Neutron and Proton Structure Functions and Duality

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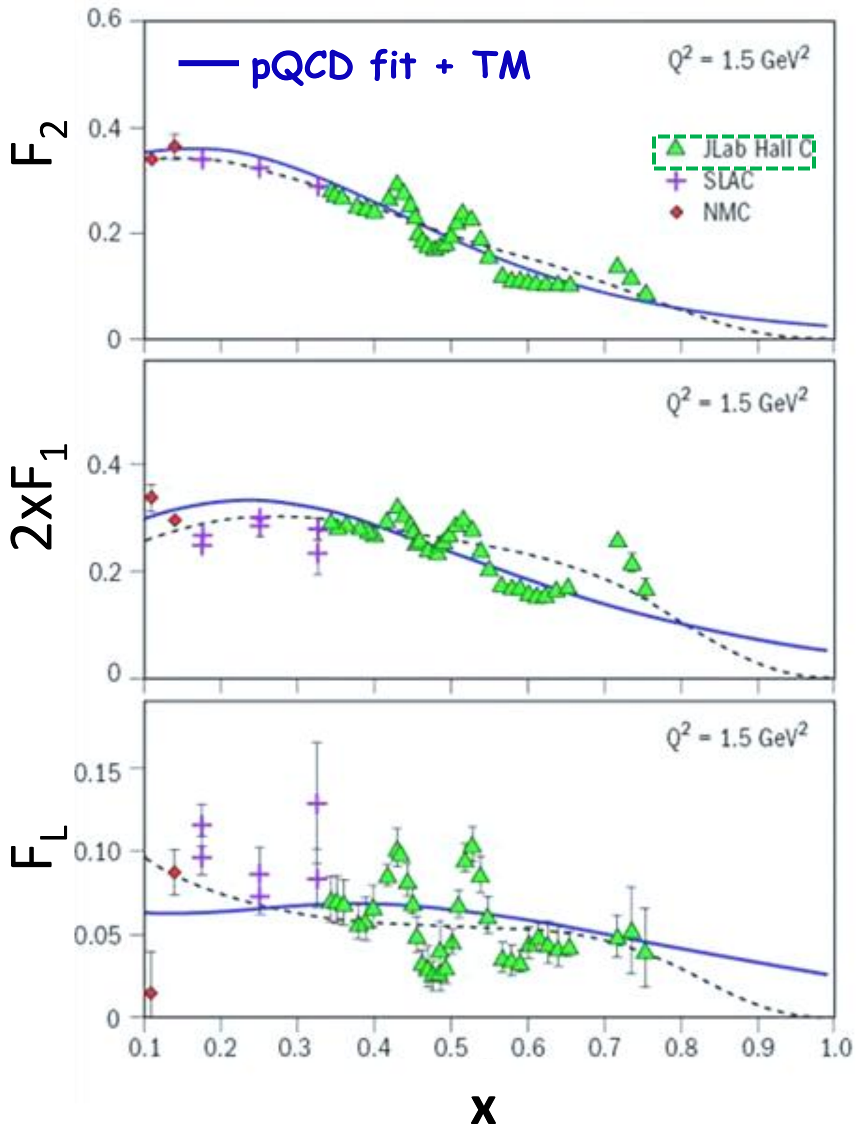
Overview

- Quark-hadron duality: non-trivial phenomenon (see Wally's talk)
  - Manifestation: insight into the dynamic of strong interactions
    Standard tests of quark-hadron duality
  - Application: could be used to access kinematic regions otherwise inaccessible
    Use averaged resonance region data to constrain PDFs at large x?
- Experimental tests of quark-hadron duality in:
  - proton F_2^p structure function
  - neutron F_2^n structure function

  → 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 + Quark-Hadron Duality in F_2^n
      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
- Plans for future

Quark-Hadron Duality

Y. Liang *et al.*, nucl-ex/0410027 (2004)



- On average, the resonance region data **mimic** the twist-2 pQCD calculation (pQCD + Target Mass corrections)

→ This happens at a **surprisingly low Q^2**

⇩

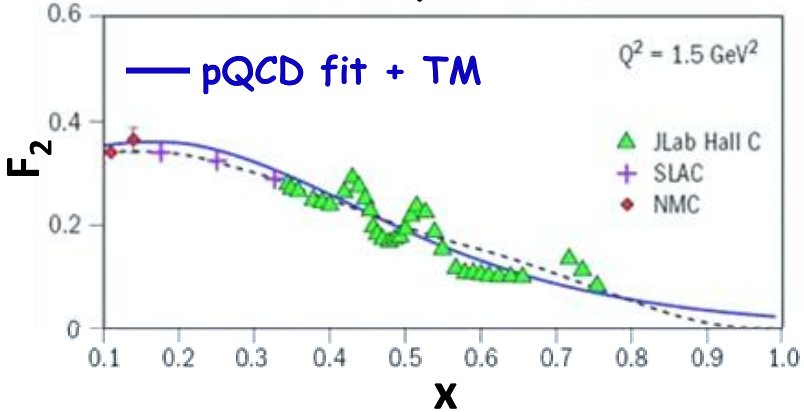
"The successful application of duality to extract known quantities suggests that it should also be possible to use it to extract quantities that are otherwise kinematically inaccessible."
(CERN Courier, 2004)

⇩

- Quark-Hadron Duality: needs to be verified and **quantified**

Standard Tests of Quark-Hadron Duality

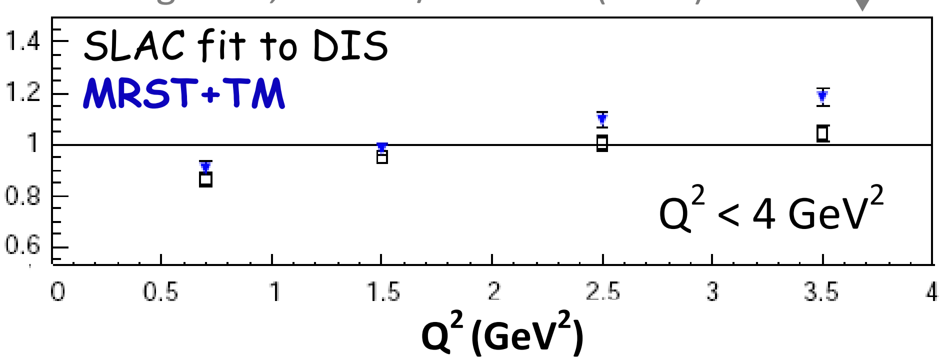
- Basic test of Duality: the Q^2 behavior of averaged resonance region data when compared to QCD calculations



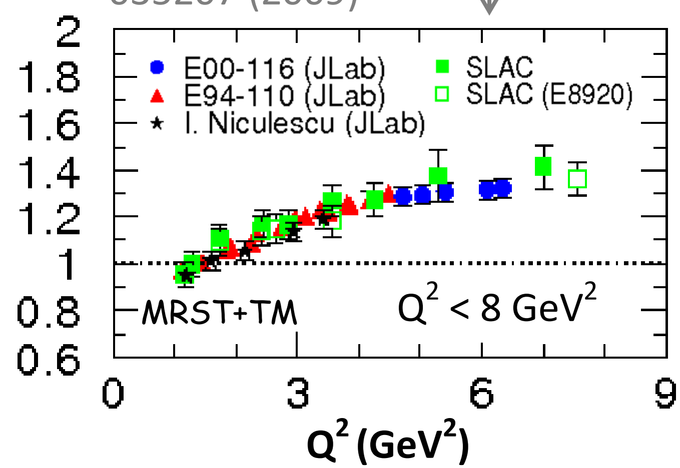
$$\int_{x_m}^{x_M} F_2^{data.}(x,Q^2)dx \Big/ \int_{x_m}^{x_M} F_2^{calc.}(x,Q^2)dx$$

- Example: integrals over RES Region (W^2 < 4 GeV^2); comparison of data to MRST+TM

Y. Liang *et al.*, nucl-ex/0410027 (2004)



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

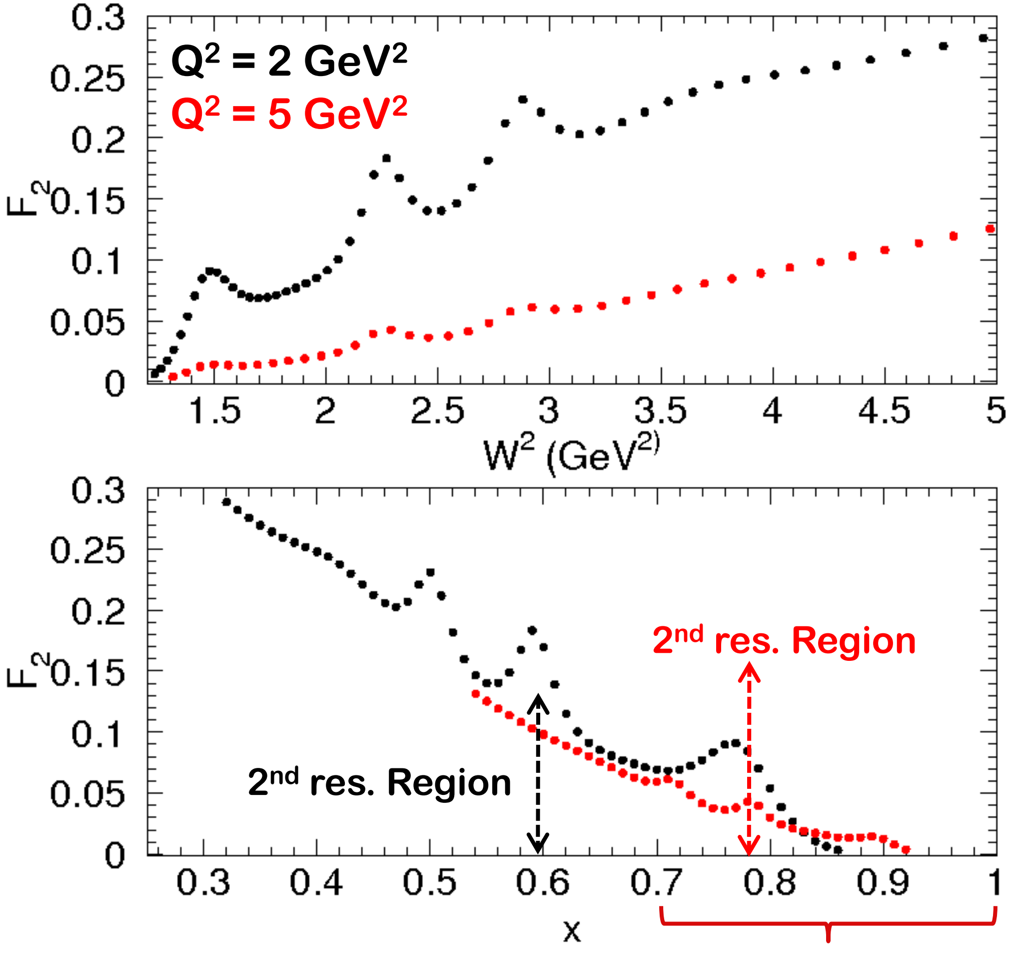


→ 2004: agreement better than 5% at Q^2 = 0.5 GeV^2 but ~ 18% at Q^2 = 3.5 GeV^2

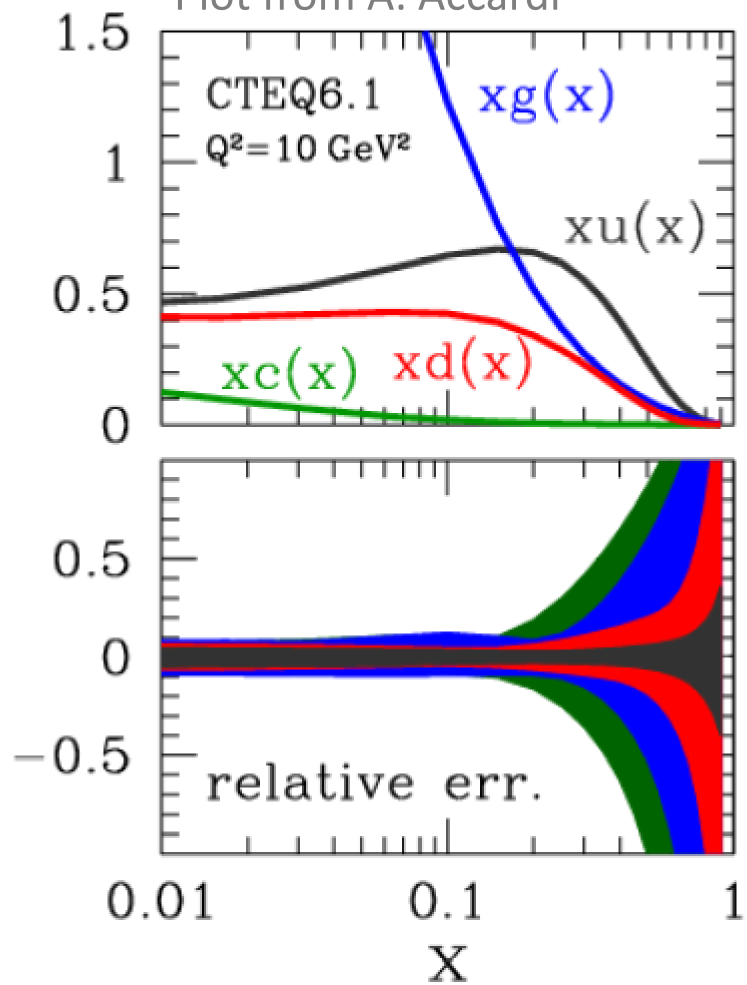
→ 2009: deviation of data from MRST+TM increases with Q^2 up to Q^2 ~ 4.5 GeV^2 then saturates

Tests of Quark-Hadron Duality at large x

- Kinematics: with increasing Q^2 resonances slide in regions of larger and larger x



Plot from A. Accardi



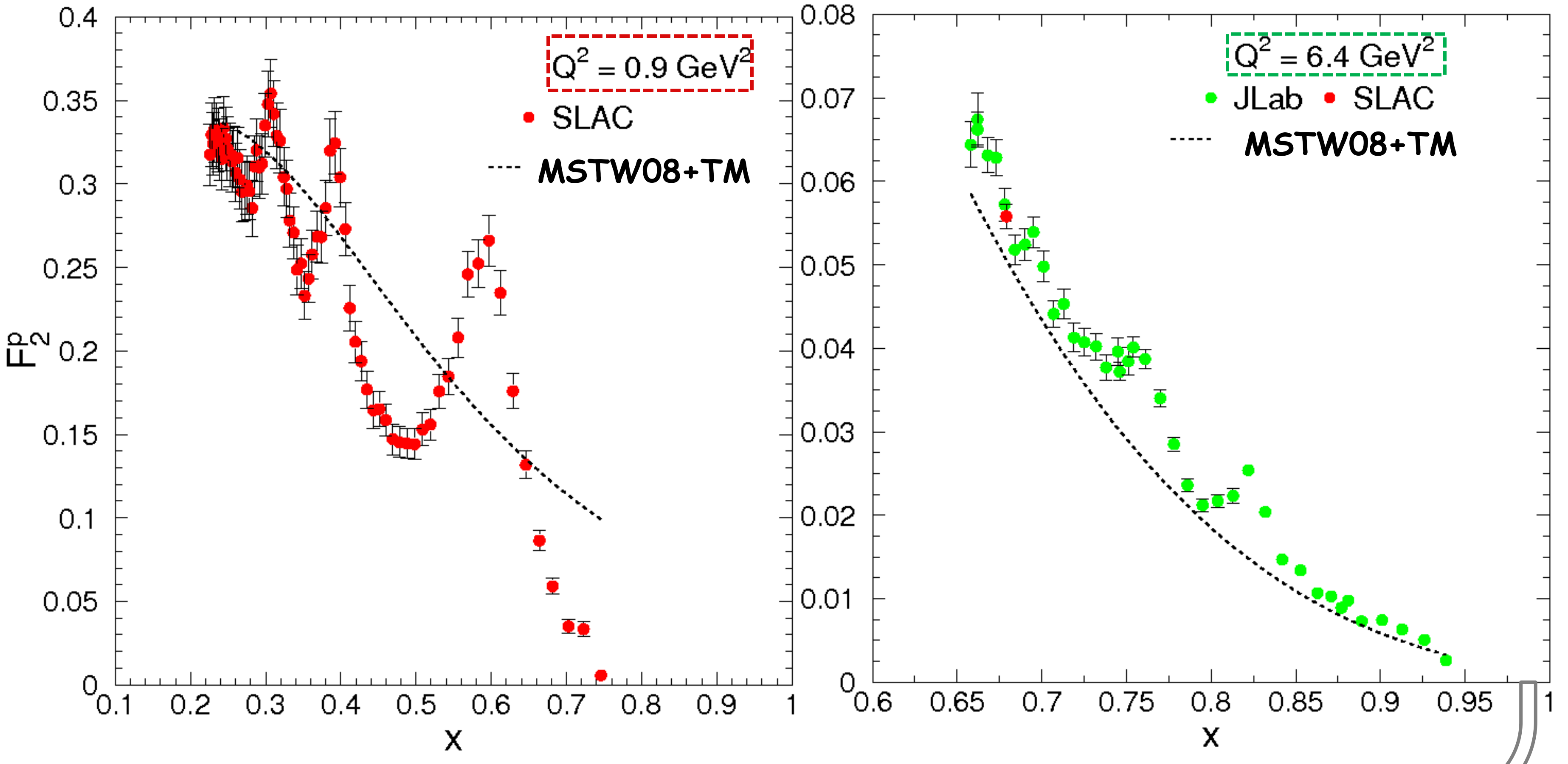
- PDFs (CTEQ, MRST, MSTW) poorly constrained at large x

Tests of Quark-Hadron Duality at large x

- It is not surprising then:

--> though RES data DO average to MSTW08+TM at Q^2 = 0.9 GeV^2, x ~ (0.25,0.7)

--> RES data DO NOT average to MSTW08+TM at Q^2 = 6.4 GeV^2, x ~ (0.7,0.95)

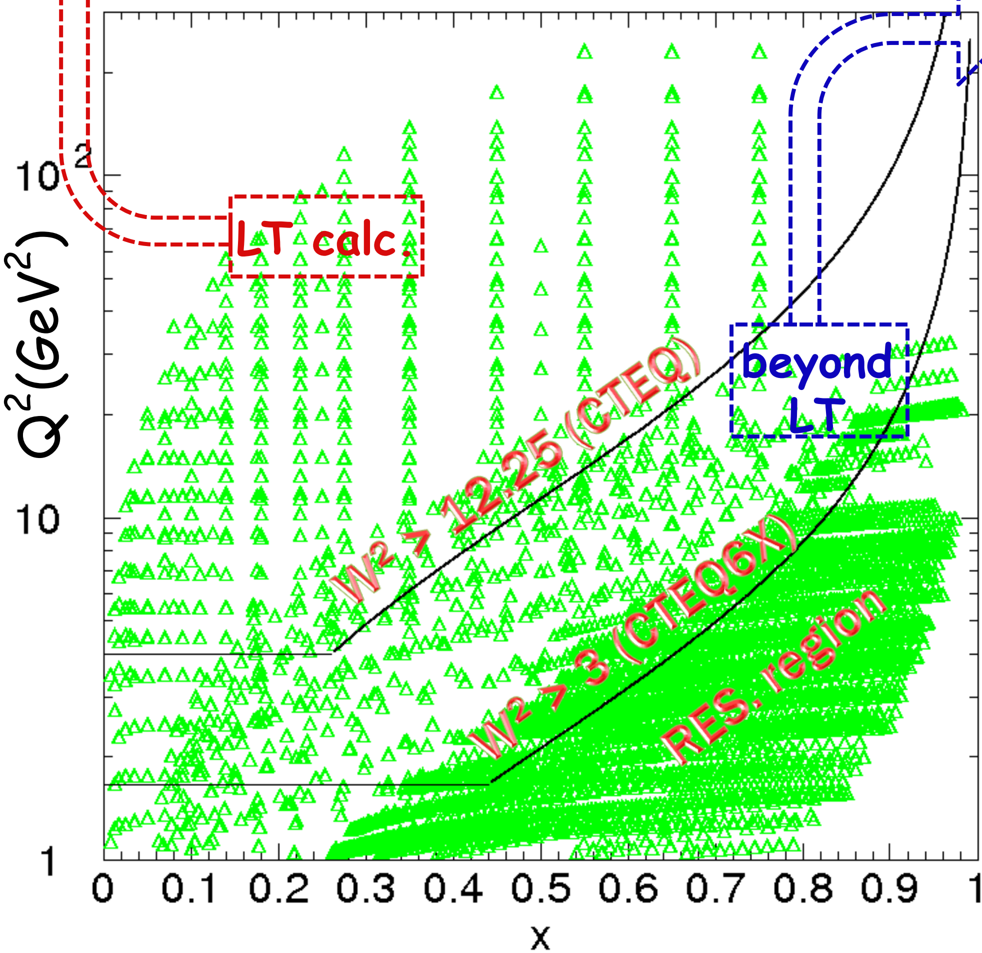


Not a violation of duality but very likely due to an underestimation of large-x strength in the pQCD parametrization

Tests of Quark-Hadron Duality at large x

What should we use for quantitative tests of Duality at large x?

- Leading Twist (LT) calculations ⇔ PDFs constrained up to **x ~ 0.65-0.7**: CTEQ, MRST (MSTW)...



- Calculations beyond LT ⇔ PDFs constrained up to **x ~ 0.8-0.9**

Alekhin et al.

S. Alekhin, Phys. Rev. D 63, 094022 (2001)

...

S. Alekhin, J. Blumlein, S. Klein, S. Moch, Phys. Rev. D 81, 014032 (2010)

CTEQ6X

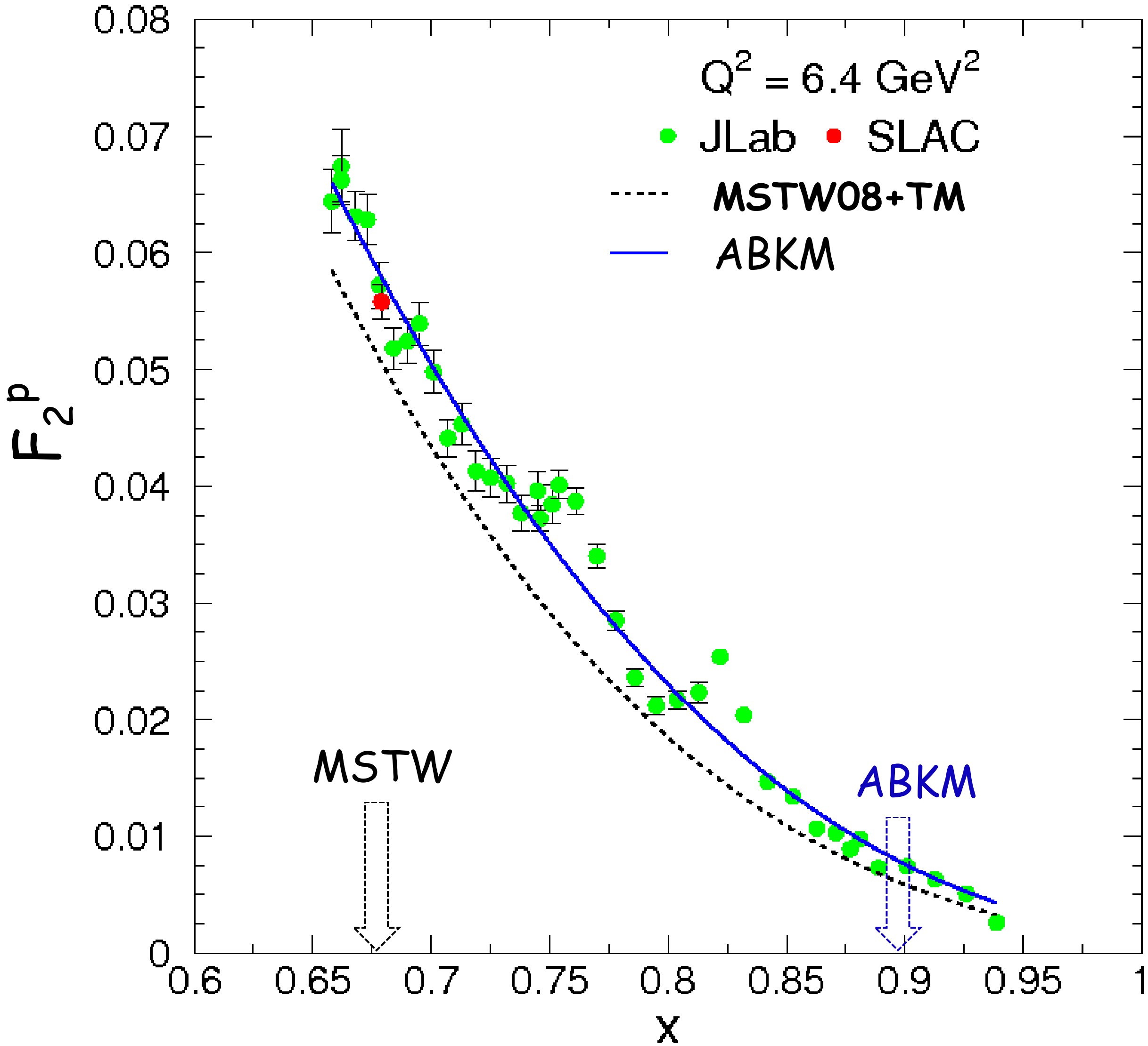
Accardi, Christy, Keppel, Melnitchouk, Monaghan, Morfín, Owens, Phys. Rev. D 81, 034016 (2010)

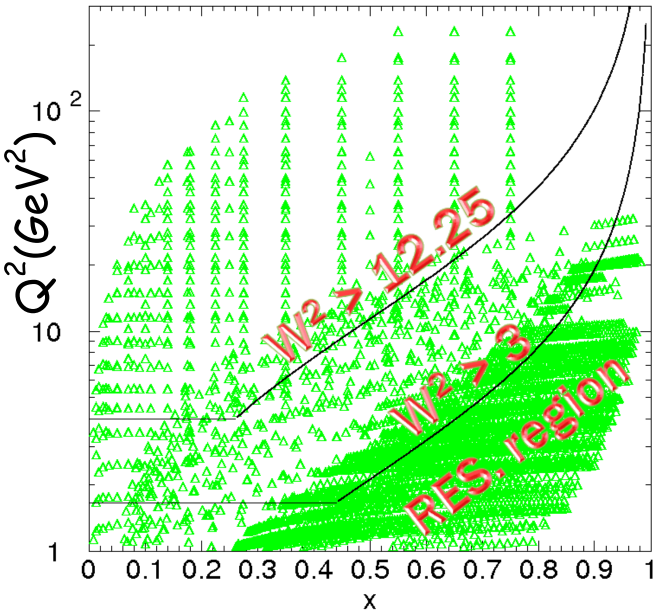
Accardi *et al.*, in preparation

Tests of Quark-Hadron Duality at large x

- Resonance region data average to the QCD (beyond LT) calculation

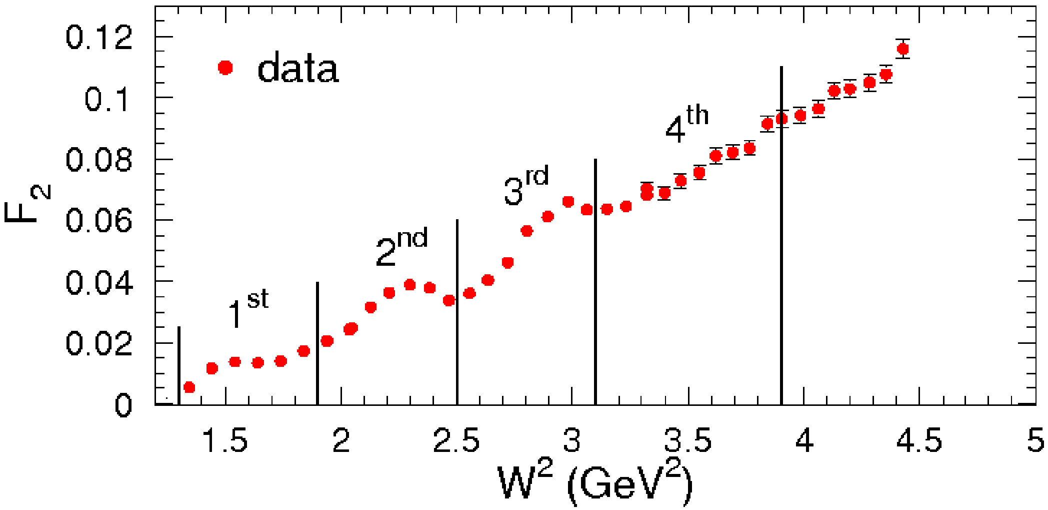
S. Alekhin, J. Blumlein, S. Klein, S. Moch, Phys. Rev. D 81, 014032 (2010)





Quantitative Tests of Local Duality

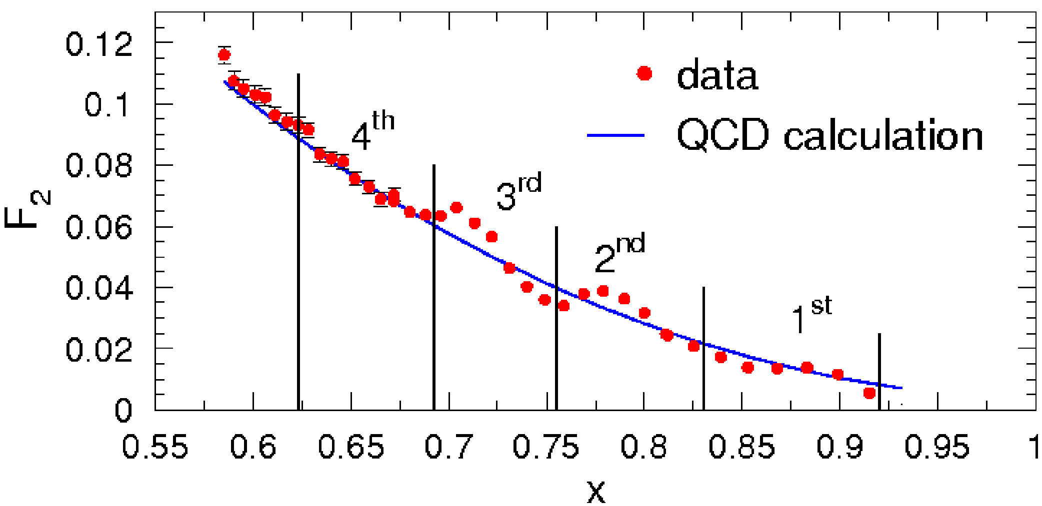
1) Delimit W regions for duality tests



Region	W^2_{min}	W^2_{max}
1st	1.3	1.9
2nd	1.9	2.5
3rd	2.5	3.1
4th	3.1	3.9
DIS	3.9	4.5

$$x = Q^2 / (W^2 + Q^2 - M^2)$$

2) F_2 from data and QCD calculation



3) Calculate:

$$\frac{\int_{x_m}^{x_M} F_2^{data}(x, Q^2)\,dx}{\int_{x_m}^{x_M} F_2^{QCD\ calc.}(x, Q^2)\,dx}$$

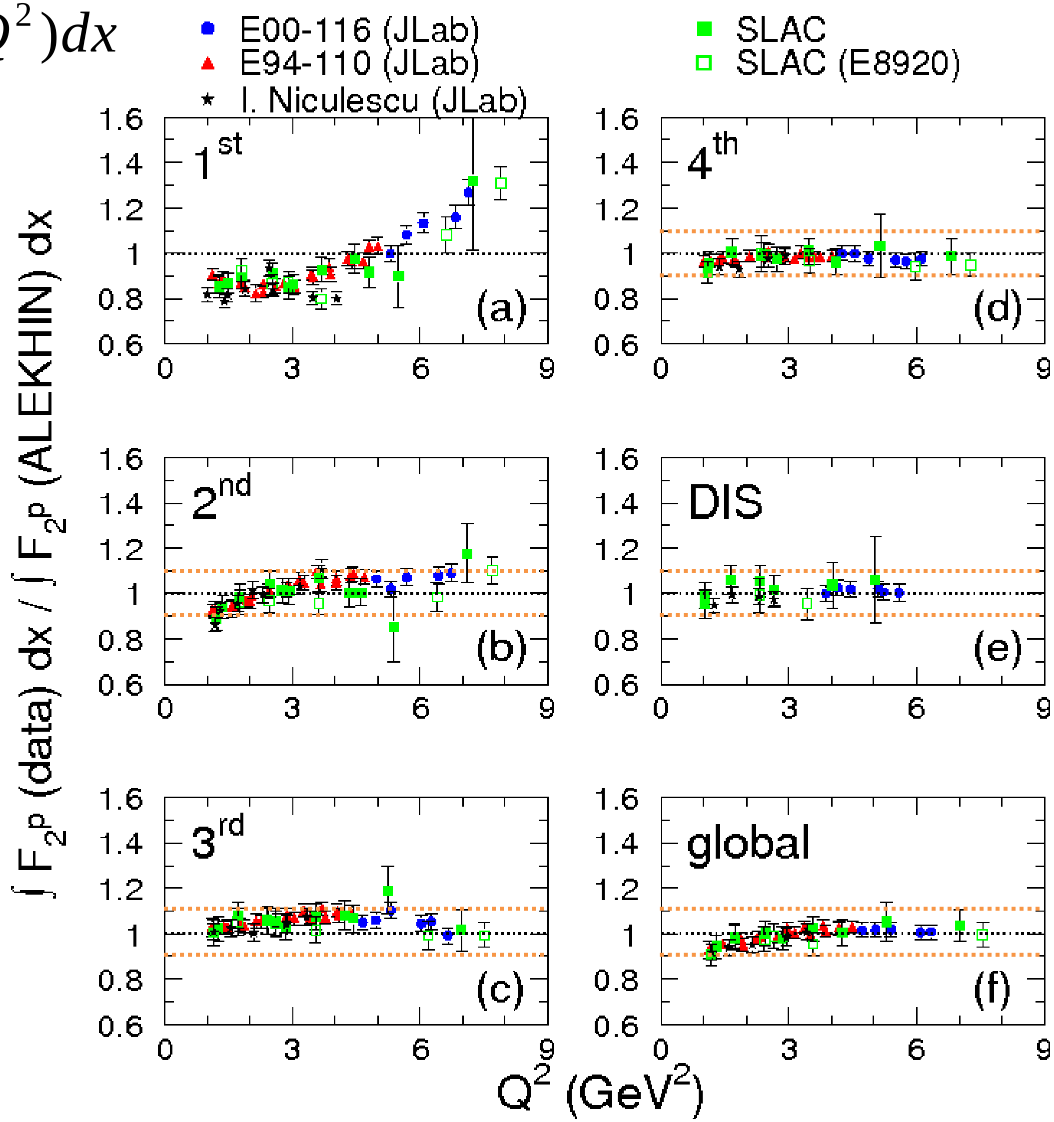
Quark-Hadron Duality in Proton F_2^p

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

QCD calculation of Alekhin

S. I. Alekhin, JETP Lett. 82, 628 (2005).
S. I. Alekhin, Phys. Rev. D 63, 094022 (2001)

- Within 10% : globally, 4th, 3rd, 2nd
- 1st : special case
  - some models predict stronger violations of duality
  - calculation based on handbag diagram may break at such low W
  - sits at the largest x (QCD fits poorly constrained) => difficult to test duality



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

Quark-Hadron Duality in Neutron F_2^n

- Verify quark-hadron duality in F_2^n

  Need F_2^n in the resonance region…

  Could use proton F_2^p and deuteron F_2^d and

New method to extract **F_2^n from F_2^p and F_2^d** : iterative procedure of solving integral convolution equations

Impulse Approximation:

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

nuclear F_2

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

nucleon F_2

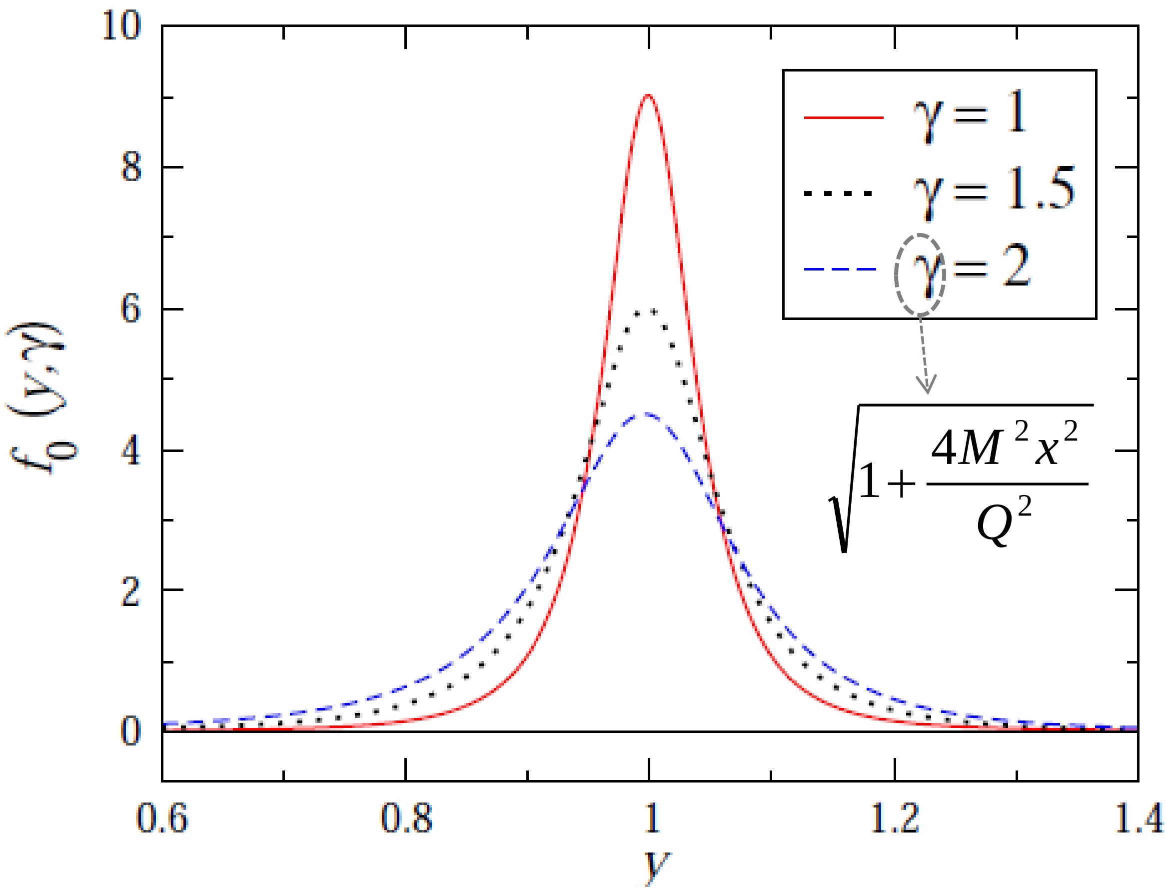
Y. Kahn, W. Melnitchouk, S.A. Kulagin, Phys. Rev. C 79, 035205 (2009)

Smearing Function for F_2^d

- Smearing function evaluated in the weak binding approximation, **including finite-Q^2 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:

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

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

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

$$f(y,\gamma) = \mathrm{N}\,\delta(y-1) + \delta f(y,\gamma)$$

finite width of smearing function

normalization of smearing function

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

perturbation

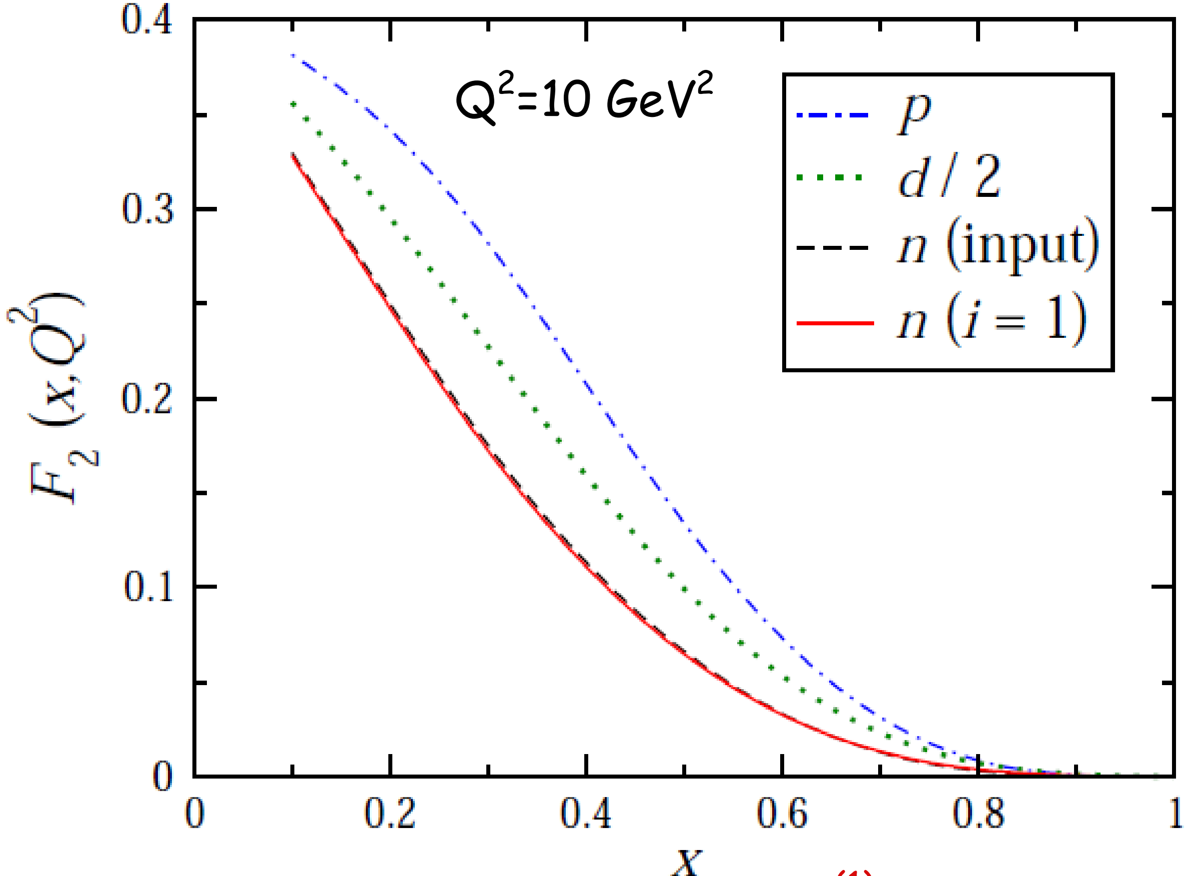
$$F_2^{n(1)}(x) = F_2^{n(0)}(x) + \frac{1}{\mathrm{N}}\left[\tilde{F}_2^n(x) - \int_x^{M_d/M} dy\, f(y,\gamma)\, F_2^{n(0)}\left(\frac{x}{y}\right)\right]$$

initial guess

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

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 $F_2^{n(0)} = 0$

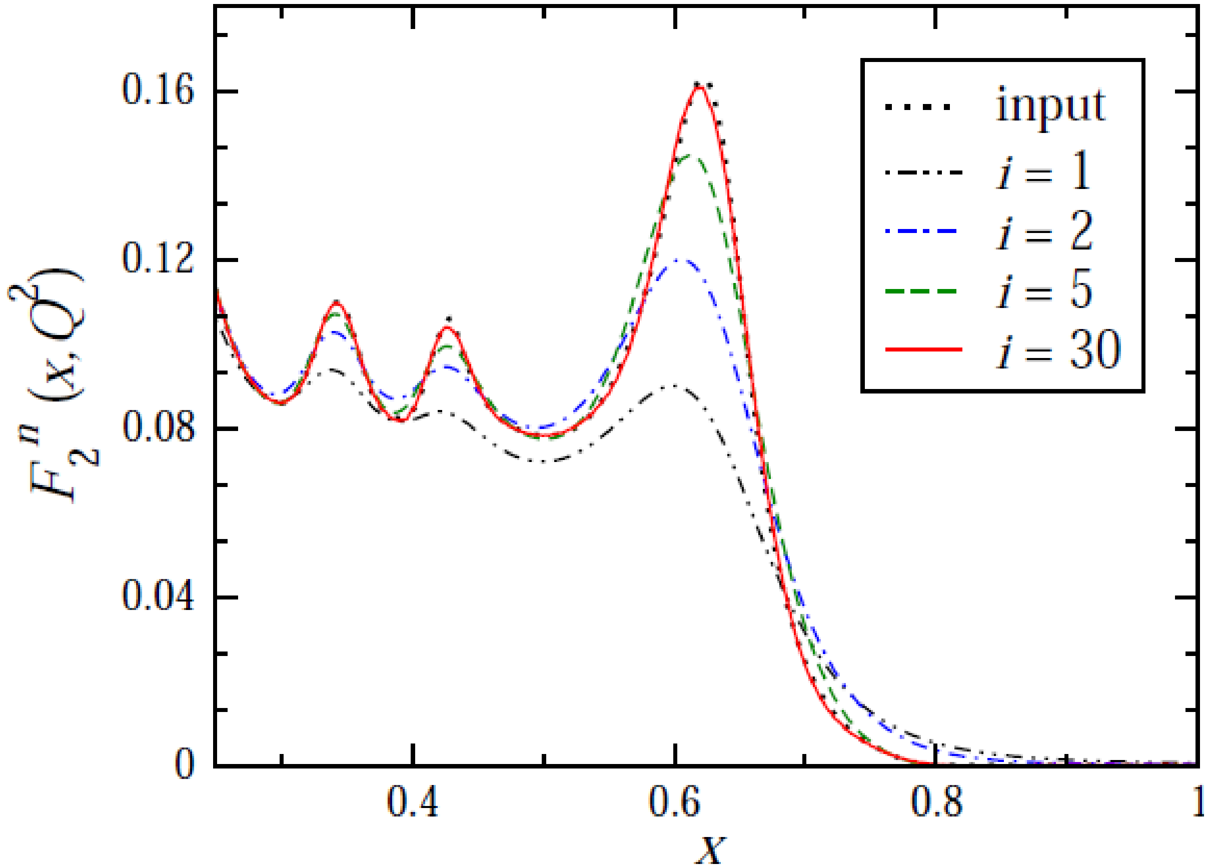


Y. Kahn, W. Melnitchouk, S.A. Kulagin, Phys. Rev. C 79, 035205 (2009)

- 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 $F_2^{n(0)} = 0$

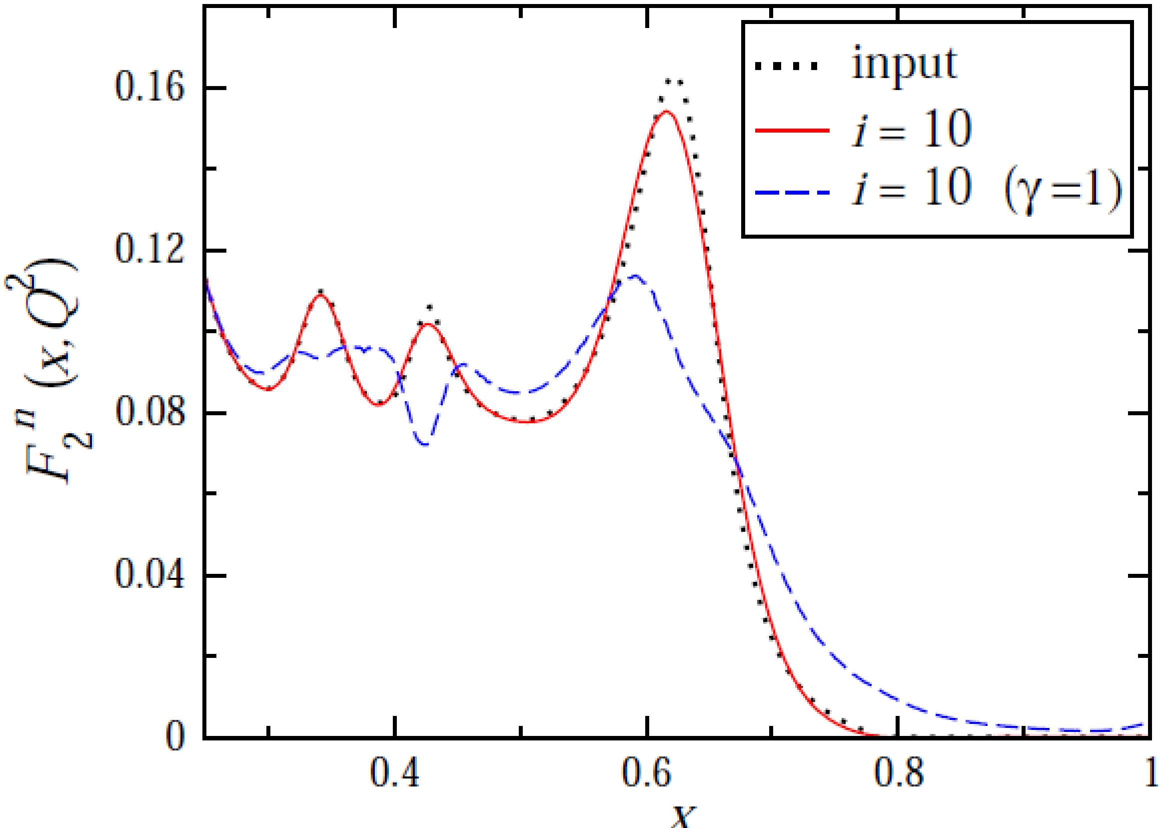


Y. Kahn, W. Melnitchouk, S.A. Kulagin, Phys. Rev. C 79, 035205 (2009)

- 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 ($F_2^{n(0)} = 0$): Q^2-dependent smearing function and 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**

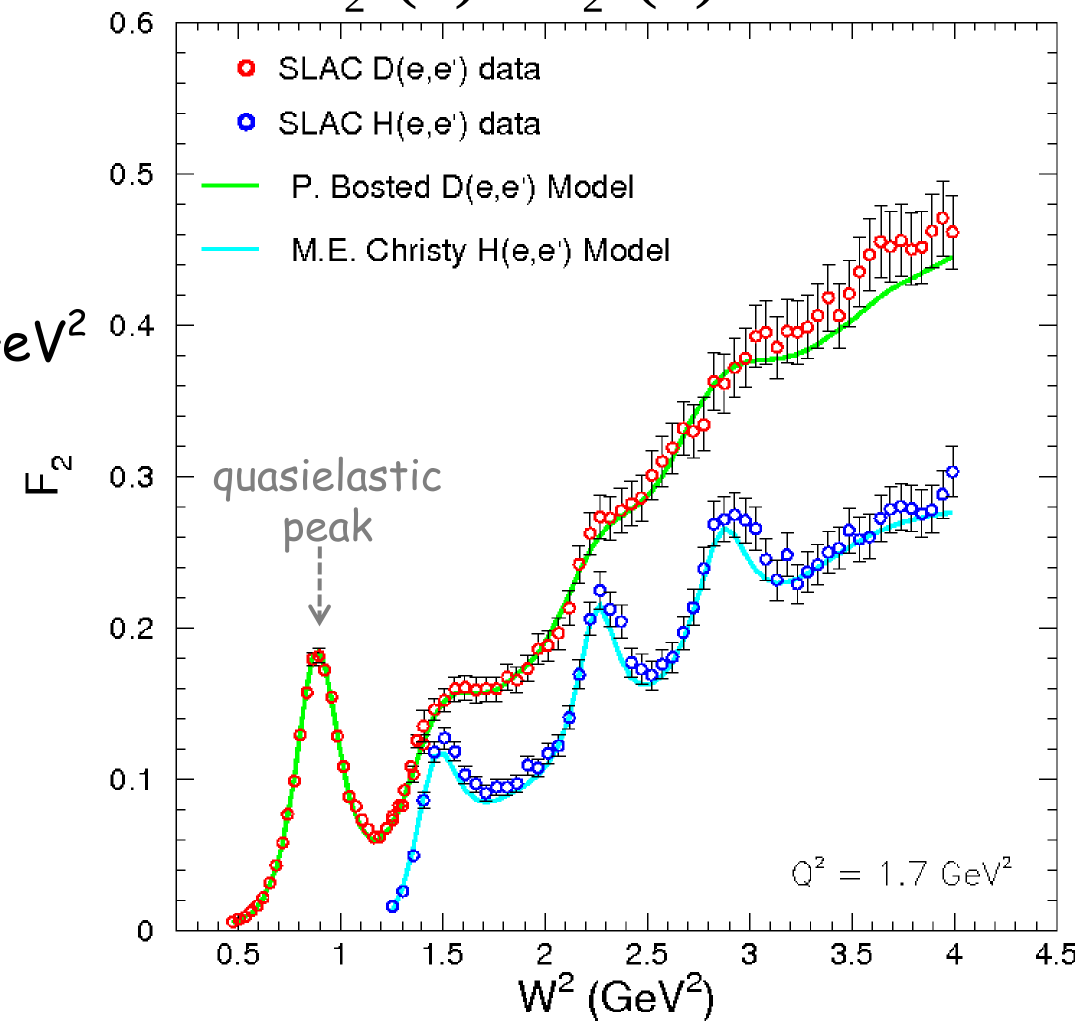
Application of Method to Data

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

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

data (↓ $F_2^d(x)$)

data (← $\widetilde{F}_2^p(x)$)



Data:

SLAC at Q^2 = 0.6, 0.9, 1.7, 2.4 GeV^2

JLab (Hall C E00-116) at Q^2 = 4.5, 5, 5.5, 6.2, 6.4 GeV^2

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

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

Application of Method to Data

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

model (↑ $\delta^{(off-shell)}$); data (↓ $F_2^d(x)$); model (↓ $F_2^{d(QE)}$); data (→ $\widetilde{F}_2^p(x)$)

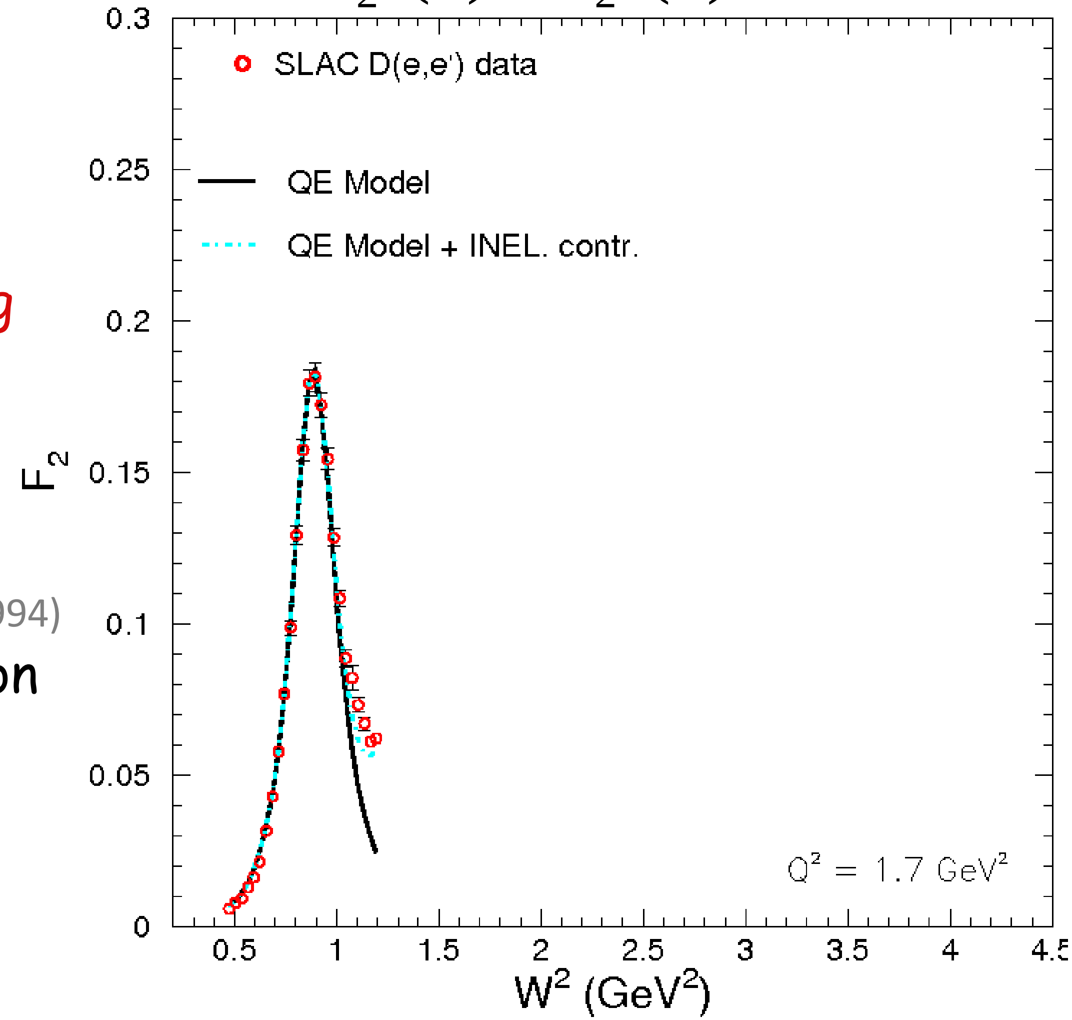
QE: extracted from data using model (form factors + smearing function)

Off-shell corrections:

- upper limit from model ~1.5%

  W. Melnitchouk *et al.*, Phys. Lett. B, 11 (1994)

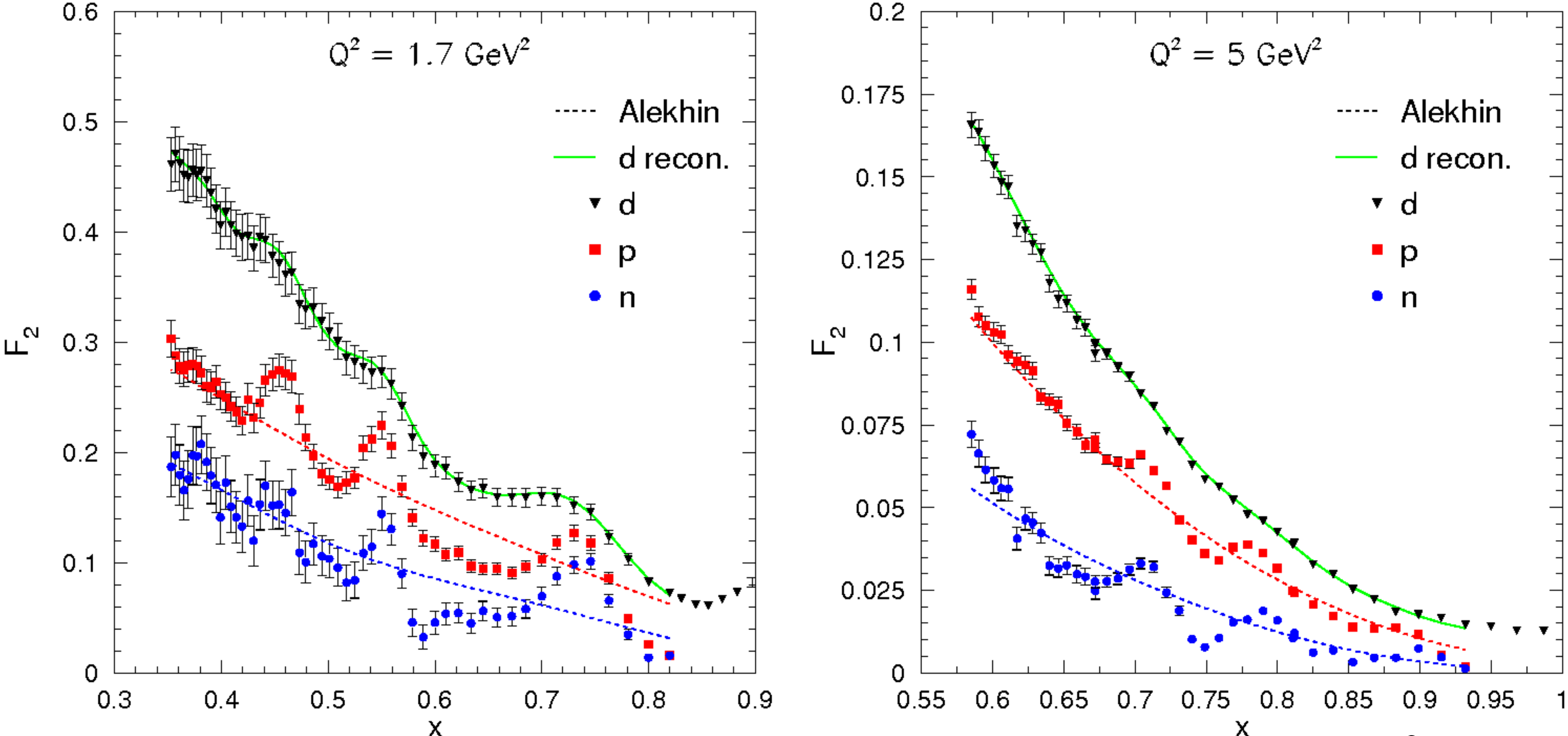
- subtract ½ of model prediction assign 100% uncertainty to correction
- contributes < 2% to total uncertainty on F_2^n



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

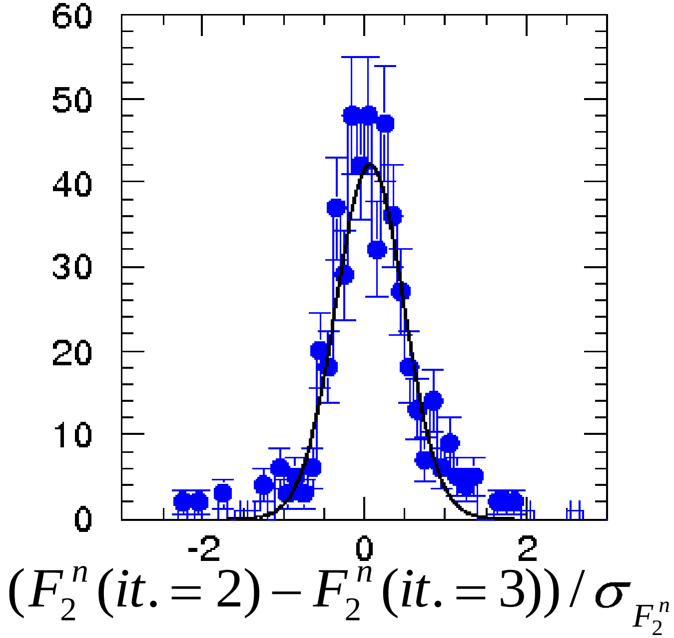


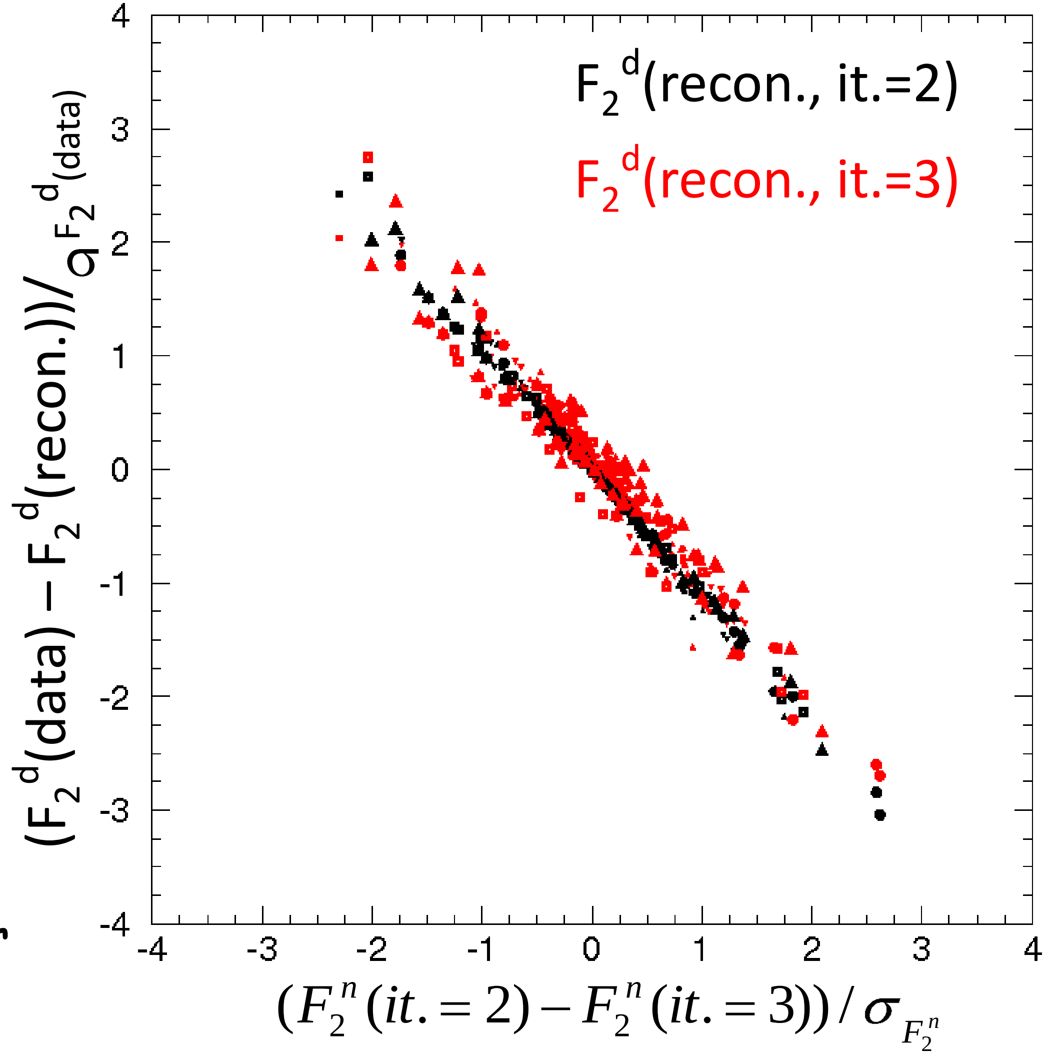
- F_2^n in resonance region: 3 resonant enhancements (fall with Q^2 at ~ rate as for F_2^p)
- F_2^d reconstructed from F_2^p(data) and F_2^n(extraction) ~ F_2^d(data) after 2 iterations

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

Application of Method to Data

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





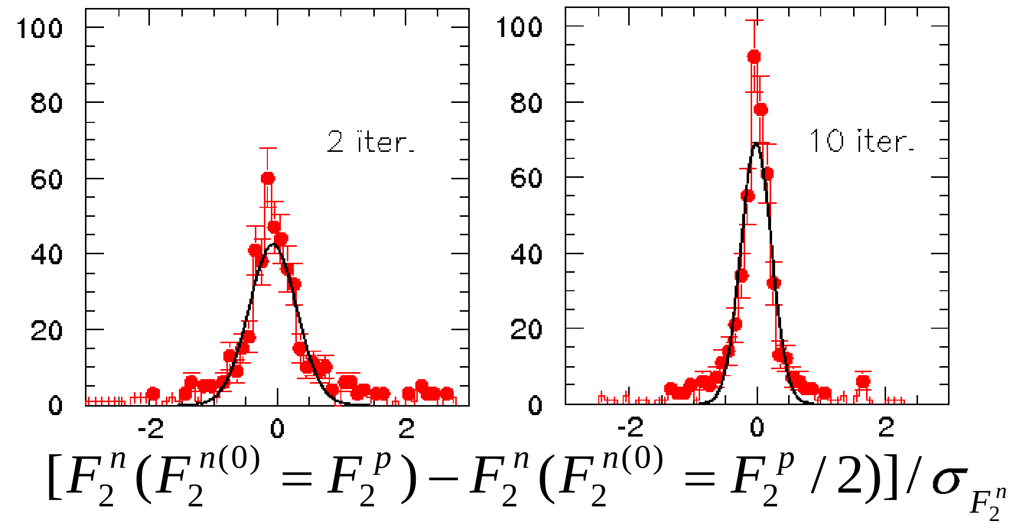
- Small change in F_2^n between iteration 2 and 3

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

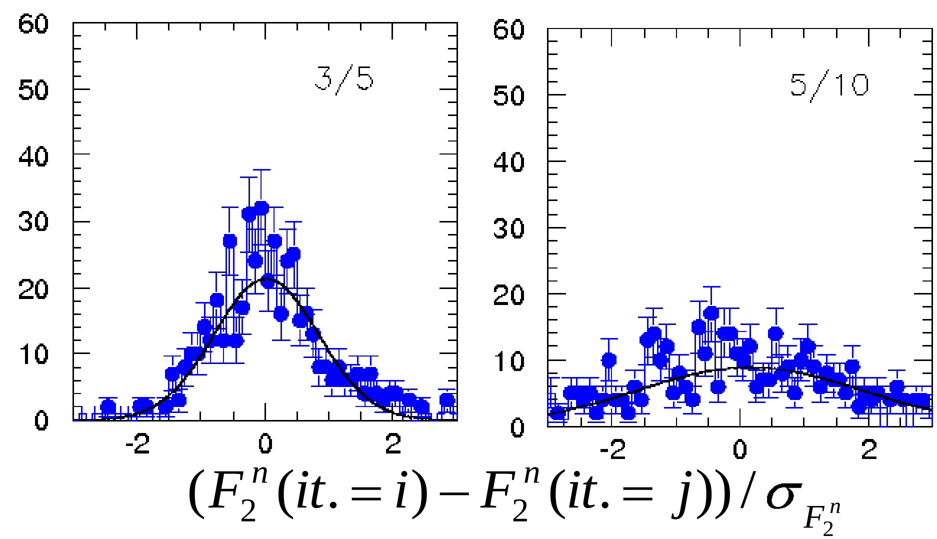
S.P. Malace, Y. Kahn, W. Melnitchouk, in preparation

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 2σ range



- Exercise caution with number of iterations: irregularities in data result in increased scattered in F_2^n with increasing number of iterations

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

Comparison to BoNuS Data

- Plots by Nathan Baillie

BoNuS: F_2^n data

Slava Tkachenko, Ph.D. thesis (2009)

Nathan Baillie, Ph.D. thesis (2009)

MALACE: F_2^n extracted from F_2^p and F_2^d

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

do not quote

BOSTED

P.E. Bosted and M.E. Christy, Phys. Rev. C 77, 065206 (2008)

Thanks to Nate, Sebastian ☺
and the BoNuS Collaboration

Quark-Hadron Duality in the Neutron F_2^n

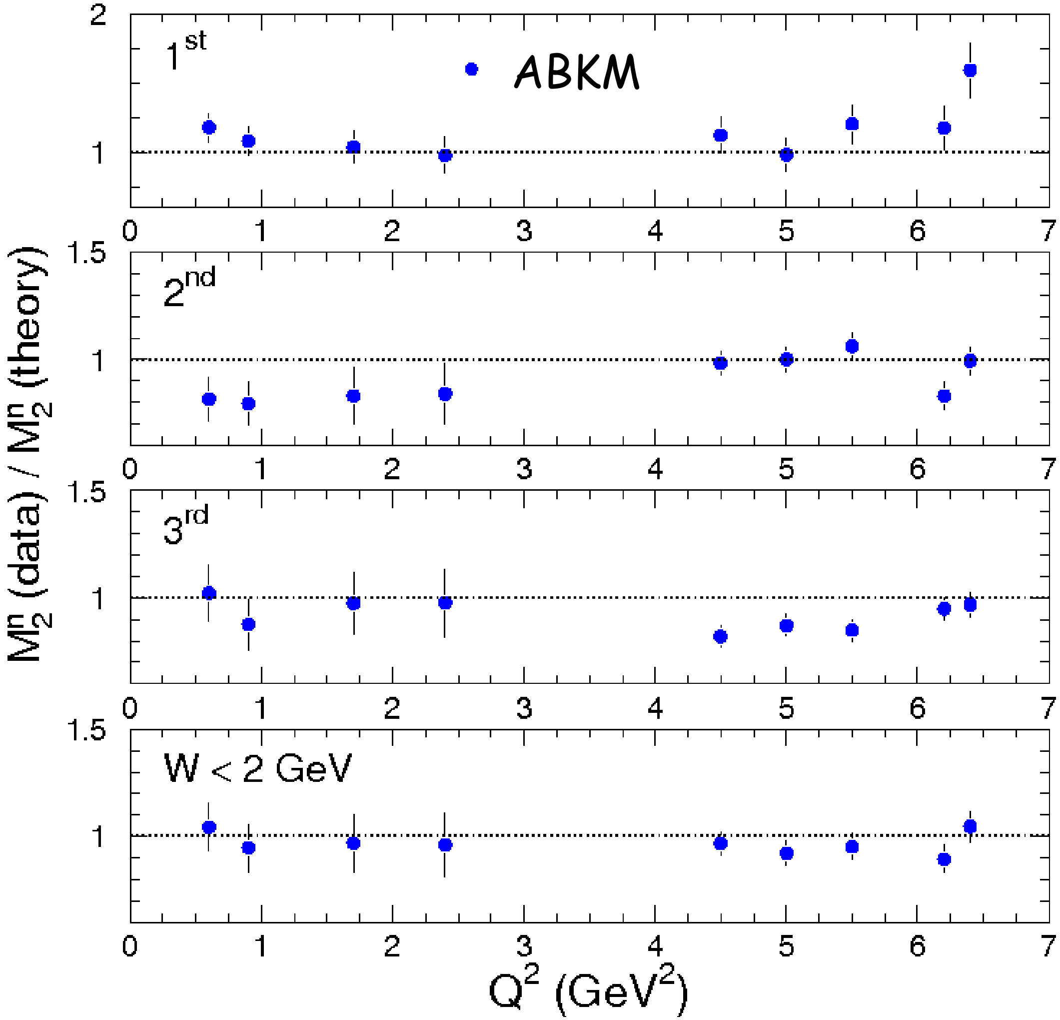
- Comparison: data to ABKM

S. Alekhin, J. Blumlein, S. Klein, S. Moch. Phys. Rev. D 81, 014032 (2010)

- 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%

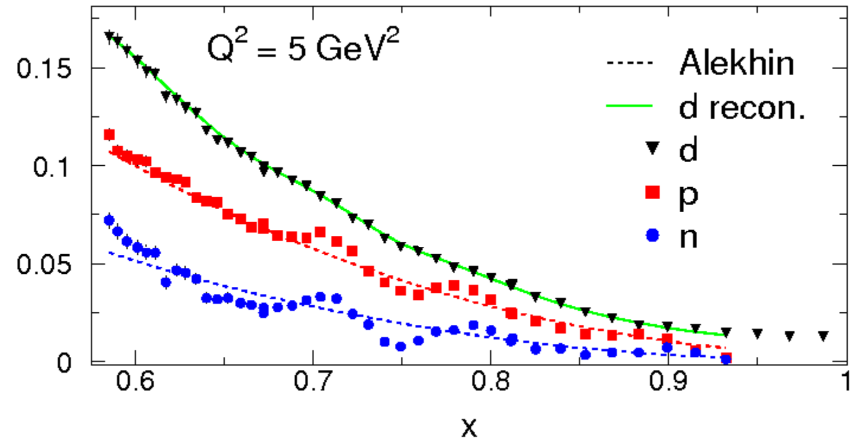
S.P. Malace, Y. Kahn, W. Melnitchouk, Phys. Rev. Lett. 104, 102001 (2010)

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



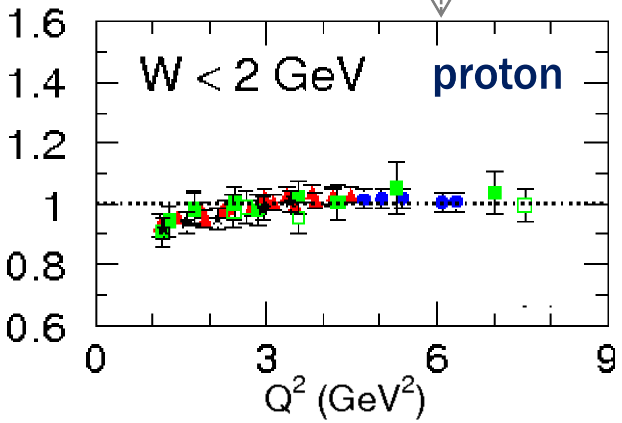
Quark-Hadron Duality: Application

- Confirmation of duality in both proton and neutron => phenomenon not accidental but a general property of nucleon structure functions

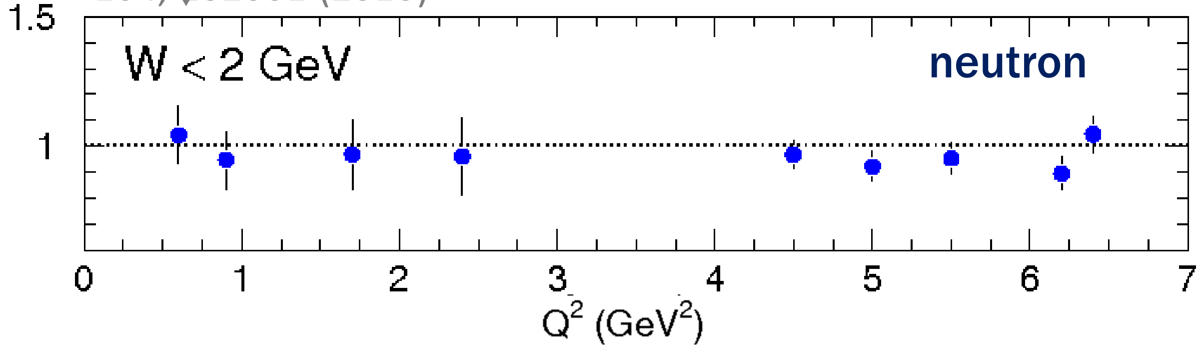


$$\int F_2(data)dx \Big/ \int F_2(QCD = Alekhin)dx$$

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)

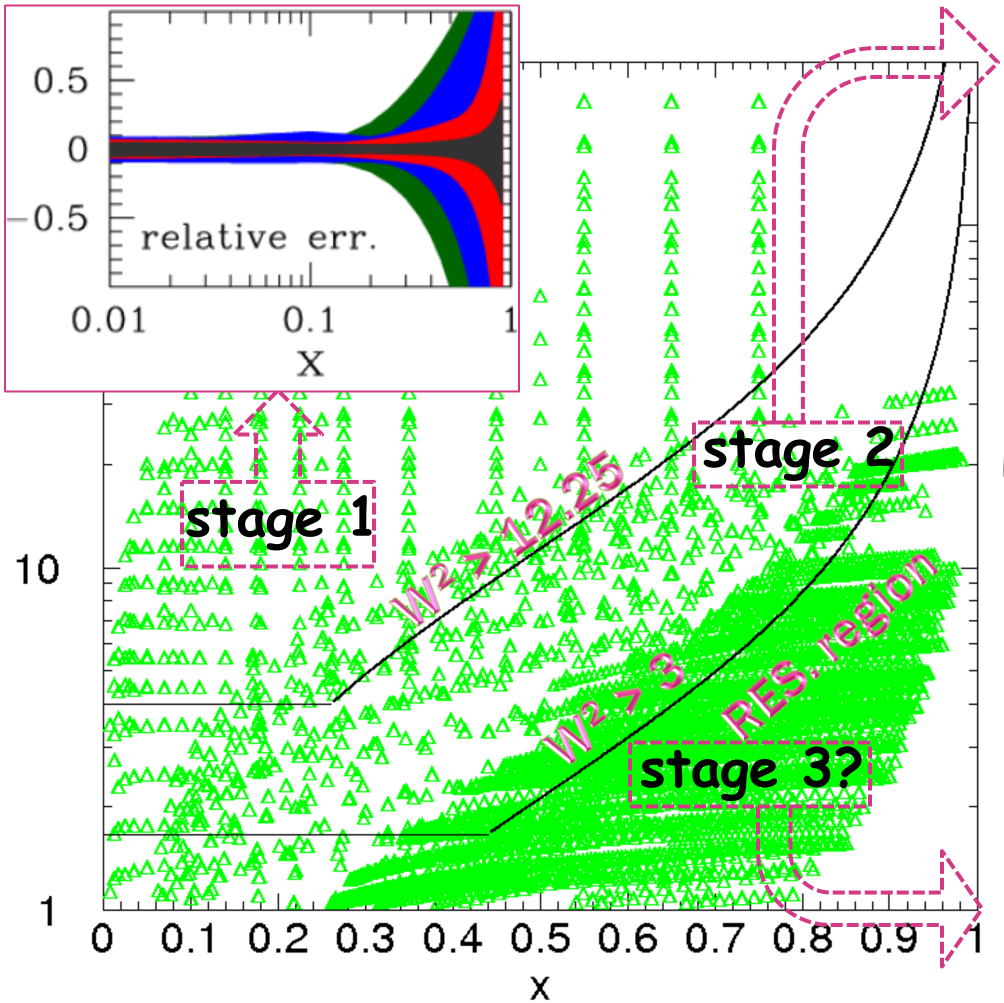


- Use averaged resonance region data (W² > 1.9 GeV²) to extend PDFs extraction to the largest x

use… use… use… use…

Quark-Hadron Duality: Application

➢ **Stage 1 (last few decades)**: LT calculations ⇔ PDFs constrained up to x ~ 0.7 (CTEQ, MRST(MSTW), GRV, etc.)



➢ **Stage 2 (last decade)**: calculations beyond LT ⇔ PDFs constrained up to x ~ 0.8-0.9

- *Alekhin et al.*

  S. Alekhin, Phys. Rev. D 63, 094022 (2001)

  ....

  S. Alekhin, J. Blumlein, S. Klein, S. Moch, Phys. Rev. D 81, 014032 (2010)

- CTEQ6X

  Accardi, Christy, Keppel, Melnitchouk, Monaghan, Morfín, Owens, Phys. Rev. D 81, 034016 (2010)

  Accardi *et al.*, in preparation

➢ **Stage 3: future**

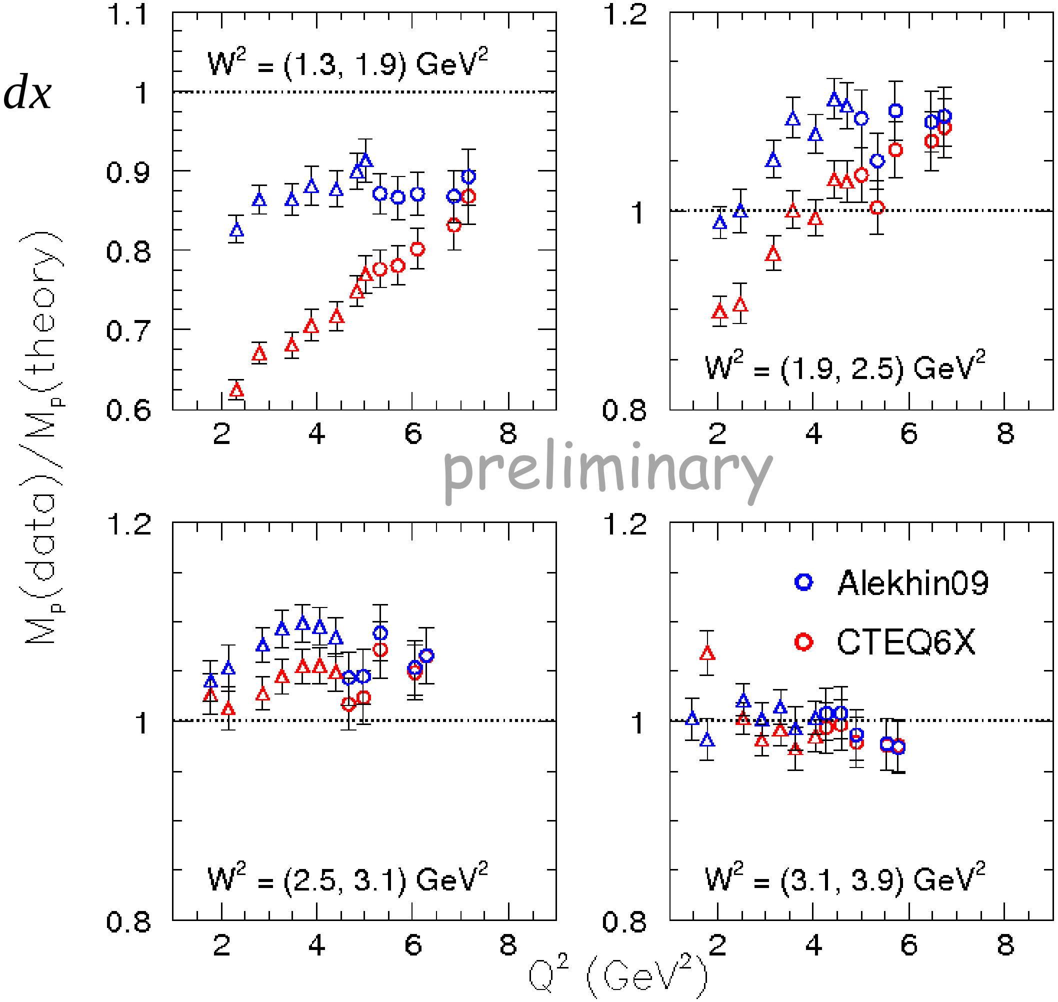
Plans for Future: Quark-Hadron Duality

A. Accardi, S.P. Malace, in preparation

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

- Study sensitivity of quark-hadron duality ratios to various prescriptions for inclusion of:
  - Higher Twist: additive vs multiplicative; HT(proton) same or different than HT(neutron)
  - Target Mass Corrections: OPE, CF…

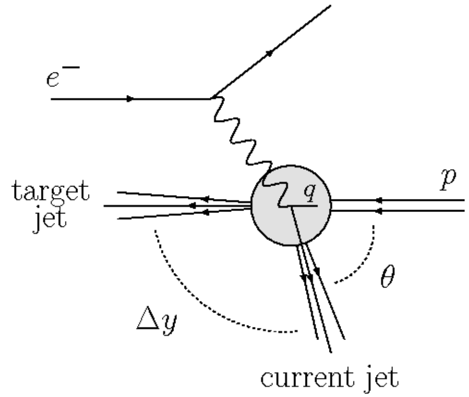
etc.

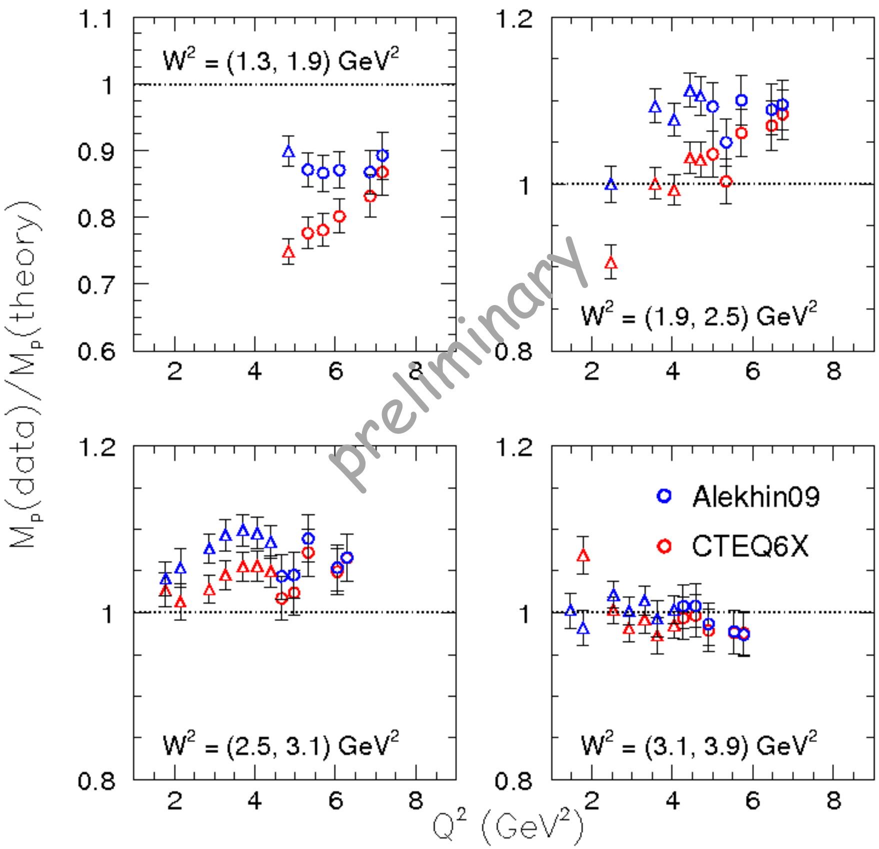


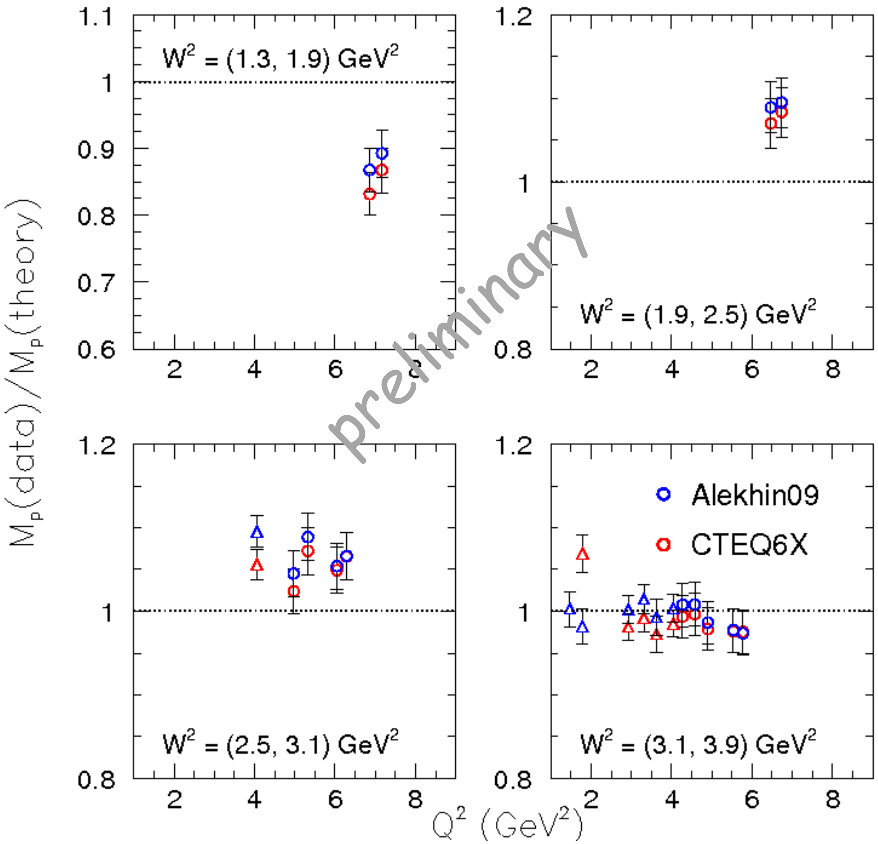
Plans for Future: Quark-Hadron Duality

A. Accardi, S.P. Malace, in preparation

- Study applicability of QCD calculation at low values of W; criterion: separation between target jet and current jet

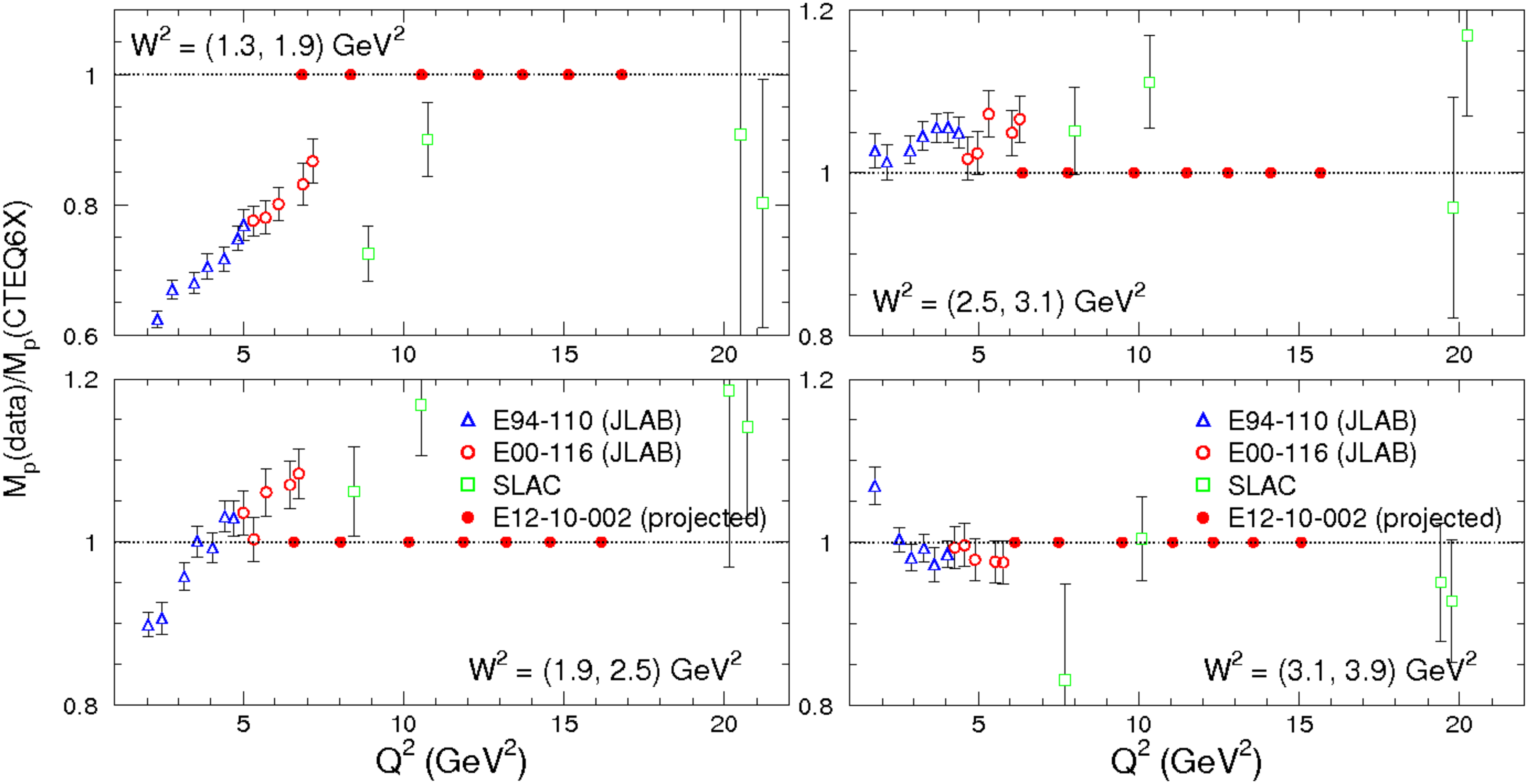




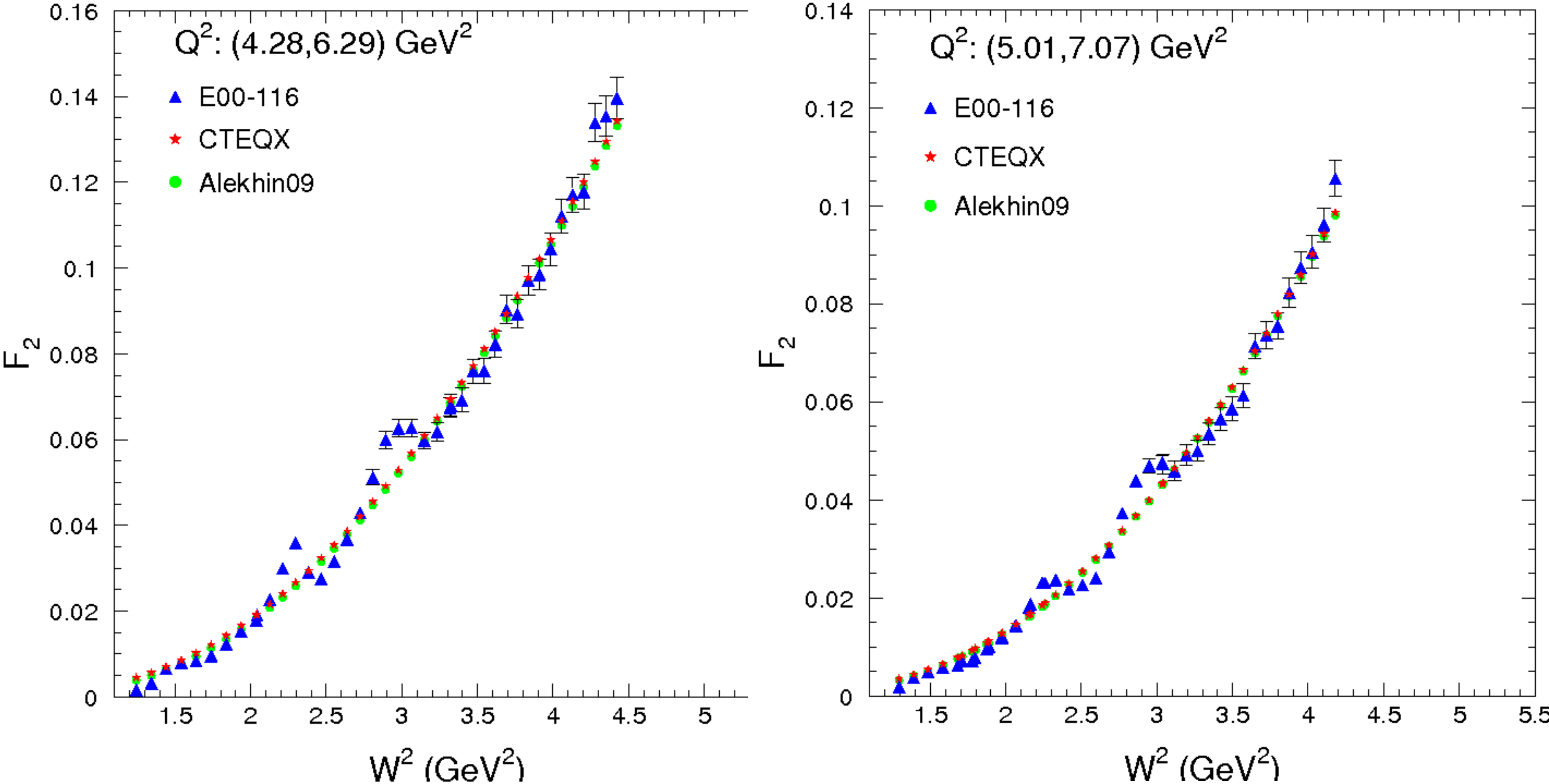


Duality @ 12 GeV: E12-10-002

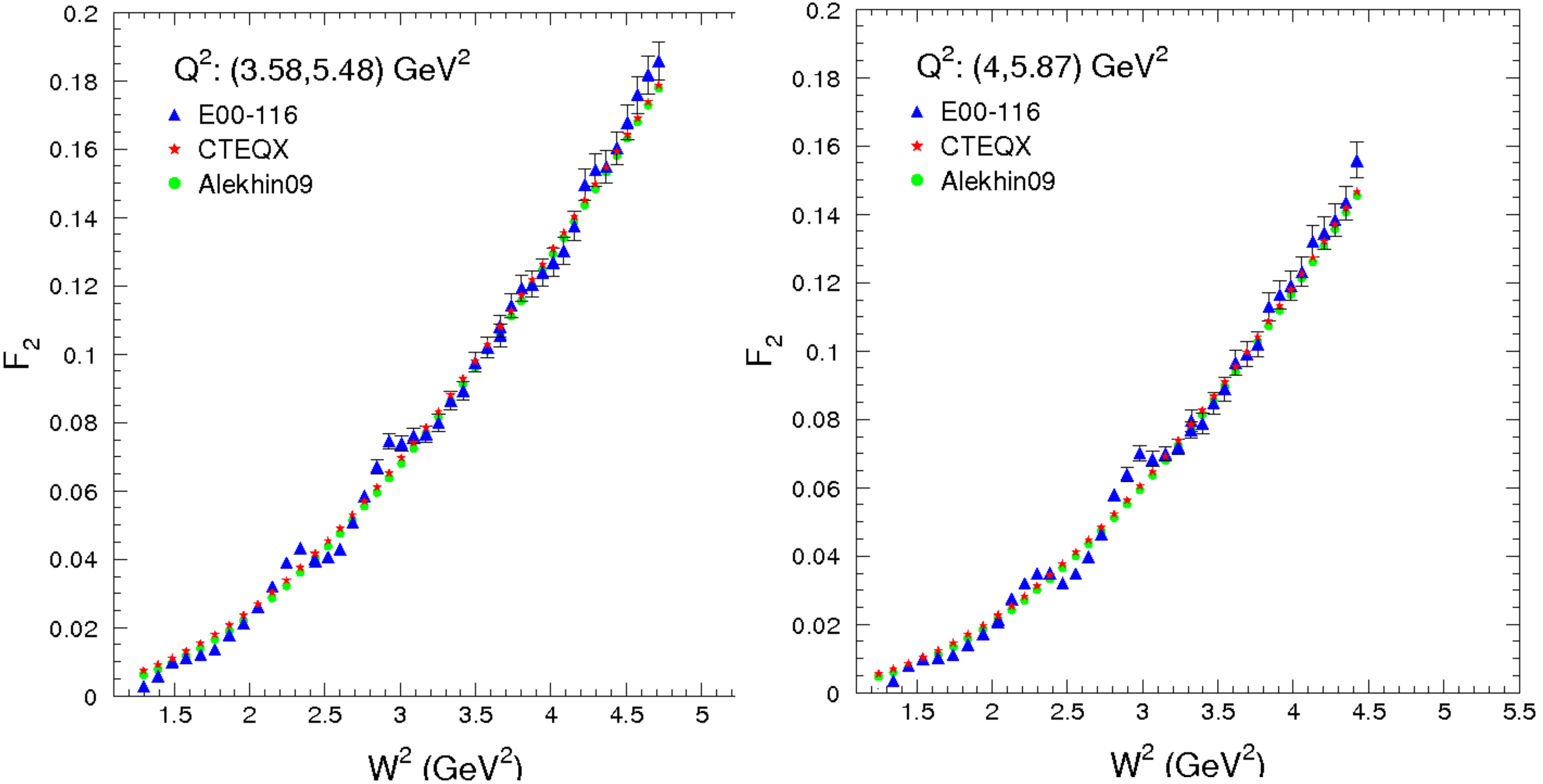
- Extend proton and deuteron F_2 structure function precision measurements to larger x and Q^2 in the resonance region and beyond up to W^2 ~ 9 GeV^2 , Q^2 ~ 17 GeV^2 and x ~ 0.99



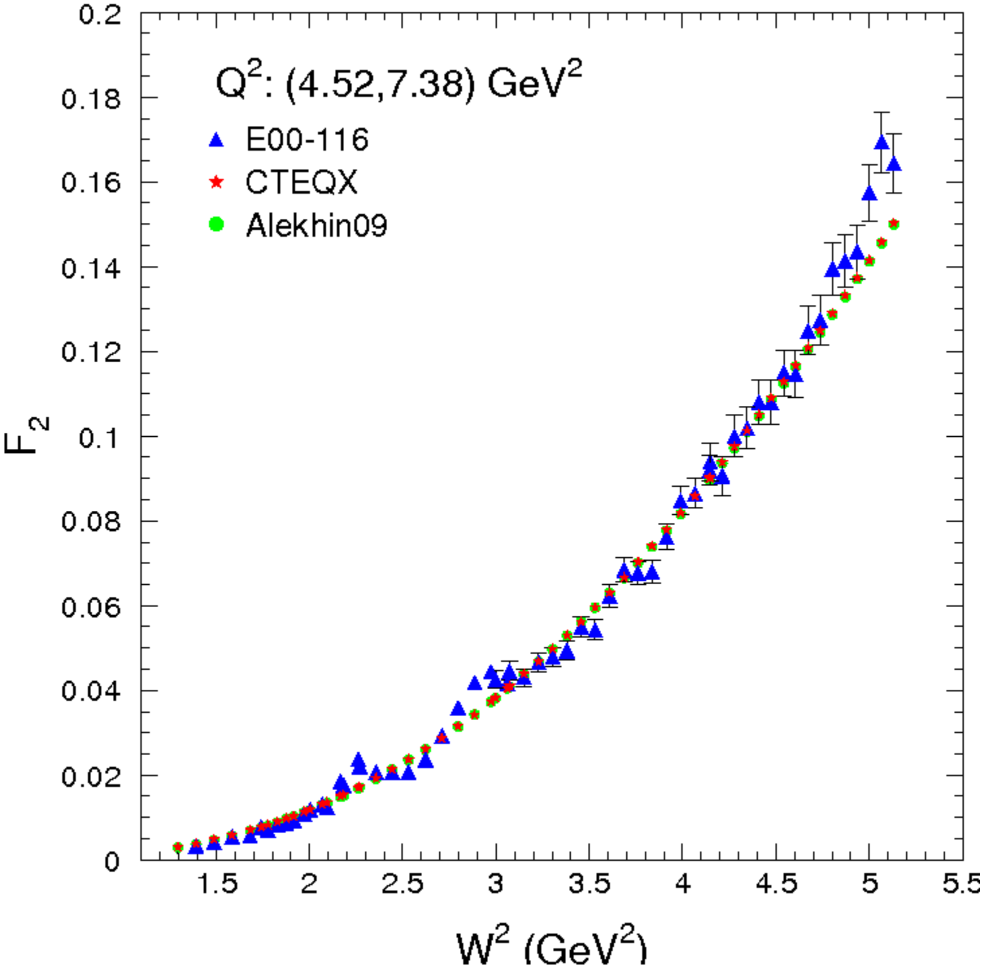
Extra Slides



Q2: (4.28,6.29) GeV2
E00-116
CTEQX
Alekhin09
F2
W2 (GeV2)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1.5
2
2.5
3
3.5
4
4.5
5
Q2: (5.01,7.07) GeV2
E00-116
CTEQX
Alekhin09
F2
W2 (GeV2)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1.5
2
2.5
3
3.5
4
4.5
5
5.5



Q^2: (3.58,5.48) GeV^2
E00-116
CTEQX
Alekhin09
F_2
W^2 (GeV^2)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1.5
2
2.5
3
3.5
4
4.5
5
Q^2: (4,5.87) GeV^2
E00-116
CTEQX
Alekhin09
F_2
W^2 (GeV^2)
5.5


Q²: (4.52,7.38) GeV²
E00-116
CTEQX
Alekhin09
F2
W² (GeV²)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1.5
2
2.5
3
3.5
4
4.5
5
5.5