Recent Results on Nucleon and Nuclei Structure from the JAM Collaboration

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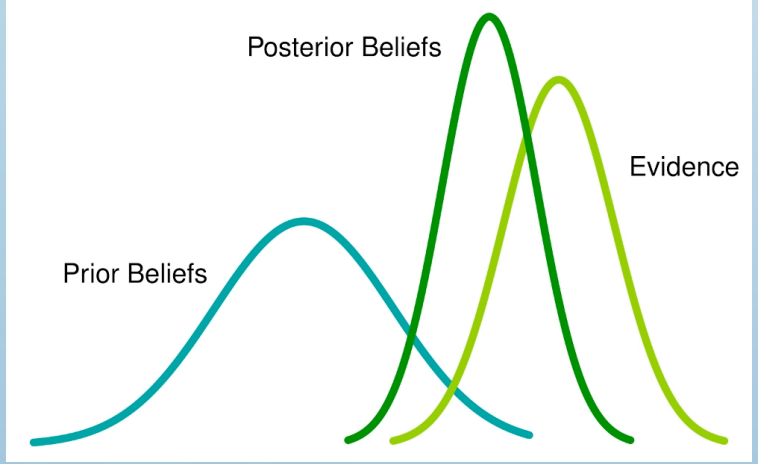
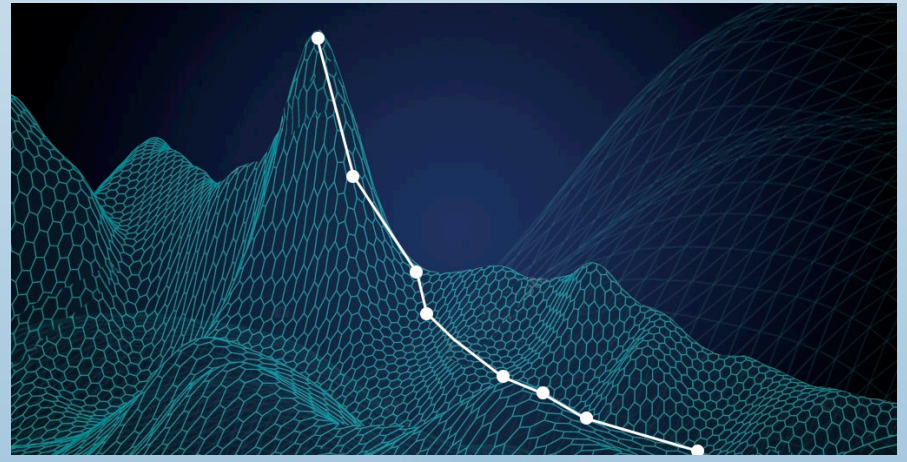
April 26, 2022

Argonne NATIONAL LABORATORY

1. Introduction

2. Spin-Averaged Sea Asymmetry
3. Helicity Sea Asymmetry
4. Isovector Nuclear Effects
5. Other JAM Results





JAM Collaboration

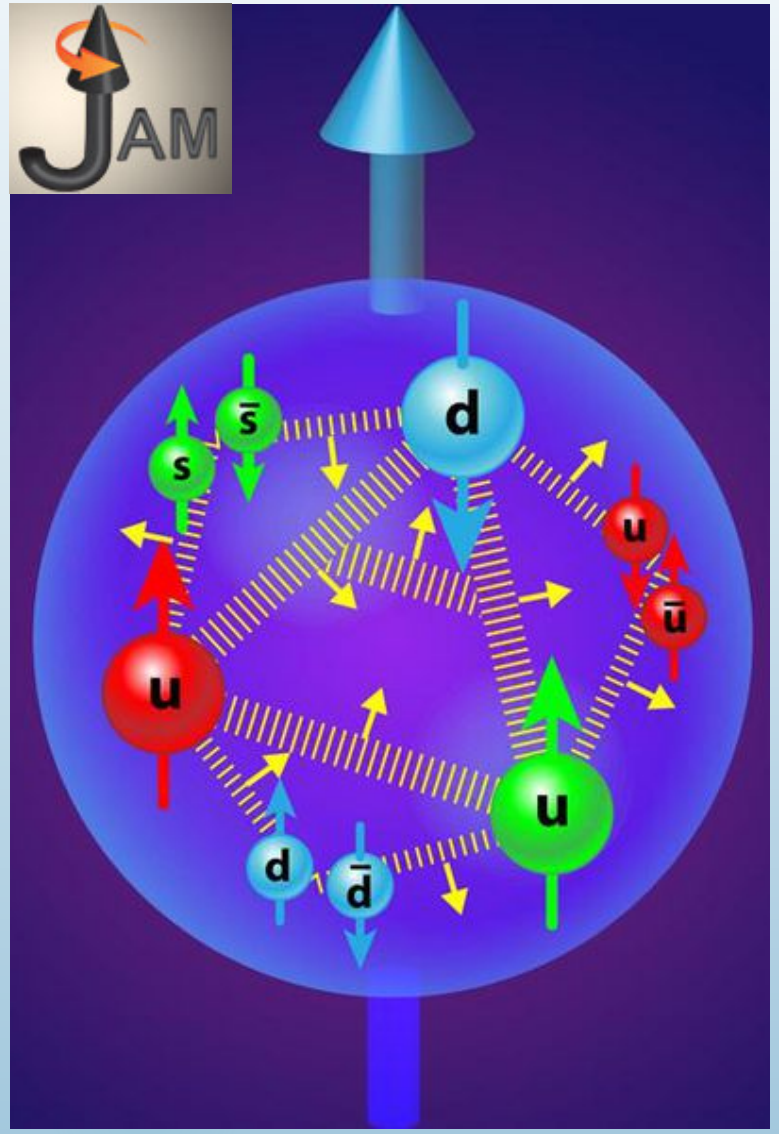
3-dimensional structure of nucleons:

- Parton distribution functions (PDFs)
- Fragmentation functions (FFs)
- Transverse momentum dependent distributions (TMDs)
- Generalized parton distributions (GPDs)

Collinear factorization in perturbative QCD

Simultaneous determinations of PDFs, FFs, etc.

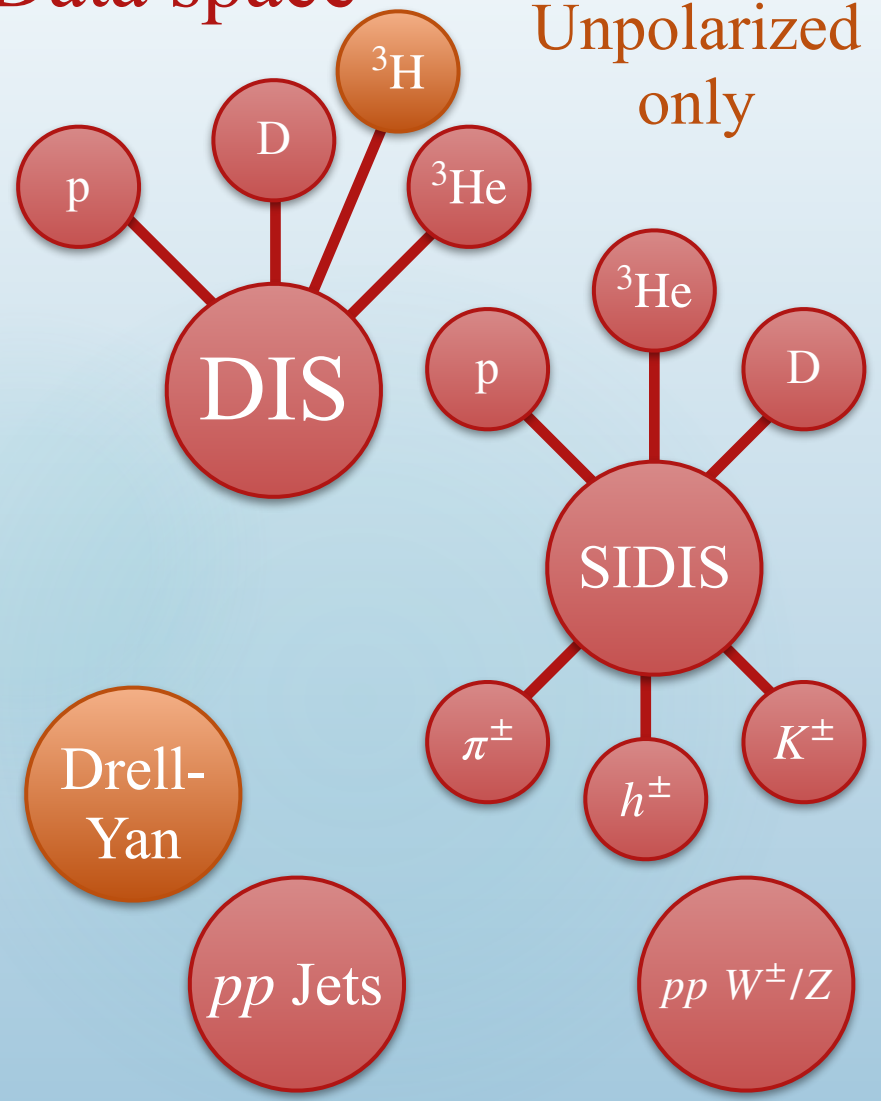
Monte Carlo methods for Bayesian inference



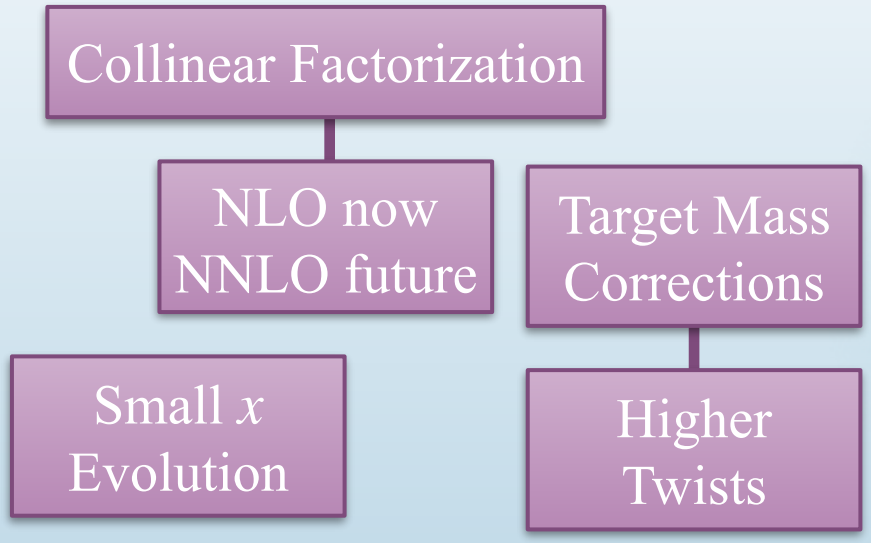
Current State of JAM Global Analyses

Data space

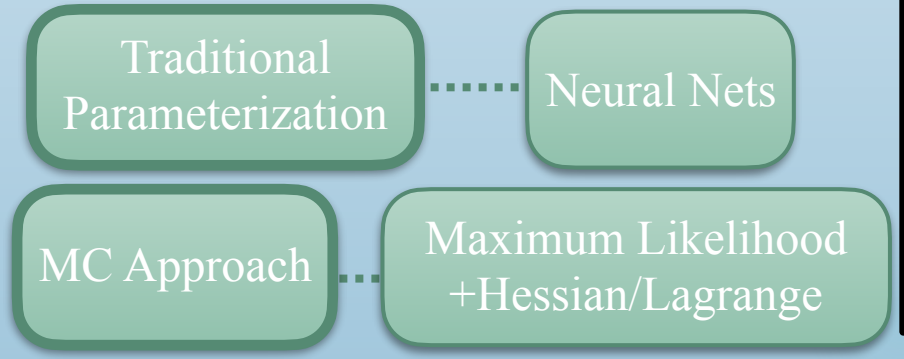
Unpolarized only



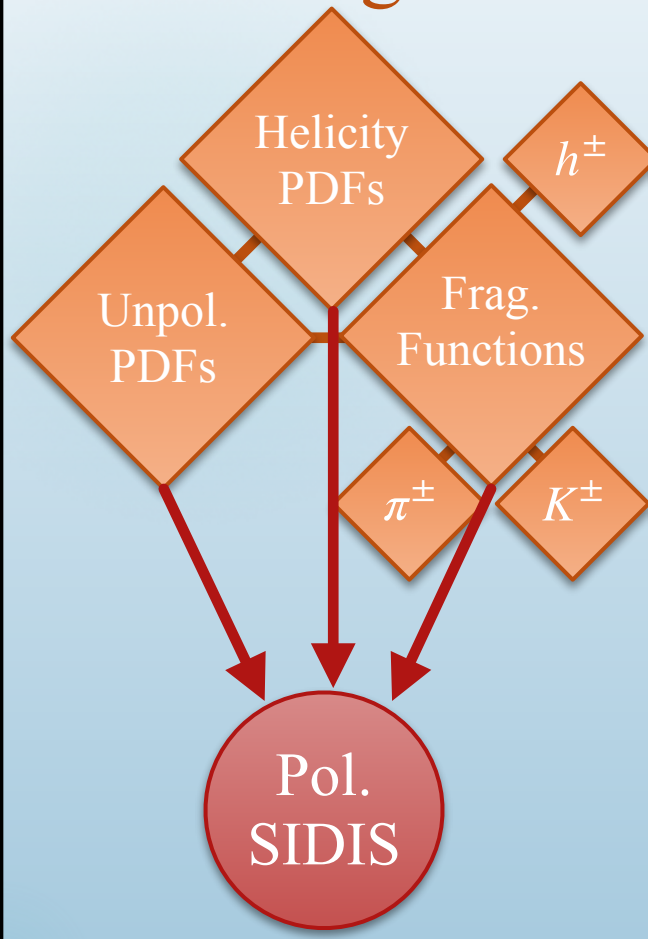
Theory



Methodology

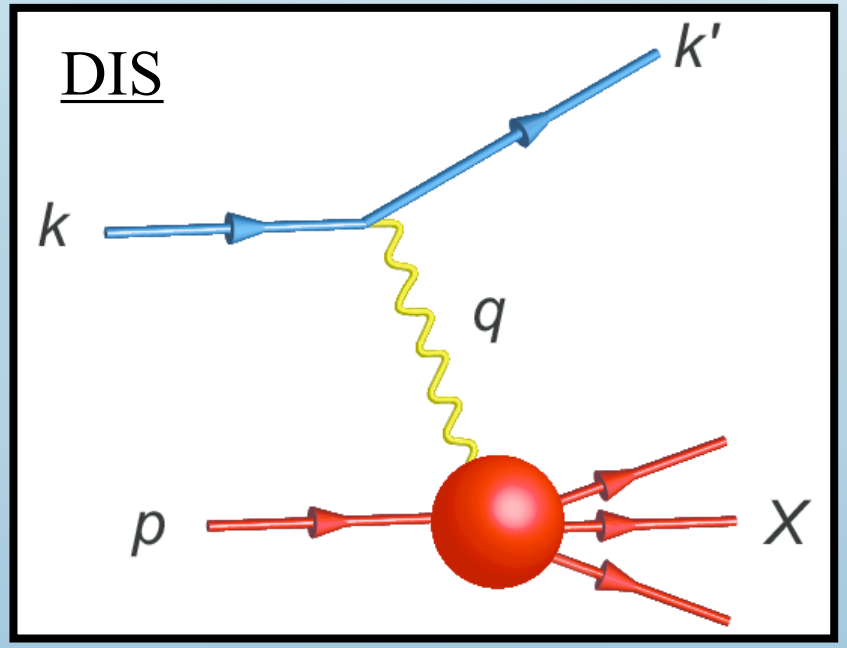


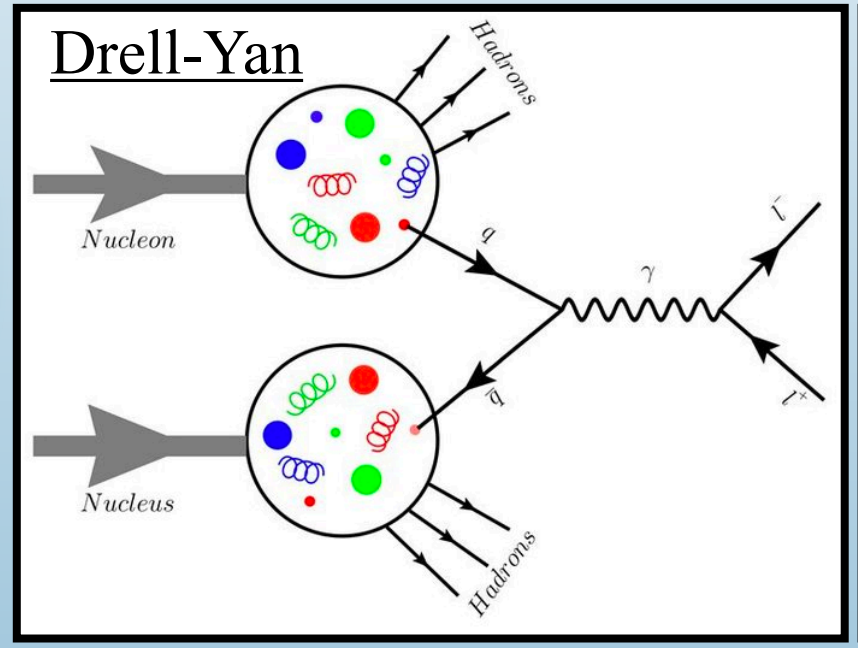
Simultaneous Paradigm

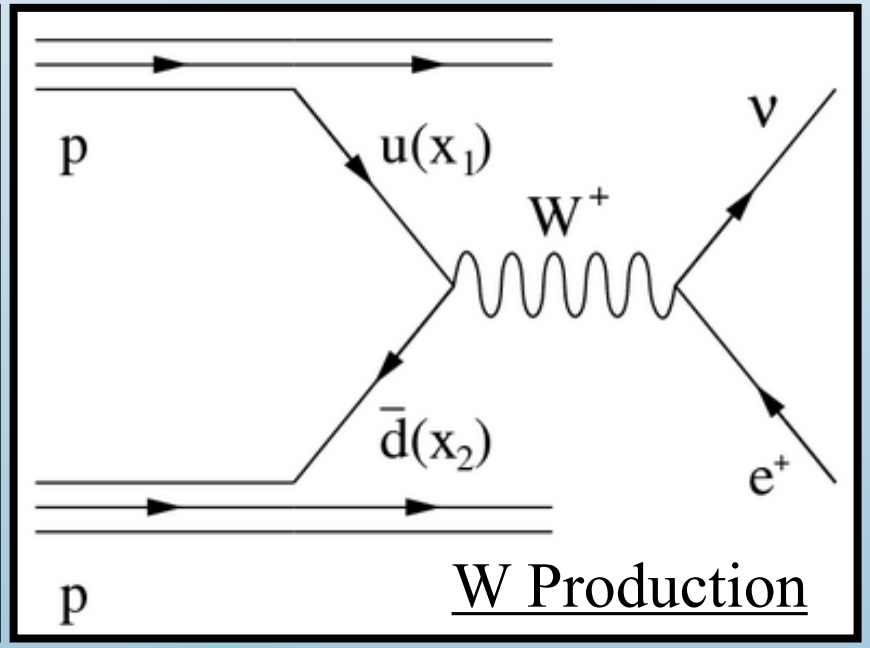


A Global Analysis

Simultaneous extractions of
spin-averaged PDFs, helicity PDFs, and FFs

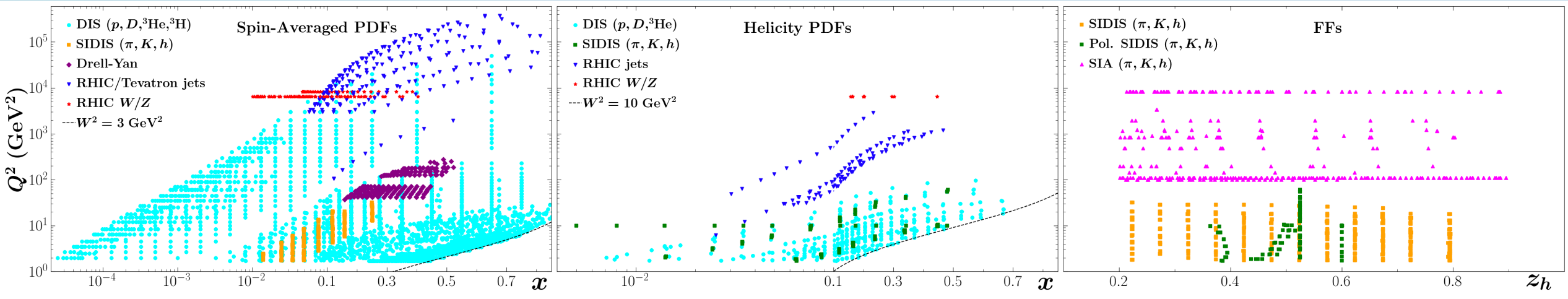






Database

Spin-Averaged PDFs		
DIS	BCDMS, NMC, SLAC, HERA, JLab	3863
Drell-Yan	Fermilab E866, E906	205
W/Z Boson	CDF/D0, STAR, LHCb, CMS	153
Jets	CDF/D0, STAR	198
Helicity PDFs		
Polarized DIS	COMPASS, EMC, HERMES, SLAC, SMC	365
Polarized W/Z Boson	STAR, PHENIX	18
Polarized Jets	STAR, PHENIX	83
π, K, h FFs + PDFs		
SIDIS	COMPASS, EMC, HERMES, SLAC, SMC	1490
Polarized SIDIS	COMPASS, HERMES, SMC	231
SIA	ARGUS, BABAR, BELLE, TASSO, TPC, TOPAZ, SLD, ALEPH, OPAL, DELPHI	564



Parameters to Observables

Parameterize PDFs at input scale $Q_0^2 = m_c^2$

$$f_i(x) = Nx^{\alpha}(1-x)^{\beta}(1+\gamma\sqrt{x}+\eta x)$$

Evolve PDFs using DGLAP

$$\frac{\mathrm{d}}{\mathrm{d}\ \ln(\mu^2)} f_i(x,\mu) = \sum_j \int_x^1 \frac{dz}{z} P_{ij}(z,\mu) f_j(\frac{x}{z},\mu)$$

Calculate Observables

$$d\sigma_{\mathrm{DY}} = \sum_{i,j} H_{ij}^{\mathrm{DY}} \otimes f_i \otimes f_j$$

The χ^2 function

Now that the observables have been calculated…

Data

Theory

Normalization

$$\chi^2(\boldsymbol{a}) = \sum_{i,e} \left(\frac{d_{i,e} - \sum_k r_e^k \beta_{i,e}^k - T_{i,e}(\boldsymbol{a})/N_e}{\alpha_{i,e}} \right)^2 + \sum_k \left(r_e^k\right)^2 + \left(\frac{1 - N_e}{\delta N_e} \right)^2$$

Uncorrelated Uncertainties

Correlated Uncertainties

Normalization Uncertainty

Bayes' Theorem

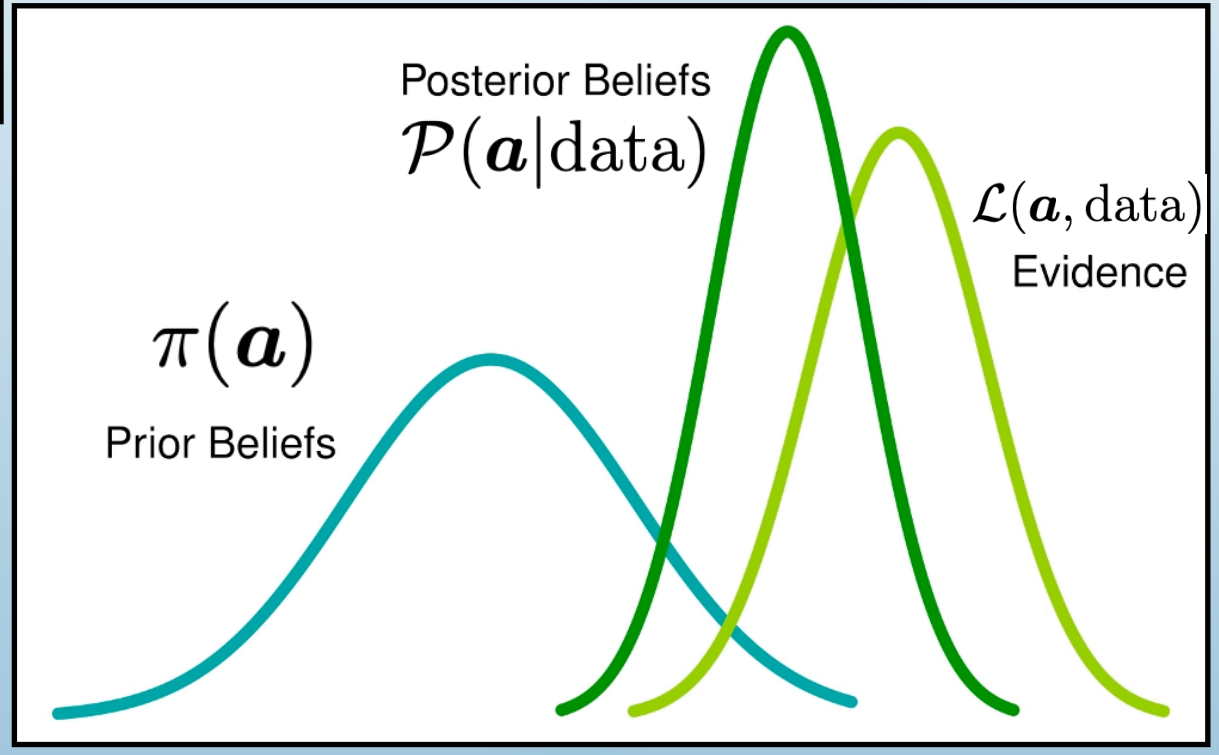
Now that we have calculated $\chi^2(\boldsymbol{a}, \text{data})$…

Likelihood Function

$$\mathcal{L}\left(\boldsymbol{a}, \text{data}\right) = \exp\left(-\frac{1}{2}\chi^2\left(\boldsymbol{a}, \text{data}\right)\right)$$

Bayes' Theorem

$$\mathcal{P}(\boldsymbol{a}|\text{data}) \sim \mathcal{L}(\boldsymbol{a}, \text{data})\,\pi(\boldsymbol{a})$$

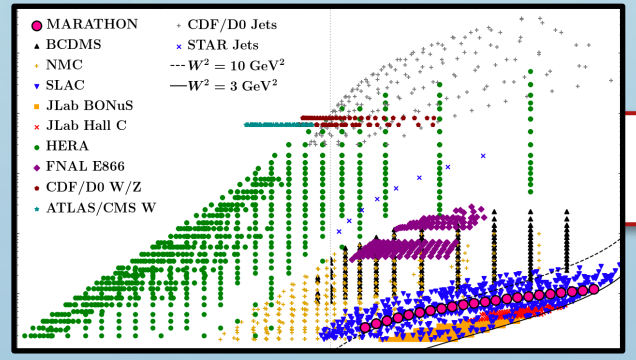


Data Resampling

Pseudo-Data → $\tilde{\sigma} = \sigma + N(0,1)\ \alpha$ ← Uncorrelated Uncertainties

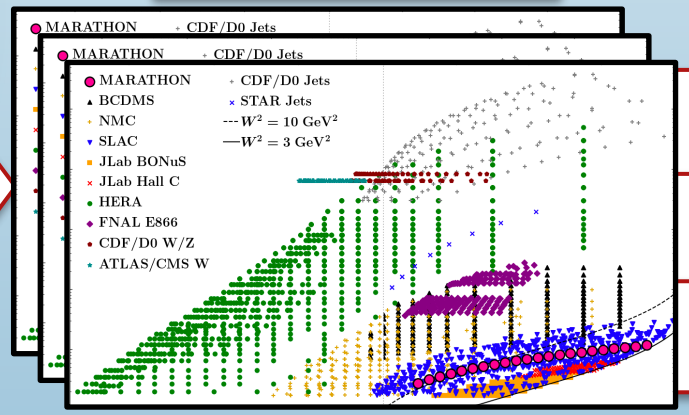
Data → σ

Original Data



DR

Replica Data

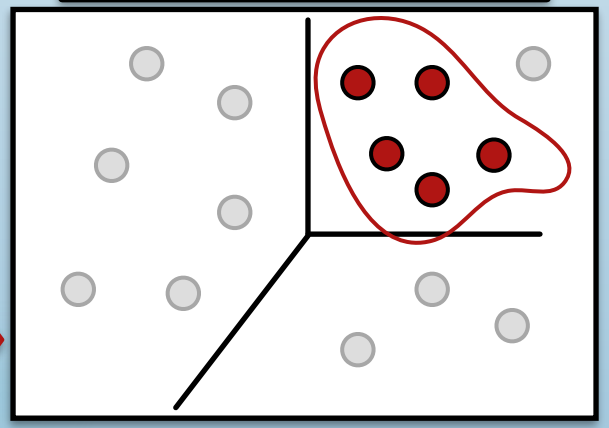


Maximum Likelihood

Maximum Likelihood

Maximum Likelihood

Parameter Space



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High Energy Physics – Phenomenology

[Submitted on 2 Sep 2021]

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

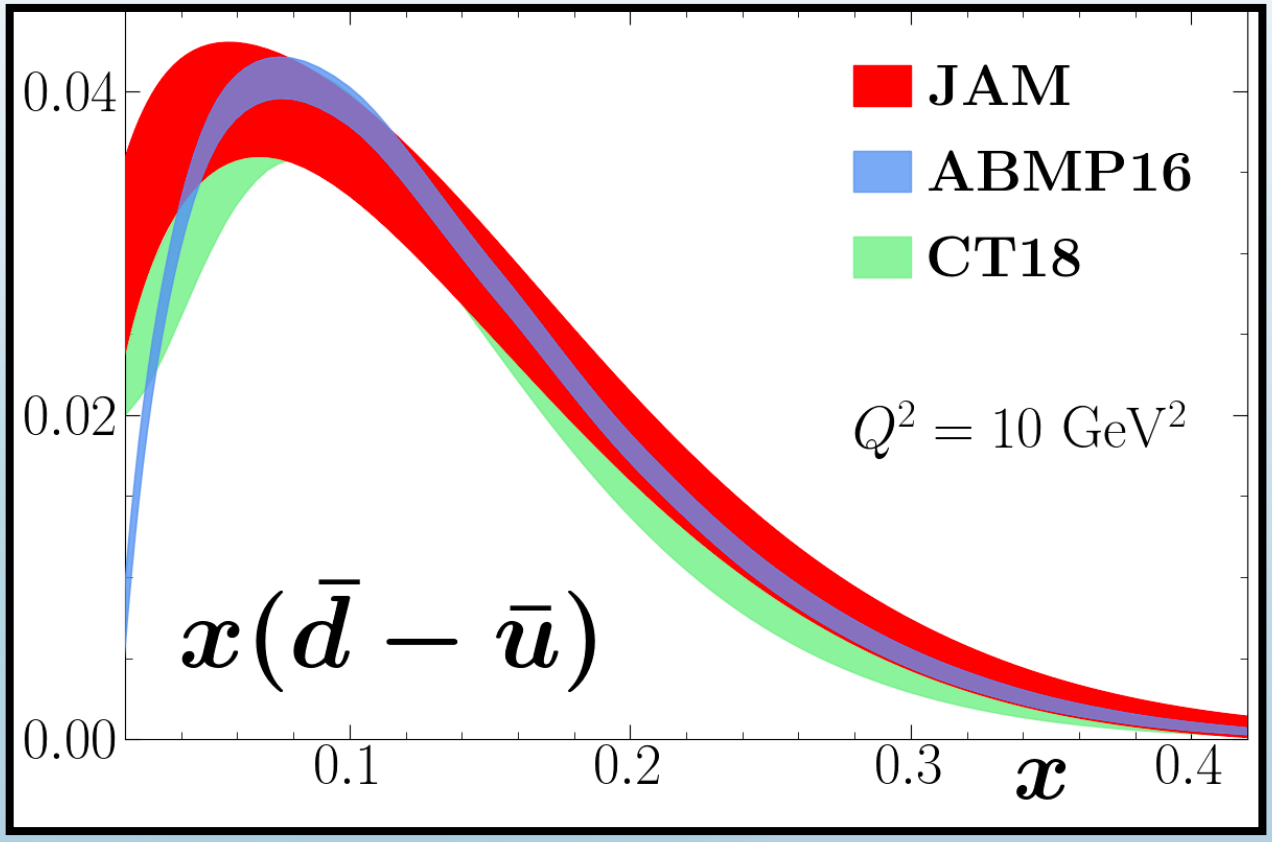
Christopher Cocuzza, Wally Melnitchouk, Andreas Metz, Nobuo Sato

We perform a global QCD analysis of unpolarized parton distributions within a Bayesian Monte Carlo framework, including the new W-lepton production data from the STAR Collaboration at RHIC and Drell-Yan di-muon data from the SeaQuest experiment at Fermilab. We assess the impact of these two new measurements on the light antiquark sea in the proton, and the $\bar{d} - \bar{u}$ asymmetry in particular. The SeaQuest data are found to significantly reduce the uncertainty on the $\bar{d}/\bar{u}$ ratio at large parton momentum fractions x, strongly favoring an enhanced $\bar{d}$ sea up to $x \approx 0.4$, in general agreement with nonperturbative calculations based on chiral symmetry breaking in QCD.

https://arxiv.org/abs/2109.00677

C. Cocuzza *et al.*, Phys. Rev. D. **104**, no. 7, 074031 (2021).

Introduction to Sea Asymmetry



Unpolarized

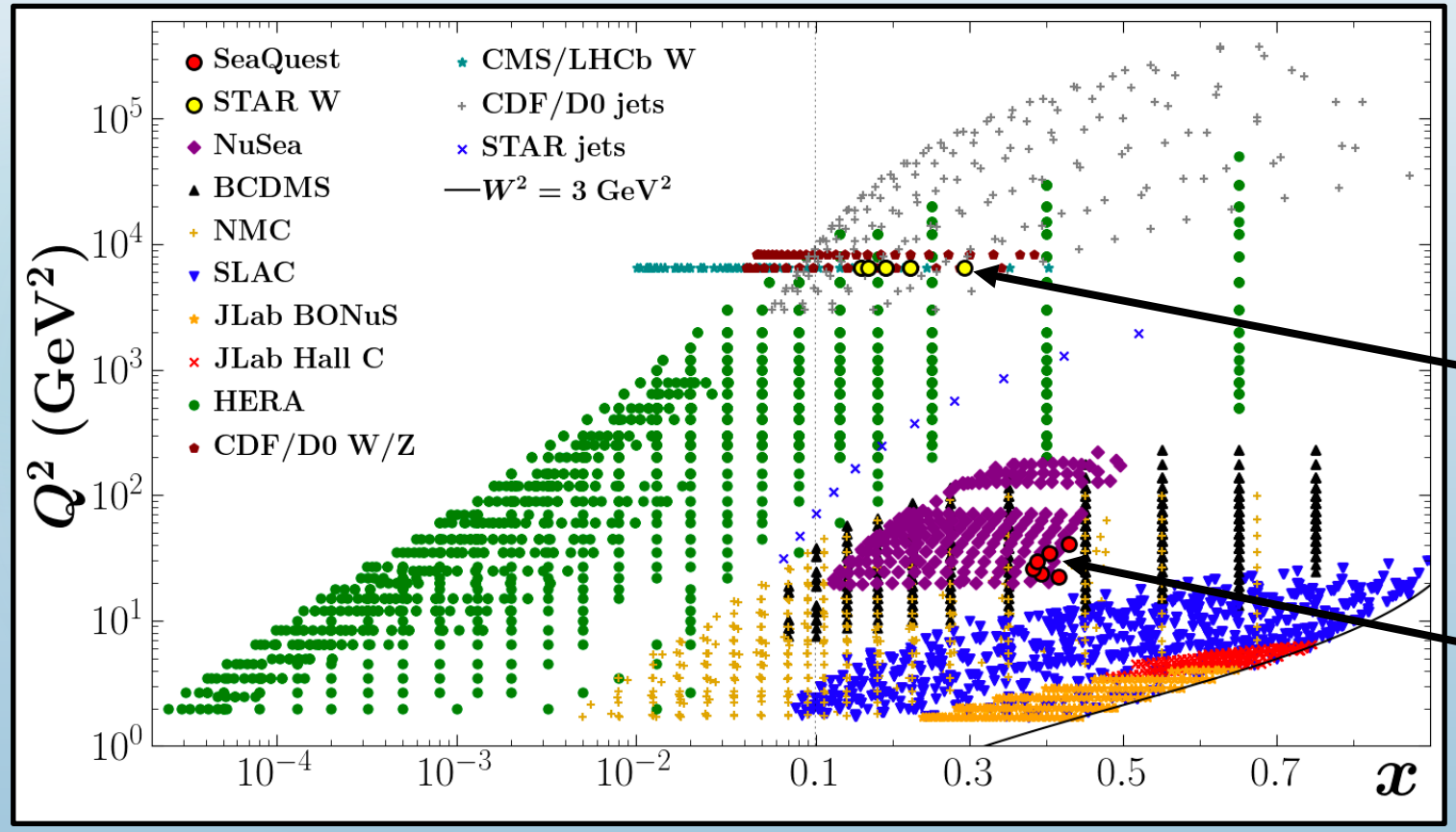
Cannot be explained from gluons splitting into quark-antiquark pairs

Meson Cloud Models
Chiral Soliton Models
Statistical Models

Still questions at high $x > 0.2$ and for helicity asymmetry

Kinematic Coverage (Spin-Averaged)

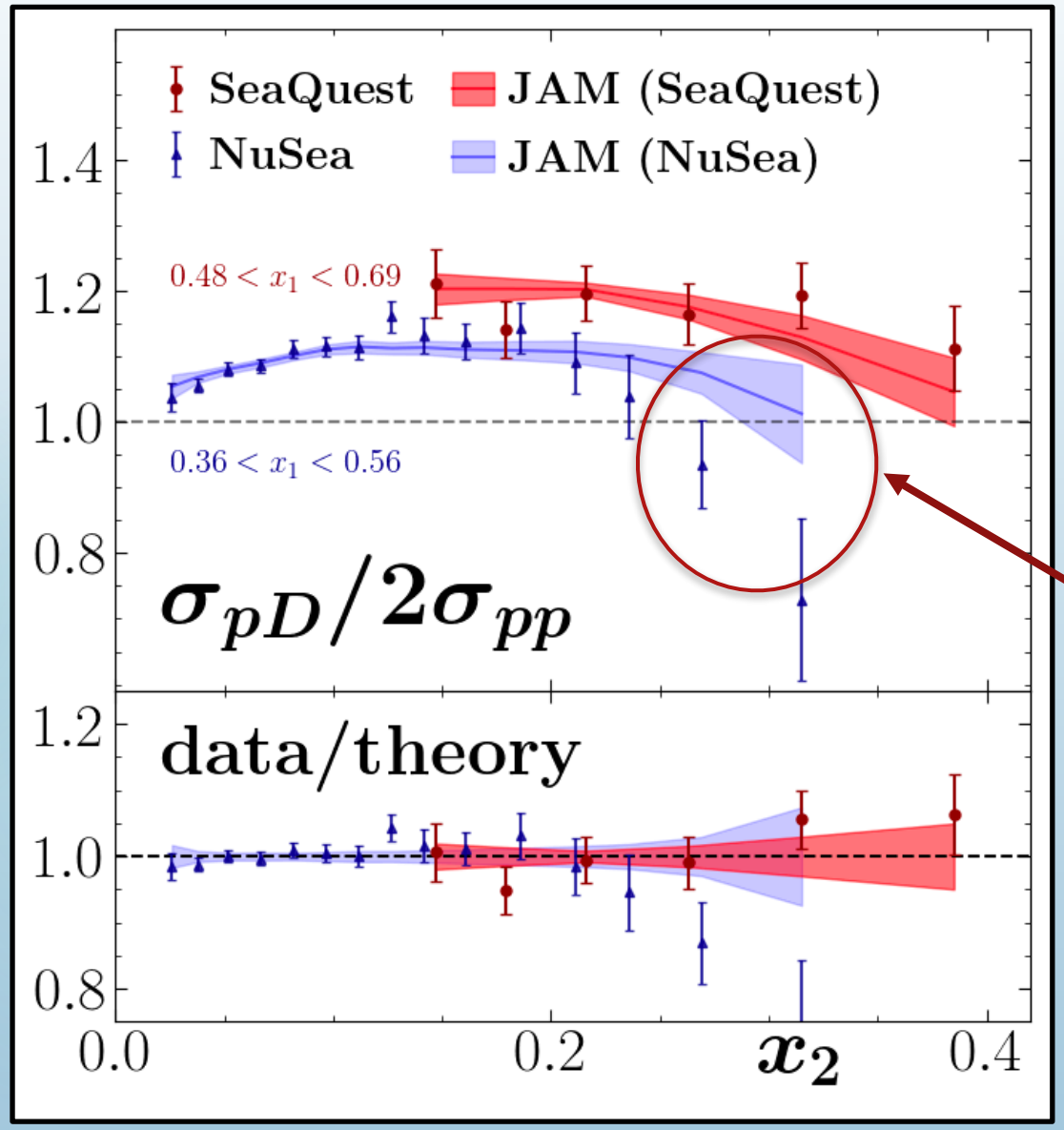
Deep Inelastic Scattering	BCDMS, NMC, SLAC, HERA, Jefferson Lab	3863	points
Drell-Yan	Fermilab E866, E906	205	points
W/Z Boson Production	CDF/D0, STAR, LHCb, CMS	153	points
Jets	CDF/D0, STAR	200	points



New STAR data

New SeaQuest data

SeaQuest and NuSea Quality of Fit

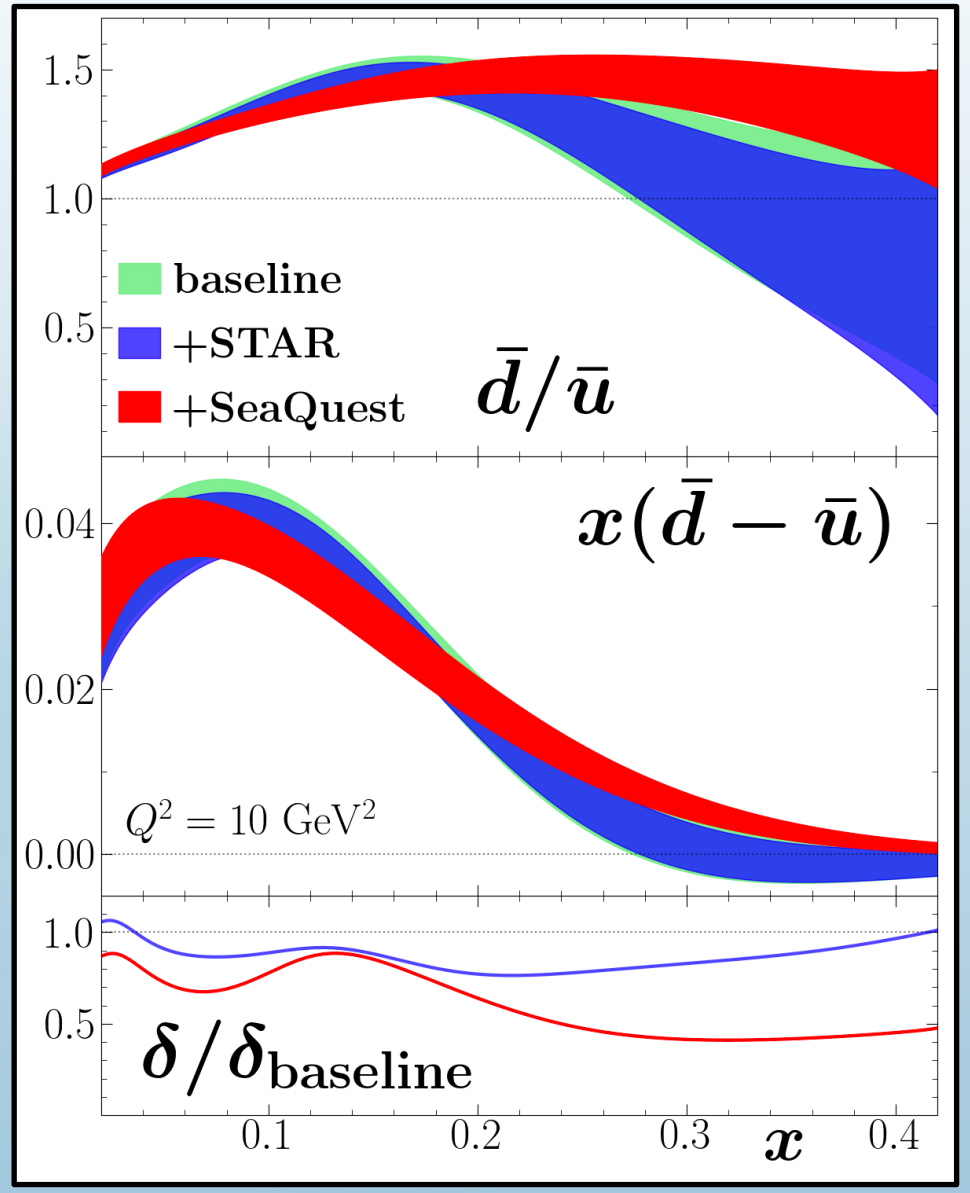


process		$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
Drell-Yan			
NuSea	pp	184	1.21
NuSea	$pD/2pp$	15	1.30
SeaQuest	$pD/2pp$	6	0.82

$$\left.\frac{\sigma_{pD}}{2\sigma_{pp}}\right|_{x_1 \gg x_2} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]$$

Well-known tension between NuSea and SeaQuest

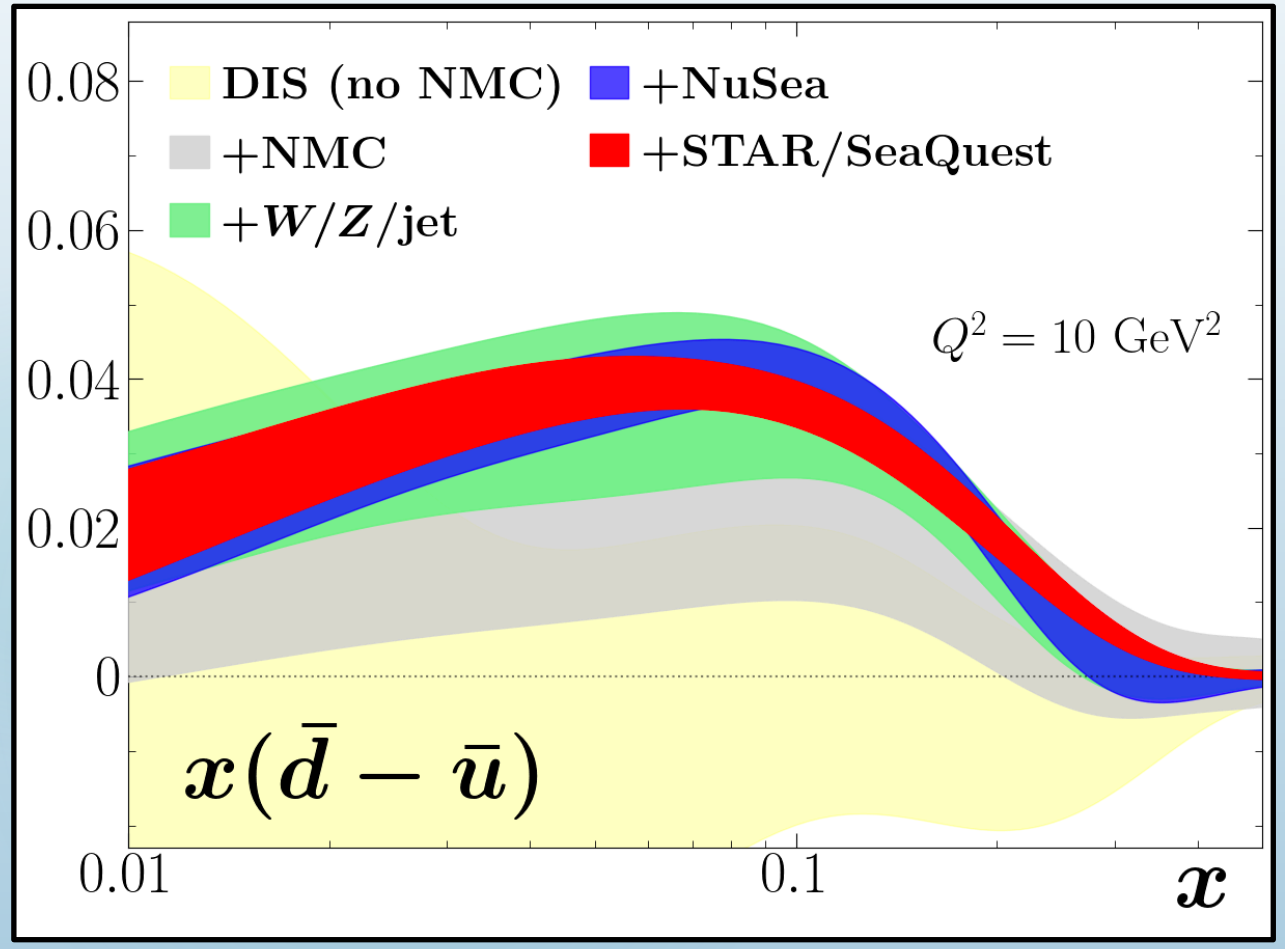
Impact from STAR and SeaQuest

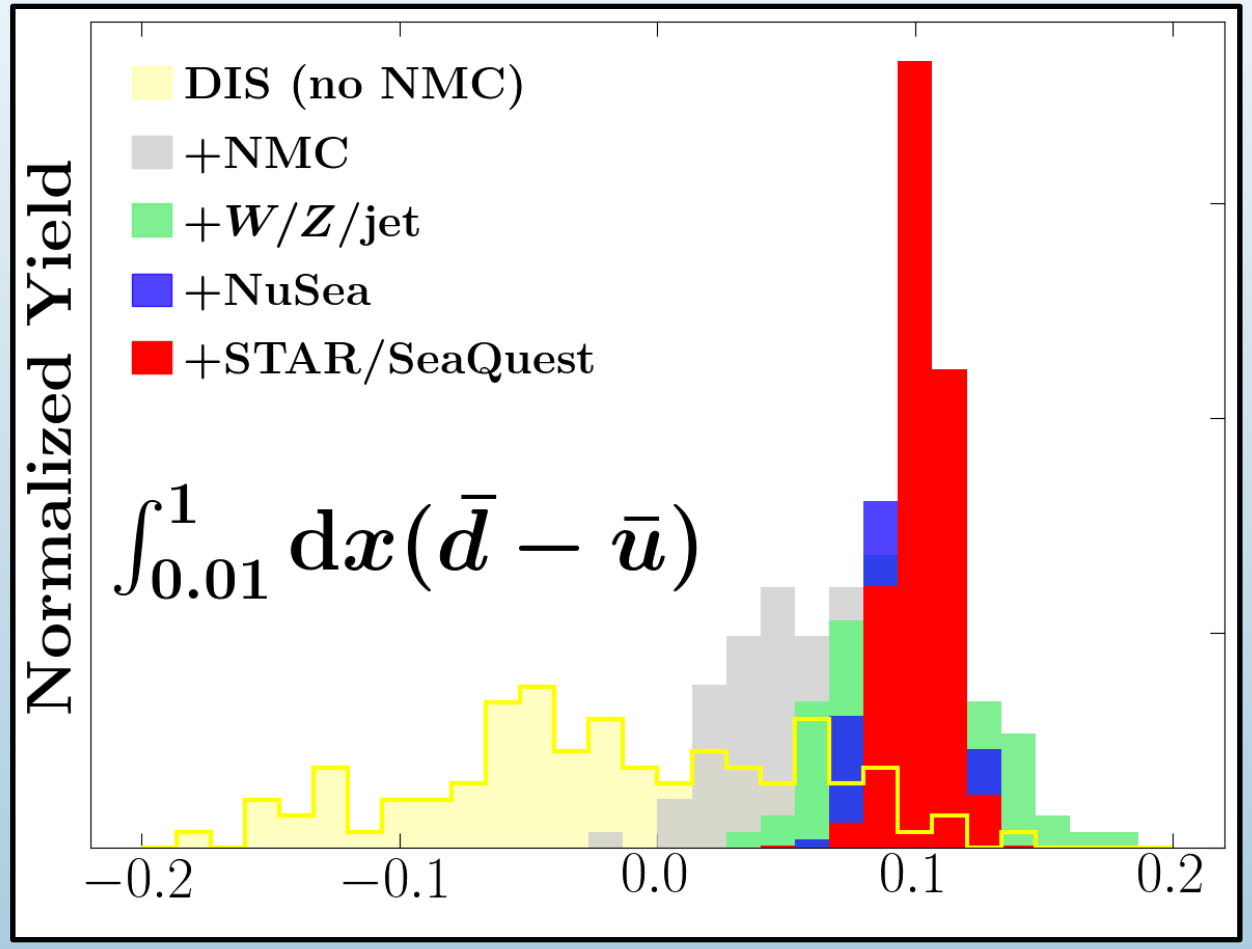


STAR: Moderate reduction of uncertainties

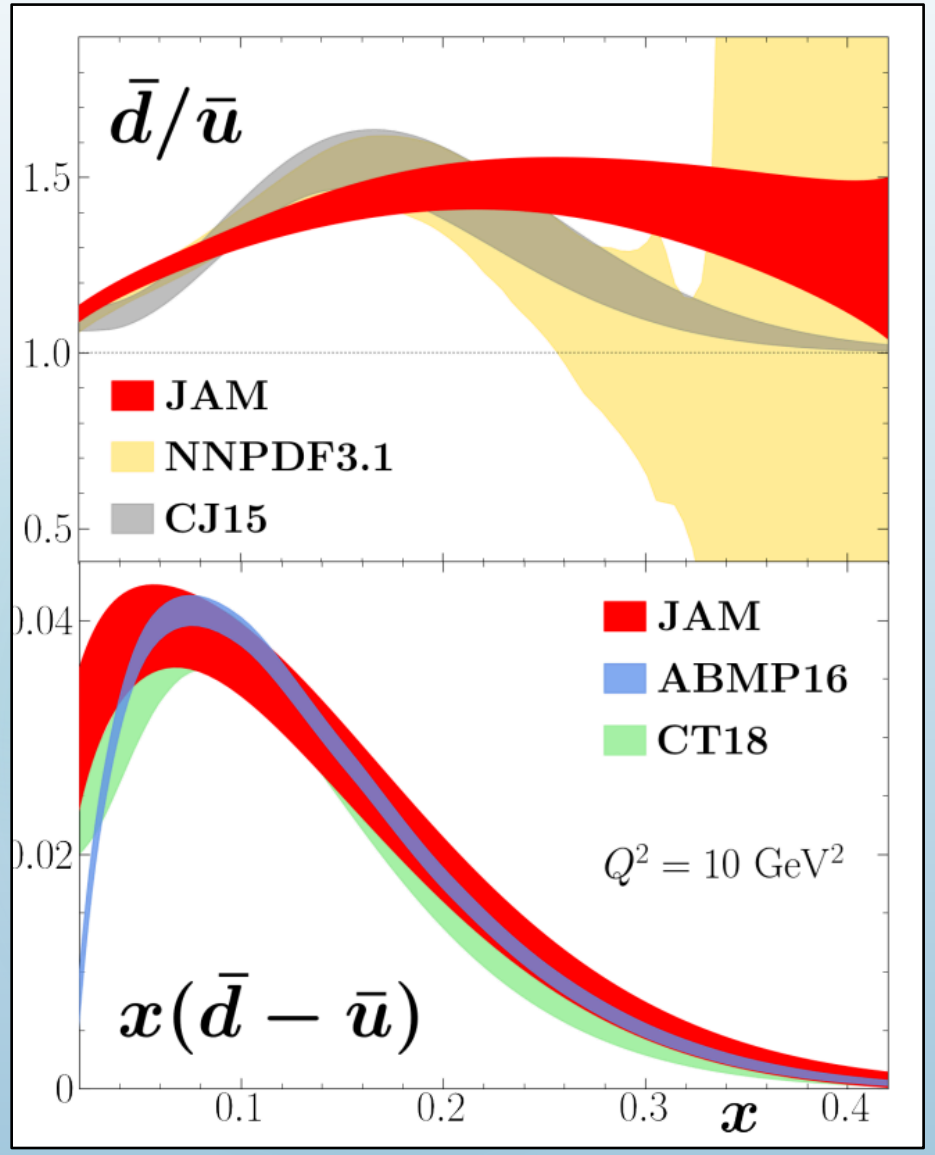
SeaQuest: Large reduction of uncertainties, especially at $x > 0.2$.
$\bar{d}/\bar{u} > 1$ up to $x \approx 0.4$, in agreement with models

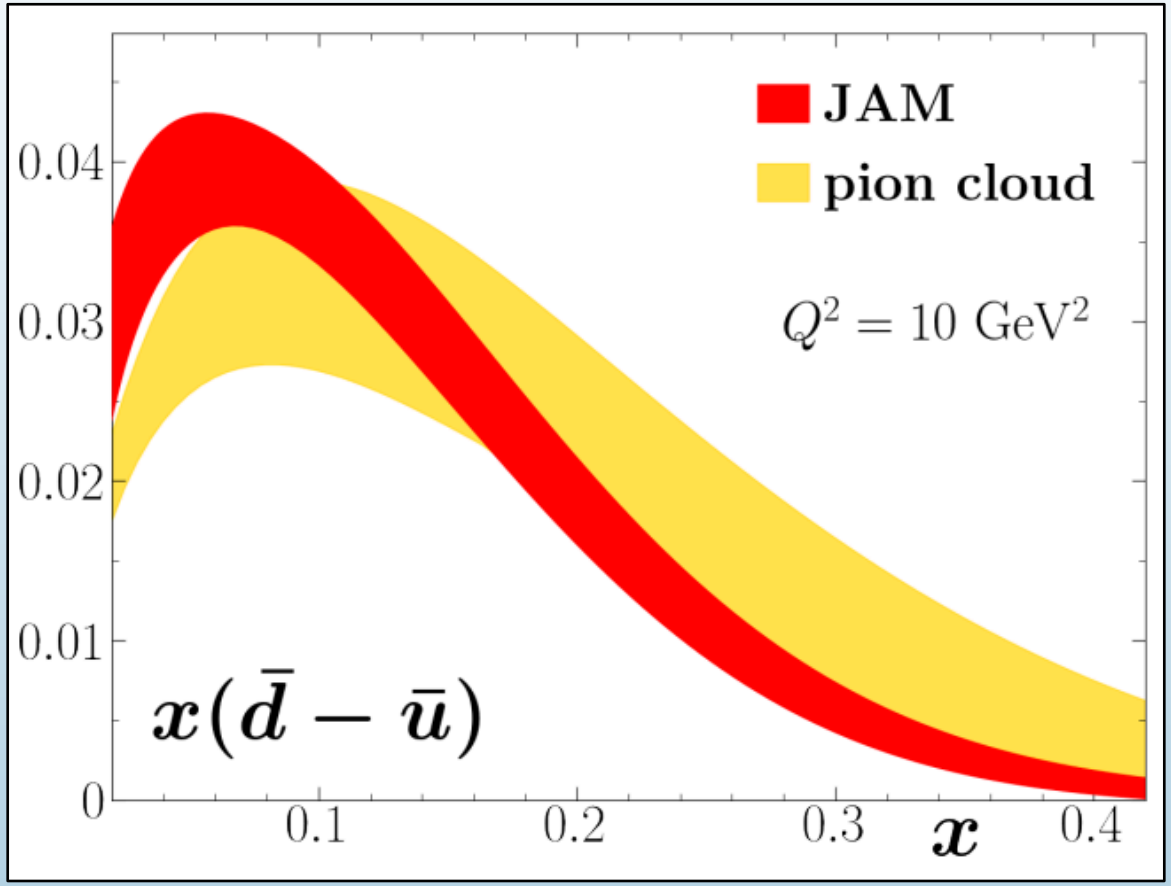
Sources of Asymmetry





Comparison to other fits and pion cloud model





Good agreement with pion cloud model

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Polarized Antimatter in the Proton from Global QCD Analysis

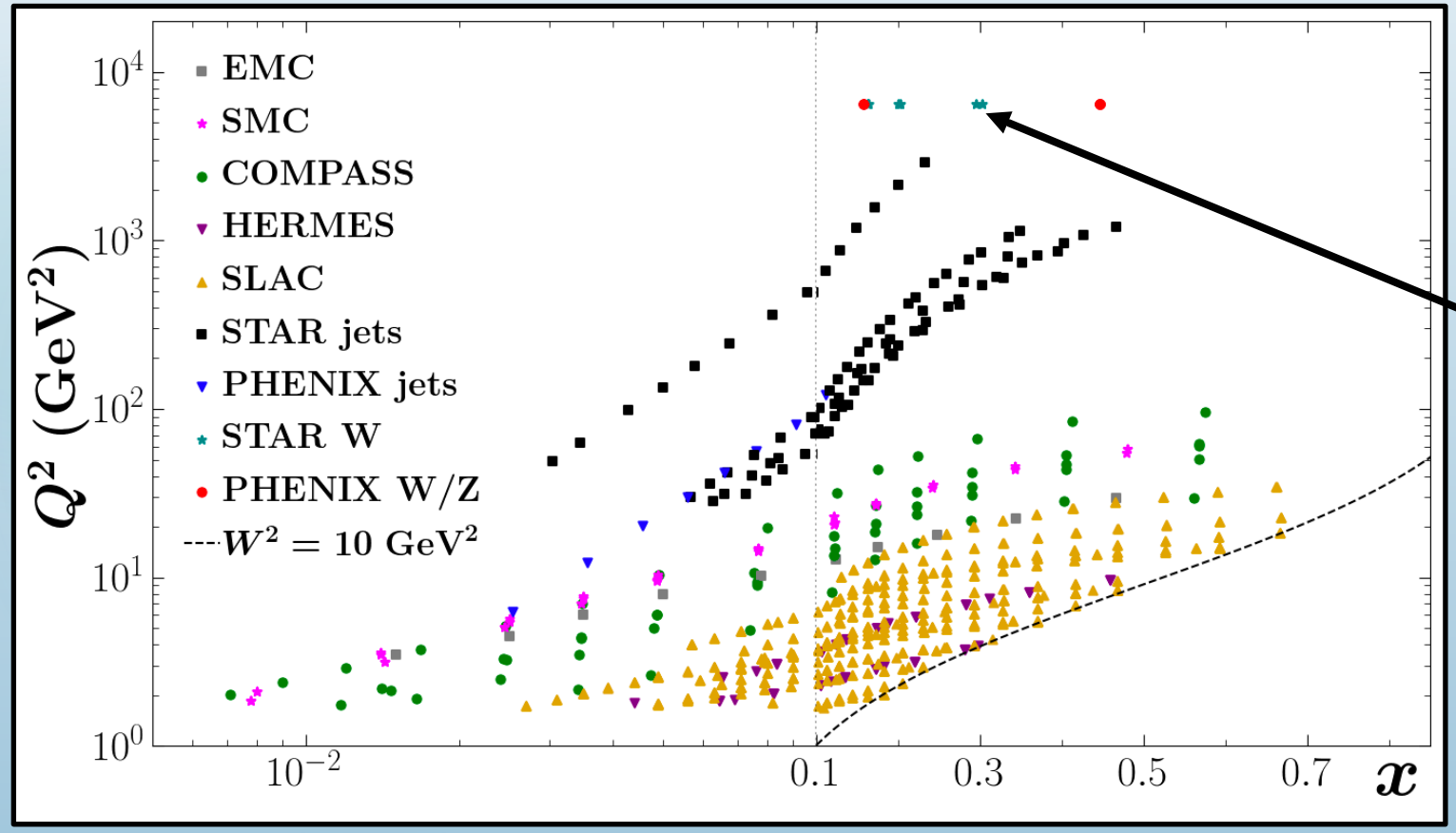
C. Cocuzza, W. Melnitchouk, A. Metz, N. Sato

We present a global QCD analysis of spin-dependent parton distribution functions (PDFs) that includes the latest polarized W-lepton production data from the STAR collaboration at RHIC. These data allow the first data-driven extraction of a nonzero polarized light quark sea asymmetry $\Delta\bar{u} - \Delta\bar{d}$ within a global QCD framework with minimal theoretical assumptions. Within our simultaneous extraction of polarized PDFs, unpolarized PDFs, and pion and kaon fragmentation functions, we also extract a self-consistent set of antiquark polarization ratios $\Delta\bar{u}/\bar{u}$ and $\Delta\bar{d}/\bar{d}$.

https://arxiv.org/abs/2202.03372

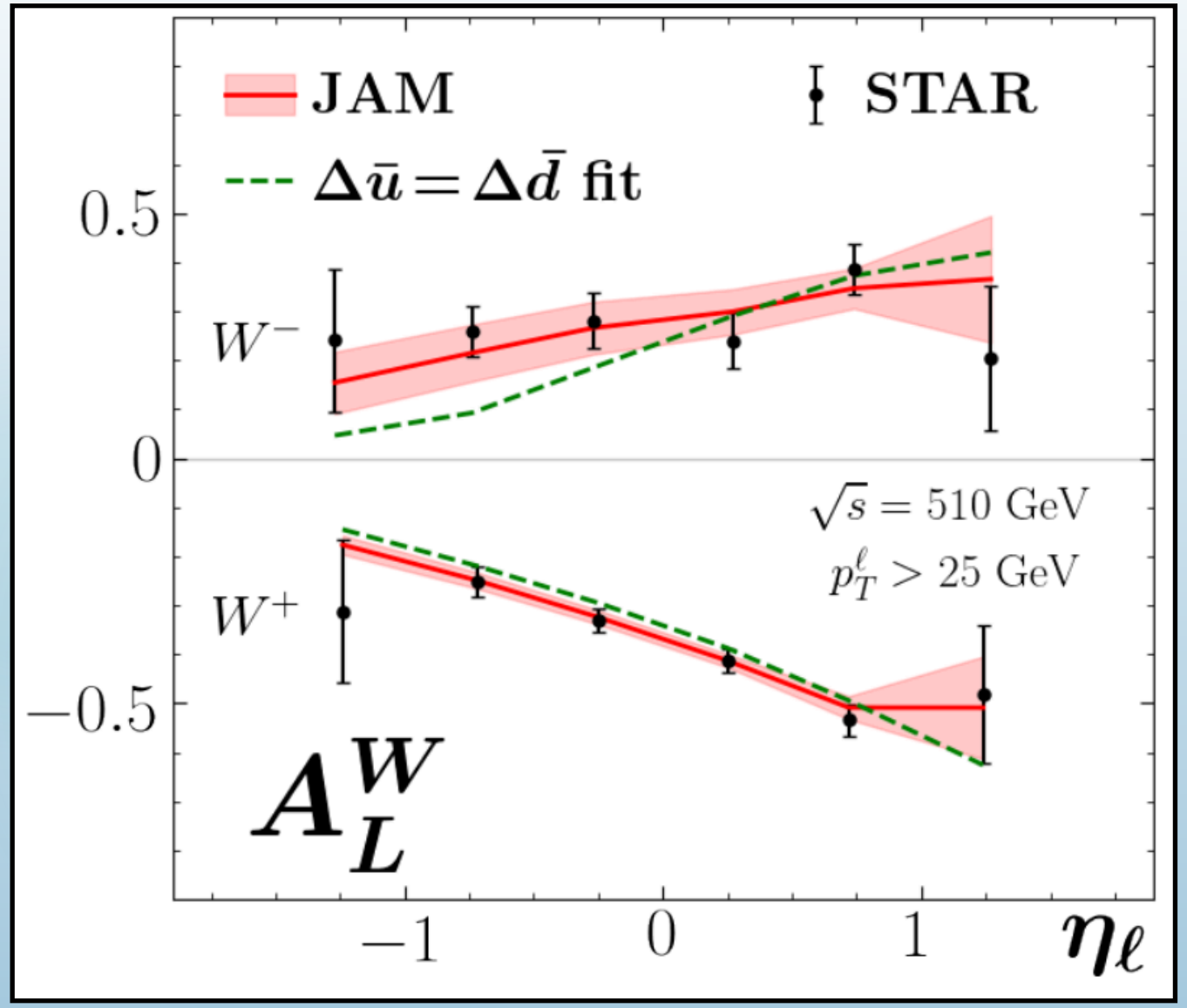
Kinematic Coverage (Helicity)

Deep Inelastic Scattering	COMPASS, EMC, HERMES, SLAC, SMC	365 points
W/Z Boson Production	STAR, PHENIX	18 points
Jets	STAR, PHENIX	61 points



STAR + PHENIX
W/Z Production

STAR Quality of Fit



process	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
polarized		
inclusive DIS	365	0.93
inclusive jets	83	0.81
SIDIS (π^+, π^-)	64	0.93
SIDIS (K^+, K^-)	57	0.36
STAR $W^\pm$	12	0.53
PHENIX $W^\pm/Z$	6	0.63
total	**587**	**0.85**
unpolarized		
inclusive DIS	3908	1.11
inclusive jets	198	1.11
Drell-Yan	205	1.19
W/Z production	153	0.99
total	**4464**	**1.11**
SIA $(\pi^\pm)$	231	0.85
SIA $(K^\pm)$	213	0.49
total	**5495**	**1.05**

$$A_L^{W^+}(y_W) \propto \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_1)u(x_2) + u(x_1)\bar{d}(x_2)}$$

$$A_L^{W^-}(y_W) \propto \frac{\Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

Resulting Asymmetry

Positivity Constraints:
$|\Delta f(x, Q^2)| < f(x, Q^2)$

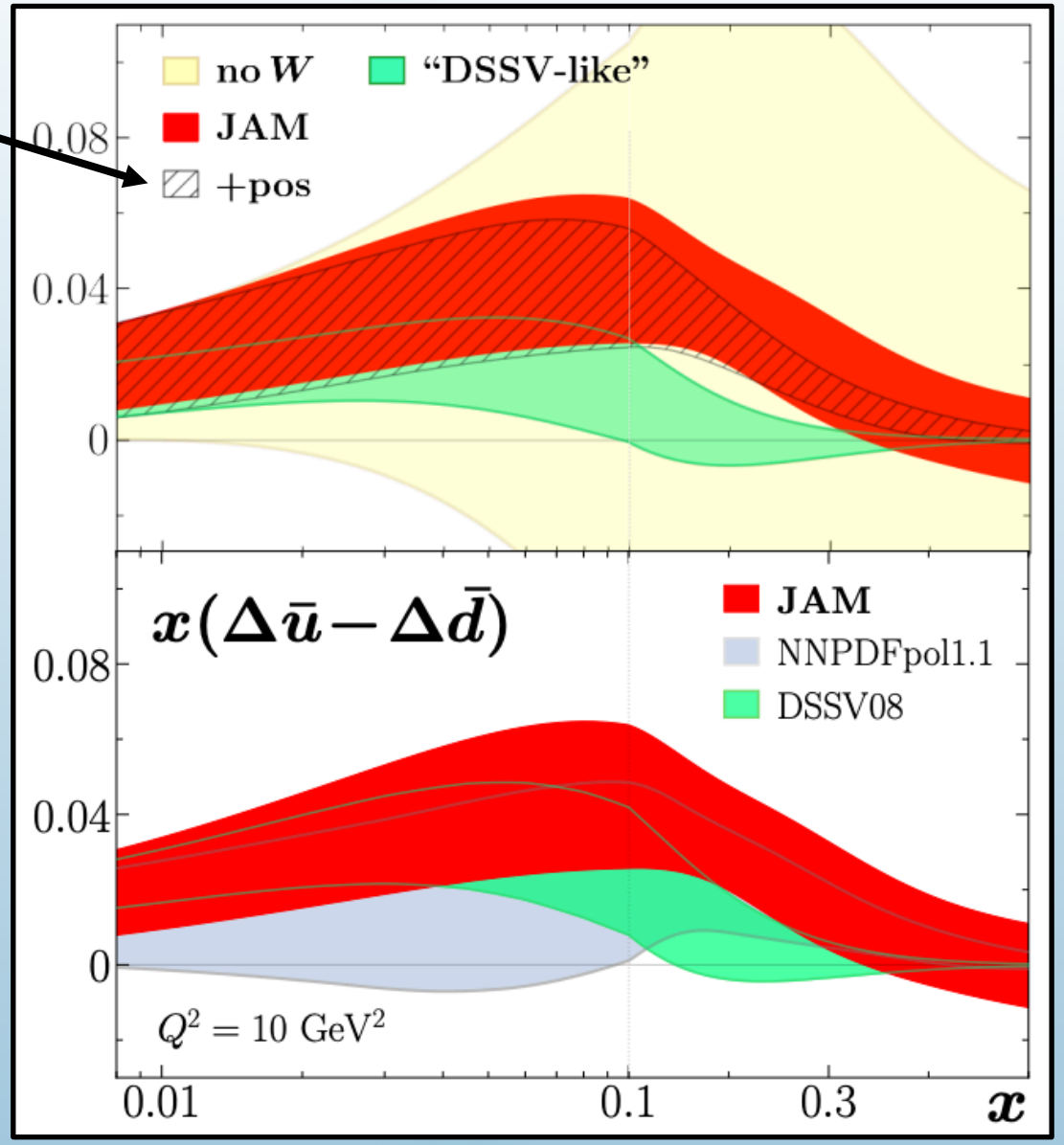
Can $\overline{\text{MS}}$ parton distributions be negative?
Alessandro Candido, Stefano Forte and Felix Hekhorn

Positivity and renormalization of parton densities
John Collins, Ted C. Rogers, Nobuo Sato

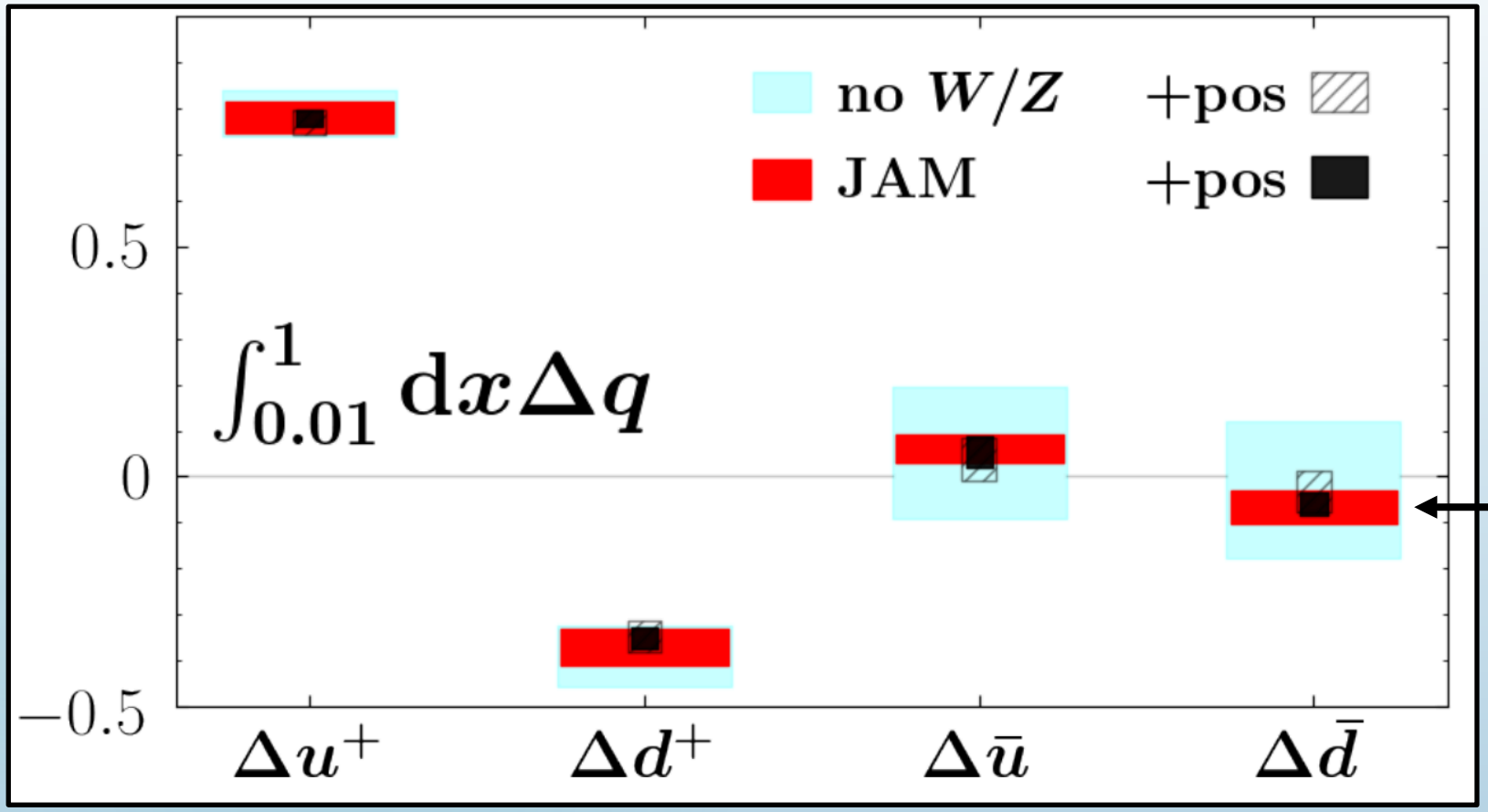
DSSV08 shows positive asymmetry at low $x < 0.1$

NNPDF shows hint of positive asymmetry at intermediate x

Our result is strongly positive in both regions of x



Proton Spin Contributions



Inclusion of RHIC W/Z data shows that $\Delta\bar{u}$ ($\Delta\bar{d}$) contribution is small and positive (negative)

Flavor	JAM moment (truncated)	Lattice Moment (full)	Difference
Δu^+	0.779(34)	0.864(16)	0.085
Δd^+	-0.370(40)	-0.426(16)	0.056

C. Alexandrou *et al.*, Phys. Rev. D **101**, 094513 (2020).

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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

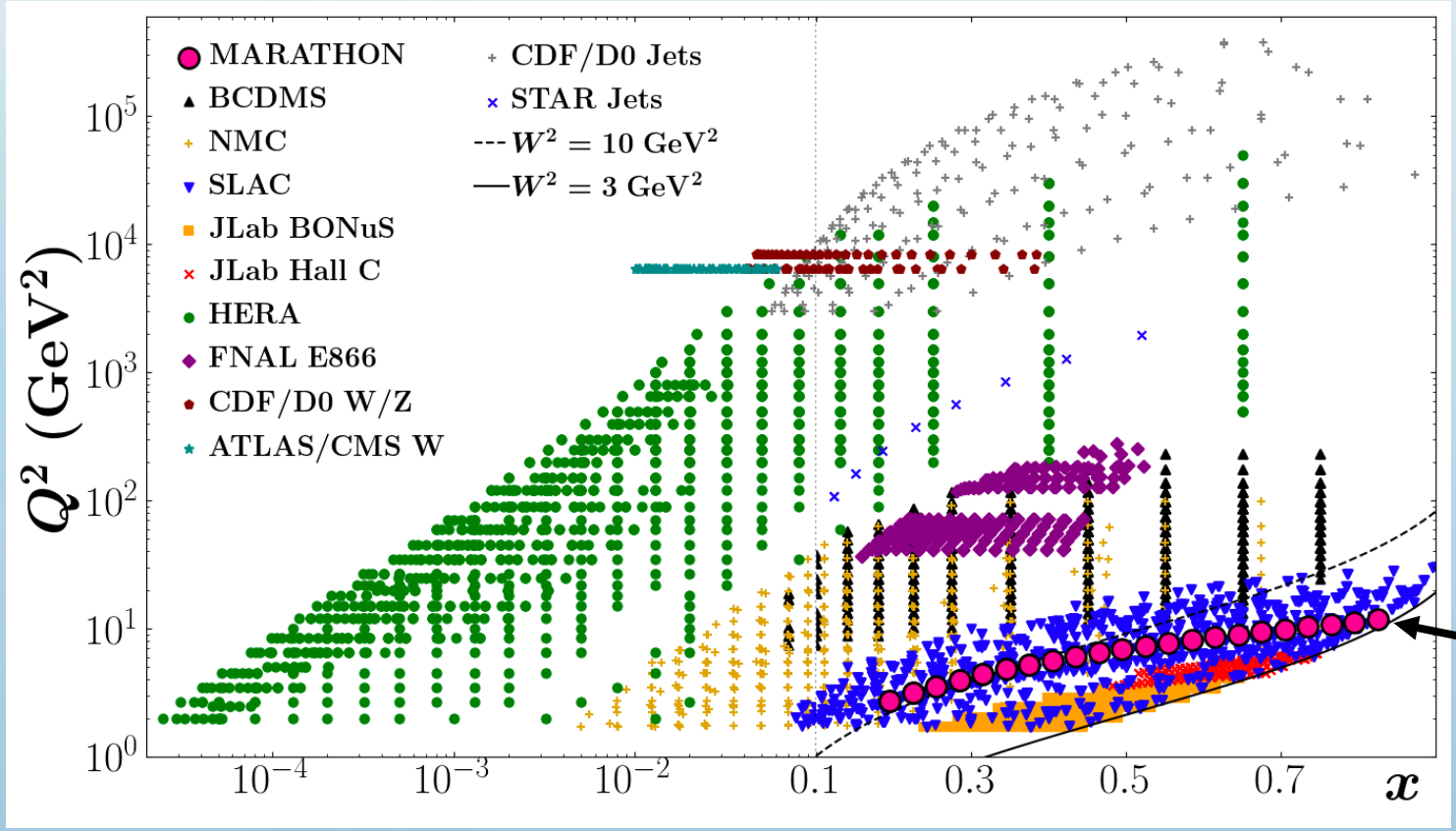
We report the results of a Monte Carlo global QCD analysis of unpolarized parton distribution functions (PDFs), including for the first time constraints from ratios of ^{3}He to ^{3}H structure functions recently obtained by the MARATHON experiment at Jefferson Lab. Our simultaneous analysis of nucleon PDFs and nuclear effects in $A = 2$ and $A = 3$ nuclei reveals the first indication for an isovector nuclear EMC effect in light nuclei. We find that while the MARATHON data yield relatively weak constraints on the F_2^n/F_2^p neutron to proton structure function ratio and on the d/u PDF ratio, they suggest an enhanced nuclear effect on the d-quark PDF in the bound proton, questioning the assumptions commonly made in nuclear PDF analyses.

https://arxiv.org/abs/2104.06946

C. Cocuzza *et al.*, Phys. Rev. Lett. **127**, no. 24, 242001 (2021).

Kinematic Coverage

Deep Inelastic Scattering	BCDMS, NMC, SLAC, HERA, Jefferson Lab	3863	points
Drell-Yan	Fermilab E866	250	points
W/Z Boson Production	Tevatron CDF/D0, LHC ATLAS/CMS	239	points
Jets	Tevatron CDF/D0, RHIC STAR	196	points



New MARATHON data

Isospin Symmetry

How to relate quarks between protons and neutrons?

It is usually approximated that:

$$u_{p/A} \approx d_{n/A}$$

$$d_{p/A} \approx u_{n/A}$$

✓ "Free" nucleon

✓ (Approx.) Symmetric Nuclei (D, ^{56}Fe)

? Asymmetric Nuclei (^{3}He, ^{3}H, ^{197}Au)

Isovector Effect

Mean Field Approximation in the valence region:

Nucleon Momentum

PDF in absence of Vector Potential

Net Vector Field on Quark

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

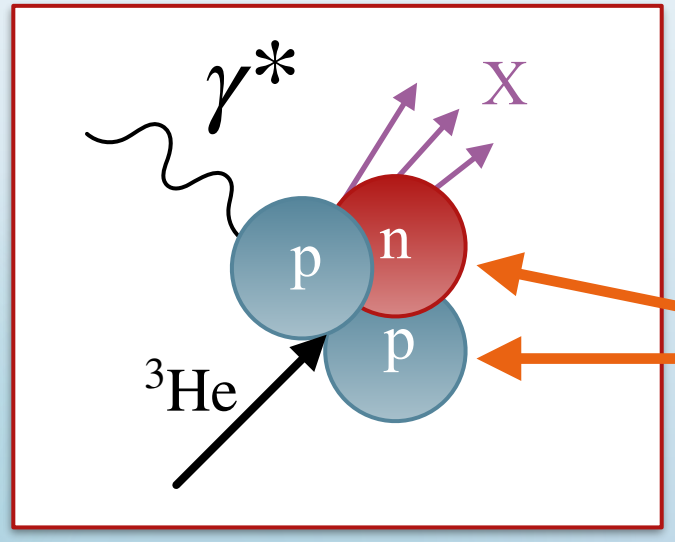
Net Vector Field on Nucleon

H. Mineo *et al.*, Nucl. Phys. A **735**, 482-514 (2004).

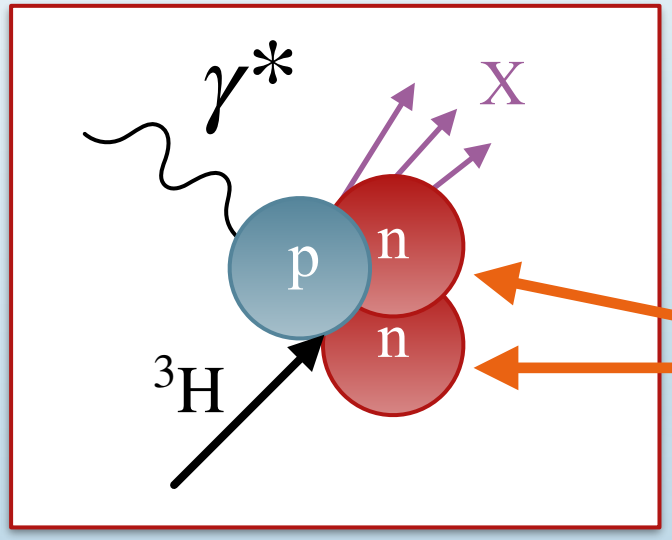
Isovector Effect

I. C. Cloet, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **102**, 252301 (2009).

Mediated by $I_3 = \pm 1$ mesons, dependent on third component of isospin



Spectators $I_3 = 0$



Spectators $I_3 = -1$

Parameterize phenomenologically:

$$\tilde{q}_{N/A}(p^2) = q_N + \nu(p^2)\ \delta q_{N/A} + \ldots$$

Virtuality

$$\nu(p^2) = (p^2 - M^2)/M^2 \ll 1$$

Symmetries

$$(u, d) \times (p, n) \times (D, {}^3\mathrm{He}, {}^3\mathrm{H}) = 12 \text{ Functions}$$

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

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

$$\delta u_{p/{}^3\mathrm{He}} = \delta d_{n/{}^3\mathrm{H}}$$

$$\delta u_{p/{}^3\mathrm{H}} = \delta d_{n/{}^3\mathrm{He}}$$

$$\delta d_{p/{}^3\mathrm{He}} = \delta u_{n/{}^3\mathrm{H}}$$

$$\delta d_{p/{}^3\mathrm{H}} = \delta u_{n/{}^3\mathrm{He}}$$

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

$$\delta u$$

$$\delta d$$

No Isovector

$$(\delta u + 2\delta d)/2$$

Just two functions!

Nuclear PDFs

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

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

Contains Virtuality

$$\nu(p^2) = (p^2 - M^2)/M^2 \ll 1$$

$$\Delta_3^u \equiv \frac{u_{p/^3\mathrm{H}} - d_{n/^3\mathrm{H}}}{u_{p/^3\mathrm{H}} + d_{n/^3\mathrm{H}}}$$

$$\Delta_3^d \equiv \frac{d_{p/^3\mathrm{H}} - u_{n/^3\mathrm{H}}}{d_{p/^3\mathrm{H}} + u_{n/^3\mathrm{H}}}$$

Measures strength of isovector effect

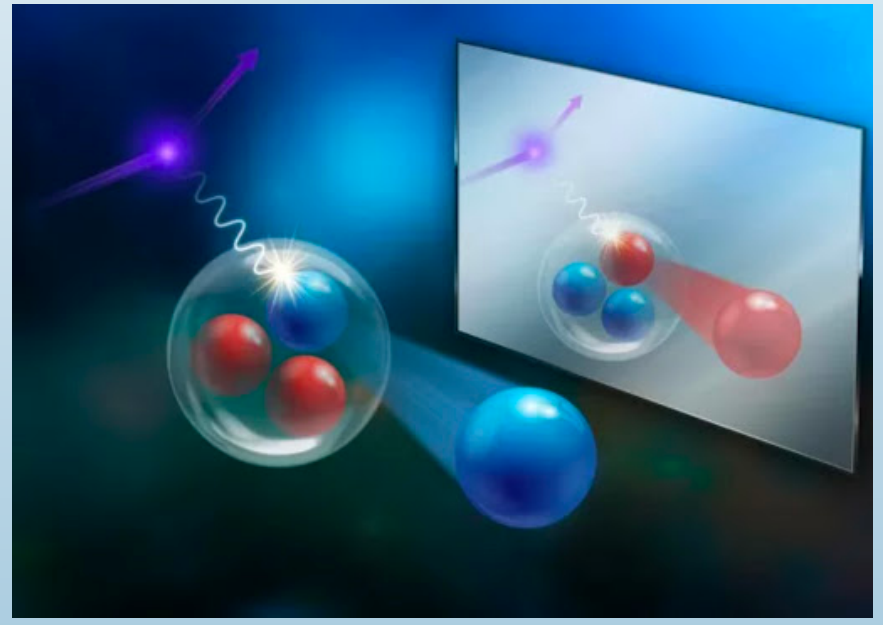
Impact from MARATHON

MeAsurement of the F_2^n/F_2^p, d/u **RA**tios and $A = 3$ EMC Effect in Deep Inelastic Electron Scattering Off the **T**ritium and **H**elium Mirr**O**r **N**uclei

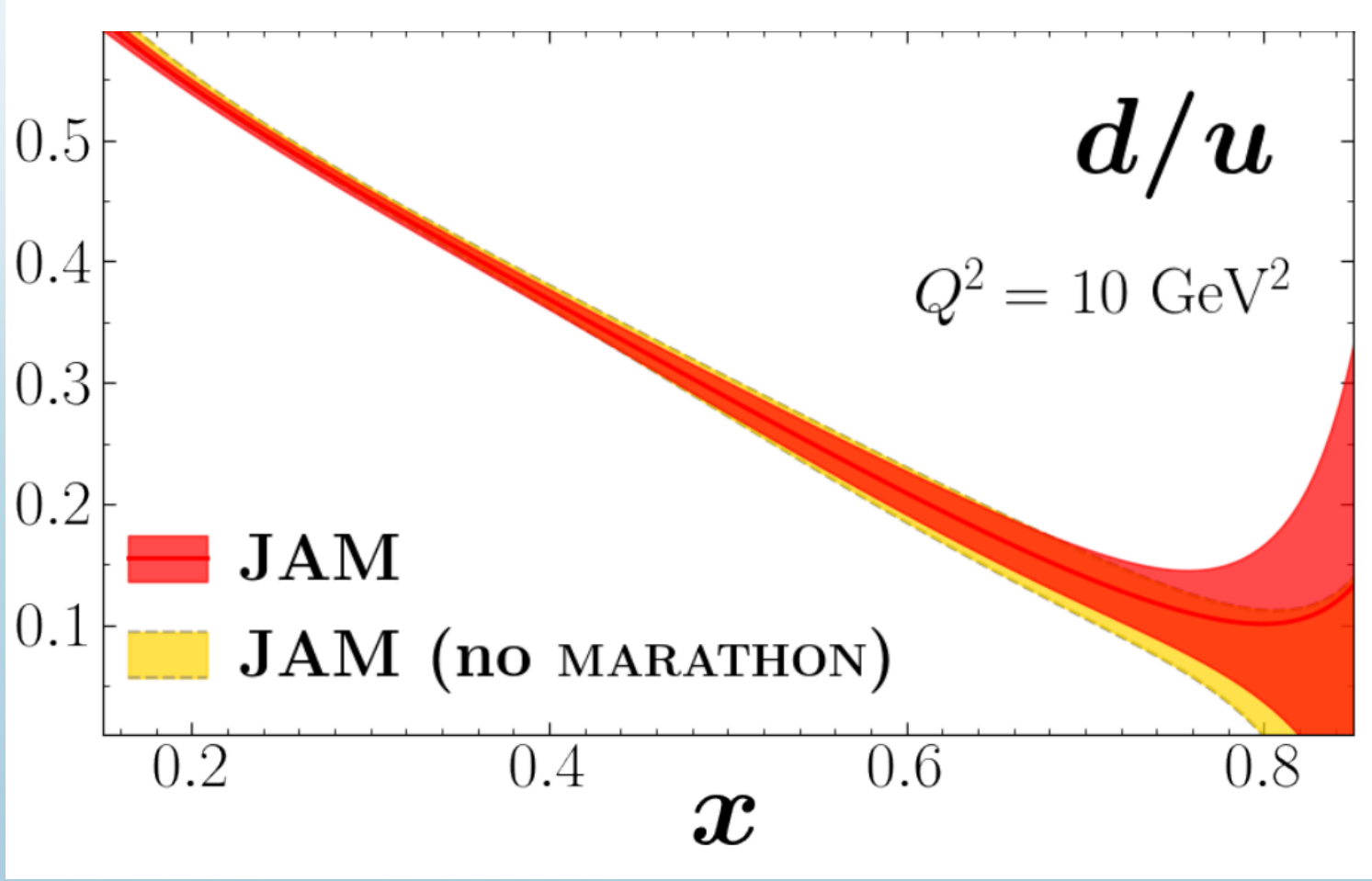
d/u Ratio ?

F_2^n/F_2^p Ratio ?

$A = 3$ EMC Effects ?

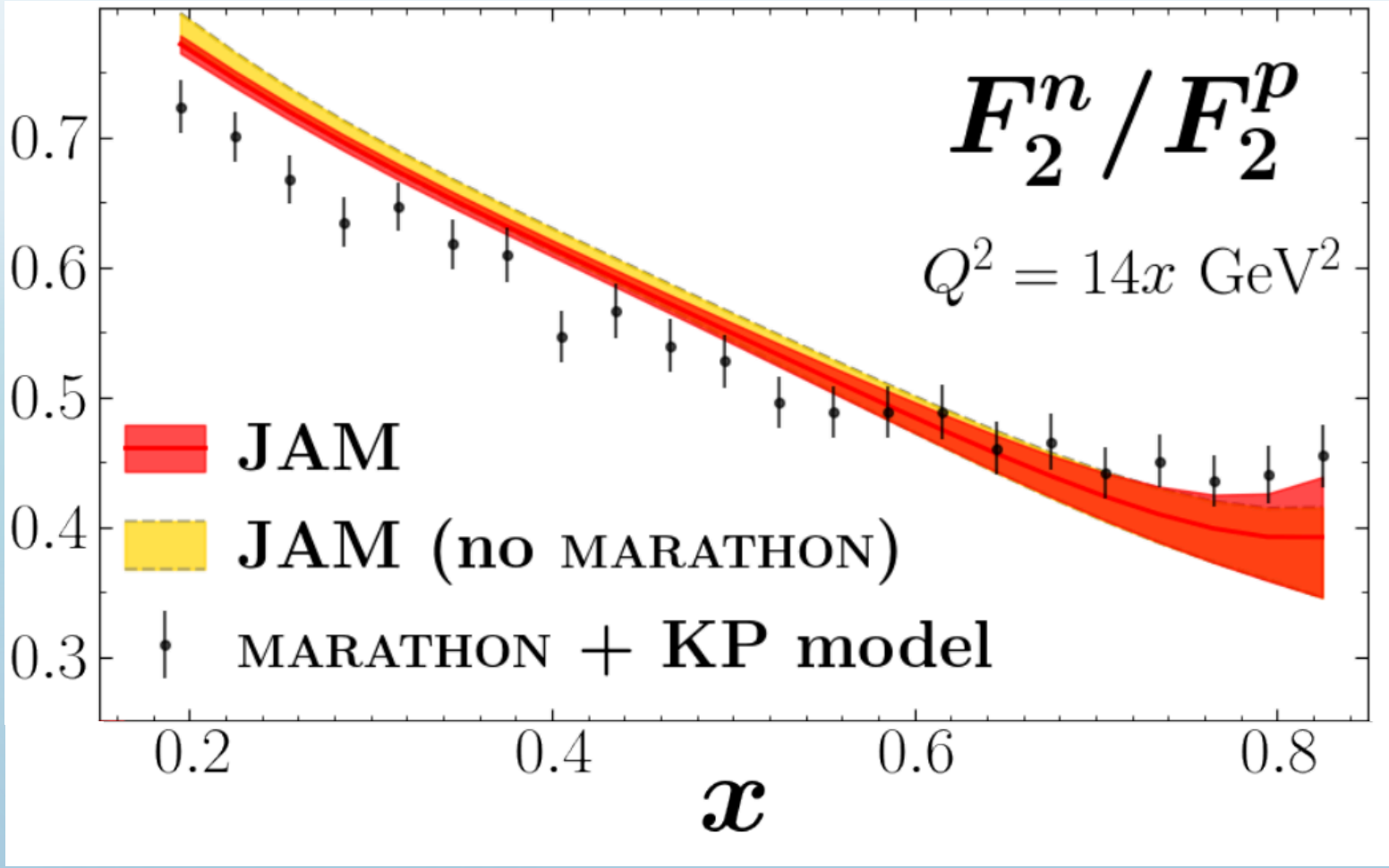


Impact on d/u



d/u ratio largely constrained by W boson production data (mostly Tevatron)

Impact on F_2^n/F_2^p



Slight shift towards MARATHON + KP model result

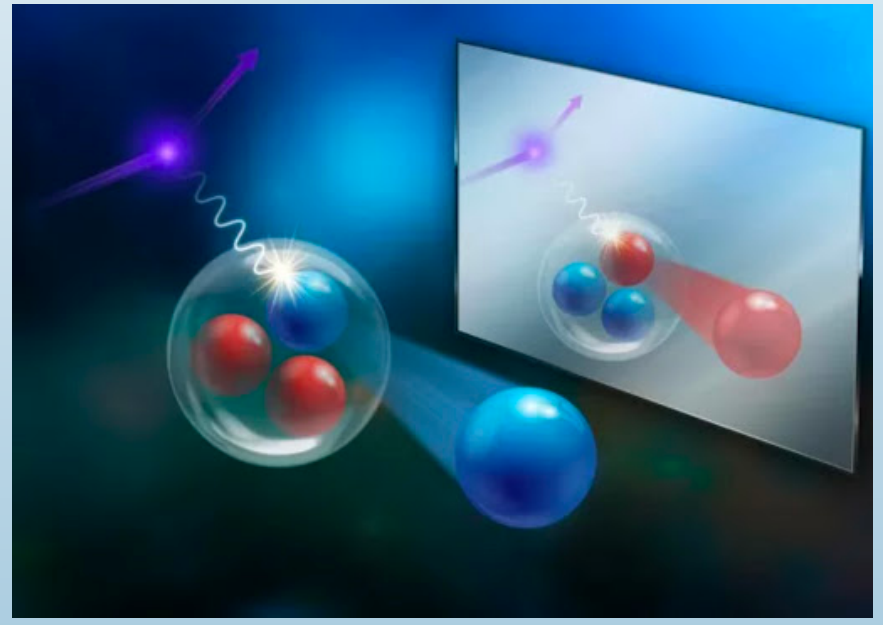
Impact from MARATHON

Me**A**surement of the F_2^n/F_2^p, d/u **RA**tios and $A = 3$ EMC Effect in Deep Inelastic Electron Scattering Off the **T**ritium and **H**elium Mirr**O**r **N**uclei

d/u Ratio ≈

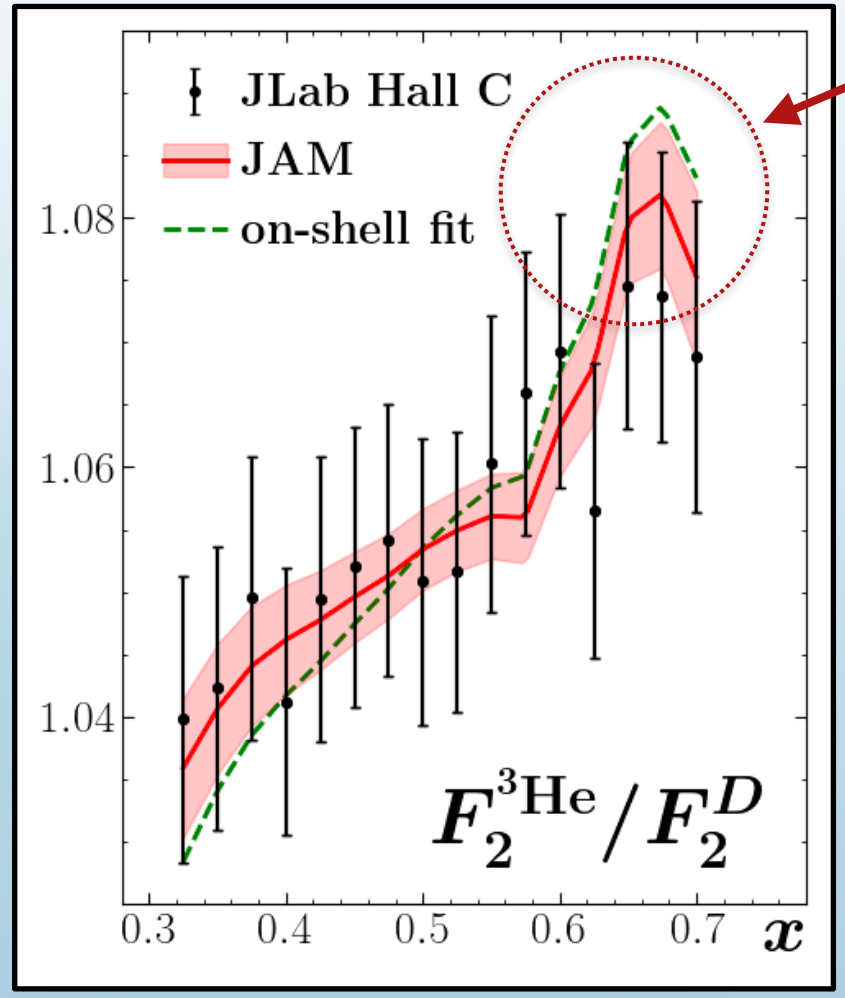
F_2^n/F_2^p Ratio ≈

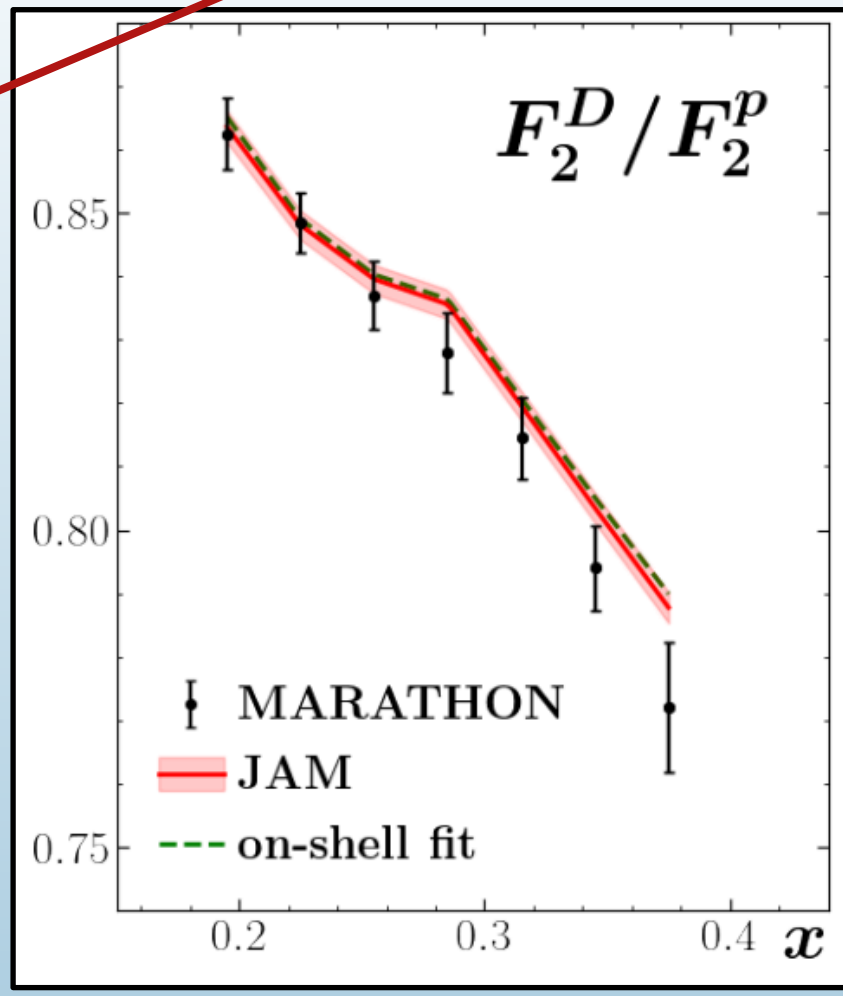
$A = 3$ EMC Effects ?

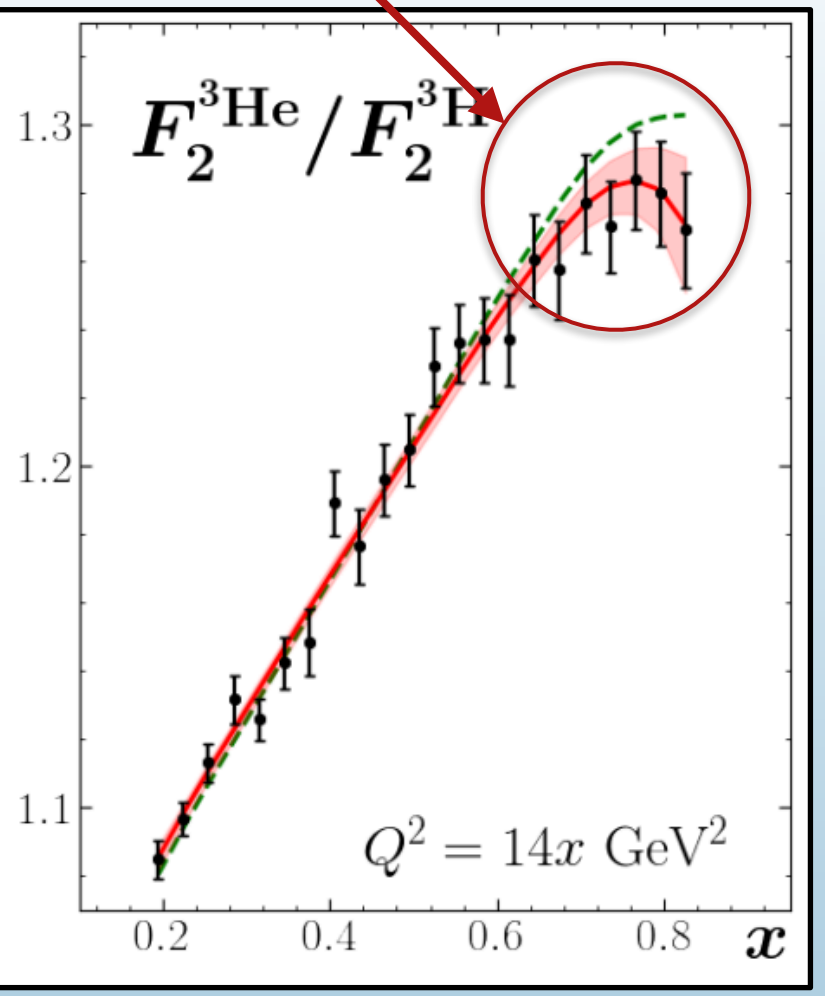


Data vs. Theory

Suggestion of off-shell effects!







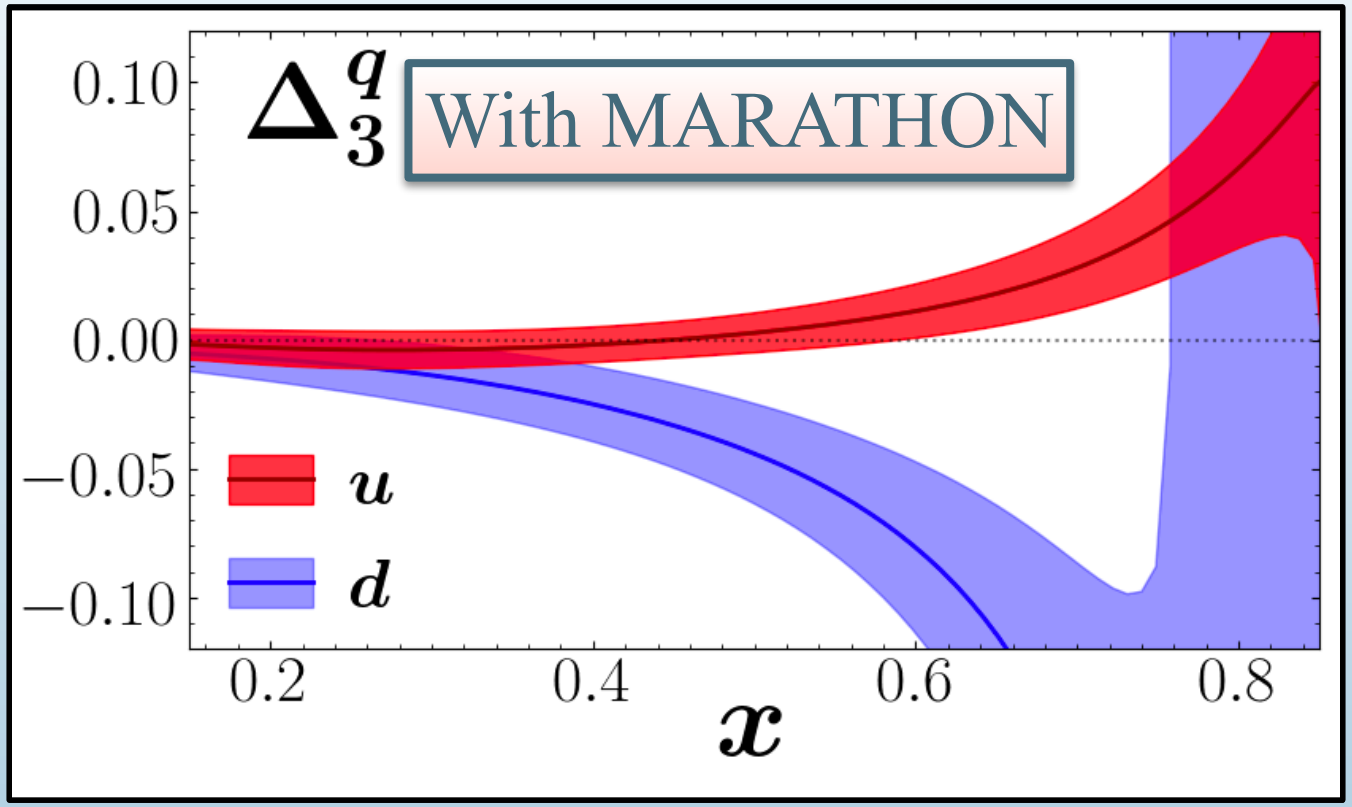
First global QCD analysis of JLab ^{3}He/D and MARATHON data

Isovector Extraction

$$\Delta_3^u \equiv \frac{u_{p/^3\mathrm{H}} - d_{n/^3\mathrm{H}}}{u_{p/^3\mathrm{H}} + d_{n/^3\mathrm{H}}}$$

$$\Delta_3^d \equiv \frac{d_{p/^3\mathrm{H}} - u_{n/^3\mathrm{H}}}{d_{p/^3\mathrm{H}} + u_{n/^3\mathrm{H}}}$$

Signal for non-zero effect above $x \gtrsim 0.4$!



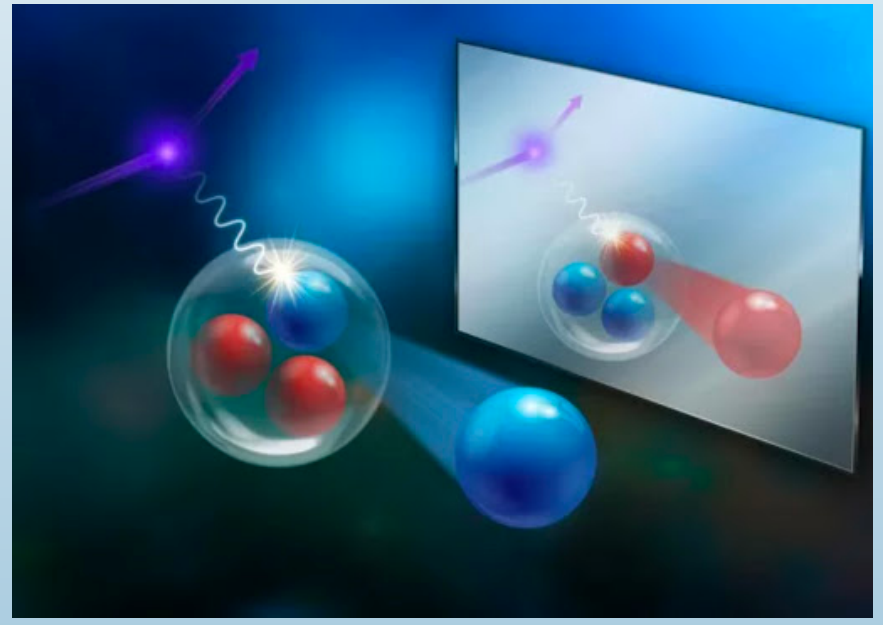
Impact from MARATHON

MeAsurement of the F_2^n/F_2^p, d/u **RA**tios and $A = 3$ EMC Effect in Deep Inelastic Electron Scattering Off the **T**ritium and **H**elium Mirr**O**r **N**uclei

d/u Ratio ≈

F_2^n/F_2^p Ratio ≈

$A = 3$ EMC Effects ✓



Isospin Symmetry

How to relate quarks between protons and neutrons?

It is usually approximated that:

$$u_{p/A} \approx d_{n/A}$$

$$d_{p/A} \approx u_{n/A}$$

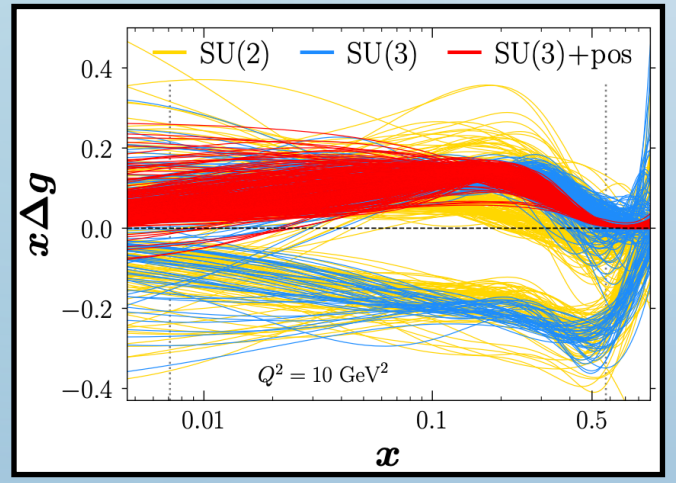
But the correct equations are:

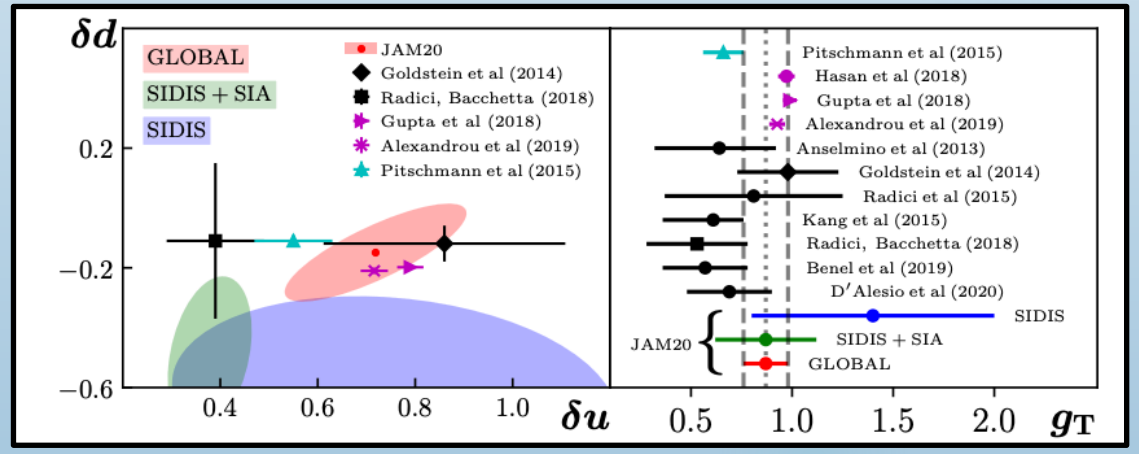
$$u_{p/A} = d_{n/A*}$$

$$d_{p/A} = u_{n/A*}$$

where $A*$ is the mirror nuclei of A

1. Introduction
2. Spin-Averaged Sea Asymmetry
3. Helicity Sea Asymmetry
4. Isovector Nuclear Effects
5. Other JAM Results





Gluon Polarization (2021)

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

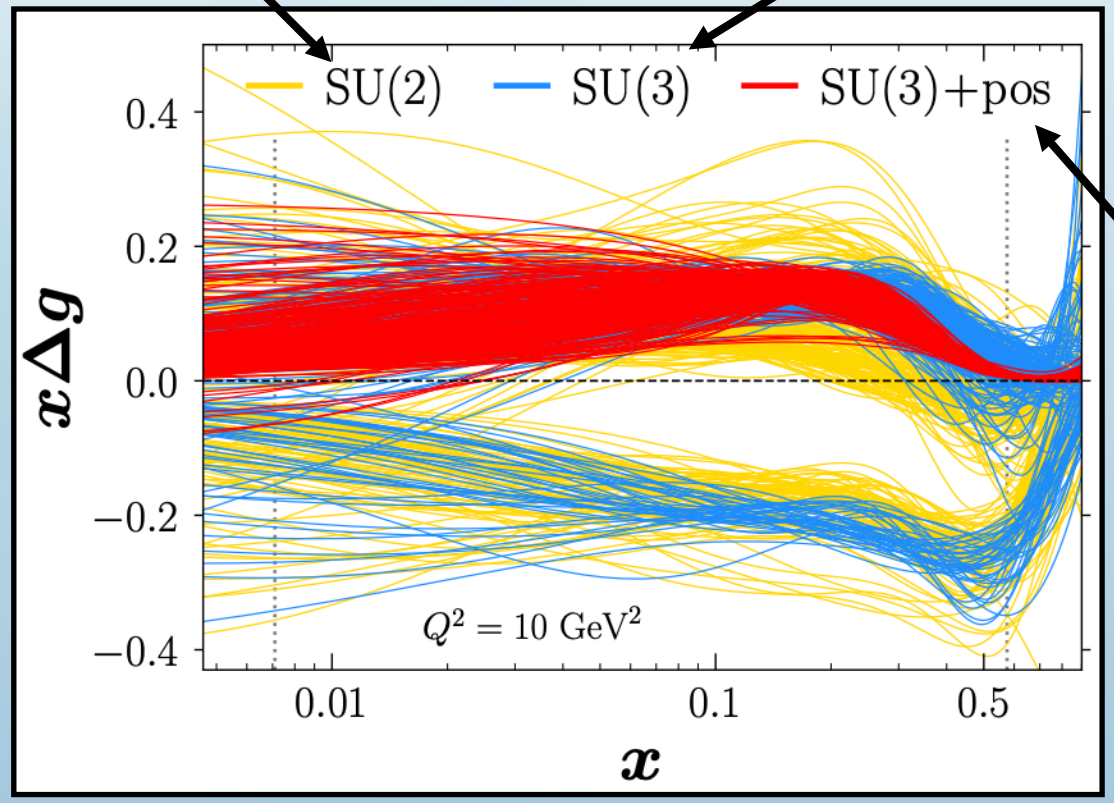
Y. Zhou, N. Sato, W. Melnitchouk

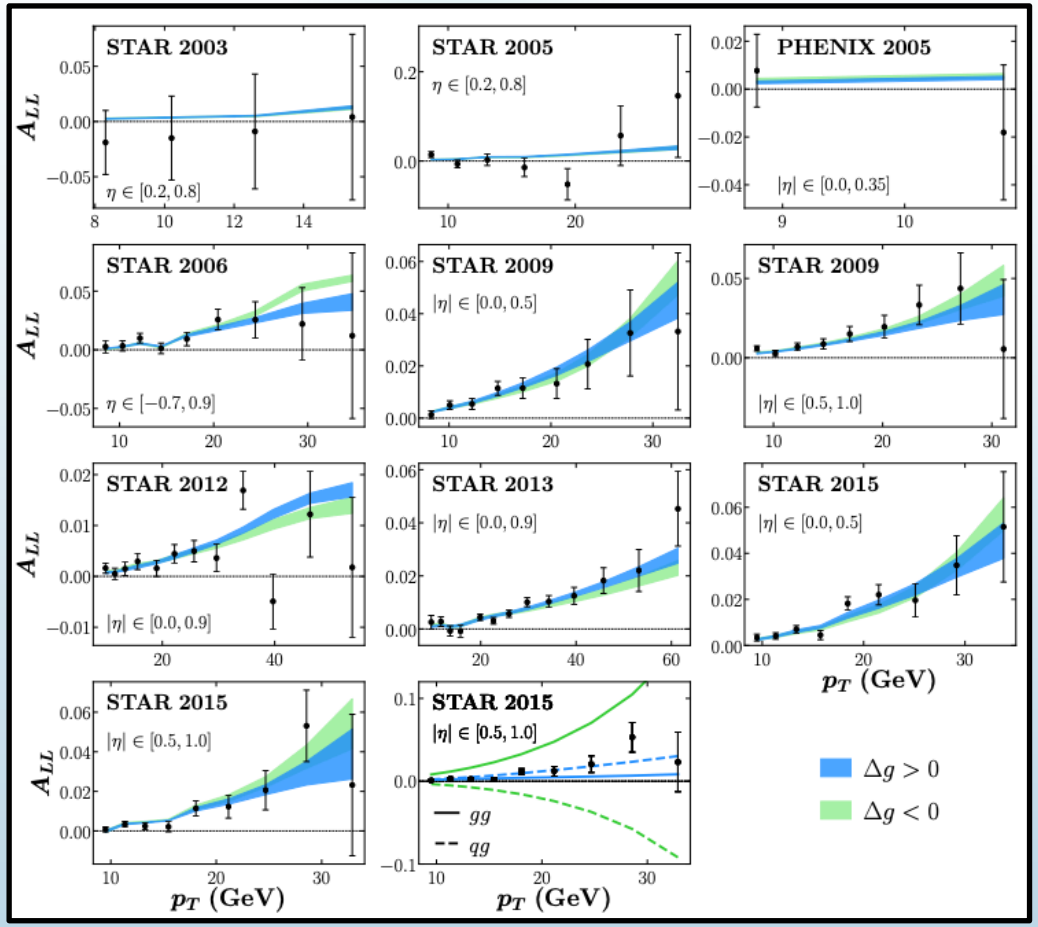
https://arxiv.org/abs/2201.02075

Y. Zhou *et al.*, Phys. Rev. D **105**, no. 7, 074022 (2022).

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

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





$$|\Delta f(x, Q^2)| < f(x, Q^2)$$

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

Alessandro Candido, Stefano Forte and Felix Hekhorn

Positivity and renormalization of parton densities

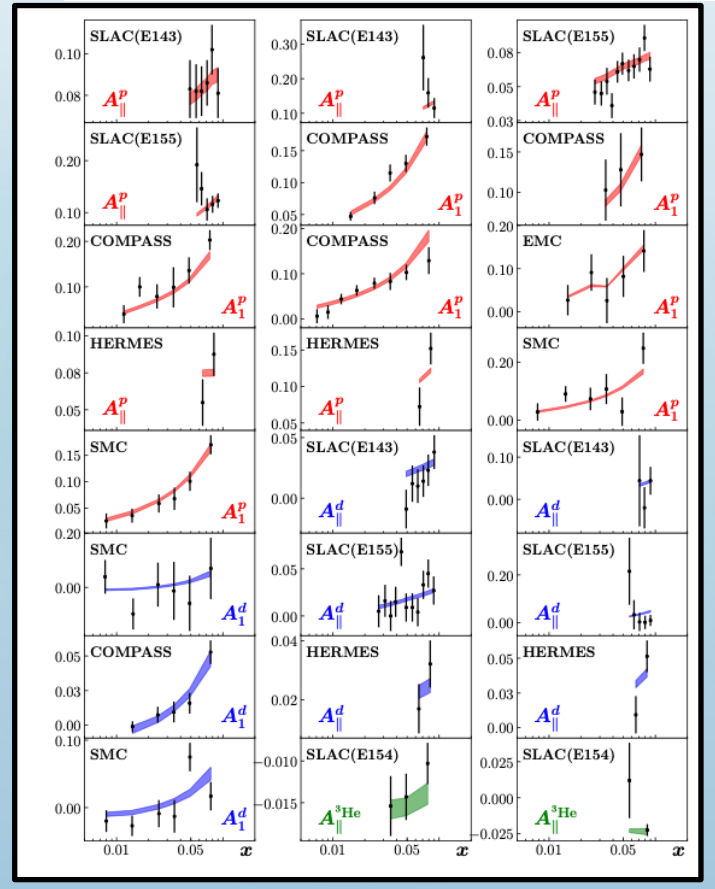
John Collins, Ted C. Rogers, Nobuo Sato

Small x Global Analysis (2021)

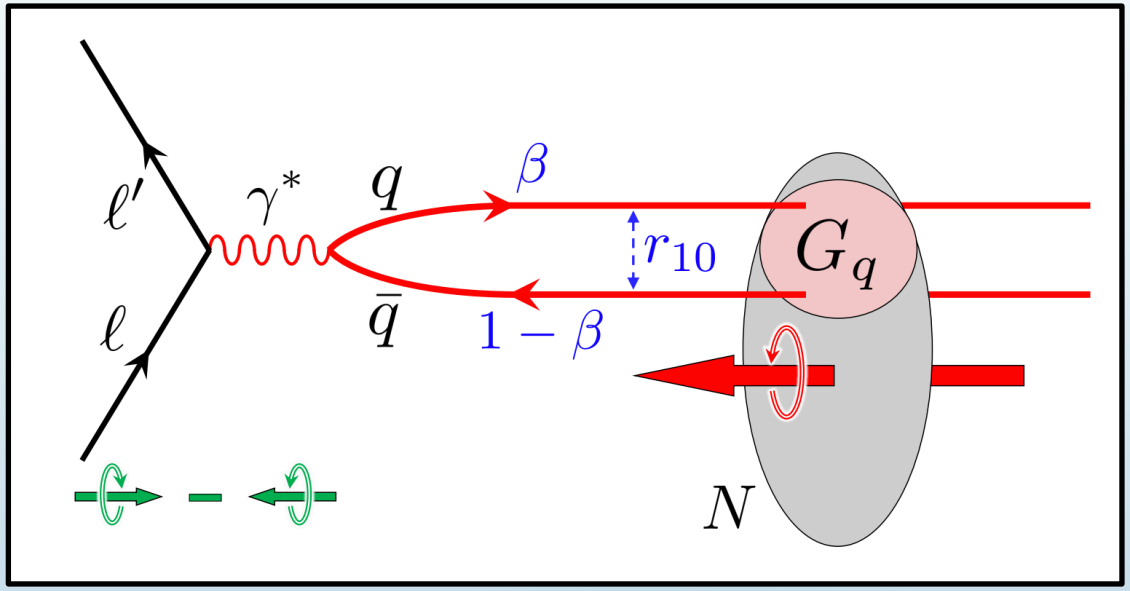
First analysis of world polarized DIS data with small-x helicity evolution

Daniel Adamiak,[1,*] Yuri V. Kovchegov,[1,†] W. Melnitchouk,[2]
Daniel Pitonyak,[3,‡] Nobuo Sato,[2,§] and Matthew D. Sievert[4,¶]

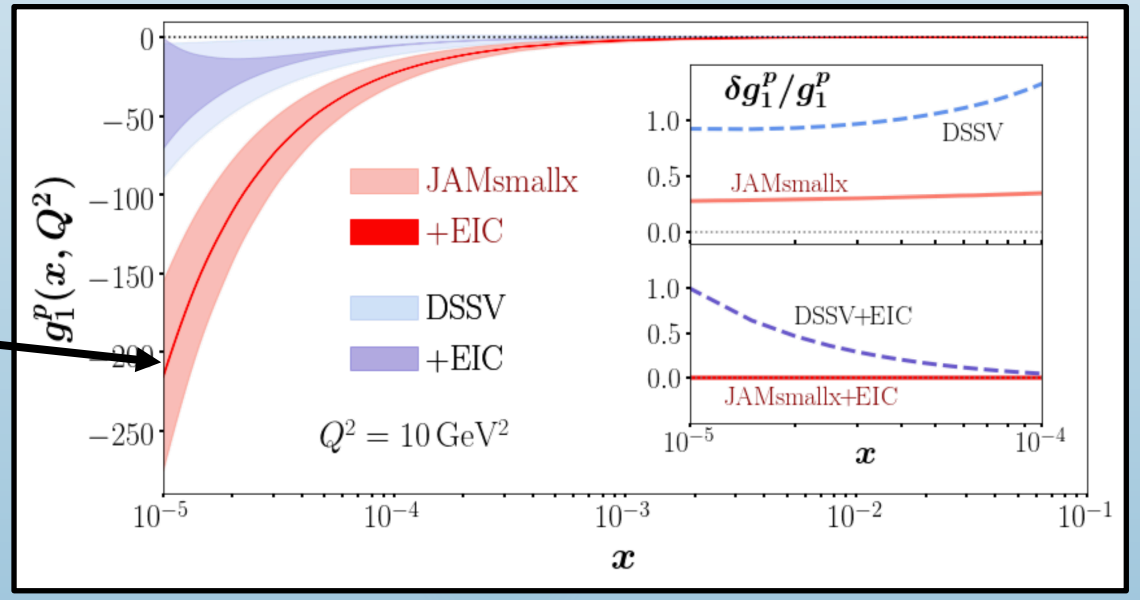
https://arxiv.org/abs/2102.06159
D. Adamiak *et al.*, Phys. Rev. D **104**, no. 3, L031501 (2021).



$x < 0.1$



Prediction, not extrapolation!



Transversity JAM20 (2020)

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

Justin Cammarota, Leonard Gamberg, Zhong-Bo Kang, Joshua A. Miller, Daniel Pitonyak, Alexei Prokudin, Ted C. Rogers, Nobuo Sato

https://arxiv.org/abs/2002.08384
J. Cammarota *et al.*, Phys. Rev. D. **102**, no. 5, 054002 (2020).

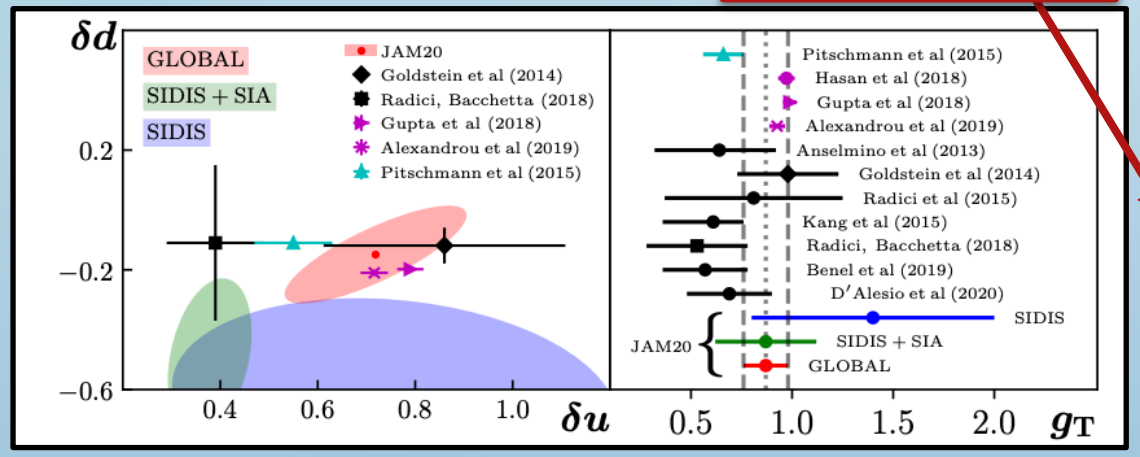
Transversity PDF

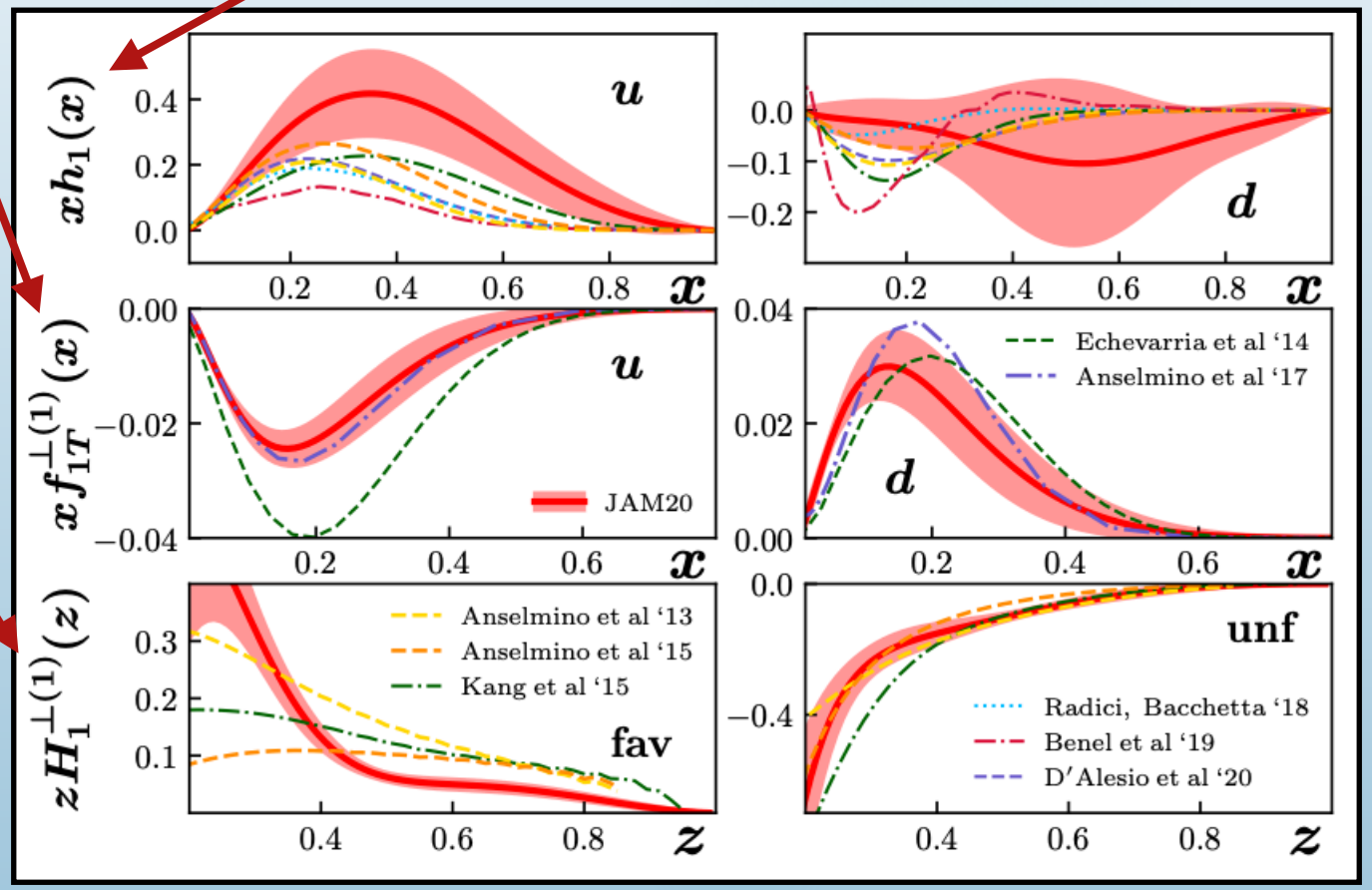
Sivers function (moment)

Collins function (moment)

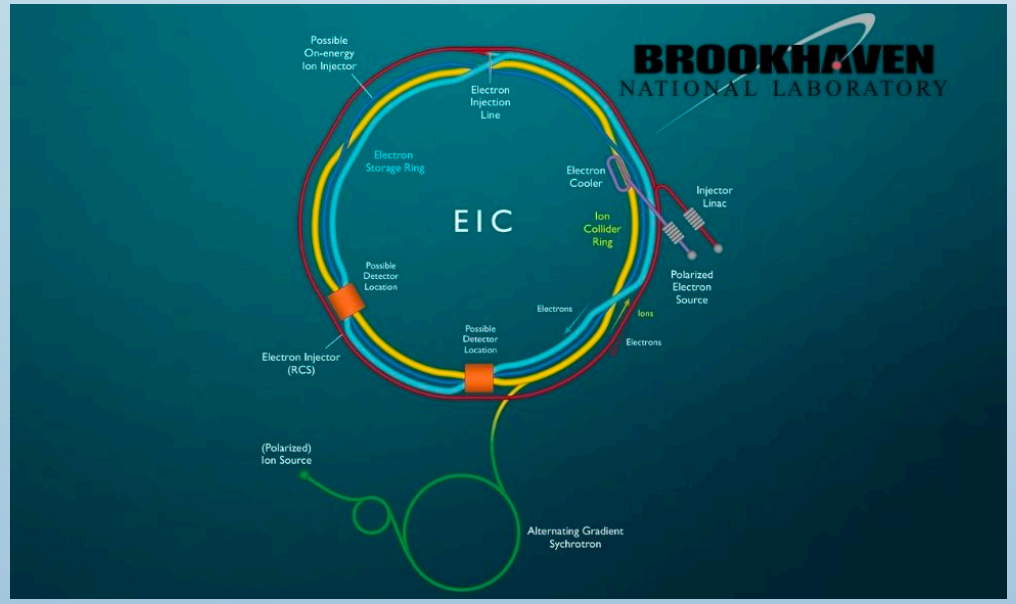
$$\delta q \equiv \int_0^1 dx[h_1^q(x) - h_1^{\bar{q}}(x)]$$

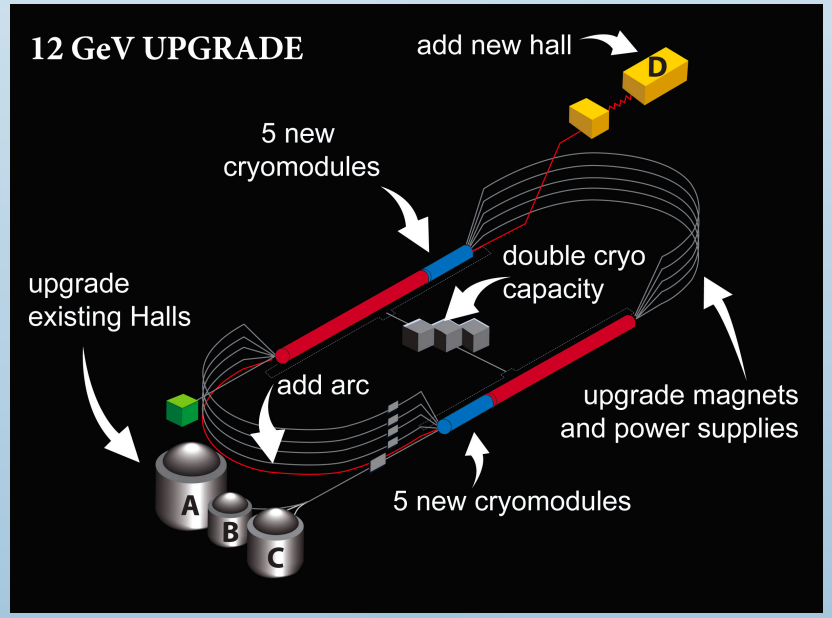
$$g_T \equiv \delta u - \delta d$$





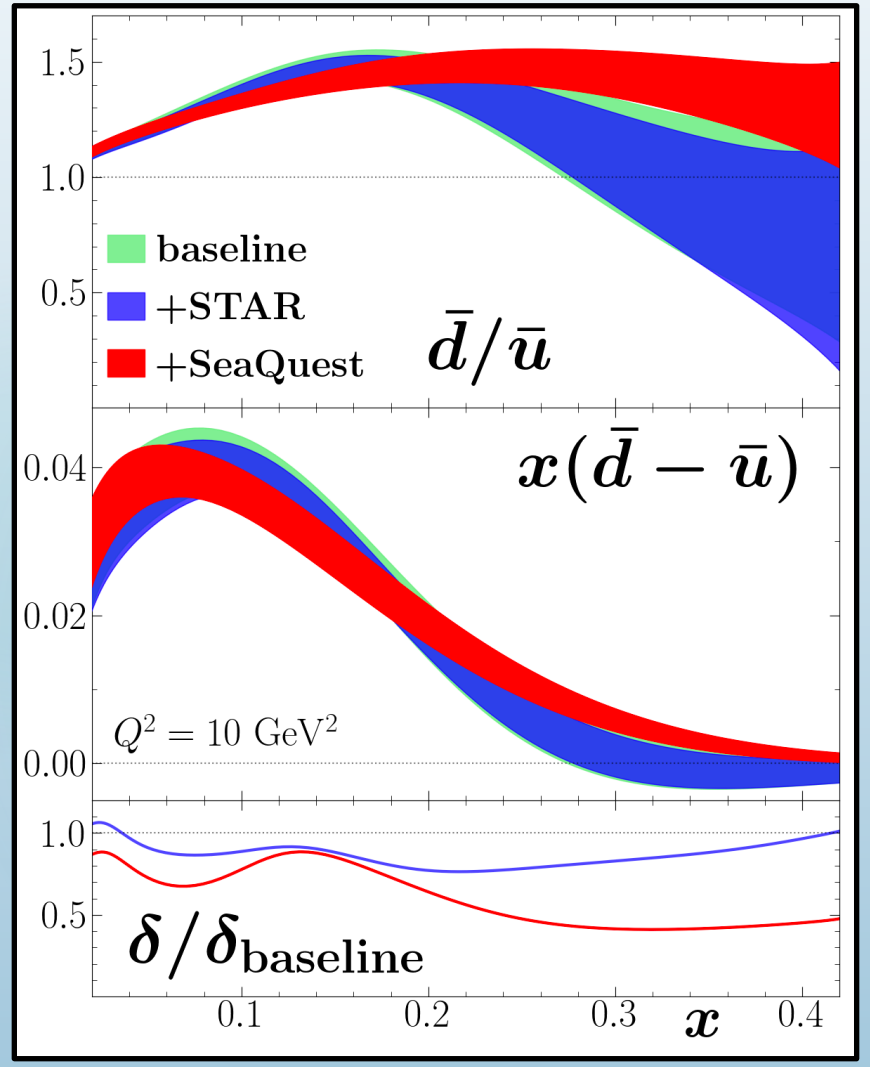
Summary and Outlook



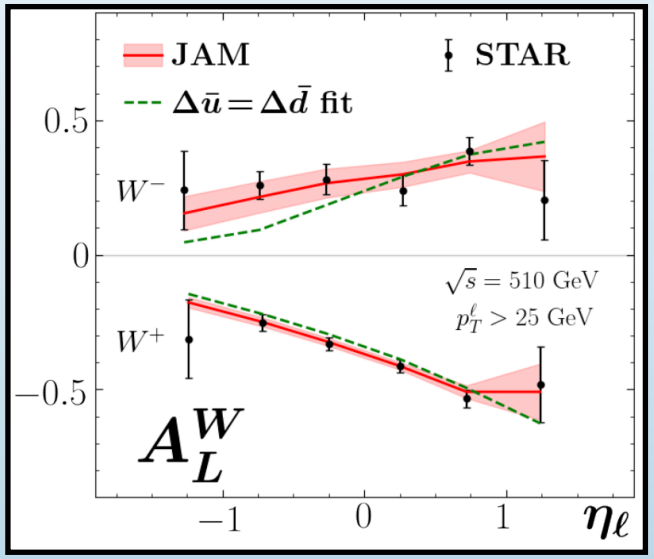


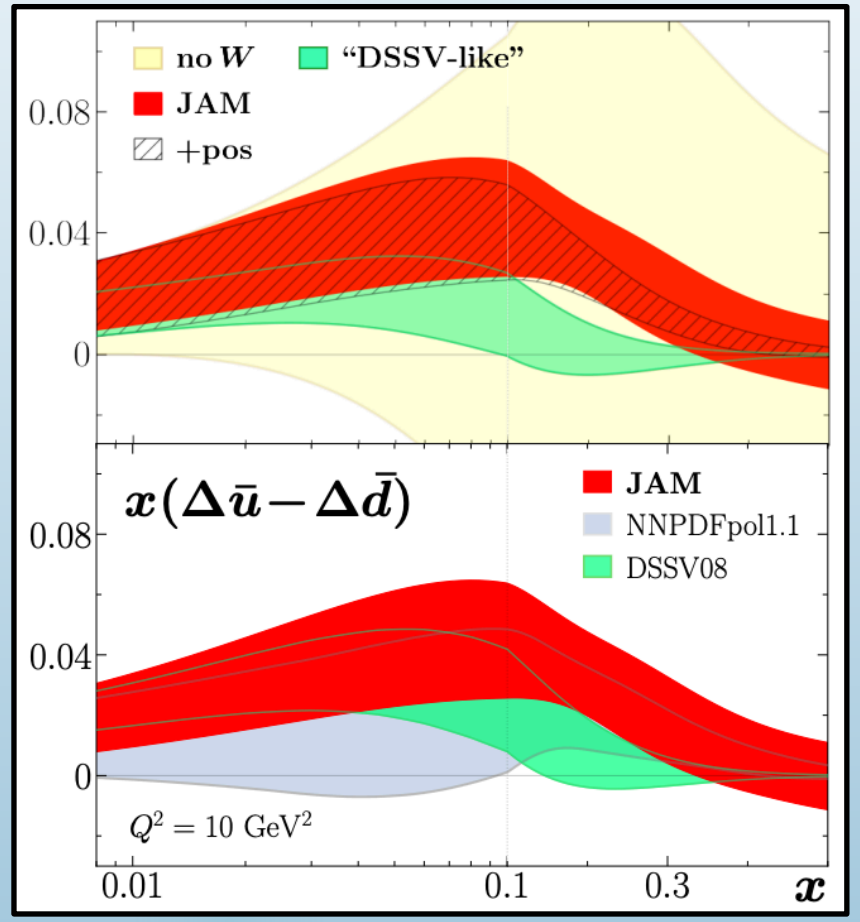
Sea Asymmetries

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



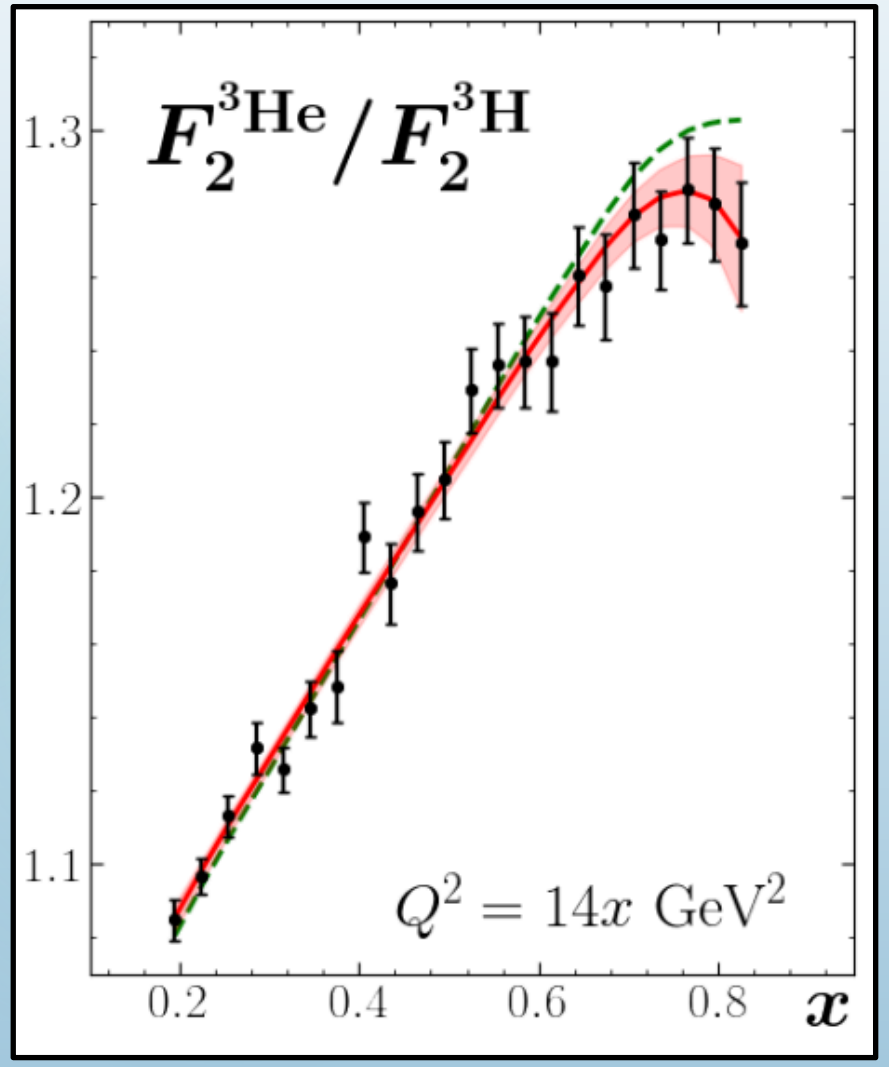
Polarized Antimatter in the Proton from Global QCD Analysis

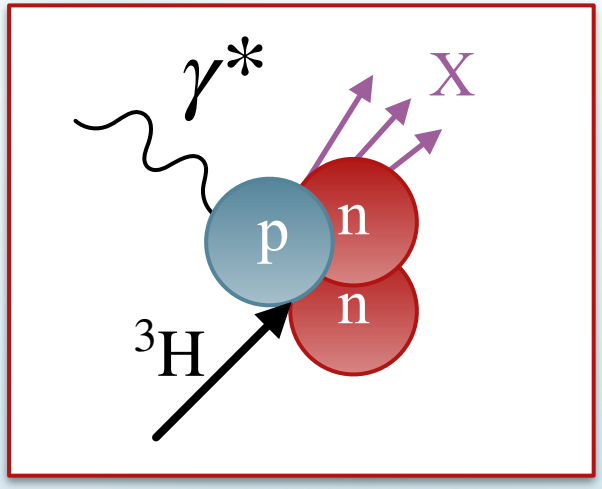


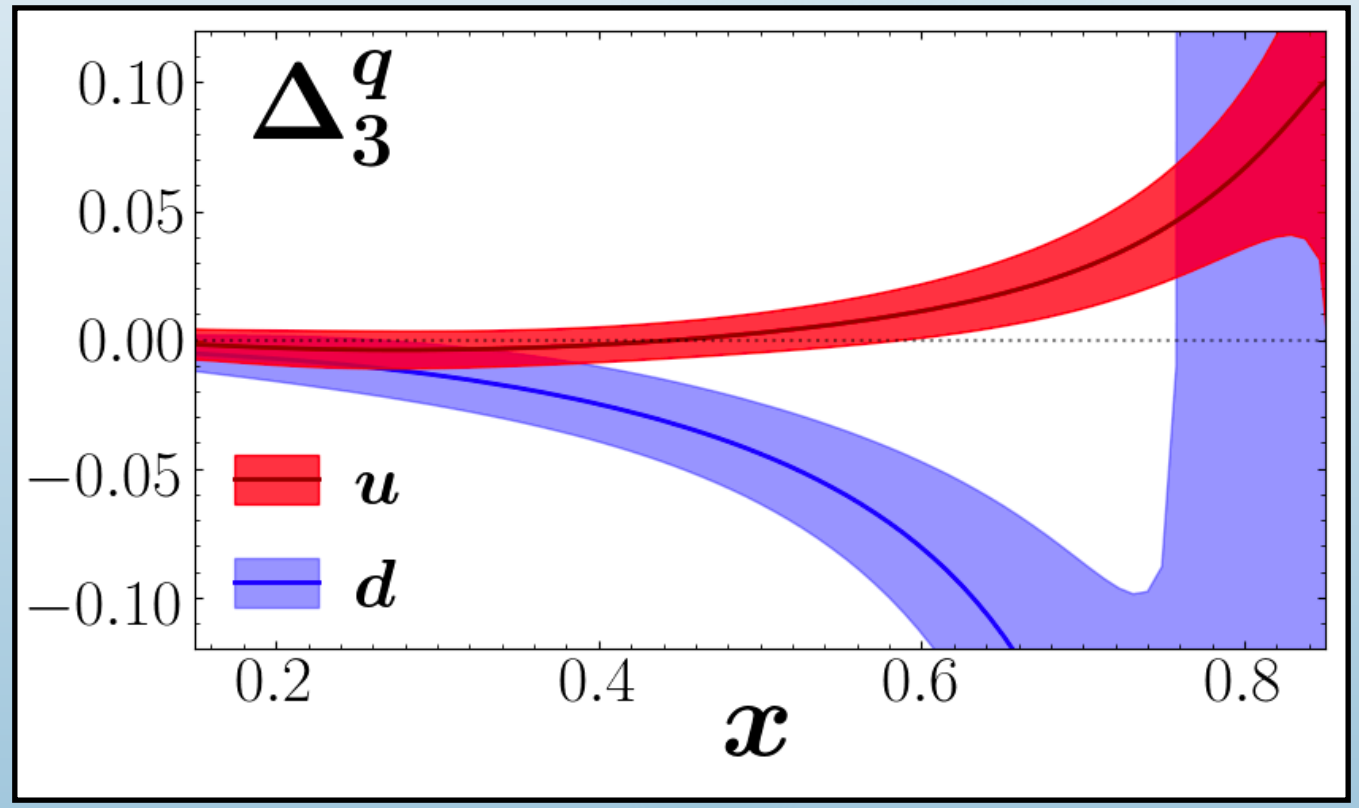


Isovector EMC Effect

Isovector EMC effect from global QCD analysis with MARATHON data

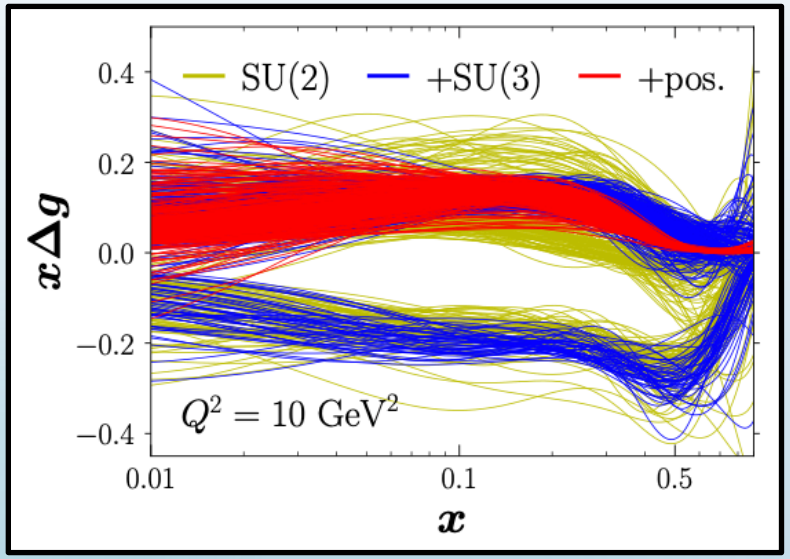




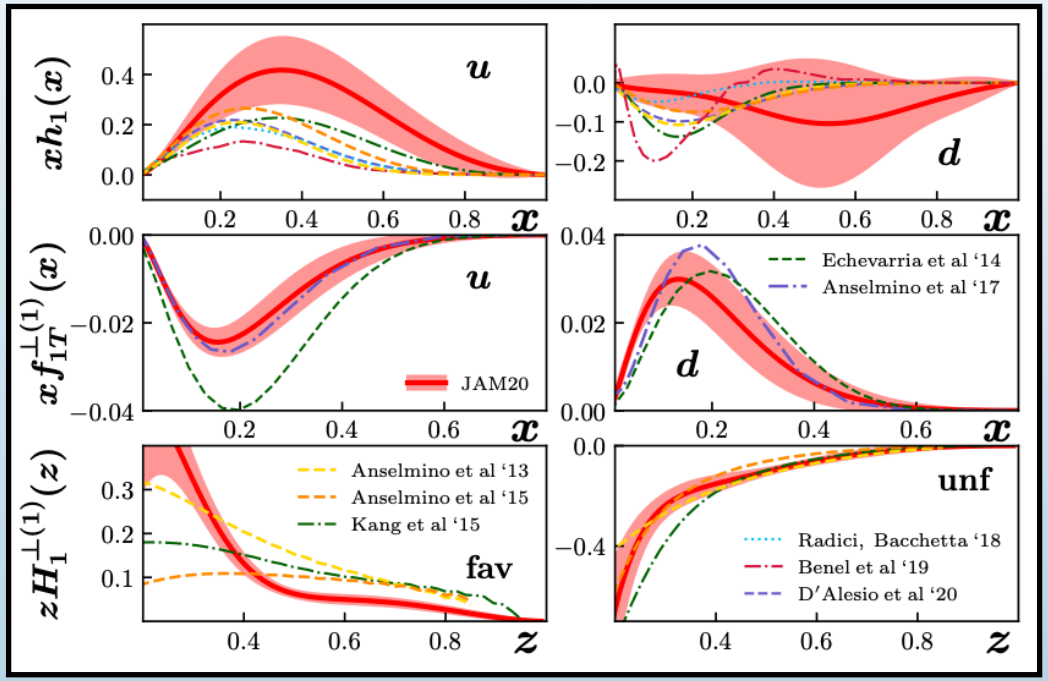


More JAM Results

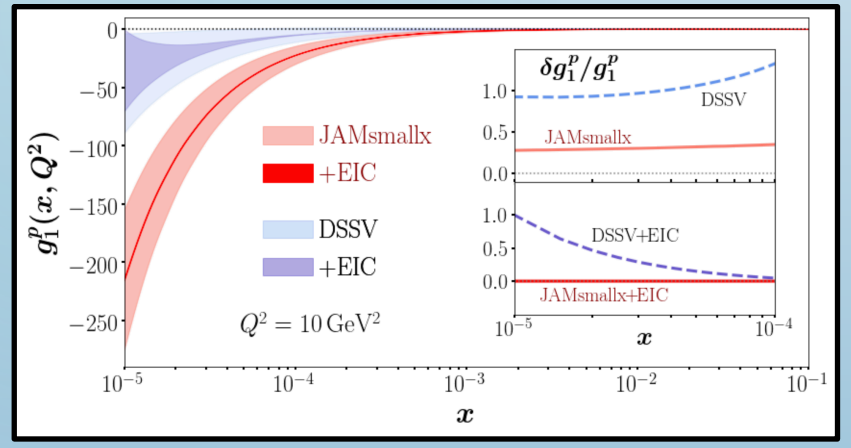
How well do we know the gluon polarization in the proton?



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



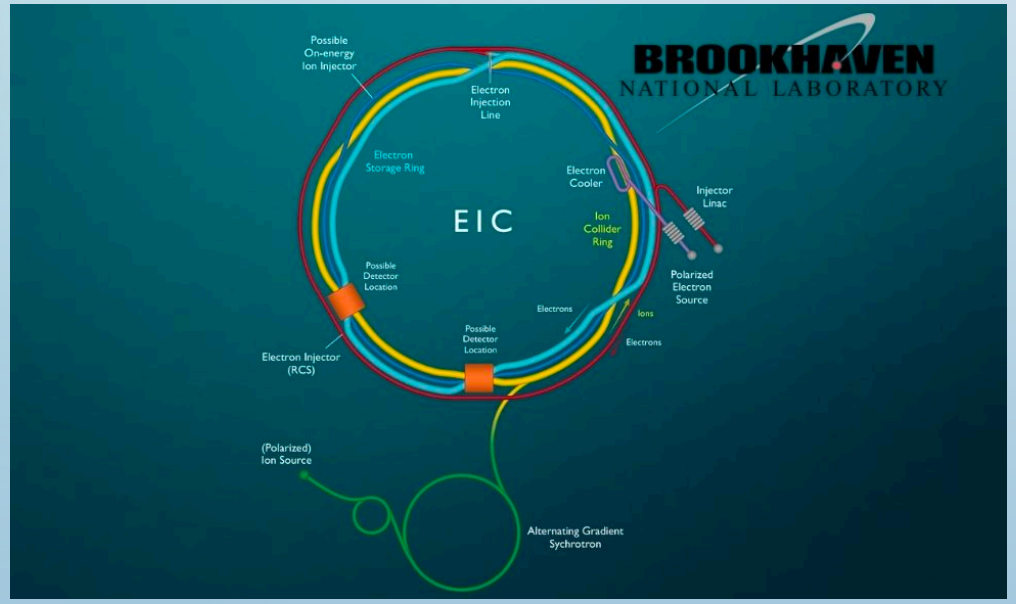
First analysis of world polarized DIS data with small-x helicity evolution

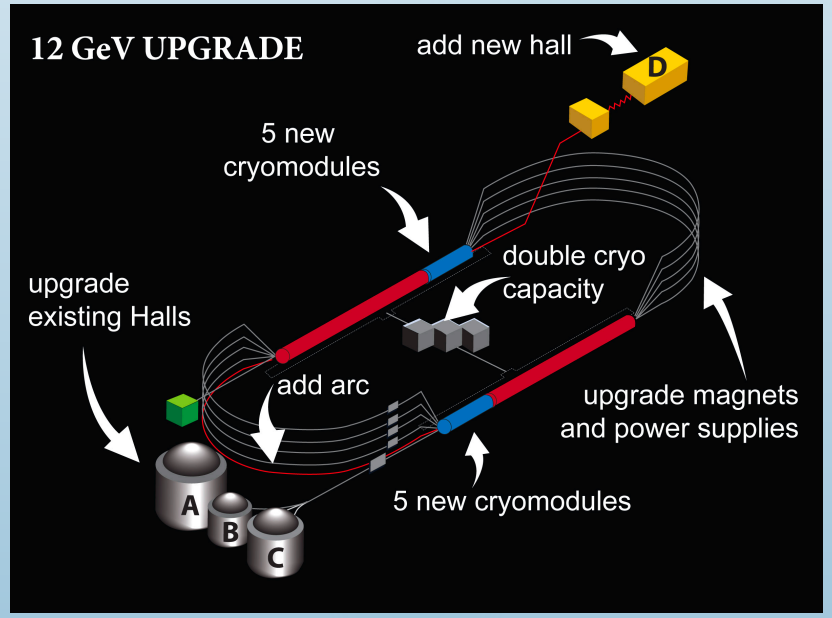


Outlook

Jefferson Lab 12 GeV will provide new information on helicity PDFs and nuclear effects at high x

EIC will provide new information on helicity PDFs at low x



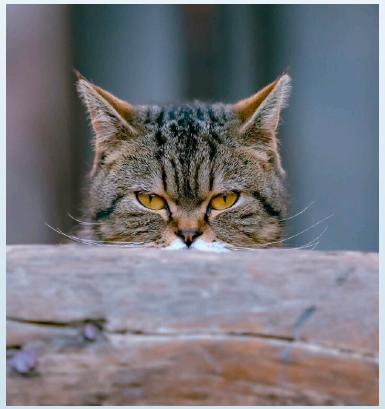


Collaboration

Andreas Metz

Wally Melnitchouk

Hanjie Liu



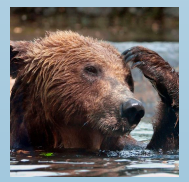
Anthony Thomas

Thia Keppel

Nobuo Sato

Jefferson Lab Angular Momentum Collaboration

Thank you to Yiyu Zhou and Patrick Barry for helpful discussions



Backup

Error Quantification

For a quantity $O(\boldsymbol{a})$: (for example, a PDF at a given value of (x, Q^2))

$$E[O] = \int d^n a \; \rho(\boldsymbol{a} \,|\, data) \; O(\boldsymbol{a})$$

$$V[O] = \int d^n a \; \rho(\boldsymbol{a} \,|\, data) \; \left[O(\boldsymbol{a}) - E[O]\right]^2$$

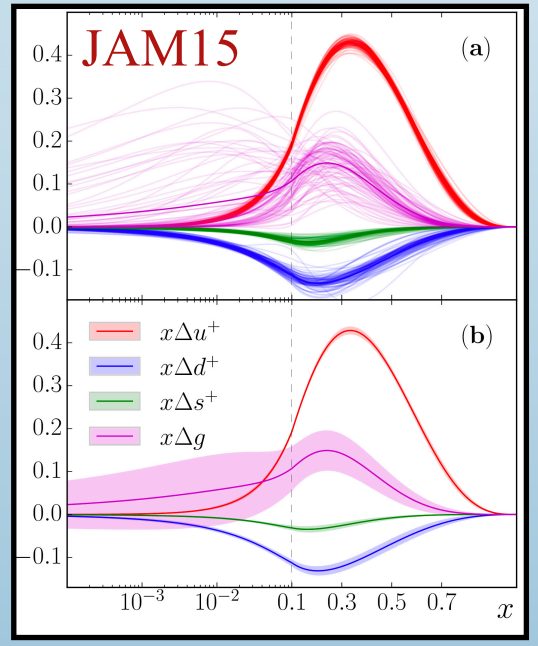
Exact, but $n = \mathcal{O}(100)$!

Build an MC ensemble

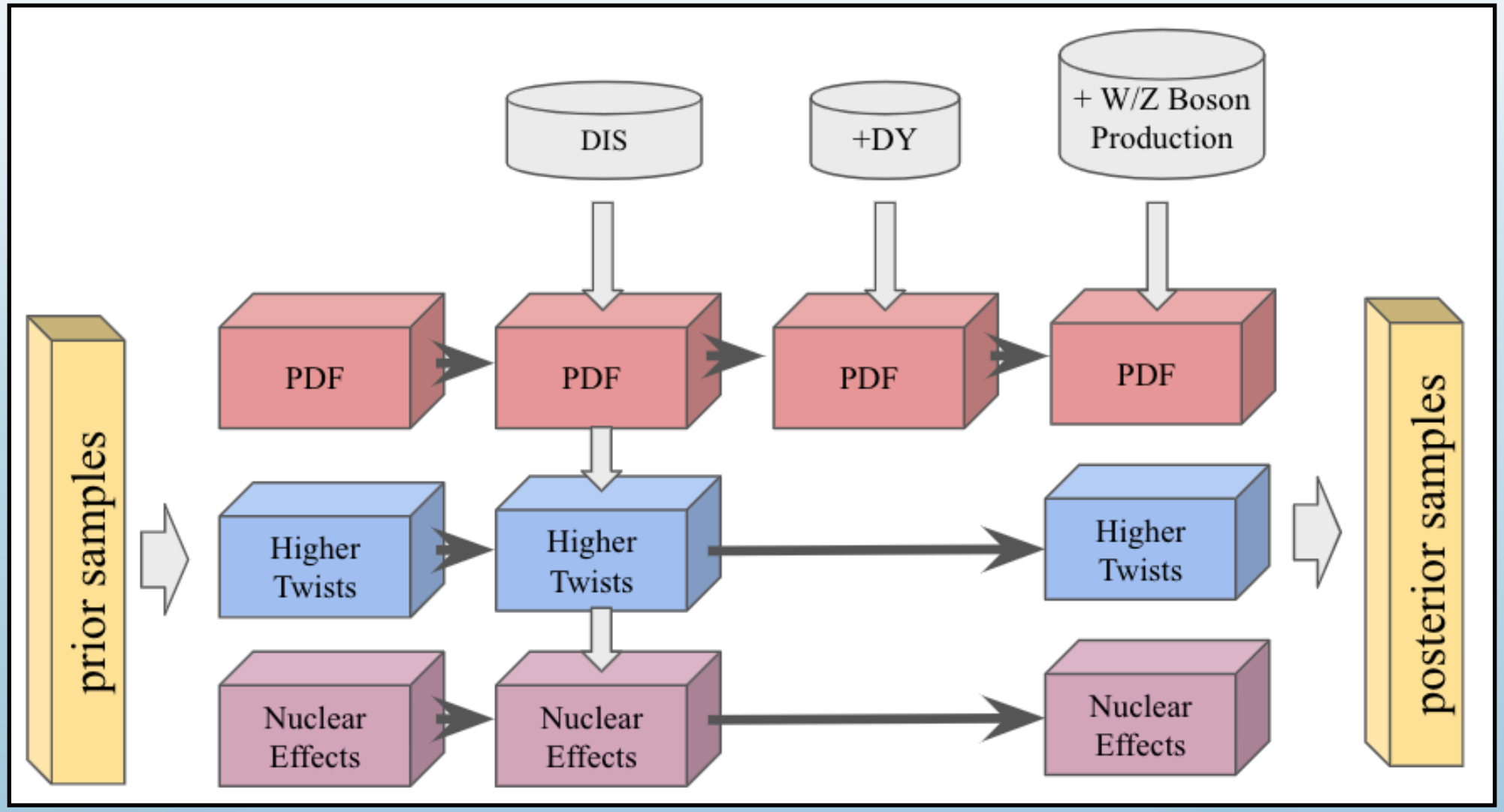
$$E[O] \approx \frac{1}{N} \sum_k O(\boldsymbol{a}_k)$$

$$V[O] \approx \frac{1}{N} \sum_k \left[O(\boldsymbol{a}_k) - E[O]\right]^2$$

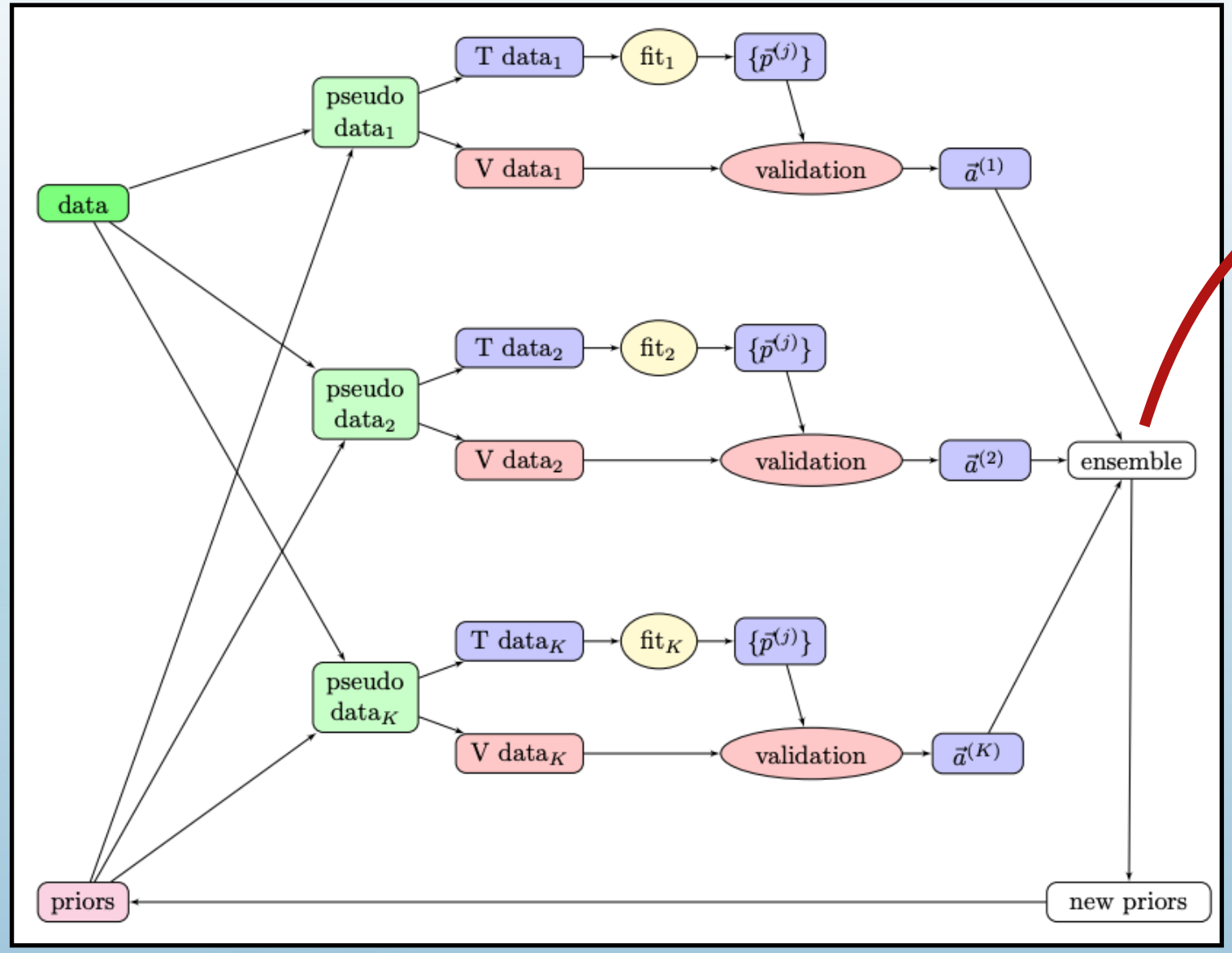
Average over k sets of the parameters (replicas)

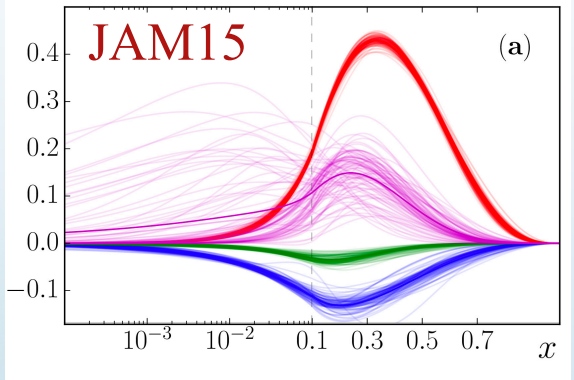


Multi-Step Strategy



Putting it all together…

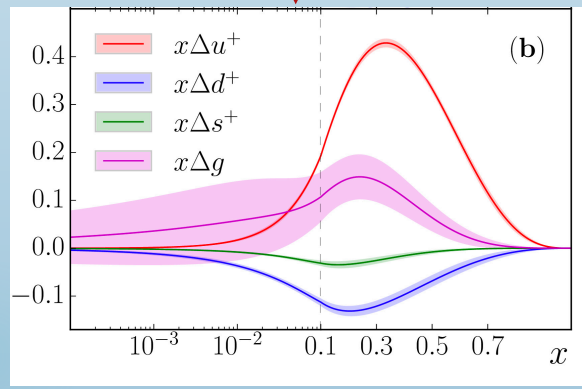




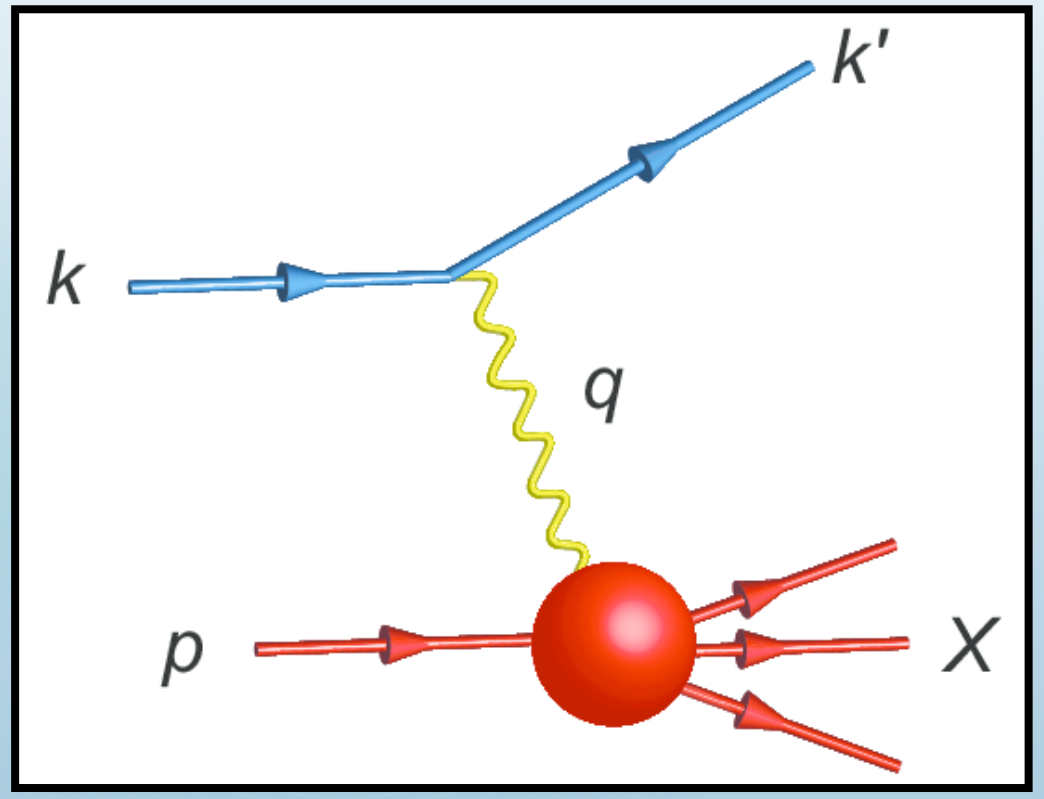
+

$$E[O] \approx \frac{1}{N}\sum_k O(\boldsymbol{a}_k)$$

$$V[O] \approx \frac{1}{N}\sum_k \left[O(\boldsymbol{a}_k) - E[O]\right]^2$$



Deep Inelastic Scattering



Virtuality:

$$Q^2 = -q^2$$

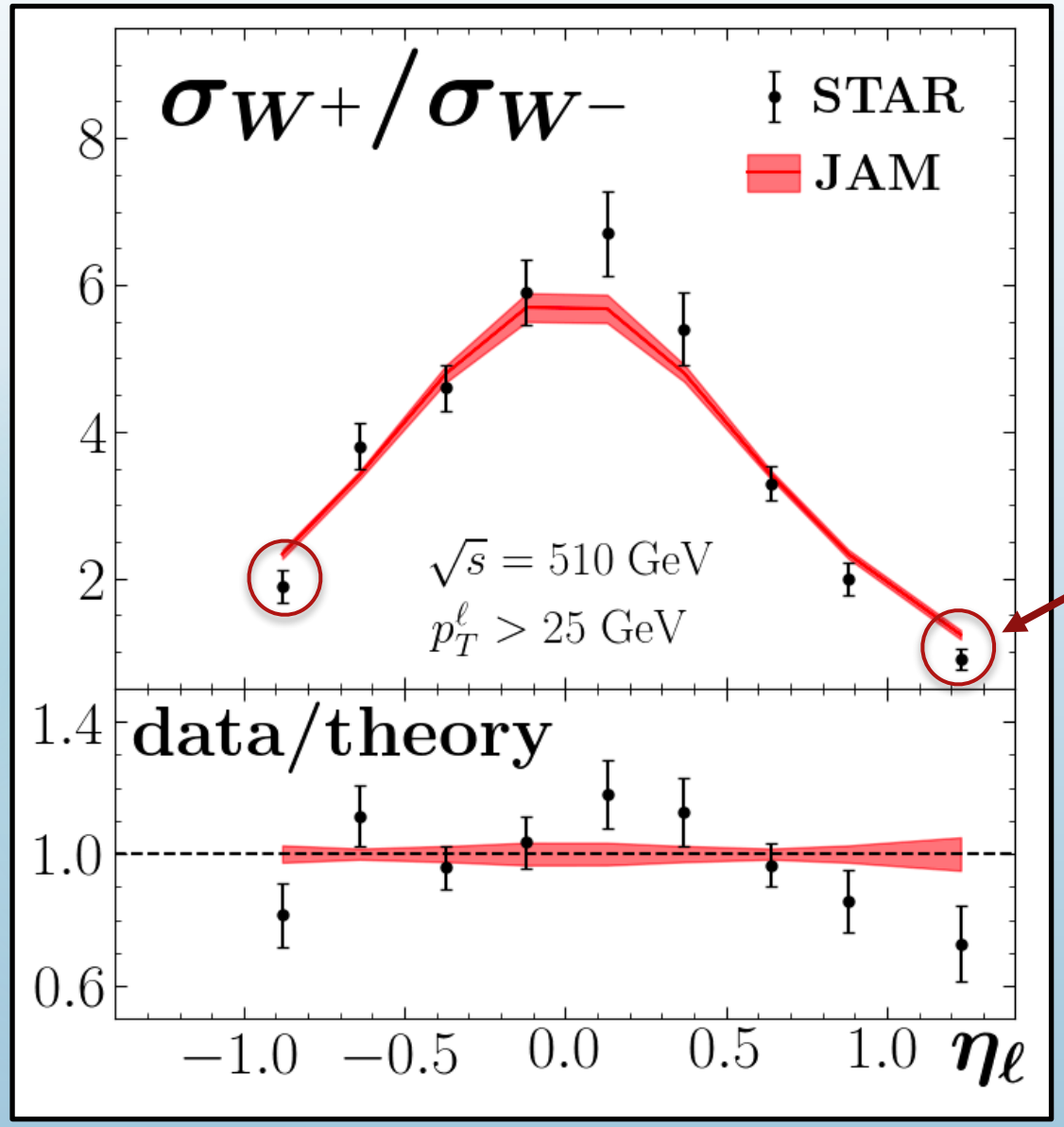
Bjorken x:

$$x = \frac{Q^2}{2p \cdot q}$$

Invariant mass of outgoing particles:

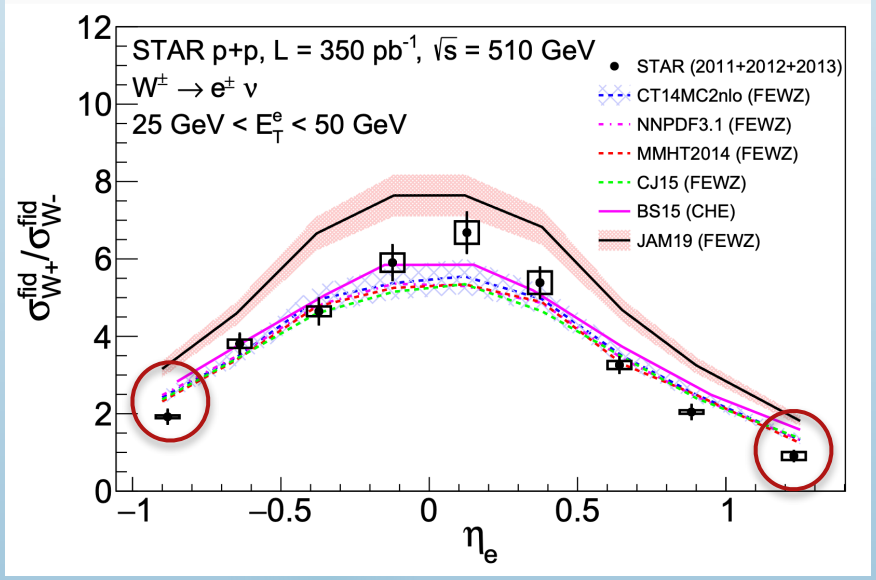
$$W^2 = (p+q)^2$$

STAR Quality of Fit



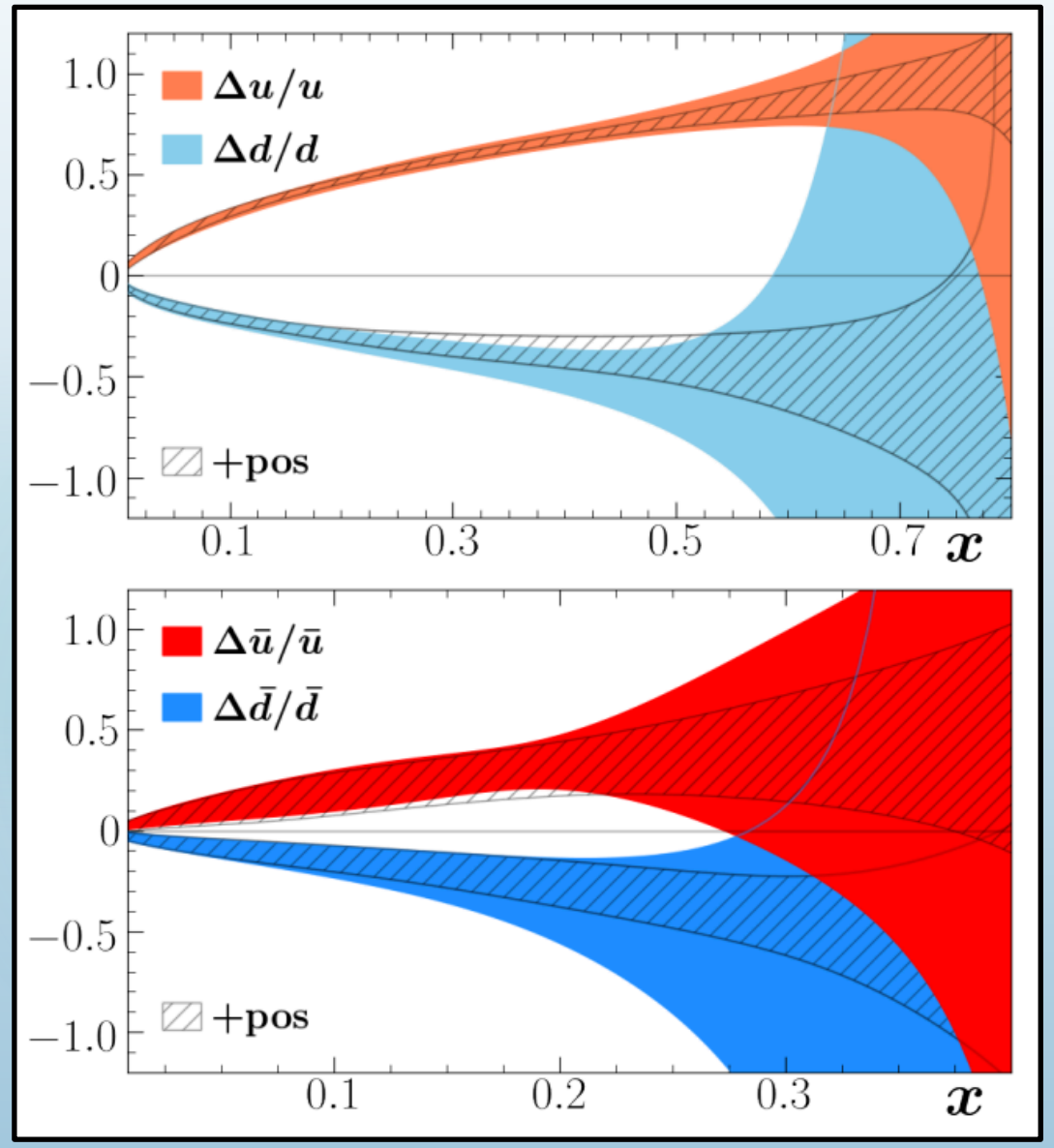
process	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
W-lepton		
STAR W^+/W^-	9	2.02

Difficult to describe at extreme rapidity

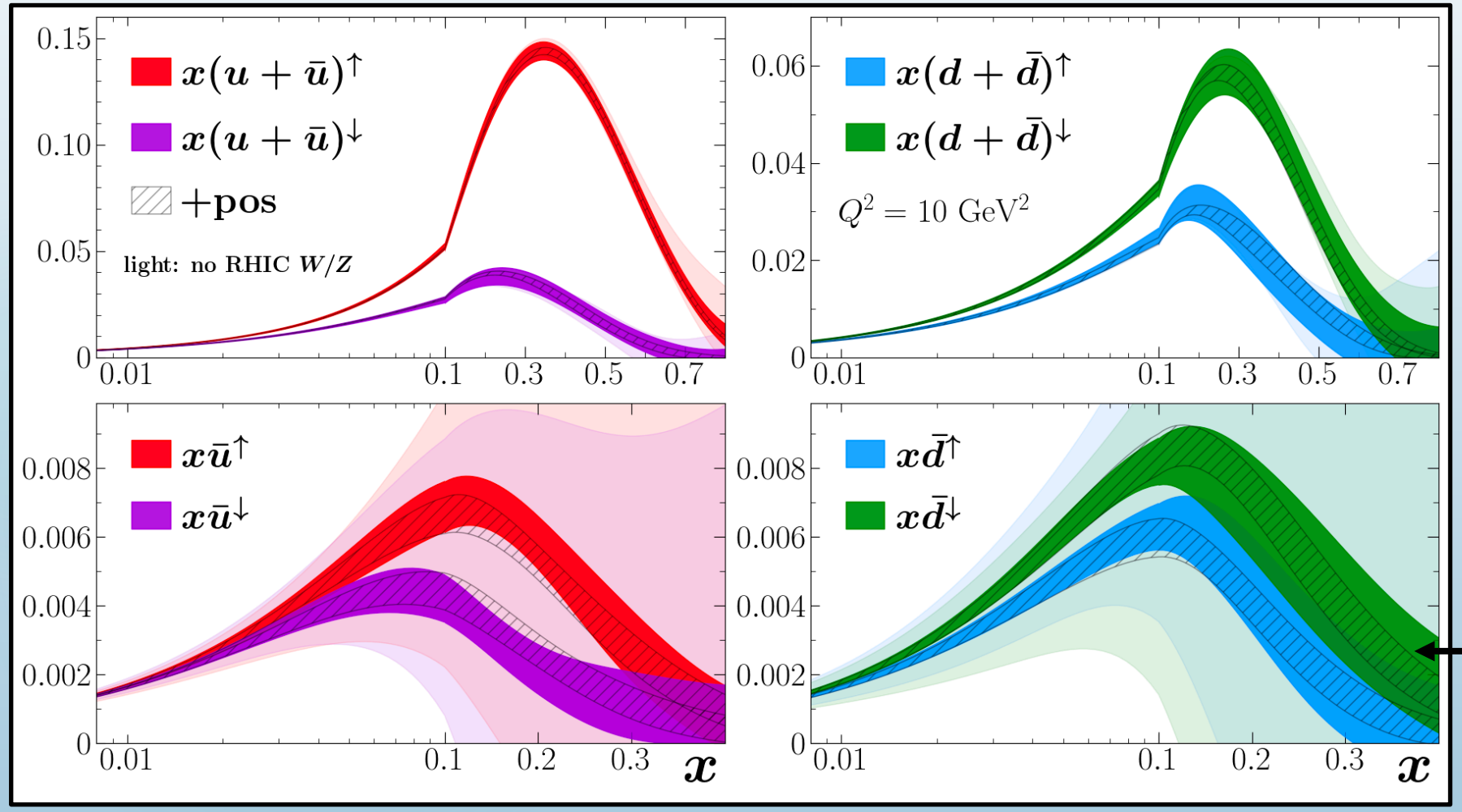


J. Adam *et al*. [STAR], Phys. Rev. D. **103**, 012001 (2021)

Quark and Antiquark Polarizations



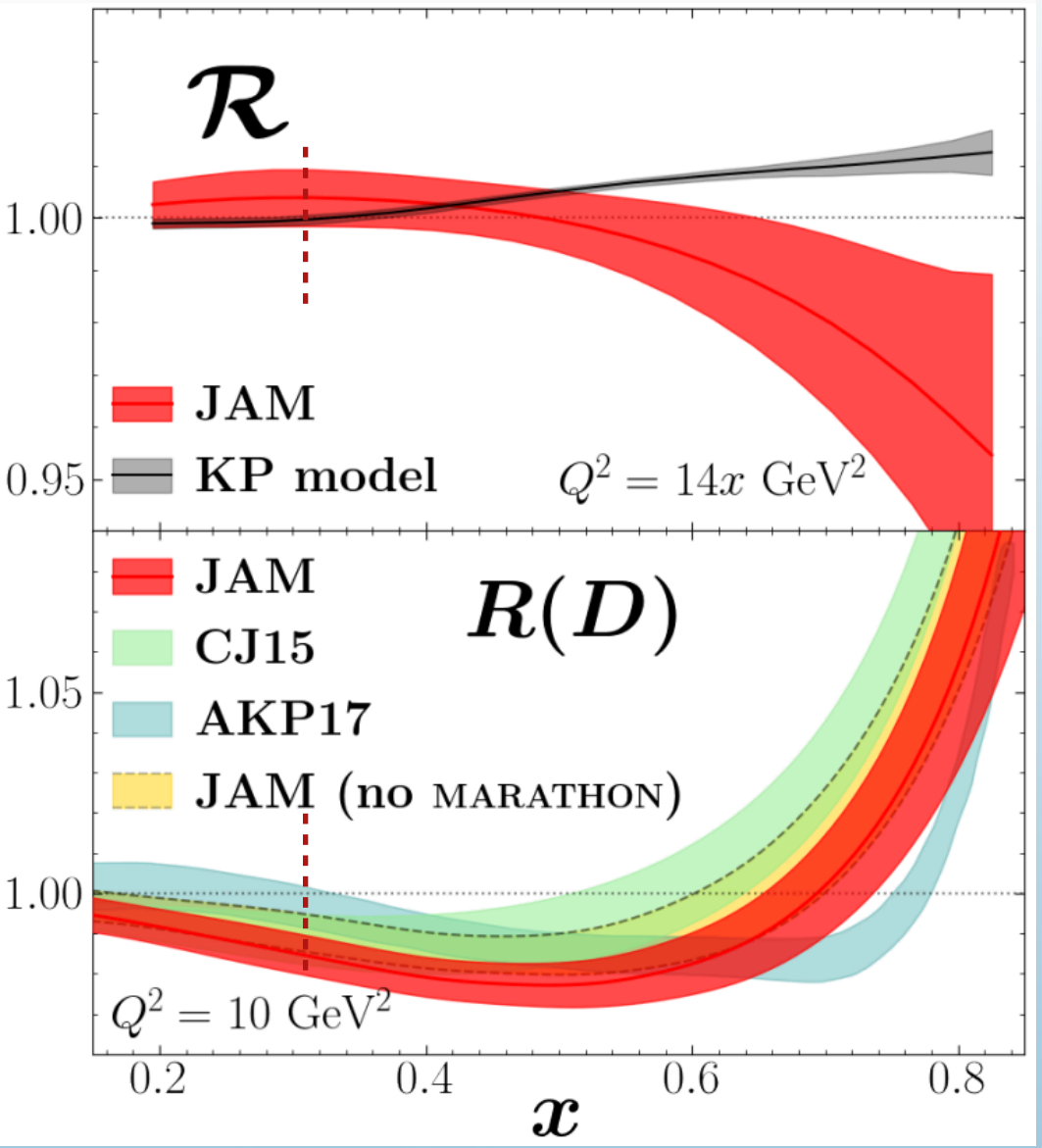
Spin Up/Down PDFs



$$q^{\uparrow\downarrow} = \frac{1}{2}(q \pm \Delta q)$$

Large impact from RHIC

EMC Ratios



$$R(D) = F_2^D / \left(F_2^p + F_2^n\right)$$

$$R(^3\mathrm{He}) = F_2^{^3\mathrm{He}} / \left(2F_2^p + F_2^n\right)$$

$$R(^3\mathrm{H}) = F_2^{^3\mathrm{H}} / \left(F_2^p + 2F_2^n\right)$$

$$\mathscr{R} = R(^3\mathrm{He})/R(^3\mathrm{H})$$

Significant differences between JAM result and KP model result

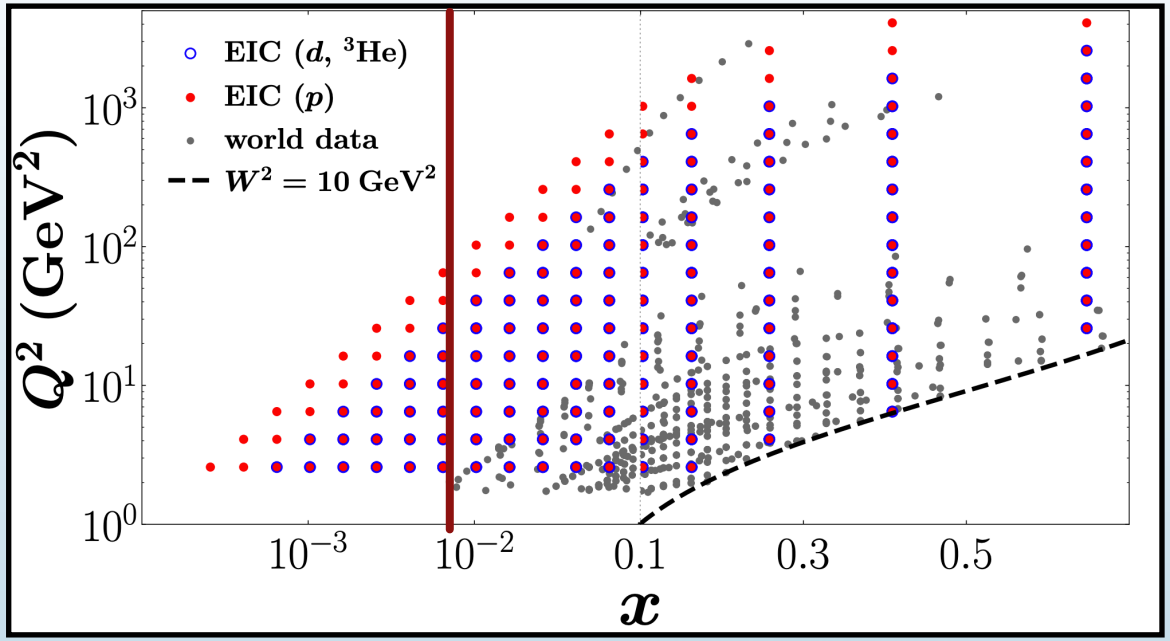
Current State of Helicity PDFs

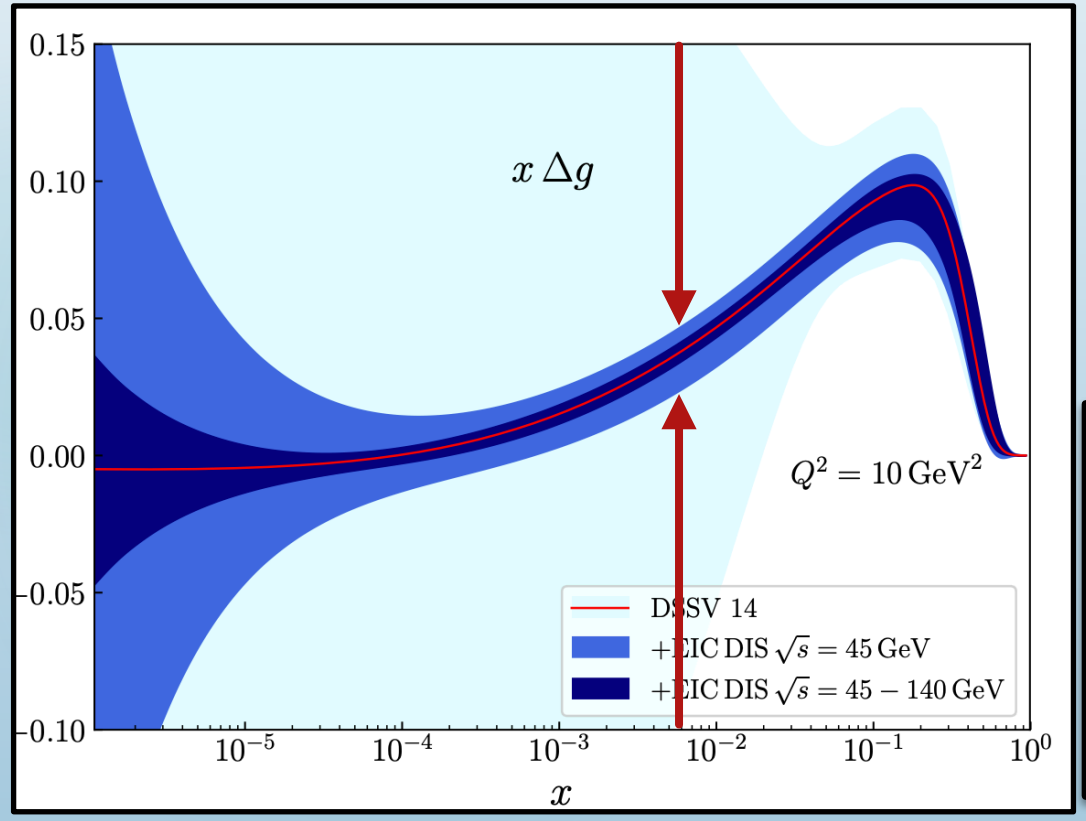
Proton spin puzzle:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

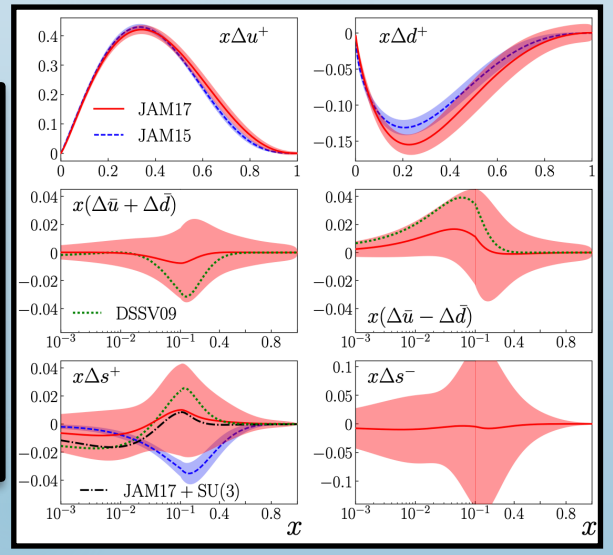
$$\Delta\Sigma = \int_0^1 dx \sum_q \Delta q^+$$

$$\Delta G = \int_0^1 dx \Delta g$$





Still a lot to learn about helicity PDFs at low x and the helicity sea quark PDFs!



Exploratory Analysis of Experiment with Lattice (2020)

Confronting lattice parton distributions with global QCD analysis

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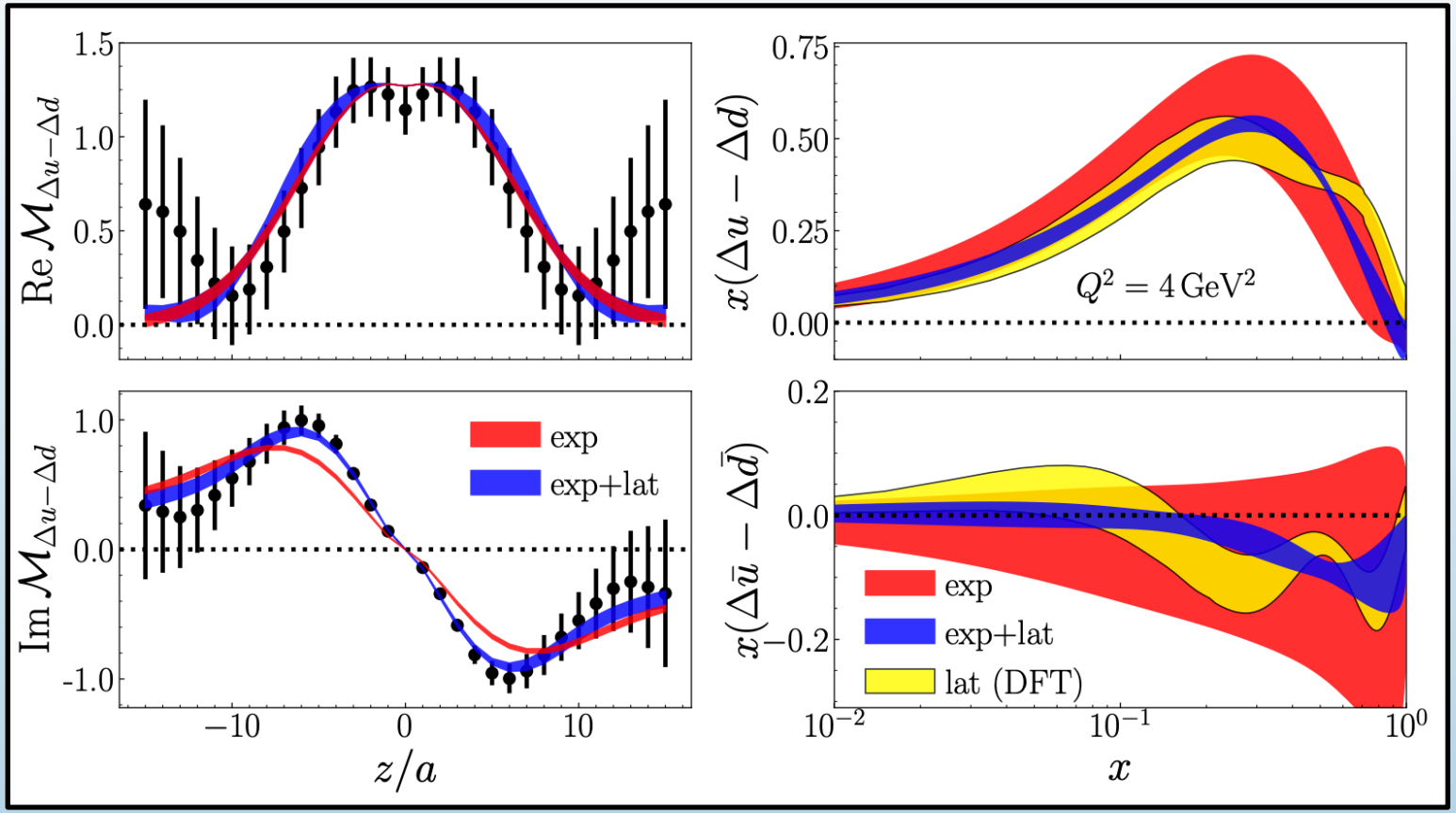
https://arxiv.org/abs/2010.00548



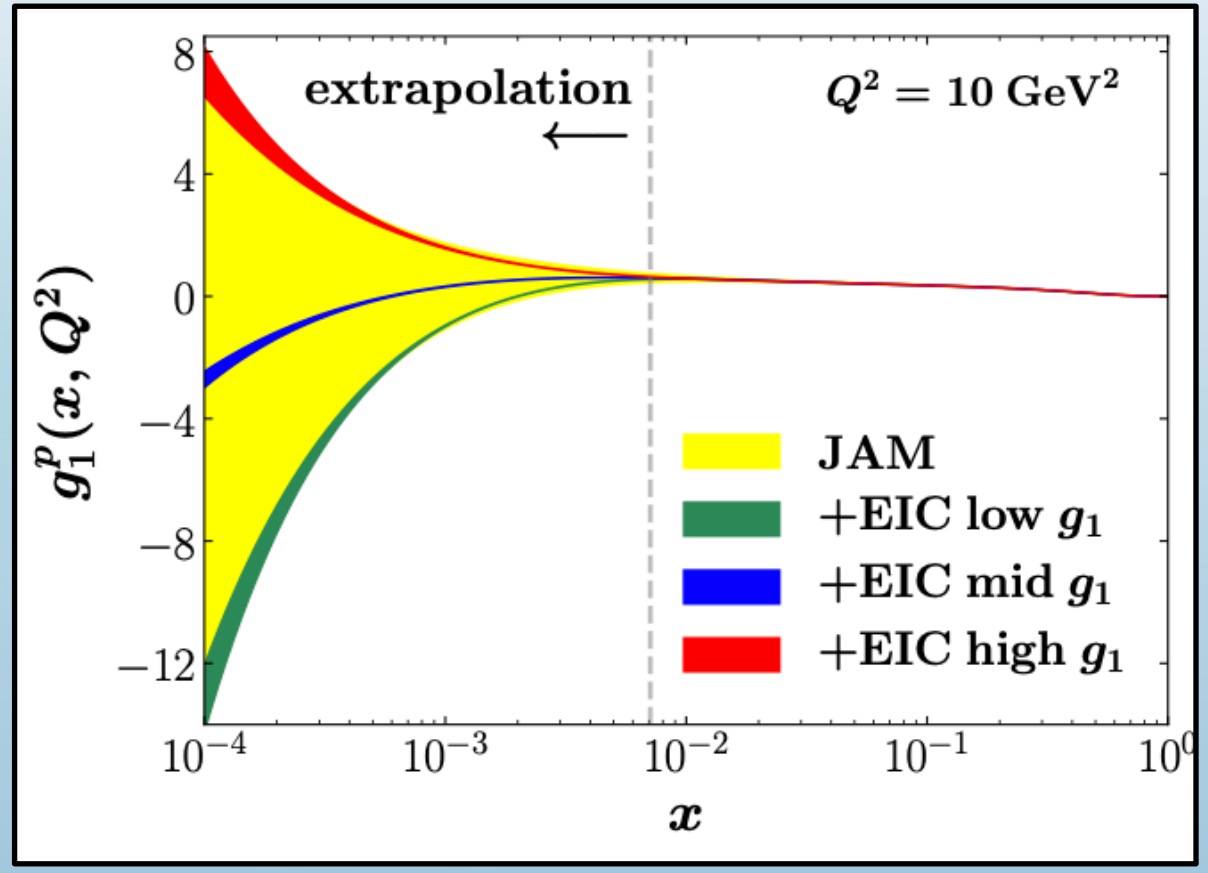
Combining experiment and lattice in a global QCD analysis is feasible!

EIC Impact on Helicity PDFs (2021)

Revisiting quark and gluon polarization in the proton at the EIC

Y. Zhou,[1] C. Cocuzza,[2] F. Delcarro,[3] W. Melnitchouk,[3] A. Metz,[2] and N. Sato[3]

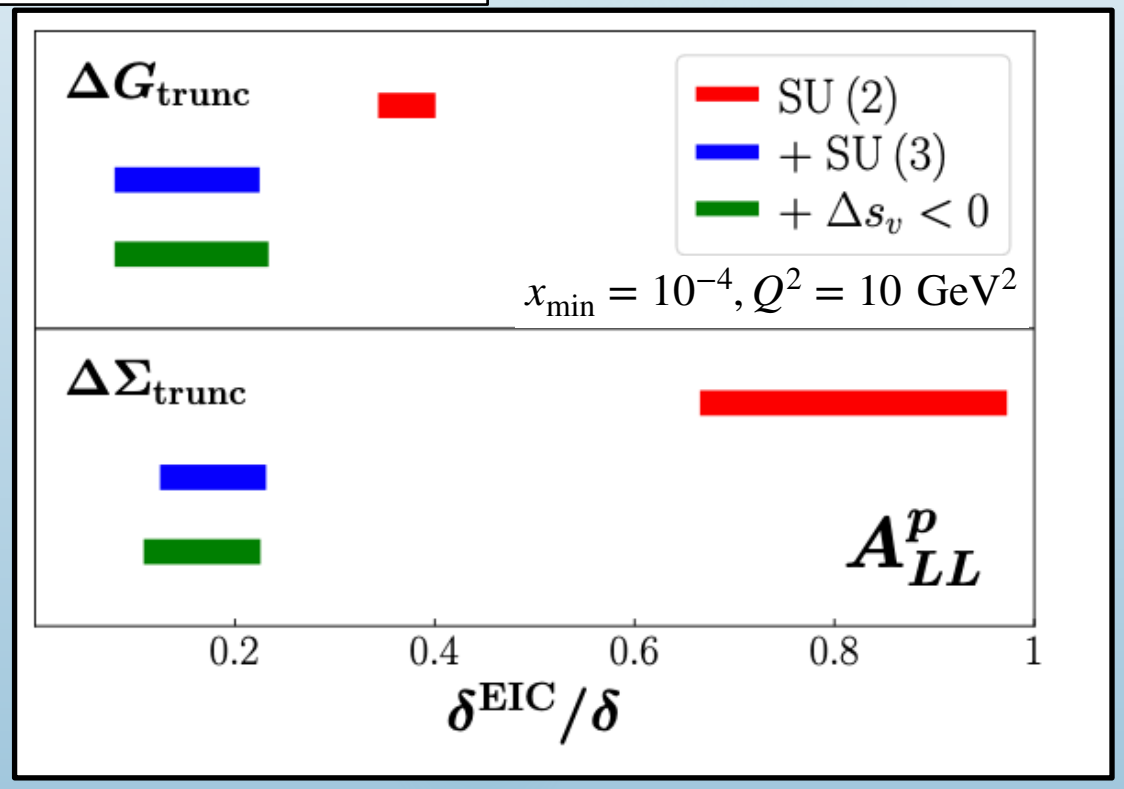
https://arxiv.org/abs/2105.04434



scenario	extrapolation	SU(2)	SU(3)
1	low	✓	
2	mid	✓	
3	high	✓	
4	low	✓	✓
5	mid	✓	✓
6	high	✓	✓

$$\Delta G_{\rm trunc}(Q^2) \equiv \int_{x_{\rm min}}^1 dx\, \Delta g(x, Q^2),$$

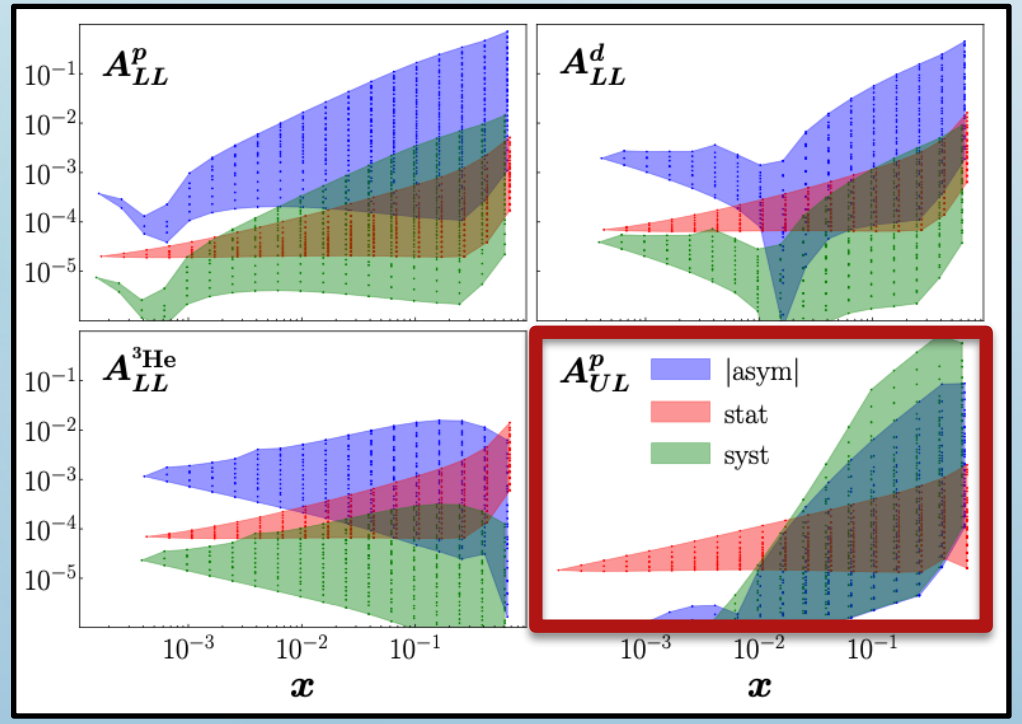
$$\Delta \Sigma_{\rm trunc}(Q^2) \equiv \int_{x_{\rm min}}^1 dx \sum_q \Delta q^+(x, Q^2)$$

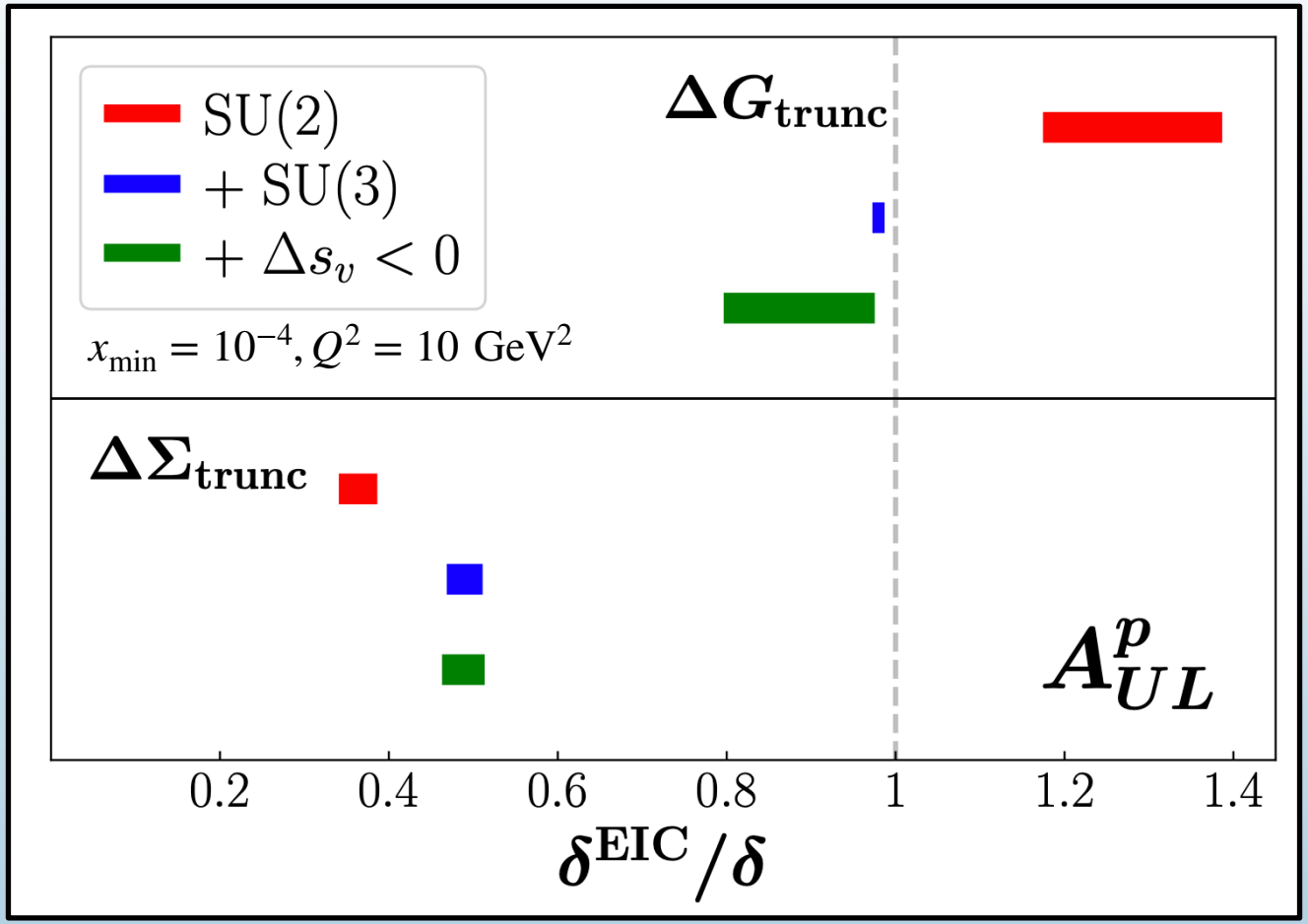


Impact of Parity Violating DIS (2021)

$$g_1^{\gamma Z} \approx \frac{1}{9}(\Delta u^+ + \Delta d^+ + \Delta s^+)$$

$$A_{UL} = \frac{G_F x Q^2}{2\sqrt{2}\pi\alpha}\left(\frac{g_A^e Y^- g_1^{\gamma Z} + g_V^e Y^+ g_5^{\gamma Z}}{xy^2 F_1 + (1-y)F_2}\right)$$





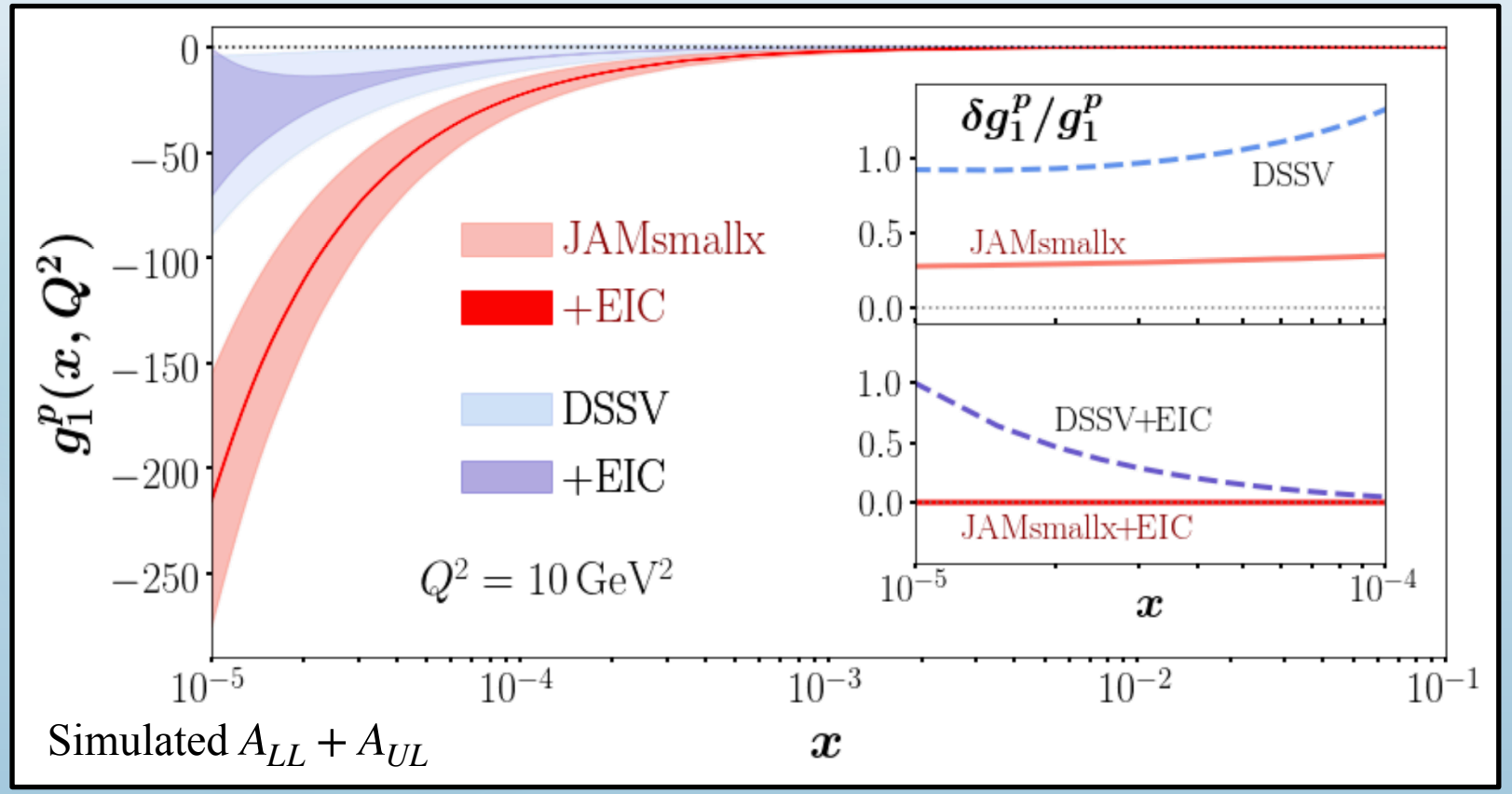
No impact on ΔG, but large impact on $\Delta\Sigma$ thanks to constraints on Δs^+

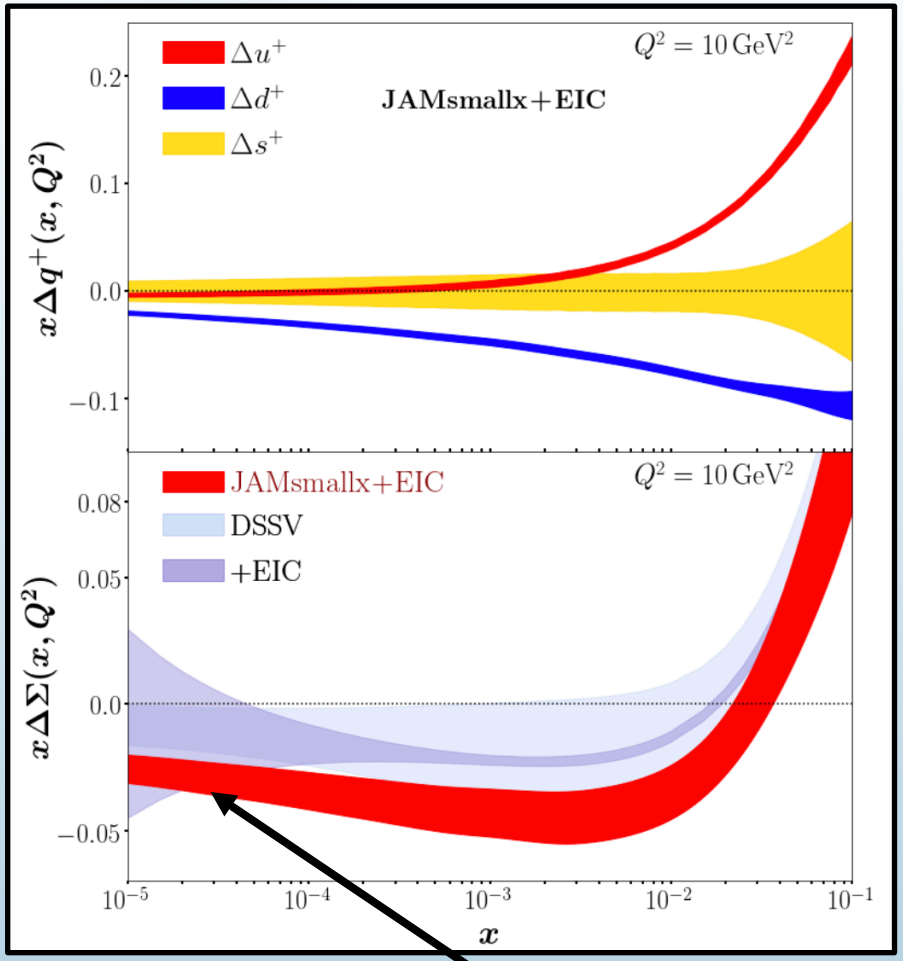
Impact of EIC at small x (2021)

First analysis of world polarized DIS data with small-x helicity evolution

Daniel Adamiak,[1,*] Yuri V. Kovchegov,[1,†] W. Melnitchouk,[2]
Daniel Pitonyak,[3,‡] Nobuo Sato,[2,§] and Matthew D. Sievert[4,¶]

https://arxiv.org/abs/2102.06159





Uncertainties remain consistent even below EIC kinematics

Latest Fragmentation Functions (2021)

Simultaneous Monte Carlo analysis of parton densities and fragmentation functions

E. Moffat, W. Melnitchouk, T. C. Rogers, N. Sato

https://arxiv.org/abs/2101.04664