Jefferson Lab

5th Int. Workshop on Nucleon Structure at Large Bjorken x
Kolympari, Greece, August 18, 2019

Isospin dependence in DIS from A=3 mirror nuclei

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Motivation

- DIS from helium-3 and tritium proposed as a unique and independent means of determining neutron/proton, and hence d/u PDF, ratio at large x

  $\longrightarrow$ MARATHON experiment at JLab Hall A $\longrightarrow$ ***G. Petratos Mon. 11:30***

- Independent determination of nuclear EMC effect in deuterium and A=3 nuclei

  $\longrightarrow$ never before been experimentally determined

- Understanding structure of helium-3 also vital for determination of polarized neutron structure

Basic idea (ca. 2001)

PHYSICAL REVIEW C **68**, 035201 (2003)

Deep inelastic scattering from $A=3$ nuclei and the neutron structure function

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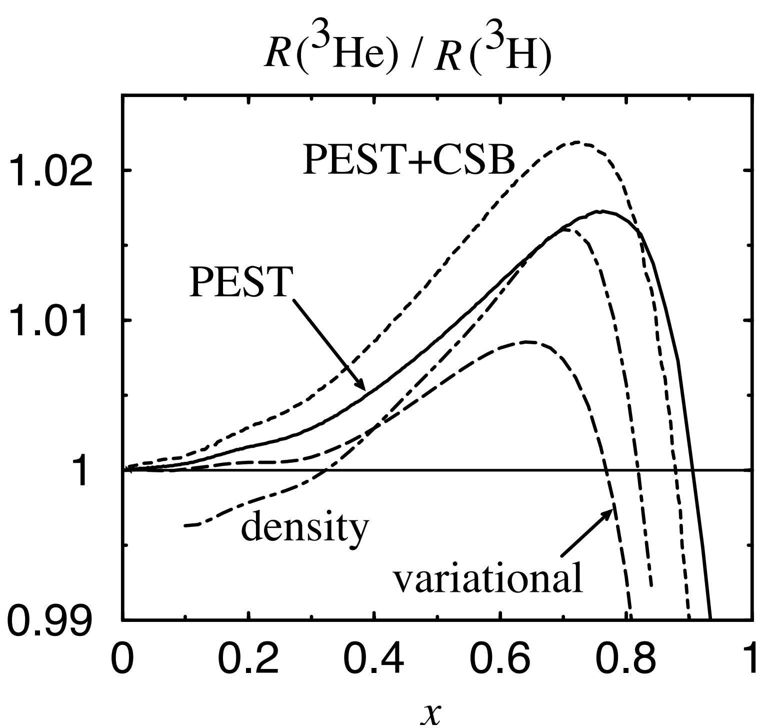
(Received 2 April 2003; published 4 September 2003)

We present a comprehensive analysis of deep inelastic scattering from ^{3}He and ^{3}H, focusing in particular on the extraction of the free neutron structure function F_2^n. Nuclear corrections are shown to cancel to within 1–2% for the isospin-weighted ratio of ^{3}He to ^{3}H structure functions, which leads to more than an order of magnitude improvement in the current uncertainty in the neutron to proton ratio F_2^n/F_2^p at large x. Theoretical uncertainties originating from the nuclear wave function, including possible non-nucleonic components, are evaluated. Measurements of the ^{3}He and ^{3}H structure functions will, in addition, determine the magnitude of the EMC effect in all $A \leqslant 3$ nuclei.



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

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

The ratio of these,

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

can be inverted to yield the ratio of free neutron to proton structure functions,

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

→ **most calculations gave ~2% variation in super-ratio**

Pace, Salme, Scopetta (2001)
Sargsian, Simula, Strikman (2002)

Update (2019)

- Revisit problem including latest theoretical developments and recent data (JLab E03-103) on helium-3 / deuterium ratios

→ generalized convolution in "weak binding approximation" (WBA)

$$F_2^A(x,Q^2) = \sum_N \int \frac{d^4p}{(2\pi)^4} \mathcal{F}_0^N(\varepsilon,\mathbf{p}) \left(1 + \frac{\gamma p_z}{M}\right) \mathcal{C}_{22}\, \widetilde{F}_2^N(x/y, Q^2, p^2)$$

nuclear spectral function

bound nucleon momentum $p = (p_0; \mathbf{p}) = (M + \varepsilon;\, \mathbf{p}_\perp,\, p_z)$

kinematic factor $\mathcal{C}_{22} = \frac{1}{\gamma^2}\left[1 + \frac{(\gamma^2-1)}{2y^2M^2}(2p^2 + 3\mathbf{p}_\perp^2)\right]$ $\gamma^2 = 1 + \frac{4M^2x^2}{Q^2}$

nuclear momentum fraction $y = \frac{M_A}{M}\frac{p\cdot q}{P\cdot q} = \frac{p_0 + \gamma p_z}{M}$

→ factorized formula valid up to $\mathcal{O}(\mathbf{p}^2/M^2)$ corrections

WM, Schreiber, Thomas (1994)
Kulagin et al. (1994)

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off-shell nucleon structure function

→ expand to lowest order in nucleon virtuality $(p^2 - M^2)$

$$\widetilde{F}_2^N(x,Q^2,p^2) = F_2^N(x,Q^2)\left(1+\frac{p^2-M^2}{M^2}\delta f^N(x)\right)$$

on-shell structure function

off-shell correction

$$\delta f^N = \left.\frac{\partial \log \widetilde{F}_2^N}{\partial \log(p^2/M^2)}\right|_{p^2=M^2}$$

Update (2019)

- Write total nuclear structure function as a sum of nucleon on-shell and off-shell contributions

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

where

$$F_2^{A(\mathrm{on})}(x,Q^2) = \sum_N \int dy\, f^{N/A}(y,\gamma)\, F_2^N(x/y,Q^2)$$

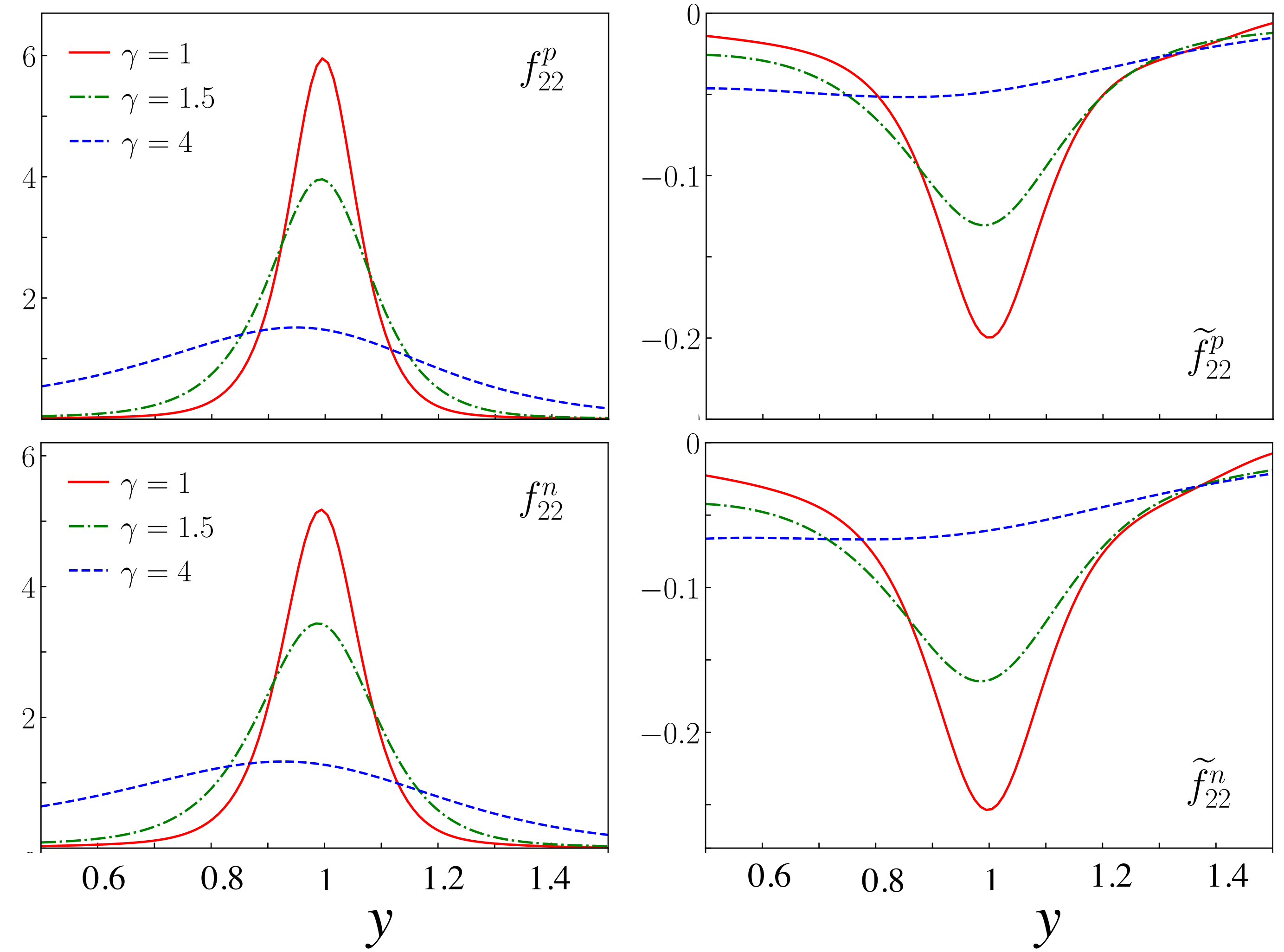
$$F_2^{A(\mathrm{off})}(x,Q^2) = \sum_N \int dy \left[\tilde{f}^{N/A}(y,\gamma)\, F_2^N(x/y,Q^2)\right] \delta f^N(x/y)$$

- Nucleon "smearing functions" (light-cone momentum distributions)

on-shell $$f^{N/A}(y,\gamma) = \int \frac{d^4p}{(2\pi)^4} \mathcal{F}_0^N(\varepsilon,\mathbf{p}) \left(1 + \frac{\gamma p_z}{M}\right) \mathcal{C}_{22}\, \delta\left(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\right)$$

off-shell $$\tilde{f}^{N/A}(y,\gamma) = \int \frac{d^4p}{(2\pi)^4} \mathcal{F}_0^N(\varepsilon,\mathbf{p}) \left(1 + \frac{\gamma p_z}{M}\right) \mathcal{C}_{22}\, \frac{(p^2 - M^2)}{M^2} \delta\left(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\right)$$

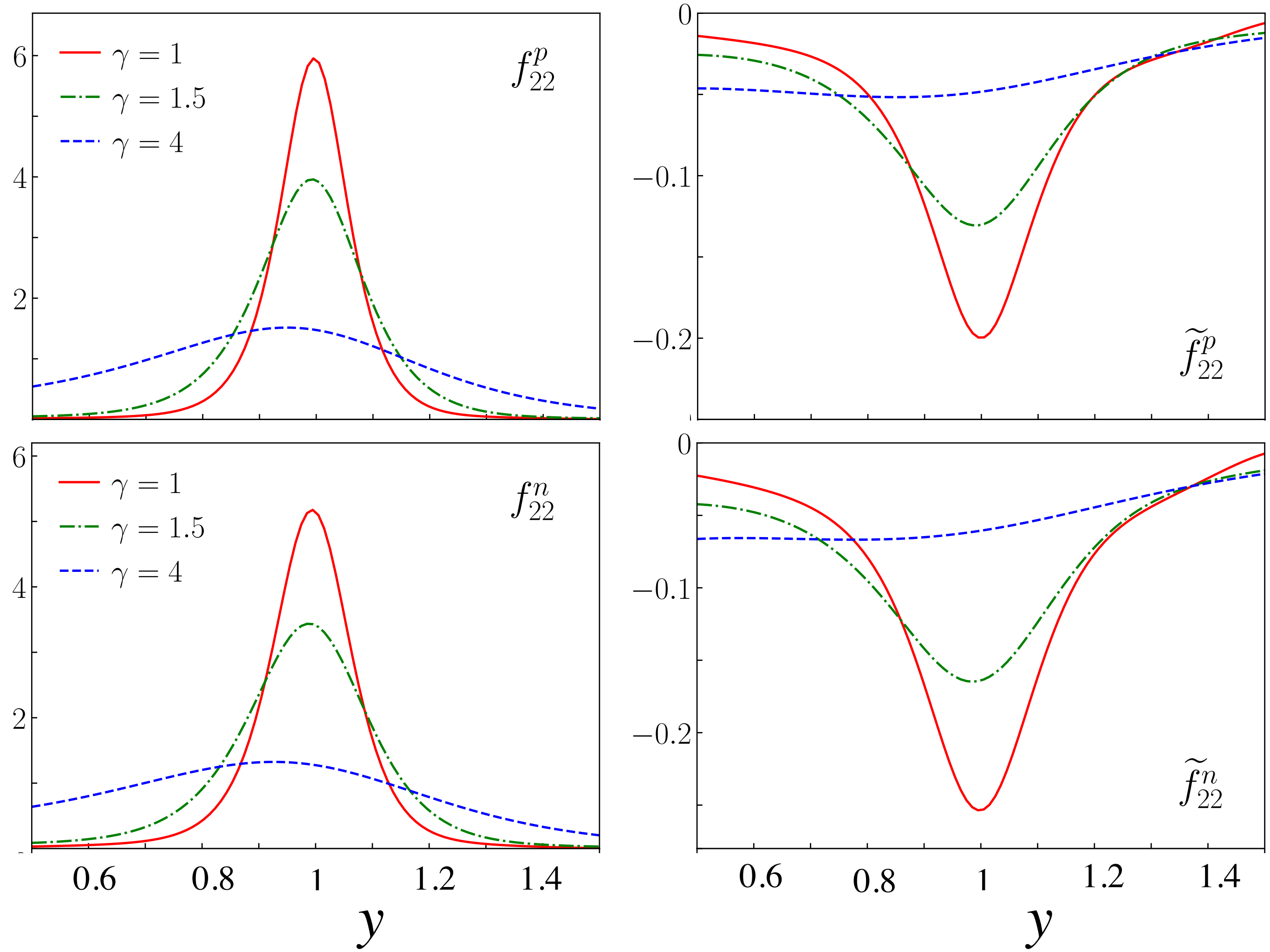
Smearing functions



Tropiano et al.,
PRC ***99****, 035201 (2019)*

→ off-shell smearing functions $\ll$ on-shell smearing functions for most kinematics of interest

Smearing functions

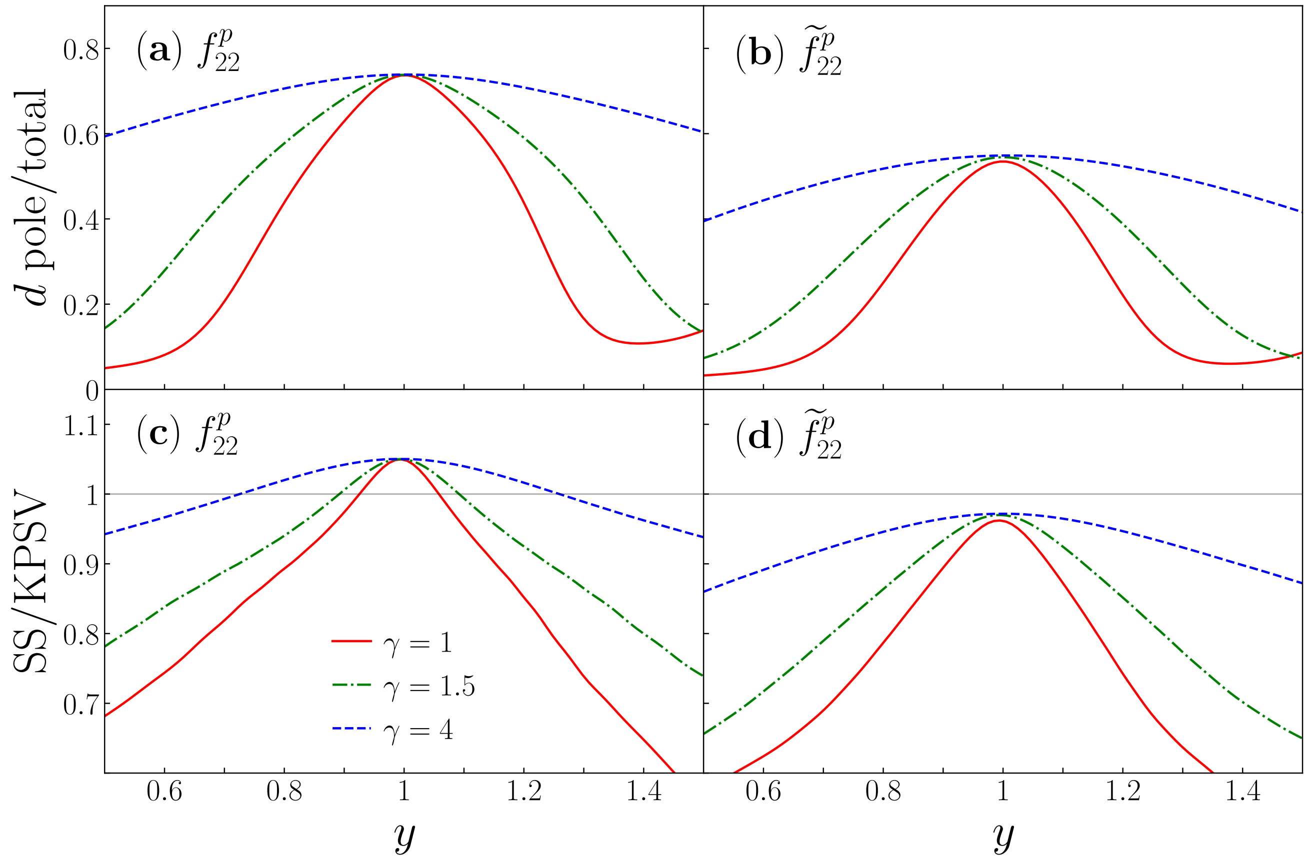


Tropiano et al.,
*PRC **99**, 035201 (2019)*

→ for tritium, assume isospin symmetry $p/^3\mathrm{H} = n/^3\mathrm{He},\ n/^3\mathrm{H} = p/^3\mathrm{He}$

→ <u>but</u> isospin symmetry does <u>not</u> imply $p/^3\mathrm{He} = n/^3\mathrm{He}\,!$

Smearing functions



→ spectral function models similar at peak

KPSV = Kievsky, Pace, Salme, Viviani
SS = Schulze, Sauer

→ large d pole contribution to proton

$$\mathcal{F}^p(\varepsilon, \mathbf{p}) = \mathcal{F}^p_{d\,\text{pole}}(\mathbf{p})\, \delta(\varepsilon + \varepsilon_{\text{He}} - \varepsilon_d) + \mathcal{F}^p_{\text{cont}}(\varepsilon, \mathbf{p})$$

$$\mathcal{F}^n(\varepsilon, \mathbf{p}) = \mathcal{F}^n_{\text{cont}}(\varepsilon, \mathbf{p})$$

Quasielastic scattering

- Check smearing functions against quasielastic ^{3}He data

$\longrightarrow$ nucleon elastic structure function given by elastic form factors

$$F_2^{N(\mathrm{el})}(x,Q^2) = \left[\frac{G_{EN}^2 + \tau G_{MN}^2}{1+\tau}\right]\delta(1-x) \qquad \tau = \frac{Q^2}{4M^2}$$

$\longrightarrow$ off-shell generalization minimally accounted for by kinematics

$$Q^2\,\delta\big((p+q)^2 - M^2\big) = \frac{x}{y}\,\delta\Big(1 - \kappa(p^2)\frac{x}{y}\Big)$$

where

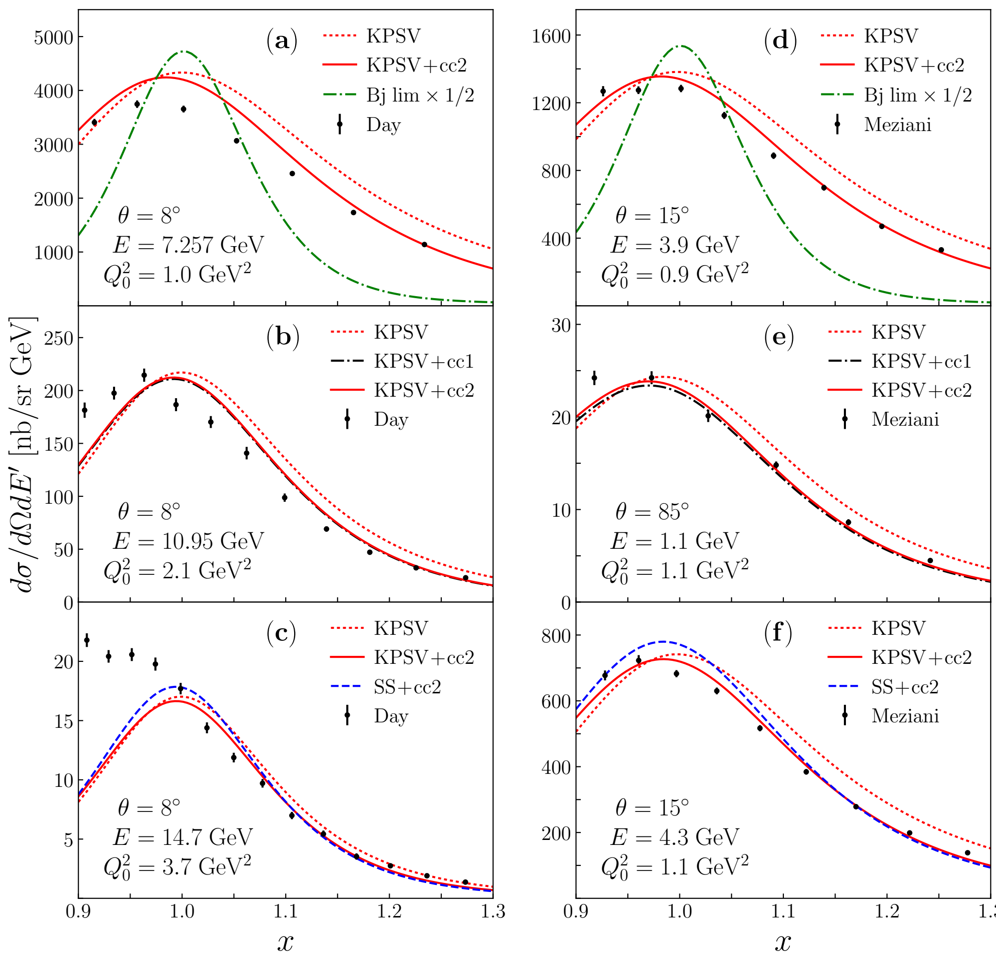
$$\kappa(p^2) = 1 - (p^2 - M^2)/Q^2$$

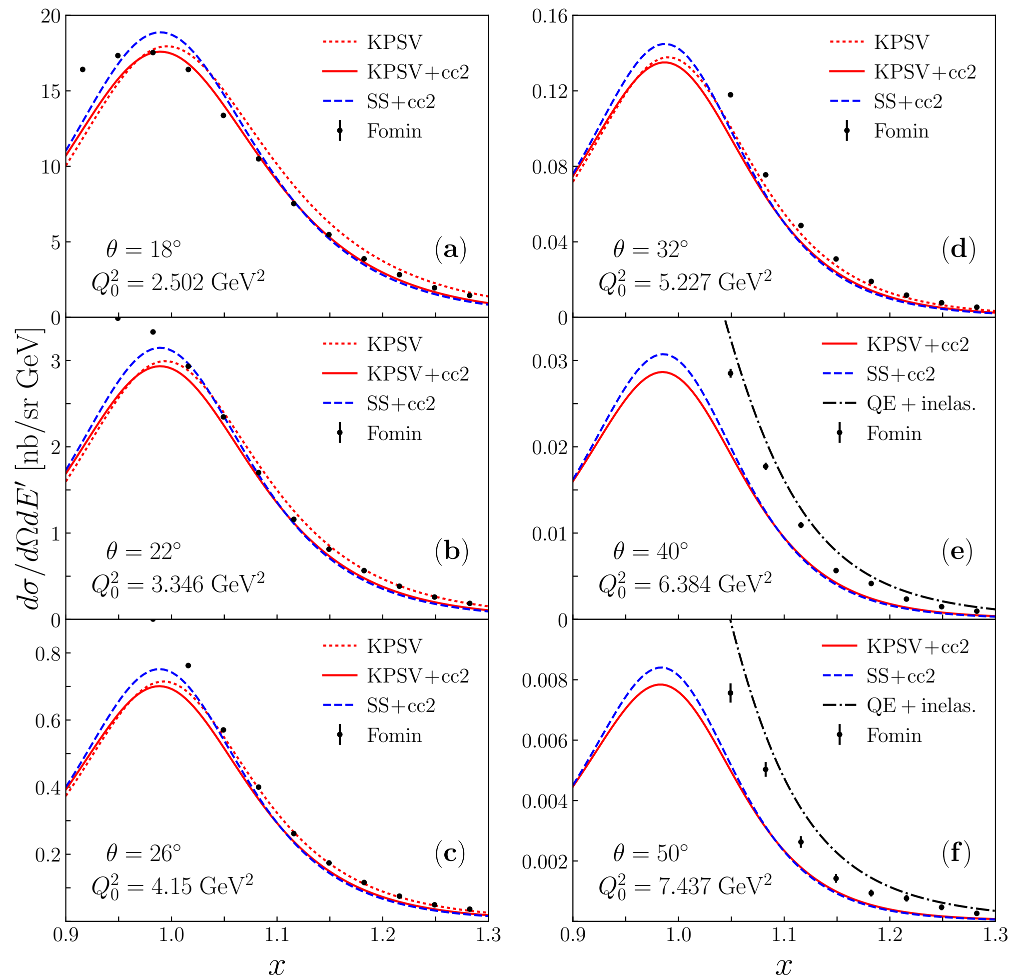
and choice of "cc1" or "cc2" prescription for off-shell nucleon current

DeForest (1983)

Quasielastic scattering

- Check smearing functions against quasielastic ^{3}He data





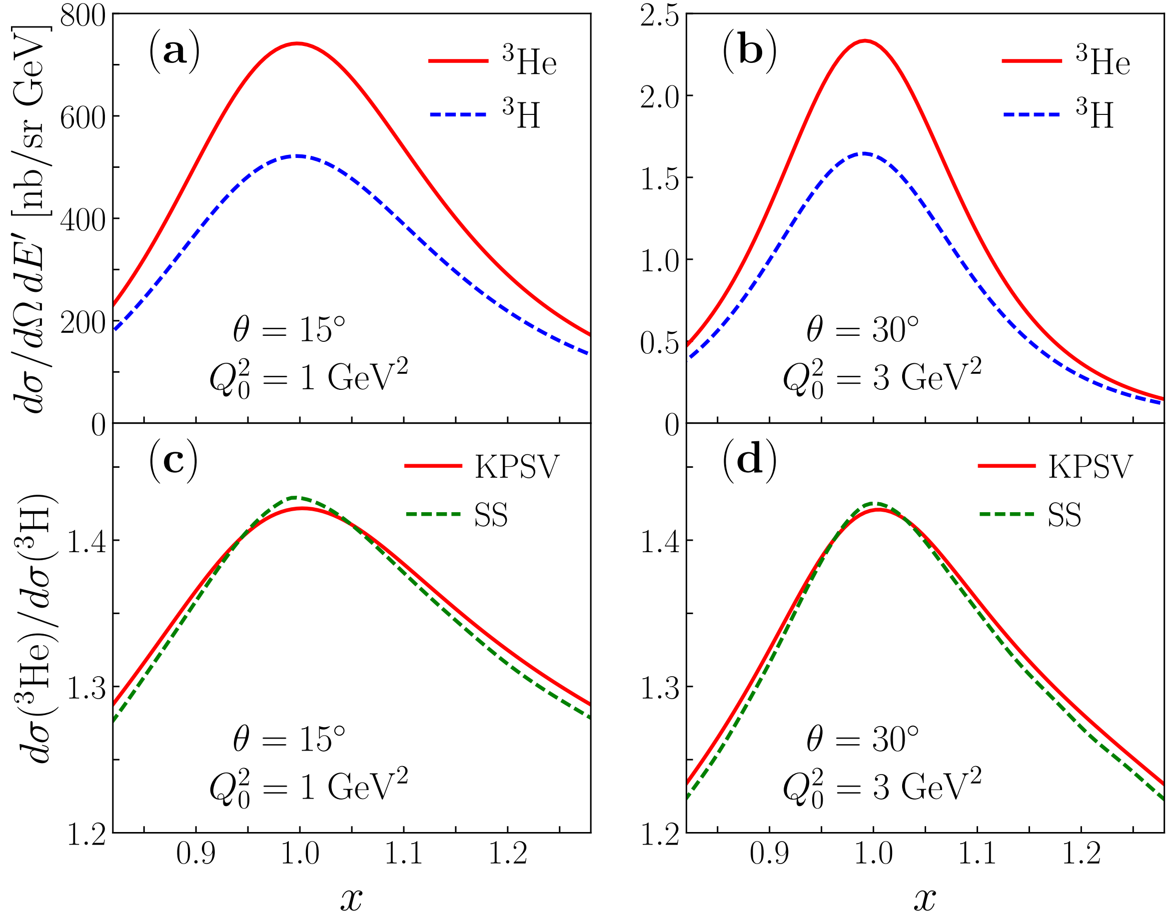
→ impulse approximation gives reasonable description of QE data at $x \gtrsim 1$ for $Q^2 \gtrsim 1\ \mathrm{GeV}^2$

*Tropiano et al., PRC **99**, 035201 (2019)*

Quasielastic scattering

- If smearing functions well constrained at $y \approx 1$, can one use QE ^{3}He and ^{3}H data to extract nucleon's e.m. form factors?

→ *e.g.*, at kinematics of JLab E12-11-112 experiment



Tropiano et al., *PRC* ***99***, *035201 (2019)*

Quasielastic scattering

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$\longrightarrow$ *e.g.*, at kinematics of JLab E12-11-112 experiment

$$R^{(\mathrm{QE})} \equiv \frac{F_2^{^3\mathrm{He(QE)}}}{F_2^{^3\mathrm{H(QE)}}} = \frac{2 + (f^n/f^p) R_{np}}{(f^n/f^p) + 2R_{np}}$$

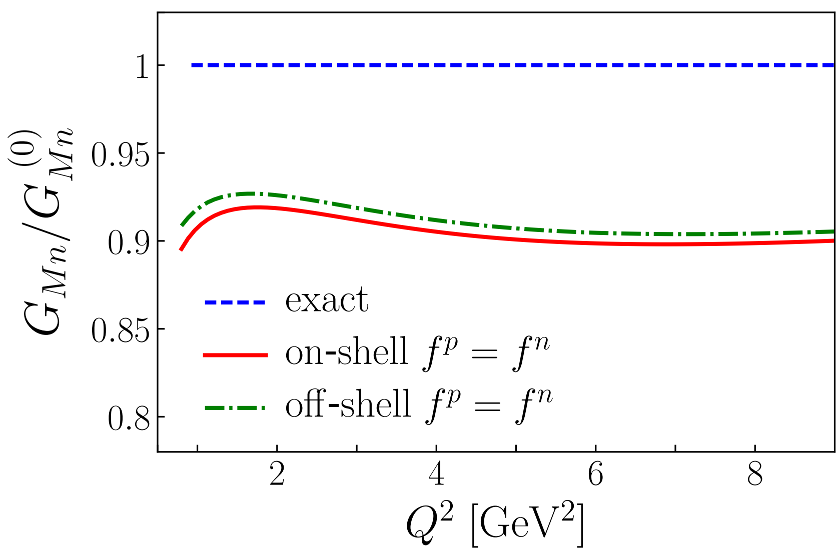
$$f^N \equiv f_{22}^N(x=1)$$

$$R_{np} = \frac{G_{En}^2 + \tau G_{Mn}^2}{G_{Ep}^2 + \tau G_{Mp}^2}$$

$\longrightarrow$ if 3 of the form factors known, can extract the remaining one, *e.g.*, for neutron magnetic

$\longrightarrow$ $f^n/f^p \approx 0.87$ at QE peak

$\approx 10\%$ error if $f^n = f^p$ assumed



Nucleon off-shell corrections

- Off-shell effects unphysical (of course), but can be discussed within a given theoretical framework

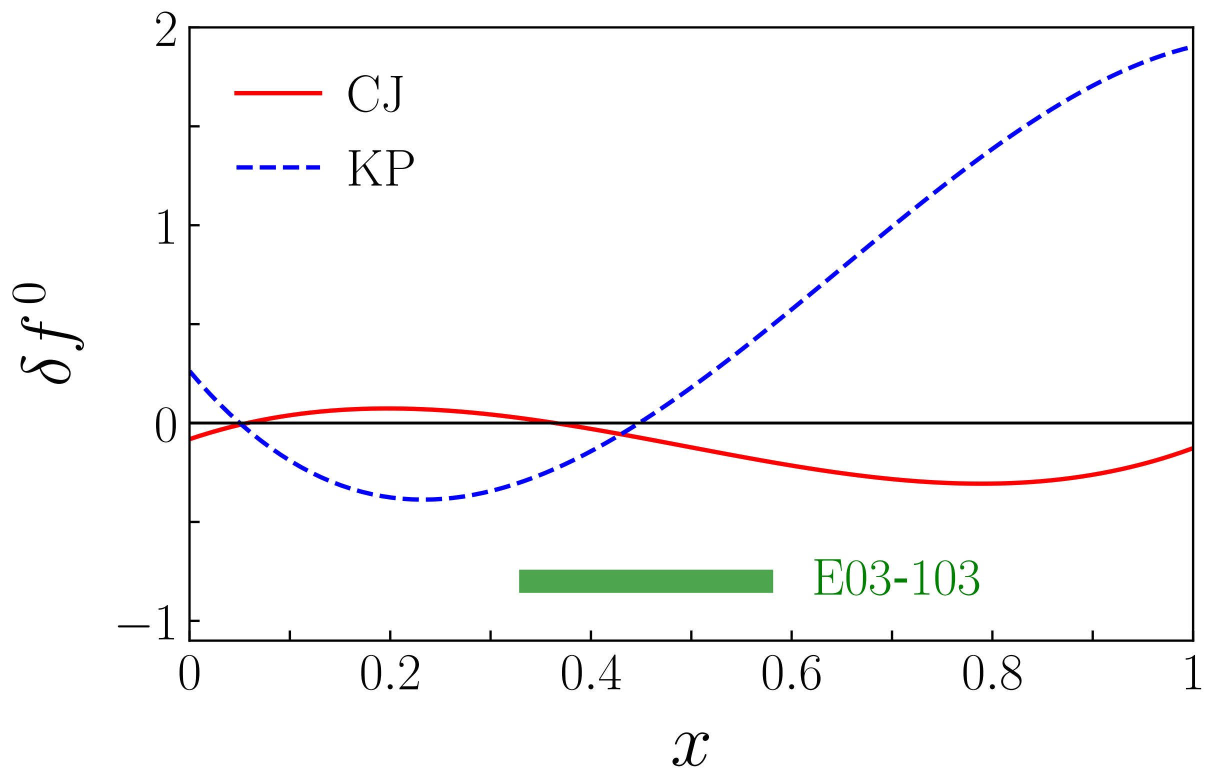
- Within WBA approach, Kulagin & Petti suggested to fit them to nuclear structure function data *Kulagin, Petti, NPA **765**, 126 (2006)*

- Similar approach adopted in CJ15 global QCD analysis of *proton* and *deuteron* data *Accardi et al., PRD **93**, 114017 (2016)*

⟶ parametrize (isoscalar) off-shell function as 3rd order polynomial, with parameters C and x_0 , with x_1 determined from normalization condition (off-shell effects do not modify valence quark number)

$$\delta f^0 = C(x - x_0)(x - x_1)(1 + x_0 - x)$$

Nucleon off-shell corrections

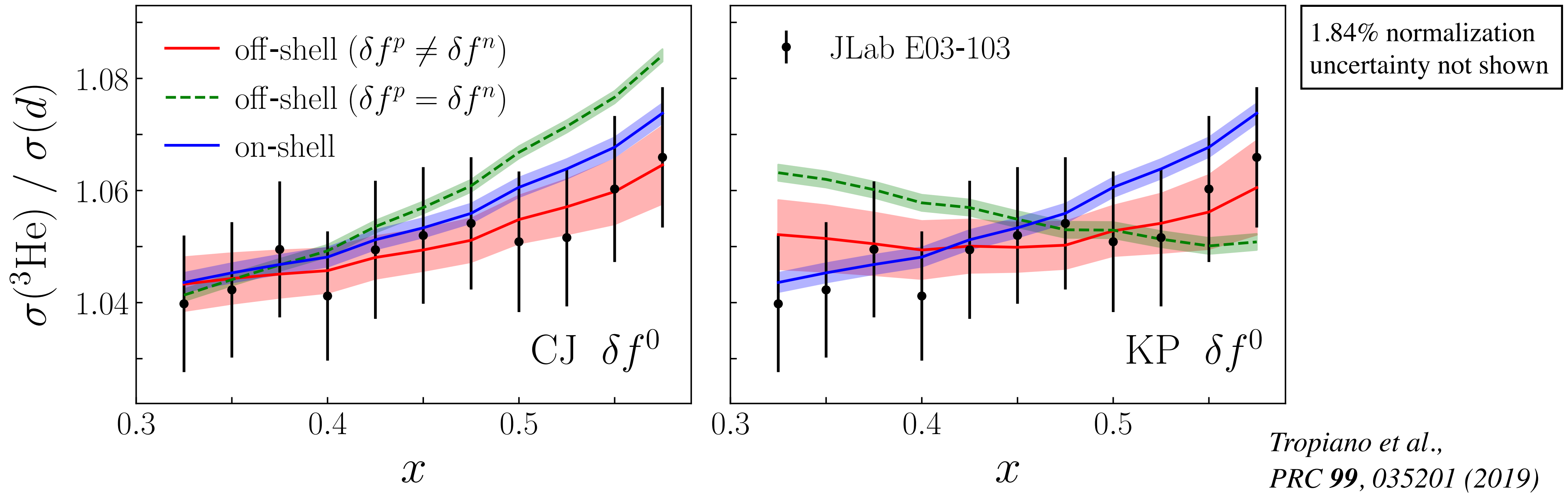


→ some difference in shape for isoscalar off-shell function from KP and CJ analyses

→ CJ sensitive only to $\delta f^p + \delta f^n$;
KP assume $\delta f^p = \delta f^n$ for heavier nuclei also

Nucleon off-shell corrections

- JLab E03-103 experiment measured ratios of cross sections for light nuclei, including helium-3 / deuterium

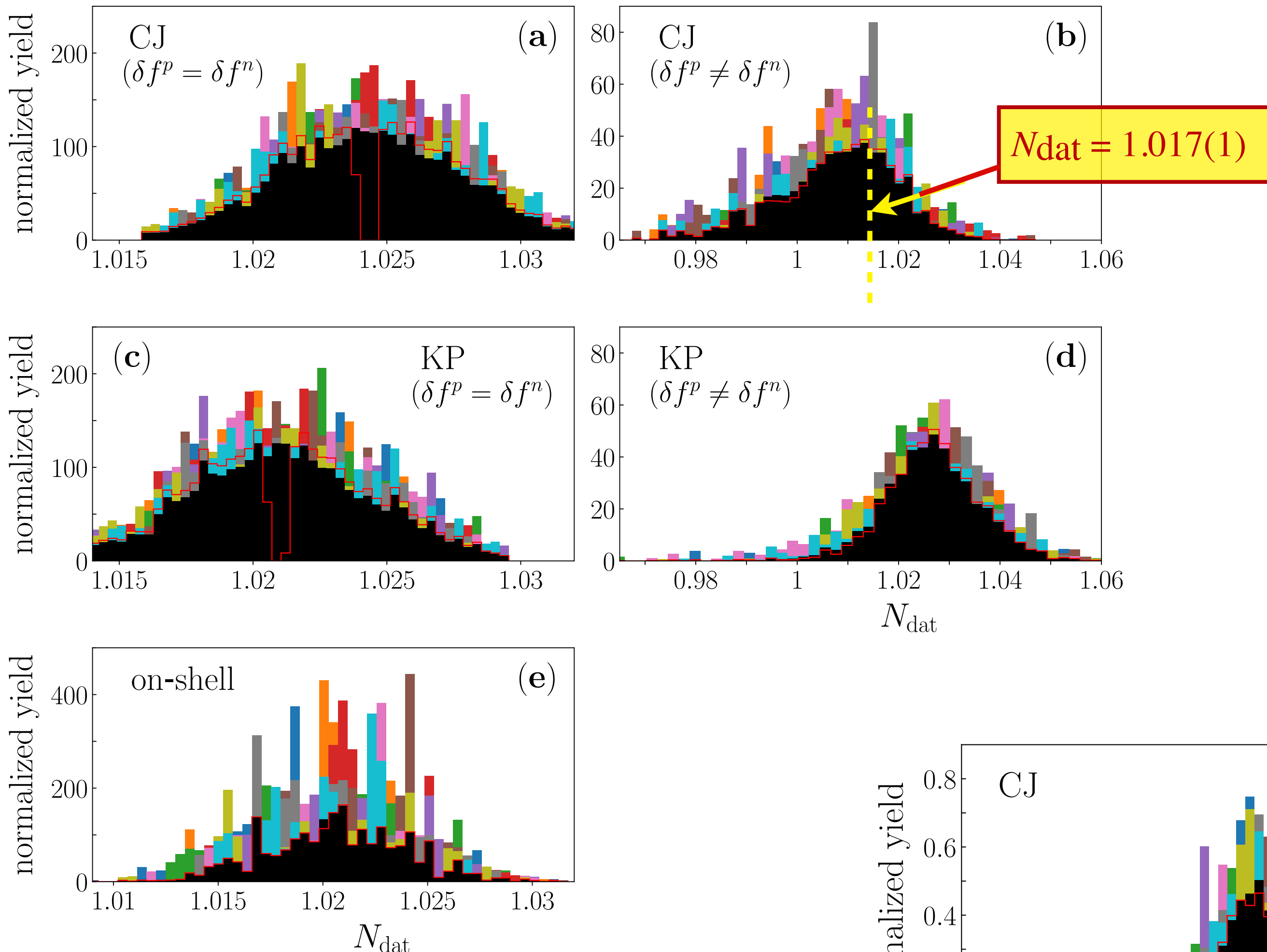


Tropiano et al., *PRC* ***99***, *035201 (2019)*

→ since helium-3 is more sensitive to proton than neutron, fit proton off-shell function and extract neutron from

$$\delta f^n = \frac{1}{F_2^n}\left[(F_2^p + F_2^n)\delta f^0 - F_2^p\,\delta f^p\right]$$

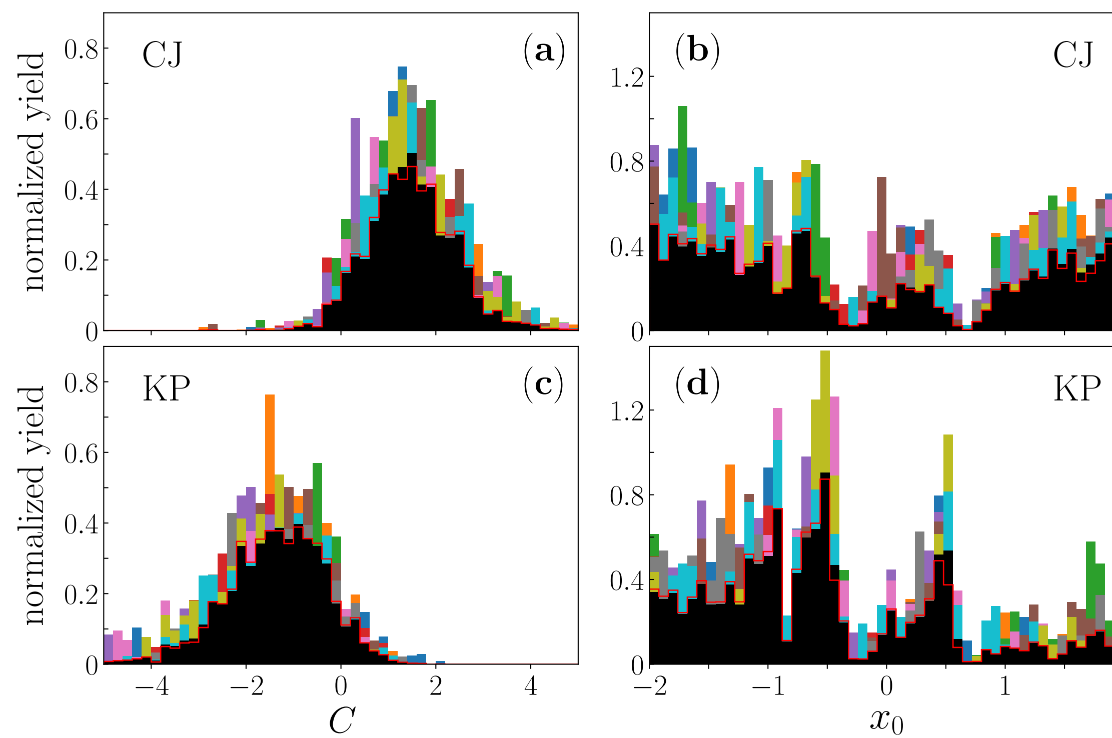
$$= \delta f^0 - \frac{F_2^p}{F_2^n}(\delta f^p - \delta f^0)$$



Monte Carlo parameter distributions

(using JAM technology)

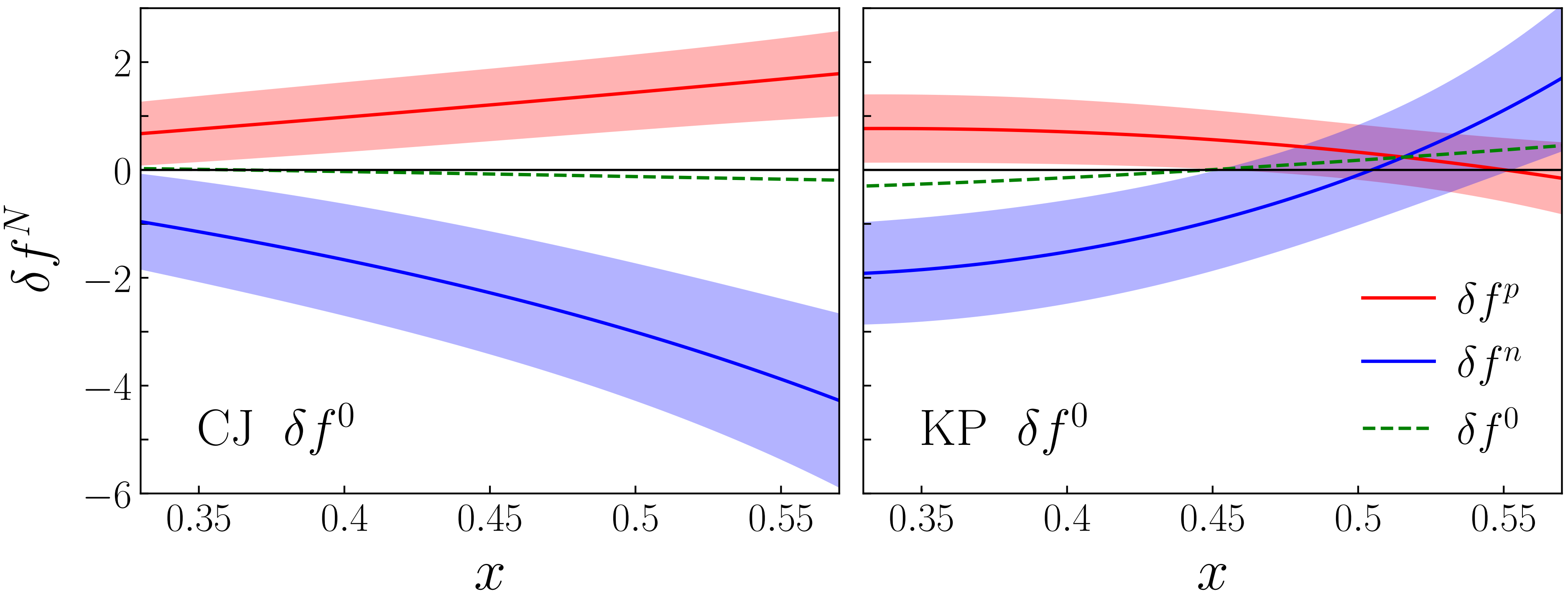
→ ***JAM talk Tue. 12:00***



→ MC fits disfavor zero off-shell correction

— easier for fit to vary one of the params. than keep same shape & compensate by normalization shift

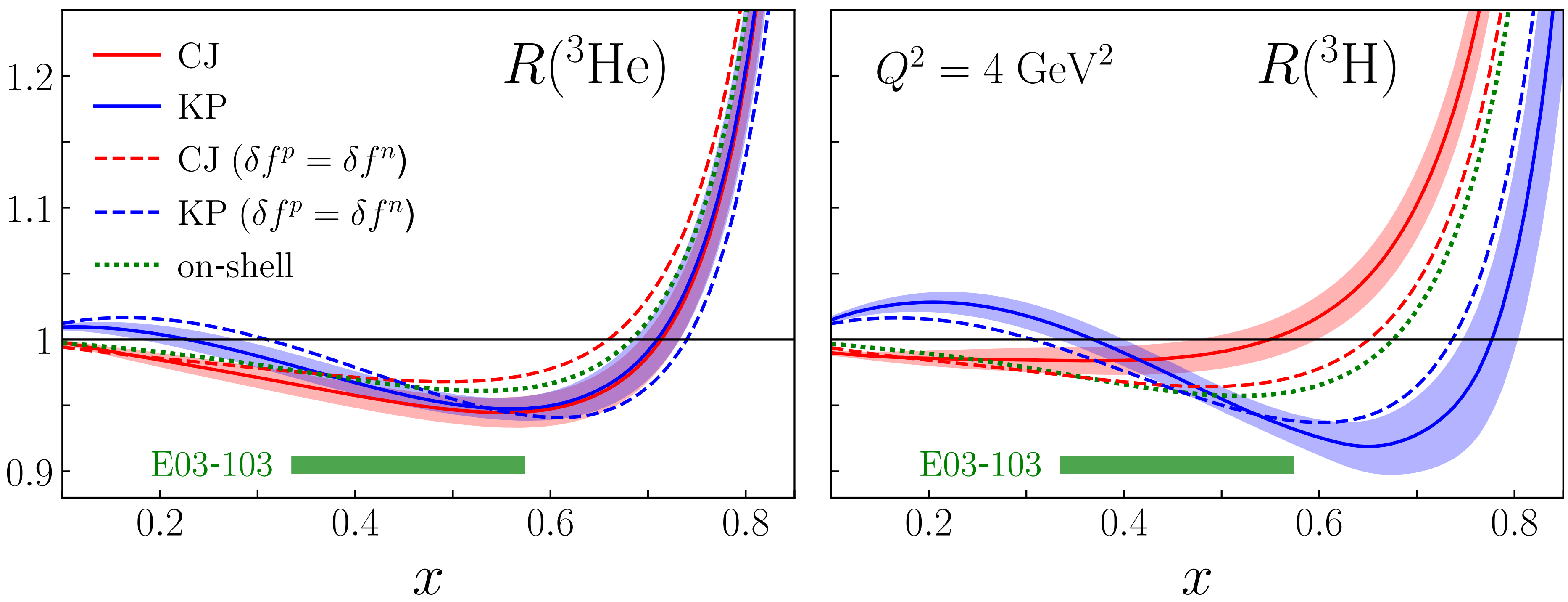
Isospin dependent off-shell functions



→ fits favor large cancellations between proton and neutron off-shell effects: isovector off-shell $\gg$ isoscalar off-shell

→ off-shell functions weighted by nucleon virtuality $|v| \ll 1$, where $v^2 = (p^2 - M^2)/M^2$
— corrections to structure functions range from ~10% for p at $x \sim 0.3$ to ~30% for n at $x \sim 0.6$

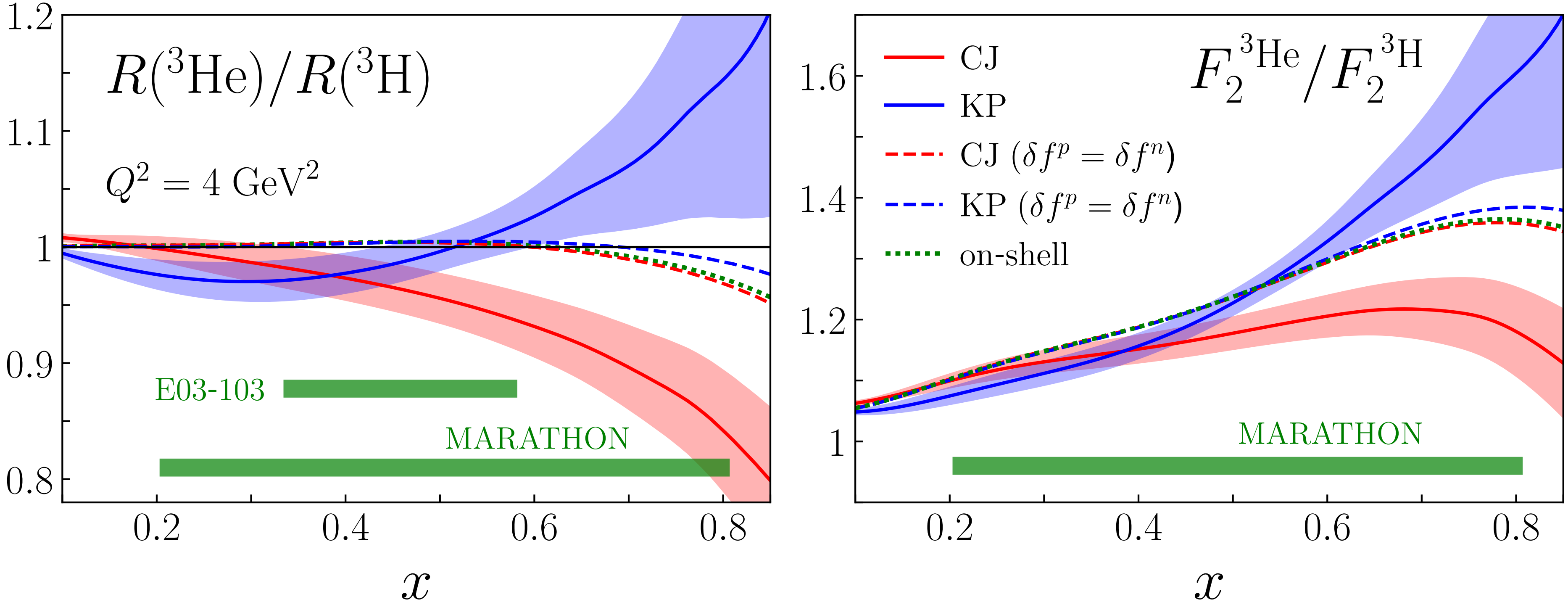
Impact on A=3 EMC ratios



→ limited model variation for helium-3 EMC ratio due to stronger sensitivity of helium-3 to proton structure

→ larger variation for tritium EMC ratio due to stronger dependence of tritium on (less well known) neutron structure

Impact on super-ratios



→ potential for sizeable isospin dependent* off-shell effects suggested (not ruled out) by E03-103 data

* note: this is not violation of any isospin/charge symmetry

Synopsis

- Assumptions made in the analysis:
  - E03-103 data & uncertainties are correct as given
  - Theoretical WBA framework valid for $A = 2$ & 3
    - — total structure function = on-shell part + off-shell part
    - — expand off-shell function to lowest order in v
    - — same off-shell functions $\delta f^p, \; \delta f^n$ in $A = 2$ & 3
  - Isospin symmetry for smearing functions in $^3\mathrm{He}$ & $^3\mathrm{H}$
  - δf^0 off-shell functions from CJ and KP analyses

- Some of these can be improved:

→ should perform <u>combined</u> fit of all p, d and A=3 data to self-consistently determine <u>on-shell neutron</u> and <u>off-shell p and n</u> functions under same set of conditions

Strategy for analyzing MARATHON data

- Least model-dependent ways to extract d/u ratio from MARATHON data, without any assumption about super-ratio:

  → with ≥ 3 observables — ${}^3\mathrm{He}/d,\ {}^3\mathrm{H}/d,\ d\ (\mathrm{or}\ d/p) + p$ — perform global fit at structure function level to extract 3 unknowns — $F_2^n,\ \delta f^p,\ \delta f^n$ — to be used as input into global QCD analysis (at parton level)

or

  → perform global QCD fit directly on all $p,\ d,\ {}^3\mathrm{He}, {}^3\mathrm{H}$ data to extract PDFs, $\delta f^p,\ \delta f^n$ — planned by CJ, JAM, … collaborations

Το τέλος.

Ευχαριστώ!