Resonant and QE Contributions to e-A Inclusive Cross Sections

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Jefferson Lab

NuInt2024 - Sao Paulo, Brazil - April 19, 2024

This talk will focus on Jefferson Lab precision inclusive cross sections and structure functions.

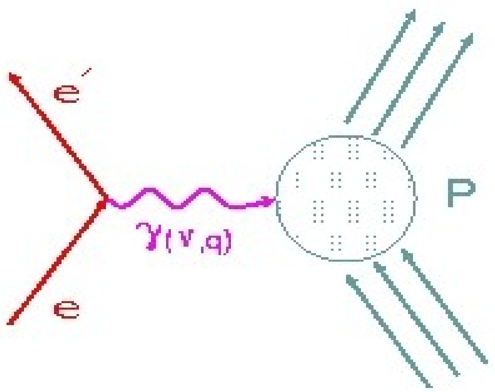
- particular emphasis on Longitudinal / Transverse separations in Hall C for proton, deuteron, and ^{12}C
- BONuS tagged neutron structure function from Hall B CLAS
- Fits to proton, deuteron (neutron), and ^{12}C cross sections

  → developed for radiative corrections and higher level analysis
  → provide baseline for validation of models and event generators in eA mode

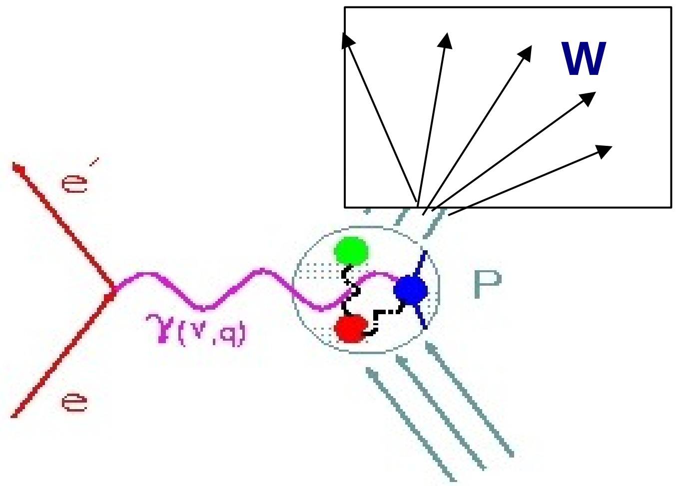
Inclusive Charged-Lepton Scattering

Elastic

W = M$_p$



Inelastic



Q^2: photon 4-momentum

ν: photon energy

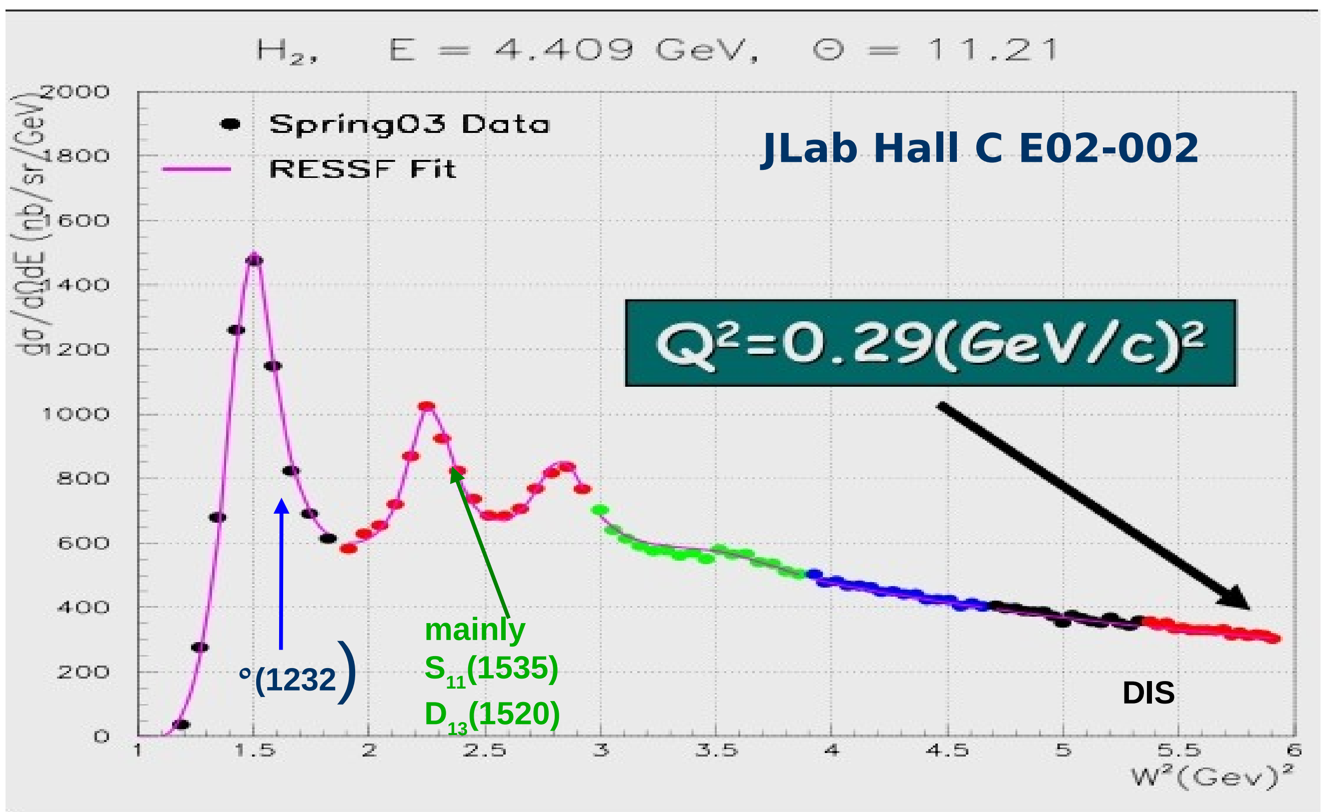
W: Final state hadron mass

x: Bjorken variable

$$\frac{d\sigma}{d\Omega\, dE'} = \Gamma\left[\sigma_T(x,Q^2) + \varepsilon\sigma_L(x,Q^2)\right]$$

$$\Gamma = (\alpha/2\pi^2 Q^2)(E'/E)K/(1-\epsilon)$$

$$\epsilon = \left[1 + 2\left(1 + \frac{\nu^2}{Q^2}\right)\tan^2\frac{\theta}{2}\right]^{-1} \qquad K = \frac{2M\nu - Q^2}{2M}$$



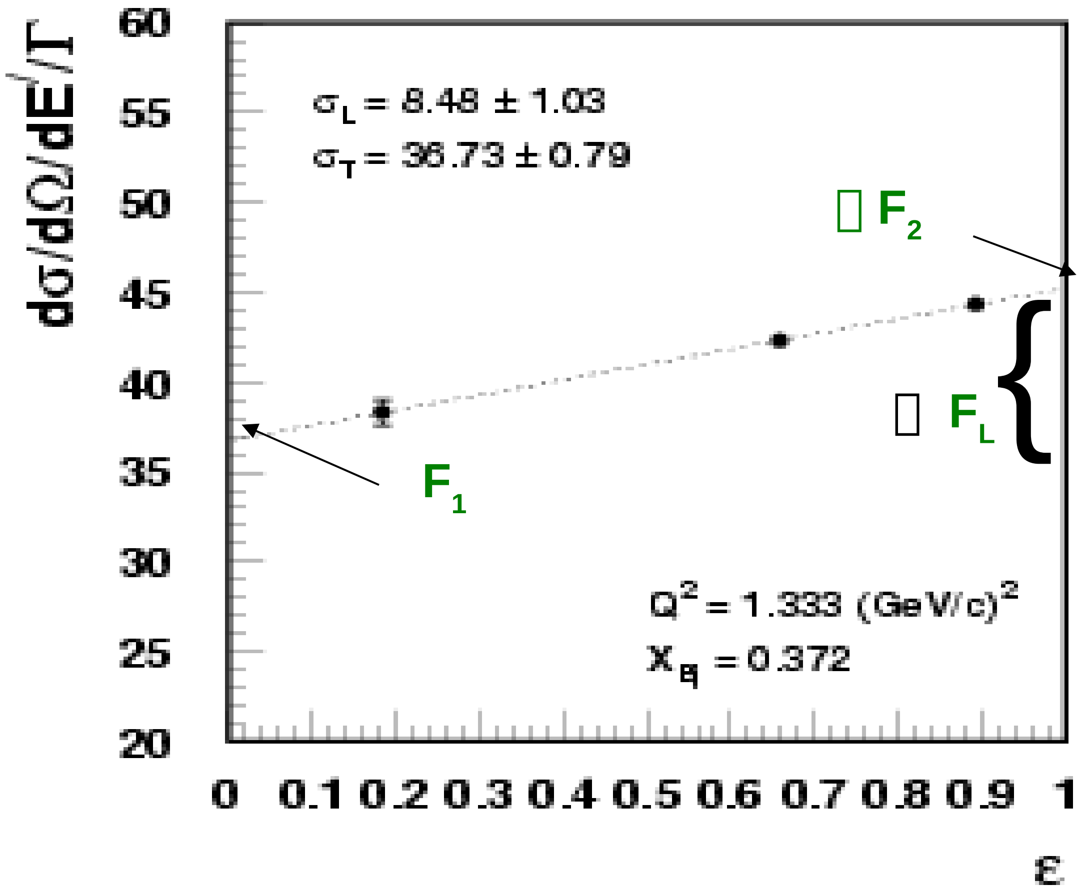
Study the W (or x), Q^2 dependence of the structure functions from

Elastic → resonance → DIS

Rosenbluth Longitudinal / Transverse separation

Reduced cross-section:

$$\frac{1}{\Gamma}\frac{d\sigma}{d\Omega\, dE'} = \sigma_T(x,Q^2) + \varepsilon\sigma_L(x,Q^2)$$



- **Fit linearly with ε at fixed W^2 and Q^2 (or x, Q^2).**

σ_L = Slope

σ_T = Intercept

$$F_1(q,\nu) = \frac{KM}{4\pi^2\alpha}\sigma_T \qquad F_L(q,\nu) = \frac{K\,Mx}{2\pi^2\alpha}\sigma_L$$

$$F_2 = (2xF_1 + F_L)/(1+Q^2/\nu^2)$$

→ need 1-2% uncertainties pt-pt in ε to provide 15-20% **ΔR** ($\Delta F_L/F_L$)

→ also requires multiple beam energies and spectrometer settings for multiple ε.

Very challenging experimentally!

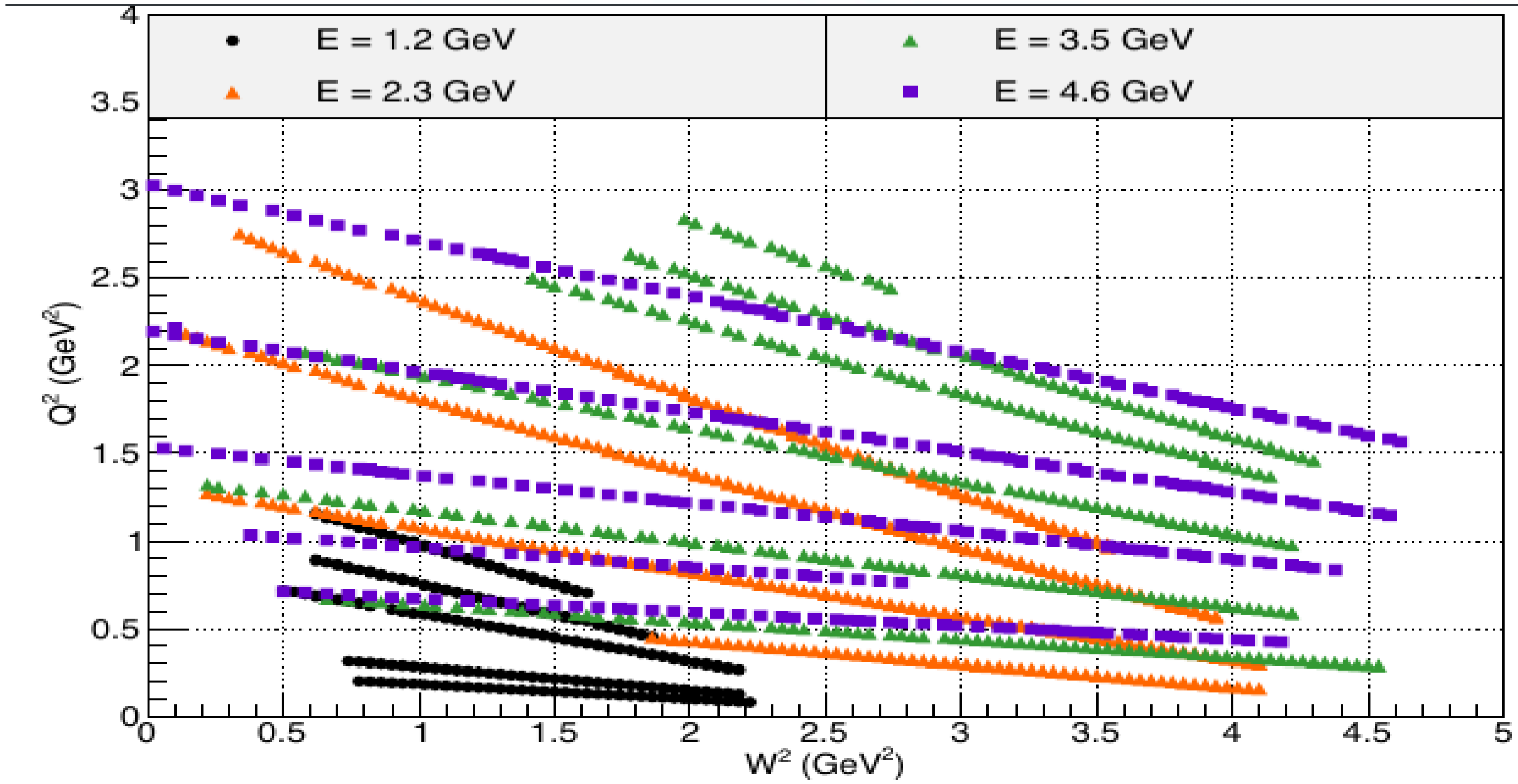
Kinematic Coverage for deuteron, nuclear target L/Ts (Similar for proton)

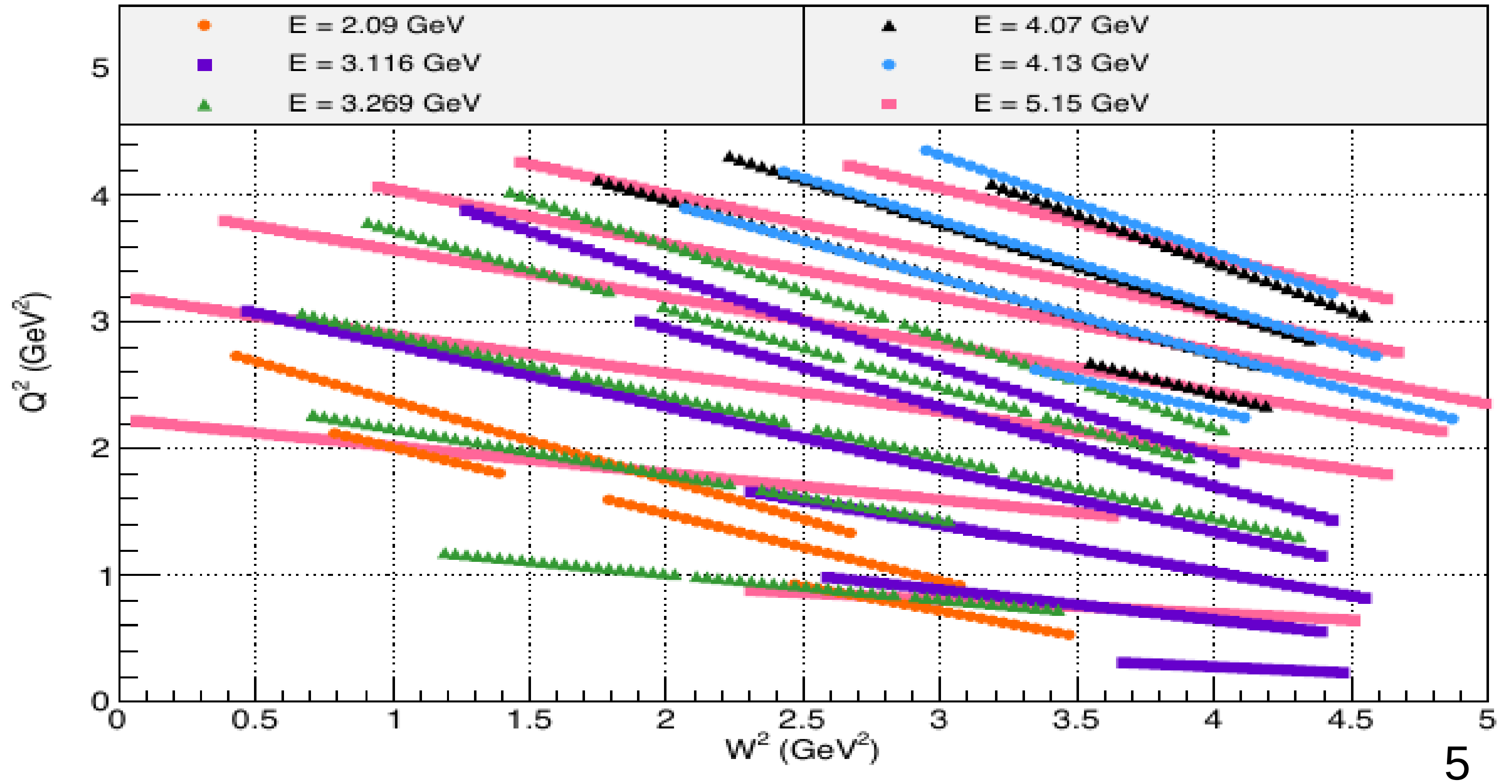
→ Different beam energies at same **W^2**, **Q^2** => different ε values.

→ Low ε : Lower E – larger angle
High ε : Higher E – Smaller angle

→ Large kinematic coverage to leverage for global fitting

→ Typical precision (pt-pt in ε) ~1.5 - 2%





Jefferson Lab

JLab inclusive cross section data

L/T separated data from Jefferson Lab Hall C

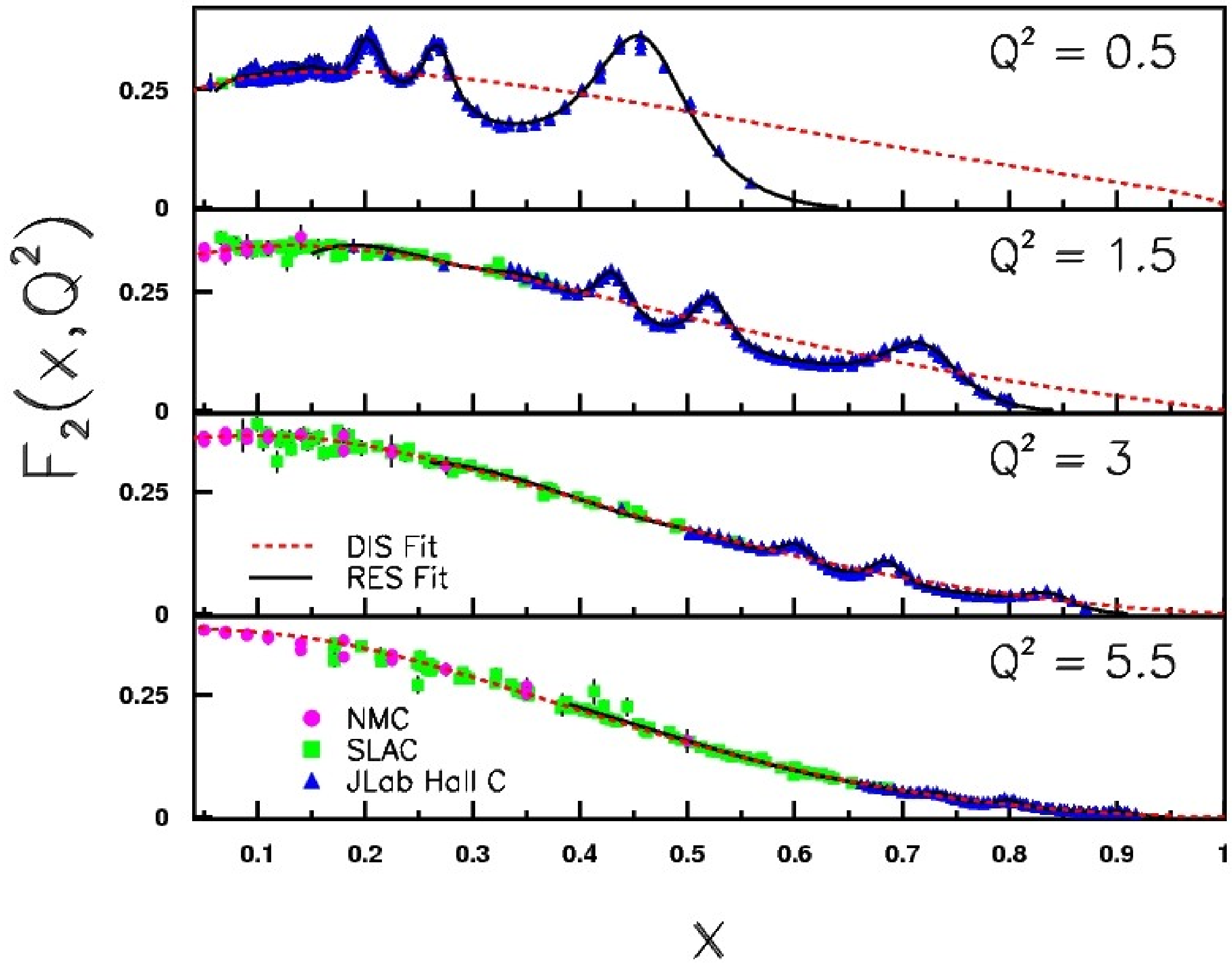
Experiment	target(s)	W range	Q^2 range	Status / Publication
E94-110	p	RR	0.3 - 4.5	Phys.Rev.C 105 (2022) 6, 065205
E99-118	p,d	DIS+RR	0.1 - 1.7	Phys.Rev.Lett. 98 (2007) 142301
E00-002	p,d	DIS+RR	0.25 - 1.5	Phys.Rev.C 97 (2018) 4, 045204
E02-109	d	RR+QE	0.2 - 2.5	Preprint soon
E06-009	d	RR+QE	2.0 - 4.0	Phys.Rev.Lett. 123 (2019) 2, 022501
E04-001 - I	12C,26Al,56Fe	RR+QE	0.2 - 2.5	^{12}C preprint soon
E04-001 - II	12C,27Al,63Cu	RR+QE	2.0 - 4.0	

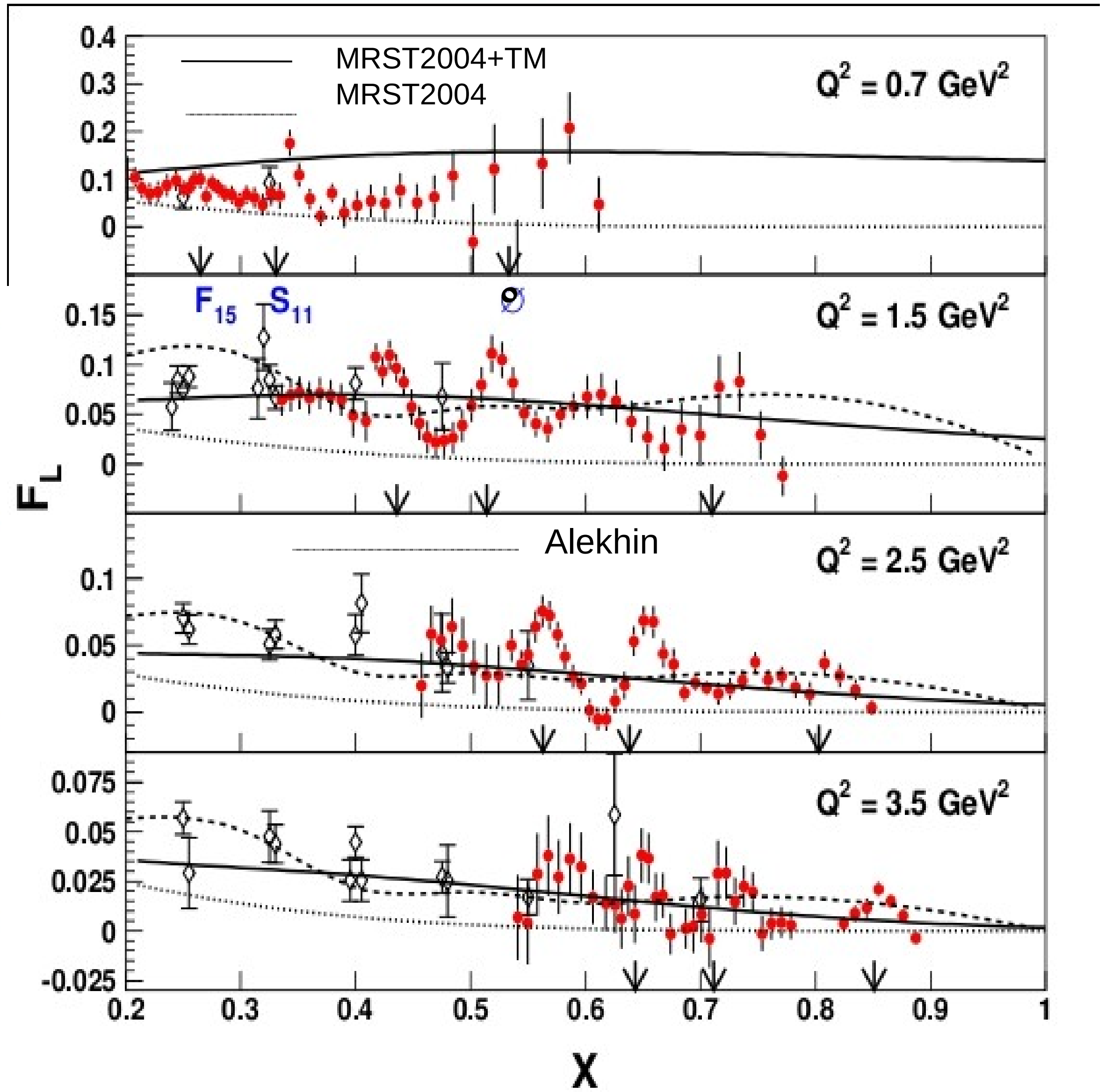
Additional Jefferson Lab inclusive data

E03-103	3He, 4He, 9Be, 12C, 63Cu, 197Au	DIS+RR	2-6	Phys. Rev. Lett. 103, 202301 (2009).
E02-019	3He, 4He, 9Be 12C, 63Cu, 197Au	QE+x>1	2.5	Phys. Rev. Lett. 105, 212502 (2010).
E12-14-012	12C, 40Ti	QE+Δ	~0.3	Phys.Rev.C 100 (2019) 5, 054606
E12-10-002	p, d	DIS+RR	4-16	Preprint soon

Proton F_2 , F_1, F_L well measured at 6 GeV

DIS fit – 'F2ALLM' H.Abramowicz and A.Levy, hep-ph/9712415
Res fit - E.C. and P.E. Bosted, PRC 81,055213





→ **Used to study Q-H duality, structure function moments, and input for other physics studies**

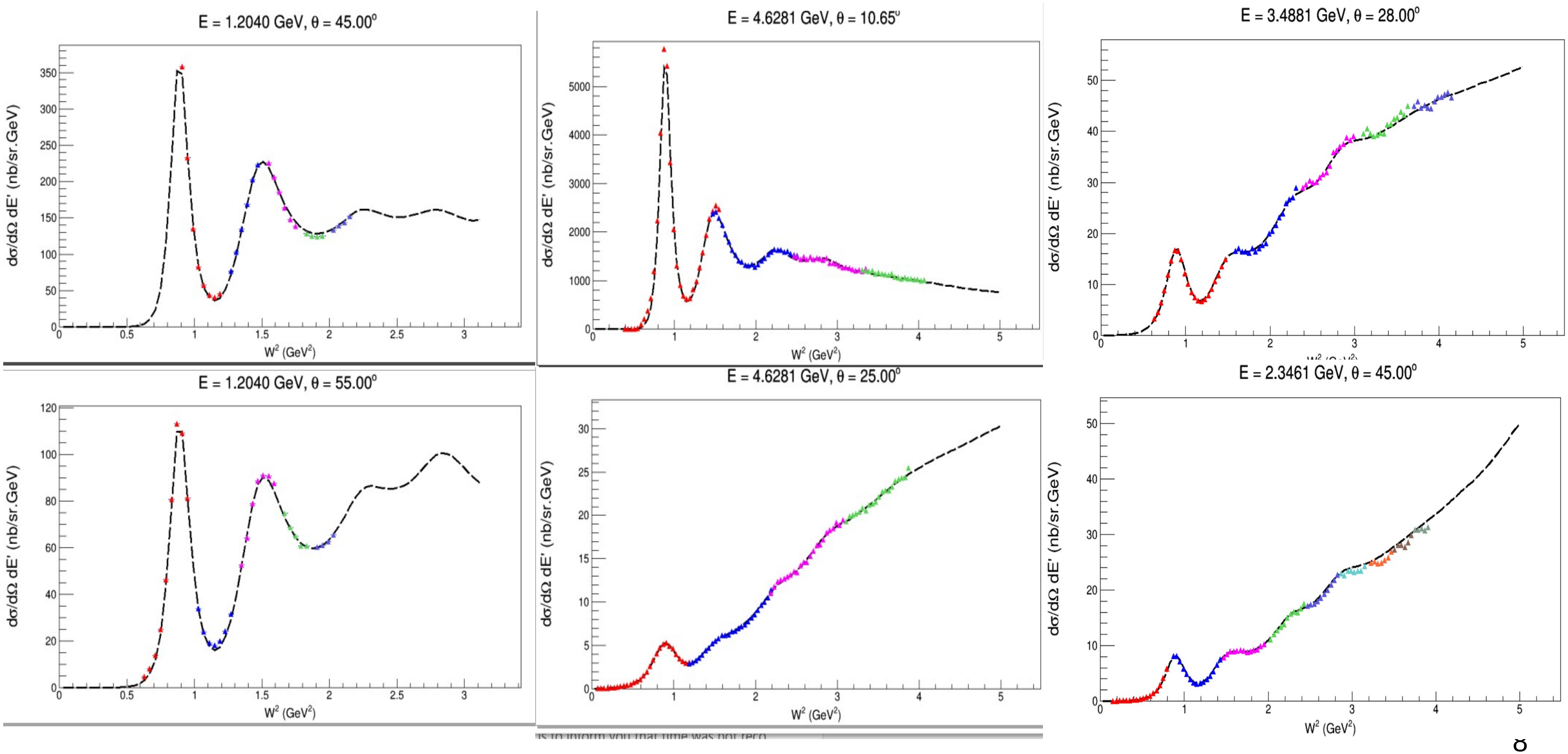
→ **Deuteron and nuclear target data of similar quality to study**
=> - duality and QCD moments of neutron and p-n (non-singlet)
- Modifications of F_1, F_L in nuclear medium

Precision e-d Cross Sections and Structure functions: Jefferson Lab E02-109

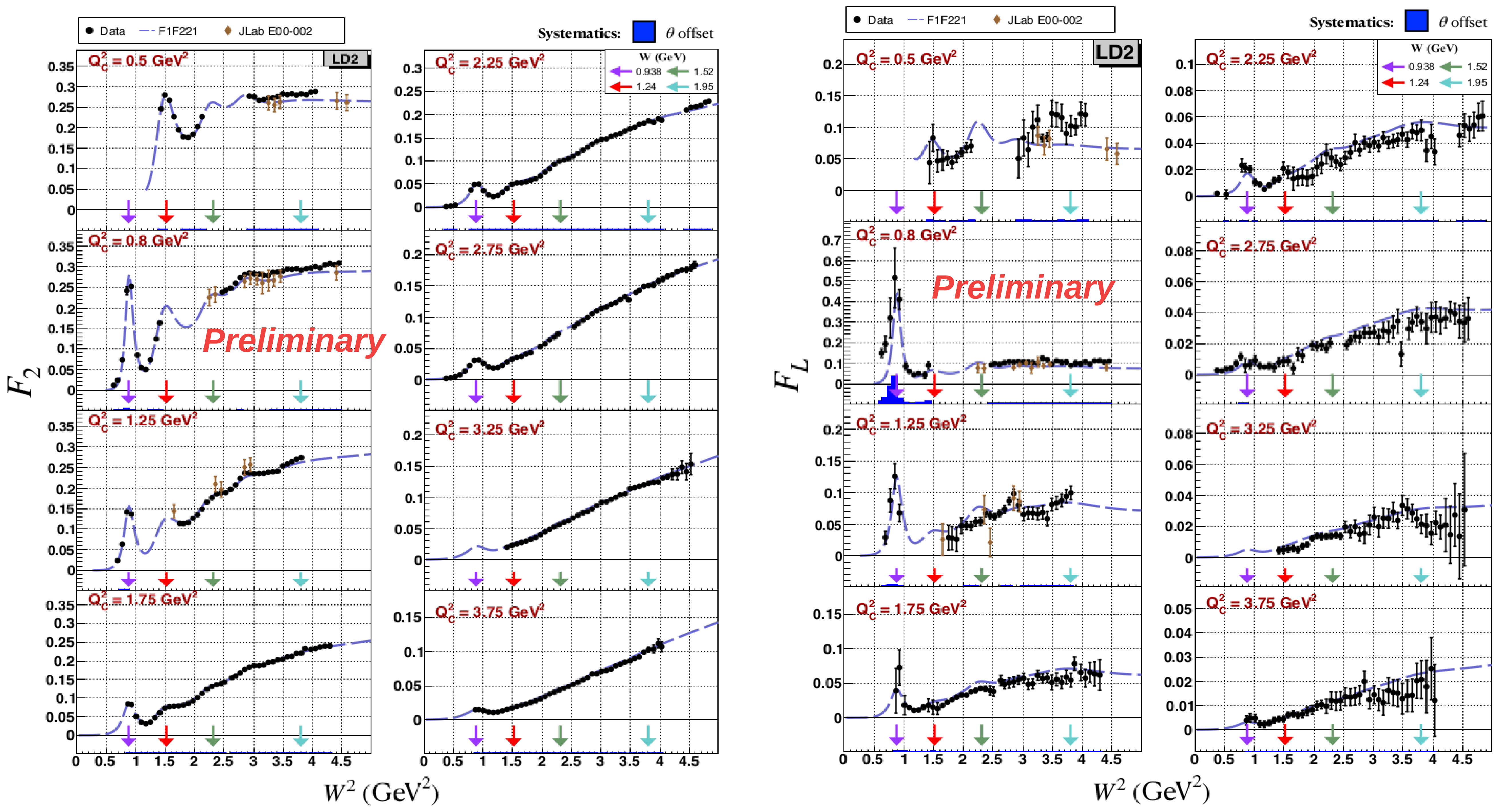
Sample Deuteron Cross Sections (47 total Spectra) - *preprint in preparation.*

- Each color is a different spectrometer central E'

- Curve is global fit (discussed later).



Deuteron separated structure functions (combined E02-109 + E06-009)

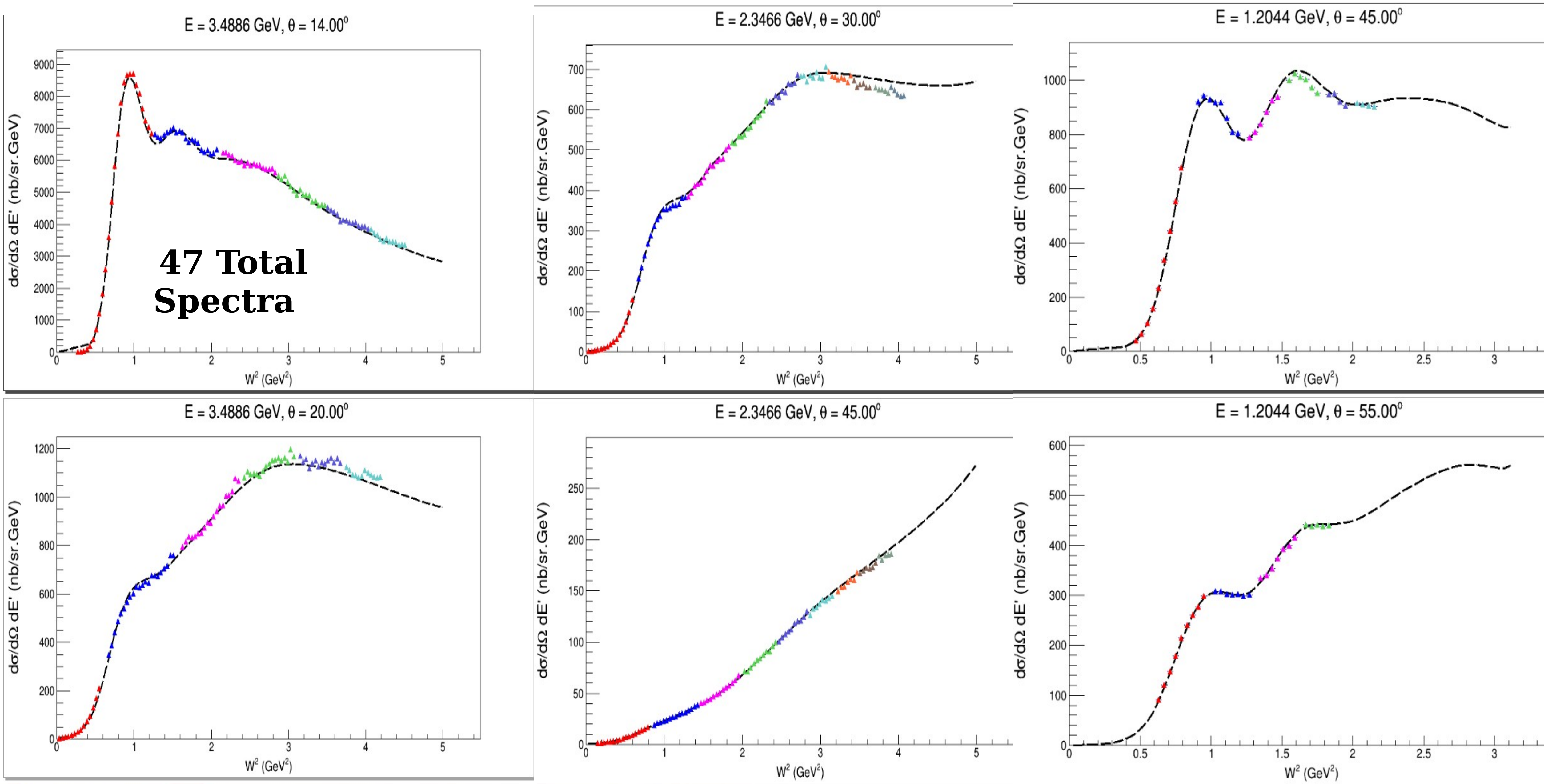


→ Separated structure function kinematic coverage and uncertainties commensurate with proton data.
→ Combined analysis results will supercede previous E06-009 published results.
→ Expect preprint to be available within 2 months.

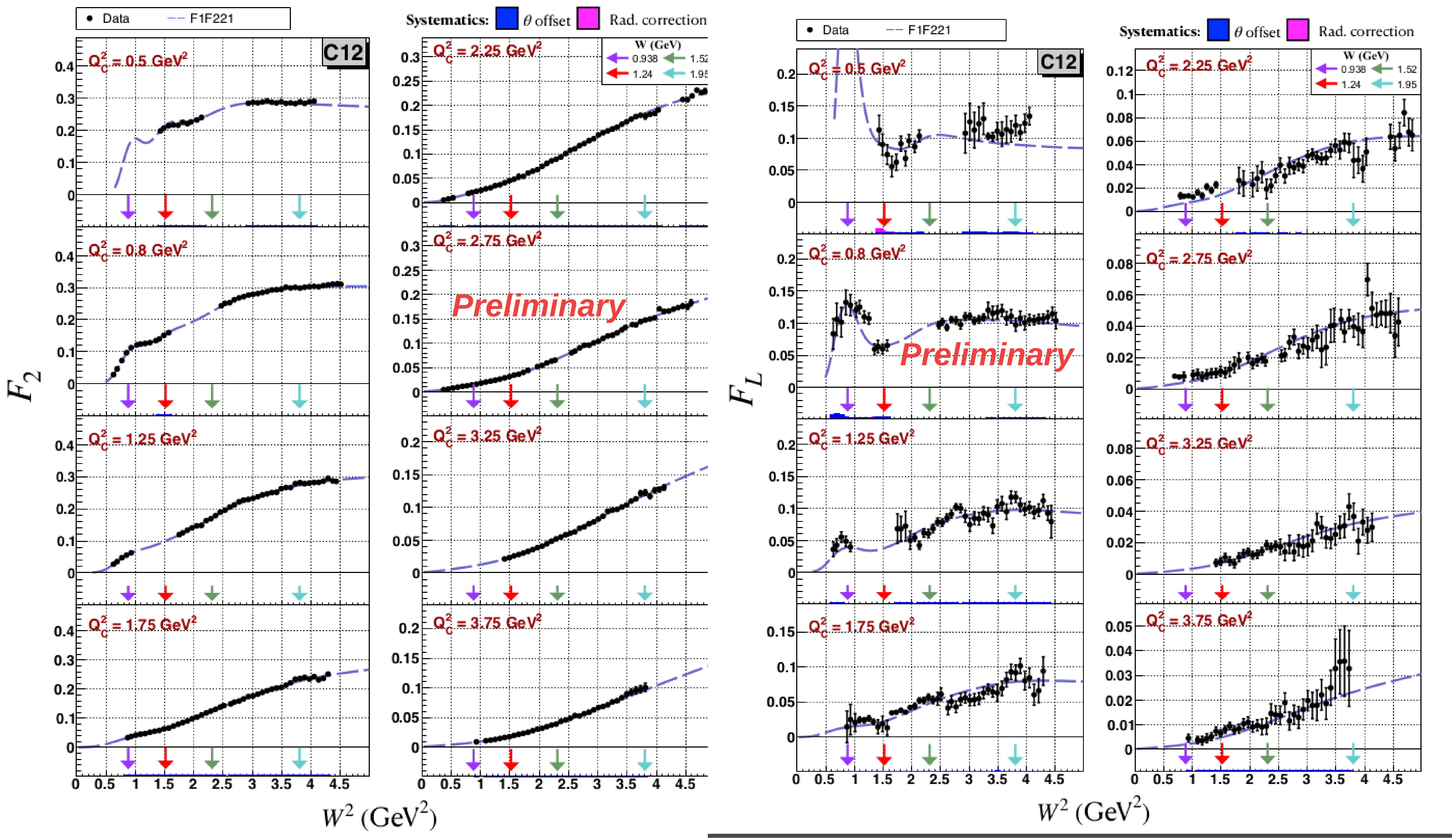
Precision e-A Cross Sections and Structure functions: Jefferson Lab E04-001 (JUPITER1)

Sample ^{12}C Cross Sections (47 total Spectra) - *preprint in preparation.*

- Each color is a different spectrometer central E’
- Curve is global fit (discussed later).

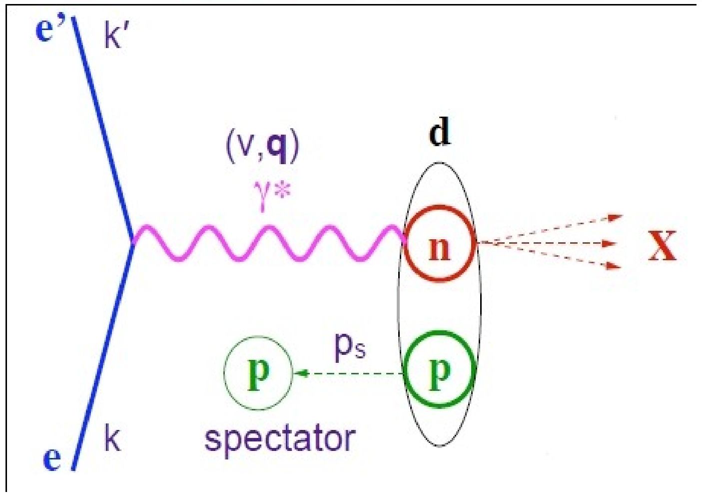


^{12}C separated structure functions from Jupiter (E04-001)



“Barely Off-Shell Neutron Structure” (BONuS) Experiment

Neutron structure function through spectator tagging
Using Hall B CLAS spectrometer for e^-
Proton detected in radial TPC



→ Nearly model-independent *neutron* data

→ Data obtained in 6 GeV JLab era

→ New 12 GeV data taken in 2020 will extend range to higher Q^2 and W

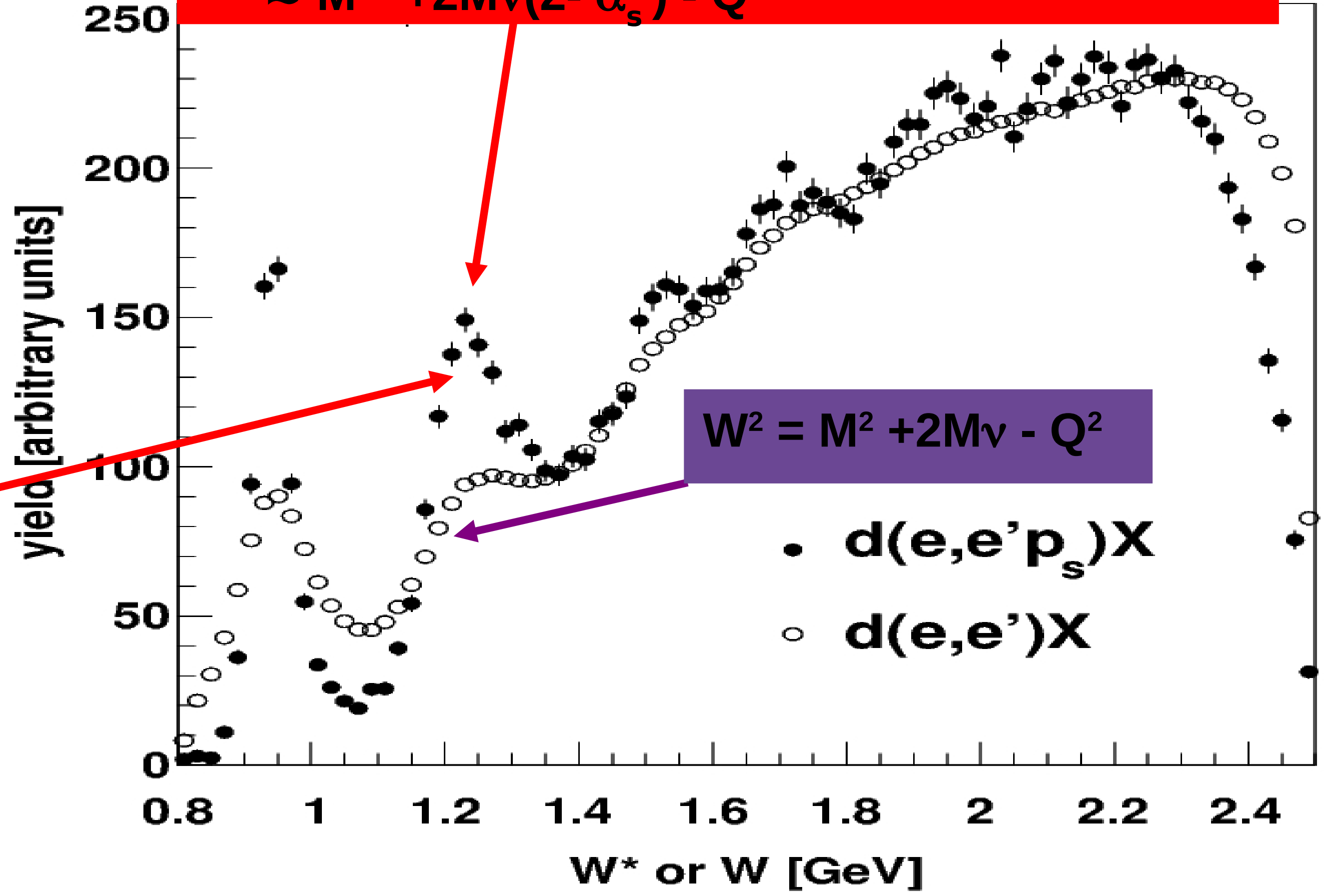
Tag slow, backward, recoil proton

→ kinematics minimize nuclear effects

=> scattering from “nearly” free neutron

→ use proton momentum to correct for Initial state neutron momentum along $\hat{\mathbf{q}}$

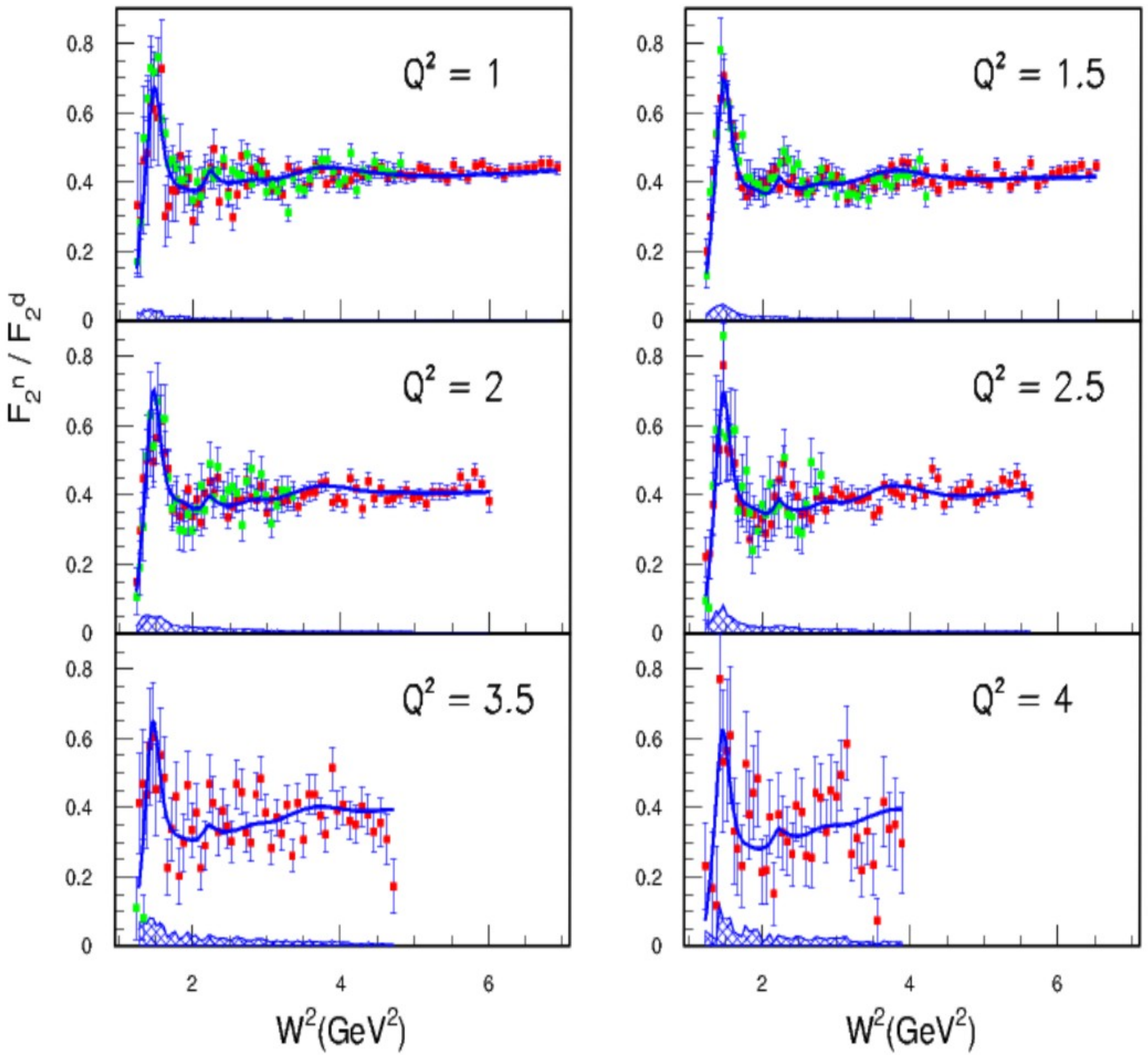
$$W^2 = (p_n + q)^2 = p_n^{\mu} p_{n\mu} + 2([M_D - E_s]\nu - p_n \cdot q) - Q^2$$
$$\approx M^{*2} + 2M\nu(2 - \alpha_s) - Q^2$$



BONuS Results - F_2^n / F_2^d

S. Tkachenko et.al PRC 89 (2014) 045206

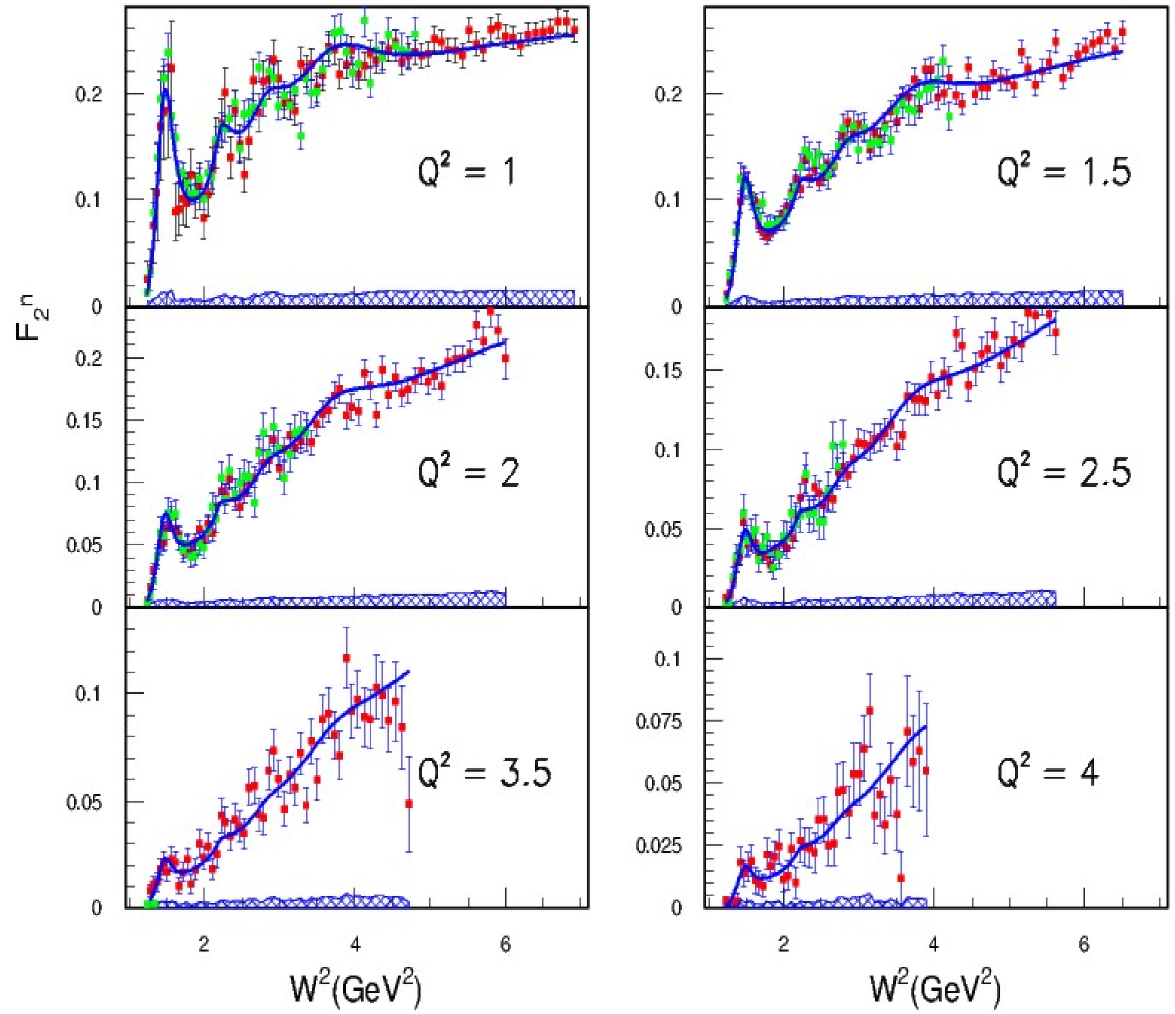
5 GeV   4 Gev



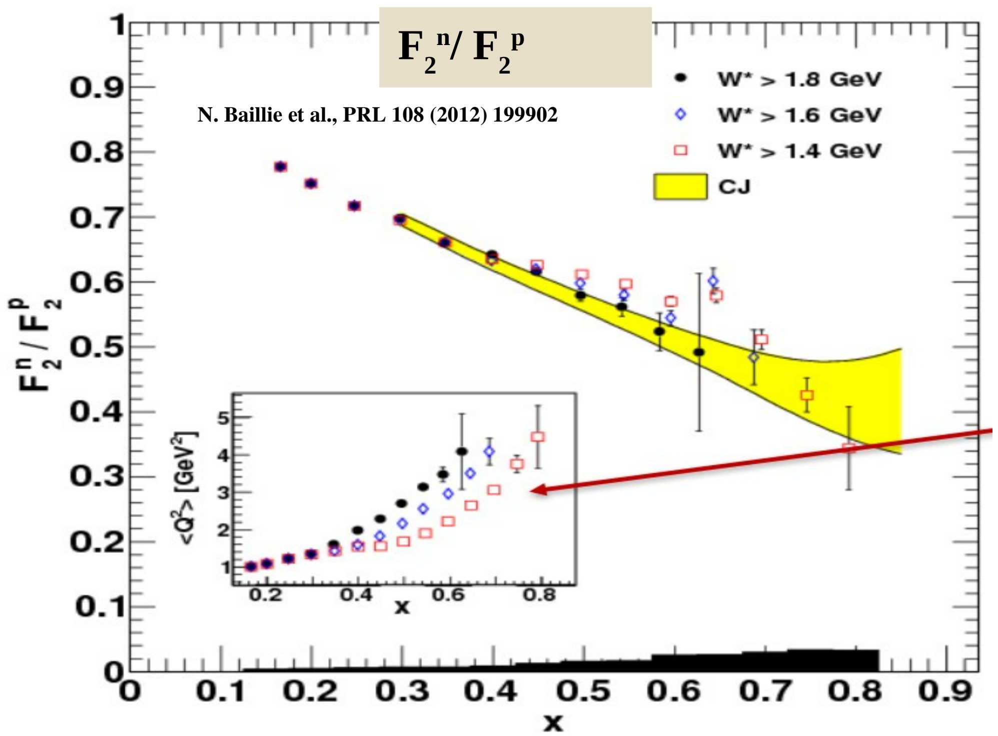
- → Curve is fit to inclusive deuteron cross section using same weak-binding Convolution formalism as CJ PDF fits.

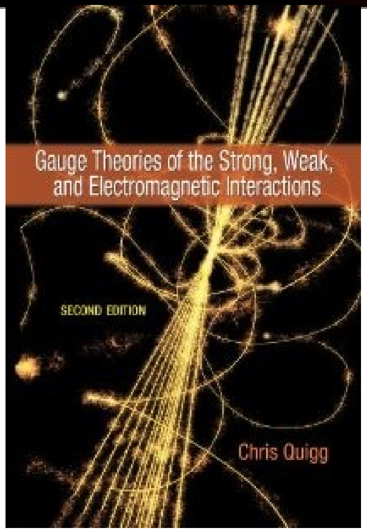
  (M.E.C, N. Kalantarians, J. Ethier, W. Melnitchouk)

- → Proton input from Christy-Bosted fit.
- → BONuS data *not* included in this version of fit.
- → Multiply by F_2^d to determine F_2^n



Results from BONuS Experiment

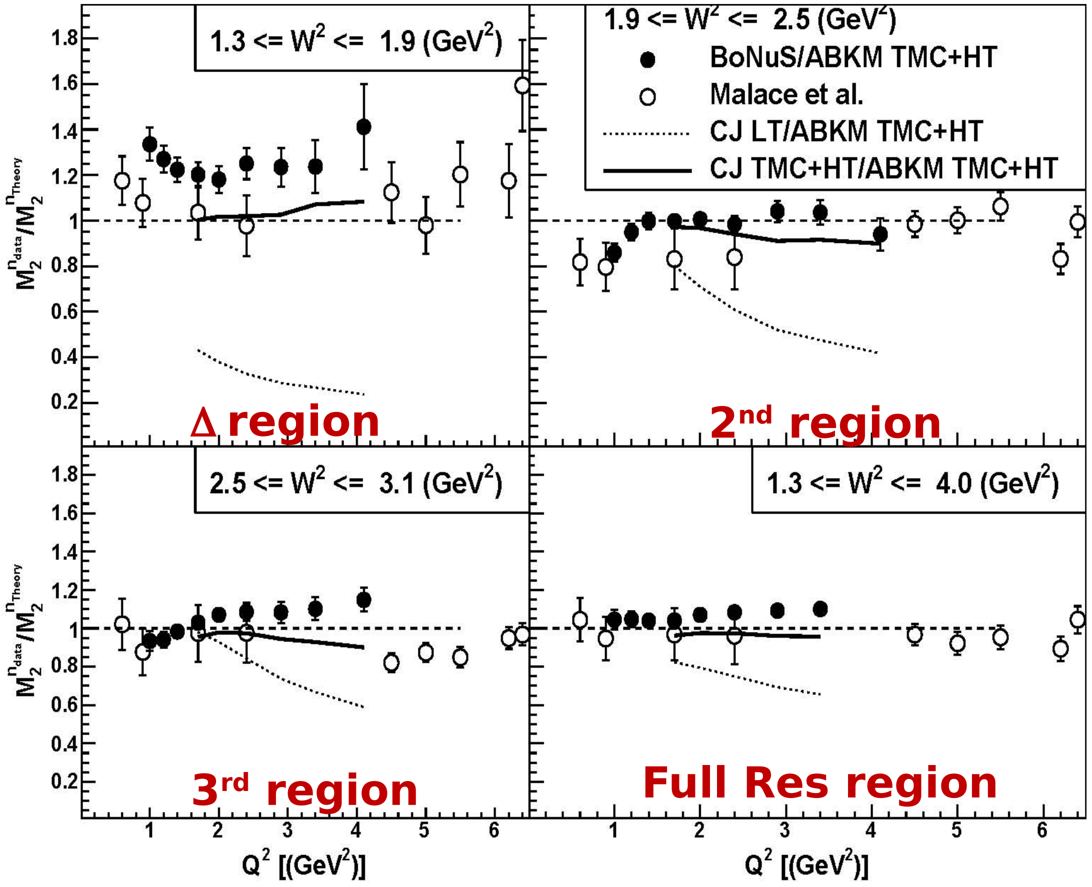




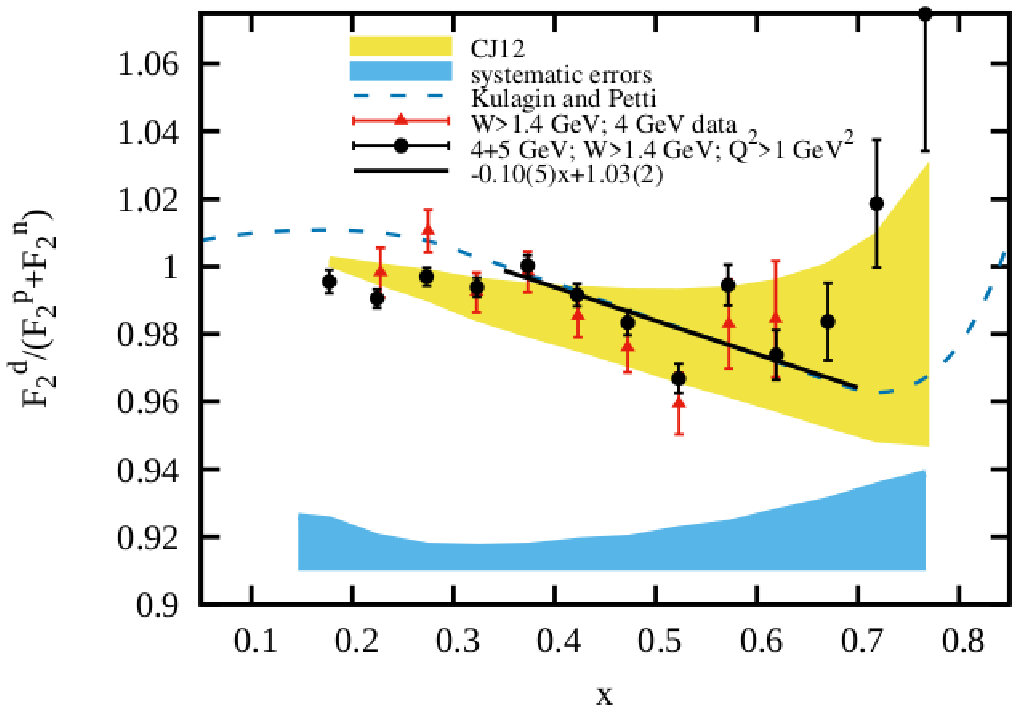
Textbook Physics!

Phys.Rev. C92 (2015) no.1, 015211
Phys.Rev. C91 (2015) no.5, 055206
Phys. Rev. C89 (2014) 045206 – editor's suggestion
Phys. Rev. Lett. 108 (2012) 199902
Nucl. Instrum. Meth. A592 (2008) 273-286

Neutron resonance states and duality



Deuteron EMC effect



Duality observed for neutron locally within: ~30% for Δ and ~10% for higher W

Proton and Deuteron Resonance Region Fit Results

M.E.C. and P.E. Bosted, PRC 81,055213 (2010) and P.E. Bosted and MEC, Phys. Rev. C 77, 065206 (2008)

Include states with largest photo-couplings:

I	State	$\beta_{1\pi}$	$\beta_{2\pi}$	β_{η}
1	$P_{33}(1232)$	1.0	0.0	0.0
2	$S_{11}(1535)$	0.45	0.10	0.45
3	$D_{13}(1520)$	0.65	0.35	0.0
4	$F_{15}(1680)$	0.65	0.35	0.0
5	$S_{15}(1650)$	0.4	0.5	0.1
6	$P_{11}(1440)$	0.65	0.35	0.0
7	($l = 3$ assumed)	0.5	0.5	0.0

$$\frac{1}{\Gamma}\frac{d\sigma}{d\Omega\, dE'} = \sigma_T(x,Q^2) + \varepsilon\sigma_L(x,Q^2)$$

proton: fits both σ_T^p and σ_L^p,

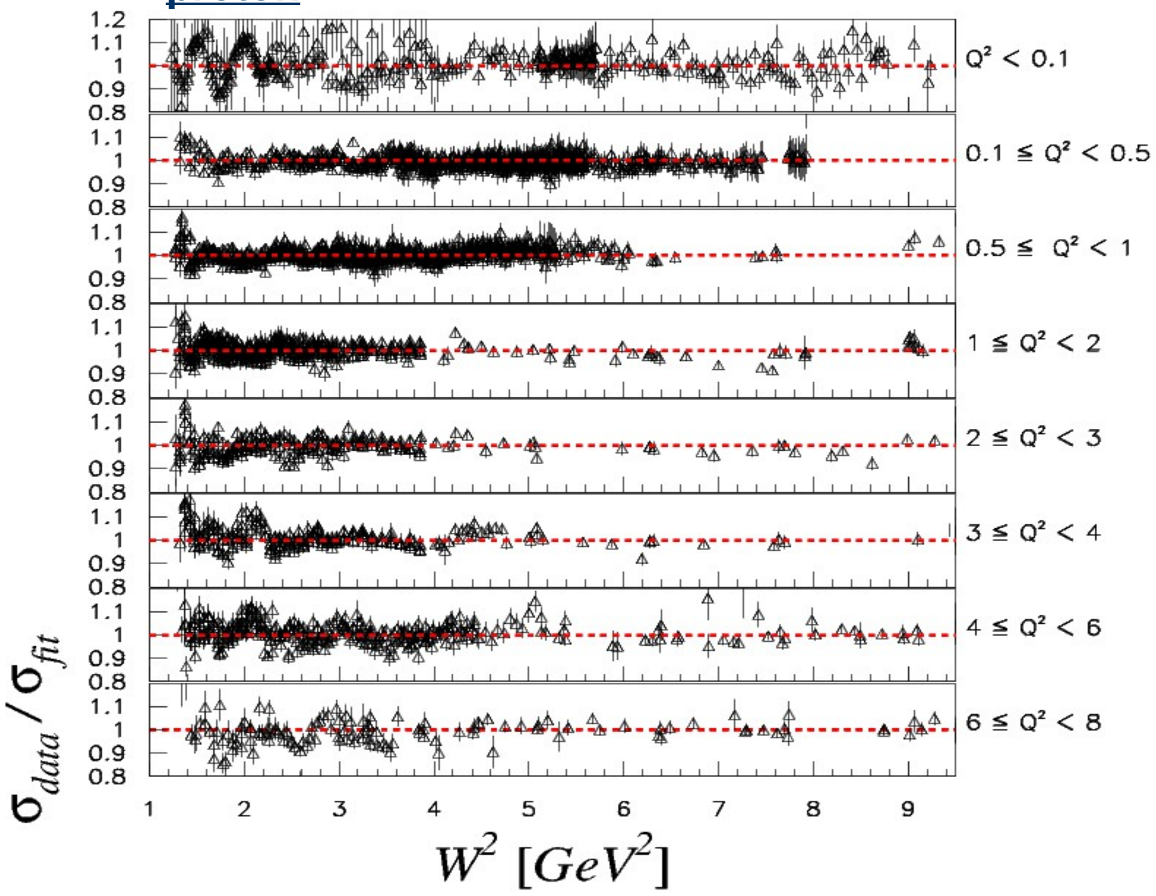
deuteron: fits σ_T^n; assumes R_n = smeared R_p

Smearing with Paris wf.

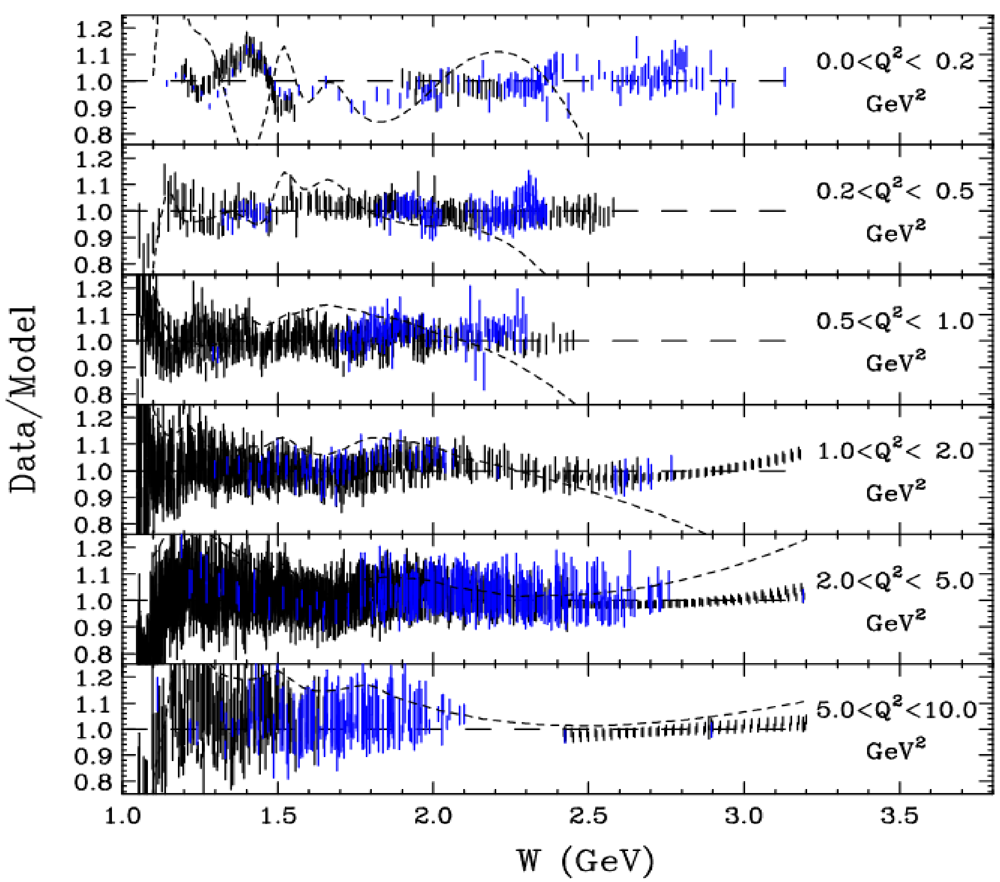
$$\sigma_T(W^2,Q^2) = \sigma_T^R(W^2,Q^2) + \sigma_T^{NR}(W^2,Q^2)$$

$$\sigma_T^R(W^2,Q^2) = W\sum BW_T^i(W^2)\cdot\left[A_T^i(Q^2)\right]^2$$

proton



deuteron



Proton and deuteron (neutron) fits have been updated

- **kinematic range expanded to cover entire kinematic range of JLab 12 GeV program and beyond**

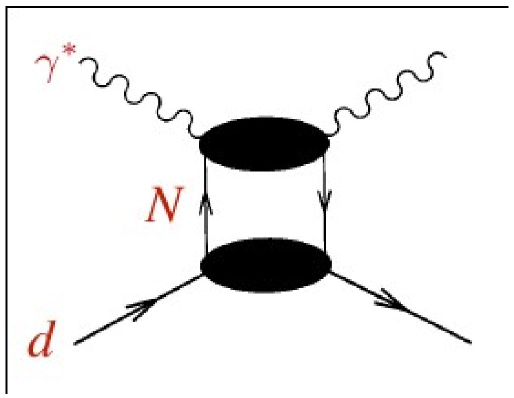
  ($W^2 < 32$ GeV^2, $Q^2 < 30$ GeV^2)

- **More robust non-resonant parameterization to better accommodate extended kinematics**

- **Additions of many data sets including new data from Hall C and the BONuS data on σ_n / σ_d**

  → **improved description of low Q^2 data**

Deuteron corrections now in weak-binding approximation using CJ12 PDF formalism



$$F_2^d(x,Q^2) = \int_x dy\, f(y,\gamma)\, F_2^N(x/y,Q^2) + \delta^{(\mathrm{off})} F_2^d$$

N=p+n

nucleon momentum distribution in d ("smearing function")

off-shell correction

Collaboration with N. Kalantarians, J. Ethier, W. Melnitchouk

- Use Deuteron as proxy
  - Neutron cross section to be fitted)
  - nuclear wave function (AV18, CD-Bonn, WJC1, ...)
  - Off-shell nucleon modification (model dependent)

  } Theoretical uncertainty

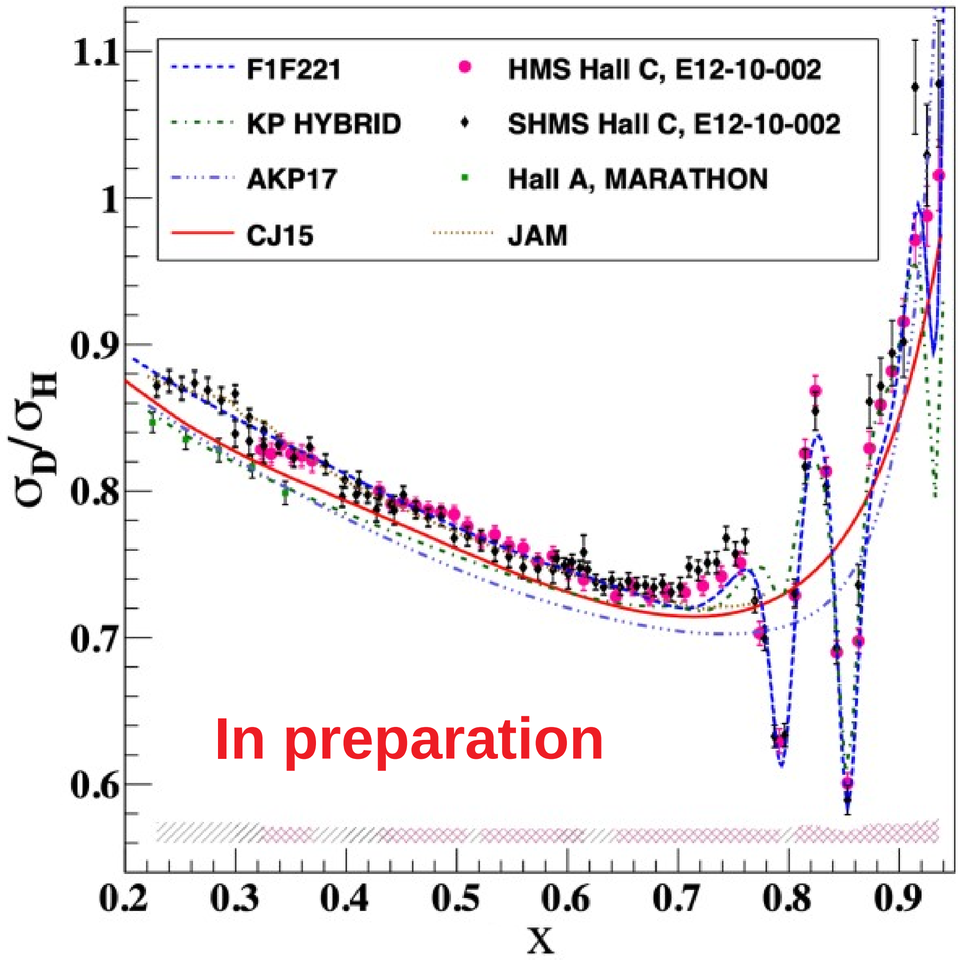
y: lightcone momentum fraction of d carried by N

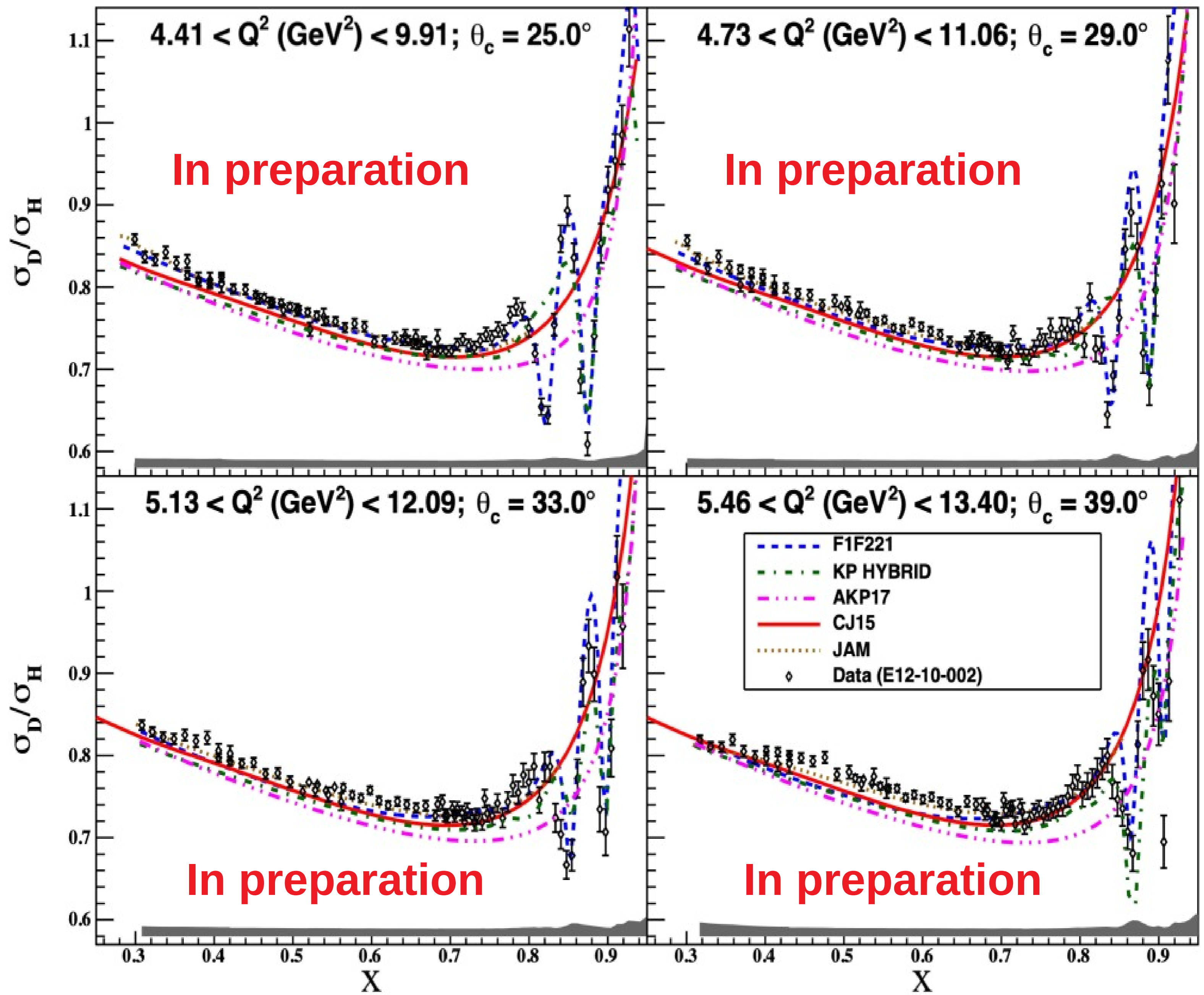
γ: kinematic factor

Comparison to new data on σ_D / σ_p from Hall C E12-10-002

→ 12 GeV Hall C commissioning experiment for SHMS spectrometer
→ Data ***not*** currently included in fits

Data at 21° used to cross check with HMS spectrometer





Summary for Inclusive Nucleon

Hopefully I have convinced you that:

- Inclusive, charged lepton, cross sections and separated structure functions well determined for proton, deuteron, and neutron.

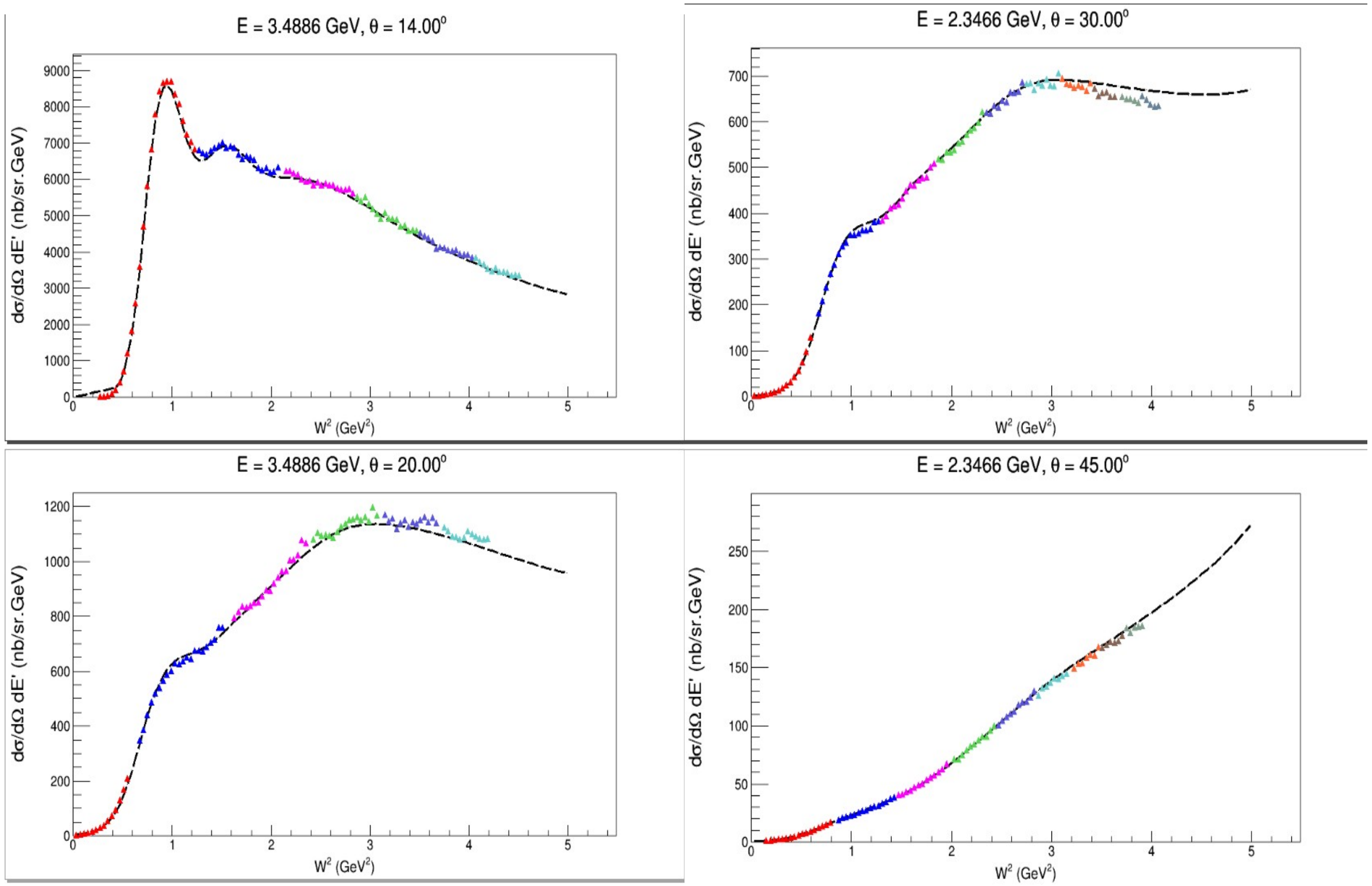
- Published fits describe these quantities to good precision (~3% for proton, ~5% for deuteron) across 6 GeV JLab kinematics extending down to $Q^2 = 0$ photoproduction.

- New fits (in preparation) covering to much higher Q^2 and W^2 and with significant improvements at lower Q^2

  → BONuS and Hall C deuteron L/T data provide strong constraints on neutron F_2, F_1 and F_L

Returning to ^{12}C

Previously shown new fit compared to precision Hall C data in QE, resonance, and SIS →DIS region for Q^2 > 0.3.



→ **Want to now examine QE + excitation region at low Q^2 important for Jupiter radiative corrections.**

→ **Due to ^{12}C elastic form factor diffractive minimum excitations can dominate tail at select kinematics.**

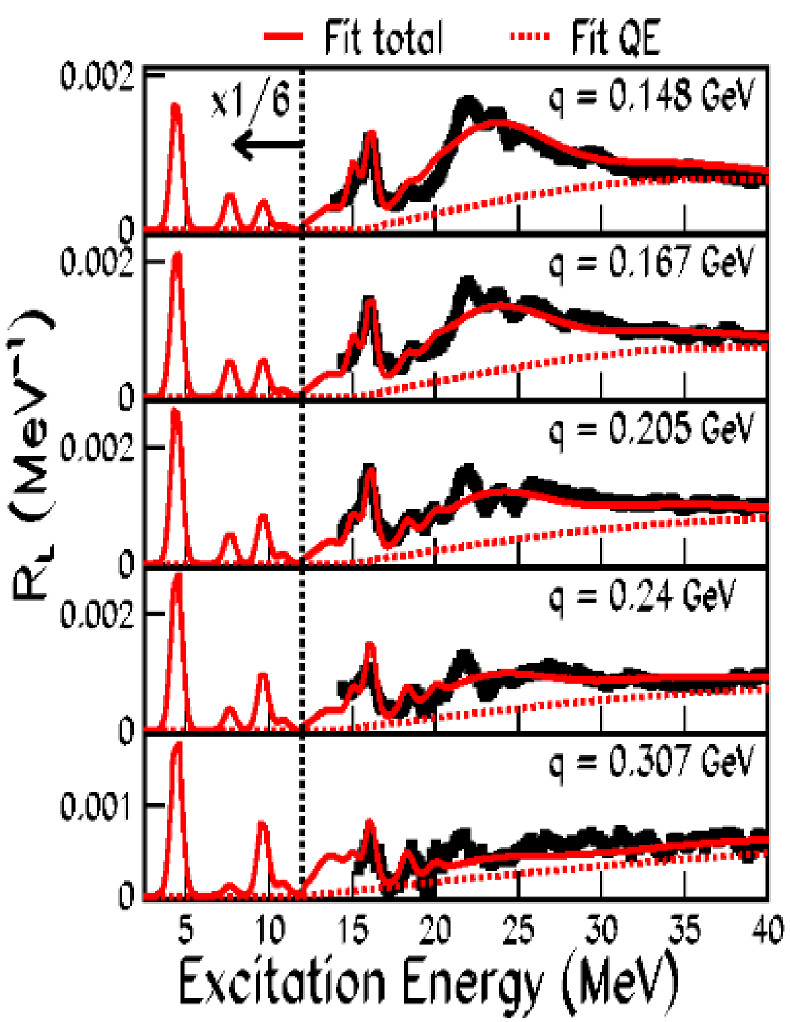
Returning to ^{12}C

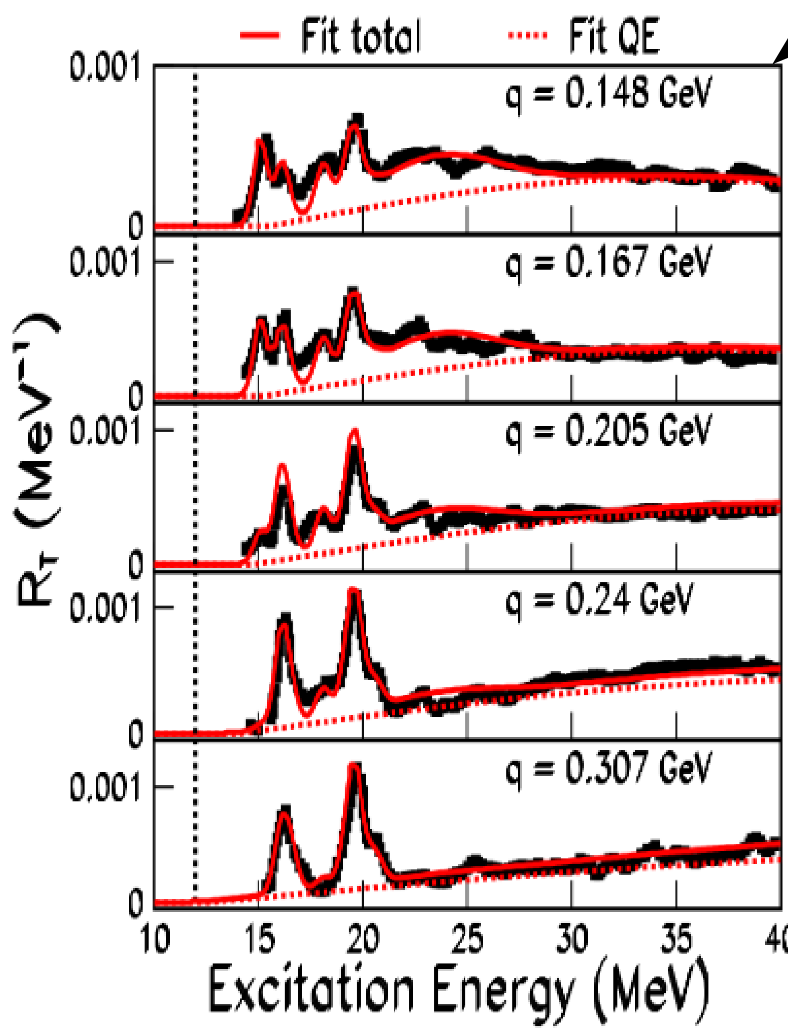
→ **Embarked on fitting form factors for 21 states with excitation energy Ex < 50 MeV**

→ **Incorporating into global fit allows studies of Q^2 (q) dependence of QE response and Coulomb Sum rule.**

**** At very low q the higher lying excited states overlap with the QE distribution**

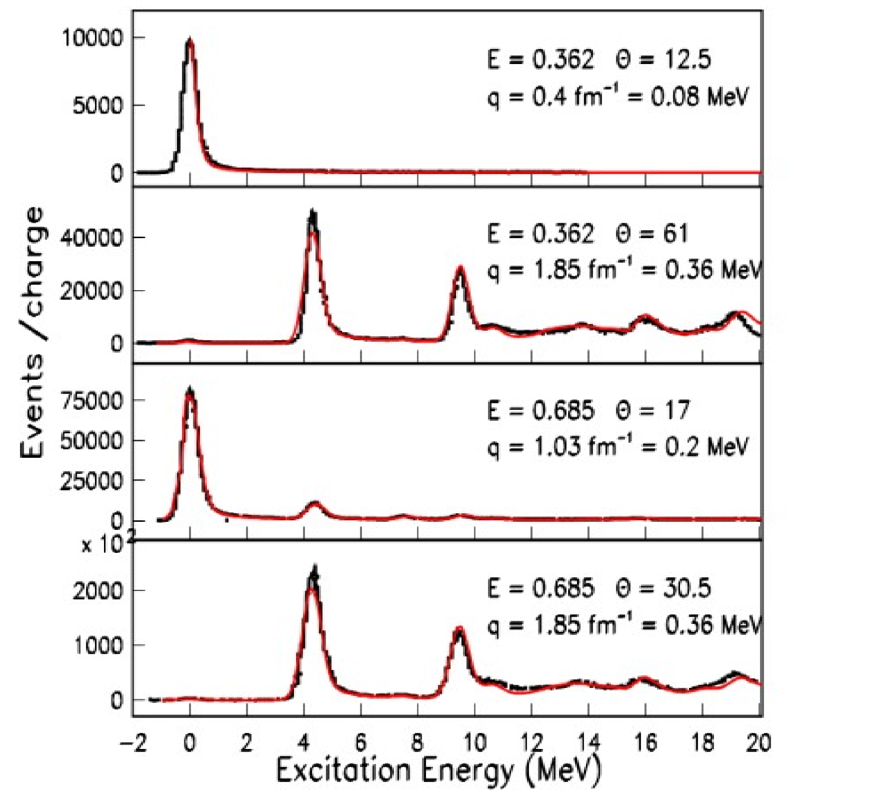
A. Bodek, MEC, Phys. Rev. C 107, 054309 (2023)





Comparison to responses extracted by Yamaguchi - 1971

LEDEX – JLab Hall A
Comparison to radiated event distribution



New Fit to e-A (^{12}C) Cross Sections for $Q^2 < 32$ and $W^2 < 32$

Goal: Provide fits which describe inclusive cross section data to adequate precision to serve as proxy for data.

→ constrained by physics to extent possible, including W^2 (Q^2) dependence

=> confidently interpolate to kinematic regions lacking in data

→ description in terms of separated cross sections and structure functions

σ_T, σ_L, R, or F_1, F_L, F_2

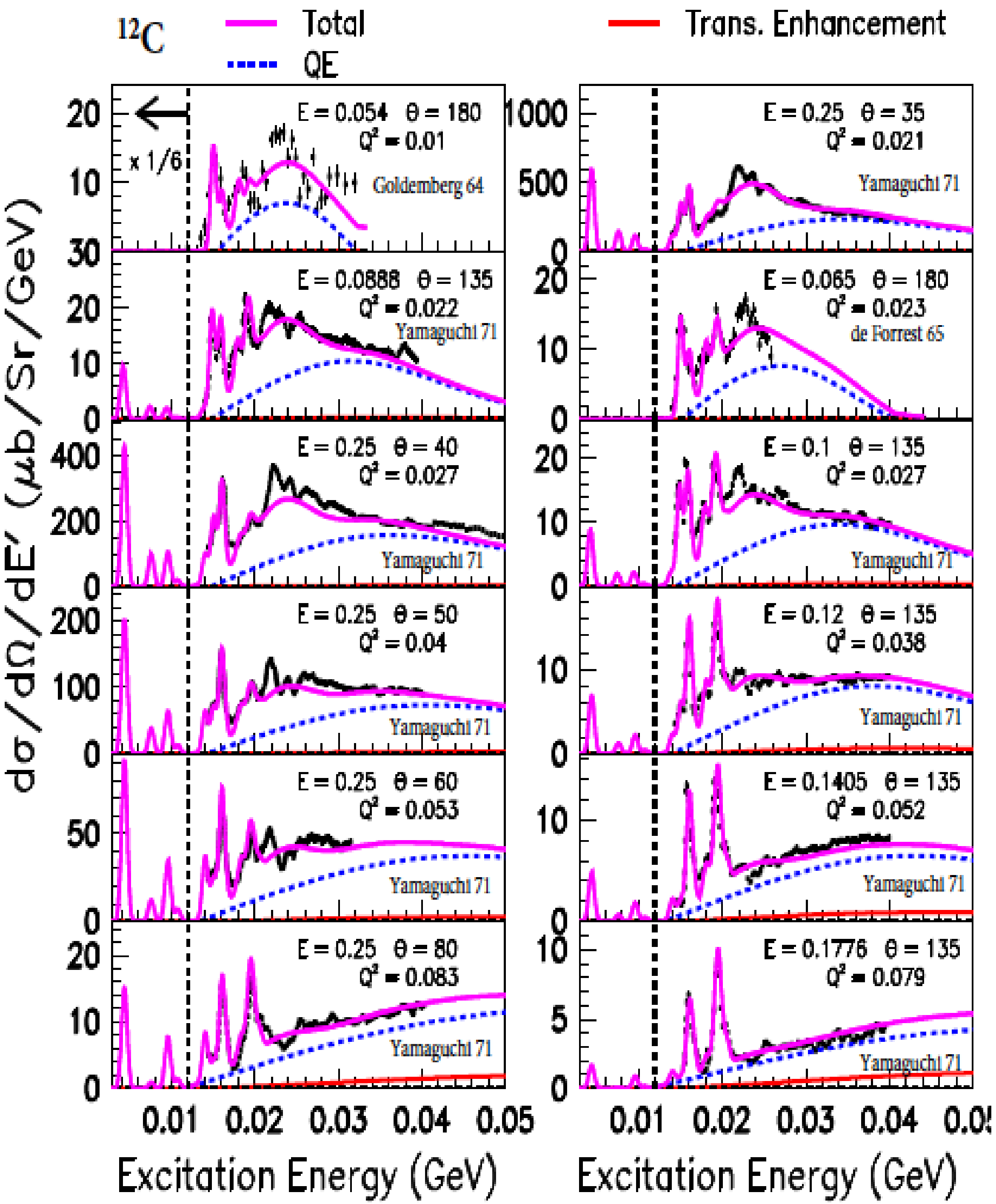
New Fit to e-A (^{12}C) Cross Sections for $Q^2 < 32$ and $W^2 < 32$

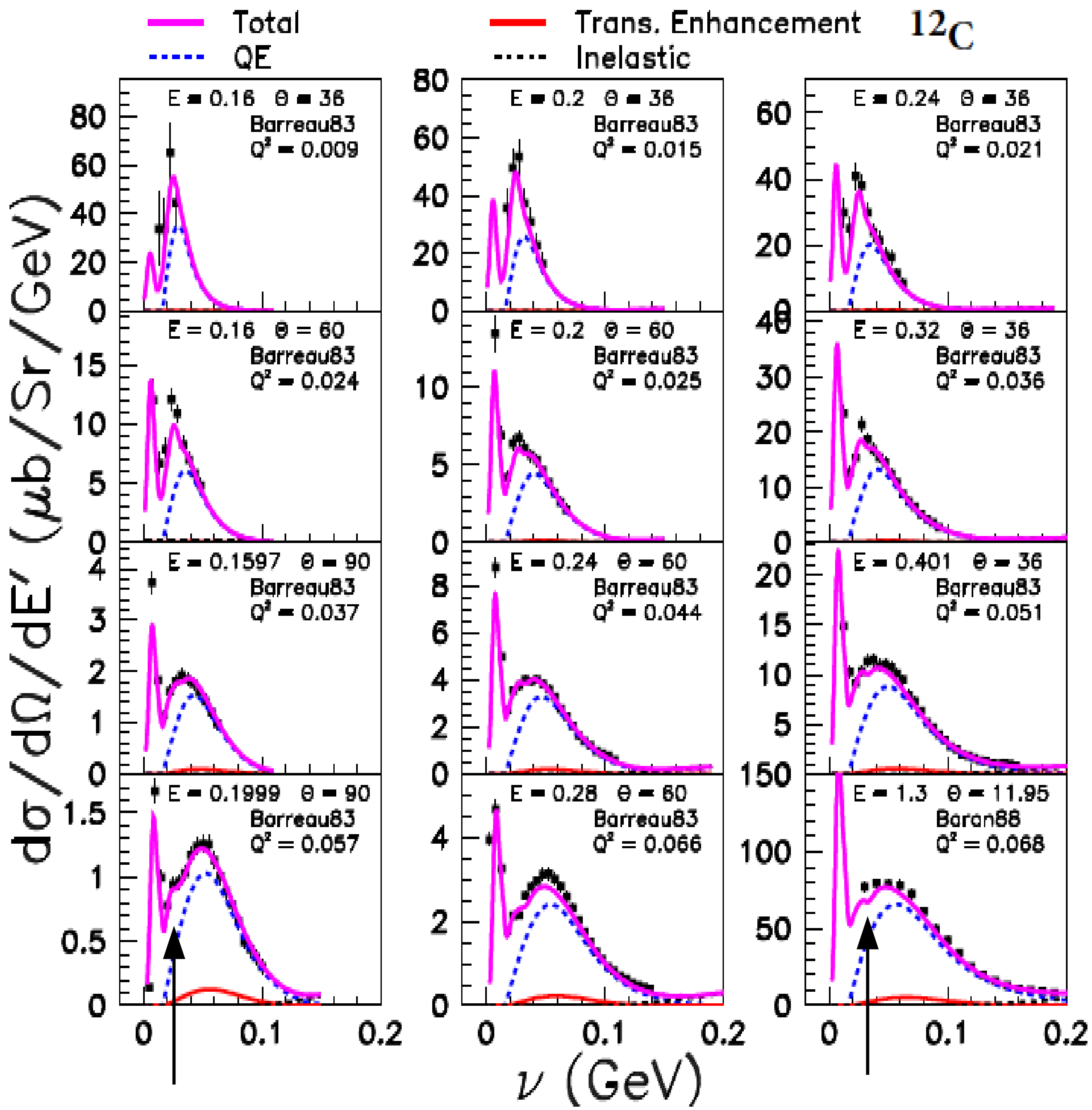
Basic ingredients to Christy-Bodek nuclear fit:

- nucleon level (p, n) $\mathbf{F_1}$, $\mathbf{F_L}$ structure functions determined from global fits to proton and deuteron data
- nucleon level $\mathbf{G_E}$, $\mathbf{G_M}$ form factors determined from fits to proton and deuteron elastic / QE data.
- **QE**: fitted Super-Scaling distribution with DeForest CC2 off-shell prescription.
- **Pauli blocking:** Rosenfelder method – mirror function $f(\psi(-\omega, q))$ subtracted from $f(\psi(\omega, q))$
- **Inelastic smearing:** Gaussian distribution (independent Fermi momentum parameter)
- **Inelastic medium modifications** parameterization applied at nucleon level (before smearing).
- **2-body Transverse Enhancement near QE / Δ** parameterized by 2 distorted Gaussians
- **Additional QE Longitudinal suppression beyond Pauli blocking at low Q^2**
- **q dependent E_{shift} in QE due to optical potential**
- **Normalization factors for each data set determined**

Comparisons to data at very low Q^2 for QE + nuclear excitations

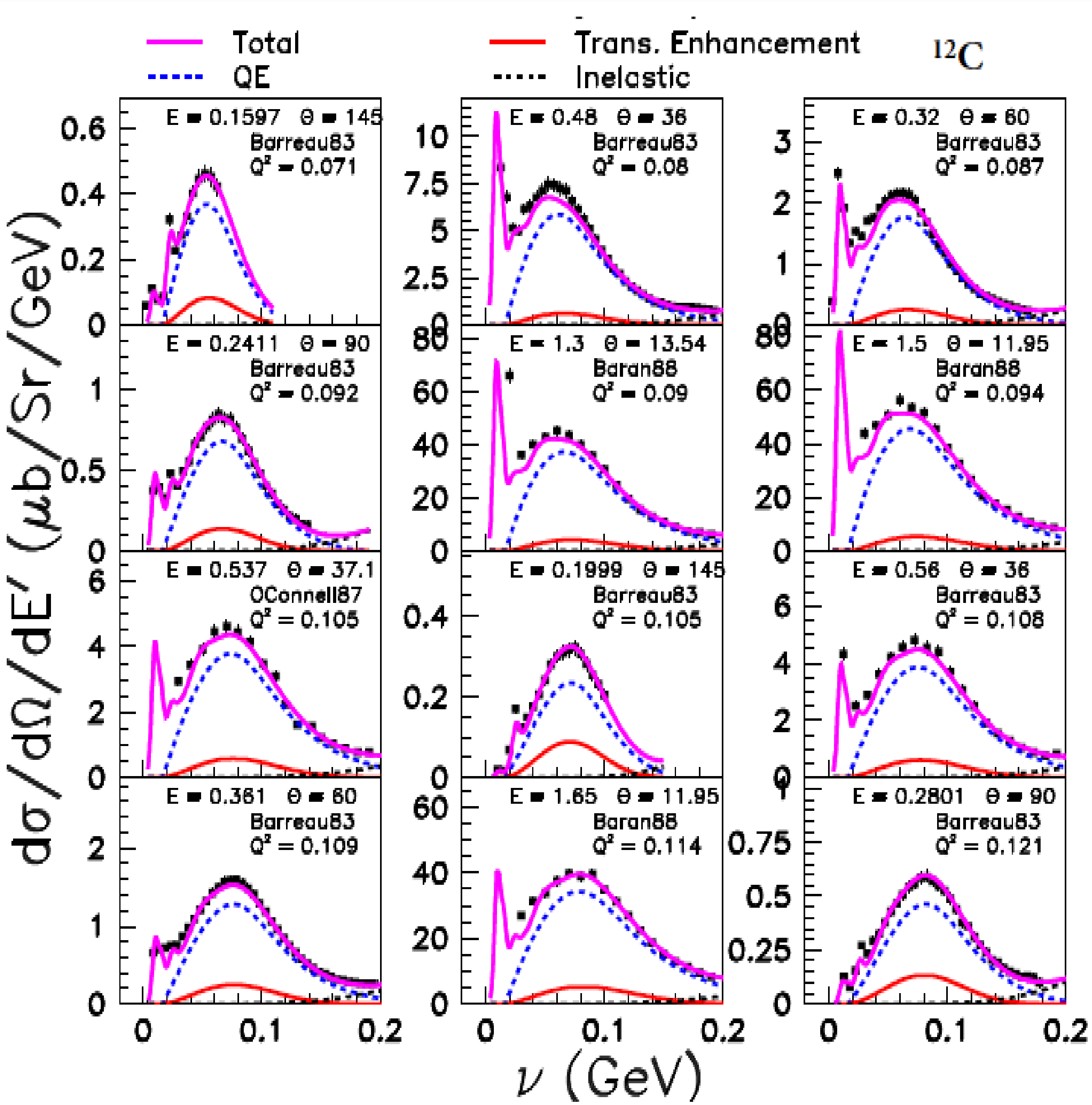
A. Bodek and MEC, Phys.Rev.C 106 (2022) 6, L061305 and Phys.Rev.C 107 (2023) 5, 054309

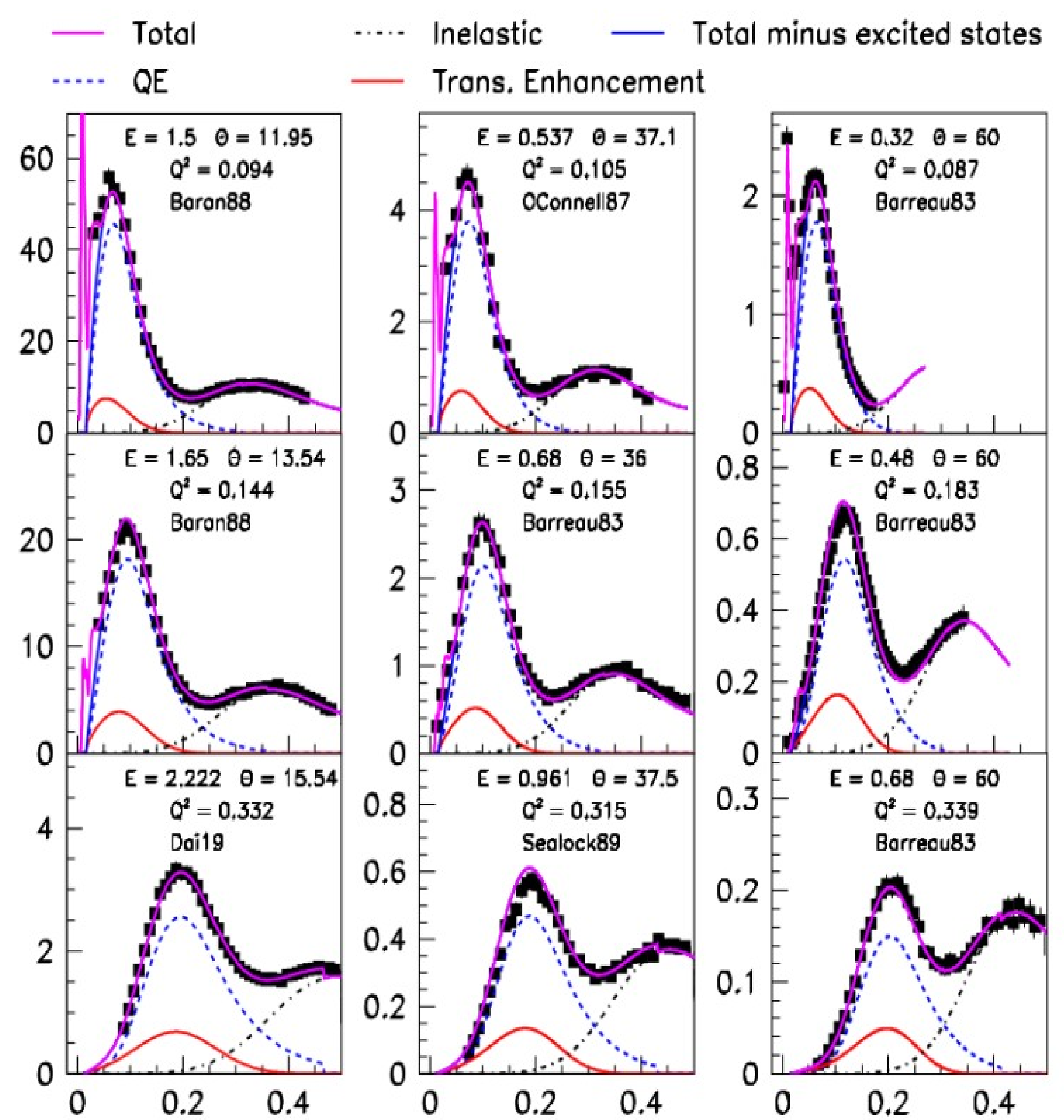




→ **Excitations smeared with estimated experimental resolution can be significant contribution under QE.**

Comparisons to data at larger Q^2



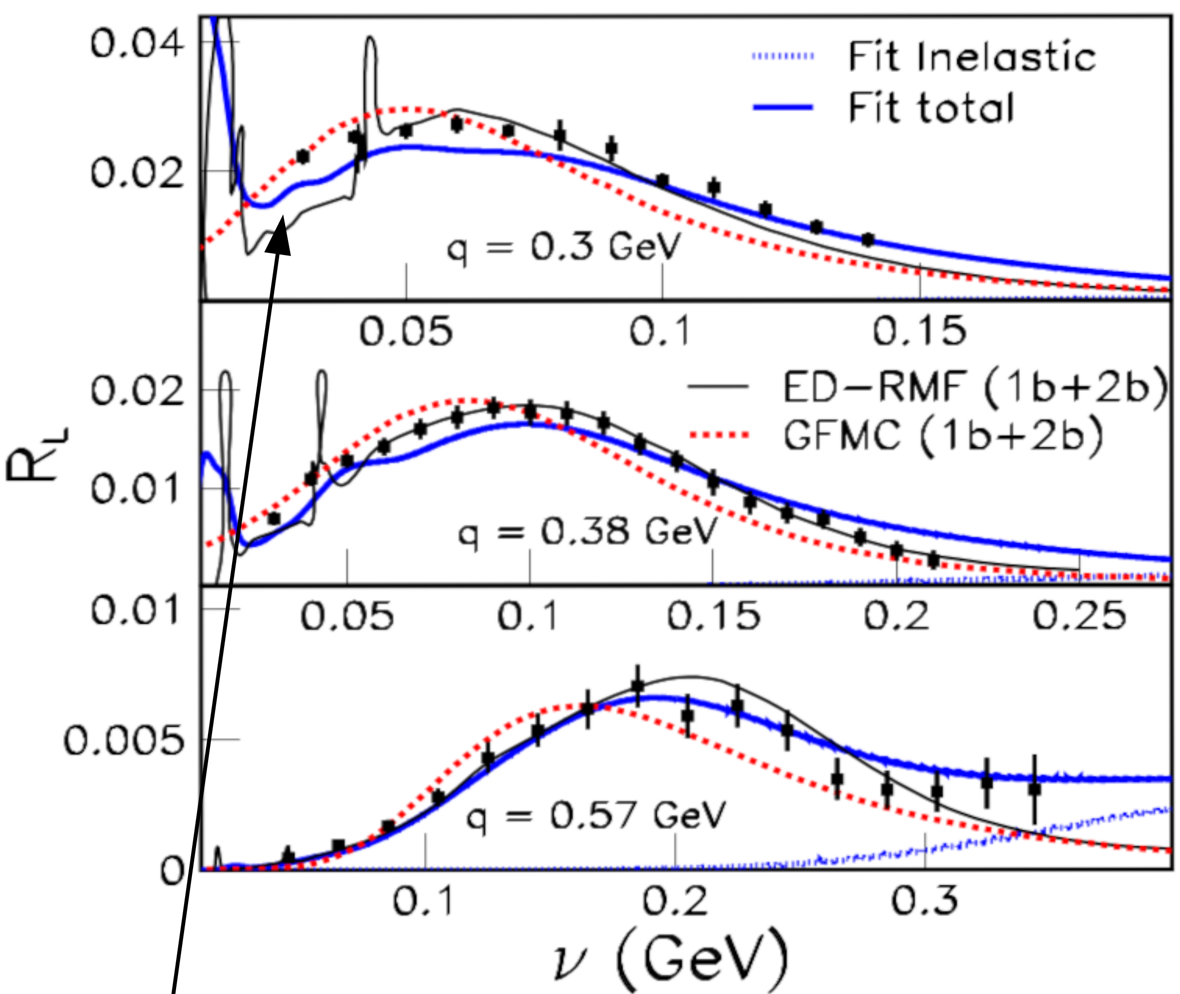


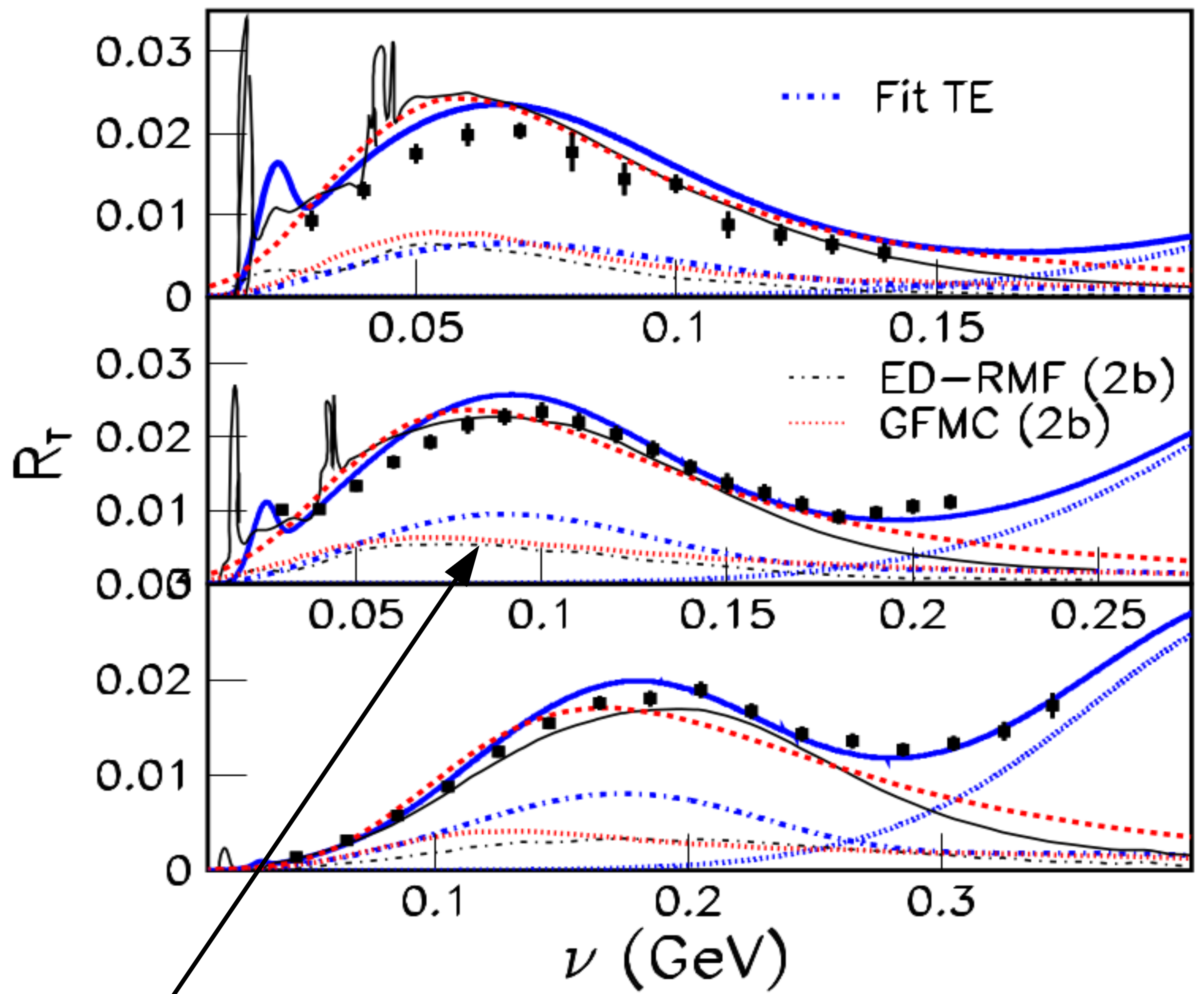
Extraction of response functions

→ Global fit provides R_L and R_T response functions from fit to all data at neighboring values of **q**
While individual L/T extractions only use data in narrow **q** range.

$$R_L(q,\nu)=\frac{q^2}{Q^2}\frac{F_L(q,\nu)}{2Mx}=\frac{q^2}{Q^2}\frac{K}{4\pi^2\alpha}\sigma_L \qquad R_T(q,\nu)=\frac{2F_1(q,\nu)}{M}=\frac{K}{2\pi^2\alpha}\sigma_T \qquad K=\frac{2M\nu-Q^2}{2M}$$

Comparison to Jourdan extractions





Contributions from excited states

Transverse Enhancement from fit and
2-body contributions from theory

Where do we go from here?

- **Currently we are uing the global fit for bin-centering in q and providing normalization factors for new extractions of ^{12}C R_L, R_T from global data set, including new Hall C data.**

(with A. Bodek and Zihao Lin)

  → **This should provide the best extraction of these quantities to date.**

  → **Doing this at fixed q has the advantage that the photoproduction data provides R_T at $q = \nu$ for any value of q**

- **Can use R_T, R_L or σ_T, σ_L vs. nu or W at various q (or Q^2) for validation of generators**

  → **provides maximal information without regard of specific E, θ.**
  → **normalization of individual data sets is already accounted for.**

Thank You for your attention…

Questions?

Backup Slides

Formalism for Christy-Bosted Inclusive proton cross section fit:

Fit reduced cross section in Rosenbluth form:

$$\frac{1}{\Gamma}\frac{d\sigma}{d\Omega\, dE'} = \sigma_T\left(x,Q^2\right) + \varepsilon\sigma_L\left(x,Q^2\right)$$

Cross section is incoherent sum of Resonant + non-resonant (*no interference*)

$$\sigma_T\left(W^2,Q^2\right) = \sigma_T^R\left(W^2,Q^2\right) + \sigma_T^{NR}\left(W^2,Q^2\right)$$

$$\sigma_L\left(W^2,Q^2\right) = \sigma_L^R\left(W^2,Q^2\right) + \sigma_L^{NR}\left(W^2,Q^2\right)$$

BW^i: relativistic Breit-Wigner with Q^2 dependent width.

A^i_T, A^i_L : resonance transition amplitudes.

$$\sigma_T^R\left(W^2,Q^2\right) = W\sum BW_T^i\left(W^2\right)\cdot\left[A_T^i\left(Q^2\right)\right]^2$$

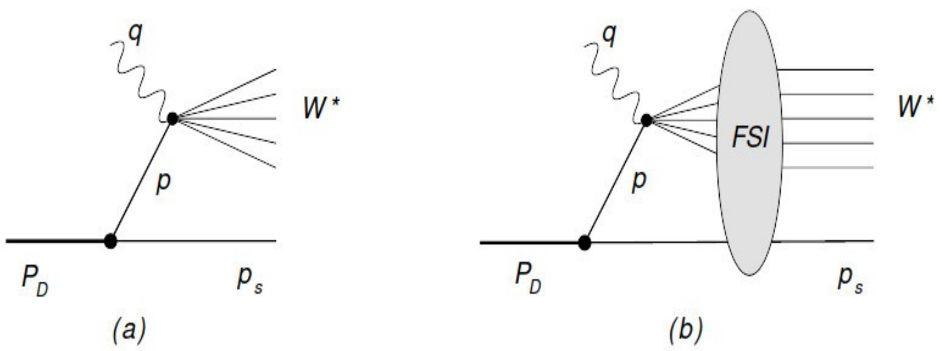
BW includes paritial widths from 3 possible decay channels

$$\left[A_T^i\right]^2 = \left[A_{1/2}^i\right]^2 + \left[A_{3/2}^i\right]^2$$

Include states with largest photo-couplings:

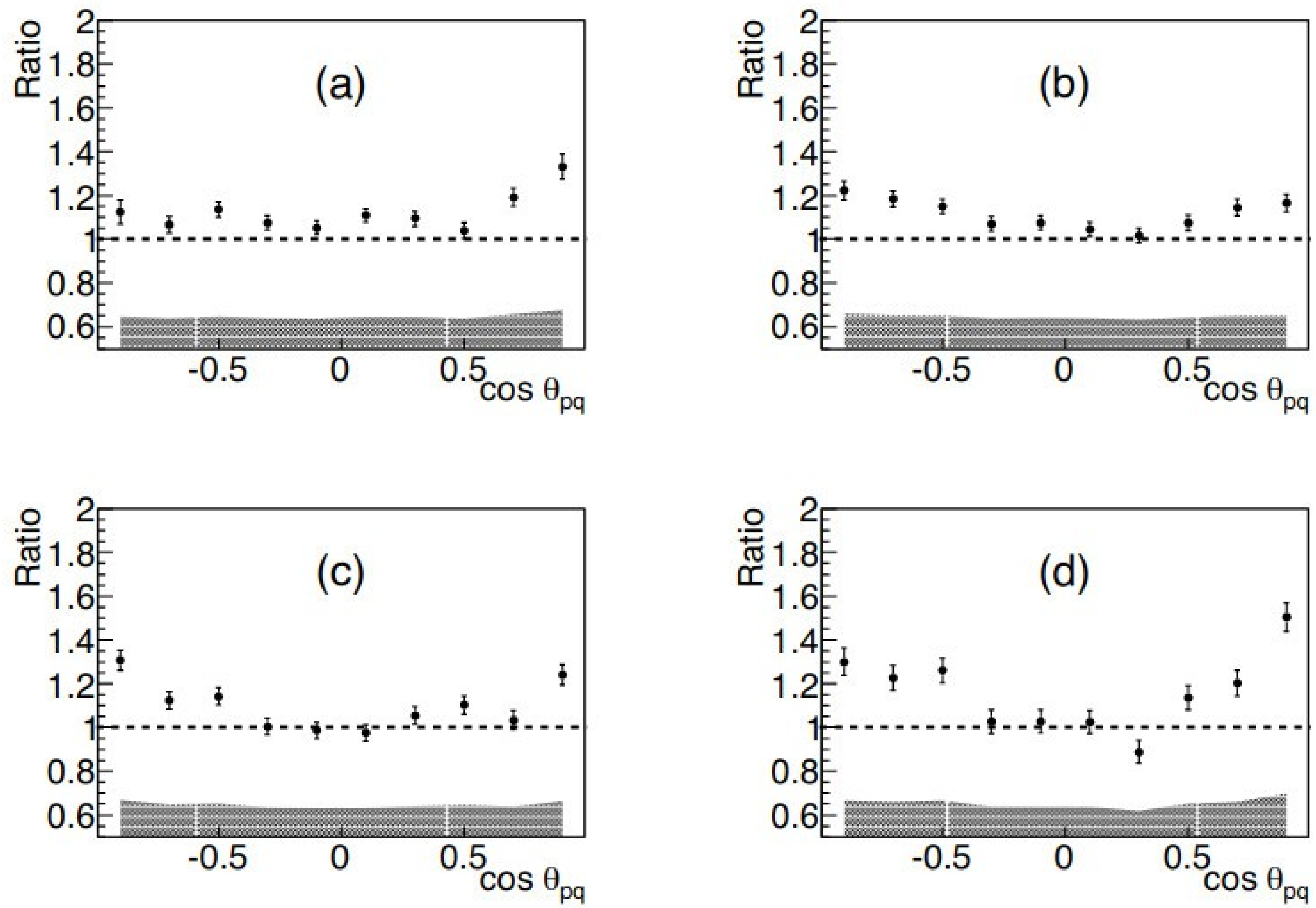
I	State	$\beta_{1\pi}$	$\beta_{2\pi}$	β_η
1	$P_{33}(1232)$	1.0	0.0	0.0
2	$S_{11}(1535)$	0.45	0.10	0.45
3	$D_{13}(1520)$	0.65	0.35	0.0
4	$F_{15}(1680)$	0.65	0.35	0.0
5	$S_{15}(1650)$	0.4	0.5	0.1
6	$P_{11}(1440)$	0.65	0.35	0.0
7	($l = 3$ assumed)	0.5	0.5	0.0

BONuS detector able to cover large enough range in spectator momentum / angle to probe onset of FSIs and validate the spectator tagging procedure



Ratio of data to PWIA

E = 5.25 GeV
$1.10 < Q^2 < 2.23$ (GeV/c)^2
$1.35 < W^* < 1.6$ GeV



→ **Simple spectator in Plane Wave Impulse Approximation (PWIA) Works well in VIP region.**

→ **Breaks down at larger p_s And smaller θ_{pq}**

Ratio Method

1st make experimental ratio:

$$R_{\exp} = \frac{N_{\text{tagged}}(\Delta Q^2, \Delta W^*, \Delta^{(\text{VIP})}\vec{p}_s)/\mathcal{A}_e(Q^2, W^*)}{N_{\text{incl}}(\Delta Q^2, \Delta W)/\mathcal{A}_e(Q^2, W)}$$

In terms of structure function ratio:

$$R_{\exp} = \frac{F_2^n(W^*, Q^2)}{F_2^d(W, Q^2)} \underbrace{\int_{\text{VIP}} d\alpha_s dp_s^{\perp} \, \mathcal{A}_p \, S(\alpha_s, p_s^{\perp})}_{I_{\text{VIP}}}$$

N_{tagged}: yield for accidental subtracted VIPs with

P_s < 100 MeV/c, θ_p > 110

A_e : CLAS electron acceptance (*mostly cancels!*)

A_p : Efficiency*acceptance for tagged proton

→ Integral I_{vip} is largely independent of W* (x*) and Q^2

→ R_{exp} determined using F_2^n / F_2^d from CJ PDF fit at x=0.3, where nuclear effects are small

Then $F_2^n / F_2^d = R_{exp} * I_{vip}$

Systematic Uncertainties (Ratio Method)

Source	Syst. uncertainty(%)	Explanation
FSI	5.0	Effect of final state interactions [22]
Target fragmentation	1.0	Effect of target fragmentation [36]
Off-shellness	1.0	Effect of nucleon off-shellness [29]
C_e^+	1.0	Effect of pair-symmetric contamination
C_π	1.0	Effect of pion contamination
r_{rc}	2.0	Each value of Born and radiated cross-sections has an uncertainty of 1%, leading to a 2% overall uncertainty
Int	5.0	Possible deviation from the assumption that the integral in Eq. (16) is constant.
F_2^d/F_2^p	4.2	Fits to structure functions have point-to-point uncertainties of 3% [65, 70], leading to a 4.2% overall uncertainty (on extracted F_2^n and F_2^n/F_2^p values only)
Total	8.7	Added in quadrature