# Advances in the lattice QCD calculation of hadron structure

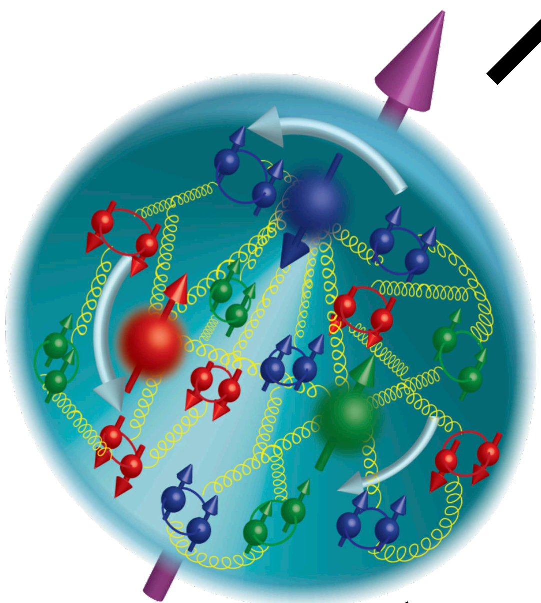
2022 Town Hall Meeting on Hot & Cold QCD

MIT, Cambridge, MA, Sep. 23—25, 2022

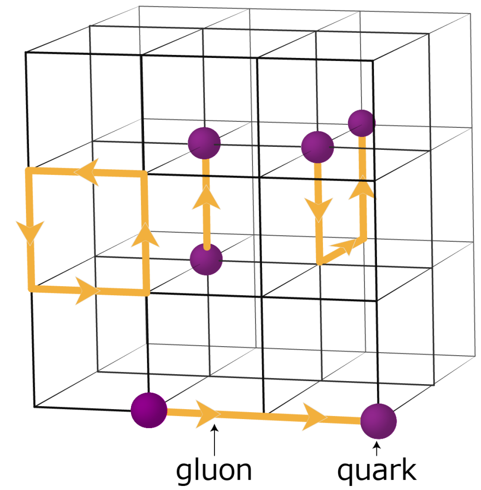
**YONG ZHAO**

**SEP 24, 2022**

Argonne NATIONAL LABORATORY



Lattice QCD

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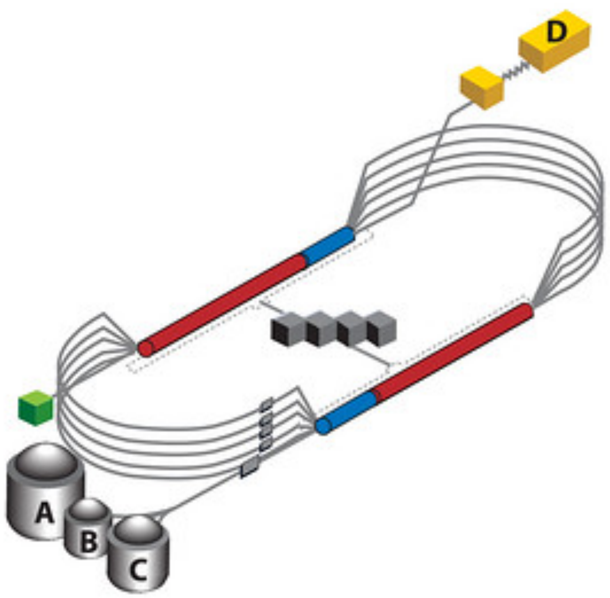
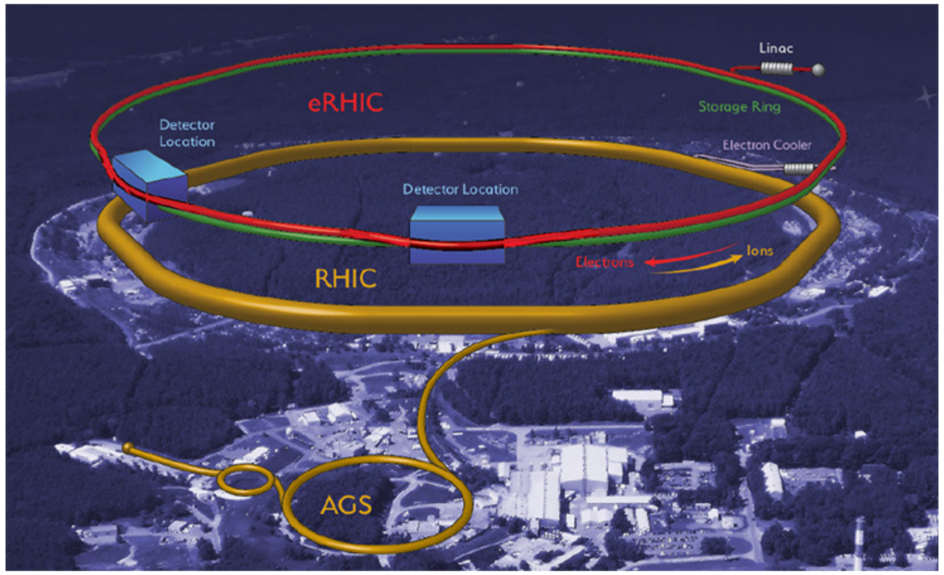
“Lattice QCD calculation of parton physics”,
M. Constantinou et al., 2202.07193.

**See also Martha Constantinou’s plenary talk.**

Hard Scattering



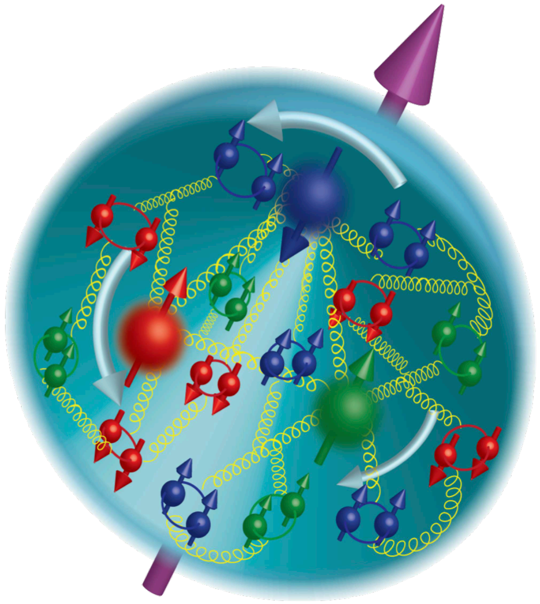

Jefferson Lab 12 GeV




The Electron-Ion Collider

3D tomography of the nucleon

Origin of nucleon spin



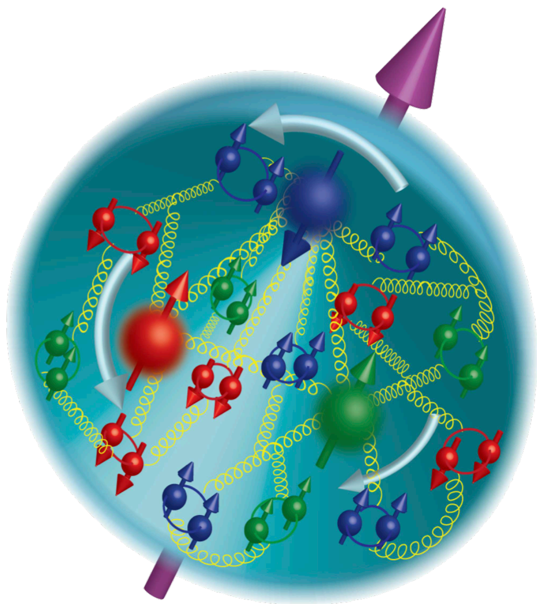
Origin of nucleon mass

Structure of nuclei

**Tremendous progress has been made in lattice QCD!**

3D tomography of the nucleon

Origin of nucleon spin

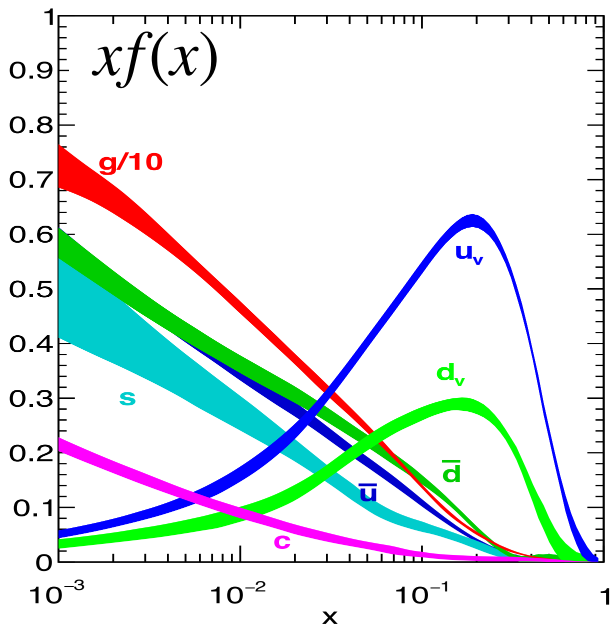


Origin of nucleon mass

Structure of nuclei

# 3D Tomography of the Nucleon

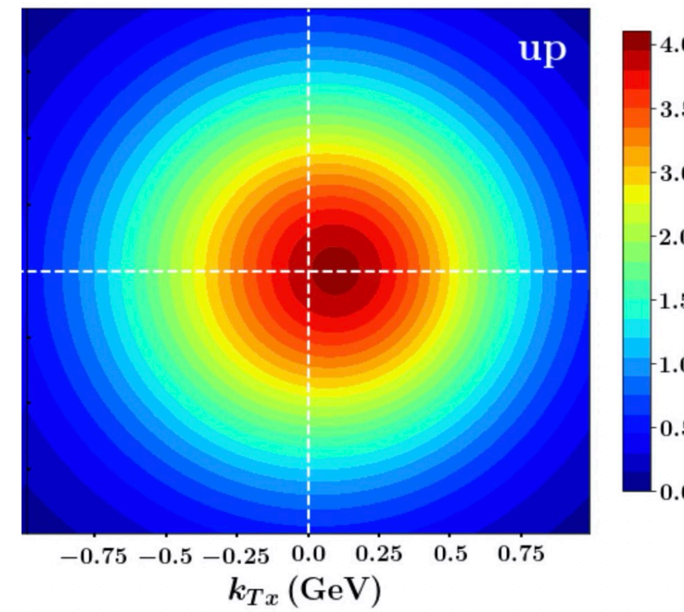
## Parton Distribution Functions (PDFs)




NNPDF, EPJ C77

$$\int d^2\vec{k}_T$$

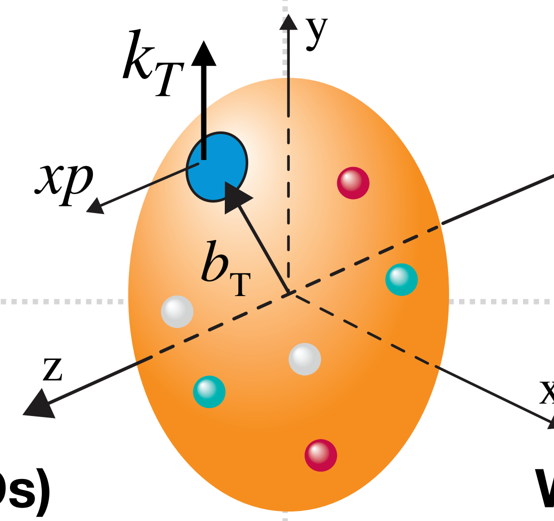
## Transvers momentum distributions (TMDs)



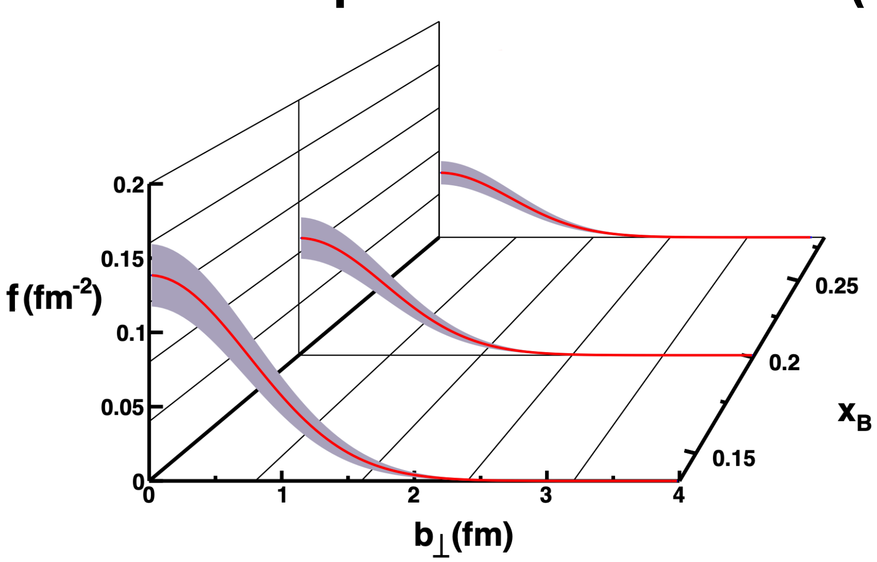

Cammarota, et al. (JAM), PRD **102** (2020).

$$\int d^2\vec{b}_T$$

$$\int d^2\vec{b}_T$$




## Generalized parton distributions (GPDs)




W. Armstrong et al., arXiv: 1708.00888.

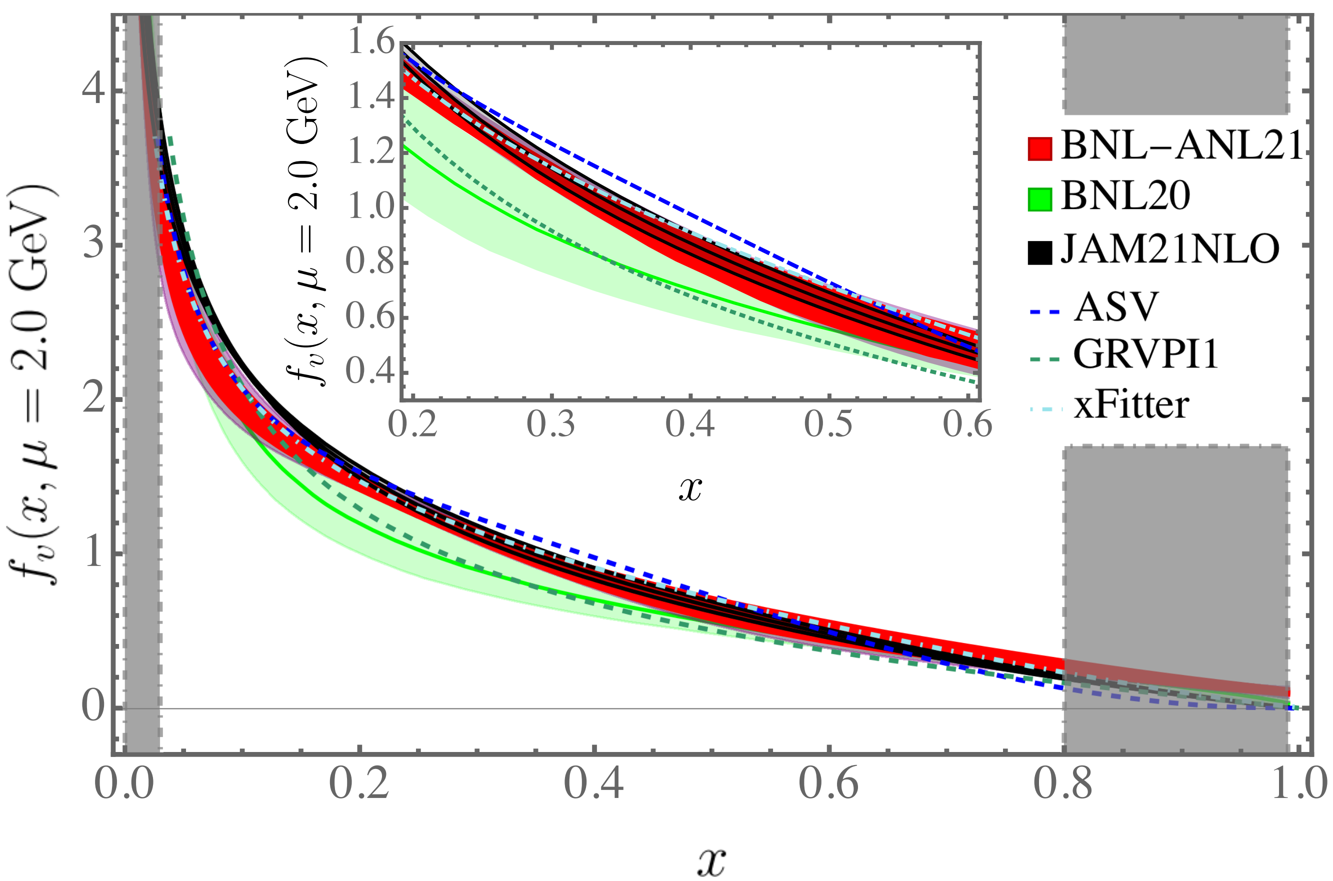
$$\int d^2\vec{k}_T$$

## Wigner distributions/Generalized TMDs

$$W(x, \vec{k}_T, \vec{b}_T)$$

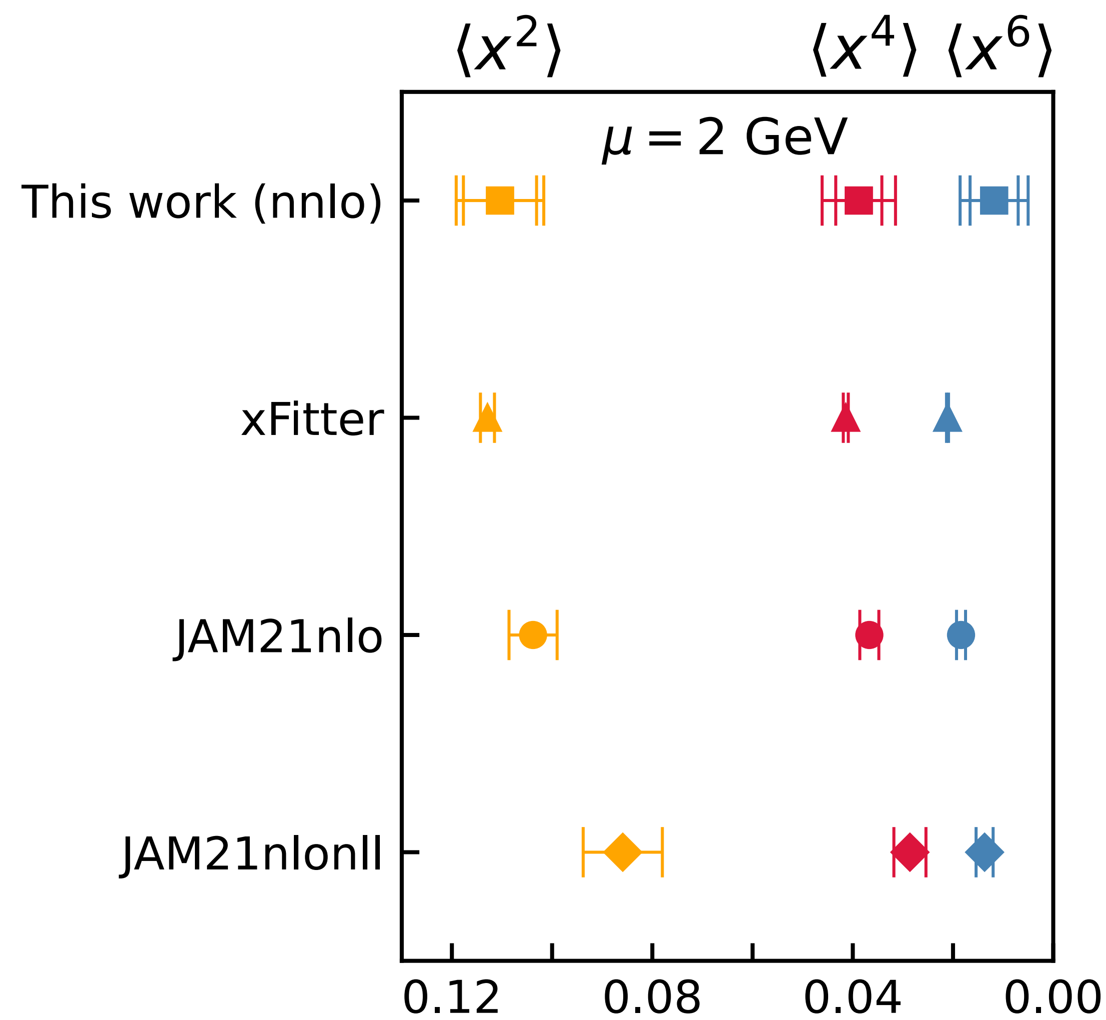
# Pion valence quark PDF (at NNLO accuracy)

### The *x*-dependence from LaMET (quasi-PDF)




X Gao, Y Zhao et al., PRL **128**, 142003 (2022).

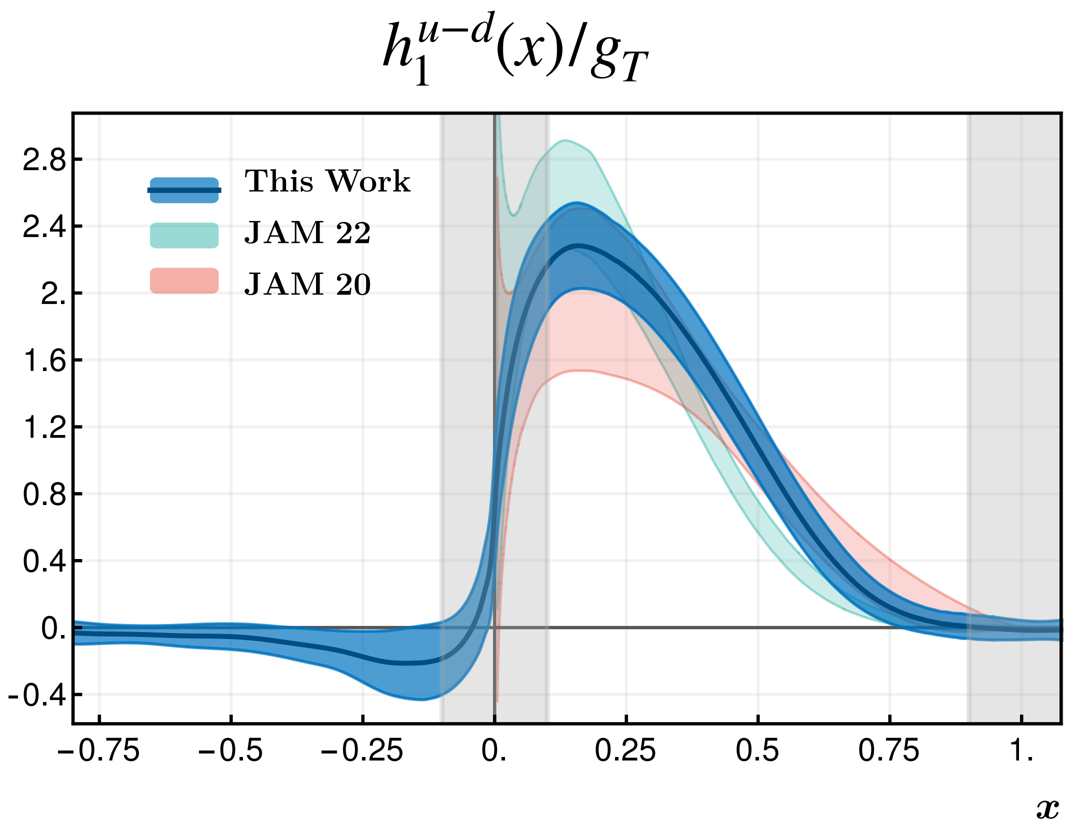
### Mellin moments from operator product expansion




X Gao et al., 2208.02297.

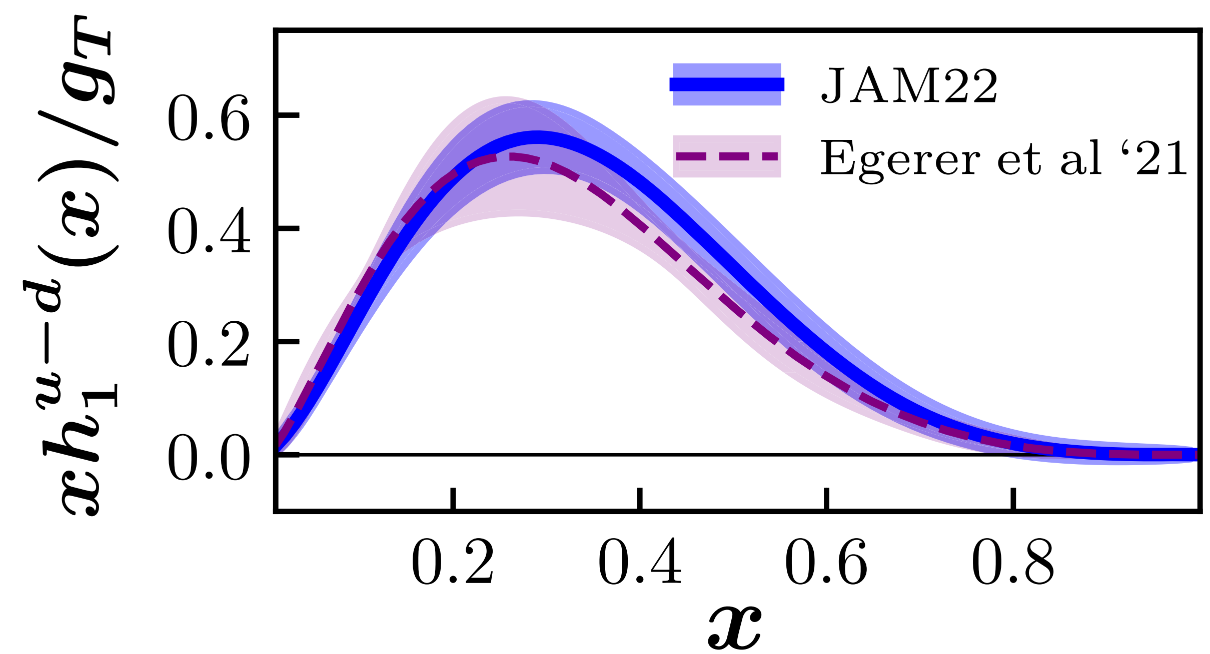
# Proton isovector quark transversity PDF

## LaMET expansion of quasi-PDF




F. Yao, L. Walter et al. (LPC), 2208.08008.

## Reconstruction from coordinate-space matrix elements (pseudo distribution)

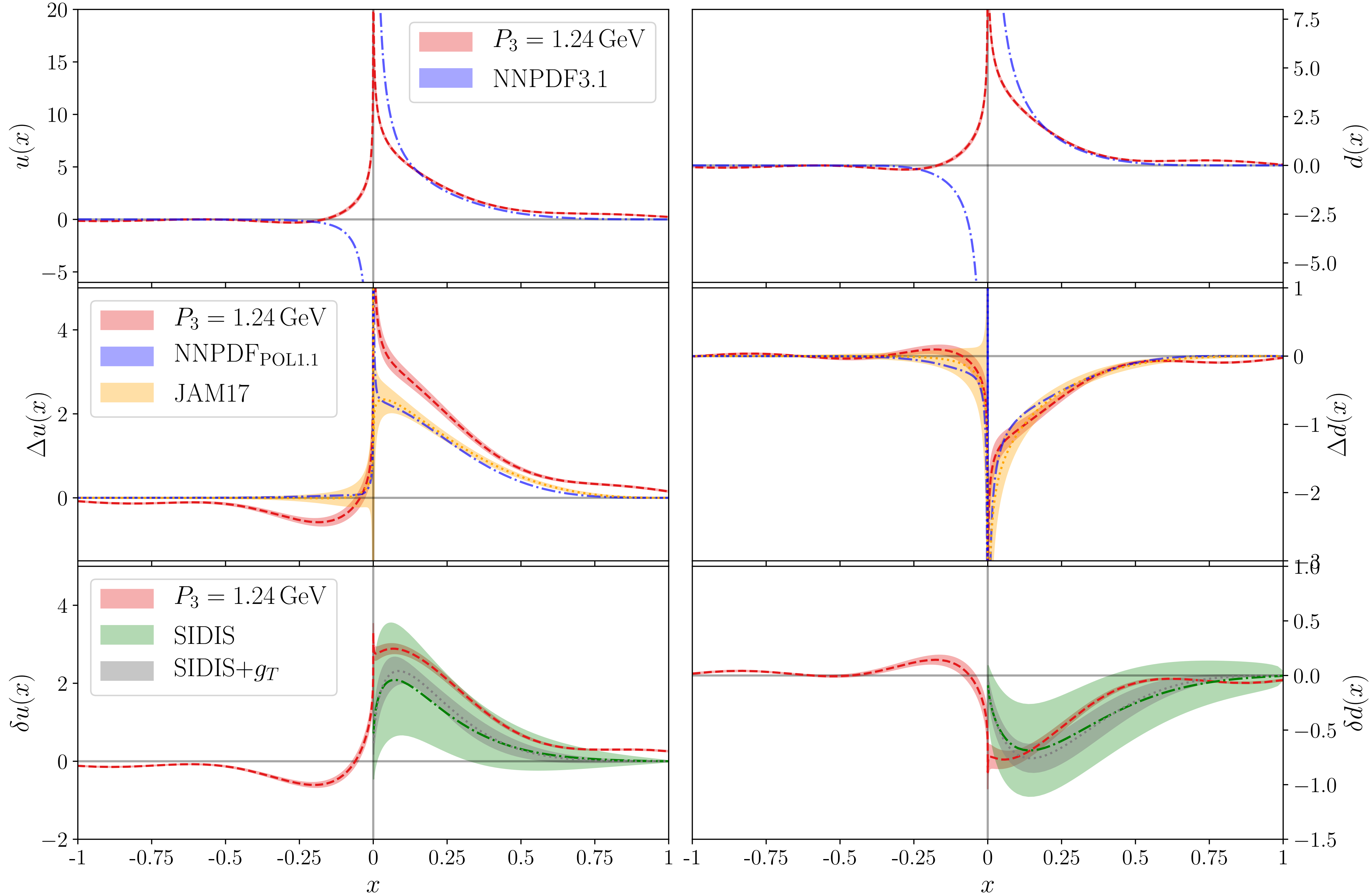



C. Egerer et al. (HadStruc), Phys.Rev.D **105**, 034507 (2022).

JAM22: global fit + lattice result of tensor charge $g_T$.

L. Gamberg et al. (JAM), Phys.Rev.D **106**, 034014 (2022).

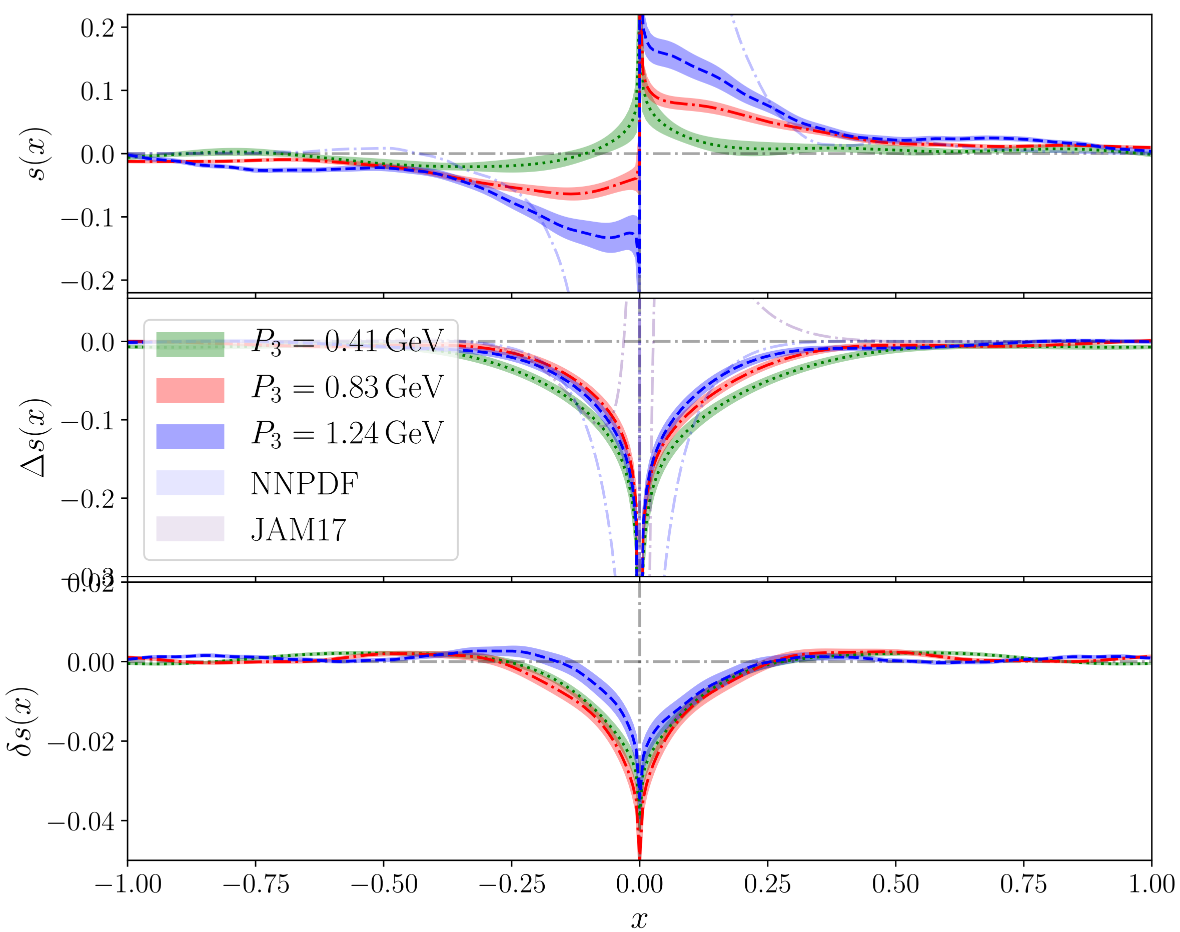
# Light-quark flavor separation




C. Alexandrou, M. Constantinou et al. (ETMC), Phys.Rev.D **104**, 054503 (2021)

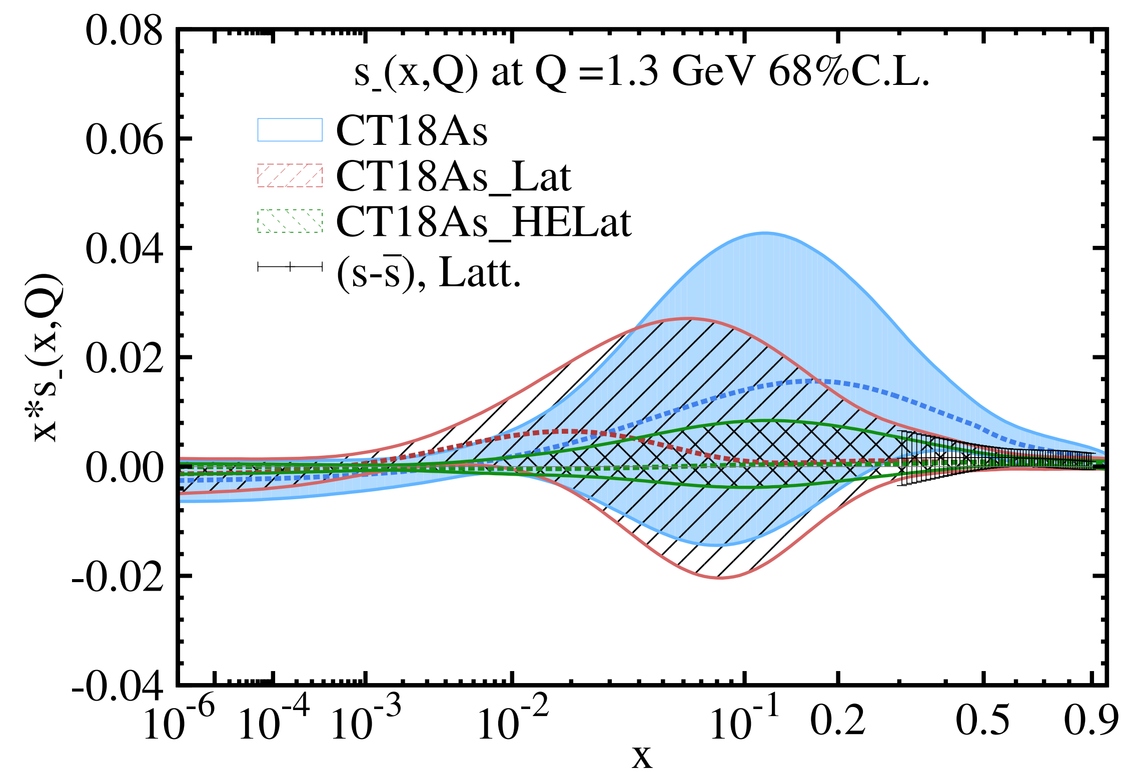
# Strange quark PDF

## Lattice QCD calculation




C. Alexandrou, M. Constantinou et al. (ETMC), Phys.Rev.D **104**, 054503 (2021)

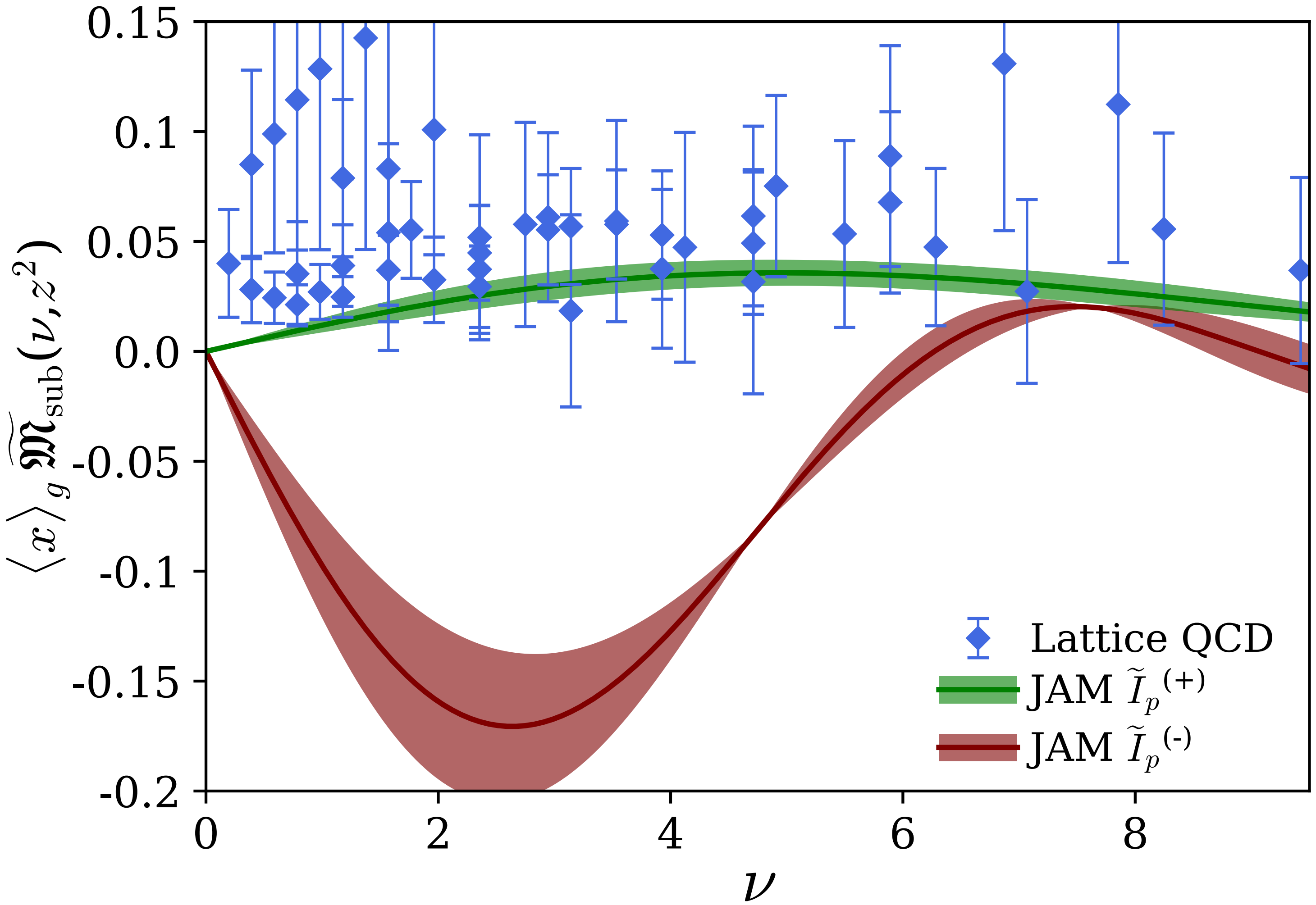
## Including lattice data in global analysis




- T.-J. Hou, H.-W. Lin et al., 2204.07944;
- R. Zhang, H.-W. Lin and B. Yoon, Phys.Rev.D **104**, 094511 (2021)

# Constraining gluon helicity PDF using lattice data

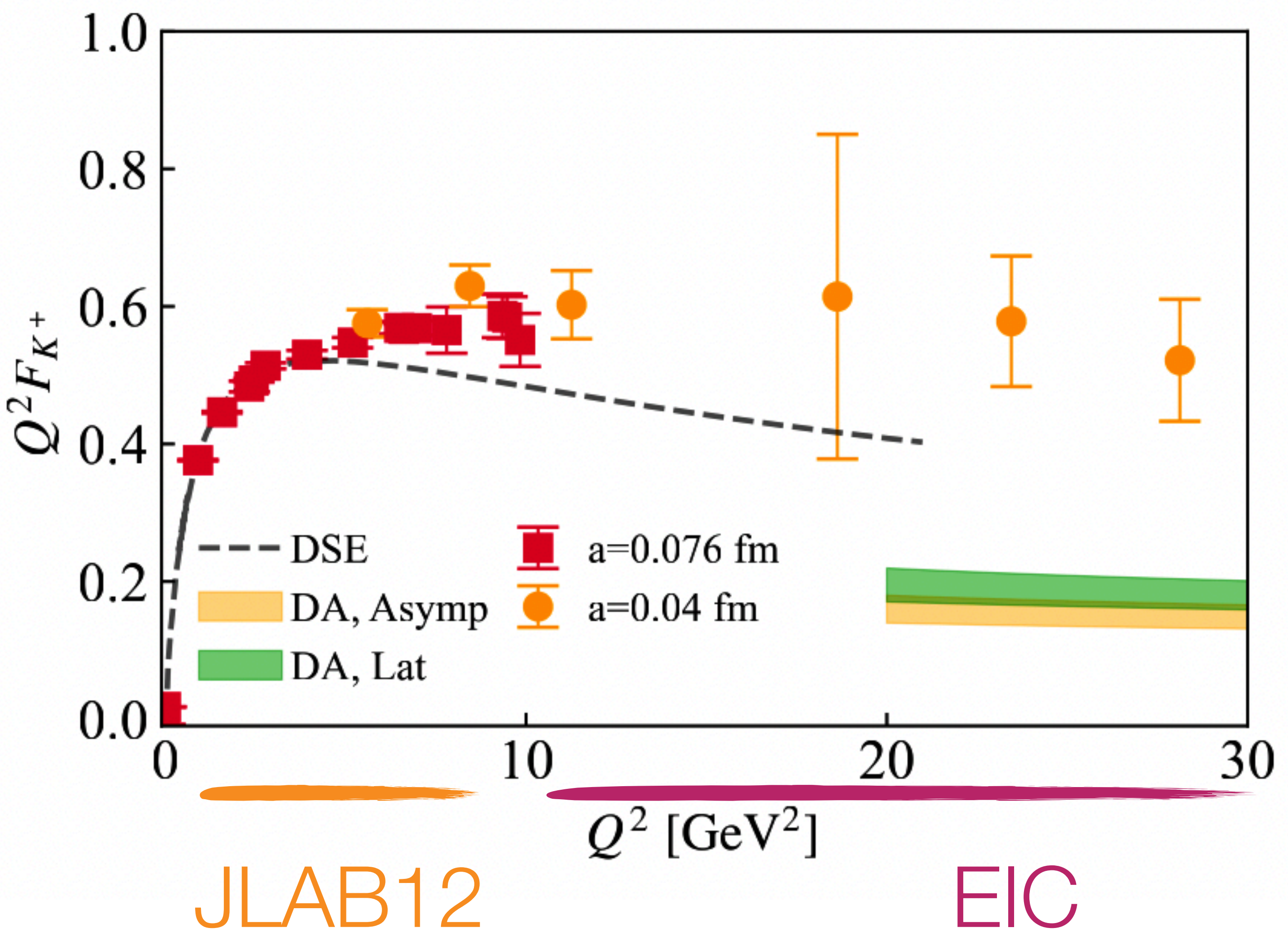
Lattice matrix elements of the reduced gluon pseudo Ioffe-time distribution




R. Sufian et al. (HadStruc), 2207.08733.

# Pion and kaon electromagnetic form factors

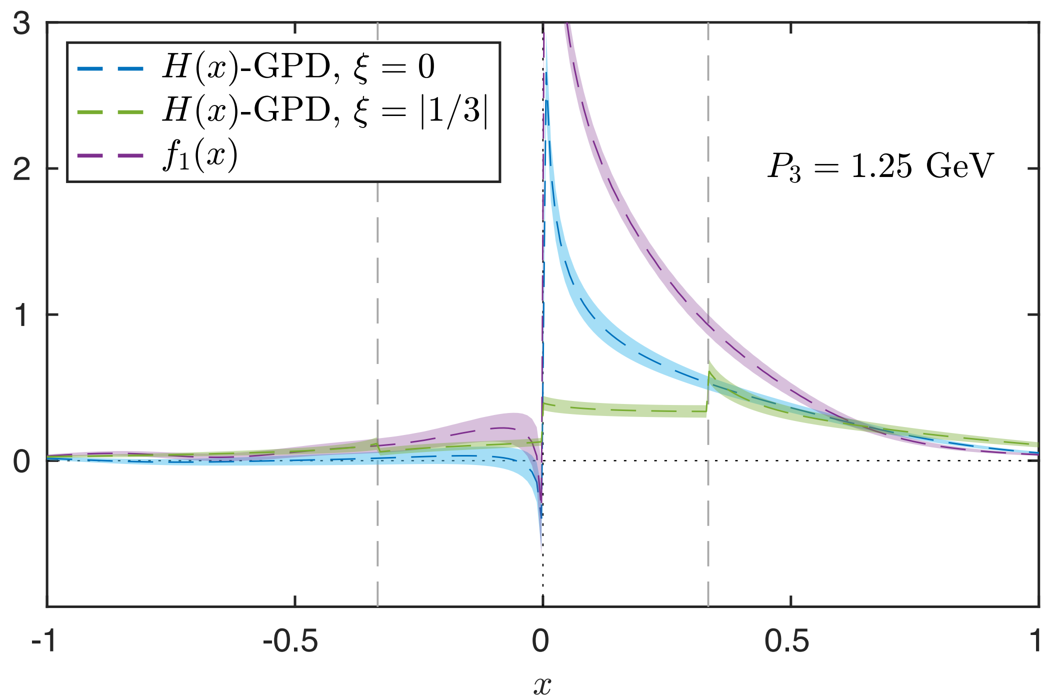
Kaon form factor at large momentum transfer




X. Gao, et al, in preparation.

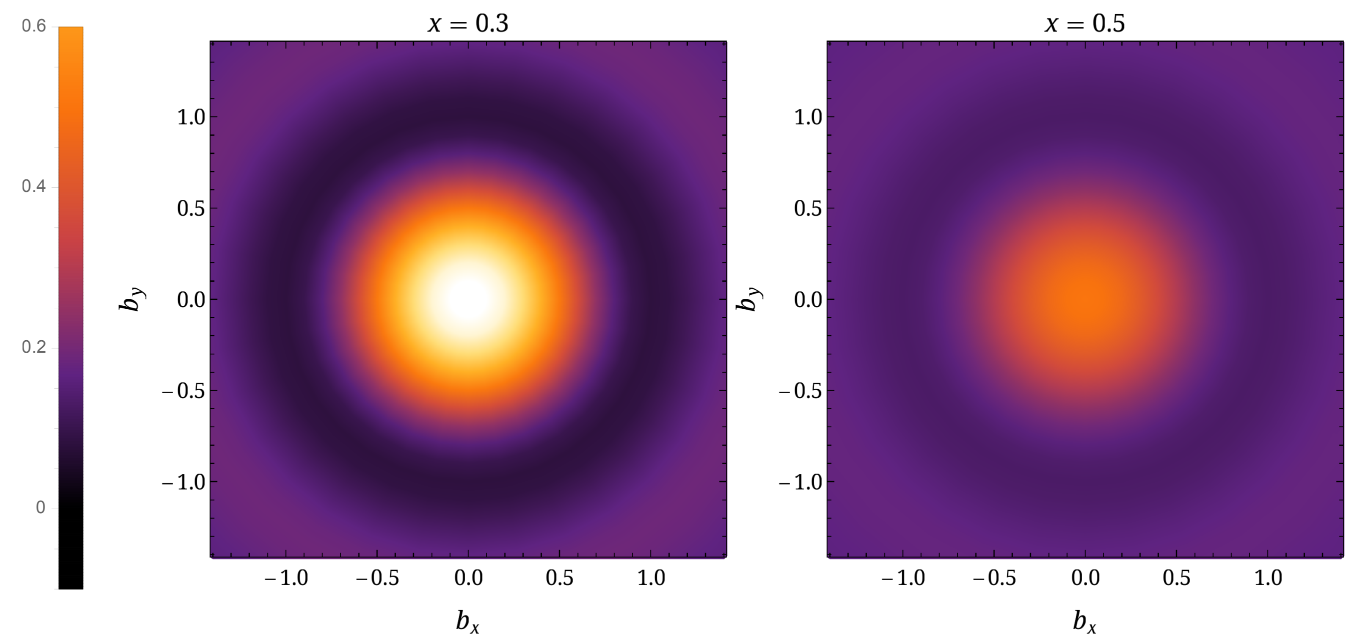
# Proton isovector GPDs

## *x*-dependence of GPD




C. Alexandrou, M. Constantinou et al. (ETMC), Phys.Rev.Lett. **125** (2020).

## Proton imaging in impact parameter space



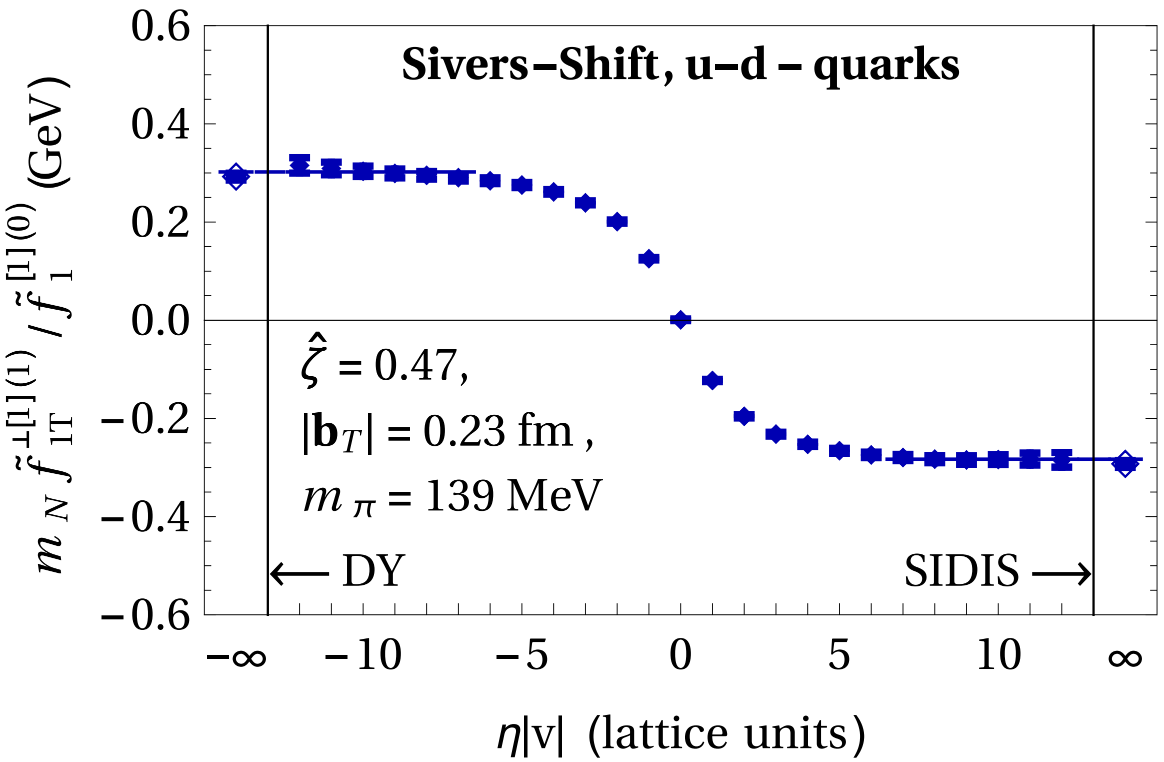

H.-W. Lin, Phys.Rev.Lett. **127** (2021).

**Lattice calculation will greatly help solve the inverse problem of extracting the *x*-dependence of GPDs from experiments**

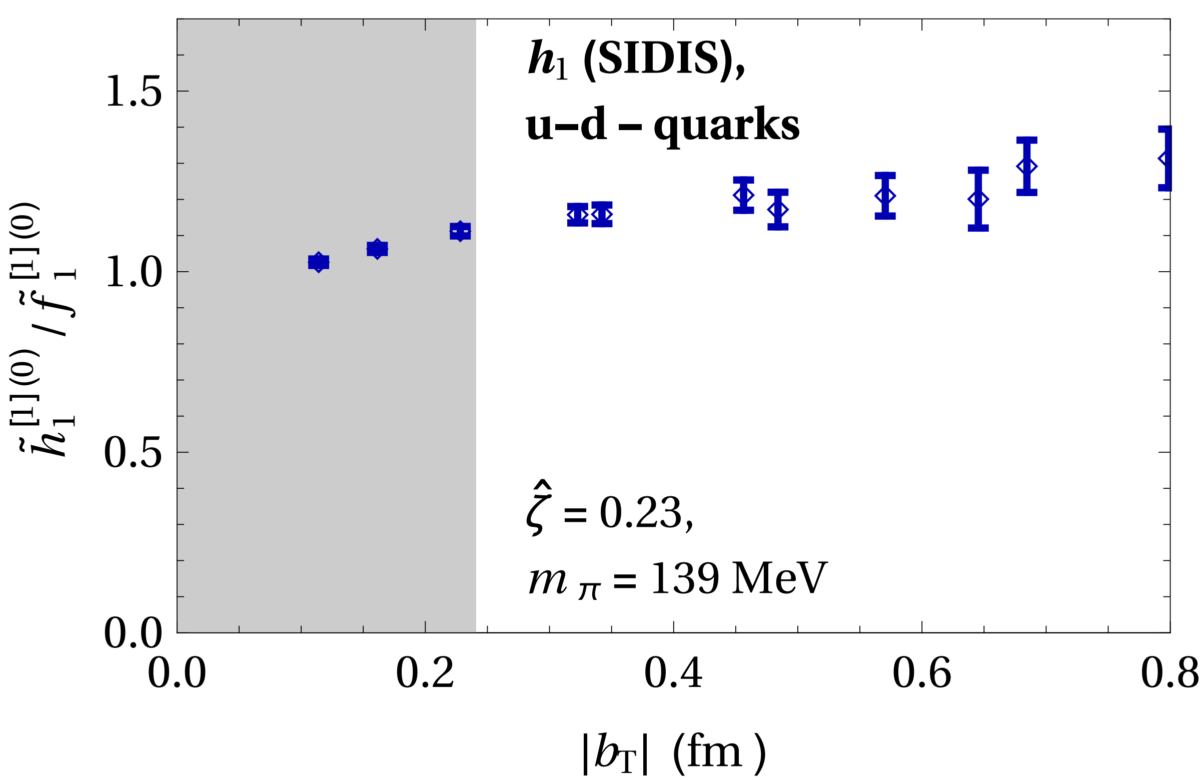
# Ratio of the *x*-moments of TMDs

$$\frac{\int dx\, f_{i/p}^{[s]}(x, \mathbf{b}_T)}{\int dx\, f_{j/p}^{[s']}(x, \mathbf{b}_T)}$$

## Sign change of T-odd TMDs




## Ratio of transversity and unpolarized TMD *x*-moments

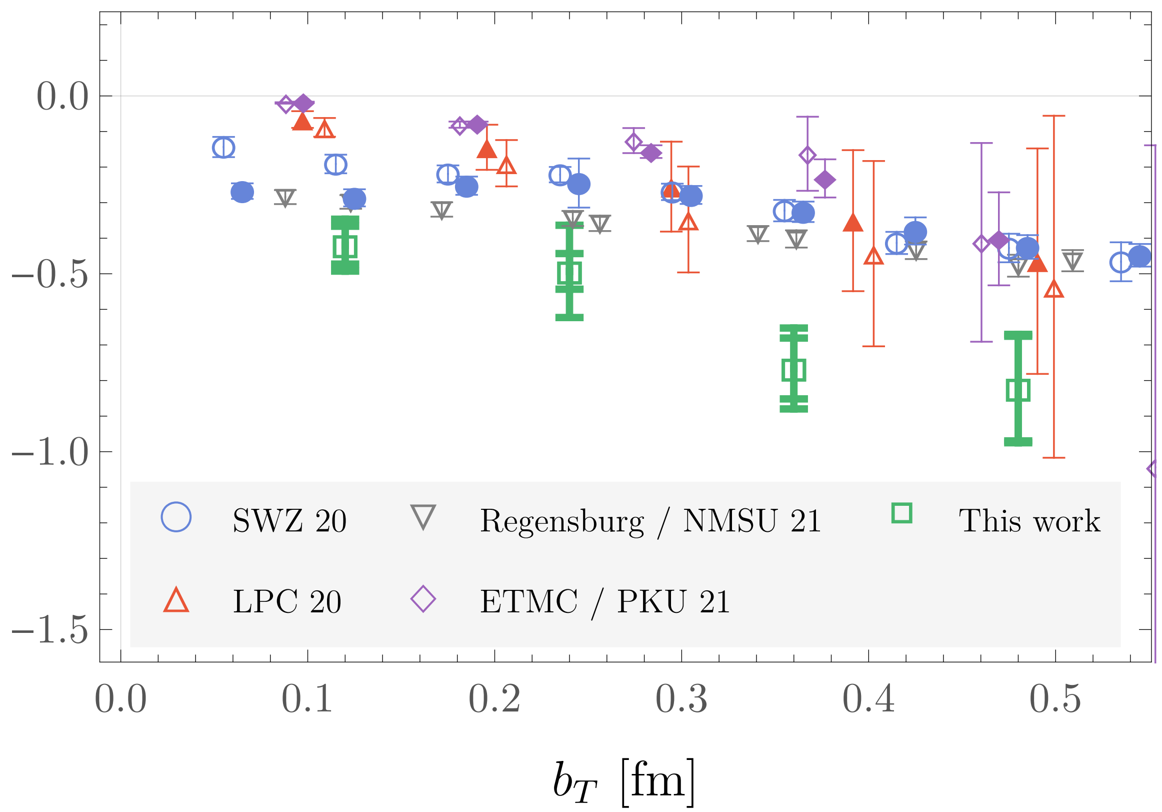



M. Engelhardt et al., in preparation.

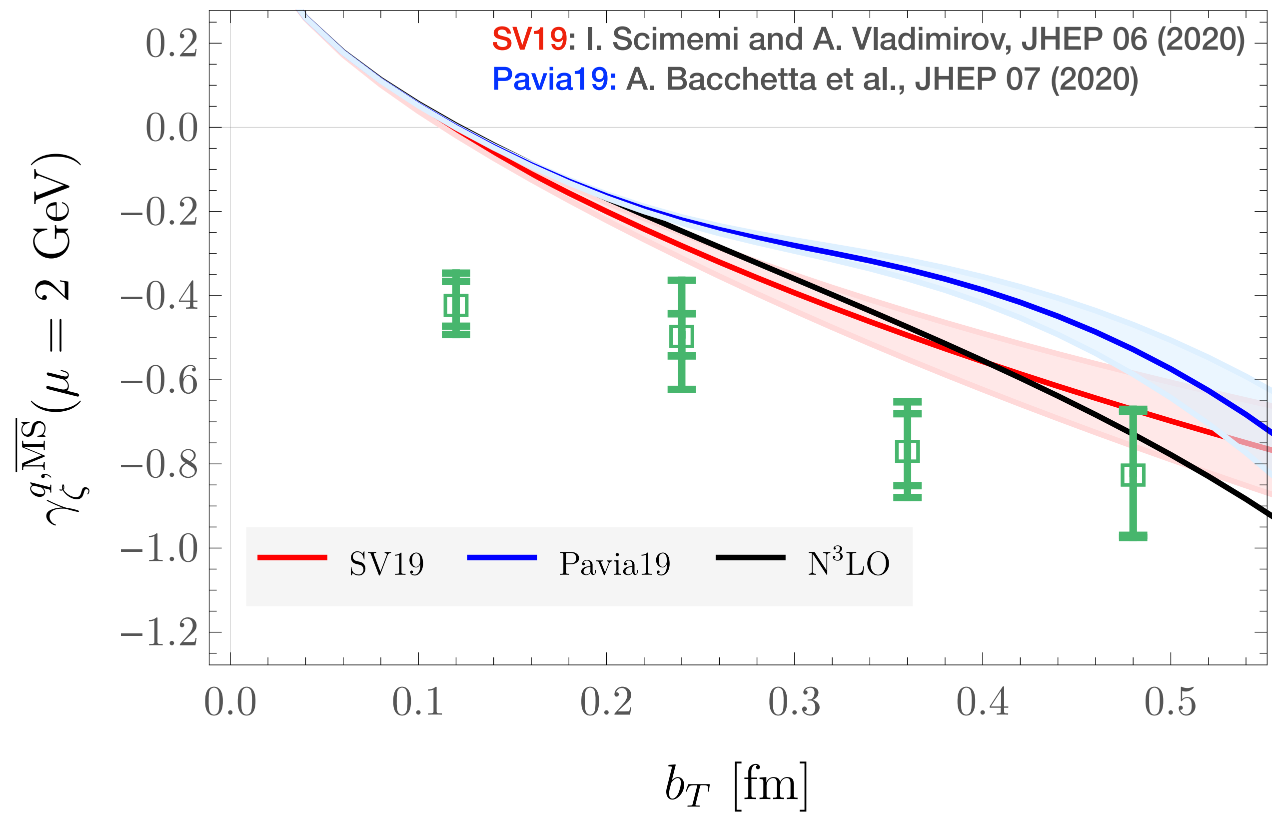
# Collins-Soper kernel for TMD evolution

M. Ebert, I. Stewart, Y. Zhao, PRD99 (2019).

## Results from different lattice groups




## Comparison with phenomenology

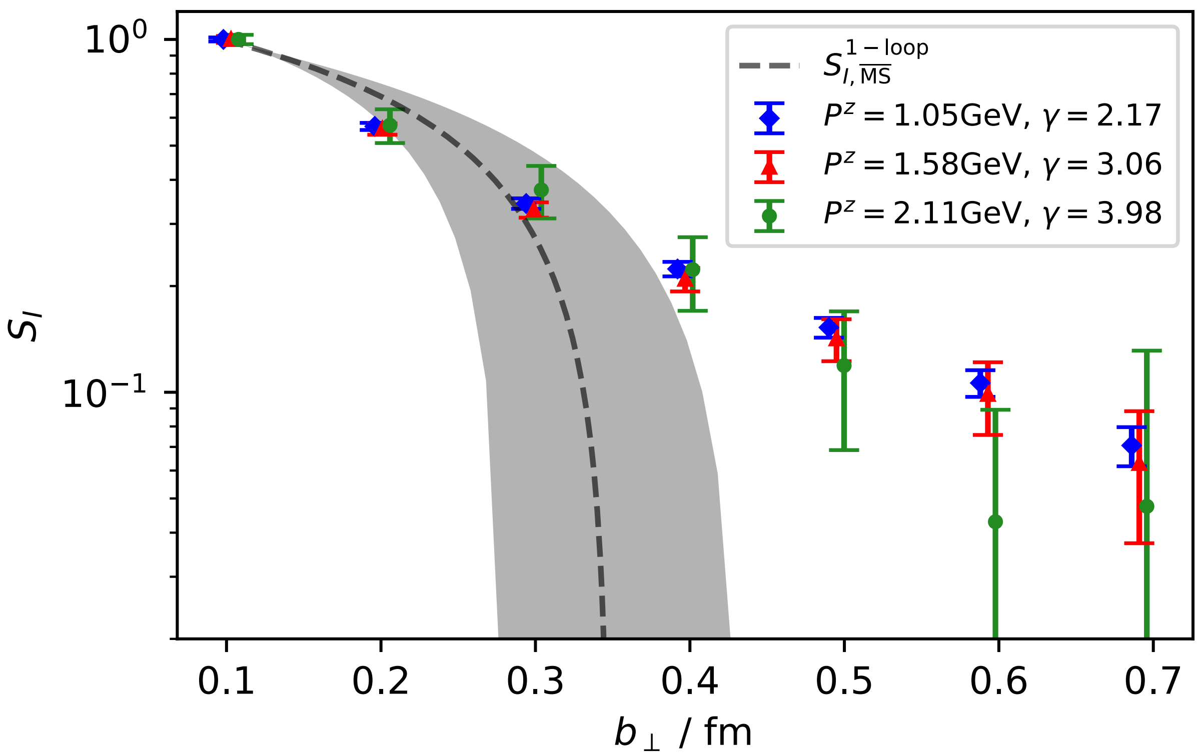



P. Shanahan, M. Wagman and Y. Zhao, PRD **104** (2021).

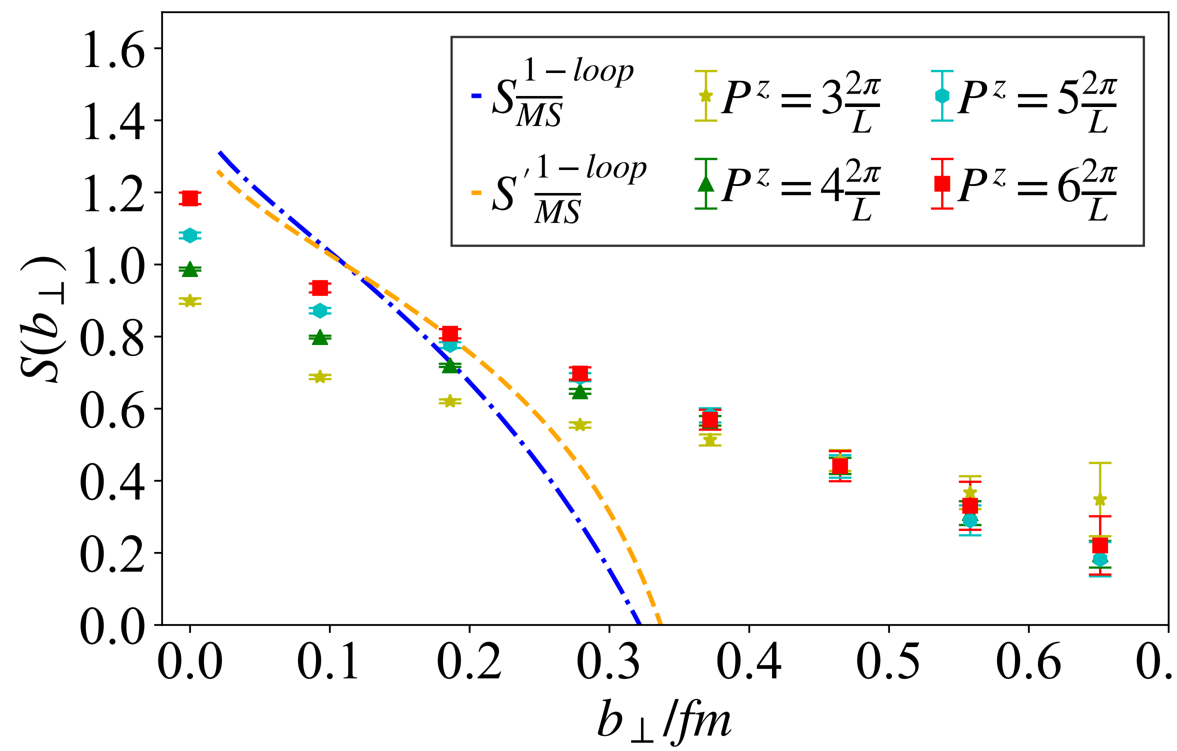
# Soft factor for full TMD calculation

- Ji, Liu and Liu, NPB 955 (2020), PLB 811 (2020);
- Ji and Liu, PRD 105, 076014 (2022).

## Exploratory calculation at leading order in $\alpha_s$



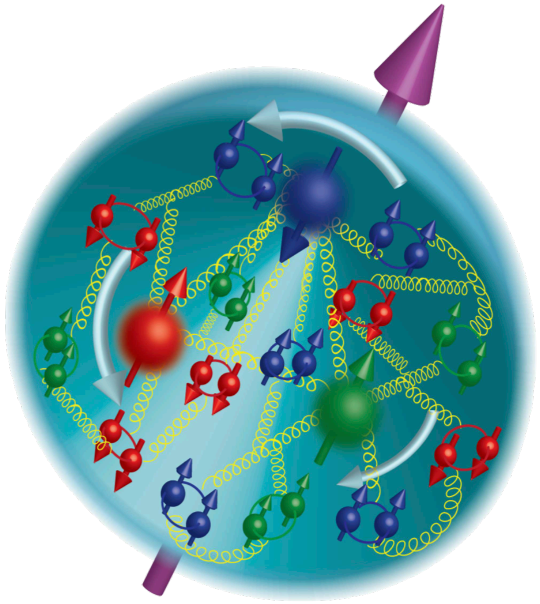

Q.-A. Zhang, et al. (LPC), Phys.Rev.Lett. **125** (2020).




Y. Li et al. (ETMC/PKU), Phys.Rev.Lett. **128** (2022).

3D tomography of the nucleon

Origin of nucleon spin

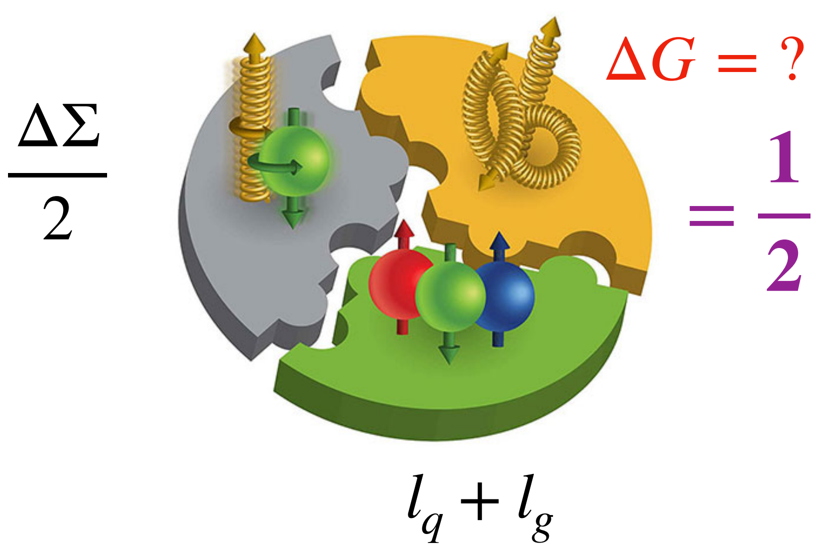


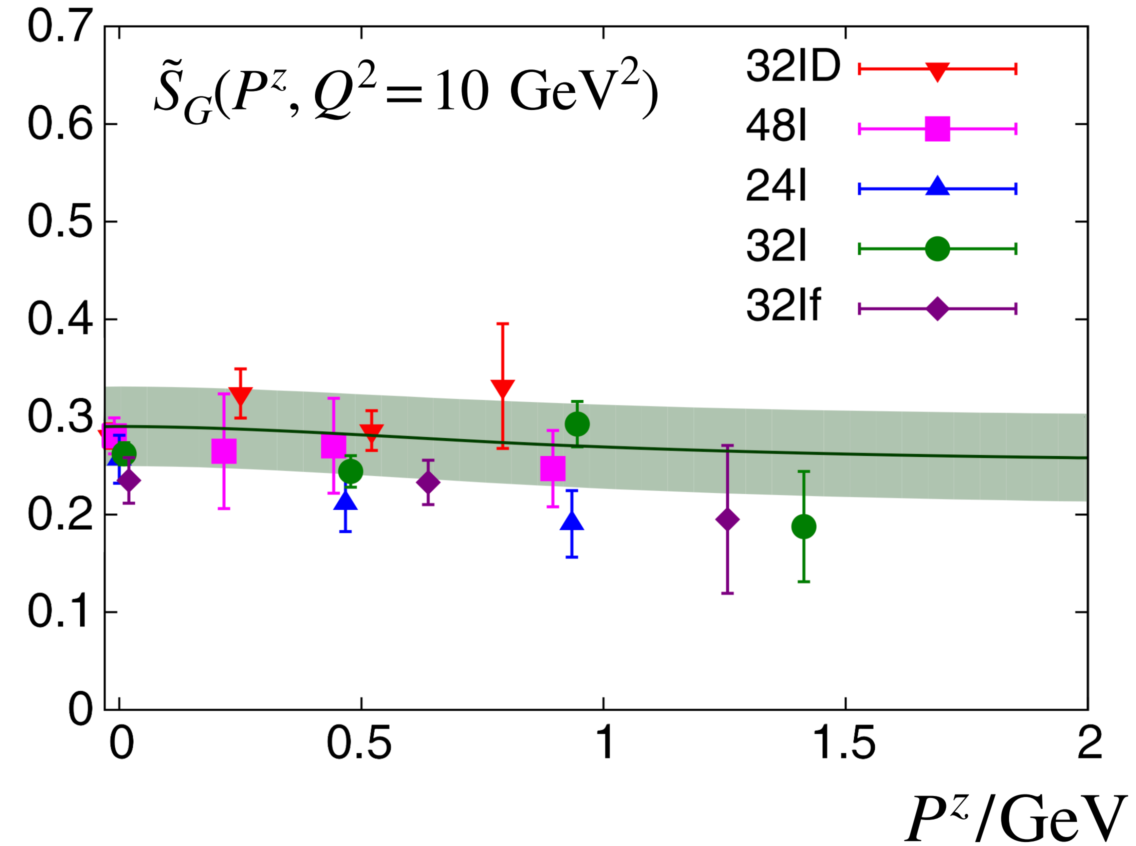
Origin of nucleon mass

Structure of nuclei

# The gluon helicity $\Delta G$

## Jaffe-Manohar sum rule

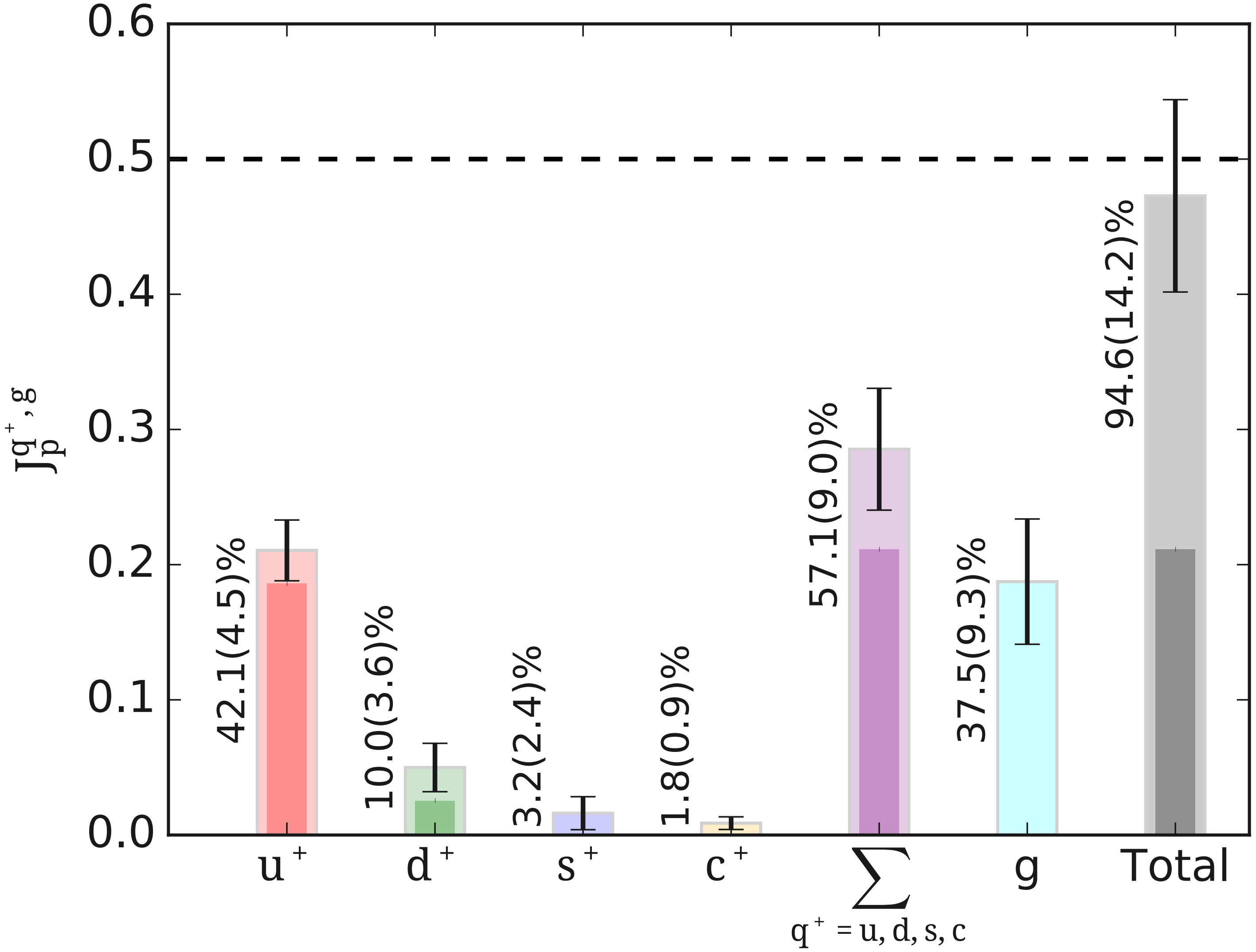



Y.-B. Yang, R. Sufian, Y. Zhao, et al. Phys. Rev. Lett. **118** (2017)

# Complete flavor decomposition of the proton spin

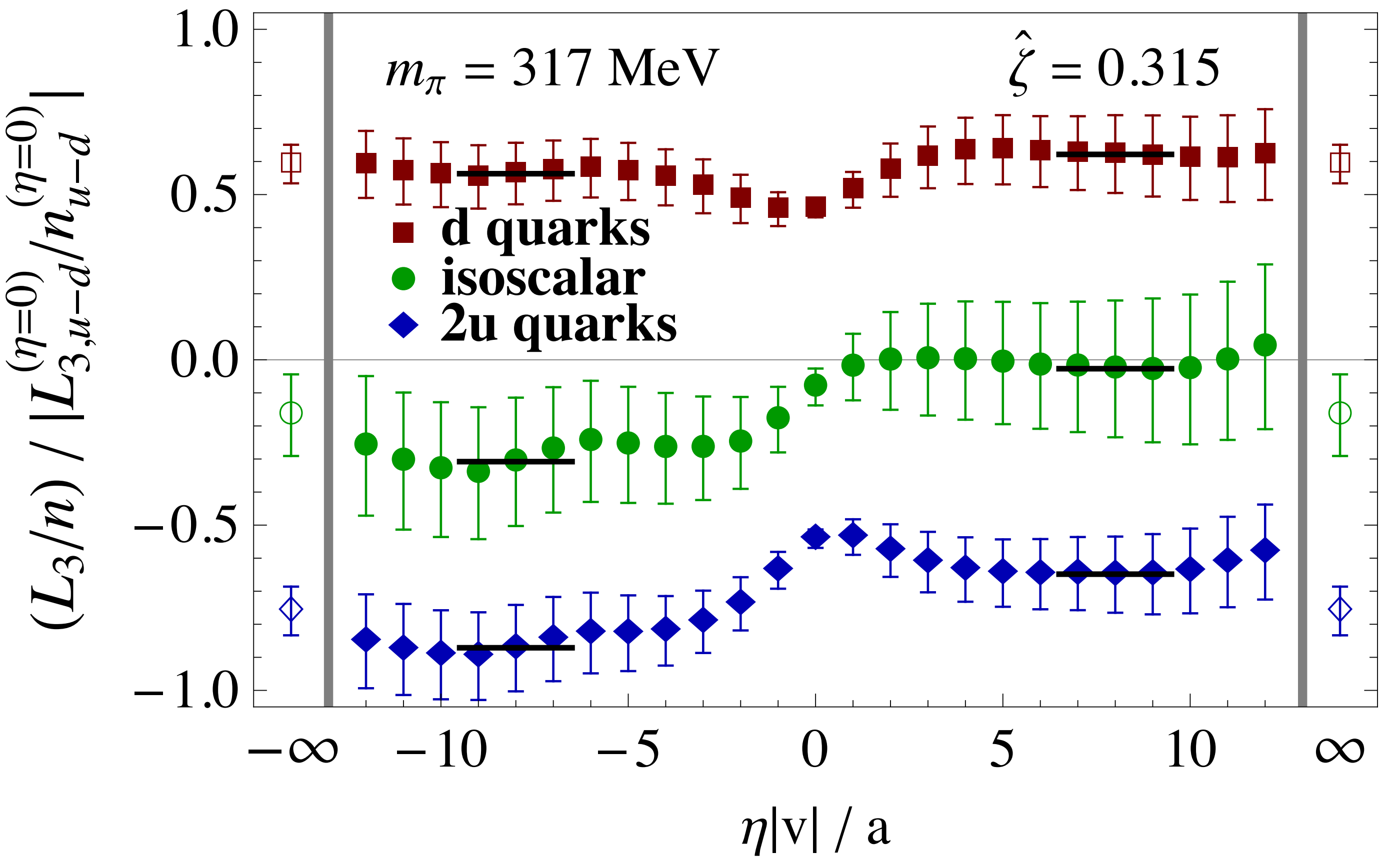
**Ji sum rule:** $$\frac{1}{2} = \frac{1}{2}\left[\sum_{q=u,d,s,\ldots} J_q + J_g\right]$$




C. Alexandrou et al. (ETMC), Phys.Rev.Lett. **125** (2020).

# Quark orbital angular momentum

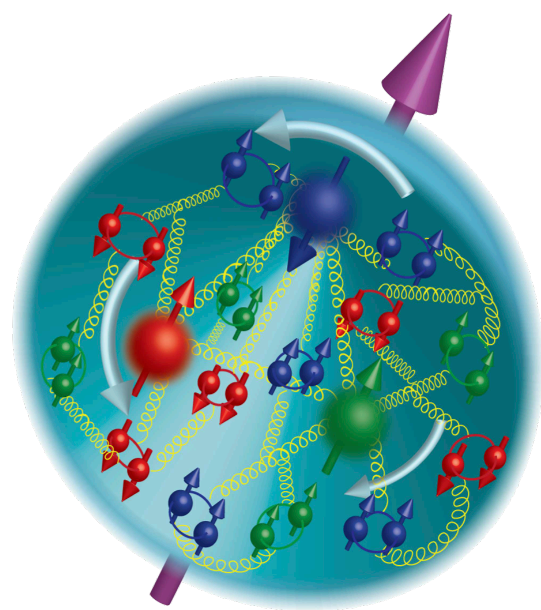
Jaffe-Manohar orbital angular momentum normalized by Ji orbital angular momentum




M. Engelhardt, et al., Phys.Rev.D **102**, 074505 (2020).

3D tomography of the nucleon

Origin of nucleon spin



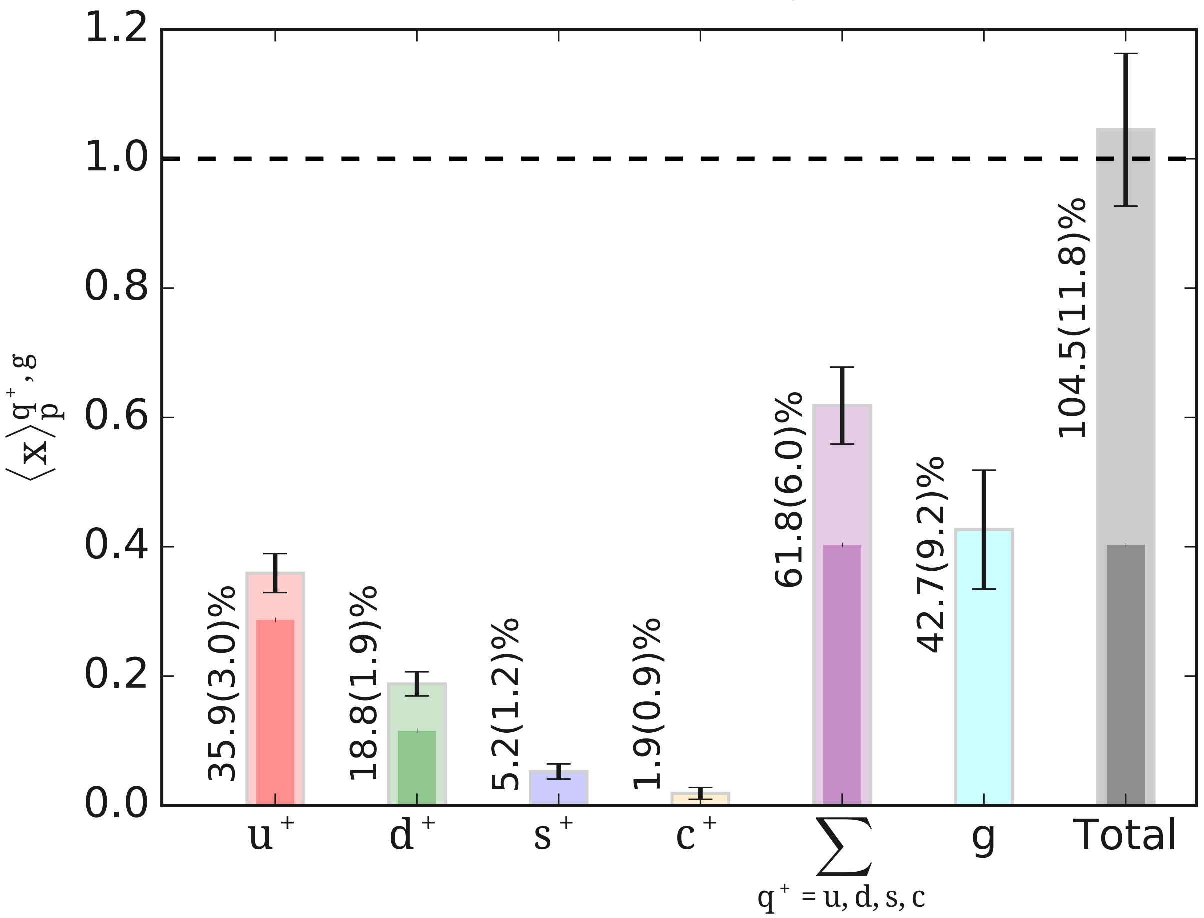
Origin of nucleon mass

Structure of nuclei

# Origin of the proton mass

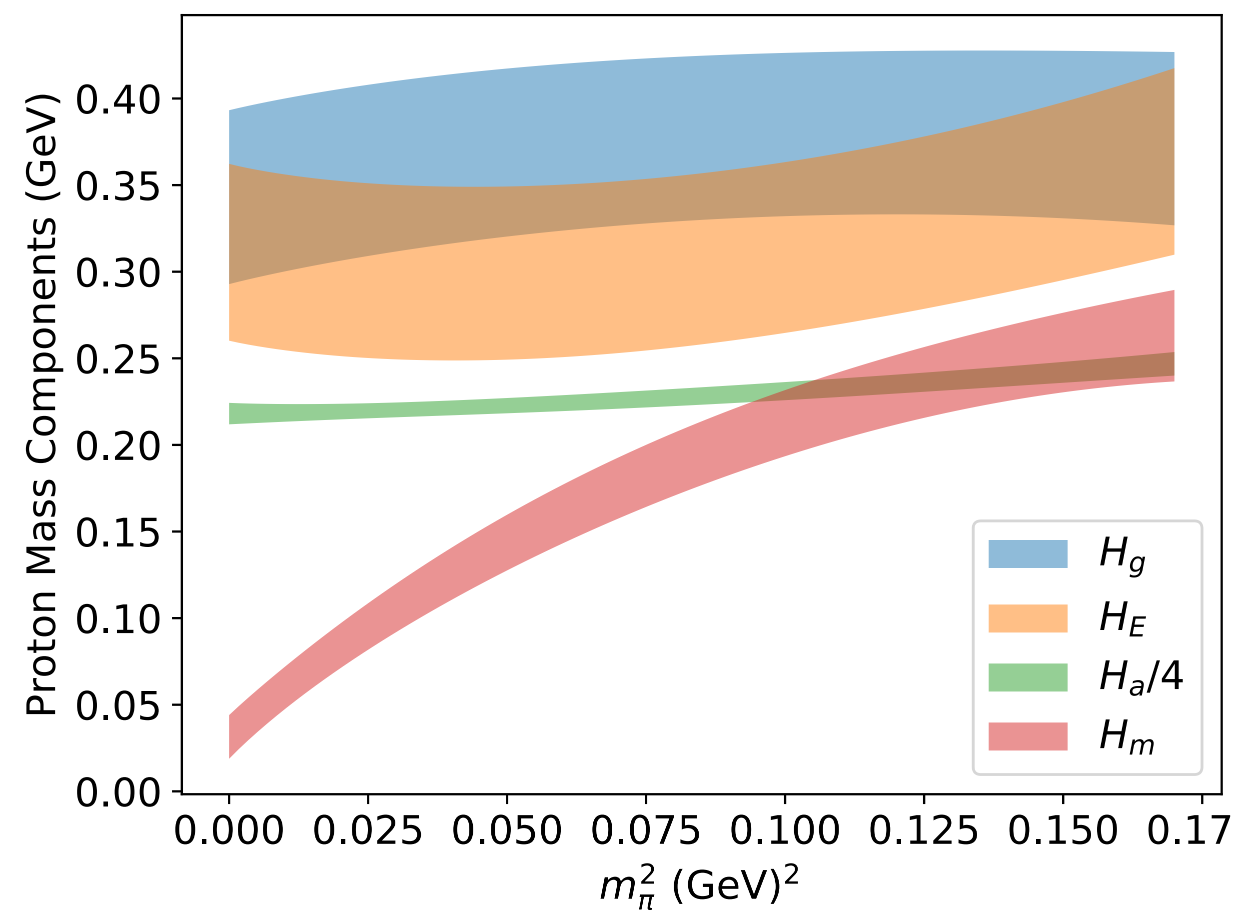
$$M = \langle H_m \rangle + \langle H_E \rangle + \langle H_g \rangle + \frac{1}{4}\langle H_a \rangle$$

## Quark and gluon momentum fractions ($H_E$ and $H_g$)




C. Alexandrou et al. (ETMC), Phys.Rev.Lett. **125** (2020).

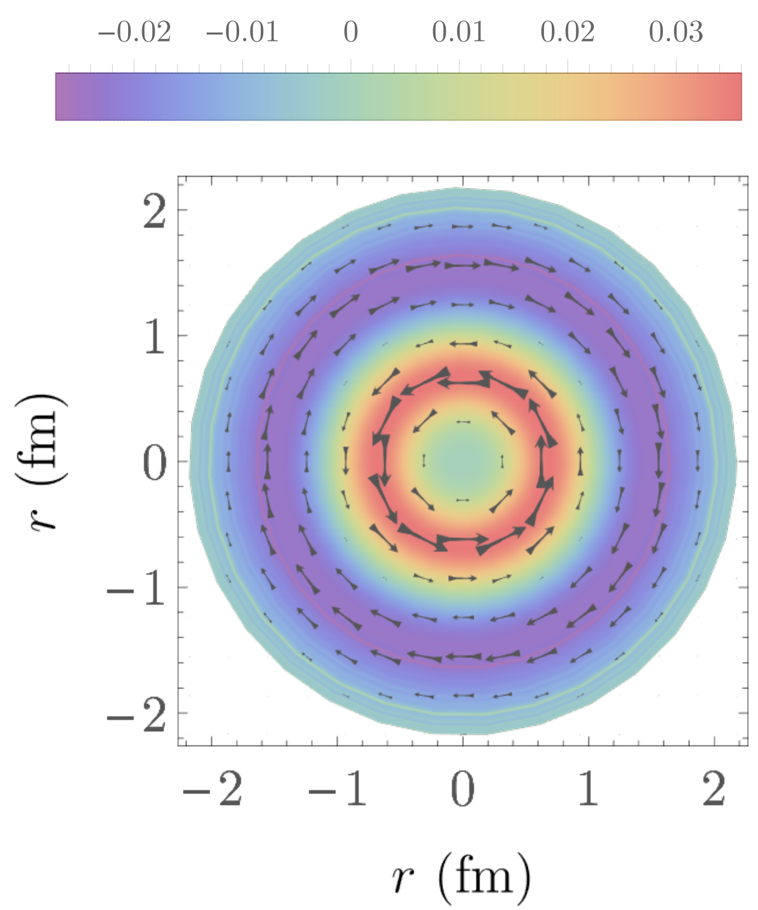
## Complete proton mass decomposition



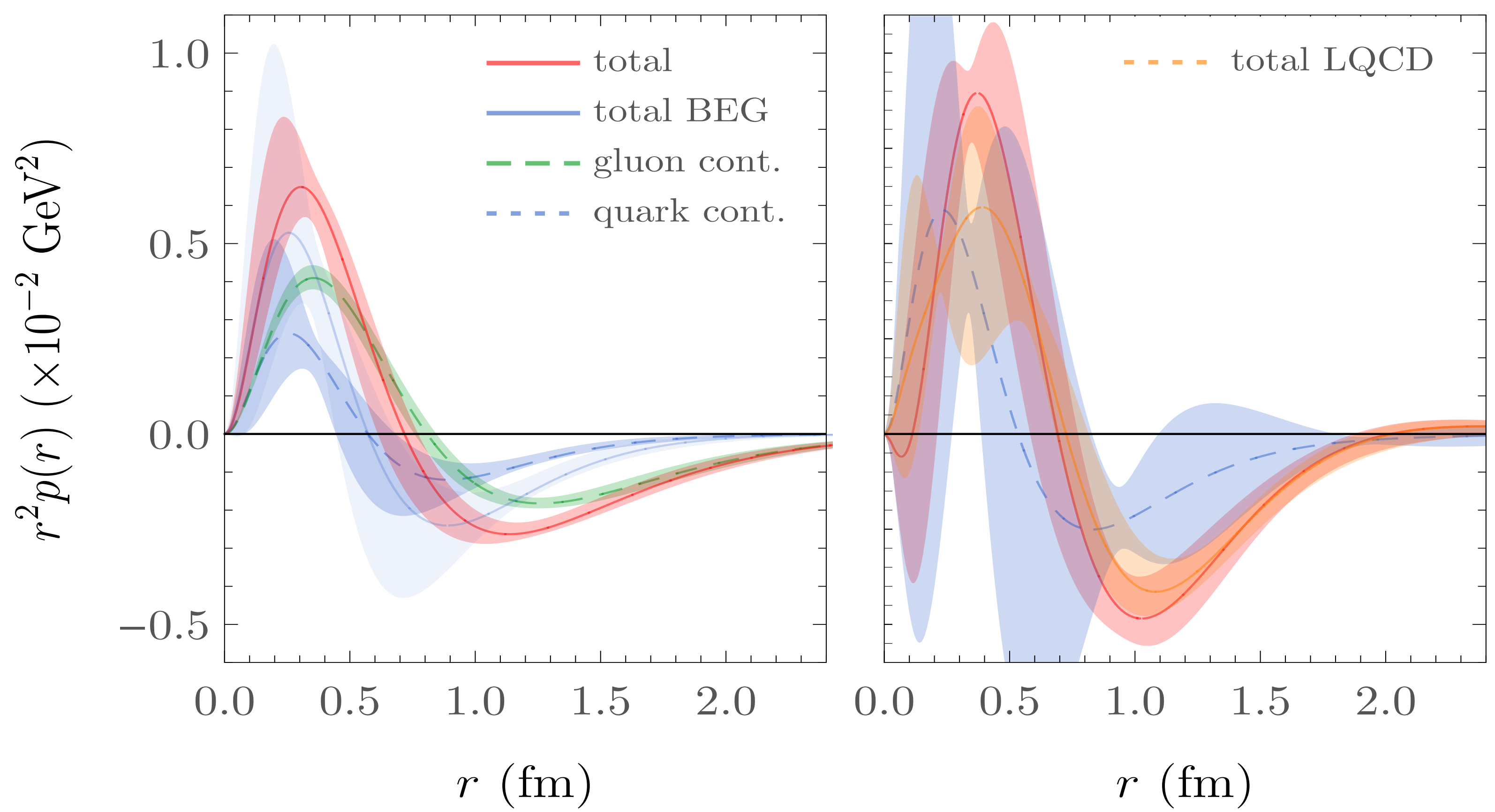

Y.-B. Yang, J. Liang, et al. (χQCD), Phys.Rev.Lett. **121**, 212001 (2018).

# Pressure distribution and shear forces inside the proton

## Tangential forces



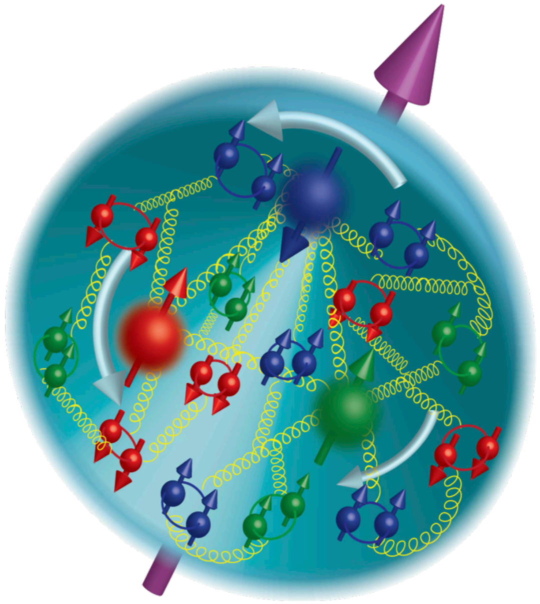

## Pressure distributions




W. Detmold and P. Shanahan, Phys.Rev.Lett. **122**, 072003 (2019).

3D tomography of the nucleon

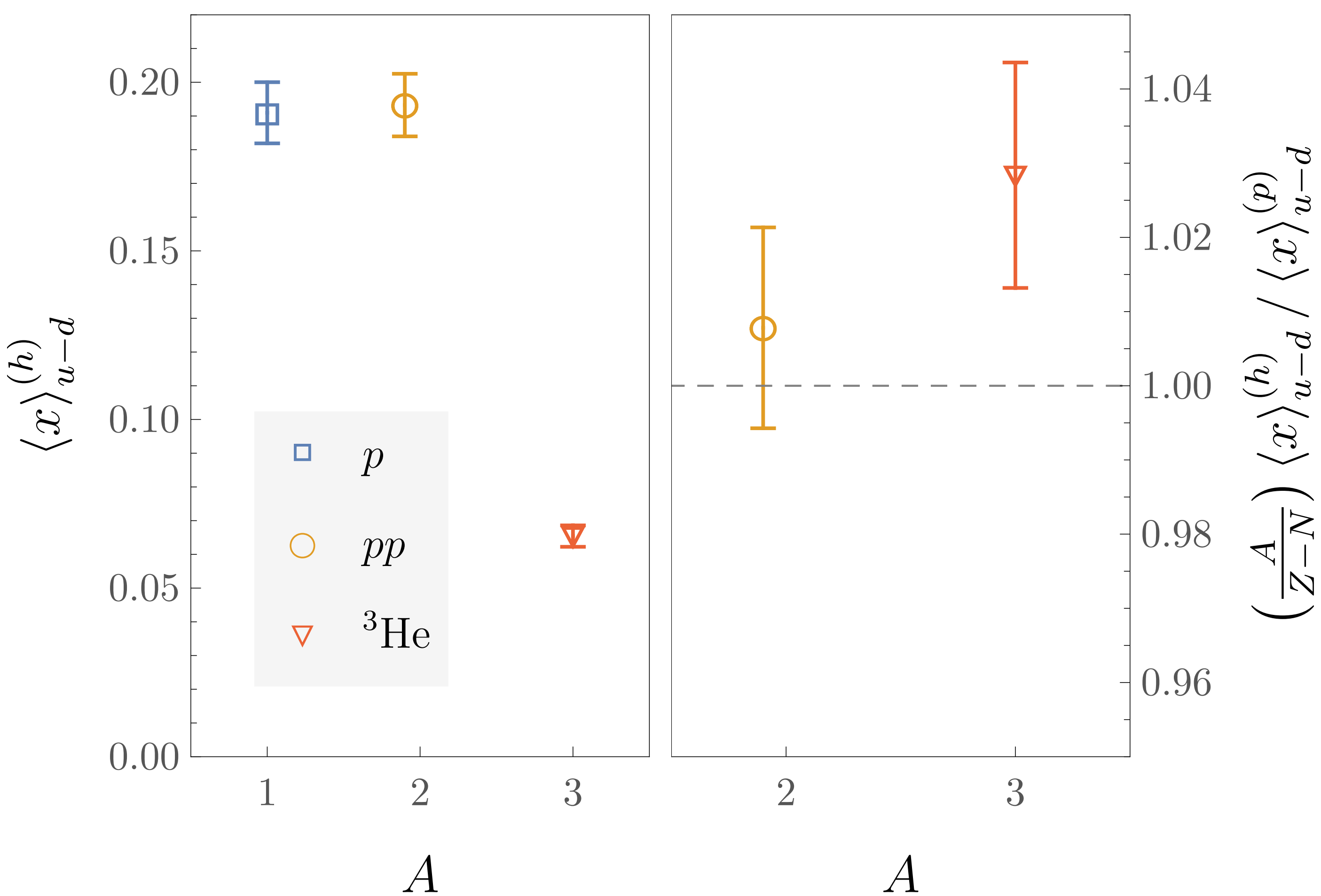
Origin of nucleon spin



Origin of nucleon mass

Structure of nuclei

# Quark momentum fraction of light nuclei




W. Detmold et al. (NPLQCD), Phys.Rev.Lett. **126**, 202001 (2021).

**All the tremendous progress would not have happened without the SciDAC program, USQCD and NERSC resources, as well as the INCITE and ALCC programs!**

## Challenges:

1) Simulating partons requires large hadron momentum, which can only be realized with smaller lattice spacings;

2) Significant noise in simulating gluonic and flavor separated observables;

3) Spin-dependent observables may be sensitive to pion mass, thus requiring more expensive calculations at physical pion mass;

4) 3D (and 5D) distributions demand much more computing time and storage;

**Cannot be solved by a single group. Needs continuous computing allocation and talent recruitment to achieve precision control for advancing JLab and EIC physics.**

# Theory for EIC in the next decade

# CFNS Workshop, MIT, Sep. 20—22, 2022

**Organizers:** Peter Petreczky (BNL), Ian Cloët (ANL), Dmitri Kharzeev (Stony Brook University/BNL), Xiangdong Ji (University of Maryland), Jianwei Qiu (JLab), Phiala Shanahan (MIT), Iain Stewart (MIT), Ivan Vitev (LANL), Feng Yuan (LBNL)

**Resolution:**

"We recommend the establishment of a national EIC theory alliance to enhance and broaden the theory community needed to advance EIC physics goals and the experimental program. This theory alliance will develop a diverse workforce through a competitive national EIC theory fellow program and tenure-track bridge positions, including appointments at minority serving institutions."

# Computational Nuclear Physics and AI/ML Workshop


- Organized by:
  - Alessandro Lovato (ANL)
  - Joe Carlson (LANL)
  - Phiala Shanahan (MIT)
  - Bronson Messer (ORNL)
  - Witold Nazarewicz (FRIB/MSU)
  - Amber Boehnlein (JLab)
  - Peter Petreczky (BNL)
  - Robert Edwards (JLab)
  - David Dean (JLab)
- 6-7 September 2022 at SURA in Washington, DC
- 60 registered participants (40 in person, 20 on line), including DOE representation
- https://indico.jlab.org/event/581/
  - All talks archived
  - Short white paper being prepared for the LRP

# Workshop Resolution

High-performance computing is essential to advance nuclear physics on the experimental and theory frontiers. Increased investments in computational nuclear physics will facilitate discoveries and capitalize on previous progress. Thus, we recommend a targeted program to ensure the utilization of ever-evolving HPC hardware via software and algorithmic development, which includes taking advantage of novel capabilities offered by AI/ML.

The key elements of this program are to:

1) Strengthen and expand programs and partnerships to support immediate needs in HPC and AI/ML, and also to target development of emerging technologies, such as quantum computing, and other opportunities.

2) Take full advantage of exciting possibilities offered by new hardware and software and AI/ML within the nuclear physics community through educational and training activities.

3) Establish programs to support cutting-edge developments of a multi-disciplinary workforce and cross-disciplinary collaborations in high-performance computing and AI/ML.

4) Expand access to computational hardware through dedicated and high-performance computing resources.

**Existing resources include SciDAC-5 project for lattice QCD, USQCD, NERSC and XSEDE resources, INCITE and ALCC programs, etc.**