JLUO Annual Meeting
Jefferson Lab, June 10, 2024

Parton structure of hadrons from the JAM Collaboration

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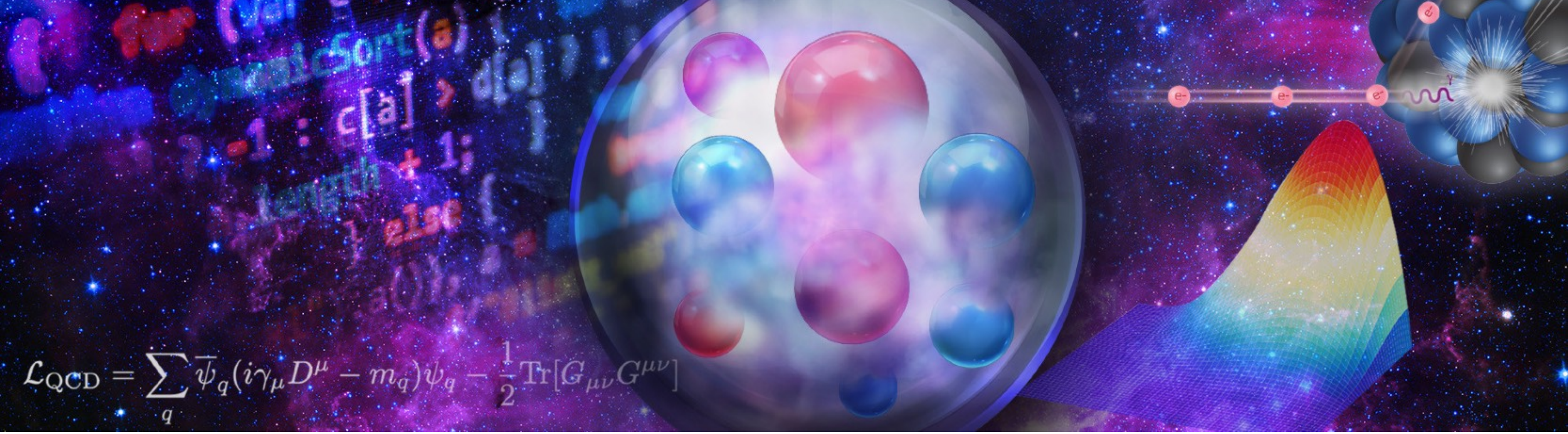
Jefferson Lab

http://www.jlab.org/jam



- Jefferson Lab Angular Momentum (JAM) collaboration — an enterprise involving <u>theorists</u>, <u>experimentalists</u>, and <u>computer scientists</u> using QCD to study internal structure of hadrons

→ analyze data using modern Monte Carlo techniques & uncertainty quantification to <u>simultaneously</u> extract various quantum correlation functions

— parton distribution functions (PDFs)
— fragmentation functions
— transverse momentum dependent (TMD) distributions
— generalized parton distributions (GPDs)

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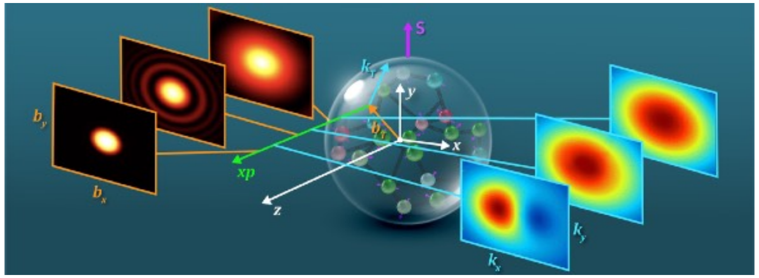
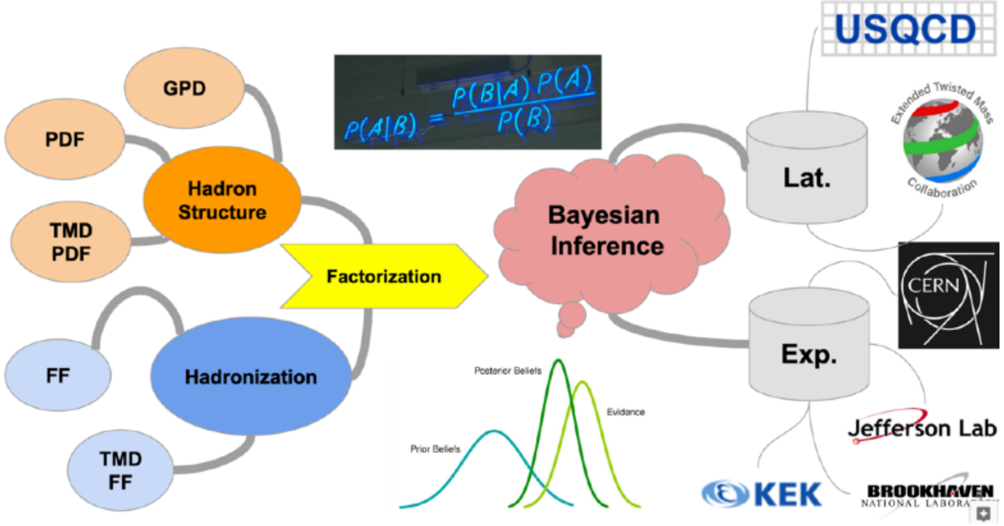
→ inclusion of lattice data and ML algorithms to potentially expand reach and efficacy of JAM analyses and understanding of hadron structure in QCD

- 3D tomography in terms of quantum correlation functions (QCFs)
  - ⟶ hadron structure (PDFs, TMD PDFs, GPDs)
  - ⟶ hadronization (FFs, TMD FFs)

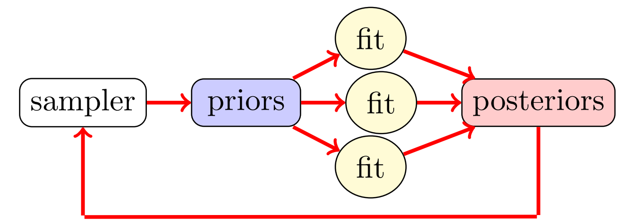


- "Holistic" approach to global QCD analysis
  - ⟶ factorization theorems
  - ⟶ Monte Carlo analysis
  - ⟶ simultaneous determination of various QCFs
  - ⟶ Bayesian inference
  - ⟶ use of lattice QCD data to supplement global analysis (with caution)



JAM global QCD analysis

- Theoretical framework
  - — collinear factorization (NLO)
  - — iterative Monte Carlo
  - — Bayesian sampling of parameter space



- Traditional functional form for PDFs

$$f(x) = N\,x^{\alpha}(1-x)^{\beta}\,P(x)$$

polynomial, neural net, ...

$\longrightarrow$ iterate until convergence (posteriors = priors)

- "Bayesian master formulas" for expectation values and variances for $\mathcal{O}$ with parameters $\vec{a}$

$$E[\mathcal{O}] = \int d^n a\,\mathcal{P}(\vec{a}|\text{data})\,\mathcal{O}(\vec{a}) \qquad V[\mathcal{O}] = \int d^n a\,\mathcal{P}(\vec{a}|\text{data})\,\big[\mathcal{O}(\vec{a}) - E[\mathcal{O}]\big]^2$$

probability distribution $\quad \mathcal{P}(\vec{a}|\text{data}) \propto \mathcal{L}(\text{data}|\vec{a})\,\pi(\vec{a})$

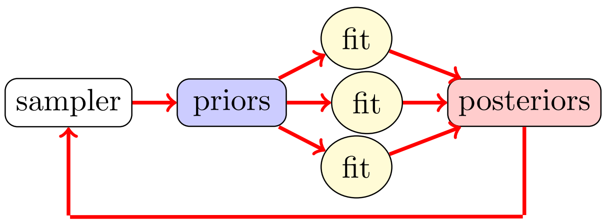
likelihood function

prior distribution

$$\mathcal{L}(\text{data}|\vec{a}) = \exp\left[-\tfrac{1}{2}\chi^2(\vec{a})\right]$$

JAM global QCD analysis

- **Theoretical framework**
  - — collinear factorization (NLO)
  - — iterative Monte Carlo
  - — Bayesian sampling of parameter space



- **Traditional functional form for PDFs**

$$f(x) = N\, x^{\alpha}(1-x)^{\beta}\, P(x)$$

polynomial, neural net, …

$\longrightarrow$ iterate until convergence (posteriors = priors)

- **Extraction of QCFs is challenging because usually there exist multiple solutions — "inverse problem"**

$\longrightarrow$ QCFs are not directly measured, but inferred from observables involving convolutions with other functions

$\longrightarrow$ reliable uncertainty quantification is essential

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]*

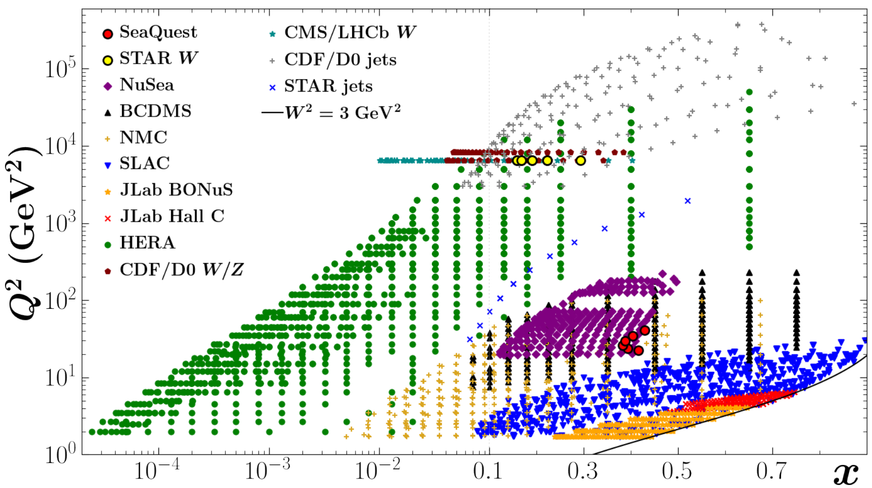
New tool for kinematic regime estimation in semi-inclusive deep-inelastic scattering
M. Boglione, M. Diefenthaler, S. Dolan, L. Gamberg, W. Melnitchouk, D. Pitonyak, A. Prokudin, N. Sato, Z. Scalyer
JHEP **04** (2022) 084, *arXiv:2201.12197 [hep-ph]*

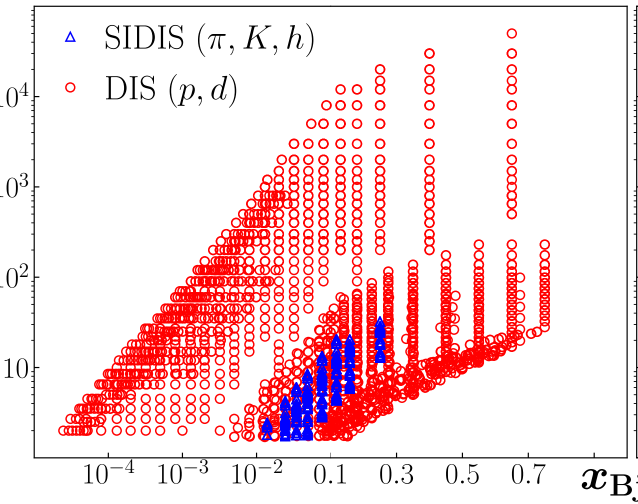
Origin of single transverse-spin asymmetries in high-energy collisions
J. Cammarota, L. Gamberg, Z.-B. Kang, J.A. Miller, D. Pitonyak, A. Prokudin, T.C. Rogers, N. Sato
Phys. Rev. D **102**, 054002 (2020), *arXiv:2002.08384 [hep-ph]*

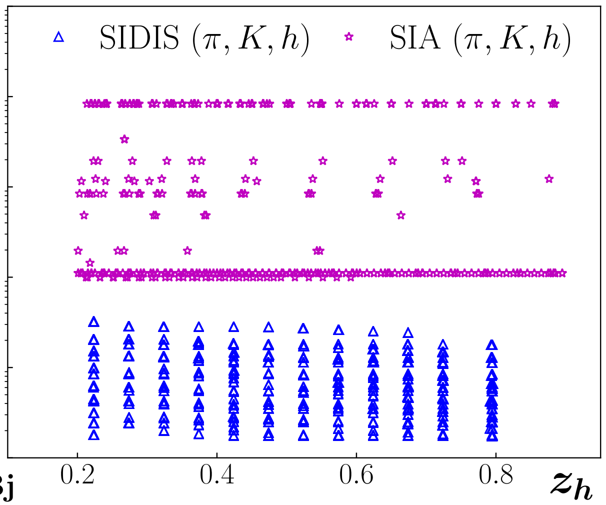
GPDs

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]*

Unpolarized proton PDFs





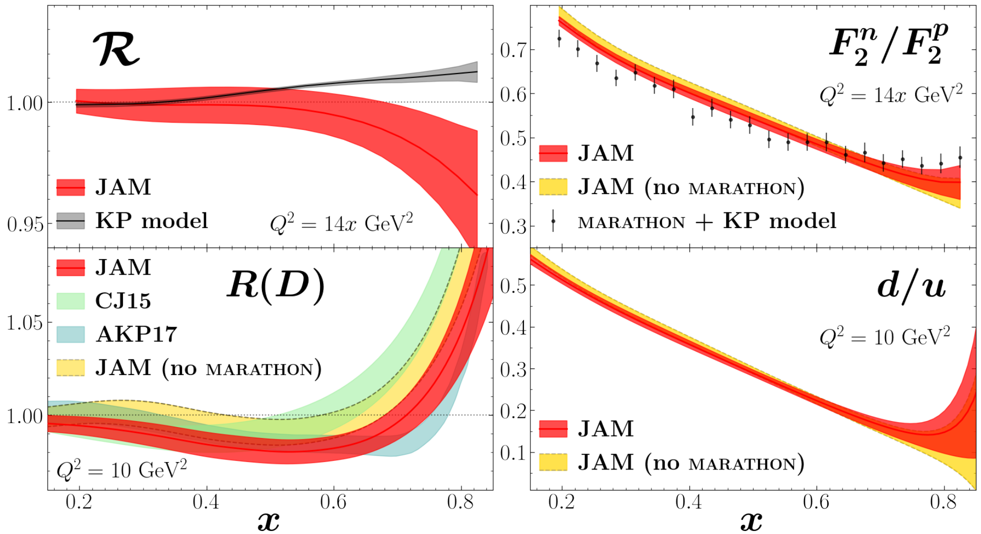


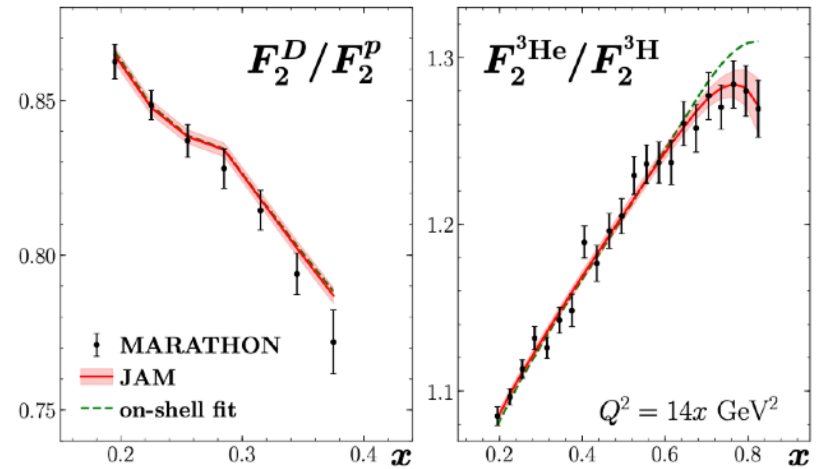
- DIS, Drell-Yan, W/Z/jet production $\longrightarrow$ PDFs $f(x)$
- SIA (single-inclusive e^+e^- annihilation $e^+e^- \to h\,X$) $\longrightarrow$ FFs $D^h(z)$
- SIDIS (semi-inclusive DIS $\ell N \to \ell'\,h\,X$) $\longrightarrow$ PDFs & FFs $f(x) \otimes D^h(z)$

$\longrightarrow$ PDFs and fragmentation functions fitted <u>simultaneously</u>

Isovector nuclear EMC effect

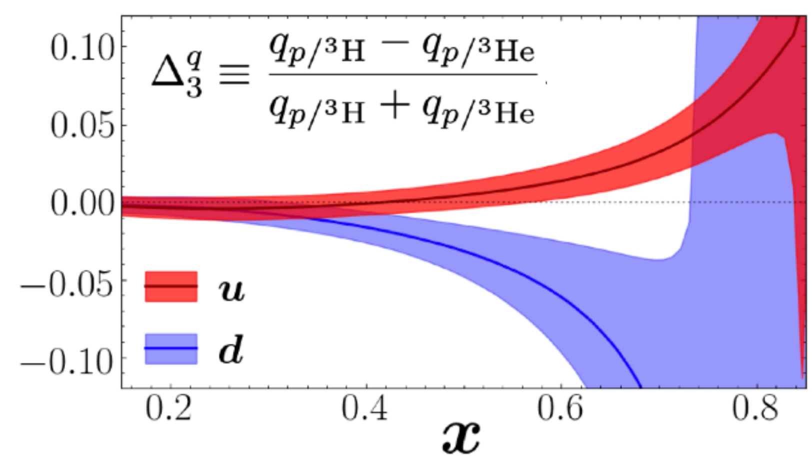
- Global analysis including MARATHON DIS data on D/p, tritium / helium





→ evidence for <u>different</u> medium modifications for u and d quarks

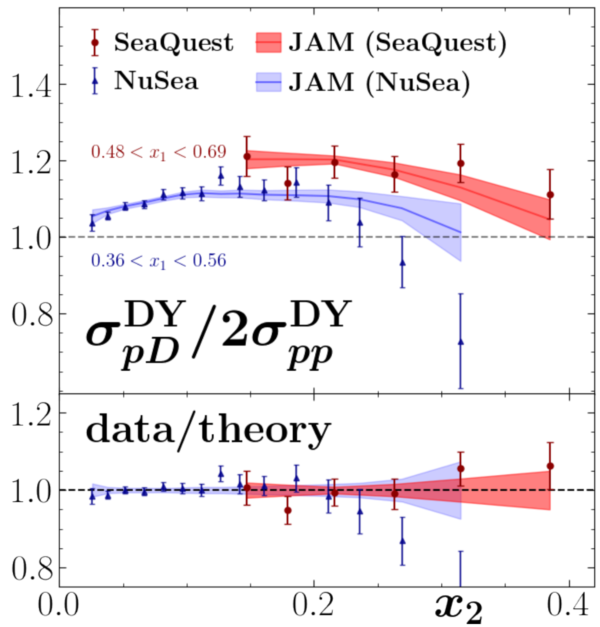
→ naive modeling of nuclear PDFs (e.g., $u/p/A = d/n/A$) violates isospin symmetry for isospin-asymmetric nuclei



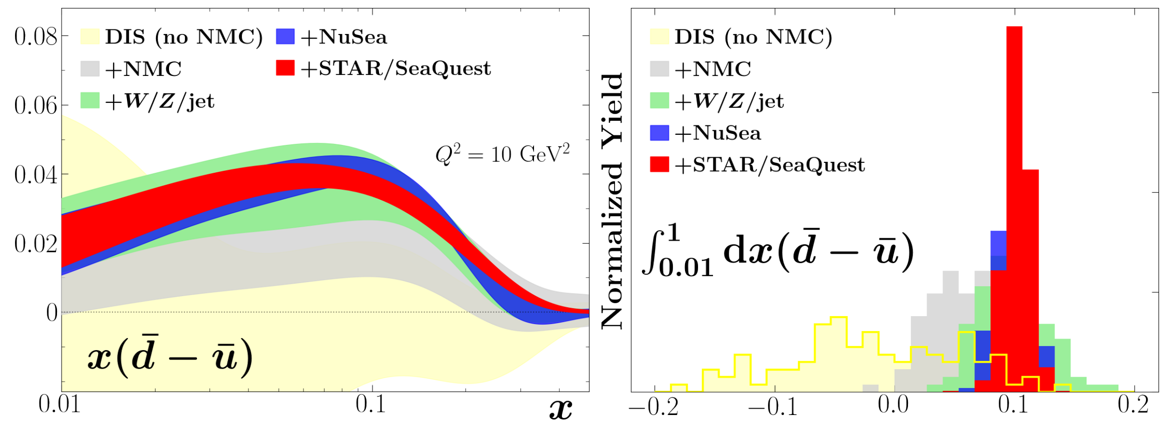
Cocuzza, Keppel, Liu, WM, Metz, Sato, Thomas
*PRL **127**, 242001 (2021)*

Sea quark asymmetries

Impact of SeaQuest & RHIC W-production data

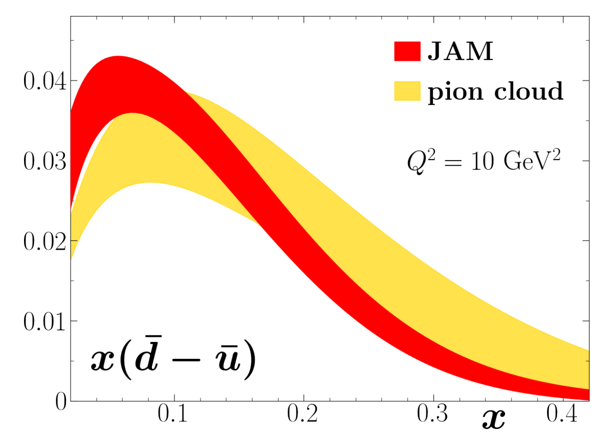


$$\frac{\sigma^{pd}}{\sigma^{pp}} \approx 1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)} \quad \text{for } x_1 \gg x_2$$



→ strong constraints on integrated $\bar{d} - \bar{u}$ in measured region

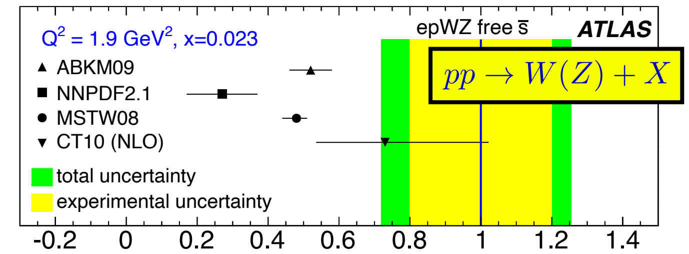
→ shape and magnitude consistent with pion cloud models of nucleon



Cocuzza, WM, Metz, Sato
*PRD **104**, 074031 (2021)*

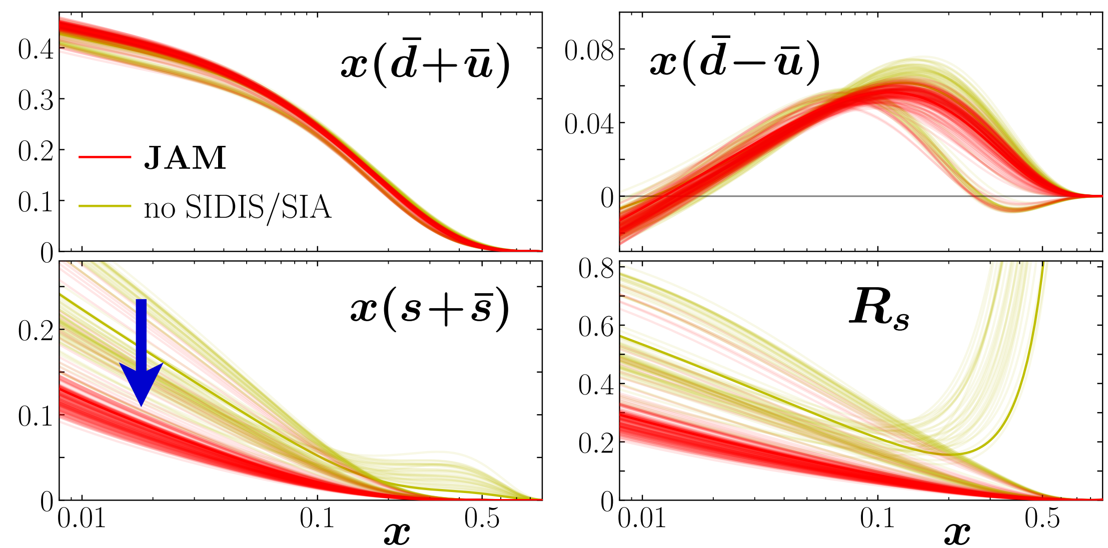
Strange quark sea

- Shape and magnitude of strange quark PDF is controversial
  - → historically, strange to nonstrange ratio $R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}} \sim 0.4$
  - → larger than expected strangeness extracted from ATLAS data



$r_s = (s+\bar{s})/2\bar{d}$
$= 1.00^{+0.25}_{-0.28}$

- Impact of SIDIS & SIA data on unpolarized PDFs
  - → SIA data at large z disfavor small $s \to K$ FF
  - → larger $s \to K$ FF requires smaller strange PDF
  - → <u>suppression of strange</u> PDF compared to ATLAS extraction



Sato, Andres, Ethier, WM
*PRD **101**, 074020 (2020)*

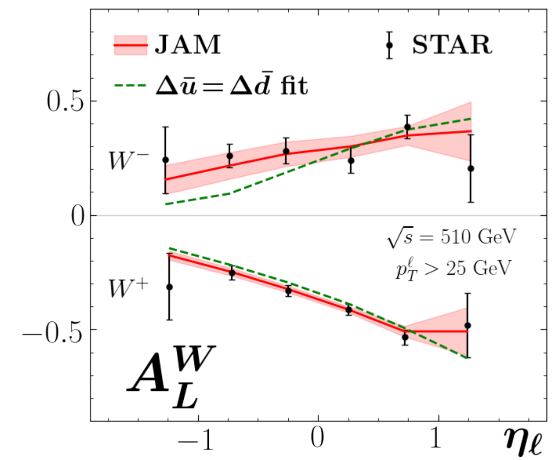
Polarized sea quarks

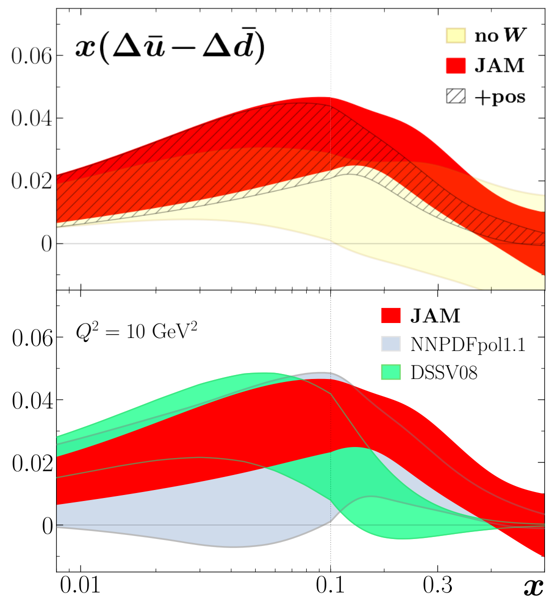
- Flavor asymmetries in spin PDFs expected from antisymmetrization

⟶ tested in W production in polarized pp collisions

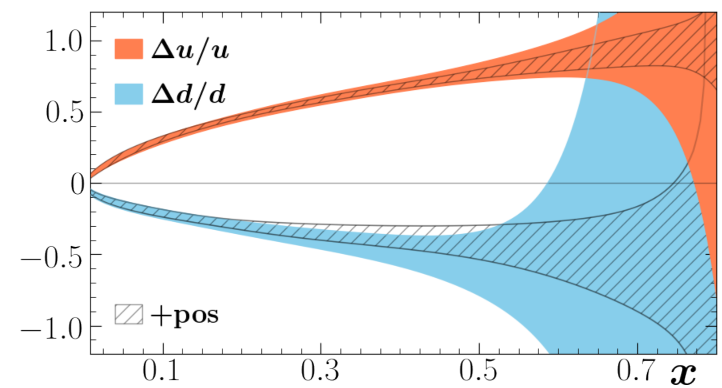
$$A_L^{W^+} \sim \Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)$$

$$A_L^{W^-} \sim \Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)$$





Cocuzza, WM, Metz, Sato
PRD ***106****, L031502 (2022)*

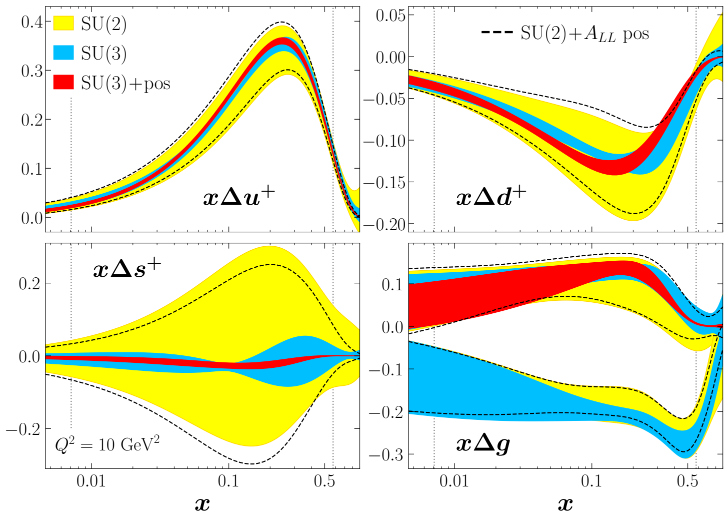


⟶ excess of $\Delta\bar{u}$ over $\Delta\bar{d}$ at intermediate x

⟶ first consistent (simultaneous) extraction of ratios $\Delta q/q$

Polarized glue

- First simultaneous analysis including polarized *and* unpolarized jets in proton-proton and proton-antiproton collisions



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

SU(2):

$$\int_0^1 dx\,[\Delta u^+ - \Delta d^+](x, Q^2) = g_A$$ ✓

SU(3):

$$\int_0^1 dx\,[\Delta u^+ + \Delta d^+ - 2\Delta s^+](x, Q^2) = a_8$$?

PDF positivity:

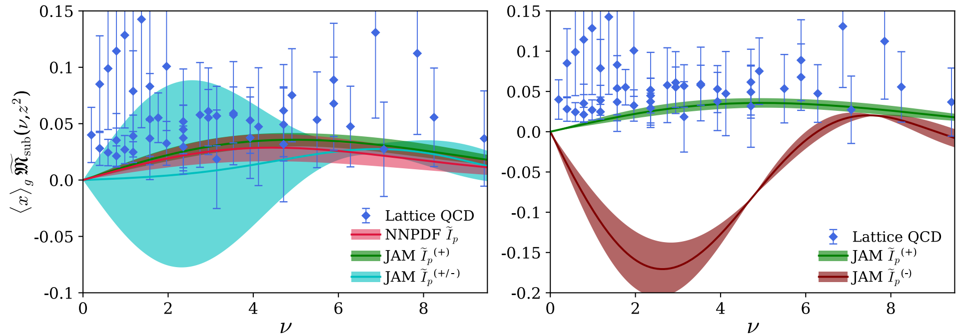
$$|\Delta f_i(x, Q^2)| \le f_i(x, Q^2)$$ ✗

$\longrightarrow$ polarized strange and gluon spin PDFs depend strongly on theoretical assumptions, especially positivity of (unpolarized) PDFs

$\longrightarrow$ cannot rule out negative gluon polarization from experiment alone!

Polarized glue

- New lattice QCD calculations of Ioffe-time pseudo-distributions



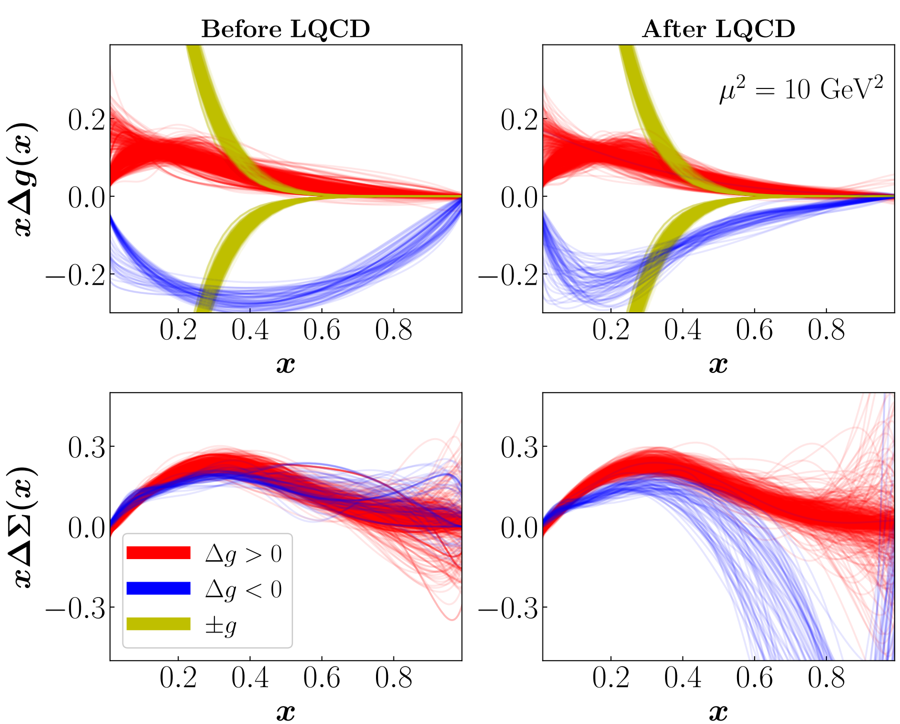
$\widetilde{\mathfrak{M}}(\nu, z^2)$ depends on

$$\widetilde{\mathcal{I}}_p(\nu) = \frac{i}{2}\int_{-1}^{1} dx\, e^{-ix\nu}\, x\,\Delta g(x)\,.$$

*Egerer et al. [HadStruc Collaboration] PRD **106**, 094511 (2022)*

⟶ favors positive gluon polarization?

⟶ fit experimental + lattice data simultaneously



*Karpie, Whitlehill, WM et al., PRD **109**, 036031 (2024)*

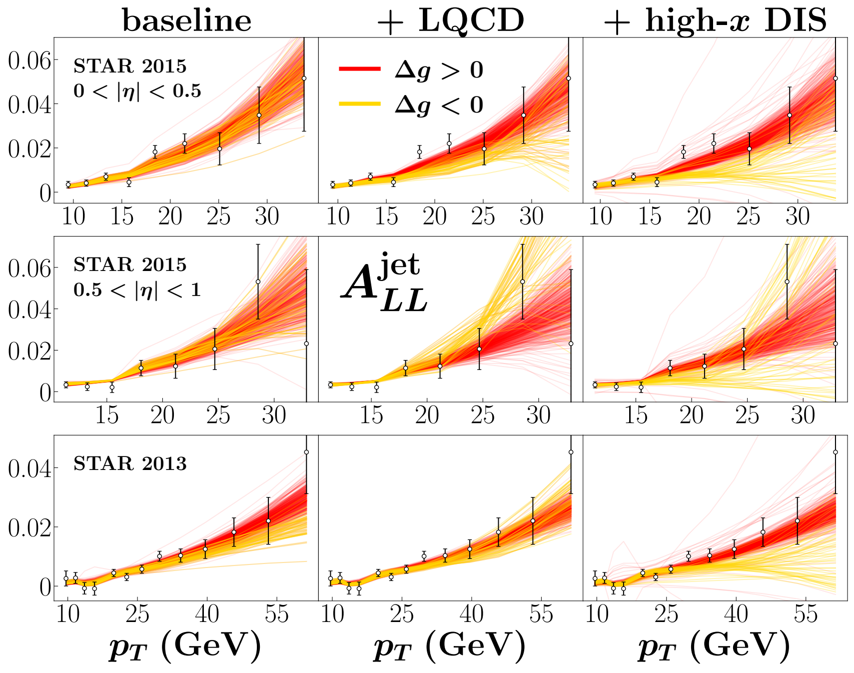
⟶ good description of data after inclusion of LQCD for both solutions for Δg

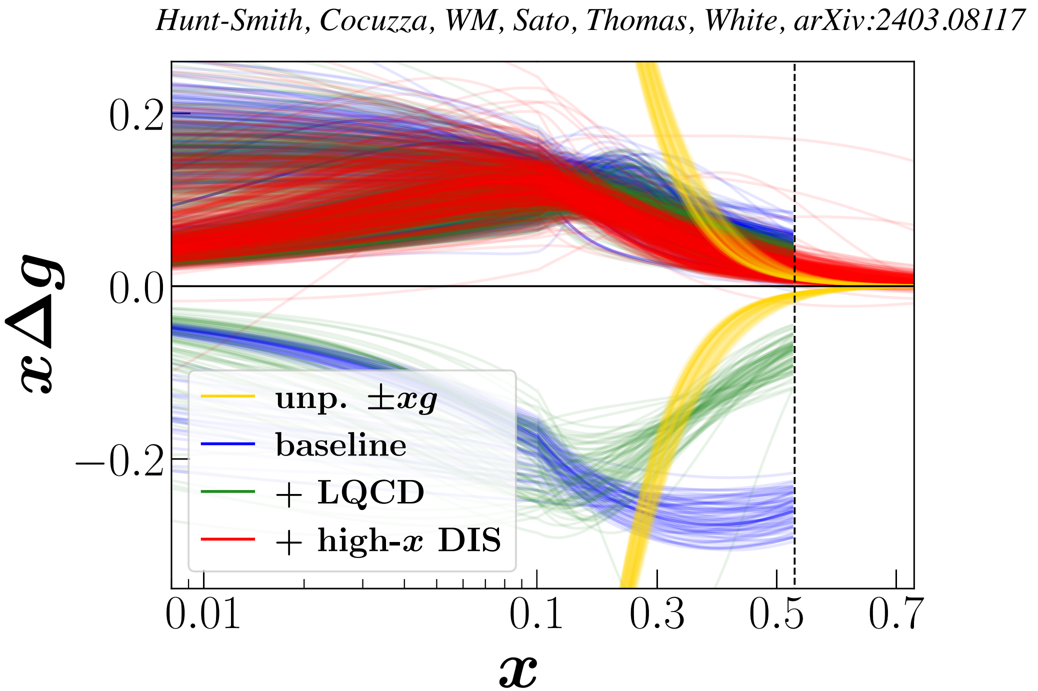
⟶ from χ^2 alone, LQCD cannot discriminate sign of Δg

but … negative Δg gives rise to negative $\Delta\Sigma$ at large x 🤔

Polarized glue

- Lower W^2 cut from $10\ \mathrm{GeV}^2$ to $4\ \mathrm{GeV}^2$ to include high-x region



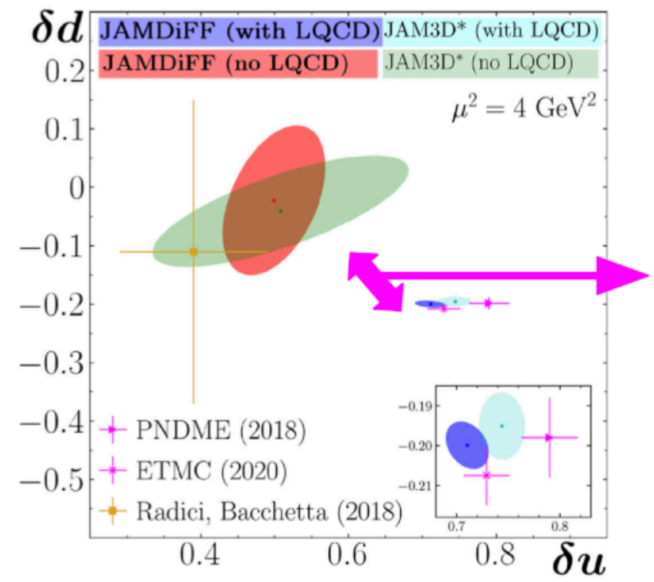


→ including high-x DIS data (CLAS, Hall A, SANE), LQCD strongly disfavors negative $\Delta\Sigma$ solutions at $x > 0.5$

→ in data-driven approach, $\Delta g < 0$ can be ruled out <u>only</u> with inclusion of polarized jet, lattice, and high-x DIS data!

Transversity

- Reconstruct transversity h_1 PDFs from
  - <u>single spin asymmetries</u> (SIDIS, pp) within TMD+CT3 framework
    $\longrightarrow$ "JAM3D"
  - <u>dihadron</u> production in SIDIS, pp and e^+e^- data
    $\longrightarrow$ "JAMDiFF"



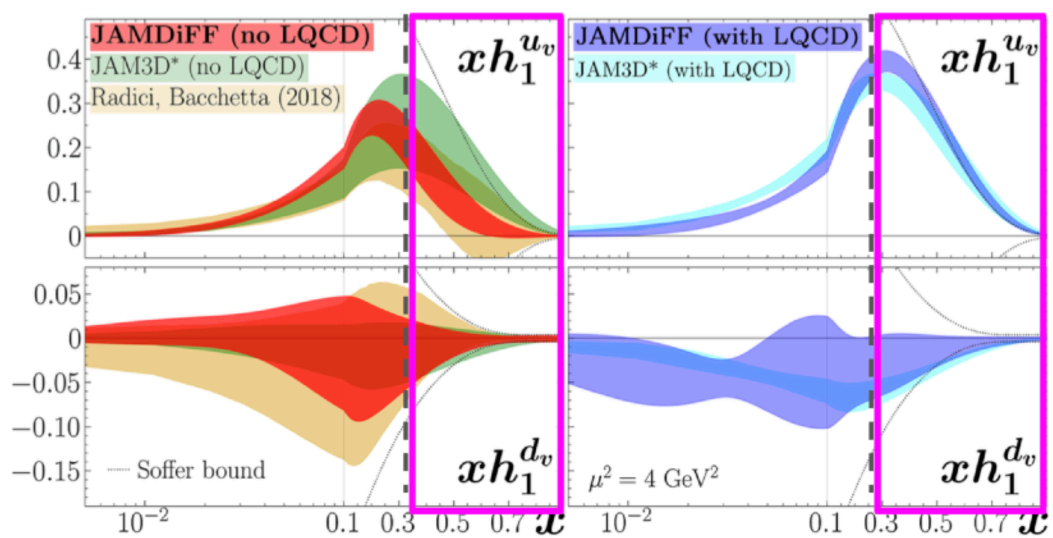
tension between LQCD & experiment removed by adjusting h_1 in (extrapolated) large-x region

- Tension between experiment and lattice QCD data?

$\longrightarrow$ weak constraints on h_1 from experiment at $x > 0.3$

$\longrightarrow$ LQCD moments suggest large contributions at high x

$\longrightarrow$ more high-x data needed to test compatibility



Cocuzza, Metz, Pitonyak, Prokudin, Sato, Seidl
*PRD **109**, 034024 (2024)*
*PRL **132**, 091901 (2024)*

Transversity

- Reconstruct transversity h_1 PDFs from
  - single spin asymmetries (SIDIS, pp) within TMD+CT3 framework
    → "JAM3D"
  - dihadron production in SIDIS, pp and e^+e^- data
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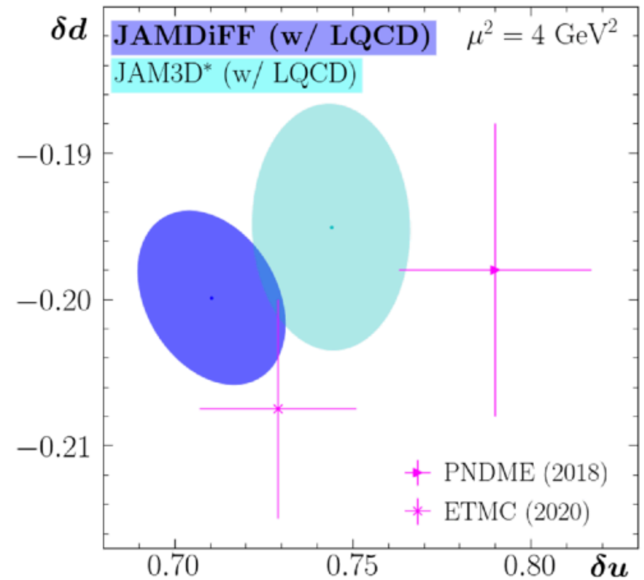

tension between LQCD & experiment removed by adjusting h_1 in (extrapolated) large-x region

- Tension between experiment and lattice QCD data?
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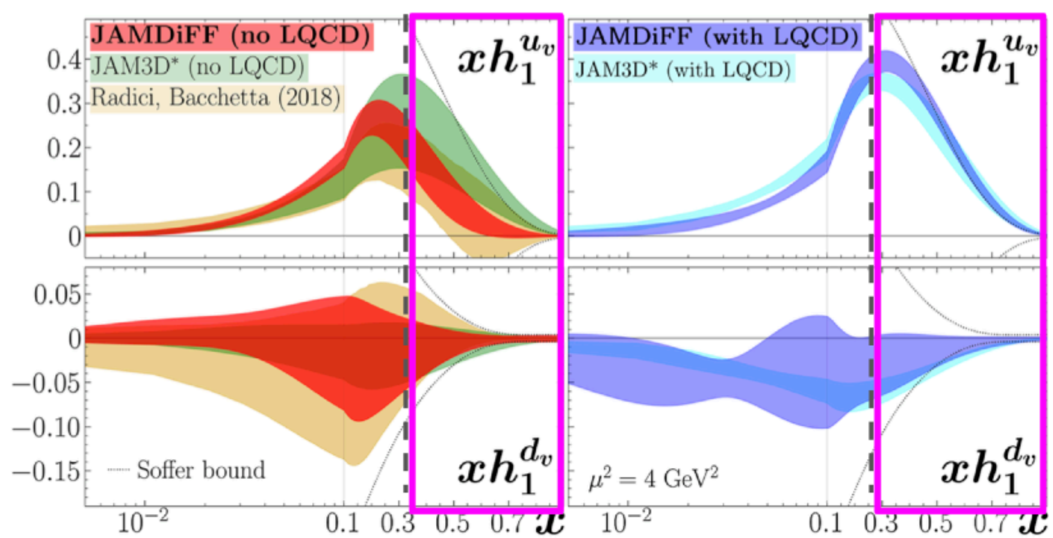


Cocuzza, Metz, Pitonyak, Prokudin, Sato, Seidl
*PRD **109**, 034024 (2024)*
*PRL **132**, 091901 (2024)*

Generalized parton distributions

- JAM's GPD efforts moving towards ML-based analysis

  → GPDs more complicated, traditional methods require more modeling

  → capitalize on tools developed for imaging in ML

  → model GPDs as pixels instead of assuming functional forms … address resolution with which images can be reconstructed

- JAM participating in multi-institutional projects

  - Quark-Gluon Tomography (QGT) Topical Collaboration
    — global analysis of GPDs from DVCS & DVMP data with LQCD

  - LDRD
    — SDHEPS to reconstruct x dependence: photproduction in Hall D

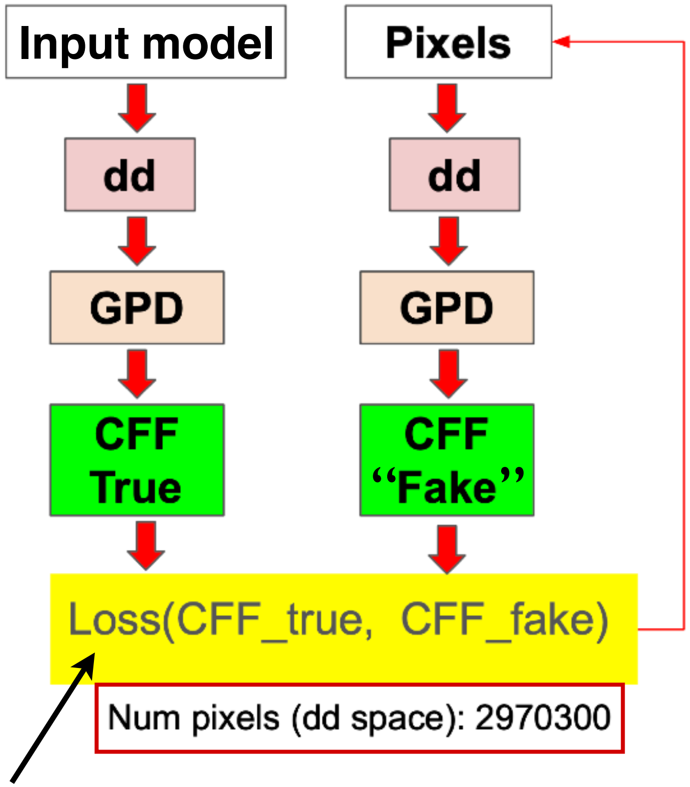
  - QuantOm
    — integrated experiment and theory event-level analysis framework for hadron structure studies: fold detector effects with QCD reaction

  → ML-enabled framework requires differentiable programming libraries (PyTorch)

  → develop data analysis framework for simultaneous extractions of QCFs
  — capitalize on JAM PDF/TMD machinery

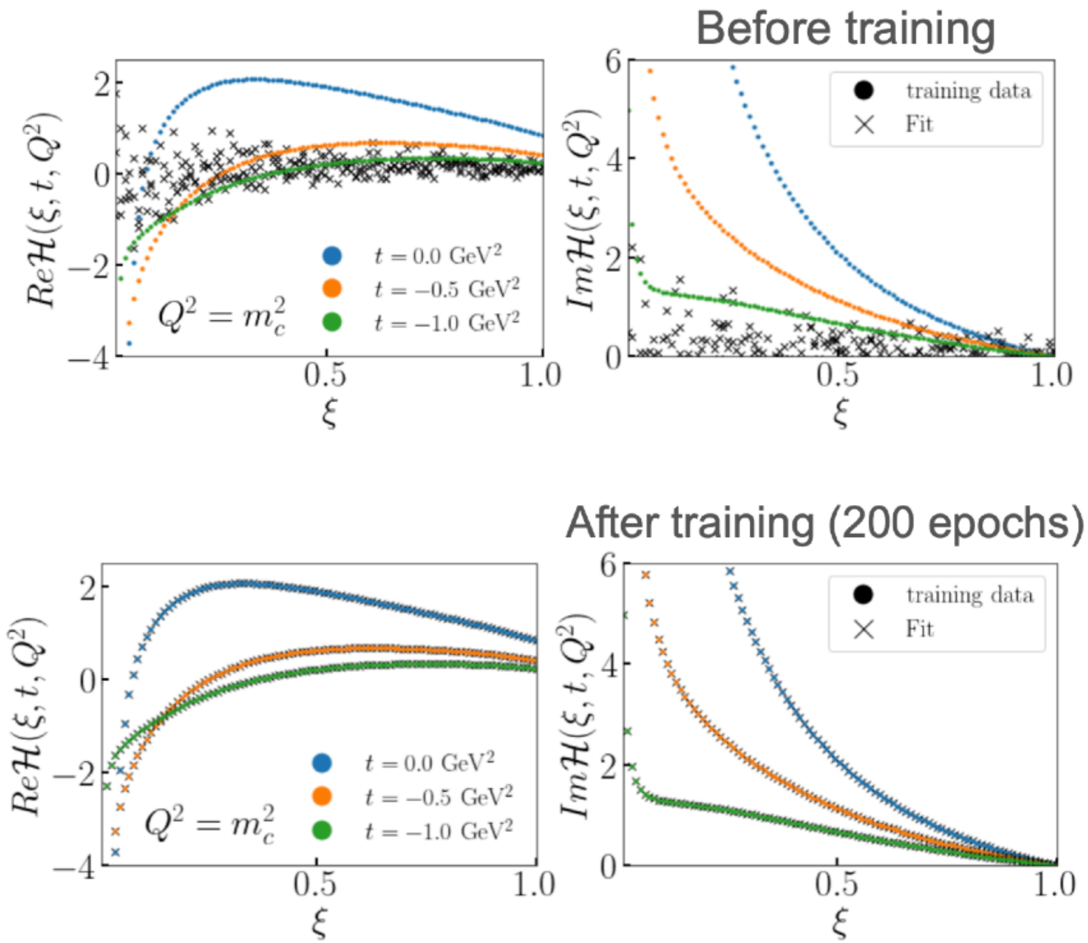
QGT: GPDs from Compton form factors

■ Closure test analysis



χ^2 between true & fake

→ differential programming essential!

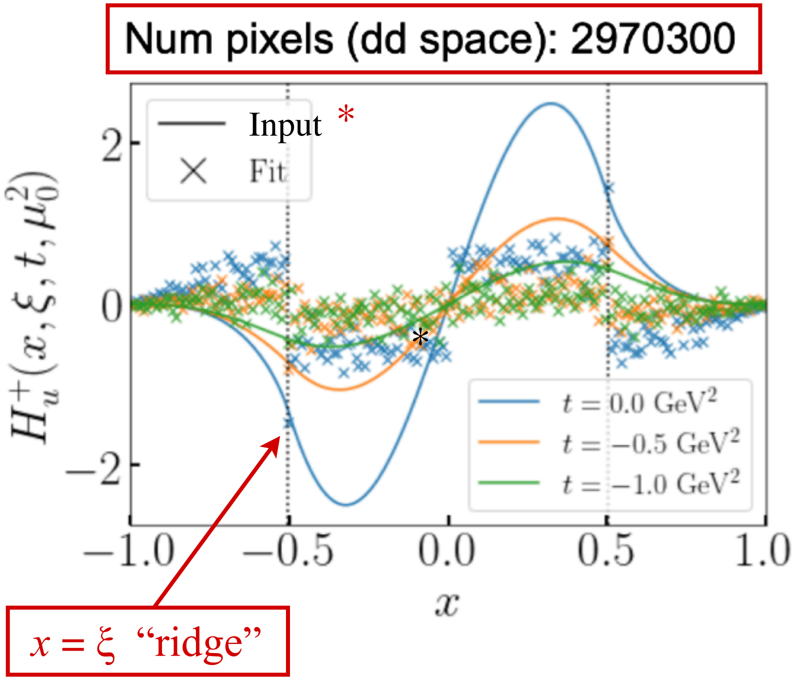


→ fit and data coincide after training — can tune 3M parameters to reproduce original "data"

→ can use setup to reconstruct CFFs from DVCS observables

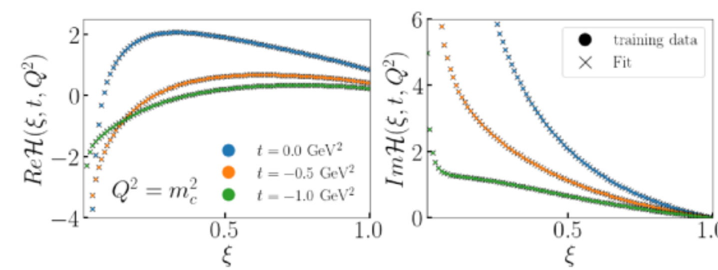
QGT: GPDs from Compton form factors

- Are GPDs reconstructed from CFFs unique?



* "toy analysis": no evolution, only u-quark flavor, CFFs only sensitive to charge-even combination, no uncertainty quantifications

→ both "input" and "fit" GPDs give same CFFs!



→ pixel-based reconstruction shows clear demonstration of <u>shadow GPDs</u>

→ more inputs needed (models and/or lattice and/or experiment) to reconstruct x dependence of GPDs

→ future of GPD reconstruction
— use lattice QCD input (QGT)
— use double DVCS, SDHEPS data (LDRD)

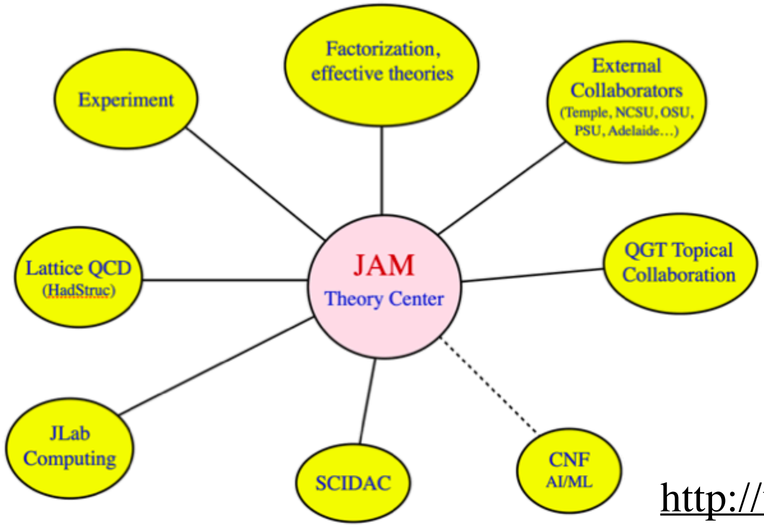
Outlook

- Progress made by JAM Collaboration towards simultaneous QCD analysis of all observables sensitive to collinear (spin-averaged and spin-dependent) PDFs and FFs, as well as TMD PDFs and TMD FFs

- Incorporation of lattice QCD data into global analysis (with caution)

- Increasing utilization of AI/ML tools to meet complexity challenge

- JAM machinery being leveraged in development of ML-based analysis framework for GPDs $\longrightarrow$ 3-D structure of hadrons



http://www.jlab.org/jam