Isovector EMC Effect from JAM Global QCD Analysis with MARATHON Data

Hanjie Liu

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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, and A. W. Thomas (Jefferson Lab Angular Momentum (JAM) Collaboration)

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Outline —— from an experimentalist point of view:

- Motivations and backgrounds
- Analysis details
- Results

From a theorist point of view:

Christopher Cocuzza (Temple University)

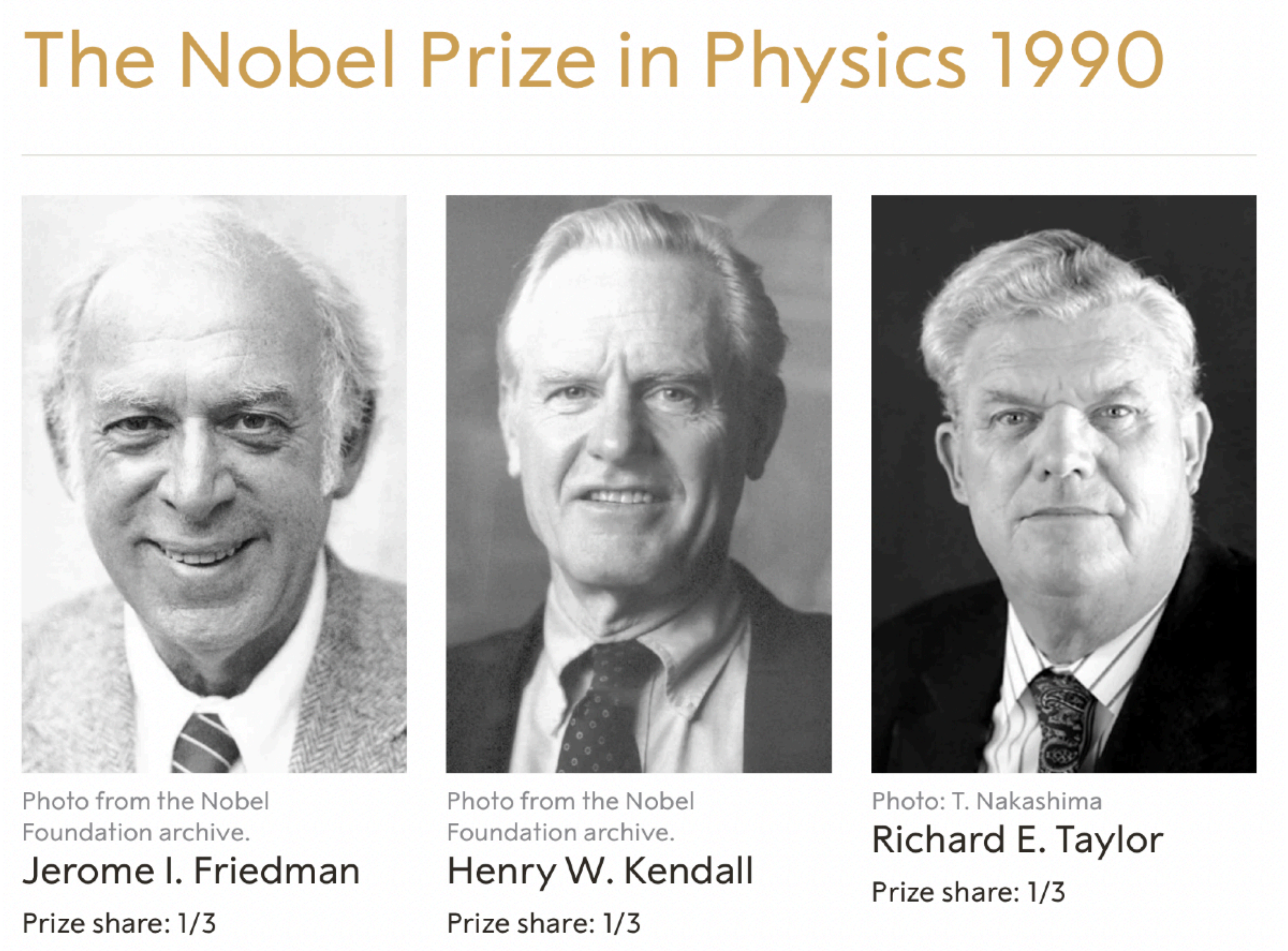
https://www.jlab.org/intralab/calendar/phys_seminar/2021/MARATHON%20Marathon%202021.pdf

MARATHON Experiment

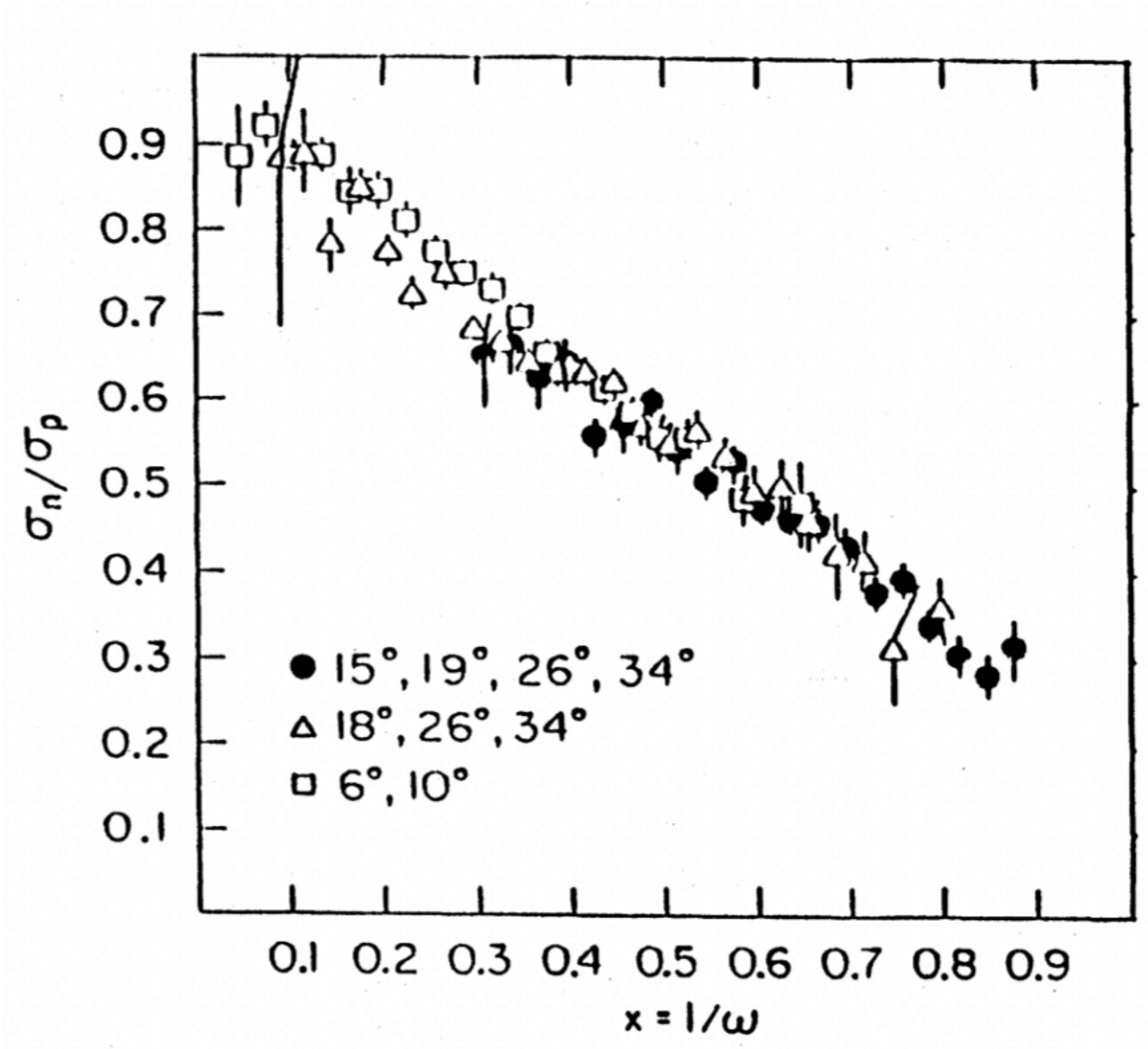
- Electron Deep Inelastic Scattering on p, D, H3, He3 fixed target @ JLab 11 GeV
- Goal is to measure F_2^n/F_2^p to put constraints on d/u quark distribution ratio at large x

Some Backgrounds about MARATHON

1960 ~ 1990



“SLAC-MIT experiment”
Electron DIS leads to the discovery of quarks



Bodek et al. Phys.Rev. D20 (1979)

Only Fermi motion is considered in the extraction

$$\frac{\sigma_n}{\sigma_p} = U\left(\frac{\sigma_{ns}}{\sigma_{ps}}\right) = U\left(S_p \frac{\sigma_d}{\sigma_p} - 1\right).$$

~ 50 years history of measuring F_2^n/F_2^p

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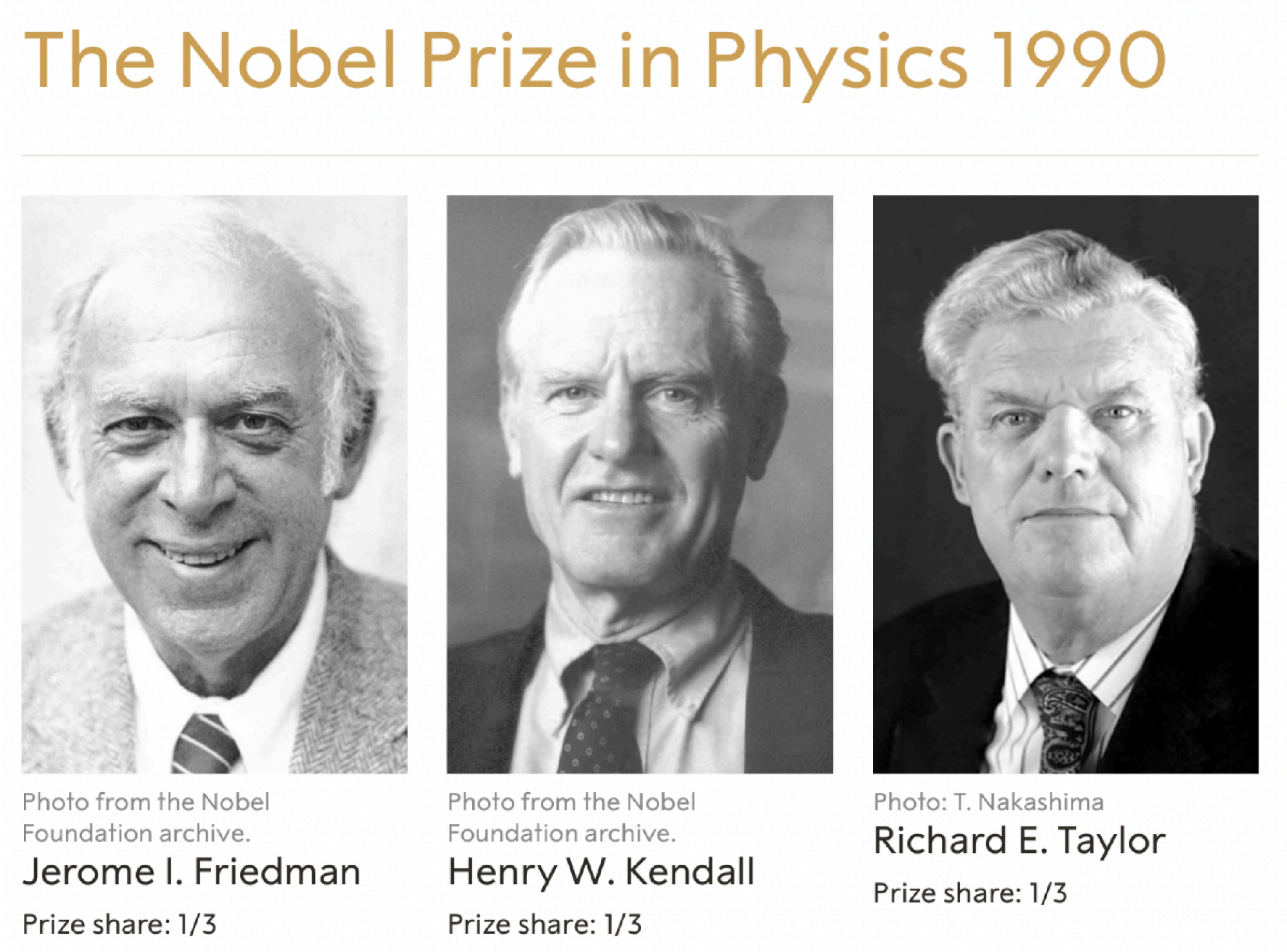

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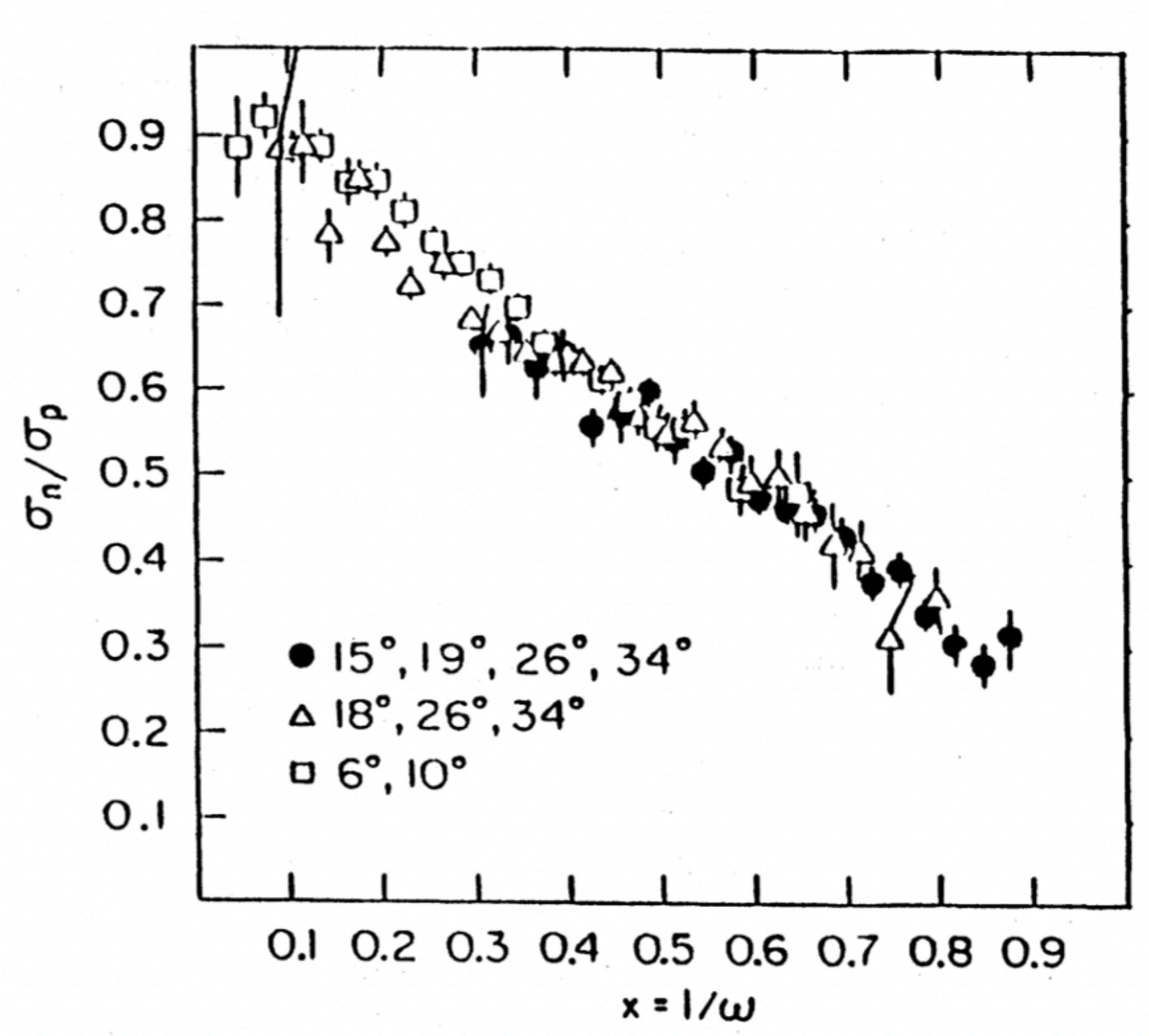
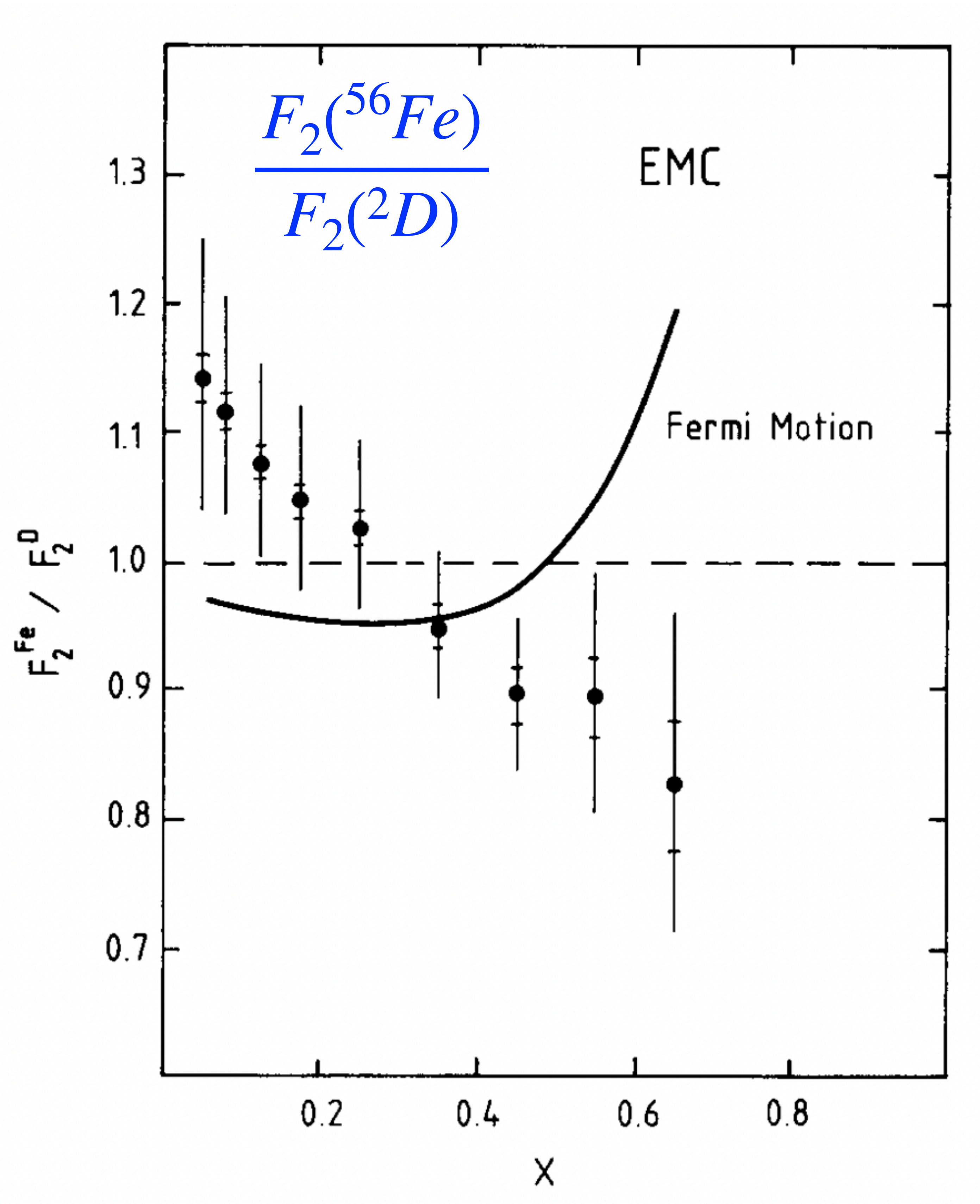


Bodek et al. Phys.Rev. D20 (1979)



Aubert J J et al. Nucl. Phys. B 293 740 (1987)

~ 50 years history of measuring F_2^n/F_2^p

MARATHON Experiment

- Electron Deep Inelastic Scattering on p, D, H3, He3 fixed target @ JLab 11 GeV
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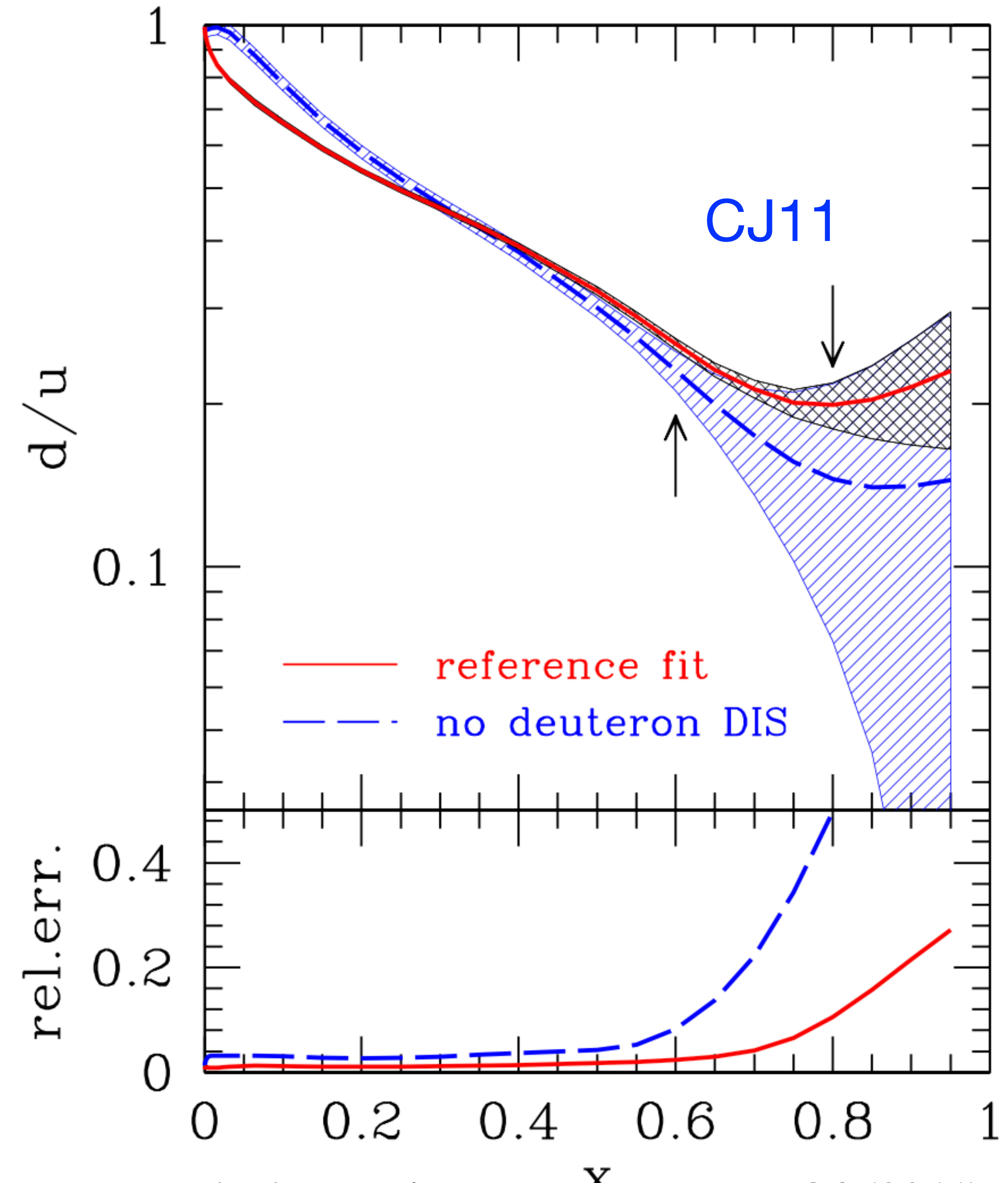
Some Backgrounds about MARATHON

Over the next 20 years

- Deep inelastic scattering is one of the primary way for PDFs parameterizations
- Lots of experiments are performed to understand the nuclear effects

			total		deuterium		
			cut0	cut3	cut0	cut3	CTEQ6.1
DIS	JLab	[58]	–	272	–	136	
	SLAC	[59]	206	1147	104	582	
	NMC	[60]	324	464	123	189	√
	BCDMS	[61]	590	605	251	254	√
	H1	[62]	230	251	–	–	√
	ZEUS	[63]	229	240	–	–	√
νA DIS	CCFR	[64, 65]	–	–	–	–	√
DY	E605	[66]	119		–		√
	E866	[67]	375		191		
W asymmetry	CDF '98 (ℓ)	[68]	11		–		√
	CDF '05 (ℓ)	[69]	11		–		
	D0 '08 (ℓ)	[70]	10		–		
	D0 '08 (e)	[71]	12		–		
	CDF '09 (W)	[72]	13		–		
jet	CDF	[73]	33		–		√
	D0	[74]	90		–		√
γ+jet	D0	[75]	56		–		
	TOTAL		2408	3709	569	1161	

A. Accardi et al. Phys. Rev. D81 (2010)



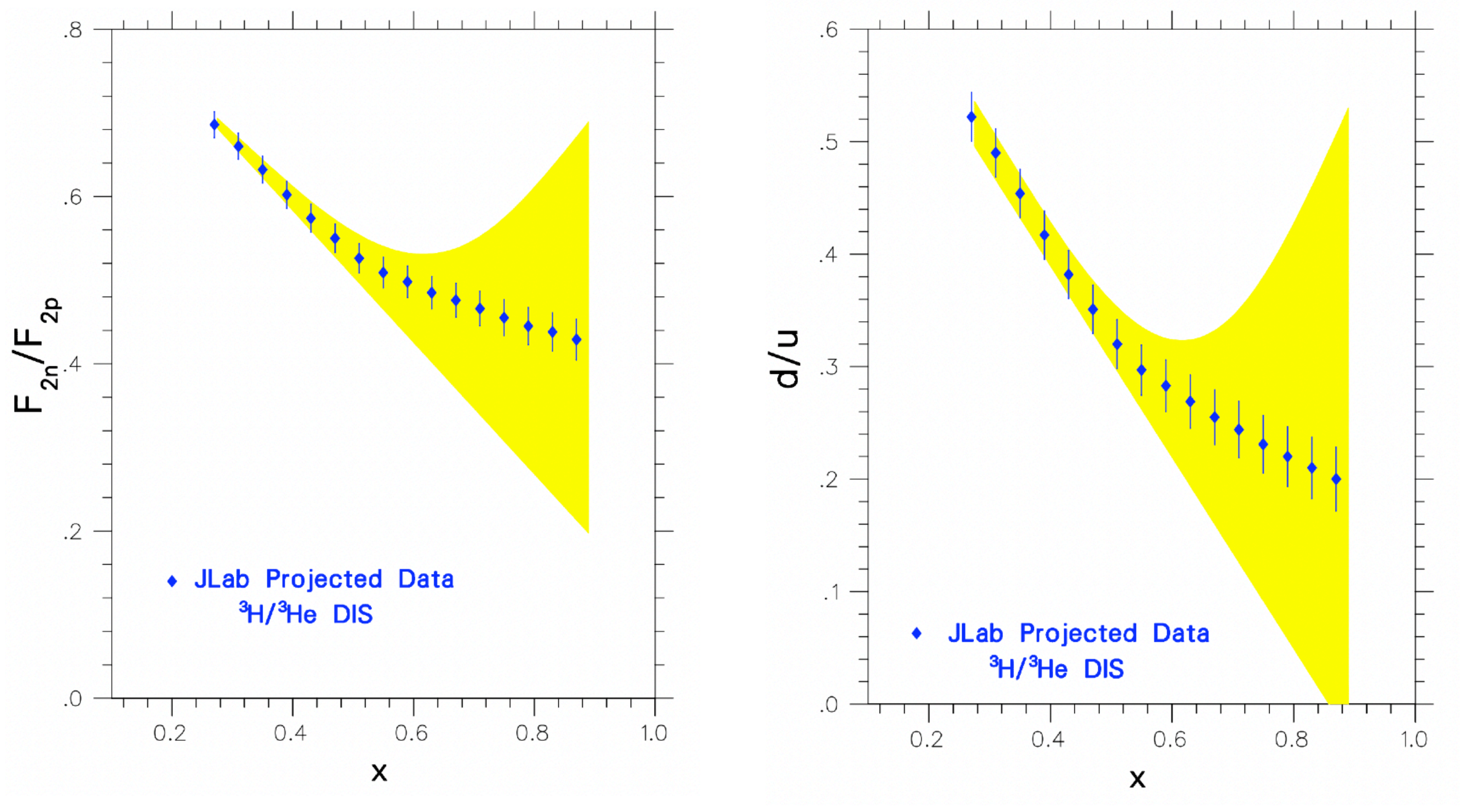
A. Accardi et al. Phys. Rev. D84 (2011)

MARATHON Experiment

- Electron Deep Inelastic Scattering on p, D, H3, He3 fixed target @ JLab 11 GeV
- Goal is to measure F_2^n/F_2^p to put constraints on d, u quark distributions at large x

Some Backgrounds about MARATHON

- The idea of using H3 and He3 to extract F_2^n/F_2^p to avoid nuclear model dependence started @ 1999
- The proposal is approved at PAC36 @ 2010



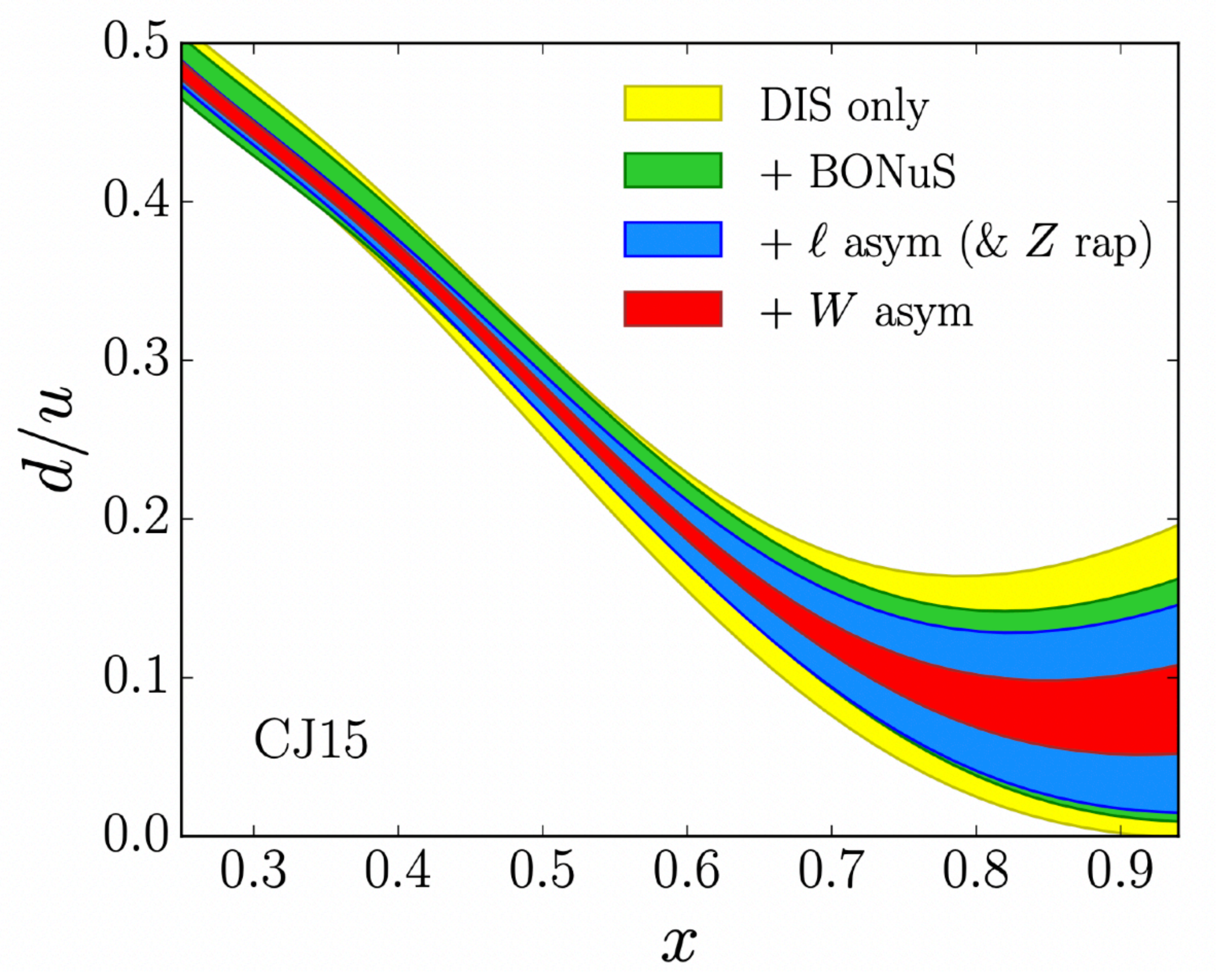
MARATHON proposal 2010

MARATHON Experiment

- Electron Deep Inelastic Scattering on p, D, H3, He3 fixed target @ JLab 11 GeV
- Goal is to measure F_2^n/F_2^p to put constraints on d, u quark distributions at large x

Some Backgrounds about MARATHON

- The idea of using H3 and He3 to extract F_2^n/F_2^p to avoid nuclear model dependence started @ 1999
- The proposal is approved at PAC36 @ 2010
- Large improvement on *d/u* with improved nuclear corrections and new high precision HEP data @ 2016



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

- MARATHON took data @ 2018 Spring

MARATHON Experiment

Experimental way of extracting F_2^n/F_2^p

$$\frac{F_2^{^3H}}{F_2^{^3He}} = \frac{\sigma(^3H)}{\sigma(^3He)}$$

- EMC type of ratio

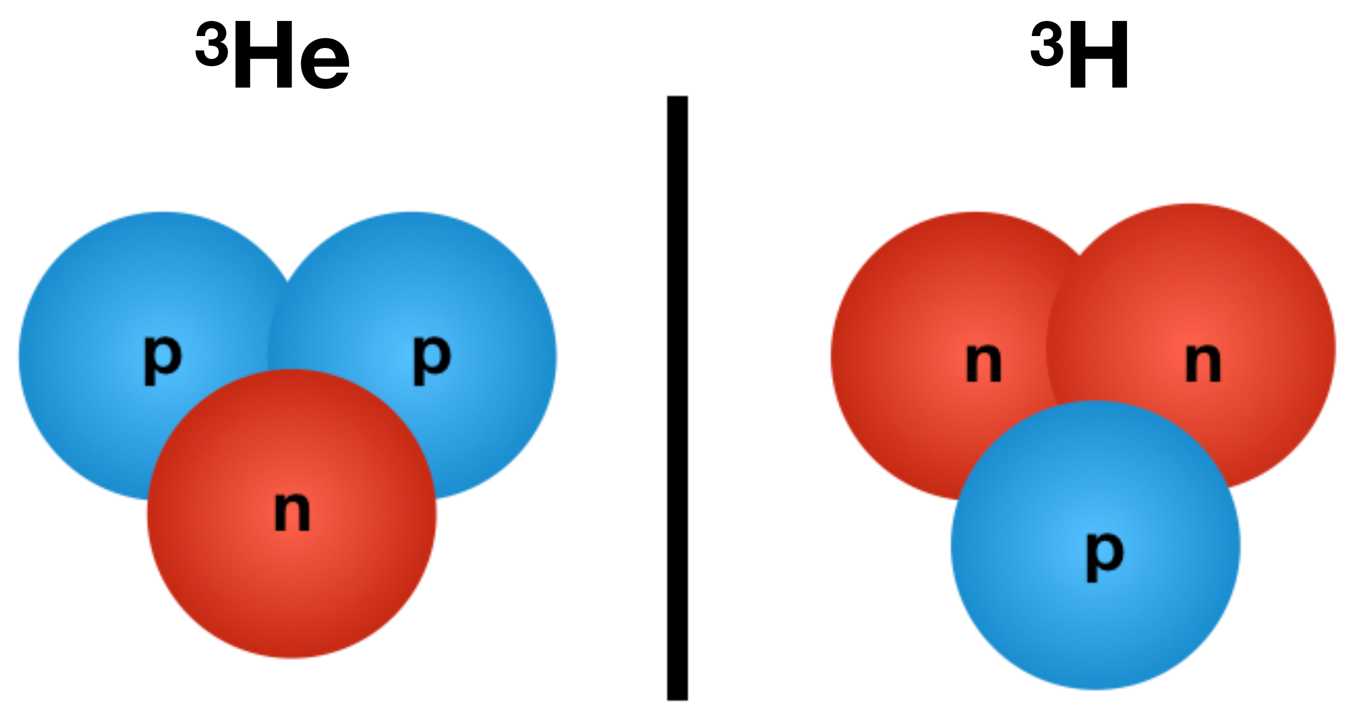
$$R(^3H) = \frac{F_2^{^3H}}{F_2^p + 2F_2^n} \qquad R(^3He) = \frac{F_2^{^3He}}{2F_2^p + F_2^n}$$

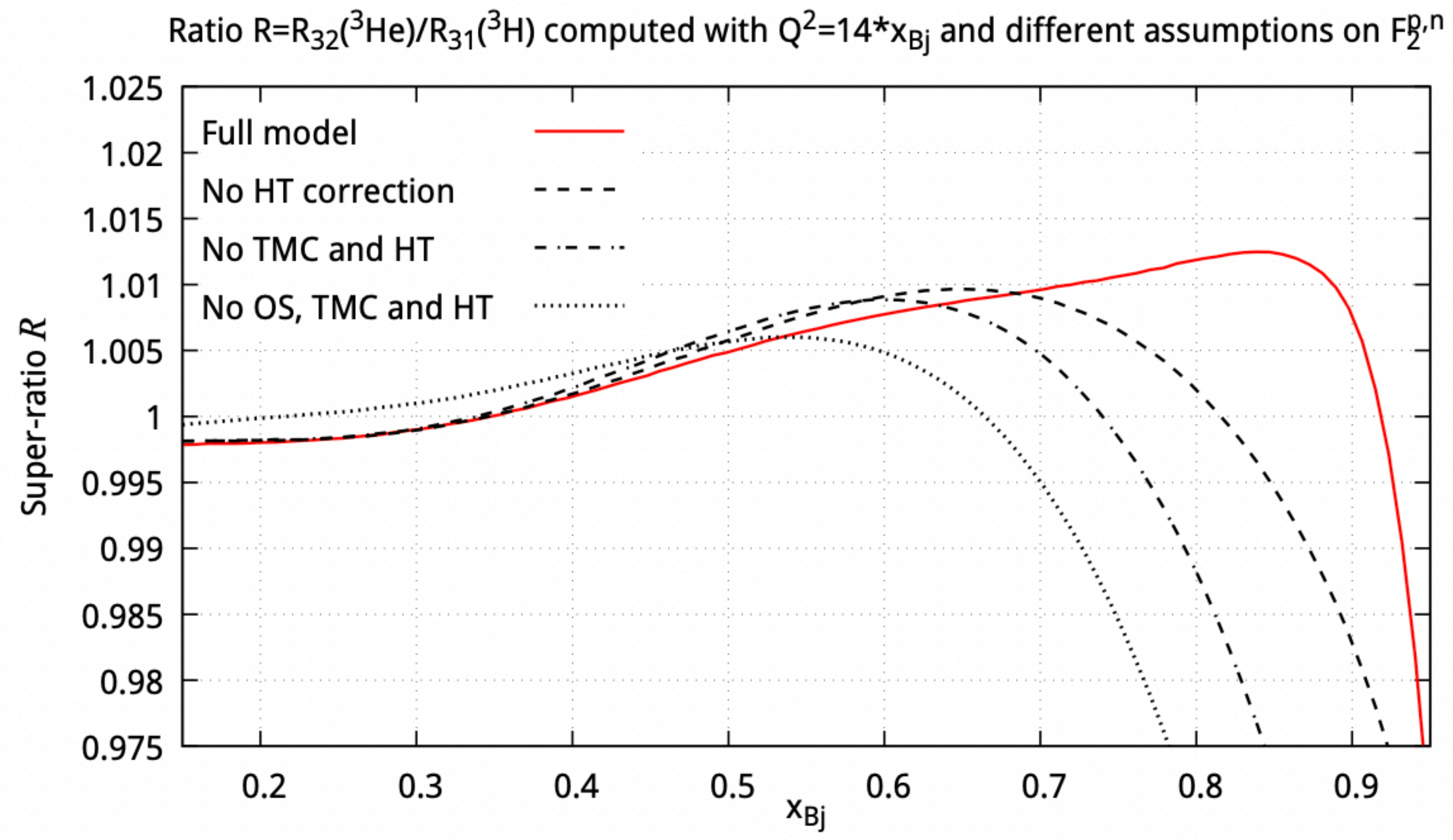
- Super ratio:

$$\mathcal{R} = \frac{R(^3He)}{R(^3H)}$$

$$\Rightarrow \quad \frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - \mathcal{R}}$$

- measure $F_2^{^3He}/F_2^{^3H}$
- $\mathcal{R}$ is determined by theory





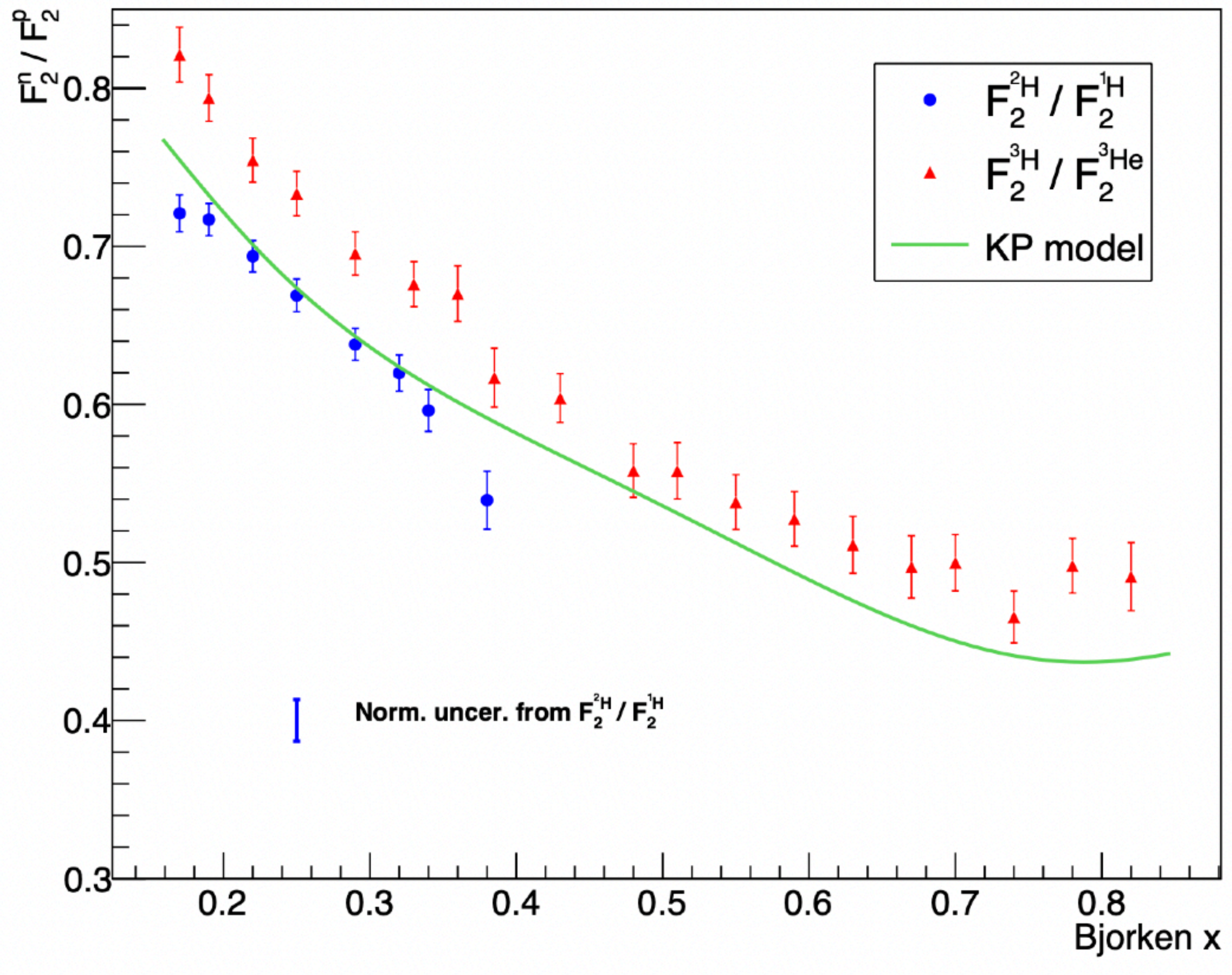
Super-ratio $\mathcal{R}$ calculated by S. Kulagin and R. Petti

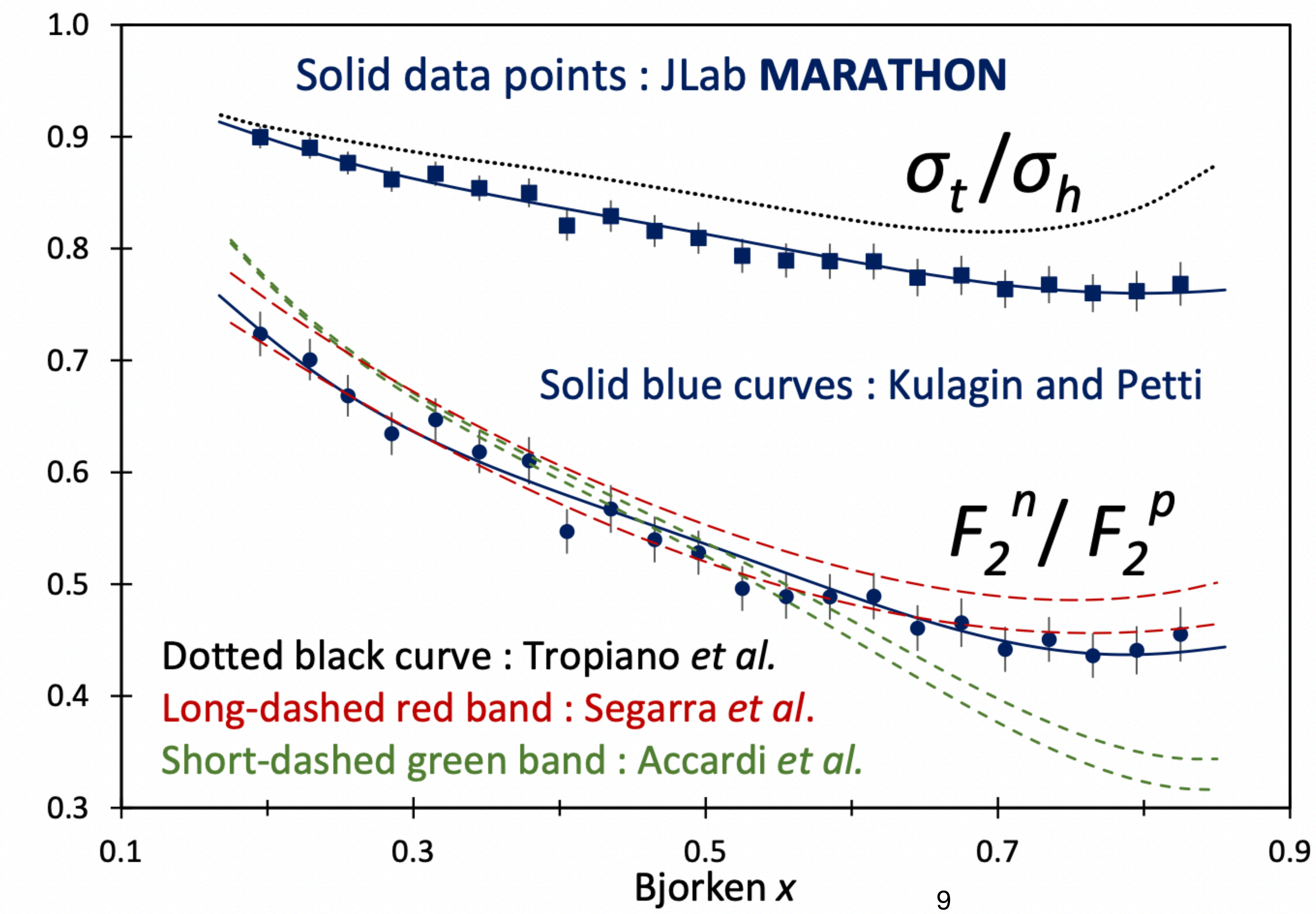
^{3}He and ^{3}H are mirror nuclei, the nuclear effect should be similar and have small model dependence

MARATHON Experiment

Experimental way of extracting F_2^n/F_2^p

In order to match the F_2^n/F_2^p extracted from $\sigma(^3He)/\sigma(^3H)$ to that from $\sigma(D)/\sigma(p)$ at $x = 0.31$, $\sigma(^3He)/\sigma(^3H)$ ratio at $x = 0.31$ had to be normalized by a multiplicative factor of 1.025 ± 0.007





Final results

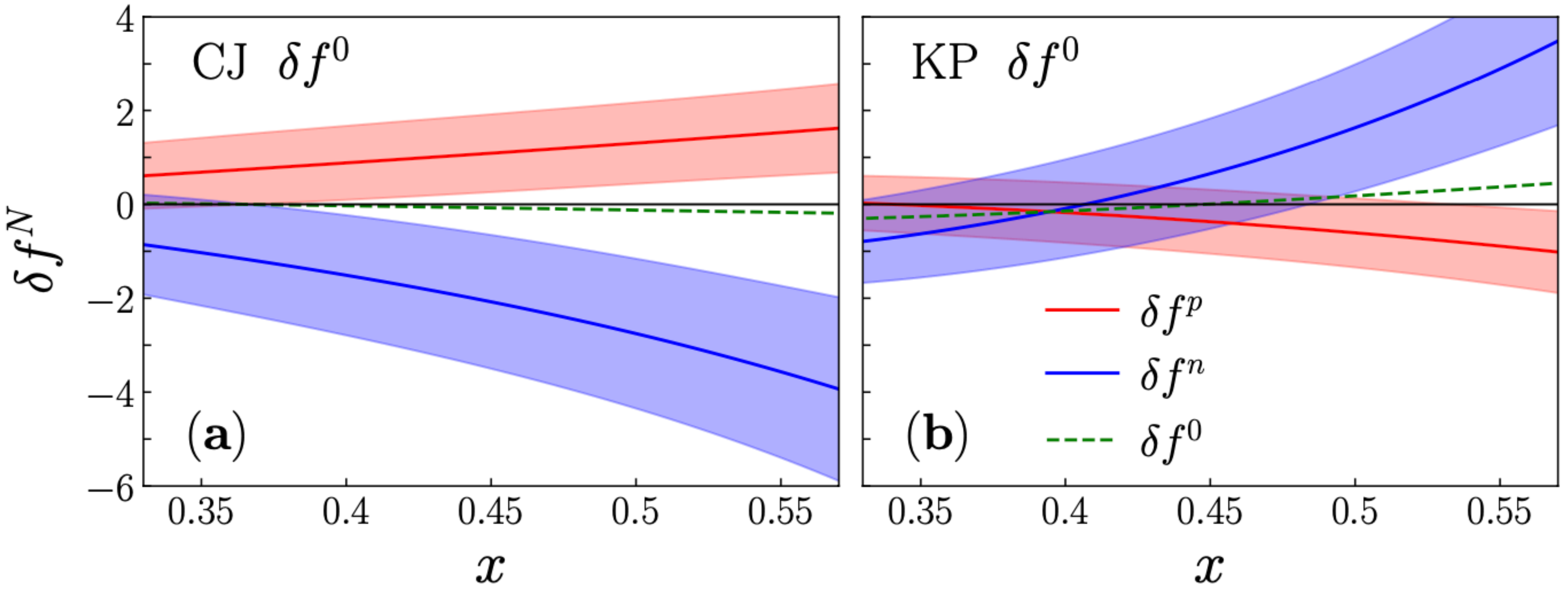
Phys. Rew. L 128, 132003 (2022)

MARATHON Experiment

Theoretical way of thinking about MARATHON data

Cross section ratios: σ(^{3}He)/σ(^{3}H), σ(D)/σ(p)

- How much impact is MARATHON data on PDFs and nucleon structure functions
- MARATHON data may help study the isovector effect
- Is the normalization on σ(^{3}He)/σ(^{3}H) necessary?



A. J. Tropiano, J. J. Ethier, W. Melnitchouk, N. Sato
Phys. Rev. C 99, 035201 (2019)

- Hall C E03-103 He3/D data needs 3% normalization if using KP model to match n/p from other datasets
- Possible isospin dependence of the nuclear effect is indicated in the fitting of He3/D data
- ^{3}He and ^{3}H are light nuclei, and n/p ratio are very different: 2 and 1/2

Jefferson Lab Angular Momentum (JAM) Collaboration

A Powerful framework utilizing the development from multiple areas

Inclusive DIS: $l + N \to l + X$

$$\frac{d\sigma_{\rm DIS}}{dQ^2 dx_{\rm Bj}} = \sum_i \mathcal{H}_i^{\rm DIS} \otimes f_i$$

Semi-inclusive DIS: $l + N \to l + h^\pm + X$

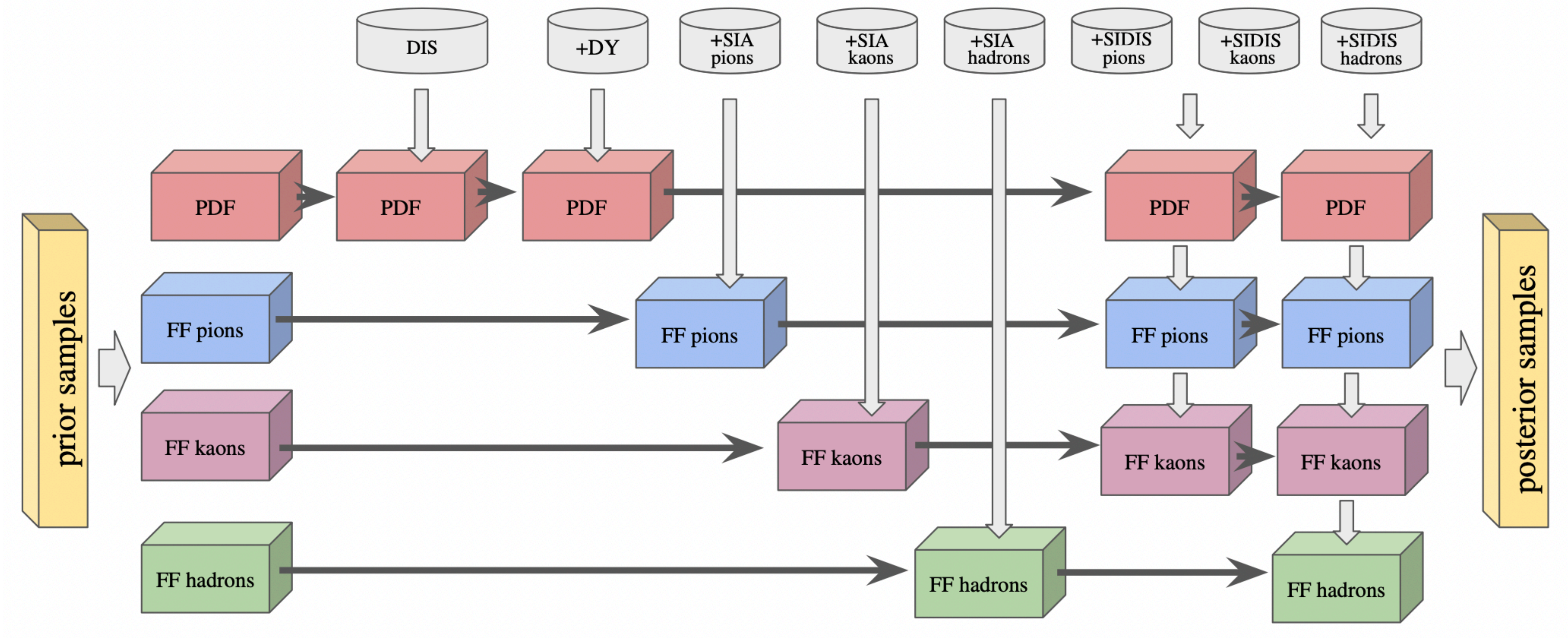
$$\frac{d\sigma_{\rm SIDIS}}{dQ^2 dx_{\rm Bj} dz_h} = \sum_{ij} \mathcal{H}_{ij}^{\rm SIDIS} \otimes f_i \otimes D_j^h$$

Drell-Yan lepton-pair production: $N_1 + N_2 \to l^+ + l^- + X$

$$\frac{d\sigma_{\rm DY}}{dQ^2 dx_{\rm F}} = \sum_{ij} \mathcal{H}_{ij}^{\rm DY} \otimes f_i \otimes f_j$$

Single-inclusive annihilation: $l^+ + l^- \to h^\pm + X$

$$\frac{d\sigma_{\rm SIA}}{dQ^2 dz_h} = \sum_j \mathcal{H}_j^{\rm SIA} \otimes D_j^h$$



Phys. Rew. D 104, 016015 (2021)

Fit simultaneously:

- PDFs
- FFs
- Nuclear effect

using a multistep Bayesian inference procedure

JAM and A=3 nuclei

$$F_2^A(x,Q^2) = F_2^{A(on)} + F_2^{A(off)}$$

$$F_2^{A(on)}(x,Q^2) = \sum_N [\, f^{N/A} \otimes F_2^{N(on)} \,] \quad , \quad N = n, p$$

on-shell smearing function

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

off-shell smearing function

computed from the nuclear wave functions or spectral functions.

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

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

off-shell corrections

$2 \times 2 \times 3 = 12$ functions

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

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

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

Offshell corrections

$\delta u_{p/D}$ $\delta u_{n/D}$ $\delta u_{p/^3He}$ $\delta u_{n/^3He}$ $\delta u_{p/^3H}$ $\delta u_{n/^3H}$

$\delta d_{p/D}$ $\delta d_{n/D}$ $\delta d_{p/^3He}$ $\delta d_{n/^3He}$ $\delta d_{p/^3H}$ $\delta d_{n/^3H}$

Offshell corrections

$$\delta u_{p/D} \quad \delta u_{n/D} \quad \delta u_{p/^3He} \quad \delta u_{n/^3He} \quad \delta u_{p/^3H} \quad \delta u_{n/^3H}$$

$$\delta d_{p/D} \quad \delta d_{n/D} \quad \delta d_{p/^3He} \quad \delta d_{n/^3He} \quad \delta d_{p/^3H} \quad \delta d_{n/^3H}$$

Charge symmetry

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

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

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

Offshell corrections

$$\delta u_{p/D} \qquad \cancel{\delta u_{n/D}} \qquad \delta u_{p/^3He} \qquad \cancel{\delta u_{n/^3He}} \qquad \delta u_{p/^3H} \qquad \cancel{\delta u_{n/^3H}}$$

$$\delta d_{p/D} \qquad \cancel{\delta d_{n/D}} \qquad \delta d_{p/^3He} \qquad \cancel{\delta d_{n/^3He}} \qquad \delta d_{p/^3H} \qquad \cancel{\delta d_{n/^3H}}$$

Charge symmetry

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

Offshell corrections

$\overset{\delta_u}{\delta u_{p/D}}$	$\cancel{\delta u_{n/D}}$	$\overset{\frac{1}{2}(\delta_u+2\delta_d)}{\delta u_{p/^3He}}$	$\cancel{\delta u_{n/^3He}}$	$\overset{\delta_u}{\delta u_{p/^3H}}$	$\cancel{\delta u_{n/^3H}}$
$\overset{\delta_d}{\delta d_{p/D}}$	$\cancel{\delta d_{n/D}}$	$\overset{\frac{1}{4}(\delta_u+2\delta_d)}{\delta d_{p/^3He}}$	$\cancel{\delta d_{n/^3He}}$	$\overset{\delta_d}{\delta d_{p/^3H}}$	$\cancel{\delta d_{n/^3H}}$

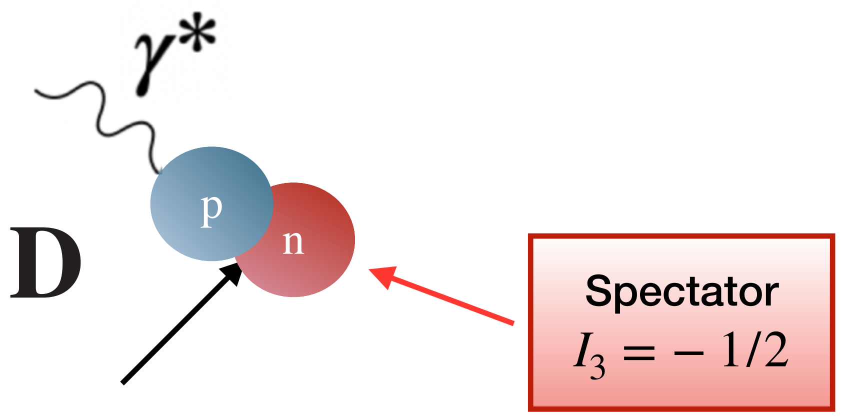
Charge symmetry

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

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

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

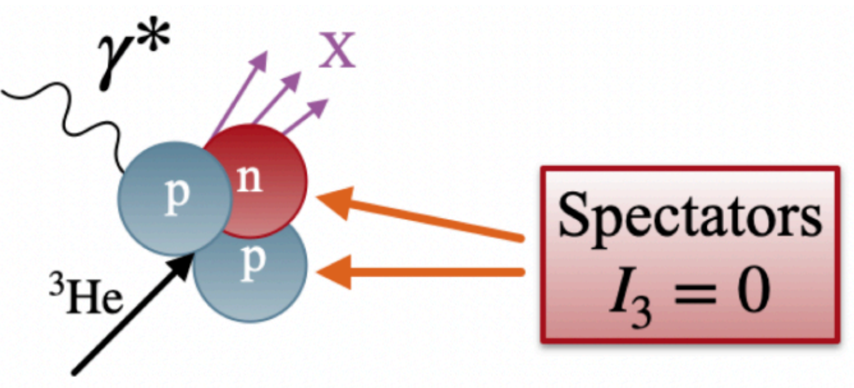
Assume a spectator system for the DIS on proton inside of a nucleus:

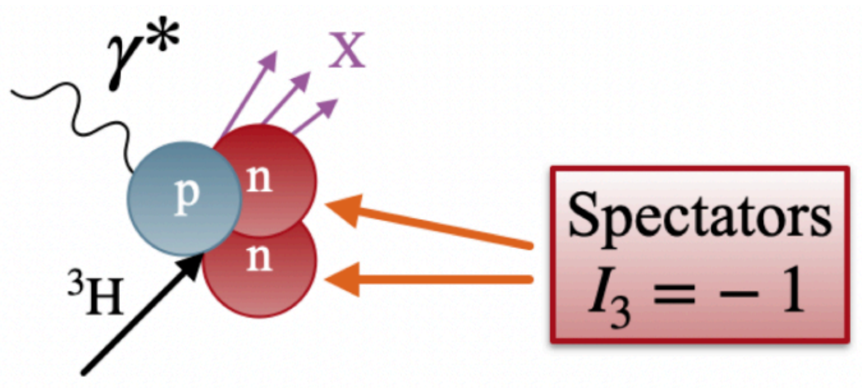


- Assume same off-shell function for D and ^{3}H

$$\delta d_{p/D} = \delta d_{p/^3H} \equiv \delta_d \qquad \delta u_{p/D} = \delta u_{p/^3H} \equiv \delta_u$$

- The isospin of ^{3}He spectators are 0, assume no isovector contribution





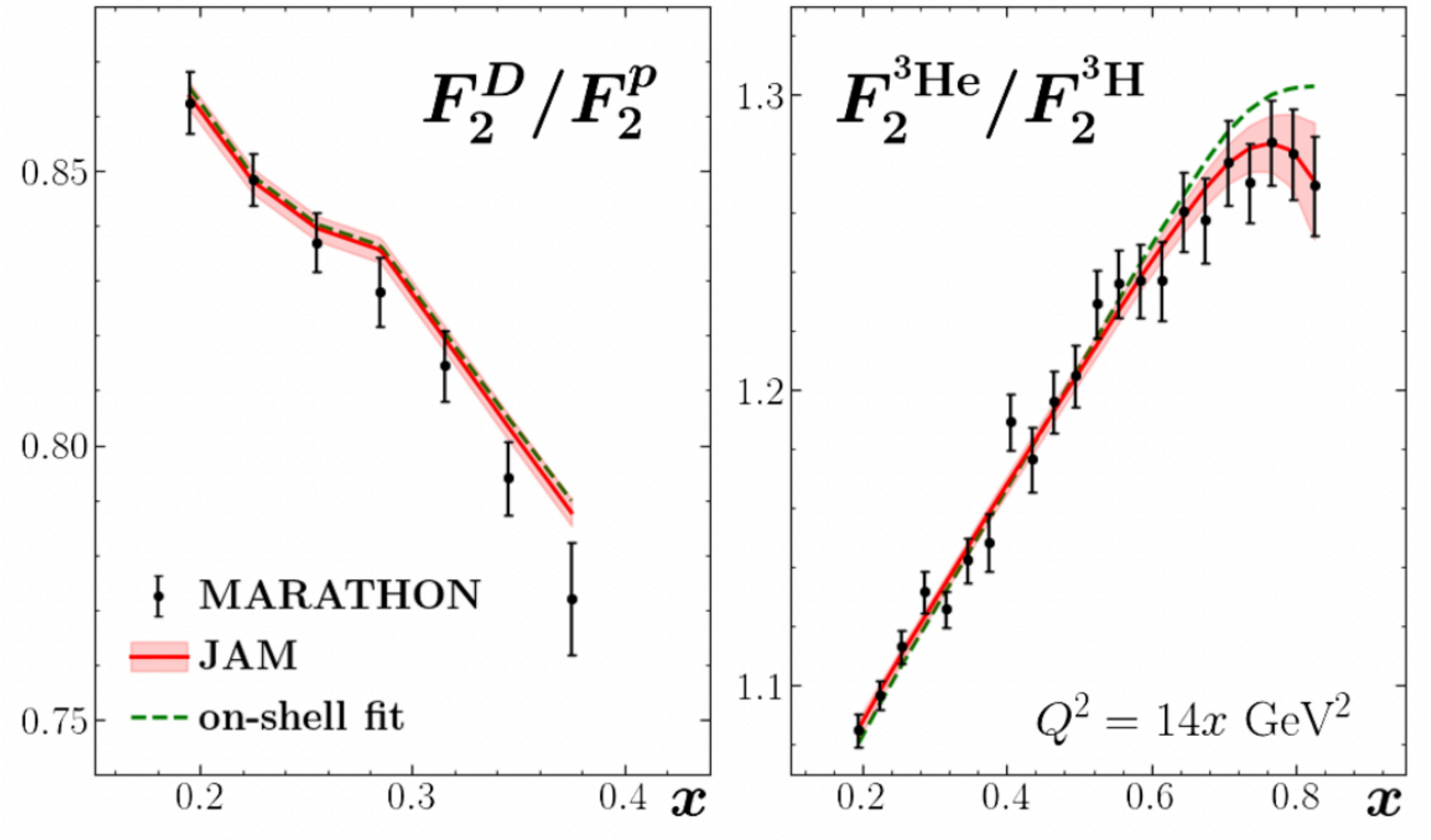
$$\delta u_{p/^3\text{He}} \approx 2\delta d_{p/^3\text{He}} = \frac{1}{2}(\delta u + 2\delta d).$$

$$\int_0^1 dx\,\delta u(x) = \int_0^1 dx\,\delta d(x) = 0.$$

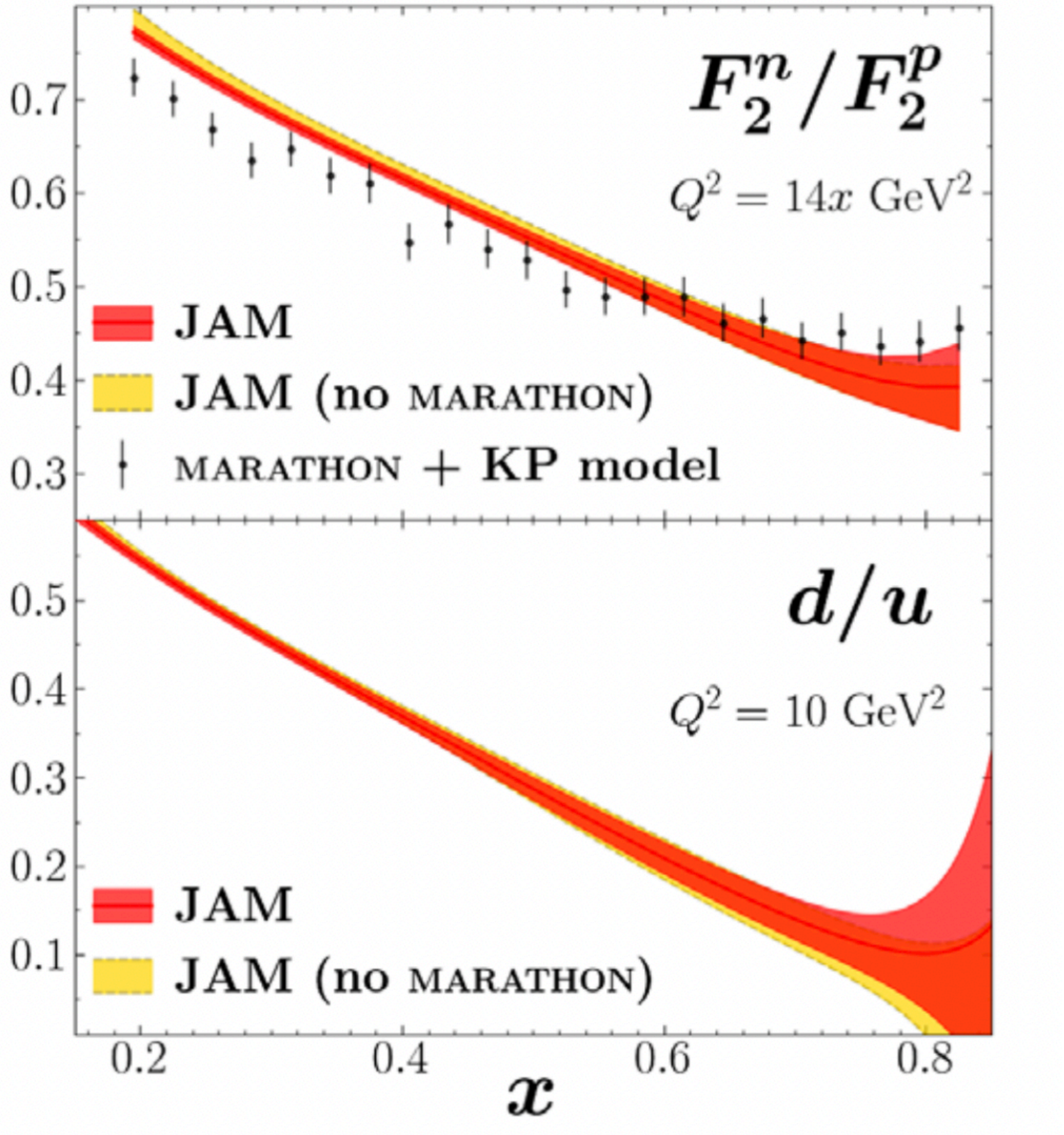
$$f_i(x) = Nx^\alpha(1-x)^\beta(1+\gamma\sqrt{x}+\eta x)\ ,\ \gamma = 0$$

Results

- It describes the data well



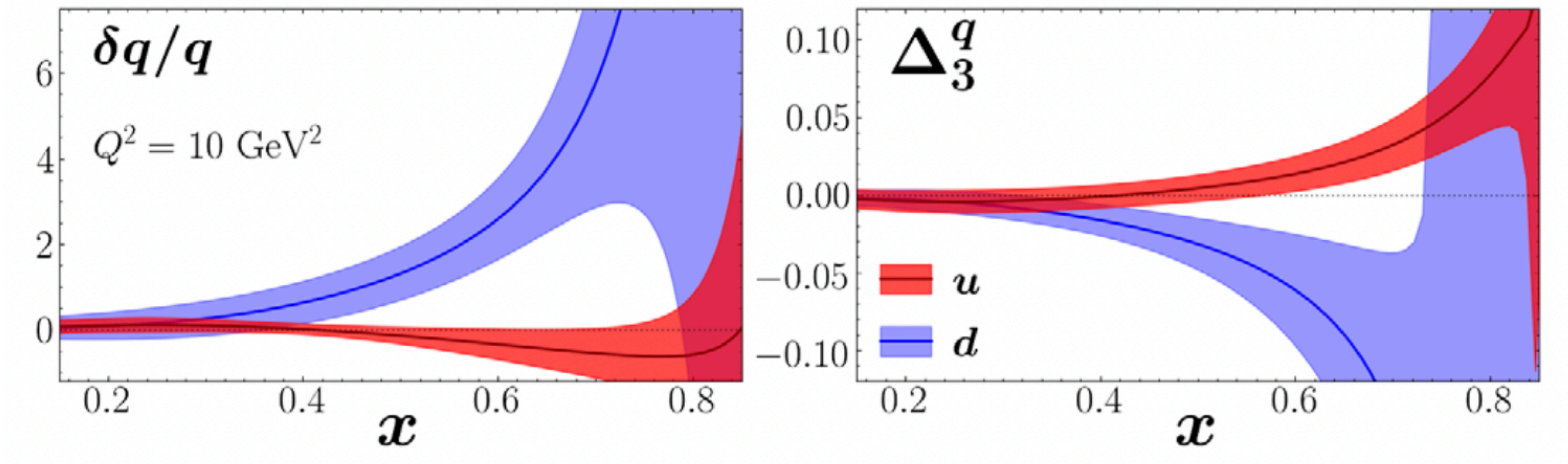
- MARATHON data on PDFs and nucleon structure functions constraints are limited
- 2.5% normalization on σ(^{3}He)/σ(^{3}H) is transferred to σ(D)/σ(p) and absorbed by nuclear effect



Process	N_{dat}	χ^2/N_{dat}	Fitted normalization
DIS			
MARATHON ^{3}He/^{3}H	22	0.63	1.007(6)
MARATHON D/p	7	0.95	1.019(4)
JLab E03-103 ^{3}He/D	16	0.25	1.006(10)

Off shell corrections results

- It indicates an isovector nuclear effect



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

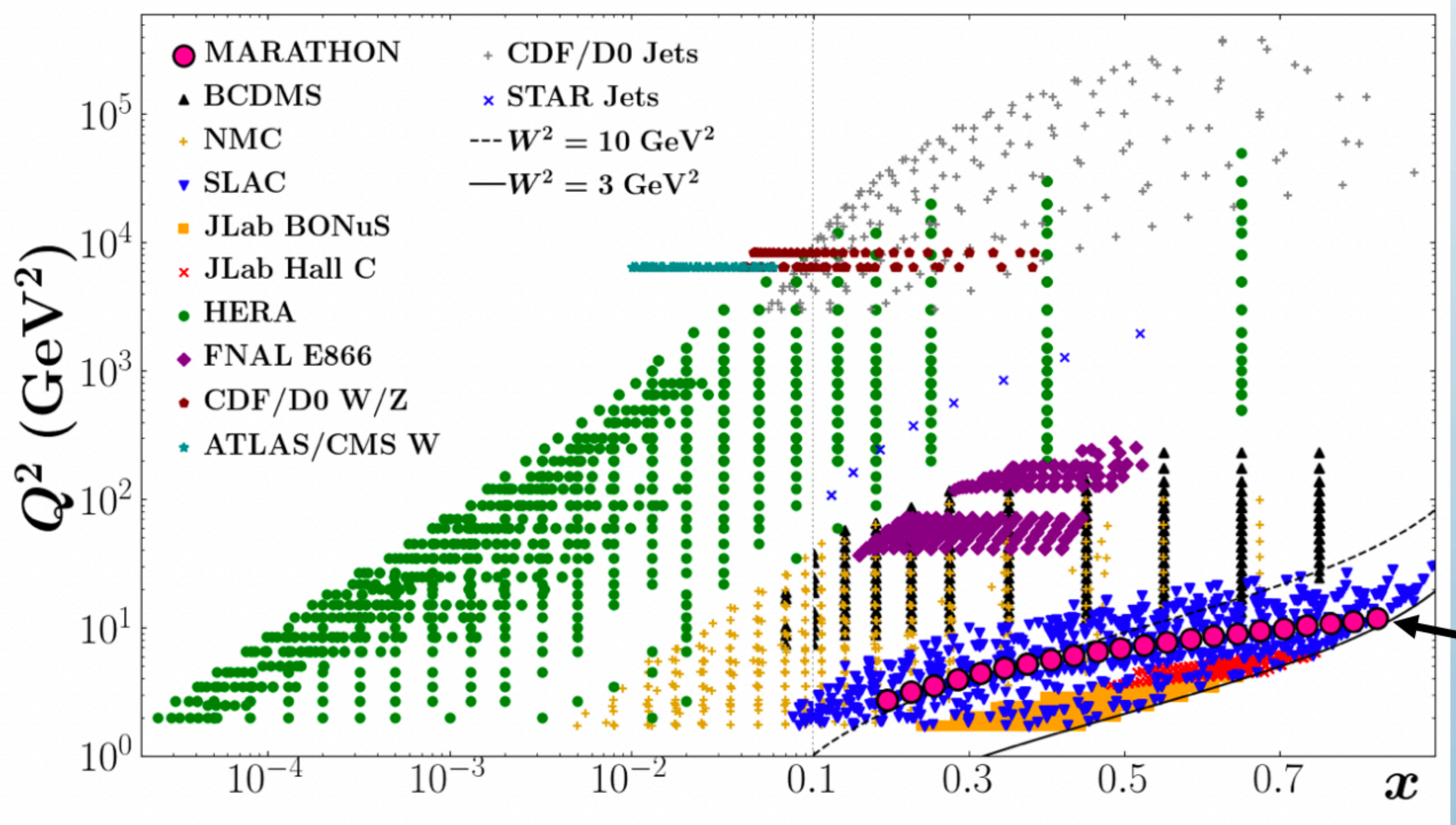
Conclusions

- A global QC analysis with MARATHON data indicates an isovector EMC effect
- Multiple assumptions are made in the analysis, more experimental data inputs are required to improve the results confidence
- Experimentalists should pay more attention to the normalization factors: normalization factor is at 1% level, while theoretical predictions are at few percent level as well. In order to pin down small effect, we would want to determine the normalization factor better
- Communication between theorists and experimentalists are important, so we can know the underlying tricks we did in each other's analysis…

Data Sets

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

Christopher Cocuzza