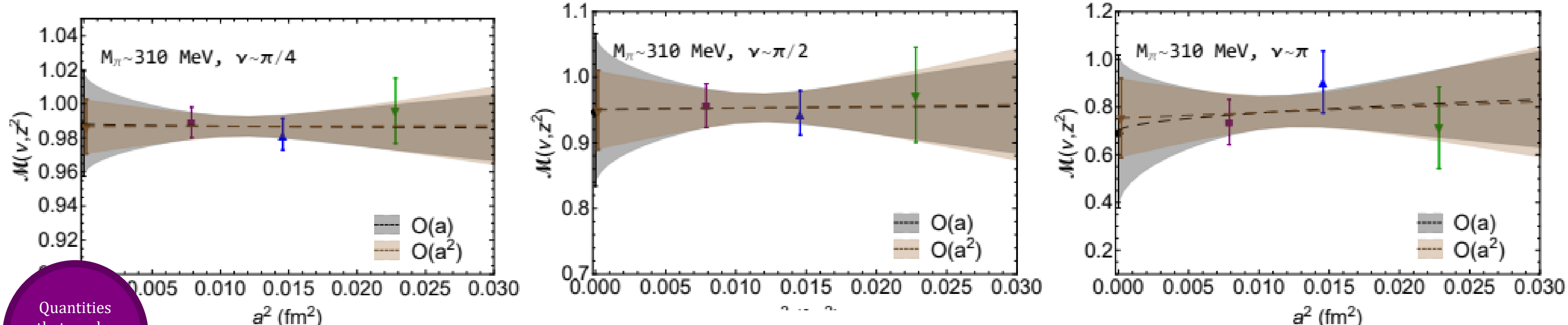
§ Continuum Gluon PDF w/ pseudo-PDF



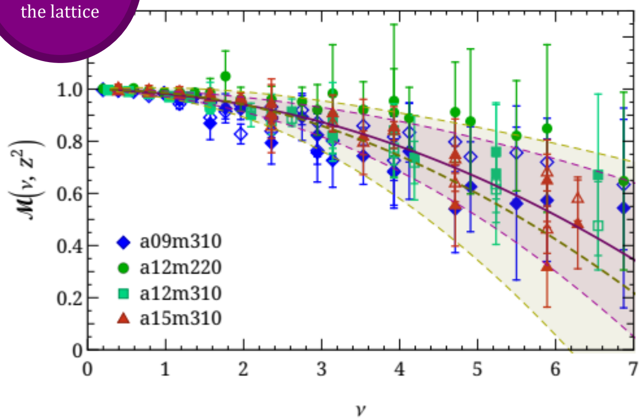


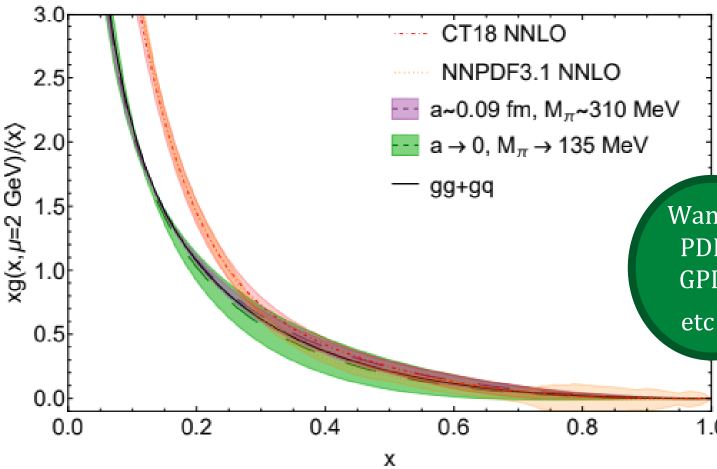
- 2+1+1 HISQ {0.09, 0.12, 0.15} fm, [220,310,700]-MeV pion, 10^5-10^6 statistics

Z. Fan et al (MSULat), 2210.09985

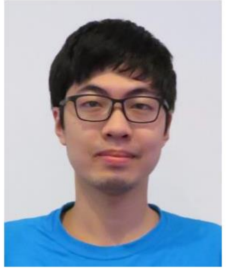


Quantities that can be calculated on the lattice





Wanted PDFs, GPDs, etc…



G: Zhouyou Fan

Outline

- § Lattice QCD in a Nutshell
- § Selected *x*-Dependent Parton Distributions
  - Nucleon PDFs
  - **Pion/Kaon PDFs**
  - GPDs
- § Impact of Lattice-QCD PDFs on Global Fits

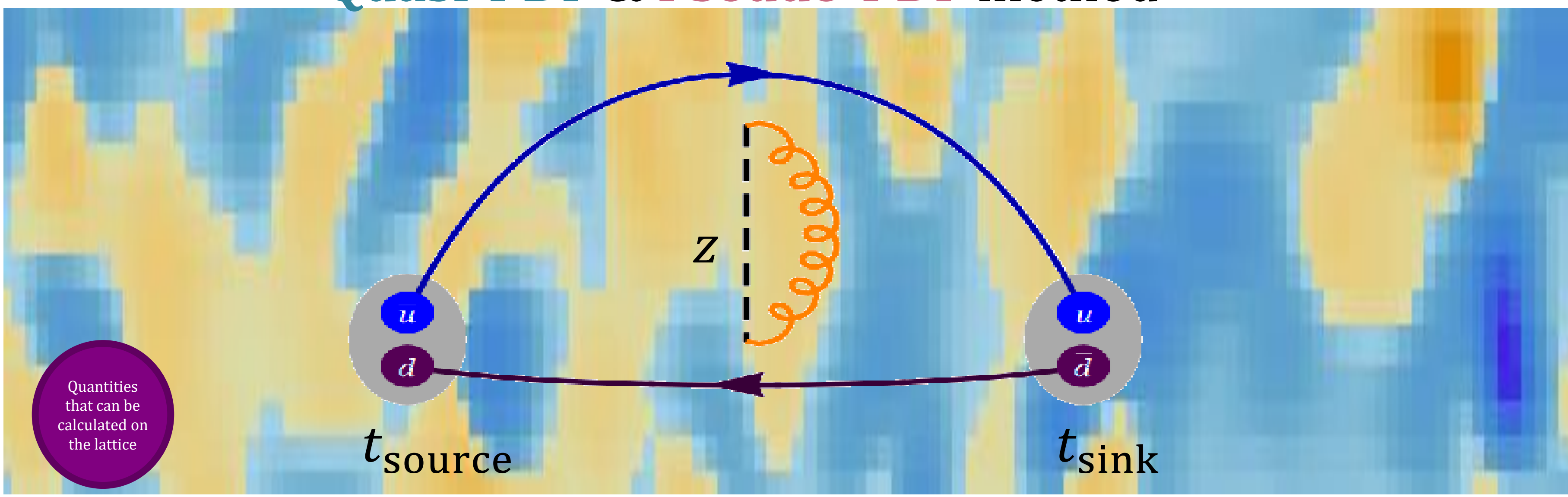
Biased selected results toward MSULat students and postdocs

Direct x-Dependent Structure

§ Longstanding obstacle to lattice calculations!

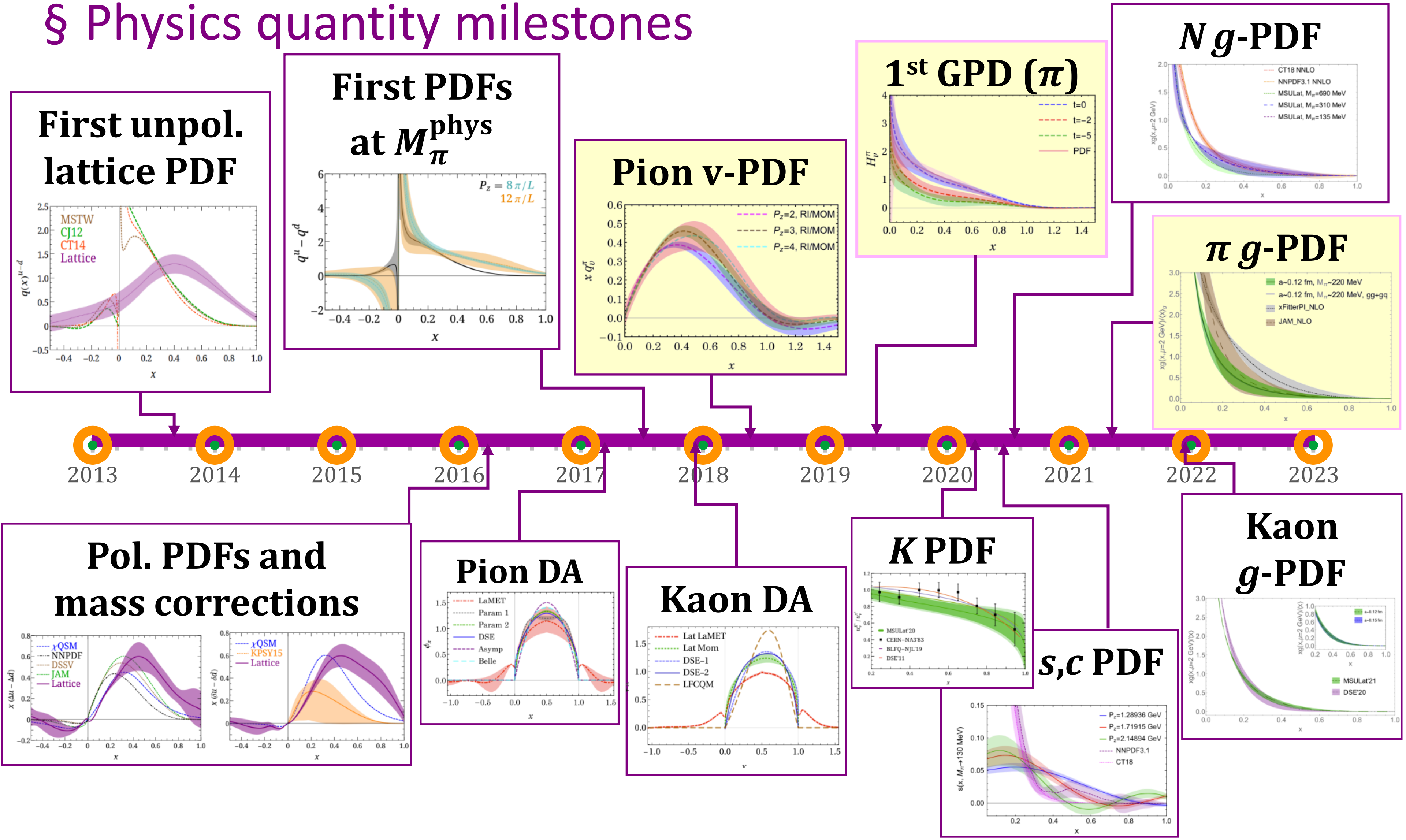
Quantities that can be calculated on the lattice today $=\sum$ Wanted PDFs, GPDs, etc. $\times$ pQCD-calculated kernel

Quasi-PDF & **Pseudo-PDF** method



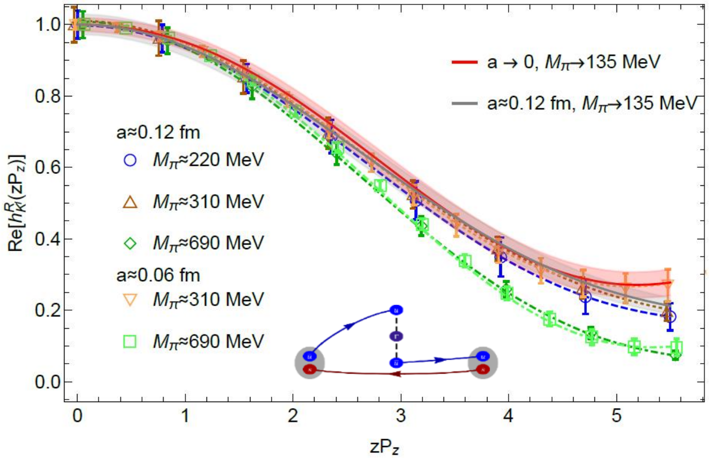
Lattice Parton Calculations

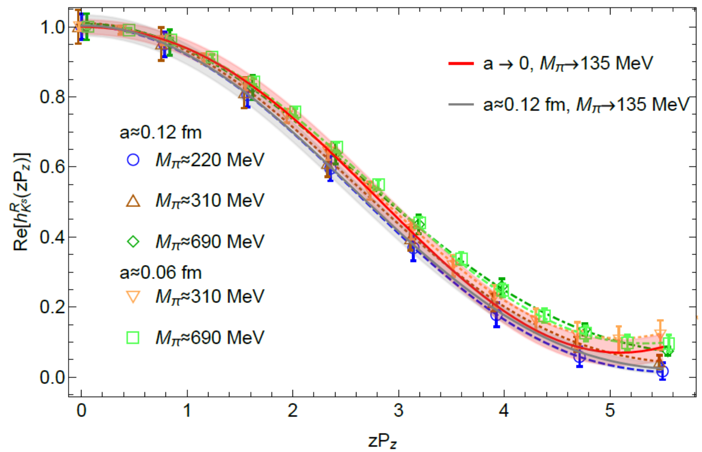
§ Physics quantity milestones



Meson Valence-quark PDFs

§ Pion/kaon PDFs using quasi-PDF in the continuum limit

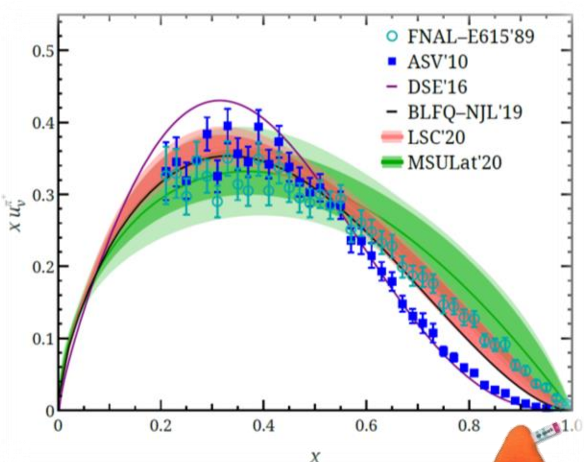


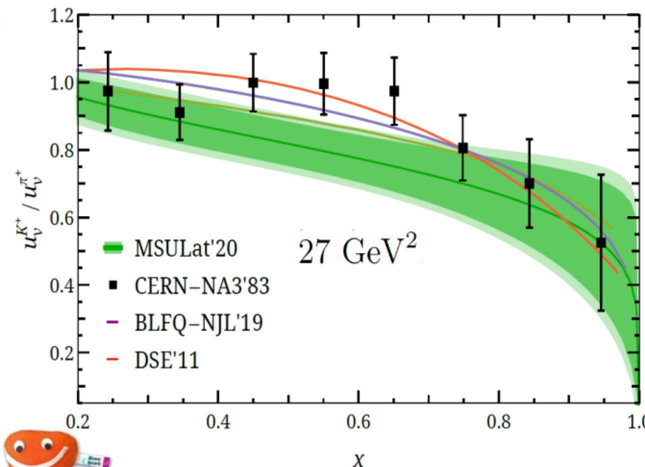


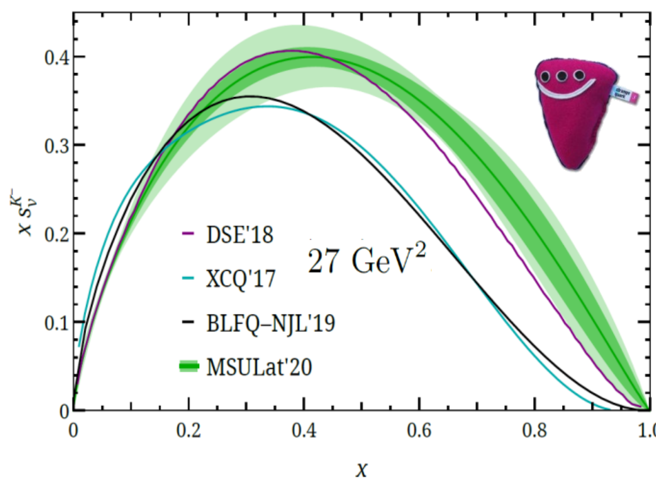
Quantities that can be calculated on the lattice

Wanted PDFs, GPDs, etc…

MSULat, 2003.14128



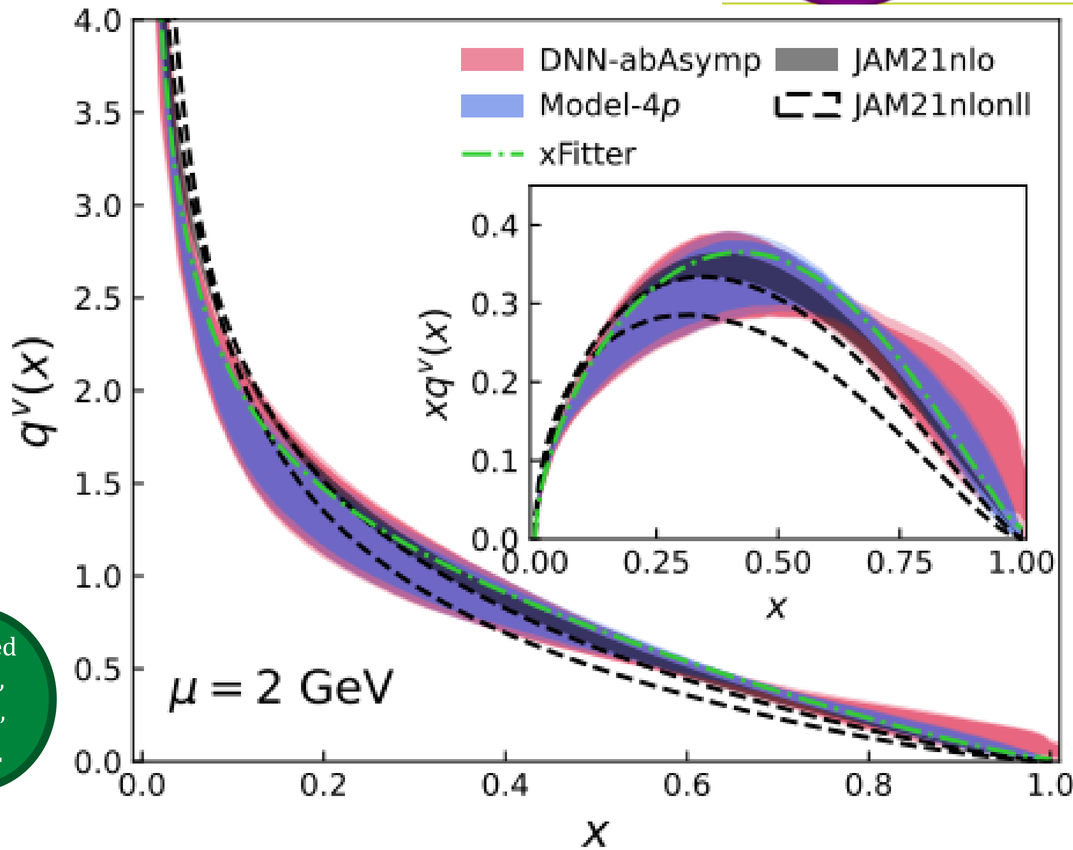




Valence-quark PDFs Update

§ Pion PDFs calculated directly at physical pion mass

- with **NNLO** matching



- N_f=2+1 clover/HISQ a~0.076 fm

Wanted PDFs, GPDs, etc…

ANL/BNL, Phys. Rev. D 106, 114510 (2022)

Valence-quark PDFs Update

§ Pion PDFs calculated directly at physical pion mass

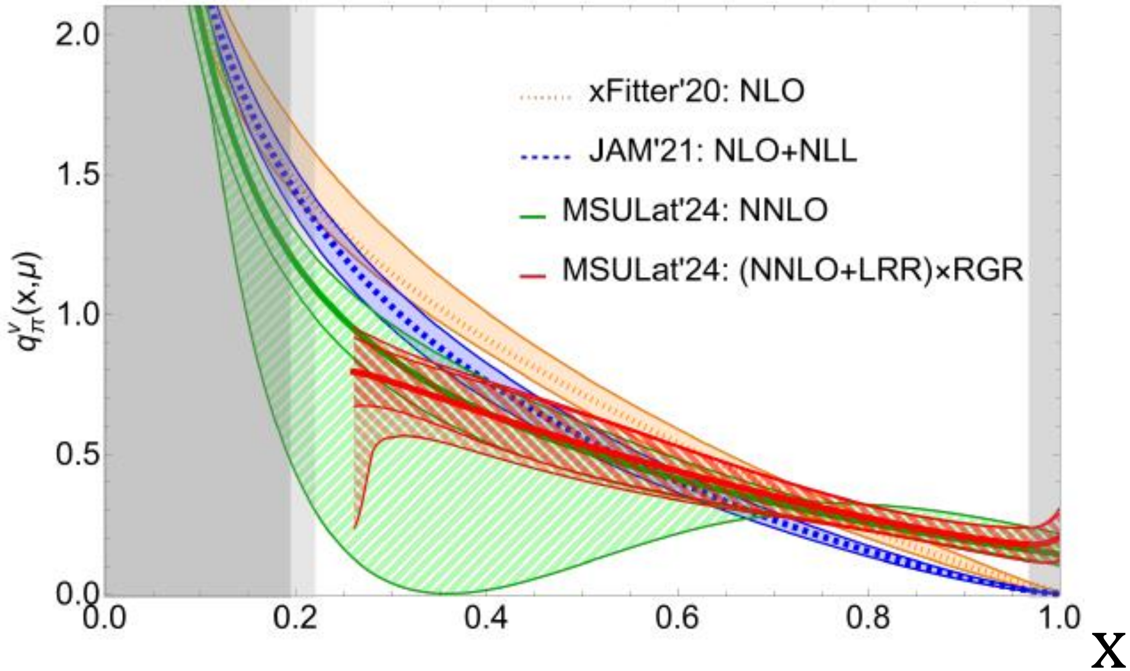
- NNLO matching & treat leading-renormalon effects
  - Leading-renormalon resummation (LRR)
  - Renormalization-group resummation (RGR)

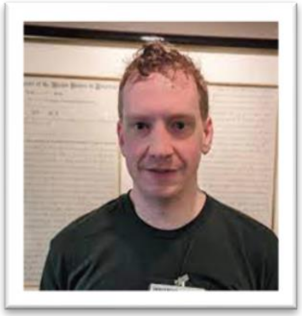
R. Zhang, et. al.
PLB 844, 138081 (2023)

- N_f=2+1+1 clover/HISQ, a~0.09 fm

J. Holligan, HL (MSULat), [10.1088/1361-6471/ad3162](https://doi.org/10.1088/1361-6471/ad3162)

Wanted PDFs, GPDs, etc…

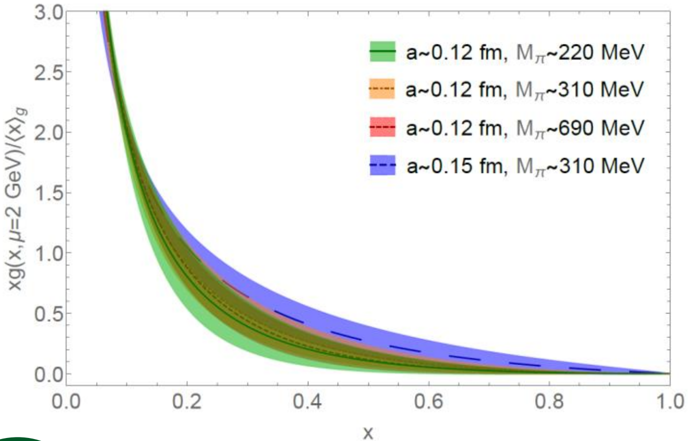


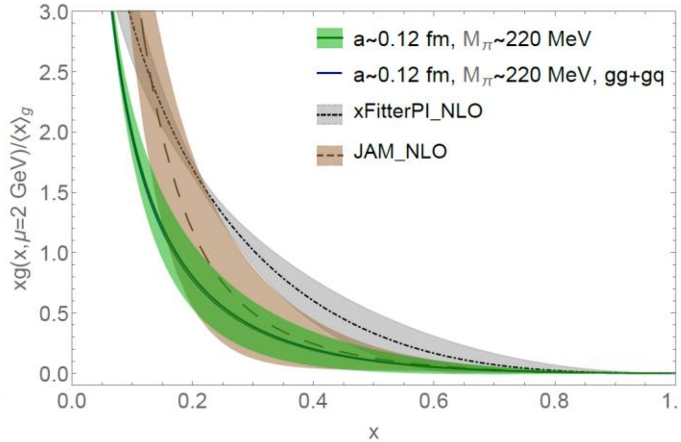


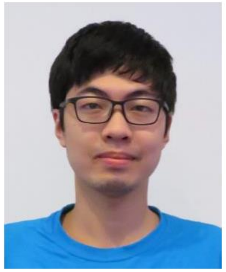
P: Jack Holligan

Meson Gluon PDFs

§ First pion and kaon gluon PDFs $g(x)/\langle x\rangle$ using pseudo-PDF



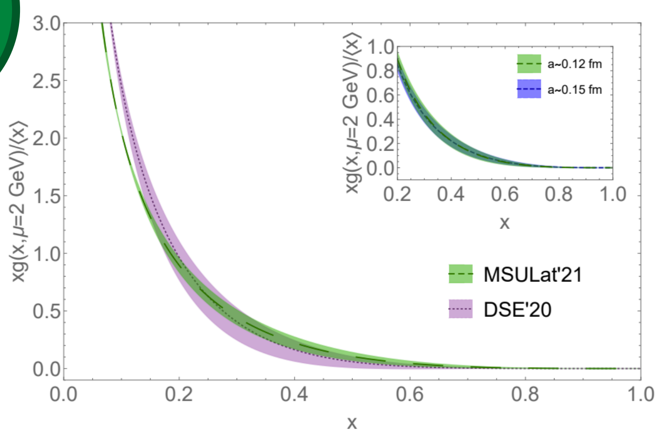




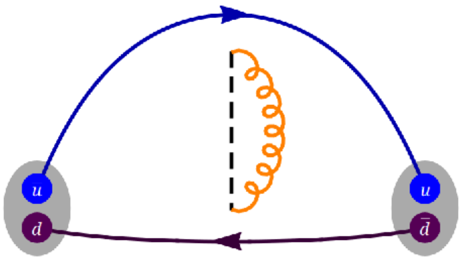
G: Zhouyou Fan

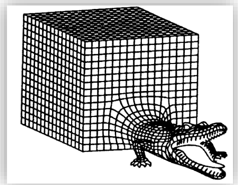
Wanted PDFs, GPDs, etc…

2104.06372, Fan et al. (MSULat); 2112.03124, Salas-Chavira et al. (MSULat)



G: Alejandro Salas-Chavira





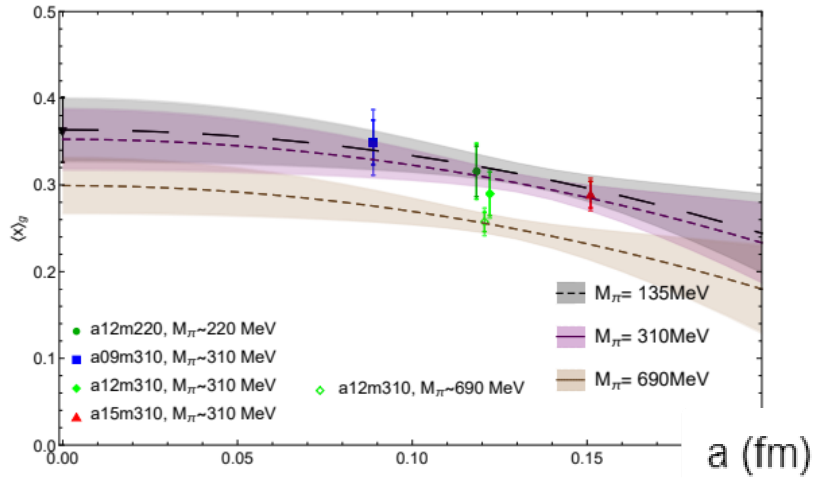
finite-volume, discretization, heavy quark mass, …

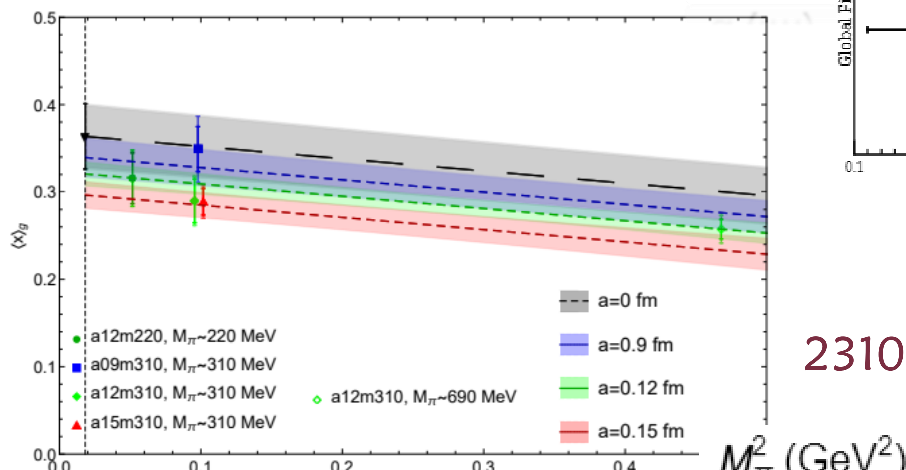
§ What does lattice QCD say about $g(x)$?

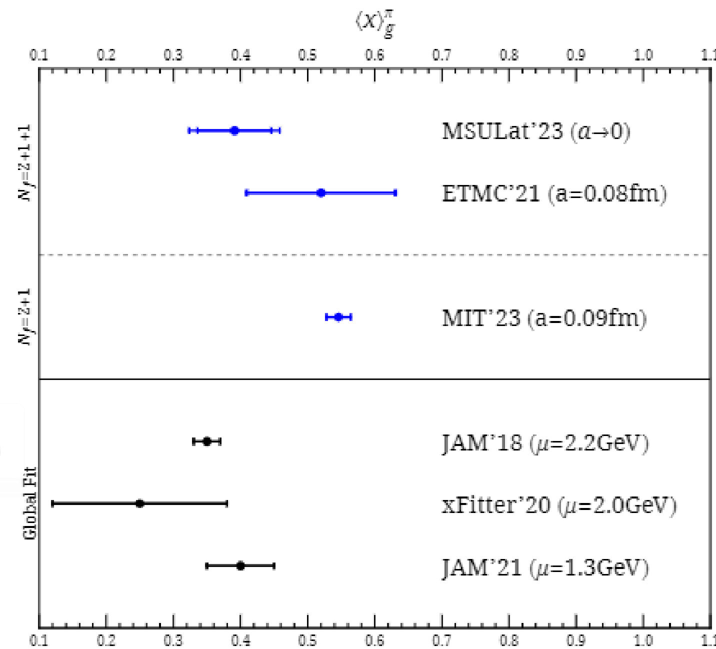
Pion Gluon PDF Update

§ Study discretization systematic in $\langle x \rangle_{\{\pi,g\}}$

- Lattice details: clover/HISQ. HISQ. a ~{0.15. 0.12. 0.09} fm







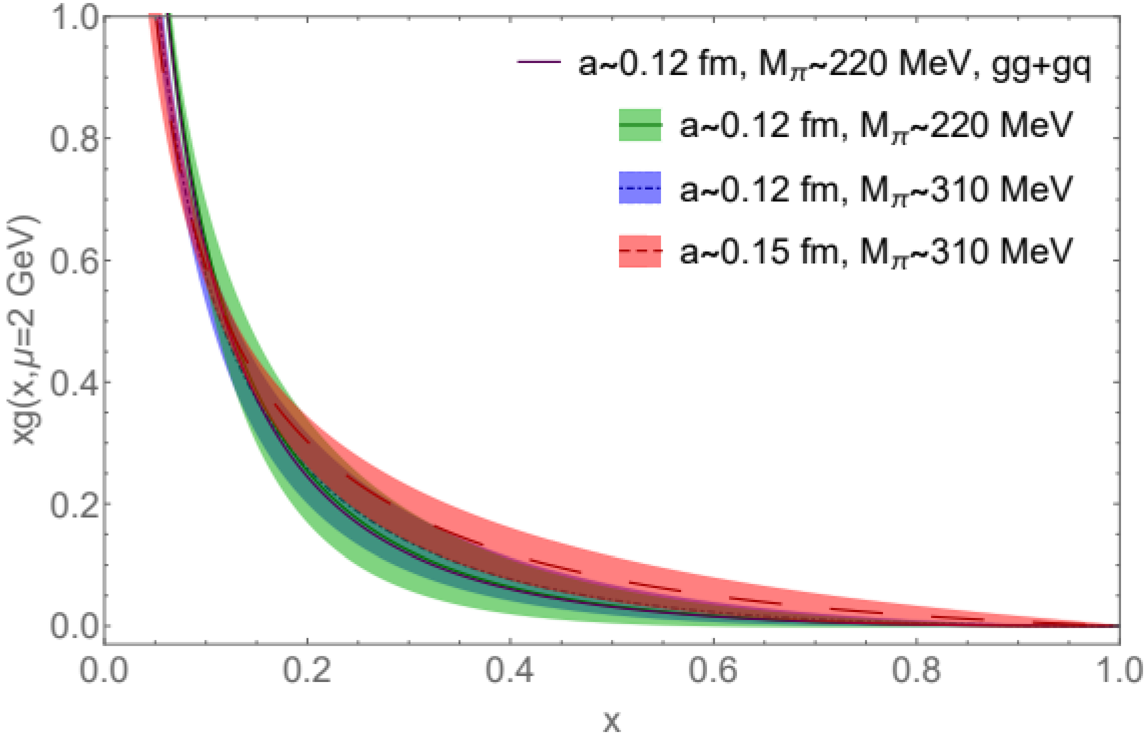
2310.12034, Good et al. (MSULat)

G: Bill Good

Pion Gluon PDF Update

§ Back to Pion gluon PDF $g(x)$

- Update previous calculated $g(x)/\langle x\rangle$ in 2021

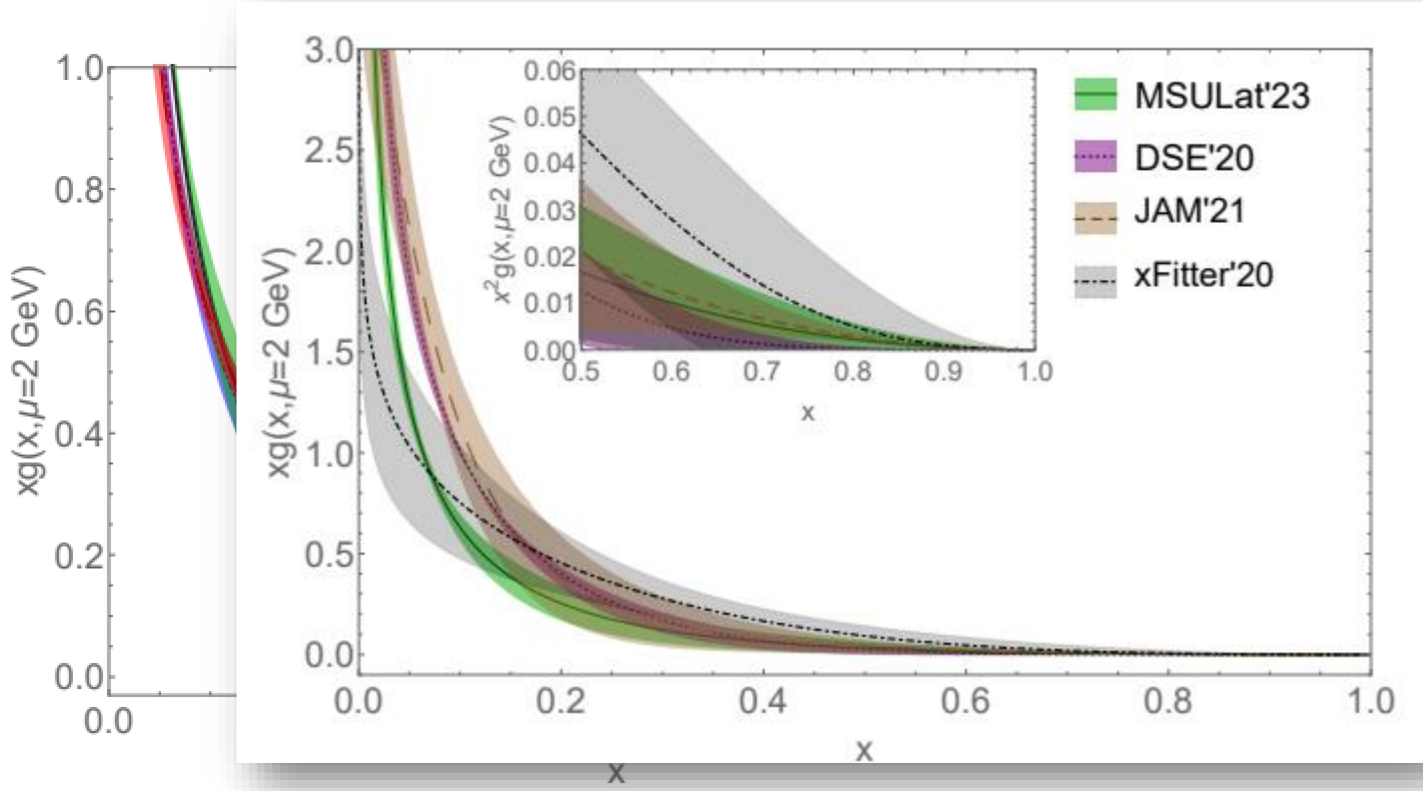


2310.12034, Good et al. (MSULat)

G: Bill Good

§ Back to Pion gluon PDF $g(x)$

- Update previous calculated $g(x)/\langle x\rangle$ in 2021

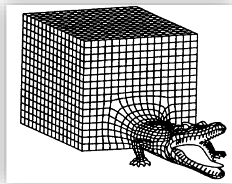


2310.12034, Good et al. (MSULat)

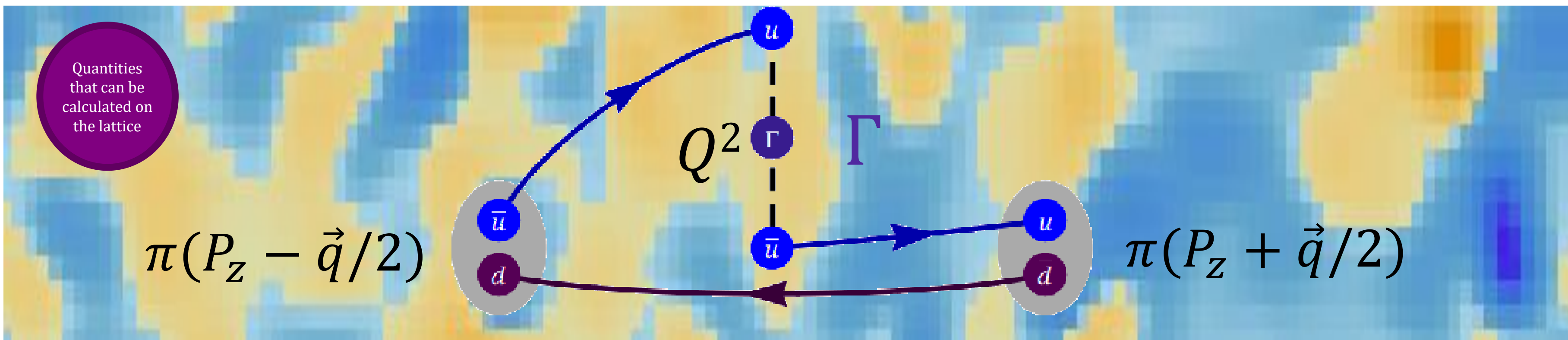
G: Bill Good

Generalized Parton Distributions

Single-ensemble result



finite-volume,
discretization,
heavy quark mass,
...



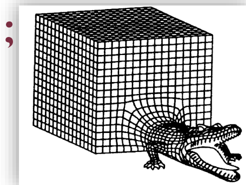
First Lattice GPDs

§ First glimpse into pion GPD using Quasi-PDF/LaMET

- Lattice details: clover/HISQ, **0.12fm**, **310-MeV** pion mass

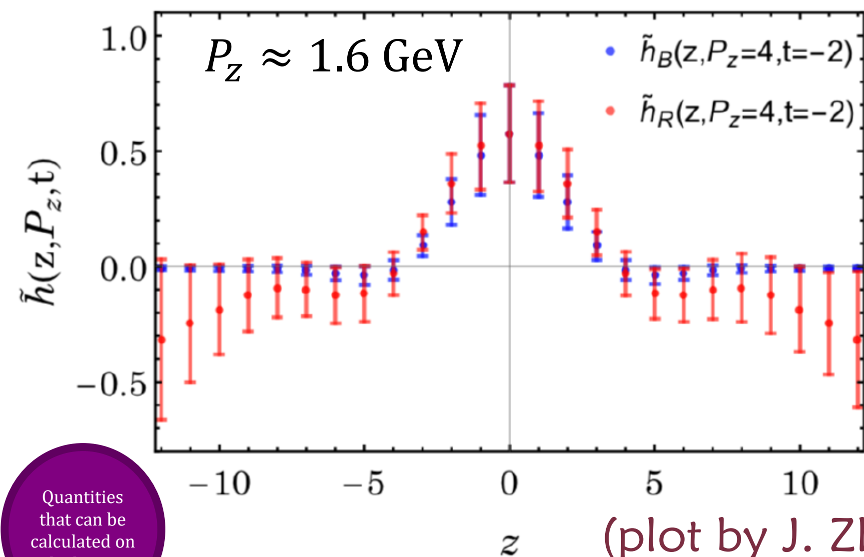
$P_z \approx 1.3, 1.6$ GeV

MILC, Phys. Rev. D, 82 (2010), 074501;
Phys. Rev. D, 87 (2013), 0545056



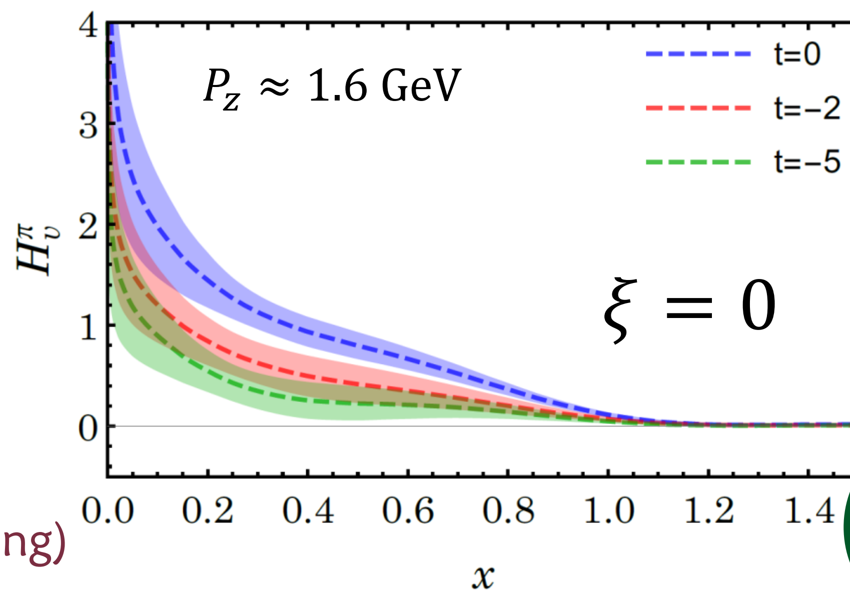
J. Chen, HL, J. Zhang, 1904.1237;

$$H_q^{\pi}(x,\xi,t,\mu) = \int \frac{d\eta^-}{4\pi} e^{-ix\eta^- P^+} \left\langle \pi(P+\Delta/2) \left| \bar{q}\left(\frac{\eta^-}{2}\right) \gamma^+ \Gamma\left(\frac{\eta^-}{2}, -\frac{\eta^-}{2}\right) q\left(-\frac{\eta^-}{2}\right) \right| \pi(P-\Delta/2) \right\rangle$$



Quantities that can be calculated on the lattice

(plot by J. Zhang)

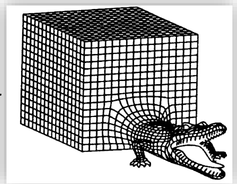


Wanted PDFs, GPDs, etc…

Valence-Quark Pion GPD

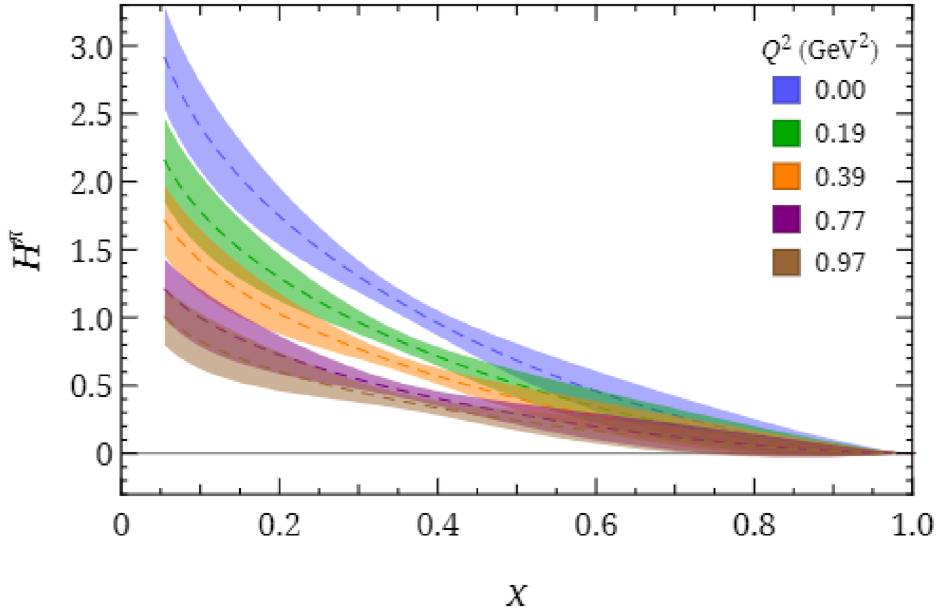
§ Pion GPD (H^π) using quasi-PDFs at physical pion mass

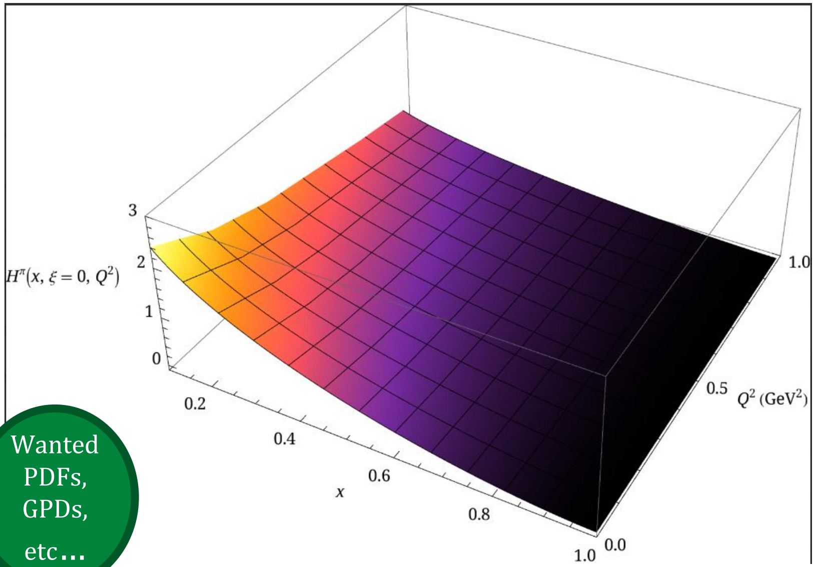
- Lattice details: clover/2+1+1 HISQ
  0.09 fm, 135-MeV pion mass, $P_z \approx 1.7$ GeV
- $\xi = 0$ valence-quark Pion GPD results



finite-volume,
discretization,

HL (MSULat), Phys. Lett. B 846 (2023) 138181



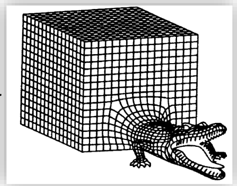


Wanted PDFs, GPDs, etc…

Valence-Quark Pion GPD

§ Pion GPD (H^π) using quasi-PDFs at physical pion mass

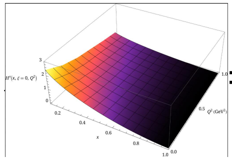
- Lattice details: clover/2+1+1 HISQ
  0.09 fm, 135-MeV pion mass, $P_z \approx 1.7$ GeV



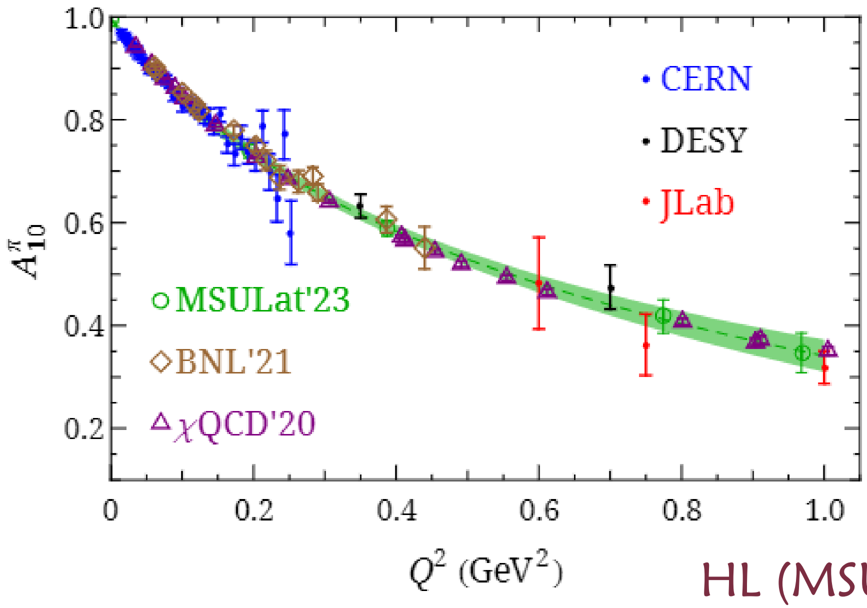
finite-volume,
discretization,

- $\xi = 0$ valence-quark Pion GPD results

$$\int_{-1}^{+1} dx\, x^{n-1}$$



$$= A^{\pi}_{ni}(t)$$

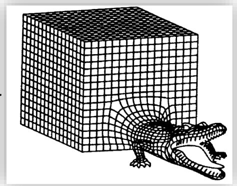


HL (MSULat), Phys. Lett. B 846 (2023) 138181

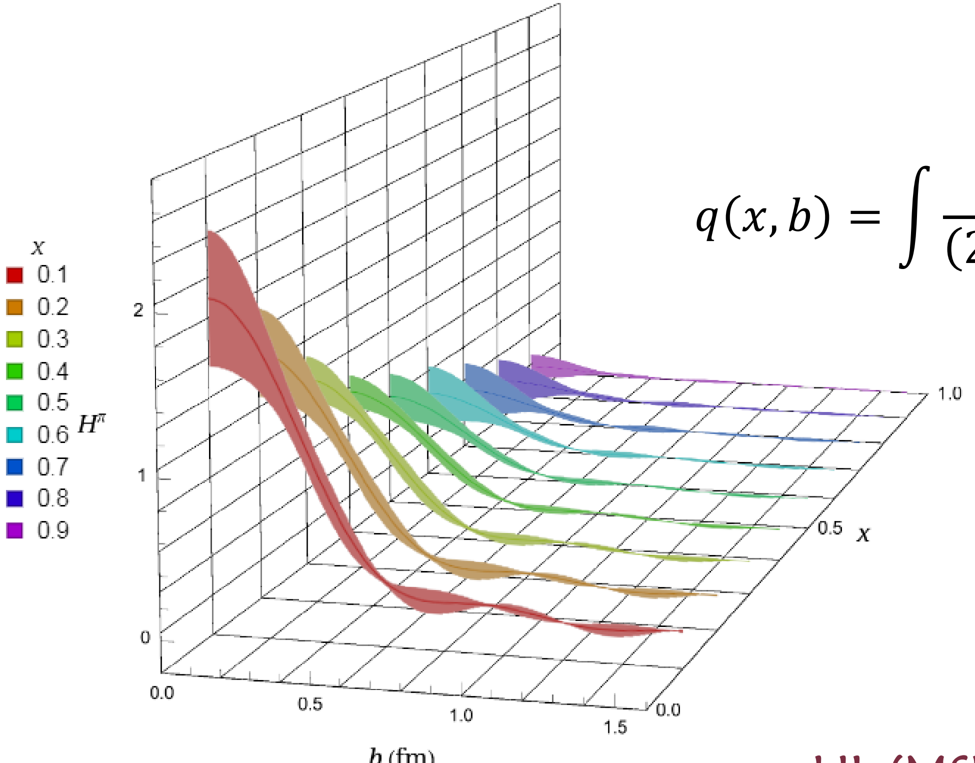
Pion Tomography

§ Nucleon GPD using quasi-PDFs at physical pion mass

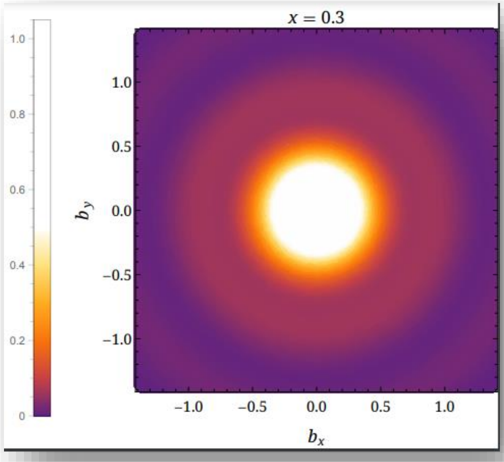
- Lattice details: clover/2+1+1 HISQ
  0.09 fm, 135-MeV pion mass, $P_z \approx 1.7$ GeV
- $\xi = 0$ valence-quark Pion GPD results



finite-volume,
discretization,



$$q(x,b) = \int \frac{d\vec{q}}{(2\pi)^2} H(x,\xi=0,t=-\vec{q}^{\,2}) e^{i\vec{q}\cdot\vec{b}}$$

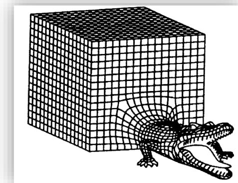


HL (MSULat), Phys. Lett. B 846 (2023) 138181

Nucleon Tomography

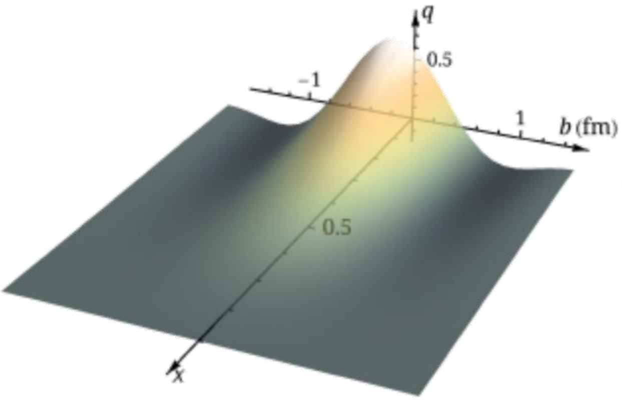
§ Nucleon GPD using quasi-PDFs at physical pion mass

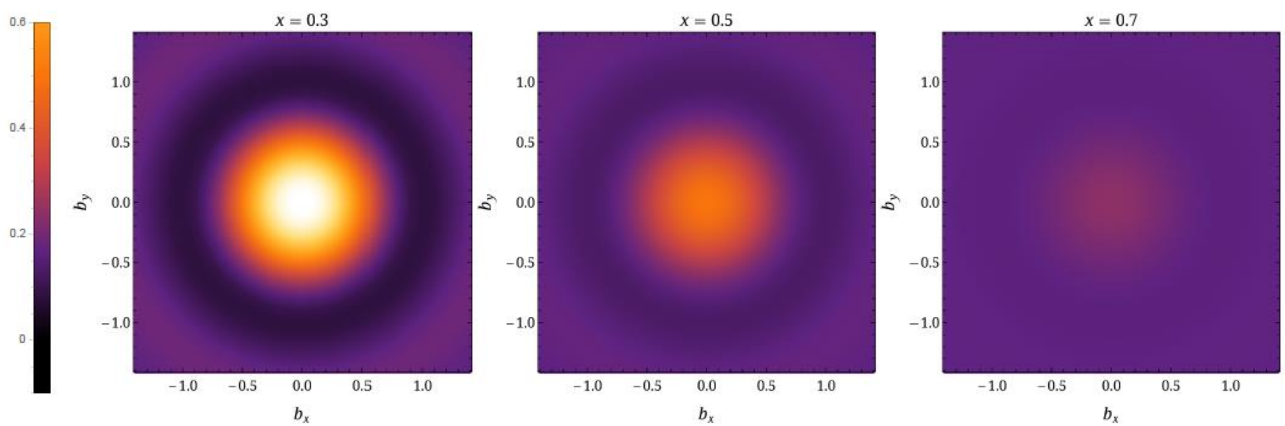
- Lattice details: clover/2+1+1 HISQ
  0.09 fm, 135-MeV pion mass, $P_z \approx 2$ GeV
- $\xi = 0$ isovector nucleon GPD results



finite-volume,
discretization,

$$q(x,b) = \int \frac{d\vec{q}}{(2\pi)^2} H(x, \xi = 0, t = -\vec{q}^2) e^{i\vec{q}\cdot\vec{b}}$$

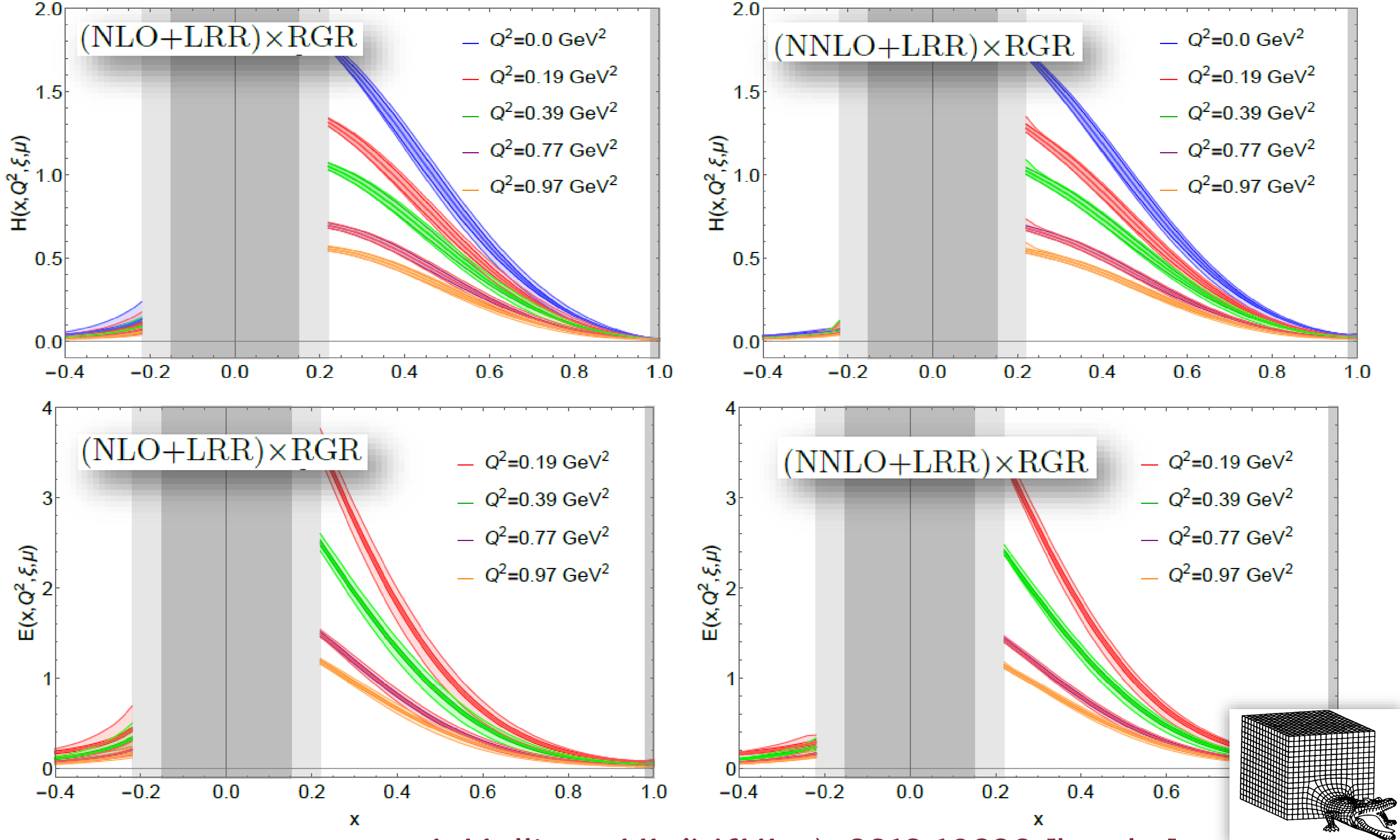




HL, Phys.Rev.Lett. 127 (2021) 18, 182001

Also see work done by ANL/BNL/ETMC, [2209.05373](2209.05373) ,[2310.13114](2310.13114)

ξ=0 GPDs



J. Holligan, HL (MSULat), 2312.10829 [hep-lat]

Outline

- § Lattice QCD in a Nutshell
- § Selected *x*-Dependent Parton Distributions
  - Nucleon PDFs
  - **Pion/Kaon PDFs**
  - GPDs
- § **Impact of Lattice-QCD PDFs on Global Fits**

Biased selected results toward MSULat students and postdocs

CTEQ

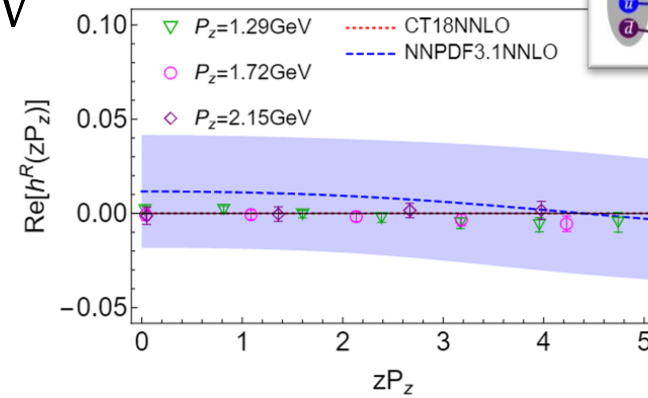
First Lattice Strange PDF

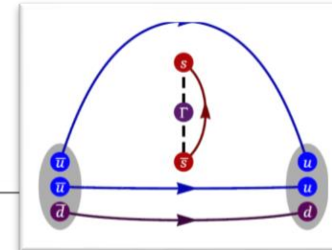
§ Results by MSULat/quasi-PDF method

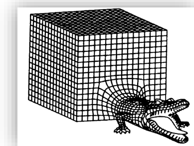
- Clover on 2+1+1 HISQ, 0.12-fm 310-MeV QCD vacuum
- Extrapolated to $M_\pi \approx 140$ MeV

R. Zhang et al (MSULat), 2005.01124

$$\mathrm{Re}[h(z)] \propto \int dx\,(s(x) - \bar{s}(x))\cos(xzP_z)$$







Quantities that can be calculated on the lattice

G: Rui Zhang

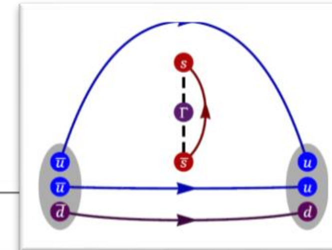
Lattice Strangeness Asymmetry Impact

§ Results by MSULat/quasi-PDF method

- Clover on 2+1+1 HISQ, 0.12-fm 310-MeV QCD vacuum
- Extrapolated to $M_\pi \approx 140$ MeV

R. Zhang et al (MSULat), 2005.01124

$$\mathrm{Re}[h(z)] \propto \int dx\,(s(x) - \bar{s}(x)) \cos(xzP_z)$$

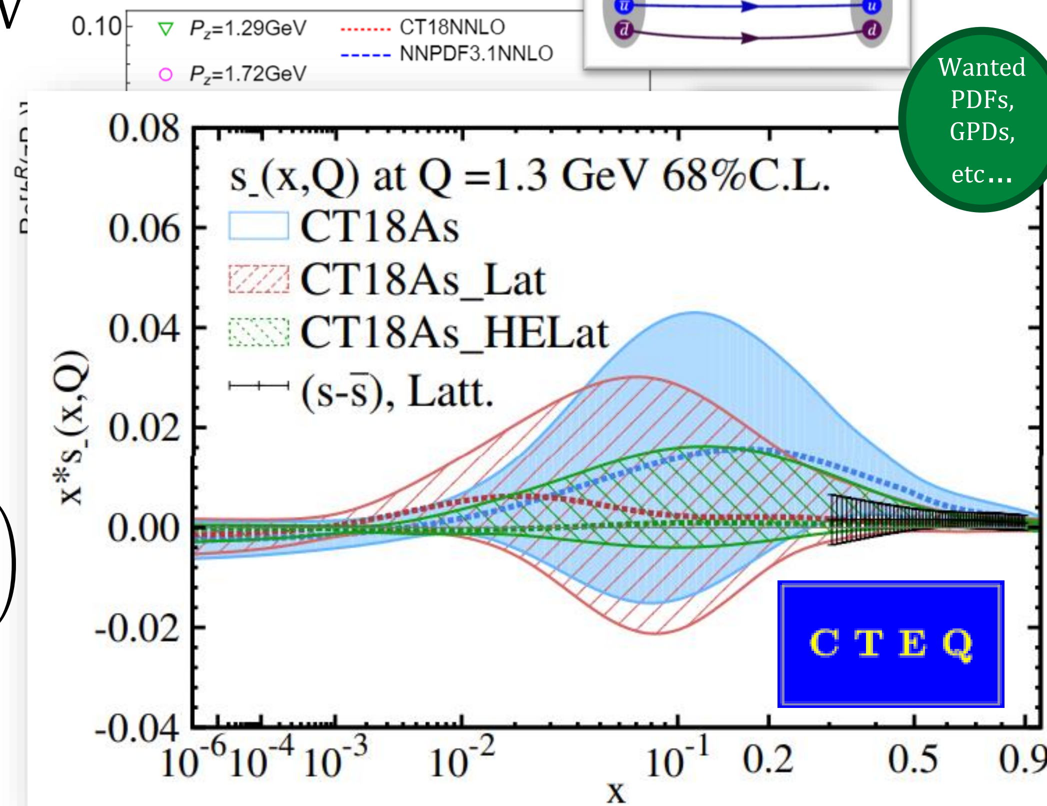


Wanted PDFs, GPDs, etc…

§ From quasi-PDF to PDF

$$\tilde{f}_q(x, P_z) = \int_{-1}^{1} \frac{dy}{|y|} f_q(y) C_{q/q}(x, y, P_z, \mu) + O\left(\frac{\Lambda_{\mathrm{QCD}}^2}{x^2 P_z^2}, \frac{\Lambda_{\mathrm{QCD}}^2}{(1-x)^2 P_z^2}\right)$$

T. Hou, HL, M. Yan, C. Yuan, 2211.11064

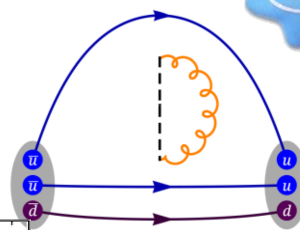


§ The strangeness asymmetry $s(x,Q) - \bar{s}(x,Q)$ at $x > 0.2$ is difficult to measure, but can be predicted in lattice QCD

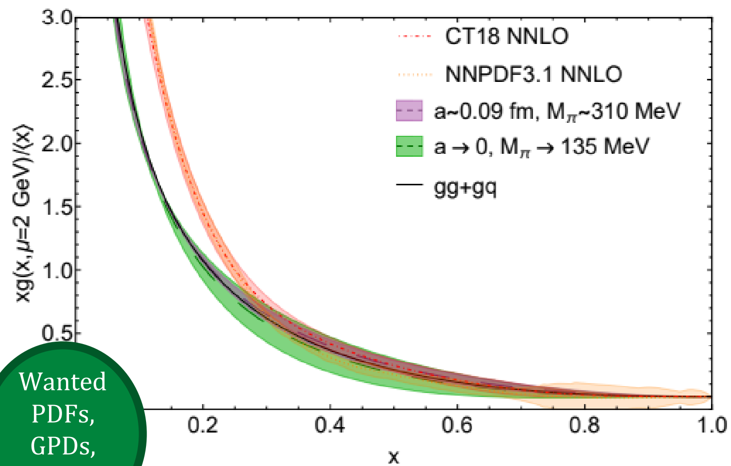
Lattice Gluon PDF Impact

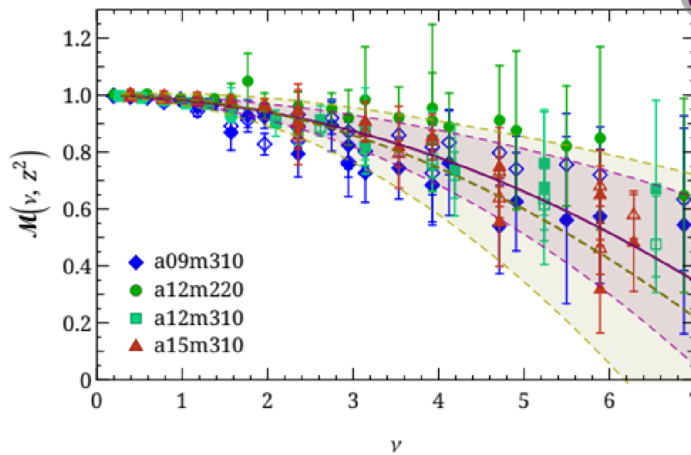
§ First continuum Gluon PDF w/ pseudo-PDF

- 2+1+1 HISQ {0.09, 0.12, 0.15} fm, [220,310,700]-MeV pion, 10^5-10^6 statistics



2210.09985, W. Good et al (MSULat)

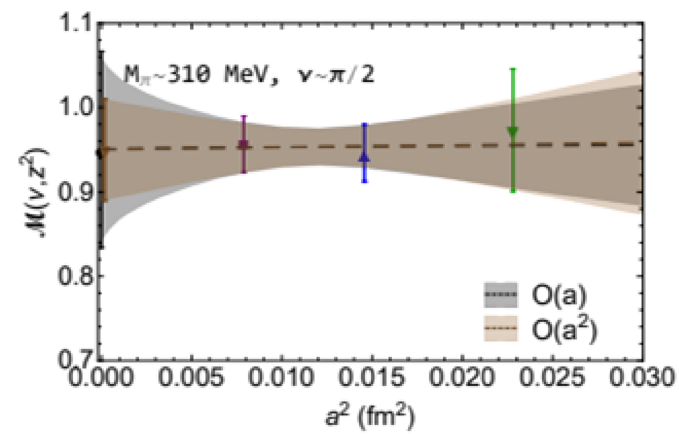




Quantities that can be calculated on the lattice

§ Can use $a \approx 0.09$ fm results as

- Best estimate of gluon PDF
- Aim for future precision



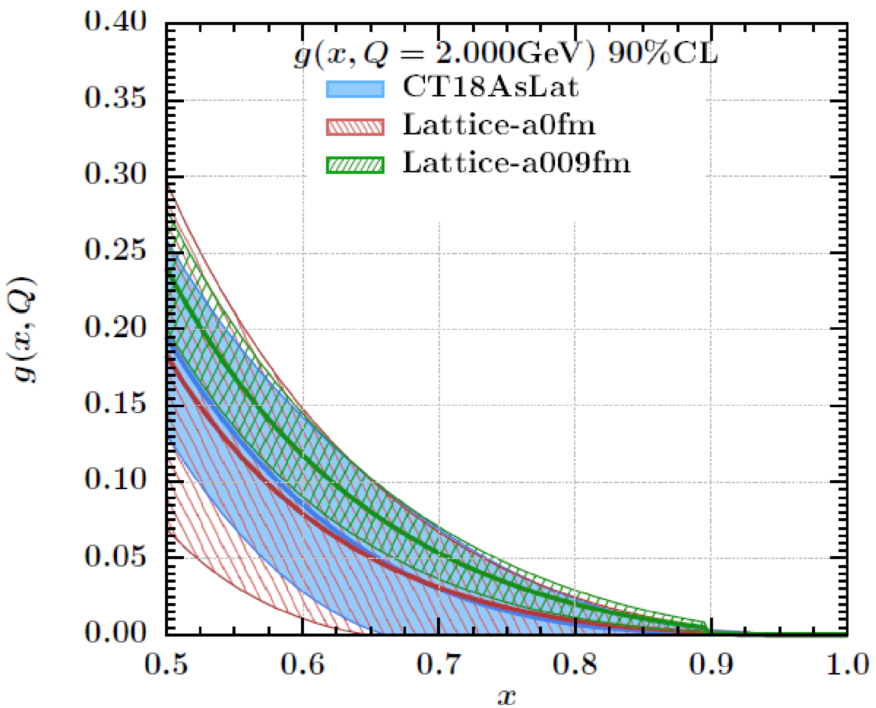
Lattice Gluon PDF Impact

§ Preliminary study with CTEQ-TEA analysis

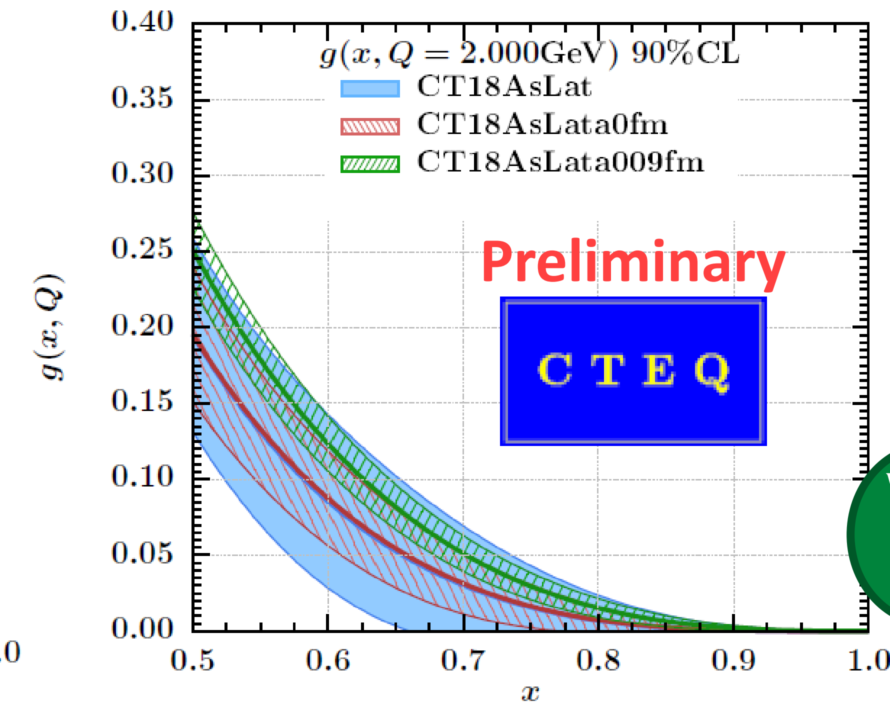
- Take lattice inputs in the region where no strong experimental data constraints, x ∈ [0.4,0.7]
- Using e-pump for re-weighting

Plots by Alim Ablat (Xinjiang U.)

Before



After

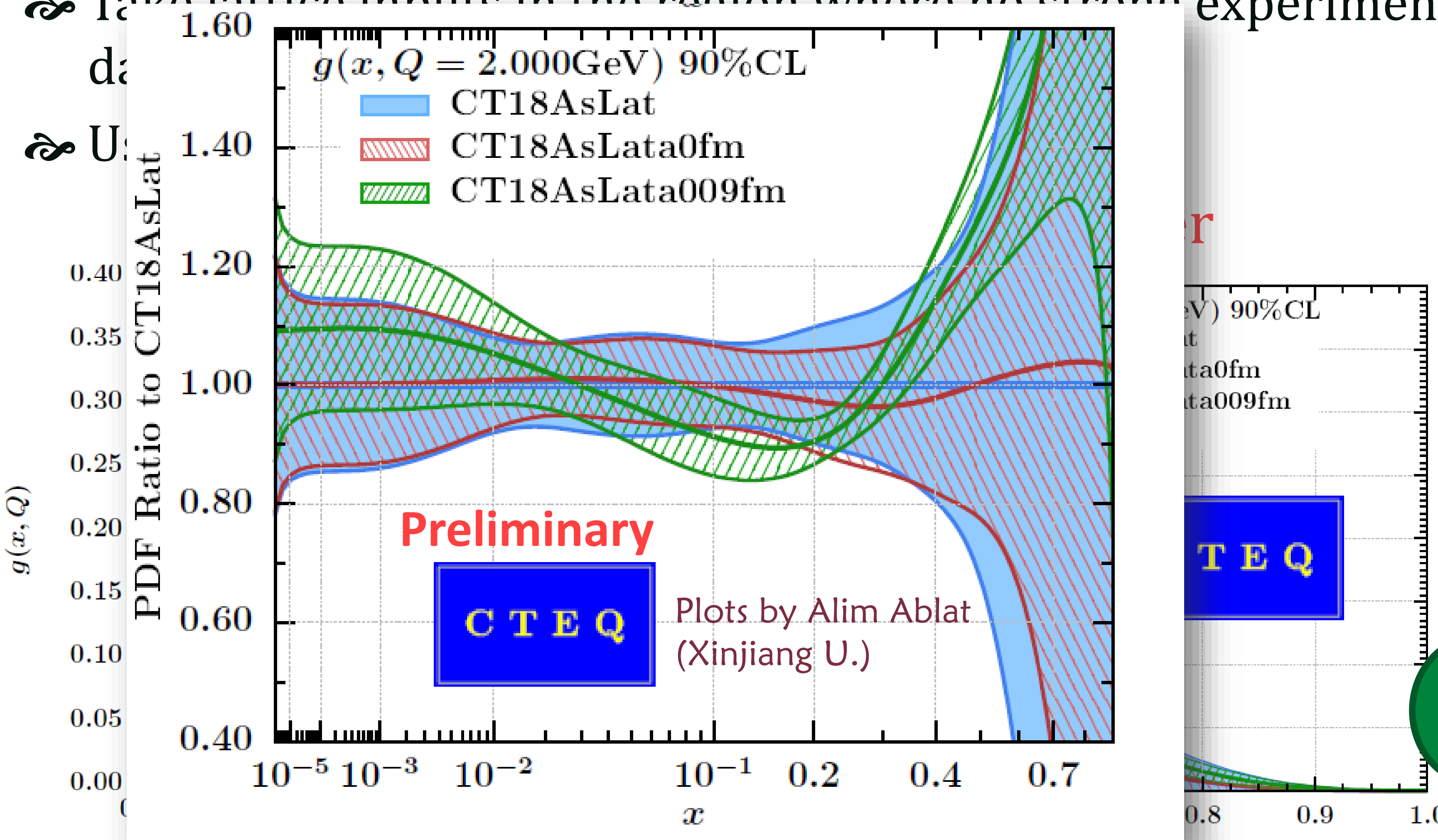


Wanted PDFs, GPDs, etc…

Lattice Gluon PDF Impact

§ Preliminary study with CTEQ-TEA analysis

- Take lattice inputs in the region where no strong experimental da
- U

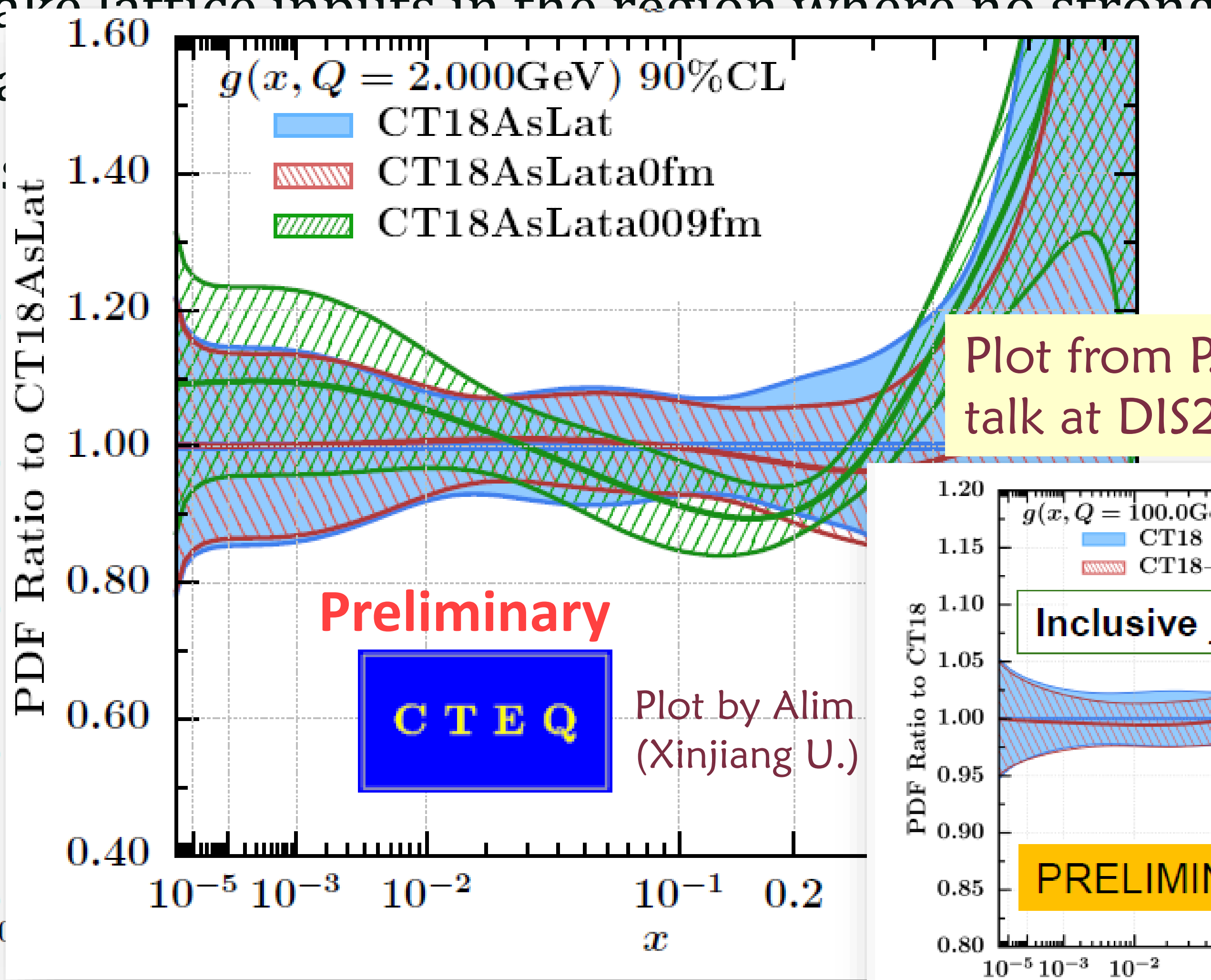


Wanted PDFs, GPDs, etc…

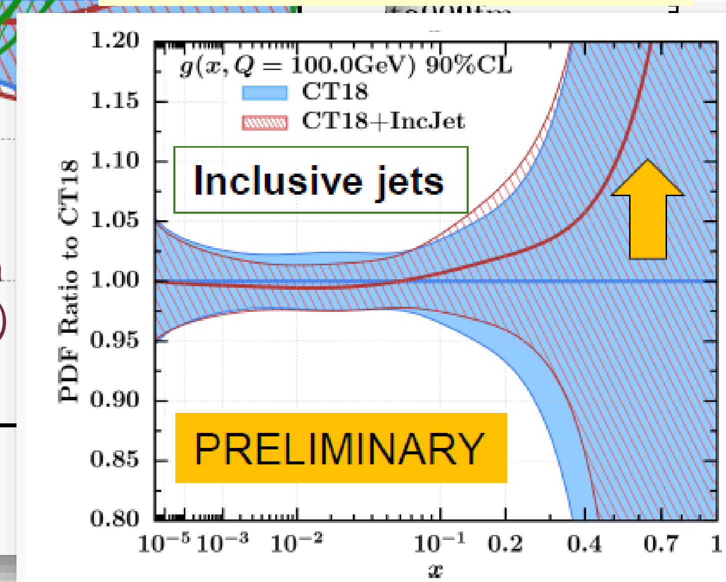
Lattice Gluon PDF Impact

§ Preliminary study with CTEQ-TEA analysis

- Take lattice inputs in the region where no strong experimental da
- Us



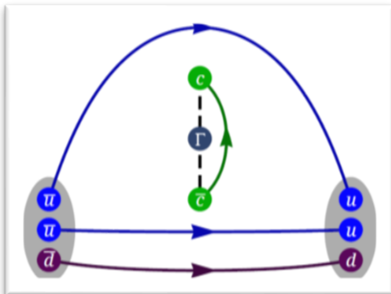
Plot from P. Nadolsky's talk at DIS2024



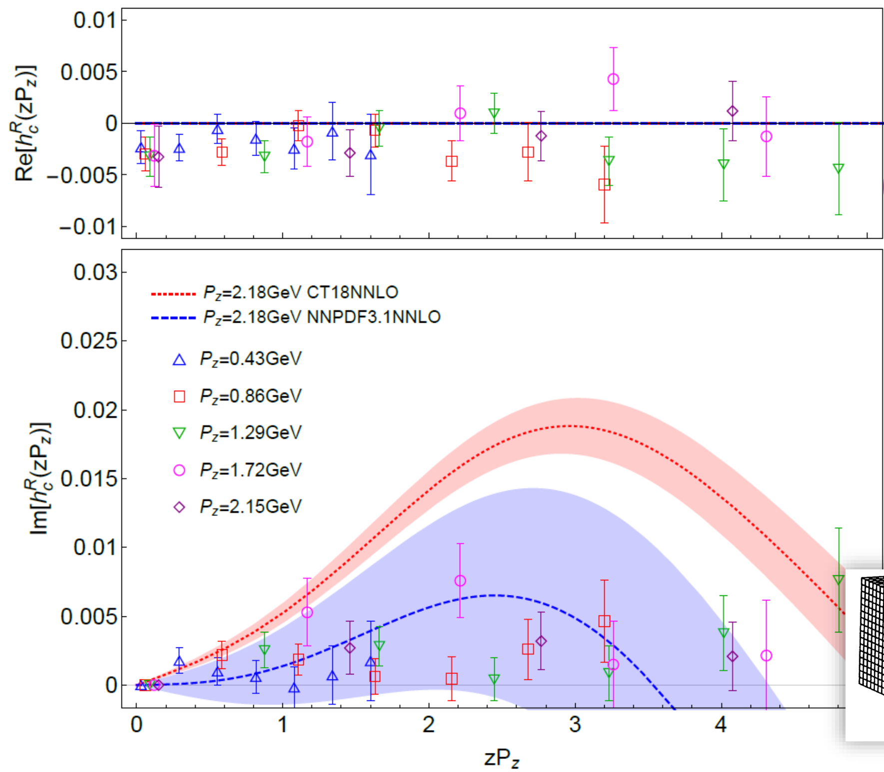
First Lattice Charm PDF

- § Large uncertainties in global PDFs
- § Results by MSULat/quasi-PDF method
  - Clover on 2+1+1 HISQ 0.12-fm 310-MeV QCD vacuum

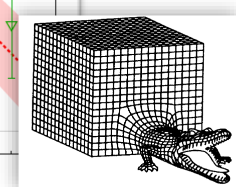
2005.01124, R. Zhang et al (MSULat)



- suggest a symmetric $c - \bar{c}$ distribution
- much smaller than strange PDF



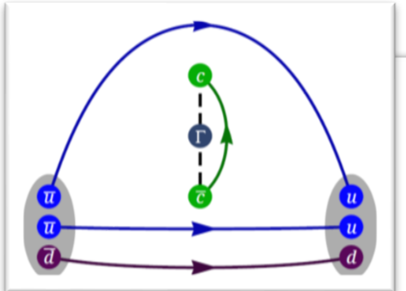
Quantities that can be calculated on the lattice



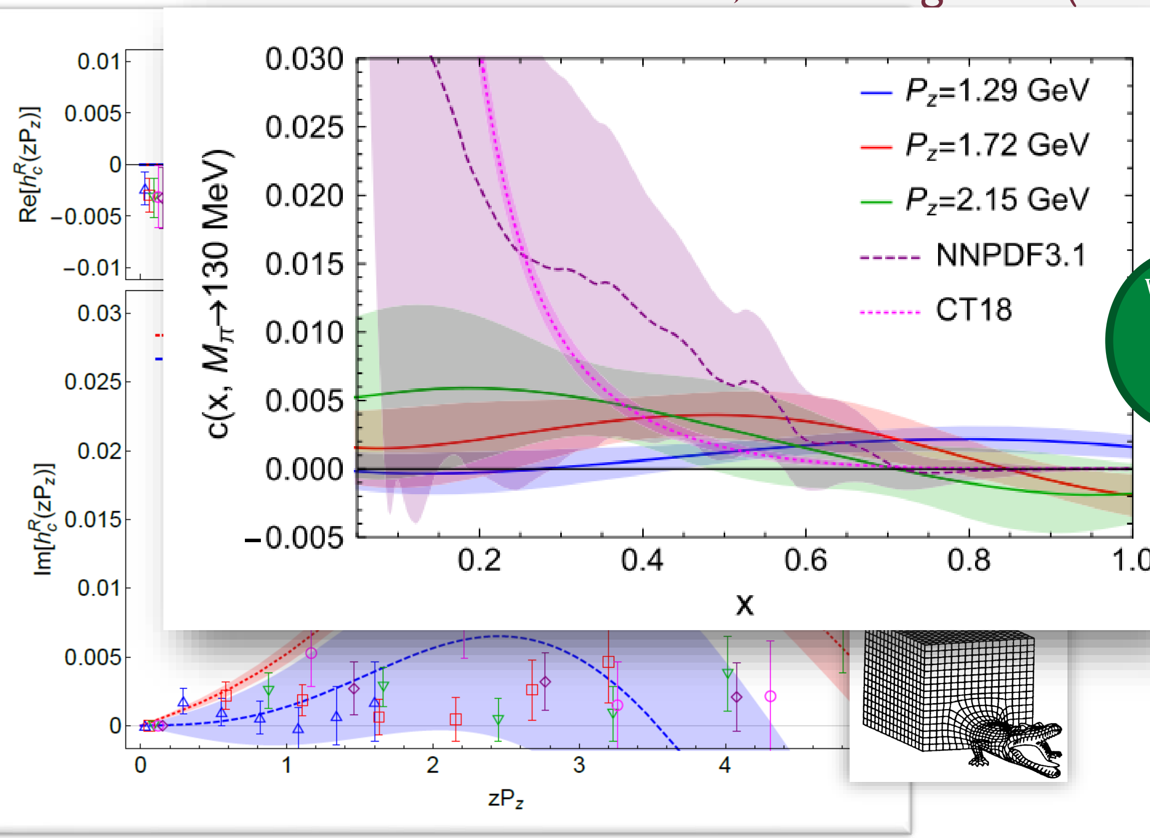
First Lattice Charm PDF

- § Large uncertainties in global PDFs
- § Results by MSULat/quasi-PDF method
  - Clover on 2+1+1 HISQ 0.12-fm 310-MeV QCD vacuum

2005.01124, R. Zhang et al (MSULat)



- suggest a symmetric $c-\bar{c}$ distribution
- much smaller than strange PDF



Wanted PDFs, GPDs, etc…

Lattice Progress & Challenges

§ Beyond the standard twist-2 collinear PDFs

- Generalized parton distributions (GPDs) for the pion and unpolarized/polarized nucleon
- Transverse-momentum– dependent distributions (TMDs)
  - Collins-Soper kernel, soft function and wavefunctions
- Twist-3 PDFs and GPDs

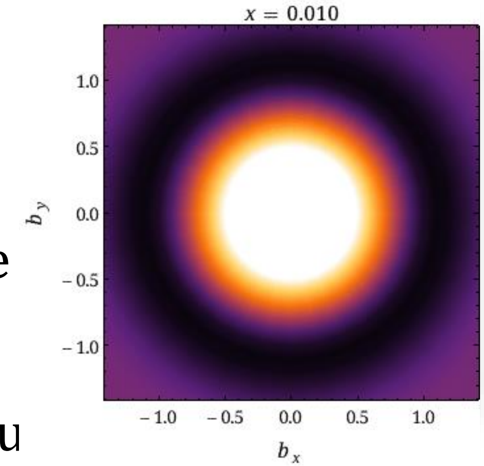
For more details and references, refer to 2202.07193

§ Challenges ahead for precision PDFs

- Large momentum is essential
  - With sufficient statistics nucleons may reach 5 GeV
- Methods for signal-to-noise improvement
  - Gluonic observables, new ideas for large momentum
- Access small-x physics; some methods have inverse problem in PDF extraction, more computational resources, etc.

Summary and Outlook

- § Exciting era using LQCD to study *x*-dependent PDFs
- § Overcoming longstanding limitations
  - Bjorken-*x* dependence of parton distributions now widely studied
  - More study of systematics planned for the near future

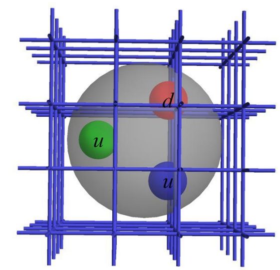


- § Lattice strange and gluon PDFs can have impacts
  - Treat lattice matrix elements as expt inputs in the futu
- § Precision and progress are limited by resources

Theory Input

Global Analysis of PDFs/GPDs

Exp't Input +



Thanks to MILC collaboration for sharing their 2+1+1 HISQ lattices & USQCD/NSF/DOE for computational resources
This work is partially sponsored by grants NSF PHY 1653405 & 1653405, DOE DE-SC0024053 & RCSA Cottrell Scholar Award

Students Wanted

LGT4HEP website: https://lgt4hep.github.io/

LGT4HEP

High Energy Physics Computing Traineeship for Lattice Gauge Theory

Apply now:

Visit lgt4hep.github.io to learn more and where to apply for the traineeship graduate school program.