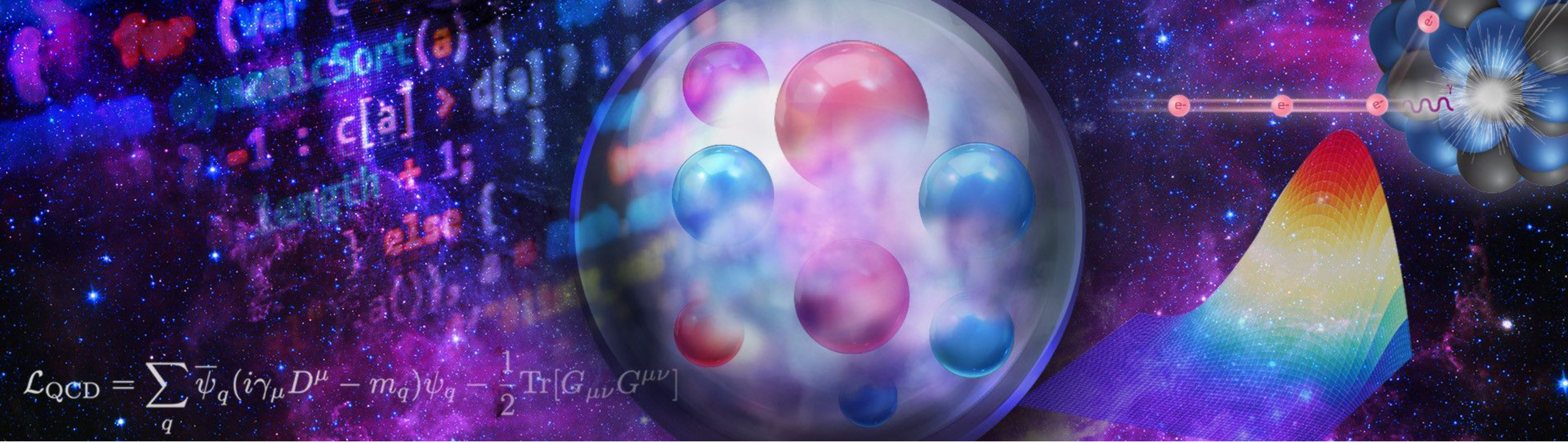
# Recent results from JAM

**Nobuo Sato**

CFNS: precision QCD predictions for *ep* physics at the EIC

Aug. 1, 2022

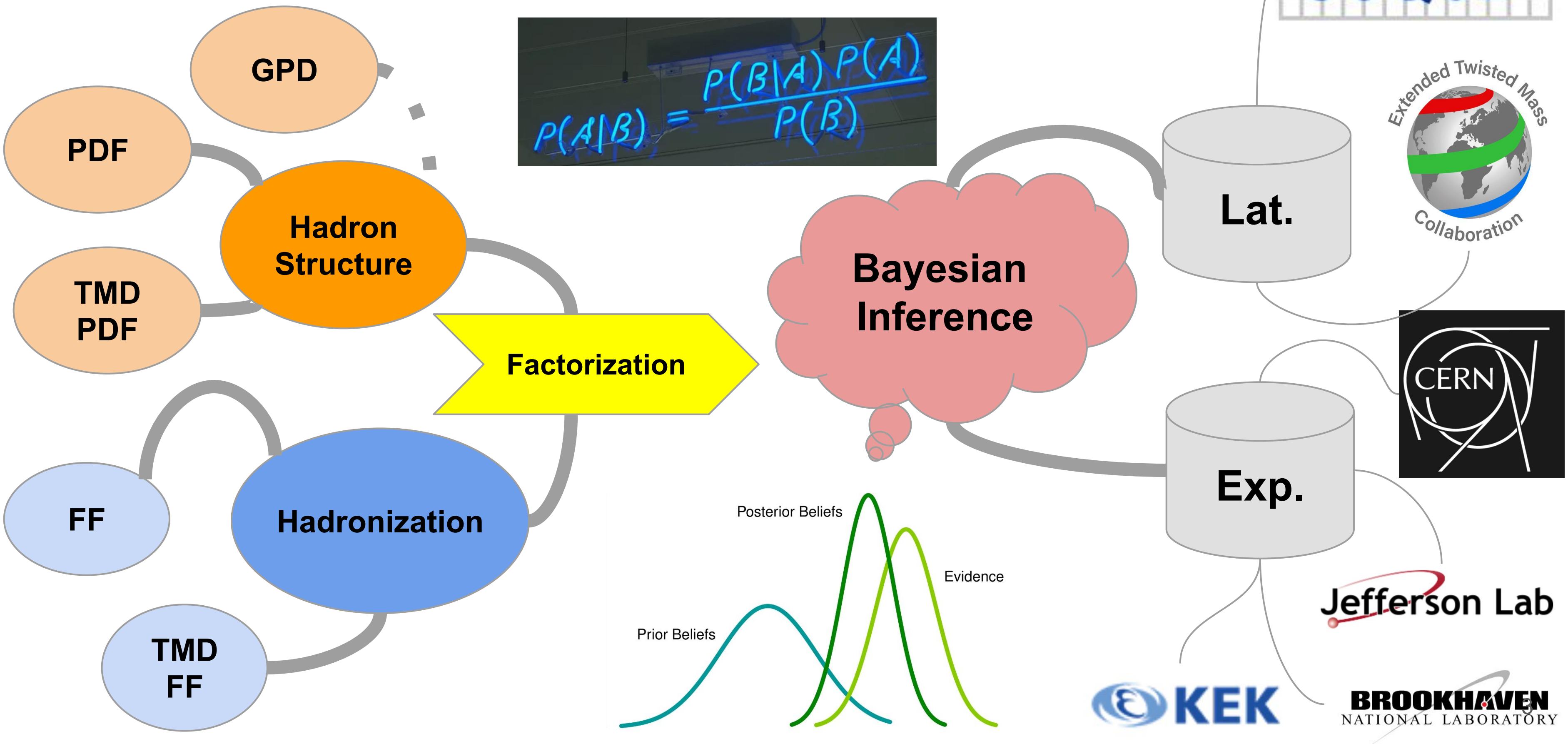
Jefferson Lab




# 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.

# A holistic approach to global analysis



# Outline

### PDFs,  helicity PDFs and fragmentation functions (FFs)

1. Isovector EMC effect with MARATHON data
2. Sea asymmetry with SeaQuest and STAR data
3. Strange suppression from simultaneous analysis of PDFs and FFs
4. Gluon polarization in the proton
5. Polarized antimatter in the proton

### TMDs

6. Origin of single transverse-spin asymmetries in high-energy collisions

### Synergies with LQCD

7. Pion PDFs with threshold resummation
8. Complementarity of experimental and lattice QCD data on pion PDFs

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arXiv.org > hep-ex > arXiv:2104.05850

Search...

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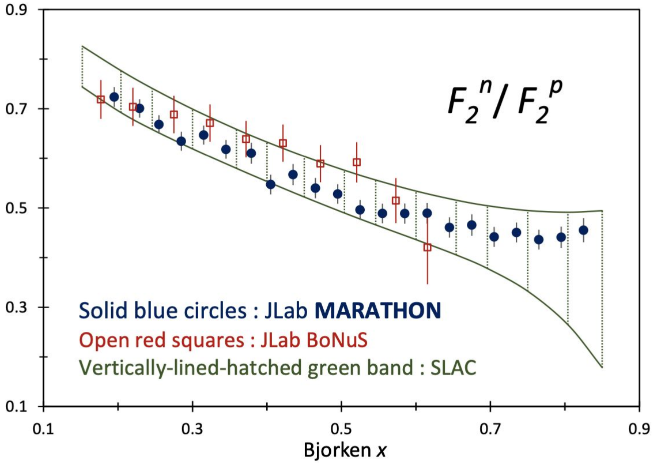
**High Energy Physics – Experiment**

*[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

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High Energy Physics – Experiment

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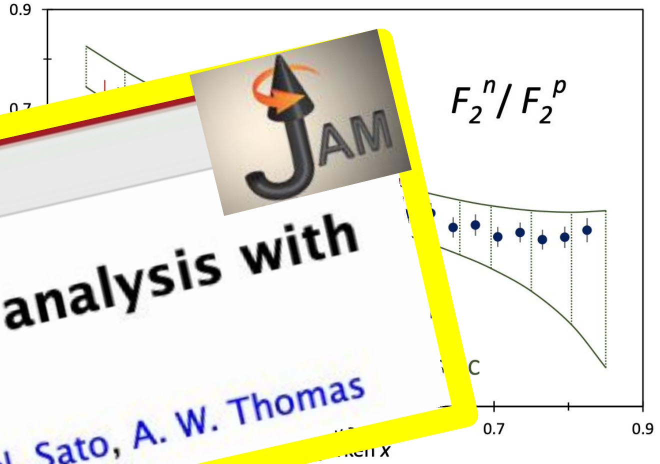
**Measurement of the Nucleon $F_2^n/F_2^p$ Structure Fun... by the Jefferson Lab MARATHON Triti... Inelastic Scattering Experim...**



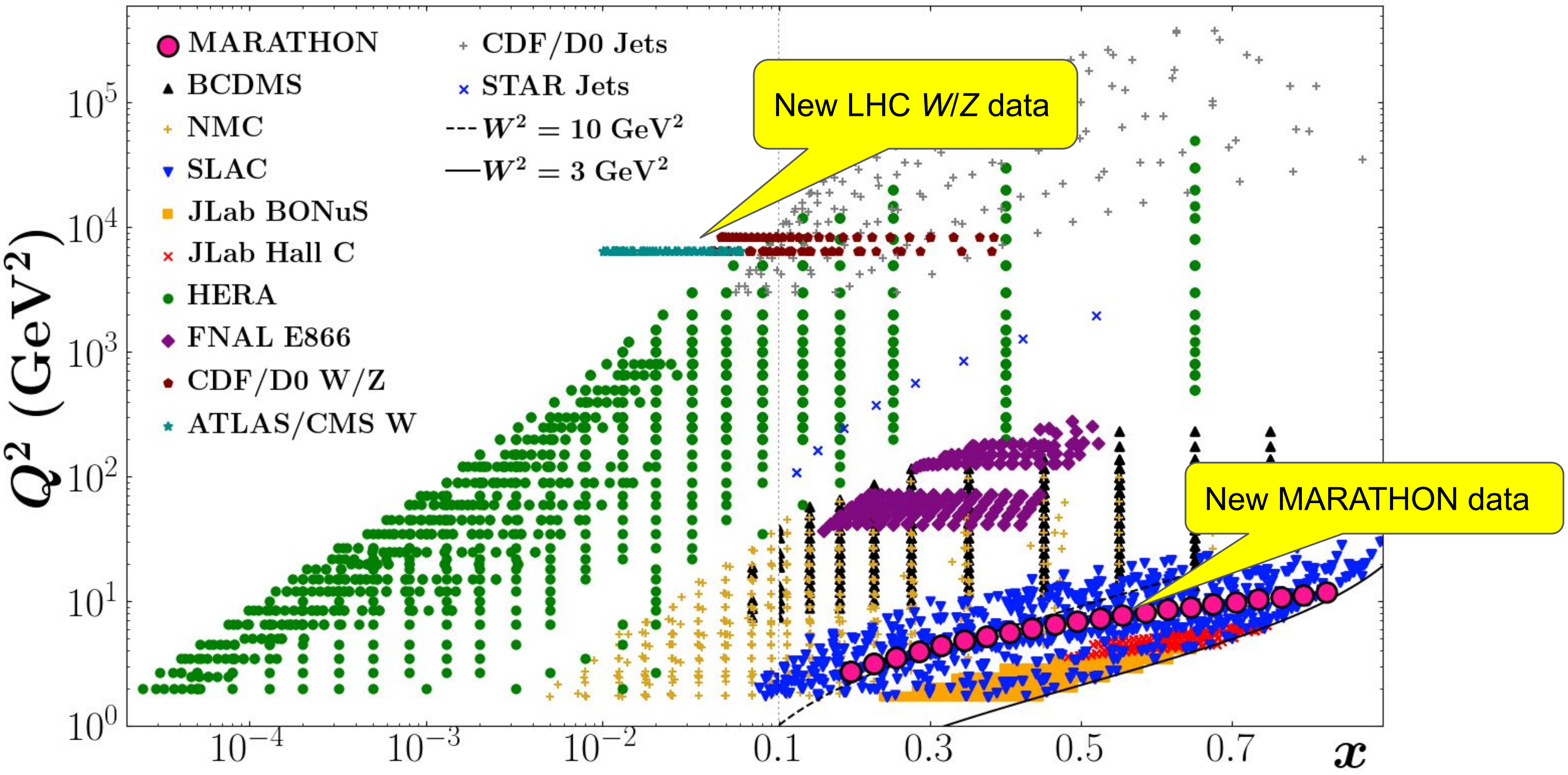

High Energy Physics – Phenomenology

*[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$^2$)
$x$

# Quick overview of the DIS theory framework in light nuclei

# 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

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

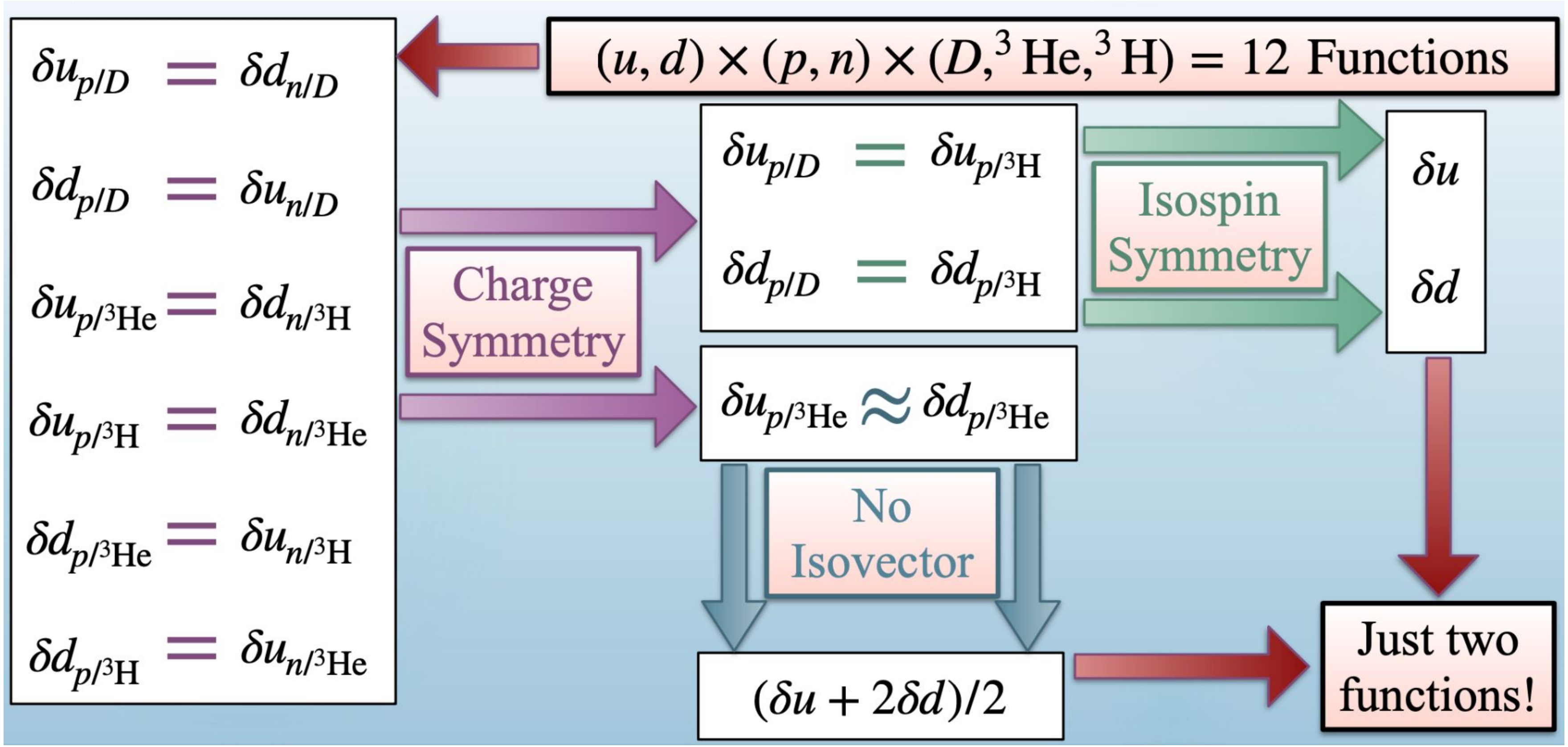
$$F_2^{A(\mathrm{off})}(x, Q^2) = \sum_N \left[ \tilde{f}^{N/A} \otimes \; F_2^{N/A(\mathrm{off})} \right]$$

Nonrelativistic nucleon spectral functions computed from quantum Monte Carlo

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

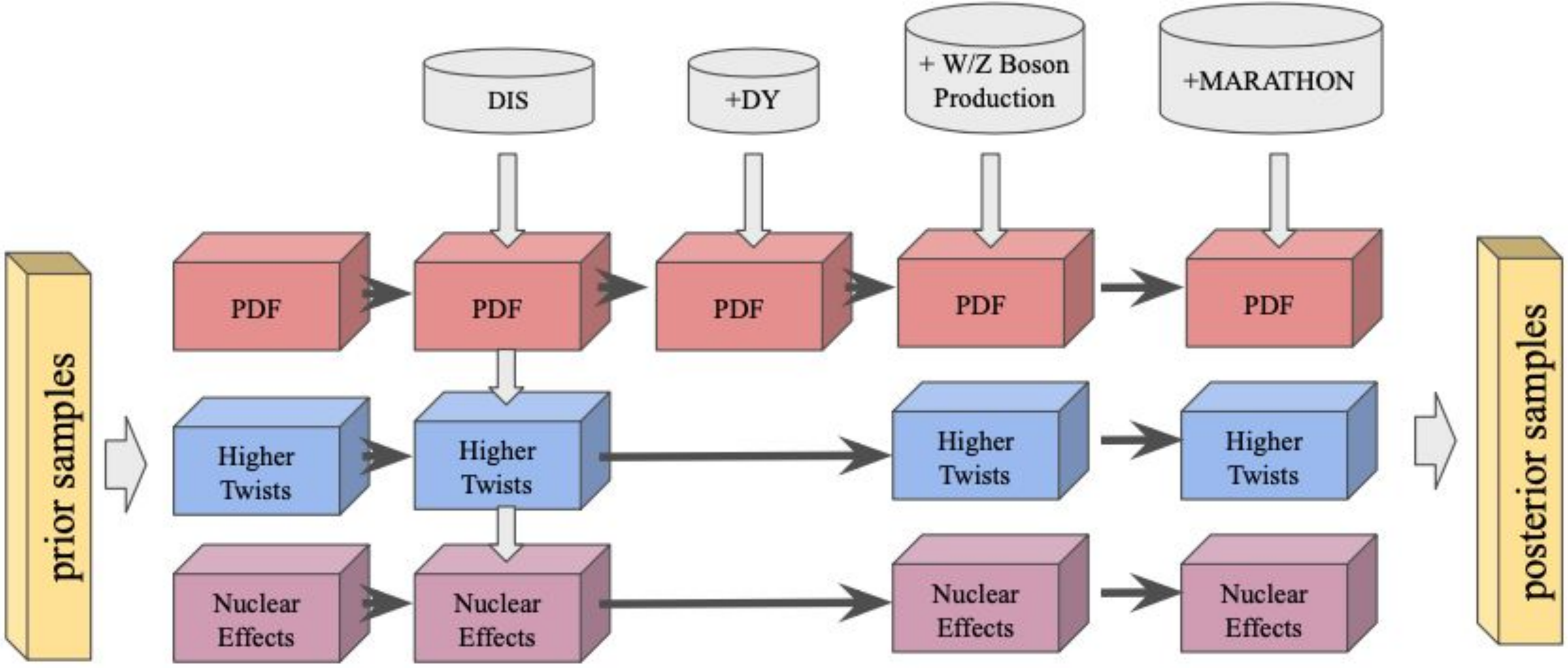
$$\widetilde{f}_{ij}^N(y,\gamma) = \int \frac{d^4p}{(2\pi)^4} \mathcal{F}_0^N(\varepsilon, \boldsymbol{p}) \left(1 + \frac{\gamma p_z}{M}\right) \mathcal{C}_{ij}\, v(p^2)\, \delta\left(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\right)$$

# Symmetries



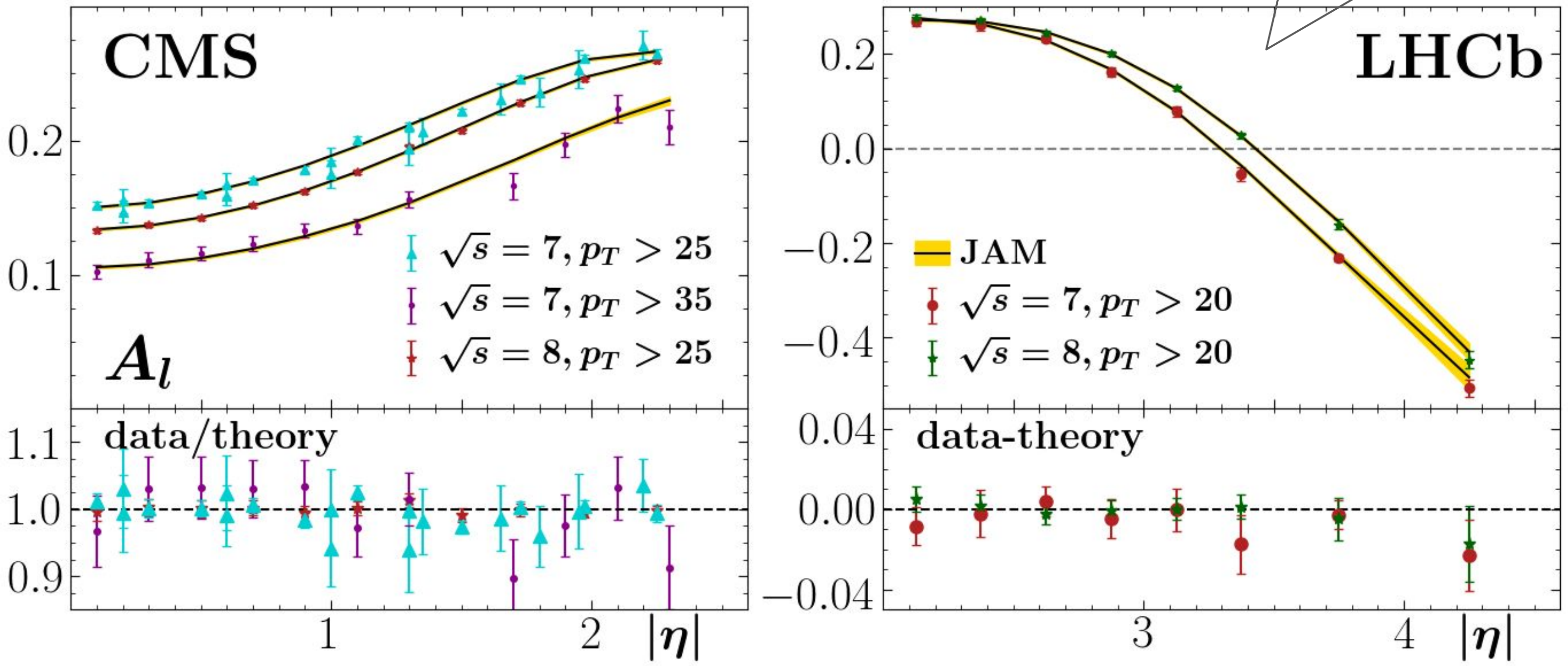
$(u, d) \times (p, n) \times (D, {}^3\text{He}, {}^3\text{H}) = 12$ Functions
$\delta u_{p/D} = \delta d_{n/D}$
$\delta d_{p/D} = \delta u_{n/D}$
$\delta u_{p/^3\text{He}} = \delta d_{n/^3\text{H}}$
$\delta u_{p/^3\text{H}} = \delta d_{n/^3\text{He}}$
$\delta d_{p/^3\text{He}} = \delta u_{n/^3\text{H}}$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

# Multi-step strategy

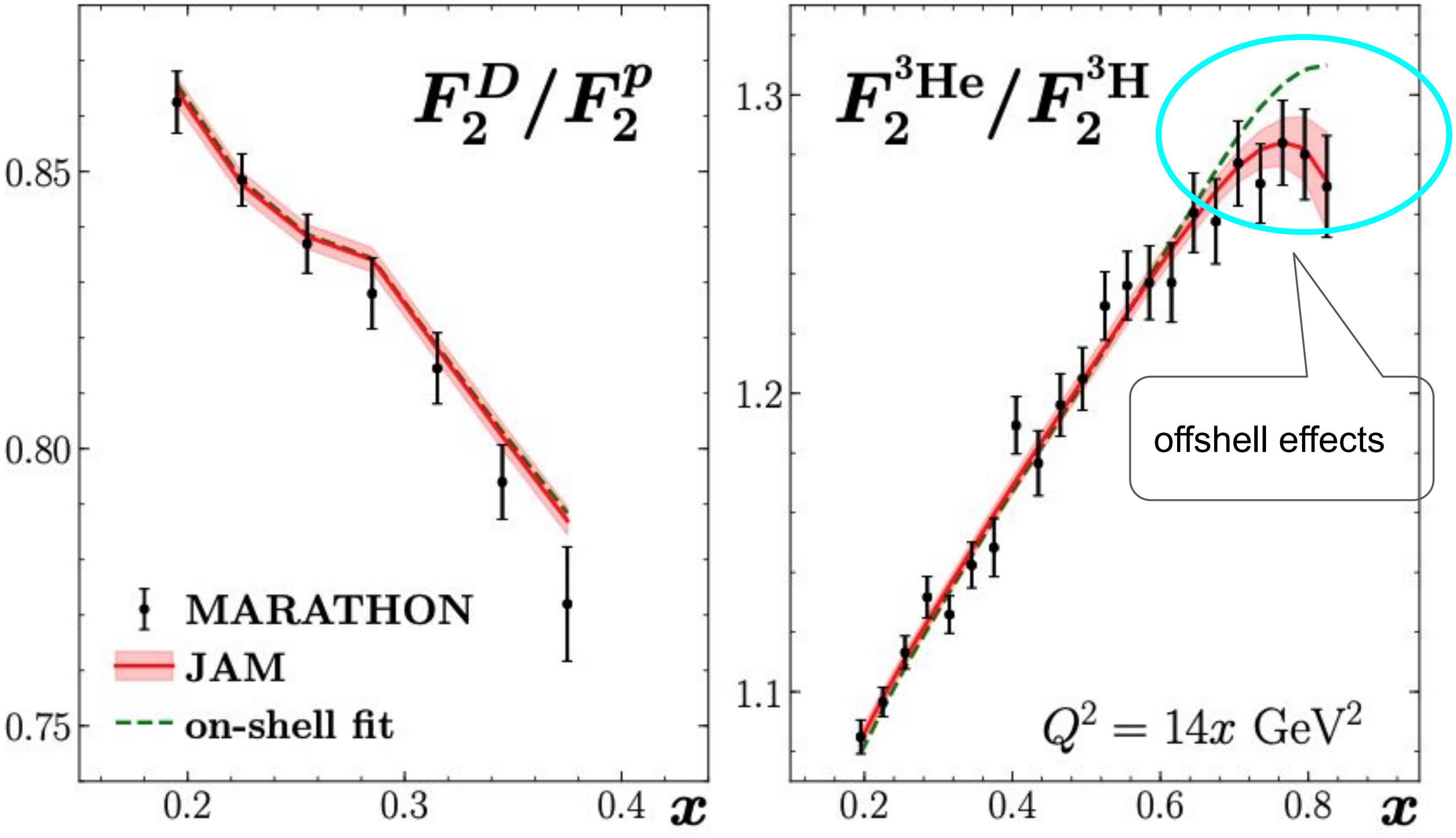


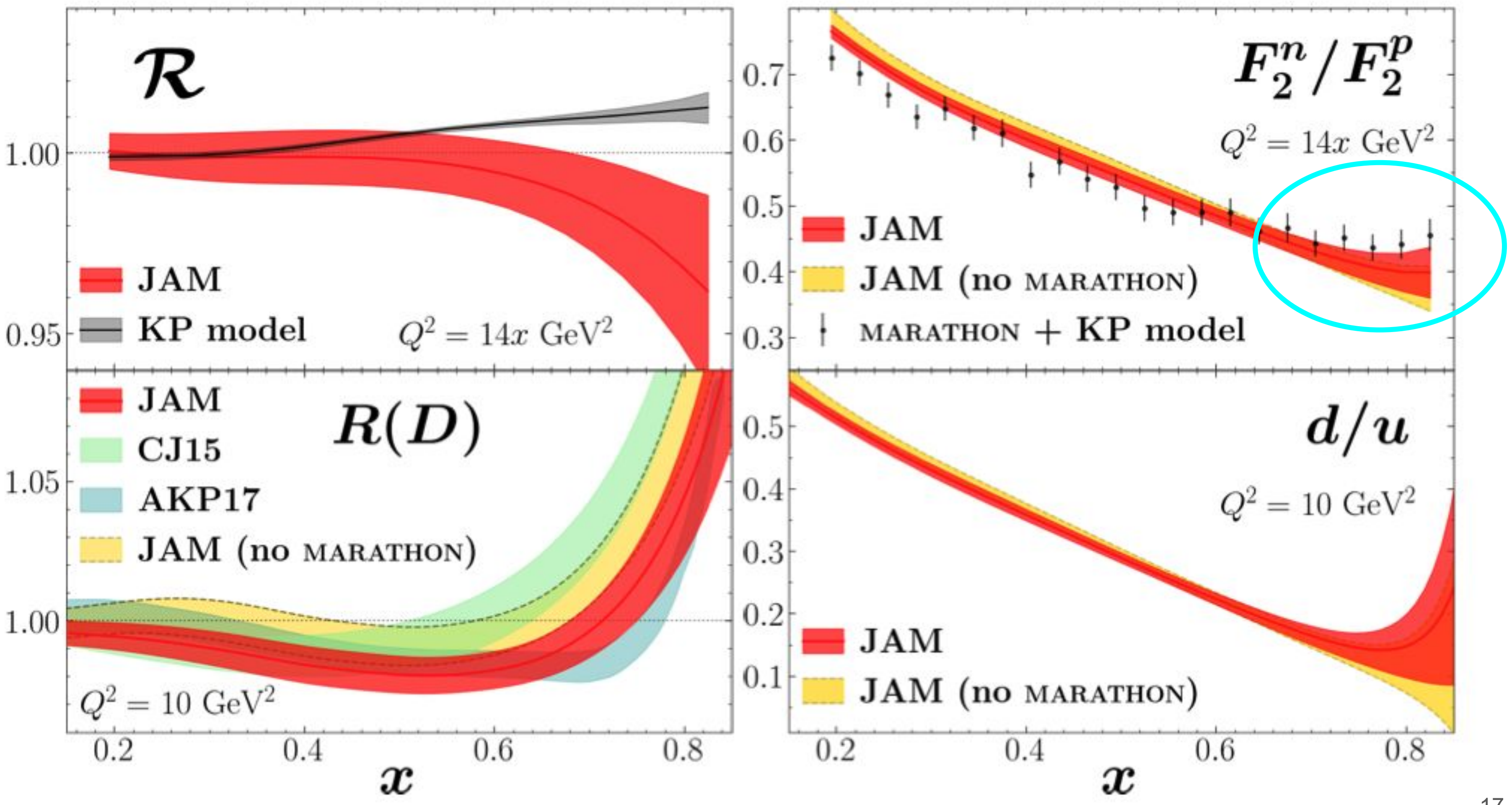
# LHC *W* data

Excent agreement between theory and data

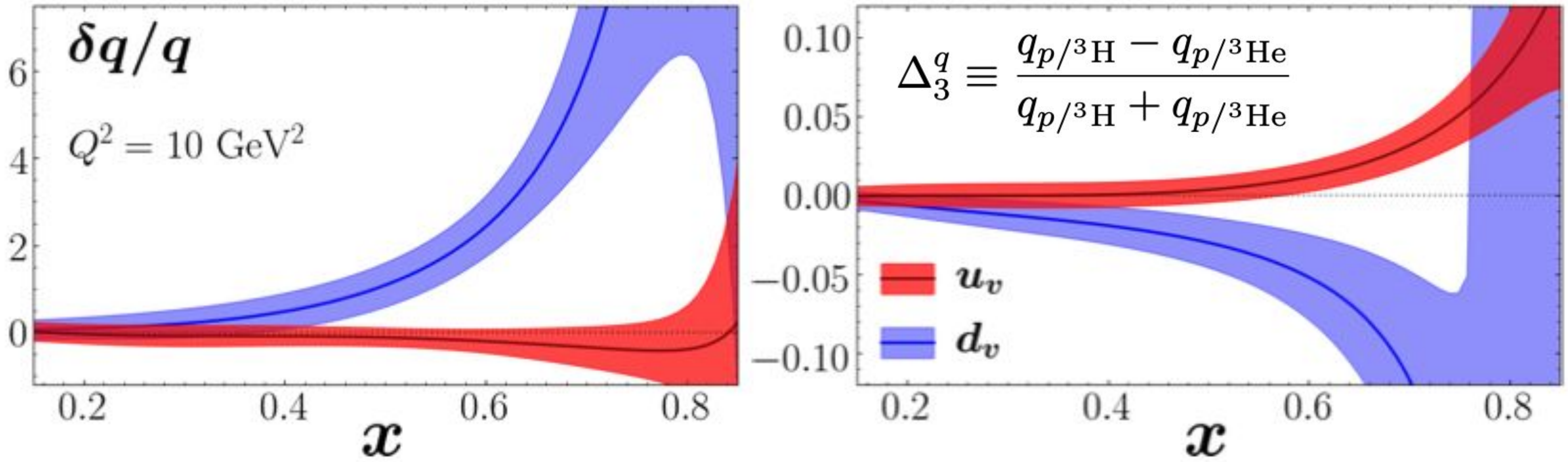


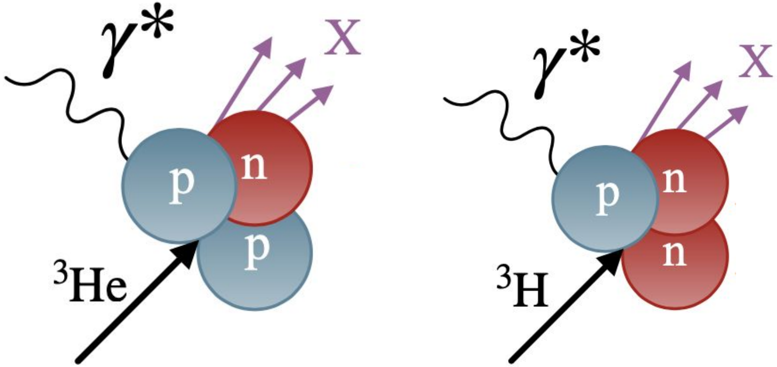
# MARATHON data





$\mathcal{R}$
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
JAM
CJ15
AKP17
JAM (no MARATHON)
$R(D)$
$Q^2 = 10$ GeV$^2$
1.05
1.00
0.2
0.4
0.6
0.8
$x$
$d/u$
$Q^2 = 10$ GeV$^2$
JAM
JAM (no MARATHON)
0.5
0.4
0.3
0.2
0.1
0.2
0.4
0.6
0.8
$x$




- 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

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nature

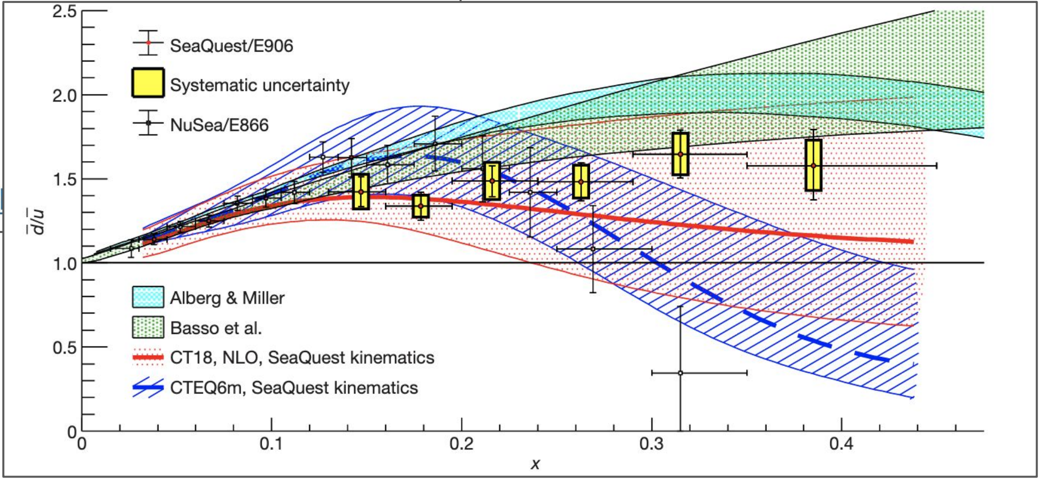
Article | Published: 24 February 2021

# 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 $Z/\gamma^*$ 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)

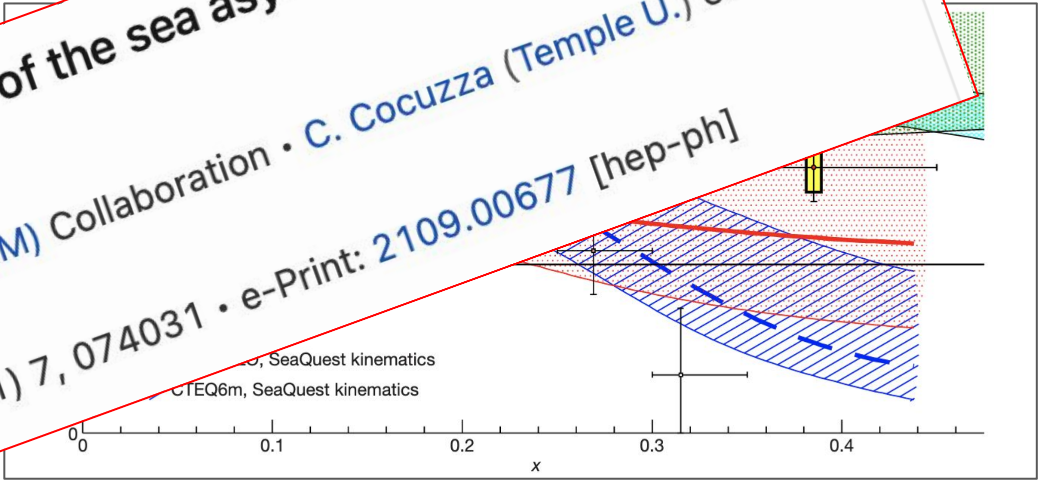


#7

**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 $Z/\gamma^*$ cross sections and their ratios in $p+p$ …sions at RHIC

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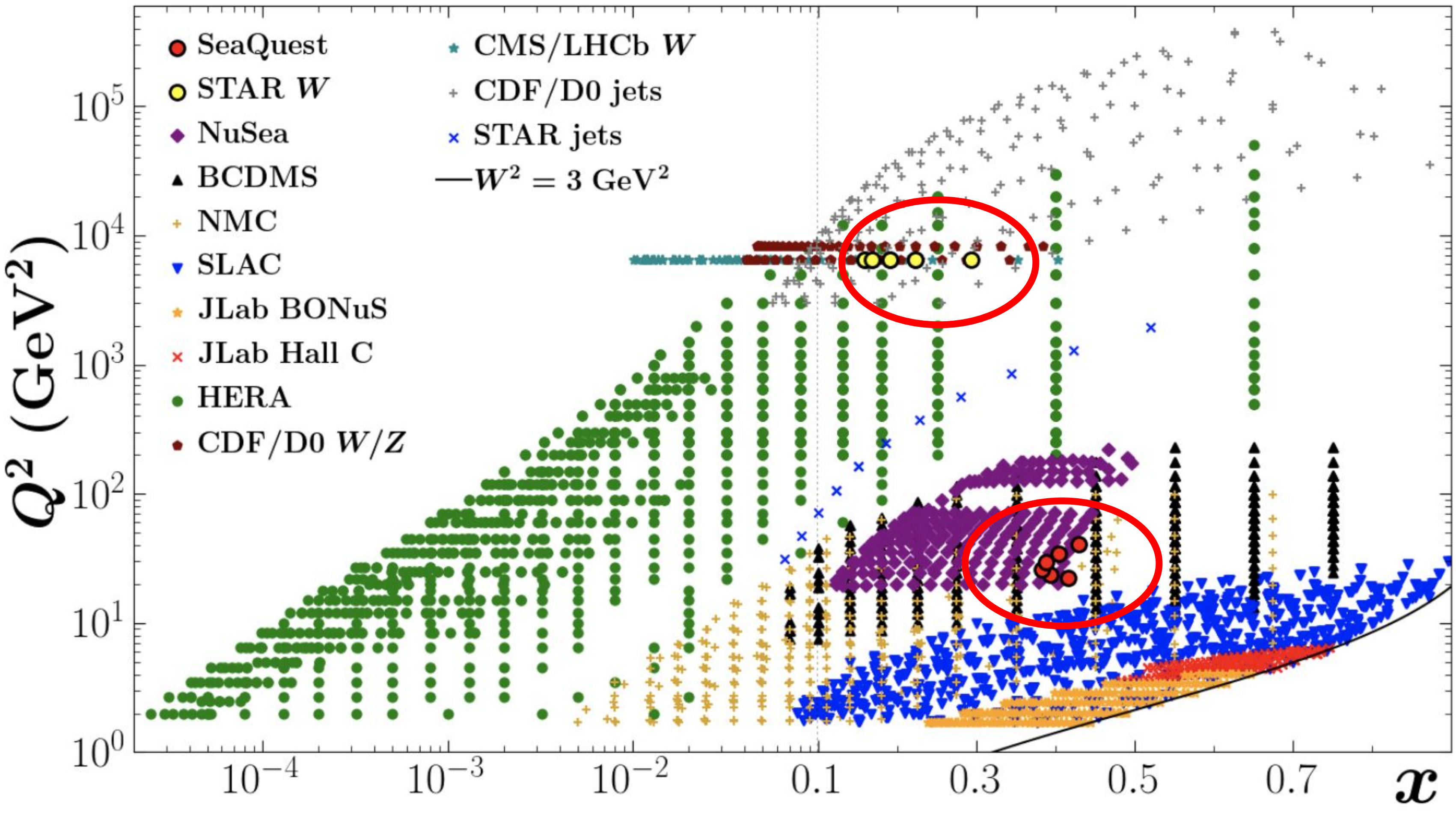
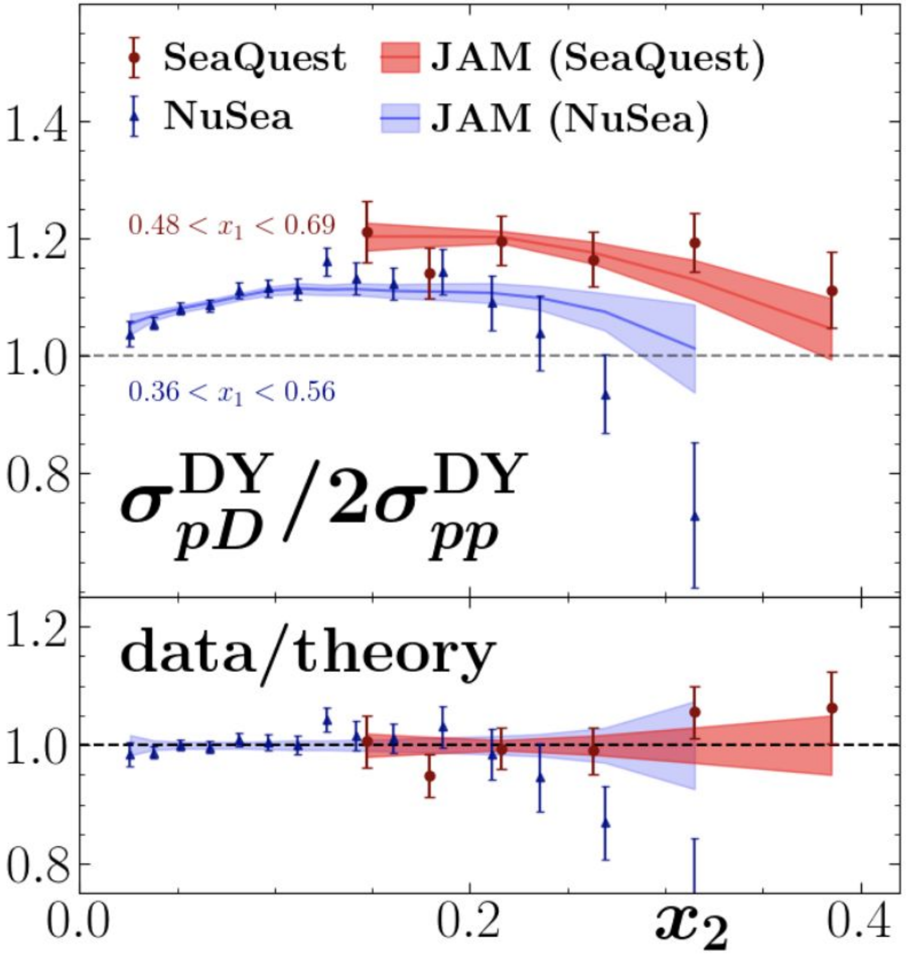
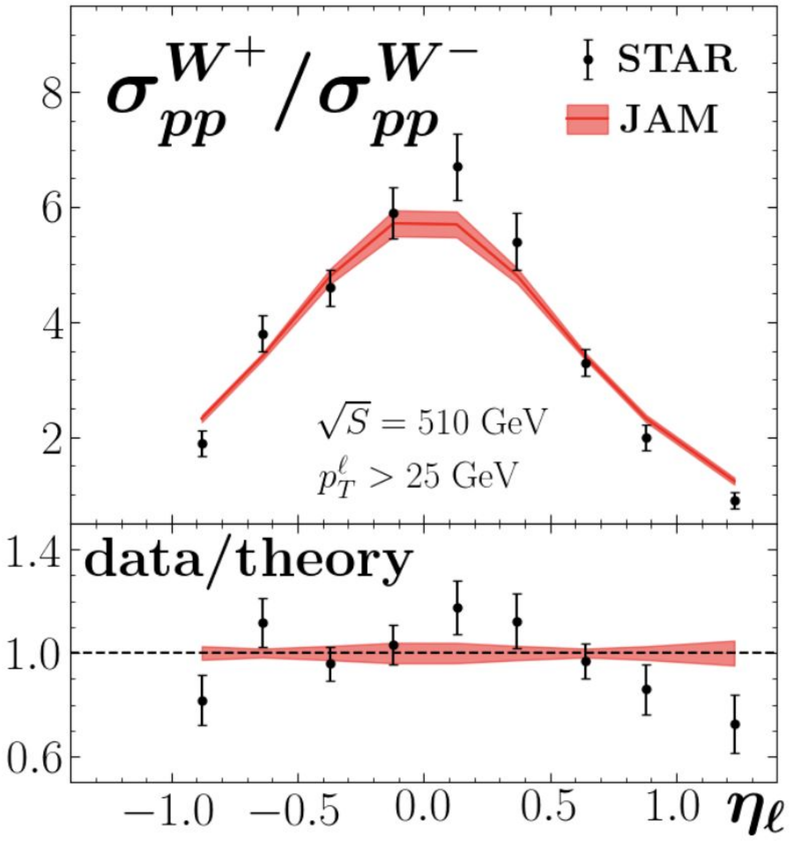
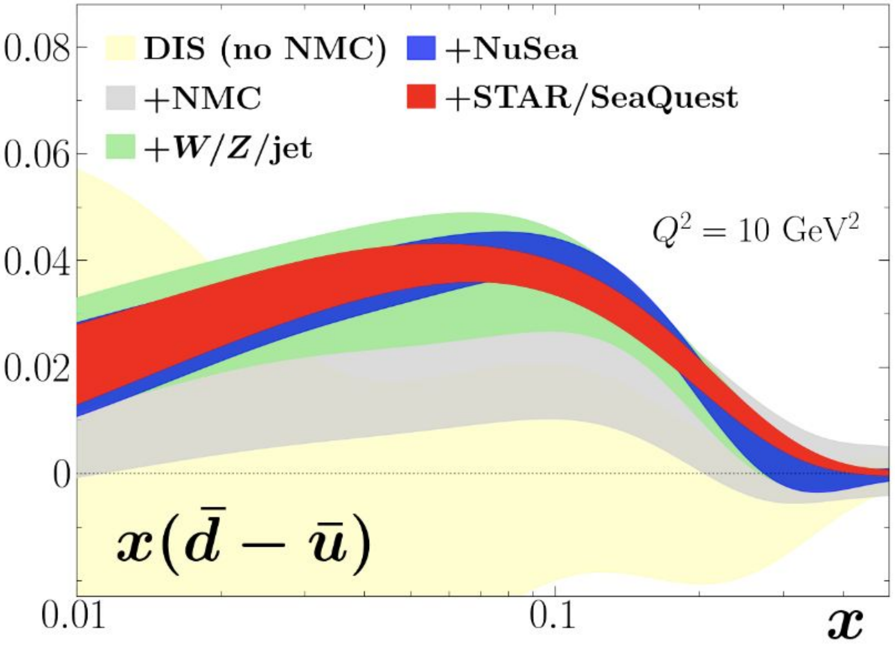
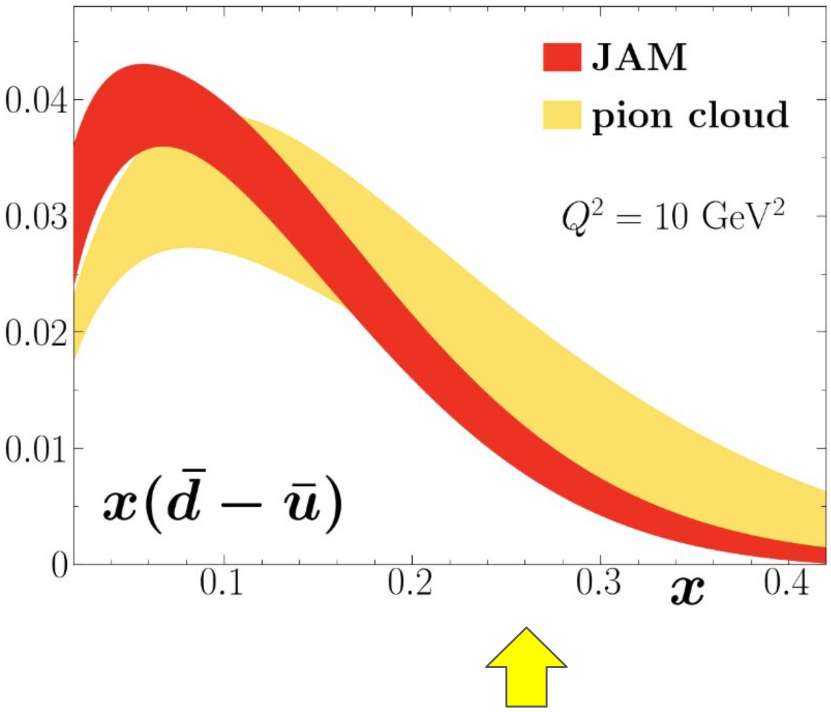
Phys. Rev. D **103**, 012001 – Published 4 January 2021


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
—W² = 3 GeV²
Q² (GeV²)
x
10⁰
10¹
10²
10³
10⁴
10⁵
10⁻⁴
10⁻³
10⁻²
0.1
0.3
0.5
0.7


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
1.4
1.2
1.0
0.8
0.0
0.2
0.4

σ^W+_pp / σ^W−_pp
STAR
JAM
√S = 510 GeV
p^ℓ_T > 25 GeV
data/theory
ηℓ
8
6
4
2
1.4
1.0
0.6
−1.0
−0.5
0.0
0.5
1.0

# 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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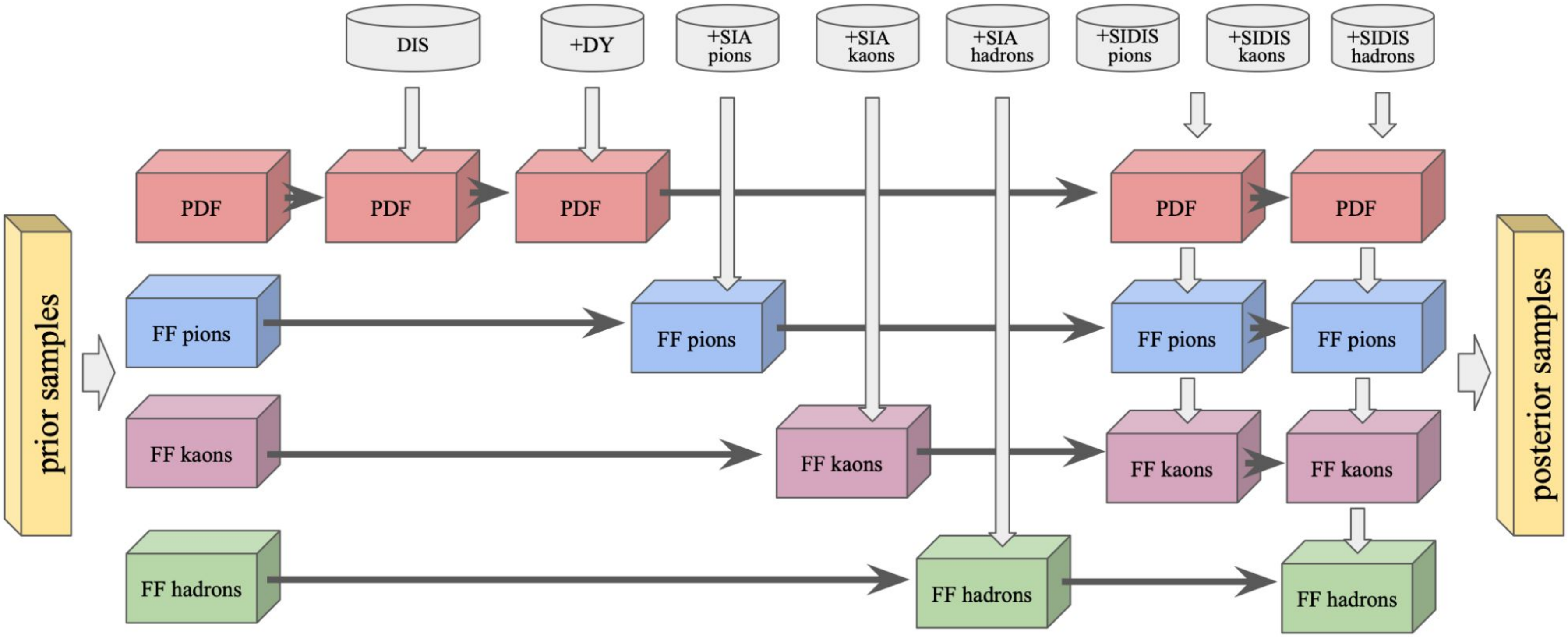
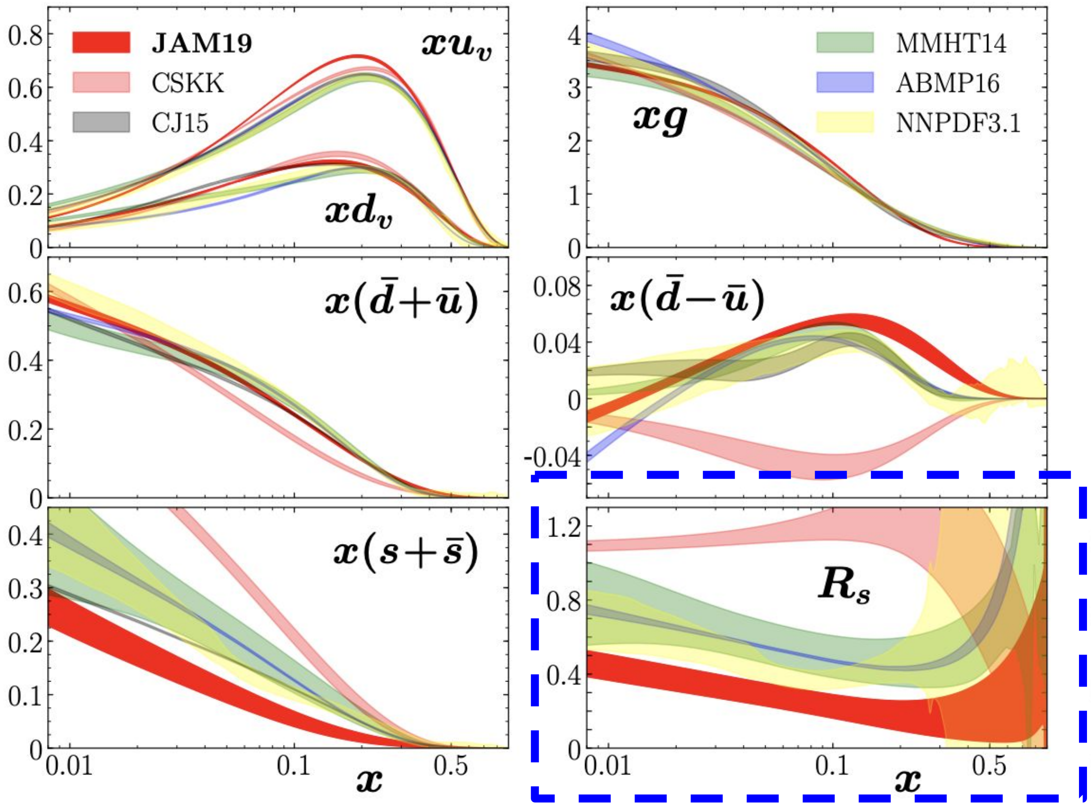
8. Complementarity of experimental and lattice QCD data on pion PDFs

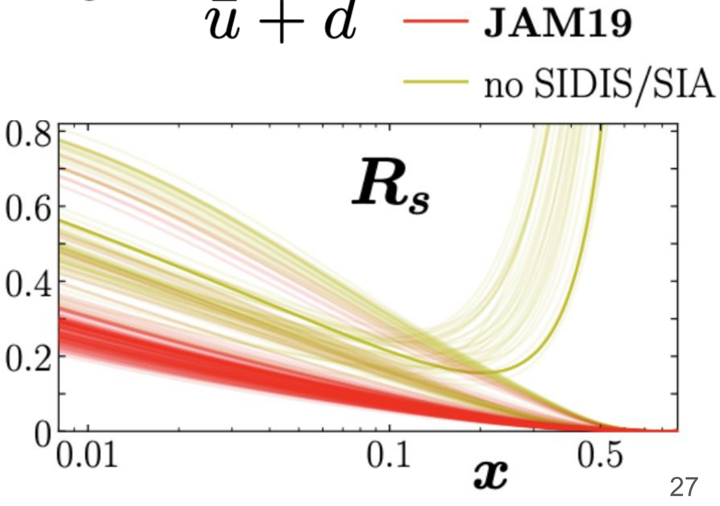
# Multi-step strategy



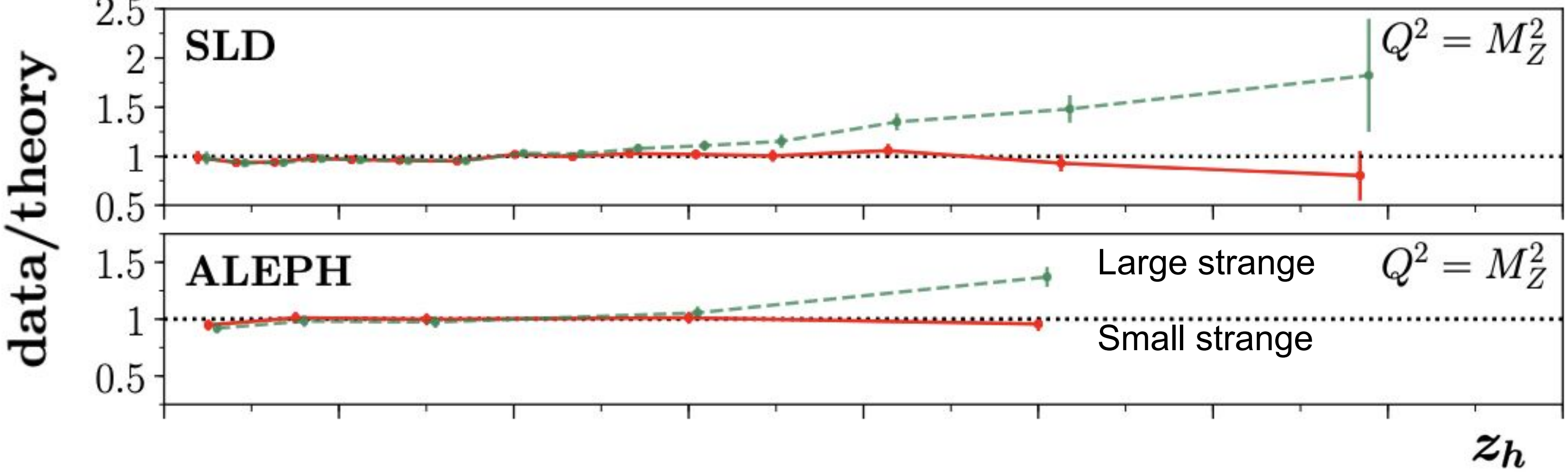
- Strange PDF is one of the least constrained unpolarized PDFs
- Different analyses have inferred different sizes of the strangeness

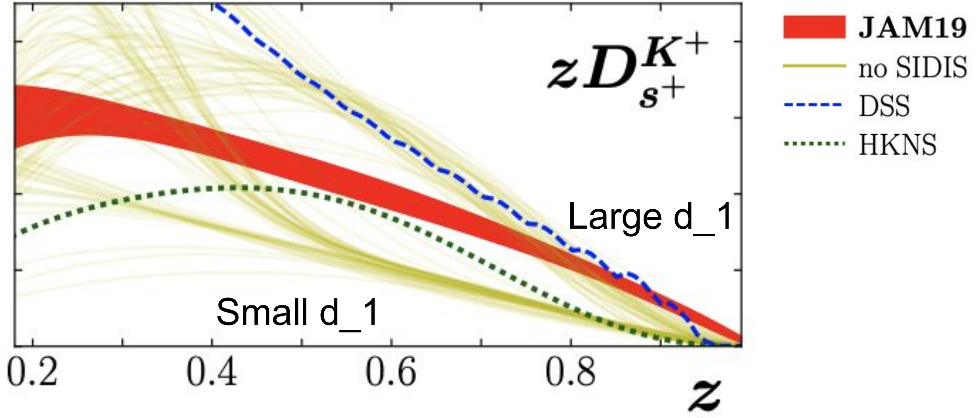



$$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$$

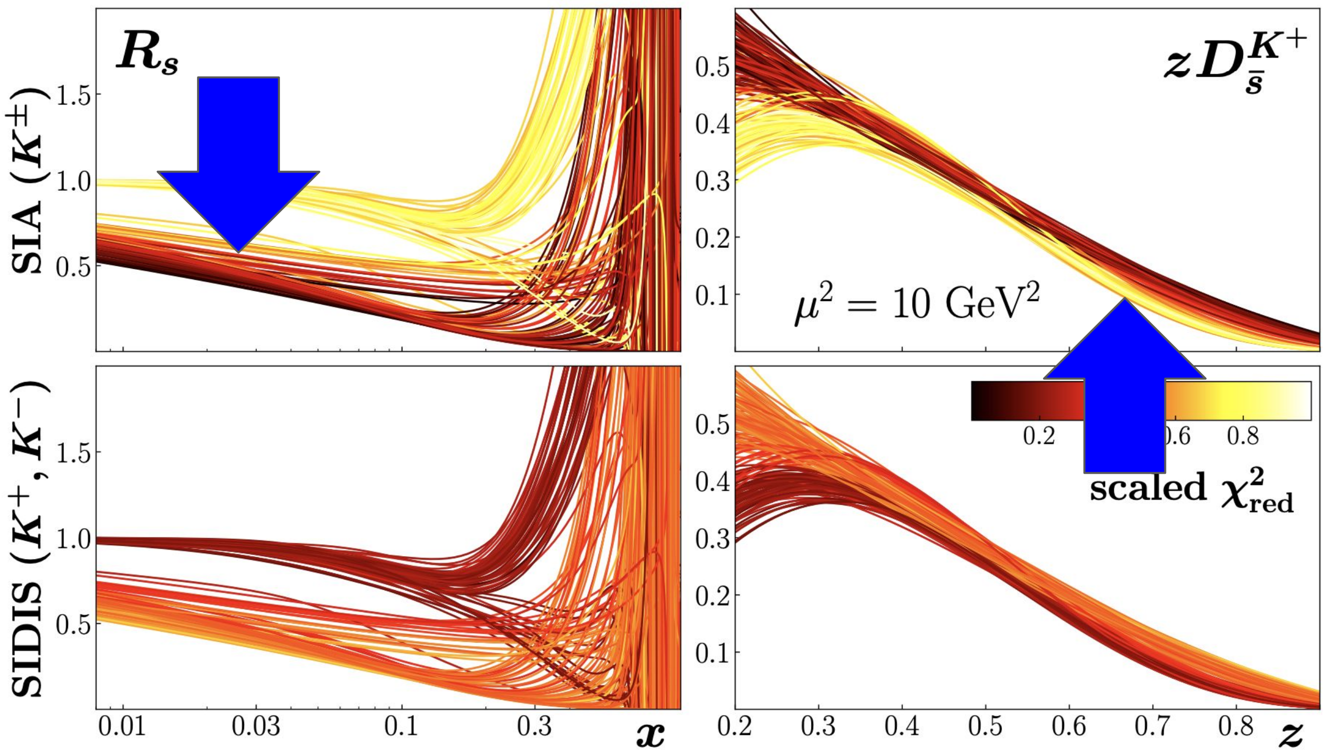


# $e^+e^- \to K^\pm + X$




- 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

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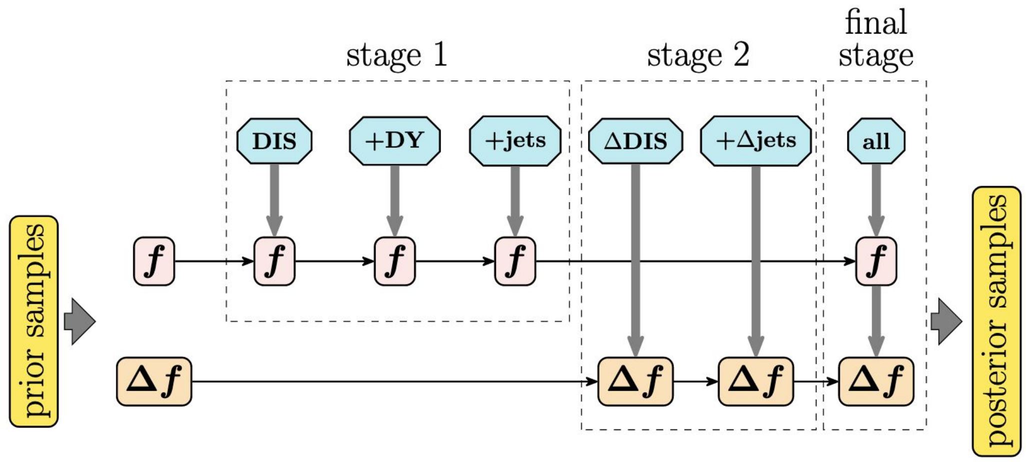
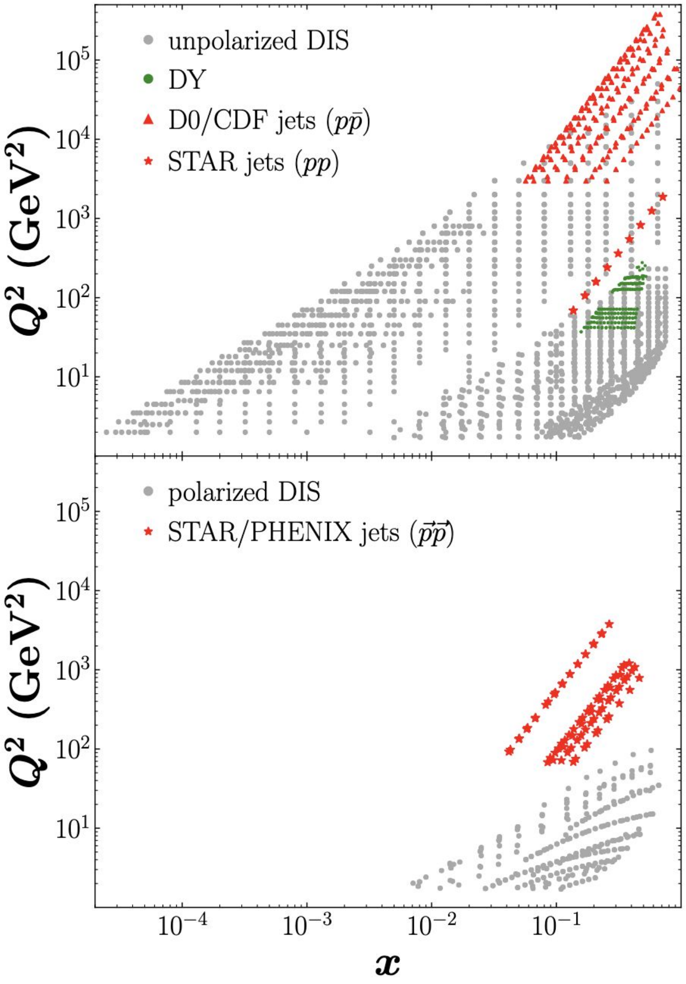
# How well do we know the gluon polarization in the proton?

Y. Zhou, N. Sato, and W. Melnitchouk (Jefferson Lab Angular Momentum (JAM) Collaboration)

Phys. Rev. D **105**, 074022 – Published 25 April 2022



# Theory biases

SU2

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

SU3

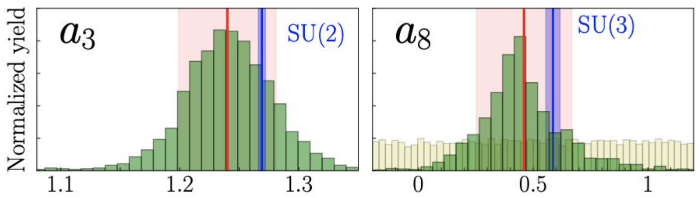
$$\int_0^1 \mathrm{d}x\, [\Delta u^+ + \Delta d^+ - 2\Delta s^+] = a_8,$$

Hyperon beta decays

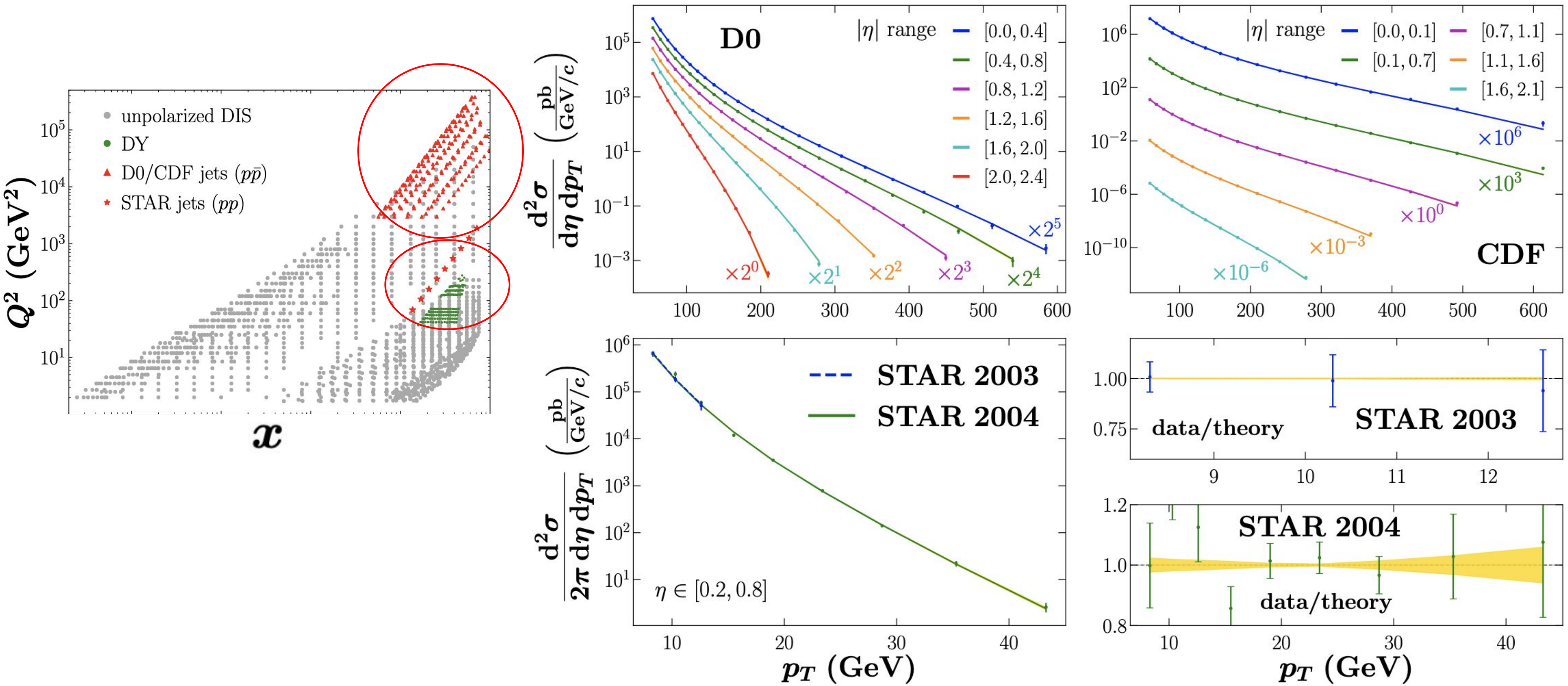
Constraints from SIDIS with kaons JAM17

Positivity

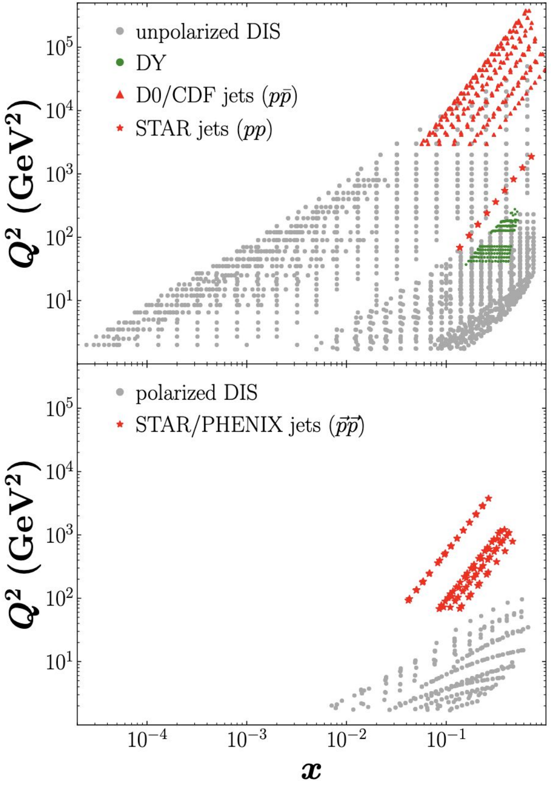
$$|\Delta q(x, Q^2)| \leqslant q(x, Q^2),$$

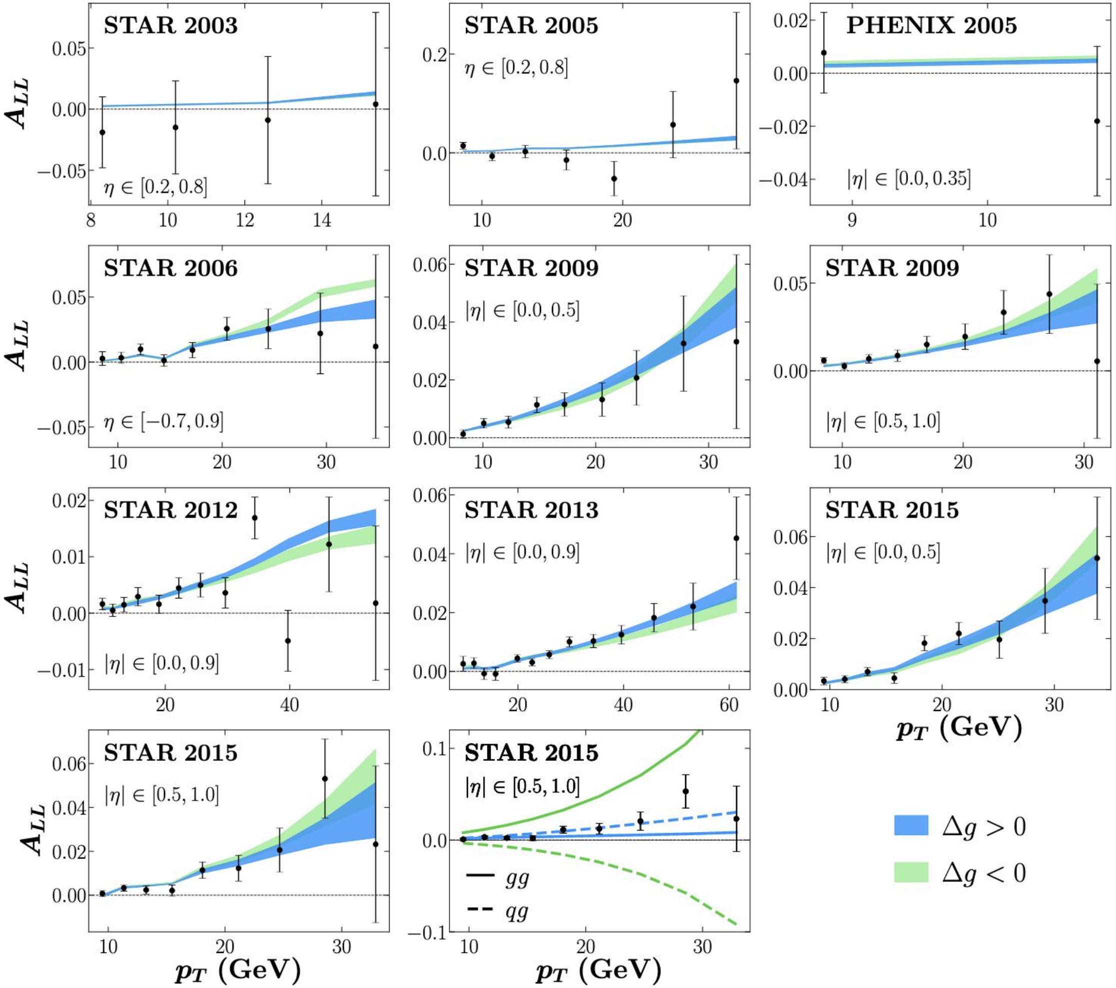


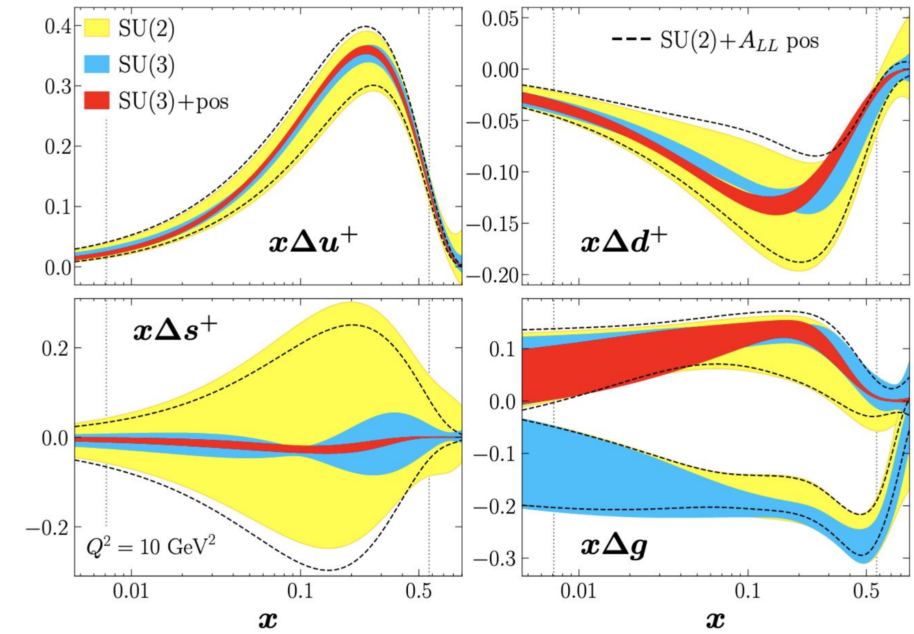
# Unpolarized jets

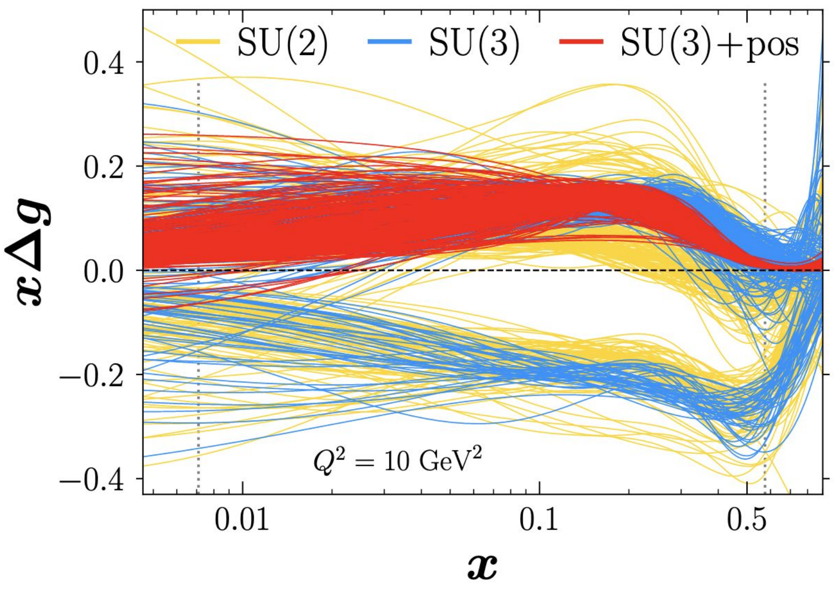


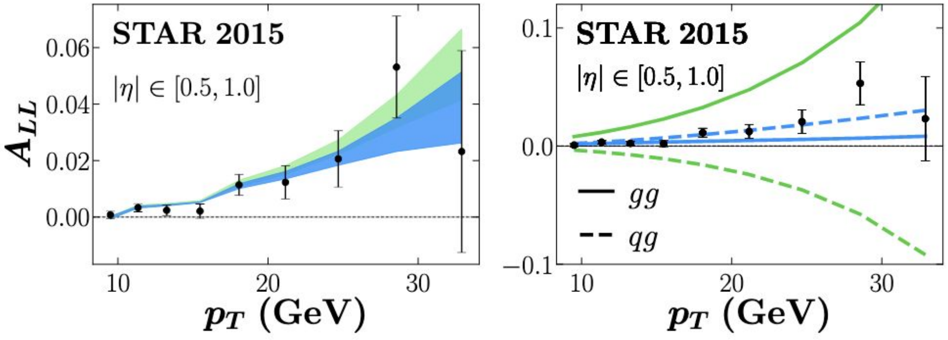
# Polarized jets

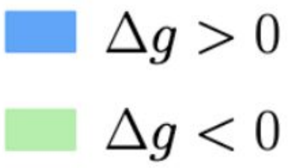




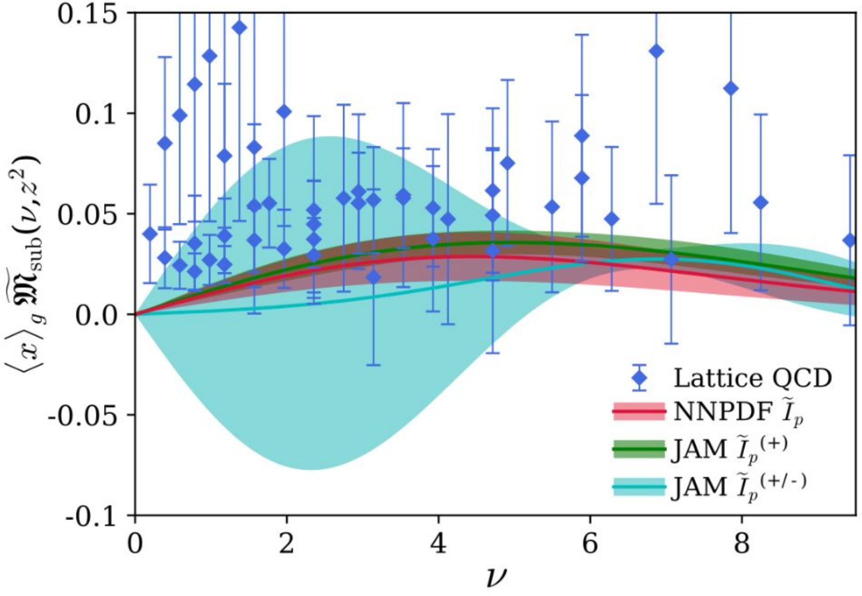



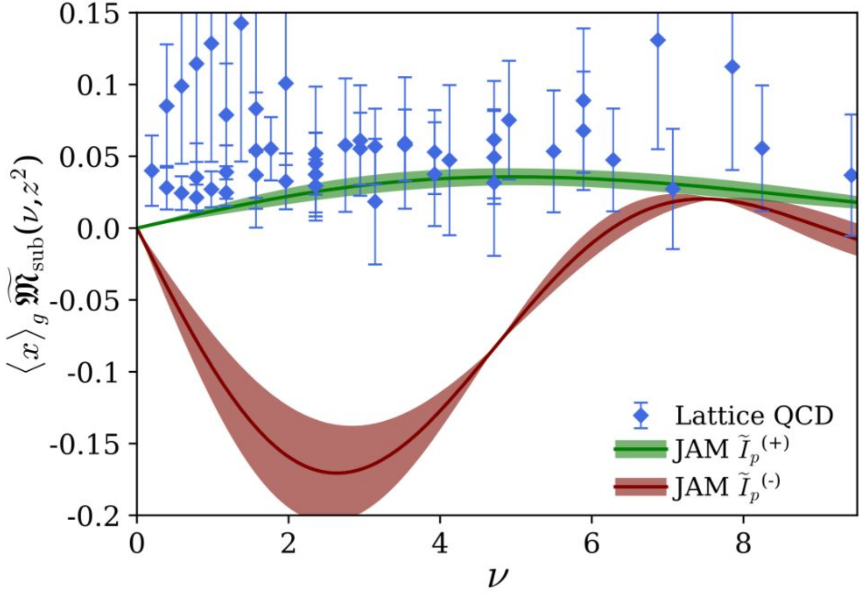




Polarized jet data cannot discriminate positive and negative solutions

# Insights from LQCD

Egerer et al ('22)




*HadStruc Collaboration*

Negative gluon helicity is ruled out by LQCD?

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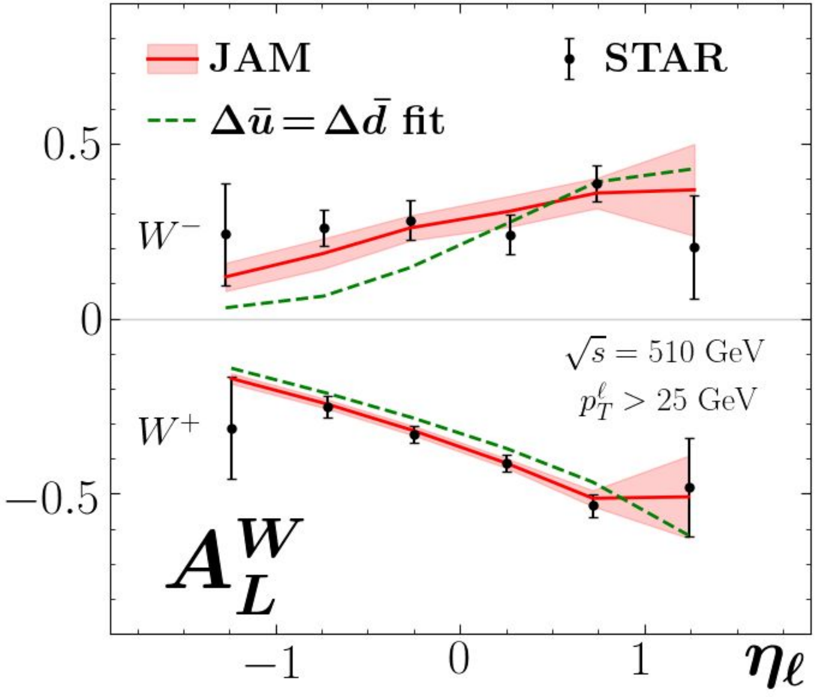
**Polarized Antimatter in the Proton from Global QCD Analysis**

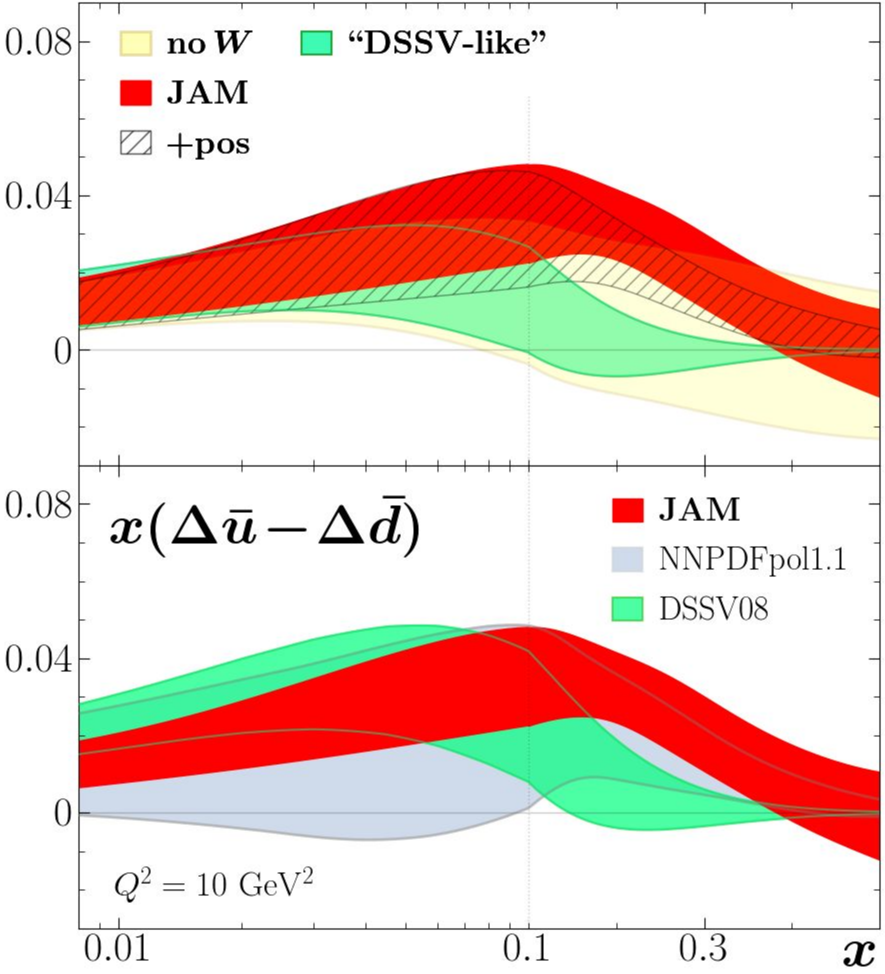
Jefferson Lab Angular Momentum (JAM) Collaboration • C. Cocuzza (Temple U.) et al. (Feb 7, 2022)

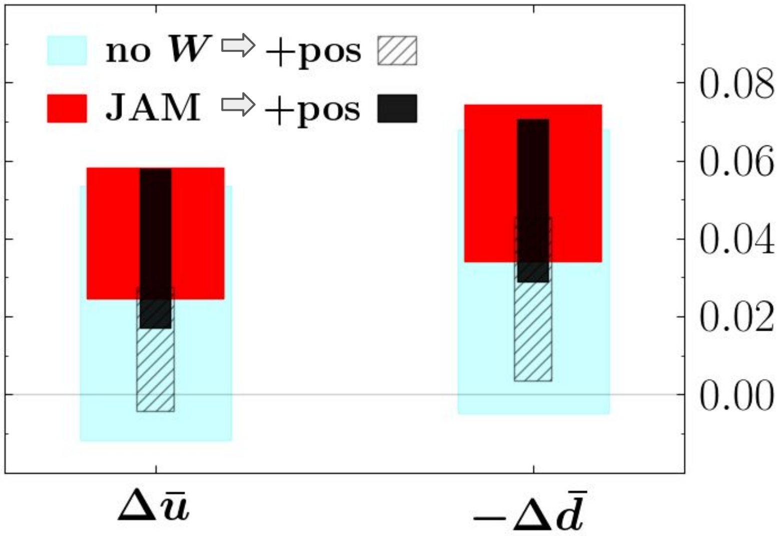
e-Print: 2202.03372 [hep-ph]

(updated version in progress)




| process | $N_{dat}$ | $\chi^2/N_{dat}$ |
|---|---|---|
| **polarized** | | |
| inclusive DIS | 365 | 0.93 |
| SIDIS $(\pi^+, \pi^-)$ | 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 $(\pi^+, \pi^-)$ | 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 the asymmetry with opposite sign compared to upol sea asymmetry

# Outline

**PDFs, helicity PDFs and fragmentation functions (FFs)**

1. Isovector EMC effect with MARATHON data
2. Sea asymmetry with SeaQuest and STAR data
3. Strange suppression from simultaneous analysis of PDFs and FFs
4. Gluon polarization in the proton
5. Polarized antimatter in the proton

**TMDs**

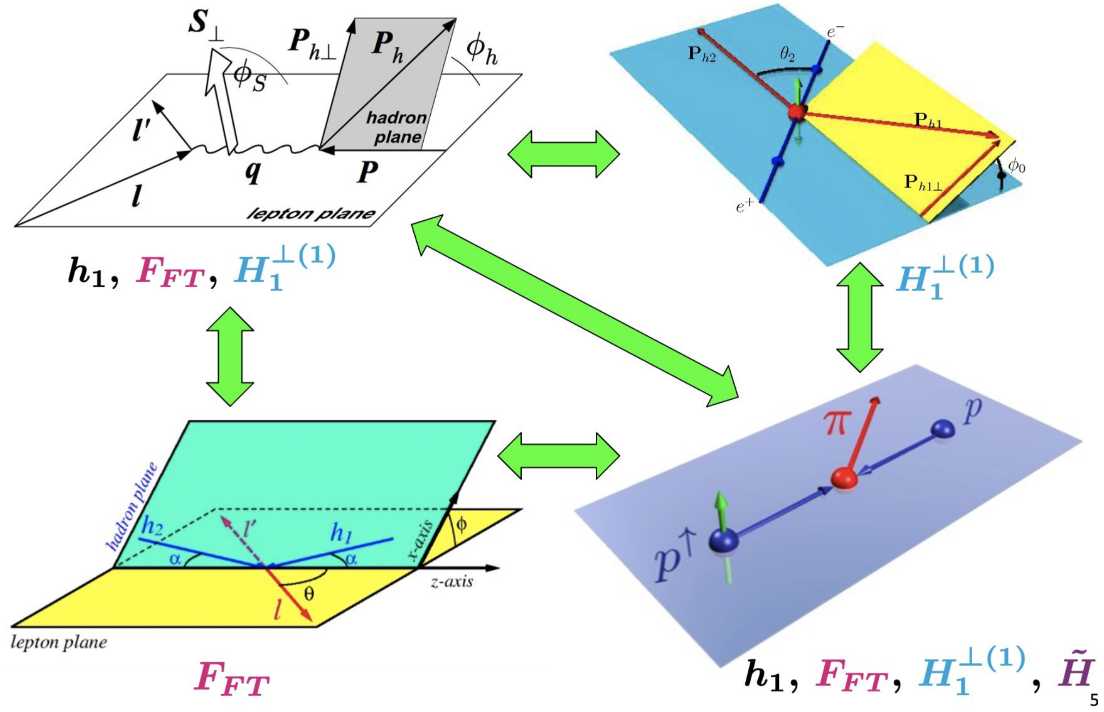
6. Origin of single transverse-spin asymmetries in high-energy collisions

**Synergies with LQCD**

7. Pion PDFs with threshold resummation
8. Complementarity of experimental and lattice QCD data on pion PDFs

# Global analysis of SSA (TMD + CT3)

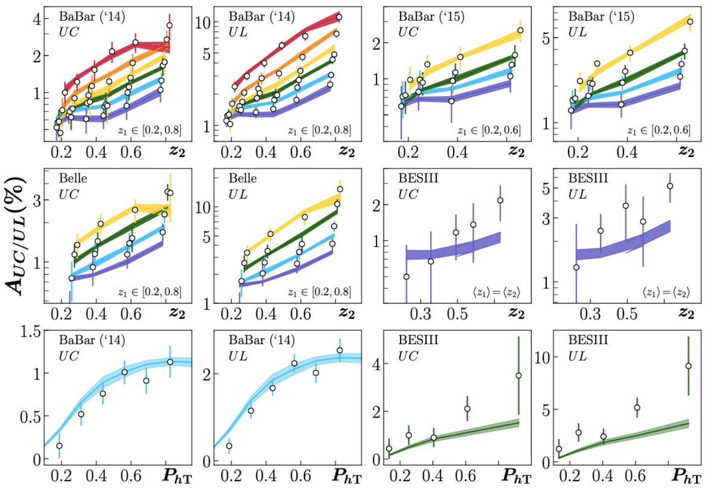
Cammarota et al ('20)



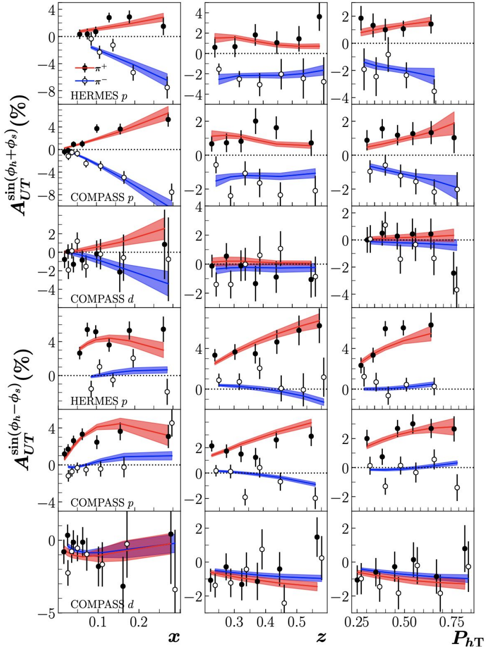

- Framework based on parton model approach to TMDs
- First steps to test universality of the combined TMD and CT3 framework
- Future analysis can build upon this work by implementing proper TMD evolution

# Data vs theory…

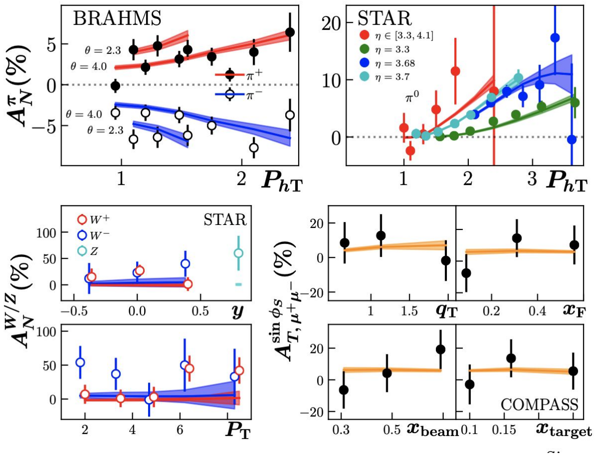
SIA




SIDIS




A_N in p+p / pi + p

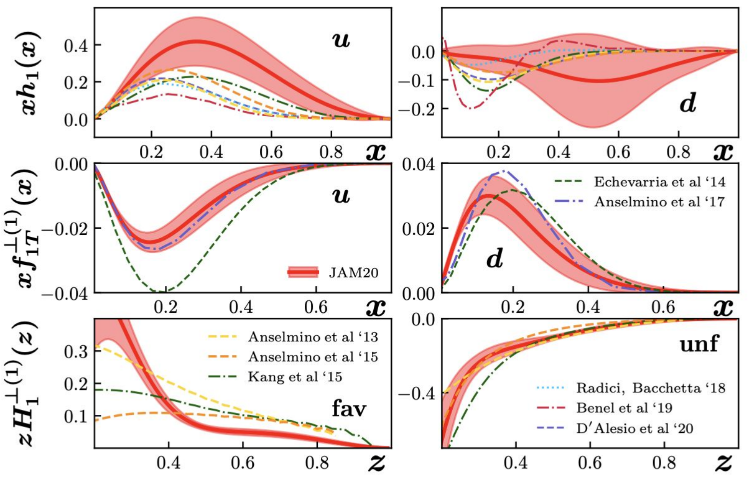


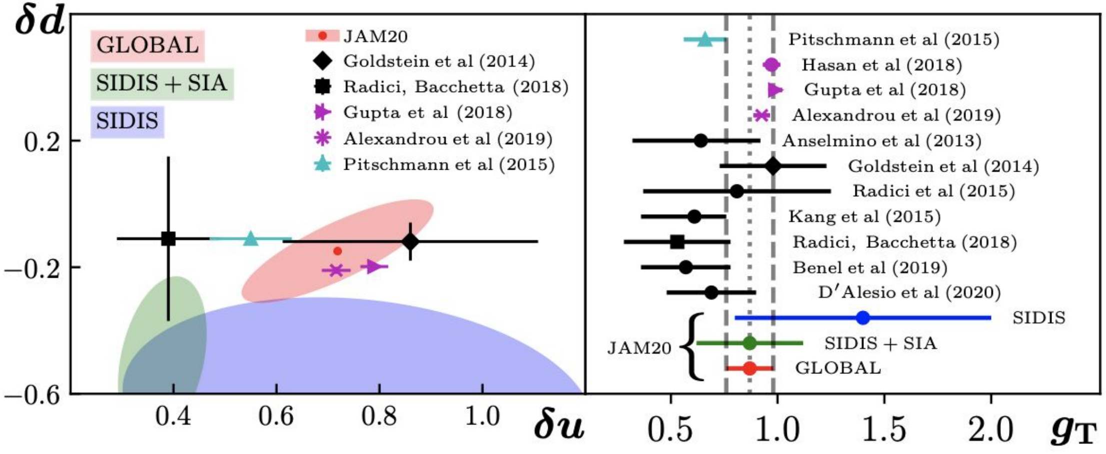

| Observable | Reactions | Non-Perturbative Function(s) | $\chi^2/N_{pts.}$ | Refs. |
|---|---|---|---|---|
| $A_{SIDIS}^{Siv}$ | $e + (p,d)^{\uparrow} \to e + (\pi^+, \pi^-, \pi^0) + X$ | $f_{1T}^{\perp}(x, k_T^2)$ | $150.0/126 = 1.19$ | [65, 66, 68] |
| $A_{SIDIS}^{Col}$ | $e + (p,d)^{\uparrow} \to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

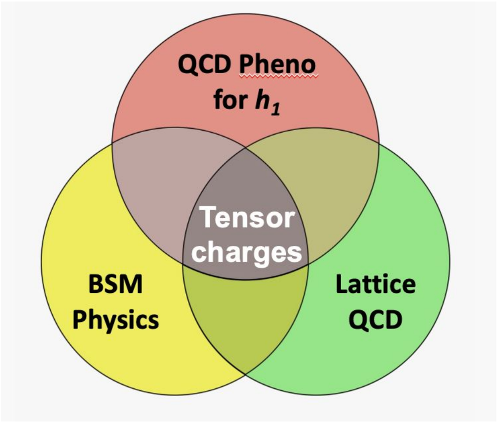
# Extraction of tensor charges

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

- In this work, Soffer bounds were not imposed



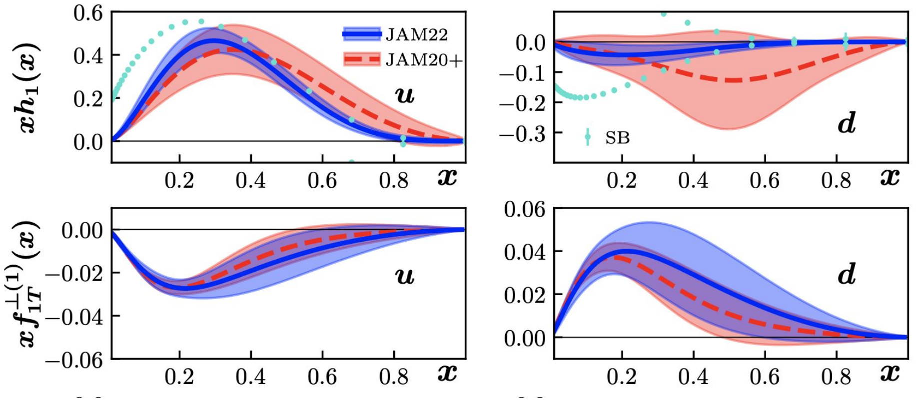



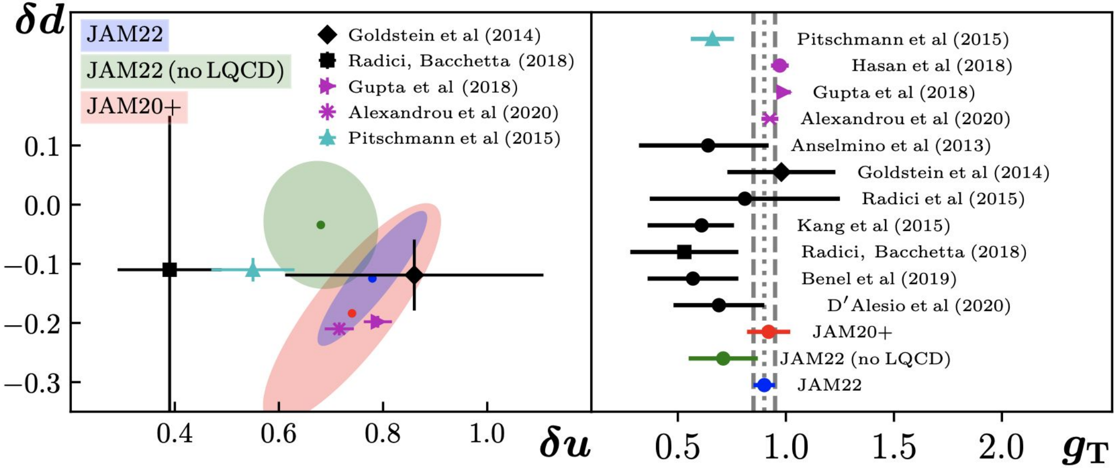



Updated QCD global analysis of single transverse-spin asymmetries I: Extracting $\tilde{H}$, and the role of the Soffer bound and lattice QCD

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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## Synergies with LQCD

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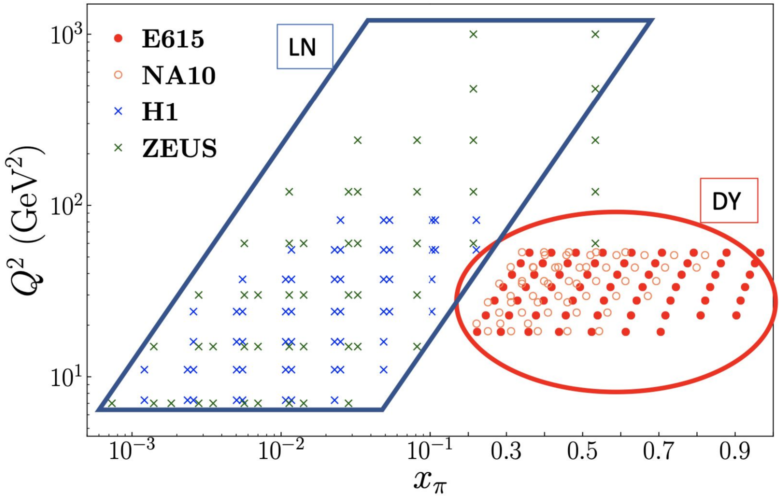
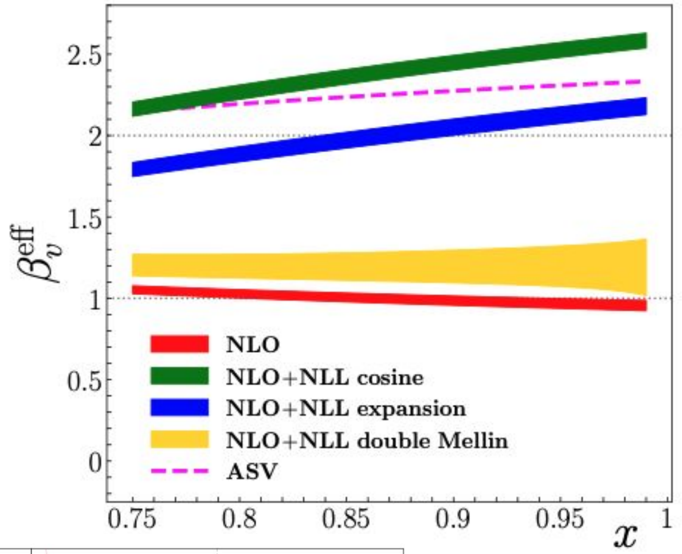
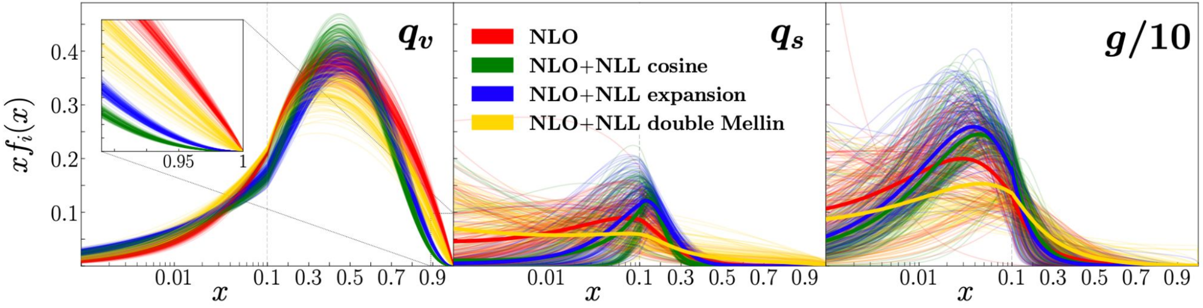
# Pion pdfs with DY threshold resummation




Barry, Ji, Melnitchouk, Sato ('21)




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

# Outline

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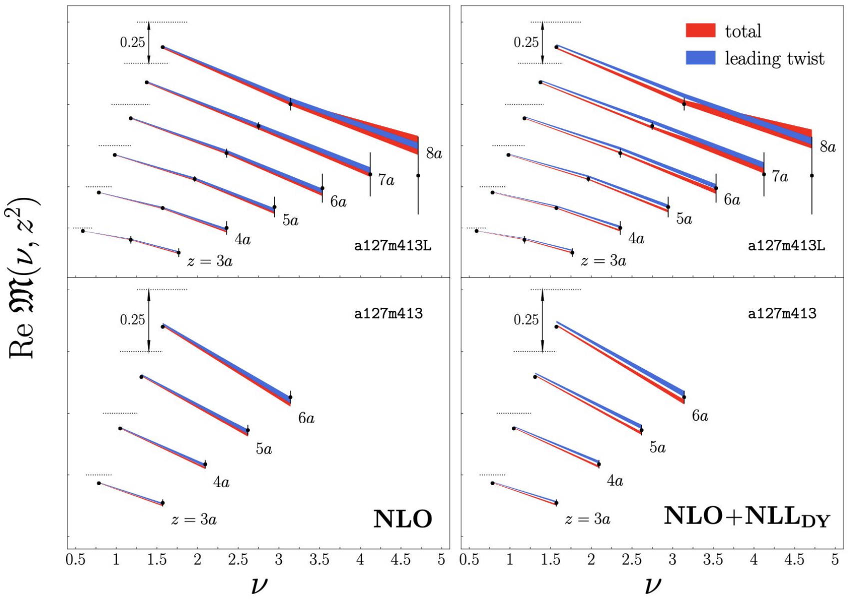
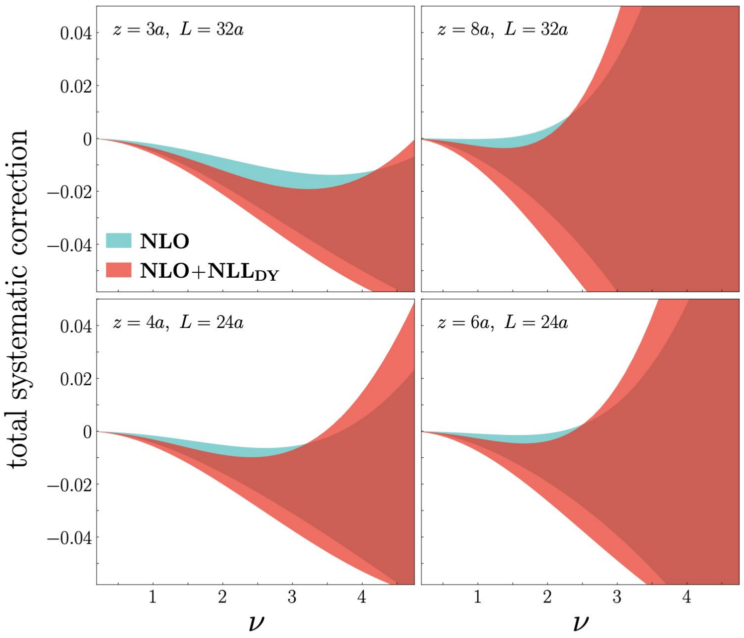
# Synergies with LQCD

Barry et al. ('22)
JAM+HadStruct

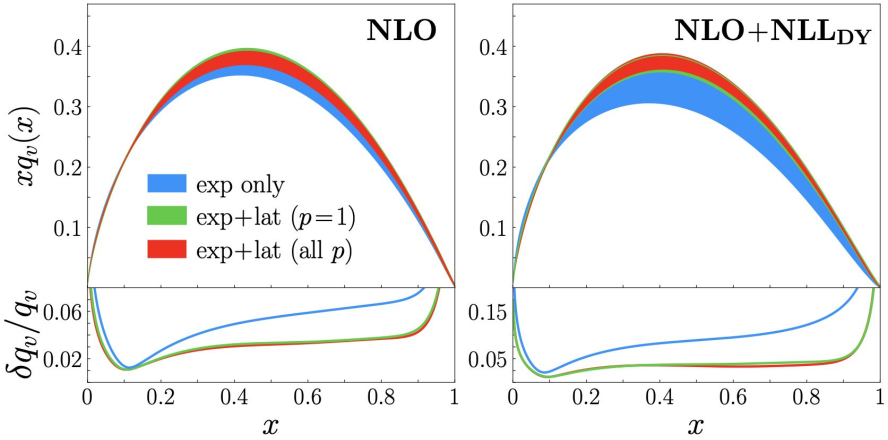


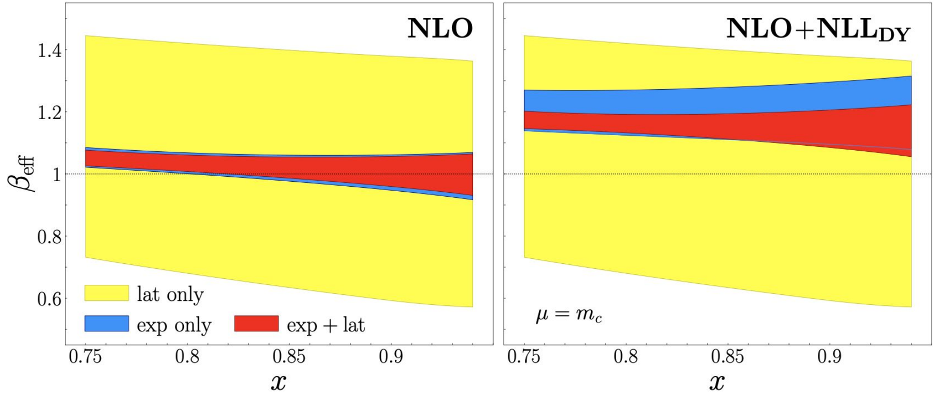




$$\mathrm{Re}\,\mathfrak{M}(\nu, z^2) = \int_0^1 \mathrm{d}x\; q_v(x, \mu_{\mathrm{lat}})\, \mathcal{C}^{\mathrm{Rp\text{-}ITD}}\left(x\nu, z^2, \mu_{\mathrm{lat}}\right)$$
$$+ \boxed{z^2 B_1(\nu) + \frac{a}{|z|} P_1(\nu) + e^{-m_\pi (L-z)} F_1(\nu)}\,.$$

Experimental data can provide insights into LQCD systematics

# Synergies with LQCD





- LQCD can aid hadron structure studies in cases where constraints from experiments are limited - *"lattice priors"*

- The Theory Center has expertise from JAM & HadStruc and has started collaborative research work

# 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

JAM collaboration

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***Students / Postdocs***

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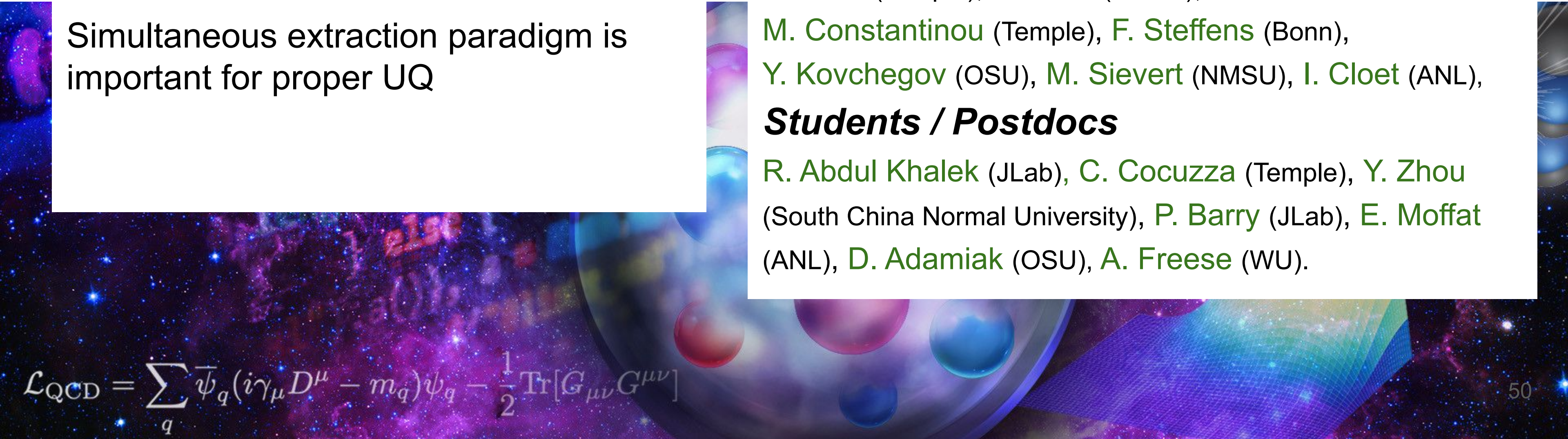

# Backup