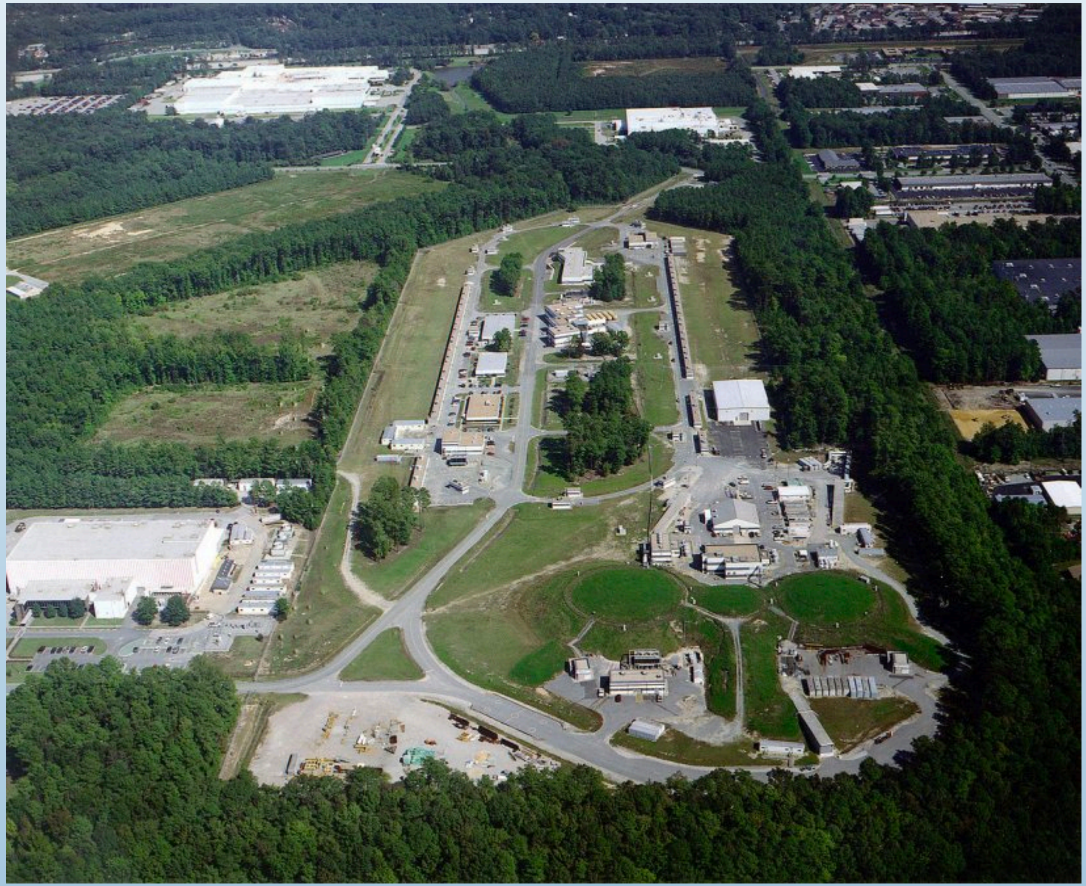
Updates on global JAM Fits

www.jlab.org/theory/jam

Chris Cocuzza (Temple U.)

June 13, 2022

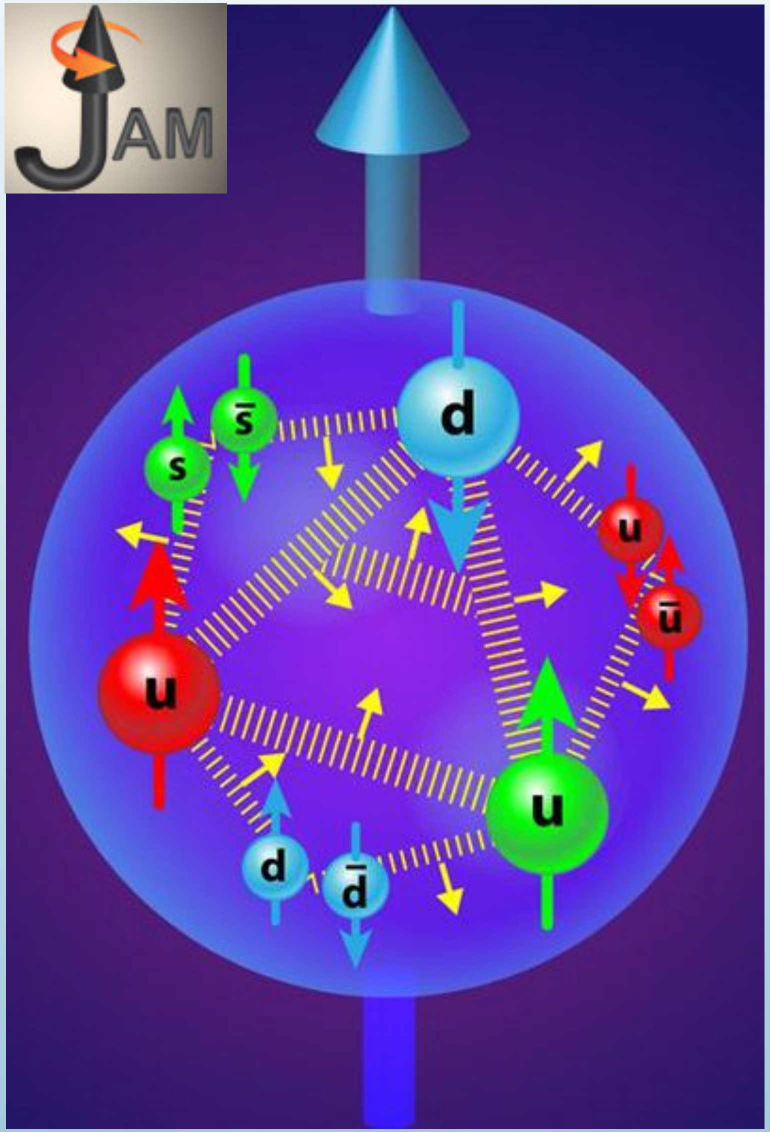


JAM Collaboration

www.jlab.org/theory/jam

Extract 3-dimensional structure of hadrons

	Abbreviation	Dimensions
Parton Distribution Functions	PDF	1
Fragmentation Functions	FF	1
Transverse momentum dependent distributions	TMD	3
Generalized parton distributions	GPD	3



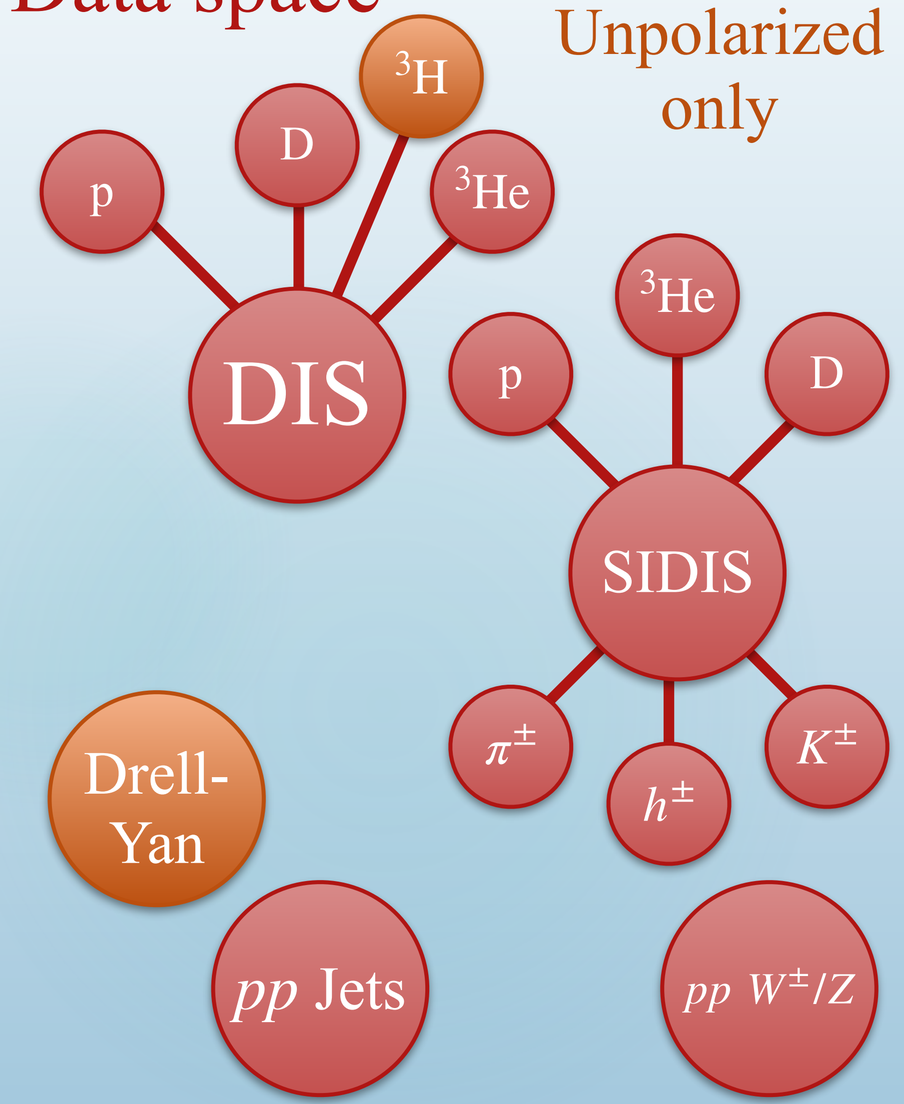
Collinear factorization in perturbative QCD

Simultaneous determinations of PDFs, FFs, etc.

Monte Carlo methods for Bayesian inference

Current State of JAM Global Analyses

Data space



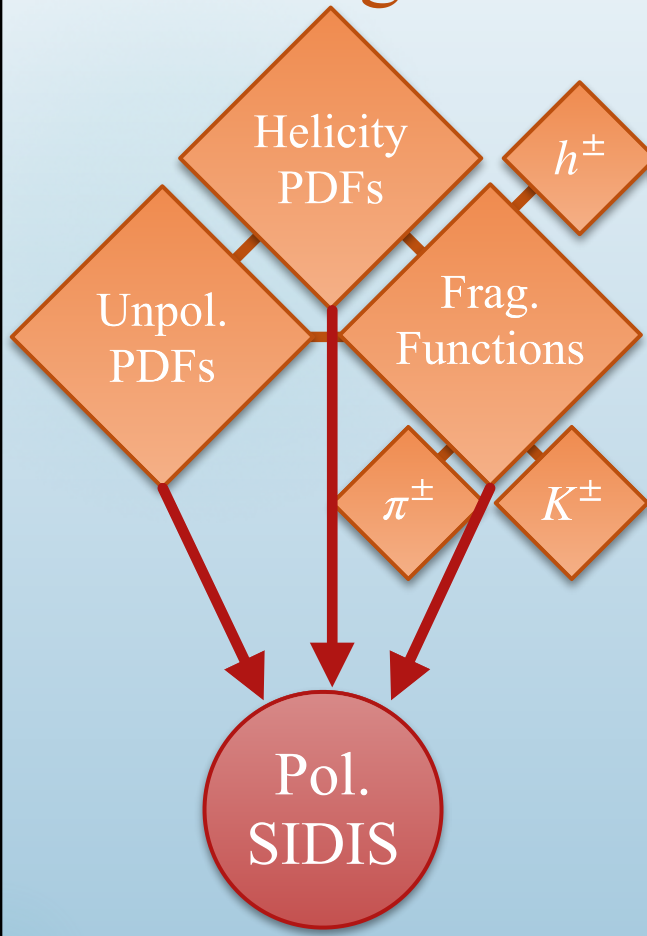
Theory

- Collinear Factorization
  - NLO now / NNLO future
- Target Mass Corrections
  - Higher Twists
- Small x Evolution

Methodology

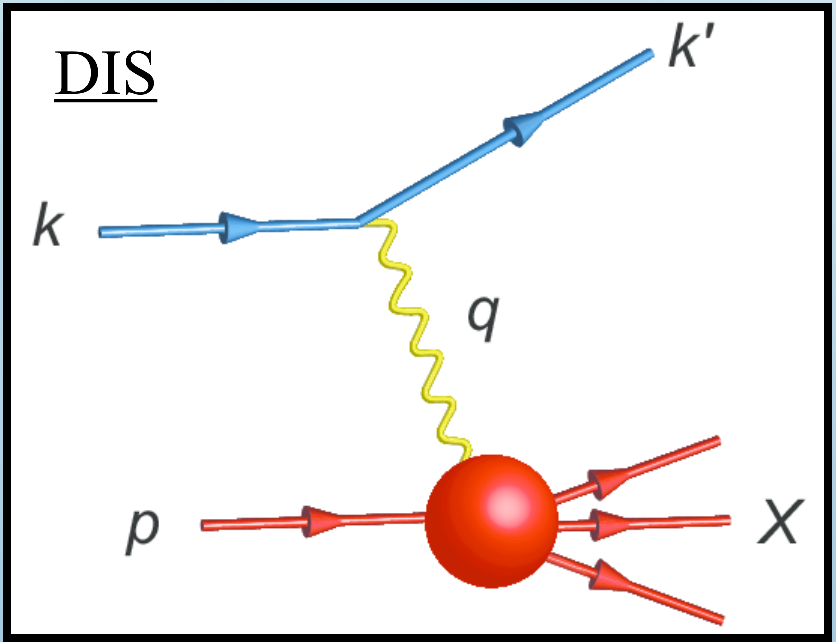
- Traditional Parameterization ⋯ Neural Nets
- MC Approach ⋯ Maximum Likelihood +Hessian/Lagrange

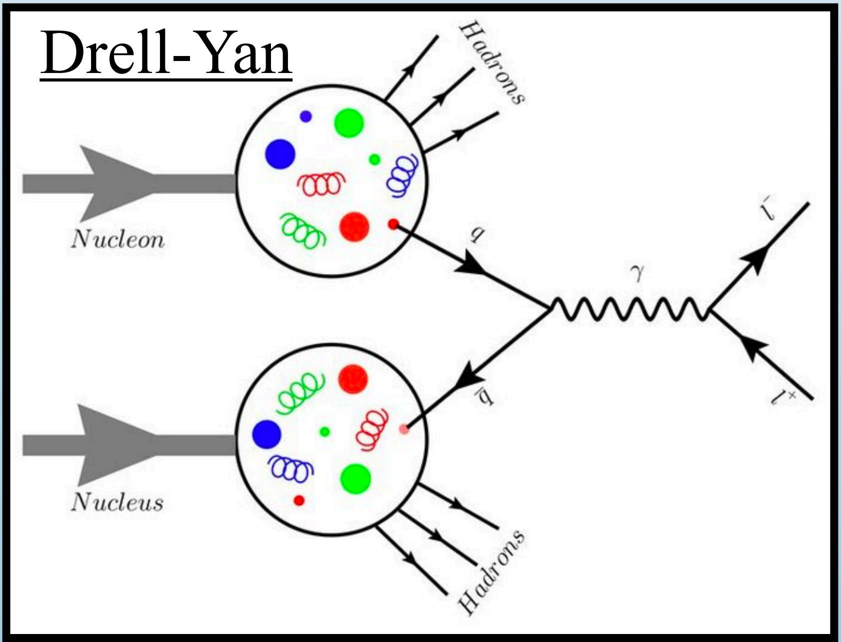
Simultaneous Paradigm

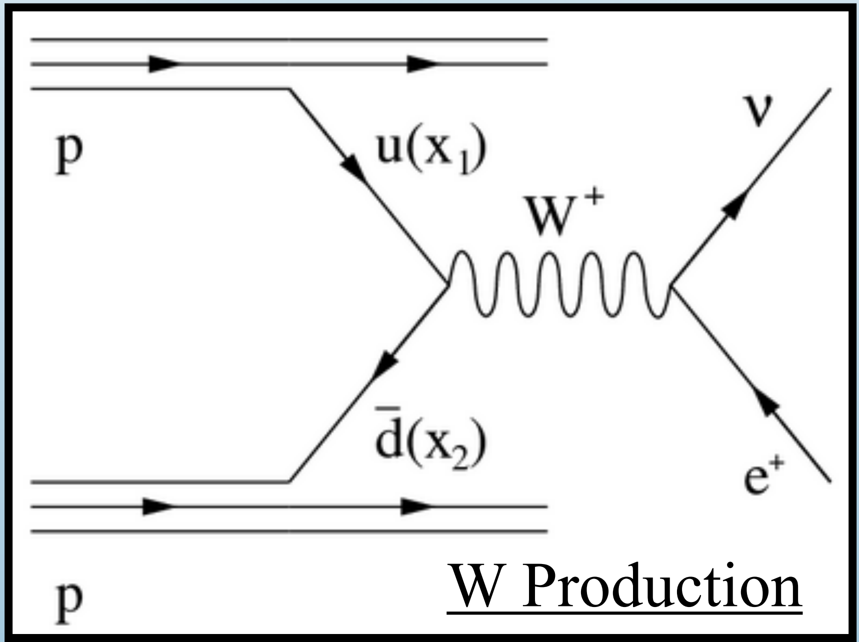


A Global Analysis

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







Database

Spin-Averaged PDFs

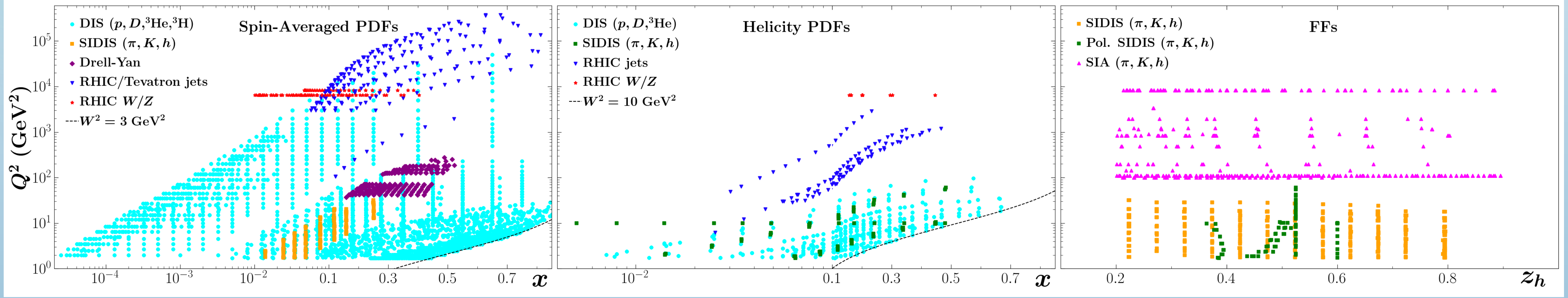
DIS	BCDMS, NMC, SLAC, HERA, JLab	3863
Drell-Yan	Fermilab E866, E906	205
W/Z Boson	CDF/D0, STAR, LHCb, CMS	153
Jets	CDF/D0, STAR	198

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



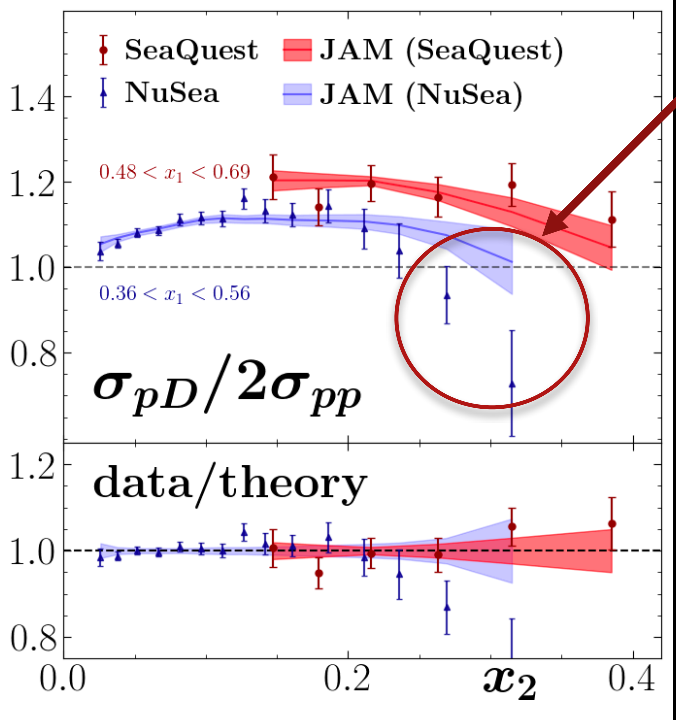
Spin-Averaged Sea Asymmetry (2021)

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

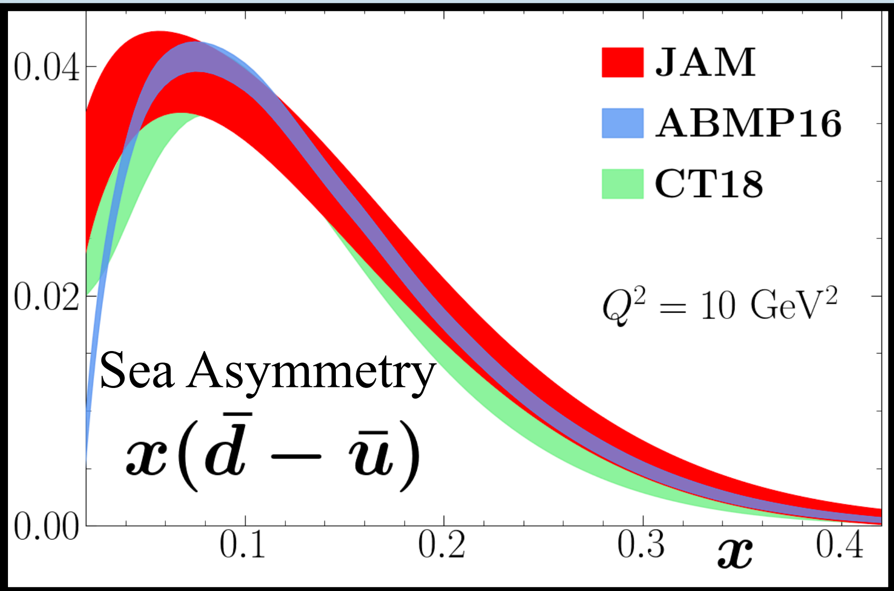
Christopher Cocuzza, Wally Melnitchouk, Andreas Metz, Nobuo Sato

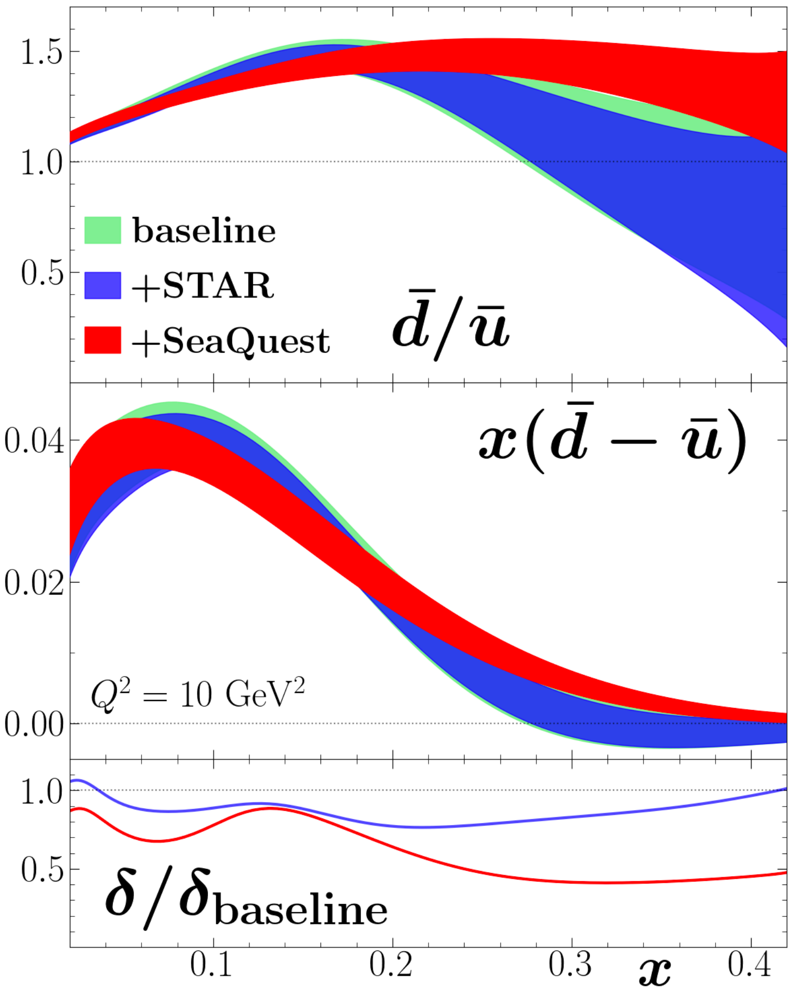
https://arxiv.org/abs/2109.00677
C. Cocuzza *et al.*, Phys. Rev. D. **104**, no. 7, 074031 (2021).

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



Well-known tension between NuSea and SeaQuest





Large reduction in uncertainties and increase in central value

Helicity Sea Asymmetry (2022)

Polarized Antimatter in the Proton from Global QCD Analysis

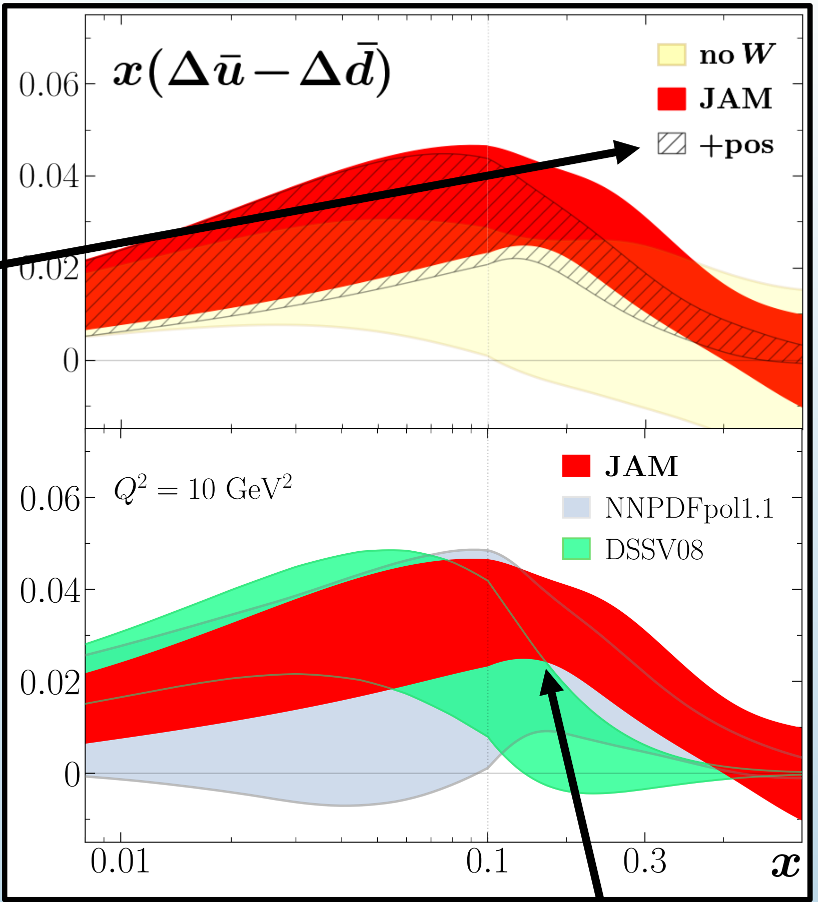
C. Cocuzza, W. Melnitchouk, A. Metz, N. Sato

https://arxiv.org/abs/2202.03372

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

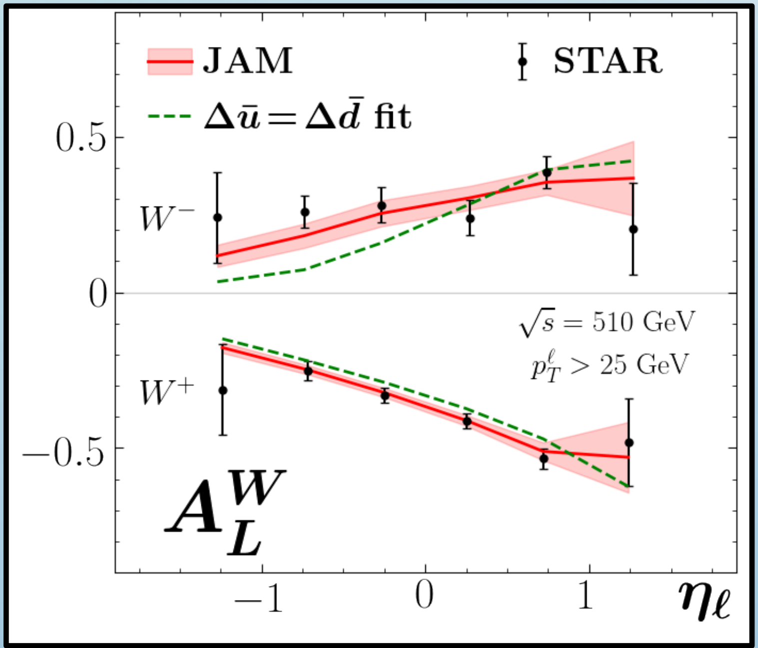
$$A_L^{W^+}(y_W) \propto \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_1)u(x_2) + u(x_1)\bar{d}(x_2)}$$

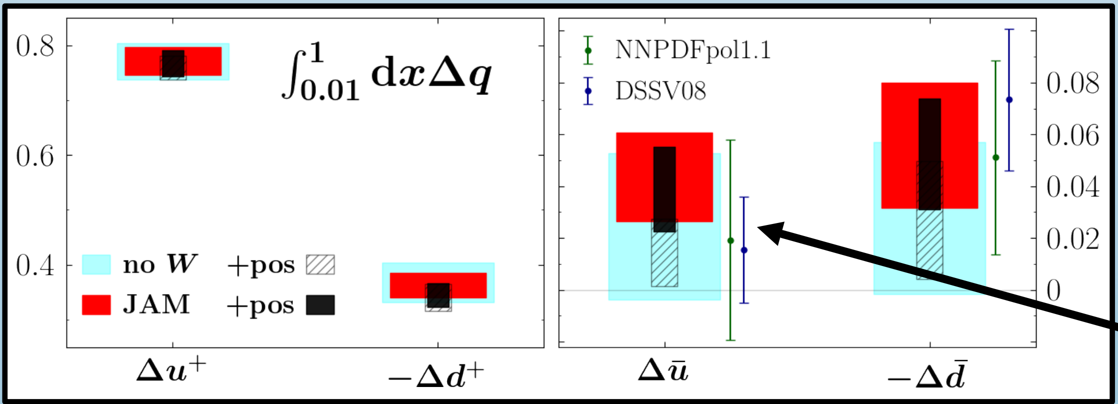
$$A_L^{W^-}(y_W) \propto \frac{\Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$



Flavor	JAM moment (truncated)	Lattice Moment (full)	Diff.
Δu^+	0.771(25)	0.864(16)	11%
Δd^+	-0.363(23)	-0.426(16)	15%
$\Delta\bar{u}$	0.044(17)		
$\Delta\bar{d}$	-0.056(24)		

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





First positive extraction at moderate x

First non-zero extraction of $\Delta\bar{u}$ moment

Gluon Polarization (2021)

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

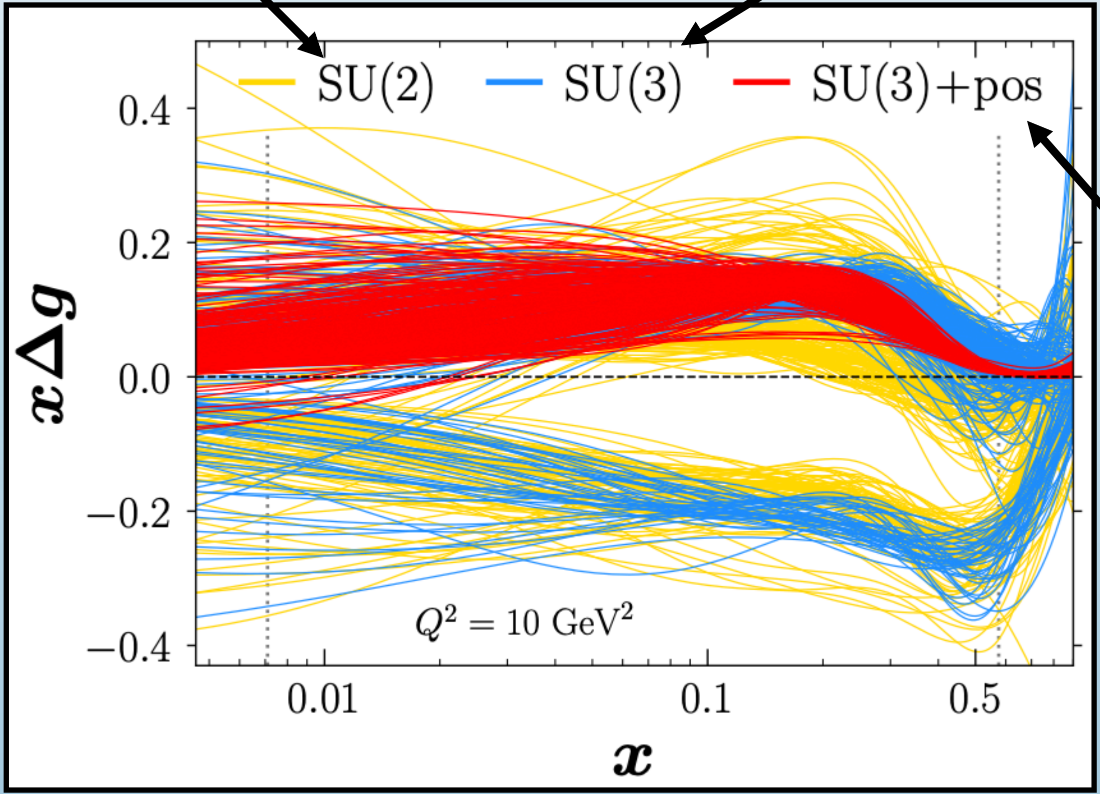
Y. Zhou, N. Sato, W. Melnitchouk

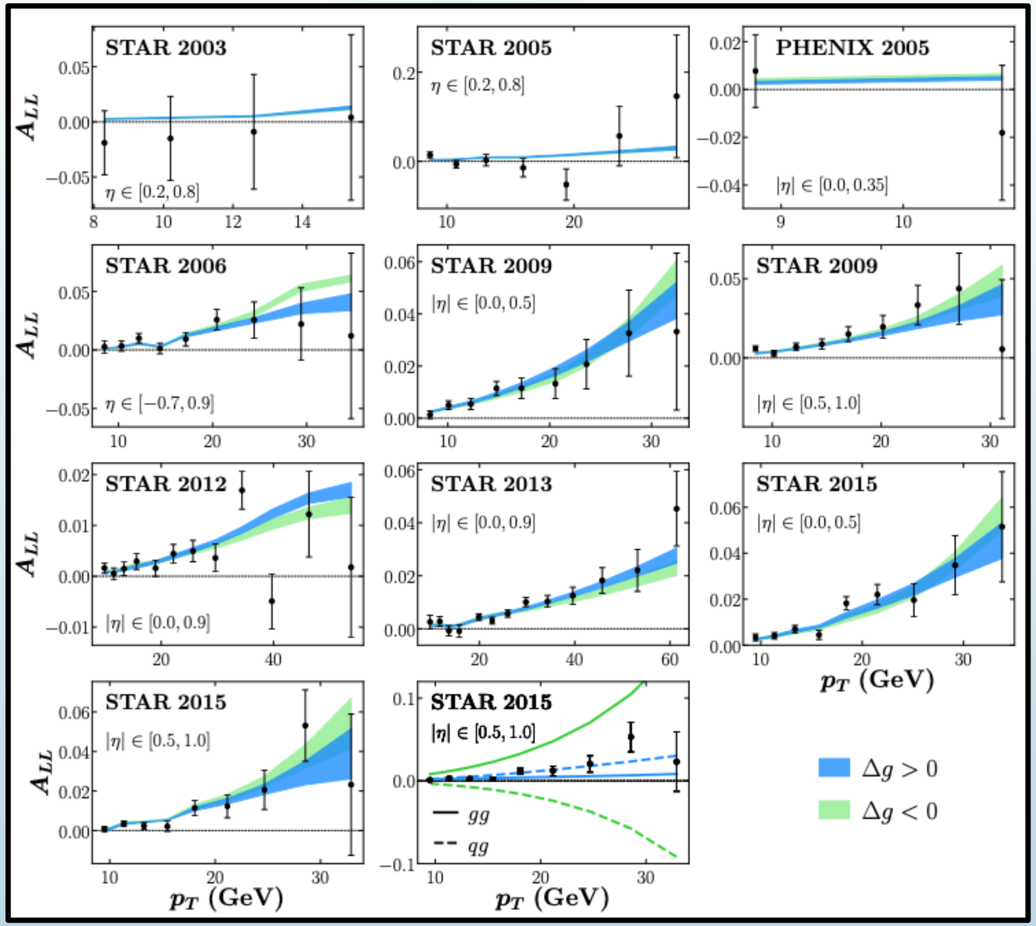
https://arxiv.org/abs/2201.02075

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

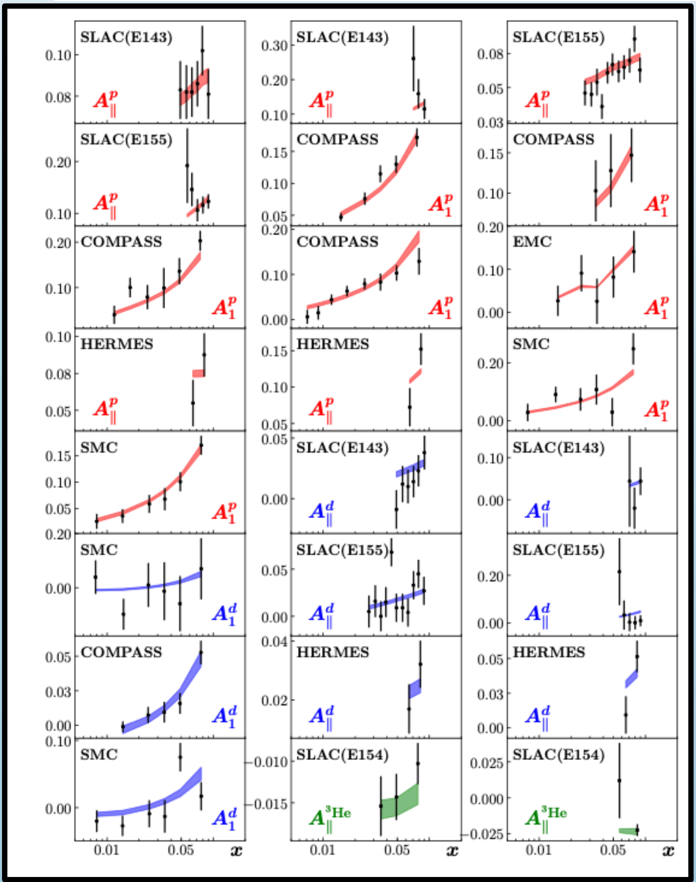
John Collins, Ted C. Rogers, Nobuo Sato

Small x Global Analysis (2021)

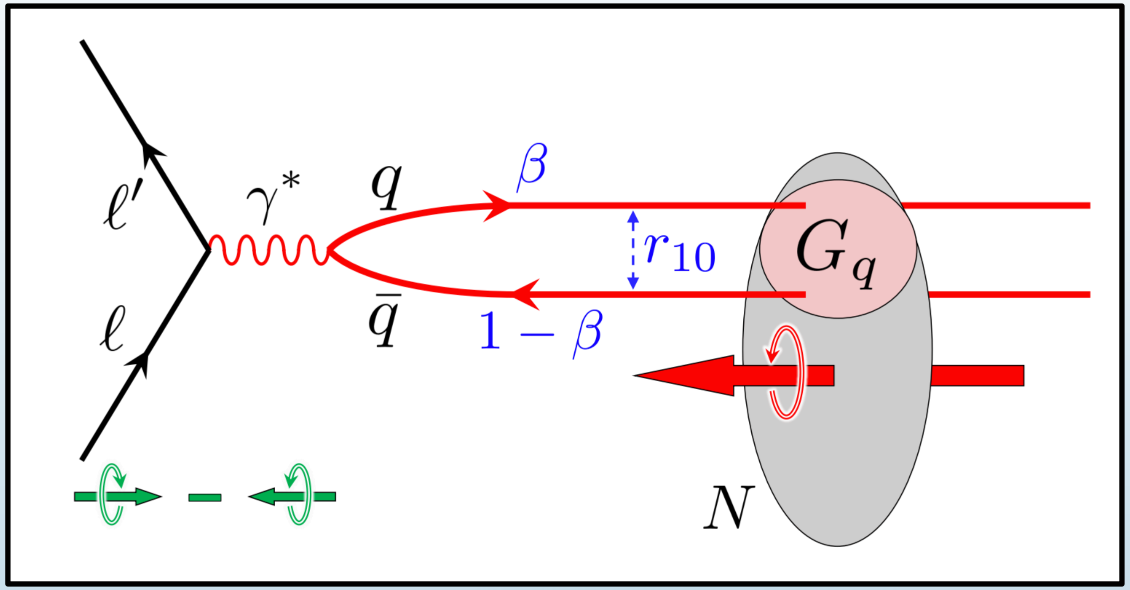
First analysis of world polarized DIS data with small-x helicity evolution

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

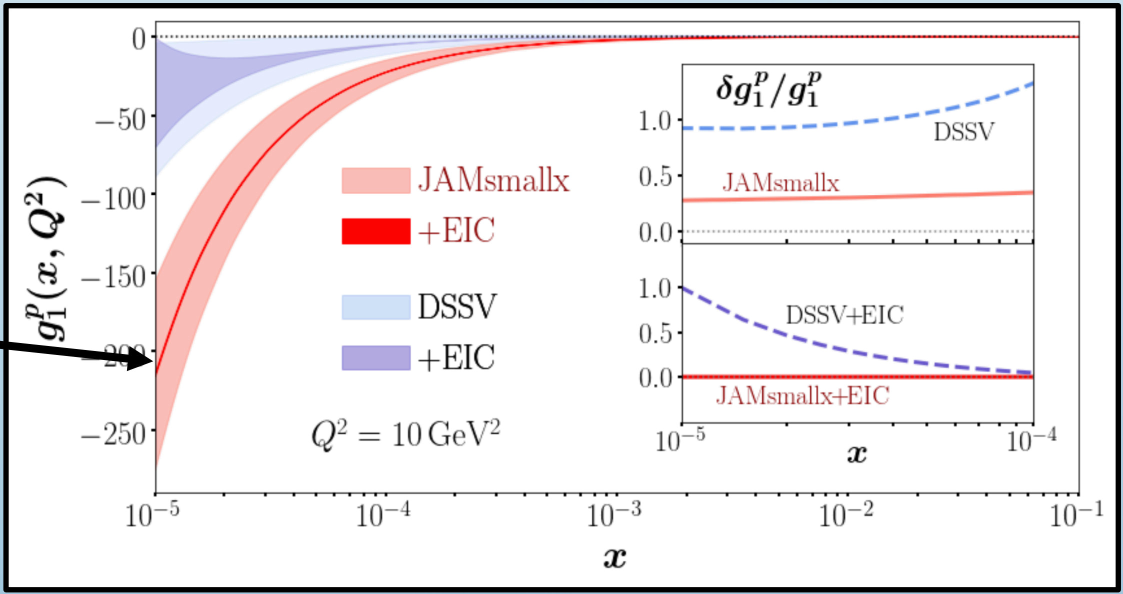
https://arxiv.org/abs/2102.06159
D. Adamiak *et al.*, Phys. Rev. D **104**, no. 3, L031501 (2021).



$x < 0.1$



Prediction, not extrapolation!



Transversity PDFs (2022)

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, Michel Malda, Joshua A. Miller, Daniel Pitonyak, Alexei Prokudin, Nobuo Sato

https://arxiv.org/abs/2205.00999

Transversity PDF

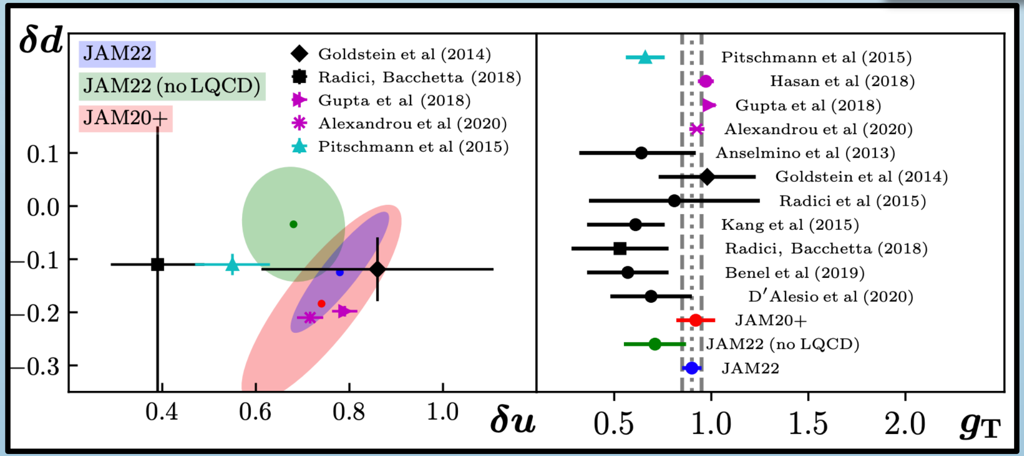
Sivers function (moment)

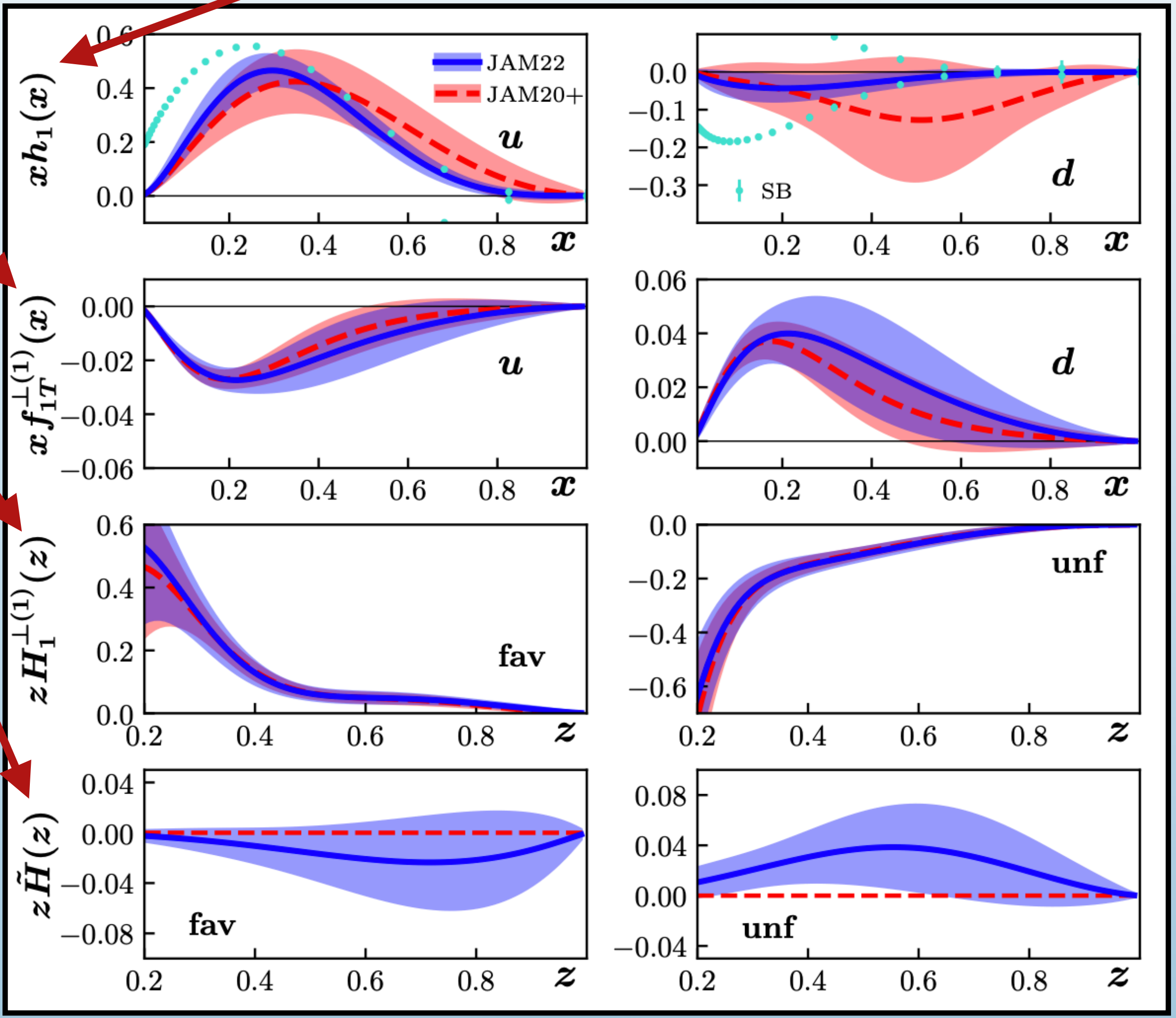
Collins function (moment)

Twist-3 FF

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

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

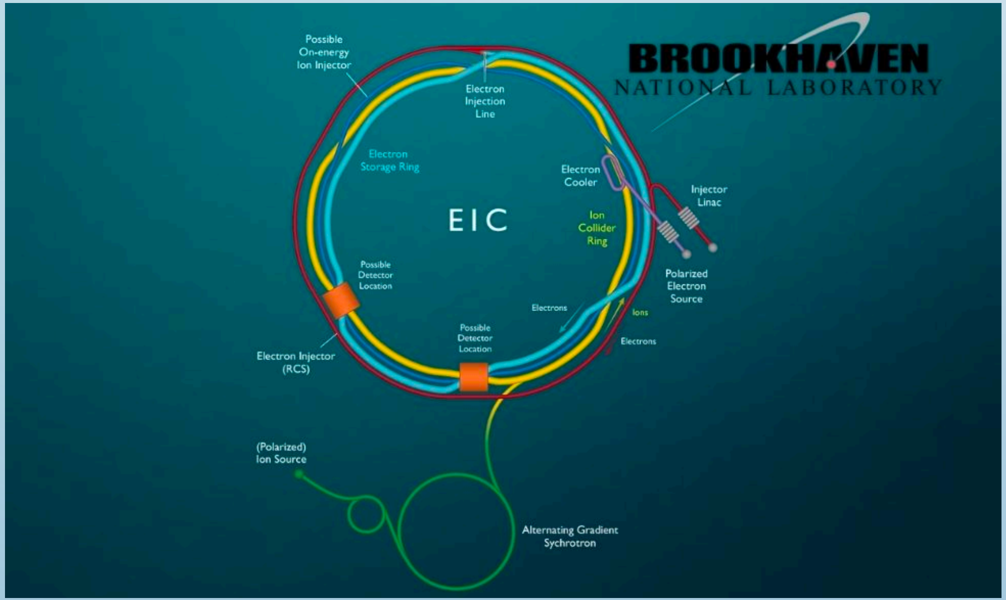


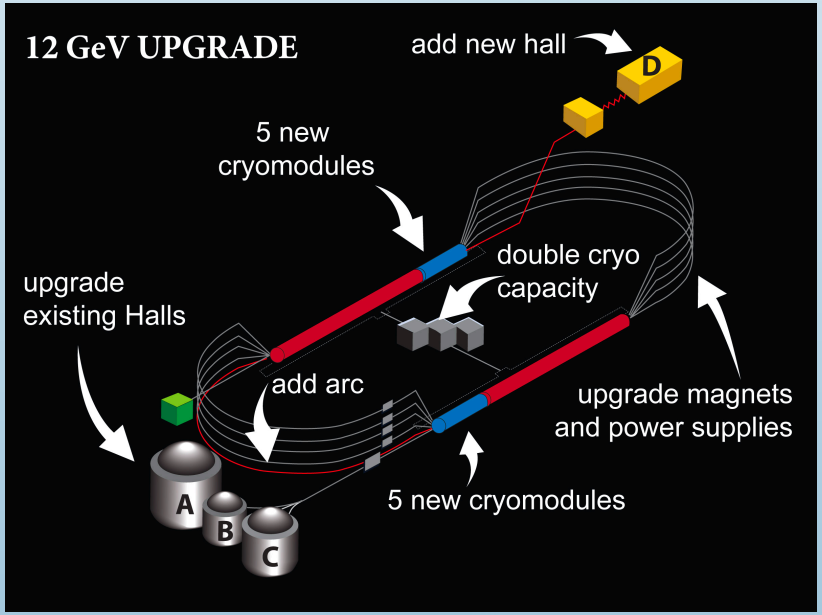


Outlook

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

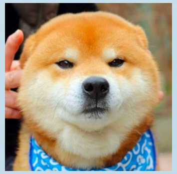
Wally Melnitchouk

Nobuo Sato

Jefferson Lab Angular Momentum Collaboration

www.jlab.org/theory/jam

Thank you to Jacob Ethier, Yiyu Zhou, and Patrick Barry for helpful discussions

Backup

Parameters to Observables

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

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

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

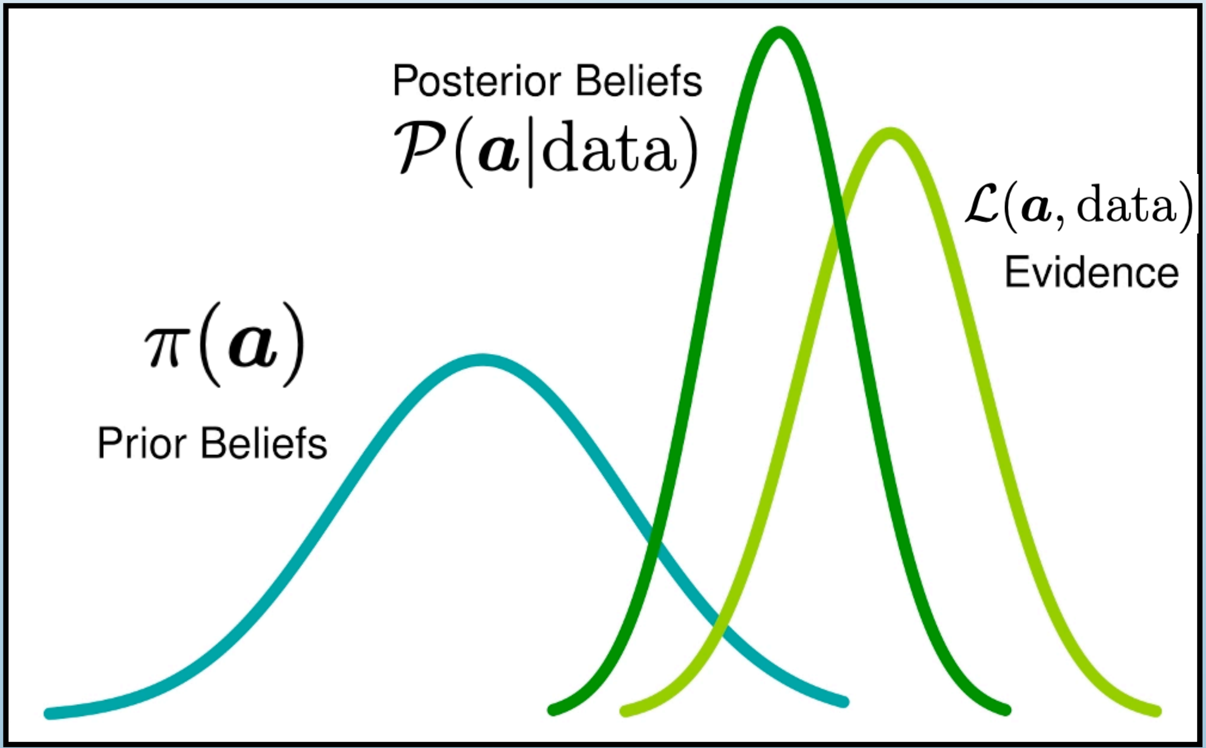
Now that we have calculated $\chi^2(\boldsymbol{a}, \text{data})$…

Likelihood Function

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

Bayes' Theorem

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

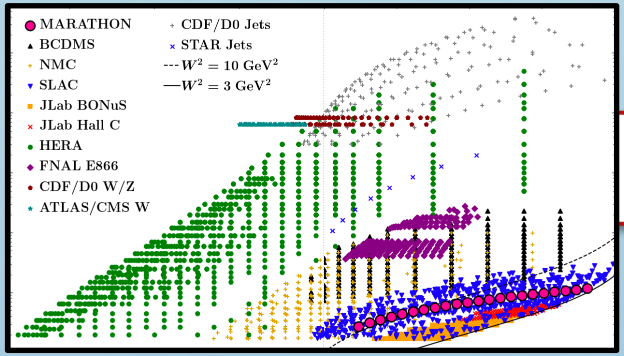


Data Resampling

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

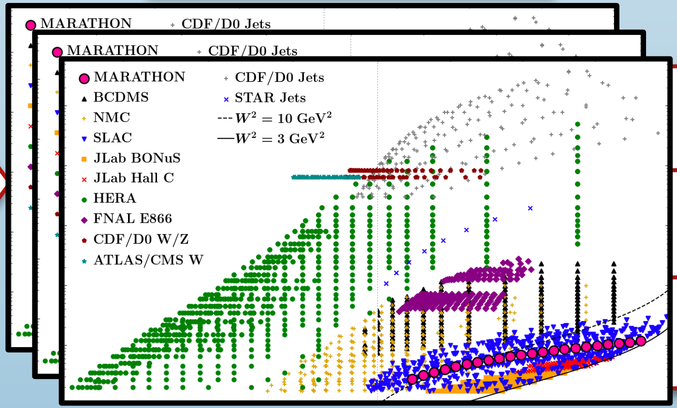
Data

Original Data



DR

Replica Data

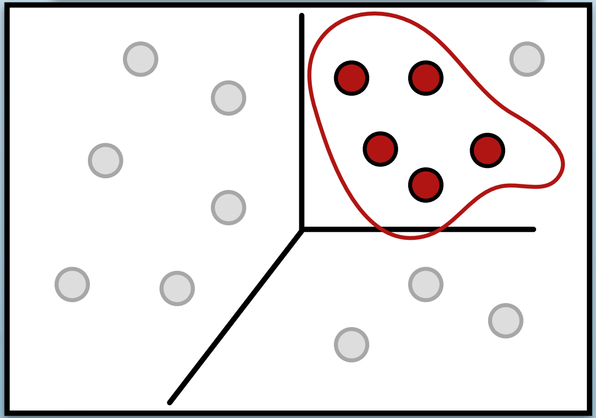


Maximum Likelihood

Maximum Likelihood

Maximum Likelihood

Parameter Space



Error Quantification

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

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

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

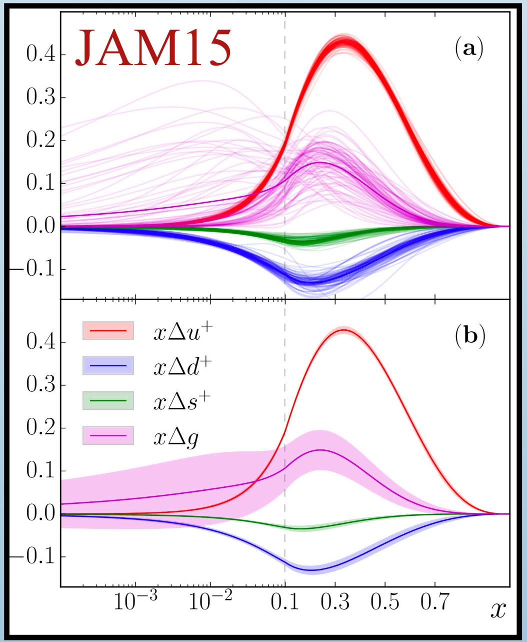
Exact, but
$n = \mathcal{O}(100)$!

Build an MC ensemble

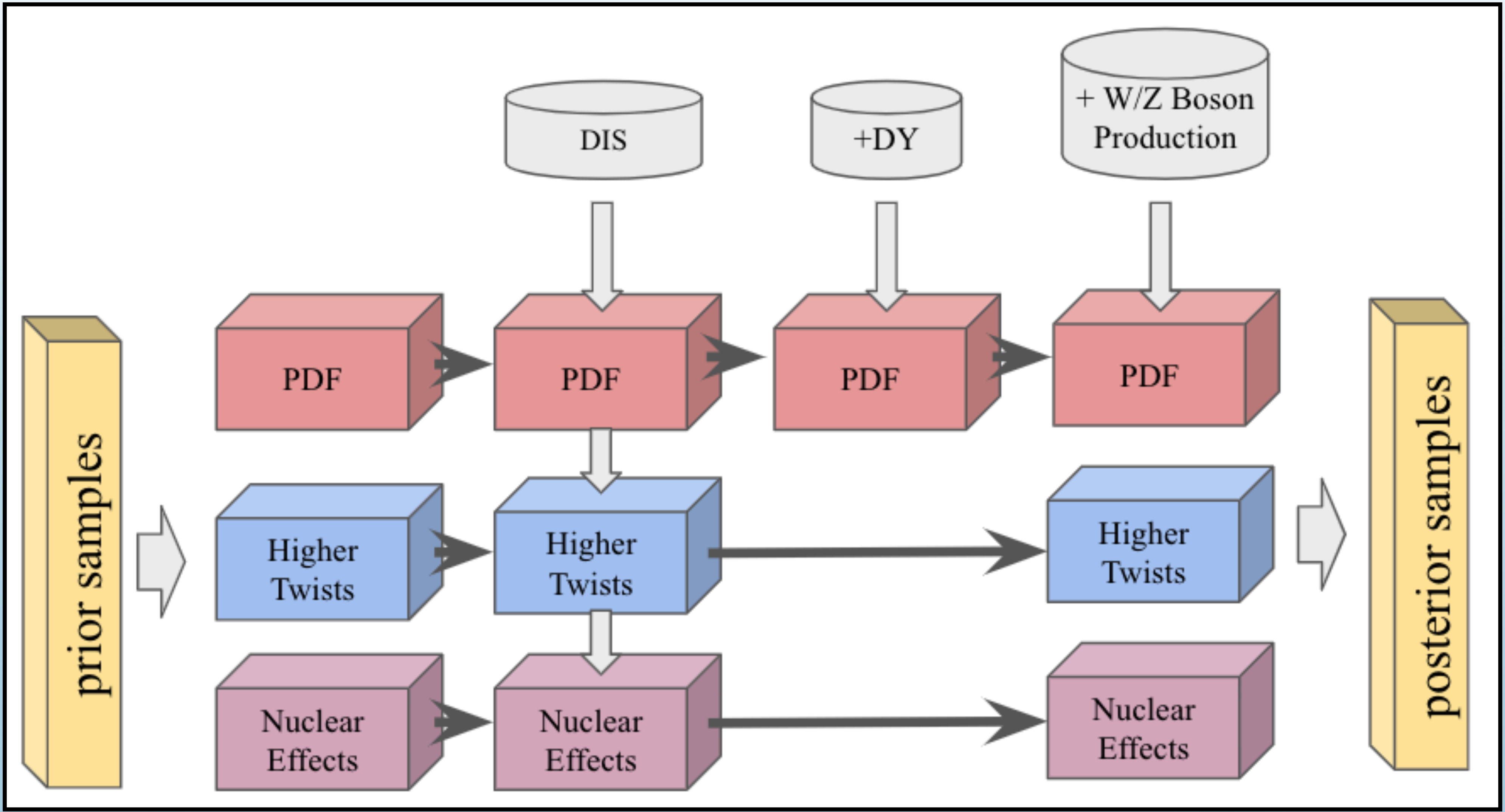
$$E[O] \approx \frac{1}{N} \sum_k O(\boldsymbol{a}_k)$$

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

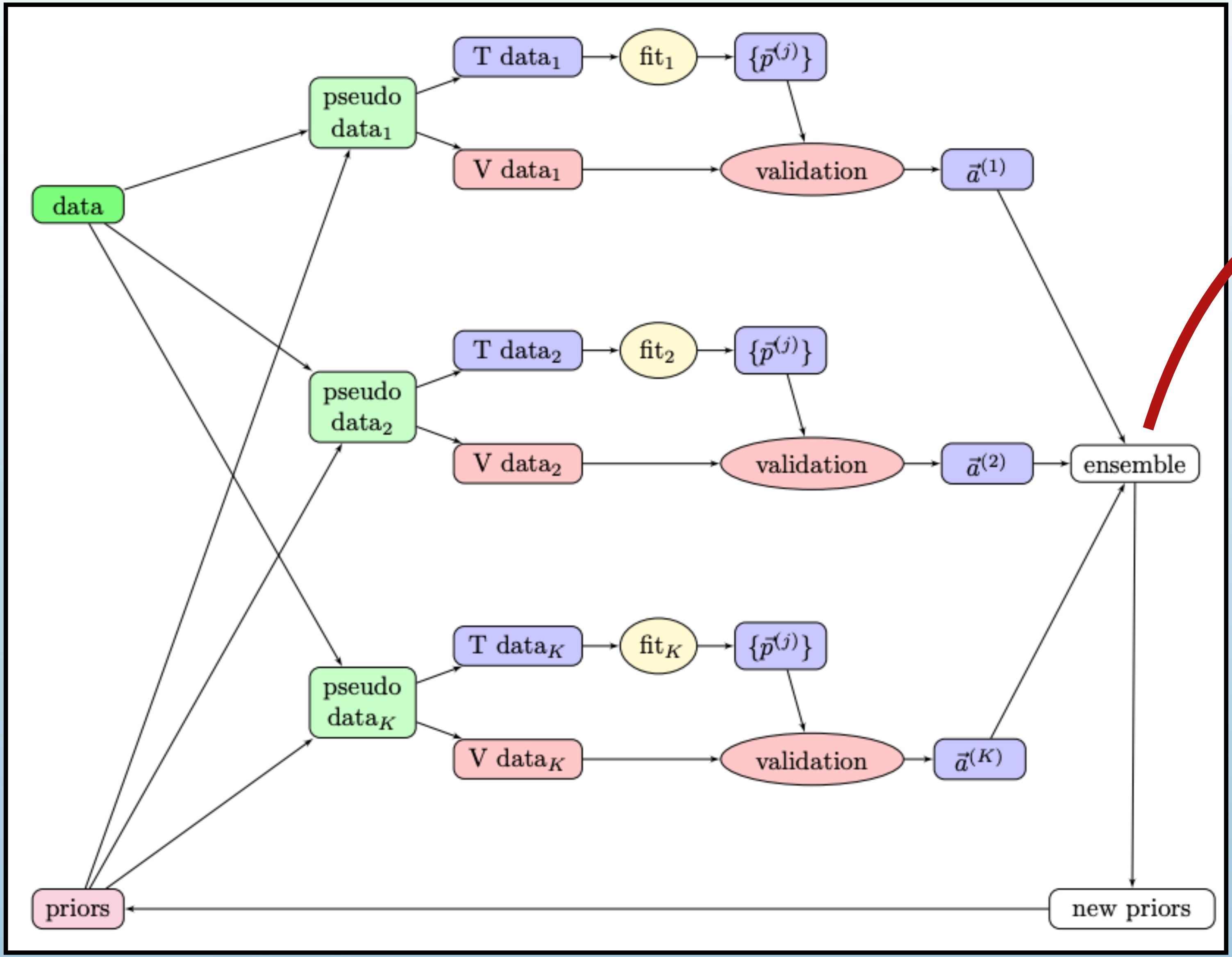
Average over k sets of the parameters (replicas)

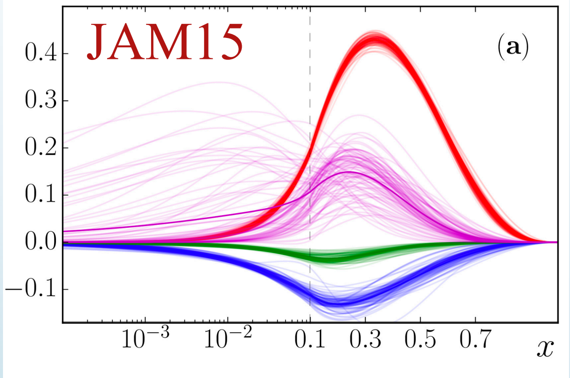


Multi-Step Strategy



Putting it all together…

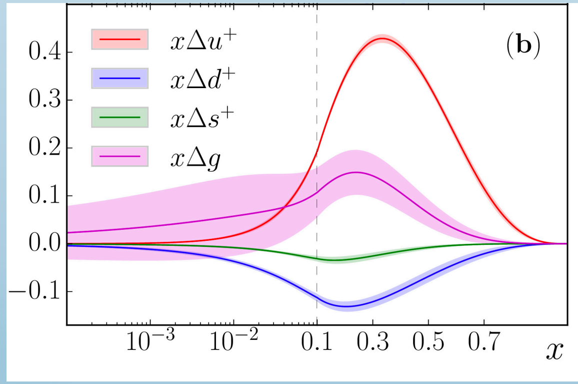




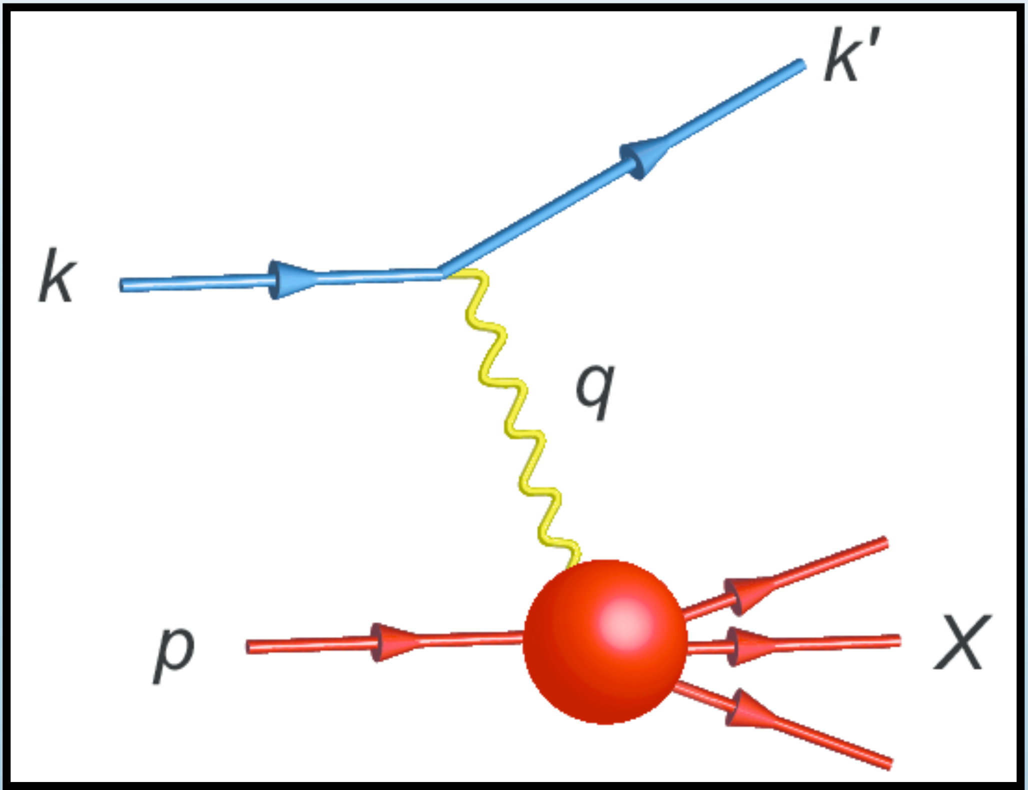
+

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

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



Deep Inelastic Scattering



Virtuality:

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

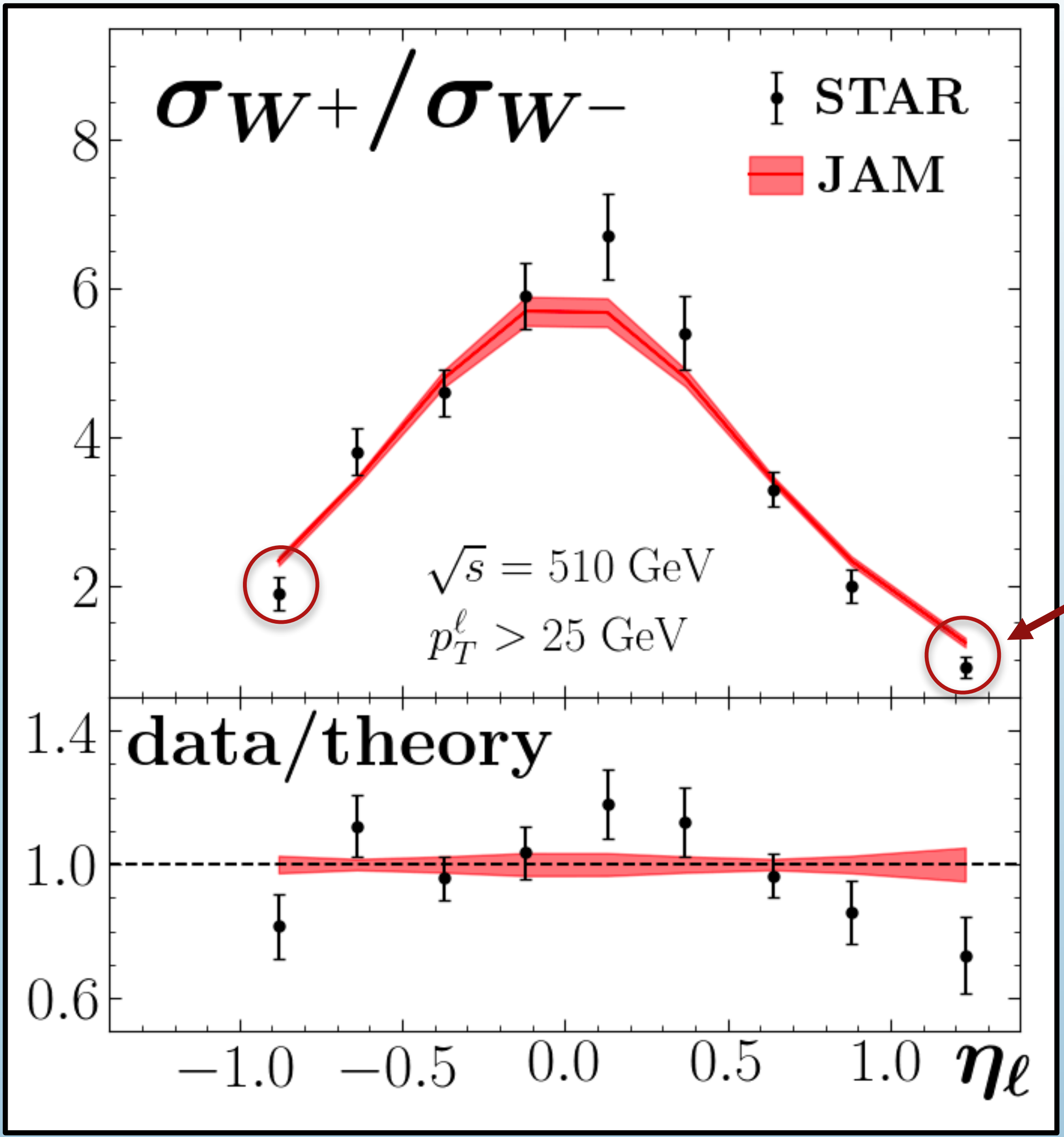
Bjorken x:

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

Invariant mass of outgoing particles:

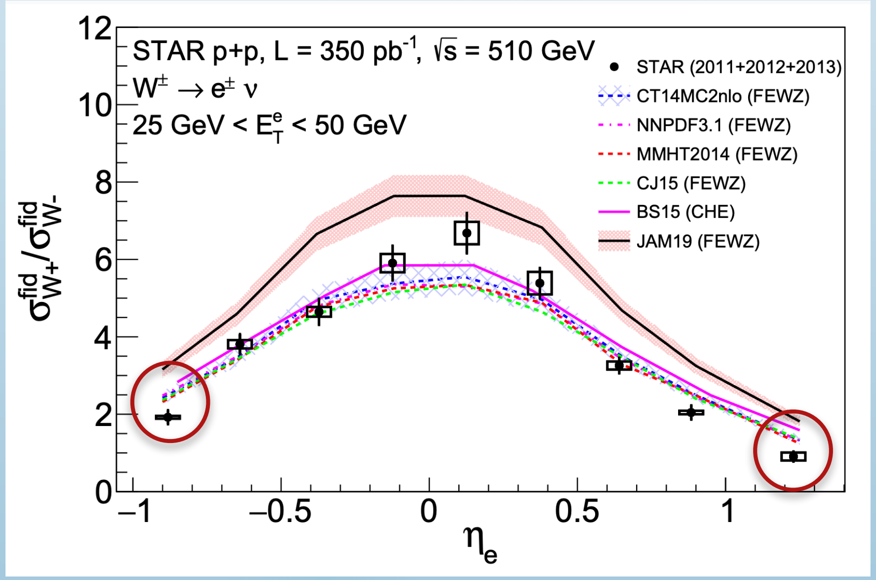
$$W^2 = (p+q)^2$$

STAR Quality of Fit



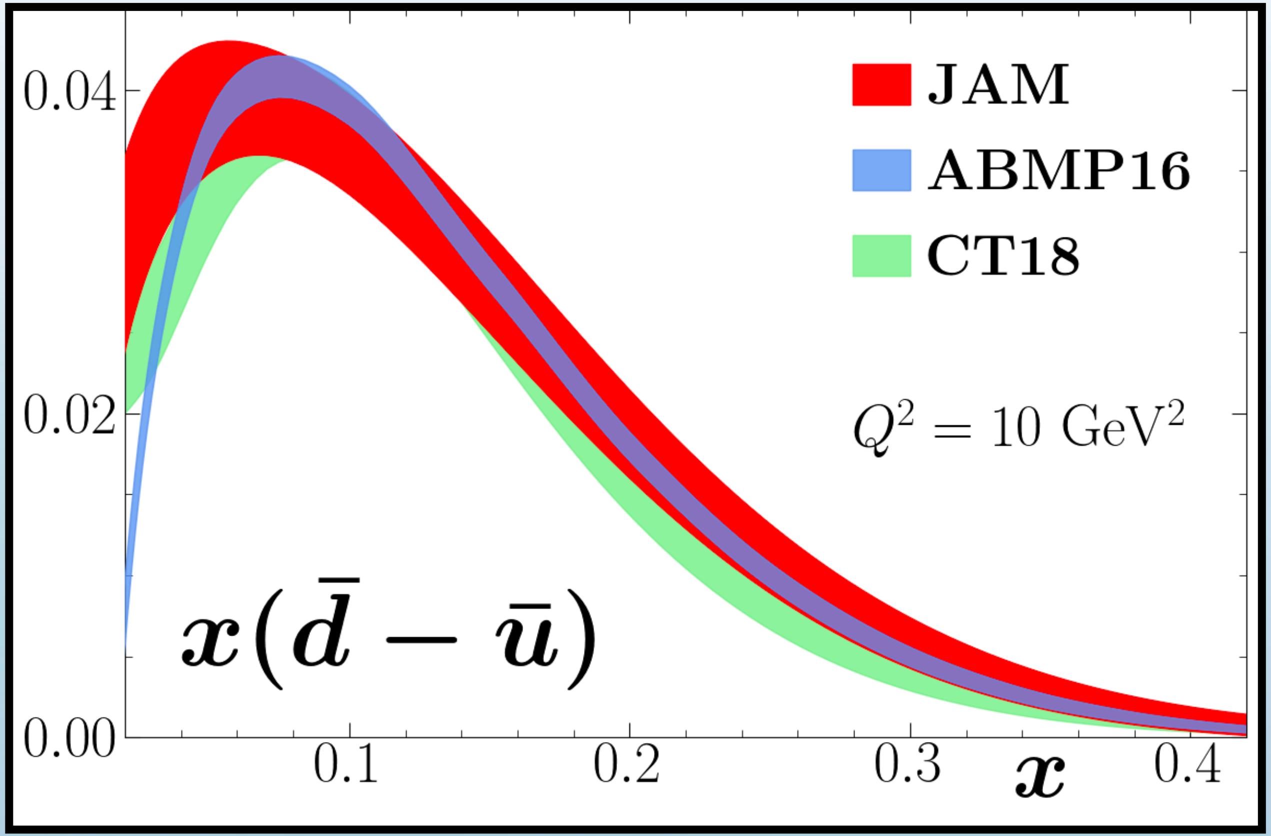
process	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
W-lepton		
STAR W^+/W^-	9	2.02

Difficult to describe at extreme rapidity



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

Introduction to Sea Asymmetry



Unpolarized

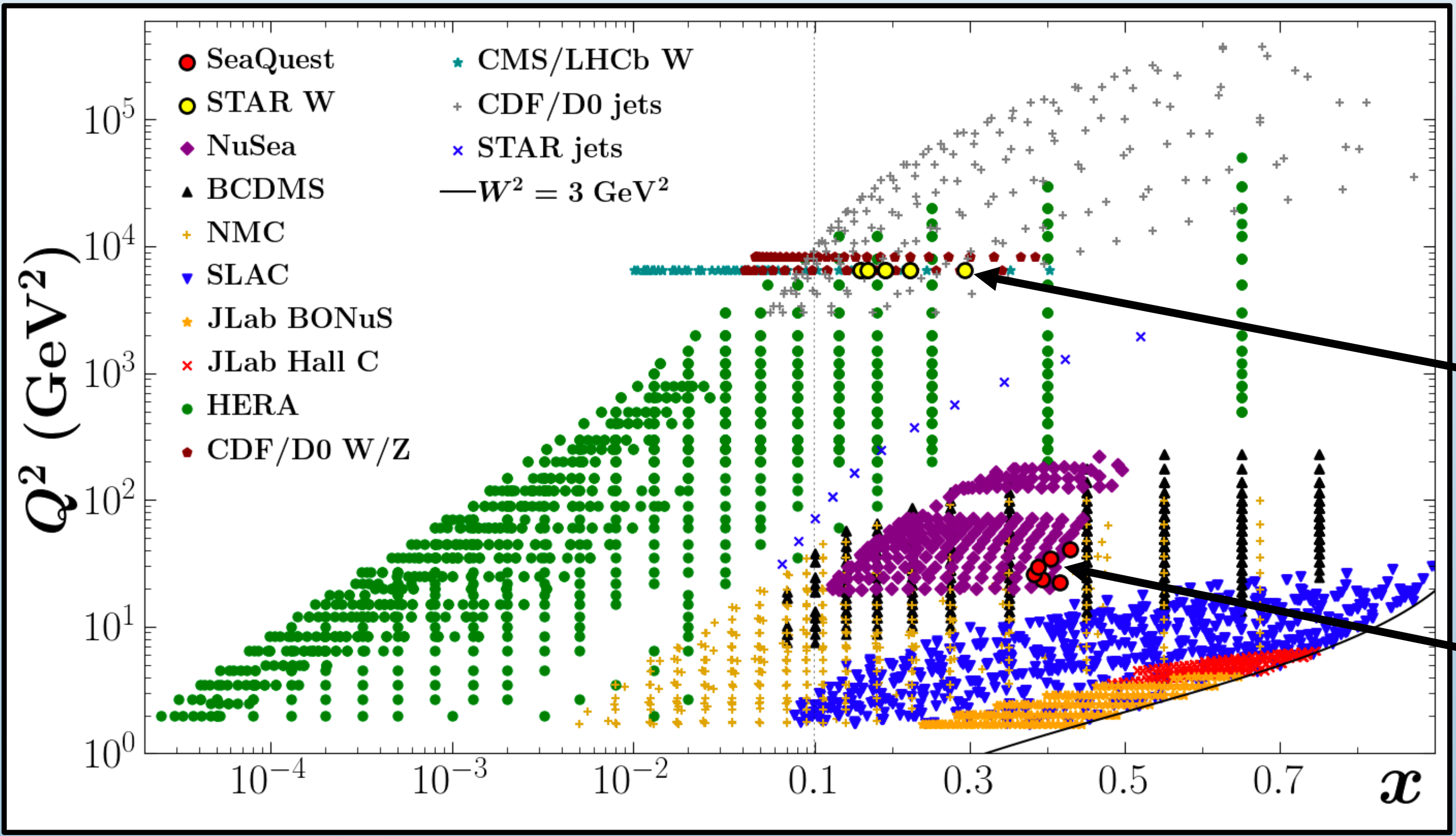
Cannot be explained from gluons splitting into quark-antiquark pairs

Meson Cloud Models
Chiral Soliton Models
Statistical Models

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

Kinematic Coverage (Spin-Averaged)

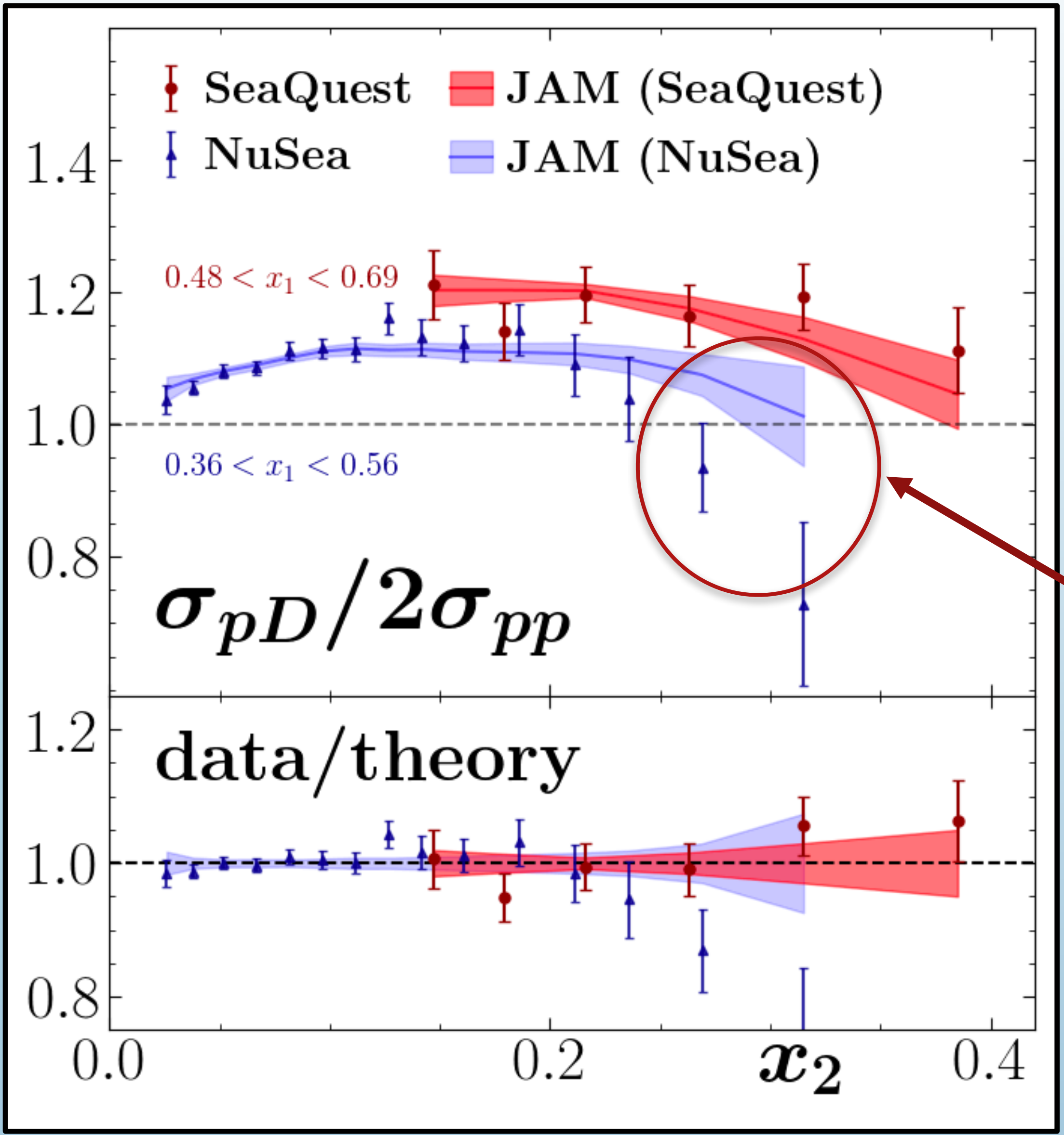
Deep Inelastic Scattering	BCDMS, NMC, SLAC, HERA, Jefferson Lab	3863	points
Drell-Yan	Fermilab E866, E906	205	points
W/Z Boson Production	CDF/D0, STAR, LHCb, CMS	153	points
Jets	CDF/D0, STAR	200	points



New STAR data

New SeaQuest data

SeaQuest and NuSea Quality of Fit

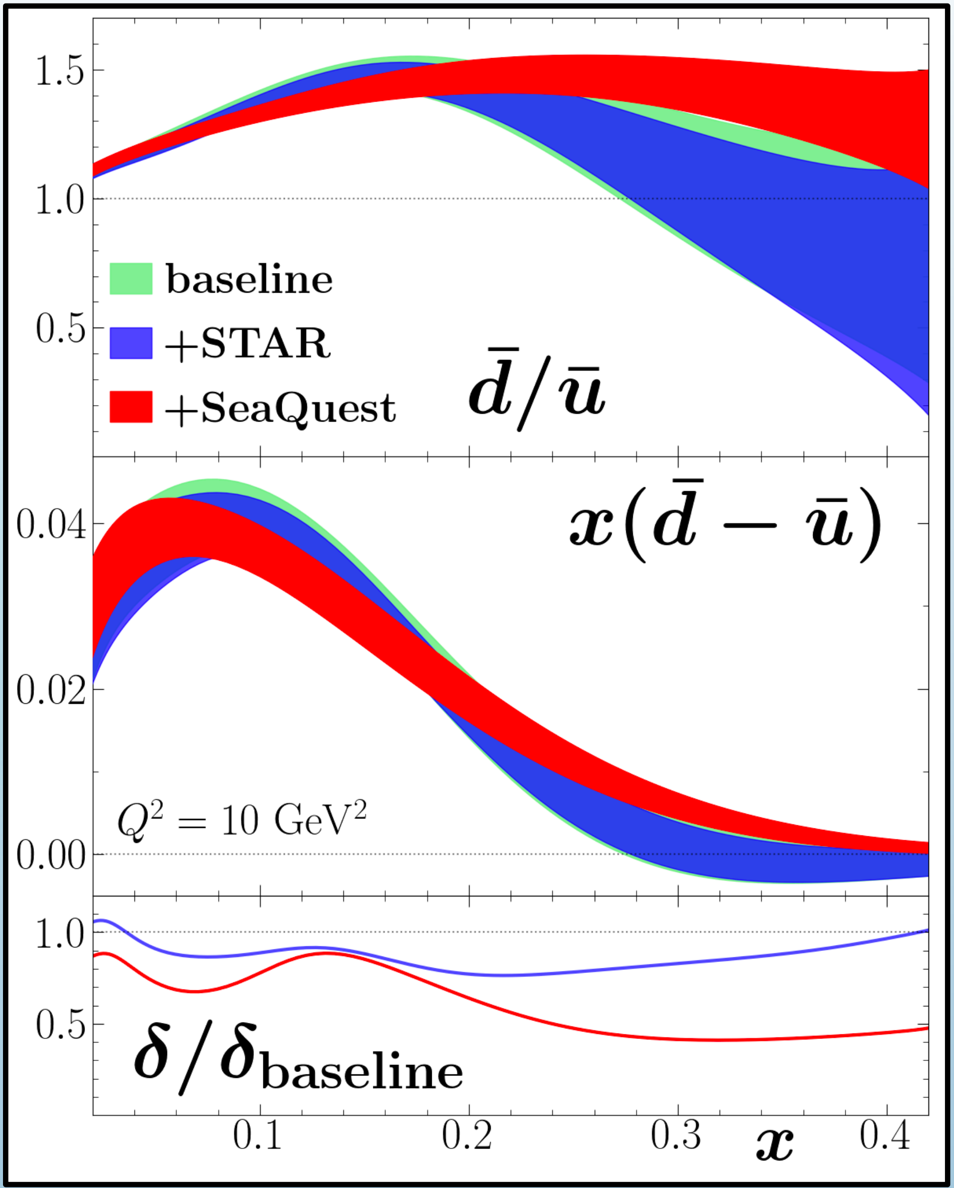


process		$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
Drell-Yan			
NuSea	pp	184	1.21
NuSea	$pD/2pp$	15	1.30
SeaQuest	$pD/2pp$	6	0.82

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

Well-known tension between NuSea and SeaQuest

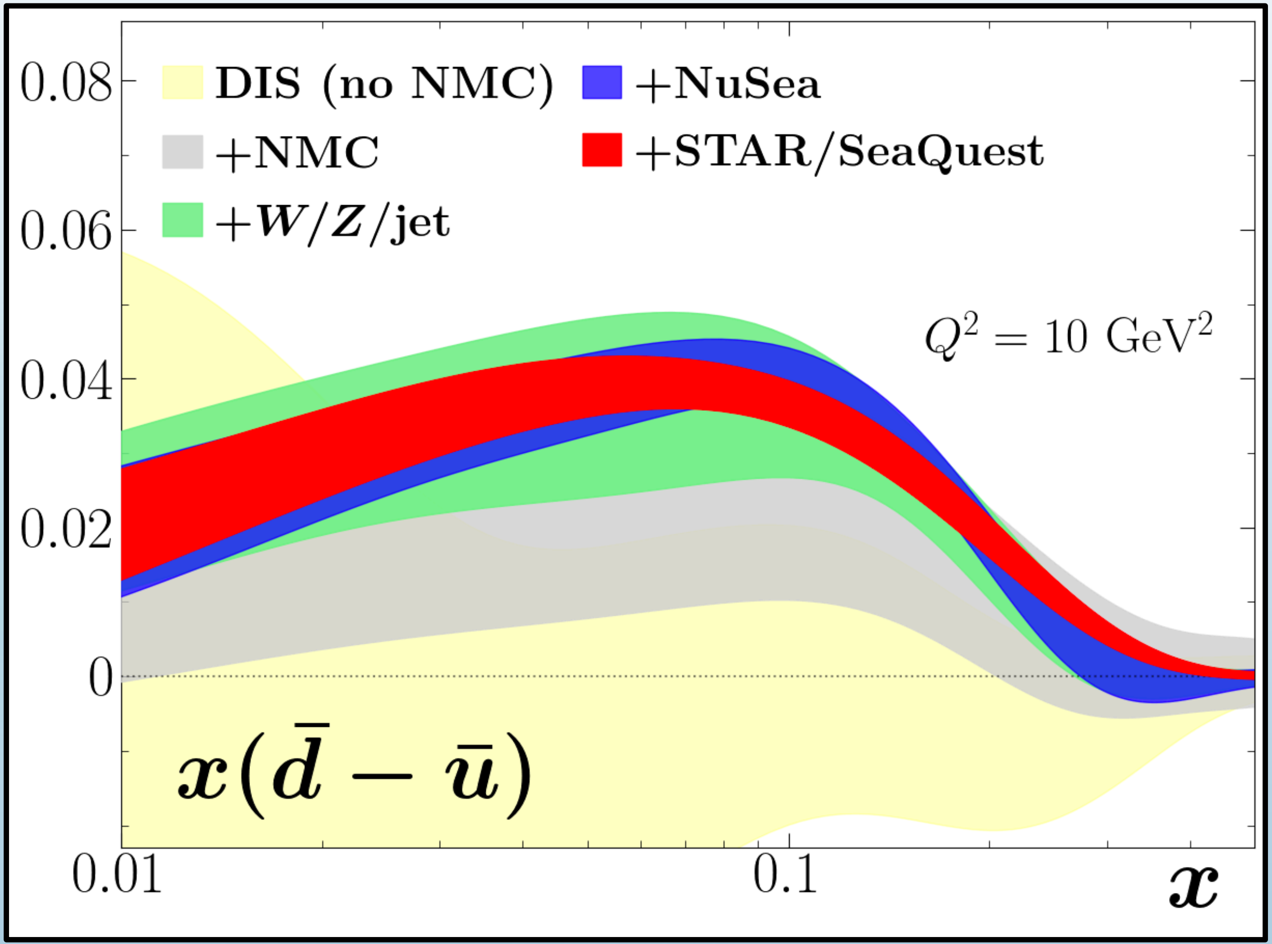
Impact from STAR and SeaQuest

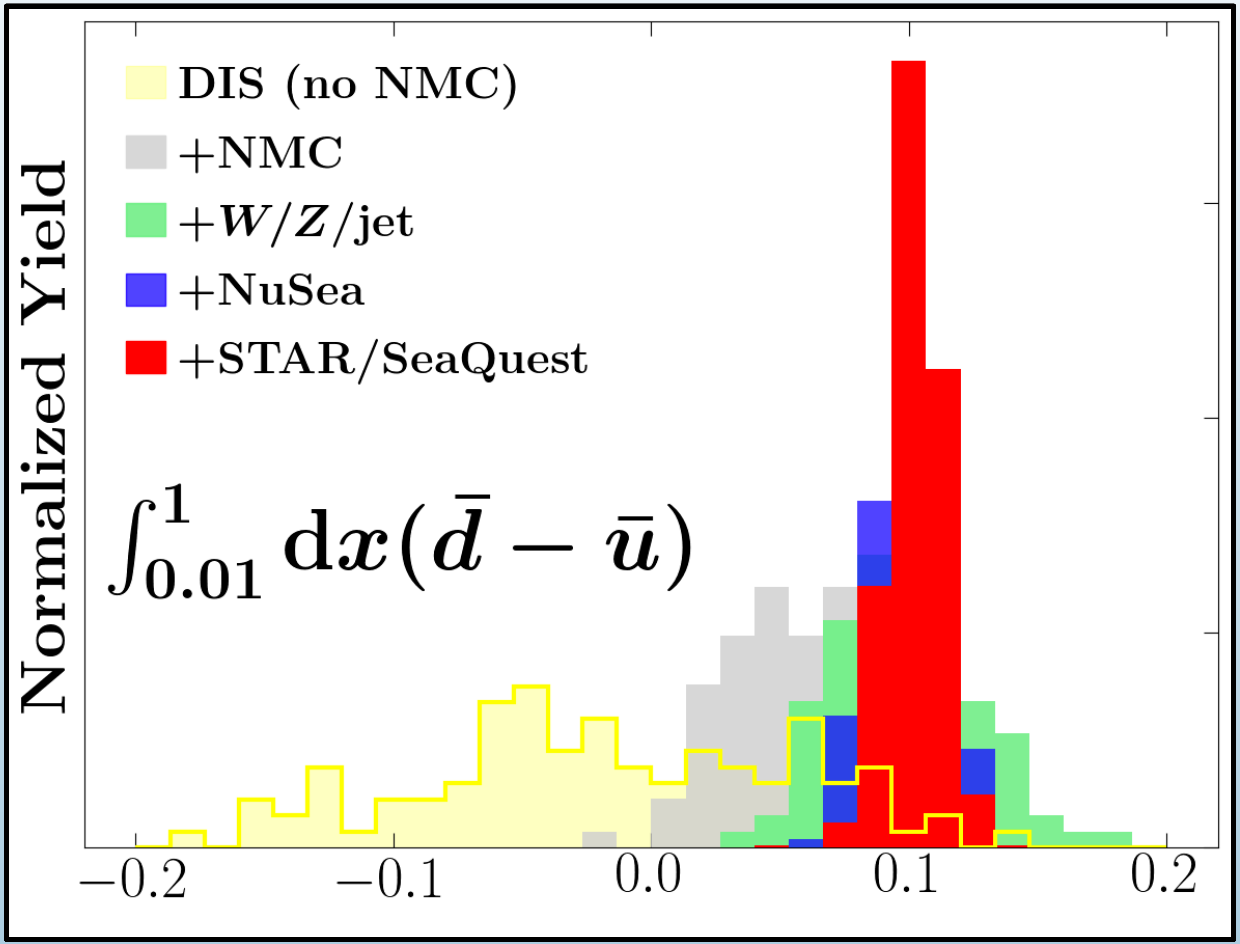


STAR: Moderate reduction of uncertainties

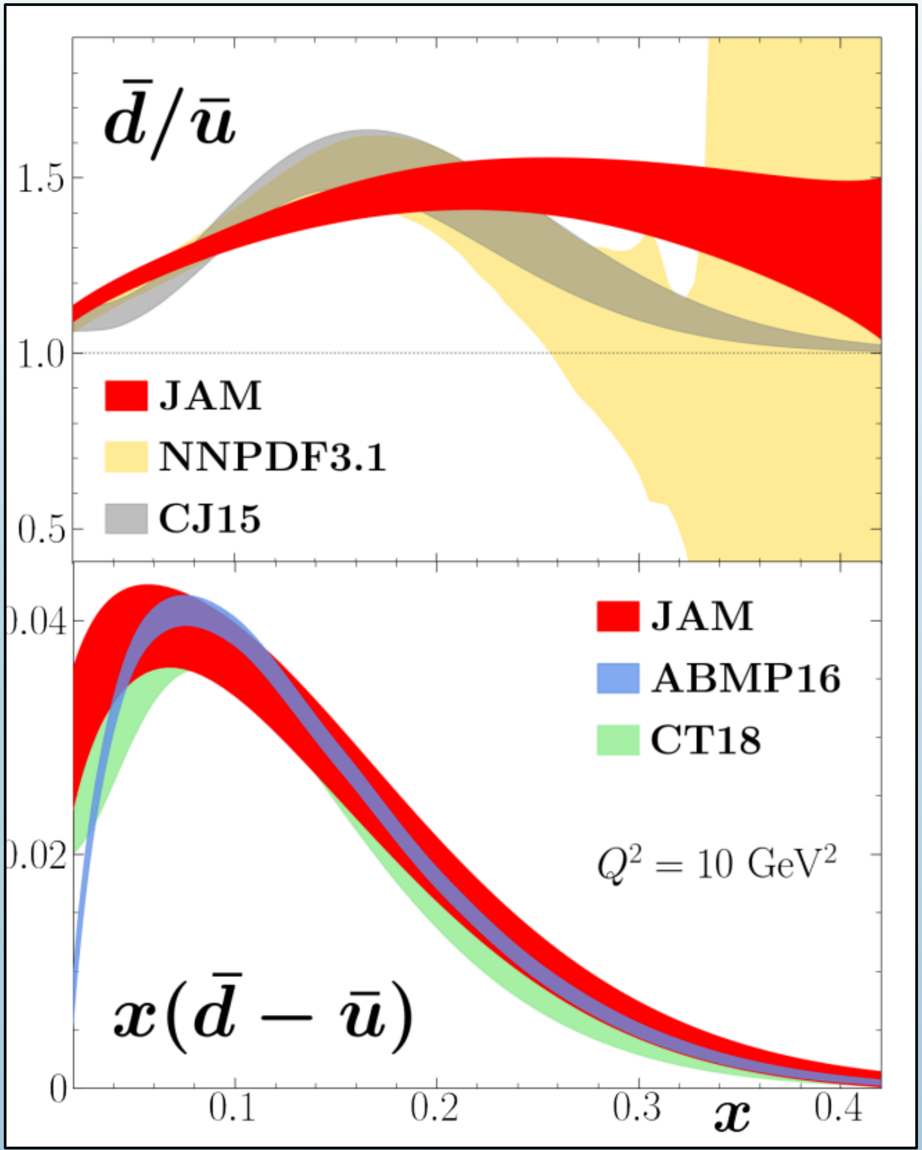
SeaQuest: Large reduction of uncertainties, especially at $x > 0.2$.
$\bar{d}/\bar{u} > 1$ up to $x \approx 0.4$, in agreement with models

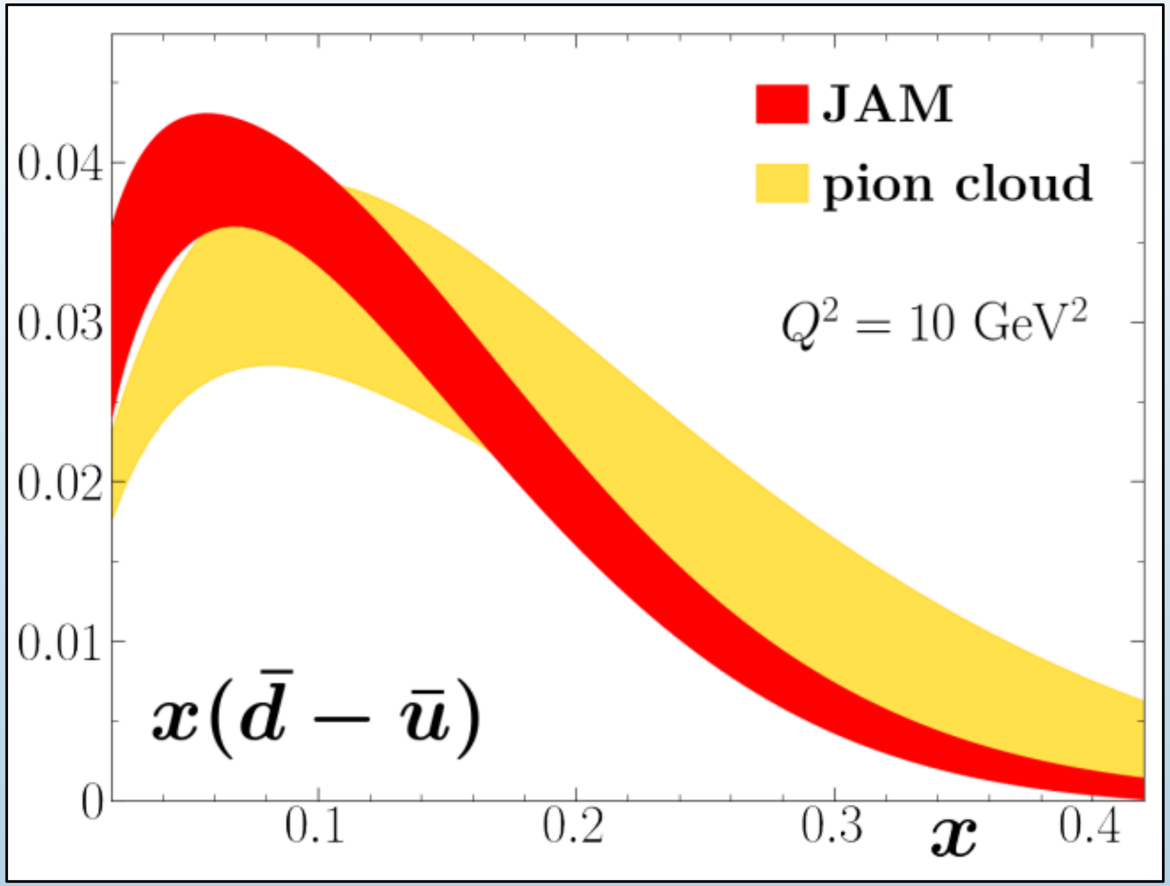
Sources of Asymmetry





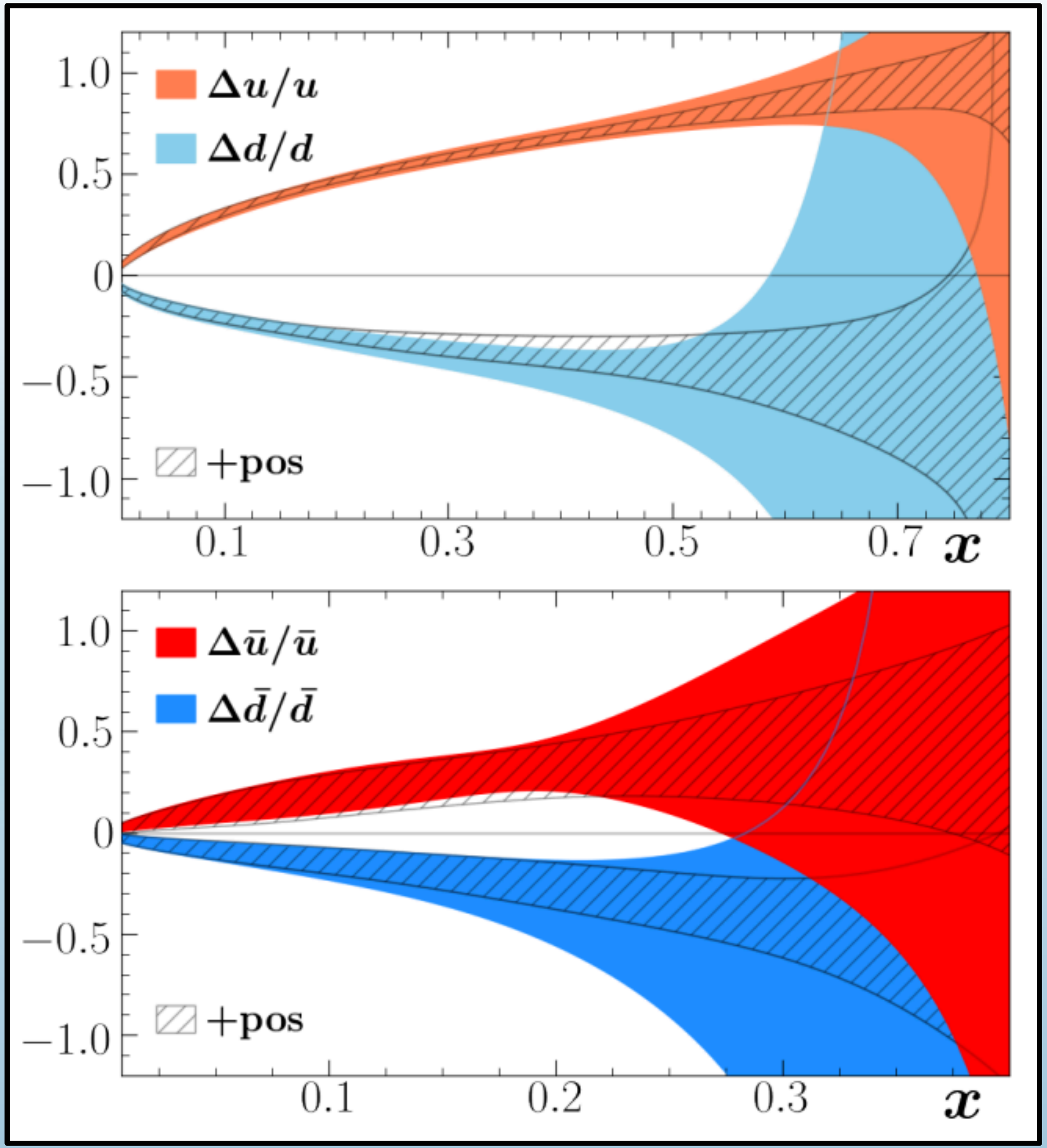
Comparison to other fits and pion cloud model



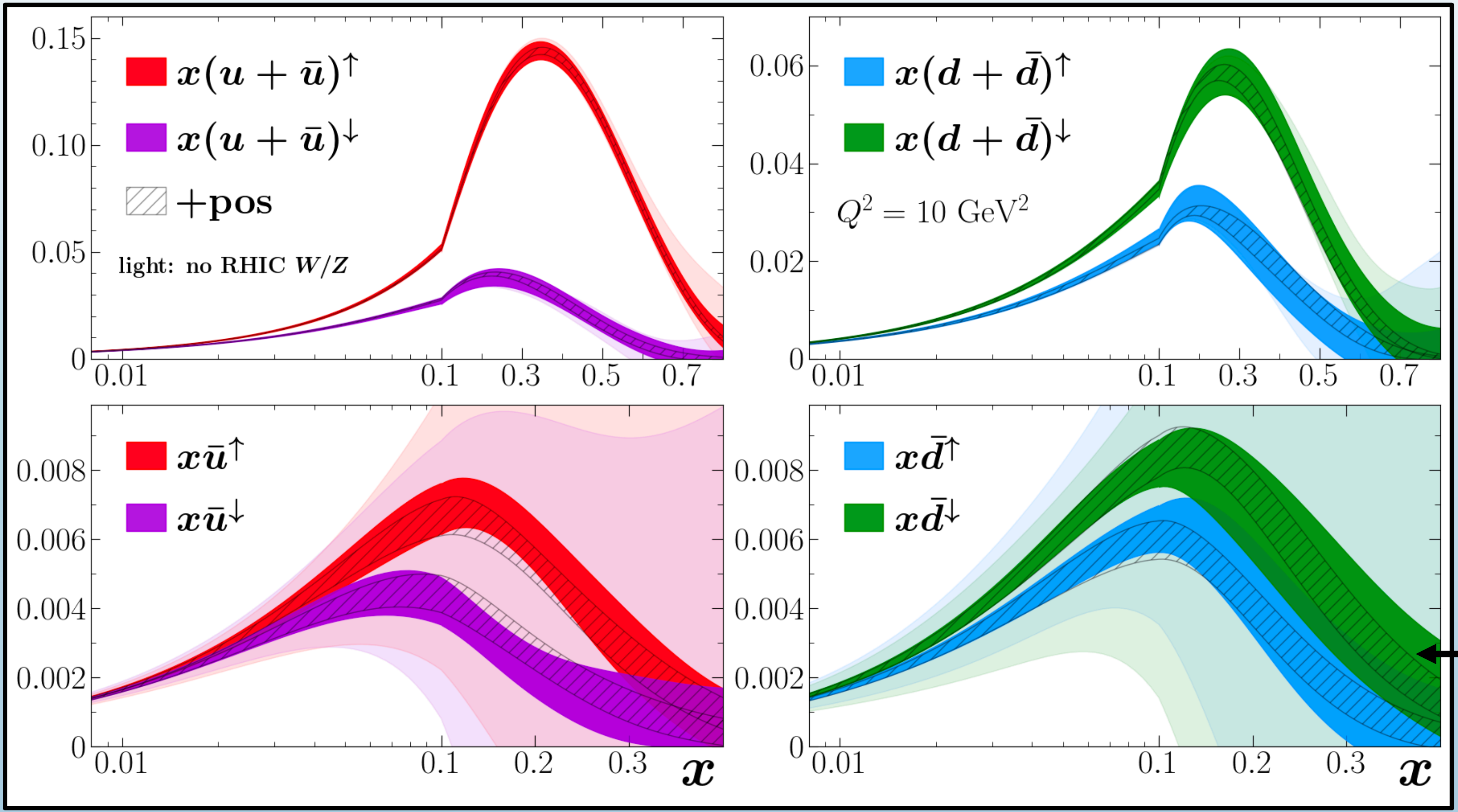


Good agreement with pion cloud model

Quark and Antiquark Polarizations



Spin Up/Down PDFs

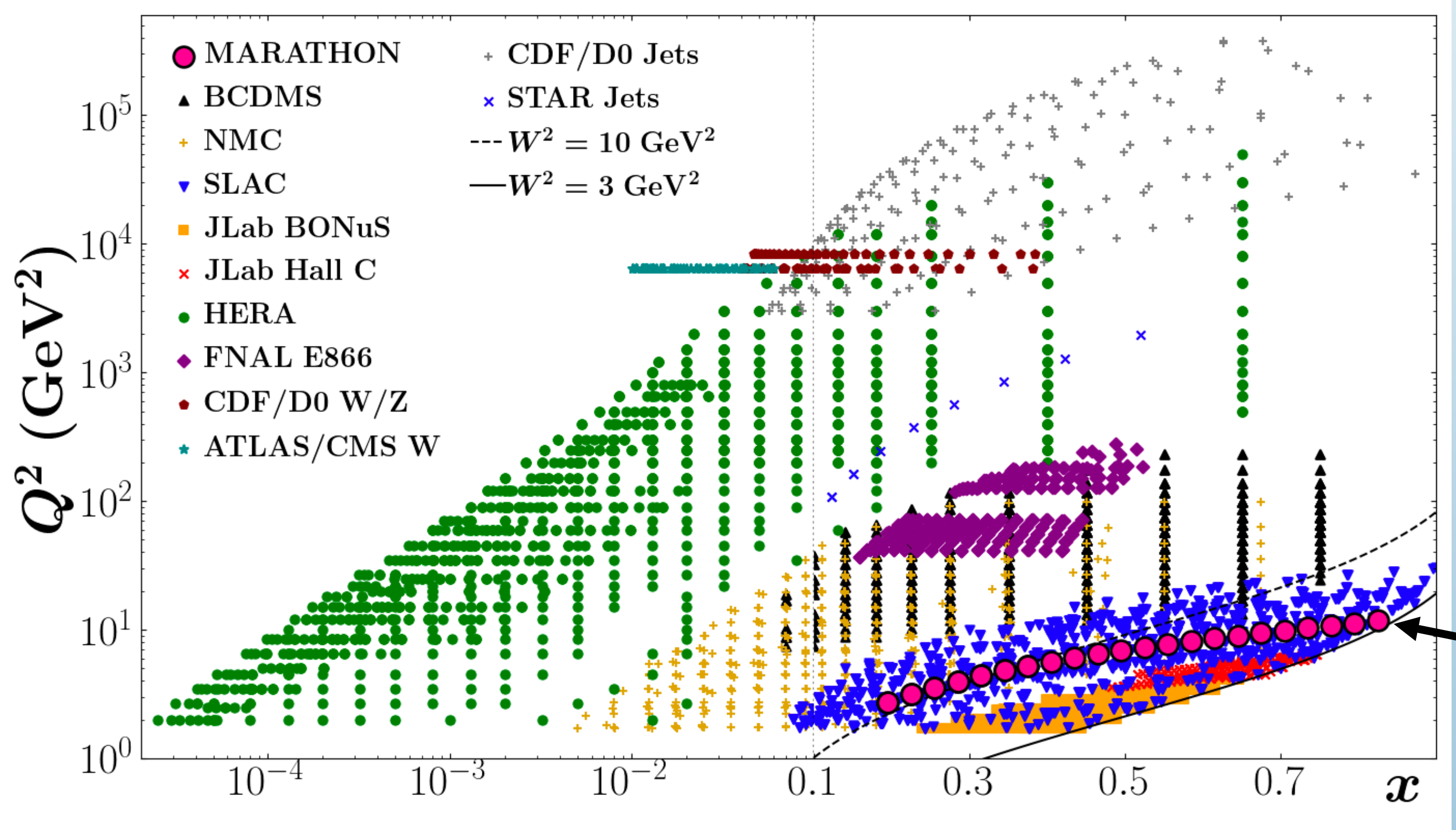


$$q^{\uparrow\downarrow} = \frac{1}{2}(q \pm \Delta q)$$

Large impact from RHIC

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

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

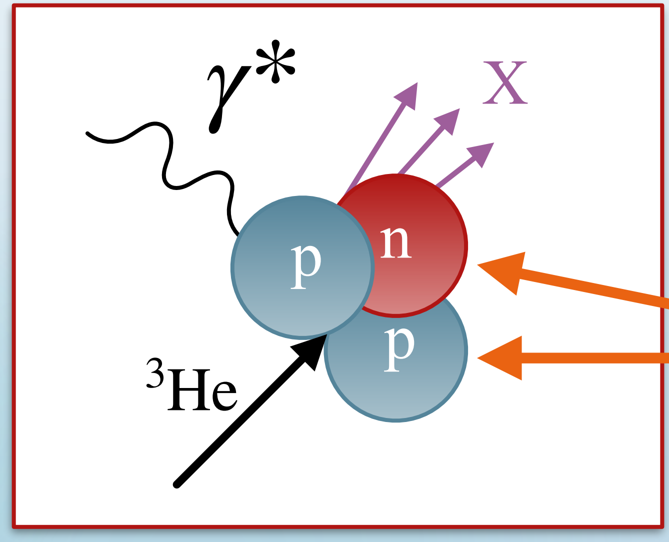
Net Vector Field on Nucleon

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

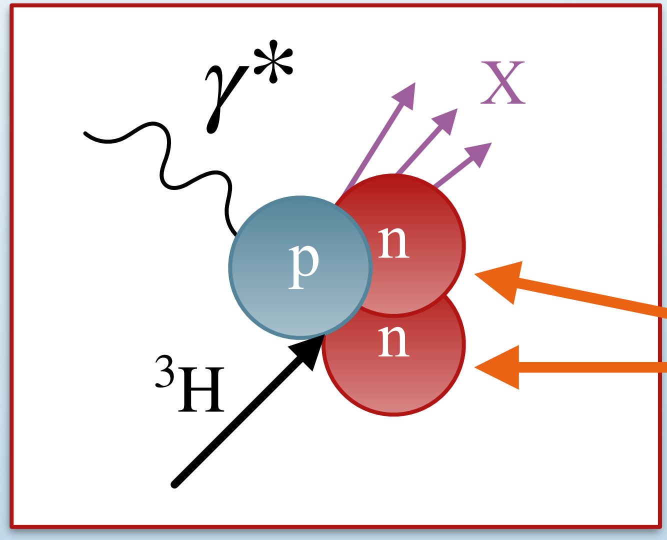
Isovector Effect

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

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

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

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

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

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

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

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

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!

Nuclear PDFs

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

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

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

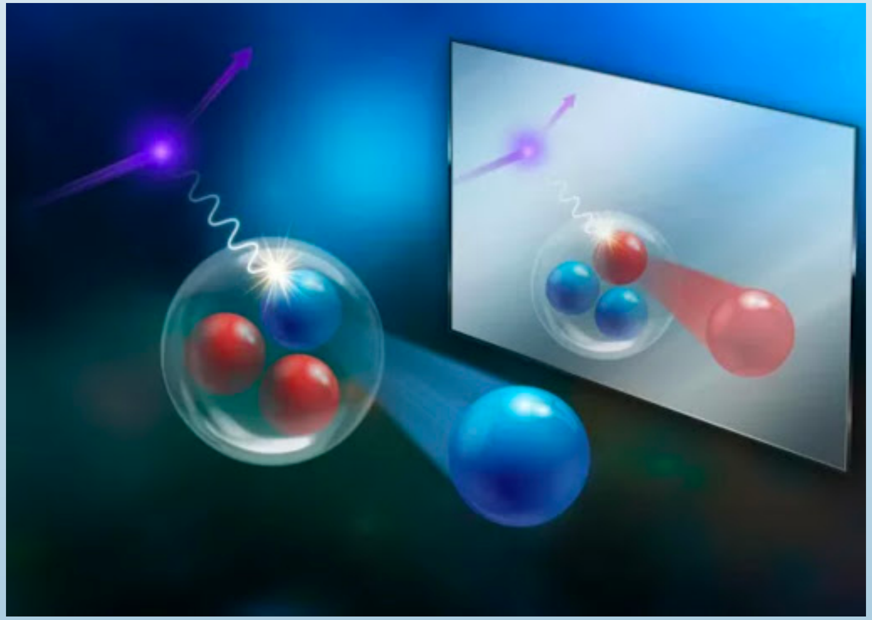
Impact from MARATHON

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

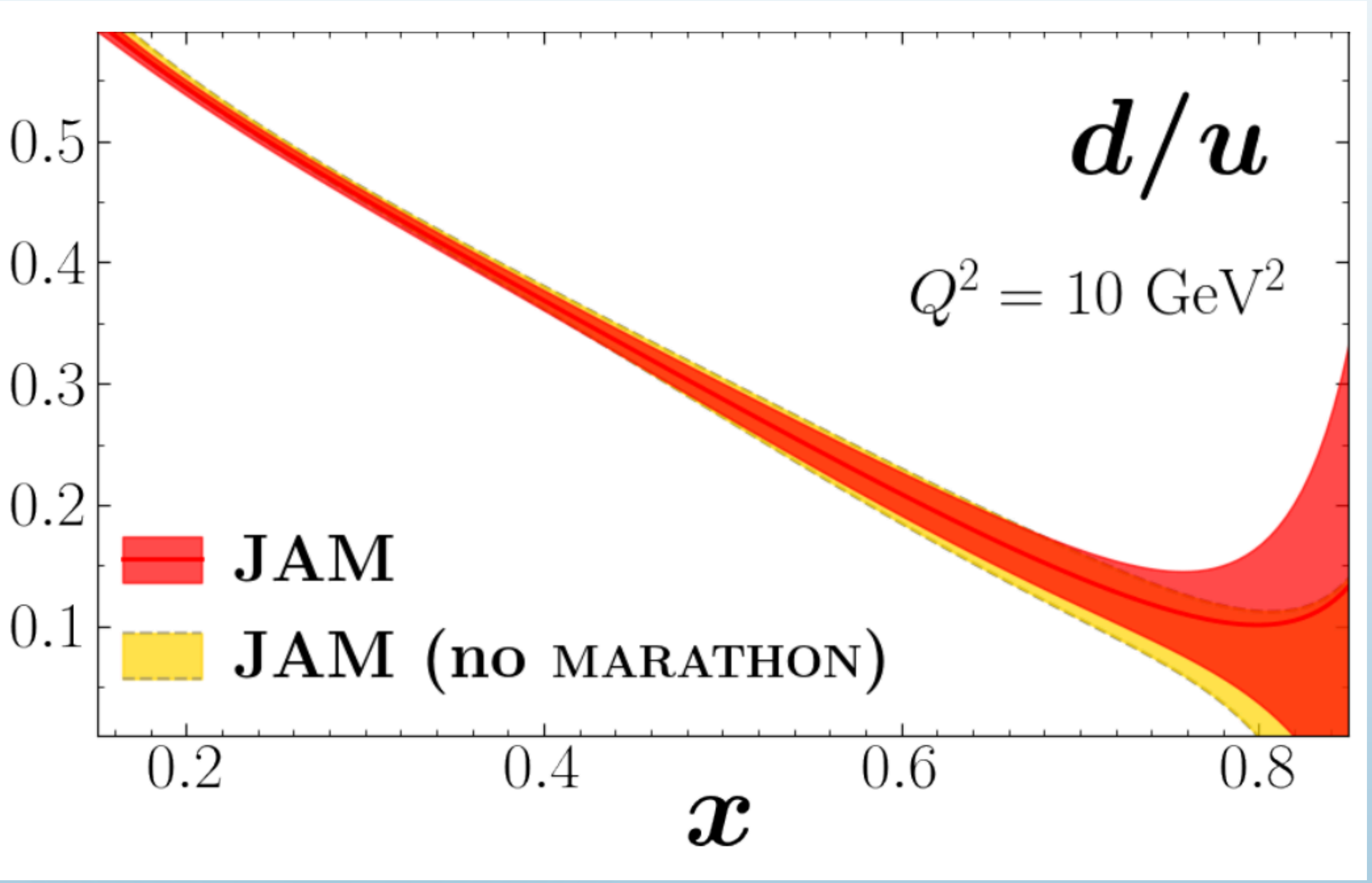
d/u Ratio ?

F_2^n/F_2^p Ratio ?

$A = 3$ EMC Effects ?

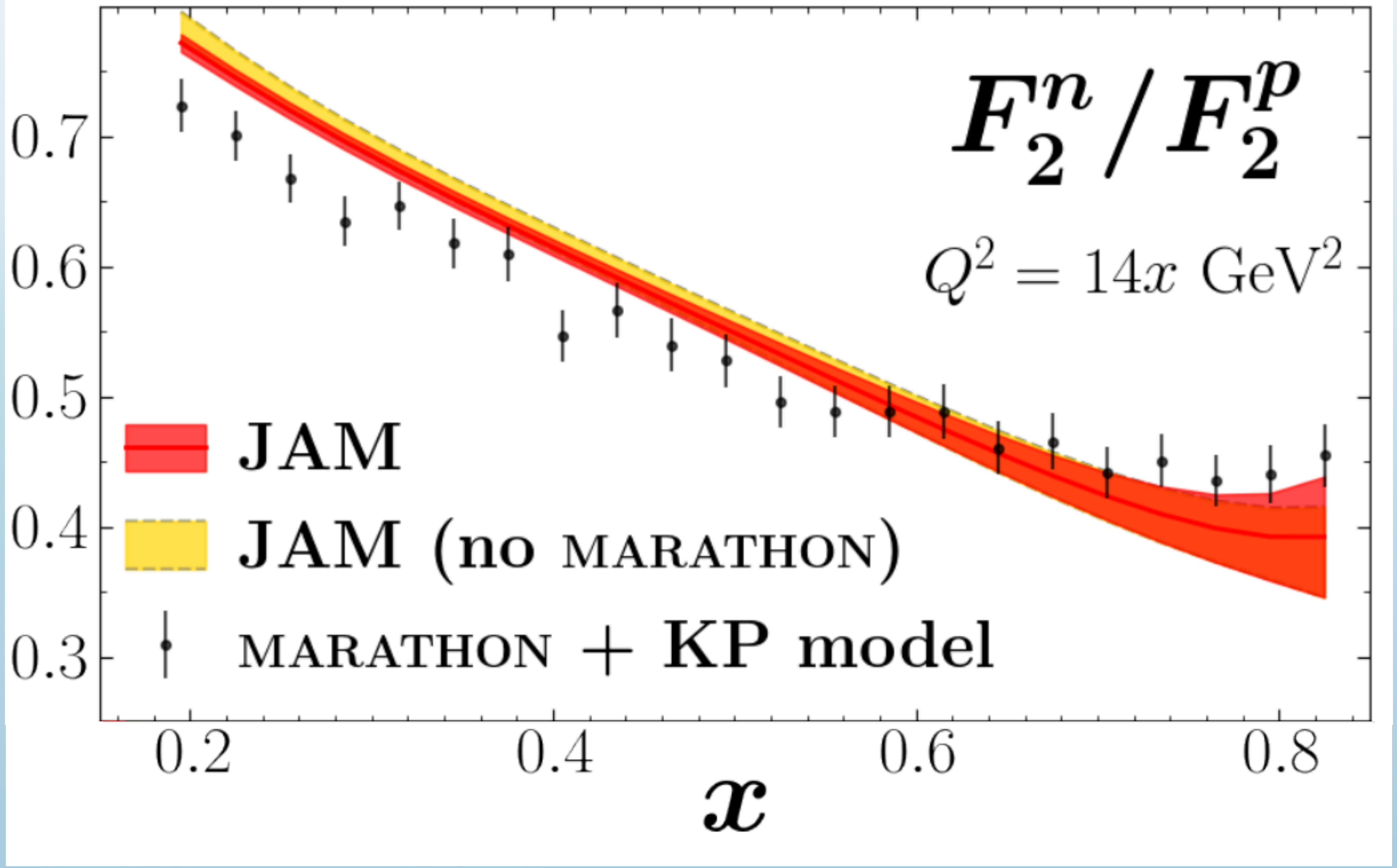


Impact on d/u



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

Impact on F_2^n/F_2^p

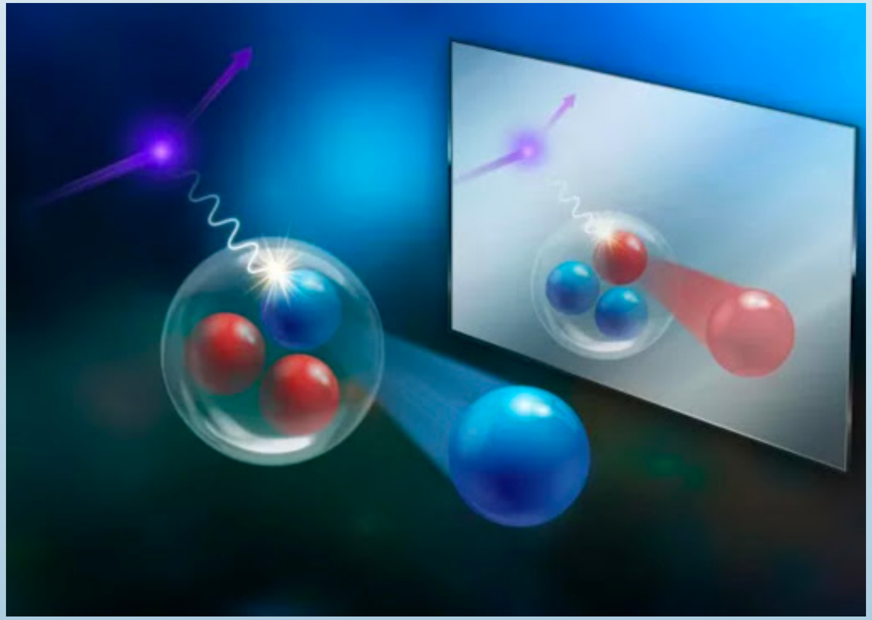


Slight shift towards MARATHON + KP model result

Impact from MARATHON

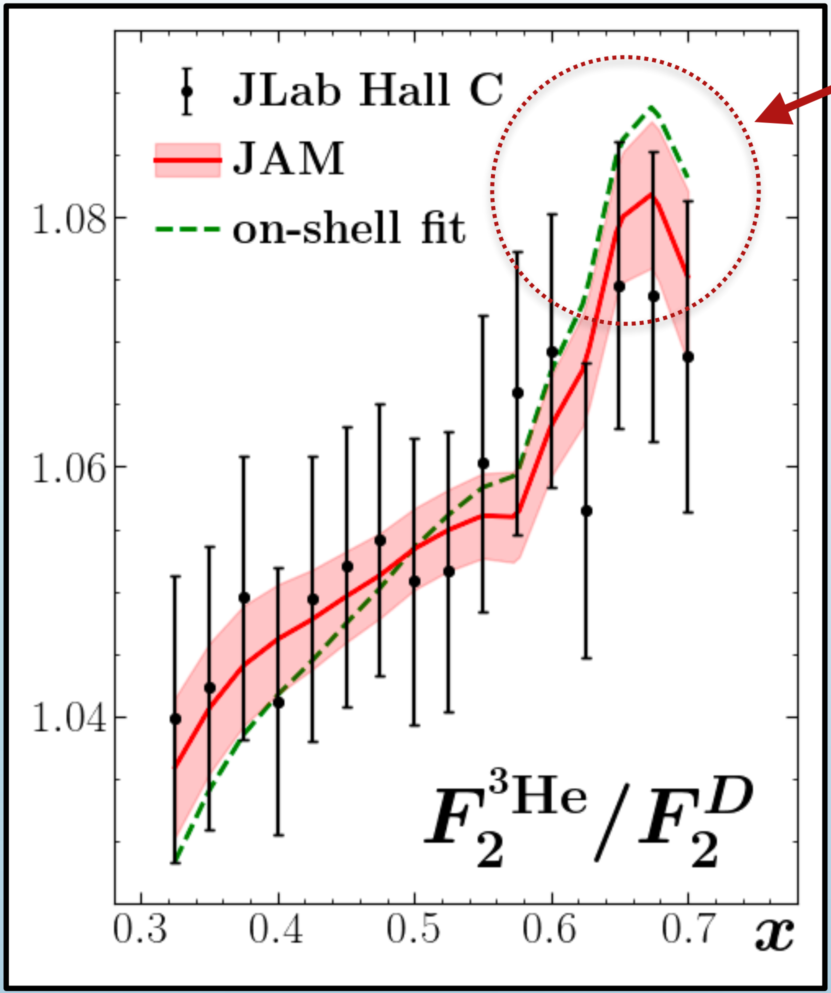
Me**A**surement of the F_2^n/F_2^p, d/u **RA**tios and $A = 3$ EMC Effect in Deep Inelastic Electron Scattering Off the **T**ritium and **H**elium Mirr**O**r **N**uclei

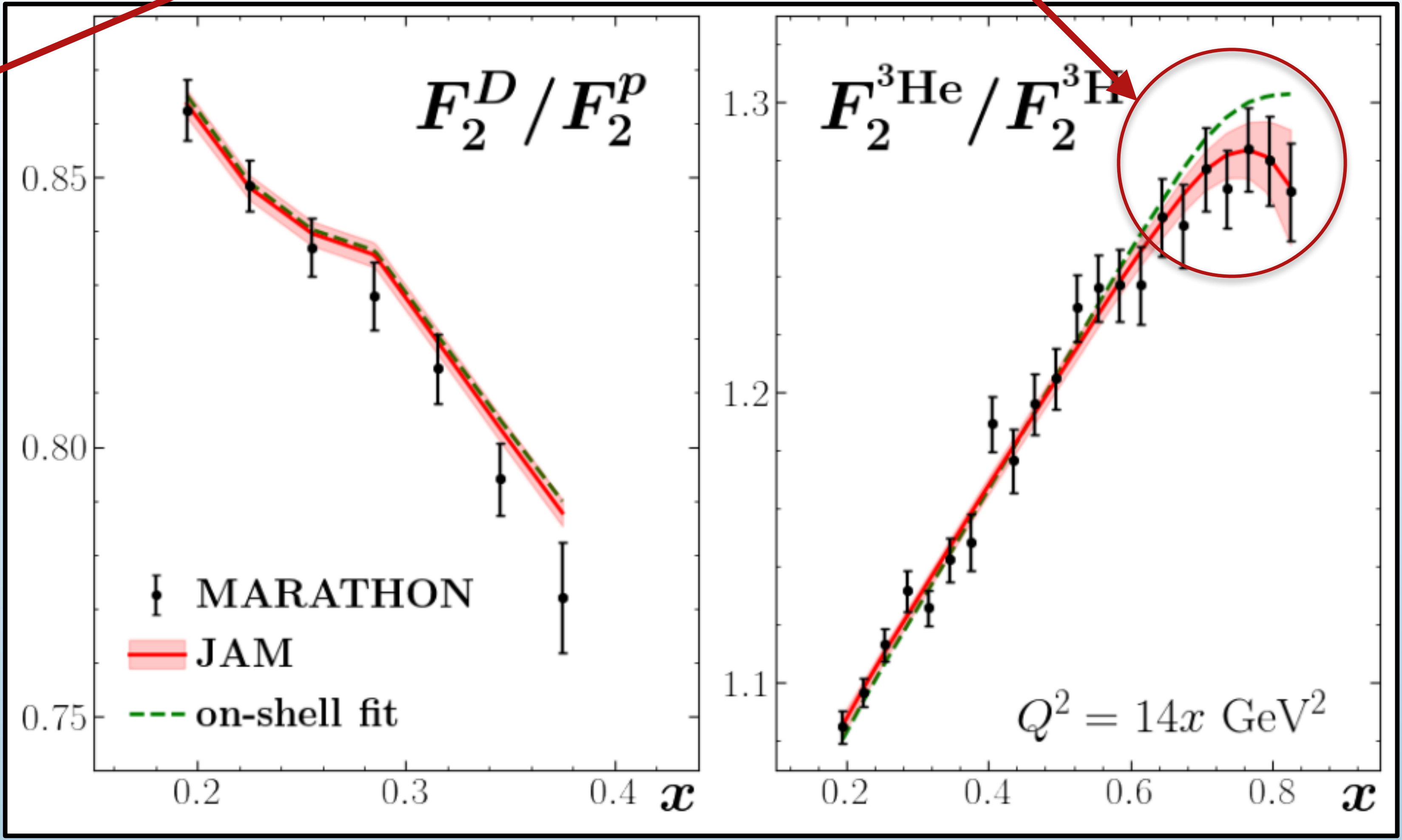
d/u Ratio	~
F_2^n/F_2^p Ratio	~
$A = 3$ EMC Effects	?



Data vs. Theory

Suggestion of off-shell effects!





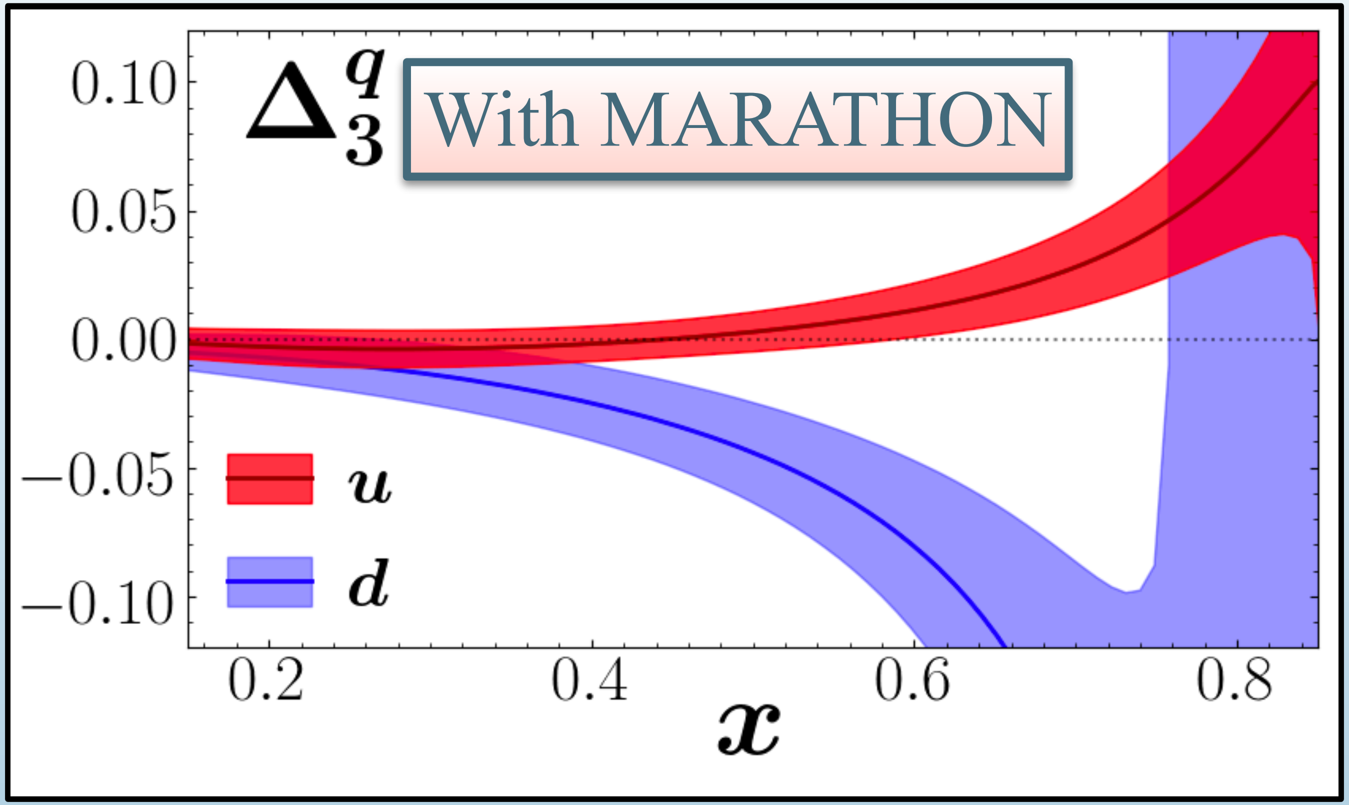
First global QCD analysis of JLab ^{3}He/D and MARATHON data

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 $x \gtrsim 0.4$!



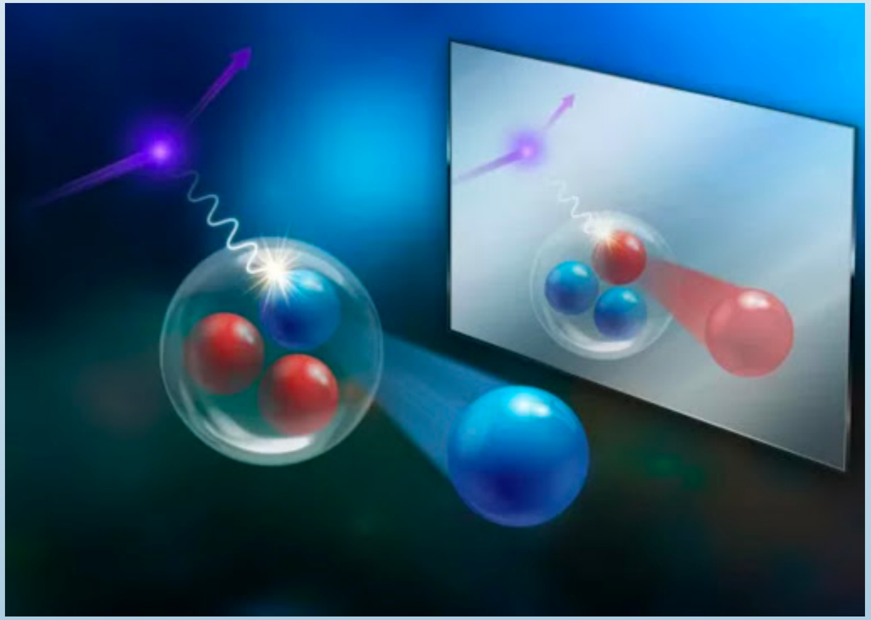
Impact from MARATHON

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



Isospin Symmetry

How to relate quarks between protons and neutrons?

It is usually approximated that:

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

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

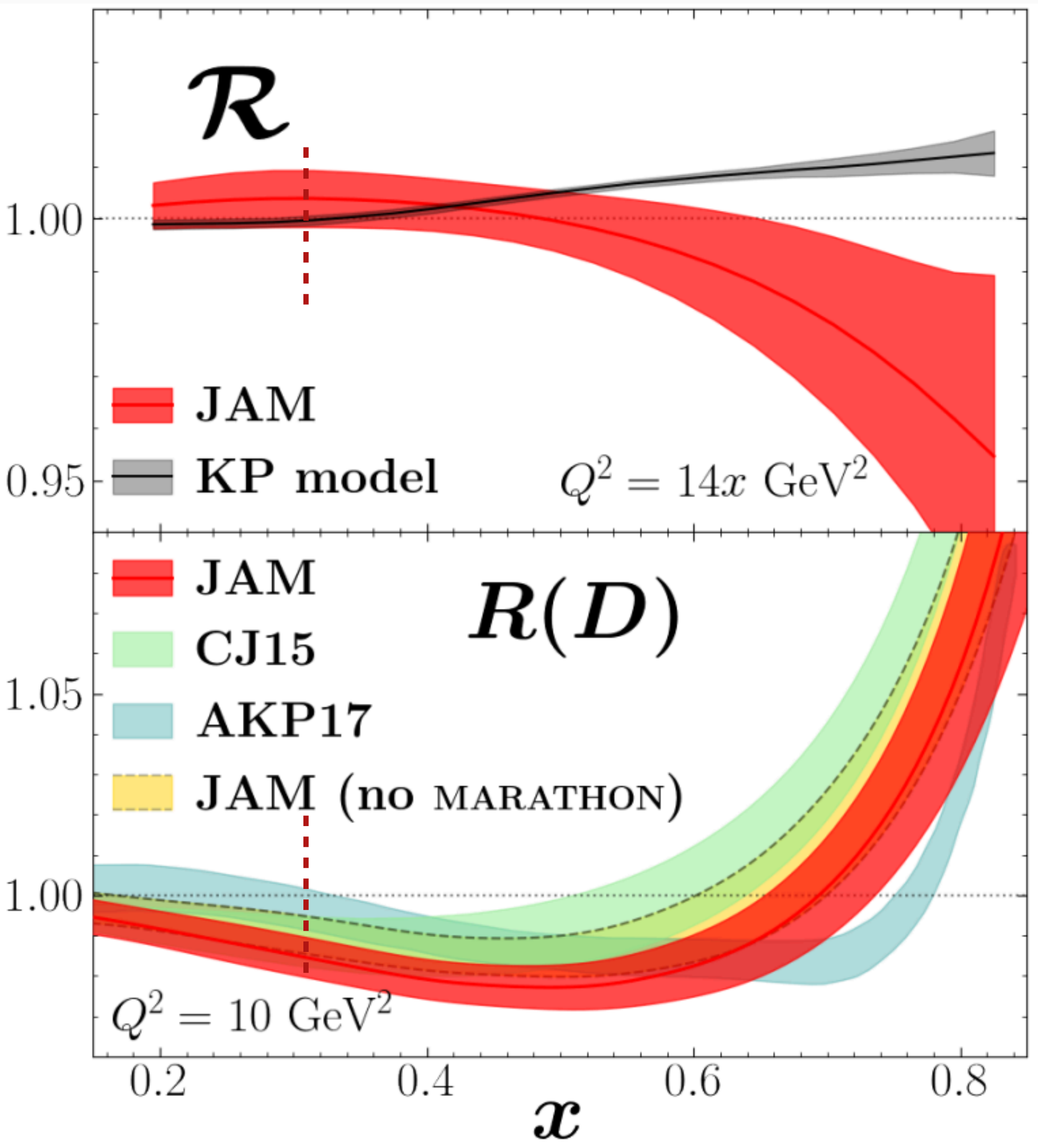
But the correct equations are:

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

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

where A^* is the mirror nuclei of A

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

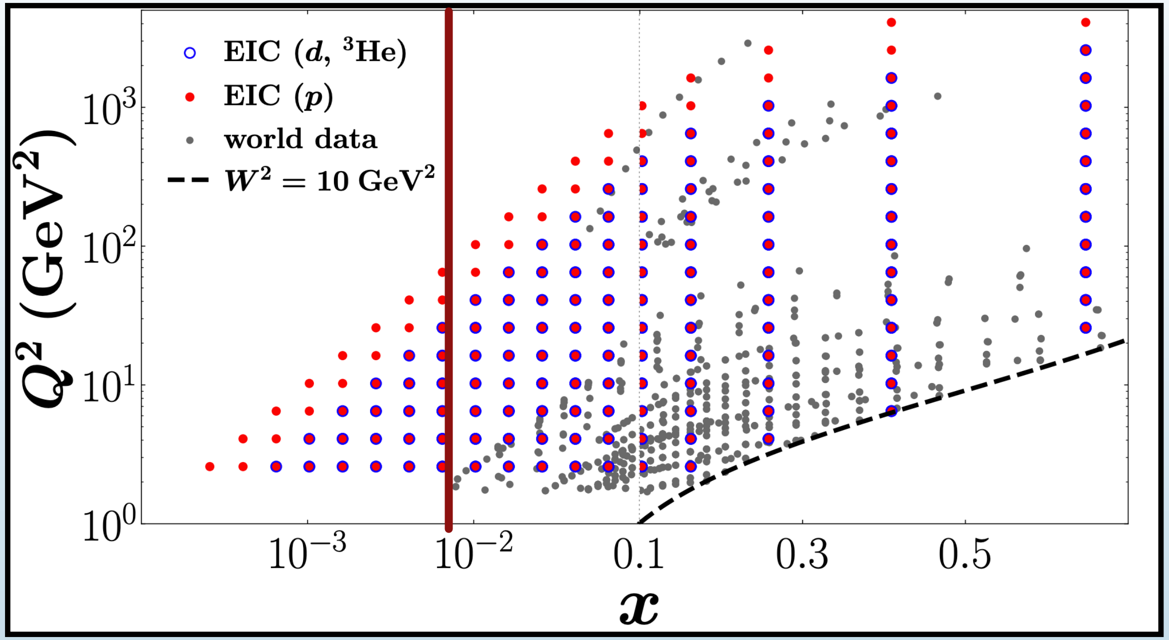
Current State of Helicity PDFs

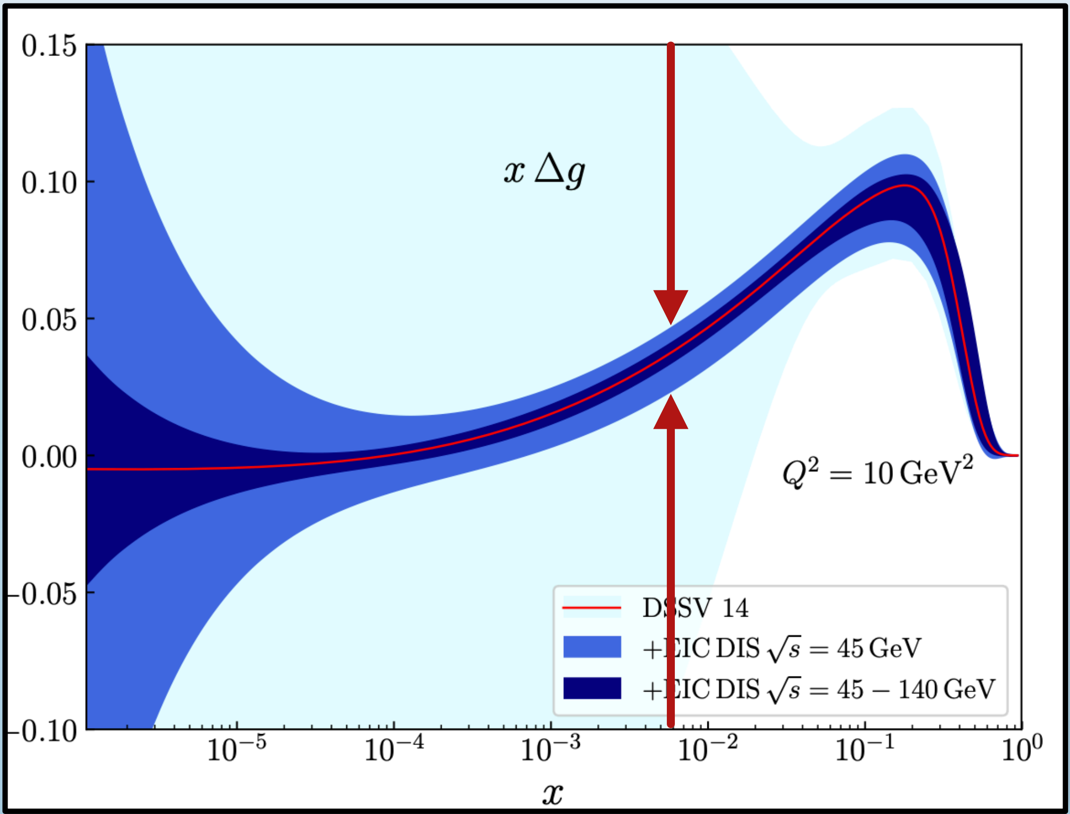
Proton spin puzzle:

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

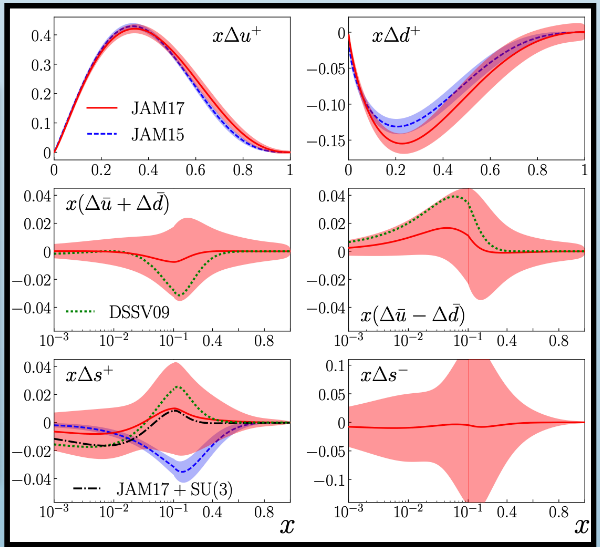
$$\Delta\Sigma = \int_0^1 dx \sum_q \Delta q^+$$

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



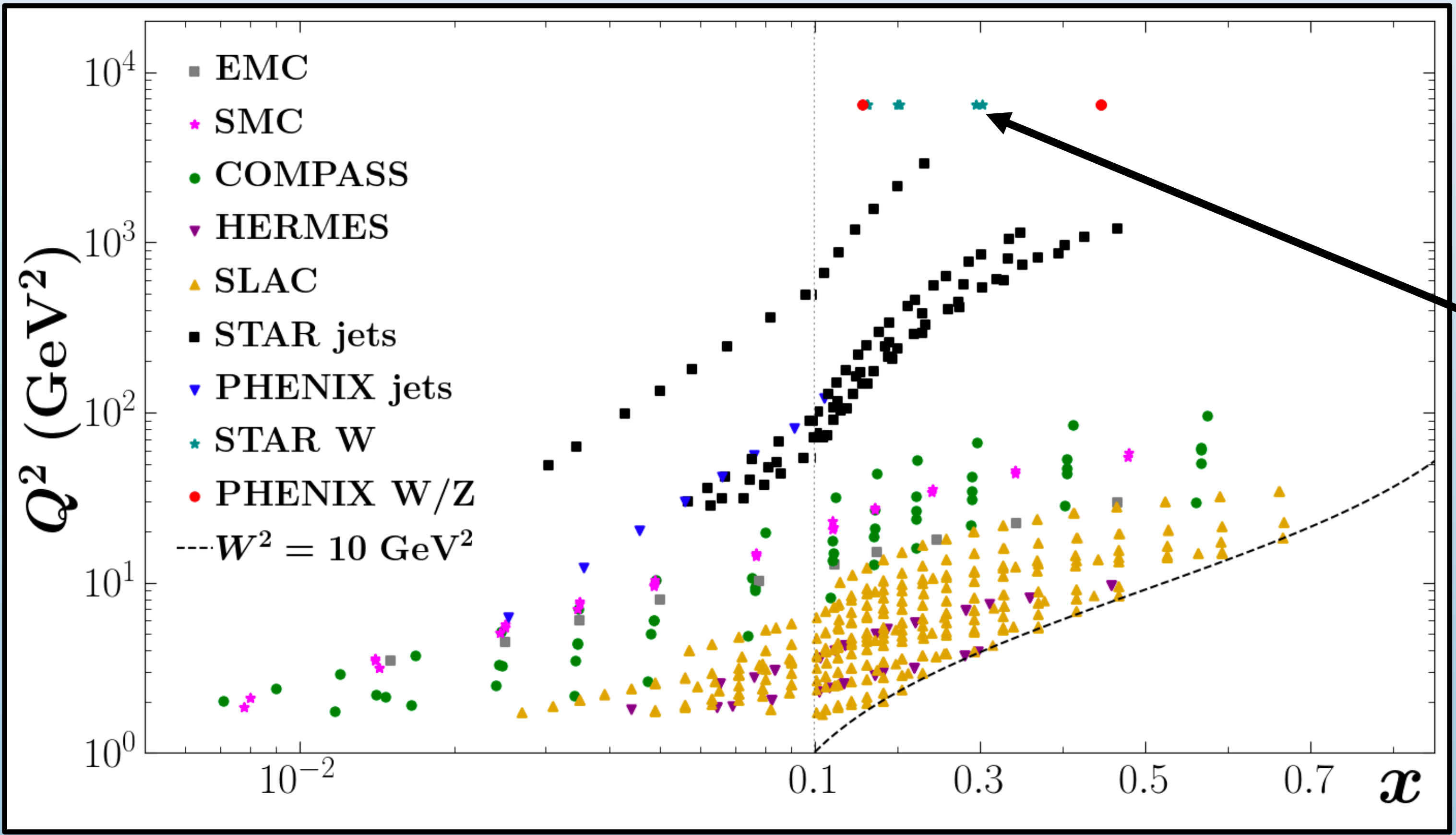


Still a lot to learn about helicity PDFs at low x and the helicity sea quark PDFs!



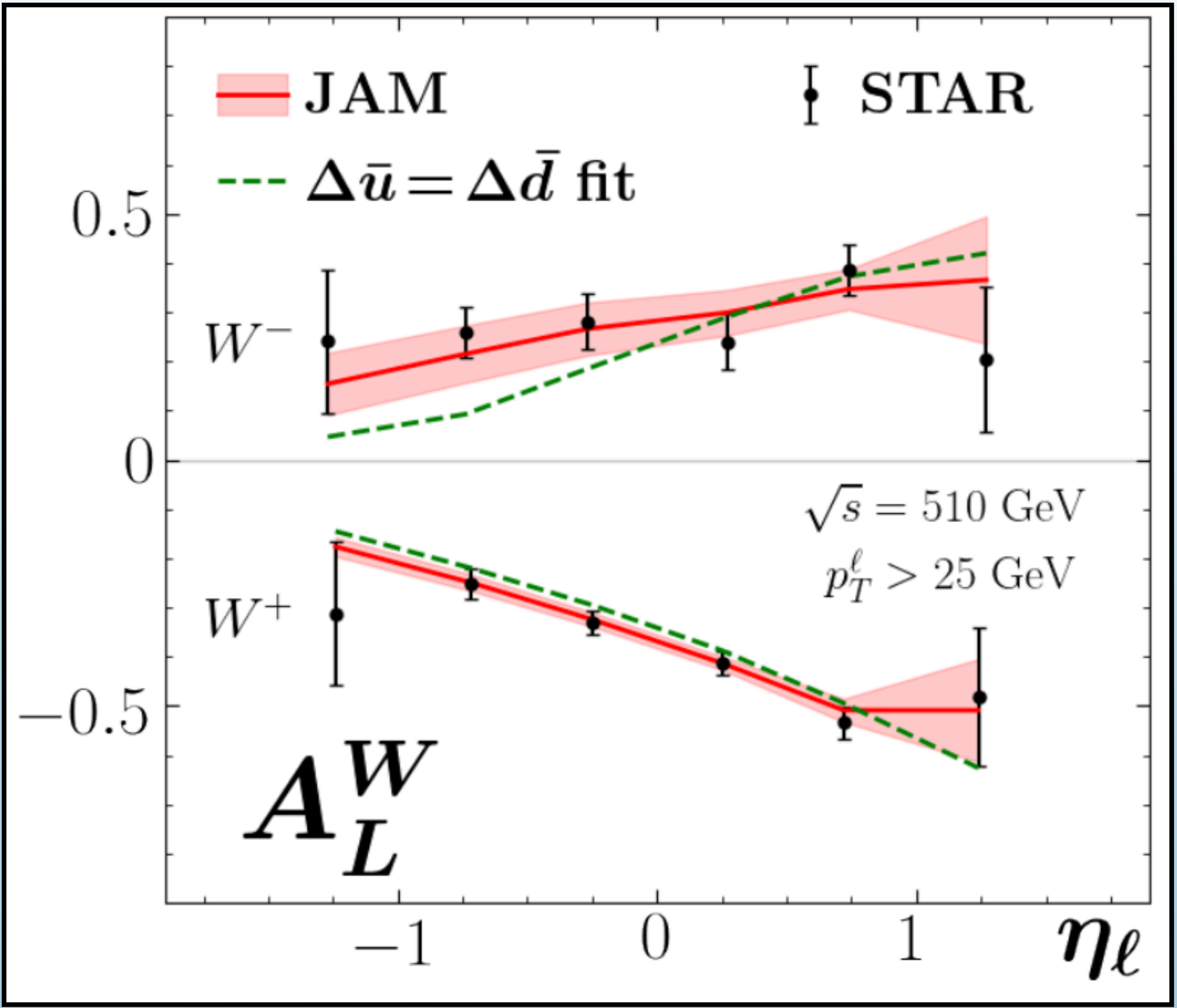
Kinematic Coverage (Helicity)

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

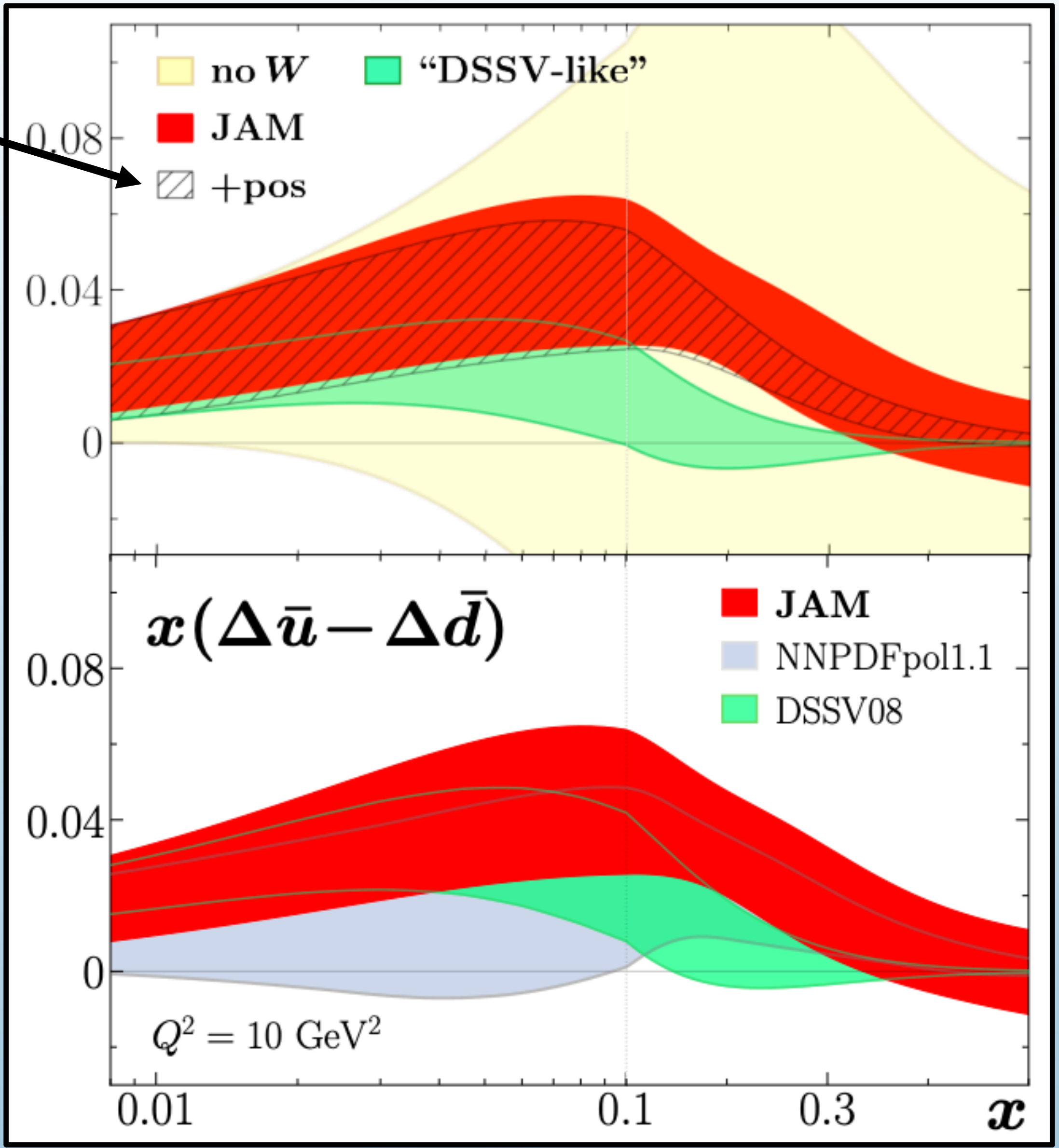
Can $\overline{\text{MS}}$ parton distributions be negative?
Alessandro Candido, Stefano Forte and Felix Hekhorn

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

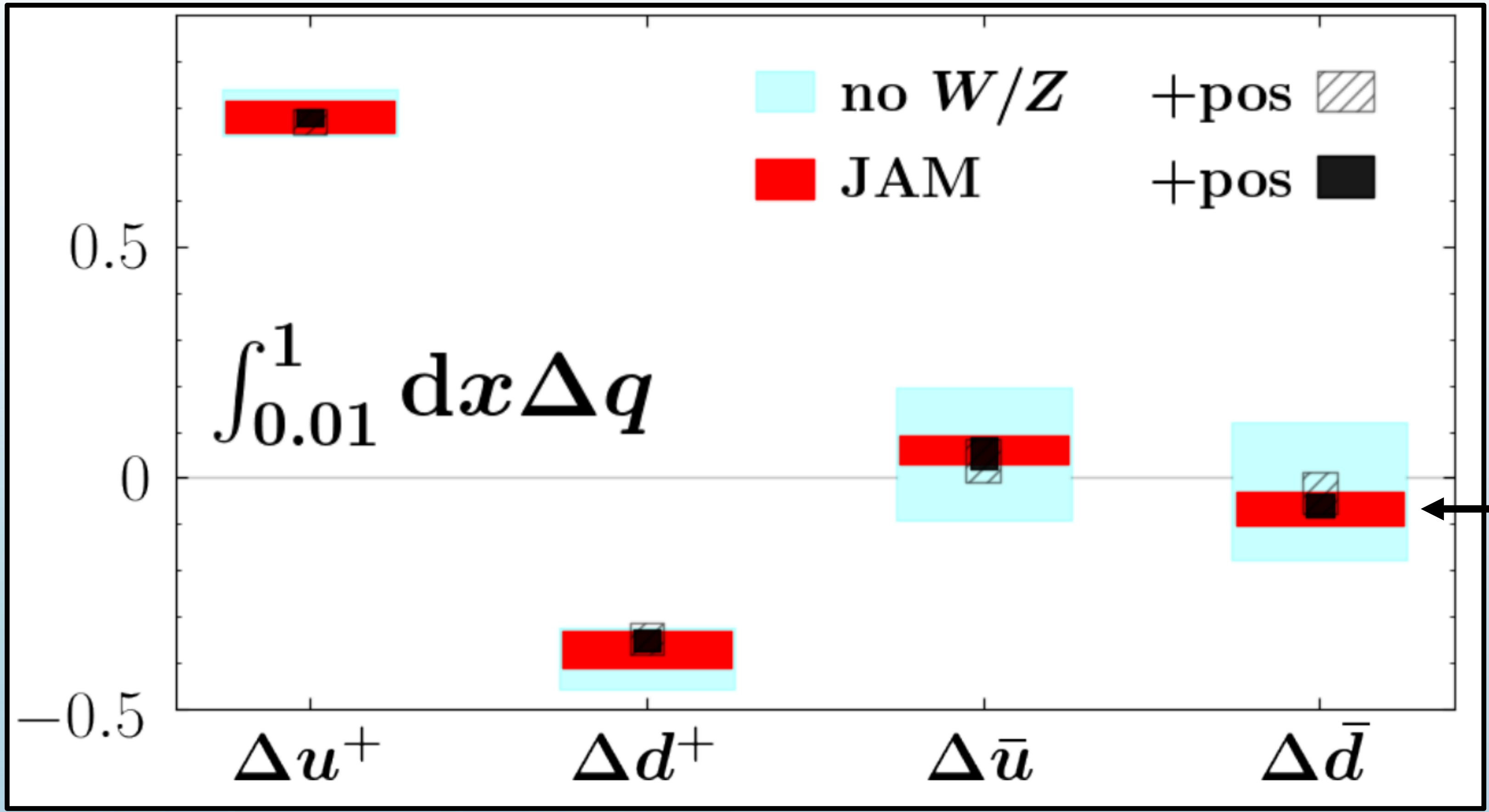
DSSV08 shows positive asymmetry at low $x < 0.1$

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).

Exploratory Analysis of Experiment with Lattice (2020)

Confronting lattice parton distributions with global QCD analysis

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N. Sato, W. Melnitchouk, and Jian-Wei Qiu

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F. Steffens

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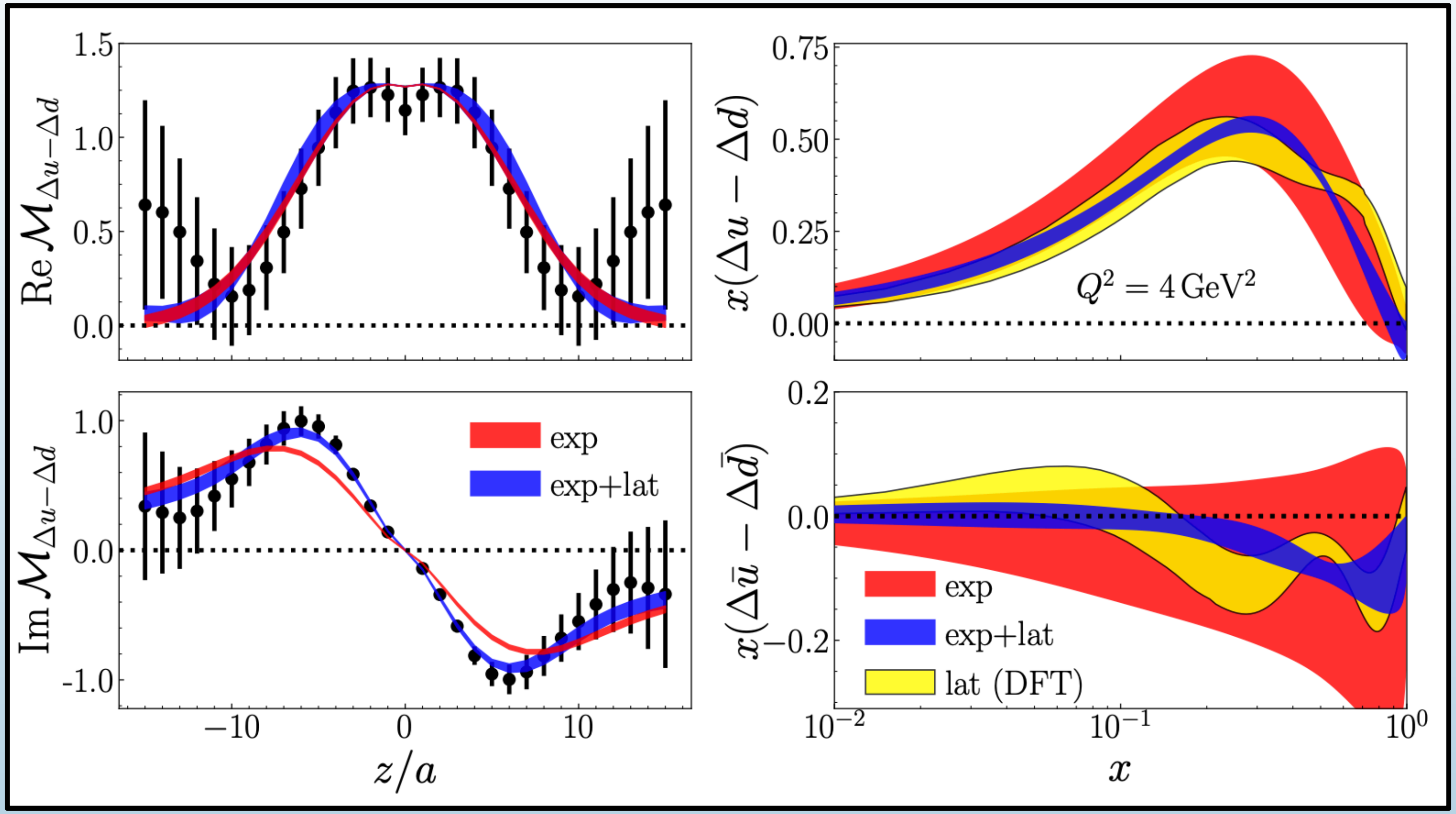
M. Constantinou

Department of Physics, Temple University, Philadelphia, Pennsylvania 19122, USA

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

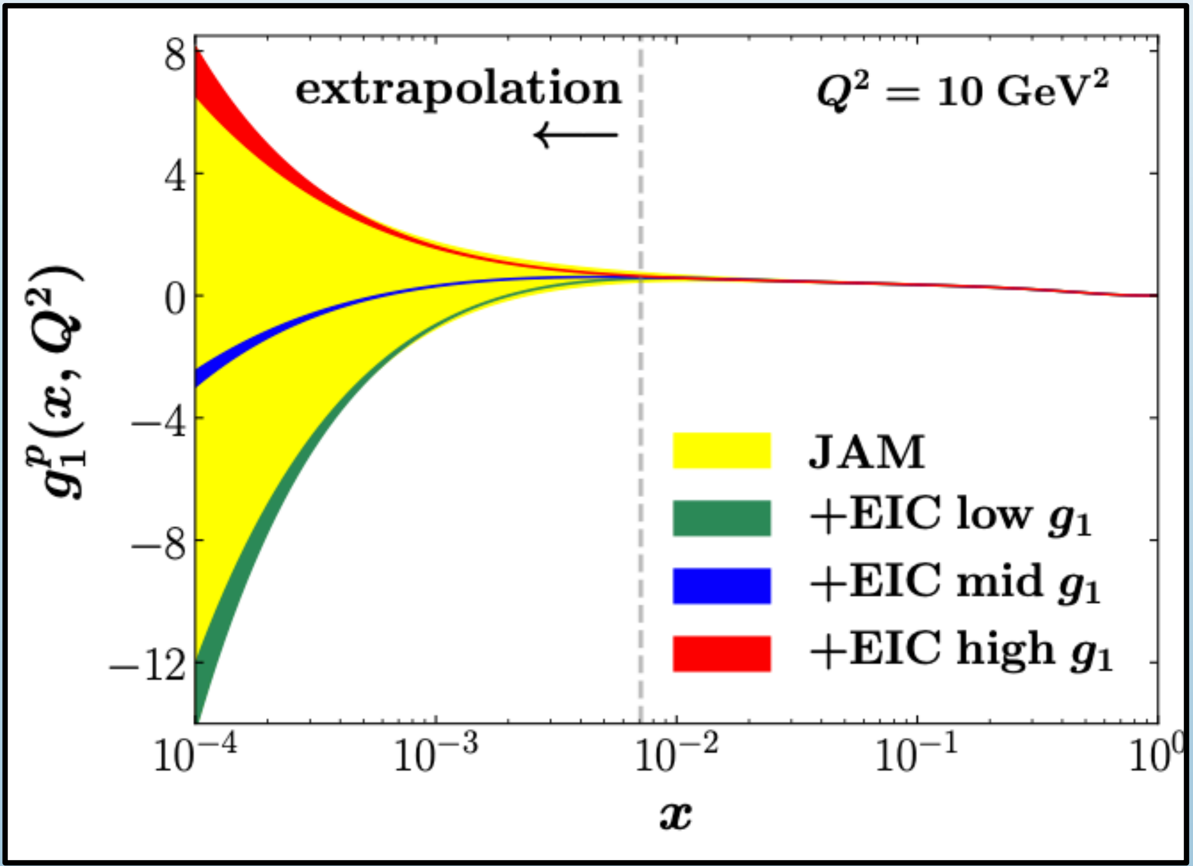
Y. Zhou,[1] C. Cocuzza,[2] F. Delcarro,[3] W. Melnitchouk,[3] A. Metz,[2] and N. Sato[3]

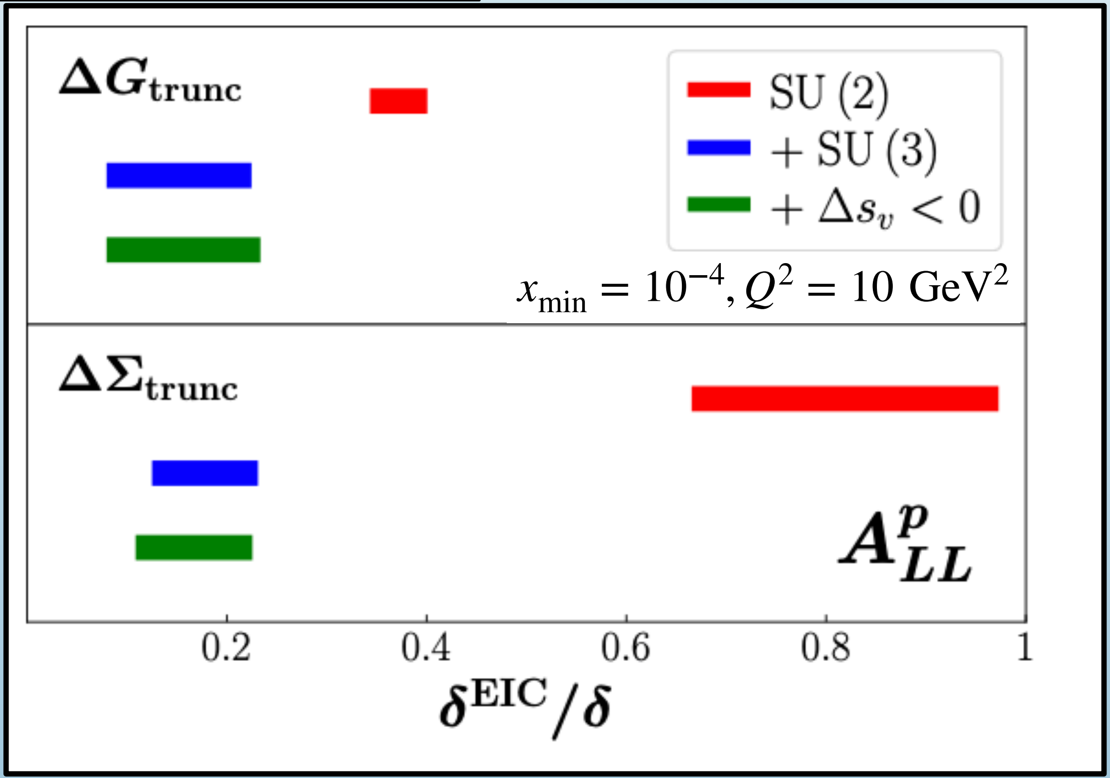
https://arxiv.org/abs/2105.04434

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

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

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

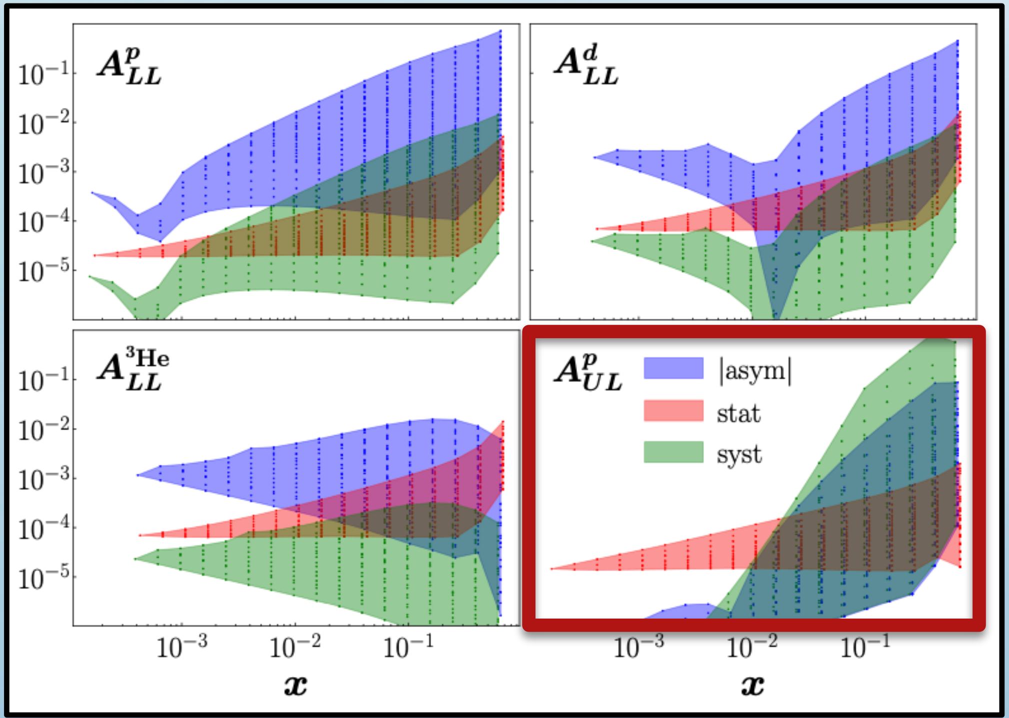


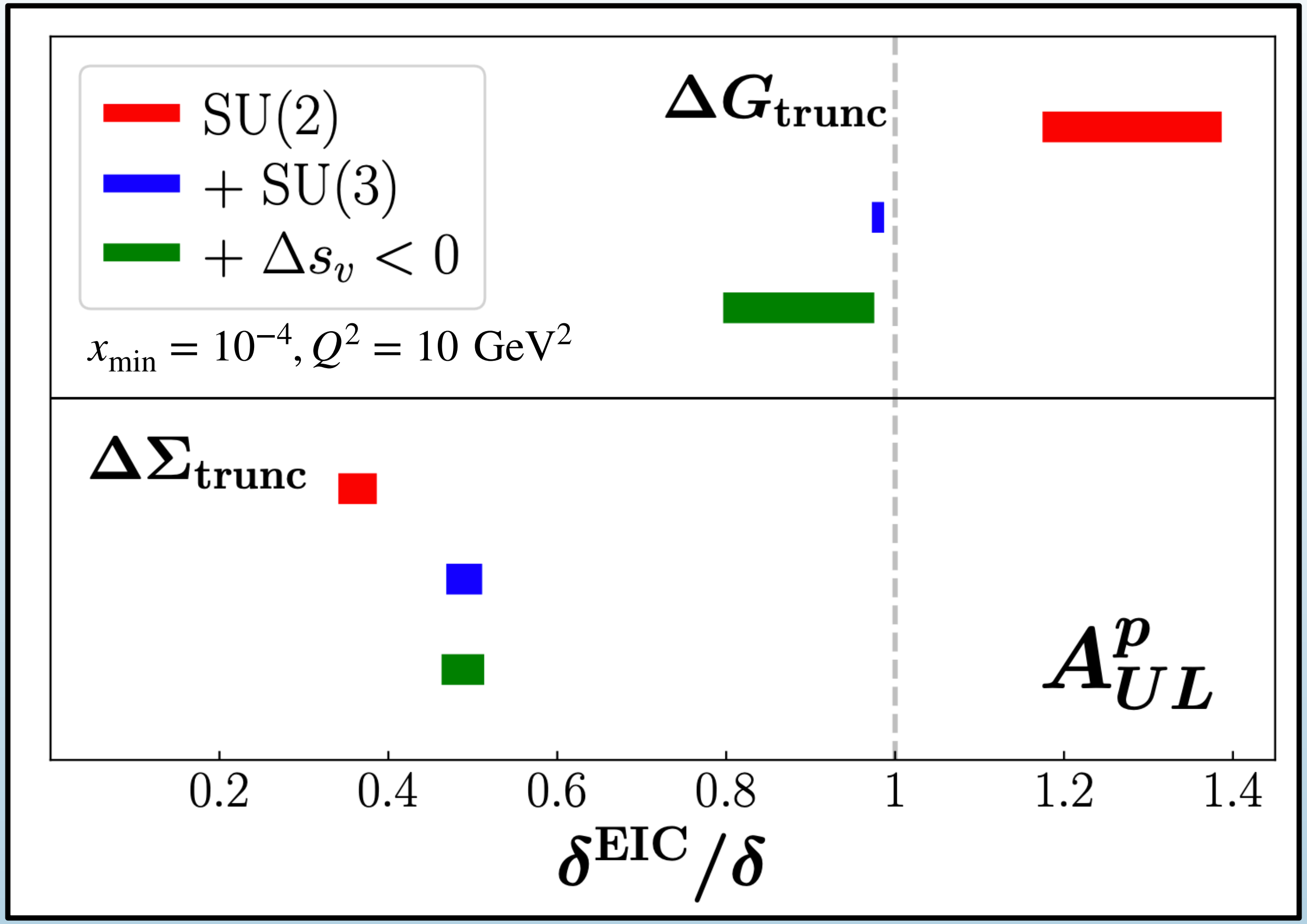


Impact of Parity Violating DIS (2021)

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

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





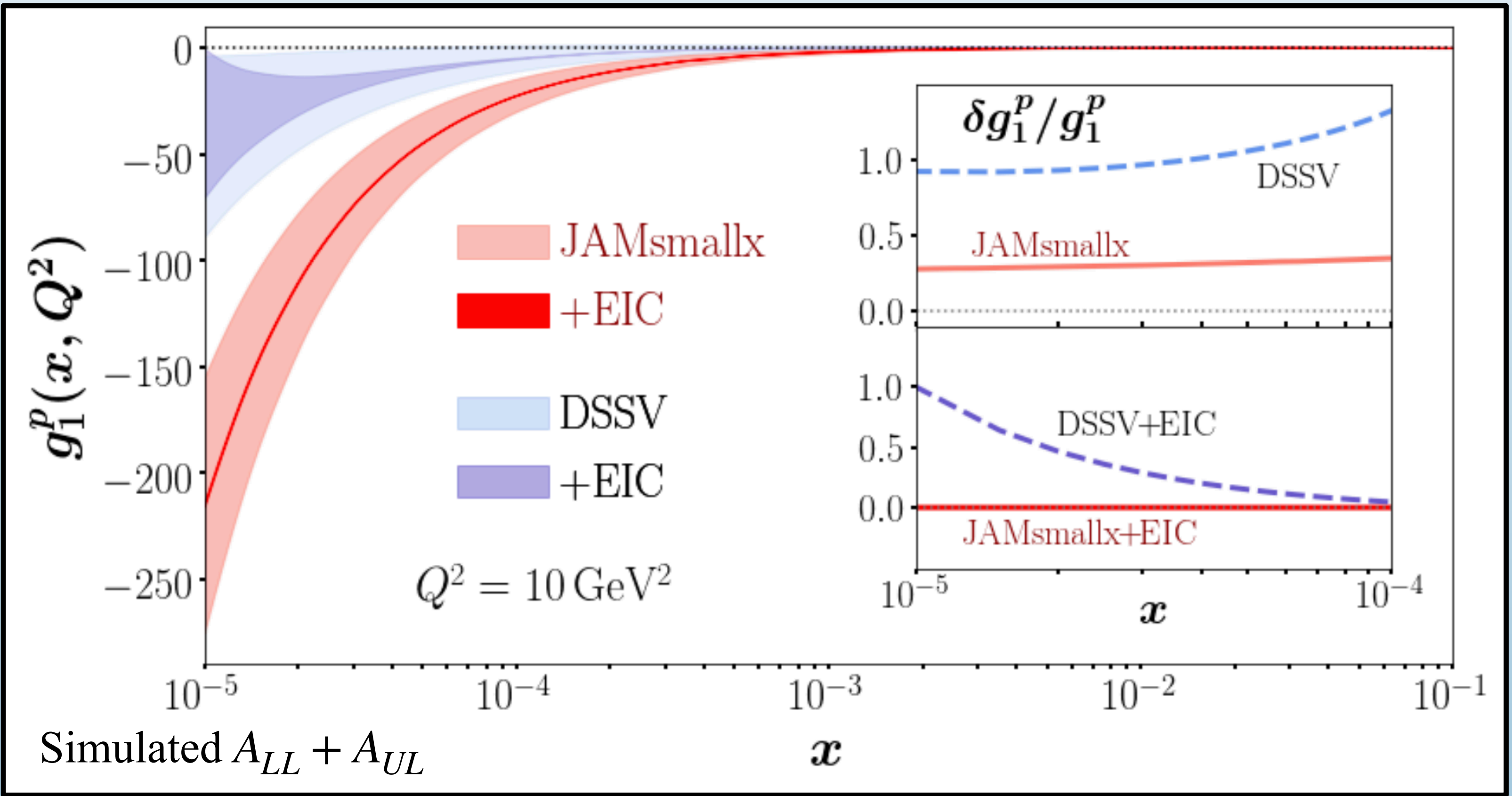
No impact on ΔG, but large impact on $\Delta\Sigma$ thanks to constraints on Δs^+

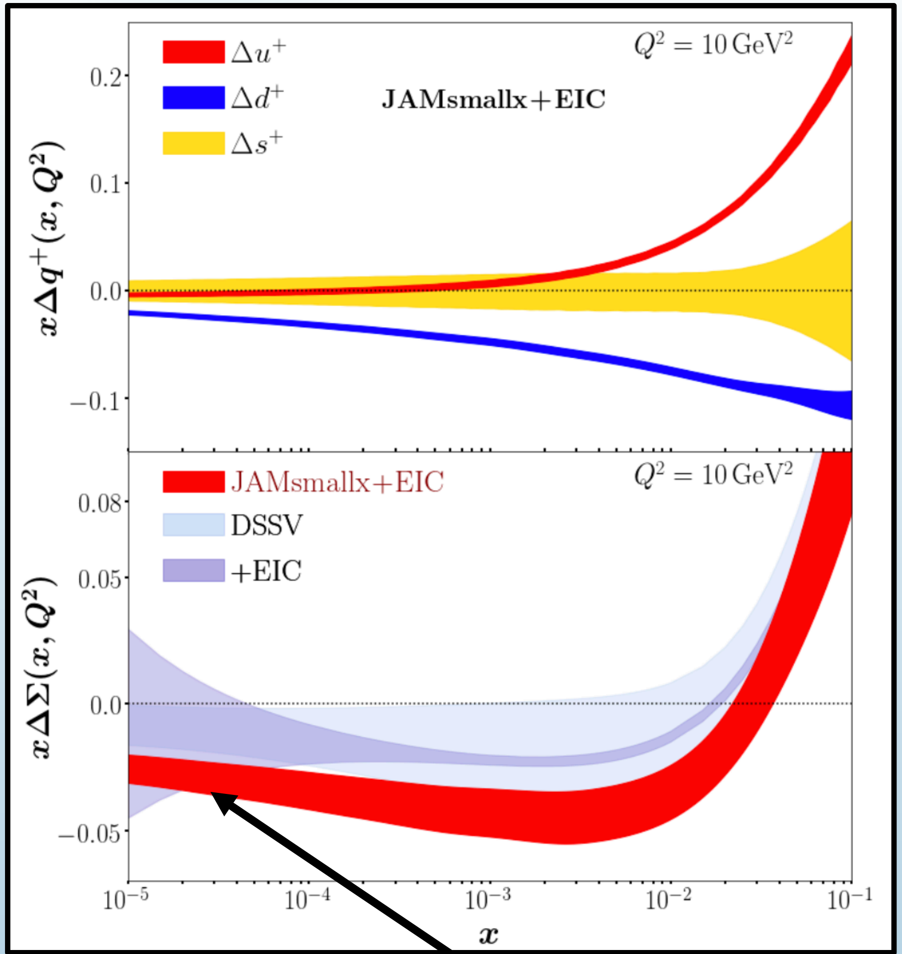
Impact of EIC at small x (2021)

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

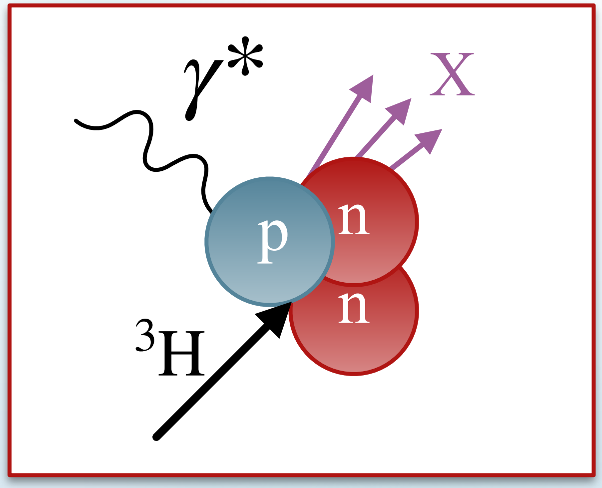
Latest Fragmentation Functions (2021)

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

Isovector EMC Effect



Isovector EMC effect from global QCD analysis with MARATHON data