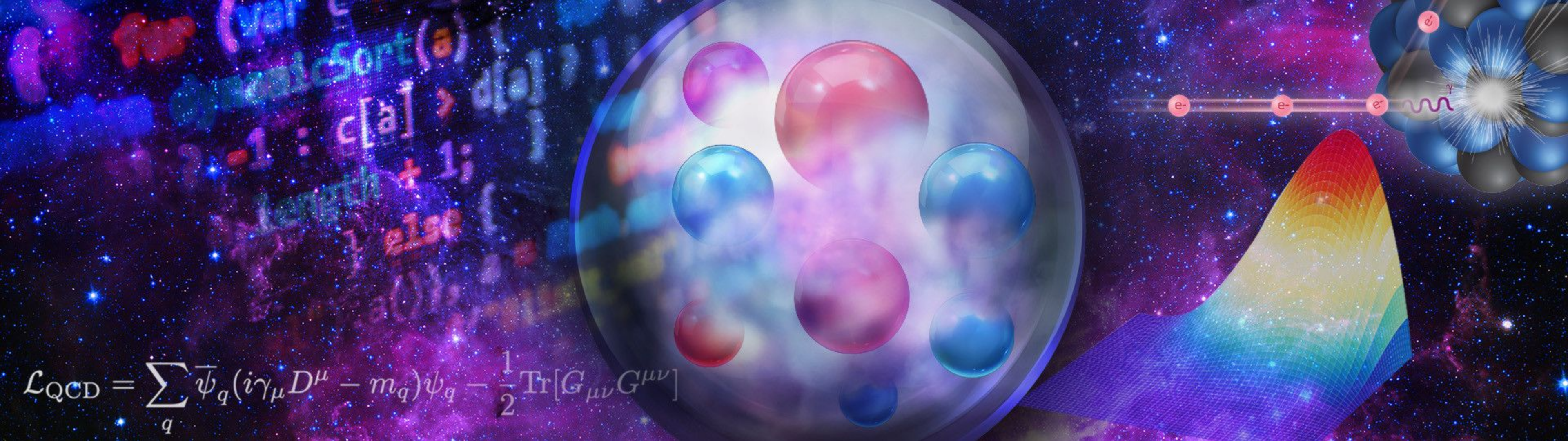
JAM perspective

Nobuo Sato

CFNS Workshop on HLEIC (Jun 2022)

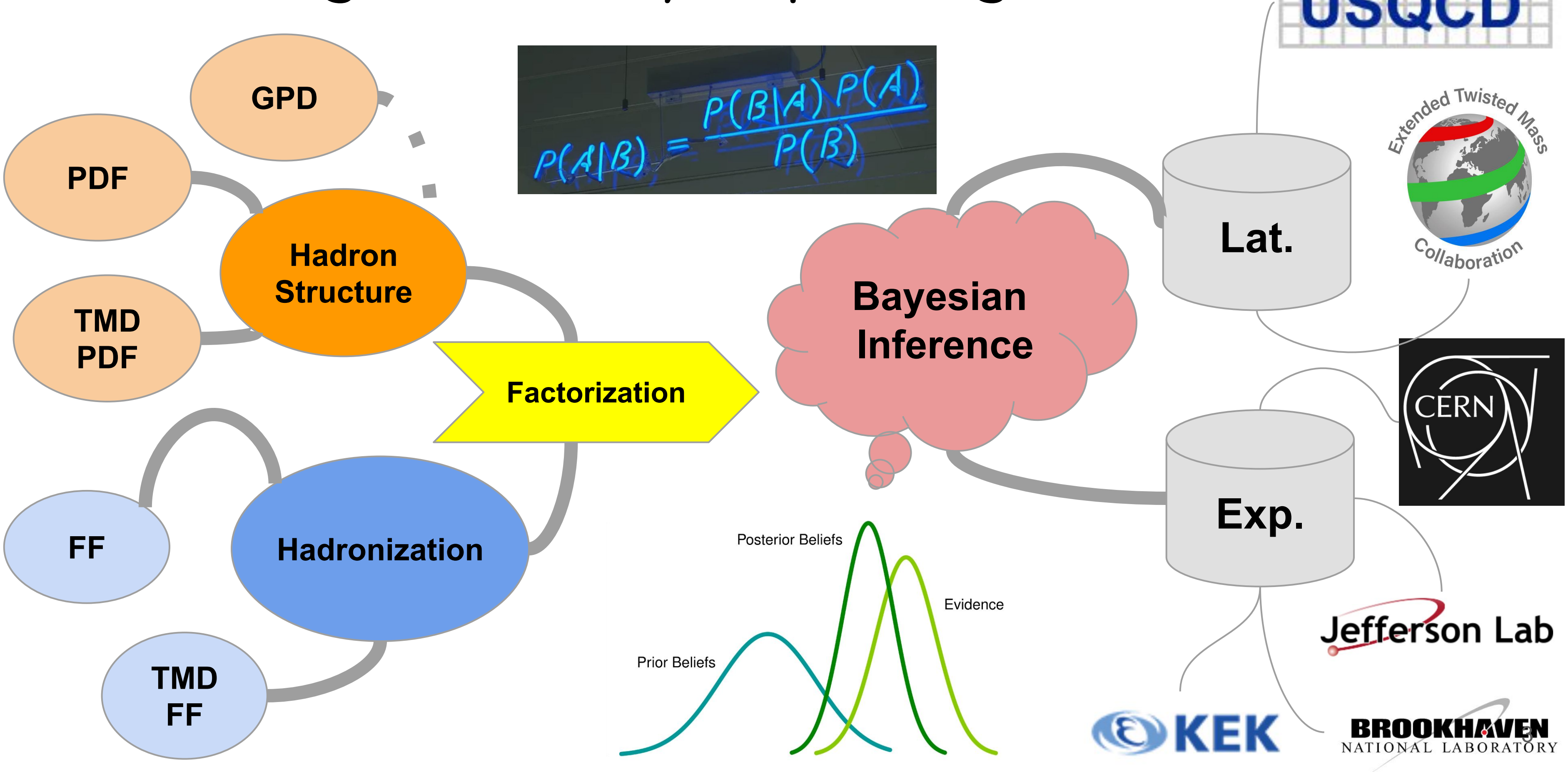
Jefferson Lab



JEFFERSON LAB ANGULAR MOMENTUM COLLABORATION

The Jefferson Lab Angular Momentum (JAM) Collaboration is an enterprise involving theorists, experimentalists, and computer scientists from the Jefferson Lab community using QCD to study the internal quark and gluon structure of hadrons and nuclei. Experimental data from high-energy scattering processes are analyzed using modern Monte Carlo techniques and state-of-the-art uncertainty quantification to simultaneously extract various quantum correlation functions, such as parton distribution functions (PDFs), fragmentation functions (FFs), transverse momemtum dependent (TMD) distributions, and generalized parton distributions (GPDs). Inclusion of lattice QCD data and machine learning algorithms are being explored to potentially expand the reach and efficacy of JAM analyses and our understanding of hadron structure in QCD.

The JAM global analysis paradigm



High-x pdfs

arXiv.org > hep-ex > arXiv:2104.05850

Search...

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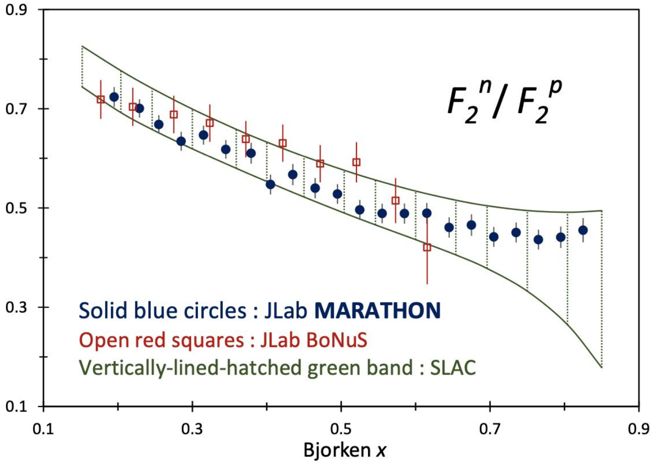
High Energy Physics – Experiment

[Submitted on 12 Apr 2021]

Measurement of the Nucleon F_2^n/F_2^p Structure Function Ratio by the Jefferson Lab MARATHON Tritium/Helium-3 Deep Inelastic Scattering Experiment



Theory input

Experimental measurement

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R}_{ht} - F_2^h/F_2^t}{2F_2^h/F_2^t - \mathcal{R}_{ht}}.$$

arXiv.org > hep-ex > arXiv:2104.05850

Search...

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High Energy Physics – Experiment

[Submitted on 12 Apr 2021]

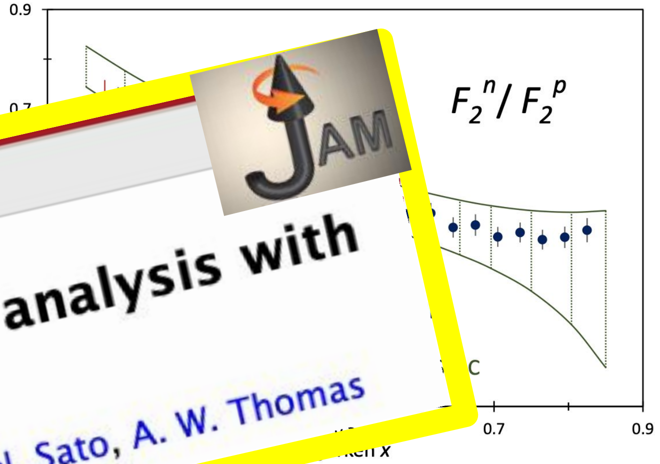
Measurement of the Nucleon F_2^n/F_2^p Structure Fun... by the Jefferson Lab MARATHON Triti... Inelastic Scattering Experim...

High Energy Physics – Phenomenology

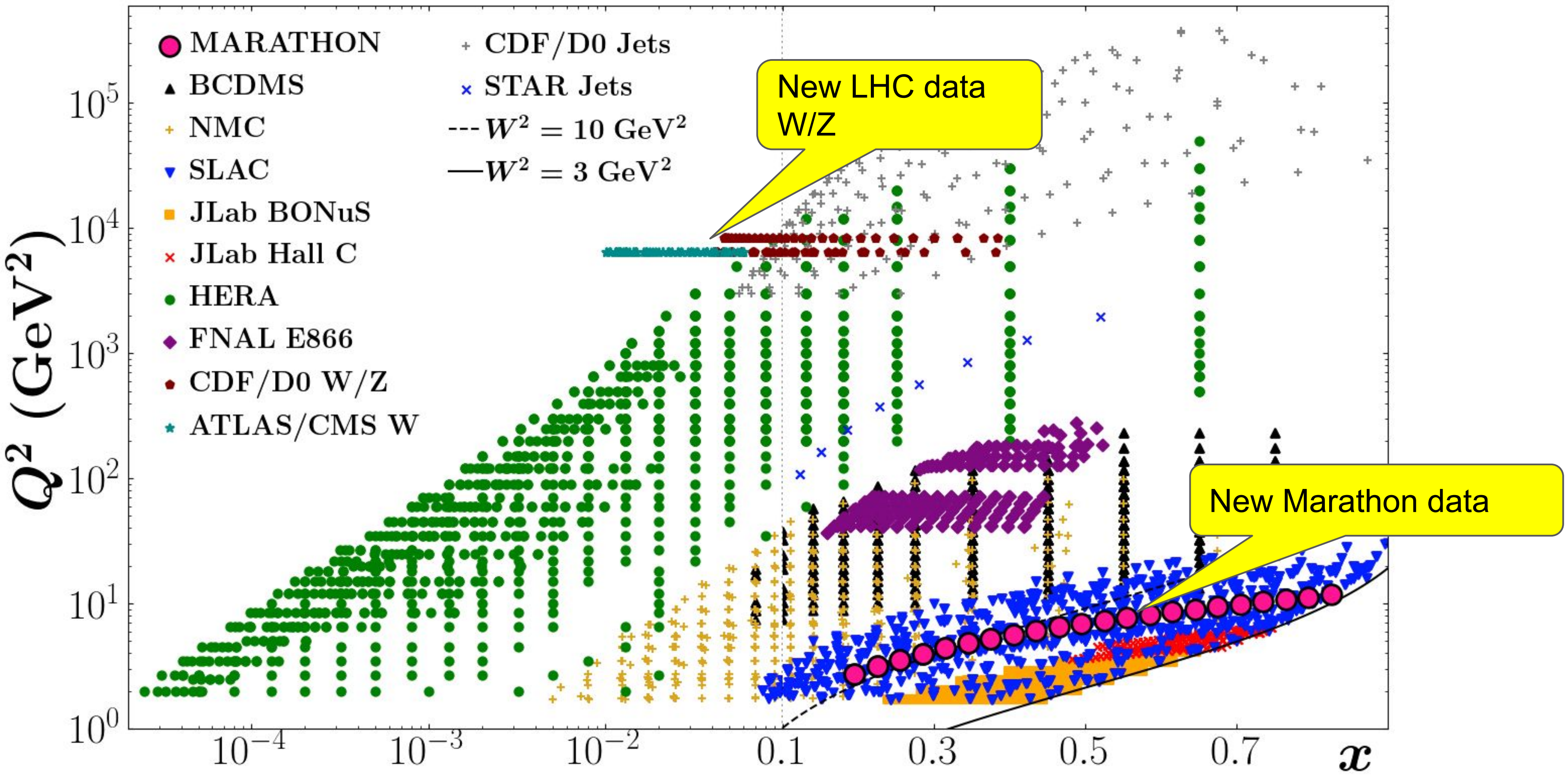
[Submitted on 14 Apr 2021]

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

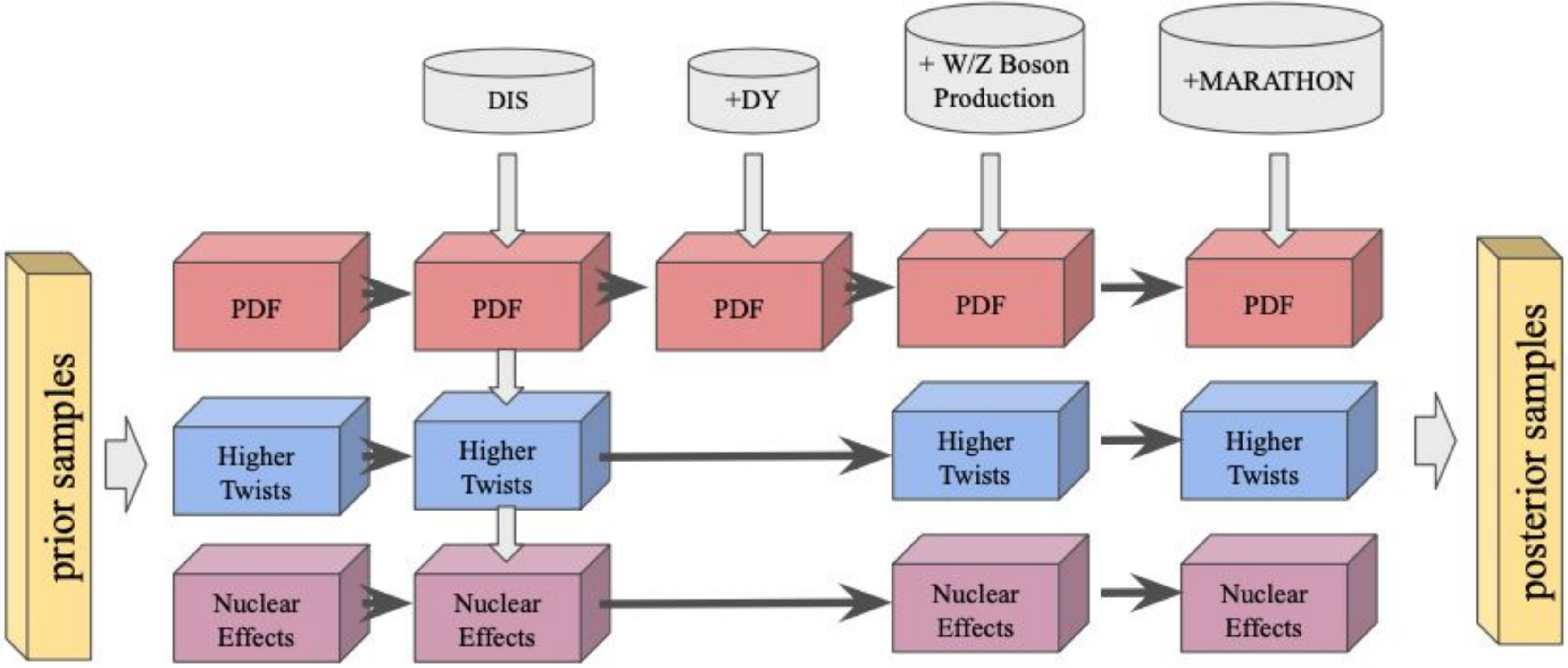


$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R}_{ht} - F_2^h/F_2^t}{2F_2^h/F_2^t - \mathcal{R}_{ht}}$$



MARATHON
BCDMS
NMC
SLAC
JLab BONuS
JLab Hall C
HERA
FNAL E866
CDF/D0 W/Z
ATLAS/CMS W
CDF/D0 Jets
STAR Jets
$W^2 = 10$ GeV^2
$W^2 = 3$ GeV^2
New LHC data W/Z
New Marathon data
Q^2 (GeV^2)
x
10^0
10^1
10^2
10^3
10^4
10^5
10^{-4}
10^{-3}
10^{-2}
0.1
0.3
0.5
0.7

Multi-step strategy



Theory details for DIS

Nucleon structure functions

$$F_2^N(x,Q^2) = \Big(\sum_q e_q^2 [C_q \otimes q_N^+] + [C_g \otimes g_N]\Big)(x,Q^2) \times \left(1 + \frac{C_N^{\mathrm{HT}}(x)}{Q^2}\right)$$

PDFs for light nuclei

$$q_A(x,Q^2) = \sum_N q_{N/A}(x,Q^2) = [q_{N/A}^{(\mathrm{on})} + q_{N/A}^{(\mathrm{off})}](x,Q^2)$$

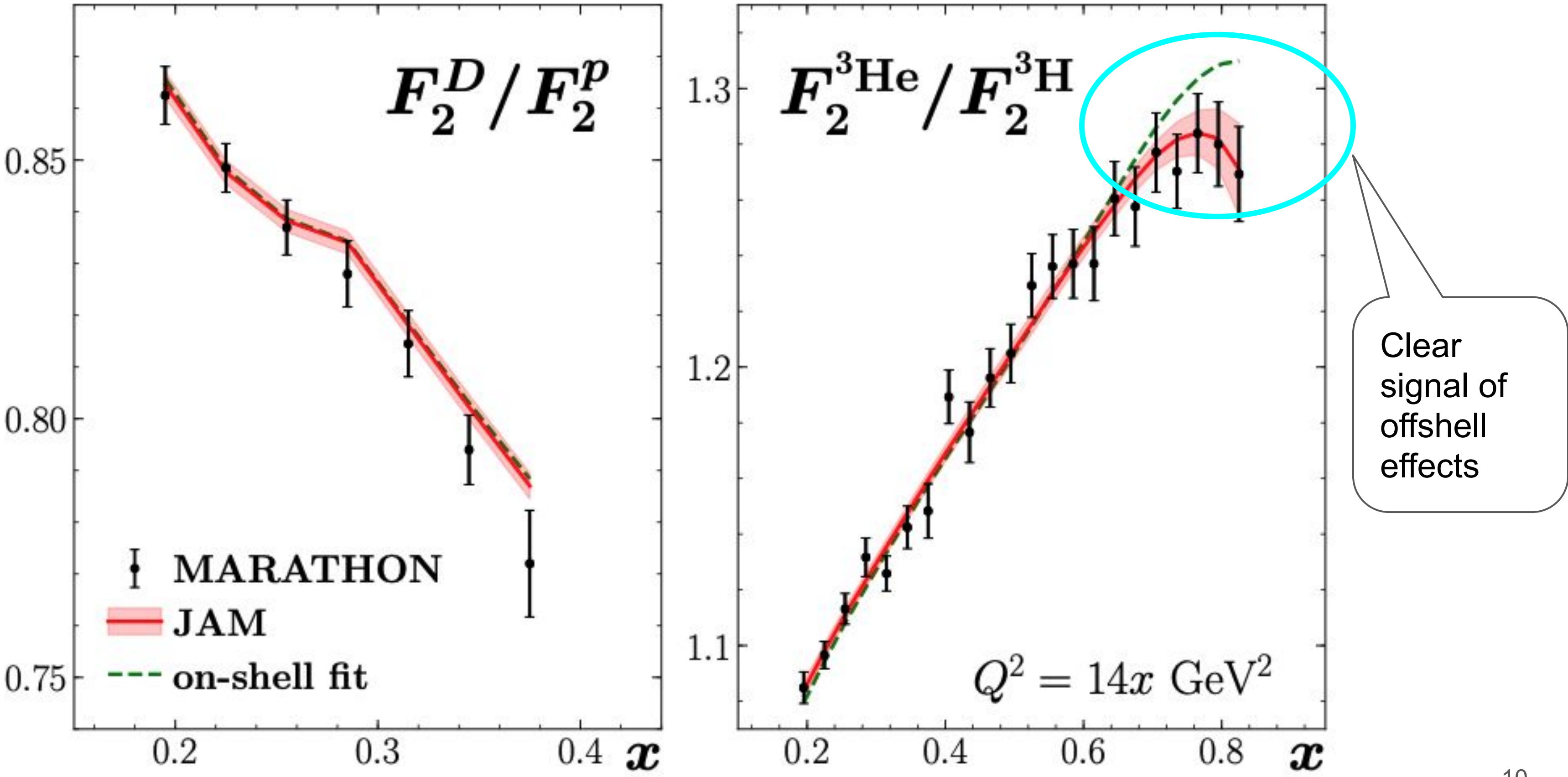
$$q_{N/A}^{(\mathrm{on})}(x,Q^2) = [f_{N/A}^{(\mathrm{on})} \otimes q_N]$$

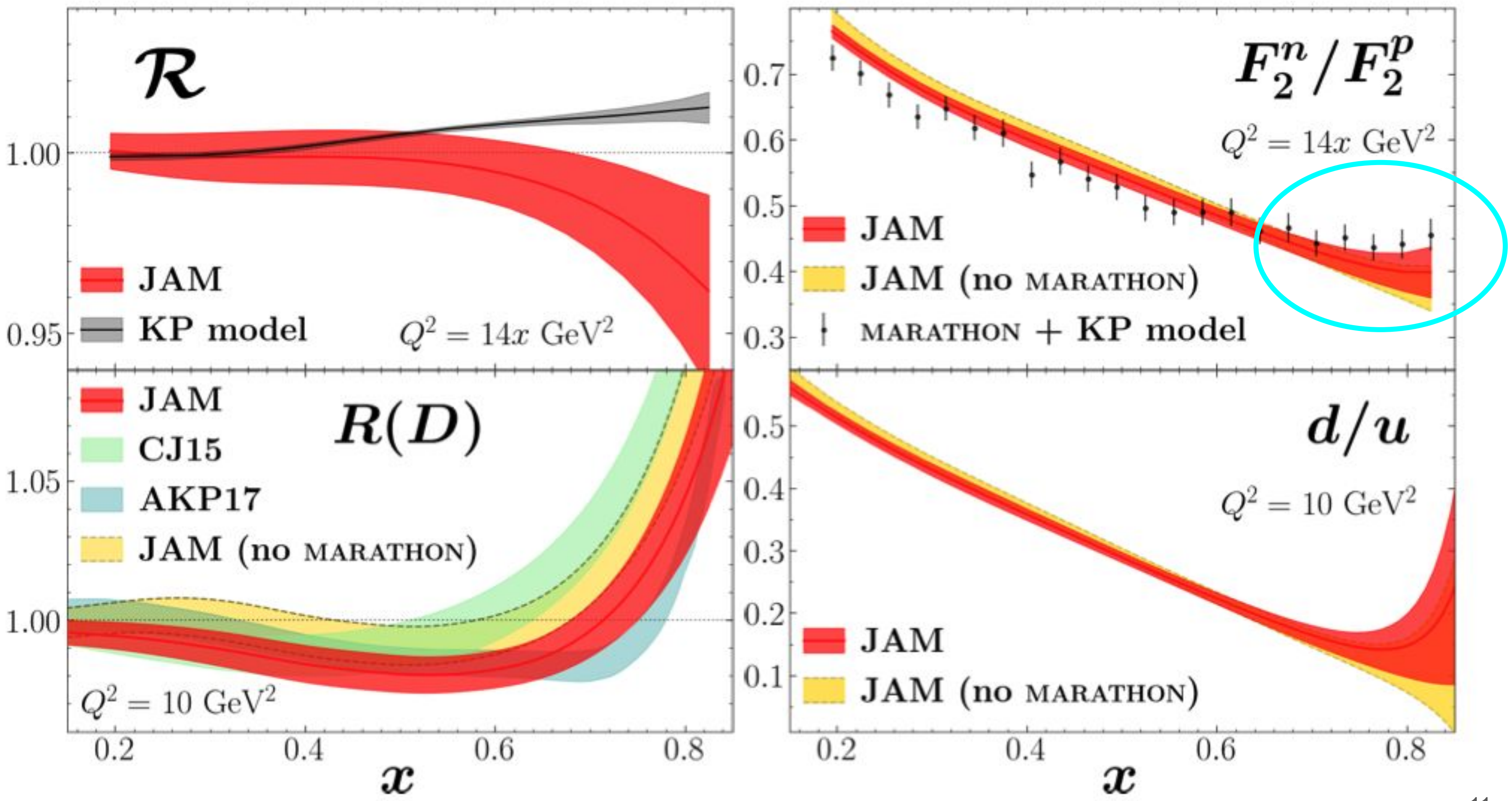
Nuclear smearing

$$q_{N/A}^{(\mathrm{off})}(x,Q^2) = [f_{N/A}^{(\mathrm{off})} \otimes \delta q_{N/A}]$$

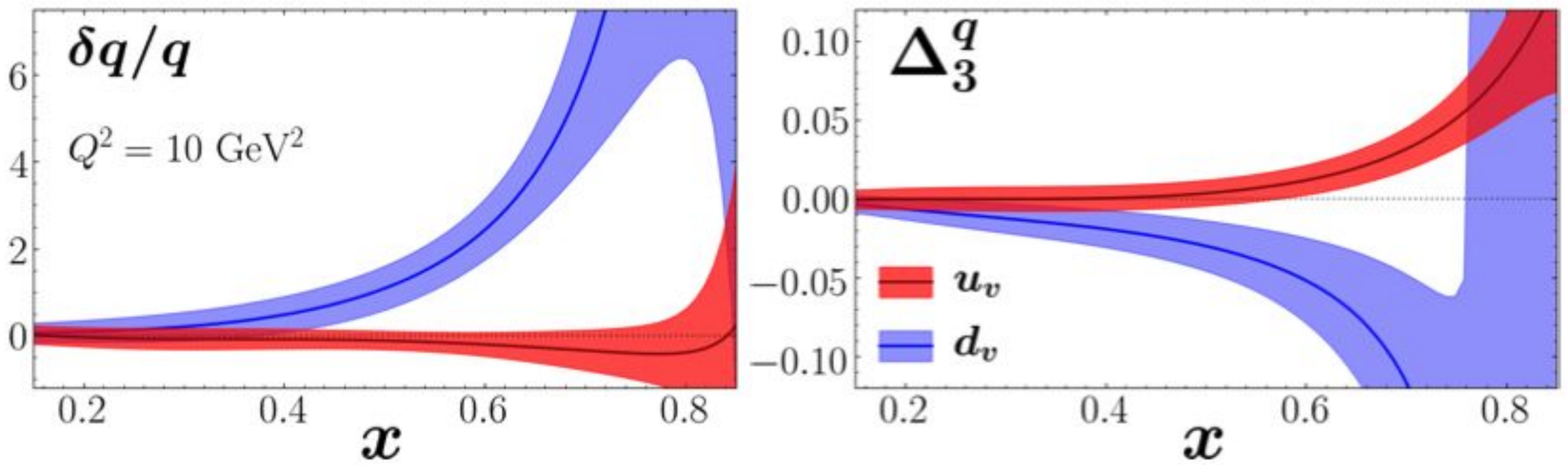
Offshell quark parametrization

Marathon data





$\mathcal{R}$
JAM
KP model
$Q^2 = 14x$ GeV^2
1.00
0.95
F_2^n / F_2^p
$Q^2 = 14x$ GeV^2
JAM
JAM (no MARATHON)
MARATHON + KP model
0.7
0.6
0.5
0.4
0.3
JAM
CJ15
AKP17
JAM (no MARATHON)
$R(D)$
$Q^2 = 10$ GeV^2
1.05
1.00
d/u
$Q^2 = 10$ GeV^2
JAM
JAM (no MARATHON)
0.5
0.4
0.3
0.2
0.1
0.2
0.4
0.6
0.8
x
0.2
0.4
0.6
0.8
x



$$\Delta_3^q \equiv \frac{q_{p/^3\mathrm{H}} - q_{p/^3\mathrm{He}}}{q_{p/^3\mathrm{H}} + q_{p/^3\mathrm{He}}}$$

Conclusions:

- pdfs of protons in A and A' can be different
- It suggest that canonical modeling of NPDFs is wrong

Sea asymmetry

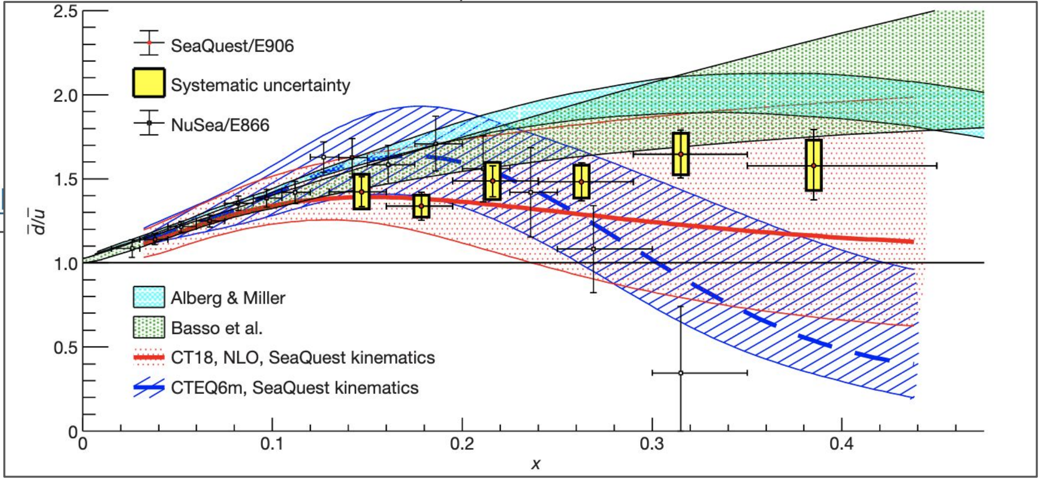
nature

Article | Published: 24 February 2021

The asymmetry of antimatter in the proton

J. Dove, B. Kerns, … Z. Ye + Show authors

Nature **590**, 561–565 (2021) | Cite this article



Measurements of W and Z/γ^* cross sections and their ratios in $p + p$ collisions at RHIC

J. Adam *et al.* (STAR Collaboration)
Phys. Rev. D **103**, 012001 – Published 4 January 2021

nature

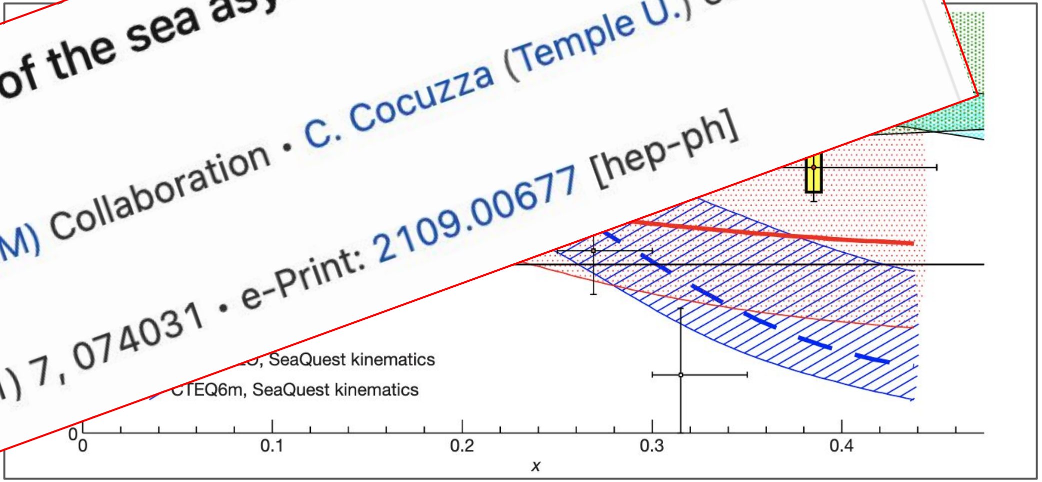
Article | Published: 24 February 2021

The asymmetry of antimatter in th…

J. Dove, B. Kerns, … Z. Ye + Show authors

Nature **590**, 561–565 (2021)

8942 Accesses



#7

Bayesian Monte Carlo extraction of the sea asymmetry with SeaQuest and STAR data

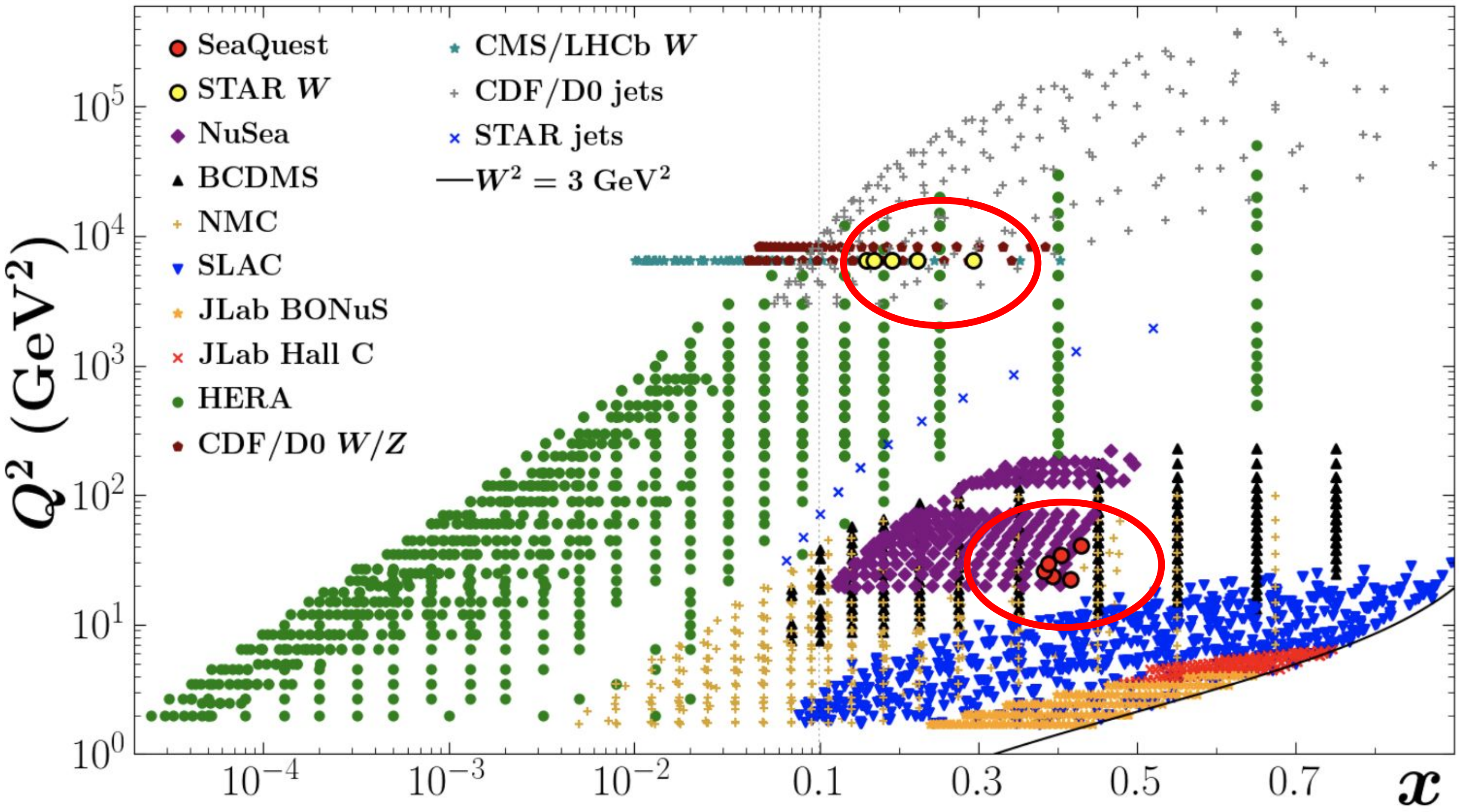
Jefferson Lab Angular Momentum (JAM) Collaboration • C. Cocuzza (Temple U.) et al. (Sep 1, 2021)

Published in: Phys.Rev.D 104 (2021) 7, 074031 • e-Print: 2109.00677 [hep-ph]

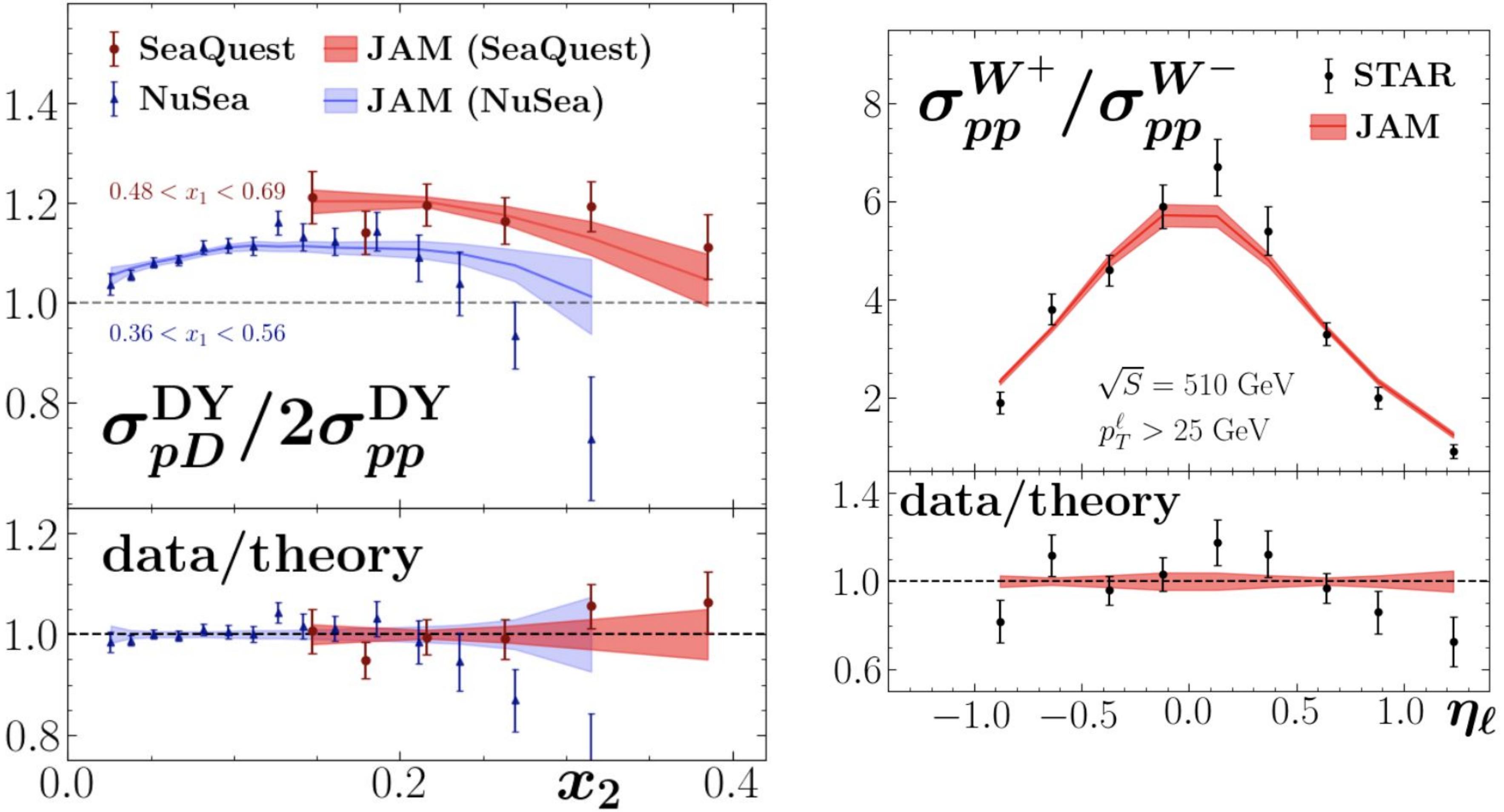
Mea… W and Z/γ^* cross sections and their ratios in $p+p$ …sions at RHIC

J. Adam *et al.* (STAR Collaboration)

Phys. Rev. D **103**, 012001 – Published 4 January 2021

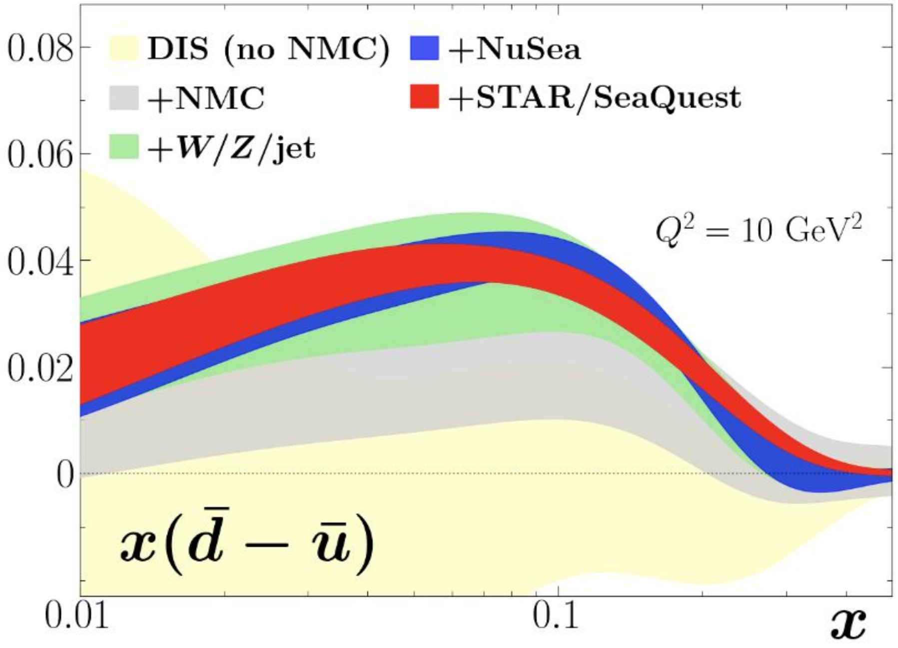


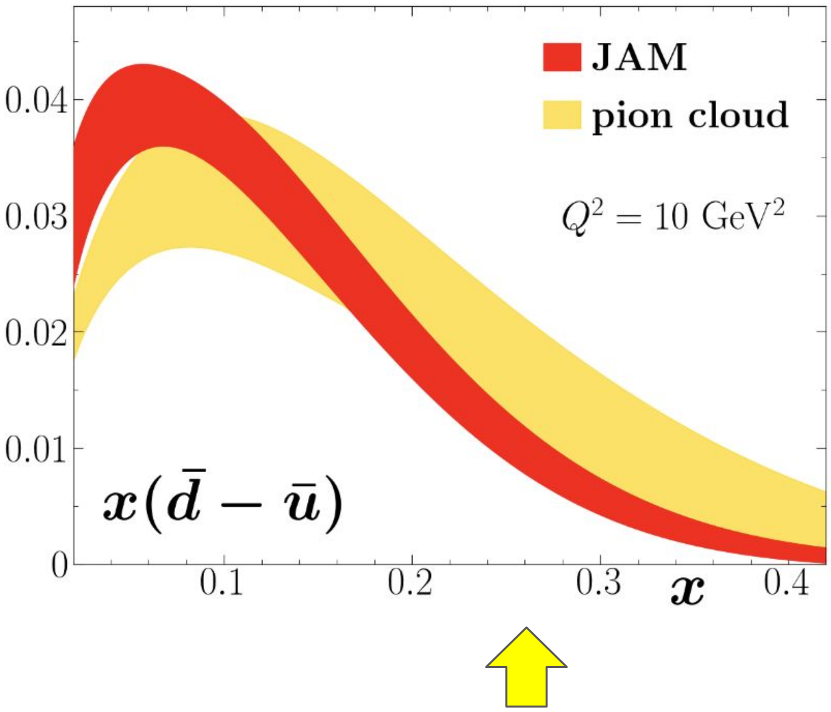
SeaQuest
STAR W
NuSea
BCDMS
NMC
SLAC
JLab BONuS
JLab Hall C
HERA
CDF/D0 W/Z
CMS/LHCb W
CDF/D0 jets
STAR jets
—$W^2 = 3$ GeV^2
Q^2 (GeV^2)
10^0
10^1
10^2
10^3
10^4
10^5
10^{-4}
10^{-3}
10^{-2}
0.1
0.3
0.5
0.7
x



SeaQuest
JAM (SeaQuest)
NuSea
JAM (NuSea)
$0.48 < x_1 < 0.69$
$0.36 < x_1 < 0.56$
$\sigma_{pD}^{\mathrm{DY}}/2\sigma_{pp}^{\mathrm{DY}}$
data/theory
x_2
$\sigma_{pp}^{W^+}/\sigma_{pp}^{W^-}$
STAR
JAM
$\sqrt{S} = 510$ GeV
$p_T^\ell > 25$ GeV
data/theory
η_ℓ

Historical progression

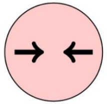




$$(\bar{d} - \bar{u})(x) = \left[\left(f_{n\pi^+} + f_{\Delta^0\pi^+} - f_{\Delta^{++}\pi^-}\right) \otimes \bar{q}_v^\pi\right](x),$$

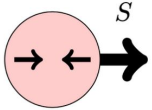
Helicity pdfs

Spin physics



$$f = f_{\rightarrow} + f_{\leftarrow}$$

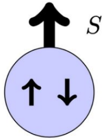
$$\langle N|\bar{\psi}_i(0, w^-, \mathbf{0}_\mathrm{T})\gamma^+\psi_i(0)|N\rangle$$



$$\Delta f = f_{\rightarrow} - f_{\leftarrow}$$

Helicity distribution

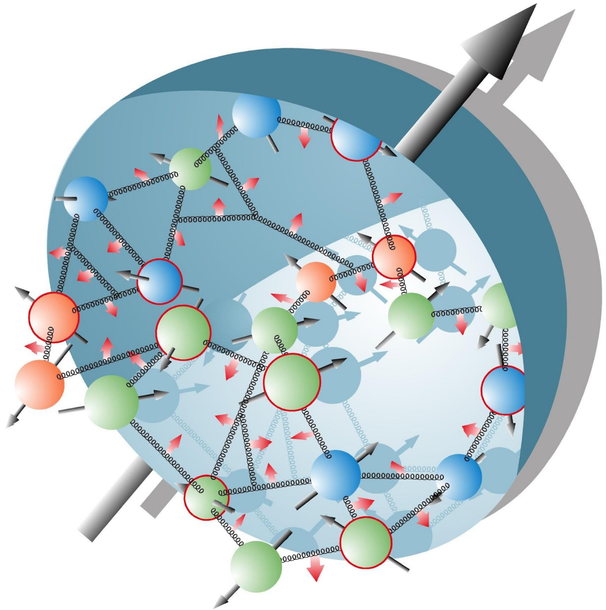
$$\langle N|\bar{\psi}_i(0, w^-, \mathbf{0}_\mathrm{T})\gamma^+\gamma_5\psi_i(0)|N\rangle$$



$$\delta_\mathrm{T} f = f_{\uparrow} - f_{\downarrow}$$

Transversity

$$\langle N|\bar{\psi}_i(0, w^-, \mathbf{0}_\mathrm{T})\gamma^+\gamma_\perp\gamma_5\psi_i(0)|N\rangle$$



"Spin crisis in the late 80's"

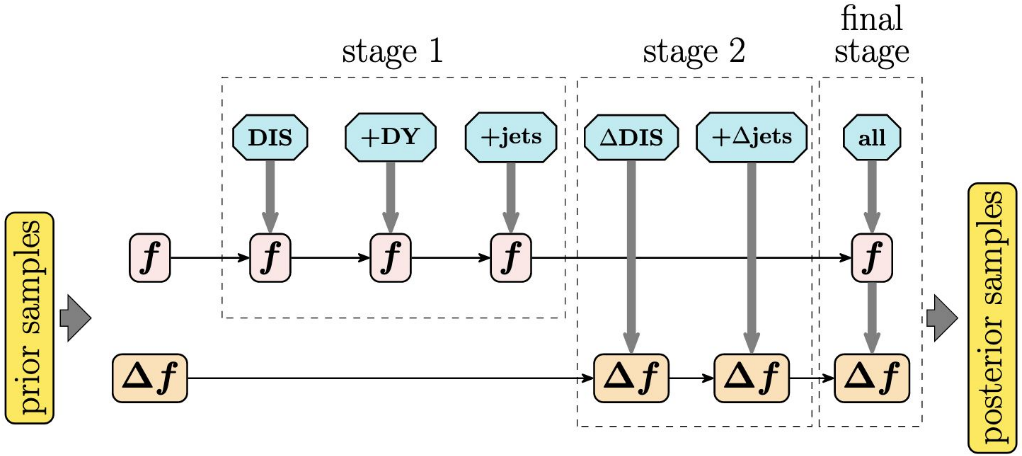
- Quark model of nucleon $\rightarrow$ 3 massive quarks
- Nucleon is in the ground state (s-state) $\rightarrow$ no OAM
- Quarks expected to carry most of the nucleon's spin

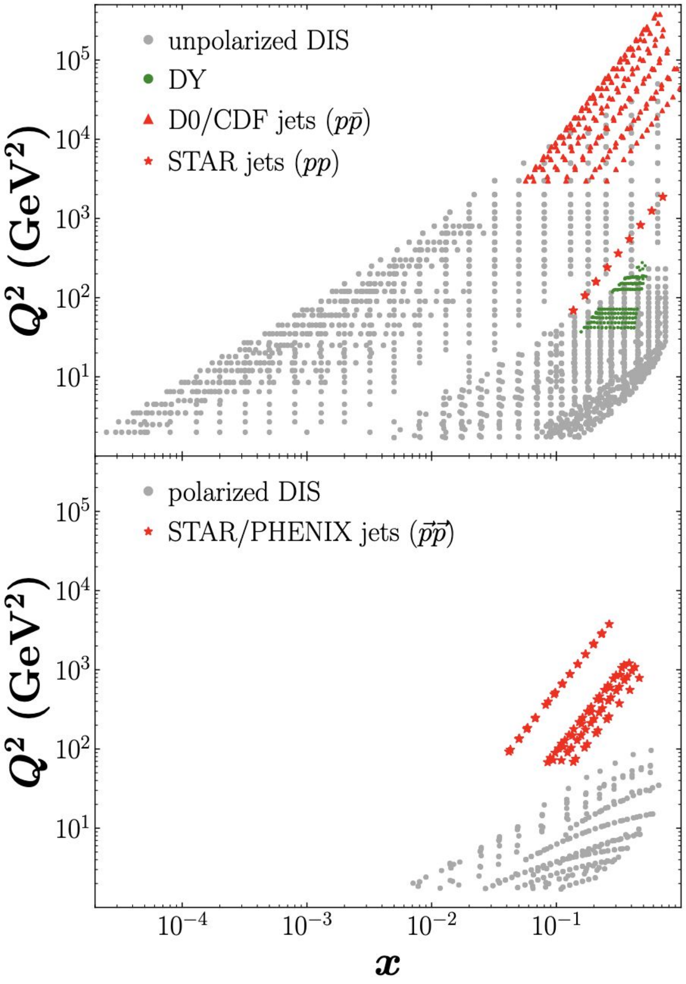
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

But $\Delta\Sigma \simeq 0.28(4)$ **JAM15**

How well do we know the gluon polarization in the proton?

Y. Zhou, N. Sato, and W. Melnitchouk (Jefferson Lab Angular Momentum (JAM) Collaboration)
Phys. Rev. D **105**, 074022 – Published 25 April 2022





Theory biases

SU2 $$\int_0^1 \mathrm{d}x \, [\Delta u^+ - \Delta d^+] = g_A$$

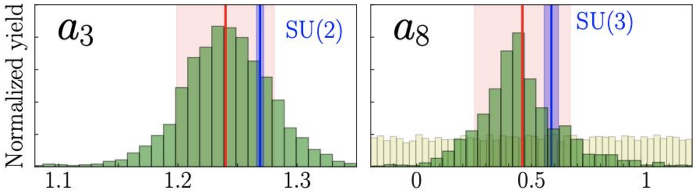
SU3 $$\int_0^1 \mathrm{d}x \, [\Delta u^+ + \Delta d^+ - 2\Delta s^+] = a_8,$$

Hyperon-beta decays

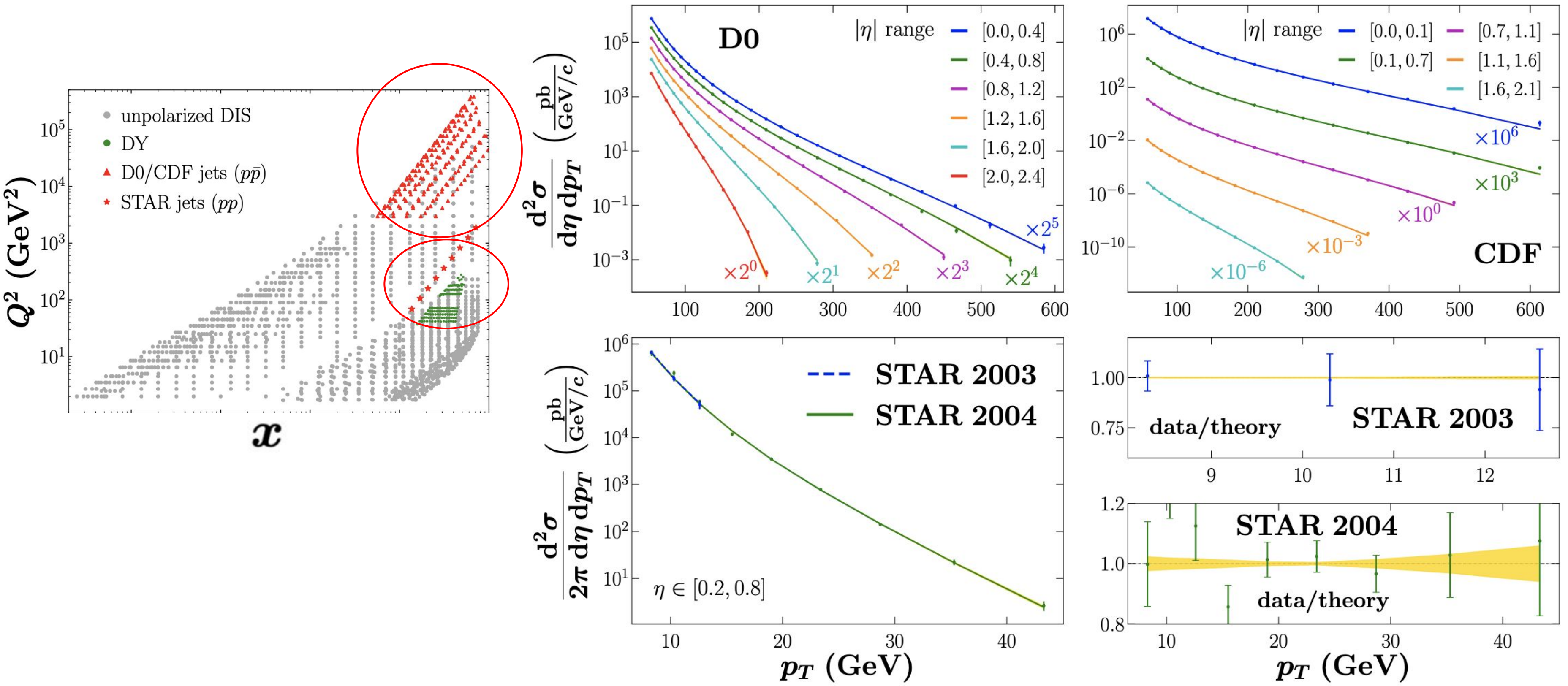
Constraints from SIDIS with Kaons JAM17

Positivity

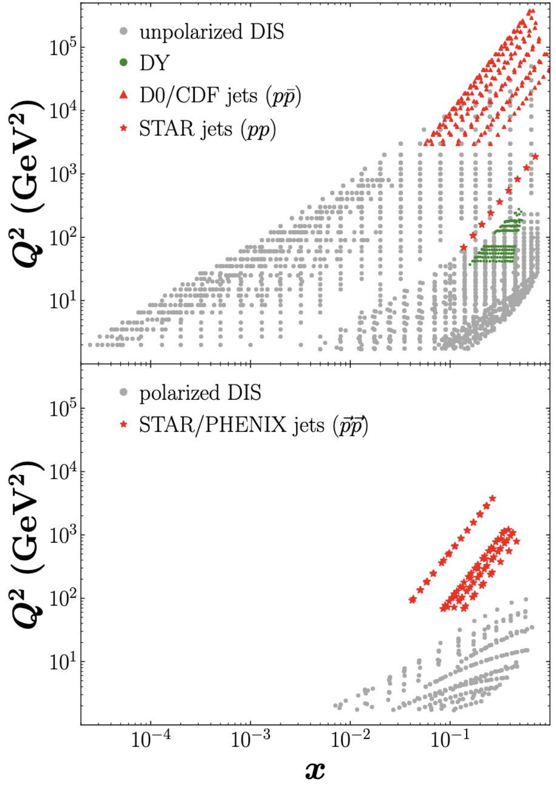
$$|\Delta q(x, Q^2)| \leqslant q(x, Q^2)$$

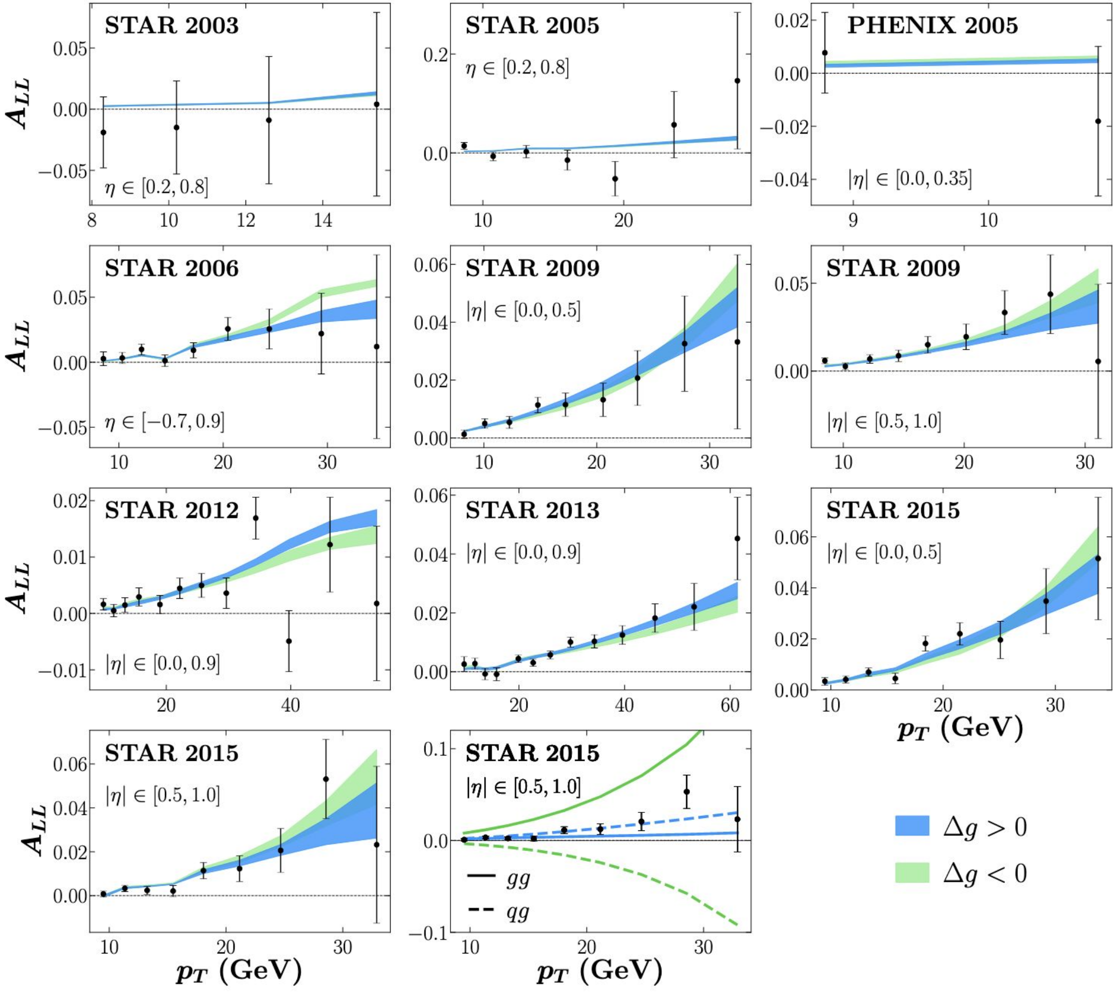


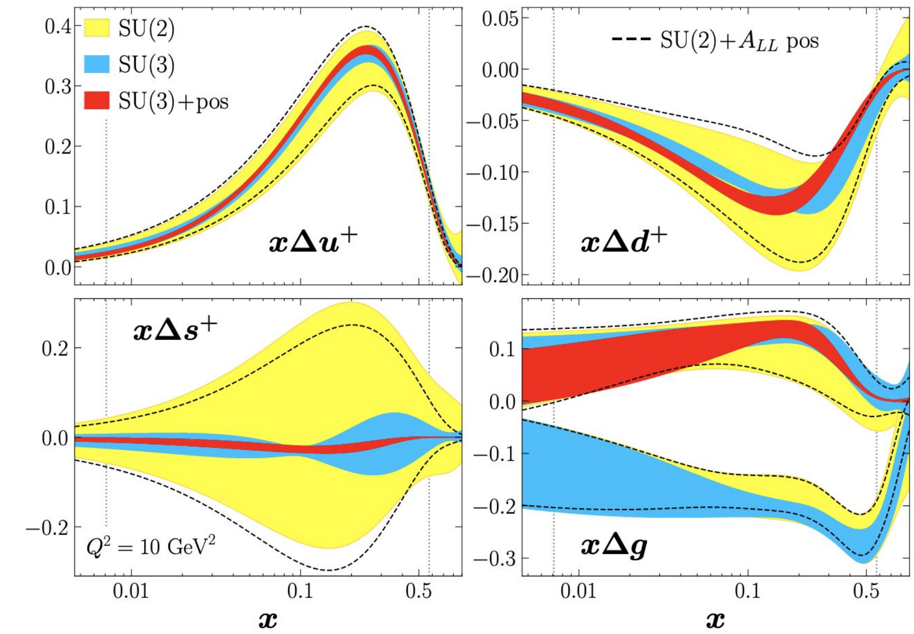
Unpolarized Jets

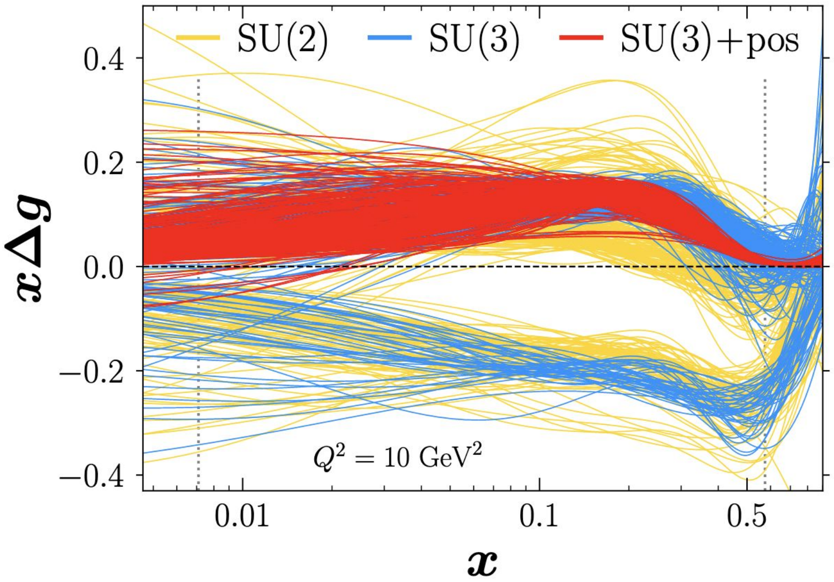


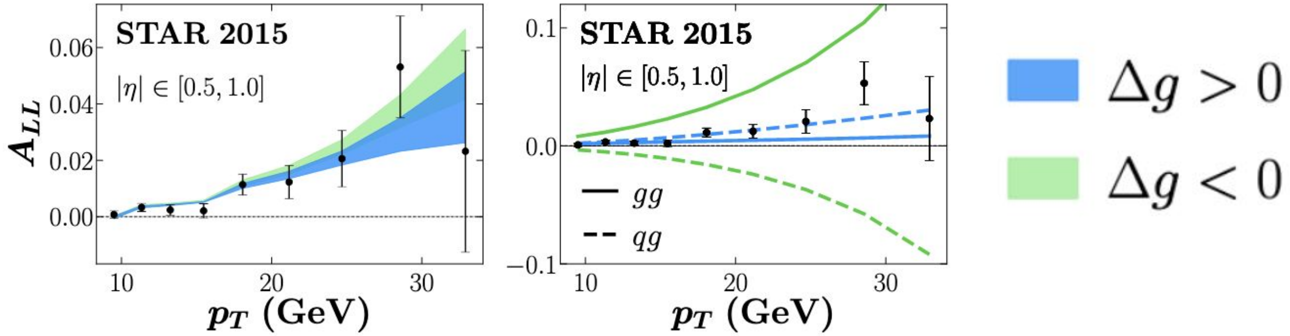
Polarized Jets











Polarized Jet data cannot discriminate positive and negative solutions pdf positivity

Regular Article - Theoretical Physics | Open Access | Published: 24 November 2020

Can $\overline{\mathrm{MS}}$ parton distributions be negative?

Alessandro Candido, Stefano Forte & Felix Hekhorn

Journal of High Energy Physics **2020**, Article number: 129 (2020) | Cite this article

161 Accesses | **6** Citations | **2** Altmetric | Metrics

Positivity and renormalization of parton densities

John Collins (Penn State U.), Ted C. Rogers (Old Dominion U. and Jefferson Lab), Nobuo Sato (Jefferson Lab) (Nov 1, 2021)

Published in: *Phys.Rev.D* 105 (2022) 7, 076010 • e-Print: 2111.01170 [hep-ph]

Can $\overline{\text{MS}}$ parton distributions be negative?

Alessandro Candido, Stefano Forte & Felix Hekhorn

Journal of High Energy Physics **2020**, Article number: 129 (2020) | Cite this article

It is common lore that Parton Distribution Functions (PDFs) in the $\overline{\text{MS}}$ factorization scheme can become negative beyond leading order due to the collinear subtraction which is needed in order to define partonic cross sections. We show that this is in fact not the case and next-to-leading order (NLO) $\overline{\text{MS}}$ PDFs are actually positive in the perturbative regime. In order to prove this, we modify the subtraction prescription, and perform the collinear subtraction in such a way that partonic cross sections remain positive. This defines a factorization scheme in which PDFs are positive. We then show that positivity of the PDFs is preserved when transforming from this scheme to $\overline{\text{MS}}$, provided only the strong coupling is in the perturbative regime, such that the NLO scheme change is smaller than the LO term.

Positivity and renormalization of parton densities

John Collins, Ted C. Rogers, and Nobuo Sato
Phys. Rev. D **105**, 076010 – Published 14 April 2022

Track A

- Start from an operator definition for pdfs
  - Only UV divergence
  - Use renormalization

$$f_{j/H}^{\mathrm{bare,A}}(\xi) \equiv \int \frac{\mathrm{d}w^-}{2\pi} e^{-i\xi p^+ w^-} \langle p|\, \bar{\psi}_{j,0}(0, w^-, \mathbf{0}_\mathrm{T}) \frac{\gamma^+}{2} W[0, w^-] \psi_{j,0}(0, 0, \mathbf{0}_\mathrm{T})\, |p\rangle\,.$$

$$f^{\mathrm{renorm,A}}(\xi) \equiv Z^A \otimes f^{\mathrm{bare,A}}$$

- Factorization
  - Region analysis (Libby Sterman)
  - Higher order corrections via nested subtractions

$$F(Q, x_{\mathrm{bj}}) = \mathcal{C}^A \otimes f^{\mathrm{renorm,A}} + \mathrm{error}$$
$$= \sum_j \int_{x_{\mathrm{bj}}}^1 \mathrm{d}\xi\, \mathcal{C}_j^A(x_{\mathrm{bj}}/\xi, \alpha_s(Q))\, f_j^{\mathrm{renorm,A}}(Q, \xi) + \mathrm{error}$$

Positivity and renormalization of parton densities

John Collins, Ted C. Rogers, and Nobuo Sato
Phys. Rev. D **105**, 076010 – Published 14 April 2022

“bare factorization”

Curci, Furmanski, Petronzio (1980)

Track B

- Assert(?) a factorization in terms of bare pdf.
- Isolate collinear divergences from partonic structure function.
- Reabsorb singularities inside bare pdf.

$$F(Q, x_{\rm bj}) = F^{\rm partonic} \otimes f^{\rm bare,B}$$

$$F^{\rm partonic} = \mathcal{C}^B \otimes Z^B$$

$$\begin{aligned} F(Q, x_{\rm bj}) &= (\mathcal{C}^B \otimes Z^B) \otimes f^{\rm bare,\ b} \\ &= \mathcal{C}^B \otimes (Z^B \otimes f^{\rm bare,B}) \\ &= \mathcal{C}^B \otimes f^{\rm renorm,B}\,, \end{aligned}$$

Positivity argument based on track B

$$F(Q, x_{\rm bj}) = \left(\mathcal{C}^B \otimes Z^B\right) \otimes f^{\rm bare,\ b}$$
$$= \mathcal{C}^B \otimes \left(Z^B \otimes f^{\rm bare,B}\right)$$
$$= \mathcal{C}^B \otimes f^{\rm renorm,B}\ ,$$

If Z^B **is positive**

If $f^{\rm bare,B}$ **is positive**

then $f^{\rm renorm,B}$ **is positive**

Can $\overline{\text{MS}}$ parton distributions be negative?

Alessandro Candido, Stefano Forte & Felix Hekhorn

$$f_i(\xi) = \frac{1}{4\pi}\int dy^- e^{-i\xi P^+ y^-}\langle P|\bar{\psi}_i(0,y^-,\vec{0}_T)\gamma^+\mathcal{P}\exp\left[ig_s\int_0^{y^-} d\bar{y}^- A_a^+(0,\bar{y}^-,\vec{0}_T)\frac{1}{2}\lambda_a\right]\psi_i(0)|P\rangle, \quad (2)$$

where $\mathcal{P}$ denotes path-ordering; P is the four-momentum of the parent hadron in light-cone components and g_s is the strong coupling, with analogous expressions for antiquarks and gluons [8]. It can be shown (see e.g. Sect. 6.7 of Ref. [10]) that the expression Eq. (2) is a number density, and as such before subtraction of divergences it is positive.

⋮

positivity of the partonic cross section at the regularized level. If all contributions which are factored away from the partonic cross section and into the PDF remain positive, then the latter also stays positive.

Track B: "bare factorization"

$$F(Q, x_{\rm bj}) = F^{\rm partonic} \otimes f^{\rm bare,B}$$

$$I^{\rm ren.\ BPHZ'} = \int \frac{d^{2-2\epsilon}\boldsymbol{k}_T}{(2\pi)^{2-2\epsilon}} \left(\frac{1}{k_T^2 + C(x)} - \frac{1}{k_T^2} \right)$$

$$-\int_{k_T<\Lambda} \frac{d^{2-2\epsilon}\boldsymbol{k}_T}{(2\pi)^{2-2\epsilon}} \frac{1}{k_T^2} = -\int_0^{\Lambda^2} \frac{dk_T^2 (k_T^2)^{-\epsilon}}{\Gamma(1-\epsilon)\,(4\pi)^{1-\epsilon}} \frac{1}{k_T^2}$$

$$= \frac{\Lambda^{-2\epsilon}}{\epsilon\,\Gamma(1-\epsilon)\,(4\pi)^{1-\epsilon}}$$

Given that $\epsilon < 0$ to regulate the collinear divergence, the collinear divergence in the counterterm is actually negative. Therefore the supposed positivity of the "bare" track-B pdfs is actually violated.

Track A

Object	Hadron structure function, F	Partonic hard part $\mathcal{C}^A$	Bare hadronic pdf $f^{\rm bare,A}$	Renormalized hadronic pdf $f^{\rm renorm,A}$
Ultraviolet behavior	*Standard Lagrangian counterterms* ⟹ UV finite	*Lagrangian counterterms & operator counterterms* ⟹ UV finite	*Bare pdf, so no counterterms* ⟹ UV divergent	*Lagrangian counterterms & operator counterterms* ⟹ UV finite
Collinear behavior	*Non-massless, finite range theory* ⟹ Collinear finite	*Double counting subtractions* ⟹ Collinear finite	*Non-massless, finite range theory* ⟹ Collinear finite	*Non-massless, finite range theory* ⟹ Collinear finite

Track B

Object	Partonic structure function $F^{\rm partonic}$	Partonic hard part $\mathcal{C}^B$	Bare hadronic pdf $f^{\rm bare,B}$
Ultraviolet behavior	*Standard Lagrangian counterterms* ⟹ UV finite	*Lagrangian counterterms & operator counterterms* ⟹ UV finite	*Track B bare pdf must be UV finite to be consistent with hadronic structure function* ⟹ UV finite
Collinear behavior	*Massless partons* ⟹ Collinear divergent	*Collinear divergence absorbed into pdf redefinition* ⟹ Collinear finite	*Track B bare pdf must be collinear divergent to cancel collinear divergence in partonic structure function* ⟹ Collinear divergent

Positivity argument

$$
\begin{aligned}
F(Q, x_{\rm bj}) &= \left(\mathcal{C}^B \otimes Z^B\right) \otimes f^{\rm bare,\ b} \\
&= \mathcal{C}^B \otimes \left(Z^B \otimes f^{\rm bare,B}\right) \\
&= \mathcal{C}^B \otimes f^{\rm renorm,B} \ ,
\end{aligned}
$$

If Z^B **is positive**

If $f^{\rm bare,B}$ **is positive**

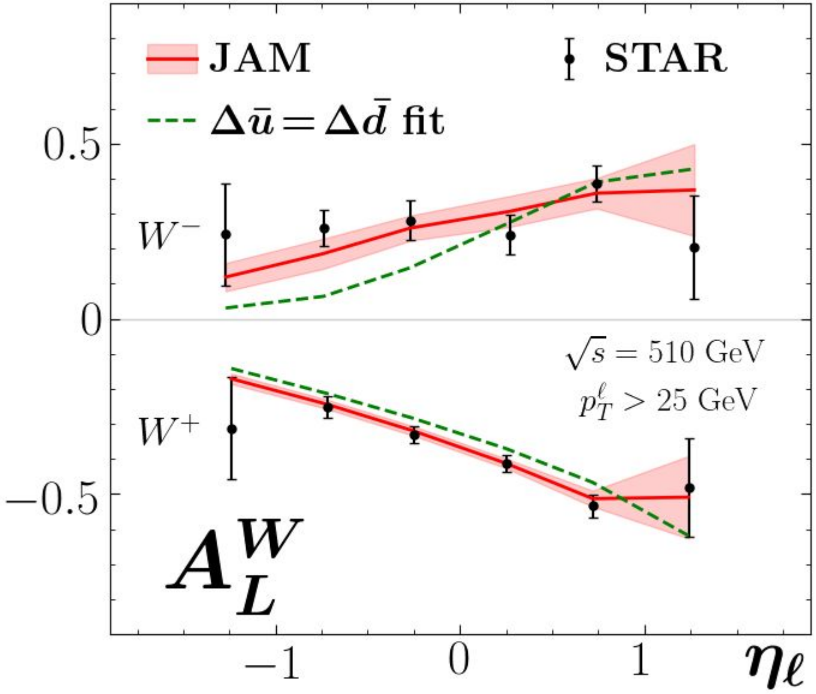
then $f^{\rm renorm,B}$ **is positive**

Polarized Antimatter in the Proton from Global QCD Analysis

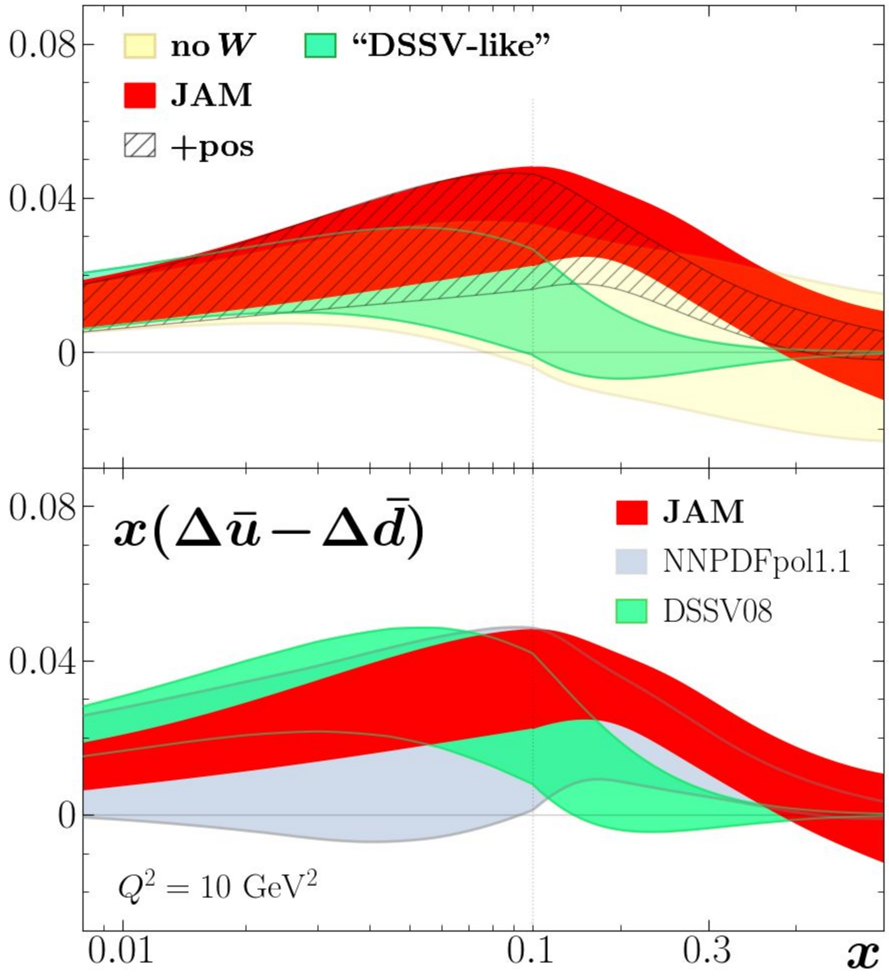
Jefferson Lab Angular Momentum (JAM) Collaboration • C. Cocuzza (Temple U.) et al. (Feb 7, 2022)

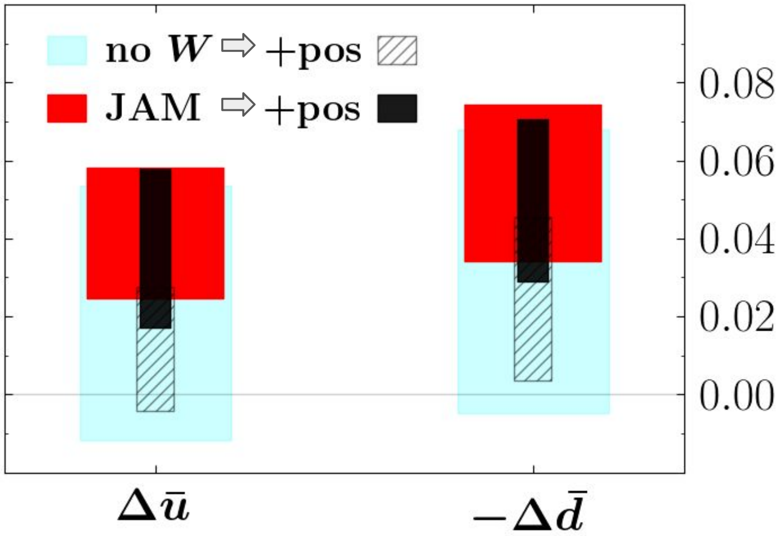
e-Print: 2202.03372 [hep-ph]

(updated version in progress)



process	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
polarized		
inclusive DIS	365	0.93
SIDIS (π^+, π^-)	64	0.93
SIDIS (K^+, K^-)	57	0.36
SIDIS (h^+, h^-)	110	0.93
inclusive jets	83	0.81
STAR $W^\pm$	12	0.53
PHENIX $W^\pm/Z$	6	0.63
total	**697**	**0.86**
unpolarized		
inclusive DIS	3908	1.11
SIDIS (π^+, π^-)	498	0.88
SIDIS (K^+, K^-)	494	1.01
SIDIS (h^+, h^-)	498	0.52
inclusive jets	198	1.11
Drell-Yan	205	1.19
W/Z production	153	0.99
total	**5954**	**1.03**
SIA $(\pi^\pm)$	231	0.85
SIA $(K^\pm)$	213	0.49
SIA $(h^\pm)$	120	1.09
total	**7215**	**0.99**





- First ever universal analysis of pol. & upol. PDFs and fragmentation functions
- Consistent UQ for polarized antiquarks in the nucleon
- Clear evidence of an asymmetry, with opposite sign compared to unpolarized sea asymmetry

Summary/Outlook

- Track B based positivity of $\overline{\text{MS}}$ PDFs are not really supported on formal grounds

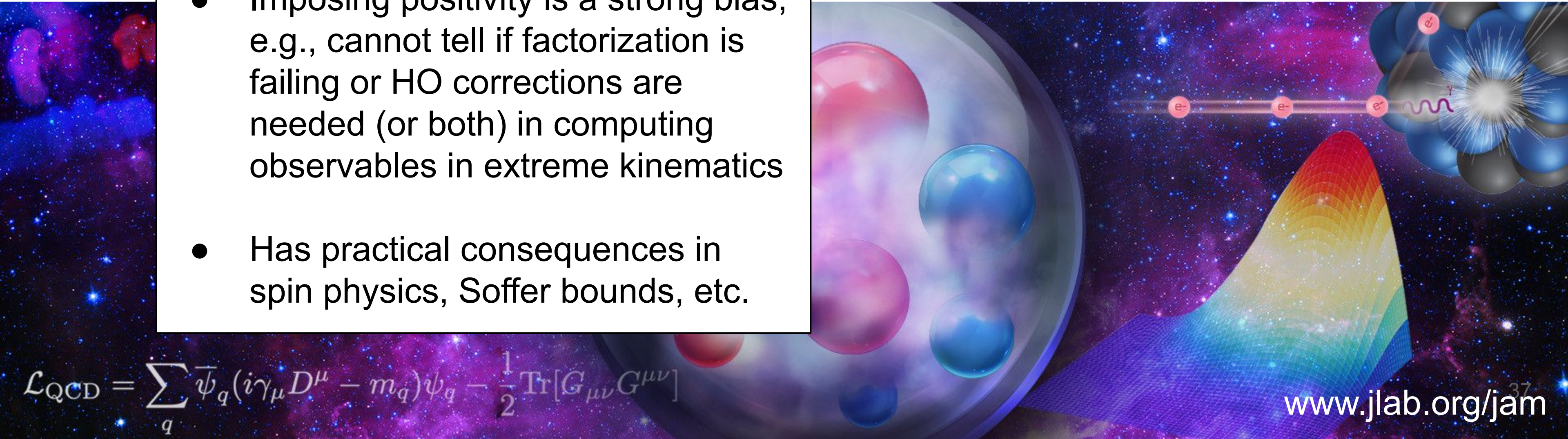
- Imposing positivity is a strong bias, e.g., cannot tell if factorization is failing or HO corrections are needed (or both) in computing observables in extreme kinematics

- Has practical consequences in spin physics, Soffer bounds, etc.

Special thanks to

C. Cocuzza

Y. Zhou



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