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 theorists, experimentalists, and computer scientists using QCD to study internal structure of hadrons

- analyze data using modern Monte Carlo techniques & uncertainty quantification to simultaneously extract various quantum correlation functions
  - parton distribution functions (PDFs)
  - fragmentation functions
  - transverse momentum dependent (TMD) distributions
  - generalized parton distributions (GPDs)

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

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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, …

- “Bayesian master formulas” for expectation values and variances for \( \mathcal{O} \) with parameters \( \vec{a} \)
  \[
  E[\mathcal{O}] = \int d^n a \, \mathcal{P}(\vec{a} | \text{data}) \, \mathcal{O}(\vec{a})
  \]
  \[
  V[\mathcal{O}] = \int d^n a \, \mathcal{P}(\vec{a} | \text{data}) \, [\mathcal{O}(\vec{a}) - E[\mathcal{O}]]^2
  \]

  probability distribution \( \mathcal{P}(\vec{a} | \text{data}) \propto \mathcal{L}(\text{data} | \vec{a}) \, \pi(\vec{a}) \)
  likelihood function \( \mathcal{L}(\text{data} | \vec{a}) = \exp \left[ -\frac{1}{2} \chi^2(\vec{a}) \right] \)
  prior distribution
JAM global QCD analysis

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

- **Traditional functional form for PDFs**

\[
f(x) = N x^\alpha (1 - x)^\beta P(x)
\]

iterate until convergence
(postersiors = priors)

- Extraction of QCFs is challenging because usually there exist multiple solutions — “inverse problem”

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

  reliable uncertainty quantification is essential
Unpolarized PDFs (and fragmentation functions)

- **Global QCD analysis and dark photons**

- **Bayesian Monte Carlo extraction of the sea asymmetry with SeaQuest and STAR data**
  C. Cocuzza, W. Melnitchouk, A. Metz, N. Sato

- **Simultaneous Monte Carlo analysis of parton densities and fragmentation functions**
  E. Moffat, W. Melnitchouk, T. C. Rogers, N. Sato

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

- **Global analysis of polarized DIS and SIDIS data with improved small-x helicity evolution**
  D. Adamia, N. Baldonado, Y. V. Kovchegov, W. Melnitchouk, D. Pitonyak, N. Sato

- **Accessing gluon polarization with high-PT hadrons in SIDIS**
  R. M. Whitehill, Y. Zhou, N. Sato, W. Melnitchouk

- **Polarized antimatter in the proton from global QCD analysis**
  C. Cocuzza, W. Melnitchouk, A. Metz, N. Sato

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

- **Transversity distributions and tensor charges of the nucleon**
  C. Cocuzza, A. Metz, D. Pitonyak, A. Prokudin, N. Sato, R. Seidl

- **Iterative Monte Carlo analysis of spin-dependent parton distributions**
  N. Sato, W. Melnitchouk, S. E. Kuhn, J. J. Ether, A. Accardi
Pion distributions (collinear and TMD)

Tomography of pions and protons via transverse momentum dependent distributions

Towards the three-dimensional parton structure of the pion: Integrating transverse momentum
N. Y. Cao, P. C. Barry, N. Sato, W. Melnitchouk

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

Global QCD analysis of pion parton distributions with threshold resummation
P. C. Barry, C.-R. Ji, N. Sato, W. Melnitchouk

First Monte Carlo global QCD analysis of pion parton distributions
P. C. Barry, N. Sato, W. Melnitchouk, C.-R. Ji

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

New tool for kinematic regime estimation in semi-inclusive deep-inelastic scattering

Origin of single transverse-spin asymmetries in high-energy collisions

GPDs

Shedding light on shadow generalized parton distributions
Unpolarized proton PDFs

- DIS, Drell-Yan, $W/Z$/jet production $\rightarrow$ PDFs $f(x)$

- SIA (single-inclusive $e^+e^-$ annihilation $e^+e^- \rightarrow hX$) $\rightarrow$ FFs $D^h(z)$

- SIDIS (semi-inclusive DIS $\ell N \rightarrow \ell^' hX$) $\rightarrow$ PDFs & FFs $f(x) \otimes D^h(z)$

$\rightarrow$ PDFs and fragmentation functions fitted simultaneously
Isovector nuclear EMC effect

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

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- 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

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Cocuzza, Keppel, Liu, WM, Metz, Sato, Thomas
PRL 127, 242001 (2021)
Sea quark asymmetries

Impact of SeaQuest & RHIC W-production data

\[ \frac{\sigma_{pd}}{\sigma_{pp}} \approx 1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)} \quad \text{for} \quad x_1 \gg x_2 \]

→ 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

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

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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

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

- 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

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

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

**PDF positivity:**

\[
|\Delta f_i(x, Q^2)| \leq f_i(x, Q^2) \quad \times
\]

\[Zhou, Sato, WM, PRD 105, 074022 (2022)\]

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

→ cannot rule out negative gluon polarization from experiment alone!
Polarized glue

New lattice QCD calculations of Ioffe-time pseudo-distributions

\[ \widetilde{M}(\nu, z^2) \] depends on

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

Egerer et al. [HadStruc Collaboration]

PRD 106, 094511 (2022)

→ favors positive gluon polarization?
→ fit experimental + lattice data simultaneously

before LQCD

\[ \Delta g(x) \]

μ² = 10 GeV²

after LQCD

\[ \Delta g > 0 \]
[Δg < 0]
[±g]

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

→ from \( \chi^2 \) alone, LQCD cannot discriminate sign of Δg

but ... negative Δg gives rise to negative ΔΣ at large x 🤔

Karpie, Whitehill, WM et al., PRD 109, 036031 (2024)
Polarized glue

- Lower $W^2$ cut from 10 GeV$^2$ to 4 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 only with inclusion of polarized jet, lattice, and high-$x$ DIS data!
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 → “JAMDiFF”

Tension between experiment and lattice QCD data?

→ weak constraints on $h_1$ from experiment at $x > 0.3$

→ LQCD moments suggest large contributions at high $x$

→ more high-$x$ data needed to test compatibility
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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: photoproduction 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**

  - **Input model** → **Pixels**
    - *dd* → **GPD** → **CFF**
      - **True** → **Loss(CFF_true, CFF_fake)**
    - *dd* → **GPD** → **CFF**
      - **“Fake”**

  - **Num pixels (dd space): 2970300**

  - **χ²** 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?
  
  - Both “input” and “fit” GPDs give same CFFs!
  
  - Pixel-based reconstruction shows clear demonstration of shadow GPDs
  
  - 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)

*“toy analysis”: no evolution, only $u$-quark flavor, CFFs only sensitive to charge-even combination, no uncertainty quantifications
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 → 3-D structure of hadrons

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