Isovector EMC Effect from Global QCD Analysis with MARATHON data

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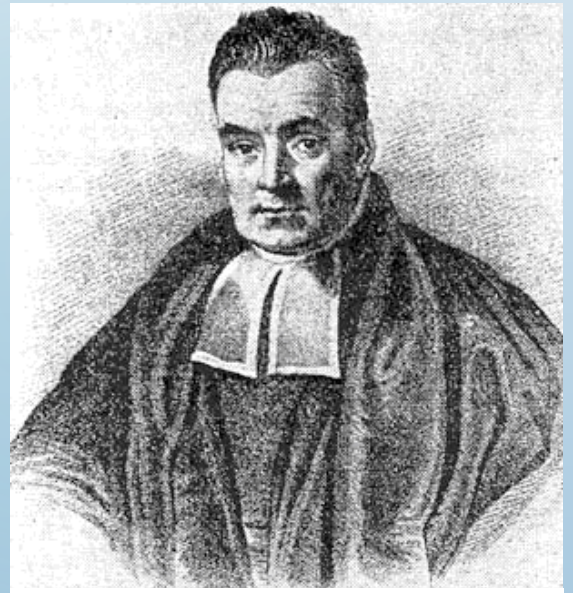
arXiv: 2104.06946

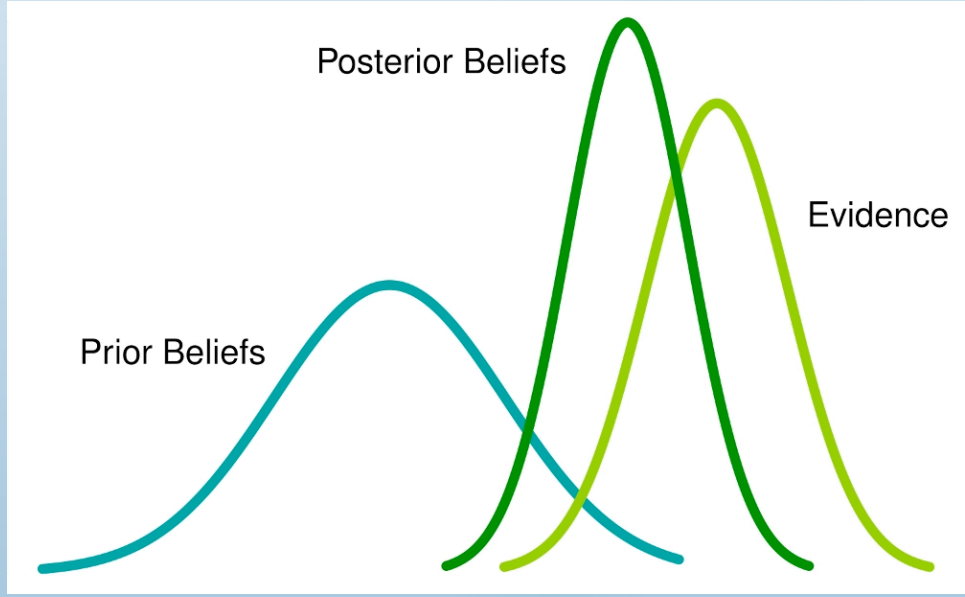
Jefferson Lab Angular Momentum Collaboration

QCD Evolution
May 13, 2021

Part 1:
JAM Methodology



T. Bayes



JAM Collaboration

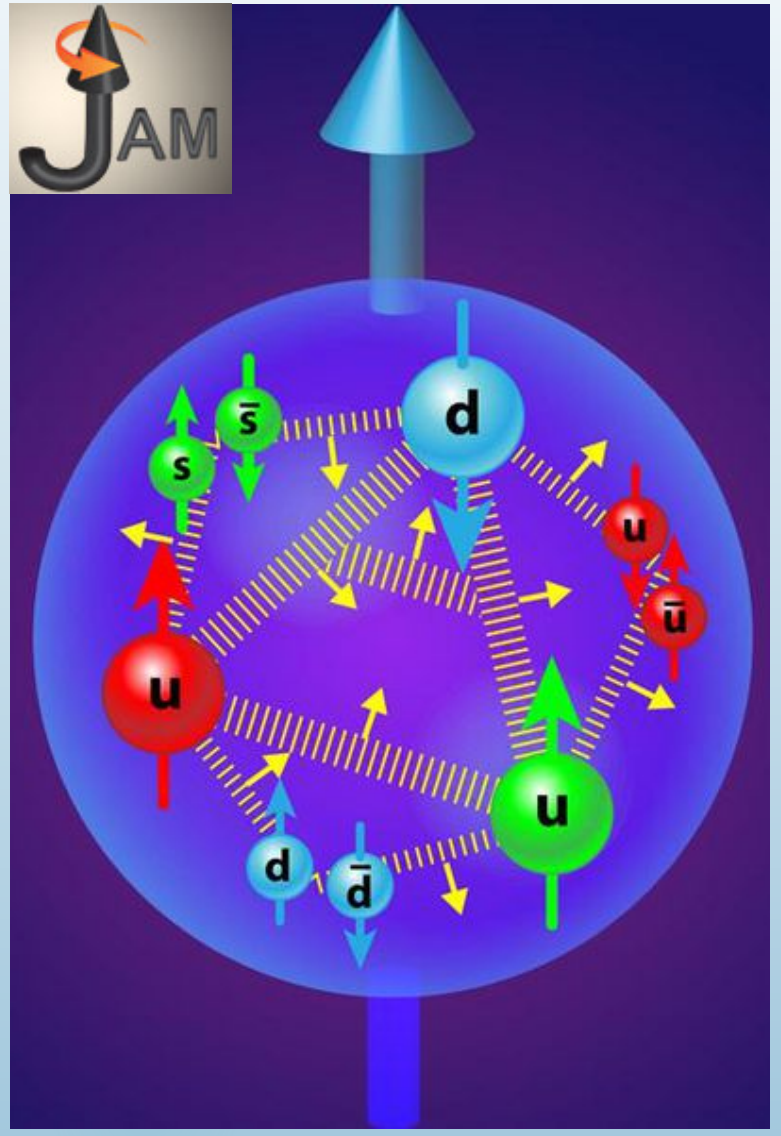
3-dimensional structure of nucleons:

- Parton distribution functions (PDFs)
- Fragmentation functions (FFs)
- Transverse momentum dependent (TMD) distributions + more!

Collinear factorization in perturbative QCD

Simultaneous determinations of PDFs, FFs, etc.

Monte Carlo methods for Bayesian inference



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

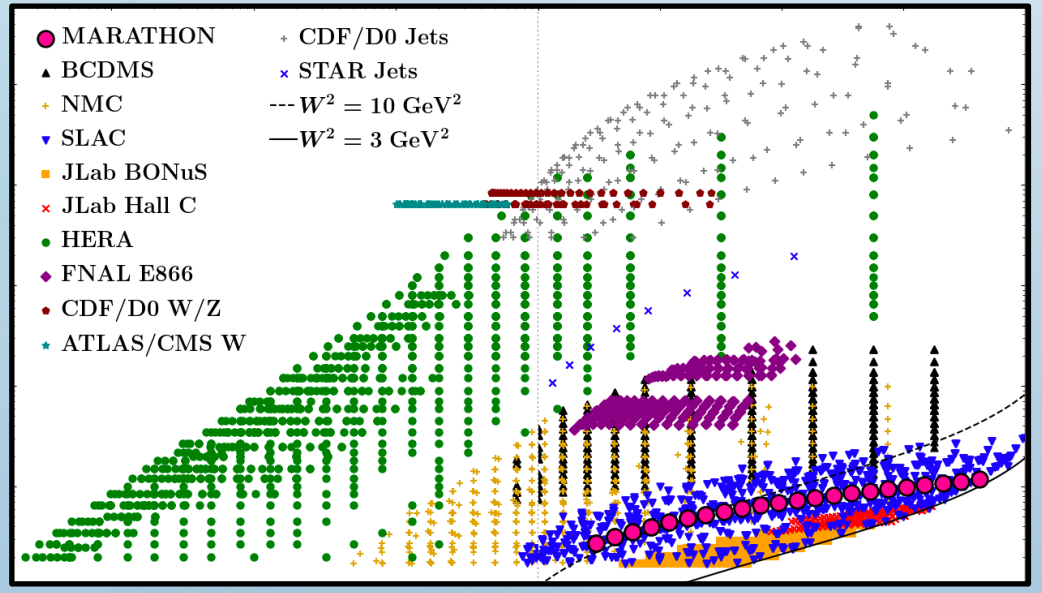
$$\frac{\mathrm{d}}{\mathrm{d}\ \ln(\mu^2)} f_i(x,\mu) = \sum_j \int_x^1 \frac{dz}{z} P_{ij}(z,\mu) f_j(\frac{x}{z},\mu)$$

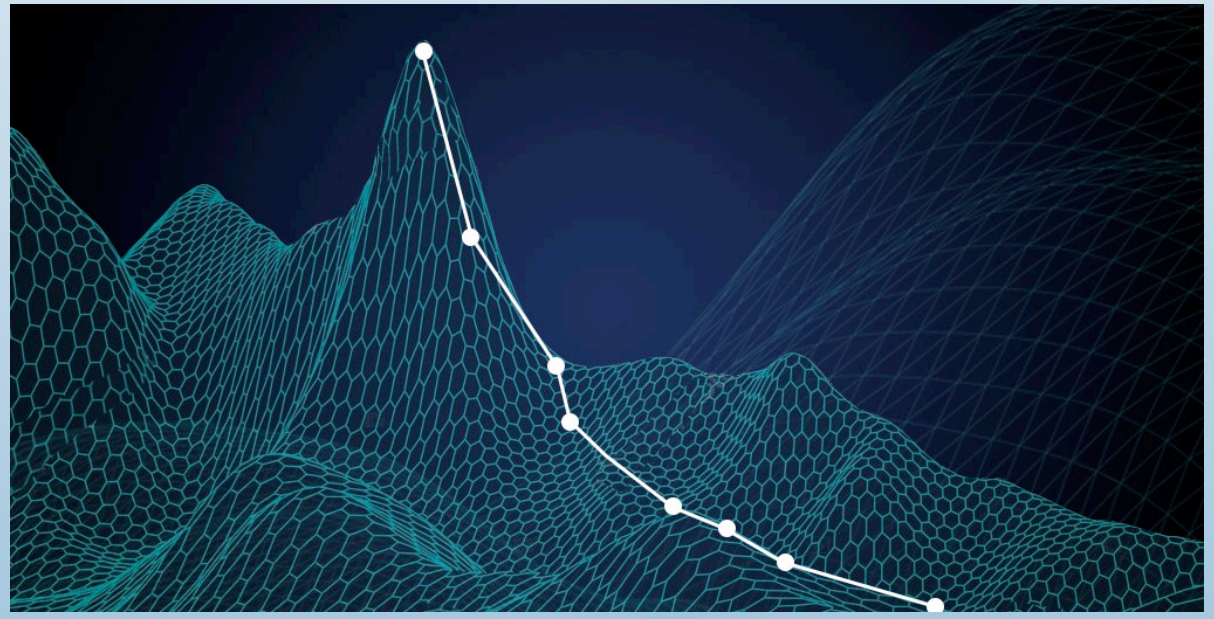
Calculate Observables

$$d\sigma_{\mathrm{DIS}} = \sum_i H_i^{\mathrm{DIS}} \otimes f_i \ + \text{off-shell corrections} + \text{higher twists}$$

To be discussed later!

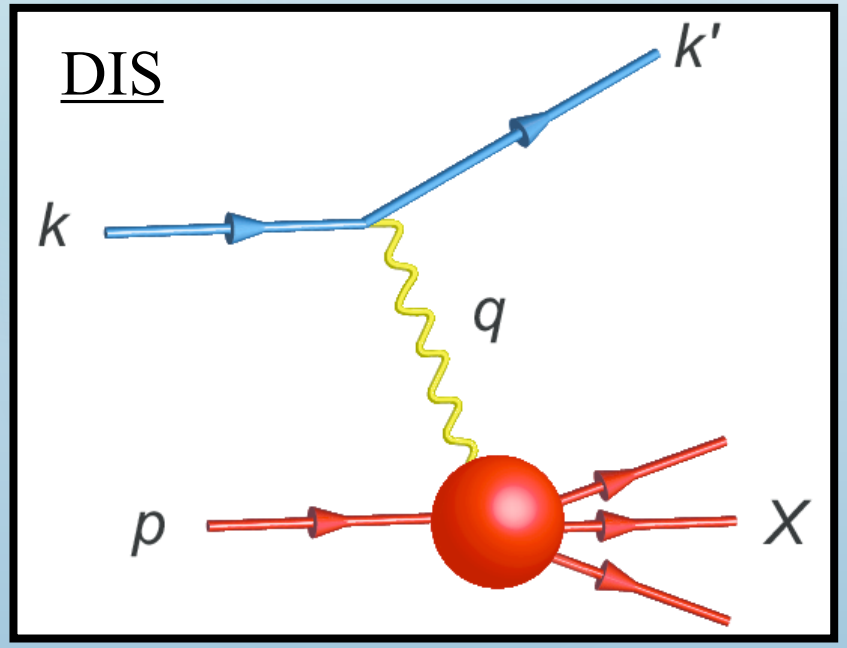
Part 2:
Data and Fitting

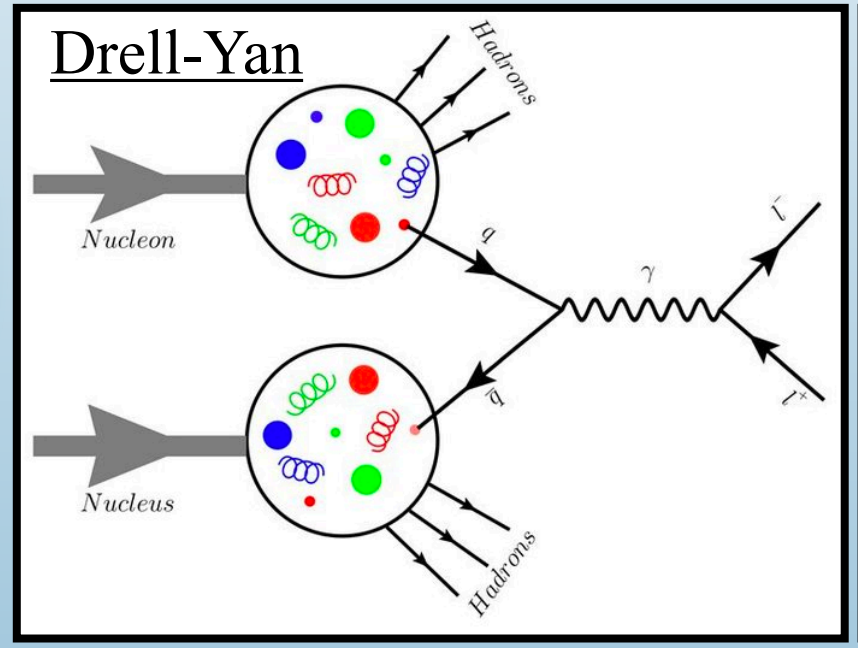


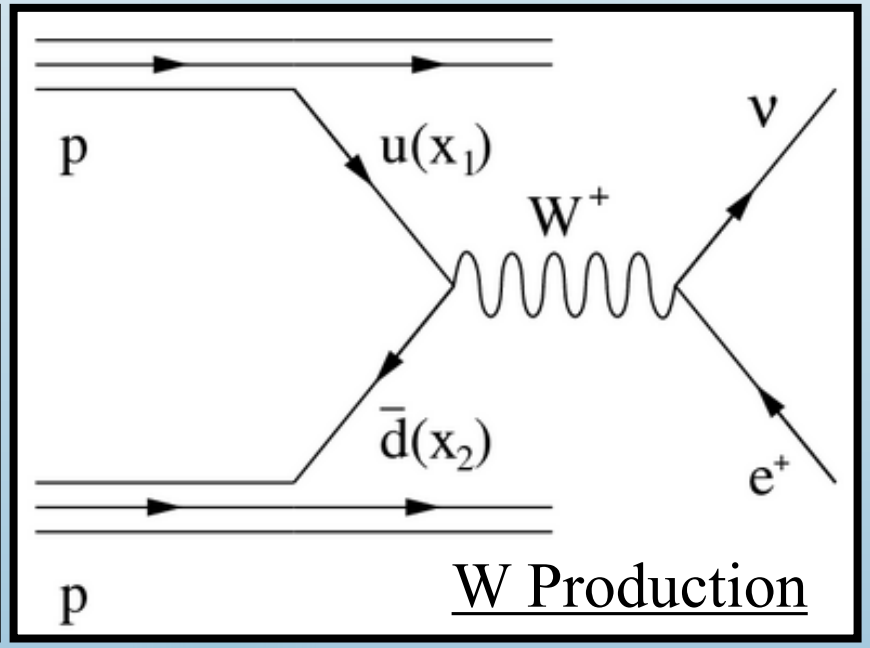


A Global Analysis

Simultaneous extraction of PDFs and nuclear effects

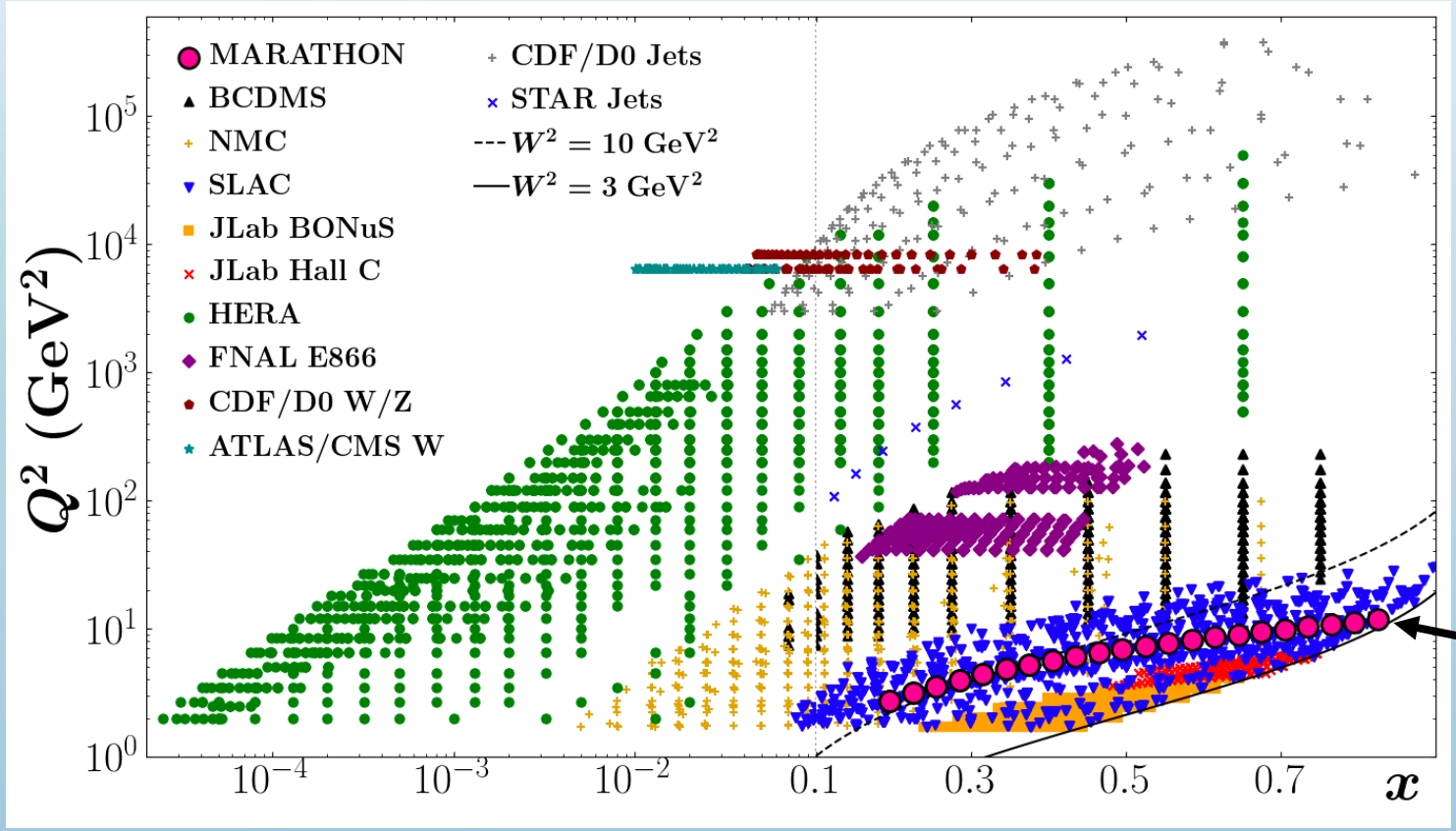






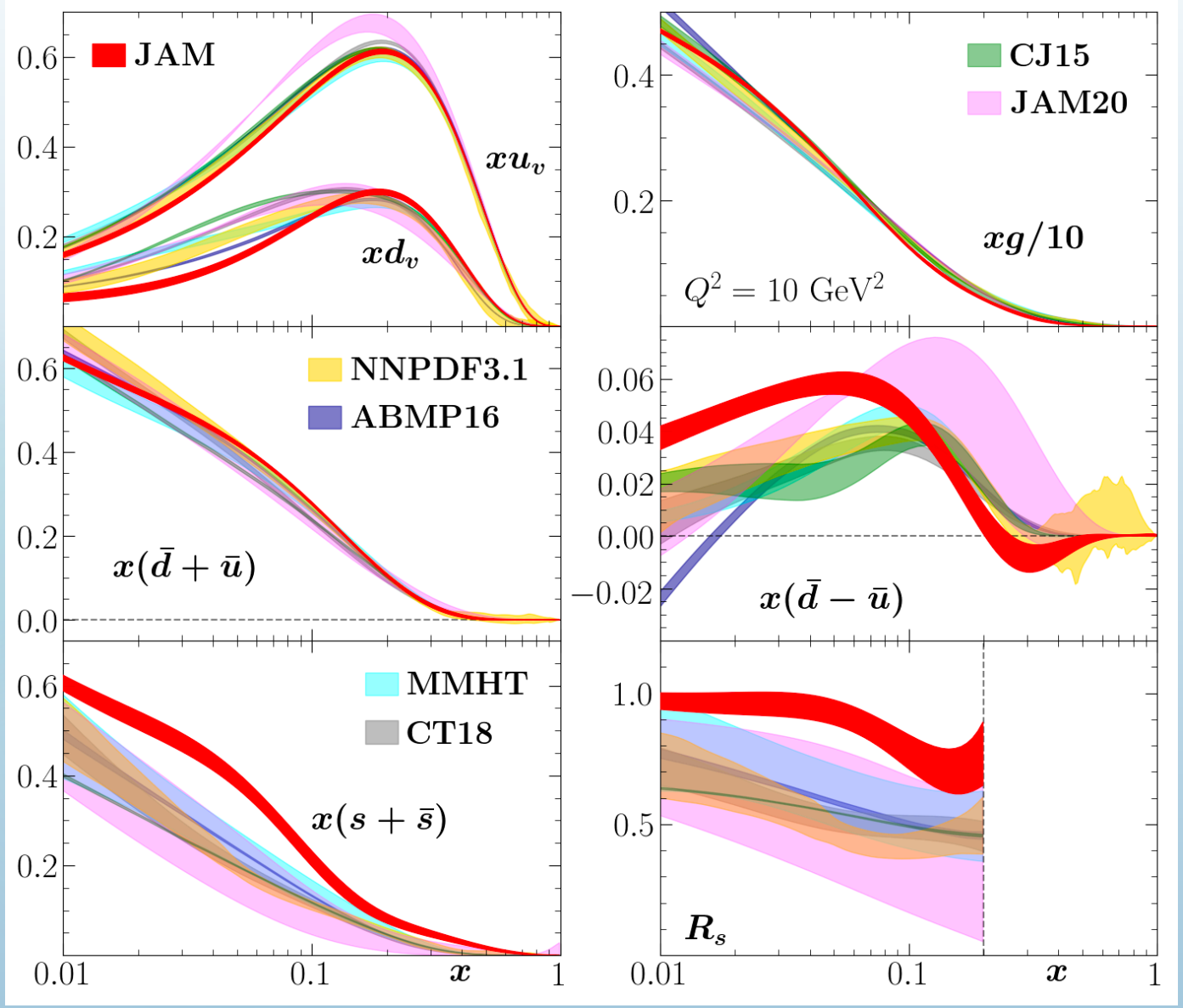
Kinematic Coverage

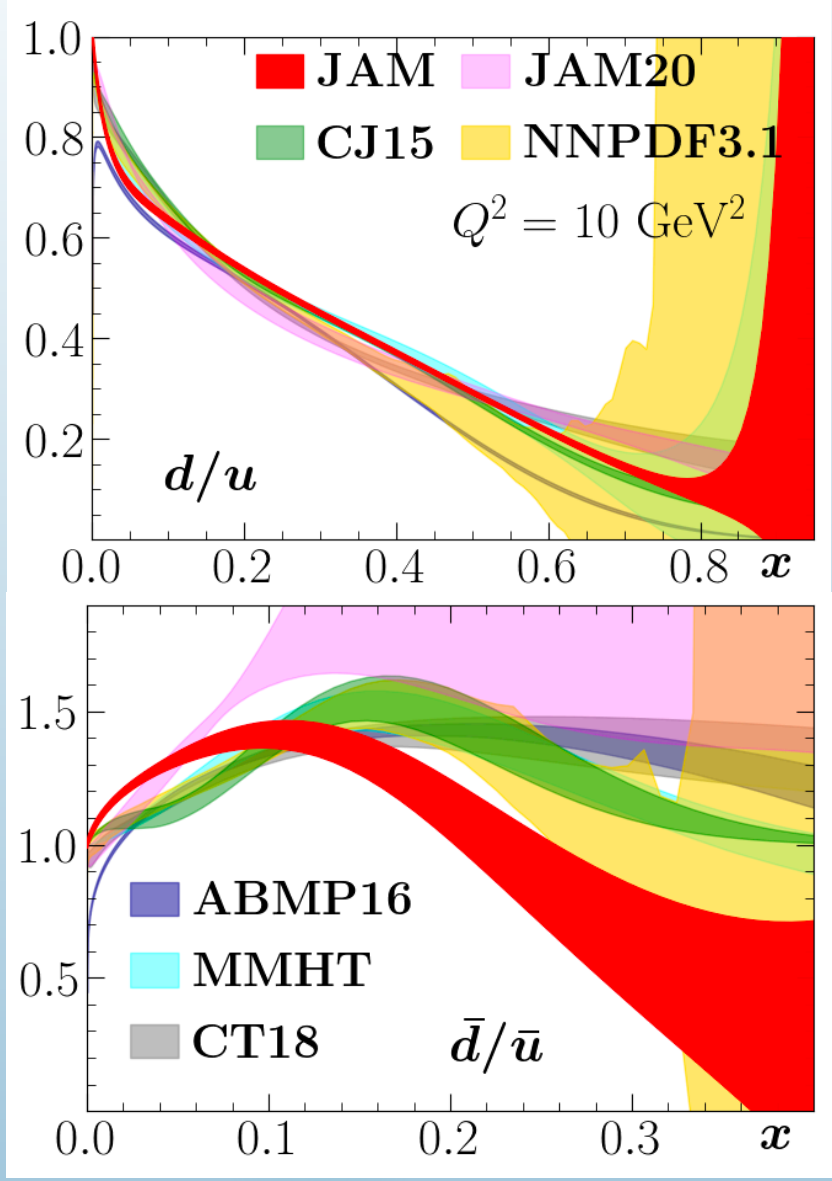
Deep Inelastic Scattering	BCDMS, NMC, SLAC, HERA, Jefferson Lab	3863	points
Drell-Yan	Fermilab E866	250	points
W/Z Boson Production	Tevatron CDF/D0, LHC ATLAS/CMS	239	points
Jets	Tevatron CDF/D0, RHIC STAR	196	points



New MARATHON data

Extracted Parton Distribution Functions



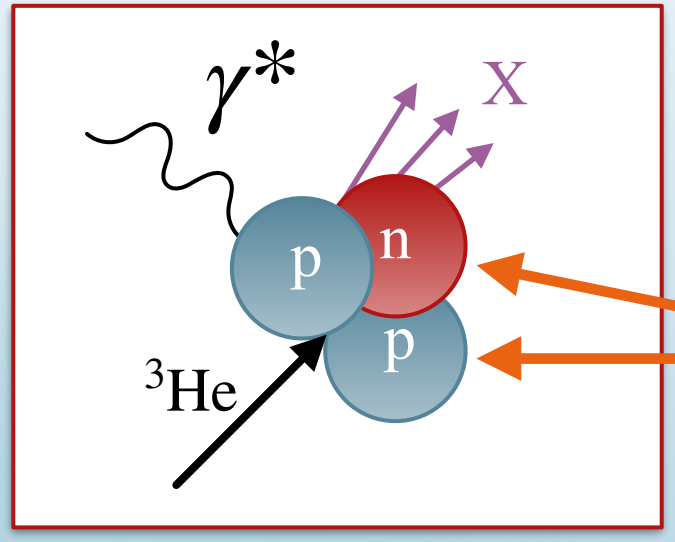


Part 3:
Nuclear Effects

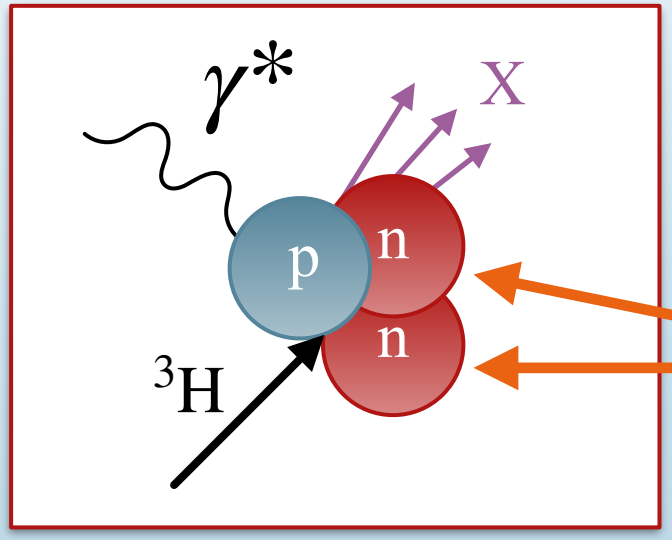
Isovector Effect

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

Mediated by $I_3 = 1$ 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

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

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

Contains Virtuality

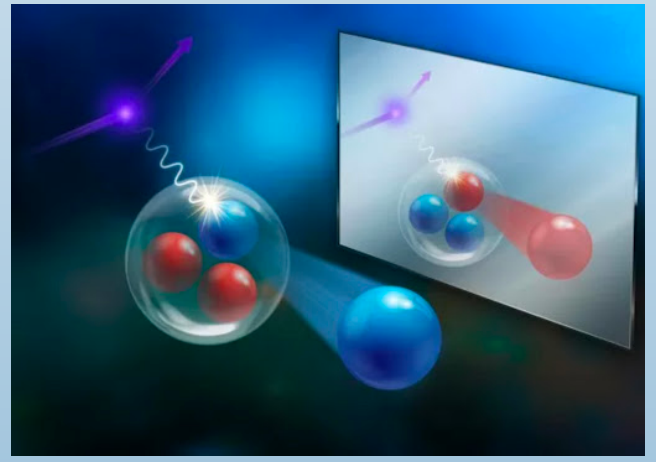
$$\nu(p^2) = (p^2 - M^2)/M^2 \ll 1$$

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

Measures strength of isovector effect

Part 4: MARATHON Impact

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



April 12, 2021

arXiv: 2104.05850

Impact from MARATHON

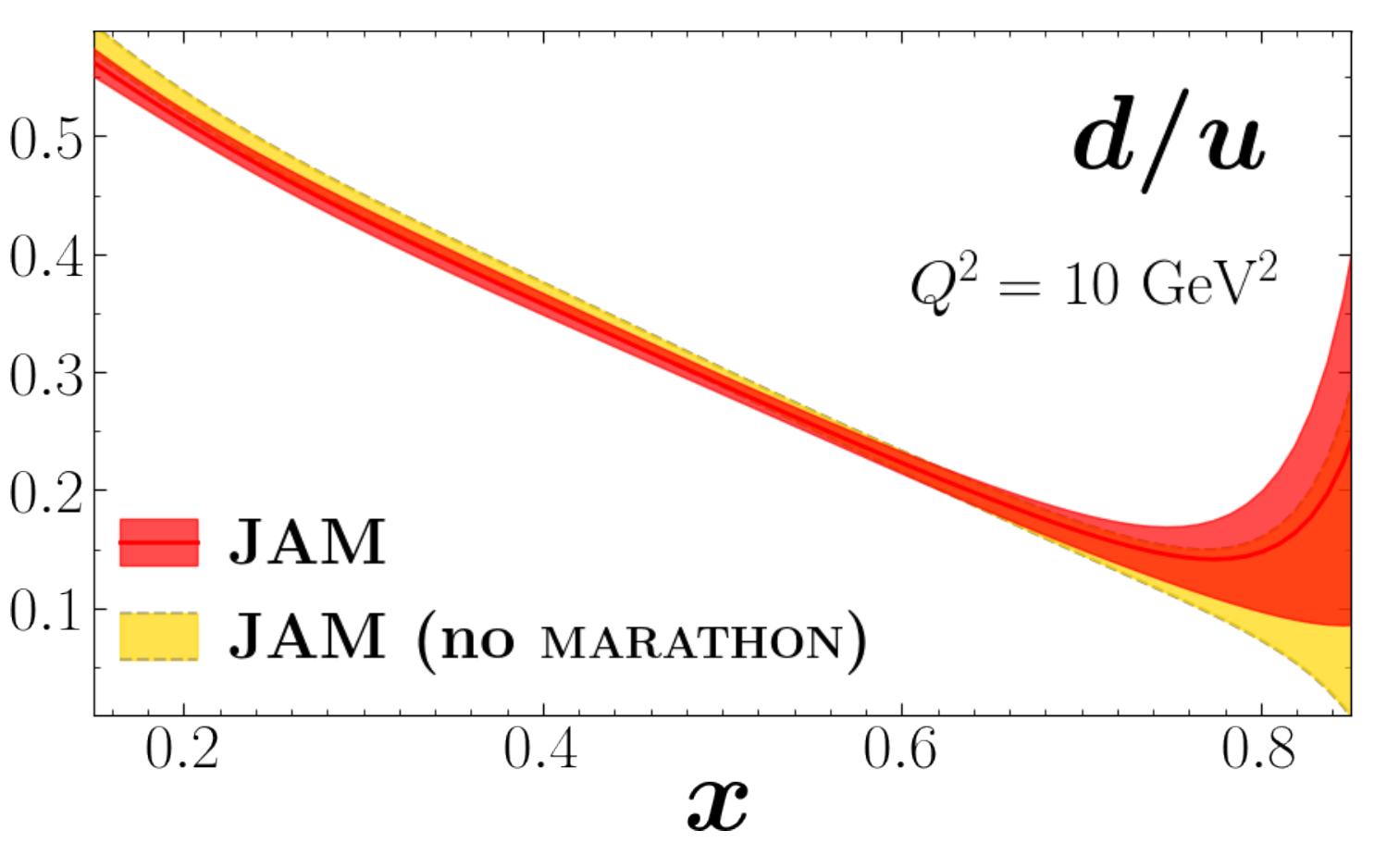
MeAsurement of the F_2^n/F_2^p, d/u **RA**tios and $A = 3$ EMC Effect in Deep Inelastic Electron Scattering Off the **T**ritium and **H**elium Mirr**O**r **N**uclei

d/u Ratio

F_2^n/F_2^p Ratio

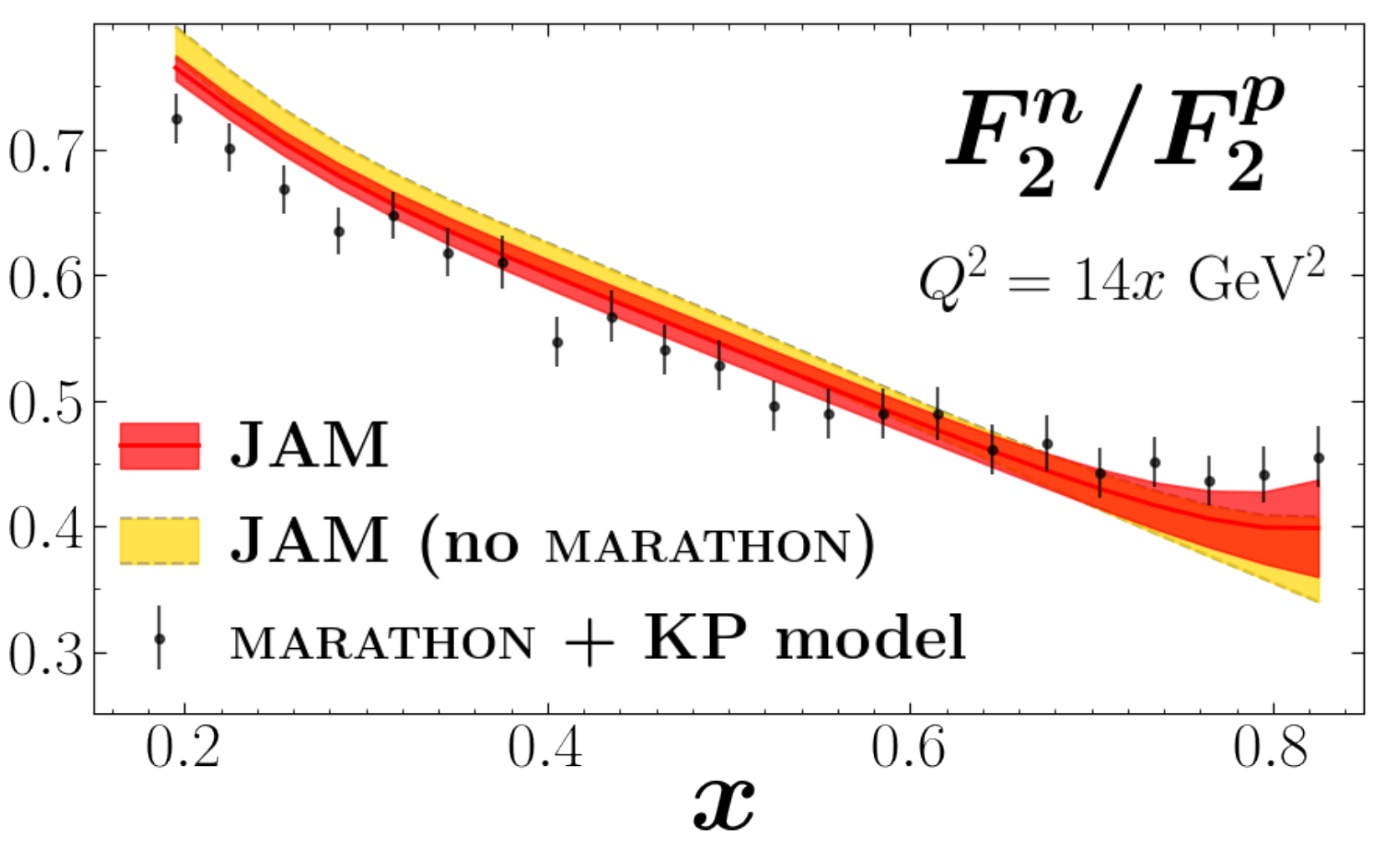
$A = 3$ EMC Effects

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

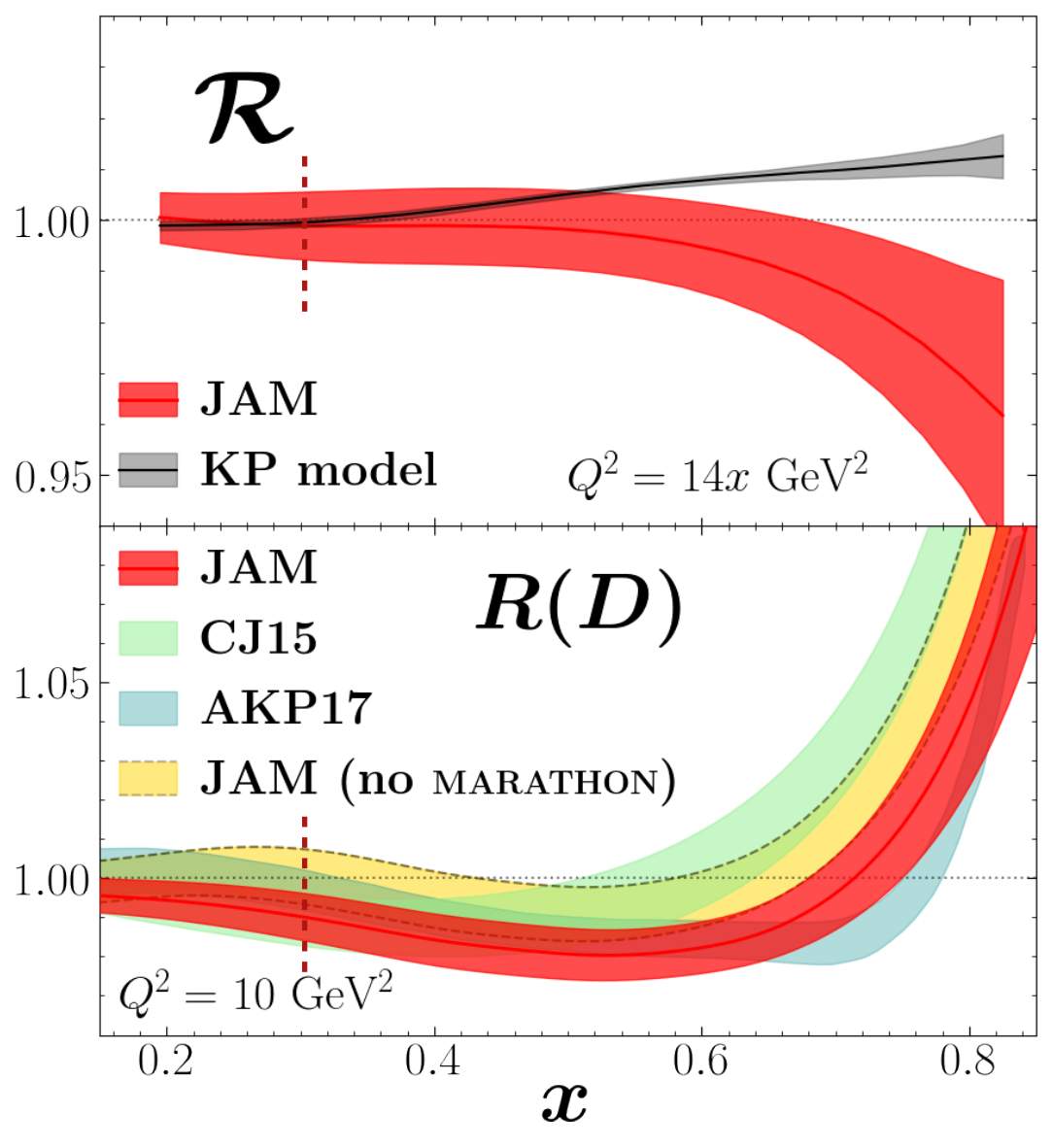
MeAsurement of the F_2^n/F_2^p, d/u **RA**tios and $A = 3$ EMC Effect in Deep Inelastic Electron Scattering Off the **T**ritium and **H**elium Mirr**O**r **N**uclei

d/u Ratio ≈

F_2^n/F_2^p Ratio ≈

$A = 3$ EMC Effects ?

EMC Ratios



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

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

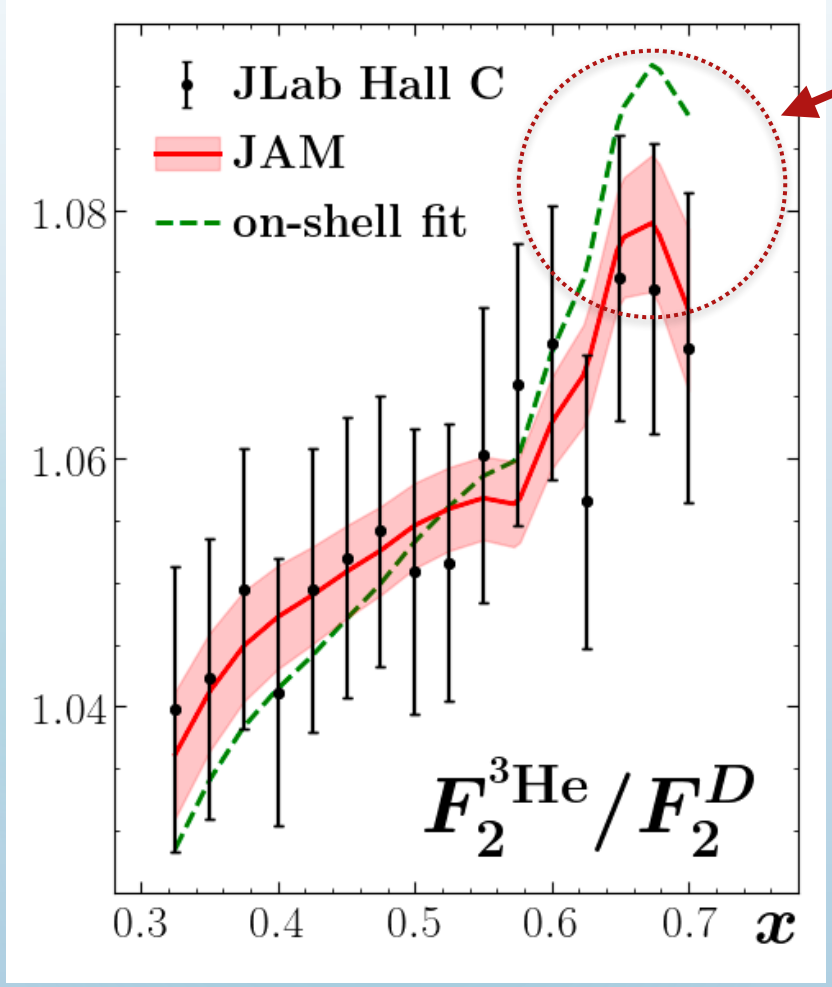
$$R(^3\mathrm{H}) = F_2^{^3\mathrm{H}} / \left(F_2^p + 2F_2^n\right)$$

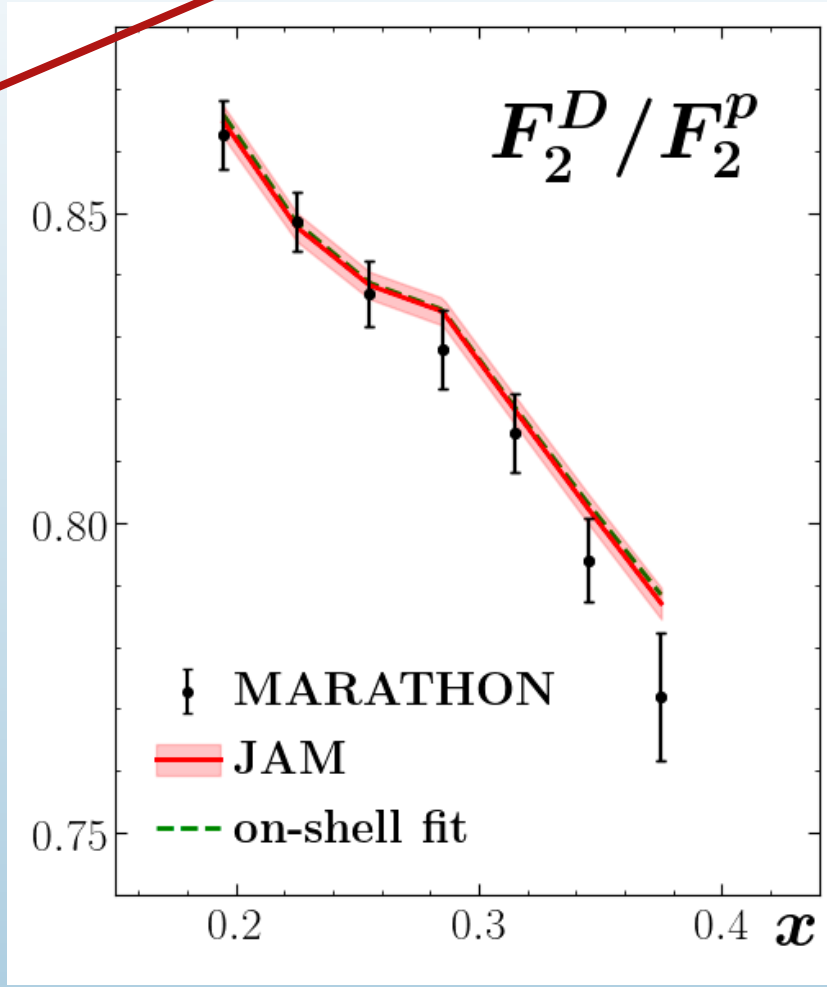
$$\mathscr{R} = R(^3\mathrm{He})/R(^3\mathrm{H})$$

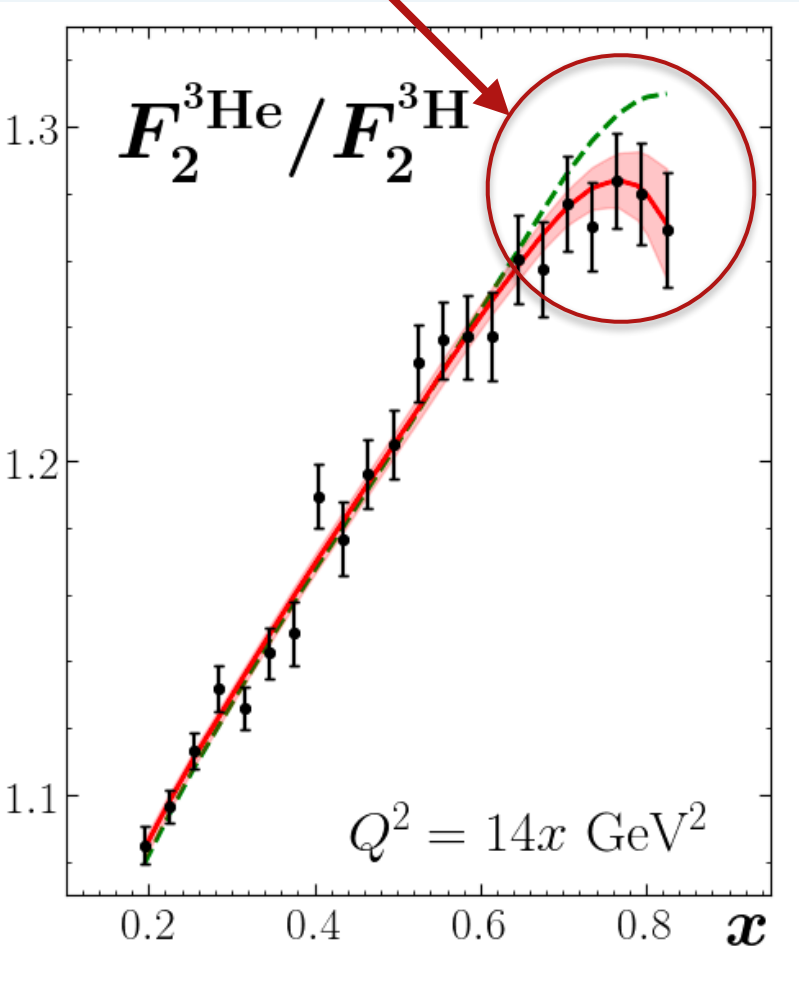
Significant differences between JAM result and KP model result

Data vs. Theory

Suggestion of off-shell effects!





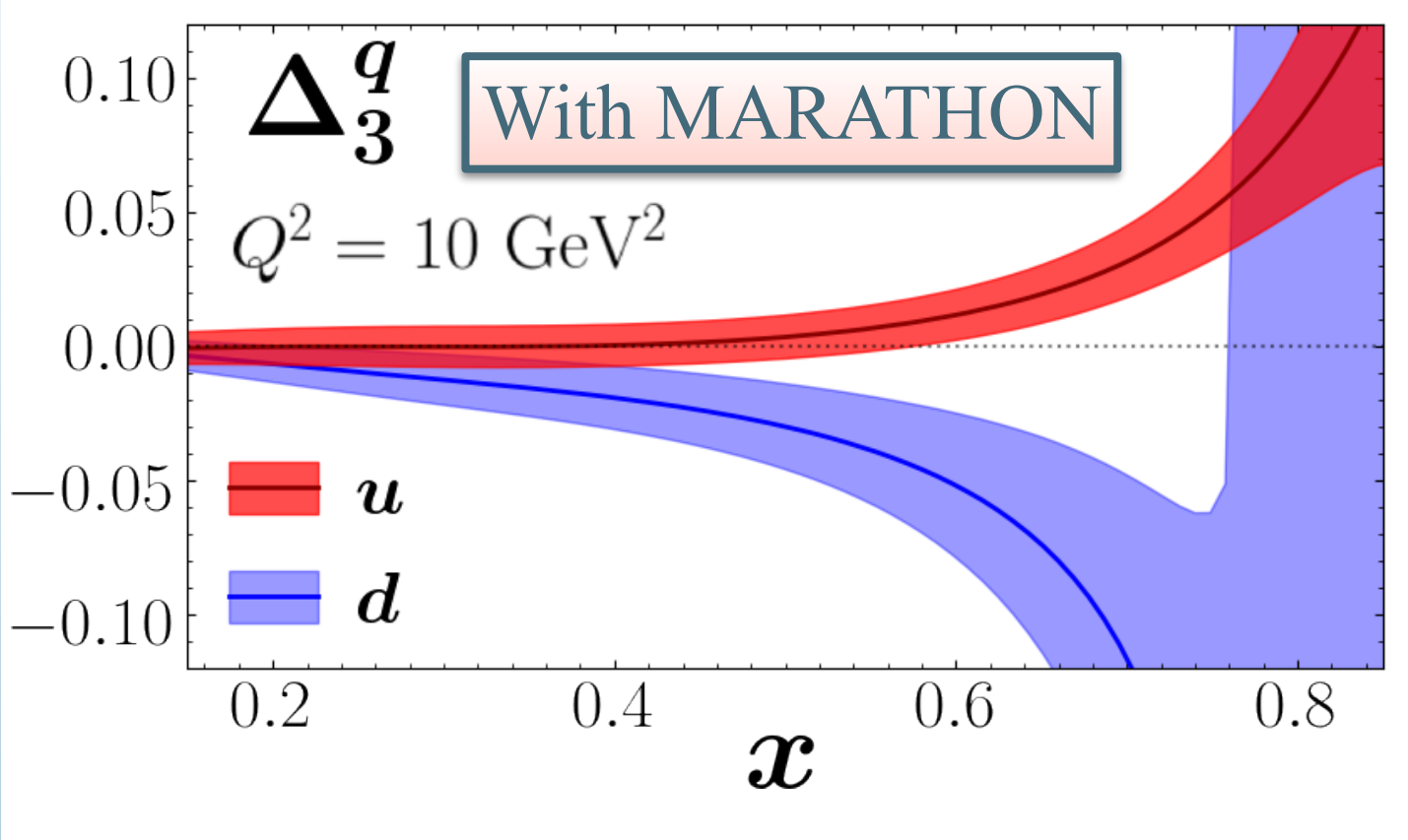


First global QCD analysis of JLab ^{3}He/D and MARATHON data

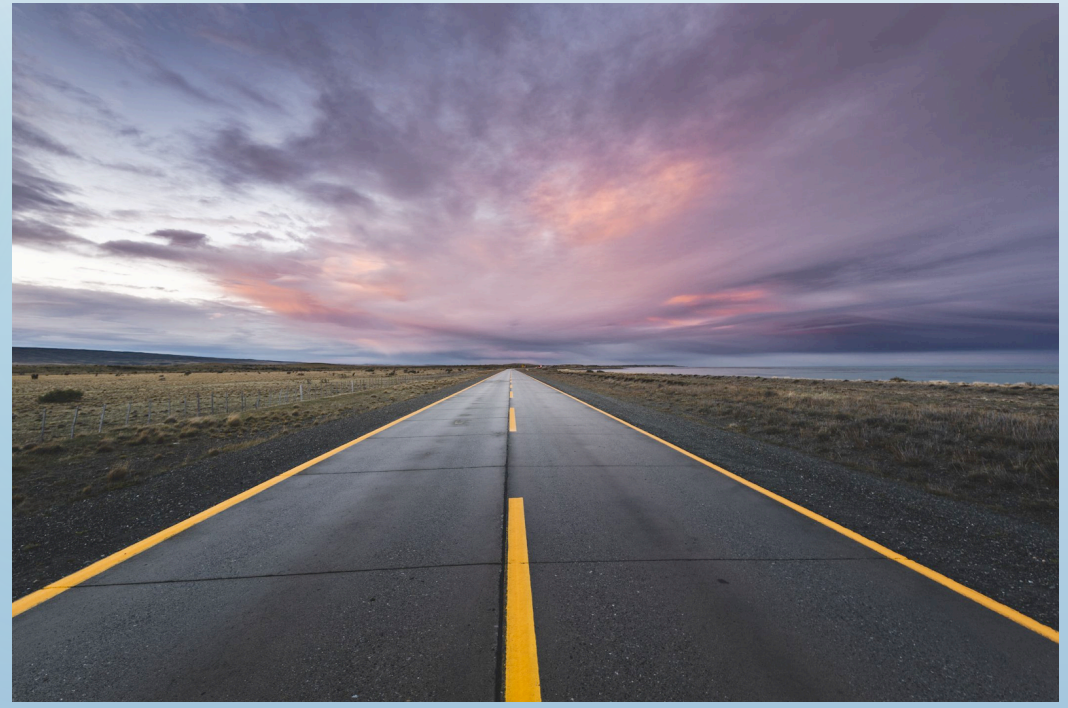
Isovector Extraction

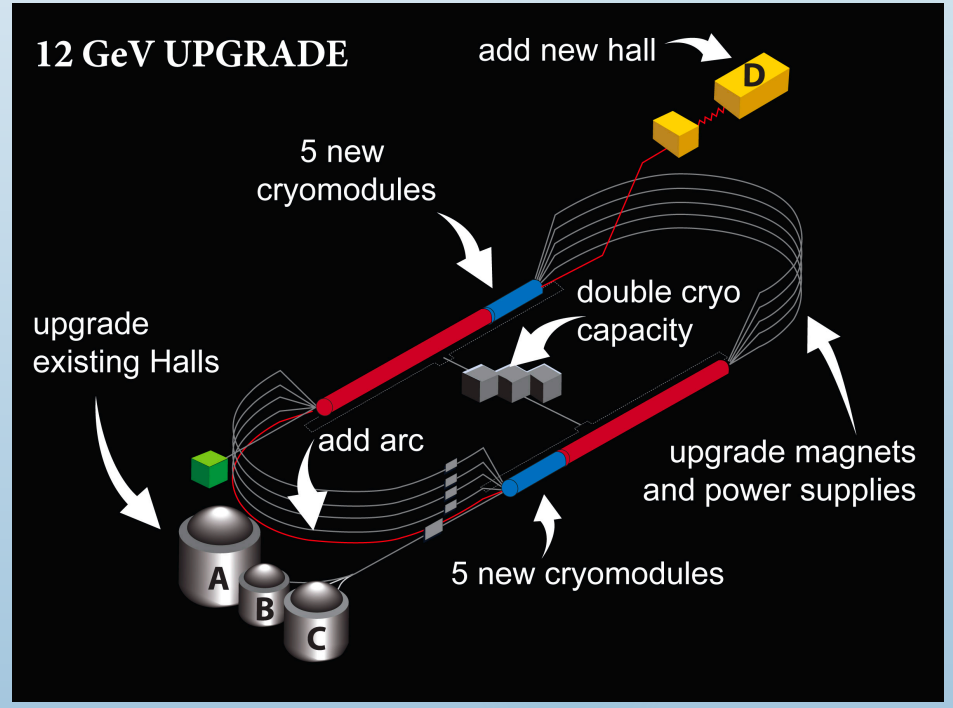
$$\Delta_3^q \equiv \frac{q_{p/^3\mathrm{H}} - q_{p/^3\mathrm{He}}}{q_{p/^3\mathrm{H}} + q_{p/^3\mathrm{He}}}$$

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



Conclusions and Outlook





Impact from MARATHON

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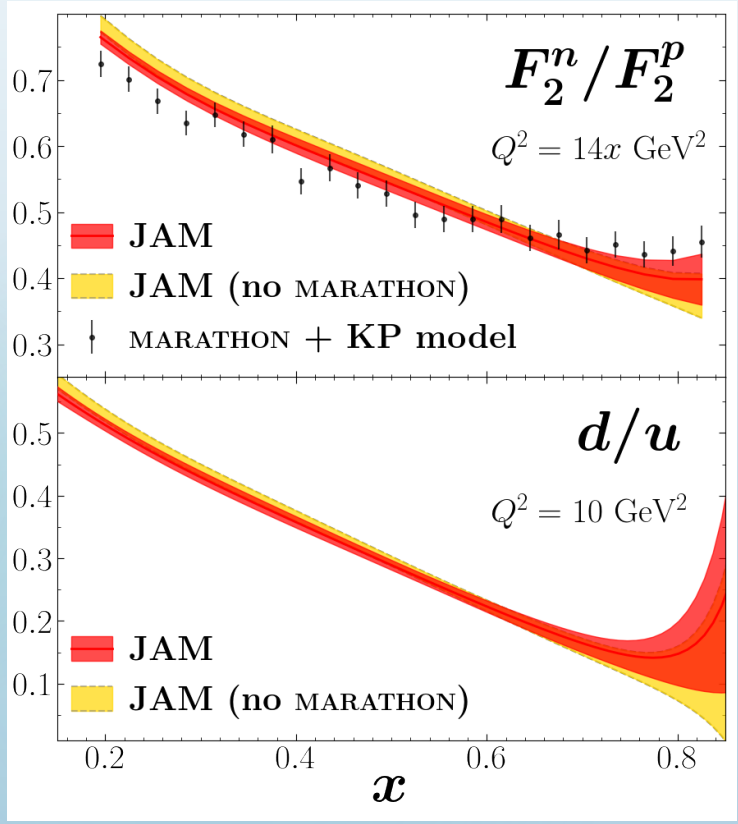
d/u Ratio ≈

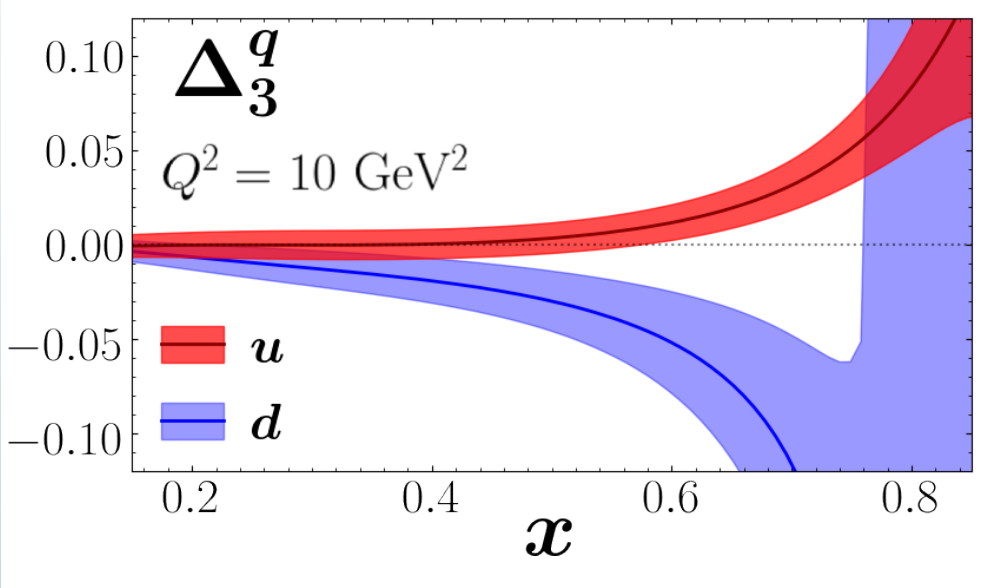
F_2^n/F_2^p Ratio ≈

$A = 3$ EMC Effects ✓

Results Summary

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





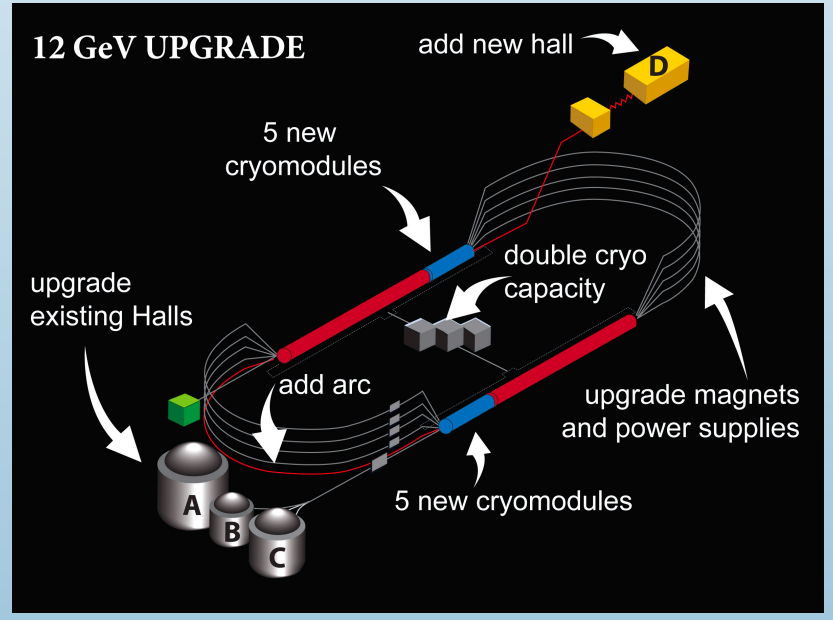
$$\Delta_3^q \equiv \frac{q_{p/^3\mathrm{H}} - q_{p/^3\mathrm{He}}}{q_{p/^3\mathrm{H}} + q_{p/^3\mathrm{He}}}$$

Simultaneous global QCD analysis of PDFs and nuclear effects essential for robust error quantification

Outlook

More data from MARATHON on ^{3}He/D and ^{3}H/D separately will provide more information on EMC effect

Beyond inclusive DIS: spectator-tagged DIS from BONuS, BAND, and LAD

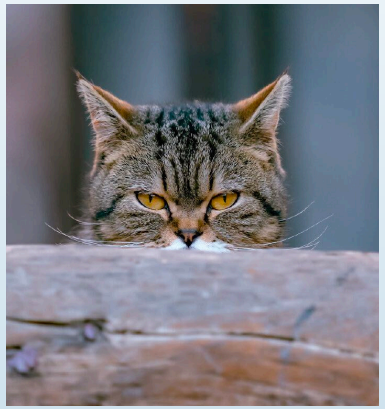


Collaboration

Andreas Metz

Wally Melnitchouk

Hanjie Liu



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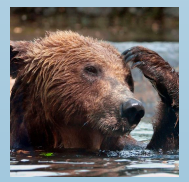
Thank you to Yiyu Zhou and Patrick Barry for helpful discussions



Extra Slides

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

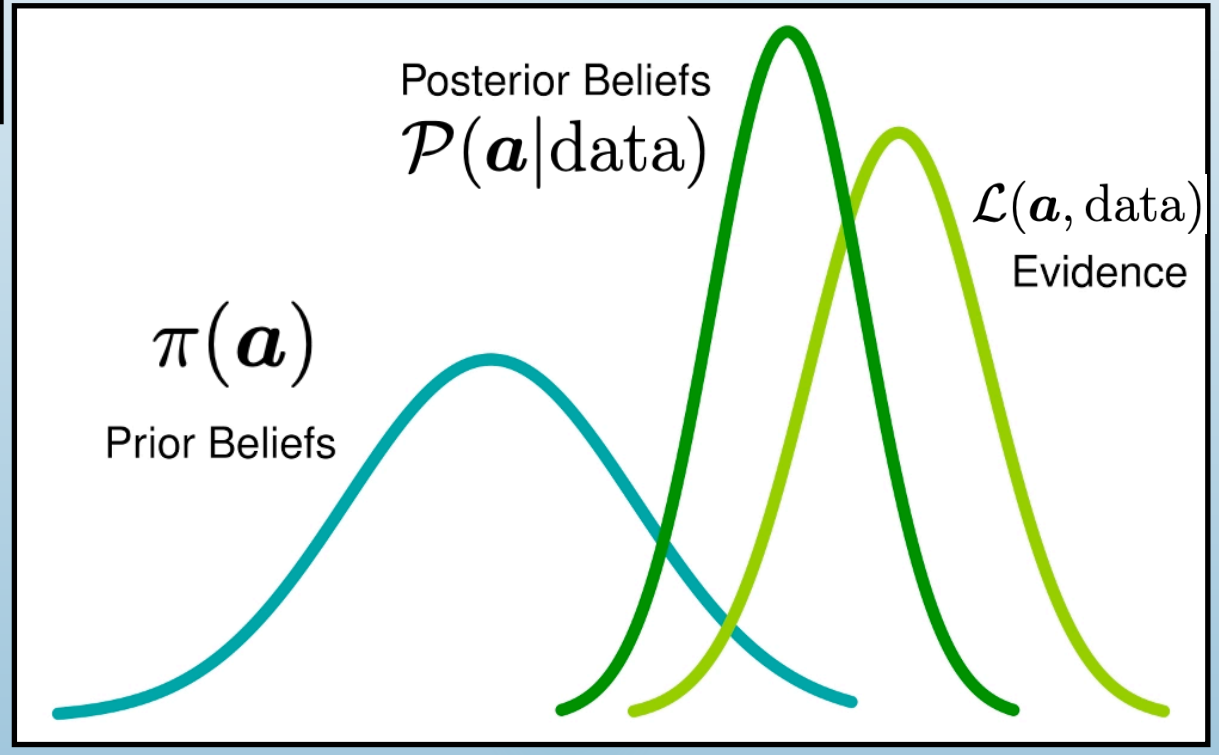
Now that we have calculated $\chi^2(\boldsymbol{a}, \text{data})$…

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

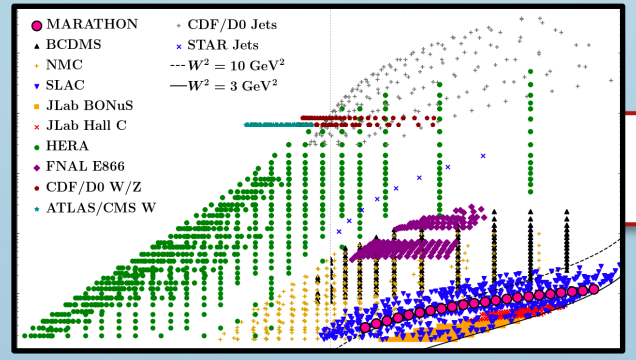
Pseudo-Data

$$\tilde{\sigma} = \sigma + N(0,1)\ \alpha$$

Uncorrelated Uncertainties

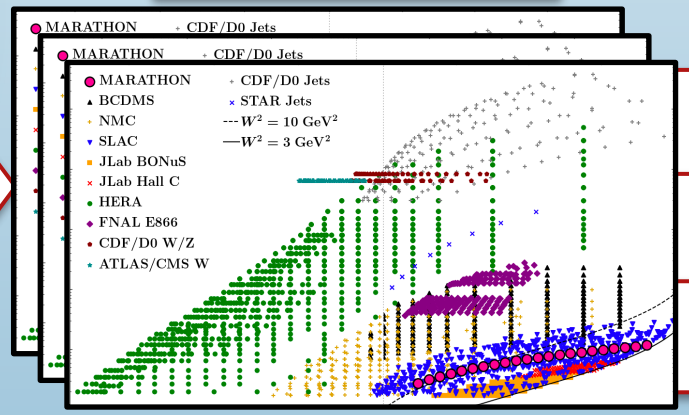
Data

Original Data



DR

Replica Data

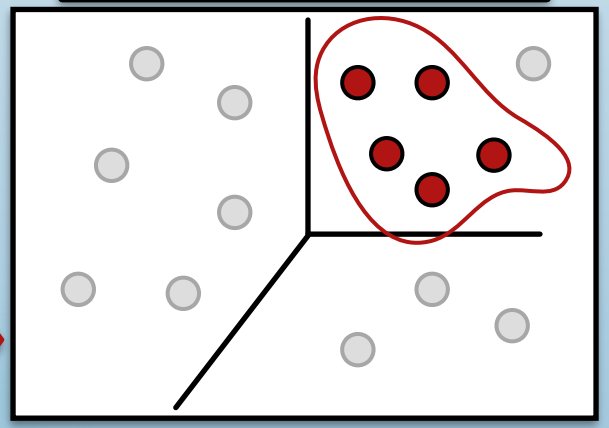


Maximum Likelihood

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))

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

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

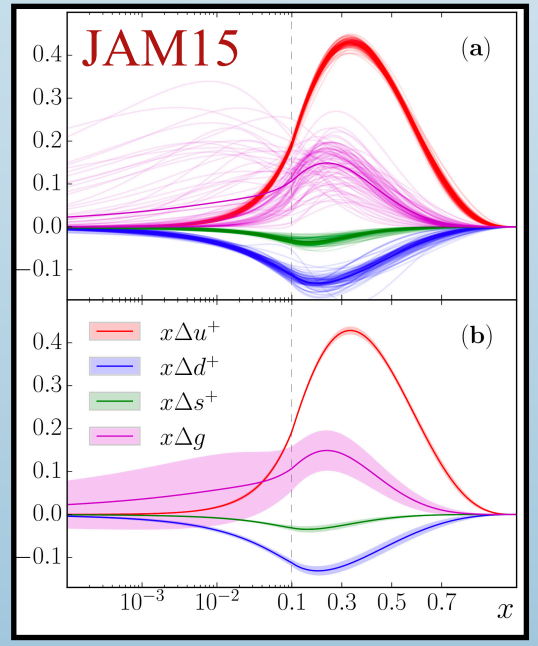
Exact, but
$n = \mathcal{O}(100)$!

Build an MC ensemble

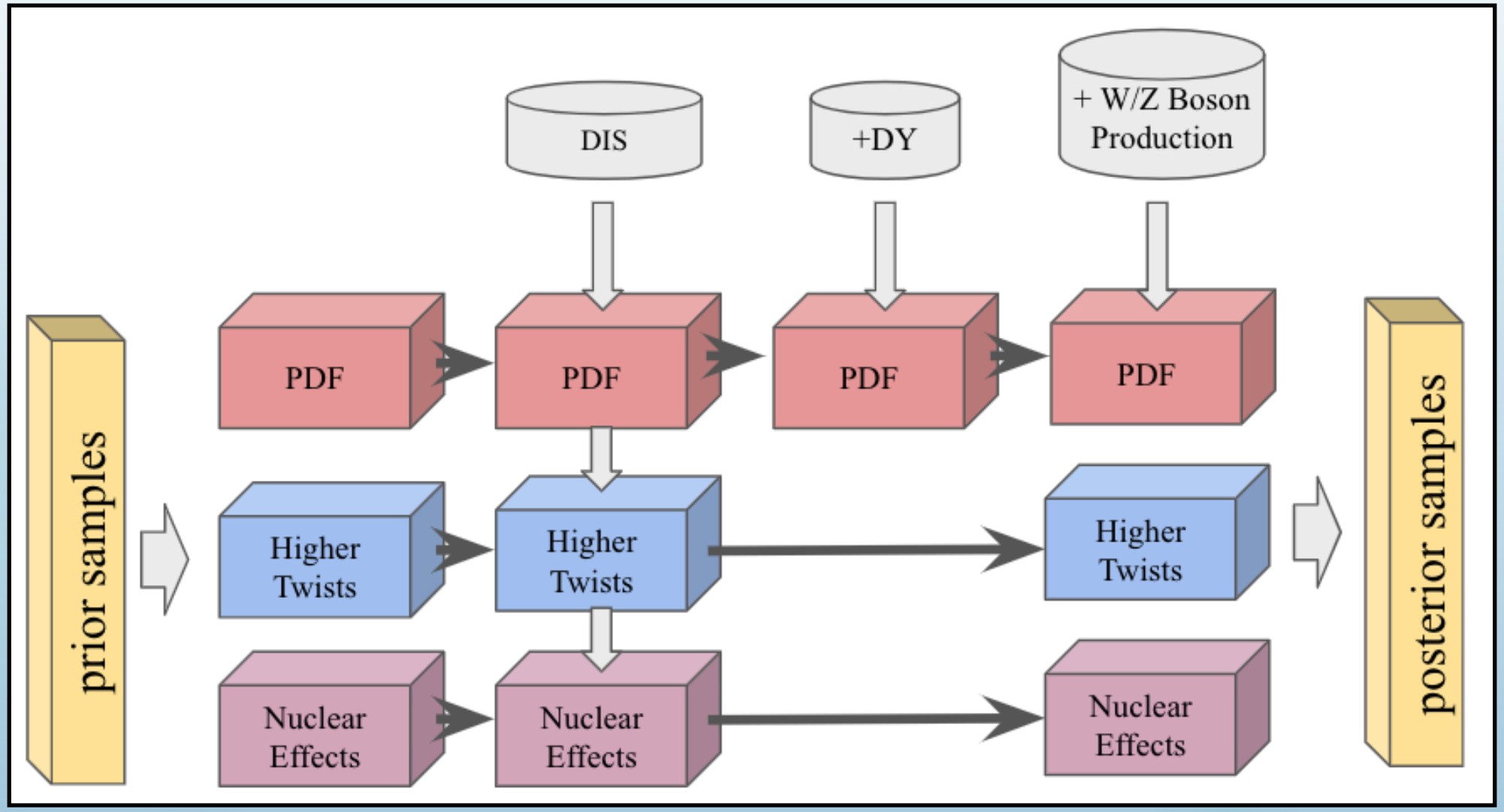
$$E[O] \approx \frac{1}{N} \sum_k O(\boldsymbol{a}_k)$$

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

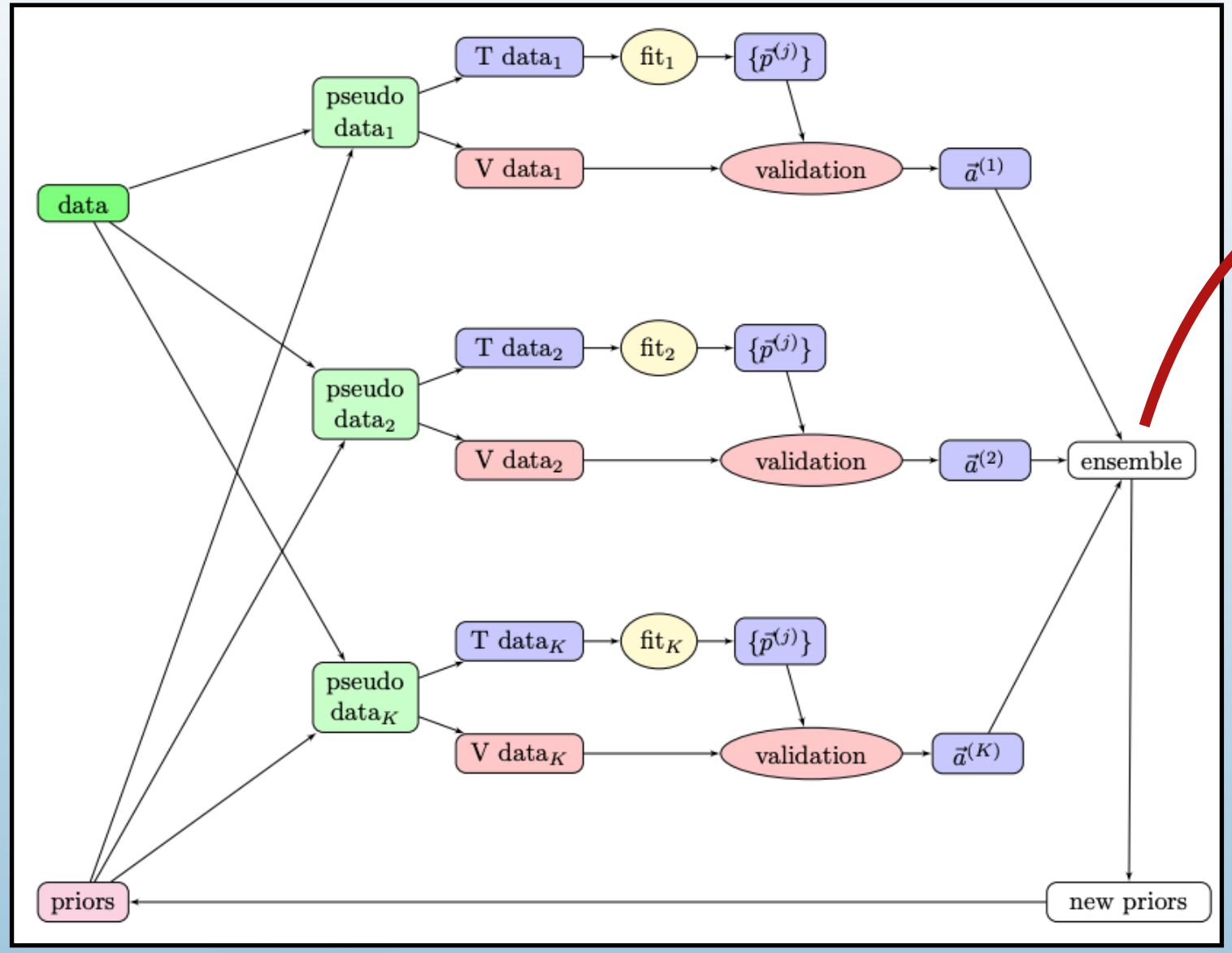
Average over k sets of the parameters (replicas)

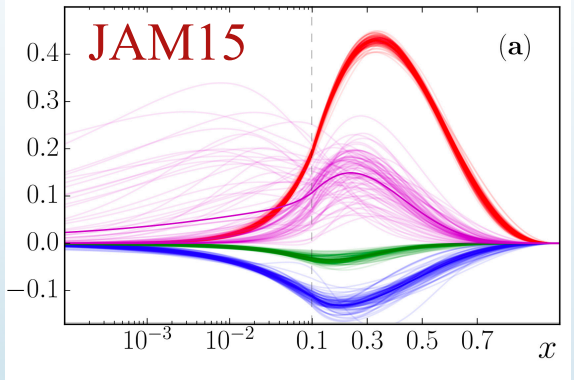


Multi-Step Strategy



Putting it all together…

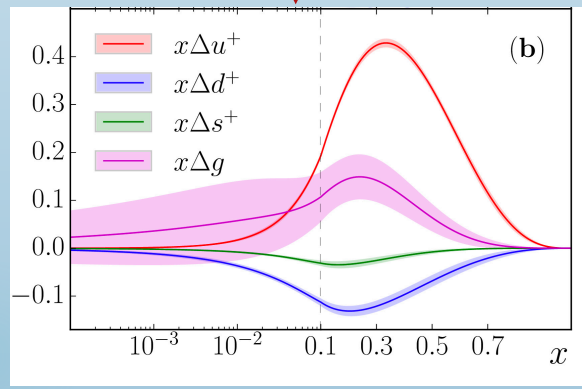




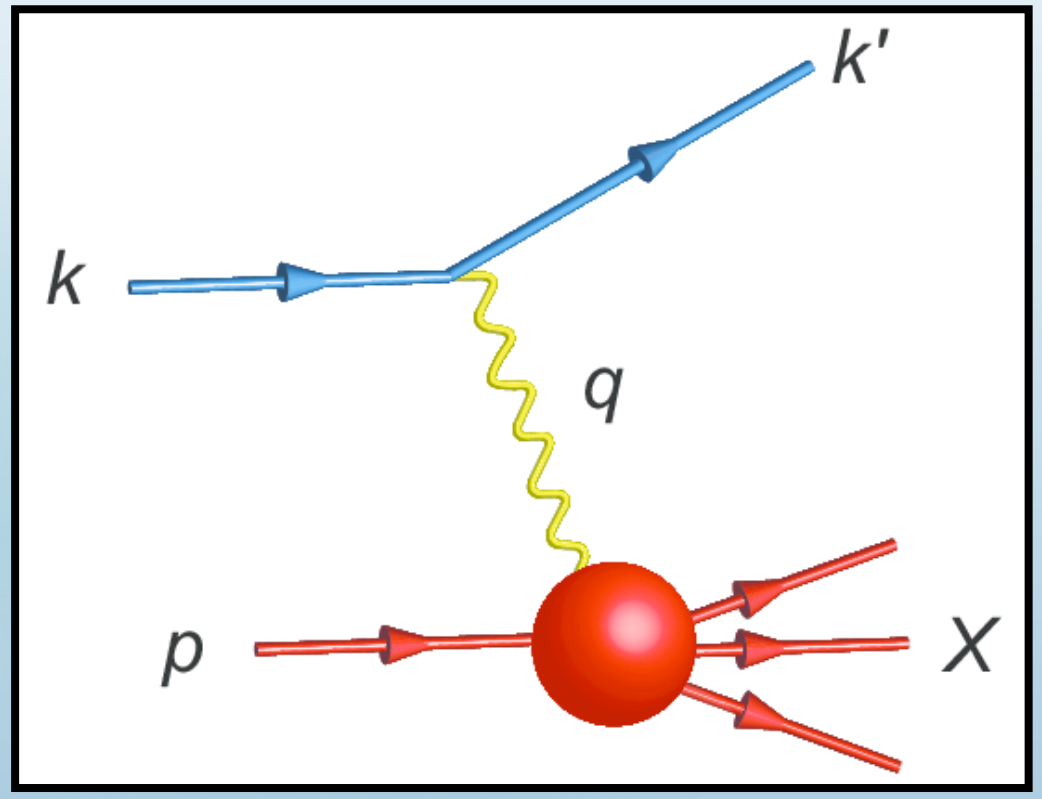
+

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

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



Deep Inelastic Scattering



Virtuality:

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

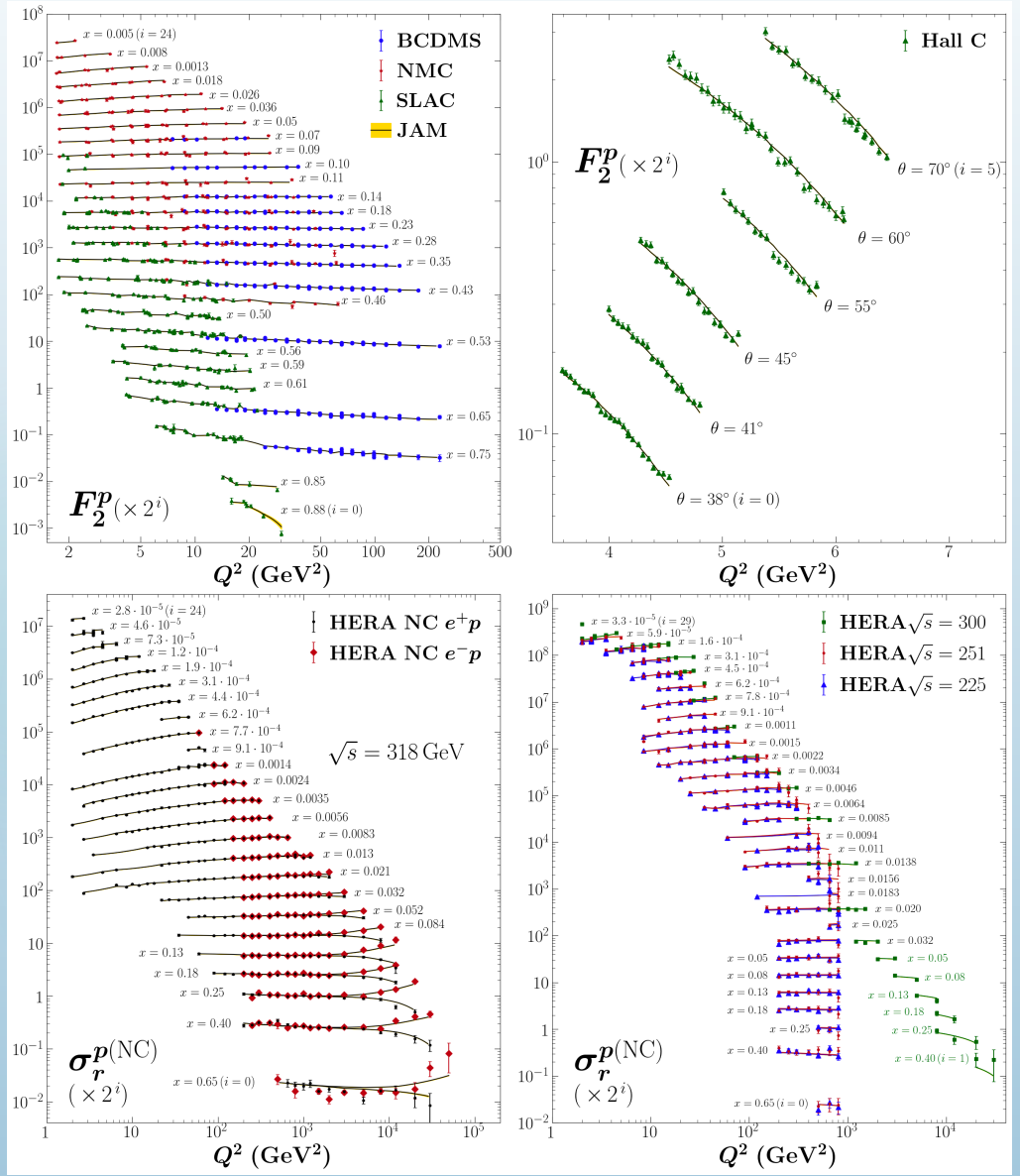
Bjorken x:

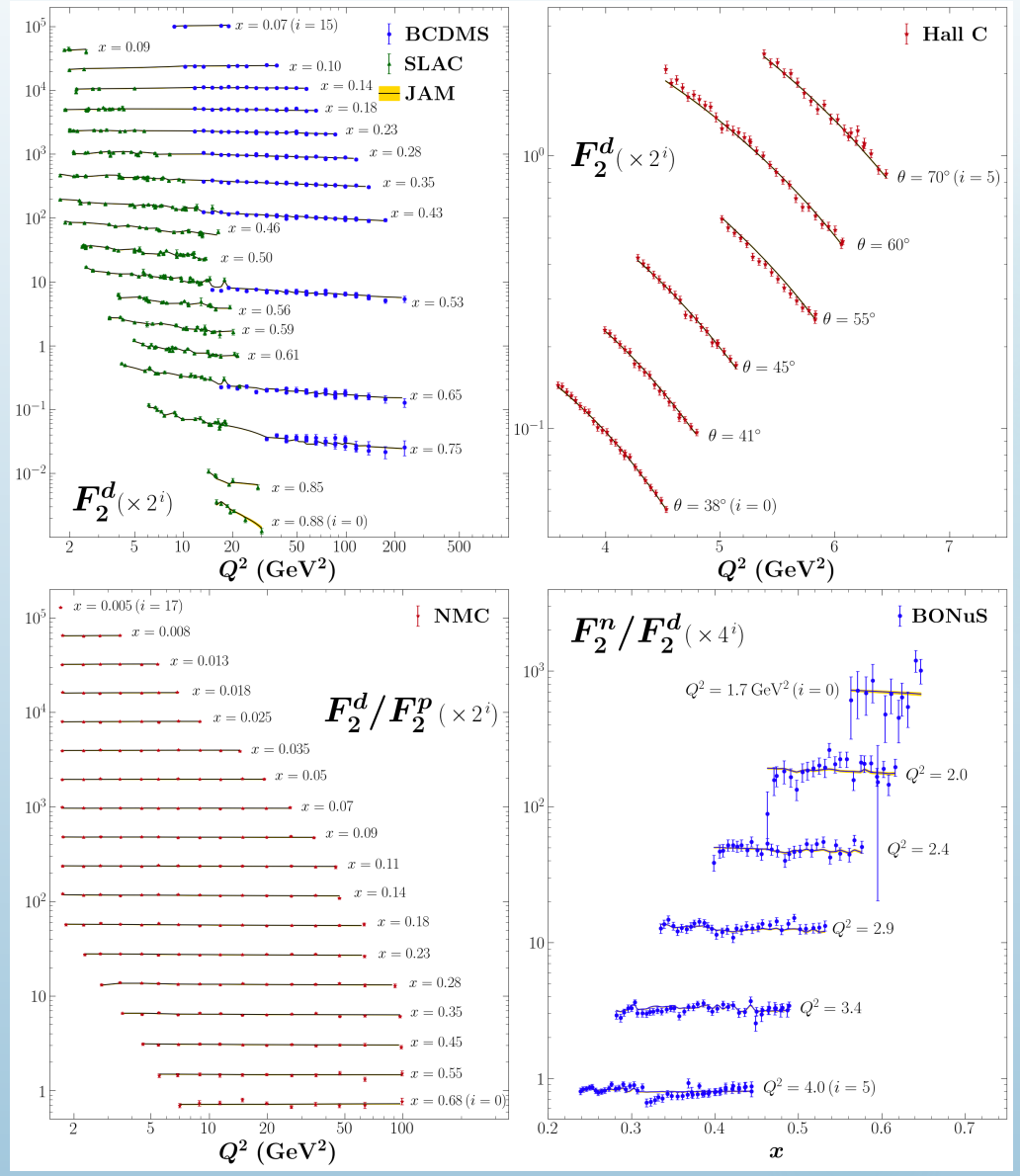
$$x = \frac{Q^2}{2p \cdot q}$$

Invariant mass of outgoing particles:

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

DIS (Neutral Current)

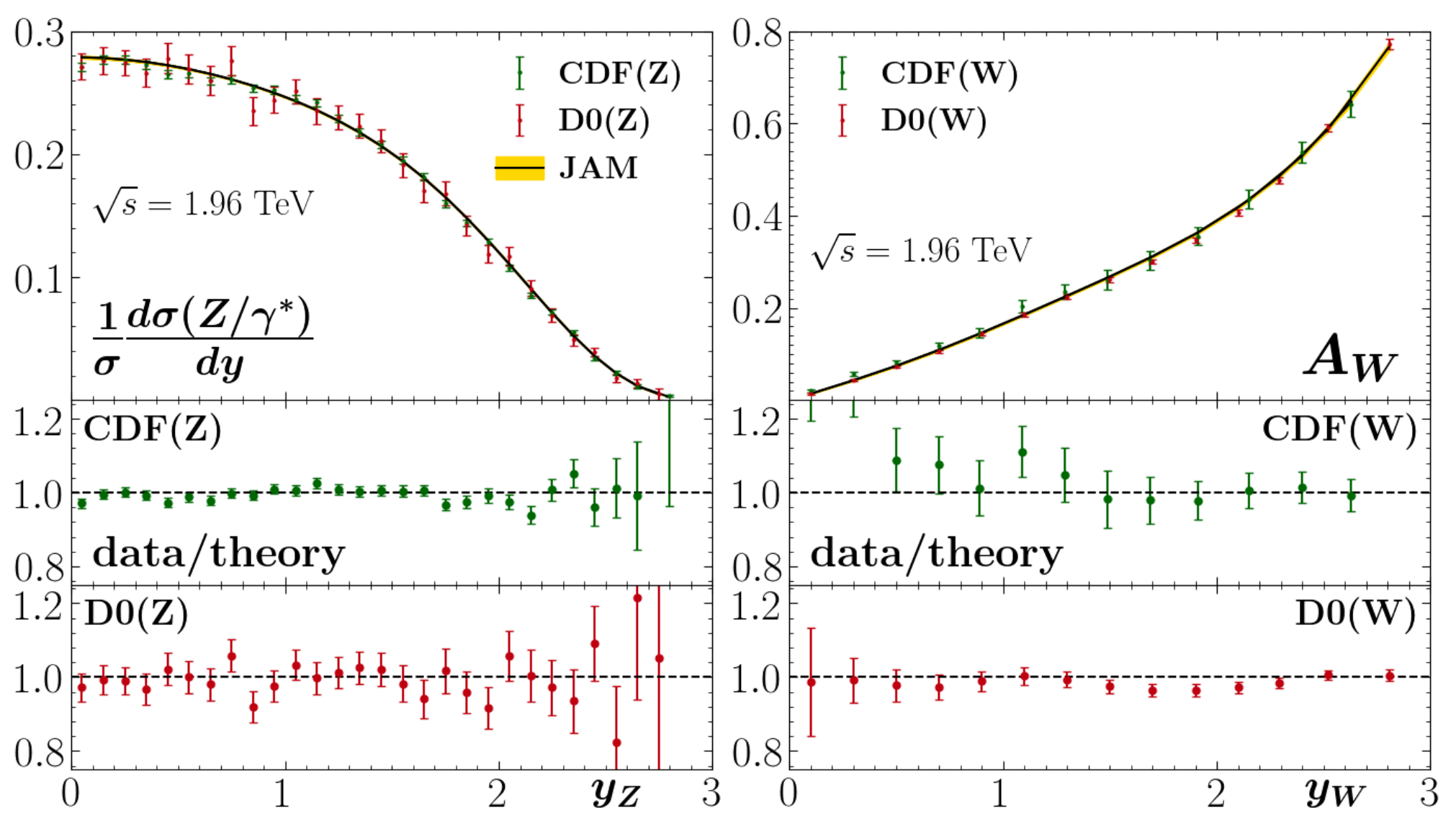




DIS

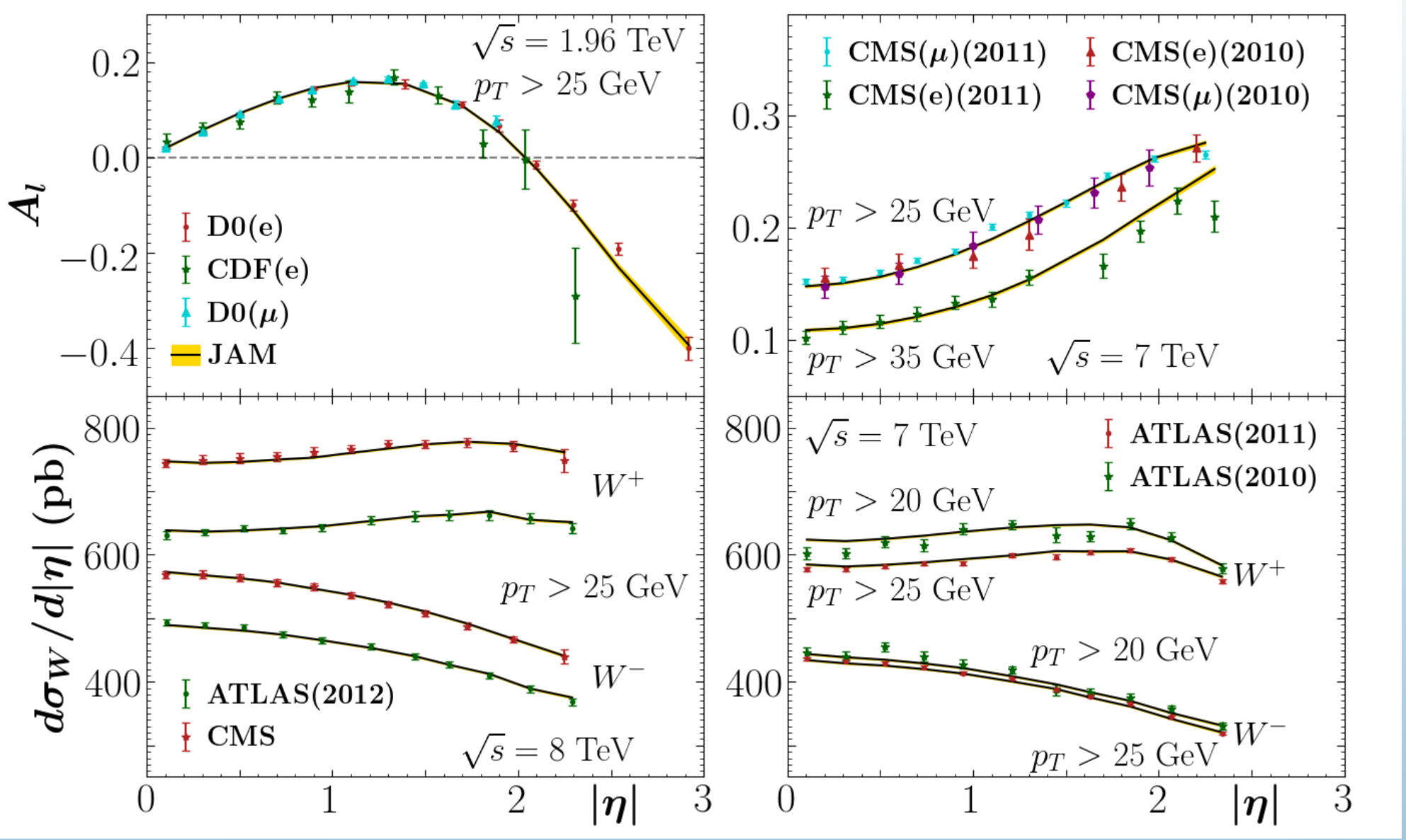
$\chi^2/N_{\text{dat}} = 1.11$

W/Z Boson Production



W/Z Boson Production
$\chi^2/N_{\text{dat}} = 1.11$

Lepton Production



Lepton Production
$\chi^2/N_{\text{dat}} = 1.57$

All Data
$\chi^2/N_{\text{dat}} = 1.11$

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)

Nucleon Structure Functions

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

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

Valence only

Nuclear Structure Functions

Nuclear Impulse Approximation + Weak Binding Approximation:

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

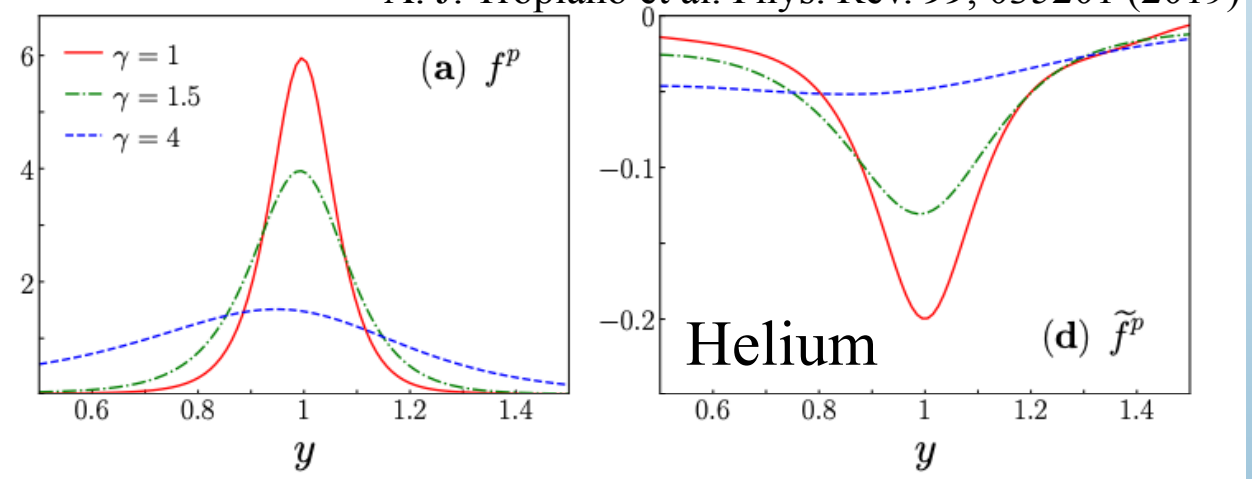
$$F_2^{A(\mathrm{off})}(x, Q^2) = \sum_N \left[\tilde{f}^{N/A} \otimes F_2^{N/A(\mathrm{off})} \right]$$

$$\gamma^2 = 1 + \frac{4x^2M^2}{Q^2}$$

Contains Virtuality

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

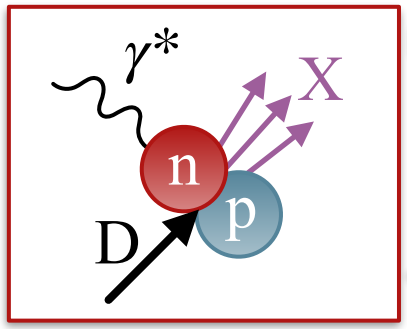
A. J. Tropiano et al. Phys. Rev. **99**, 035201 (2019)



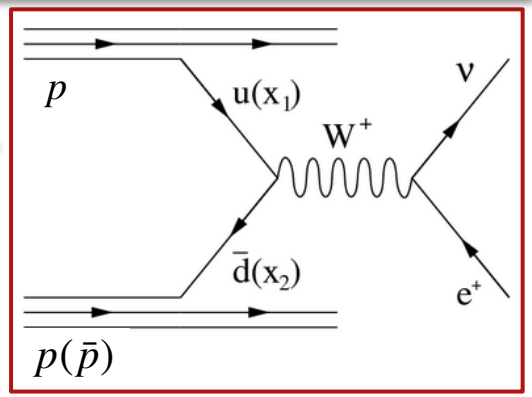
The Global Analysis Soup

Nuclear Scattering

$$F_2^D \propto f^D \otimes x\left[\delta u + \delta d\right]$$



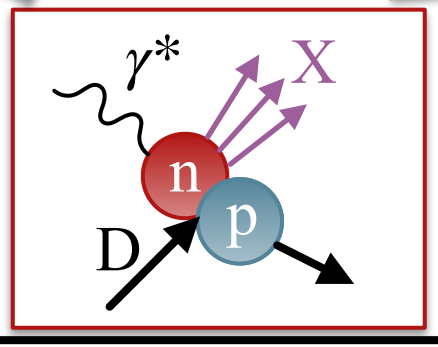
W Asymmetries



d/u
$+$
Nuclear/off-shell effects

$$A_W(y) \xrightarrow[y \to y_{max}]{} \frac{1 - d/u}{1 + d/u}$$

$$\frac{F_2^n}{F_2^D} \propto xu + 4xd$$

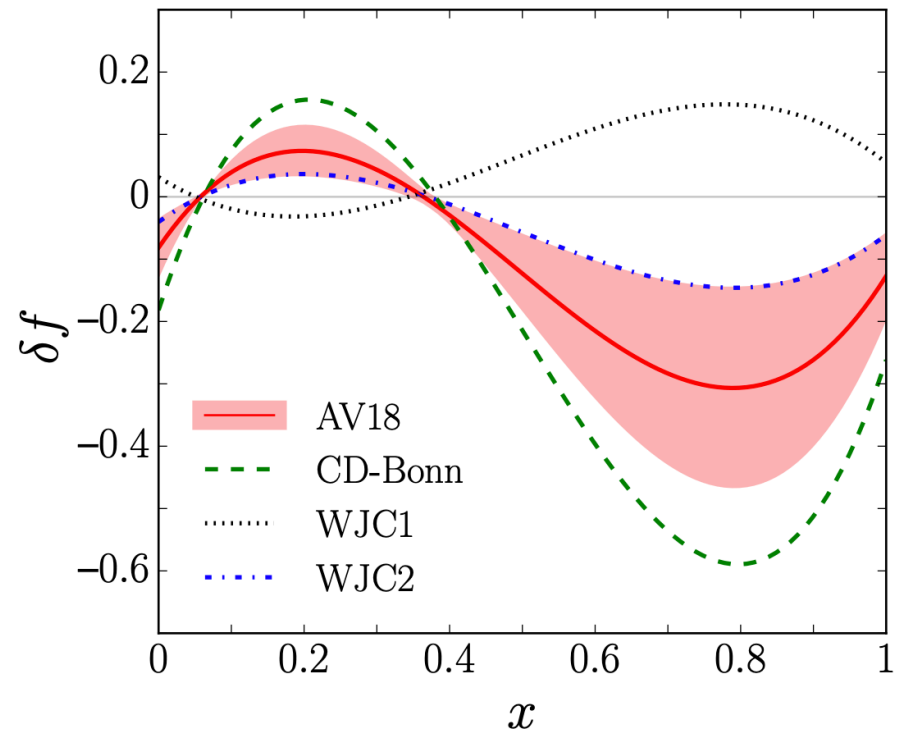


Tagged Neutron Scattering

Figure inspired by Alberto Accardi's

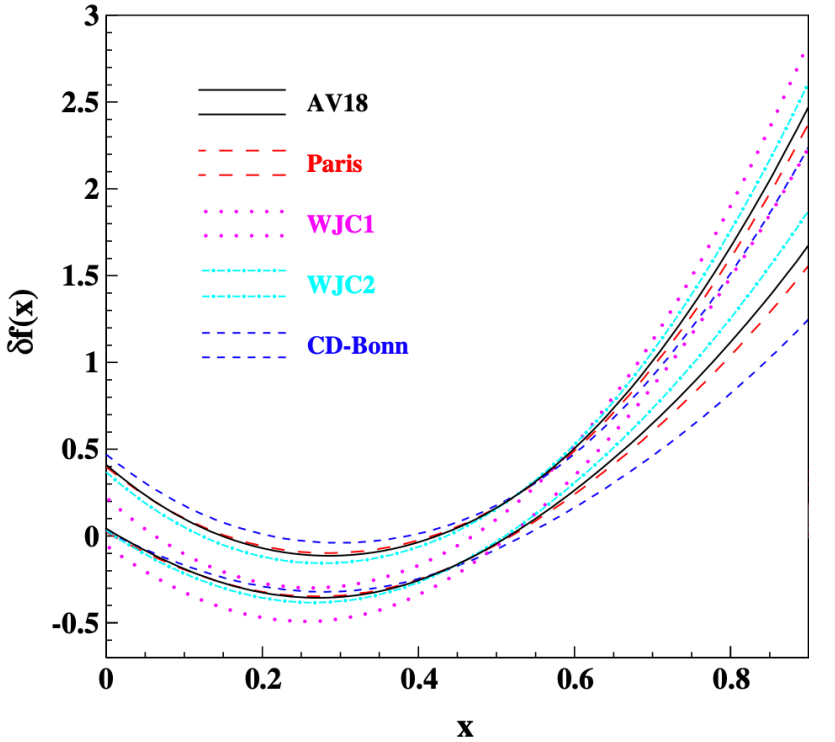
Previous Global Analyses

$$\delta q^{N/A} \xrightarrow[\text{dependence}]{\text{No flavor}} \delta f^{N/A} \xrightarrow[\text{dependence}]{\text{No nuclear}} \delta f^{N} \xrightarrow[\text{dependence}]{\text{No nucleon}} \delta f$$



A. Accardi et. al. Phys. Rev. D **93**, 114017 (2016)

CJ15



S. I. Alekhin et. al. Phys. Rev. D **96**, 054005 (2017)

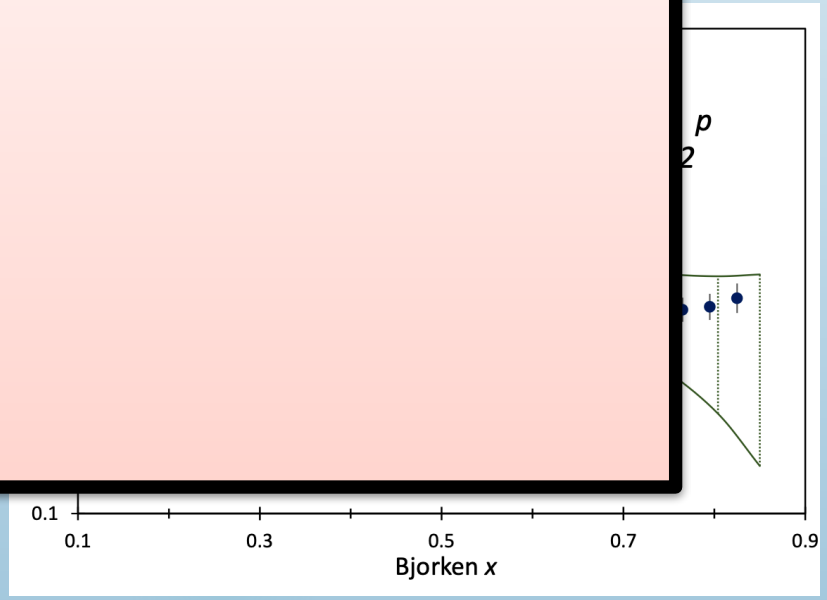
AKP17

Which Came First?

Theory/

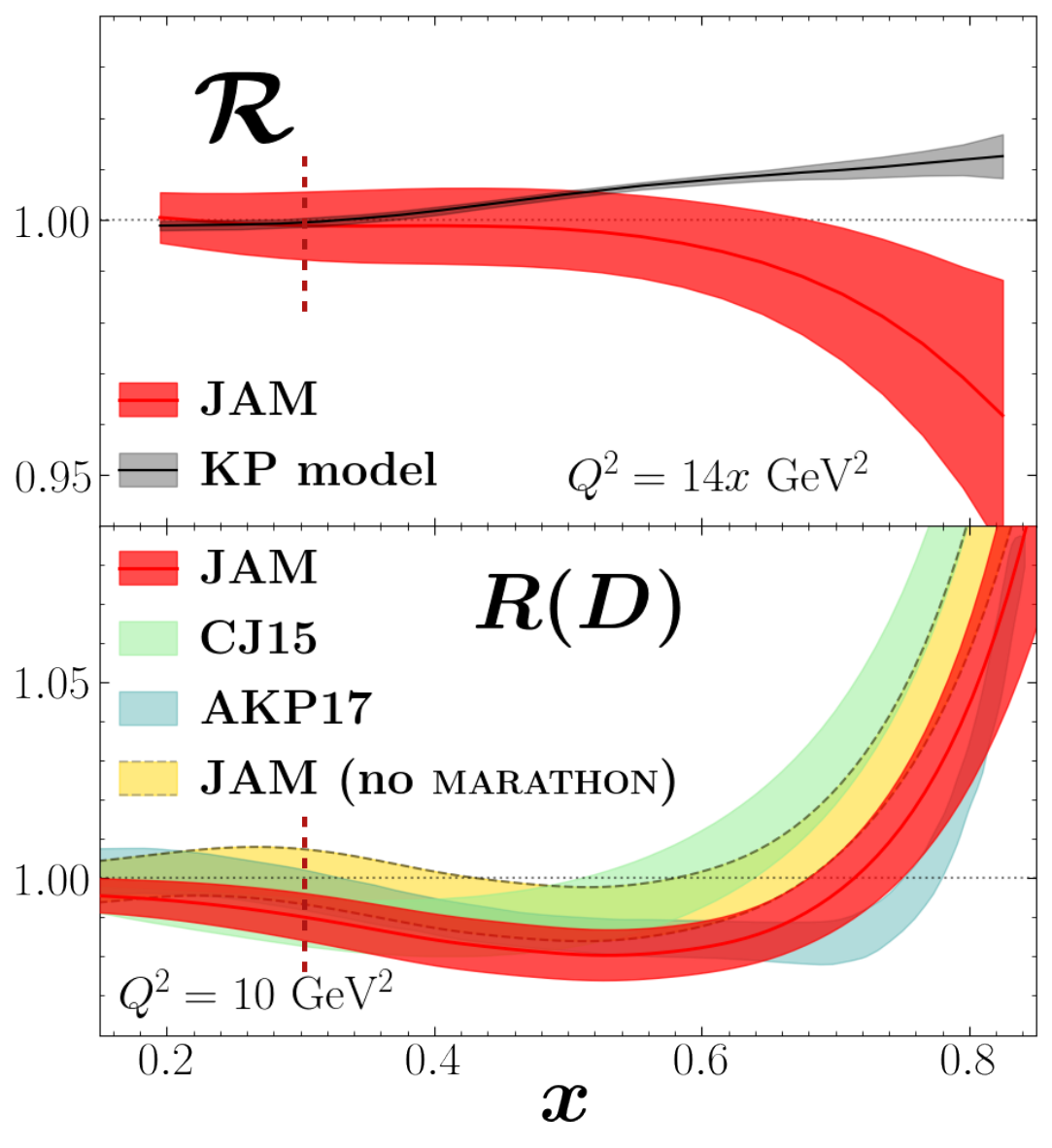
MARATHON

K



NEED GLOBAL ANALYSIS!

KP Model Assumptions



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

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

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

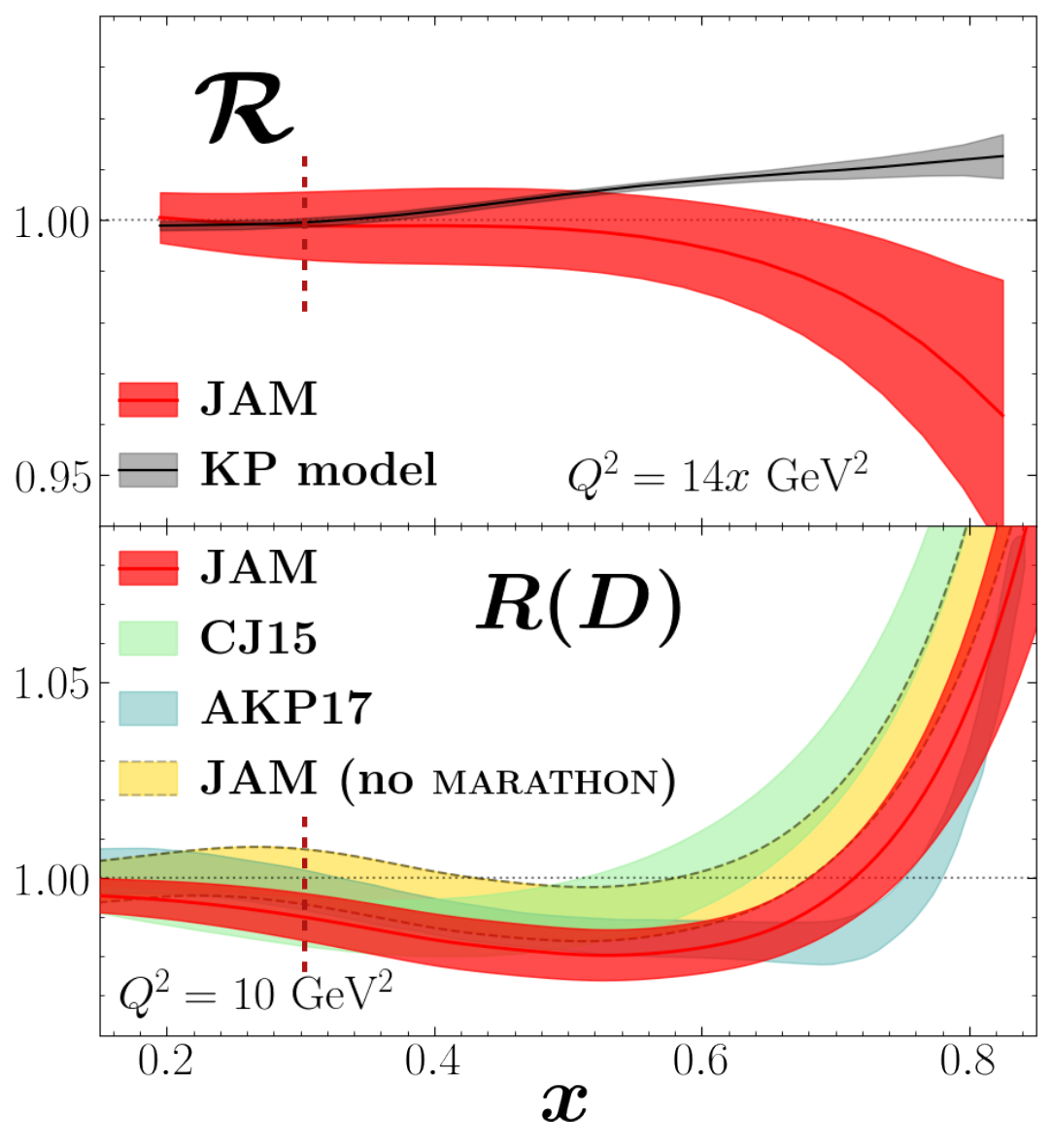
$$\mathscr{R} = R(^3\mathrm{He})/R(^3\mathrm{H})$$

KP Model states that

$$R(D)\big|_{x=0.31} = \mathscr{R}\big|_{x=0.31} = 1$$

Apply 1.025(7) normalization for $F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}$

Data Driven Approach



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

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

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

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

Allow data to decide values of $R(D)$ and $\mathscr{R}$ and normalizations

$R(D)|_{x=0.31} \neq 1$ and a normalization of 1.009(5) for $F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}$ (vs. 1.025(7))

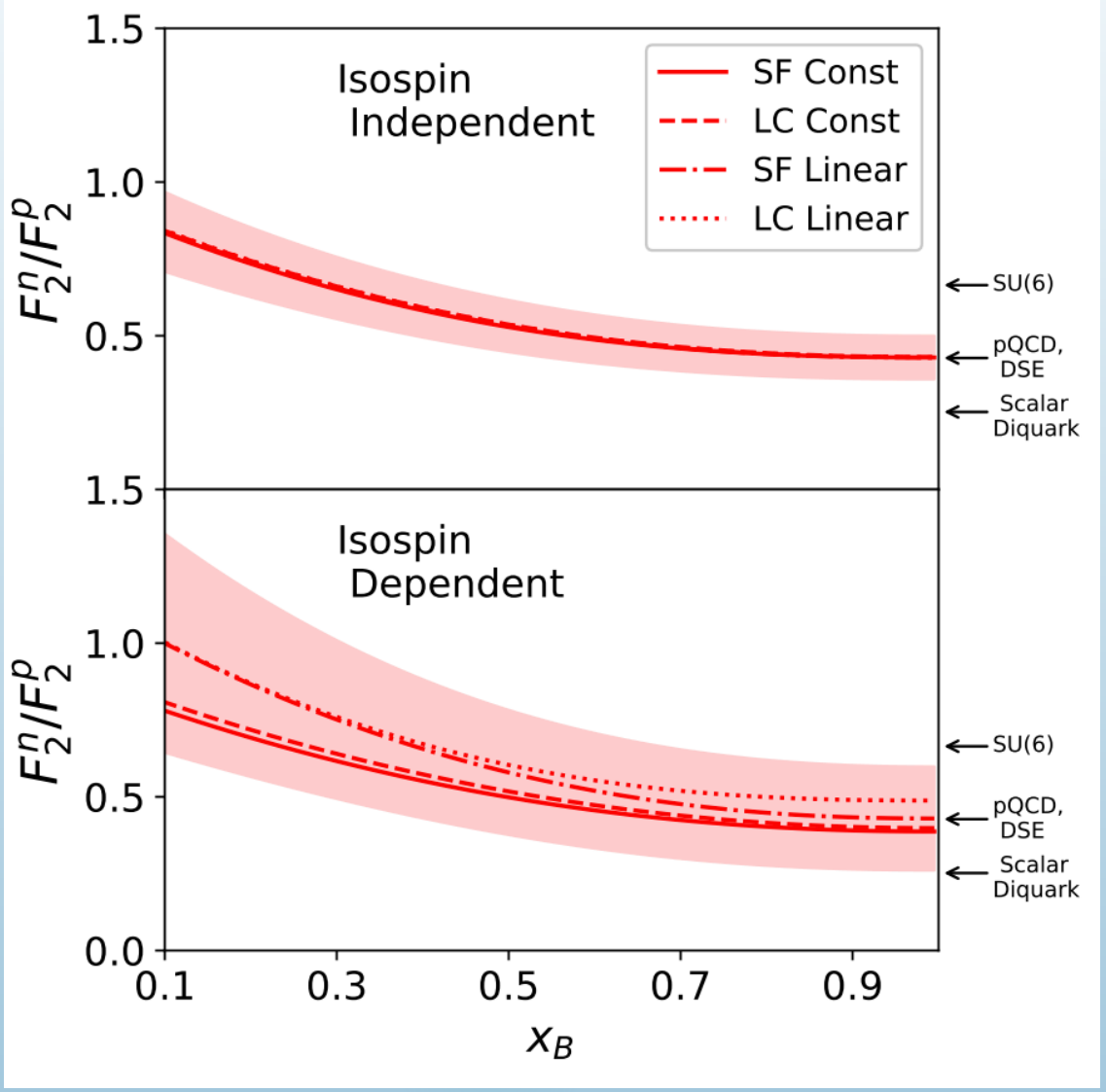
Results from Segarra et al. (arXiv: 2104.07130)

April 14, 2021

Conclusions

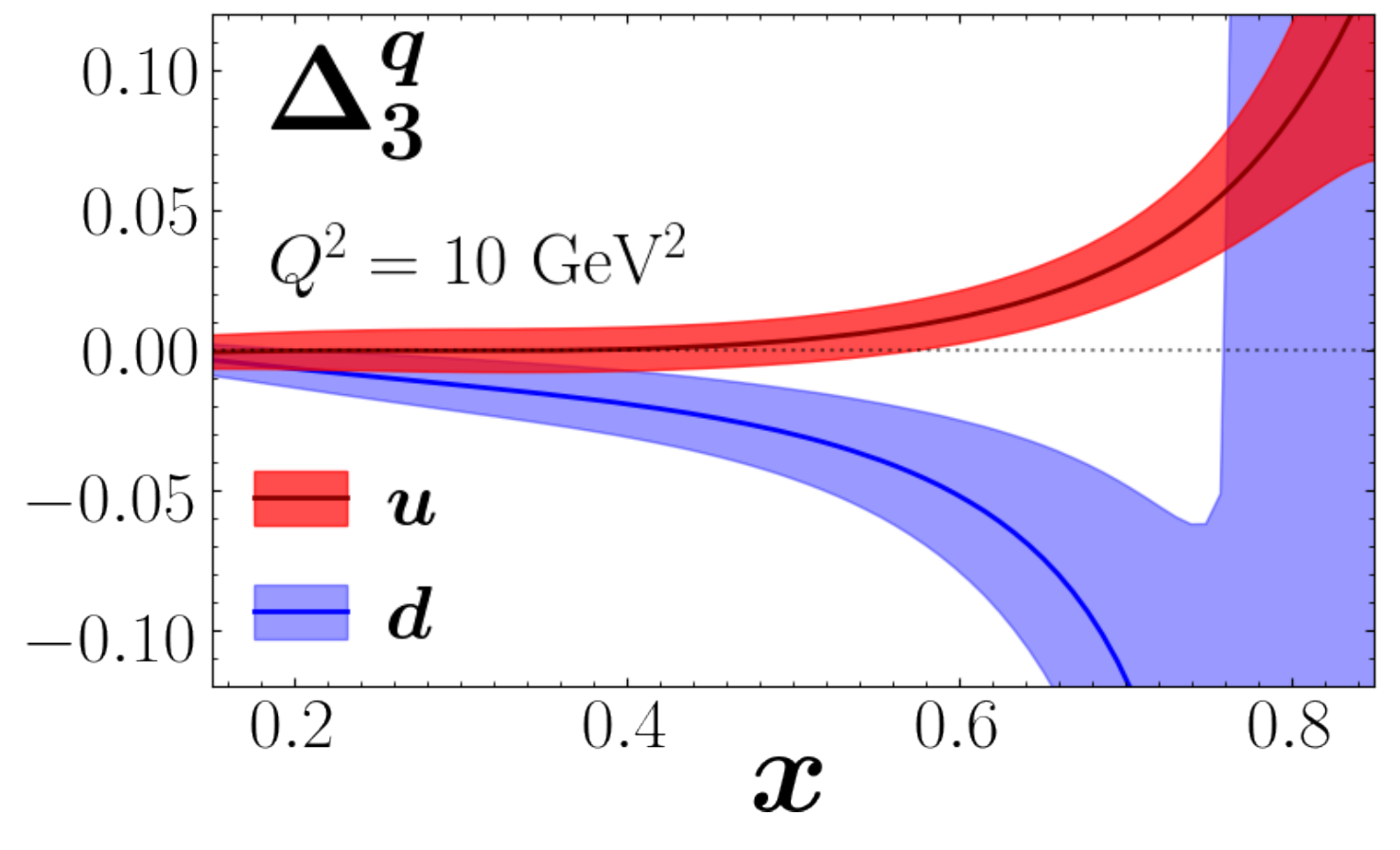
1. Extrapolation of $F_2^n/F_2^p|_{x_B \to 1}$ with MARATHON data included is model-dependent

2. "…the inclusion of the MARATHON data … sheds little light on the nature of the EMC effect."



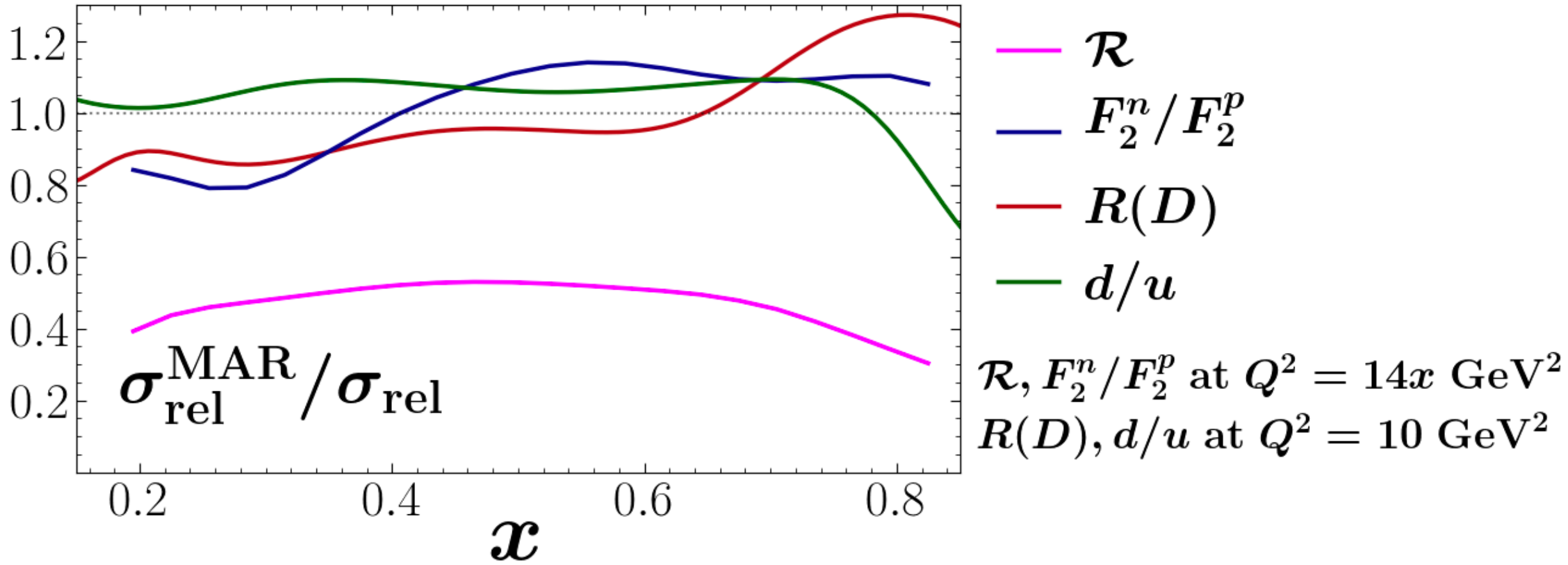
Stability of Result

	A = 2 WF	A = 3 WF	TMC
Main	Paris	KPSV	AOT
AV18	AV18	KPSV	AOT
CD-Bonn	CD-Bonn	KPSV	AOT
WJC-1	WJC-1	KPSV	AOT
WJC-2	WJC-2	KPSV	AOT
SS	Paris	SS	AOT
GP	Paris	KPSV	GP



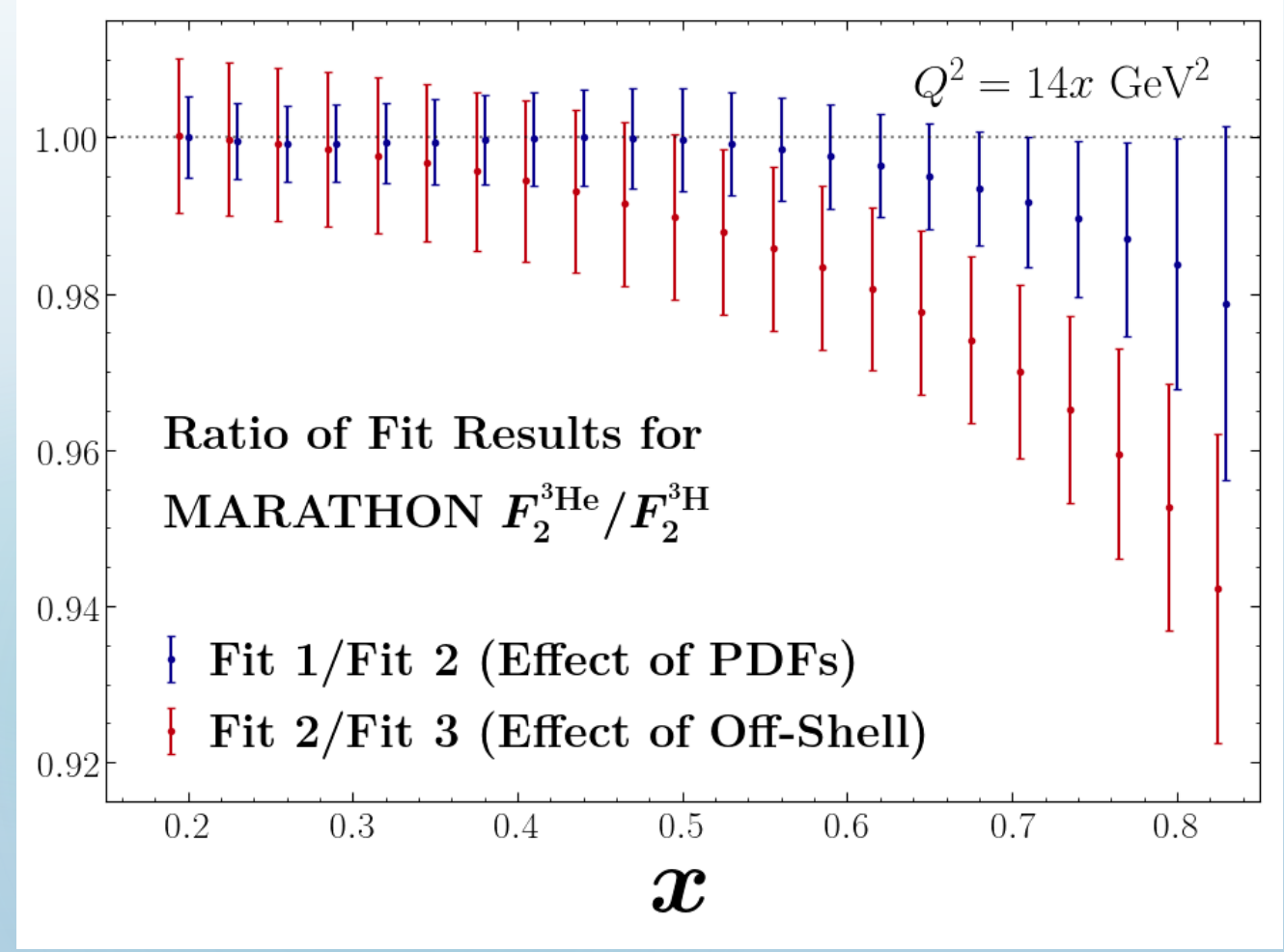
A = 2 Wavefunction: Paris
A = 3 Wavefunction: KPSV
Target Mass Corrections: AOT

Uncertainty Reduction



MARATHON greatly reduces uncertainties on $\mathscr{R}$ (~60%)

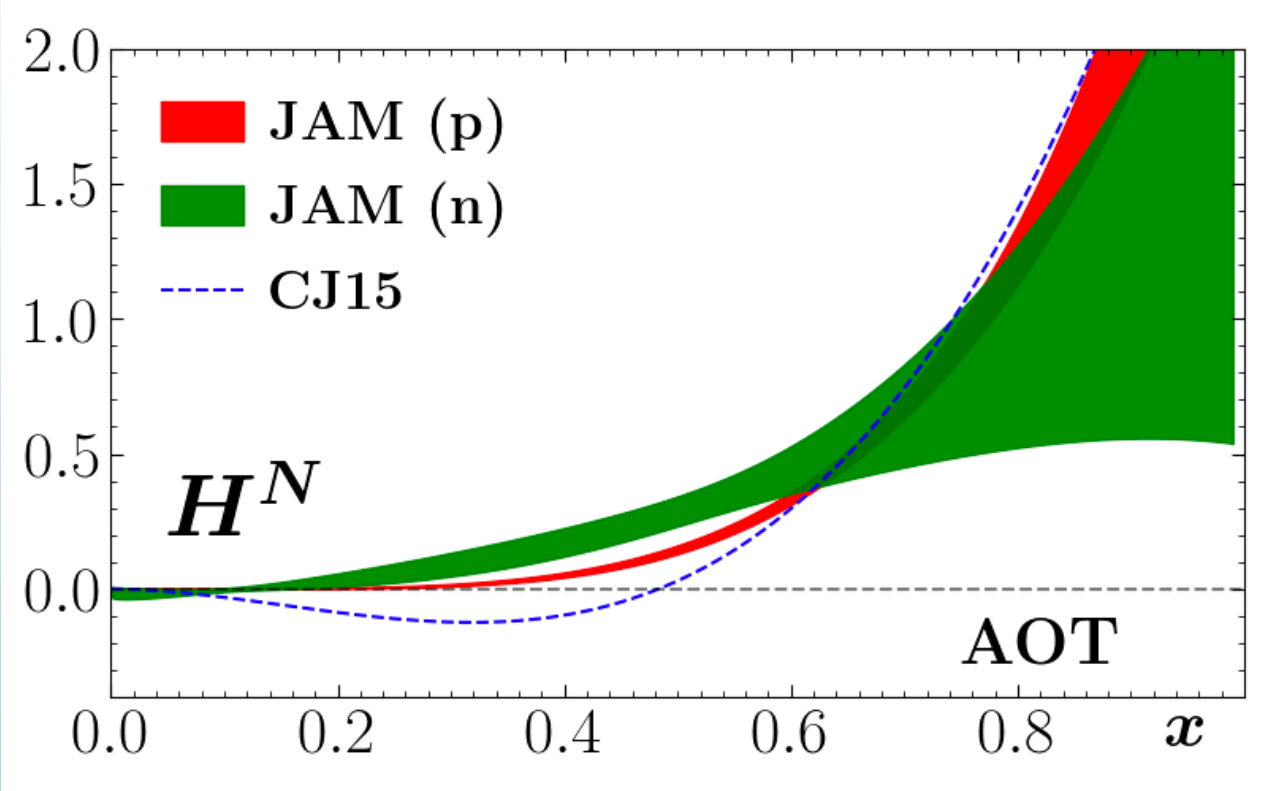
MARATHON Sensitivity

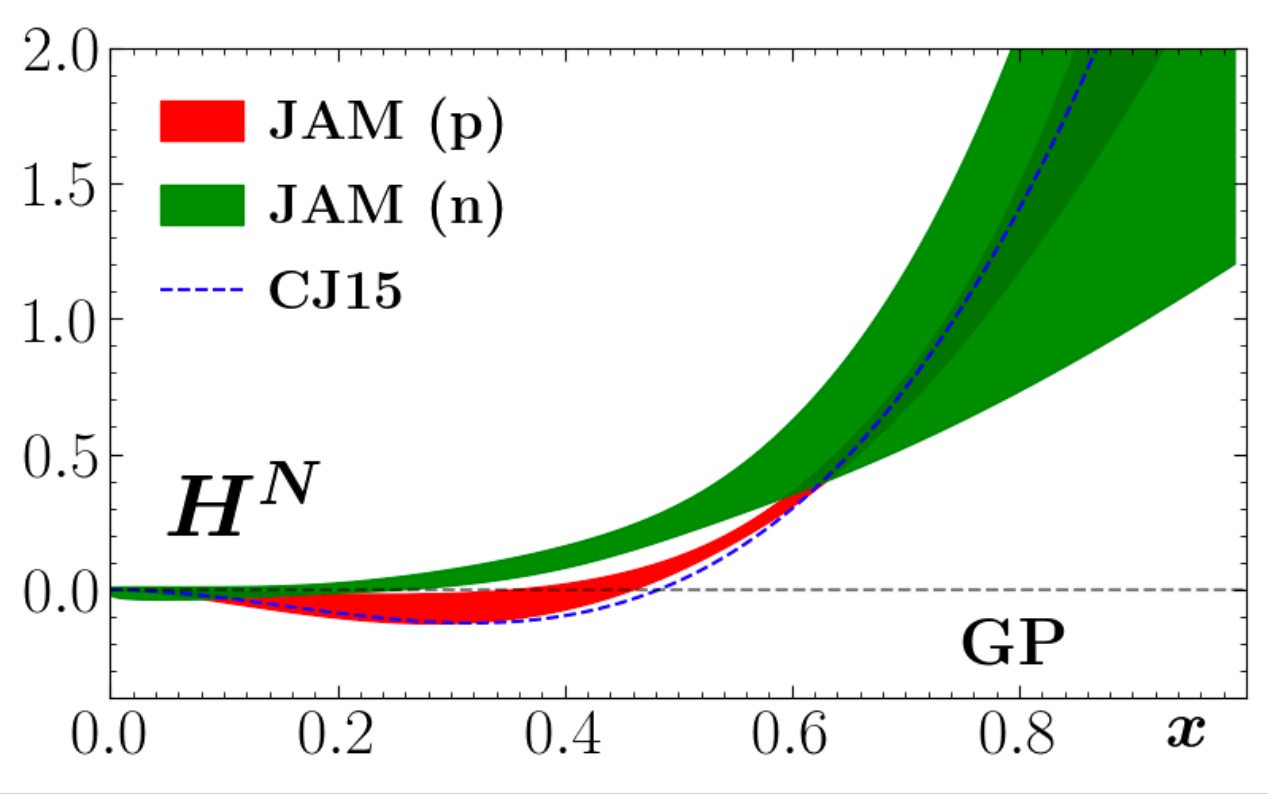


	PDFs	Off-Shell
Fit 1	Fitted	Fitted
Fit 2	Fixed	Fitted
Fit 3	Fixed	Zero

MARATHON $F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}$ data more sensitive to off-shell effects than PDFs

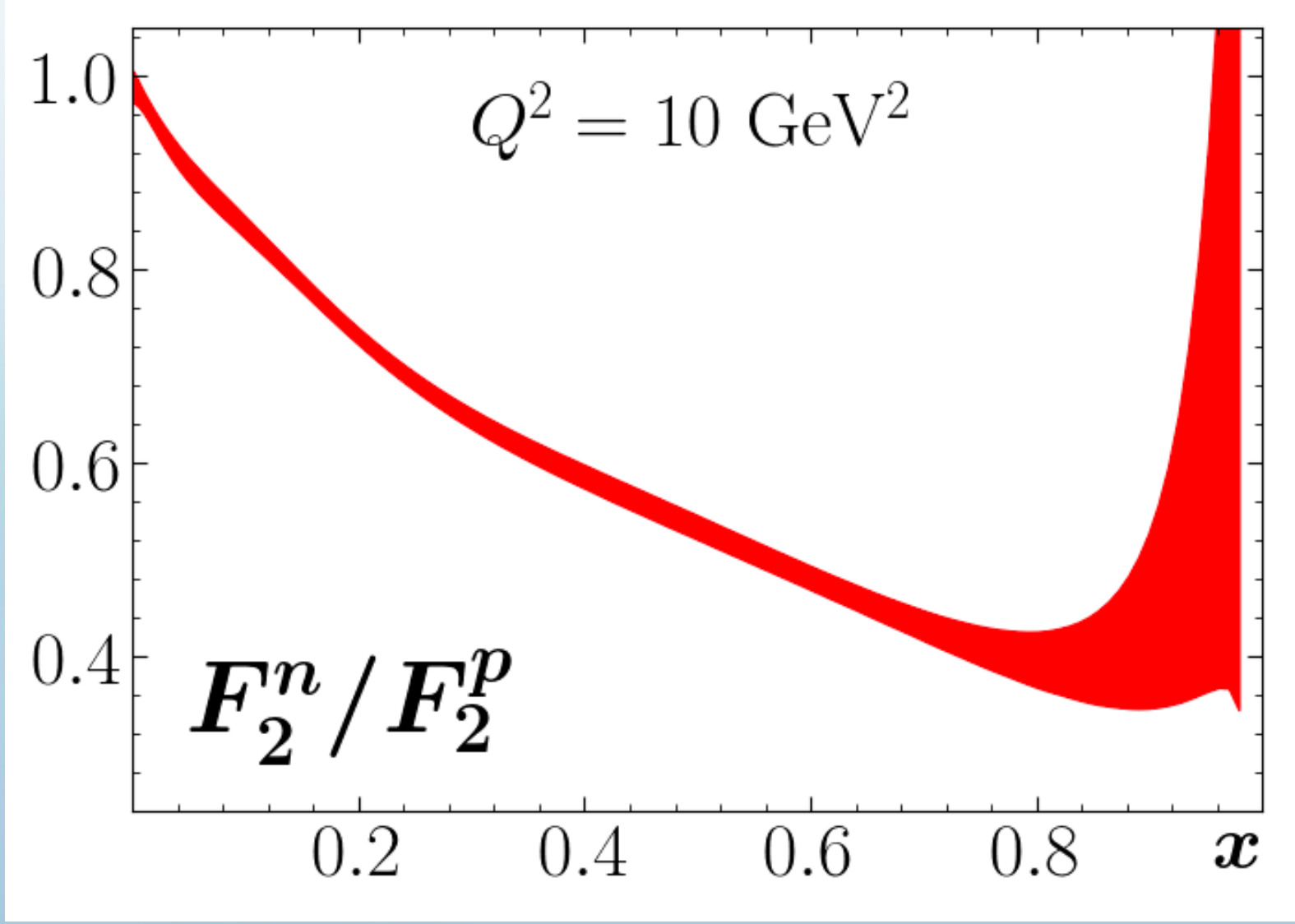
Higher Twist



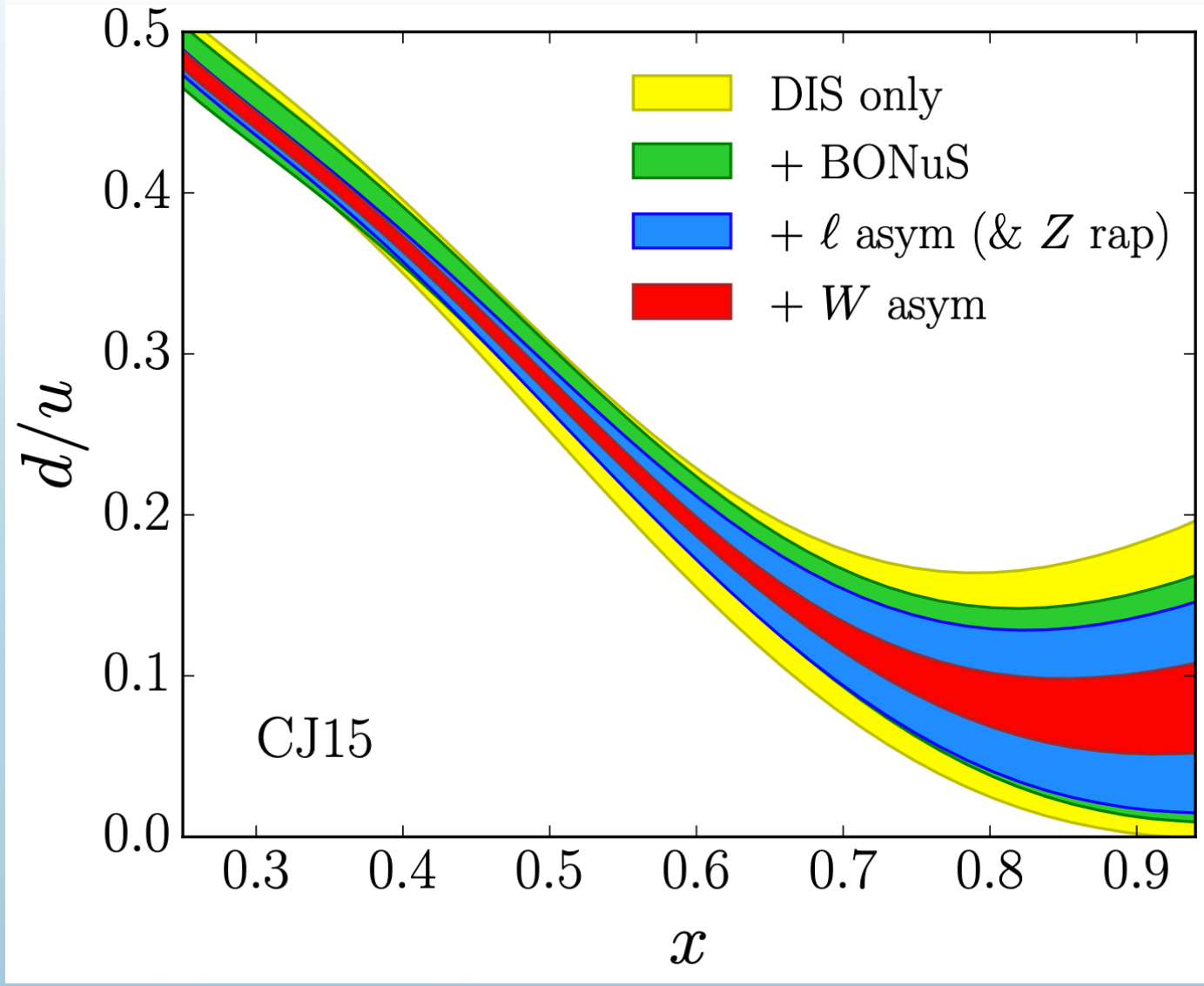


$$H^N(x) = C^N x^{a^N}(1 + d^N x)$$

Extrapolation

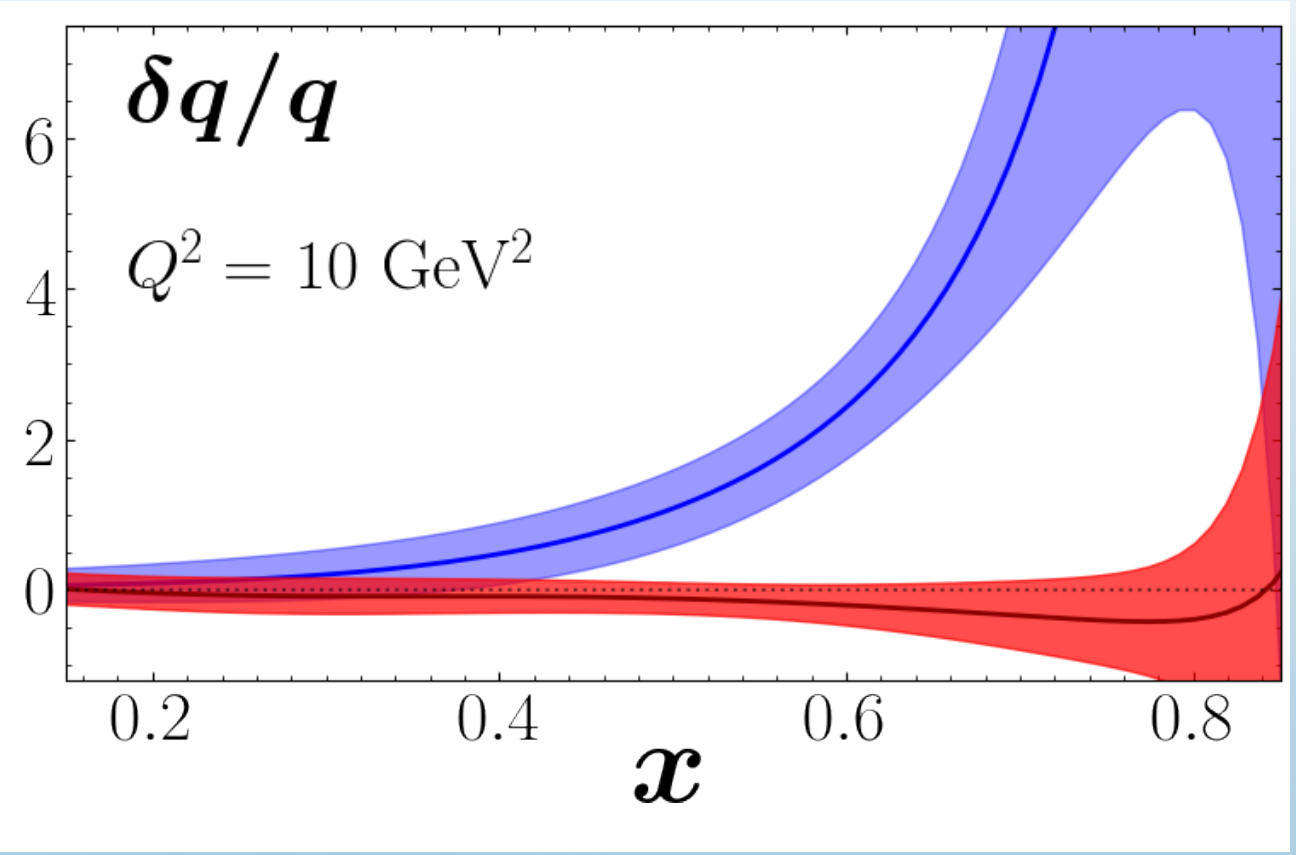


W Boson Production Impact on d/u



A. Accardi et al. Phys. Rev. D **93**, 114017 (2016)

PDF Correction Ratios



χ^2 and Normalization Table

TABLE I. Summary of the χ^2 values per number of points $N_{\rm dat}$ for the data used in this analysis. The MARATHON, JLab E03-103 ^{3}He/D, and NMC D/p datasets are separated from the rest of the fixed target data, and their fitted normalizations are shown.

process	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$	fitted norm.
DIS			
MARATHON ^{3}He/^{3}H	22	0.64	1.009(5)
MARATHON D/p	7	0.72	1.016(4)
JLab E03-103 ^{3}He/D	16	0.20	1.012(8)
NMC D/p	189	0.89	0.991(5)
other fixed target	2489	1.06	
HERA	1185	1.28	
Drell-Yan	250	1.08	
lepton rapidity	156	1.57	
W charge asym.	27	1.48	
Z rapidity	56	0.94	
jet	196	0.87	
total	**4593**	**1.11**	