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

Hadron structure from JAM global QCD analysis

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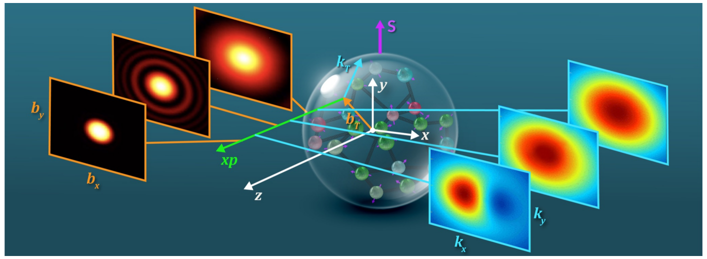
Global QCD analysis with JAM

- 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 distributi
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 function
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 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]*

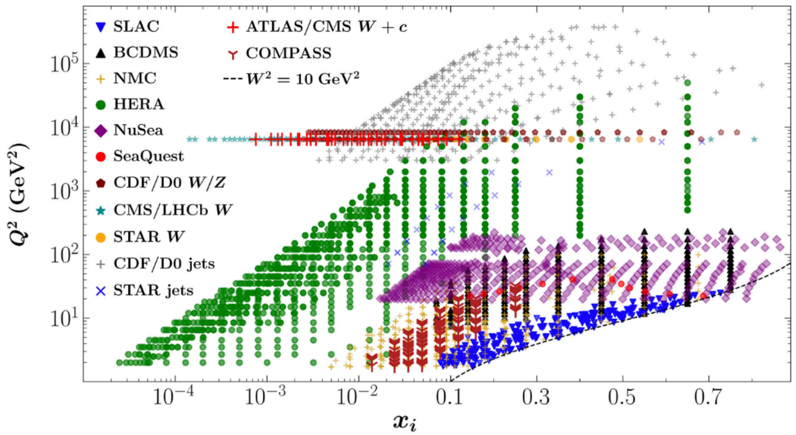
GPDs

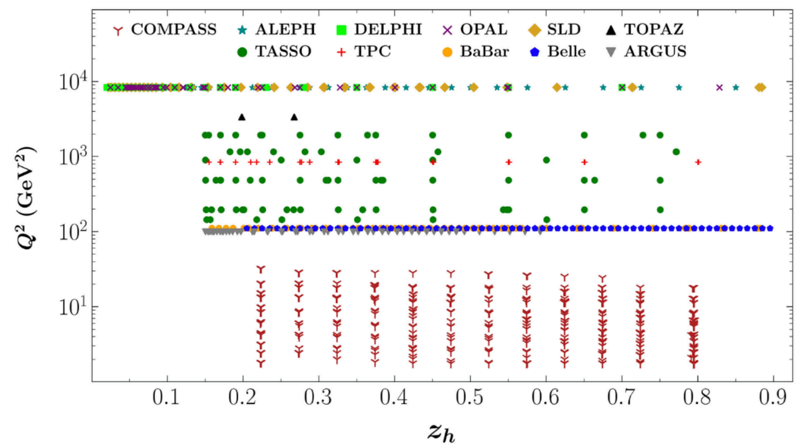
Kernel methods for evolution of GPDs
A. Freese, D. Adamiak, I. Cloët, W. Melnitchouk, J.-W. Qiu, N. Sato, M. Zaccheddu
Comput. Phys. Commun. 311, 109552 (2025), *arXiv:2412.13450 [hep-ph]*

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 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



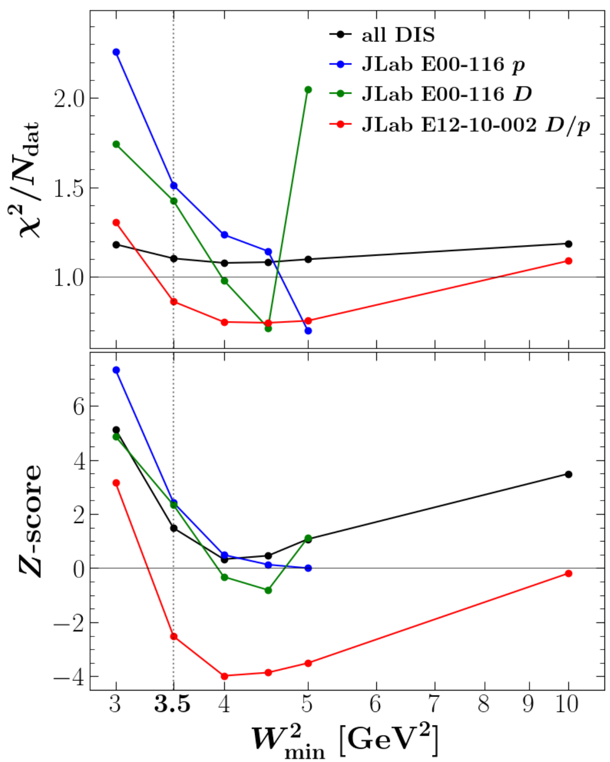


		$\chi^2_{\rm red}$ (Z-score)			
Process	$N_{\rm dat}$	Baseline	+SIDIS	$+W$-charm	**JAM**
DIS					
fixed target [39–42]	1495	1.07(+1.95)	1.08(+2.23)	1.07(+1.92)	**1.08**(+**2.25**)
HERA [43]	1185	1.16(+3.64)	1.18(+4.22)	1.15(+3.57)	**1.18**(+**4.22**)
Drell-Yan [2,3]	205	1.15(+1.50)	1.17(+1.69)	1.14(+1.43)	**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**)

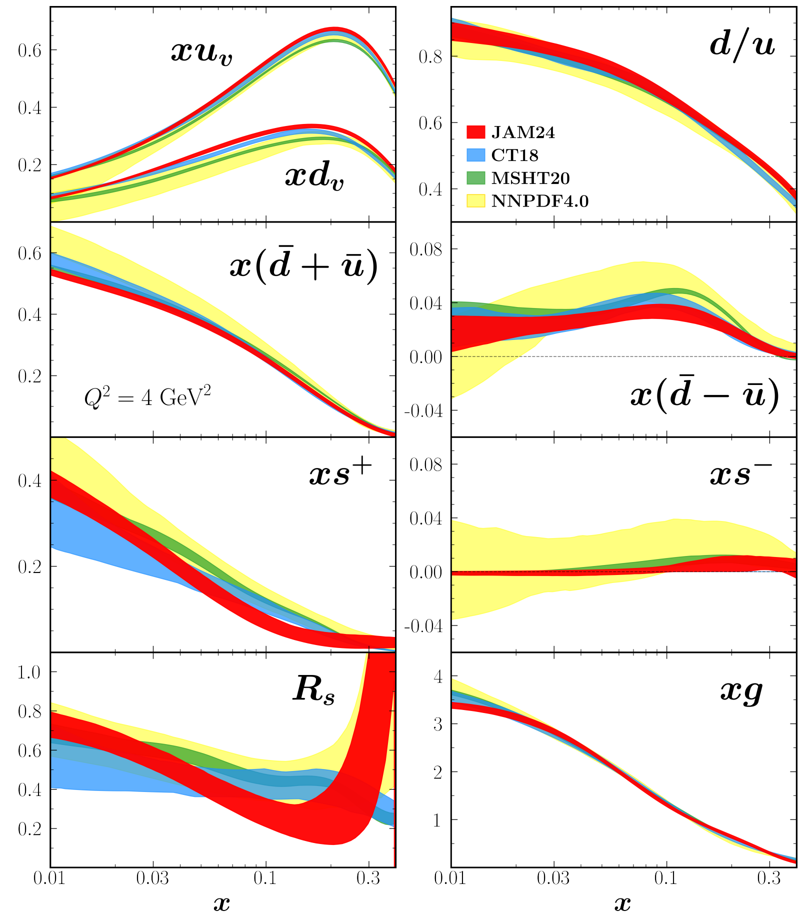
*Anderson, WM, Sato, PRD **112**, 094011 (2025)*
Cocuzza, WM, Sato, Thomas, arXiv:2605.00666

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



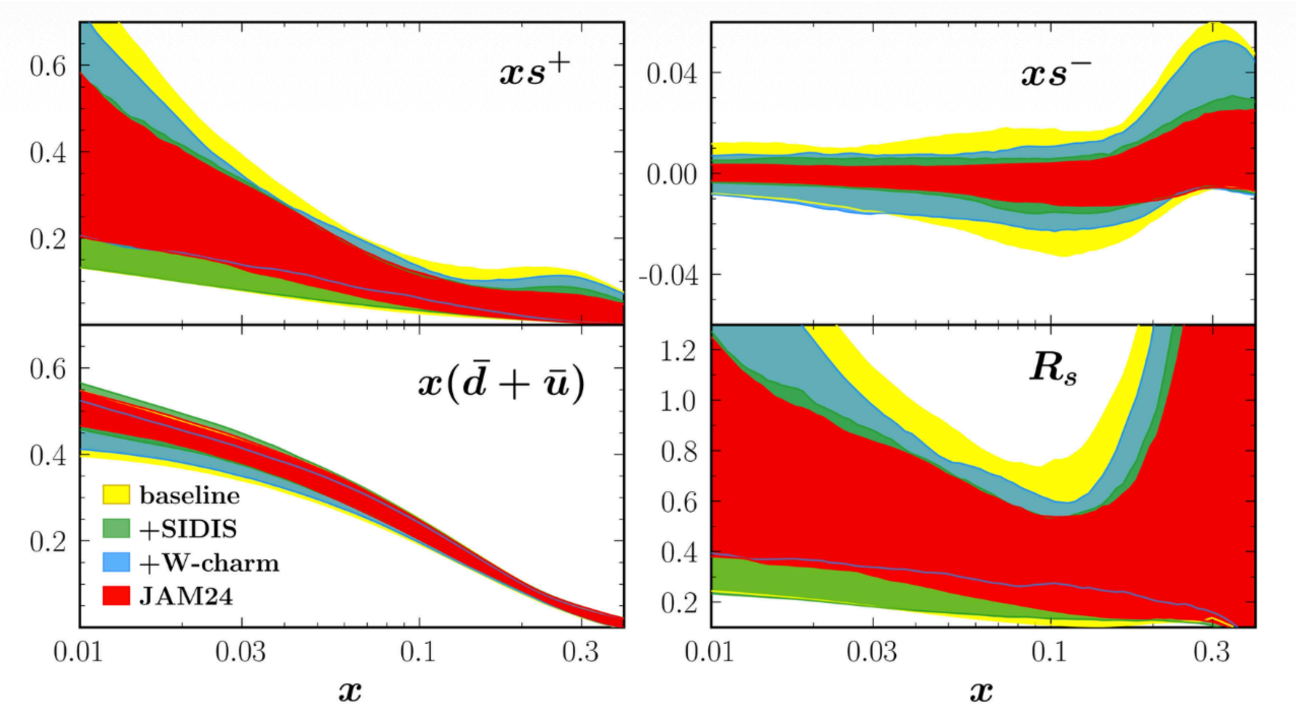
Cocuzza, WM, Sato, Thomas, arXiv:2605.00666



→ stability of fits down to $W^2 = 3.5\ \mathrm{GeV}^2$

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

Impact of SIDIS and $W{+}c$ data



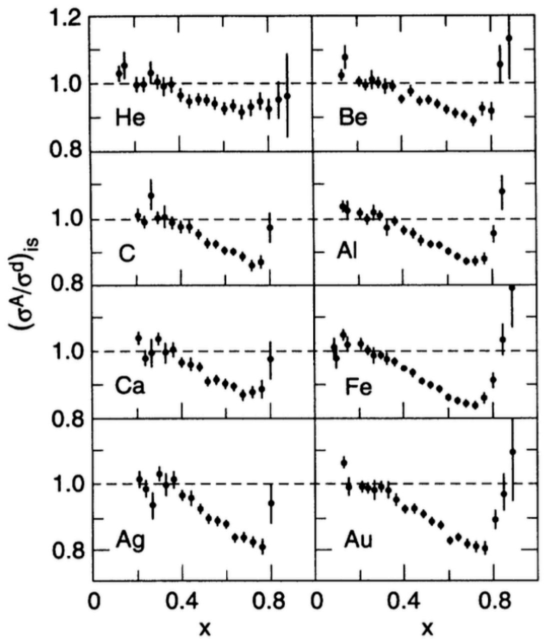
→ SIDIS data have slight preference for <u>smaller</u> strangeness

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

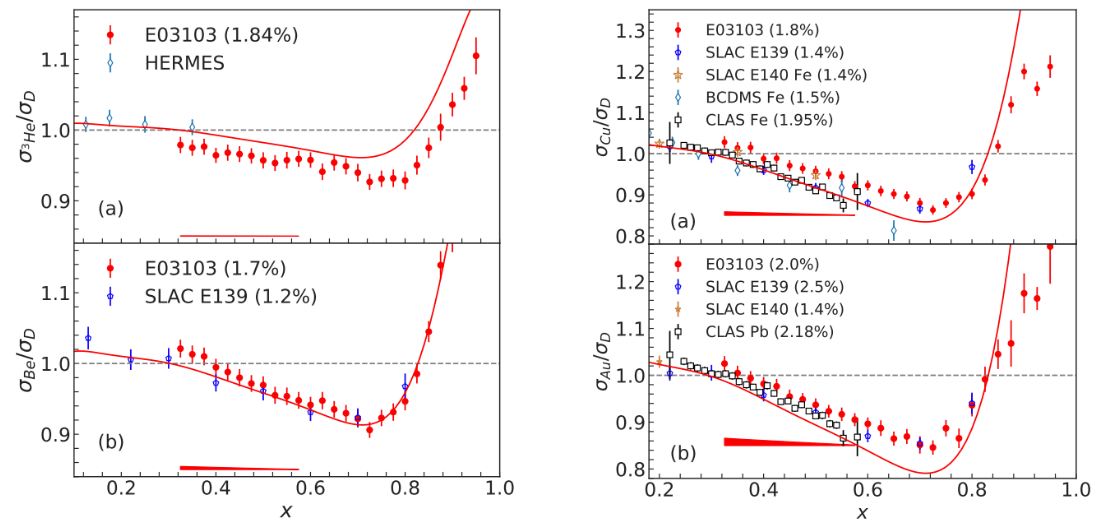
→ strange/nonstrange ratio compatible with SU(3) at $x < 0.02$, suppressed at higher x

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

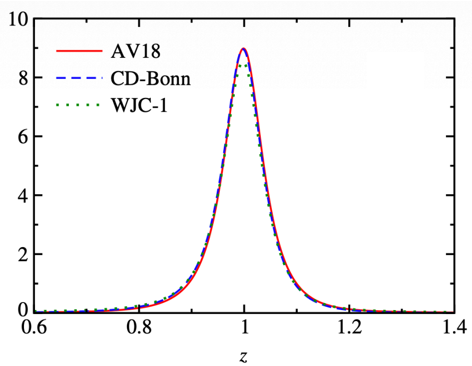
$$F_2^D(x_B, Q^2) = \sum_N \left[f_{N/D}^{(\mathrm{on})} \otimes F_2^N + f_{N/D}^{(\mathrm{off})} \otimes \delta F_2^{N/D} \right] (x_B, Q^2)$$

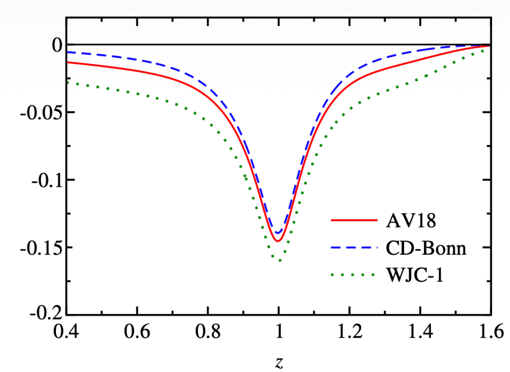
$$[f_{N/A} \otimes F_2](x_B, Q^2) \equiv \int_{x_B}^{M_A/M} \mathrm{d}y\, f_{N/A}(y,\rho)\, F_2\Big(\frac{x_B}{y}, Q^2\Big)$$

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

on-shell smearing function

off-shell smearing function





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on-shell smearing function

off-shell smearing function

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

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

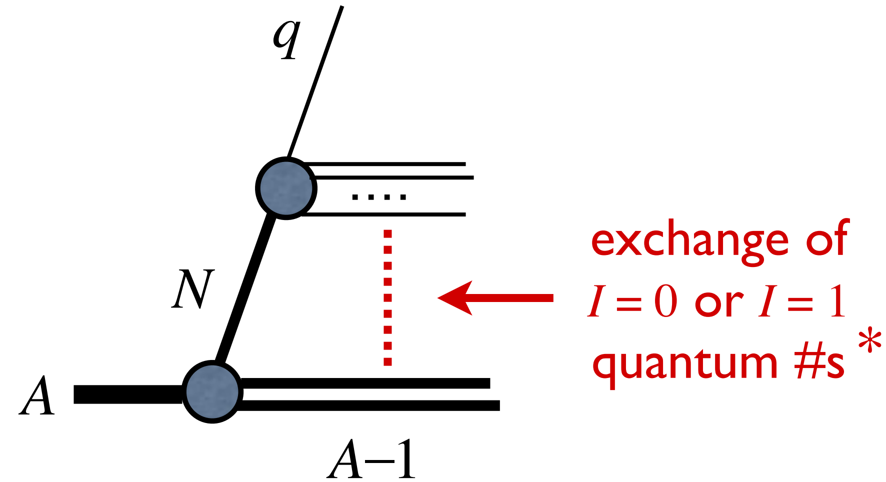
on-shell proton PDF
(fitted to world proton data, generally well constrained)

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

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



$\longrightarrow$ depends also on the nature of interaction between spectator partons ("diquark") and residual (A-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

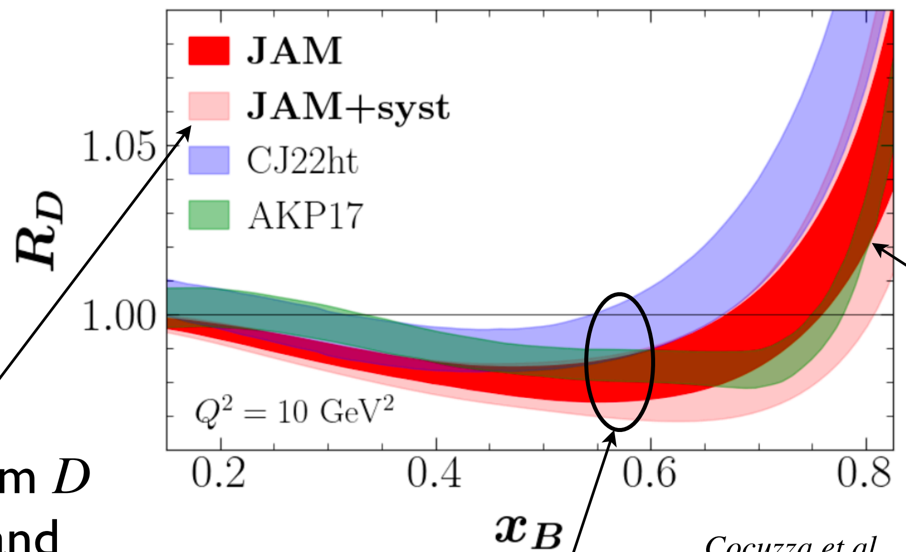
(not to be confused with isospin of exchanged state *)

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



uncertainties from D wave function and fitted off-shell PDFs

rapid rise due to Fermi motion

Cocuzza et al. arXiv:2602.16589

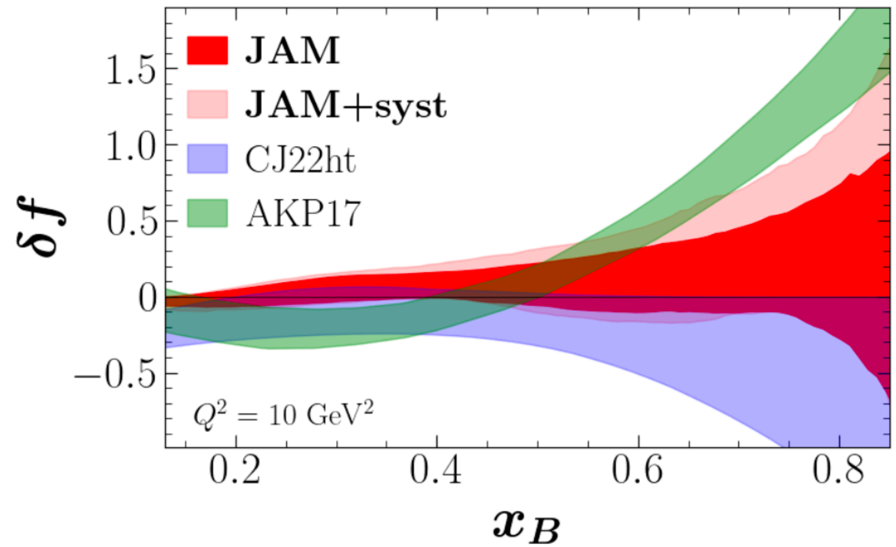
$\sim 1\%$–3% depletion at $x \sim 0.6$

Deuteron EMC effect

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

  $\longrightarrow$ 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

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

$\longrightarrow$ need other nuclei to determine flavor dependence

$\longrightarrow$ ^{3}He, ^{3}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

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

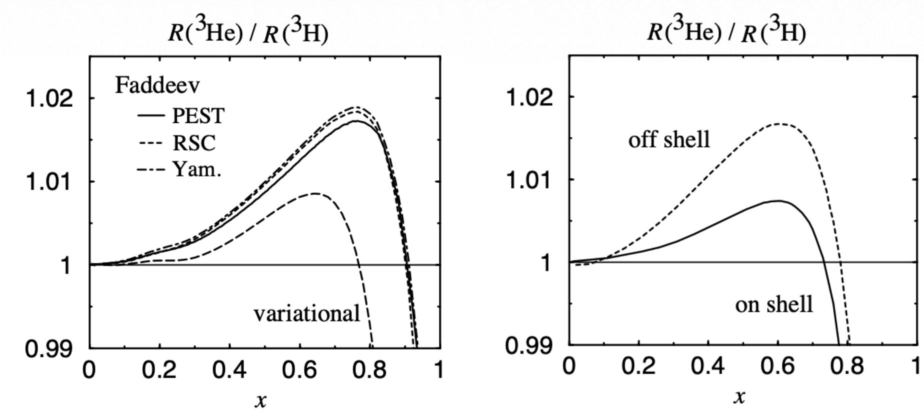
  and determination of d/u PDF ratio
  … assuming knowledge of nuclear effects!

- Early calculations predicted a small, ~1%–2% effect for the "super-ratio"
  … but effectively assumed isospin independence of off-shell effects

PHYSICAL REVIEW C **68**, 035201 (2003)

Deep inelastic scattering from $A=3$ nuclei and the neutron structure function

I. R. Afnan,[1] F. Bissey,[2] J. Gomez,[3] A. T. Katramatou,[4] S. Liuti,[5] W. Melnitchouk,[3] G. G. Petratos,[4] and A. W. Thomas[6]



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

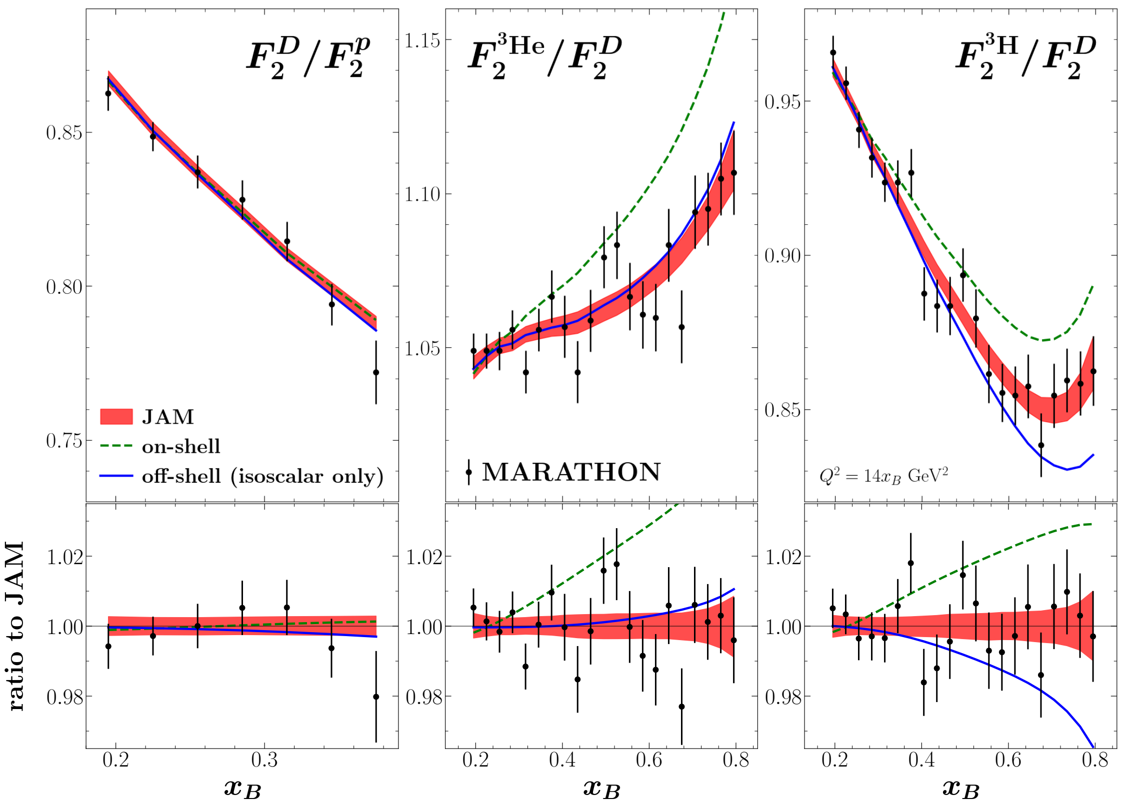
  … assuming knowledge of nuclear effects!

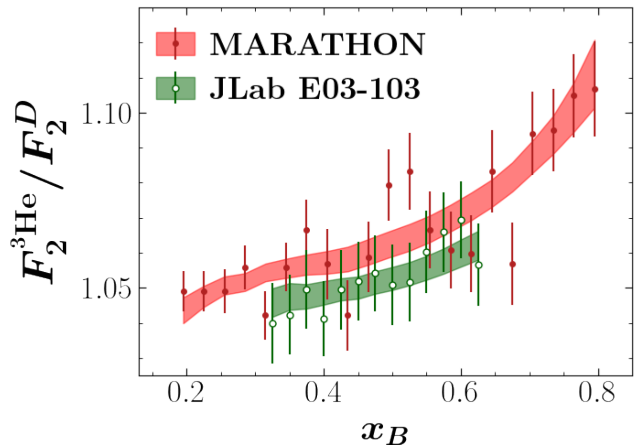
- Can we learn about *both* on-shell proton PDFs *and* off-shell functions (nuclear effects)?

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

Global QCD analysis with MARATHON data

MARATHON data versus theory comparisons





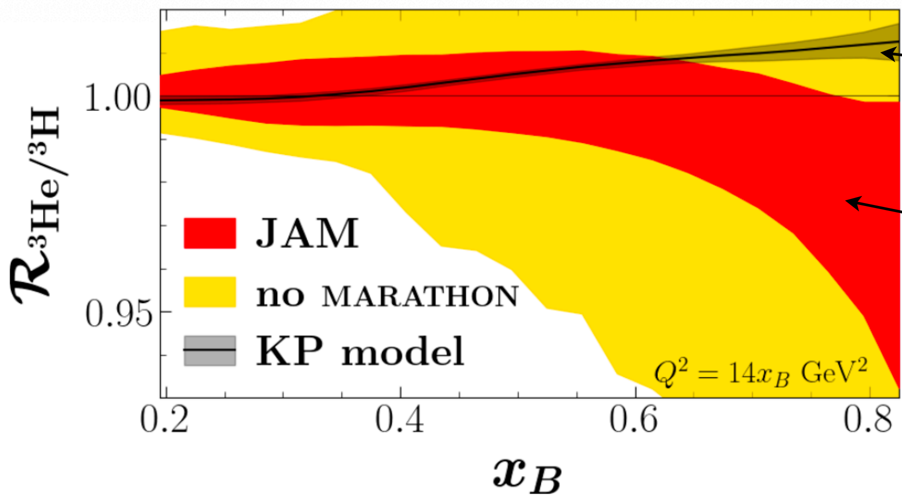
→ good agreement between data (including MARATHON and E03-103) and theory in global fit

Process	N_{dat}	χ^2_{red} on-shell fit	χ^2_{red} full fit
DIS			
MARATHON D/p [30]	7	0.68	0.70
MARATHON $^3\text{He}/D$ [31]	21	5.10	1.04
MARATHON $^3\text{H}/D$ [31]	21	2.20	0.83
JLab E03-103 $^3\text{He}/D$ [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**

Cocuzza et al., arXiv:2602.16589

Global QCD analysis with MARATHON data

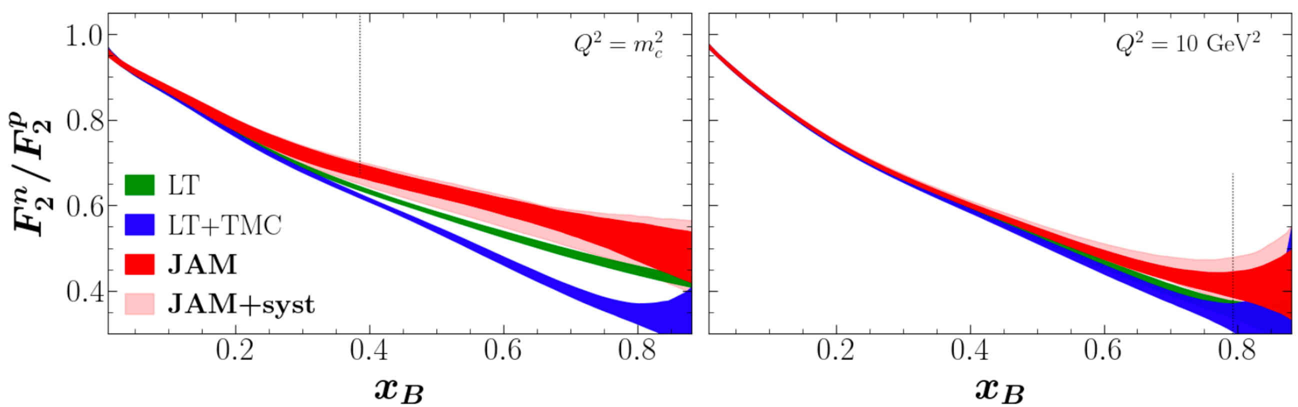
Super-ratio of ^{3}He and ^{3}H EMC ratios



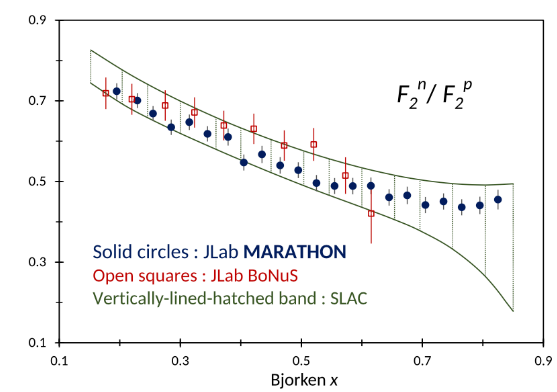
assumed in MARATHON analysis

significant uncertainty reduction with MARATHON data

Fitted neutron to proton structure function ratio



Cocuzza et al., arXiv:2602.16589

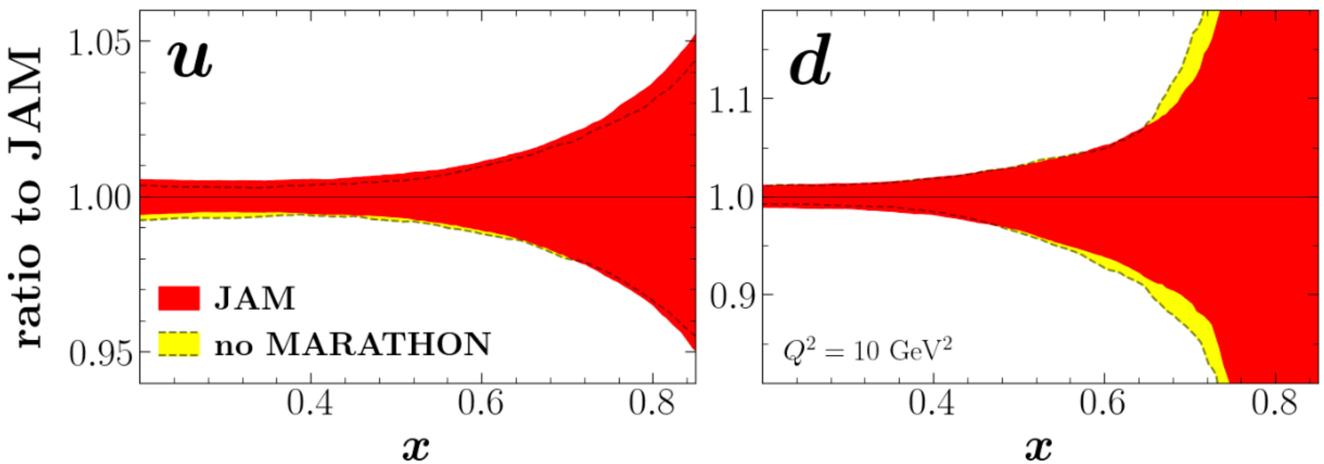


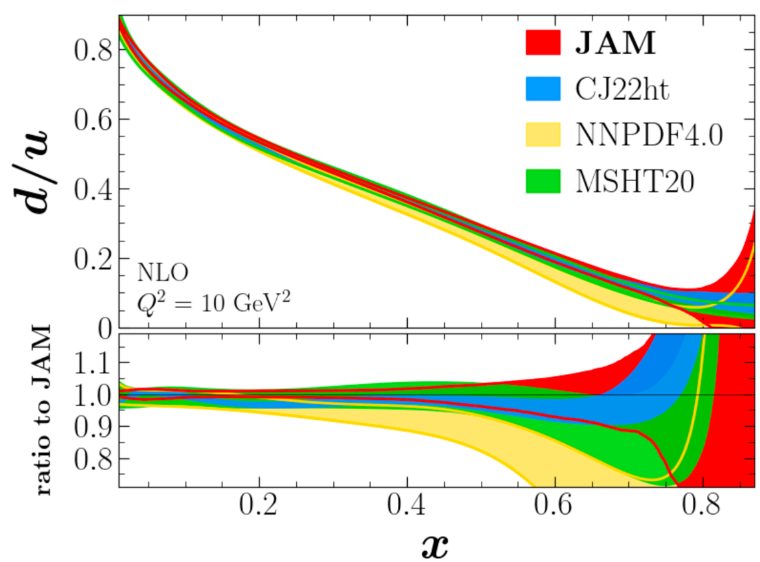
*Abrams et al., PRL **128**, 132003 (2022)*

→ 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





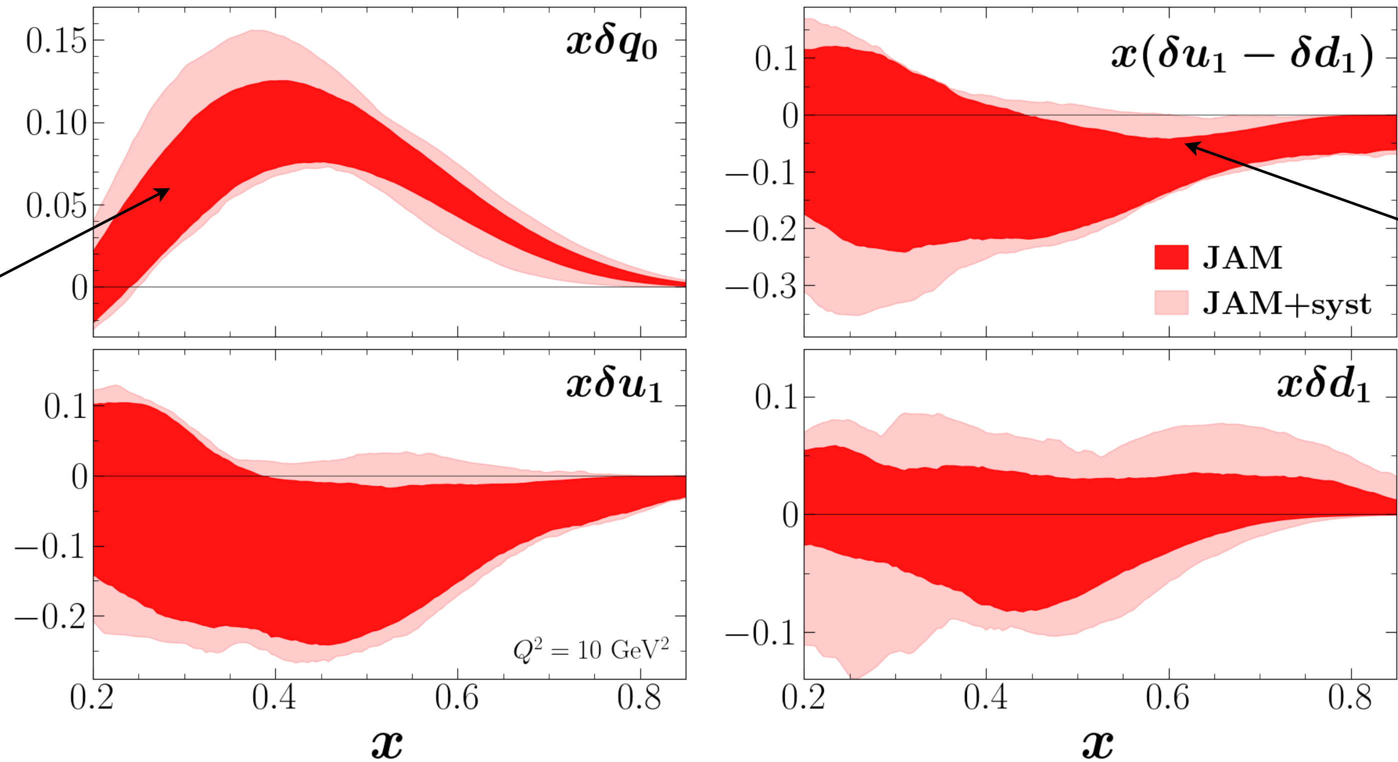
→ relatively small effect on u and d PDFs

… already constrained by global dataset

Global QCD analysis with MARATHON data

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

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



nonzero
asymmetry?

Cocuzza et al.
arXiv:2602.16589

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

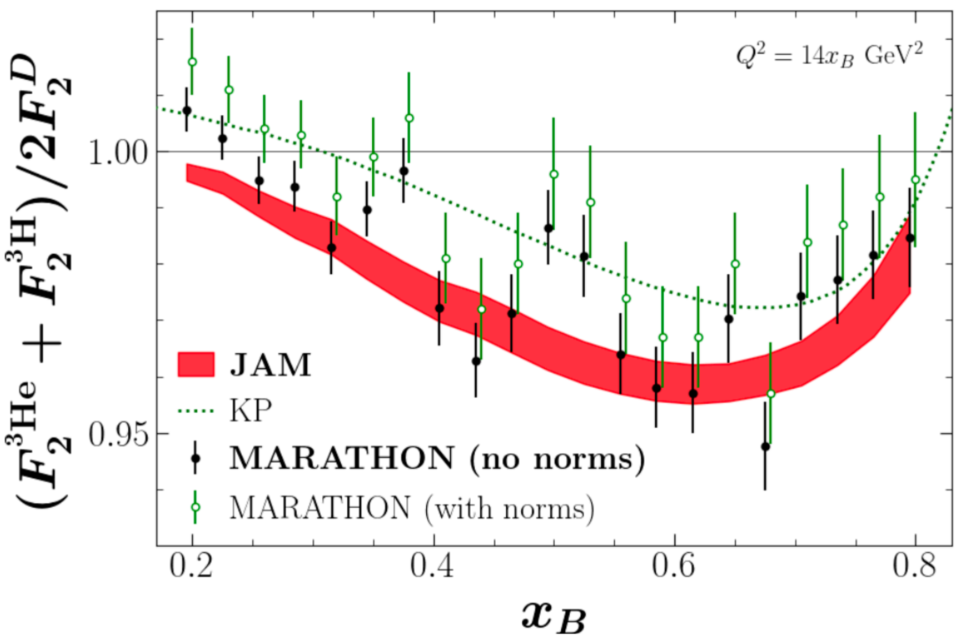
$$\delta u^{(1)}_{p/^3\mathrm{He}} = 0, \quad \delta u^{(1)}_{p/^3\mathrm{H}} = 2\,\delta u^{(1)}_{p/D} \equiv \delta u_1$$
$$\delta d^{(1)}_{p/^3\mathrm{He}} = 0, \quad \delta d^{(1)}_{p/^3\mathrm{H}} = 2\,\delta d^{(1)}_{p/D} \equiv \delta d_1$$

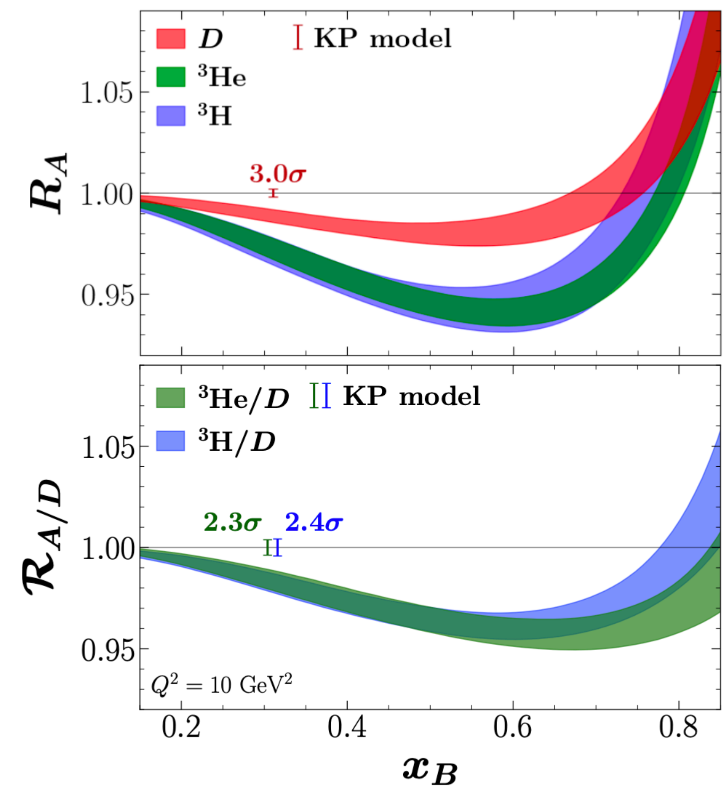
$\longrightarrow$ large nonzero isoscalar off-shell PDF

$\longrightarrow$ 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)



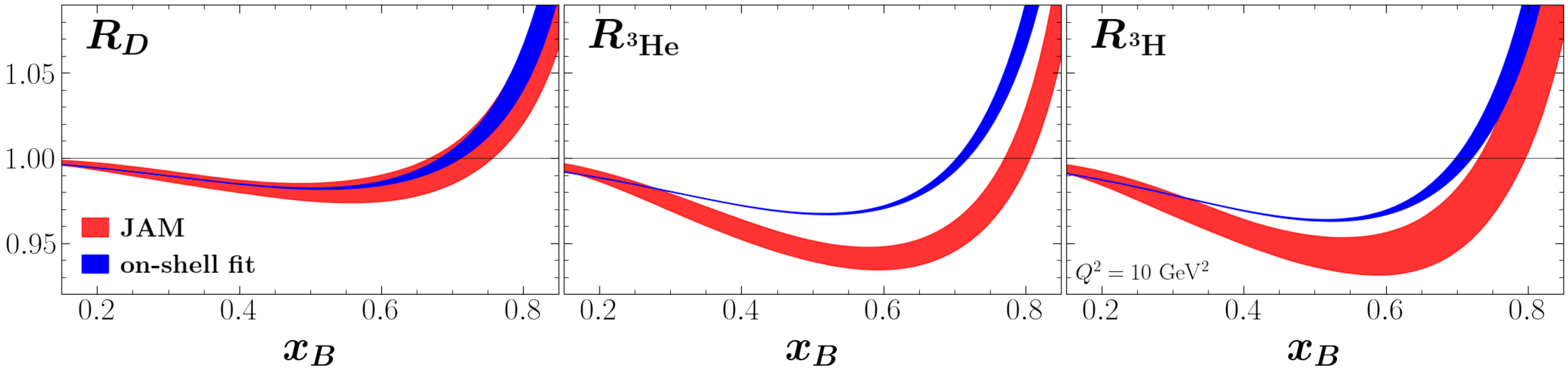


dataset	experimental norm. uncertainty	fitted normalization	MARATHON +KP model	significa of difference
MARATHON D/p	0.8%	**1.017(4)**	—	—
MARATHON ^{3}He$/D$	1.2%	**0.996(6)**	1.021(5)	3.2σ
MARATHON ^{3}H$/D$	0.8%	**0.991(5)**	0.996(5)	0.7σ

→ 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



$$\delta u_{p/D} = \frac{1}{2}(\delta u_0 + \delta u_1) \qquad \delta u_{p/^3\mathrm{He}} = \delta u_0, \qquad \delta u_{p/^3\mathrm{H}} = \delta u_0 + \delta u_1,$$

$$\delta d_{p/D} = \frac{1}{2}(\delta d_0 + \delta d_1), \qquad \delta d_{p/^3\mathrm{He}} = \delta d_0, \qquad \delta d_{p/^3\mathrm{H}} = \delta d_0 + \delta d_1,$$

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

$\longrightarrow$ essentially no off-shell effect in deuteron

$\longrightarrow$ significant off-shell effect in ^{3}He, slightly smaller in ^{3}H

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