Software Infrastructure for Advanced Nuclear Physics Computing
Jefferson Lab, June 20, 2024

Global QCD analysis of quantum correlation functions

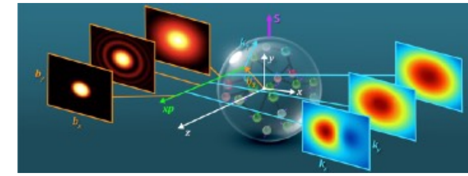
Wally Melnitchouk, Nobuo Sato

— JAM Collaboration —

http://www.jlab.org/jam

Research scope

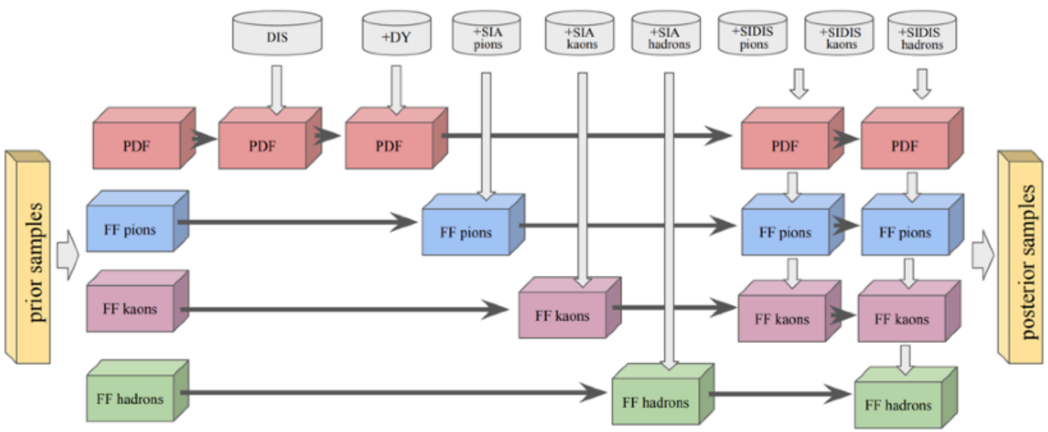
→ reconstruct quantum correlation functions (PDFs, FFs, TMDs, GPDs) from experiment to map out quark & gluon structure of hadrons & nuclei

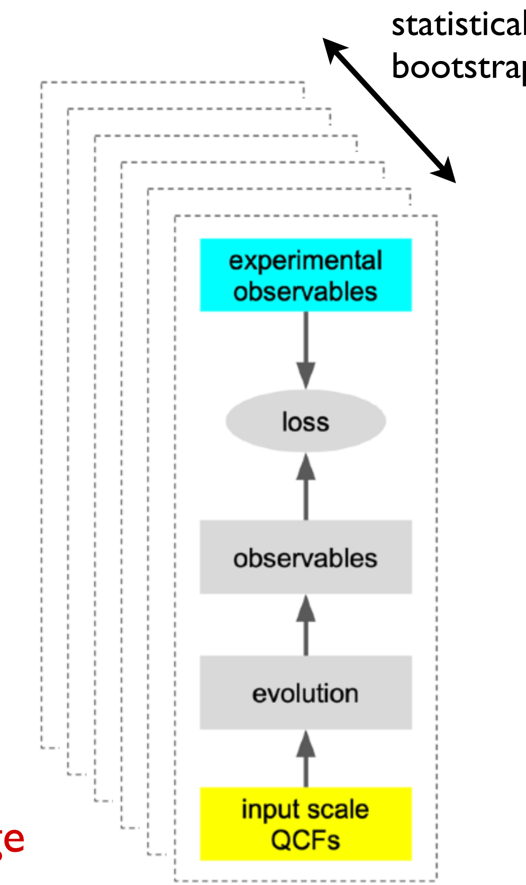


Computational challenge

→ inference task involving layers of inverse problems (factorization, evolution, …)

→ Bayesian MC approach — data resampling; multi-step strategy to scan parameter space (nested sampling for pions ✓ , not feasible for protons)





Tools

→ code base in Python+NumPy, CPU parallelization using ZeroMQ

Workforce

→ mostly theorists, some experimentalists

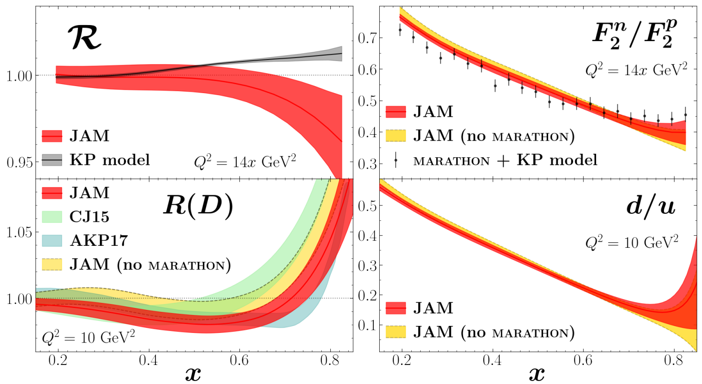
→ publish in high-impact journals, but reaching limit

→ need synergistic collaboration between NP and ASCR to meet challenge

Research scope

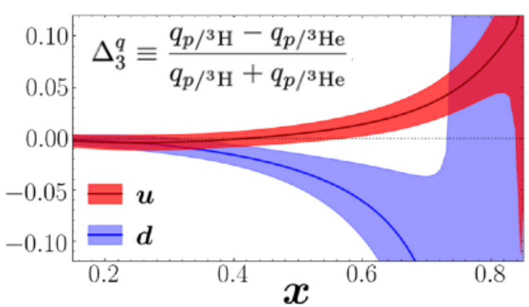
Isovector EMC effect

Global analysis including MARATHON DIS data on D/p, tritium/helium



→ first evidence for different medium modifications for u and d quarks

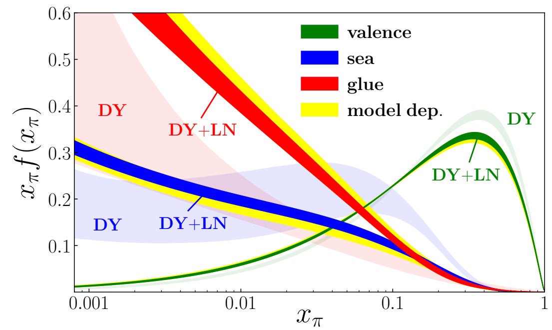
→ naive modeling of nuclear PDFs (e.g., $u/p/A = d/n/A$) violates isospin symmetry for isospin-asymmetric nuclei

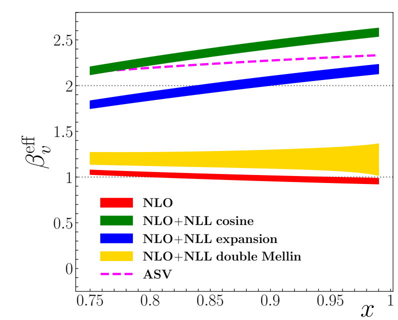


Cocuzza, Keppel, Liu, WM, Metz, Sato, Thomas
PRL **127**, *242001 (2021)*

Parton structure of the pion

Combine pQCD with chiral EFT to fit πN Drell-Yan + HERA neutron electroproduction

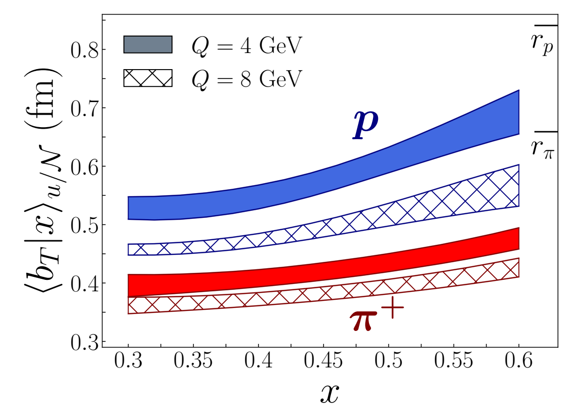




→ first constraints on glue & sea quark PDFs

→ including threshold resummation, effective large-x PDF exponent $\beta \sim 1$

→ transverse separation of quarks in pion ~ 20% smaller in π than in p



50 Years of QCD Frontiers of QCD research in *Physical Review*

To mark the 50th anniversary of this significant development in particle and nuclear physics, the editors of the *Physical Review* journals have curated a collection of landmark papers appearing in our journals. The papers trace key developments in QCD leading up to 1973, and some of the many discoveries since.

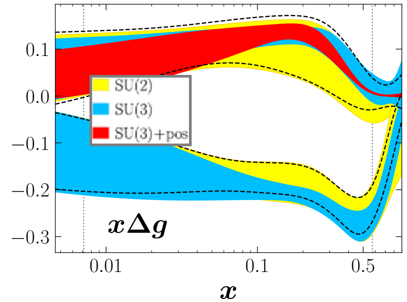
First Monte Carlo Global QCD Analysis of Pion Parton Distributions
P.C. Barry, N. Sato, W. Melnitchouk, and Chueng-Ryong Ji (Jefferson Lab Angular Momentum (JAM) Collaboration)
Phys. Rev. Lett. **121**, 152001 (2018)

Research scope

Gluon polarization

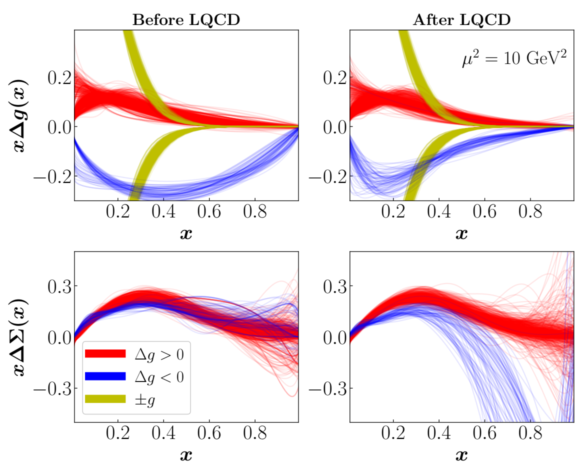
Jet data cannot rule out $\Delta g < 0$ without theoretical assumptions (*e.g.* PDF positivity)

Zhou, Sato, WM, PRD ***105****, 074022 (2022)*

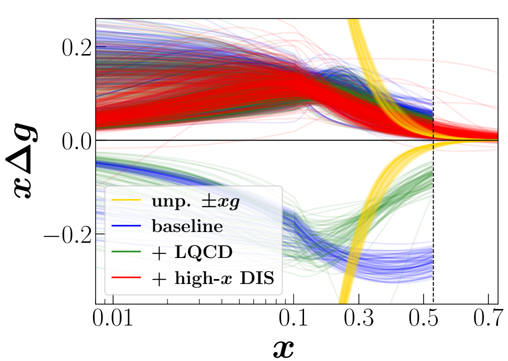


⟶ lattice QCD data [HadStruc] on pseudo Ioffe-time distributions sensitive to Δg

χ^2 alone cannot discriminate sign… but $\Delta g < 0$ leads to $\Delta\Sigma < 0$ at large x



⟶ including high-x JLab data and LQCD strongly disfavors negative $\Delta\Sigma$ at $x > 0.5$

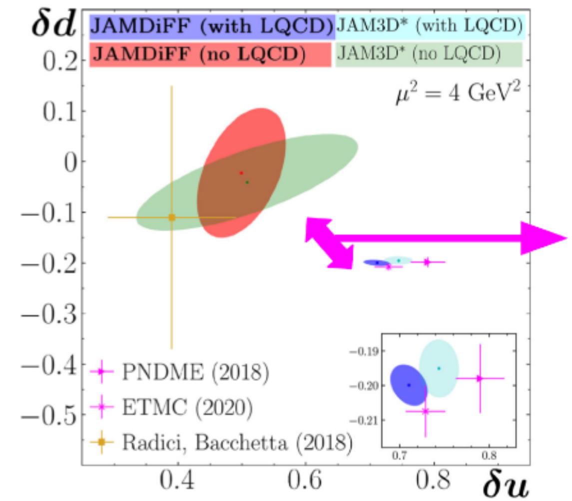


$\Delta g < 0$ ruled out only with inclusion of polarized jet, lattice, and high-x DIS data!

Hunt-Smith, Cocuzza, WM, Sato, Thomas, White arXiv:2403.08117

Tensor charge

Reconstruct transversity h_1 PDFs from SSAs (SIDIS, pp) & dihadron production (SIDIS, pp, e^+e^-)



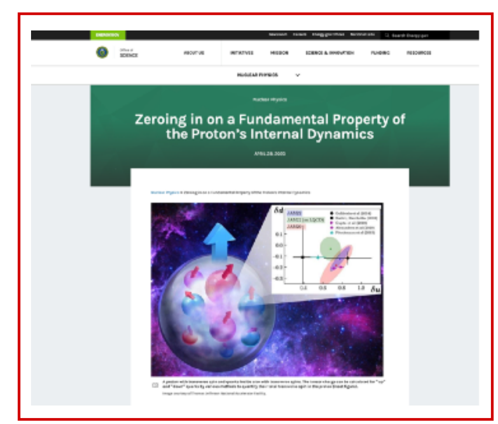
tension between LQCD & experiment removed by adjusting h_1 in (extrapolated) large-x region

Cocuzza et al. PRL ***132****, 091901 (2024)*

⟶ LQCD moments suggest large contributions at high x

⟶ high-x data needed to test compatibility

DOE Science Highlight
4/2023

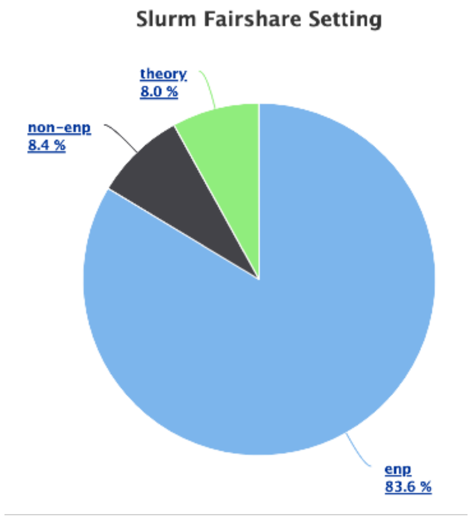


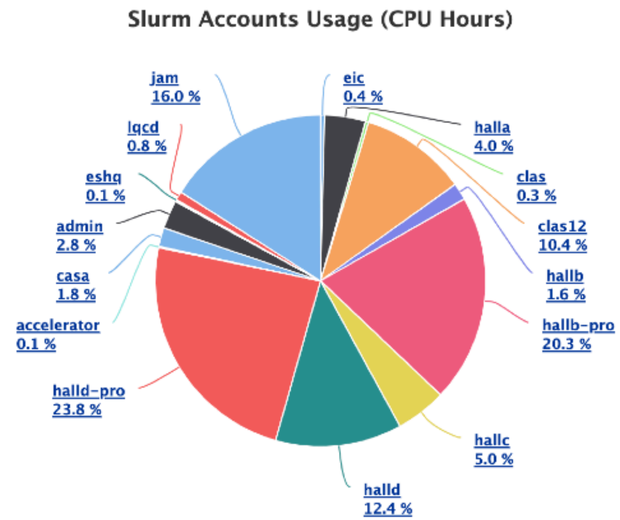
JAM computer resources at JLab

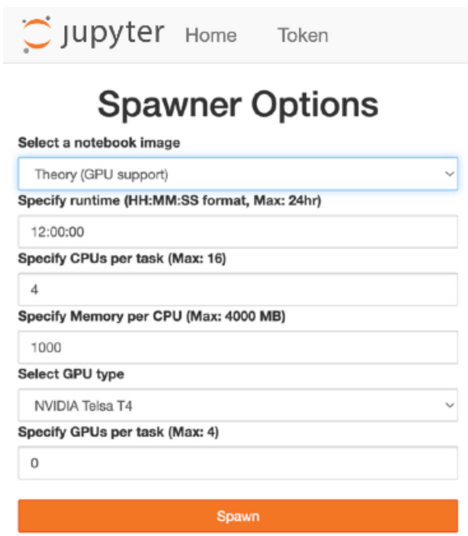
- JupyterHub support (JLab CST Division) with dedicated images (containers) has become essential for JAM analysis

  → long runs sent to slurm using image containers (apptainer)

  → submission & analysis of results all done with jupyter-notebooks



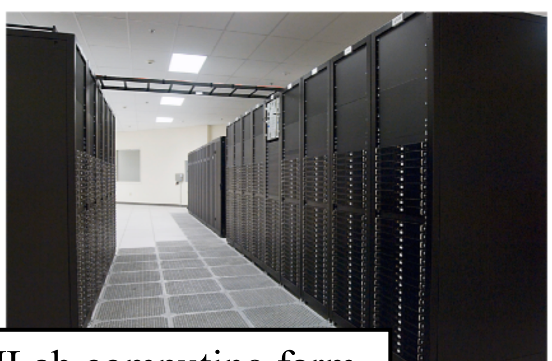




→ 12M CPU hours used by JAM since 1/1/24

→ JAM used ~ 3-4 times nominal allocated farm resources

	# params.	# points	core hours (M)
1D hadron structure (collinear PDFs, FFs)	~150	5,323	2.7
3D structure - TMD from LHC (TMD PDFs)	~30	457	1.6
3D structure - TMD @ JLab (TMD PDFs,TMD FFs)	~100	10,000	~35



JLab computing farm

→ reaching maximum capacity to perform analysis needed to deliver JLab 12 GeV science

→ opportunities to collaborate with HPC/CS

Summary

- **Research scope**

  ⟶ reconstruct QCFs from experiment to map out parton structure of hadrons and nuclei

- **Computational challenge**

  ⟶ inference task involving layers of inverse problems (factorization, evolution, …)

- **Tools**

  ⟶ code base in Python+NumPy, CPU parallelization using ZeroMQ

- **Workforce**

  ⟶ need synergistic collaboration between NP and ASCR to meet challenge

need investment to meet the challenges and scientific opportunities of JLab 12 GeV program

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need investment to meet the challenges and scientific opportunities of JLab 12 GeV program

- For GPD studies, traditional methods are not adequate — need to use ML

  ⟶ JAM is collaborating with other projects (QGT, JLab LDRD, QuanTom) to perform phenomenology using GPU hardware, which requires tuning pixelated images ($\sim 10^6$ pixels)

JAM analysis groups

Unpolarized PDFs (and fragmentation functions)

Global QCD analysis and dark photons
N. T. Hunt-Smith, W. Melnitchouk, N. Sato, A. W. Thomas, X. G. Wang, M. J. White
JHEP **09**, 096 (2023), *arXiv:2302.11126 [hep-ph]*

Bayesian Monte Carlo extraction of the sea asymmetry with SeaQuest and STAR data
C. Cocuzza, W. Meltnichouk, A. Metz, N. Sato
Phys. Rev. D **104**, 074031 (2021), *arXiv:2109.00677 [hep-ph]*

Simultaneous Monte Carlo analysis of parton densities and fragmentation functions
E. Moffat, W. Melnitchouk, T. C. Rogers, N. Sato
Phys. Rev. D **104**, 016015 (2021), *arXiv:2101.04664 [hep-ph]*

Isovector EMC effect from global QCD analysis with MARATHON data
C. Cocuzza, C. E. Keppel, H. Liu, W. Melnitchouk, A. Metz, N. Sato, A. W. Thomas
Phys. Rev. Lett. **127**, 242001 (2021), *arXiv:2104.06946 [hep-ph]*

Strange quark suppression from a simultaneous Monte Carlo analysis of parton distributions an
N. Sato, C. Andres, J.J. Ethier, W. Melnitchouk
Phys. Rev. D **101**, 074020 (2020), *arXiv:1905.03788 [hep-ph]*

First Monte Carlo analysis of fragmentation functions from e^+e^- annihilation
N. Sato, J. J. Ethier, M. Hirai, S. Kumano, W. Melnitchouk
Phys. Rev. D **94**, 114004 (2016), *arXiv:1609.00899 [hep-ph]*

Helicity PDFs

On the resolution of the sign of gluon polarization in the proton
N. T. Hunt-Smith, C. Cocuzza, W. Melnitchouk, N. Sato, A. W. Thomas, M. J. White
arXiv:2403.08117 [hep-ph]

Global analysis of polarized DIS and SIDIS data with improved small-x helicity evolution
D. Adamiak, N. Baldonado, Y. V. Kovchegov, W. Melnitchouk, D. Pitonyak, N. Sato
Phys. Rev. D **108**, 114007 (2023), *arXiv:2308.07461 [hep-ph]*

Accessing gluon polarization with high-PT hadrons in SIDIS
R. M. Whitehill, Y. Zhou, N. Sato, W. Melnitchouk
Phys. Rev. D **107**, 034033 (2023), *arXiv:2210.12295 [hep-ph]*

Polarized antimatter in the proton from global QCD analysis
C. Cocuzza, W. Melnitchouk, A. Metz, N. Sato
Phys. Rev. D **106**, L031502 (2022), *arXiv:2202.03372 [hep-ph]*

How well do we know the gluon polarization in the proton?
Y. Zhou, N. Sato, W. Melnitchouk
Phys. Rev. D **105**, 074022 (2022), *arXiv:2201.02075 [hep-ph]*

First analysis of world polarized DIS data with small-x helicity evolution
D. Adamiak, Y. V. Kovchegov, W. Melnitchouk, D. Pitonyak, N. Sato, M. D. Sievert
Phys. Rev. D **104**, L031501 (2021), *arXiv:2102.06159 [hep-ph]*

First simultaneous extraction of spin-dependent parton distributions and fragmentation functio
J. J. Ethier, N. Sato, W. Melnitchouk
Phys. Rev. Lett. **119**, 132001 (2017), *arXiv:1705.05889 [hep-ph]*

Iterative Monte Carlo analysis of spin-dependent parton distributions
N. Sato, W. Melnitchouk, S. E. Kuhn, J. J. Ethier, A. Accardi
Phys. Rev. D **93**, 074005 (2016), *arXiv:1601.07782 [hep-ph]*

Transversity PDFs

First simultaneous global QCD analysis of dihadron fragmentation functions and transversity parton distribution functions
C. Cocuzza, A. Metz, D. Pitonyak, A. Prokudin, N. Sato, R. Seidl
Phys. Rev. D **109**, 034024 (2024), *arXiv:2308.14857 [hep-ph]*

Transversity distributions and tensor charges of the nucleon
C. Cocuzza, A. Metz, D. Pitonyak, A. Prokudin, N. Sato, R. Seidl
Phys. Rev. Lett. **132**, 091901 (2024), *arXiv:2306.12998 [hep-ph]*

First Monte Carlo global analysis of nucleon transversity with lattice QCD constraints
H.-W. Lin, W. Melnitchouk, A. Prokudin, N. Sato, H. Shows
Phys. Rev. Lett. **120**, 152502 (2018), *arXiv:1710.09858 [hep-ph]*

JAM analysis groups

Pion distributions (collinear and TMD)

Tomography of pions and protons via transverse momentum dependent distributions
P. C. Barry, L. Gamberg, W. Melnitchouk, E. Moffat, D. Pitonyak, A. Prokudin, N. Sato
Phys. Rev. D **108**, L091504 (2023), *arXiv:2302.01192 [hep-ph]*

Towards the three-dimensional parton structure of the pion: Integrating transverse momentu
N. Y. Cao, P. C. Barry, N. Sato, W. Melnitchouk
Phys. Rev. D **103**, 114014 (2021), *arXiv:2103.02159 [hep-ph]*

Complementarity of experimental and lattice QCD data on pion parton distributions
P. C. Barry, C. Egerer, J. Karpie, W. Melnitchouk, C. Monahan, K. Orginos, Jian-Wei Qiu, D. Richards, N. Sato, R. S. Sufian, S. Zafeiropoulos
Phys. Rev. D **105**, 114051 (2022), *arXiv:2204.00543 [hep-ph]*

Global QCD analysis of pion parton distributions with threshold resummation
P. C. Barry, C.-R. Ji, N. Sato, W. Melnitchouk
Phys. Rev. Lett. **127**, 232001 (2021), *arXiv:2108.05822 [hep-ph]*

First Monte Carlo global QCD analysis of pion parton distributions
P. C. Barry, N. Sato, W. Melnitchouk, C.-R. Ji
Phys. Rev. Lett. **121**, 152001 (2018), *arXiv:1804.01965 [hep-ph]*

TMD PDFs

Updated QCD global analysis of single transverse-spin asymmetries: Extracting H˜, and the role of the Soffer bound and lattice QCD
L. Gamberg, M. Malda, J. A. Miller, D. Pitonyak, A. Prokudin, N. Sato
Phys. Rev. D **106**, 034014 (2022), *arXiv:2205.00999 [hep-ph]*

New tool for kinematic regime estimation in semi-inclusive deep-inelastic scattering
M. Boglione, M. Diefenthaler, S. Dolan, L. Gamberg, W. Melnitchouk, D. Pitonyak, A. Prokudin, N. Sato, Z. Scalyer
JHEP **04** (2022) 084, *arXiv:2201.12197 [hep-ph]*

Origin of single transverse-spin asymmetries in high-energy collisions
J. Cammarota, L. Gamberg, Z.-B. Kang, J.A. Miller, D. Pitonyak, A. Prokudin, T.C. Rogers, N. Sato
Phys. Rev. D **102**, 054002 (2020), *arXiv:2002.08384 [hep-ph]*

GPDs

Shedding light on shadow generalized parton distributions
E. Moffat, A. Freese, I. Cloët, T. Donohoe, L. Gamberg, W. Melnitchouk, A. Metz, A. Prokudin, N. Sato
Phys. Rev. D **108**, 036027 (2023), *arXiv:2303.12006 [hep-ph]*