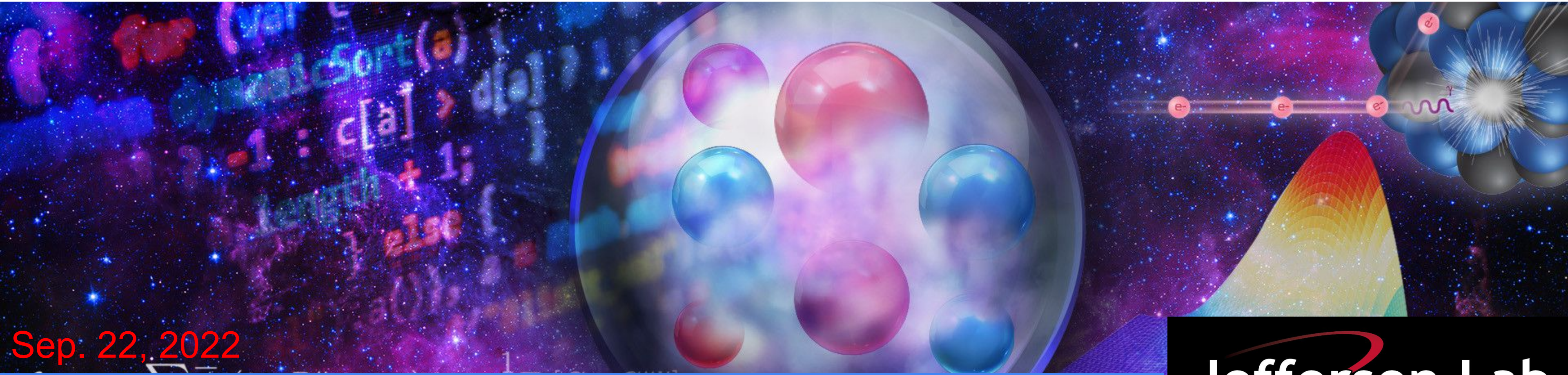
Proton internal structure

Nobuo Sato



Sep. 22, 2022

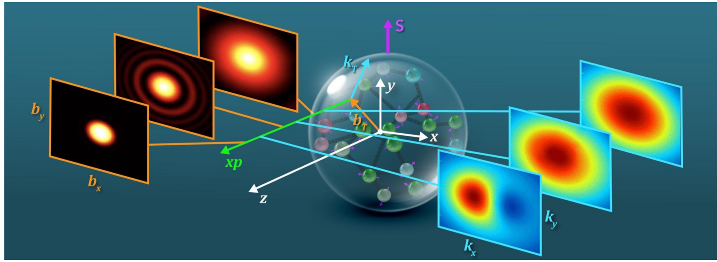
Advancing the understanding of non-perturbative QCD using energy flows

Jefferson Lab

Motivations

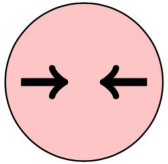
- **Synthesis of 3D tomography/nuclear imaging**: quantum correlation functions (QCFs)
  - hadron structure (PDFs, TMDs, GPDs, HT, ...)
  - hadronization (FFs, TMDFFs)

- **Test of universality & theory predictive power**
  - systematic improvements (resummation, evolution, HO calculations)
  - synergy with lattice calculations (Bayesian priors)
  - identification of regions of phase space where existing theory framework is applicable (phenomenology)



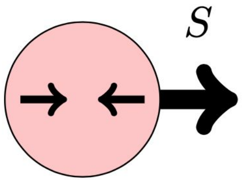
- **Opportunities**
  - origin of proton spin
  - quark and gluon tomography
  - structure of proton sea (strangeness / antimatter asymmetry)
  - origin of nuclear EMC effect
  - precision EW physics (Weinberg angle)
  - …

Collinear Spin structures



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

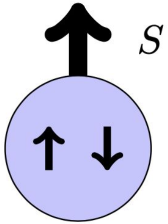
$$\langle N|\bar{\psi}_i(0, w^-, \mathbf{0}_\mathrm{T})\gamma^+\psi_i(0)|N\rangle$$



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

Helicity distribution

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



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

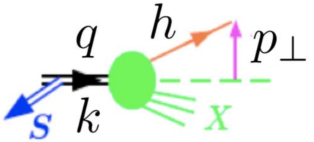
Transversity

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

TMD Spin structures

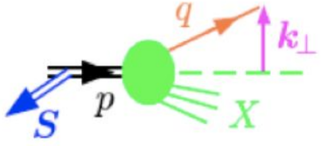
Sivers `89

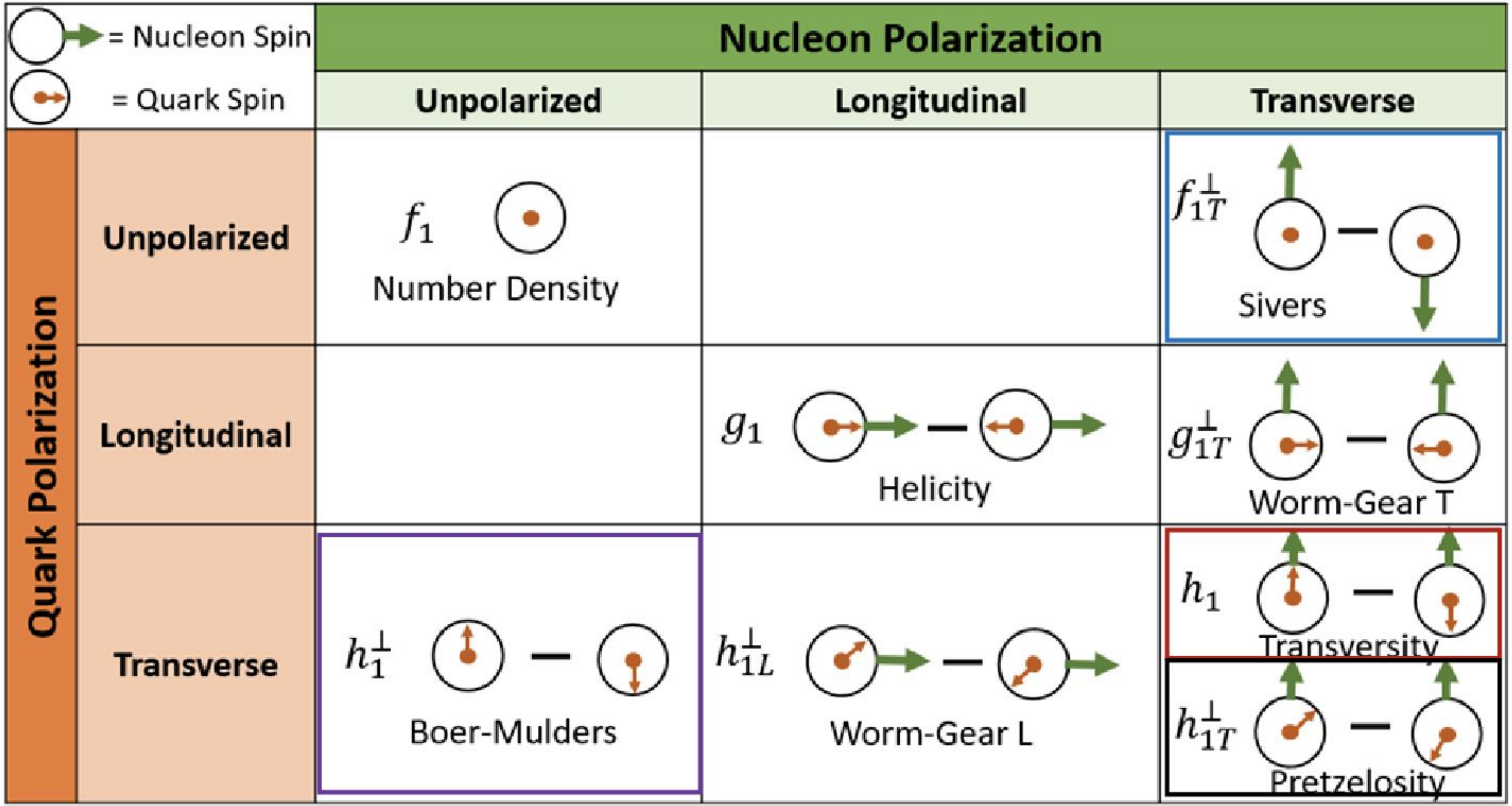
$$f_{q/h^\uparrow}(x,\vec{k}_\perp,\vec{S}) = f_{q/h}(x,k_\perp^2) - \frac{1}{M} f_{1T}^{\perp q}(x,k_\perp^2)\vec{S}\cdot(\hat{P}\times\vec{k}_\perp)$$



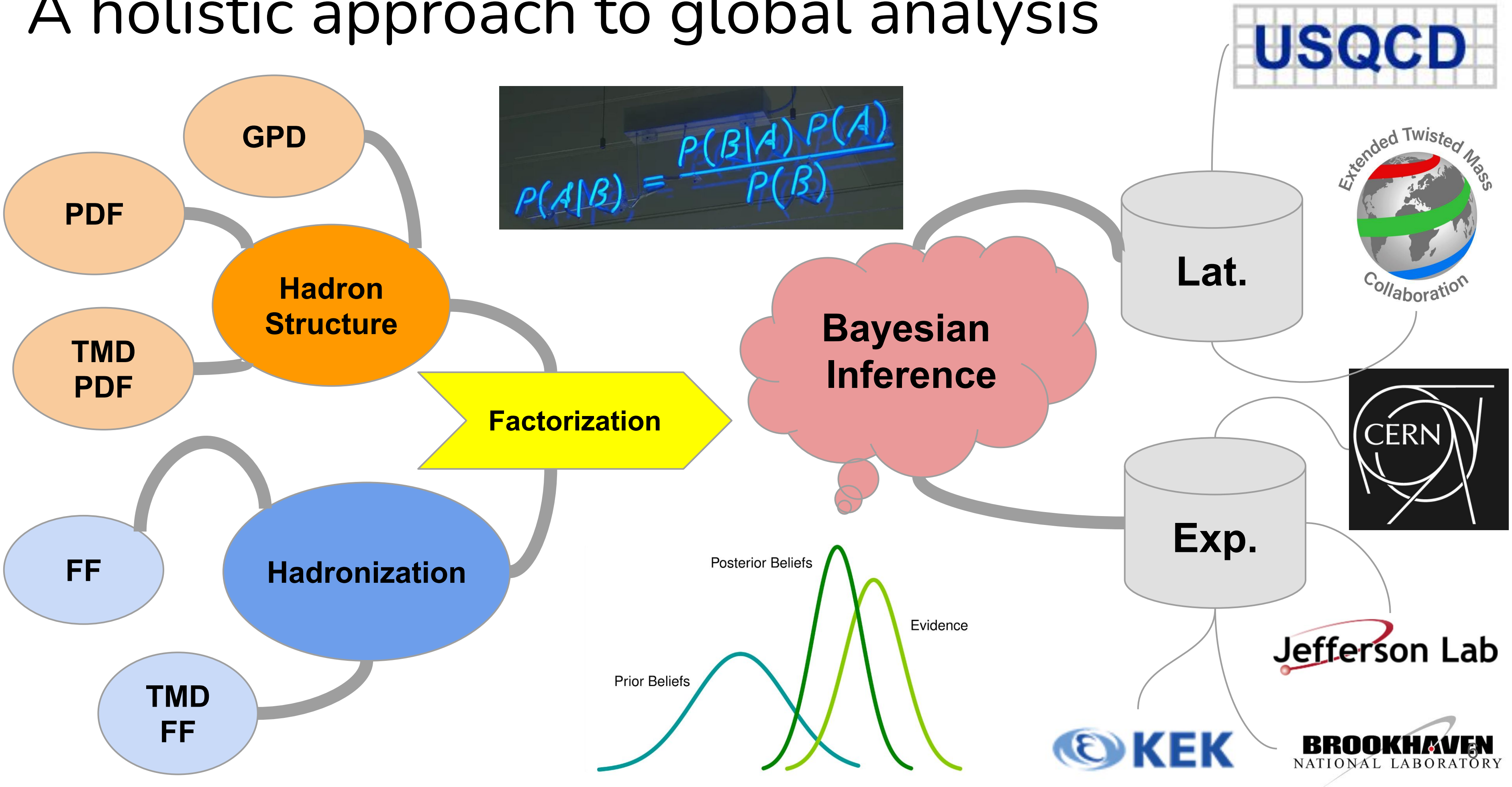
Collins `92

$$D_{q/h}(z,\vec{p}_\perp,\vec{s}_q) = D_{q/h}(z,p_\perp^2) + \frac{1}{zM_h} H_1^{\perp q}(z,p_\perp^2)\vec{s}_q\cdot(\hat{k}\times\vec{p}_\perp)$$




= Nucleon Spin
= Quark Spin
Nucleon Polarization
Unpolarized
Longitudinal
Transverse
Quark Polarization
Unpolarized
Longitudinal
Transverse
f_1
Number Density
$f_{1T}^{\perp}$
Sivers
g_1
Helicity
$g_{1T}^{\perp}$
Worm-Gear T
$h_1^{\perp}$
Boer-Mulders
$h_{1L}^{\perp}$
Worm-Gear L
h_1
Transversity
$h_{1T}^{\perp}$
Pretzelosity

A holistic approach to global analysis



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arXiv.org > hep-ex > arXiv:2104.05850

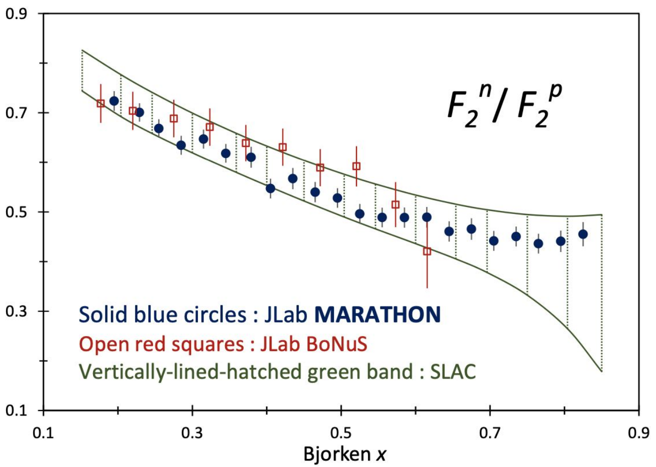
Search...

Help | Advanc

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

High Energy Physics – Experiment

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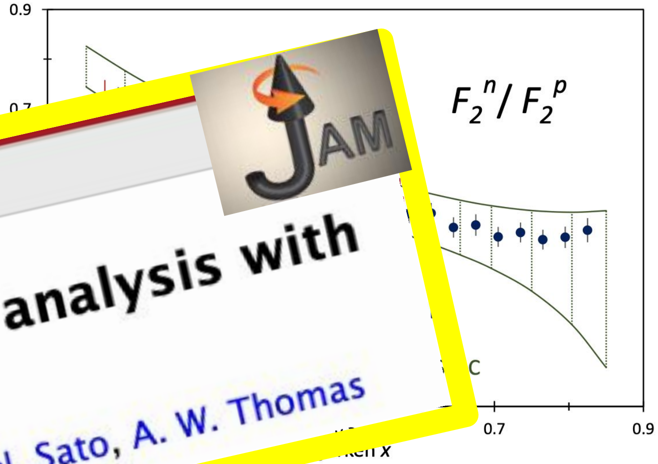
Measurement of the Nucleon F_2^n/F_2^p Structure Fun... by the Jefferson Lab MARATHON Triti... Inelastic Scattering Experim...



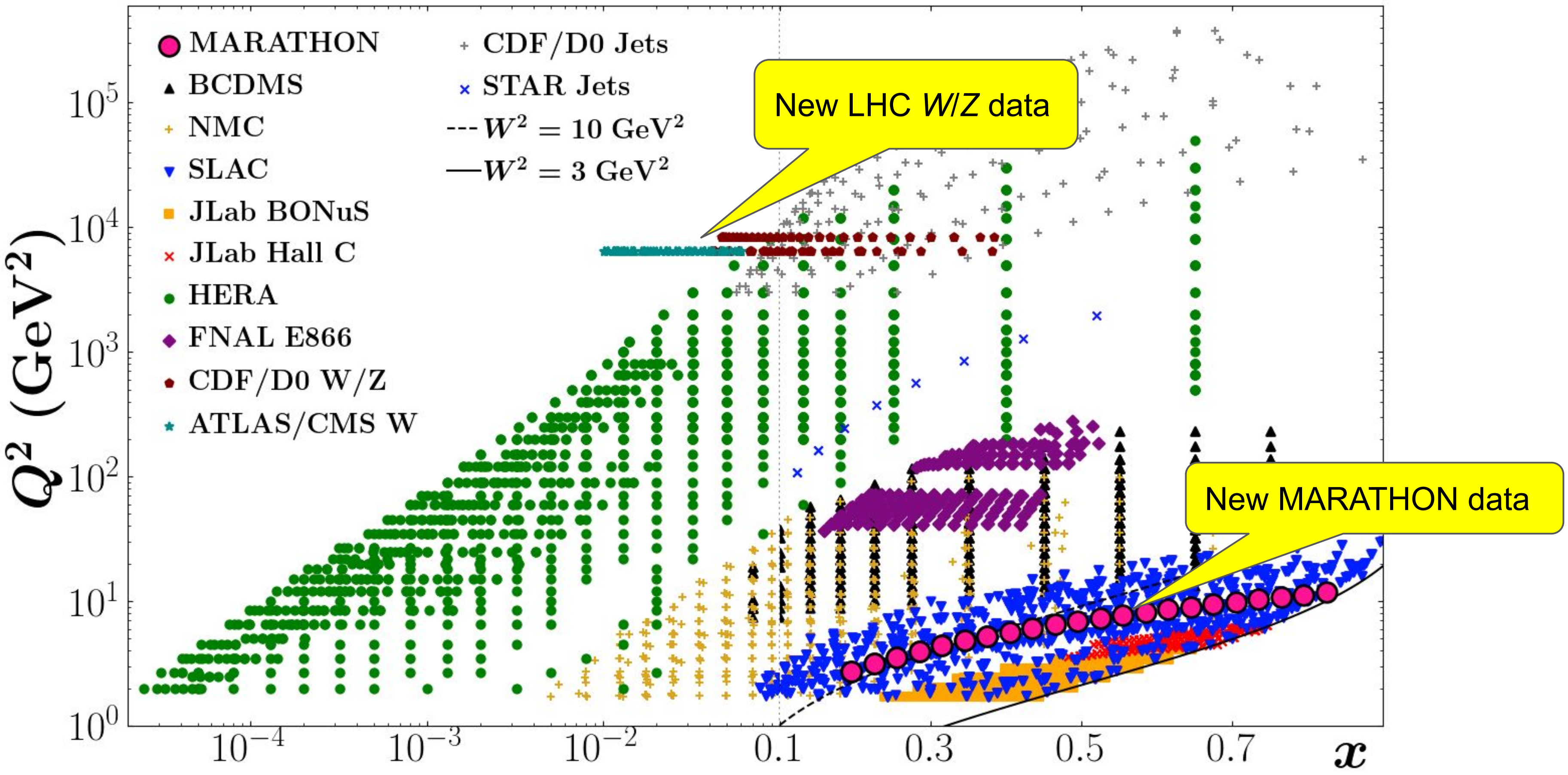
High Energy Physics – Phenomenology

[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 *W/Z* data
New MARATHON data
Q^2 (GeV^2)
x

Insights from mean field theory

Mineo, Bentz, Ishii, Thomas, Yazaki ('04)

$$\hat{H}_q = \hat{h}_q + V_0\,\hat{Q}$$

$$V^\mu = (V_0, \mathbf{0})$$

constant mean vector field acting on a quark in the nuclear medium

$$q(x) = \frac{p^+}{p^+ - V^+} q_0 \left(\frac{p^+}{p^+ - V^+} x - \frac{V_q^+}{p^+ - V^+} \right)$$

PDF in the absence of a vector potential

Phenomenological approach

$$\tilde{q}_{N/A}(x, p^2) = q_N(x) + v(p^2)\delta q_{N/A} + \dots$$

$$v(p^2) = (p^2 - M^2)/M^2$$

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

$$F_2^{N/A(\mathrm{off})}(x, Q^2) = \left(\sum_q \left[C_q \otimes \delta q_{N/A}\right]\right) \times \left(1 + \frac{C_N^{\mathrm{HT}}(x)}{Q^2}\right)$$

Nuclear impulse approximation

$$F_2^{A(\mathrm{on})}(x, Q^2) = \sum_N \left[f^{N/A} \otimes F_2^{N(\mathrm{on})} \right]$$

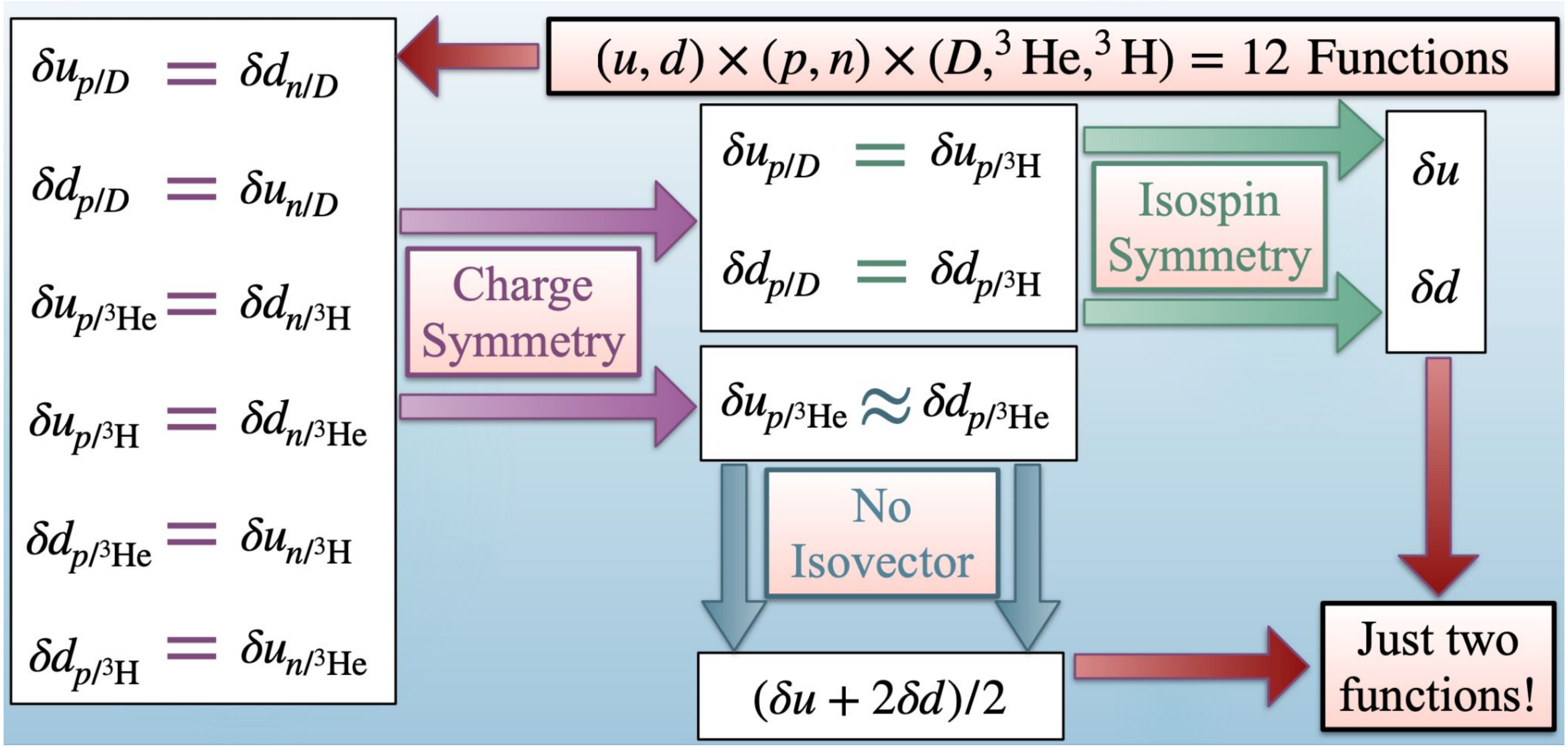
$$F_2^{A(\mathrm{off})}(x, Q^2) = \sum_N \left[\tilde{f}^{N/A} \otimes F_2^{N/A(\mathrm{off})} \right]$$

Nonrelativistic nucleon spectral functions computed from quantum Monte Carlo

$$f_{ij}^N(y, \gamma) = \int \frac{d^4p}{(2\pi)^4} \mathcal{F}_0^N(\varepsilon, \boldsymbol{p}) \left(1 + \frac{\gamma p_z}{M}\right) \mathcal{C}_{ij}\, \delta\left(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\right)$$

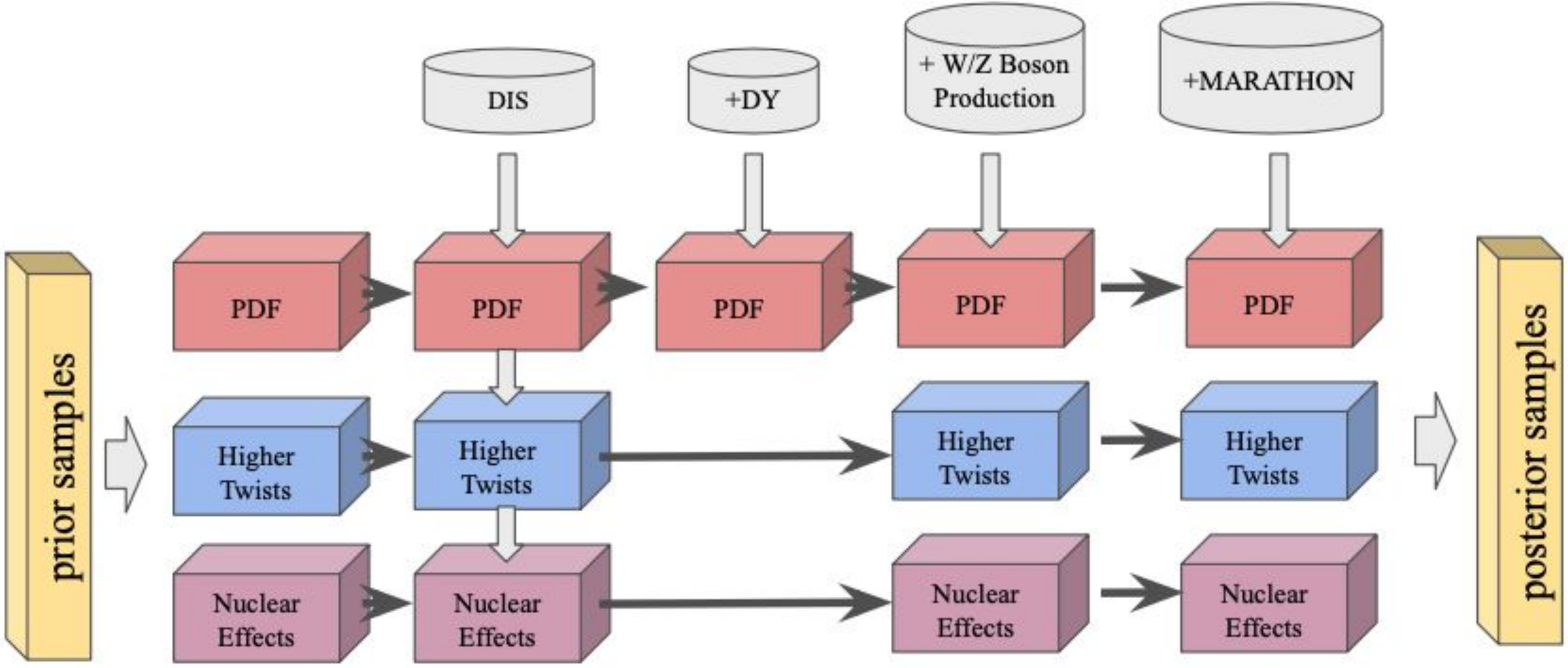
$$\widetilde{f}_{ij}^N(y, \gamma) = \int \frac{d^4p}{(2\pi)^4} \mathcal{F}_0^N(\varepsilon, \boldsymbol{p}) \left(1 + \frac{\gamma p_z}{M}\right) \mathcal{C}_{ij}\, v(p^2)\, \delta\left(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\right)$$

Symmetries



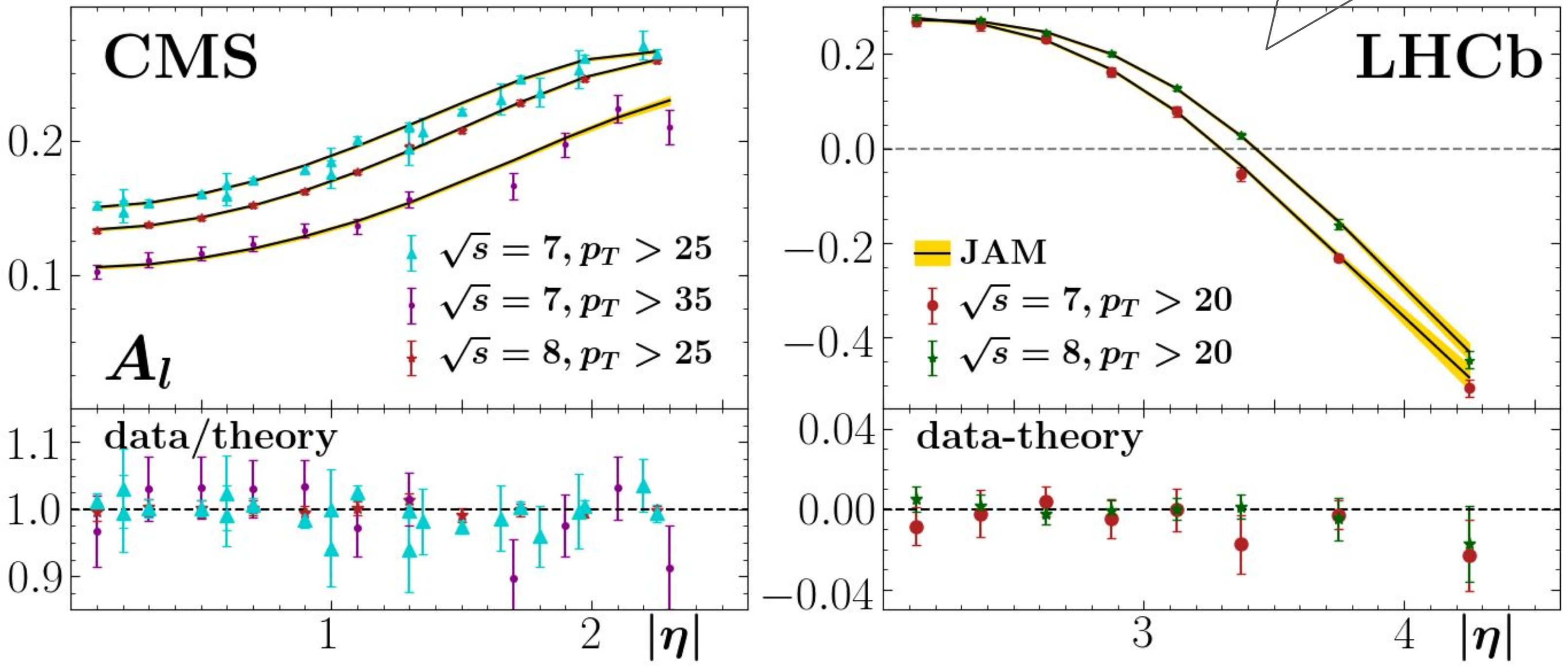
$(u,d)\times(p,n)\times(D,{}^3\mathrm{He},{}^3\mathrm{H}) = 12$ Functions
$\delta u_{p/D} = \delta d_{n/D}$
$\delta d_{p/D} = \delta u_{n/D}$
$\delta u_{p/^3\mathrm{He}} = \delta d_{n/^3\mathrm{H}}$
$\delta u_{p/^3\mathrm{H}} = \delta d_{n/^3\mathrm{He}}$
$\delta d_{p/^3\mathrm{He}} = \delta u_{n/^3\mathrm{H}}$
$\delta d_{p/^3\mathrm{H}} = \delta u_{n/^3\mathrm{He}}$
Charge Symmetry
$\delta u_{p/D} = \delta u_{p/^3\mathrm{H}}$
$\delta d_{p/D} = \delta d_{p/^3\mathrm{H}}$
$\delta u_{p/^3\mathrm{He}} \approx \delta d_{p/^3\mathrm{He}}$
Isospin Symmetry
δu
δd
No Isovector
$(\delta u + 2\delta d)/2$
Just two functions!

Multi-step strategy

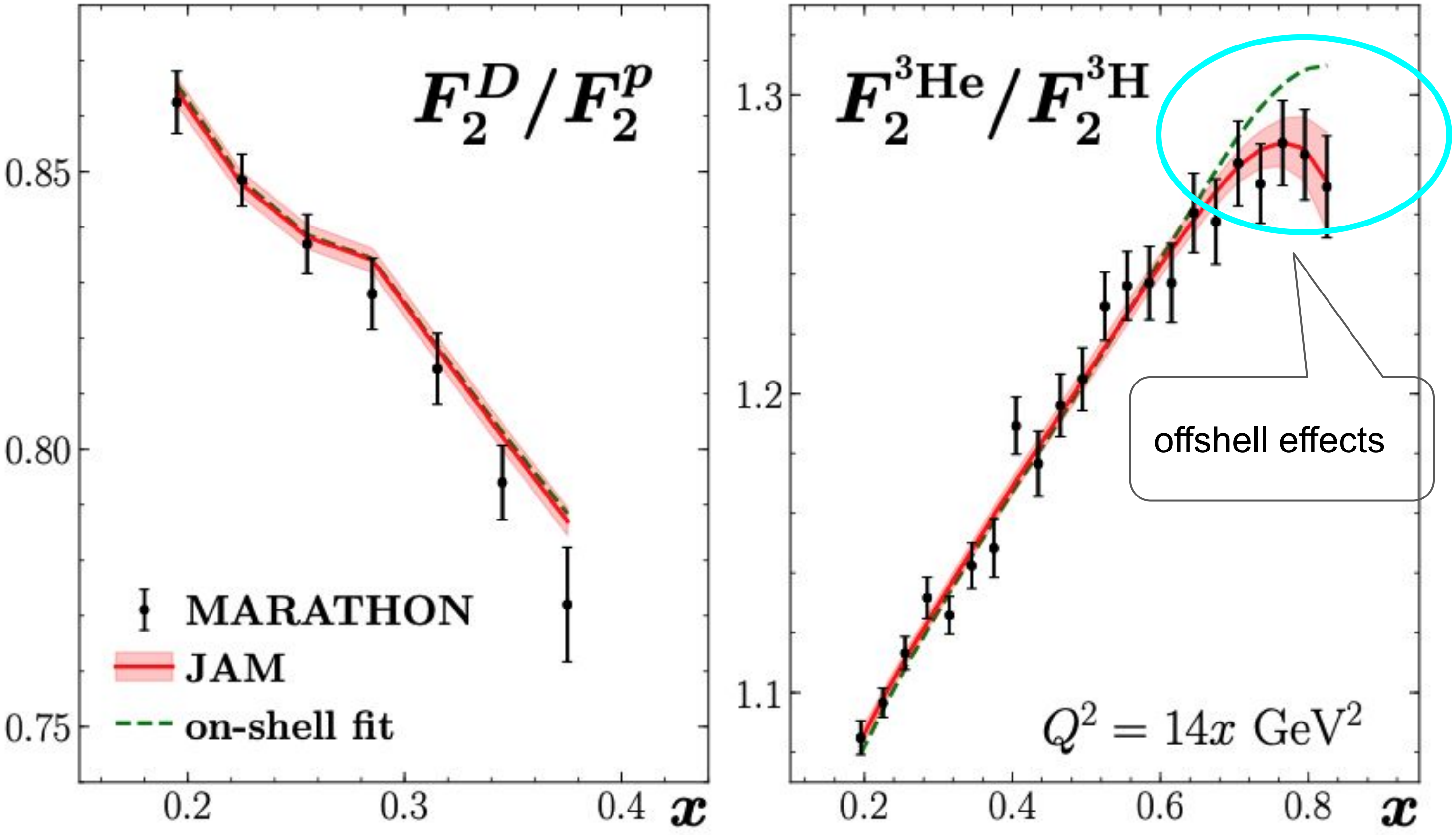


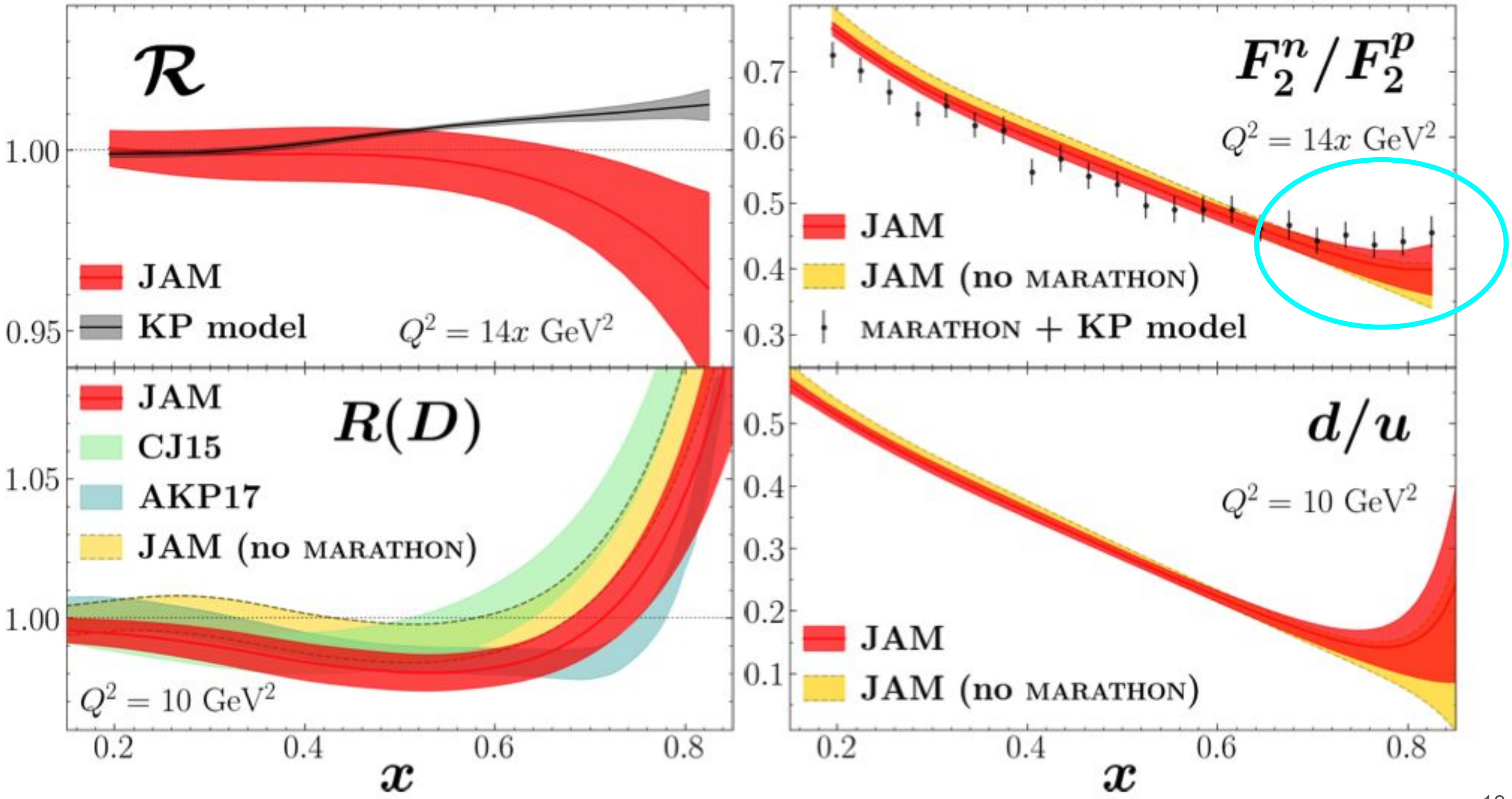
LHC W data

Excent agreement between theory and data

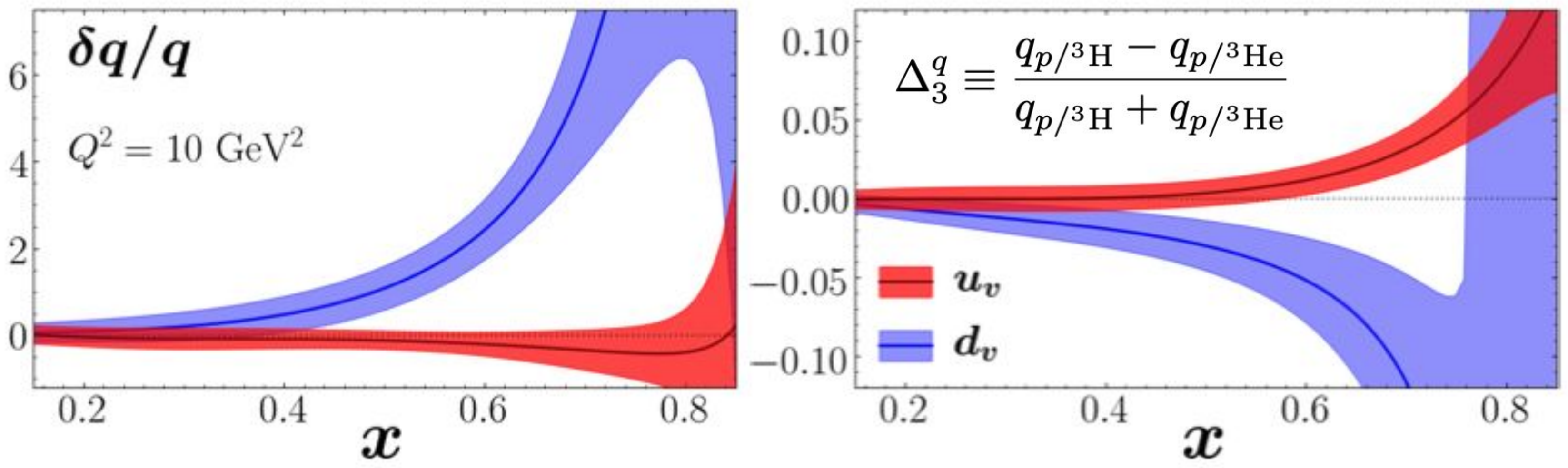


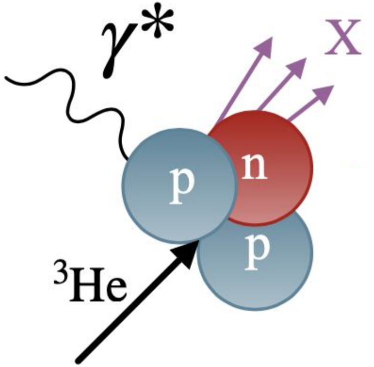
MARATHON data

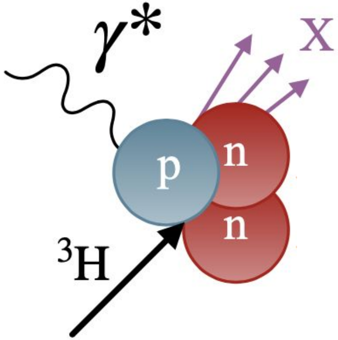




$\mathcal{R}$
JAM
KP model
$Q^2 = 14x$ GeV^2
1.00
0.95
F_2^n/F_2^p
$Q^2 = 14x$ GeV^2
JAM
JAM (no MARATHON)
MARATHON + KP model
0.7
0.6
0.5
0.4
0.3
$R(D)$
JAM
CJ15
AKP17
JAM (no MARATHON)
$Q^2 = 10$ GeV^2
1.05
1.00
d/u
$Q^2 = 10$ GeV^2
JAM
JAM (no MARATHON)
0.5
0.4
0.3
0.2
0.1
0.2
0.4
0.6
0.8
x
0.2
0.4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







- Evidence of different medium modifications for *u* and *d* quarks
- Naive modeling of nuclear PDFs, *e.g. u/p/A=d/n/A* (violates isospin for non-isoscalar *A*) is wrong
- Proposals to explore isovector effects in SIDIS at JLab

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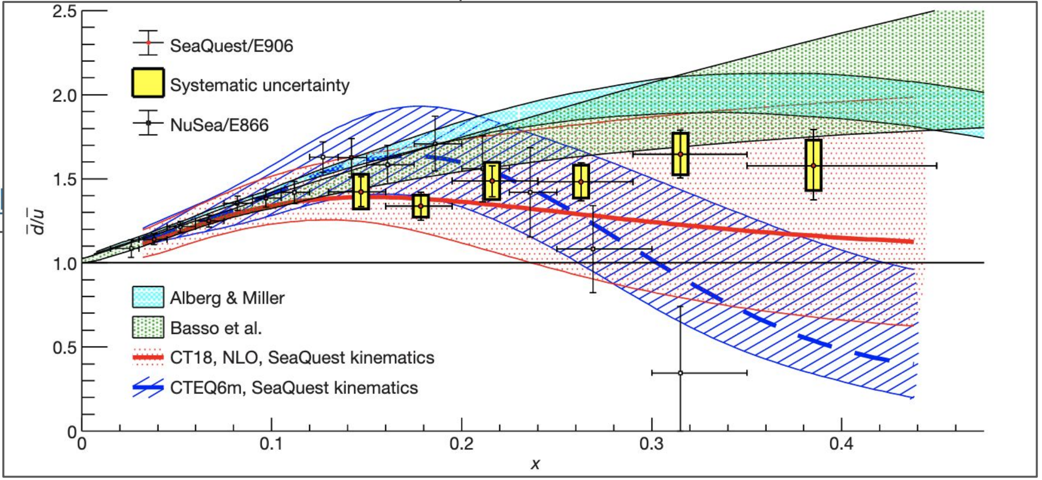
nature

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...

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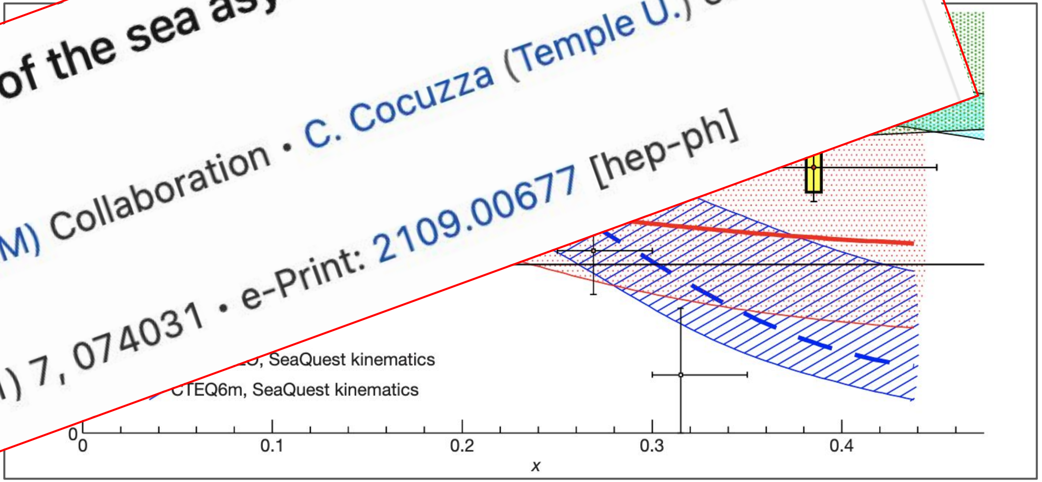
8942 Accesses



Bayesian Monte Carlo extraction of the sea asymmetry with SeaQuest and STAR data #7

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

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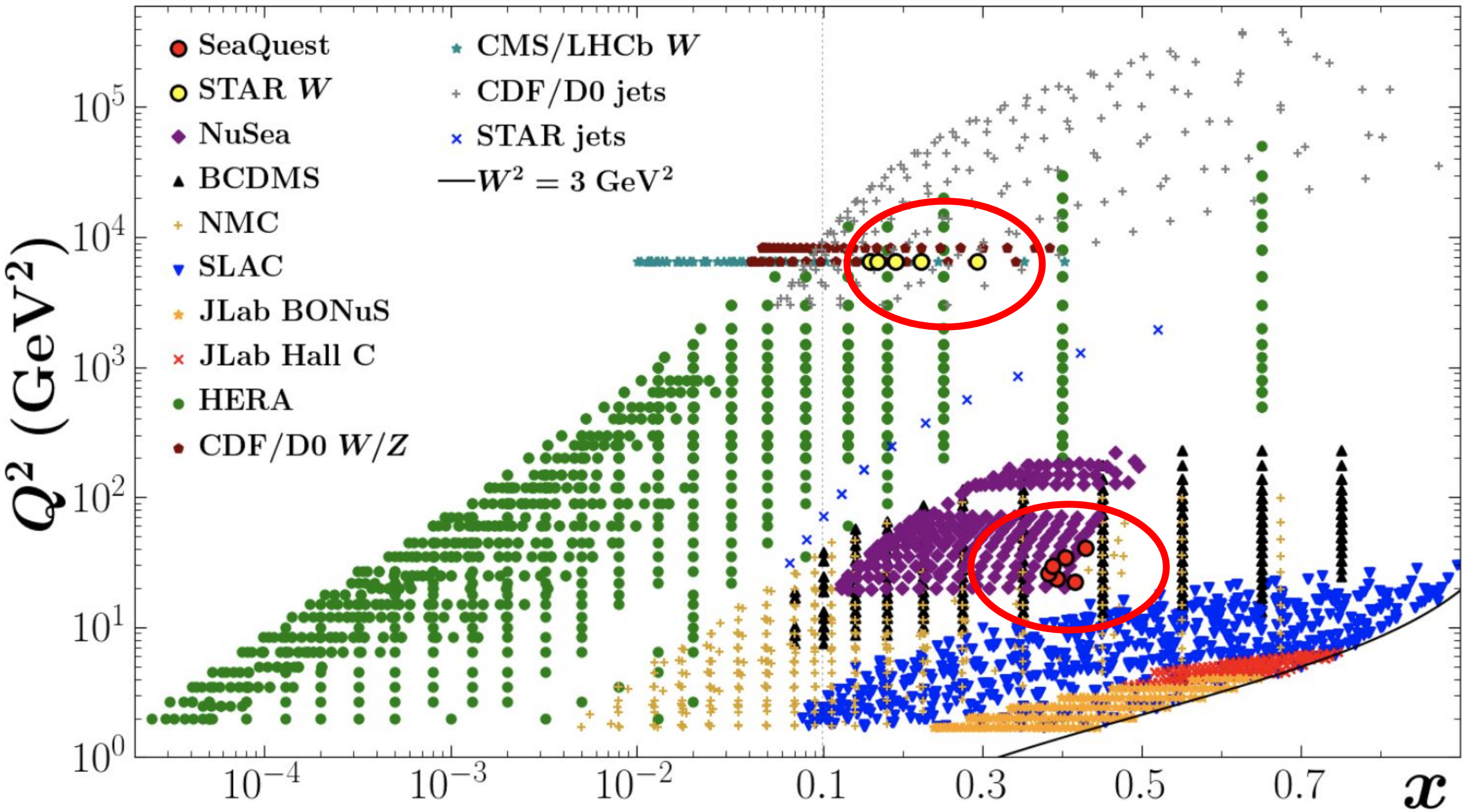
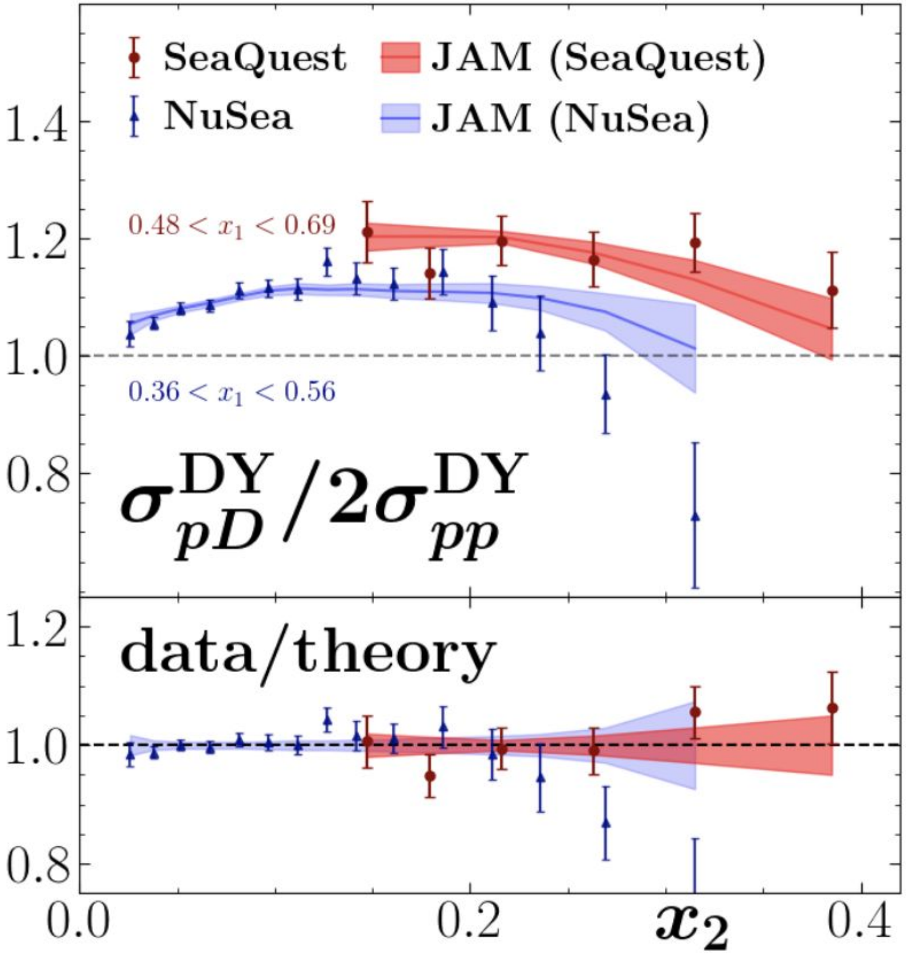
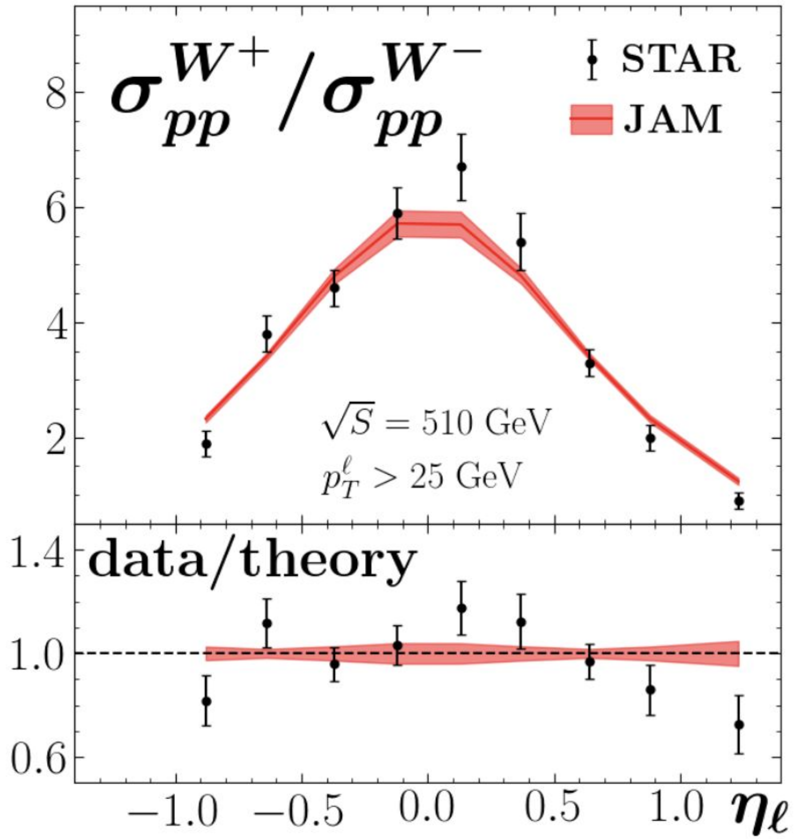
Phys. Rev. D **103**, 012001 – Published 4 January 2021


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

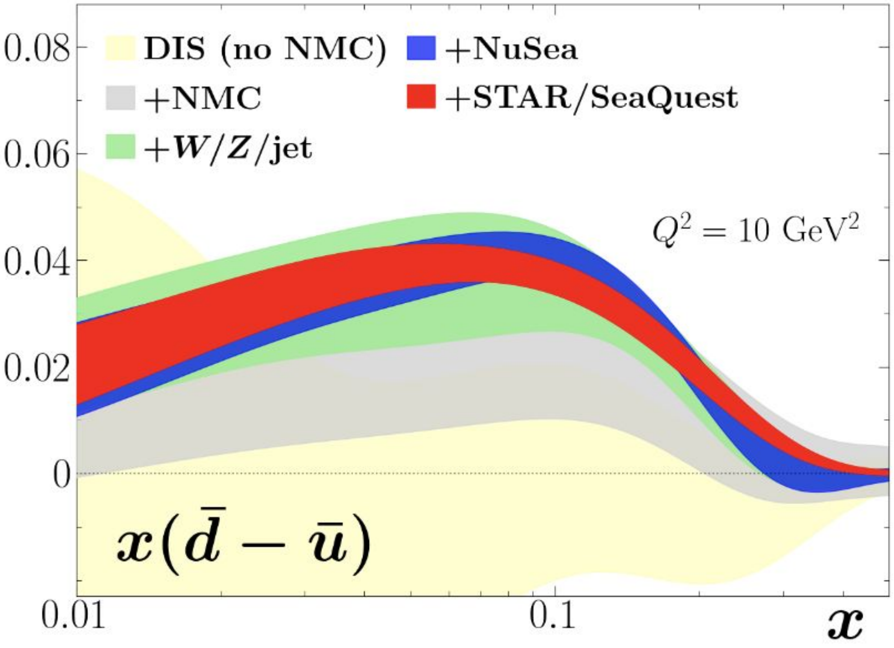


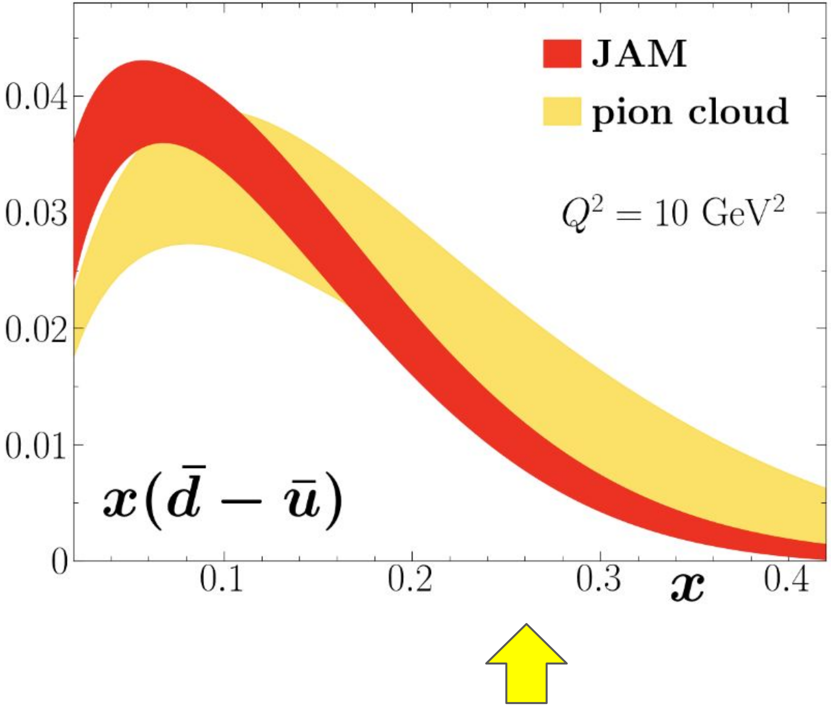
SeaQuest
NuSea
JAM (SeaQuest)
JAM (NuSea)
0.48 < x1 < 0.69
0.36 < x1 < 0.56
σ DY pD / 2σ DY pp
data/theory
x2



σ W+ pp / σ W− pp
STAR
JAM
√S = 510 GeV
pT ℓ > 25 GeV
data/theory
ηℓ

The historical progression of sea asymmetry





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

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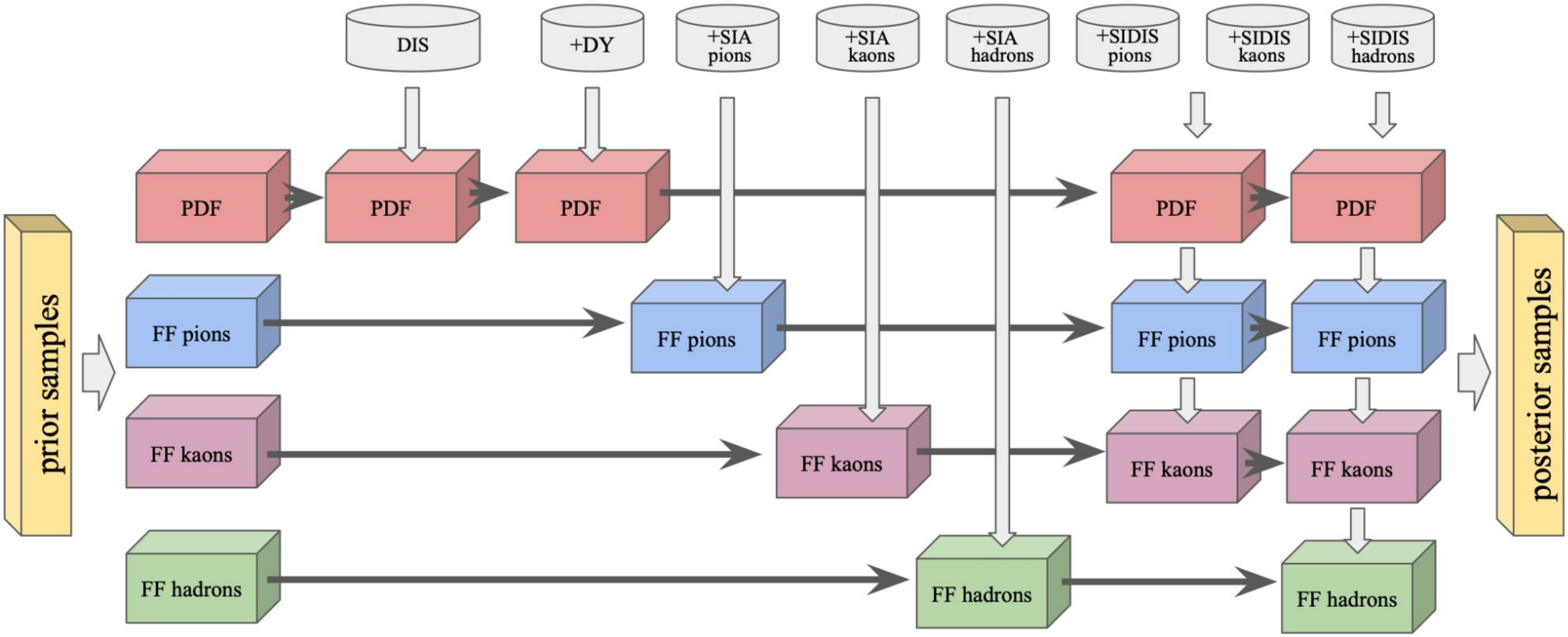
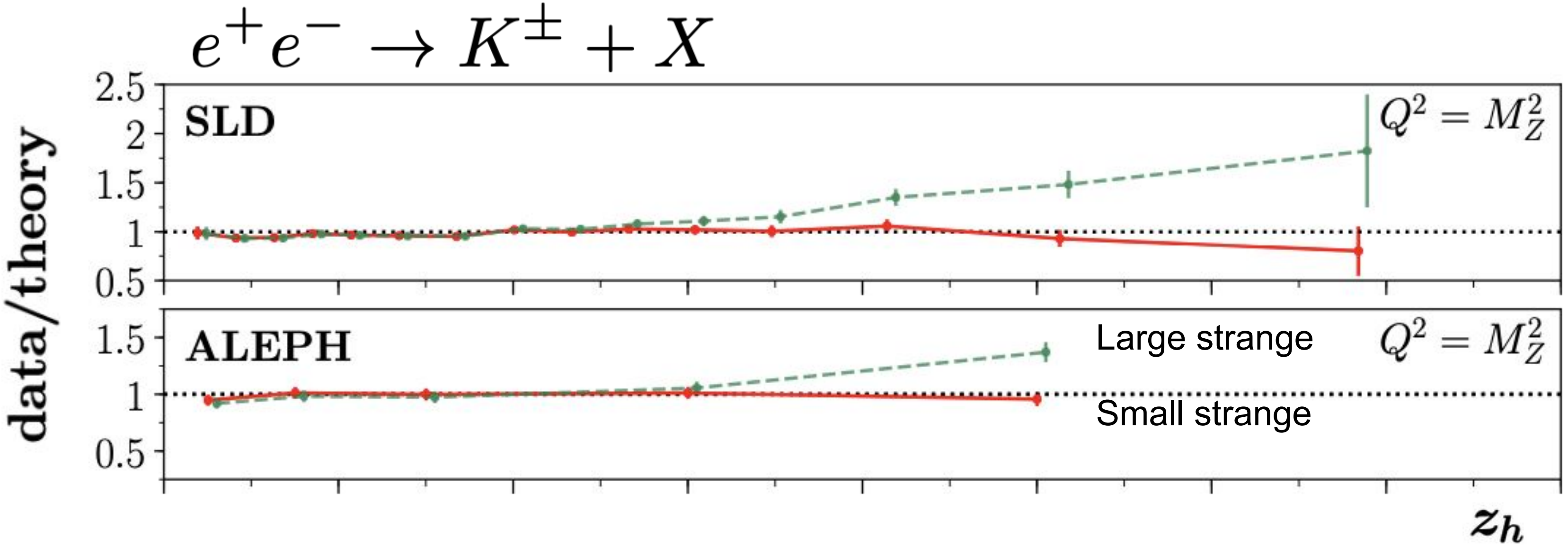
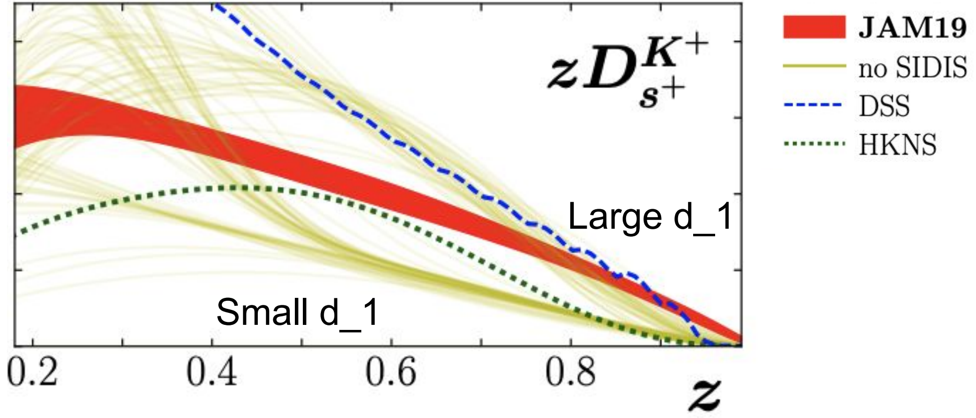
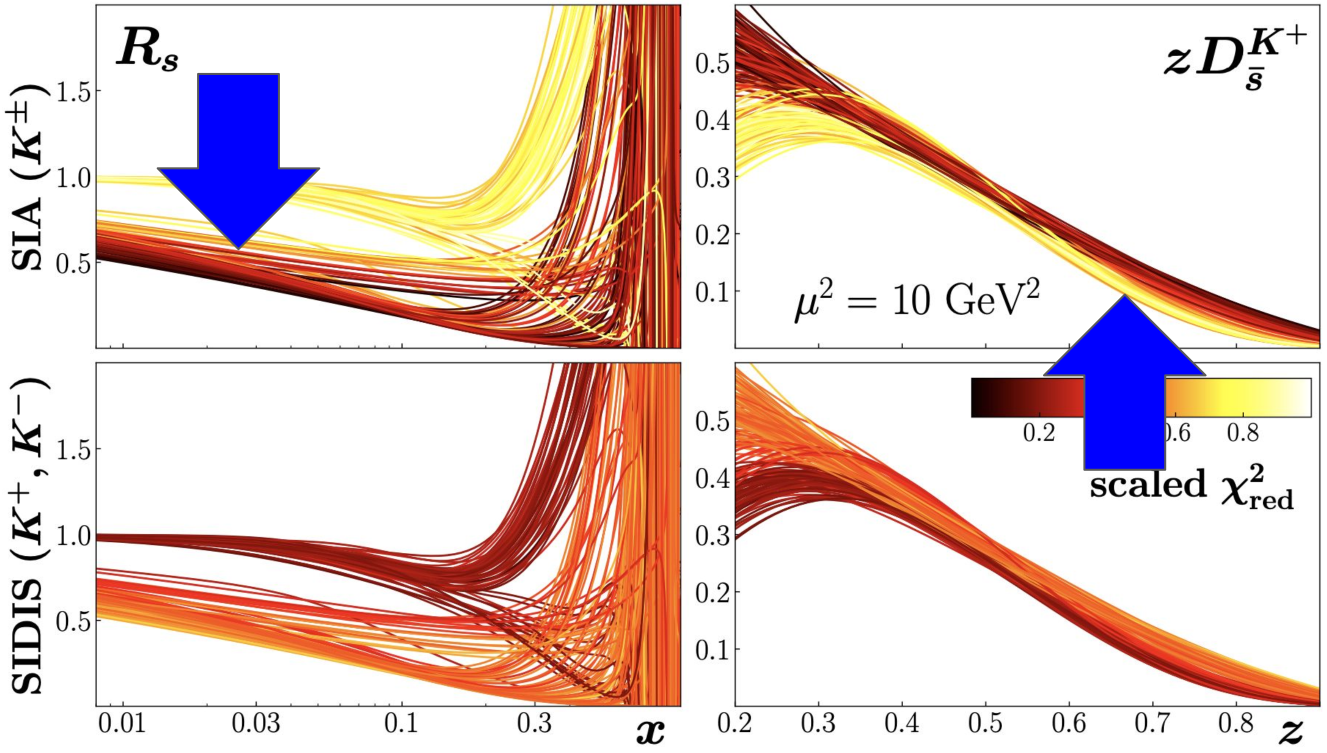
Multi-step strategy







- LEP kaon data disfavor small *s* --> *K* fragmentation
- SIDIS data compensate large strange FF by suppressing strange PDF



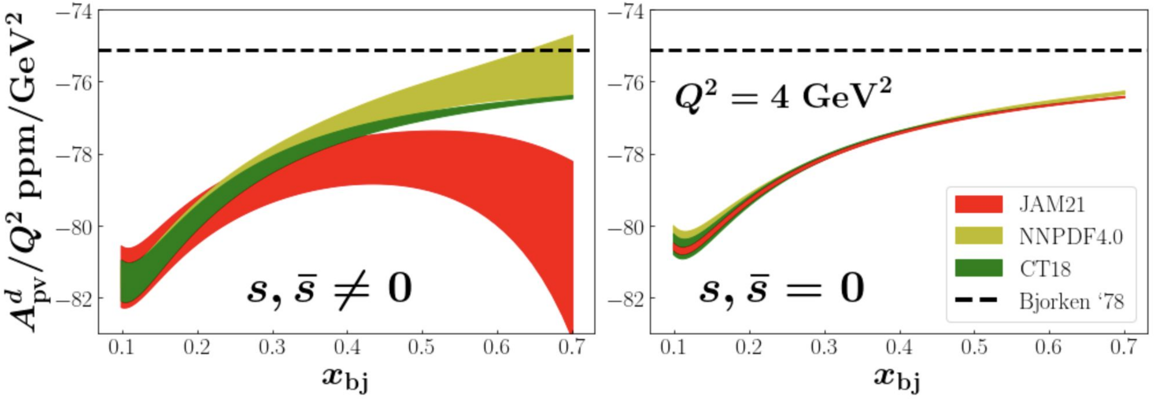
Bottom line:

Simultaneous analysis suggests a strong strange suppression, and differs from other global analyses using LHC data alone

Strangeness & Apv deuteron

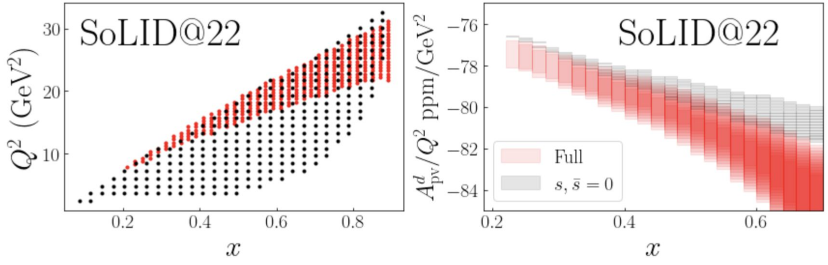
$$\frac{A^{eD}}{Q^2}\Big|_{y=0} = -\frac{3G}{10\pi\alpha\sqrt{2}}\left[2\epsilon_{AV}(e,u)\left(1+\tfrac{3}{10}\delta\right) - \epsilon_{AV}(e,d)\left(1-\tfrac{6}{5}\delta\right)\right].$$

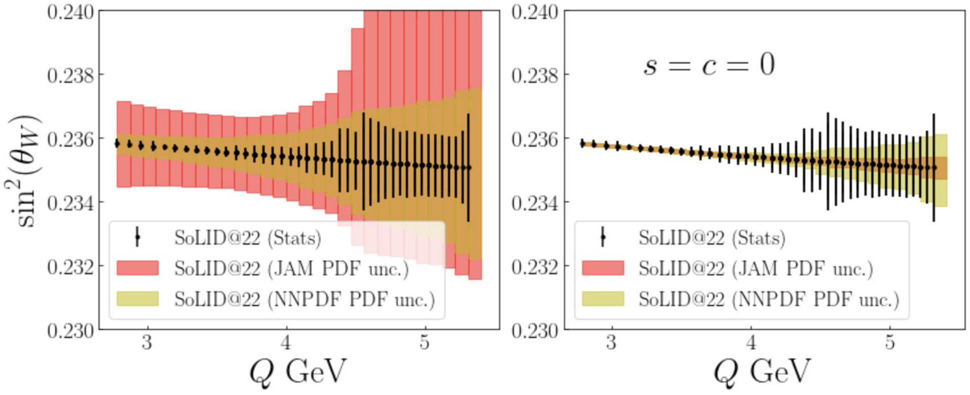
Bjorken `78



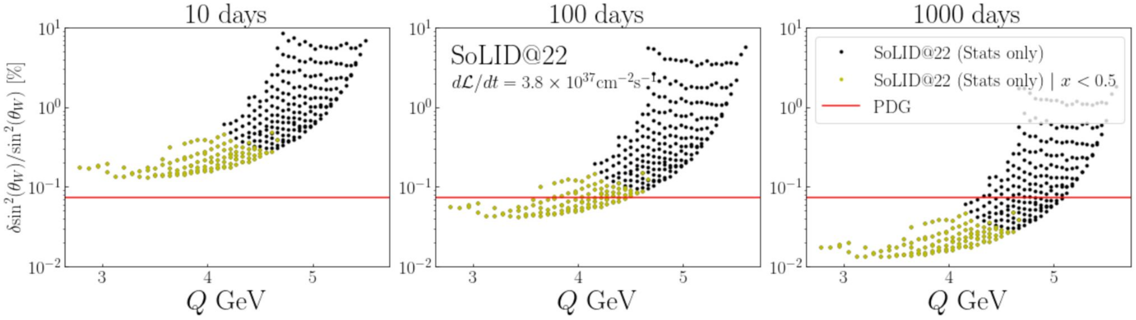
- Apv on deuteron has the opportunity to access directly Weinberg angle
- However, limited knowledge of strange quark PDF induces larger uncertainties for sin^2θw from Apv D
- On the other hand, under the SM hypothesis, Apv D can explore strangeness in the large-x region

Strangeness & Apv deuteron @ JLab++





- Apv D has significant constraining power on strange PDF –> tested on two PDFs sets (JAM, NNPDF)
- Luminosity is critical to discover how strange the proton is!



- If strangeness is constrained elsewhere (LQCD, other HEP observables), high luminosity Apv D will deliver precision EW measurements

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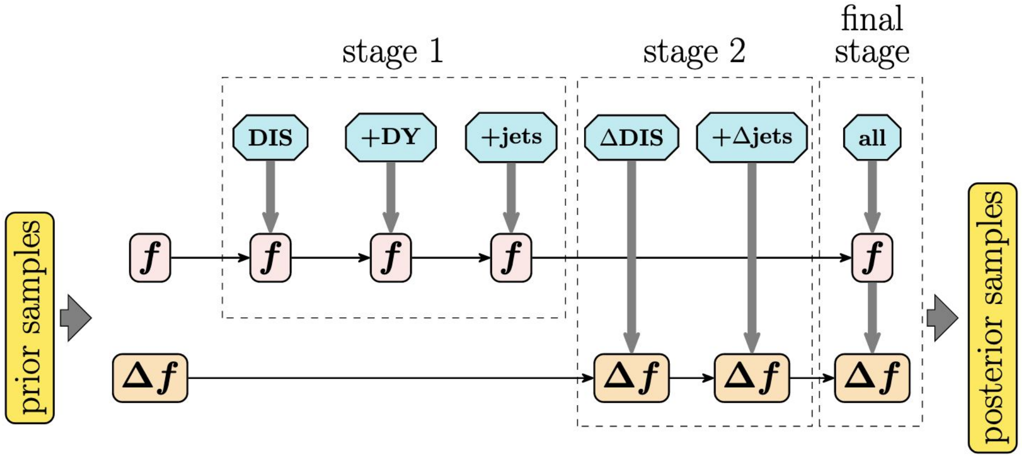
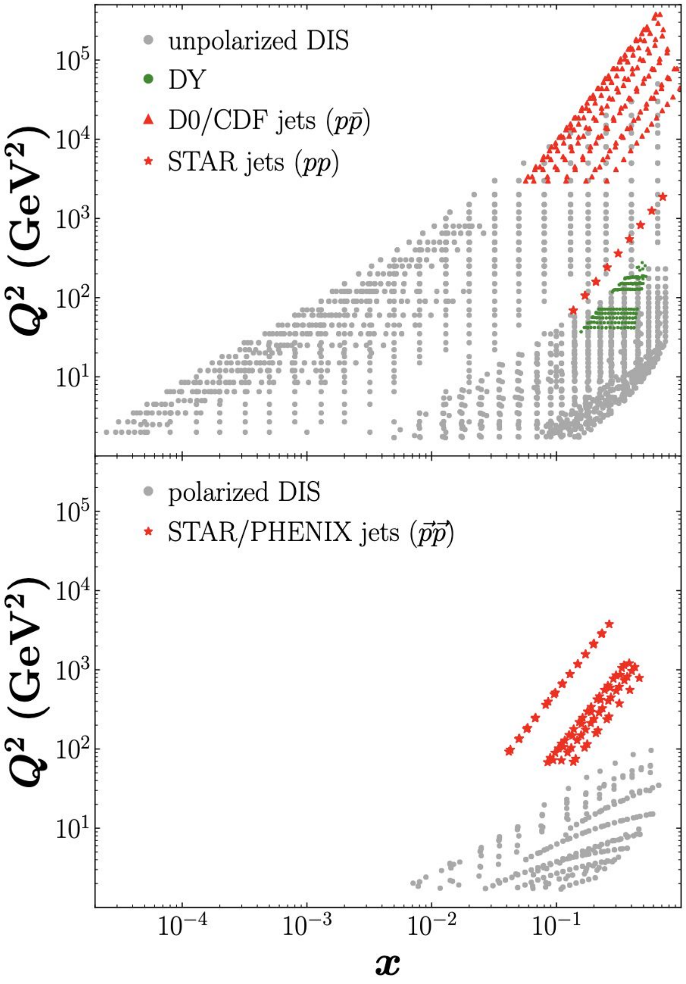
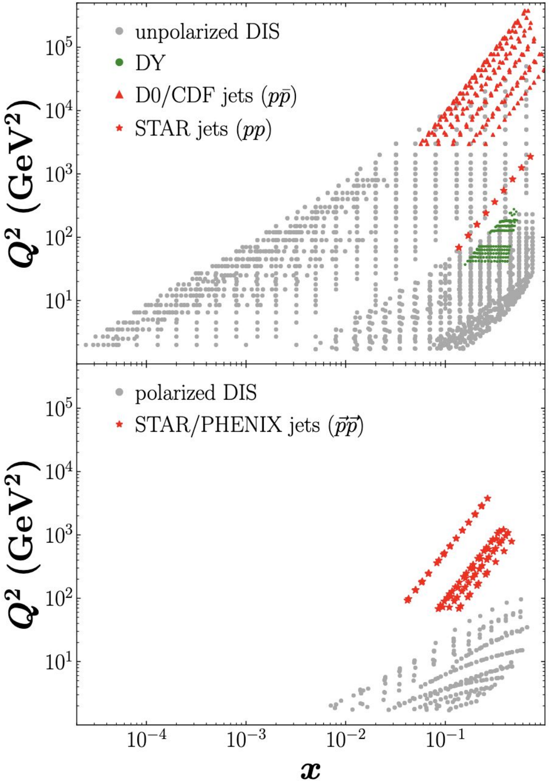
How well do we know the gluon polarization in the proton?

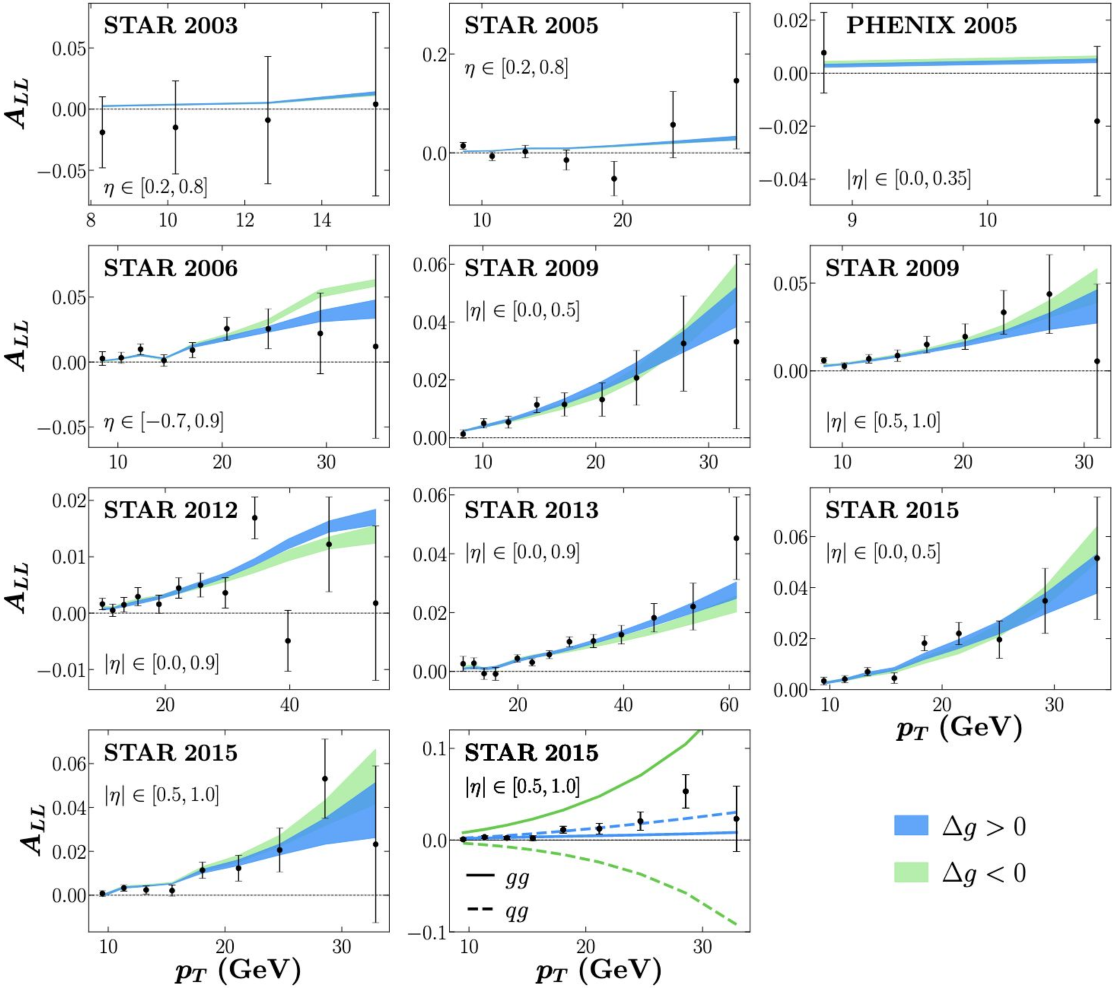
Y. Zhou, N. Sato, and W. Melnitchouk (Jefferson Lab Angular Momentum (JAM) Collaboration)
Phys. Rev. D **105**, 074022 – Published 25 April 2022





Polarized jets

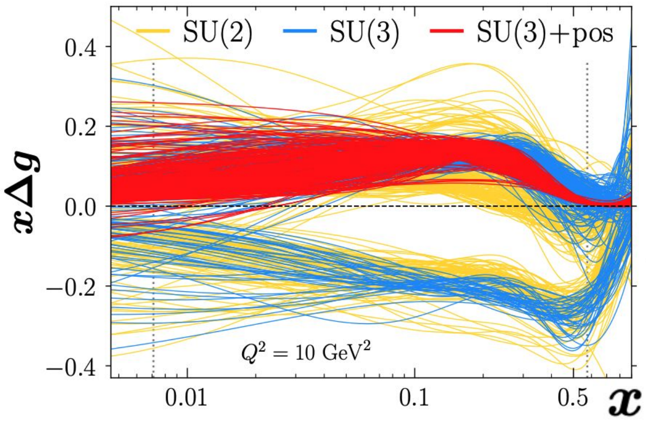


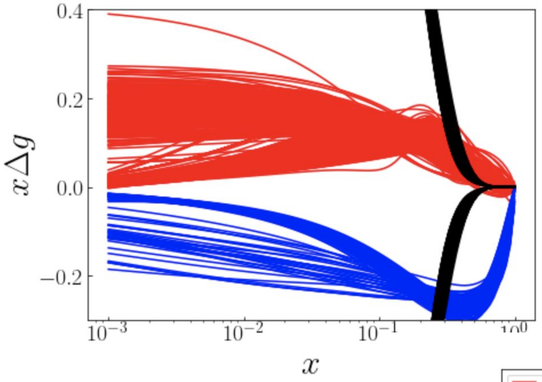


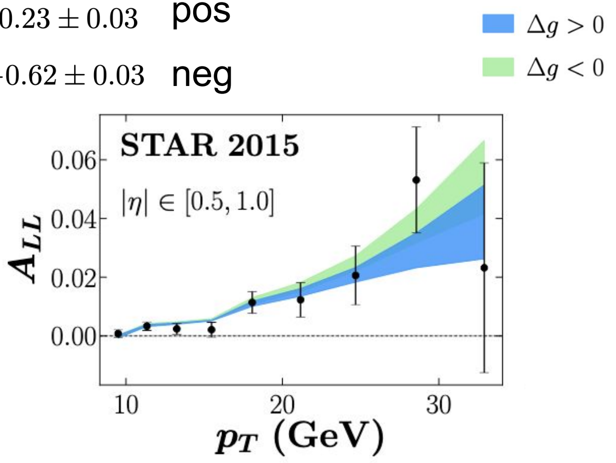
Negative gluon polarization?

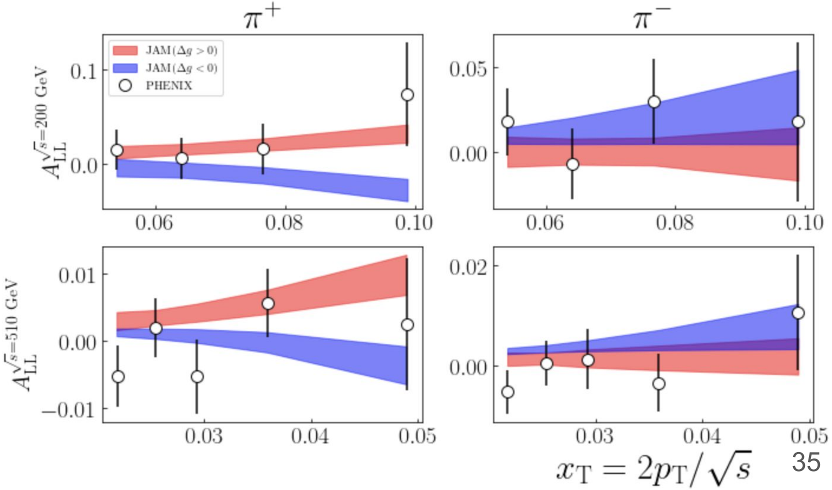
$$\int_{0.05}^{1} dx \Delta g(x) = \begin{matrix} 0.23 \pm 0.03 & \text{pos} \\ -0.62 \pm 0.03 & \text{neg} \end{matrix}$$

Zhou, Melnitchouk, Sato (PRD)





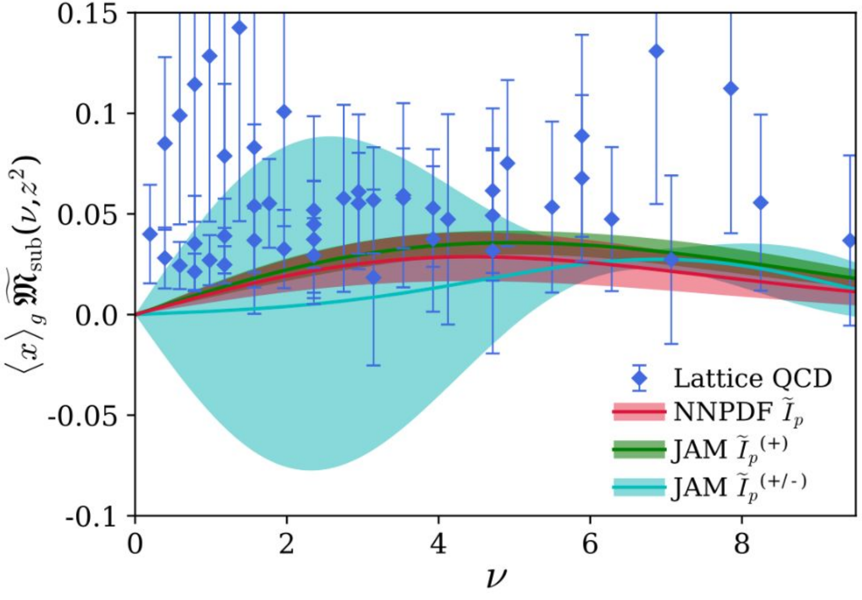


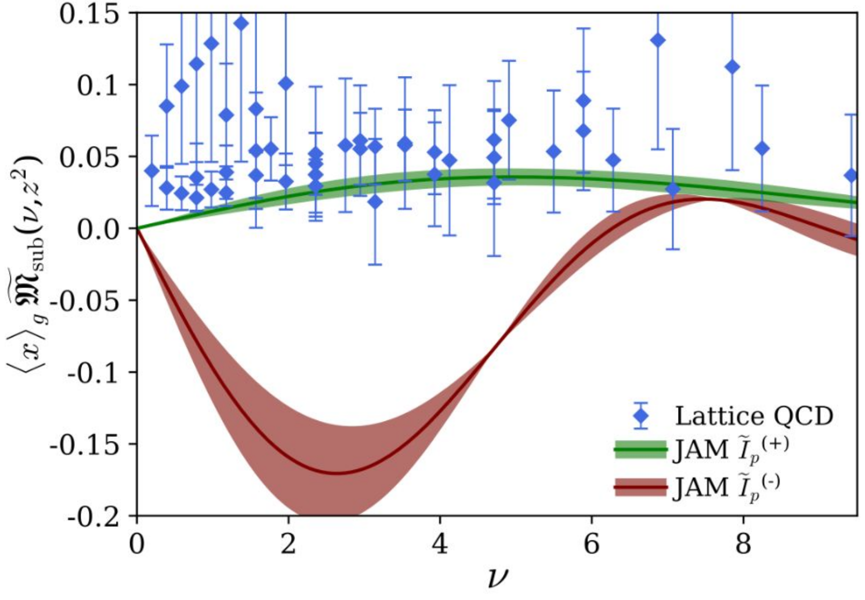


- Inclusion of RHIC polarized jet data allows both positive and negative gluon helicity solutions (in absence of positivity constraints on unpolarized gluon PDF)
- PHENIX has attempted to have empirical confirmation of gluon helicity sign (PRD102.032001, PRD91.032001)
- *Gluon helicity currently not as well constrained as was believed (independent of theory bias)*

Insights from LQCD

Egerer et al ('22)

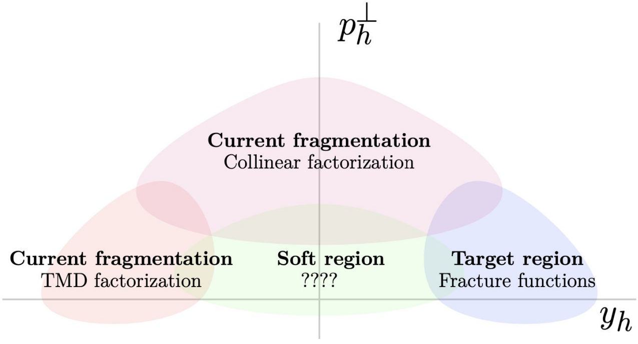


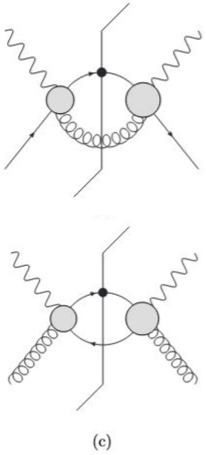


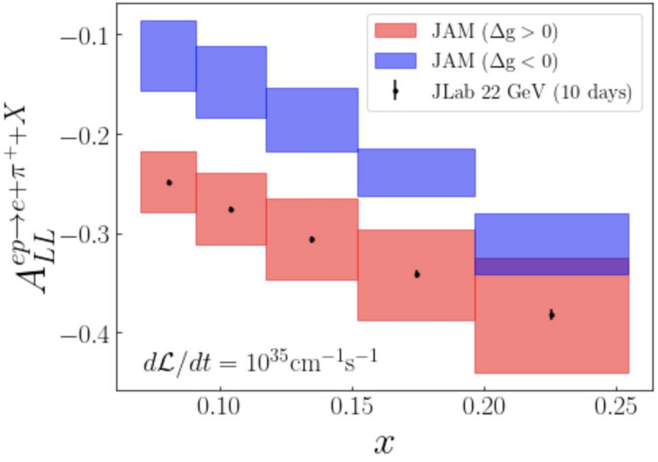
HadStruc Collaboration

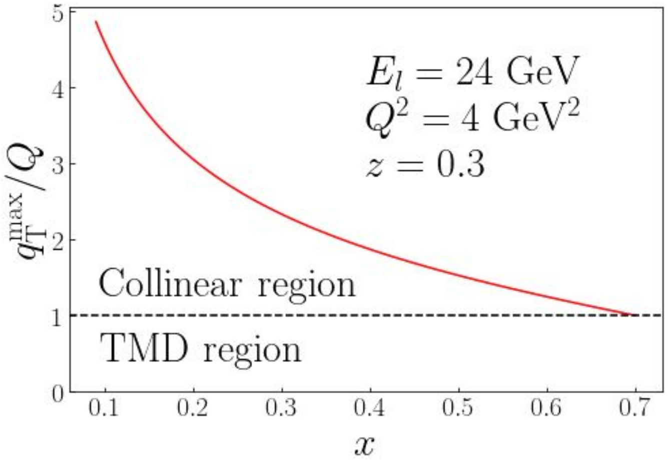
Negative gluon helicity is ruled out by LQCD?

Gluon helicity @ JLab++









- Hadron production with large transverse momentum has an opportunity to discriminate the sign of gluon polarization
- For JLab 22 as well as EIC, there would be plenty of phase space to use collinear factorization
- More dedicated studies are on the way

Outline

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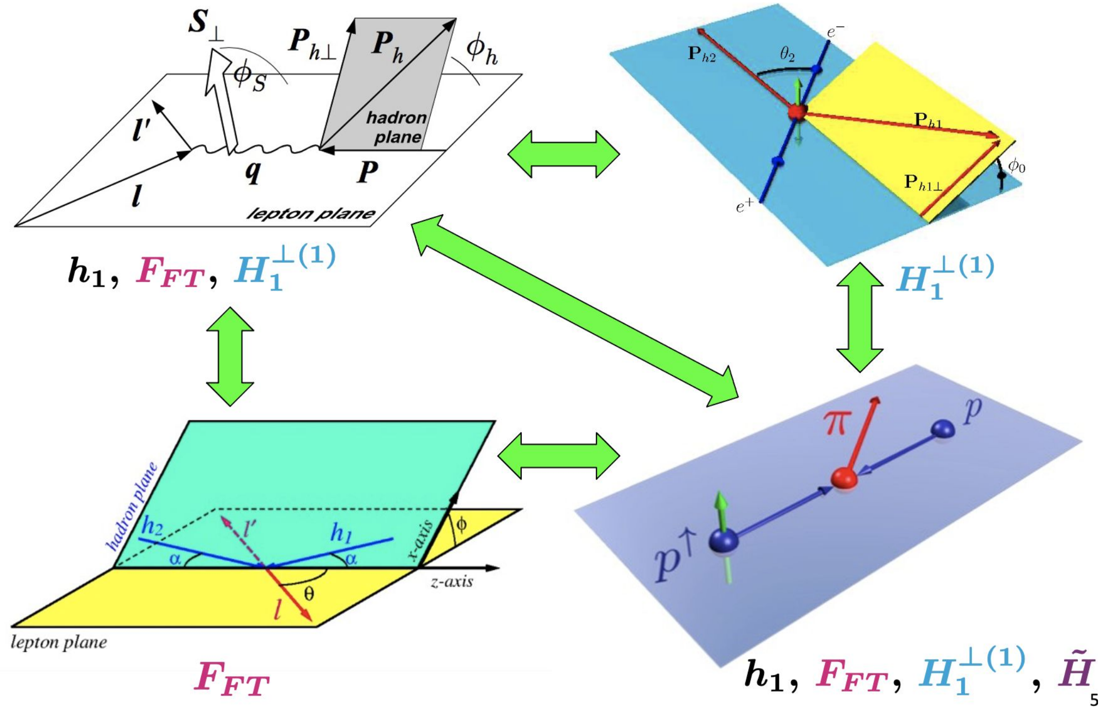
Global analysis of SSA (TMD + CT3)

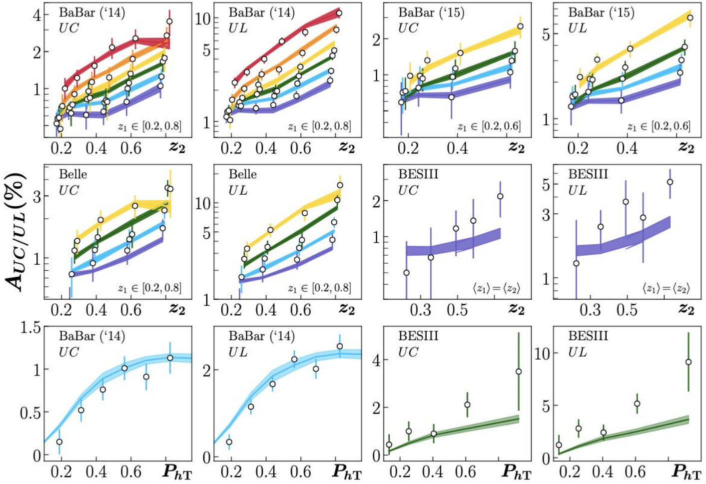
Cammarota et al ('20)



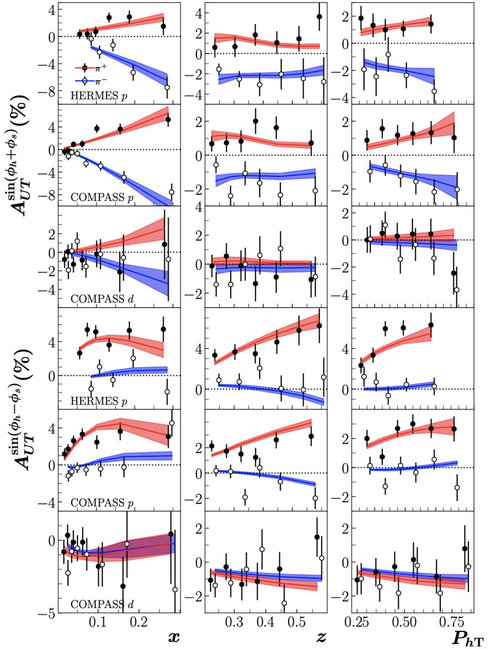
- Framework based on parton model approach to TMDs
- First steps to test universality of the combined TMD and CT3 framework
- Future analysis can build upon this work by implementing proper TMD evolution

Data vs theory…

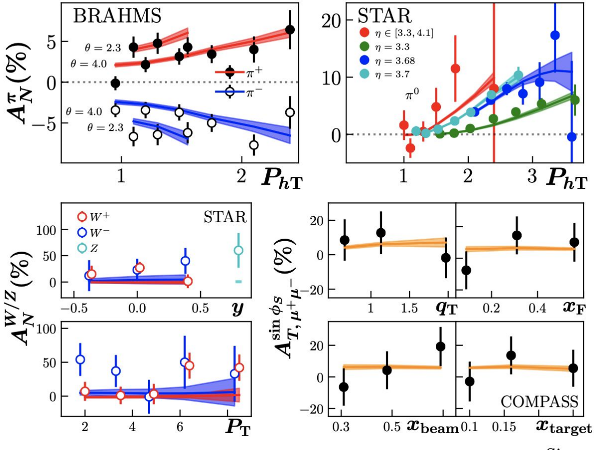
SIA



SIDIS



A_N in p+p / pi + p

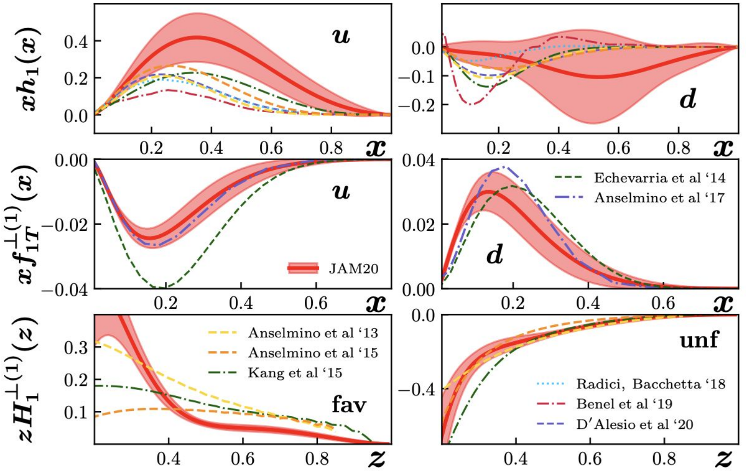


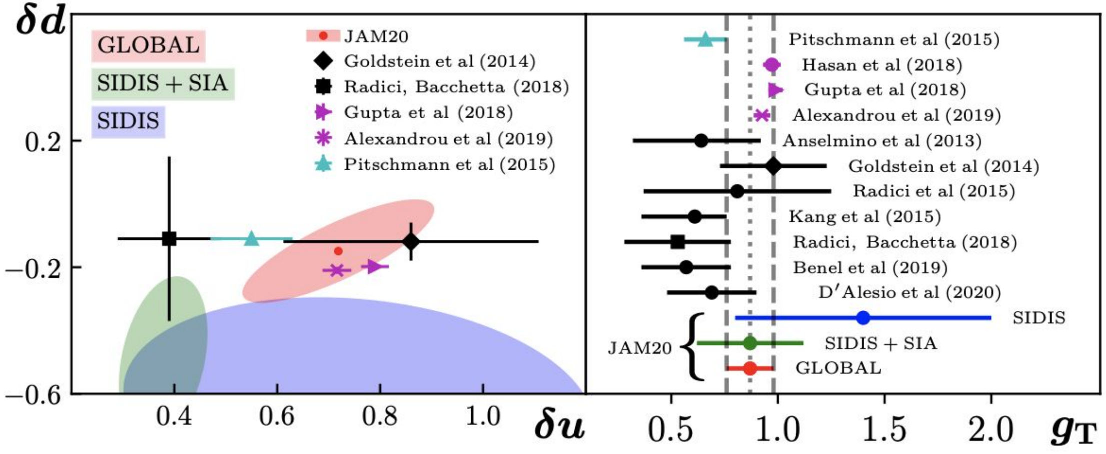
Observable	Reactions	Non-Perturbative Function(s)	$\chi^2/N_{\text{pts.}}$	Refs.
$A_{\text{SIDIS}}^{\text{Siv}}$	$e+(p,d)^{\uparrow} \to e+(\pi^+,\pi^-,\pi^0)+X$	$f_{1T}^{\perp}(x,k_T^2)$	$150.0/126 = 1.19$	[65, 66, 68]
$A_{\text{SIDIS}}^{\text{Col}}$	$e+(p,d)^{\uparrow} \to e+(\pi^+,\pi^-,\pi^0)+X$	$h_1(x,k_T^2), H_1^{\perp}(z,z^2p_{\perp}^2)$	$111.3/126 = 0.88$	[66, 68, 71]
$A_{\text{SIA}}^{\text{Col}}$	$e^+ + e^- \to \pi^+\pi^-(UC,UL)+X$	$H_1^{\perp}(z,z^2p_{\perp}^2)$	$154.5/176 = 0.88$	[74–77]
$A_{\text{DY}}^{\text{Siv}}$	$\pi^- + p^{\uparrow} \to \mu^+\mu^- + X$	$f_{1T}^{\perp}(x,k_T^2)$	$5.96/12 = 0.50$	[73]
$A_{\text{DY}}^{\text{Siv}}$	$p^{\uparrow}+p \to (W^+,W^-,Z)+X$	$f_{1T}^{\perp}(x,k_T^2)$	$31.8/17 = 1.87$	[72]
A_N^h	$p^{\uparrow}+p \to (\pi^+,\pi^-,\pi^0)+X$	$h_1(x), F_{FT}(x,x) = \frac{1}{\pi}f_{1T}^{\perp(1)}(x), H_1^{\perp(1)}(z)$	$66.5/60 = 1.11$	[7, 9, 10, 13]

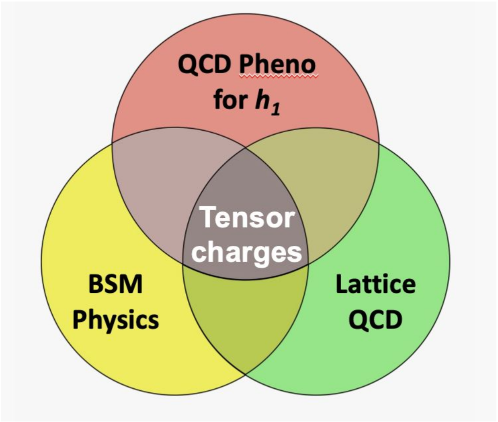
Extraction of tensor charges

- Empirical confirmation that tensor charges inferred from data agree with LQCD within uncertainties

- In this work, Soffer bounds were not imposed



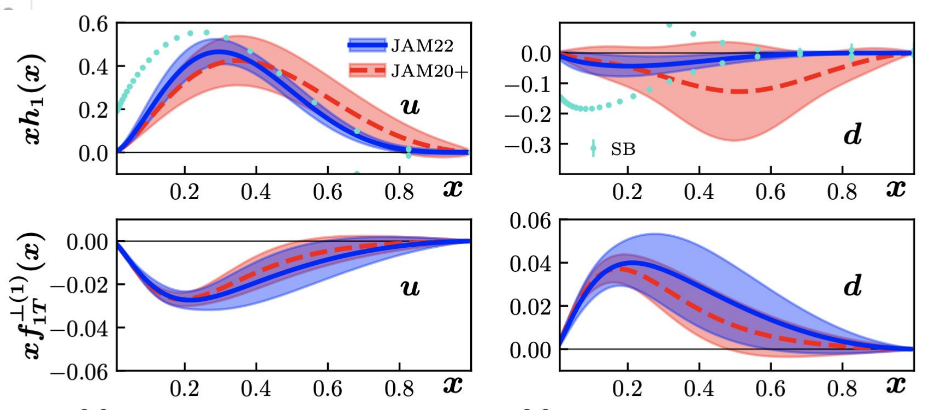


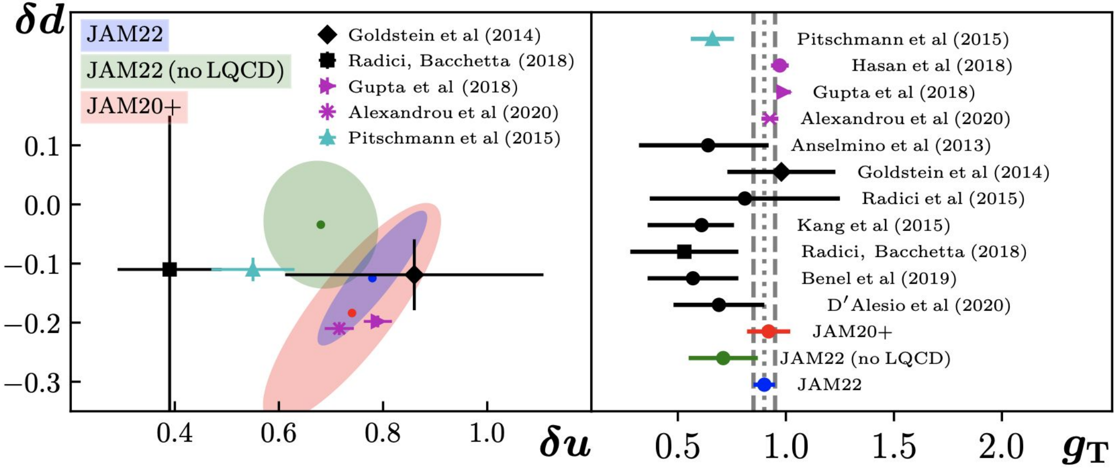


Updated QCD global analysis of single transverse-spin asymmetries I: Extracting $\tilde{H}$, and the role of the Soffer bound and lattice QCD

Leonard Gamberg (Penn State U., Berks-Lehigh Valley), Michel Malda (Lebanon Valley Coll.), Joshua A. Miller (Lebanon Valley Coll. and Temple U.), Daniel Pitonyak (Lebanon Valley Coll.), Alexei Prokudin (Penn State U., Berks-Lehigh Valley and Jefferson Lab) et al. (May 2, 2022)

e-Print: 2205.00999 [hep-ph]





- Updated HERMES data with the recent multi-dimensional bins
- Inclusion of Soffer bounds and lattice tensor charges does not spoil universal agreement

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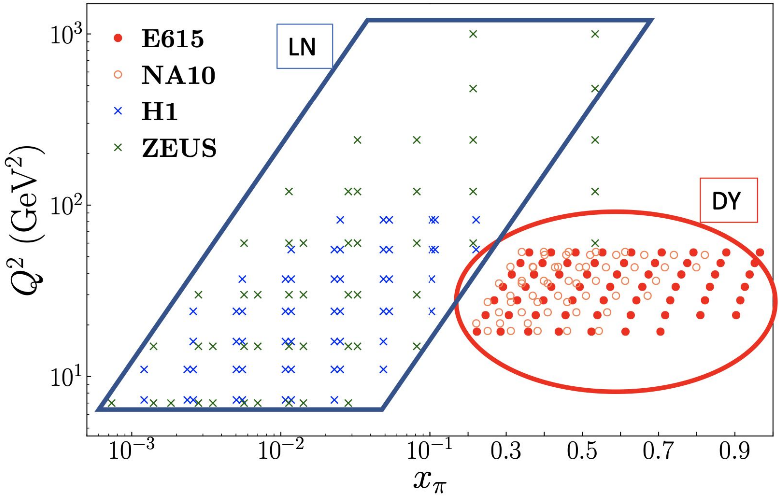
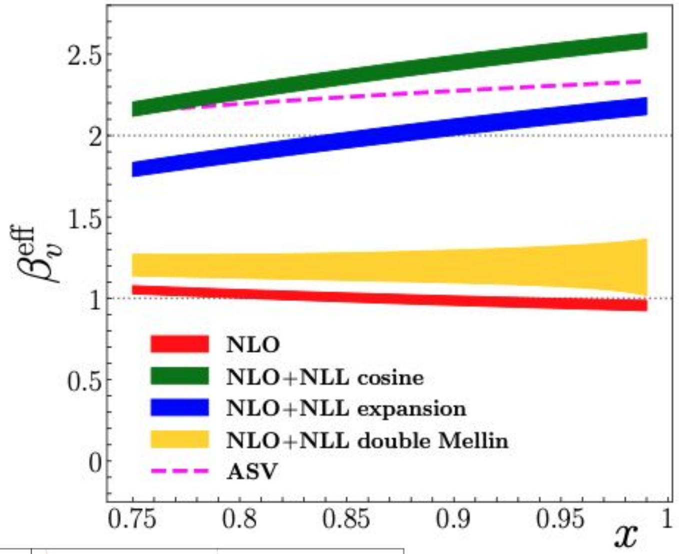
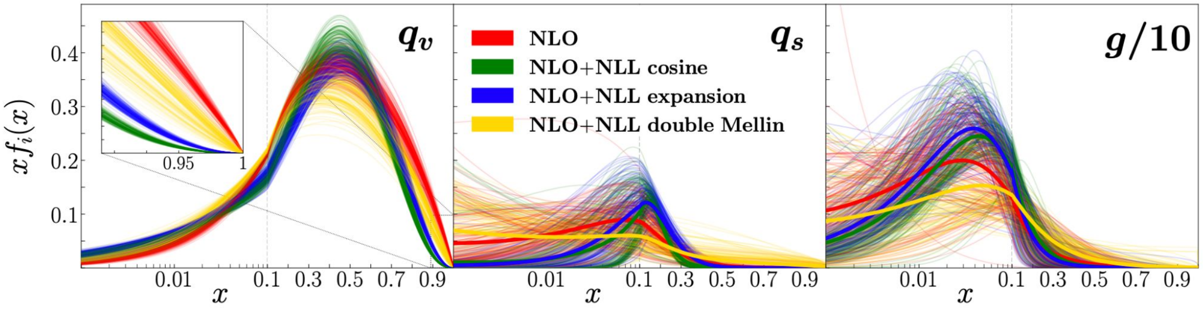
Pion pdfs with DY threshold resummation





Barry, Ji, Melnitchouk, Sato ('21)



The large-*x* asymptote of pion PDFs are more consistent with 1, despite expectation from QCD models

Summary/Outlook

New era of global analysis of hadron structure –> new tools, new tricks (theory + experiment + data analysis)

Simultaneous extraction paradigm is important for proper UQ

Need for new observables to be included global analysis

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

JAM collaboration

Staff / Faculty

W. Melnitchouk (JLab), T. Rogers (ODU/JLab), A. Prokudin (PSU), D. Pitonyak (LVC), L. Gamberg (PSU), Z. Kang (UCLA) J. Qiu (JLab), A. Accardi (Hampton/JLab), A. Metz (Temple), C.-R. Ji (NCSU), M. Constantinou (Temple), F. Steffens (Bonn), Y. Kovchegov (OSU), M. Sievert (NMSU), I. Cloet (ANL),

Students / Postdocs

R. Abdul Khalek (JLab), C. Cocuzza (Temple), Y. Zhou (South China Normal University), P. Barry (JLab), E. Moffat (ANL), D. Adamiak (OSU), A. Freese (WU).