Tensor SIDIS Workshop
Jefferson Lab, June 5, 2026

Deuteron PDFs from global QCD analysis

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Jefferson Lab

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \bar{\psi}_q (i\gamma_\mu D^\mu - m_q)\psi_q - \frac{1}{2}\mathrm{Tr}[G_{\mu\nu}G^{\mu\nu}]$$

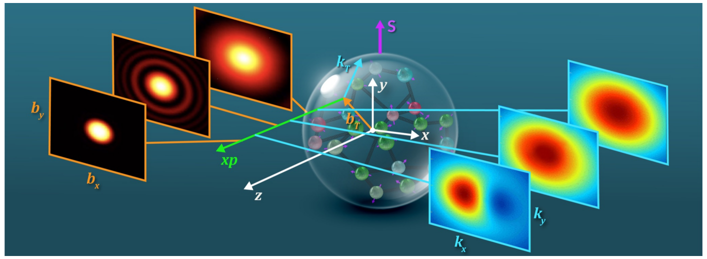
http://www.jlab.org/jam

Global QCD analysis with JAM

- Jefferson Lab Angular Momentum (JAM) collaboration — an enterprise involving theorists, experimentalists, and data scientists using QCD to extract internal quark & gluon structure of hadrons from data

  → analyze data using modern MC techniques & uncertainty quantification to simultaneously extract various quantum correlation functions (QCFs)

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



  → inclusion of lattice QCD data to supplement global analysis (with caution!) in the absence of experimental constraints

- Bayesian Monte Carlo approach, multi-step strategy to scan parameter space

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

  → iterative Monte Carlo

  → data resampling

  → uncertainty quantification from replica ensembles

Global QCD analysis with JAM

Unpolarized PDFs (and fragmentation functions)

Stability of parton distributions at high x: Impact of nuclear and power corrections
C. Cocuzza, W. Melnitchouk, N. Sato, A.W. Thomas
arXiv:2605.00666 [hep-ph]

Isospin dependence of nuclear EMC effect from global QCD analysis
C. Cocuzza, T.J. Hague, W. Melnitchouk, N. Sato, A.W. Thomas
arXiv:2602.16589 [hep-ph]

Strangeness in the proton from W+charm production and SIDIS data
T. Anderson, W. Melnitchouk, N. Sato
Phys. Rev. D 112, 094011 (2025), *arXiv:2501.00665 [hep-ph]*

Constraints on the $U(1)_{B\text{-}L}$ *model from global QCD analysis*
X. Wang, N. Hunt-Smith, W. Melnitchouk, N. Sato, A.W. Thomas
Phys. Rev. D 111, 015019 (2025), *arXiv:2410.01205 [hep-ph]*

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. Melnitchouk, 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

Global QCD analysis of spin PDFs in the proton with high-x and lattice constraints
C. Cocuzza, N. T. Hunt-Smith, W. Melnitchouk, N. Sato, A. W. Thomas
Phys. Rev. D 112, 114017 (2025), *arXiv:2506.13616 [hep-ph]*

New data-driven constraints on the sign of gluon polarization in the proton
N. T. Hunt-Smith, C. Cocuzza, W. Melnitchouk, N. Sato, A. W. Thomas, M. J. White
Phys. Rev. Lett. 133, 161901 (2024), *arXiv:2403.08117 [hep-ph]*

Gluon helicity from global analysis of experimental data and lattice QCD Ioffe time distribut
J. Karpie, R.M. Whitehill, W. Melnitchouk, C. Monahan, K. Orginos, J.-W. Qiu, D.G. Richards,
Phys. Rev. D 109, 036031 (2024), *arXiv:2310.18179 [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]*

Confronting lattice parton distributions with global QCD analysis
J. Bringewatt, N. Sato, W. Melnitchouk, Jian-Wei Qiu, F. Steffens, M. Constantinou
Phys. Rev. D 103, 016003 (2021), *arXiv:2010.00548 [hep-ph]*

First simultaneous extraction of spin-dependent parton distributions and fragmentation functions
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]*

Global QCD analysis with JAM

Small-x PDFs

First study of polarized proton-proton scattering with small-x helicity evolution
D. Adamiak, N. Baldonado, Y. Kovchegov, M. Li, W. Melnitchouk, D. Pitonyak, N. Sato,
Phys. Rev. D 112, 094032 (2025), *arXiv:2503.21006 [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, M. D. Sievert, A. Tarasov, Y. Tawabutr
Phys. Rev. D **108**, 114007 (2023), *arXiv:2308.07461 [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]*

Transversity PDFs

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

Updated QCD global analysis of single transverse-spin asymmetries: Extracting H˜, and the rol
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]*

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]*

Pion distributions

First simultaneous global QCD analysis of kaon and pion parton distributions
P. C. Barry, C.-R. Ji, W. Melnitchouk, N. Sato, F. Steffens
arXiv:2510.11979 [hep-ph]

Pionic gluons from global QCD analysis of experimental and lattice data
W. Good, P. C. Barry, H.-W. Lin, W. Melnitchouk, A. NieMiera, N. Sato
arXiv:2507.22730 [hep-ph]

First simultaneous analysis of transverse momentum dependent and collinear
P. C. Barry, A. Prokudin, T. Anderson, C. Cocuzza, L. Gamberg, W. Melnitchouk
Vladimirov, R.M. Whitehill
arXiv:2510.13771 [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
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]*

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

Global QCD analysis with JAM

TMD PDFs

TMDs in the lens of generative AI: A pixel-based approach to partonic Imaging
M. Zaccheddu, L. Gamberg, W. Melnitchouk, D. Pitonyak, A. Prokudin, J.-W. Qiu, N. Sato
arXiv:2605.06606 [hep-ph]

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]*

Updated QCD global analysis of single transverse-spin asymmetries: Extracting $\tilde{H}$*, 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]*

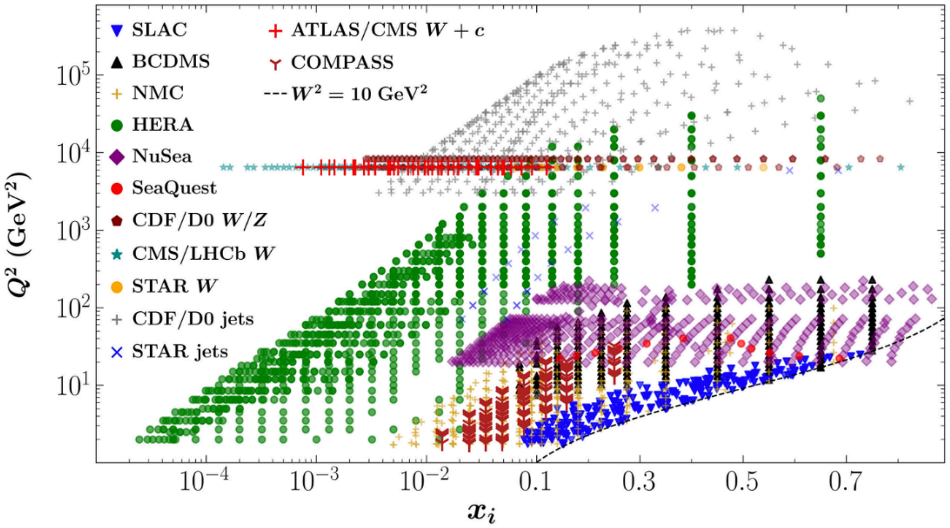
GPDs

Kernel methods for evolution of GPDs
A. Freese, D. Adamiak, I. Cloët, W. Melnitchouk, J.-W. Qiu, N. Sato, M. Zaccheddu
Comput. Phys. Commun. 311, 109552 (2025), *arXiv:2412.13450 [hep-ph]*

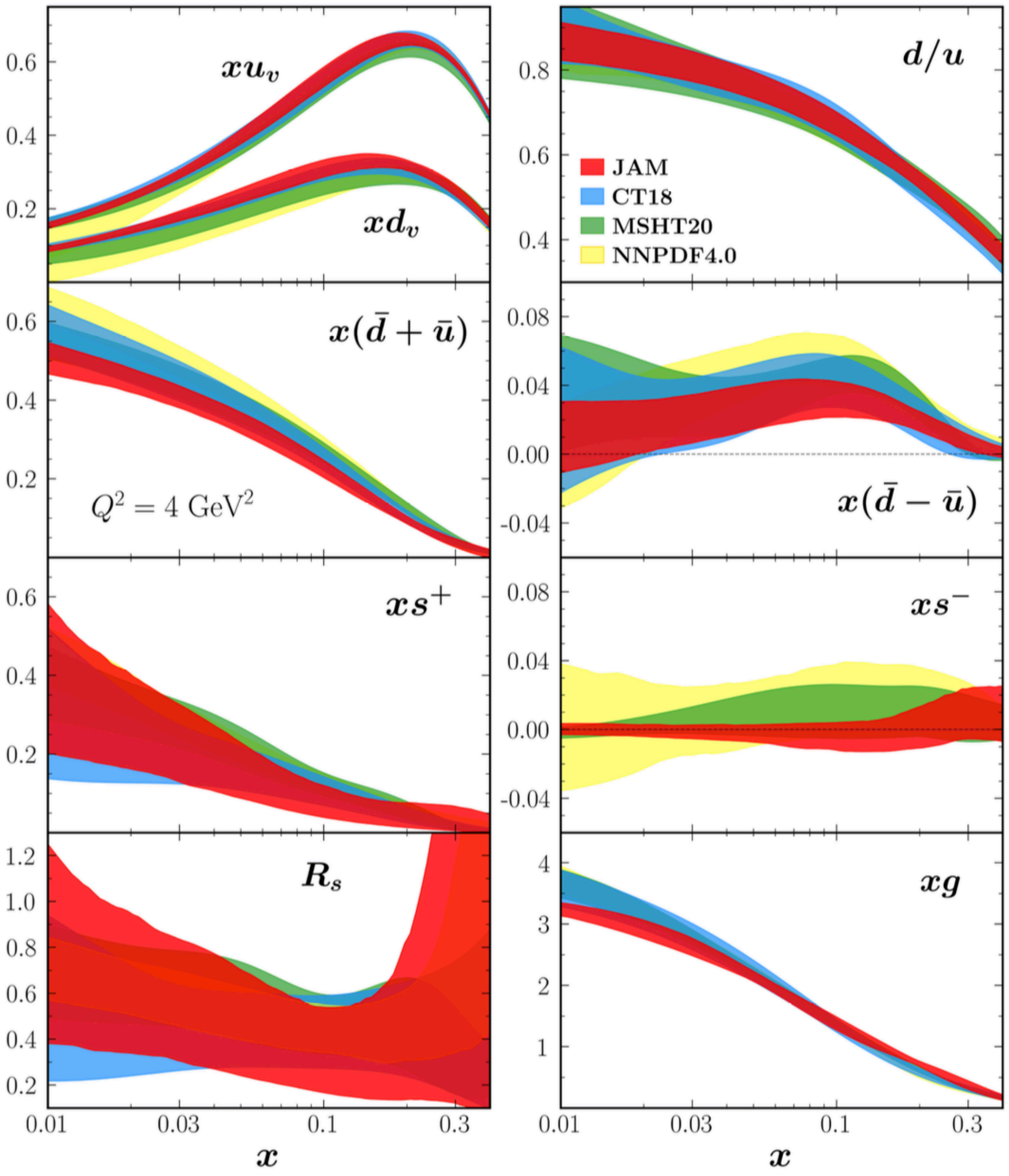
Shedding light on shadow generalized parton distributions
E. Moffat, A. Freese, I. Cloët, T. Donohoe, L. Gamberg, W. Melnitchouk, A. Metz, A. Prokudin, N. Sato
Phys. Rev. D **108**, 036027 (2023), *arXiv:2303.12006 [hep-ph]*

Unpolarized proton PDFs

- Global QCD analysis of unpolarized PDFs based on ~6,000 data points



Process	$N_{\rm dat}$	JAM
DIS		$\chi^2_{\rm red}$ (*Z*-score)
fixed target [39–42]	1495	**1.08**(+2.25)
HERA [43]	1185	**1.18**(+4.22)
Drell-Yan [2,3]	205	**1.17**(+1.69)
W-lepton asymmetry [19–21,23,46,47,50]	70	**0.91**(−0.52)
W charge asymmetry [48,49]	27	**1.00**(+0.08)
Z rapidity [51,52]	56	**1.24**(+1.24)
Inclusive jets [53–55]	198	**0.94**(−0.54)
W + charm [25–27]	37	**0.59**(−1.99)
SIDIS		
$\pi^\pm$ [44]	498	**0.89**(−1.74)
$K^\pm$ [45]	494	**0.88**(−1.96)
$h^\pm$ [44]	498	**0.86**(−2.22)
SIA		
$\pi^\pm$ [56–62,64–68]	403	**0.82**(−2.67)
$K^\pm$ [56–61,63–68]	377	**0.79**(−3.04)
$h^\pm$ [59,61,63,66,68–72]	310	**0.73**(−3.69)
Total	**5853**	**0.99**(−0.51)



Anderson, WM, Sato, PRD ***112****, 094011 (2025)*

Deuteron targets

- A lot of the data used in global analysis are taken on deuteron targets

→ primarily as a means of obtaining neutron structure information

$$n \overset{?}{=} d - p$$

→ depends also on deuteron structure

"nuclear correction"

$$n = d - p + \delta d$$

- Assuming scattering takes place from individual nucleons in the deuteron, deuteron and nucleon structure related via generalized convolution

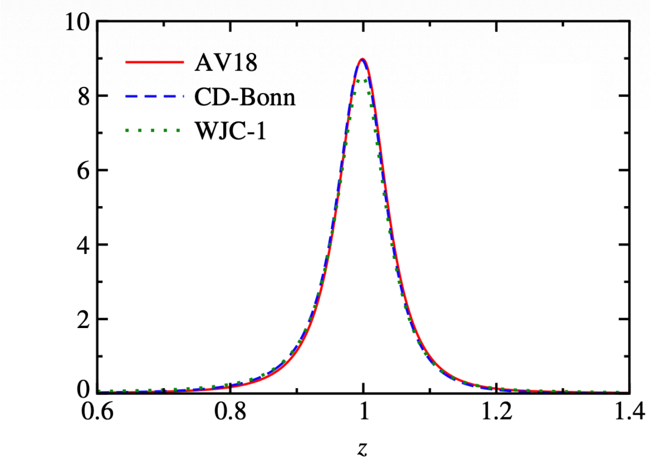
$$F_2^A(x_B, Q^2) = \sum_N \left[f_{N/A}^{(\mathrm{on})} \otimes F_2^N + f_{N/A}^{(\mathrm{off})} \otimes \delta F_2^{N/A} \right](x_B, Q^2)$$

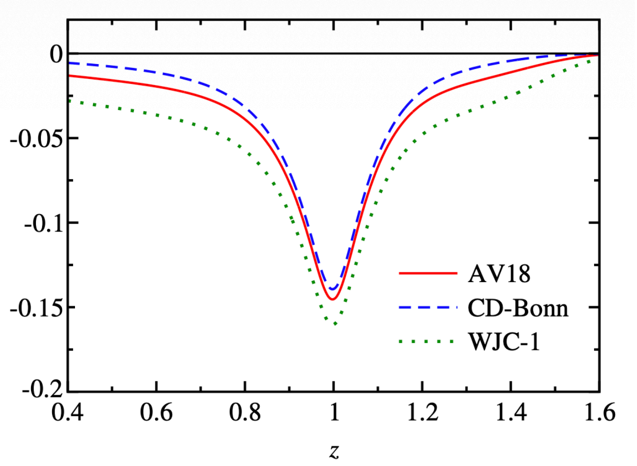
$$[f_{N/A} \otimes F_2](x_B, Q^2) \equiv \int_{x_B}^{M_A/M} \mathrm{d}y\, f_{N/A}(y, \rho)\, F_2\!\left(\frac{x_B}{y}, Q^2\right)$$

$$\rho^2 = 1 + 4M^2 x_B^2 / Q^2$$

on-shell smearing function

off-shell smearing function





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$$\rho^2 = 1 + 4M^2x_B^2/Q^2$$

on-shell nucleon structure function

off-shell nucleon structure function

$$F_2^N(x_B,Q^2) = x_B \sum_q e_q^2 \left[C_q \otimes q_N^+ \right](x_B,Q^2) + \cdots$$

$$\delta F_2^{N/A}(x_B,Q^2) = x_B \sum_q e_q^2 \left[C_q \otimes \delta q_{N/A} \right](x_B,Q^2) + \cdots$$

on-shell proton PDF
(fitted to world proton data,
generally well constrained)

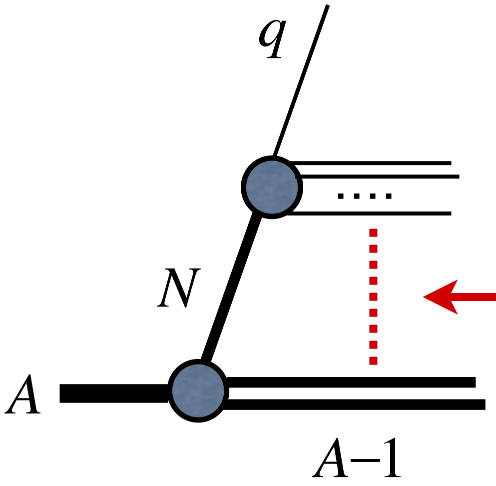
off-shell PDF
(fitted to nuclear data,
not well understood)

Off-shell nucleon PDFs

- Off-shell nucleon PDF depends on the nucleon species, and on the specific nucleus in which the nucleon is bound

$$\delta q_{N/A} \;=\; \delta q^{(0)}_{N/A} + \delta q^{(1)}_{N/A}$$

⟶ depends also on the nature of interaction between spectator partons ("diquark") and residual $(A\text{-}1)$ nuclear system



exchange of $I = 0$ or $I = 1$ quantum #s *

⟶ normalization condition (valence quark number the same in free & bound nucleon)

$$\int_0^1 \mathrm{d}x\ \delta q^{(0)}_{N/A}(x) \;=\; 0 \;=\; \int_0^1 \mathrm{d}x\ \delta q^{(1)}_{N/A}(x)$$

⟶ assume isospin symmetry for all (on-shell and off-shell) PDFs

$$\delta u_{n/A} = \delta d_{p/A^*}$$

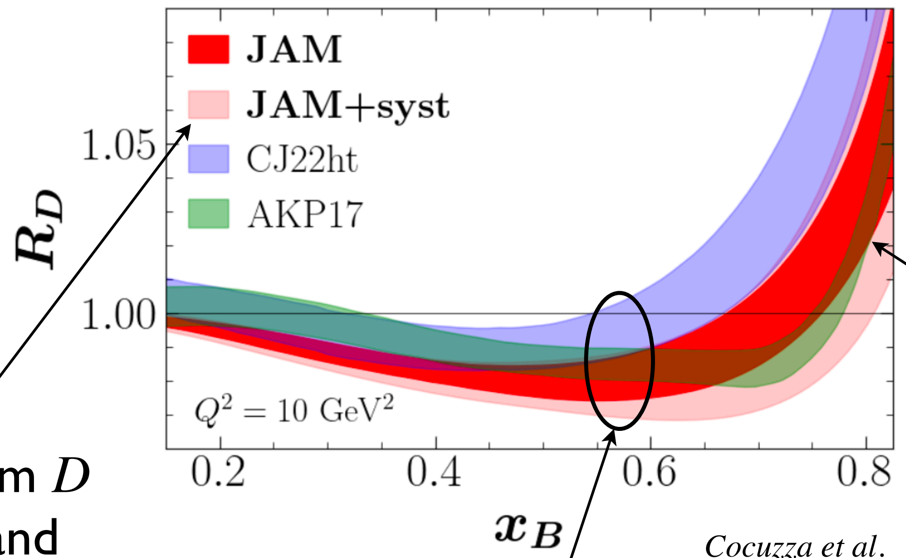
⟶ for $A = D$, only the isoscalar $u + d$ combination enters
(not to be confused with isospin of exchanged state *)

Deuteron EMC effect

- Ratio of deuteron to free nucleon structure functions (“EMC ratio”)

$$R_D = \frac{F_2^D}{F_2^p + F_2^n}$$

has nontrivial dependence on Bjorken-x, especially at large x



uncertainties from D wave function and fitted off-shell PDFs

rapid rise due to Fermi motion

~ 1%–3% depletion at $x \sim 0.6$

Cocuzza et al. arXiv:2602.16589

Deuteron EMC effect

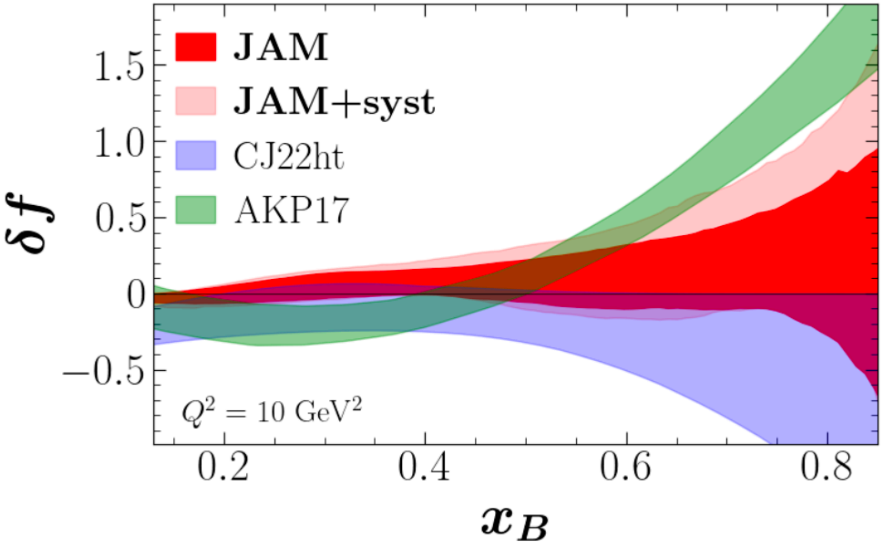
- Shape of EMC ratio depends (partly) on sign and magnitude of off-shell effects

⟶ for the deuteron the overall effect is small

$$\delta f = \frac{\delta F_2^{p/D} + \delta F_2^{n/D}}{F_2^p + F_2^n}$$

$$\delta u_{n/D} = \delta d_{p/D}$$

$$\delta d_{n/D} = \delta u_{p/D}$$



Cocuzza et al.
arXiv:2602.16589

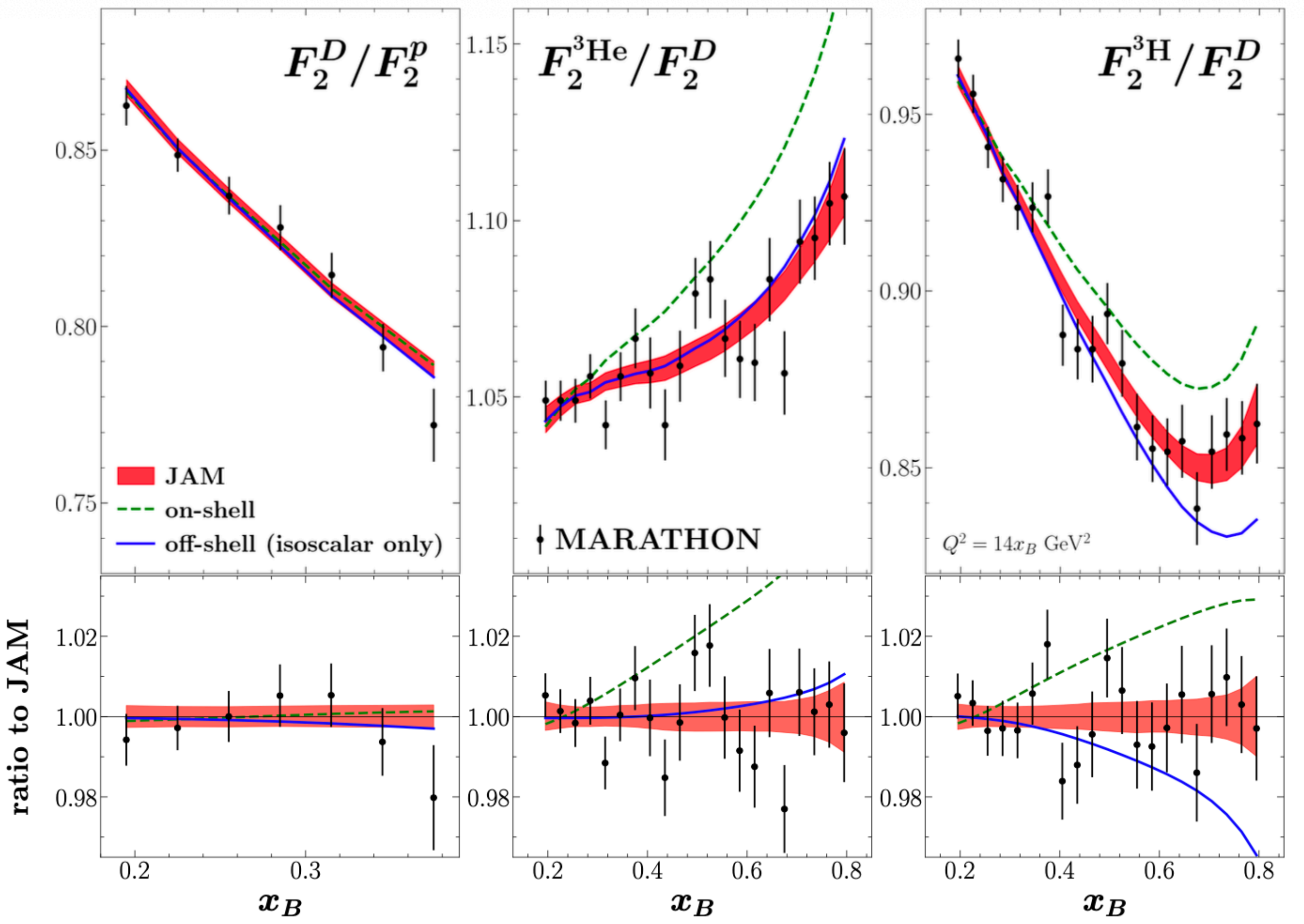
⟶ is effect intrinsically small, or are there cancellations between different flavors, since deuteron is only sensitive to u+d combination?

⟶ need other nuclei to determine flavor dependence

⟶ ^{3}He, ^{3}H

EMC effect in ^{3}He and ^{3}H

- Recent data from MARATHON experiment at JLab gives first information about flavor dependence of nucleon off-shell corrections



Cocuzza et al.
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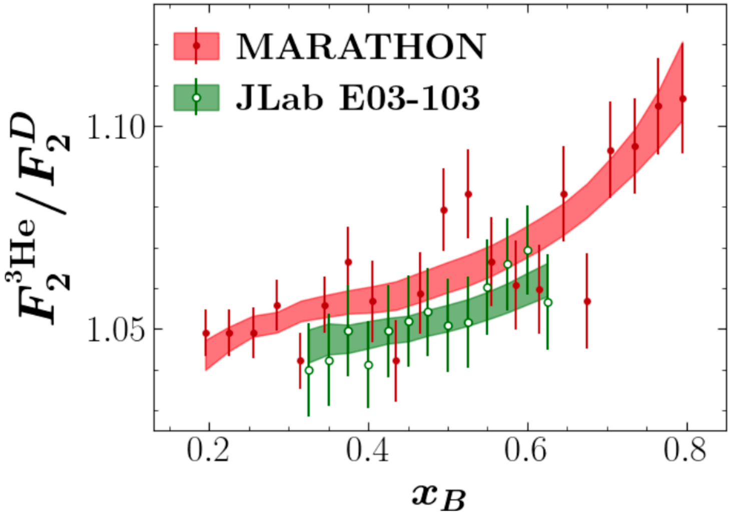
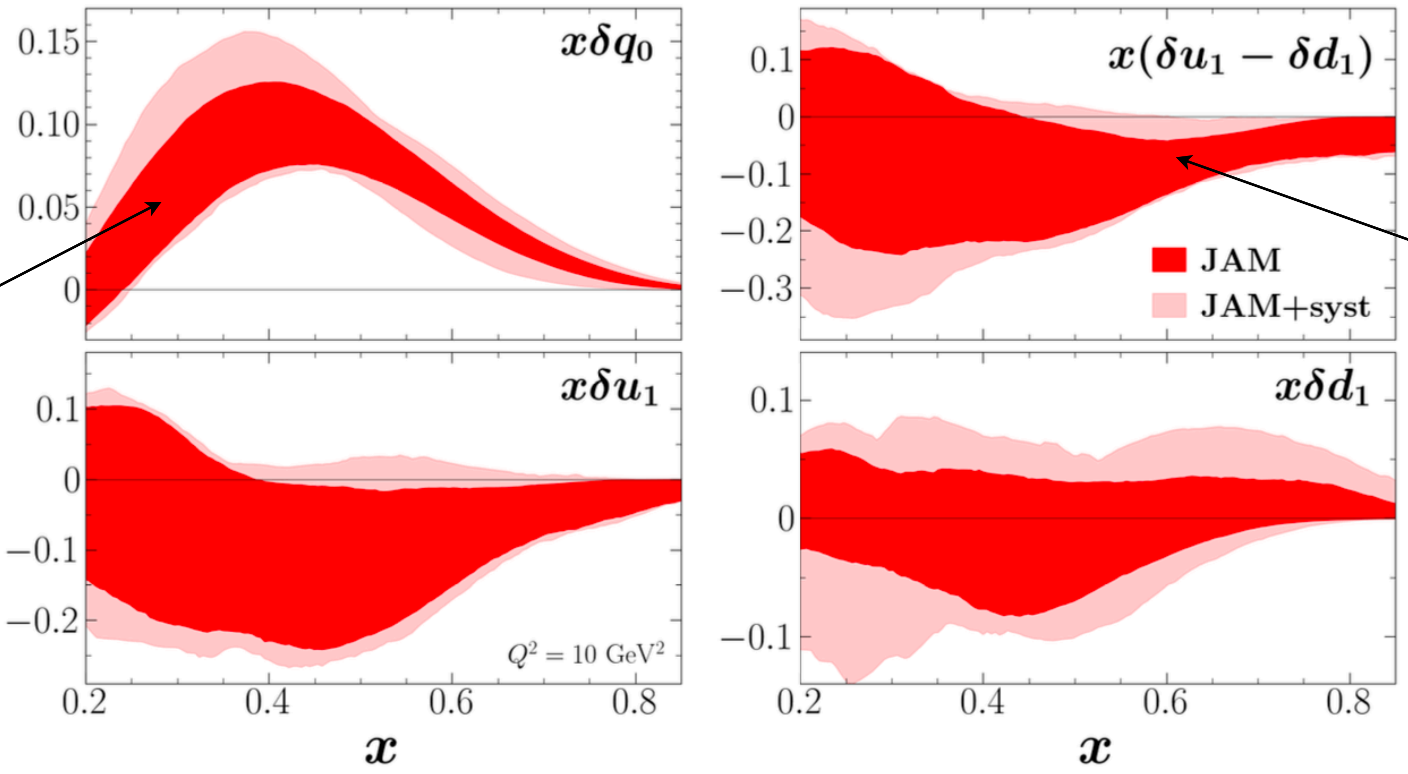


→ comparison of MARATHON and earlier Hall C data

→ excellent agreement with all data

EMC effect in ^{3}He and ^{3}H

- Resulting off-shell PDFs, fitted in global QCD analysis of all p, D, A=3 data, show interesting flavor dependence



$$\delta q_0 = \delta u_0 = \delta d_0$$

nonzero asymmetry?

Cocuzza et al. arXiv:2602.16589

$$\delta u^{(0)}_{p/{}^3\mathrm{He}} = \delta u^{(0)}_{p/{}^3\mathrm{H}} = 2\,\delta u^{(0)}_{p/D} \equiv \delta u_0$$

$$\delta d^{(0)}_{p/{}^3\mathrm{He}} = \delta d^{(0)}_{p/{}^3\mathrm{H}} = 2\,\delta d^{(0)}_{p/D} \equiv \delta d_0.$$

$$\delta u^{(1)}_{p/{}^3\mathrm{He}} = 0, \quad \delta u^{(1)}_{p/{}^3\mathrm{H}} = 2\,\delta u^{(1)}_{p/D} \equiv \delta u_1$$

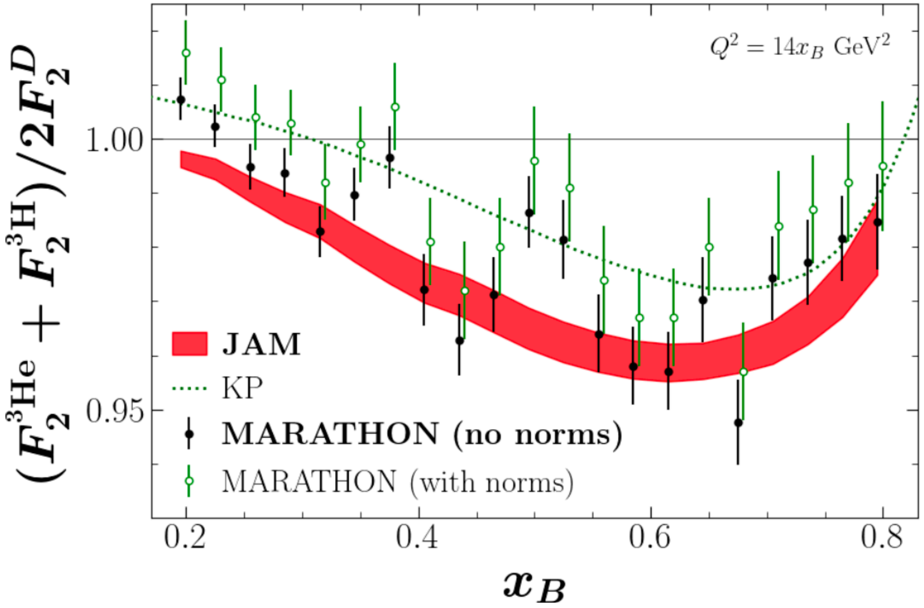
$$\delta d^{(1)}_{p/{}^3\mathrm{He}} = 0, \quad \delta d^{(1)}_{p/{}^3\mathrm{H}} = 2\,\delta d^{(1)}_{p/D} \equiv \delta d_1$$

⟶ large nonzero isoscalar PDF

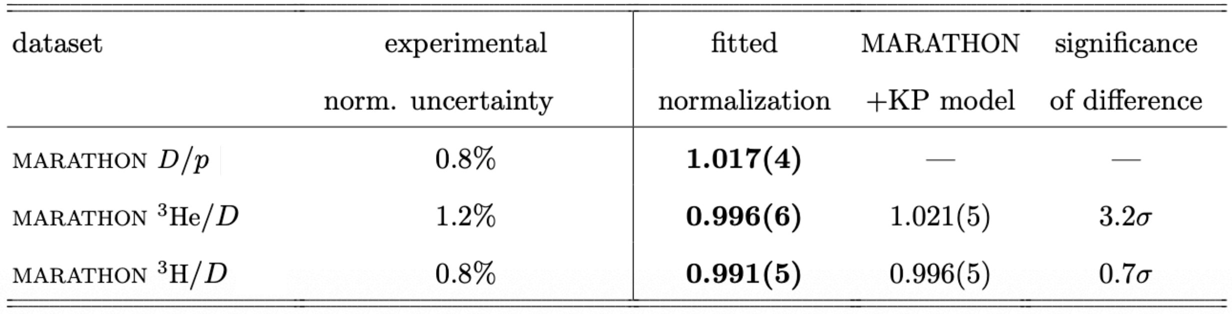
⟶ hint of flavor asymmetric isovector PDF

EMC effect in ^{3}He and ^{3}H

- JAM analysis fits all overall normalization uncertainties, within quoted uncertainties … MARATHON experiment <u>fixed</u> normalization assuming no EMC effect at $x = 0.31$ as in Kulagin-Petti (KP) model



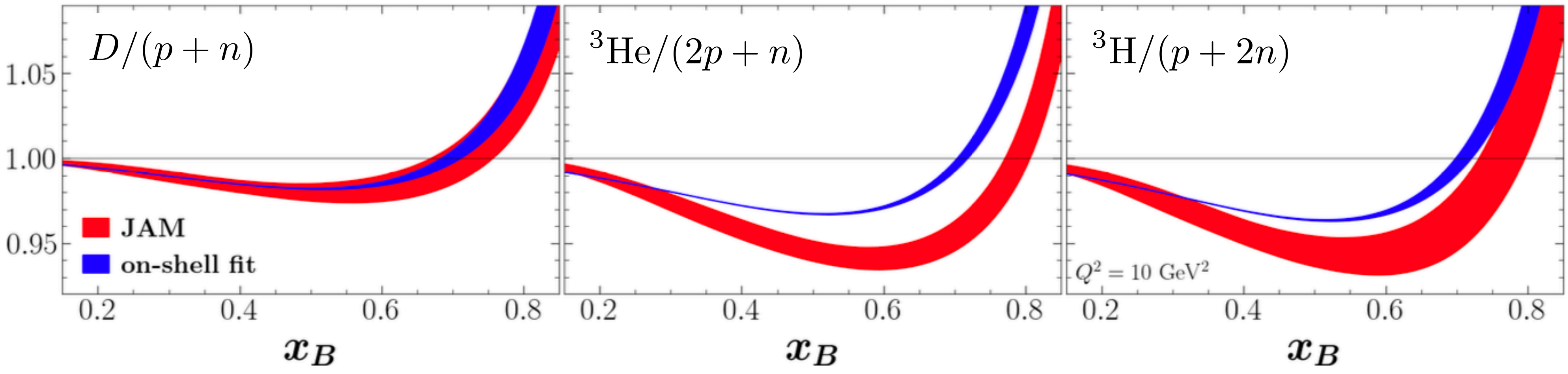
⟶ significant difference between (globally) fitted and (MARATHON+KP) assumed normalizations for ^{3}He/D data



dataset	experimental norm. uncertainty	fitted normalization	MARATHON +KP model	significance of difference
MARATHON D/p	0.8%	**1.017(4)**	—	—
MARATHON ^{3}He$/D$	1.2%	**0.996(6)**	1.021(5)	3.2σ
MARATHON ^{3}H$/D$	0.8%	**0.991(5)**	0.996(5)	0.7σ

EMC effect in ^{3}He and ^{3}H

- Shape of EMC ratio depends on sign and magnitude of off-shell effects



$$\delta u_{p/D} = \frac{1}{2}(\delta u_0 + \delta u_1)$$
$$\delta d_{p/D} = \frac{1}{2}(\delta d_0 + \delta d_1).$$

$$\delta u_{p/^3\mathrm{He}} = \delta u_0,$$
$$\delta d_{p/^3\mathrm{He}} = \delta d_0,$$

$$\delta u_{p/^3\mathrm{H}} = \delta u_0 + \delta u_1,$$
$$\delta d_{p/^3\mathrm{H}} = \delta d_0 + \delta d_1,$$

$D: \ \delta u_0 + \delta d_0 + \delta u_1 + \delta d_1$

$^3\mathrm{He}: \ 9\delta u_0 + 6\delta d_0 + \delta u_1 + 4\delta d_1$

$^3\mathrm{H}: \ 6\delta u_0 + 9\delta d_0 + 4\delta u_1 + \delta d_1$

largest effect in ^{3}He EMC ratio

Deuteron PDFs

- Can also write D structure function directly in terms of deuteron PDFs

$$F_2^A(x_B, Q^2) = x_B \sum_q e_q^2 \left[C_q \otimes q_A^+\right](x_B, Q^2) \qquad\qquad u_D = d_D$$

⟶ can perform global QCD analysis to extract deuteron PDFs, without reference to nucleon PDFs (nCTEQ, EPS, …)

- Since deuteron is spin-1 nucleus, there are additional twist-2 structure functions and PDFs (at LO)

$$F_1^D = \frac{1}{3}\left(q_\uparrow^1 + q_\downarrow^1 + q_\uparrow^0\right)$$

$$g_1^D = \frac{1}{2}\left(q_\uparrow^1 - q_\downarrow^1\right)$$

$$b_1^D = \frac{1}{2}\left(2q_\uparrow^0 - q_\uparrow^1 - q_\downarrow^1\right)$$

⟶ deuteron PDFs $q_\uparrow^1$ and $q_\downarrow^1$ can be related to nucleon PDFs $q_\uparrow^{\frac{1}{2}}$ and $q_\downarrow^{\frac{1}{2}}$ $e.g.$, via convolution, but $q_\uparrow^0$ PDF is unique to the deuteron

Deuteron PDFs

- Needs simultaneous global QCD analysis of unpolarized F_1^D (or F_2^D), helicity dependent g_1^D (or A_1^D, $A_\parallel^D$), and tensor b_1^D structure functions
    - $\sim 1{,}100$ F_2^D points (SLAC, BCDMS, NMC, JLab)
    - ~ 400 g_1^D points (SLAC, COMPASS, HERMES, JLab)
    - 6 b_1^D points (HERMES)

- JAM framework ideally suited to such (simultaneous) analysis

  ⟶ will allow first comparisons between helicity-projected PDFs in nucleon ($q_\uparrow^{\frac{1}{2}}$, $q_\downarrow^{\frac{1}{2}}$) and deuteron ($q_\uparrow^1$, $q_\downarrow^1$)

  ⟶ will give first glimpse of pure deuteron PDF $q_\uparrow^0$ (non-nucleonic DOF)

- SIDIS deuteron observables (p_T integrated) can give additional combinations of deuteron PDFs

- JAM-TMD framework can be extended to include tensor TMDs

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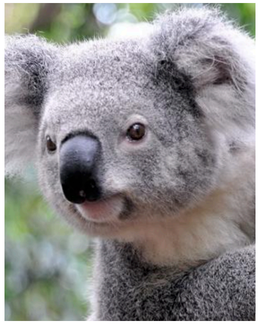

WM

Stay tuned…

http://www.jlab.org/jam