# Extraction of Neutron Structure Functions in the Resonance Region and Tests of Quark-Hadron Duality

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# Outline

- New method : extract $F_2^n$ from nuclear $F_2$

  - Application of method to smooth curves

    Y. Kahn, W. Melnitchouk, S.A. Kulagin, Phys. Rev. C 79, 035205 (2009)

  - Application of method to data (resonance region) + Quark-Hadron Duality in $F_2^n$ structure function

    S.P. Malace, Y. Kahn, W. Melnitchouk, C. Keppel, Phys. Rev. Lett. 104 102001 (2010)

    - Application of method to data: (a lot of) technical details

      S.P. Malace, Y. Kahn, W. Melnitchouk, in preparation

# Extraction of $F_2^n$ from Nuclear $F_2$

<u>New method</u> : employs iterative procedure of solving integral convolution equations

Y. Kahn, W. Melnitchouk, S.A. Kulagin, Phys. Rev. C 79, 035205 (2009)

- Impulse Approximation – virtual photon scatters incoherently from individual nucleons

(Beyond IA: FSI not addressed in present analysis)

$$\boxed{F_2^A(x,Q^2)} = \sum_{N=p,n} \int_x^{M_A/M} dy\, \boxed{f_0^{N/A}(y,\gamma)}\, \boxed{F_2^N\left(\frac{x}{y},Q^2\right)} \qquad \gamma = \sqrt{1+\frac{4M^2x^2}{Q^2}}$$

nuclear $F_2$

light-cone momentum distribution of nucleons in nucleus (smearing function)

nucleon $F_2$

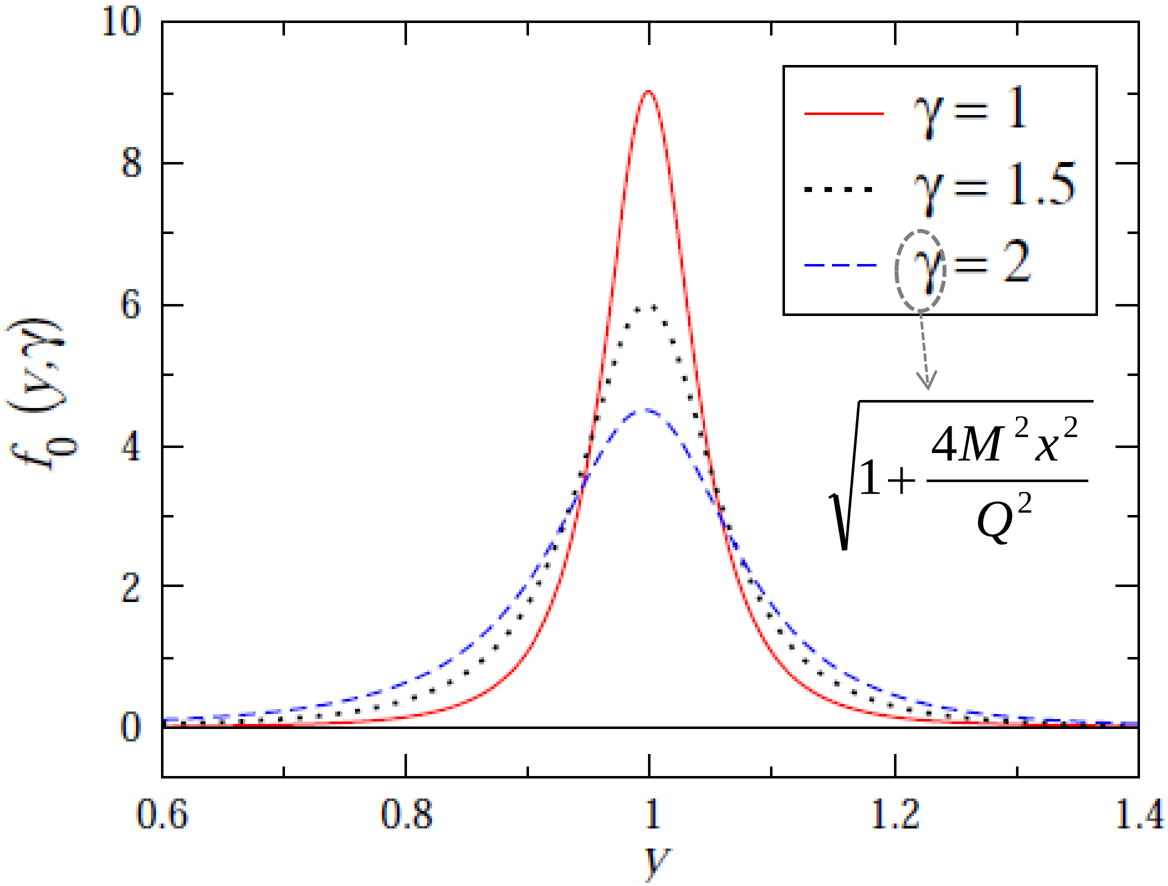
Application to Deuterium…

# Smearing Function for $F_2^d$

- Smearing function evaluated in the weak binding approximation, **including finite-Q2 corrections**

S.A. Kulagin and R. Petti, Nucl. Phys. A 765, 126 (2006)

Y. Kahn, W. Melnitchouk, S.A. Kulagin, Phys. Rev. C 79, 035205 (2009)



# Extraction Method

- We need $F_2^n$ from:

$$F_2^d = \tilde{F}_2^p + \tilde{F}_2^n + \delta^{(off)} F_2^d, \quad \tilde{F}_2^{n,p} = \int_x^{M_d/M} dy\, f(y,\gamma)\, F_2^{n,p}\left(\frac{x}{y}\right)$$

$$\Downarrow$$

$$\tilde{F}_2^n = F_2^d - F_2^{d(QE)} - \delta^{(off)} F_2^d - \tilde{F}_2^p$$

Y. Kahn, W. Melnitchouk, S.A. Kulagin, Phys. Rev. C 79, 035205 (2009)

**<u>Additive extraction method</u>: solve equation iteratively**

$$f(y,\gamma) = \underbrace{\boxed{\mathrm{N}}}_{\text{normalization of smearing function}}\delta(y-1) + \underbrace{\boxed{\delta f(y,\gamma)}}_{\text{finite width of smearing function}}$$

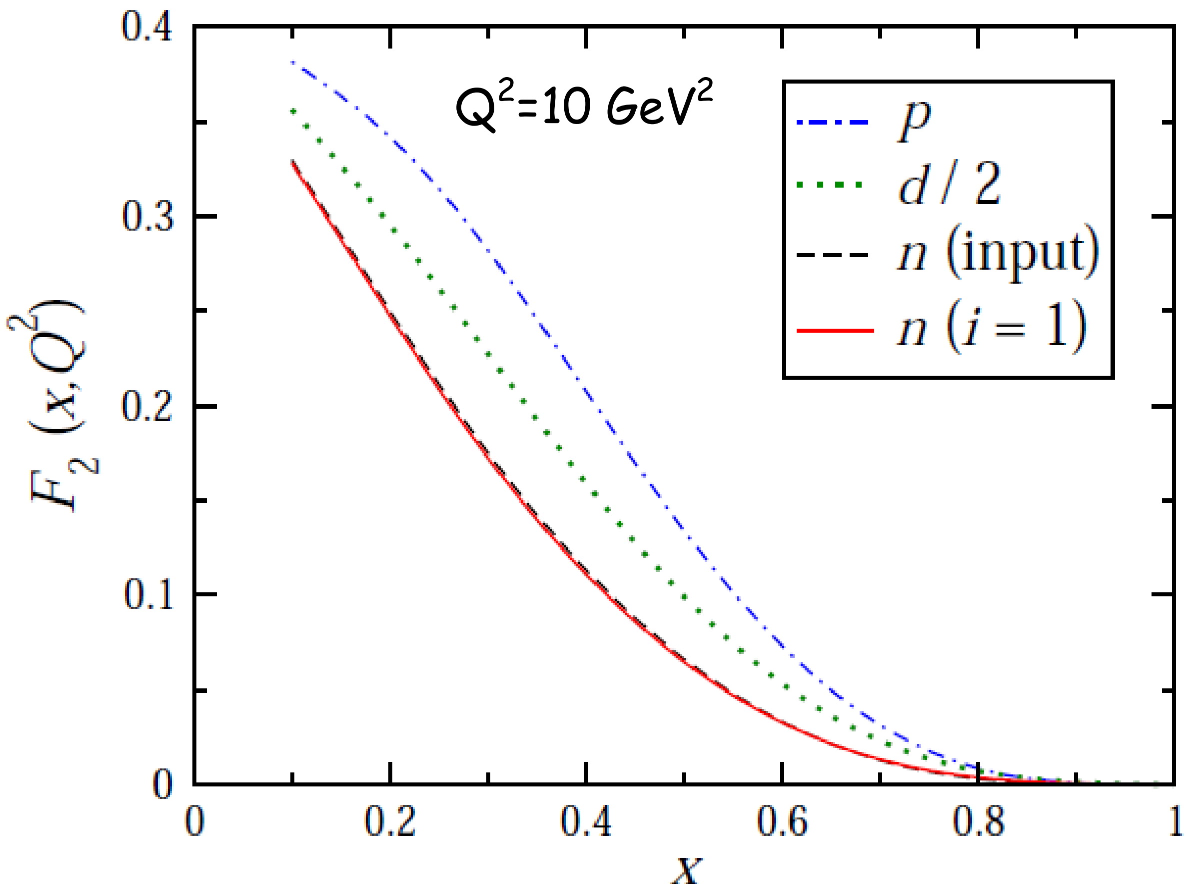
$$\tilde{F}_2^n(x) = \mathrm{N} F_2^n(x) + \underbrace{\boxed{\int_x^{M_d/M} dy\, \delta f(y,\gamma)\, F_2^n\left(\frac{x}{y}\right)}}_{\text{perturbation}}$$

$$F_2^{n(1)}(x) = \boxed{F_2^{n(0)}}(x) + \frac{1}{\mathrm{N}}\left[\tilde{F}_2^n(x) - \int_x^{M_d/M} dy\, f(y,\gamma)\, \boxed{F_2^{n(0)}}\left(\frac{x}{y}\right)\right]$$

initial guess

# Application of Method to Smooth Curves

- Monotonic curves: $F_2^p$ and $F_2^n$ input from MRST; $F_2^d$ is simulated using the finite-$Q^2$ smearing function
  - Additive method applied with initial guess $F_2^{n(0)} = 0$

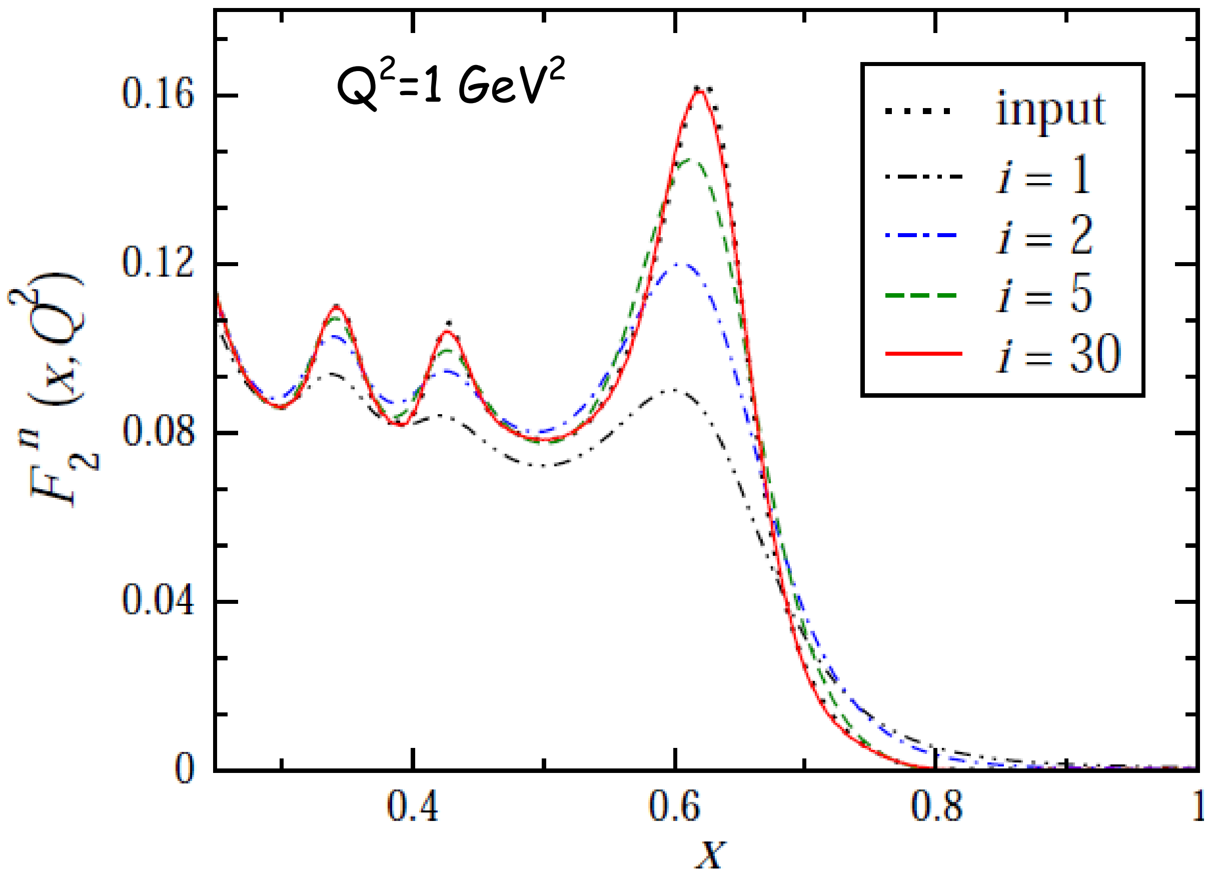



Y. Kahn, W. Melnitchouk, S.A. Kulagin, Phys. Rev. C 79, 035205 (2009)

- Fast convergence: extracted $F_2^{n(1)}$ almost indistinguishable from $F_2^n$ input after only 1 iteration (smearing function sharply peaked around y = 1)

# Application of Method to Smooth Curves

- Curves with resonant structures: $F_2^n$ input from MAID
  - Additive method applied with initial guess $F_2^{n(0)} = 0$

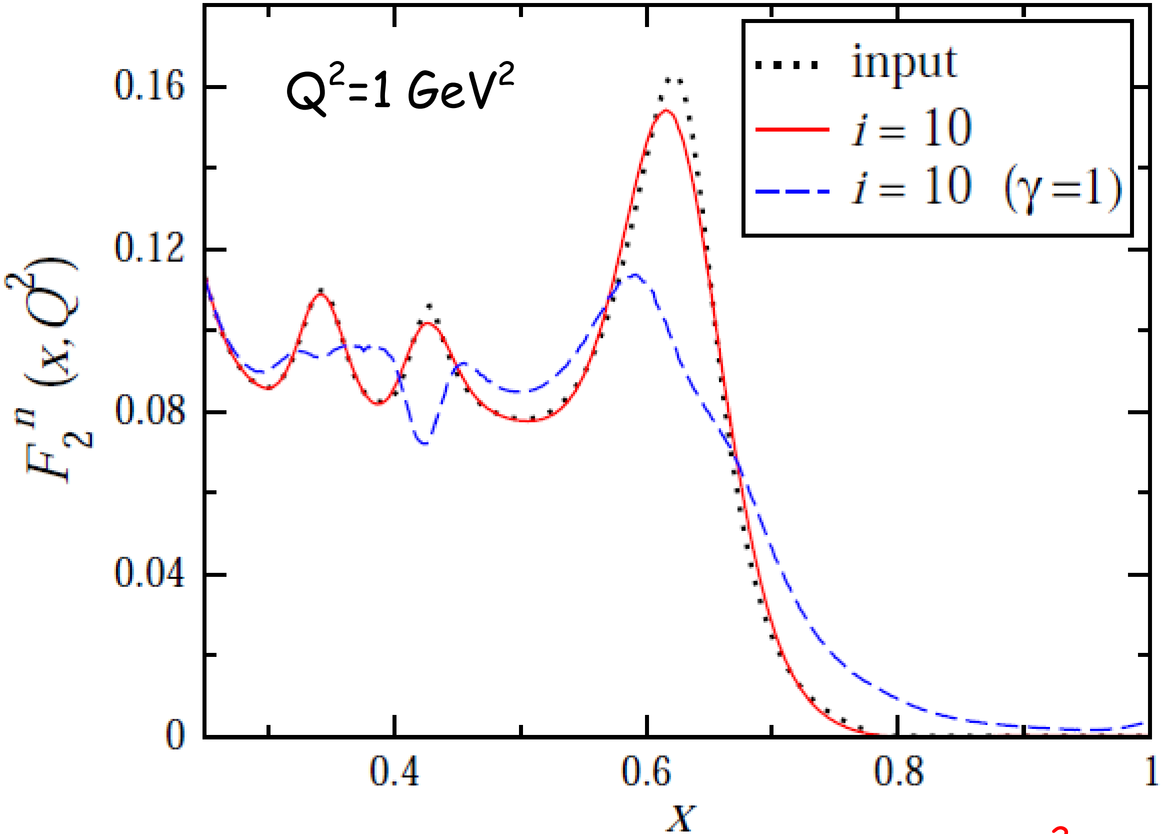



Y. Kahn, W. Melnitchouk, S.A. Kulagin, Phys. Rev. C 79, 035205 (2009)

- After 1 or 2 iterations: resonant peaks clearly visible; after 5 iterations extracted result very close to “true” result

# Application of Method to Smooth Curves

- Essential to take into account $Q^2$ effects in the smearing function
  - Additive method ($F_2^{n(0)} = 0$): and $Q^2$-dependent smearing function
  - Additive method ($F_2^{n(0)} = 0$): $Q^2$-independent smearing function




Y. Kahn, W. Melnitchouk, S.A. Kulagin, Phys. Rev. C 79, 035205 (2009)

- After 10 iterations: extraction with $Q^2$-dependent smearing function converges to the input; extraction with $Q^2$-independent smearing function **does not**

# Application of Method to Data

➢ Use proton and deuteron data at fixed $Q^2$ (matched kinematics)

$$\tilde{F}_2^n(x) = F_2^d(x) - F_2^{d(QE)} - \delta^{(off-shell)} F_2^d(x) - \tilde{F}_2^p(x)$$

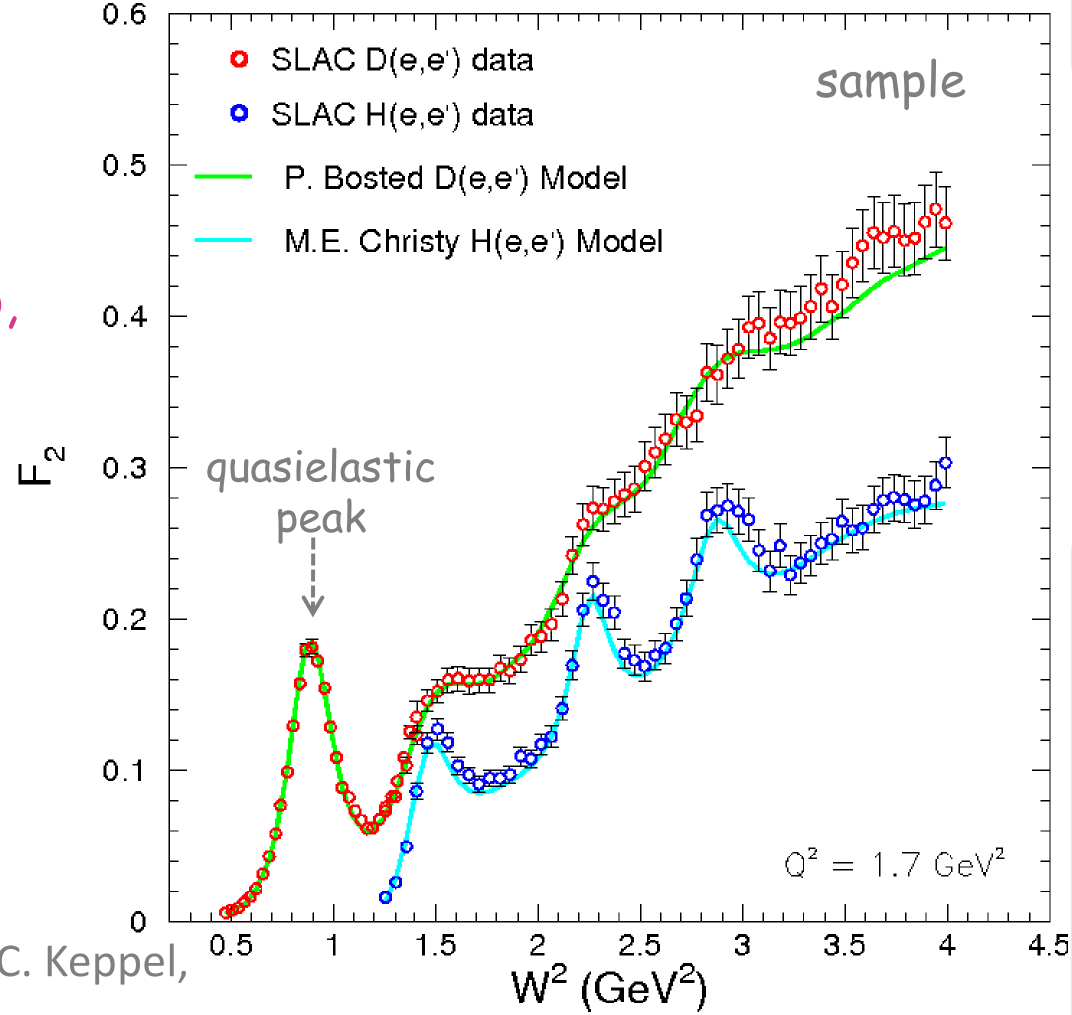
data

data

- Data: SLAC at $Q^2$ = 0.6, 0.9, 1.7, 2.4 GeV$^2$ + data from Jlab (Hall C E00-116) at $Q^2$ = 4.5, 5, 5.5, 6.2, 6.4 GeV$^2$

- Data taken at fixed angle and running momentum of scattered electron => running x and $Q^2$

- Bin-centering at cross section level using 2 different models => data at fixed $Q^2$



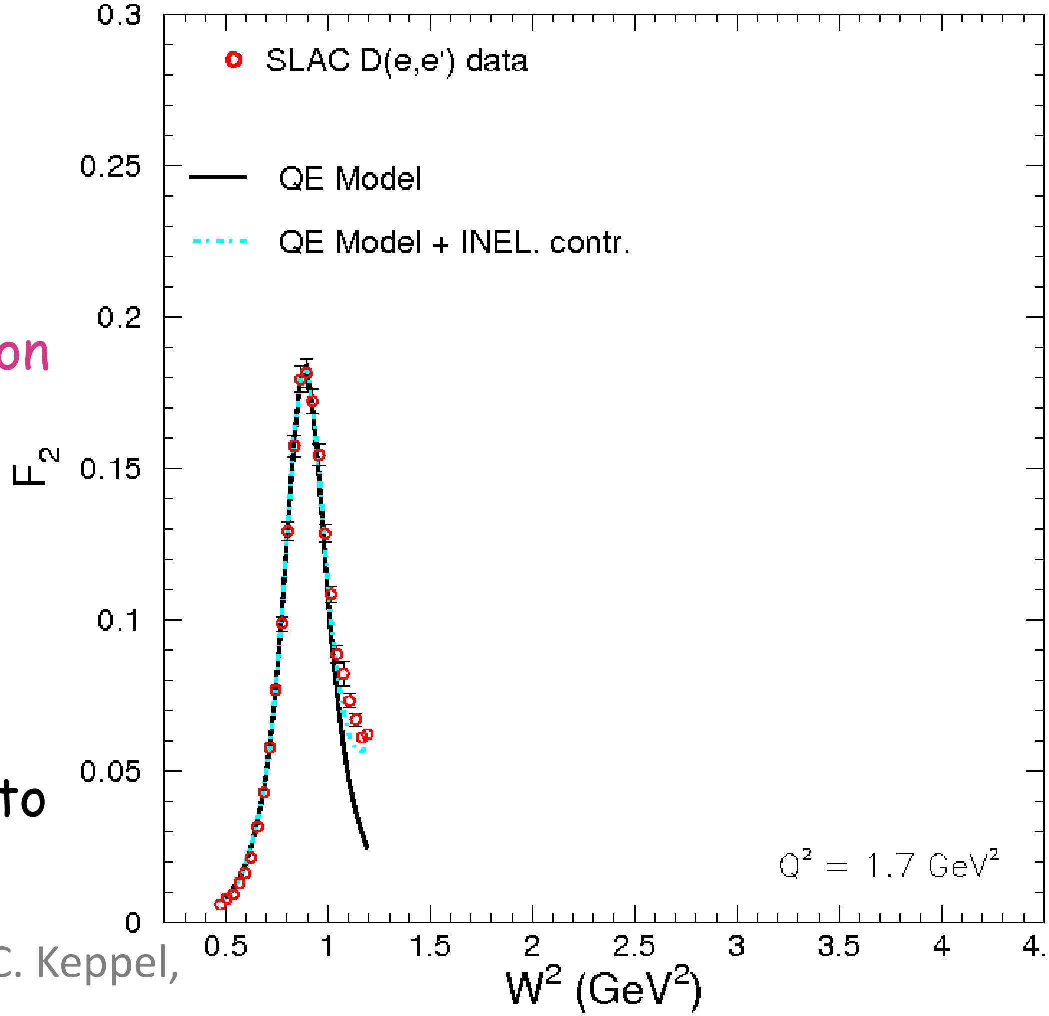

S.P. Malace, Y. Kahn, W. Melnitchouk, C. Keppel, Phys. Rev. Lett. 104 102001 (2010)

# Application of Method to Data

$$\tilde{F}_2^n(x) = \underbrace{F_2^d(x)}_{\text{data}} - \underbrace{F_2^{d(QE)}}_{\text{model}} - \overbrace{\delta^{(off-shell)}}^{\text{model}} F_2^d(x) - \underbrace{\tilde{F}_2^p(x)}_{\text{data}}$$

- QE contribution extracted from data using model (form factors + same smearing function as for extraction)

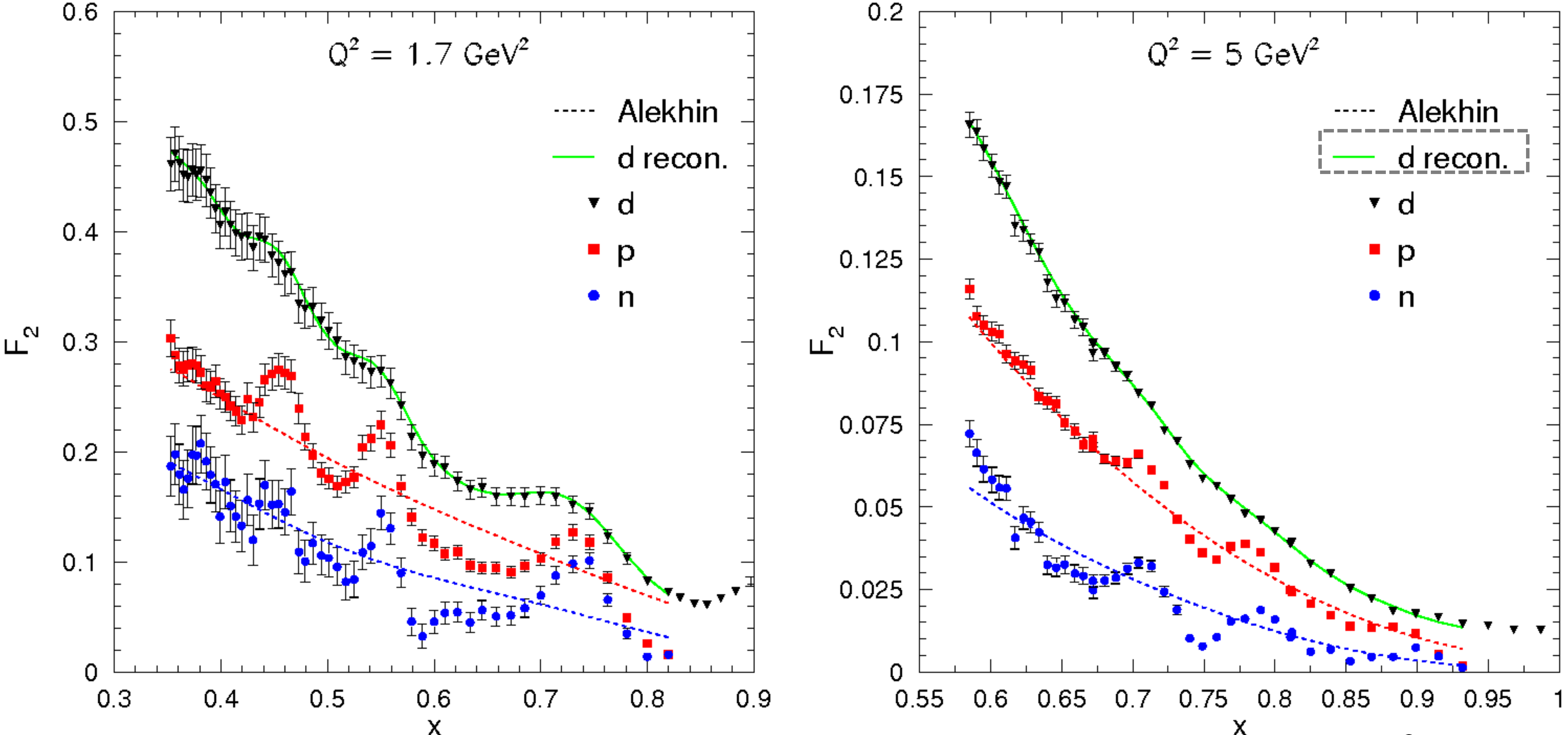
- Off-shell corrections: upper limit from model ~1.5%; we subtract ½ of model prediction and assign 100% uncertainty to correction => contributes < 2% to total uncertainty on $F_2^n$




S.P. Malace, Y. Kahn, W. Melnitchouk, C. Keppel, Phys. Rev. Lett. 104 102001 (2010)

# Application of Method to Data

- $F_2^n$ extraction: initial guess $F_2^{n(0)} = F_2^p$; number of iterations = 2




- $F_2^n$ in resonance region: 3 resonant enhancements (fall with $Q^2$ at ~ rate as for $F_2^p$)
- $F_2^d$ reconstructed from $F_2^p$(data) and $F_2^n$(extraction) ~ $F_2^d$(data) after 2 iterations

S.P. Malace, Y. Kahn, W. Melnitchouk, C. Keppel, Phys. Rev. Lett. 104 102001 (2010)

# Application of Method to Data

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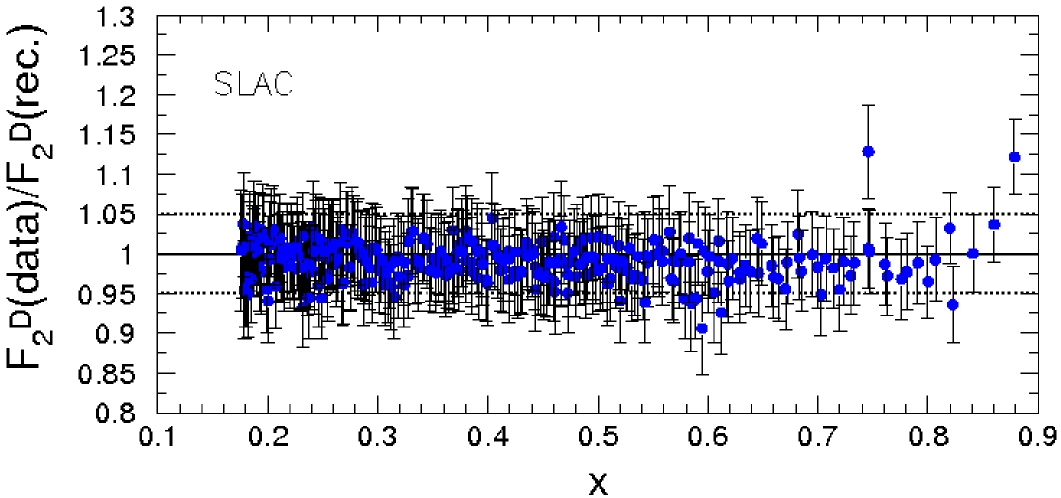
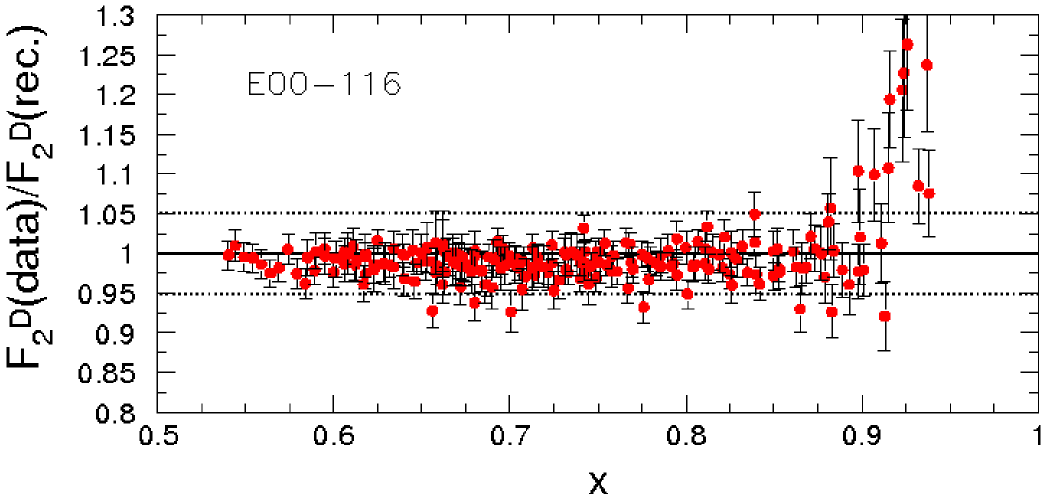



- For all $Q^2$ studied: $F_2^d$ reconstructed in agreement with data within experimental uncertainties




- Agreement between $F_2^d$ reconstructed and data slightly worsens at the very large x (x > 0.9)

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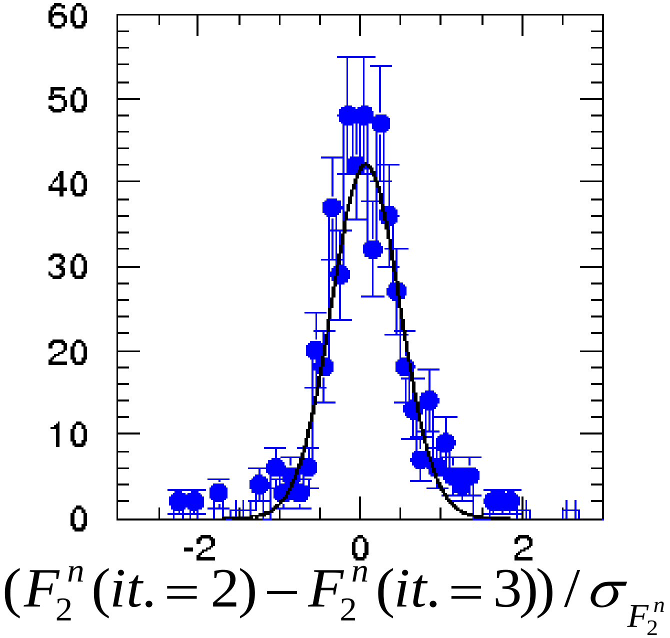
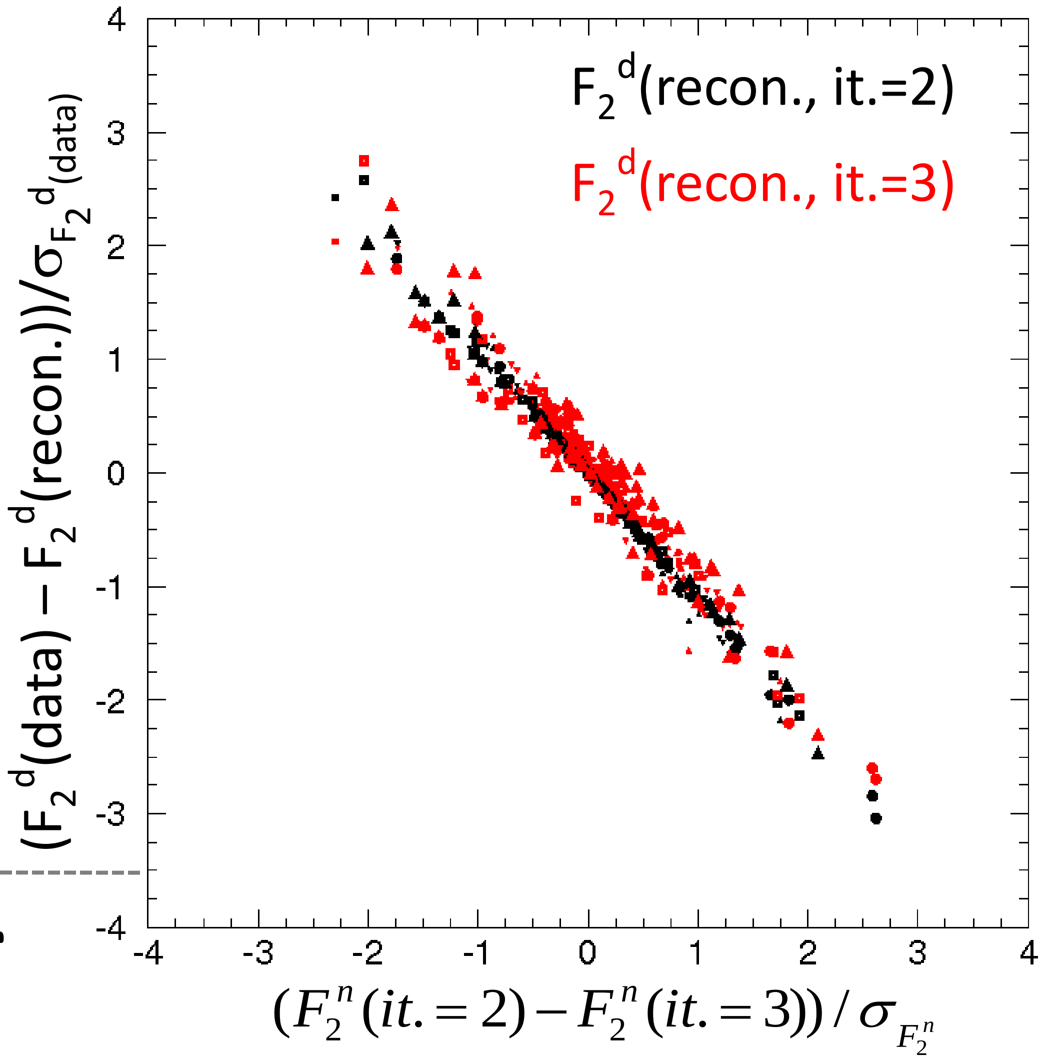
# Application of Method to Data

➢ Study dependence of result on number of iterations: compare extractions with 2 and 3 iterations




- Small change in $F_2^n$ between iteration 2 and 3

- Extracted $F_2^n$ changes to bring $F_2^d$ reconstructed closer to $F_2^d$ data; small differences between it. 2 and 3

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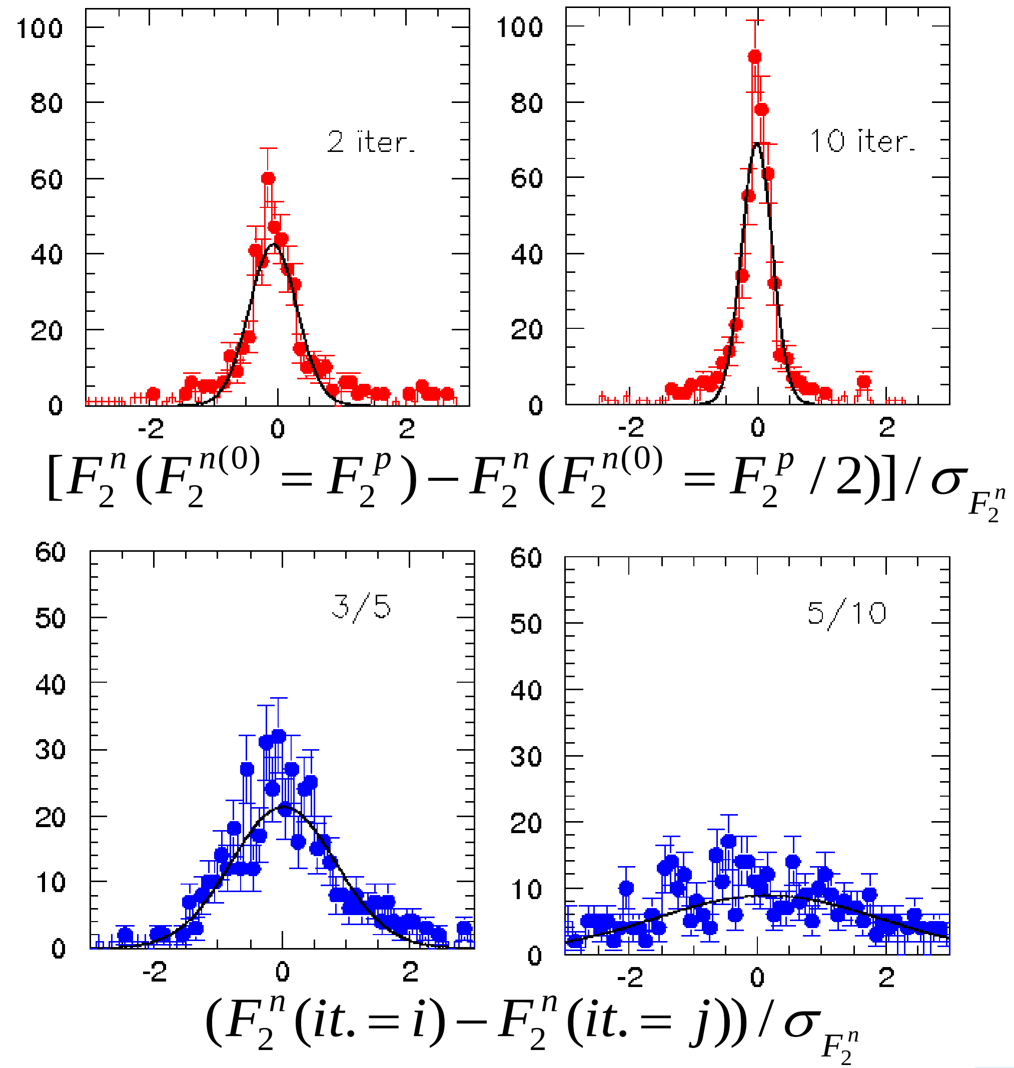
# Application of Method to Data

- Study dependence of result on initial guess $F_2^{n(0)}$ : compare $F_2^n$ extracted with 2 different inputs for initial guess: $F_2^{n(0)} = F_2^p$ vs $F_2^{n(0)} = F_2^p / 2$

  - After 2 iterations: only 6% of all data lay outside a 2$\sigma$ range

  - Exercise caution with number of iterations: irregularities in data (especially deuterium) result in increased scattered in $F_2^n$ with increasing number of iterations



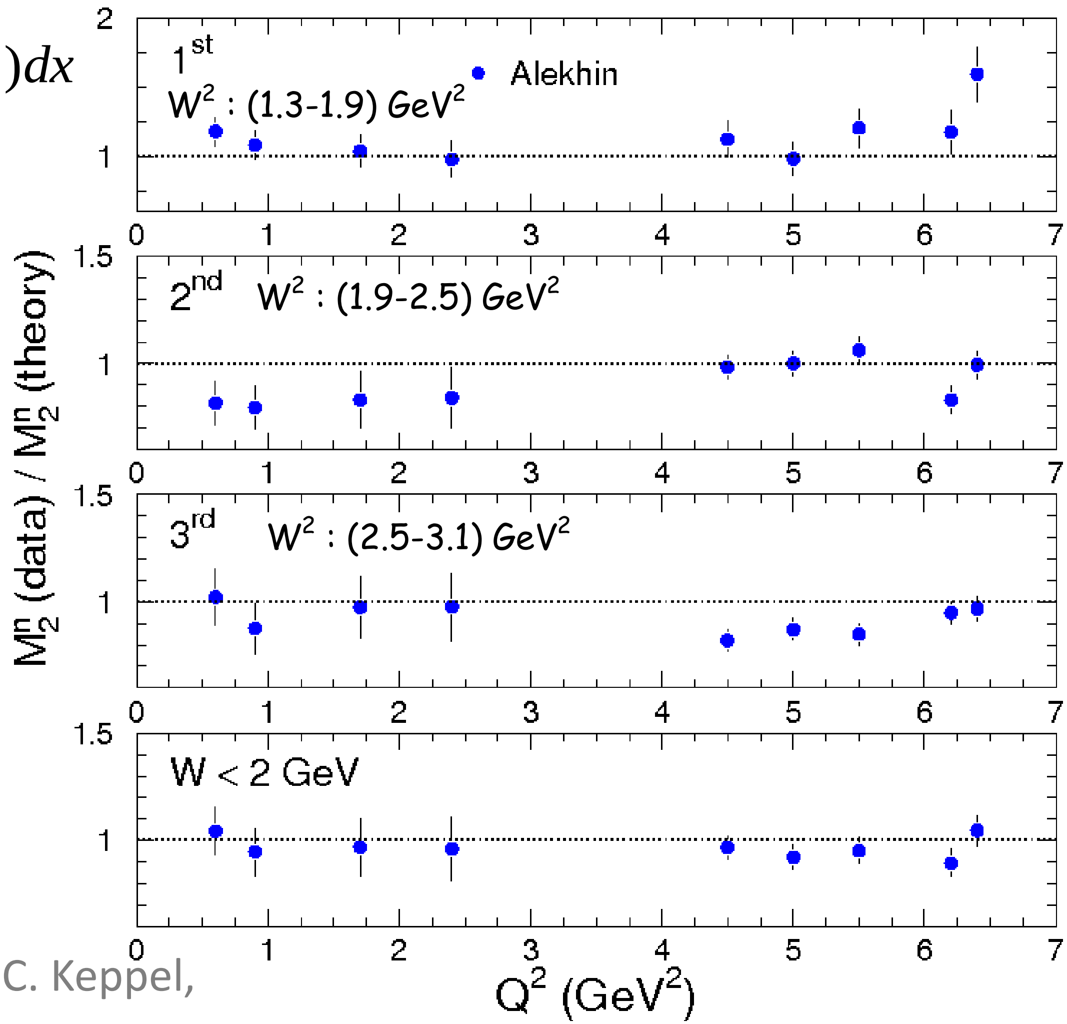

S.P. Malace, Y. Kahn, W. Melnitchouk, in preparation

# Quark-Hadron Duality in the Neutron $F_2$ Structure Function

- Comparison: data to ALEKHIN (PDF fits with $W^2 > 3.24$ GeV$^2$)

$$\int_{x_m}^{x_M} F_2^{n,data}(x,Q^2)dx \Big/ \int_{x_m}^{x_M} F_2^{n,param}(x,Q^2)dx$$

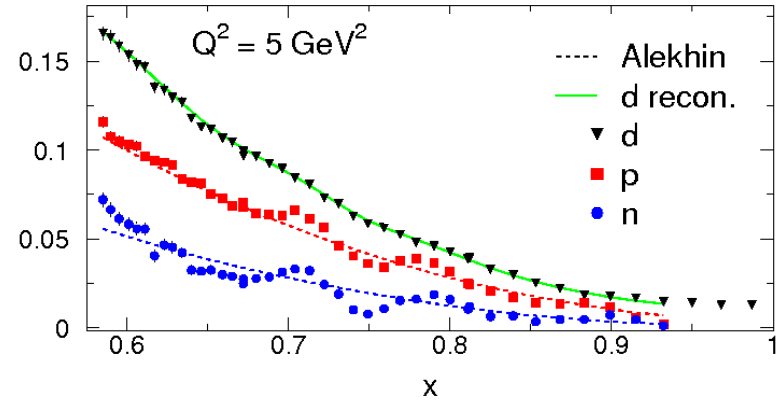
- 2nd and 3rd RES regions: agreement within 15-20%, on average
- 1st RES region: agreement worsens at the highest $Q^2$ (corresponds to the largest x)
- globally remarkable agreement: within 10%



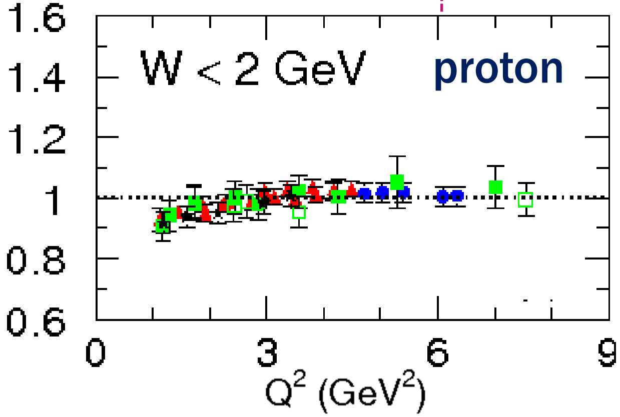

S.P. Malace, Y. Kahn, W. Melnitchouk, C. Keppel, Phys. Rev. Lett. 104 102001 (2010)

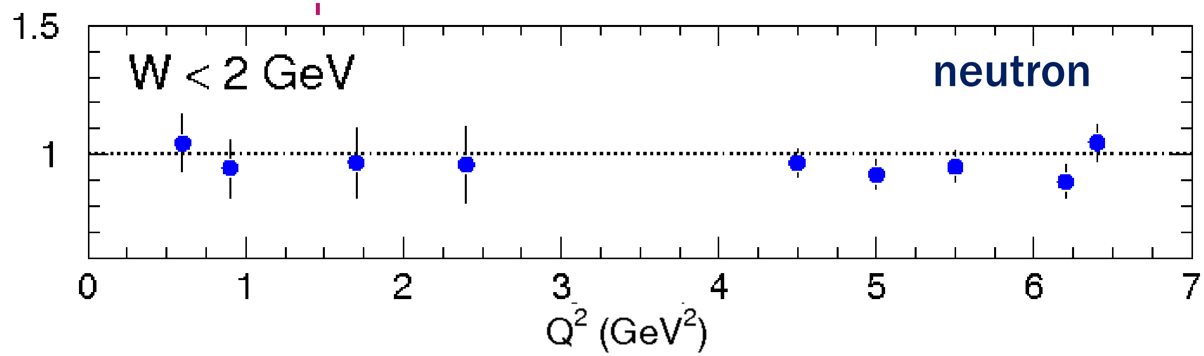
# Quark-Hadron Duality

- Established in $F_2^p$ from $Q^2 \sim 1$ to $Q^2 \sim 7$ GeV$^2$
- Now acknowledged in $F_2^n$




$$\int F_2(data)dx \Big/ \int F_2(QCD = Alekhin)dx$$




S.P. Malace *et al.*, Phys. Rev. C 80 035207 (2009)

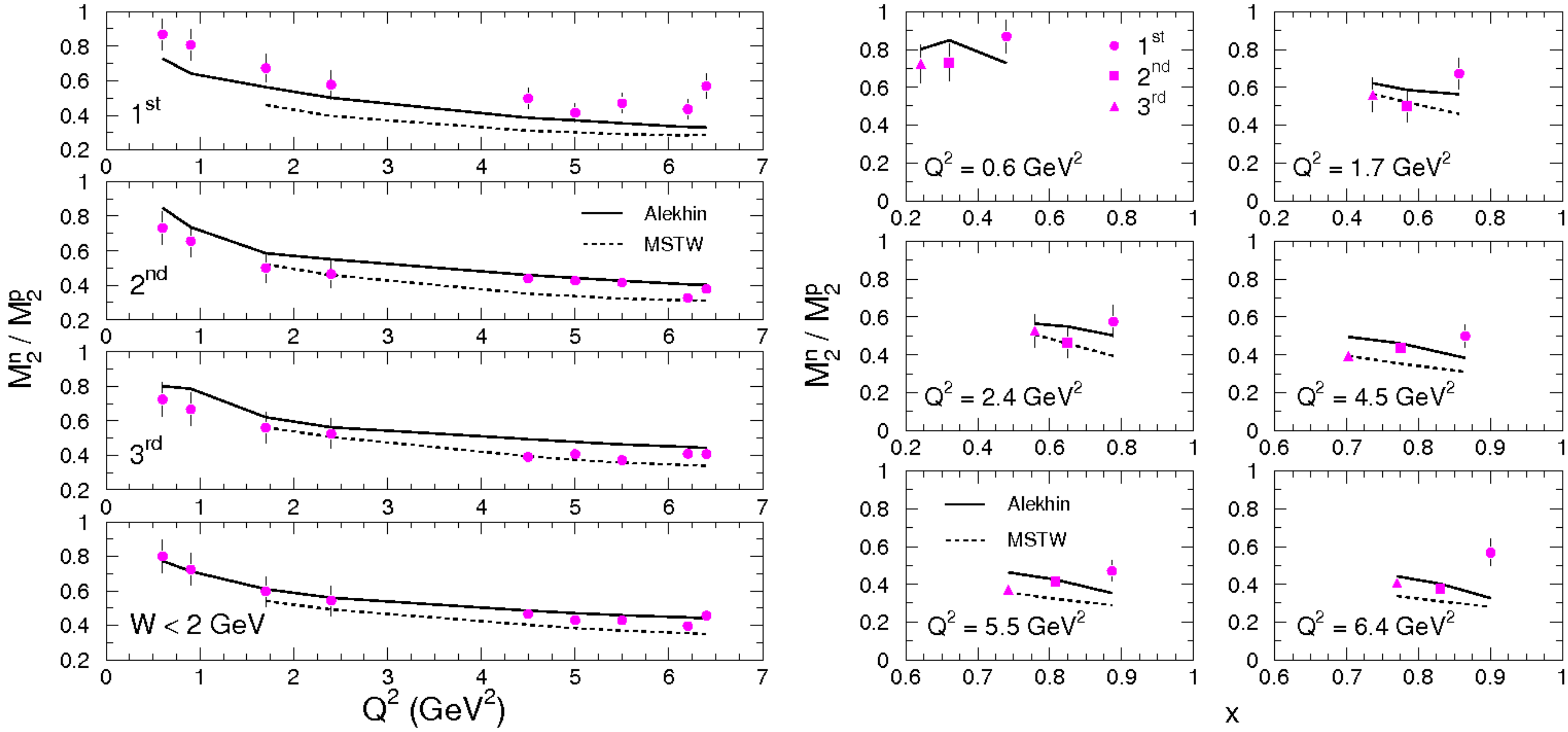
S.P. Malace, Y. Kahn, W. Melnitchouk, C. Keppel, Phys. Rev. Lett. 104, 102001 (2010)

- Confirmation of duality in both proton and neutron => phenomenon not accidental but a general property of nucleon structure functions => use it to access the large-x region

# n/p

➢ Ratio of neutron to proton truncated moments: compare data to ALEKHIN and MSTW

$$\int_{x_m}^{x_M} F_2^n(x,Q^2)dx \Big/ \int_{x_m}^{x_M} F_2^p(x,Q^2)dx$$




S.P. Malace, Y. Kahn, W. Melnitchouk, C. Keppel, Phys. Rev. Lett. 104 102001 (2010)

# Summary

- We extracted $F_2^n$ from proton and deuteron $F_2$ in resonance region

  → Quark-Hadron Duality in the Neutron $F_2^n$ Structure Function: (comparisons of truncated moments from data to those from QCD)

  - globally ($W^2 < 4$ GeV$^2$) remarkable agreement: within 10%
  - locally: 2nd ($W^2$: 1.9-2.5 GeV$^2$) and 3rd ($W^2$: 2.5-3.1 GeV$^2$) RES regions, agreement within 15-20%, on average; 1st ($W^2$: 1.3-1.9 GeV$^2$) RES region, agreement worsens at the highest $Q^2$ (corresponds to the largest x)

  → Confirmation of duality in the neutron (already confirmed for proton) => phenomenon is a general property of structure functions

  → Can be used to access the large-x region

- Detailed discussion of extraction method (application to data) in upcoming paper