Towards Improved Hadron Femtography with Hard Exclusive Reactions
University of Virginia, July 23, 2026

Hadron structure from JAM global QCD analysis

Wally Melnitchouk

Jefferson Lab

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

  $\longrightarrow$ 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)

  $\longrightarrow$ 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

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

  $\longrightarrow$ iterative Monte Carlo

  $\longrightarrow$ data resampling

  $\longrightarrow$ 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 $\tilde{H}$, 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 (& kaon) distributions

First simultaneous global QCD analysis of kaon and pion parton distributions with lattice
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]

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
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 c
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]

First simultaneous analysis of transverse momentum dependent and collinear parton distributions in the proton
P. C. Barry, A. Prokudin, T. Anderson, C. Cocuzza, L. Gamberg, W. Melnitchouk, E. Moffat, D. Pitonyak, J.-W. Qiu, Vladimirov, R.M. Whitehill
arXiv:2510.13771 [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 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]*

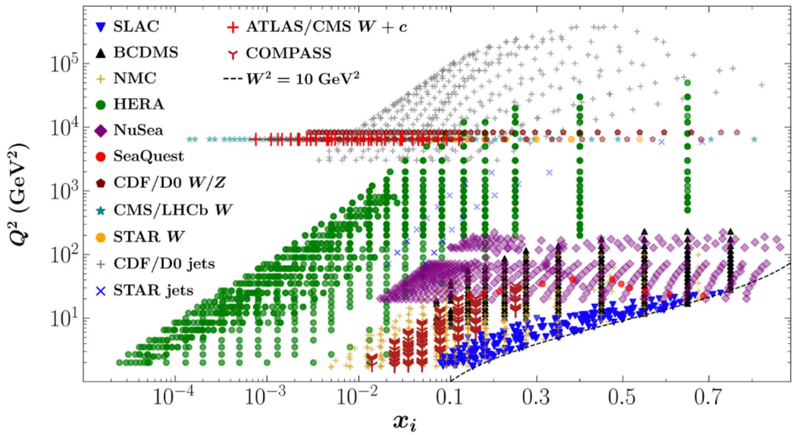
GPDs

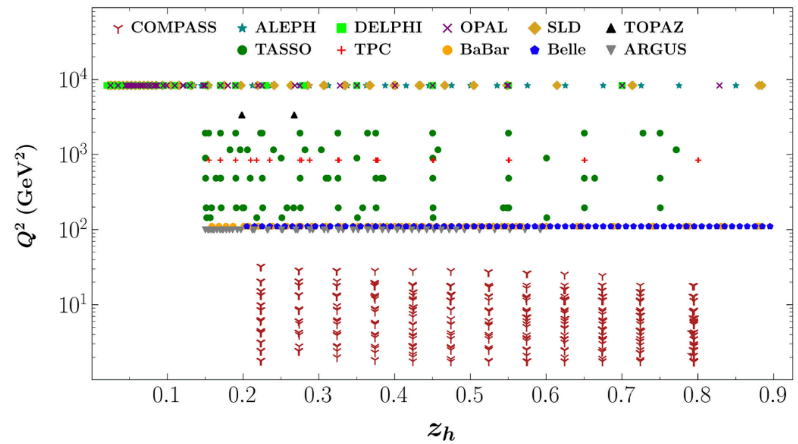
Kernel methods for evolution of GPDs
A. Freese, D. Adamiak, I. Cloët, W. Melnitchouk, J.-W. Qiu, N. Sato, M. Zaccheddu
Comput. Phys. Commun. 311, 109552 (2025), *arXiv:2412.13450 [hep-ph]*

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 collinear PDFs

- Simultaneously extract PDFs and fragmentation functions from inclusive DIS, SIDIS, Drell-Yan, W/Z boson and jet production, $W{+}c$ production, single-inclusive e^+e^- annihilation



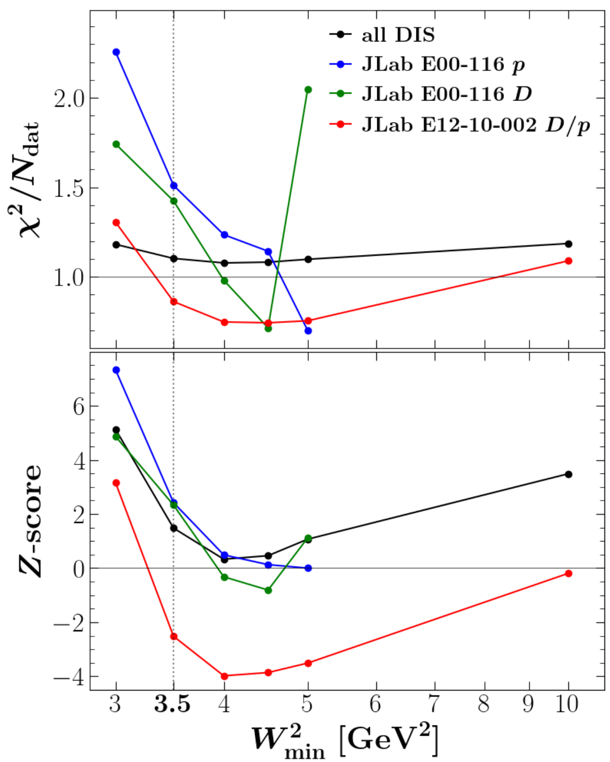


Process	N_{dat}	Baseline	+SIDIS	+W-charm	JAM
		χ^2_{red} (*Z*-score)			
DIS					
fixed target [39–42]	1495	1.07(+1.95)	1.08(+2.23)	1.07(+1.92)	**1.08**(+**2.25**)
HERA [43]	1185	1.16(+3.64)	1.18(+4.22)	1.15(+3.57)	**1.18**(+**4.22**)
Drell-Yan [2,3]	205	1.15(+1.50)	1.17(+1.69)	1.14(+1.43)	**1.17**(+**1.69**)
W-lepton asymmetry [19–21,23,46,47,50]	70	0.88(−0.69)	0.91(−0.50)	0.87(−0.72)	**0.91**(−**0.52**)
W charge asymmetry [48,49]	27	0.91(−0.24)	1.00(+0.08)	0.91(−0.25)	**1.00**(+**0.08**)
Z rapidity [51,52]	56	1.18(+0.98)	1.22(+1.15)	1.24(+1.25)	**1.24**(+**1.24**)
Inclusive jets [53–55]	198	1.02(+0.27)	0.94(−0.56)	1.04(+0.41)	**0.94**(−**0.54**)
W + charm [25–27]	37	…	…	0.57(−2.10)	**0.59**(−**1.99**)
SIDIS					
$\pi^\pm$ [44]	498	…	0.91(−1.42)	…	**0.89**(−**1.74**)
$K^\pm$ [45]	494	…	0.91(−1.50)	…	**0.88**(−**1.96**)
$h^\pm$ [44]	498	…	0.90(−1.65)	…	**0.86**(−**2.22**)
SIA					
$\pi^\pm$ [56–62,64–68]	403	0.73(−4.30)	0.82(−2.77)	0.73(−4.30)	**0.82**(−**2.67**)
$K^\pm$ [56–61,63–68]	377	0.65(−5.55)	0.78(−3.20)	0.65(−5.55)	**0.79**(−**3.04**)
$h^\pm$ [59,61,63,66,68–72]	310	0.76(−3.29)	0.73(−3.73)	0.76(−3.29)	**0.73**(−**3.69**)
Total	**5853**	1.00(+0.11)	1.00(−0.09)	1.00(−0.06)	**0.99**(−**0.51**)

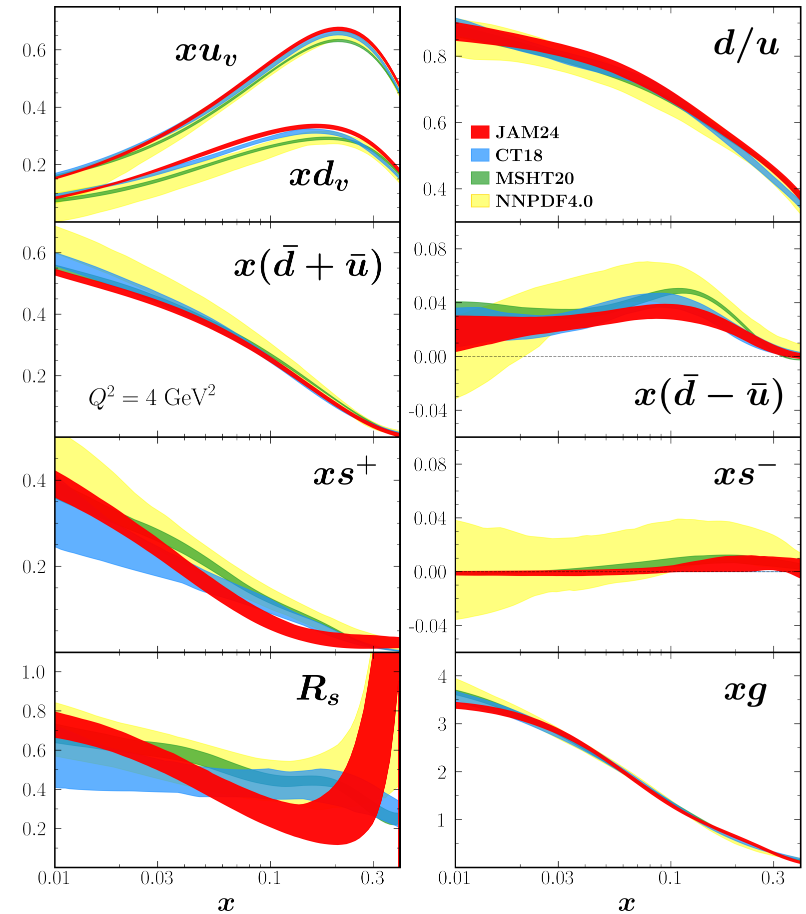
*Anderson, WM, Sato, PRD **112**, 094011 (2025)*
Cocuzza, WM, Sato, Thomas, arXiv:2605.00666

Unpolarized collinear PDFs

- Simultaneously extract PDFs and fragmentation functions from inclusive DIS, SIDIS, Drell-Yan, W/Z boson and jet production, $W{+}c$ production, single-inclusive e^+e^- annihilation



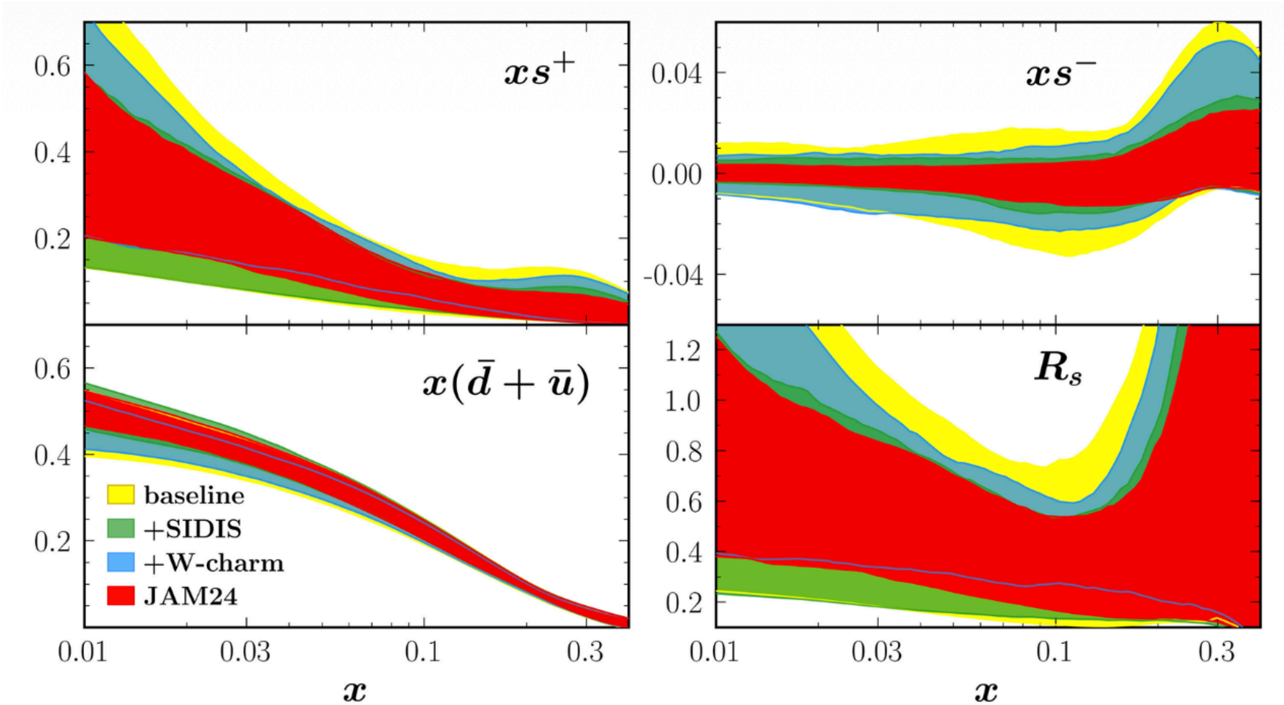
Cocuzza, WM, Sato, Thomas, arXiv:2605.00666



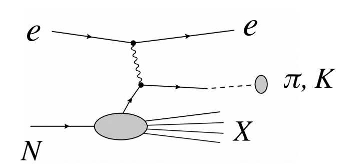
Anderson, WM, Sato, PRD ***112****, 094011 (2025)*

$\longrightarrow$ stability of fits down to $W^2 = 3.5$ GeV^2

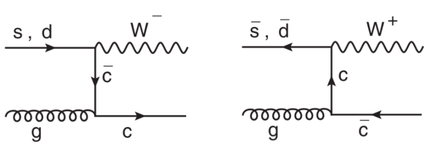
Impact of SIDIS and W+c data



→ SIDIS data have slight preference for <u>smaller</u> strangeness



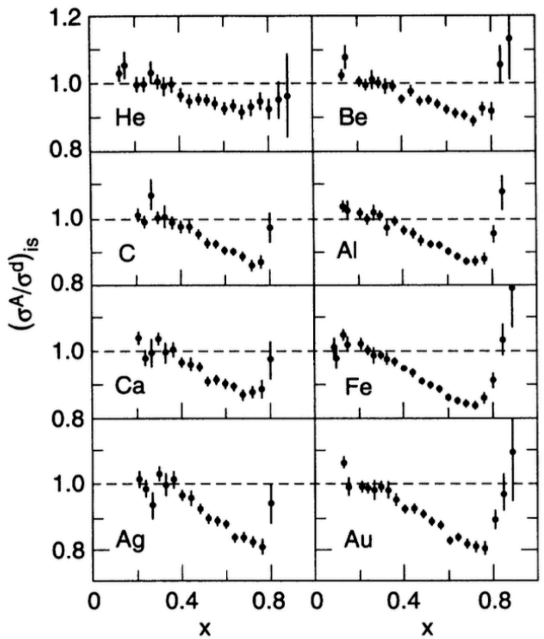
→ W+c data have slight preference for <u>larger</u> strangeness



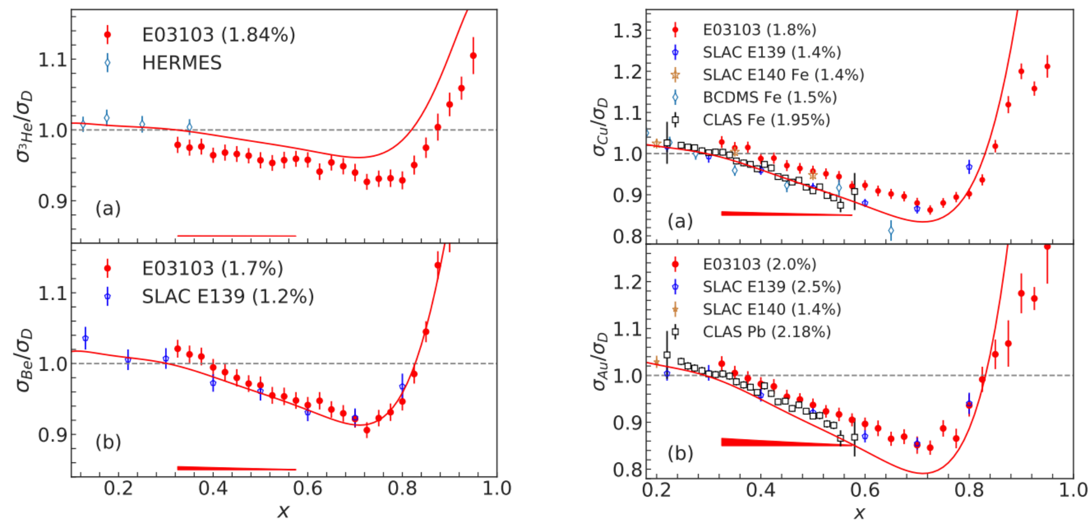
→ strange/nonstrange ratio compatible with SU(3) at $x < 0.02$, suppressed at higher x

Nuclear EMC effect

- Ratios of cross sections of nuclei to "isoscalar nucleon" (often deuteron)



Gomez et al., PRD **49**, 4348 (1994)



Arrington et al., PRC **104**, 065203 (2021)

$\longrightarrow$ similar general shape observed for all nuclei from ^{3}He to ^{208}Pb

$\longrightarrow$ for isospin asymmetric nuclei, denominator is effectively "corrected" by

$$Z\,\sigma^p \left(1 + \frac{A-Z}{Z}\,\frac{\sigma^n}{\sigma^p}\right)$$

depends on neutron/proton ratio, which is *not directly measured*

Nuclear EMC effect

- Neutron to proton cross section (or structure function) ratio traditionally obtained from deuteron to proton ratio

$$\frac{F_2^n}{F_2^p} \approx \frac{F_2^D}{F_2^p} - 1$$

$\longrightarrow$ requires model of deuteron structure

$\longrightarrow$ cannot use extracted n/p ratio to then study EMC effect in deuteron!

$\longrightarrow$ can we determine EMC effect in light nuclei independently of n/p input?

- Typically assume scattering takes place from individual nucleons in the deuteron
  $\longrightarrow$ deuteron and nucleon structure related via generalized convolution

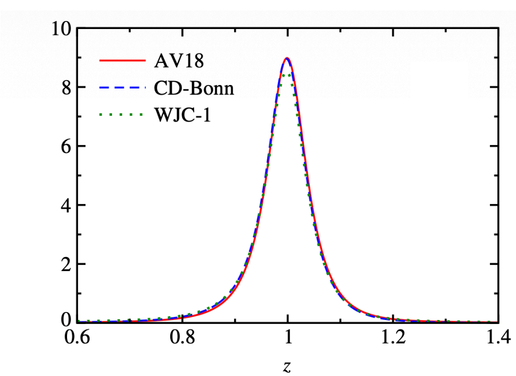
$$F_2^D(x_B,Q^2) = \sum_N \left[f_{N/D}^{(\mathrm{on})} \otimes F_2^N + f_{N/D}^{(\mathrm{off})} \otimes \delta F_2^{N/D} \right] (x_B,Q^2)$$

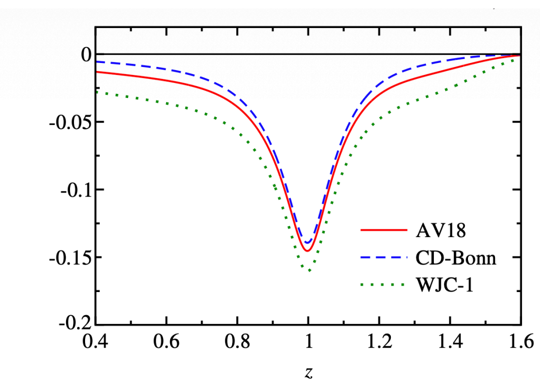
$$[f_{N/A} \otimes F_2](x_B,Q^2) \equiv \int_{x_B}^{M_A/M} \mathrm{d}y\, f_{N/A}(y,\rho)\, F_2\Big(\frac{x_B}{y},Q^2\Big)$$

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

on-shell smearing function

off-shell smearing function





Nuclear EMC effect

- Neutron to proton cross section (or structure function) ratio traditionally obtained from deuteron to proton ratio
$$\frac{F_2^n}{F_2^p} \approx \frac{F_2^D}{F_2^p} - 1$$

$\longrightarrow$ requires model of deuteron structure

$\longrightarrow$ cannot use extracted n/p ratio to then study EMC effect in deuteron!

$\longrightarrow$ can we determine EMC effect in light nuclei independently of n/p input?

- Typically assume scattering takes place from individual nucleons in the deuteron
  $\longrightarrow$ deuteron and nucleon structure related via generalized convolution

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

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

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

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

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

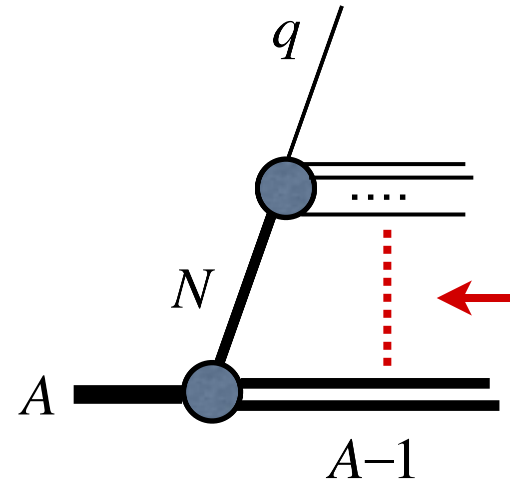
on-shell proton PDF
(fitted to world proton data,
generally well constrained)

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

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



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

$\longrightarrow$ normalization condition (valence quark number the same in free & bound nucleon)

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

$\longrightarrow$ assume isospin symmetry for all (on-shell and off-shell) PDFs

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

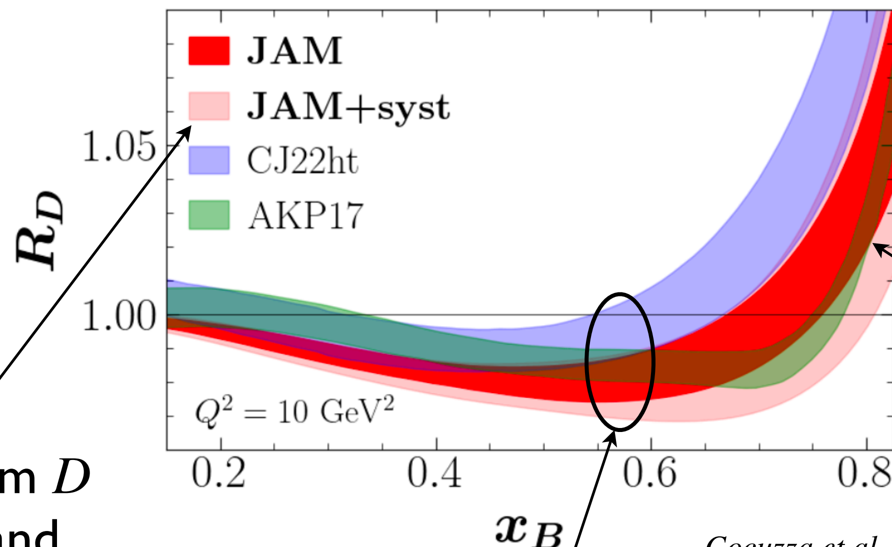
$\longrightarrow$ for $A = D$, only the isoscalar $u + d$ combination enters
(not to be confused with isospin of exchanged state *)

Deuteron EMC effect

- Ratio of deuteron to free nucleon structure functions

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

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



Cocuzza et al.
arXiv:2602.16589

uncertainties from D wave function and fitted off-shell PDFs

rapid rise due to Fermi motion

$\sim 1\%$–3% depletion at $x \sim 0.6$

Deuteron EMC effect

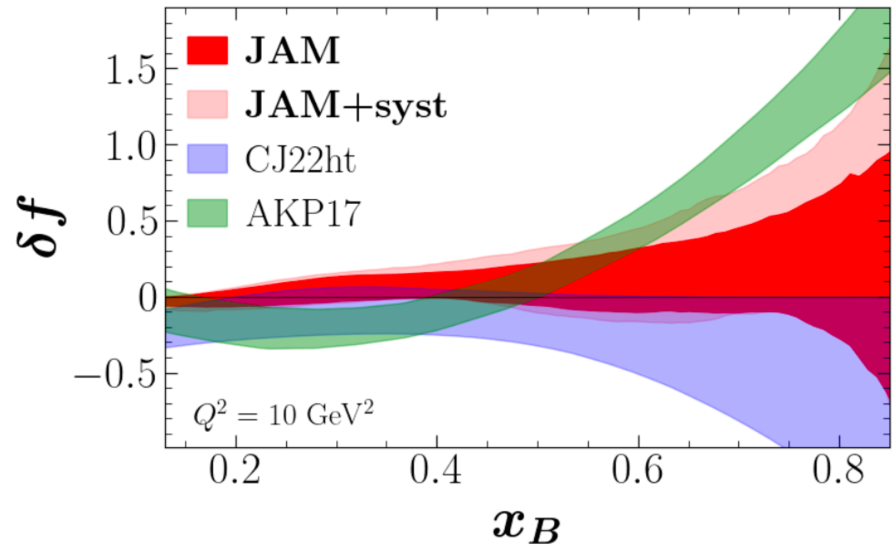
- Shape of EMC ratio depends (partly) on sign and magnitude of off-shell effects

  ⟶ for the deuteron the overall effect is small

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

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

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



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

⟶ $^3\mathrm{He}, ^3\mathrm{H}$

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

- First ever measurement of ratio of $^3\mathrm{H}/D$ and $^3\mathrm{He}/D$ (and $^3\mathrm{He}/^3\mathrm{H}$) cross sections in MARATHON experiment

  $\longrightarrow$ original motivation was extraction of ratio of neutron to proton structure functions

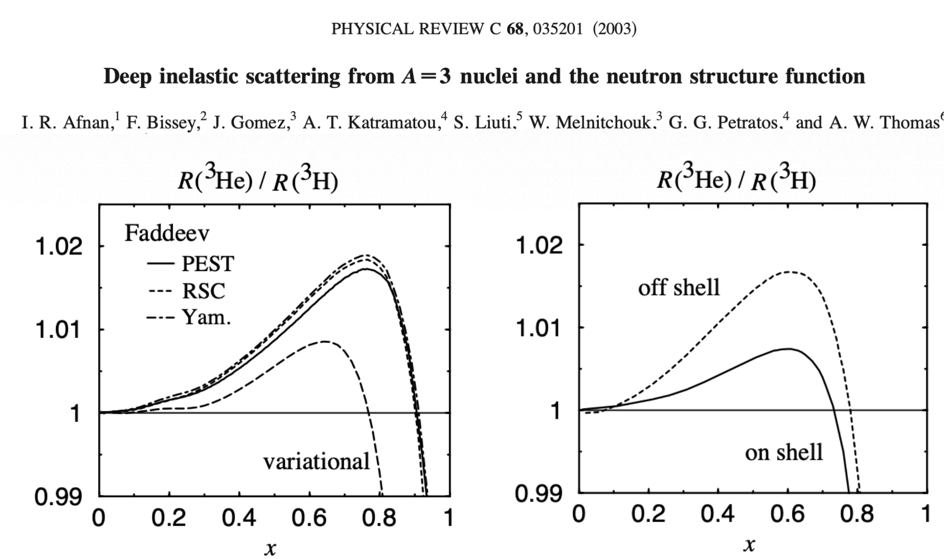
$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}}{2F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}} - \mathcal{R}} \longleftarrow \mathcal{R} \equiv \mathcal{R}_{^3\mathrm{He}/^3\mathrm{H}} = \frac{R_{^3\mathrm{He}}}{R_{^3\mathrm{H}}} \longleftarrow \left\{ \begin{array}{l} R_{^3\mathrm{He}} = \dfrac{F_2^{^3\mathrm{He}}}{2F_2^p + F_2^n} \\[2ex] R_{^3\mathrm{H}} = \dfrac{F_2^{^3\mathrm{H}}}{F_2^p + 2F_2^n} \end{array} \right.$$

  and determination of d/u PDF ratio

  … assuming knowledge of nuclear effects!

- Early calculations predicted a small, $\sim 1\%$–2% effect for the "super-ratio"

  … but effectively assumed isospin independence of off-shell effects



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

- First ever measurement of ratio of $^3\mathrm{H}/D$ and $^3\mathrm{He}/D$ (and $^3\mathrm{He}/^3\mathrm{H}$) cross sections in MARATHON experiment

  $\longrightarrow$ original motivation was extraction of ratio of neutron to proton structure functions

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}}{2F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}} - \mathcal{R}} \longleftarrow \mathcal{R} \equiv \mathcal{R}_{^3\mathrm{He}/^3\mathrm{H}} = \frac{R_{^3\mathrm{He}}}{R_{^3\mathrm{H}}} \longleftarrow \begin{cases} R_{^3\mathrm{He}} = \dfrac{F_2^{^3\mathrm{He}}}{2F_2^p + F_2^n} \\ R_{^3\mathrm{H}} = \dfrac{F_2^{^3\mathrm{H}}}{F_2^p + 2F_2^n} \end{cases}$$

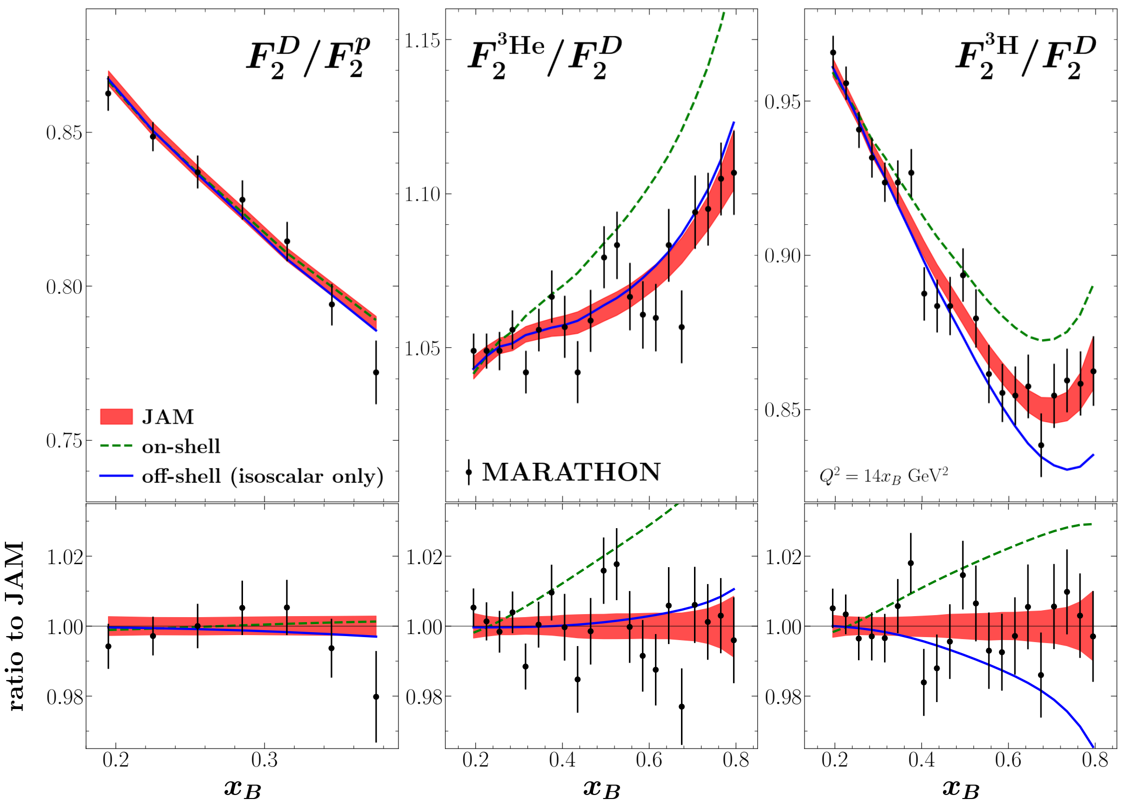
  and determination of d/u PDF ratio
  … assuming knowledge of nuclear effects!

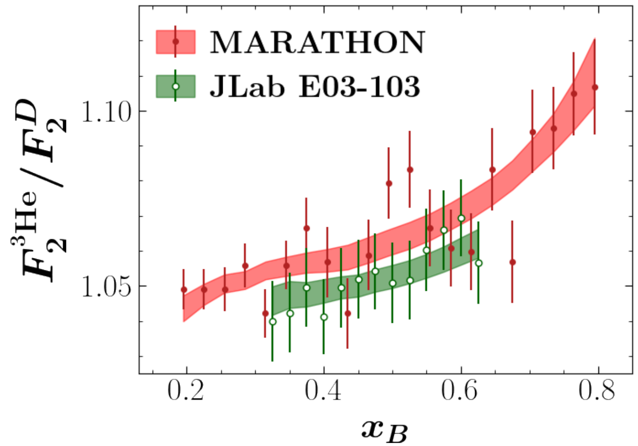
- Can we learn about *both* on-shell proton PDFs *and* off-shell functions (nuclear effects)?

  $\longrightarrow$ JAM framework ideally suited to such (simultaneous) analysis

Global QCD analysis with MARATHON data

MARATHON data versus theory comparisons





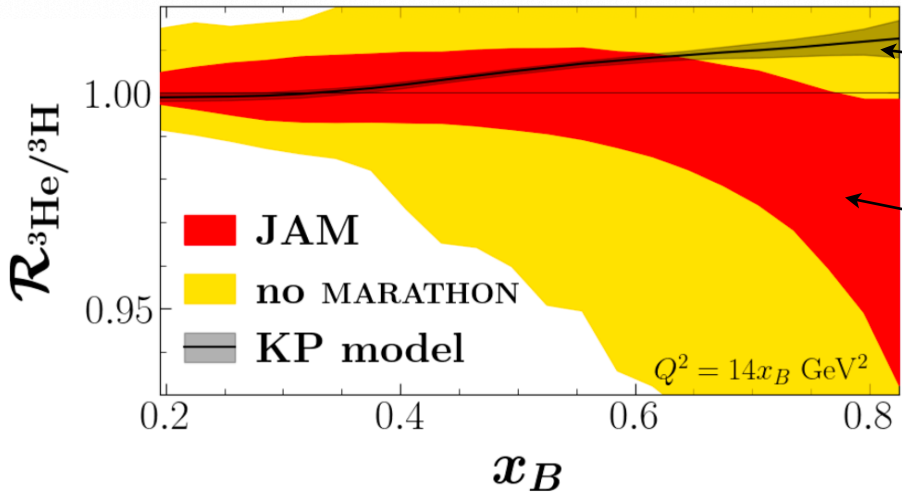
Process	N_{dat}	χ^2_{red} on-shell fit	full fit
DIS			
MARATHON D/p [30]	7	0.68	0.70
MARATHON ^{3}He$/D$ [31]	21	5.10	1.04
MARATHON ^{3}H$/D$ [31]	21	2.20	0.83
JLab E03-103 ^{3}He$/D$ [48]	13	0.33	0.22
other fixed target	2793	0.99	0.99
HERA	1185	1.17	1.16
Drell-Yan	205	1.18	1.18
W-lepton asymmetry	70	0.82	0.82
W charge asymmetry	27	1.03	1.03
Z rapidity	56	1.10	1.11
jet	200	1.12	1.10
Total	**4598**	**1.07**	**1.04**

$\longrightarrow$ good agreement between data (including MARATHON and E03-103) and theory in global fit

Cocuzza et al., arXiv:2602.16589

Global QCD analysis with MARATHON data

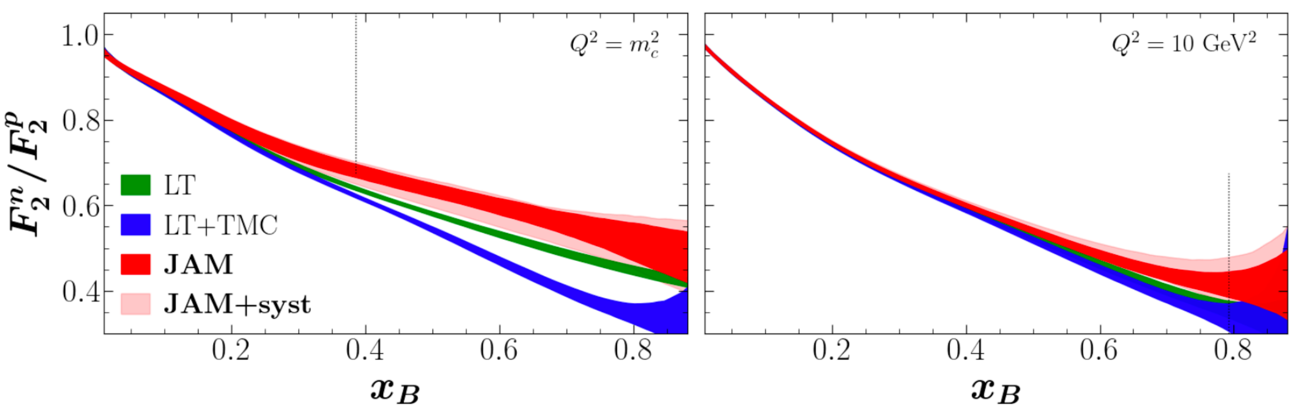
Super-ratio of ^{3}He and ^{3}H EMC ratios



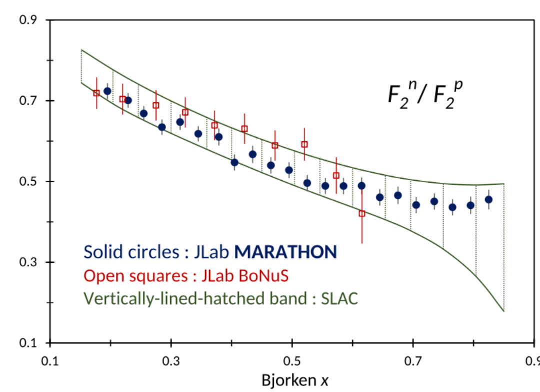
assumed in MARATHON analysis

significant uncertainty reduction with MARATHON data

Fitted neutron to proton structure function ratio



Cocuzza et al., arXiv:2602.16589

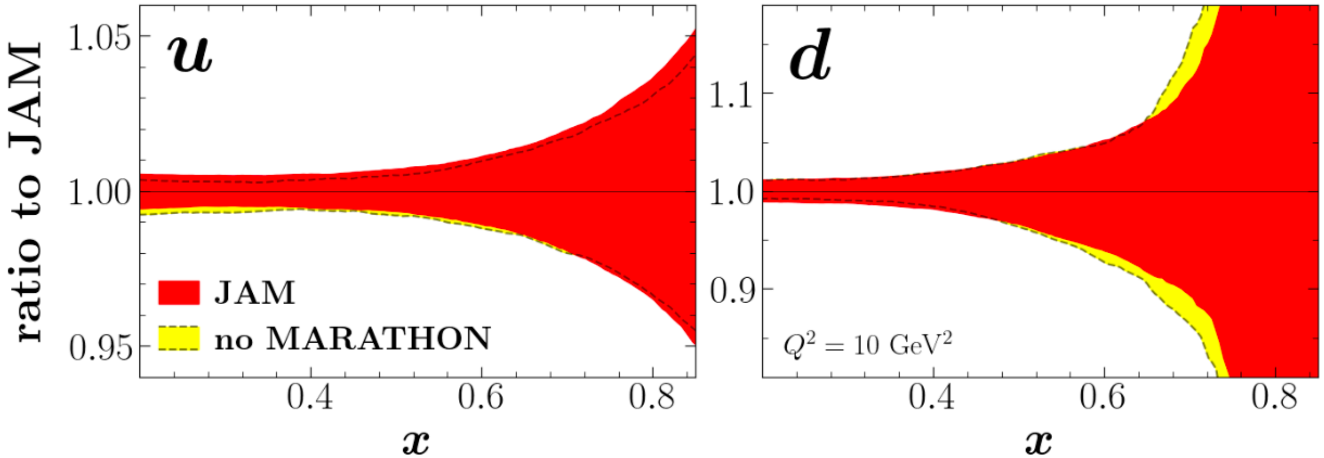


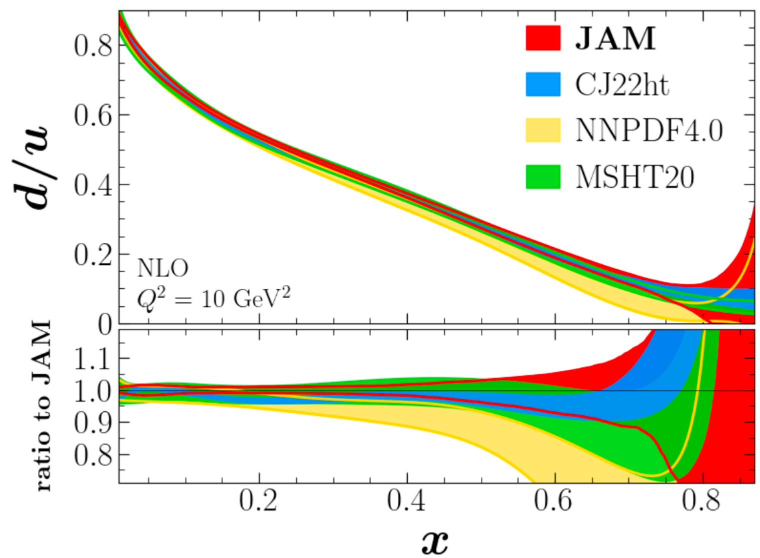
*Abrams et al., PRL **128**, 132003 (2022)*

$\longrightarrow$ relatively small difference between JAM global fit and MARATHON extraction

Global QCD analysis with MARATHON data

- Impact of MARATHON data on u and d PDFs in the proton

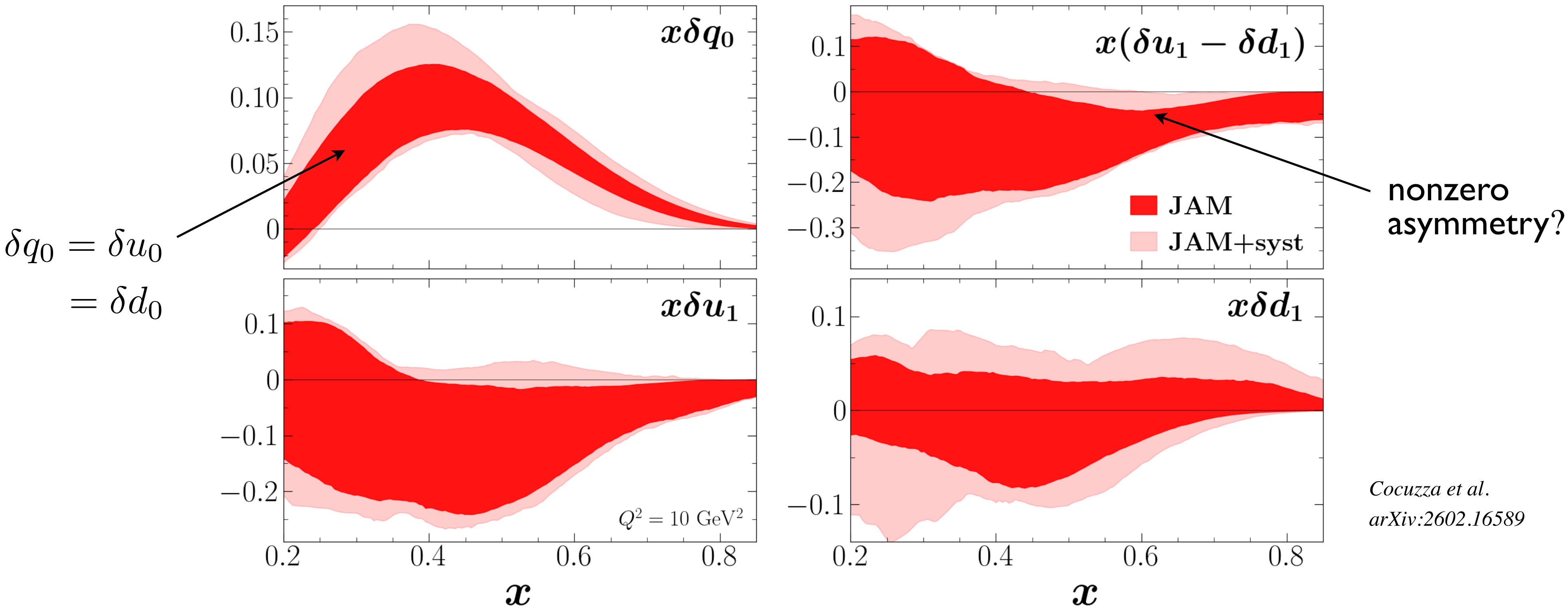




$\longrightarrow$ relatively small effect on u and d PDFs
… already constrained by global dataset

Global QCD analysis with MARATHON data

- First ever extraction of isospin and flavor dependence of off-shell PDFs



Cocuzza et al.
arXiv:2602.16589

$$\delta u^{(0)}_{p/^3\mathrm{He}} = \delta u^{(0)}_{p/^3\mathrm{H}} = 2\,\delta u^{(0)}_{p/D} \equiv \delta u_0$$
$$\delta d^{(0)}_{p/^3\mathrm{He}} = \delta d^{(0)}_{p/^3\mathrm{H}} = 2\,\delta d^{(0)}_{p/D} \equiv \delta d_0.$$

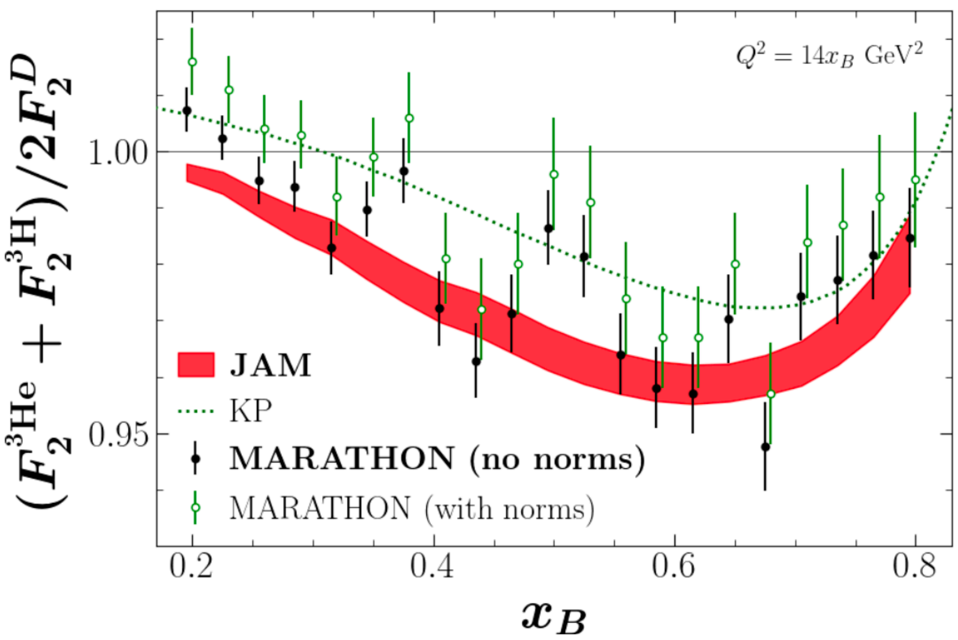
$$\delta u^{(1)}_{p/^3\mathrm{He}} = 0, \quad \delta u^{(1)}_{p/^3\mathrm{H}} = 2\,\delta u^{(1)}_{p/D} \equiv \delta u_1$$
$$\delta d^{(1)}_{p/^3\mathrm{He}} = 0, \quad \delta d^{(1)}_{p/^3\mathrm{H}} = 2\,\delta d^{(1)}_{p/D} \equiv \delta d_1$$

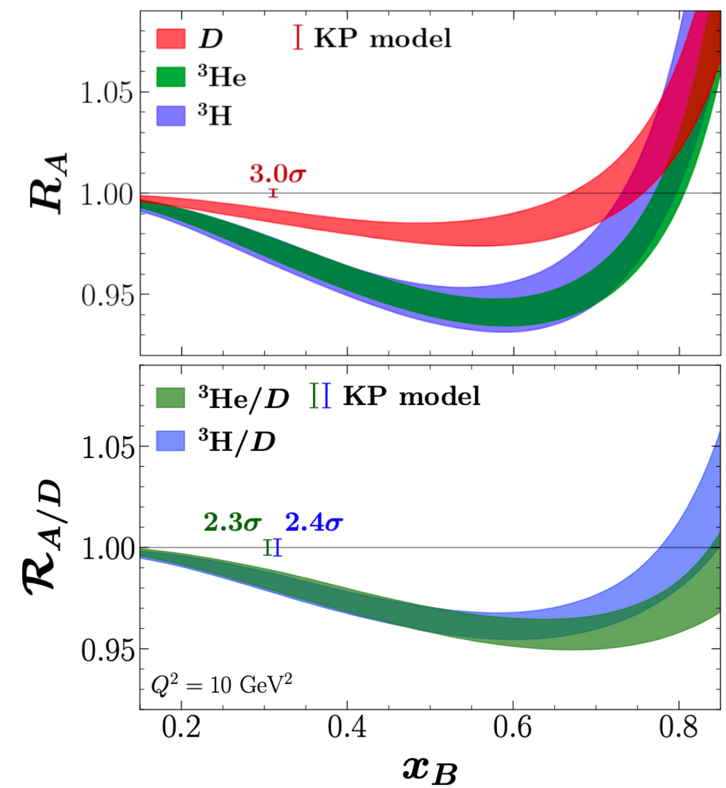
$\longrightarrow$ large nonzero isoscalar off-shell PDF

$\longrightarrow$ hint of flavor asymmetric isovector off-shell PDF

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

- JAM analysis fits all overall normalization uncertainties, within quoted uncertainties — *cf.* MARATHON experiment, fixed normalization assuming no EMC effect at $x = 0.31$ for all nuclei (as in Kulagin-Petti model)



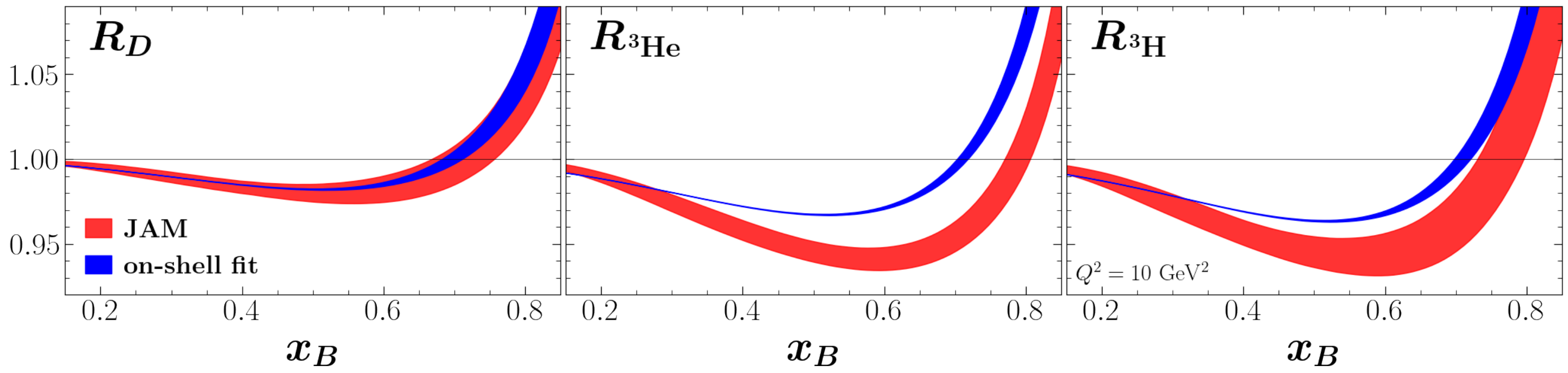


dataset	experimental norm. uncertainty	fitted normalization	MARATHON +KP model	significa of difference
MARATHON D/p	0.8%	**1.017(4)**	—	—
MARATHON ^{3}He$/D$	1.2%	**0.996(6)**	1.021(5)	3.2σ
MARATHON ^{3}H$/D$	0.8%	**0.991(5)**	0.996(5)	0.7σ

→ significant difference between globally fitted and MARATHON+KP normalizations for ^{3}He$/D$ data

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

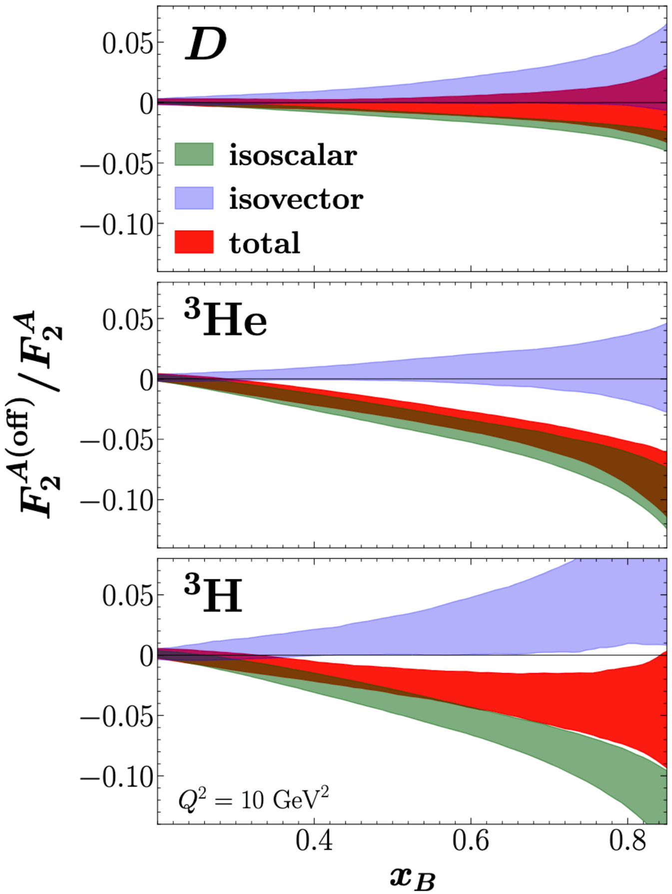
- Shape of EMC ratio depends on sign and magnitude of off-shell effects



→ D: cancellation of small isovector (>0) and isoscalar (<0) contributions

→ ^{3}He: almost no contribution from isovector; entire effect from isoscalar

→ ^{3}H: large isoscalar, partially cancelling smaller isovector



Outlook

- Performed comprehensive global QCD analysis of unpolarized PDFs in the proton from world p, D, A=3 data, including latest MARATHON data
  - ⟶ JAM framework ideally suited to such (simultaneous) analysis
  - ⟶ no need to fix normalization of MARATHON data to models

- Observations
  - ⟶ nucleon off-shell contributions to PDFs essential to fit A=3 data
  - ⟶ sizable isoscalar off-shell corrections, hint of isovector effect
  - ⟶ first information on flavor dependence on EMC effect in light nuclei

- Future
  - ⟶ proposal to redo ^{3}He/^{3}H in Hall C — PR12-26-011 (Tyler Hague *et al.*)
    - — test MARATHON test normalization procedure
  - ⟶ SIDIS with ^{3}He/^{3}H
    - — additional, independent combinations of u, d flavors