Structure Functions at large x and low Q^2:

from DIS to the resonance region

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Special thanks to Alberto Accardi for assistance with slides from CJ PDF Collaboration

In this talk I will give an overview of the large x, low Q^2 landscape for inclusive Structure functions.

Outline

1. Inclusive structure functions and cross sections

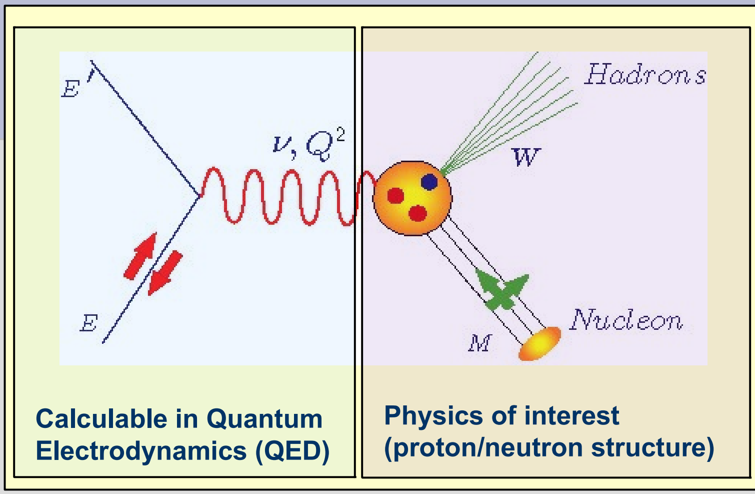
2. Status of charged-lepton proton, deuteron, and nuclear structure functions at large *x* and low Q^2

3. CJ collaboration fits: Minimizing parton distribution and *d/u* uncertainties at large *x*.

4. BoNuS neutron data and building F_2^d from F_2^p, F_2^n for the simplest nucleus

5. Quark-Hadron duality, status and possible application

Scattering of virtual photons from nucleons

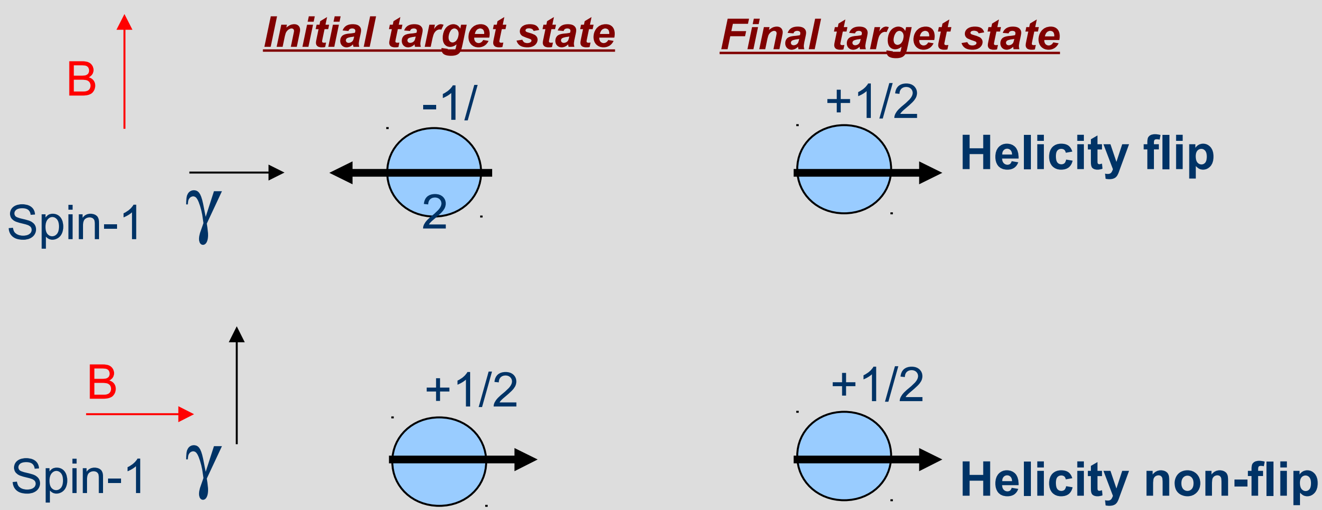


→ Virtual photon scatters from nucleon or from constituents.

→ Exchanged photon can have helicity (0,+/-1) corresponding to **B**-field (longitudinal, transverse)

Transverse Photon exchange (helicity -1 or +1)

Longitudinal Photon exchange (helicity 0)



Inclusive Charged-Lepton Scattering

$$\frac{d\sigma}{d\Omega\, dE'} \propto \Gamma\, [2xF_1(x,Q^2) + \varepsilon\, F_L(x,Q^2)]$$

Q^2 : photon 4-momentum

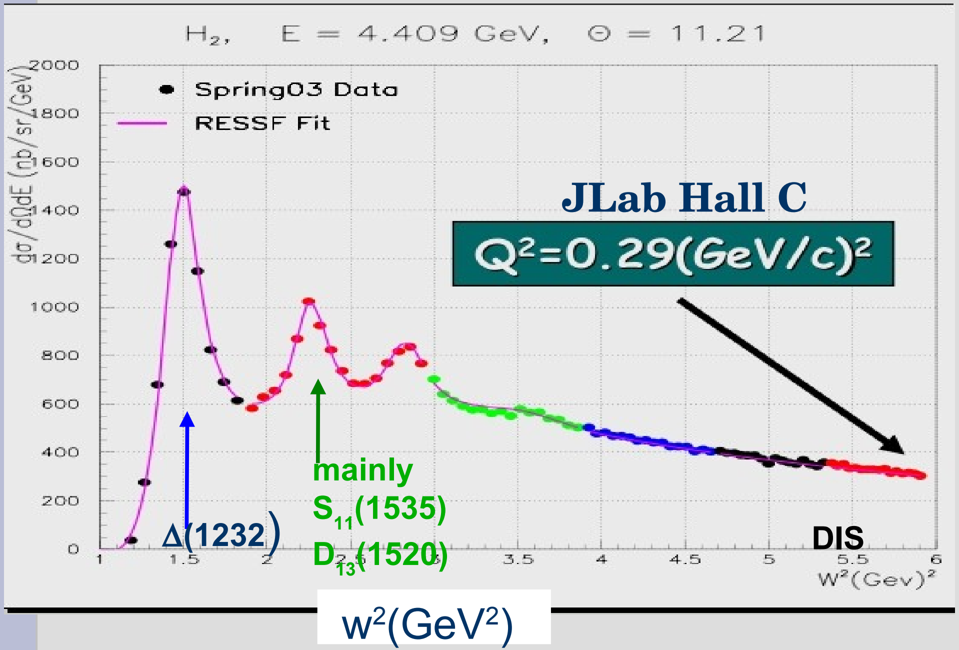
ν: photon energy

W: Final state hadron mass

x: Bjorken variable

Corresponding to absorption of transverse (longitudinal) photon

with polarization ε and flux Γ (given by kinematic factors)



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

Elastic → resonance → Continuum

Charged lepton scattering:

$$\frac{d^2\sigma^{e^\pm p}}{dxdy} = \frac{4\pi\alpha^2 s}{Q^4}\left[(1-y)F_2(x,Q^2) + y^2 x F_1(x,Q^2)\right]$$

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

(at LO) $F_2^{eN} = 5/18x\,(u + \bar{u} + d + \bar{d} + 2/5s + 2/5\,\bar{s})$

Neutrino scattering:

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 ME}{\pi}\left(\left[1 - y\left(1+\frac{Mx}{2E}\right) + \frac{y^2}{2} \times \left(\frac{1+\left(\frac{2Mx}{Q}\right)^2}{1+\mathcal{R}}\right)\right]\mathcal{F}_2 \pm \left[y - \frac{y^2}{2}\right]x\mathcal{F}_3\right)$$

$F_2^{\nu N} = x\,(u + \bar{u} + d + \bar{d} + s + \bar{s})$

R is difficult to measure in neutrino scattering and is typically assumed to the be same as for charged leptons.

=> Nuclear data on R at low W, Q^2 is important

but additional contributions at finite Q^2, e.g.

Kinematic 'Target Mass' Corrections

Fractional nucleon momentum carried by the struck quark away from Bjorken limit

$$\xi = 2x/(1+r)$$

With

$$r = 1 + \nu^2/Q^2 = \sqrt{1 + \frac{4M^2x^2}{Q^2}}$$

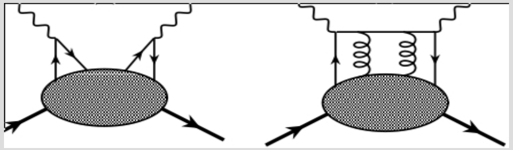
$$F_2^{TM}(x,Q^2) = \frac{x^2}{r^3}\frac{F_2^{(0)}(\xi,Q^2)}{\xi^2} + 6\frac{M^2}{Q^2}\frac{x^3}{r^4}\int_\xi^1 dx' \frac{F_2^{(0)}(x',Q^2)}{x'^2} + 12\frac{M^4}{Q^4}\frac{x^4}{r^5}\int_\xi^1 dx' \int_{x'}^1 dx'' \frac{F_2^{(0)}(x'',Q^2)}{x''^2}$$

What experiments measure **'Massless' limit described by PDFs**

Geogi, Politzer / Barbieri, et.al, '76

Higher Twist contributions (H-T):

Quark-Quark correlations: eg. gluon exchange between struck and spectator quarks.

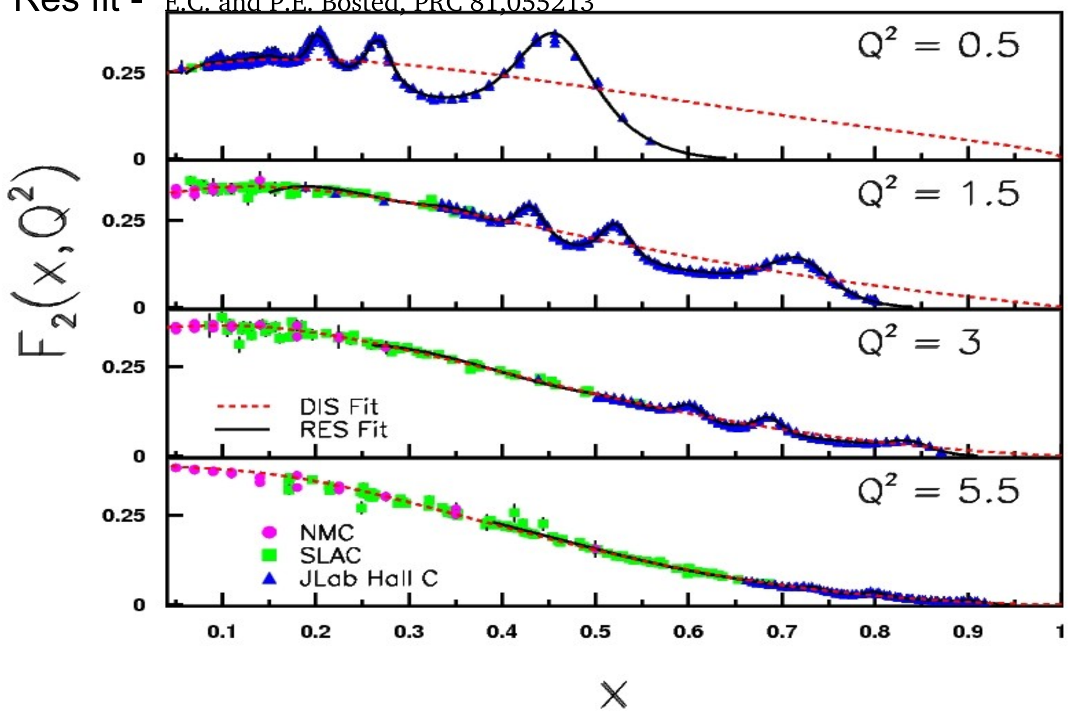


Suppressed as powers of $1/Q^2$

Status of charged lepton structure function data

Proton F_2 extremely well measured

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



Deuteron data of same quality

→ At low Q^2 resonances dominate high-x behavior

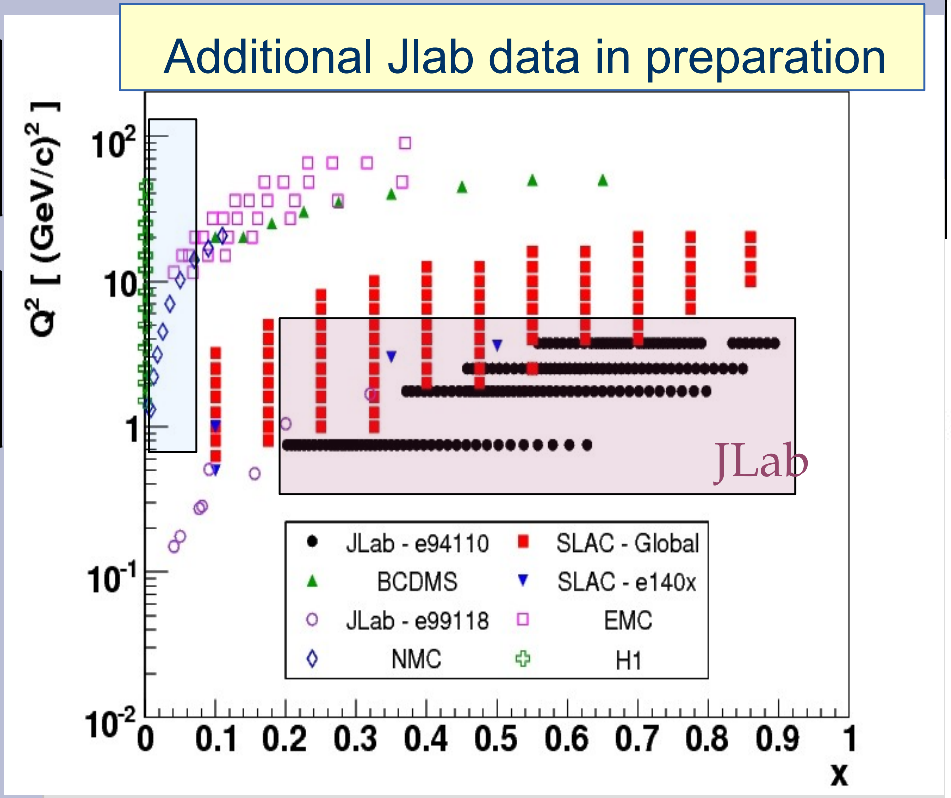
→ As Q^2 increases resonances at fixed W Appear to slide down the DIS scaling curve to higher x

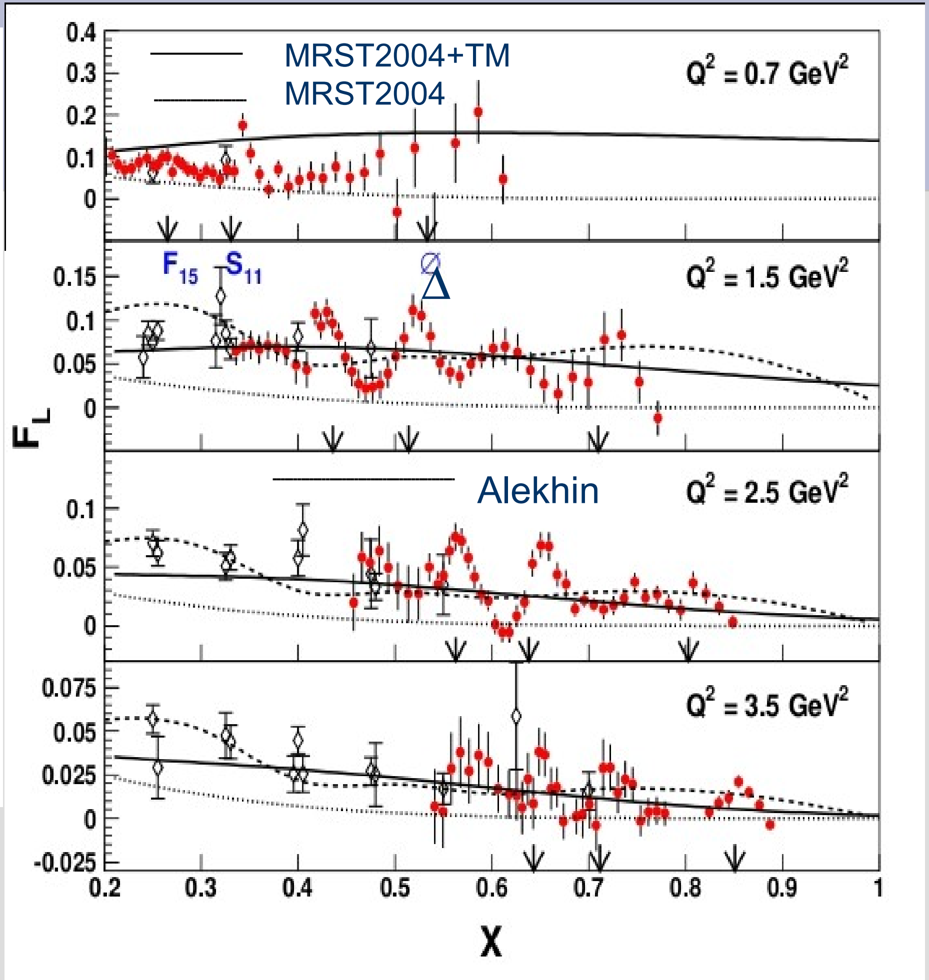
→ *Resonant production sits a top a smooth non-resonant Background.*

To model neutrino scattering cross sections we need to know:

1. DIS (reasonably well known except at large x)
2. Resonance (limited measurements of a few resonances, eg P_{33} (1232).
3. Non-Res continuum (very little is known)

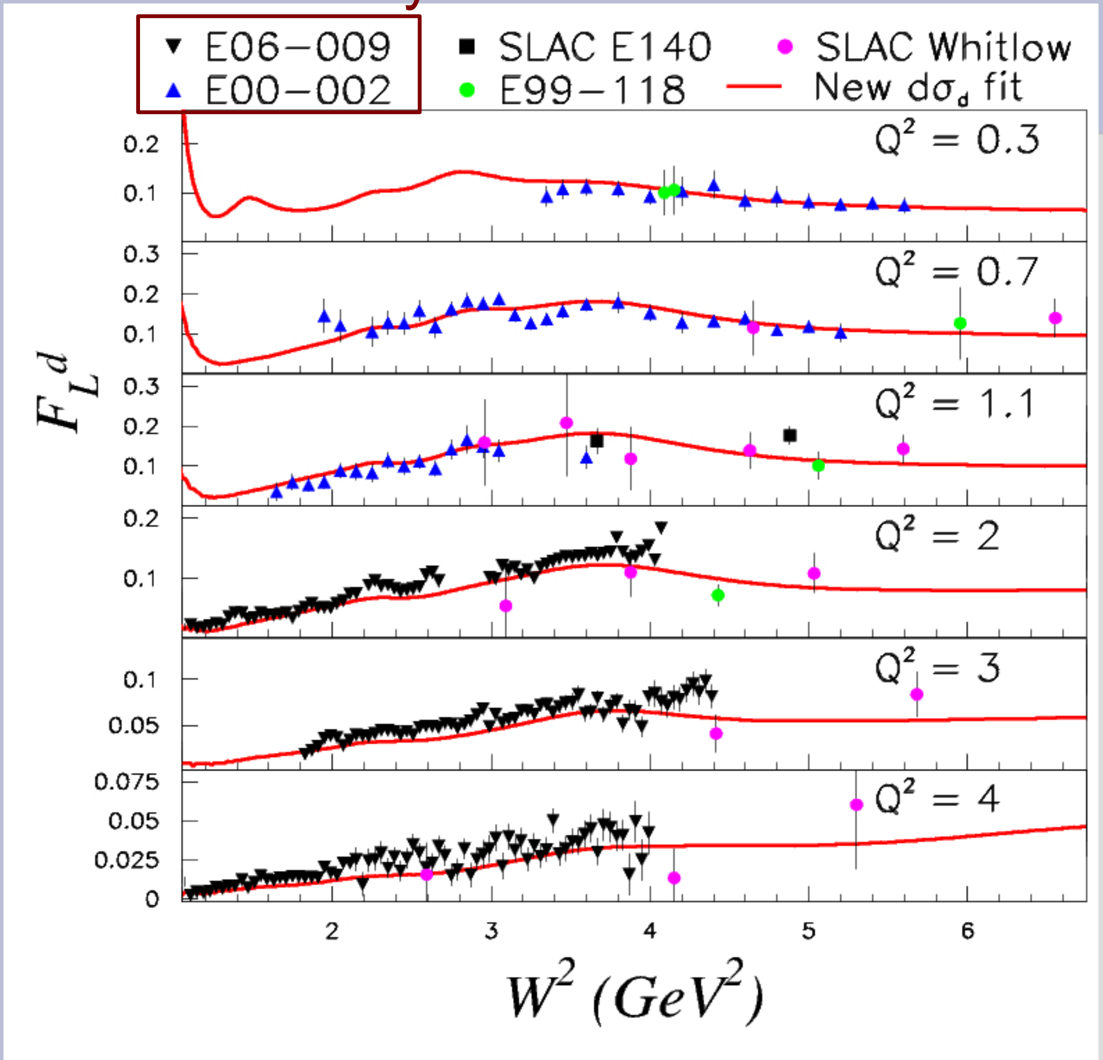
Status of F_L proton data





Status of F_L deuteron data

Preliminary

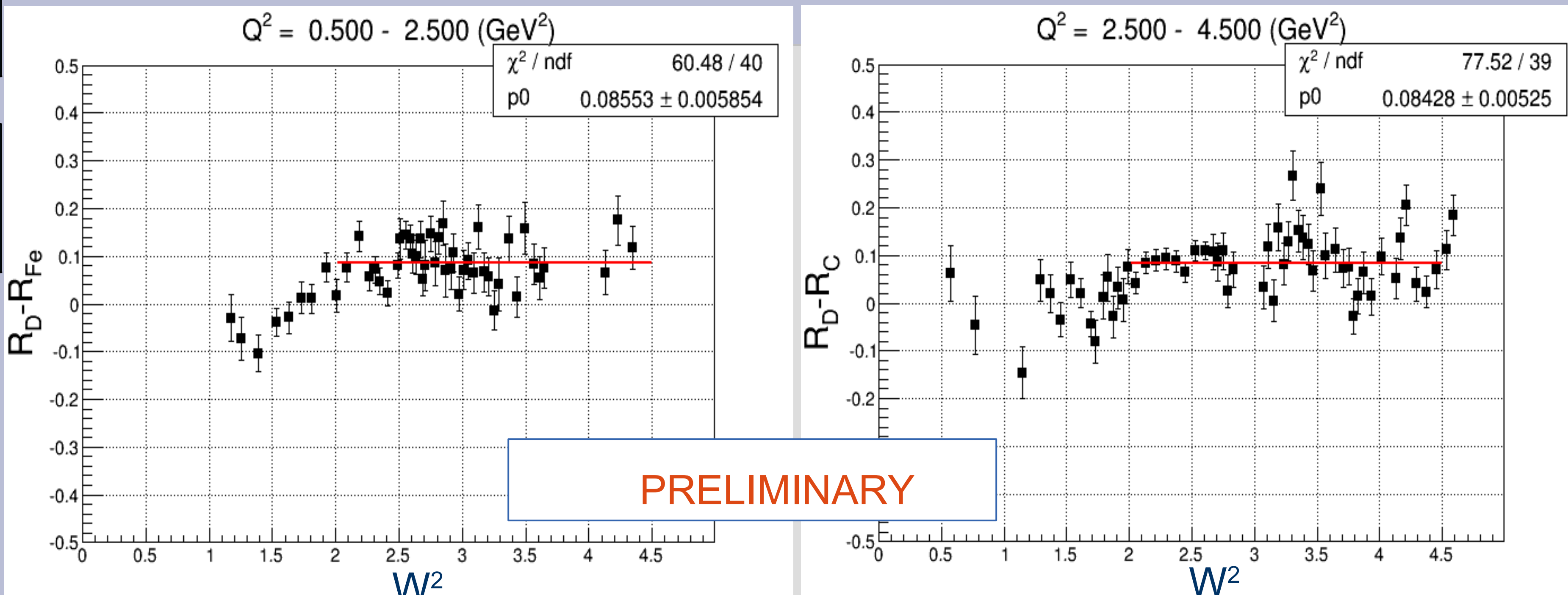


→ Finalizing precision deuteron data covering most of available Kinematic range at low Q^2

→ additional data at lowest Q^2 forthcoming.

Also R, F_L nuclear target data

E04-001 (Jupiter Collaboration)



→ First hint of nuclear dependence in R

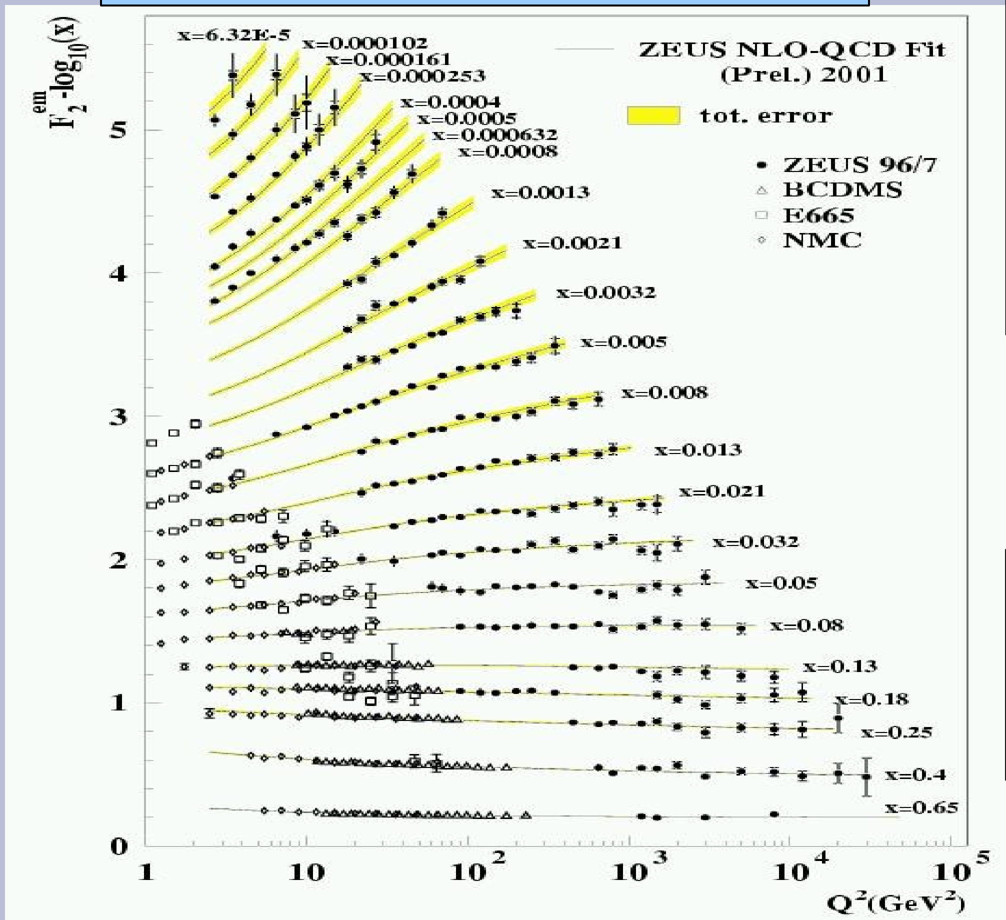
=> Different nuclear dependence in F_2, F_1, F_L

→ Final results in this Summer.

Precise proton, deuteron and nuclear structure functions F_2, F_1, F_L measured at large x during Jlab 6 GeV era.

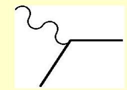
DIS Q^2 Evolution governed by perturbative QCD

Example from ZEUS NLO fit



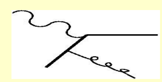
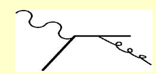
Single quark scattering (LO)

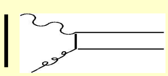
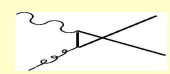
$F_2(x,Q^2) = x \sum e_q^{\,2}\, \mathbf{q}(x,Q^2)$

|  |^2

$F_L = 0 \Rightarrow F_2 = 2xF_1$, $R = 0$:
No transverse quark momentum

(NLO) order $\alpha_s(Q^2)$ corrections

|  +  |^2

and |  +  /2

=> transverse momentum and F_L ,
***F_L directly sensitive to the gluon, g(x).**

$$F_L(x,Q^2) = \frac{\alpha_s(Q)}{2\pi} x^2 \int_0^1 \frac{dy}{y^3} \left(\frac{8}{3} F_2(y,Q^2) + \sum_{i=1}^{2f} e_j^2 (y-x) g(y,Q^2) \right) + \ldots.$$

Much can be learned about pQCD from charged lepton DIS on a neutron target

At Leading order

$$F_2^p = x[4/9u(x) + 1/9d(x)]$$

$$F_2^n = x[4/9d(x) + 1/9u(x)]$$

At large x proton dominated by $u(x)$
neutron by $d(x)$
due to charge weighting.

→ u quark is well determined from proton data
→ Free neutron target would provide comparable information on d quark

Problem: no high density neutron target exists, and no high precision ν, νbar data on hydrogen!

The CTEQ-JLab global fits

- **Collaborators:**
  - **Theory:** A.Accardi, K.Kovarik, W.Melnitchouk, J.Owens
  - **Experiment:** M.E.Christy, C.Keppel, P.Monaghan
- **Goals:**
  - Improve large-*x* precision with larger DIS data set
  - Include all relevant large-*x* / small-Q^2 theory corrections
  - ***Quantitatively evaluate theoretical systematic errors***
  - ***Use PDFs as tools for nuclear and particle physics***

  Next: Expand focus to smaller x (strange, dbar-ubar, ….)

- **Public release: CJ12** – (will become CJ14 soon)
  - **Owens, Accardi, Melnitchouk, PRD87 (2013) 094012**
    - www.jlab.org/cj
    - Included in LHAPDF

Why? *[hadronic, nuclear, particle physics]*

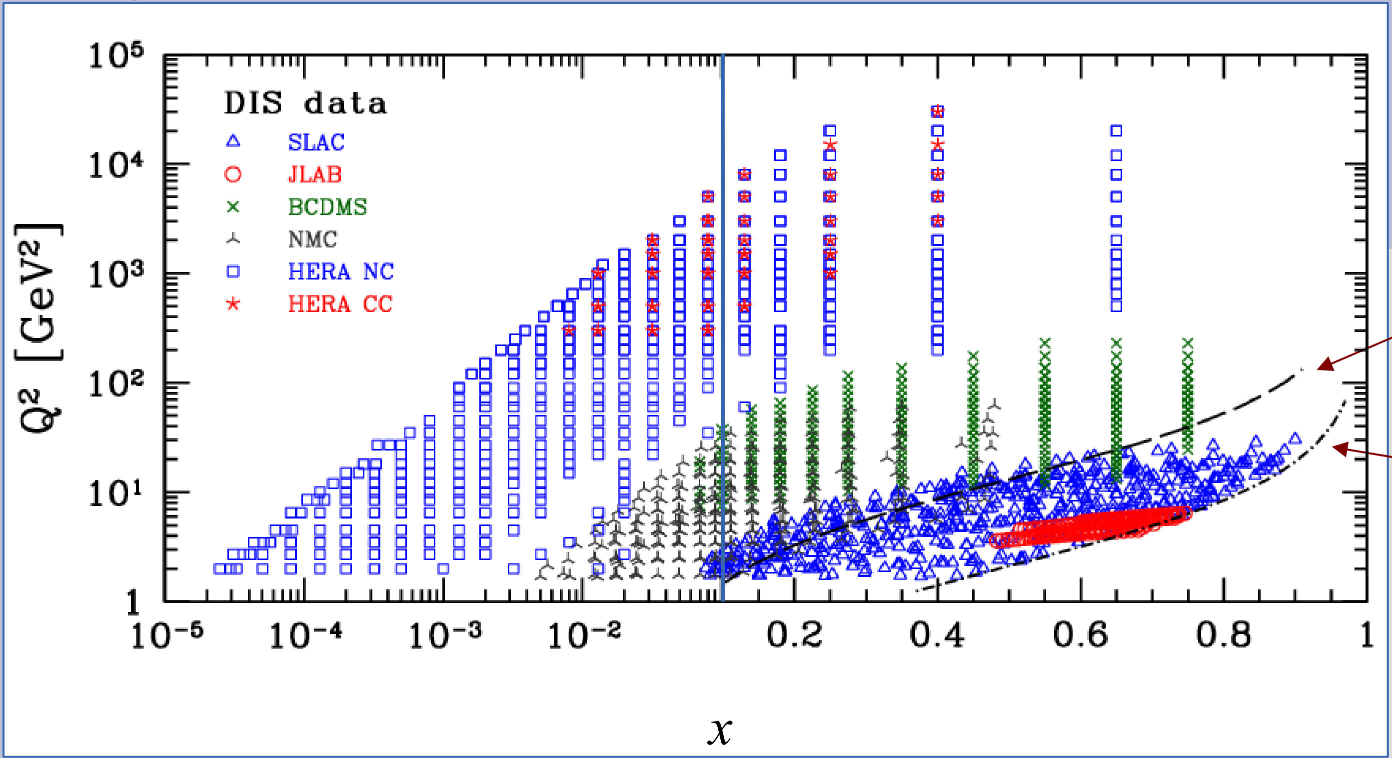
Accardi, Mod.Phys.Lett. A28(2013)35

- **LHC:** Increase potential for discoveries
  Precision measurements of particle properties

- **Non-perturbative structure of the proton**
  - Confinement effects on valence quarks
  - q – qbar asymmetries
  - Isospin symmetry violation
  - Intrinsic sea generation
  - Comparison to lattice QCD
  - ...

- **New handles on structure of the nucleus**
  - Nuclear targets for PDF fits (d-quark, neutrinos, ...)
  - Proton vs. nuclear targets → constraints on nuclear effects
  - Reduce DIS uncertainty in neutrino experiments

Large-x, small-Q^2 corrections



standard cut
$W^2 \gtrsim 14$ GeV^2

CJ12
$W^2 \gtrsim 3$ GeV^2

- **$1/Q^{2n}$ suppressed:**
  - Target mass corrections (TMC), higher-twists (HT)
  - Current jet mass, heavy quark masses

Accardi et al.
PRD ***D81*** *(2010)*

included in CJ fits

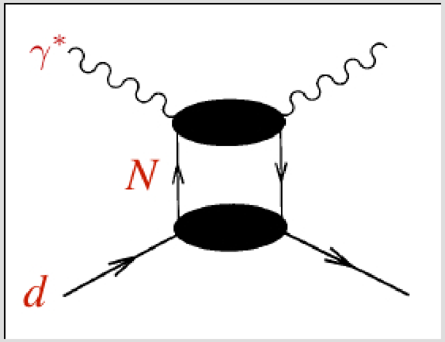
- **Non-suppressed**
  - Nuclear corrections, threshold resum., parton recomb.
- **New d-quark parametrization:**

$$d'(x) = d(x) + \alpha\, x^3 u(x)$$

Deuteron corrections

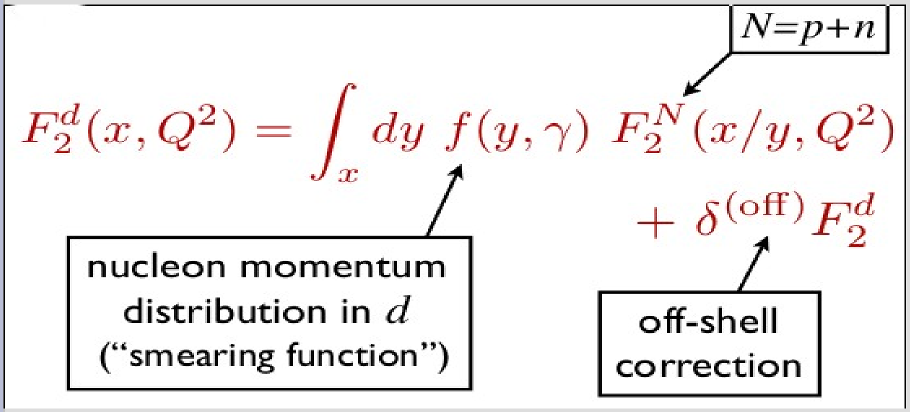
- No free neutron! Best proxy: Deuteron
  - Parton distributions (to be fitted)
  - nuclear wave function (AV18, CD-Bonn, WJC1, ...)
  - Off-shell nucleon modification (model dependent)

} Theoretical uncertainty

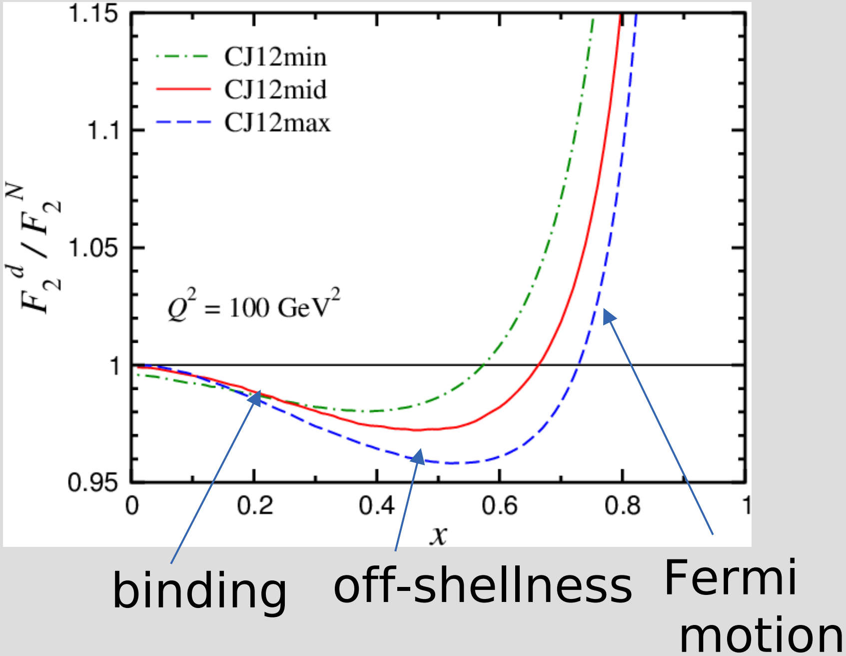


y: lightcone momentum fraction of d carried by N

γ: kinematic factor



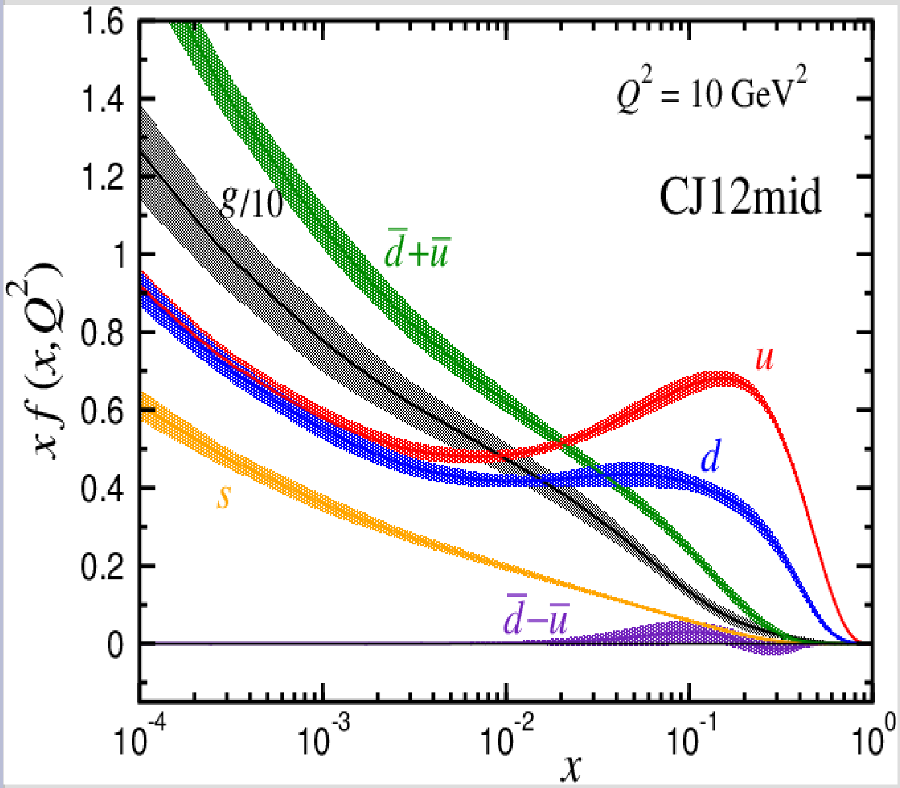
Bound vs. free proton+neutron



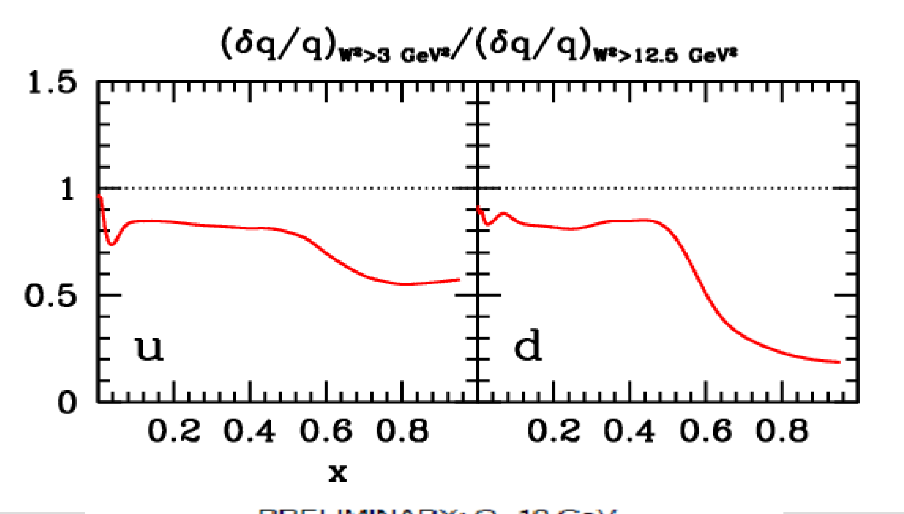
CJ12 parton distributions

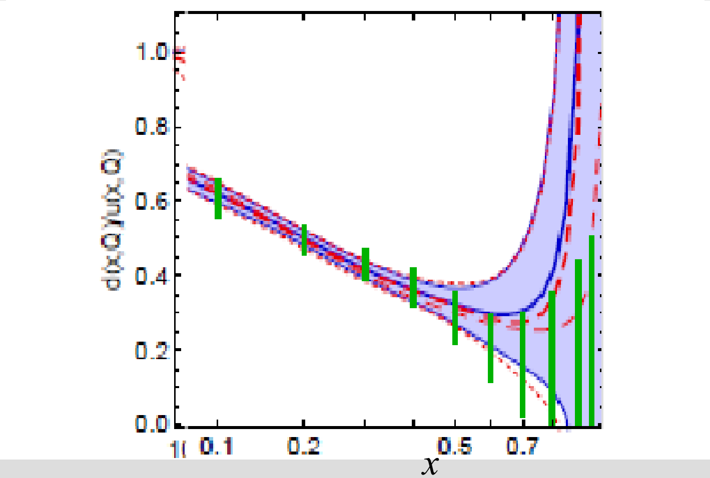
Owens, Accardi, Melnitchouk, PRD87 (2013) 094012

All-x parton distributions:



Large reduction in *d*-quark error:



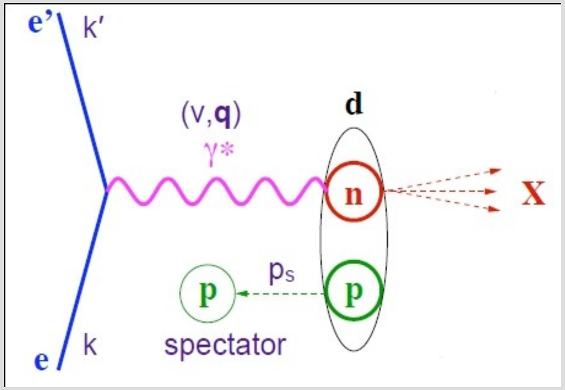


A free neutron target would provide:

1. direct access to *d/u* in DIS.
2. A systematic check on the nuclear modeling uncertainties.

The BoNuS experiment at JLab has final data on F_{2n}/F_{2p} utilizing the Spectator tagging method

N. Ballie et.al PRL 108 (2012) 199902
S. Tkachenko et.al PRC 89 (2014) 045206

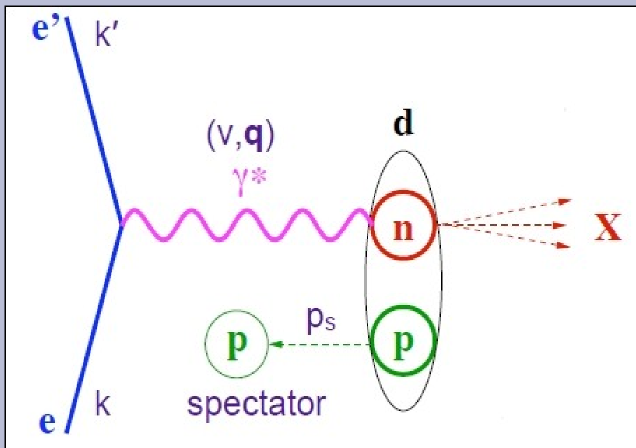


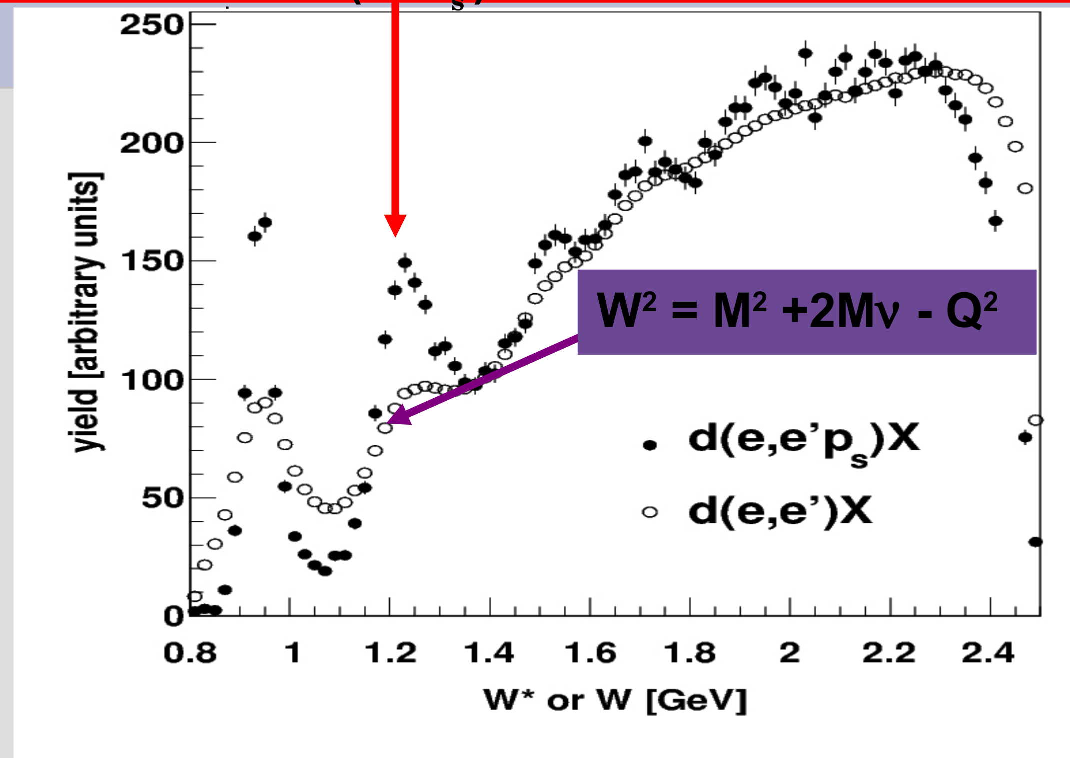
Tagging backward, low momentum spectator proton Minimizes effects due to

1. Final state interactions
2. Off-shell
3. Target fragmentation backgrounds

Spectator Tagging (BoNuS)

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

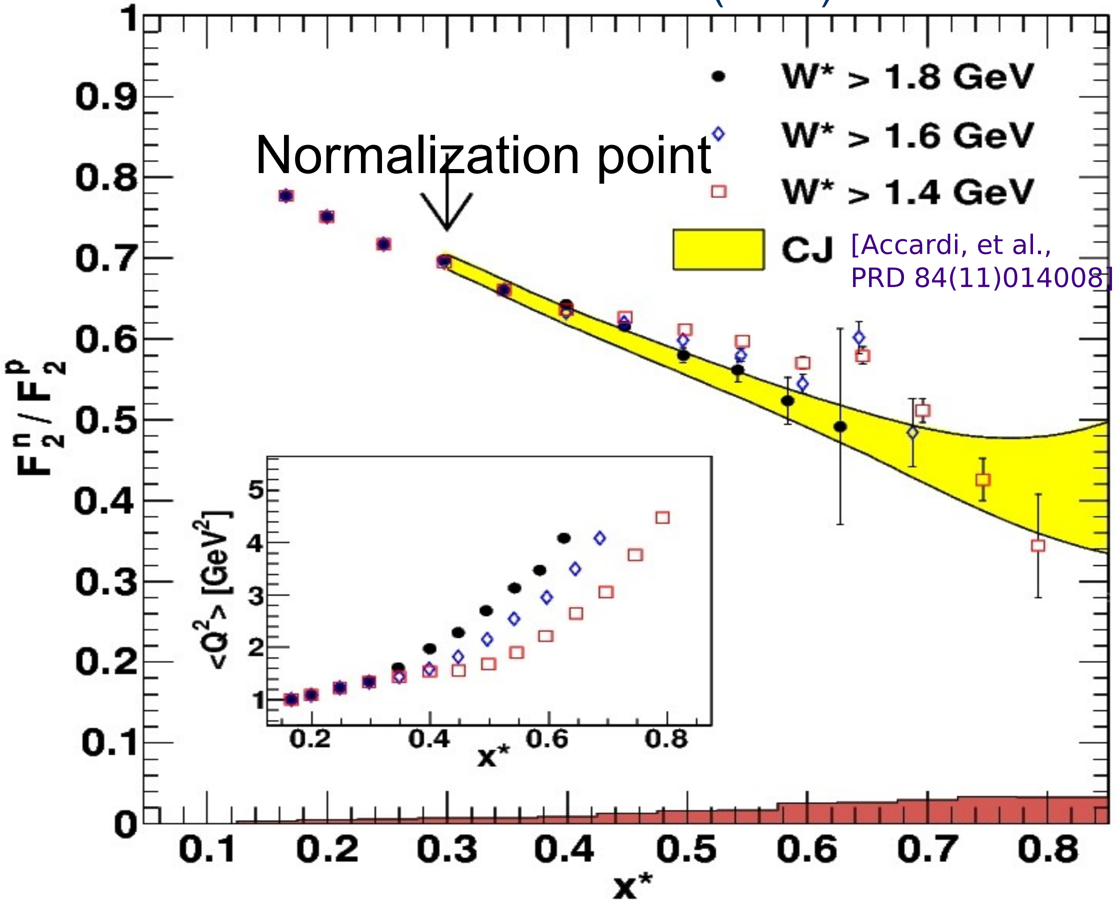




PWIA: → Backward P is spectator
→ Neutron is offshell
→ $\mathbf{p}_n = -\mathbf{p}_p$
=> correct for neutron momentum

'DIS' Results on F_2^n / F_2^p

N. Ballie et.al PRL 108 (2012) 199902

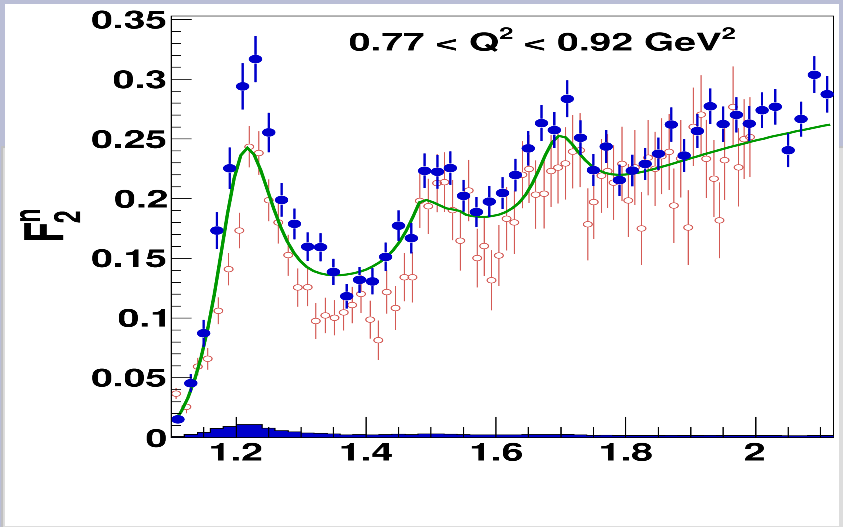


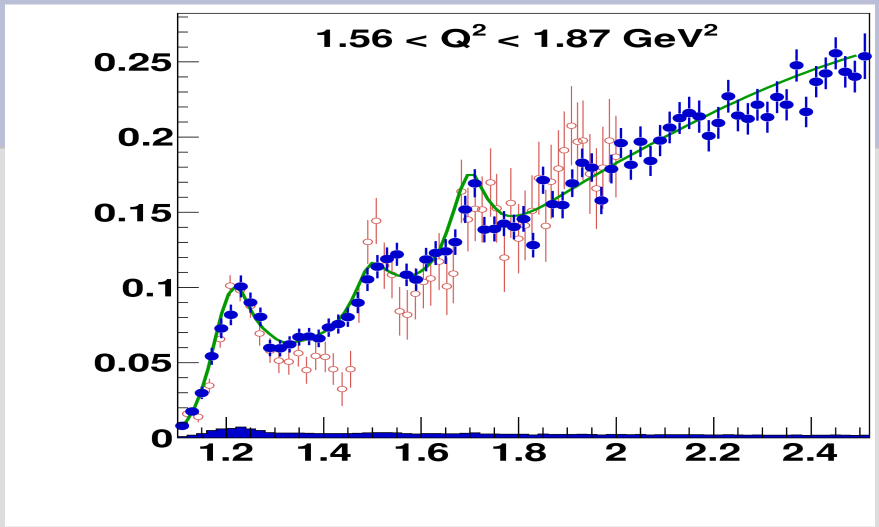
→ F2n/F2p = F2n/F2d * F2d/F2p with F2d/F2p from Bosted/Christy fits PRC77(08)065206, PRC81(10)055213

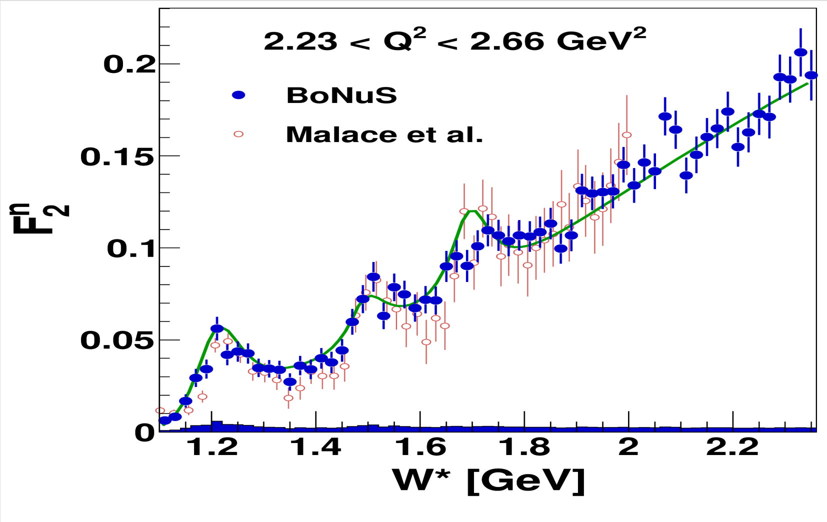
→ Trend in x consistent with CJ11.

→ Lower W* cuts reduce stat. uncertainty, but increase resonant contribution at x >0.6

Resonance F_2^n results







Neutron resonance region structure functions

Utilize same theoretical framework as CJ

Fit inclusive deuteron data with $1.05 < W^2 < 11$, $0.04 < Q^2 < 10.5$, and all ε

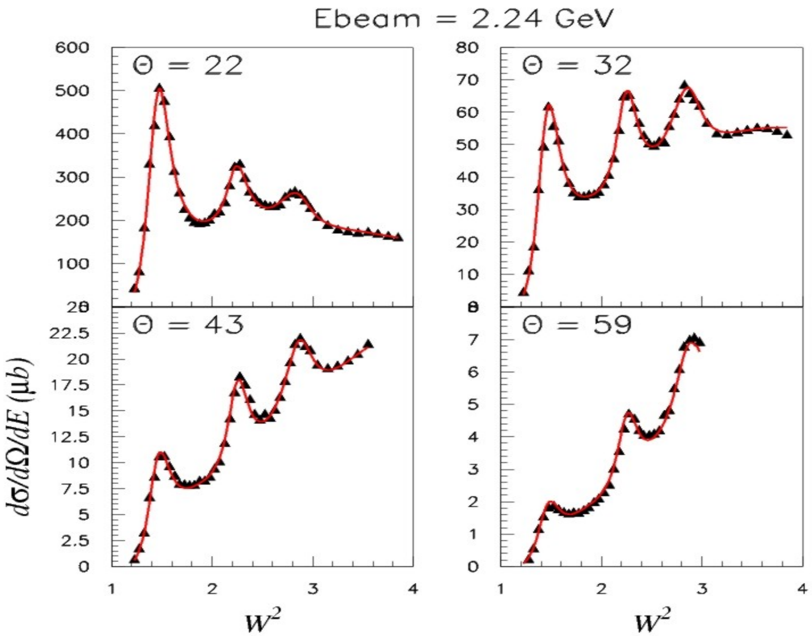
→ parameterization of neutron resonance region SFs. (parameters determined from fit) and utilize existing fit to proton data

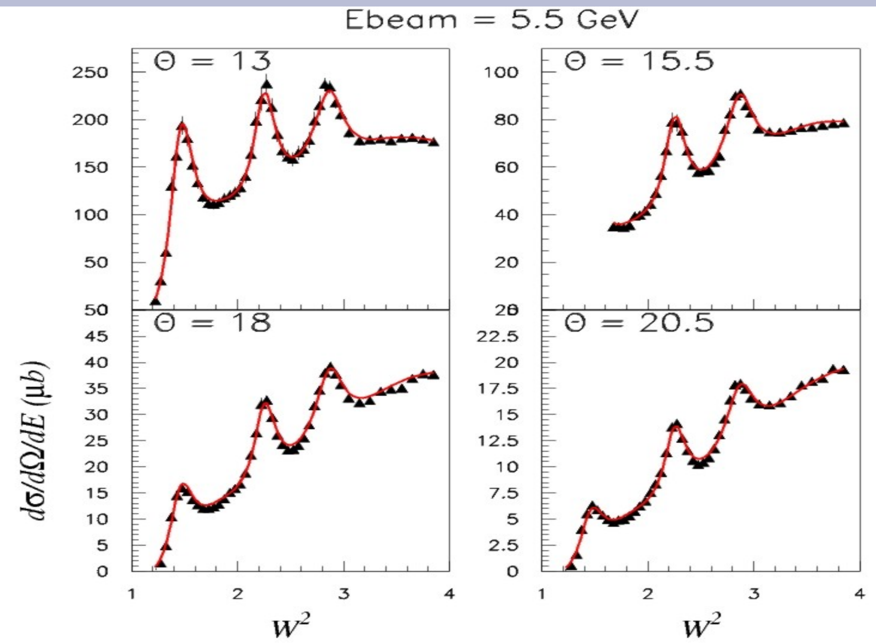
→ Provide improved deuteron fit to F_2,F_1,F_L.

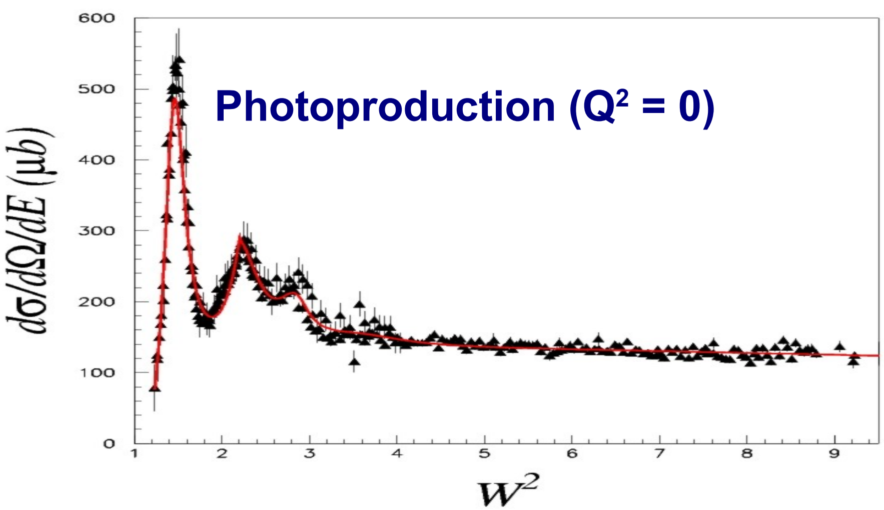
→ Comparison of F_2^n to BoNuS data provide check on theoretical Framework.

Utilize existing resonance proton fit

M.E.C. and P.E. Bosted, PRC 81,055213







Kinematic range of fit:

$0 < Q^2 < 8$ and $W < 3$

- **reproduces cross section data to ~3%**
- **Fit to both σ_T and σ_L**
- **Similar fit to deuteron (smeared n+p)**

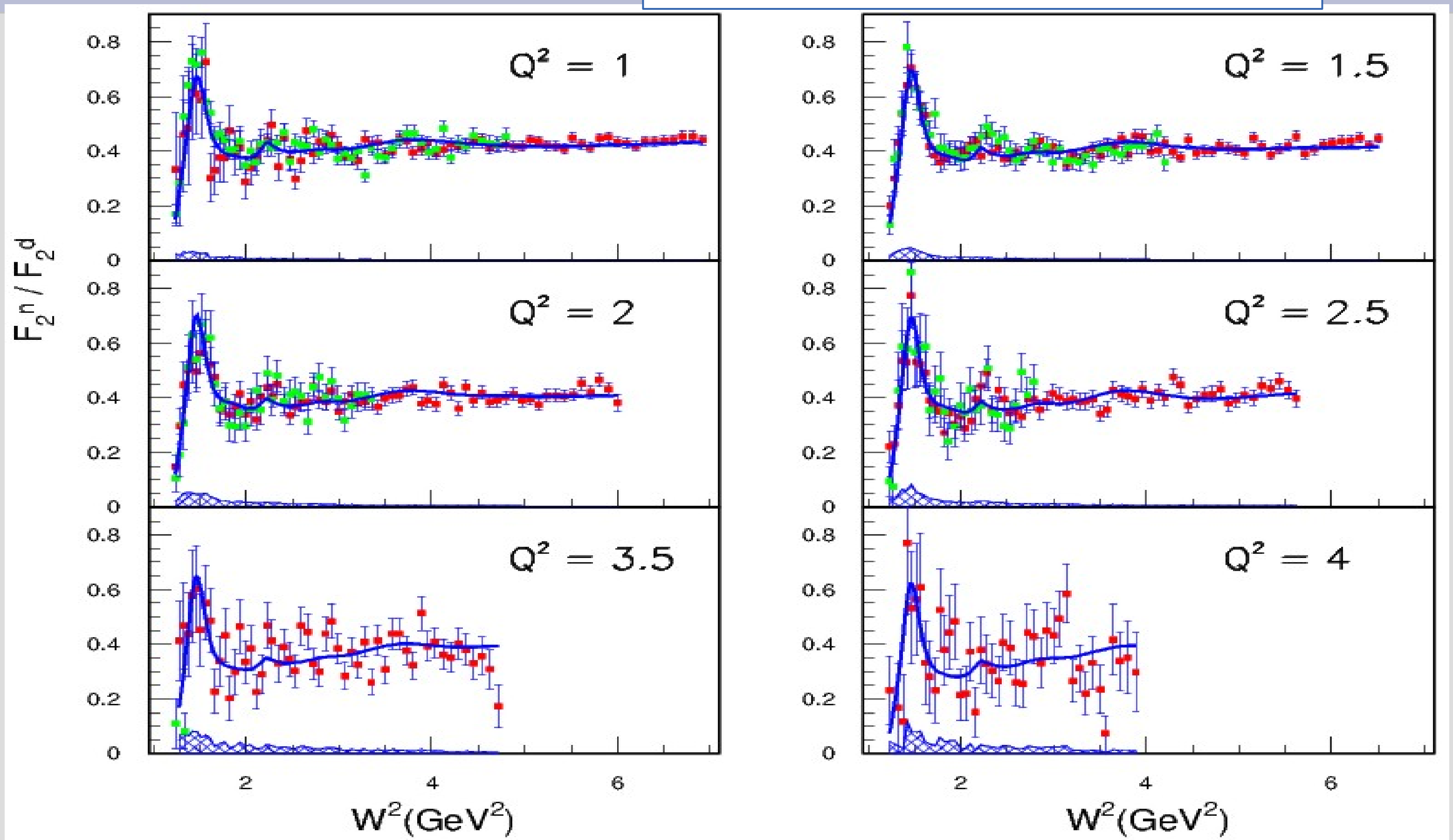
P.E. Bosted and MEC , PRC 77, 065206

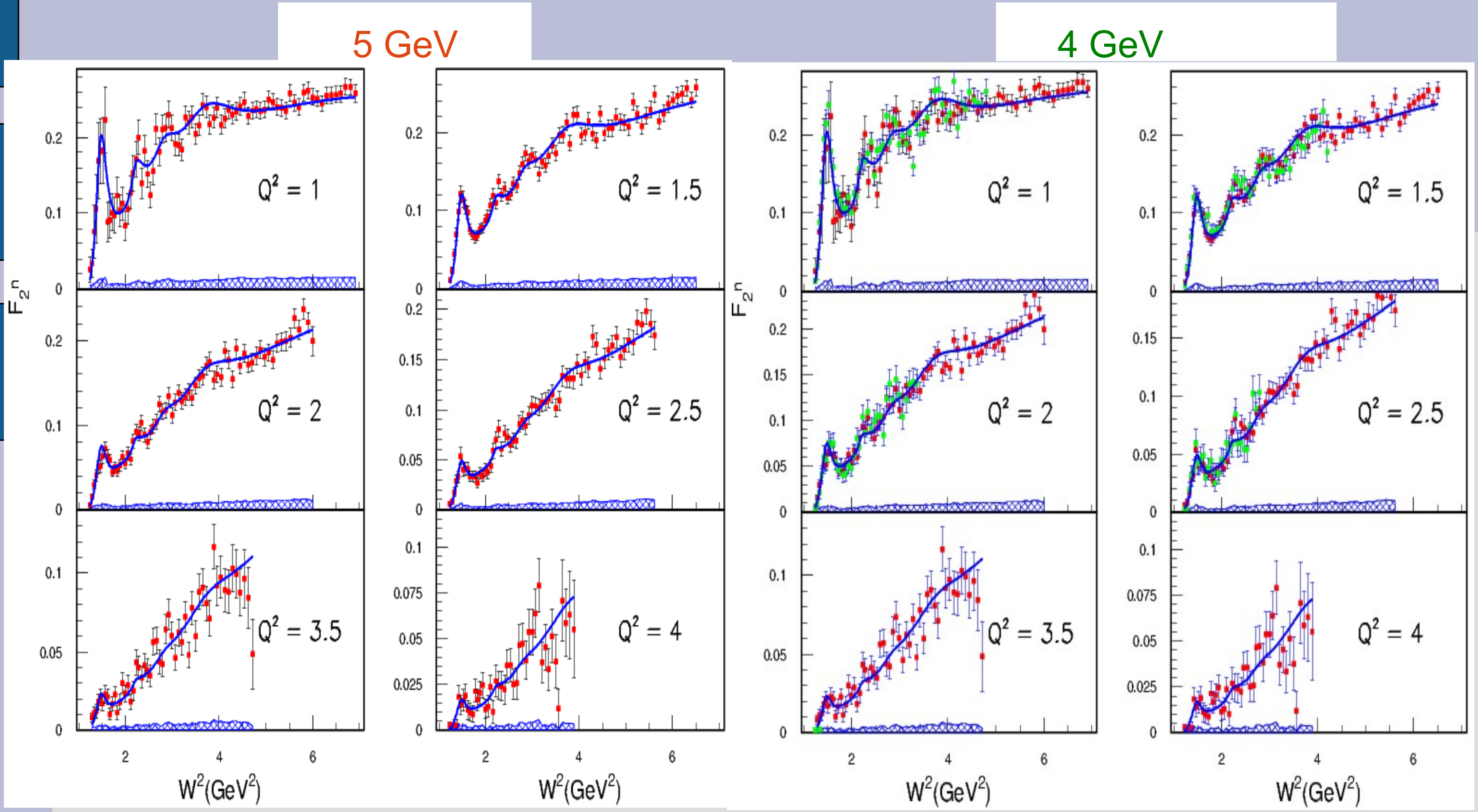
Results from fitting to inclusive D_2 data comparable to proton fit.

Comparison to Bonus F_{2n}/F_{2d}

M.E. Christy, N. Kalantarians, J. Ethier, W. Melnitchouk

5 GeV 4 Gev





→ ***Not*** a fit to this data

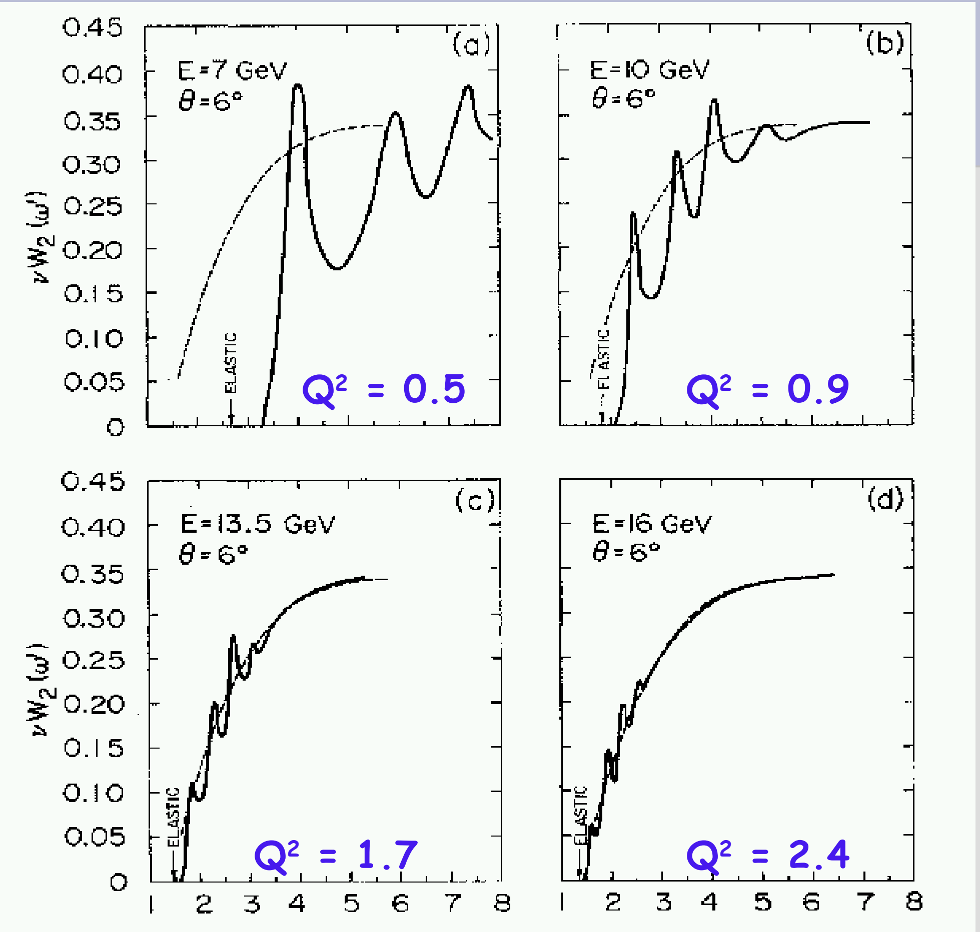
=> Provides check on theoretical construction of deuteron and parametrization of neutron structure functions

Phenomena of Quark-Hadron Duality

- First observed by Bloom and Gilman At SLAC ~1970, prior to development of QCD.

  Phys.Rev.Lett.25:1140,1970.

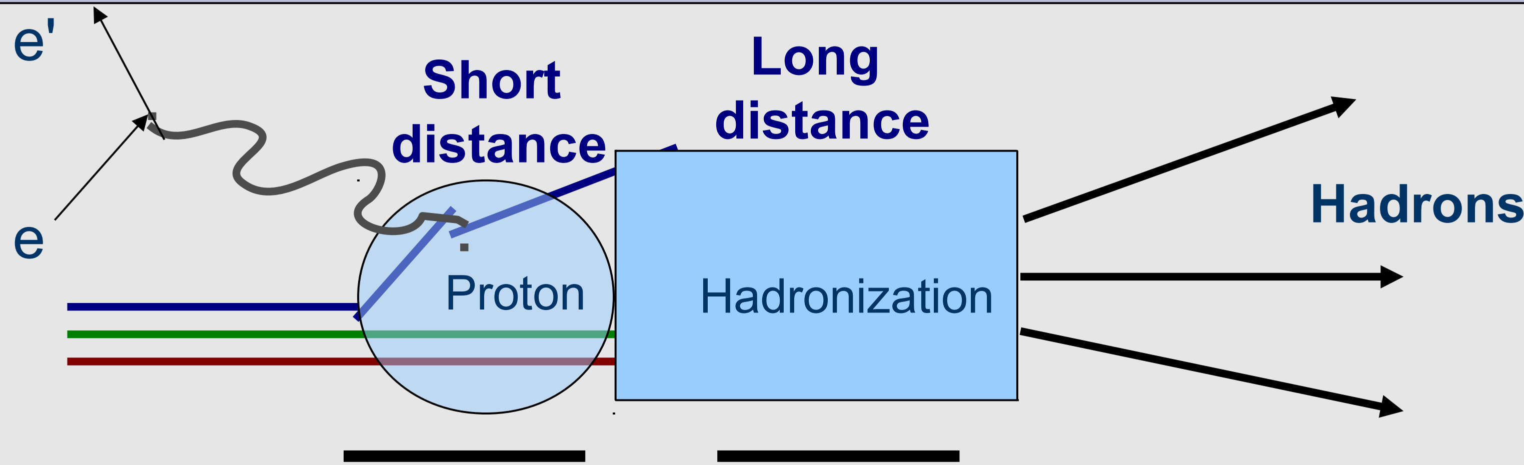
- Noted that resonances oscillate around a 'scaling' curve at all Q^2.
  - hadrons follow the DIS scaling behavior.



$\omega' = 1 + W^2/Q^2$

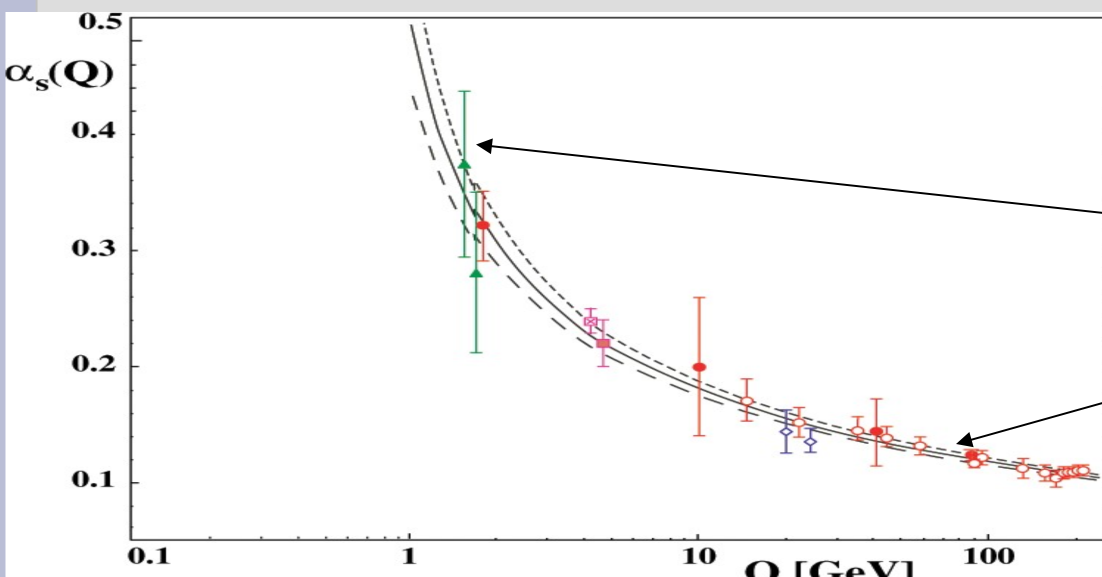
Novel observation that was generally left unstudied for next 30 years.
Now observed in a range of observables at JLab... eg. spin structure functions.

2 Defining Properties of QCD



Asymptotic Freedom ensures coupling to nearly free partons at high enough energies.

Confinement ensures that only hadrons are directly observed.



quarks are far apart

=> restoring force is large enough to pull q qbar pairs from vacuum.

quarks are close (~< 1fm)

=> strong coupling is small

When describing properties of hadrons:

1. At low energies effective theories with baryons and mesons as degrees of freedom often work well.

2. quarks and gluons are manifest at large energies as the fundamental constituents.

The transition between these 2 QCD regimes is *not* understood, and solutions to full QCD are primarily limited to the Lattice in the non-perturbative regime.

Quark-Hadron Duality

complementarity between quark and hadron descriptions of observables

At high enough energy:

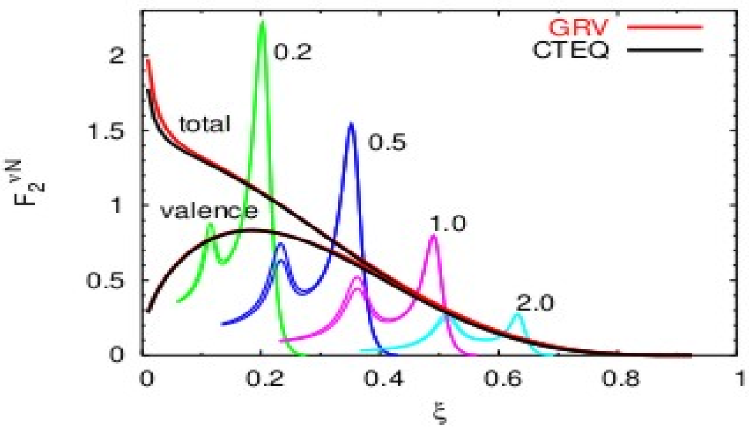
Hadronic Cross Sections averaged over appropriate energy range	=	Perturbative (Quark-Gluon)
Σ_{hadrons}		Σ_{quarks}

Can use either set of complete basis states to describe physical phenomena provided you sum over enough states

Predictions for neutrino scattering from a number of groups (see talk by O. Lalakulich NuInt 2009)

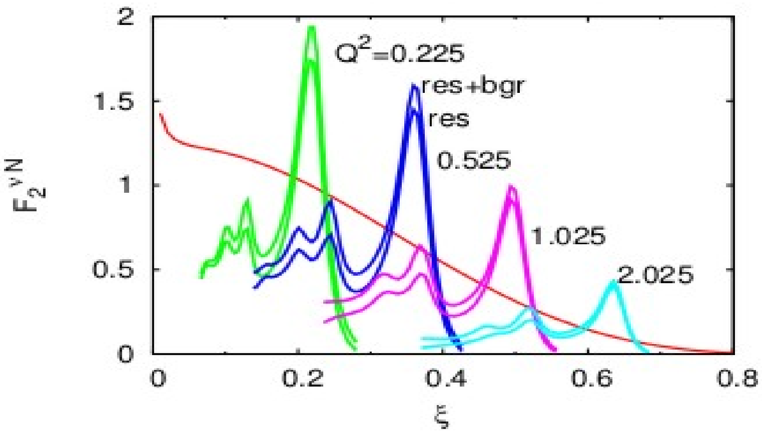
$F_2^{\nu p,\nu n}$: Duality HOLDS for the averaged structure functions

Duality: on average the resonances appear to oscillate around and slide down the leading twist function



OL, Melnitchouk, Paschos, PRC 75

included: 4 resonances
F_2 calculated analytically
investigation of F_3 and $2xF_1$ is also done



Giessen BUU

included: 12 resonances + phenomenological 1-pion background
F_2 is restored from xsec

Predictions for neutrino scattering from a number of groups (see talk by O. Lalakulich NuInt 2009)

$F_2^{\nu p, \nu n}$: In neutrino–nucleon scattering duality does NOT hold for proton and neutron targets separately

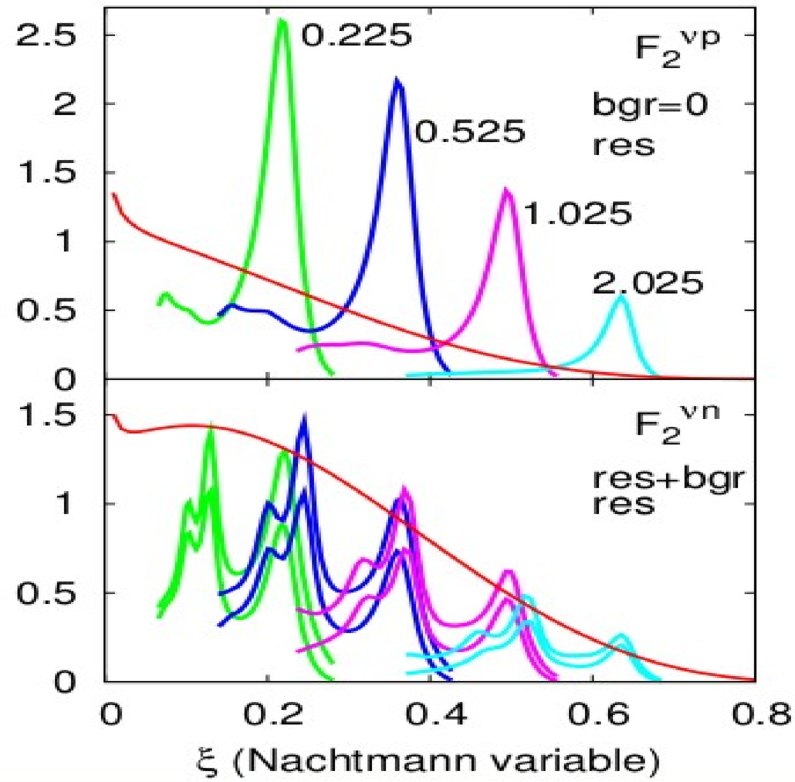
Low-lying resonances: $F_2^{\nu n(res)} < F_2^{\nu p(res)}$
neutron<proton

DIS: $F_2^{\nu n(DIS)} > F_2^{\nu p(DIS)}$
neutron>proton

$F_2^{\nu p(res-3/2)} = 3 F_2^{\nu n(res-3/2)}$
$F_2^{\nu p(res-1/2)} \equiv 0$

$F_2^{\nu n(res)}$: finite contributions from isospin-3/2 and -1/2 resonances

Interplay between the resonances with different isospins: isospin-3/2 resonances give strength to the proton structure functions, while isospin-1/2 resonances contribute to the neutron structure function only

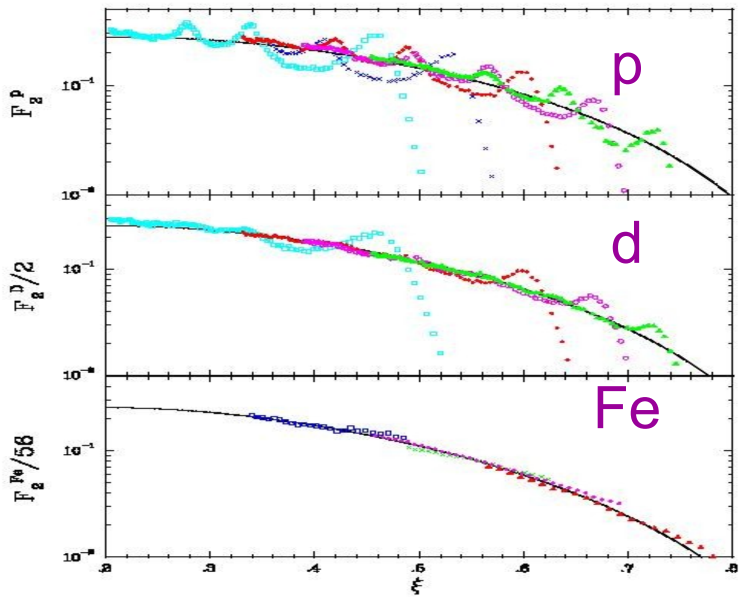


Olga Lalakulich (Justus–Liebig University, Giessen) Duality and neutrinos NuInt 09, Sitges, 21 May 2009 6 / 22

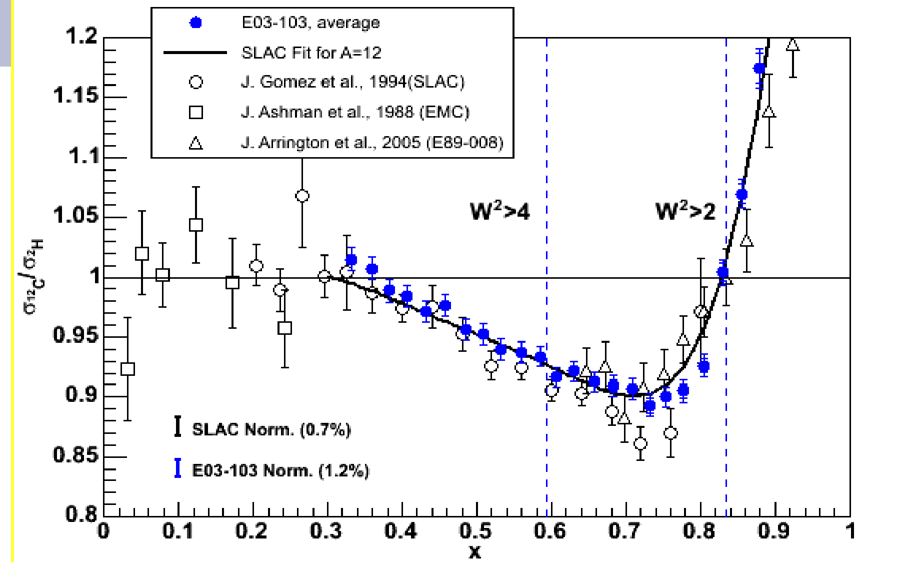
→ Important consequences for non-isoscalar targets such as 56Fe.

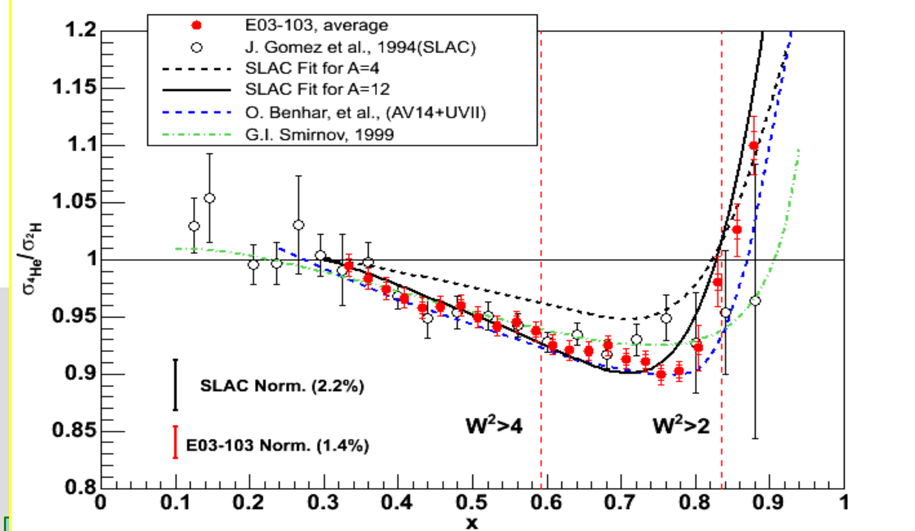
Duality in Nuclei

$\xi = 2x / [1 + (1 + 4M^2x^2/Q^2)^{1/2}]$



Jlab E03-103

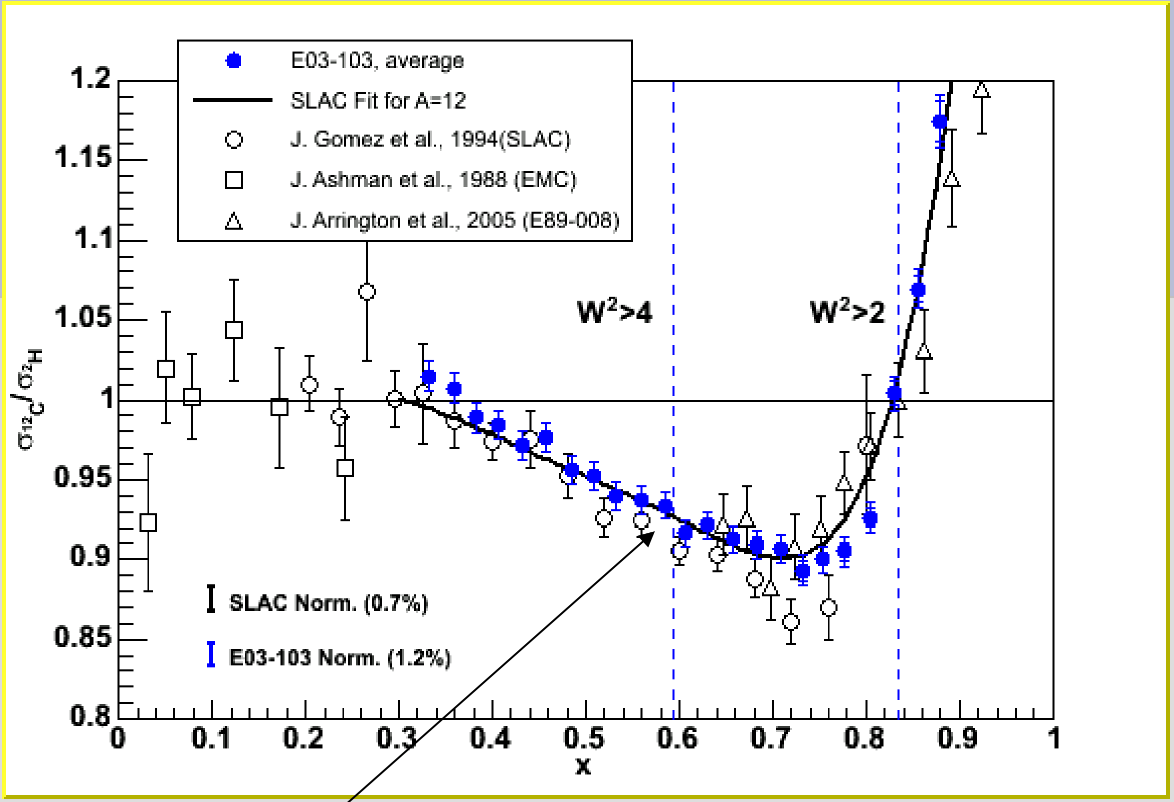




- Fermi motion in the nucleus accomplishes averaging in x, ξ.

=> Duality works even better in nuclei

Duality is also observed in the EMC effect!



Warning:

Significant fraction of EMC depletion is due to kinematic smearing.

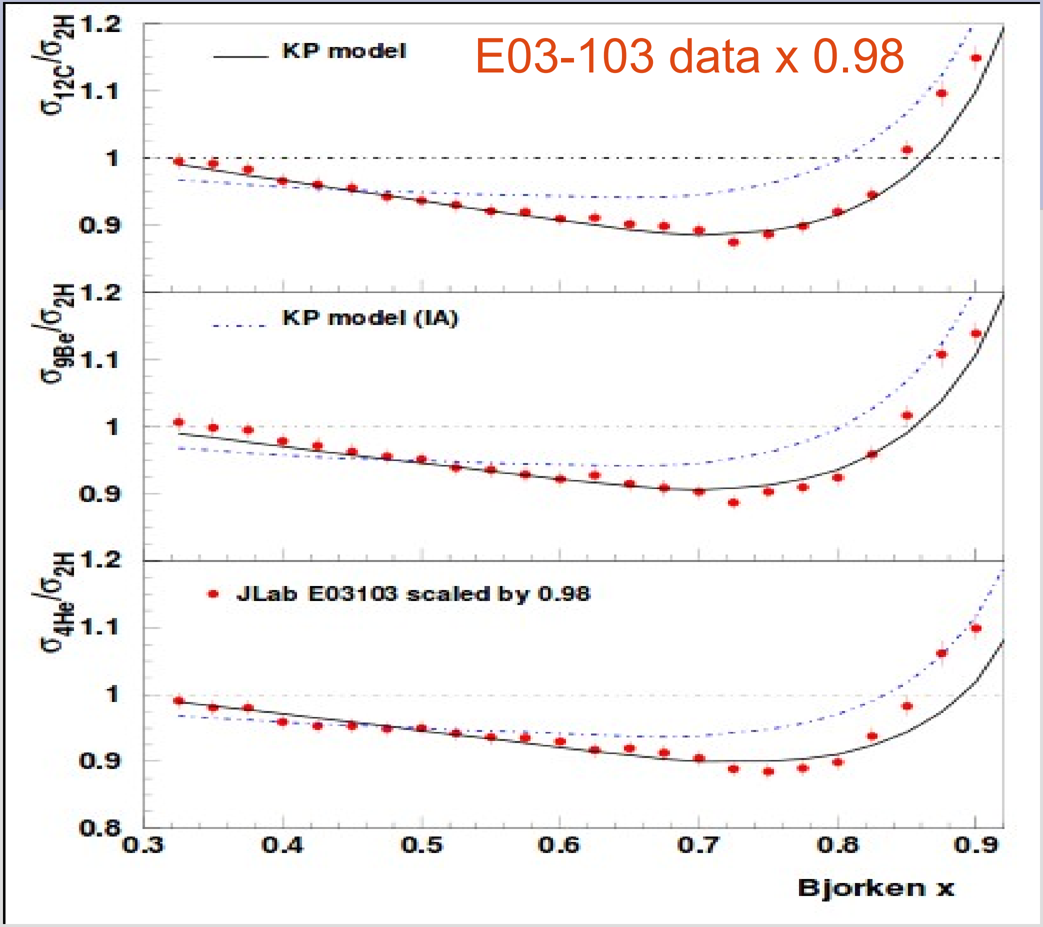
=> This is **not** the ratio that should be applied in the nucleon rest frame!!!

Kulagin-Petti model

S.Kulagin & R.Petti, PRC82 (2010) 054614

→ significant fraction of depletion due to impulse approximation smearing.

→ Off-shell correction is necessary to fully describe shape.

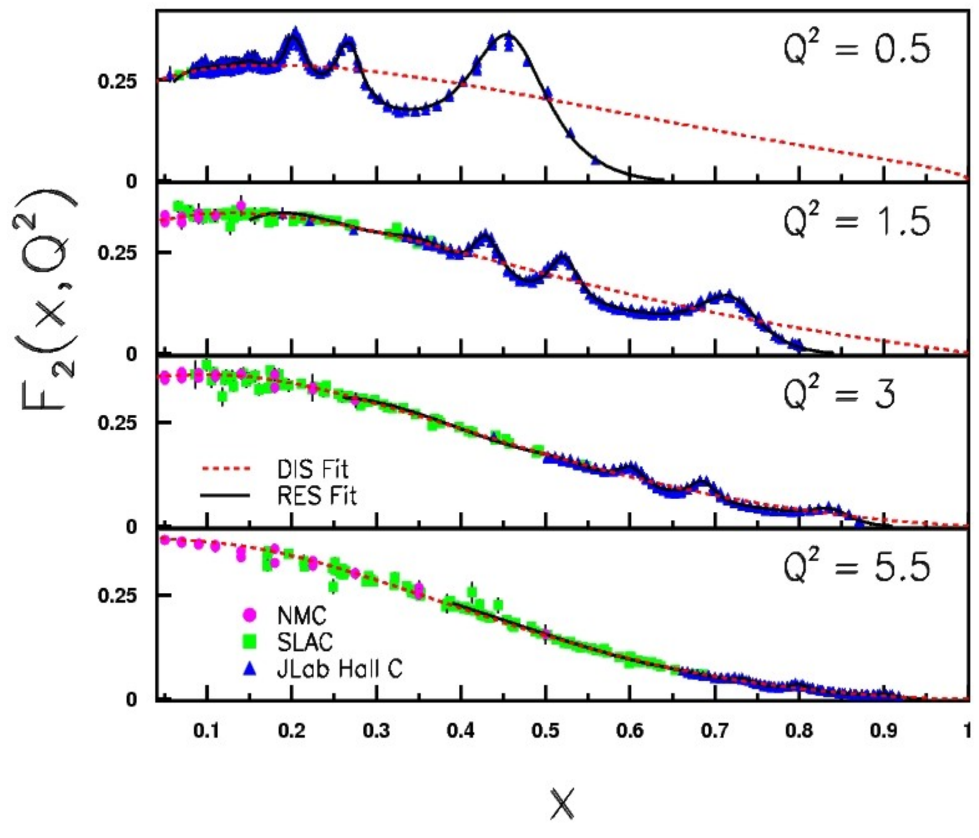


Duality and scaling

What does it mean?

Resonances have same Q^2 dependence as scaling curve.

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



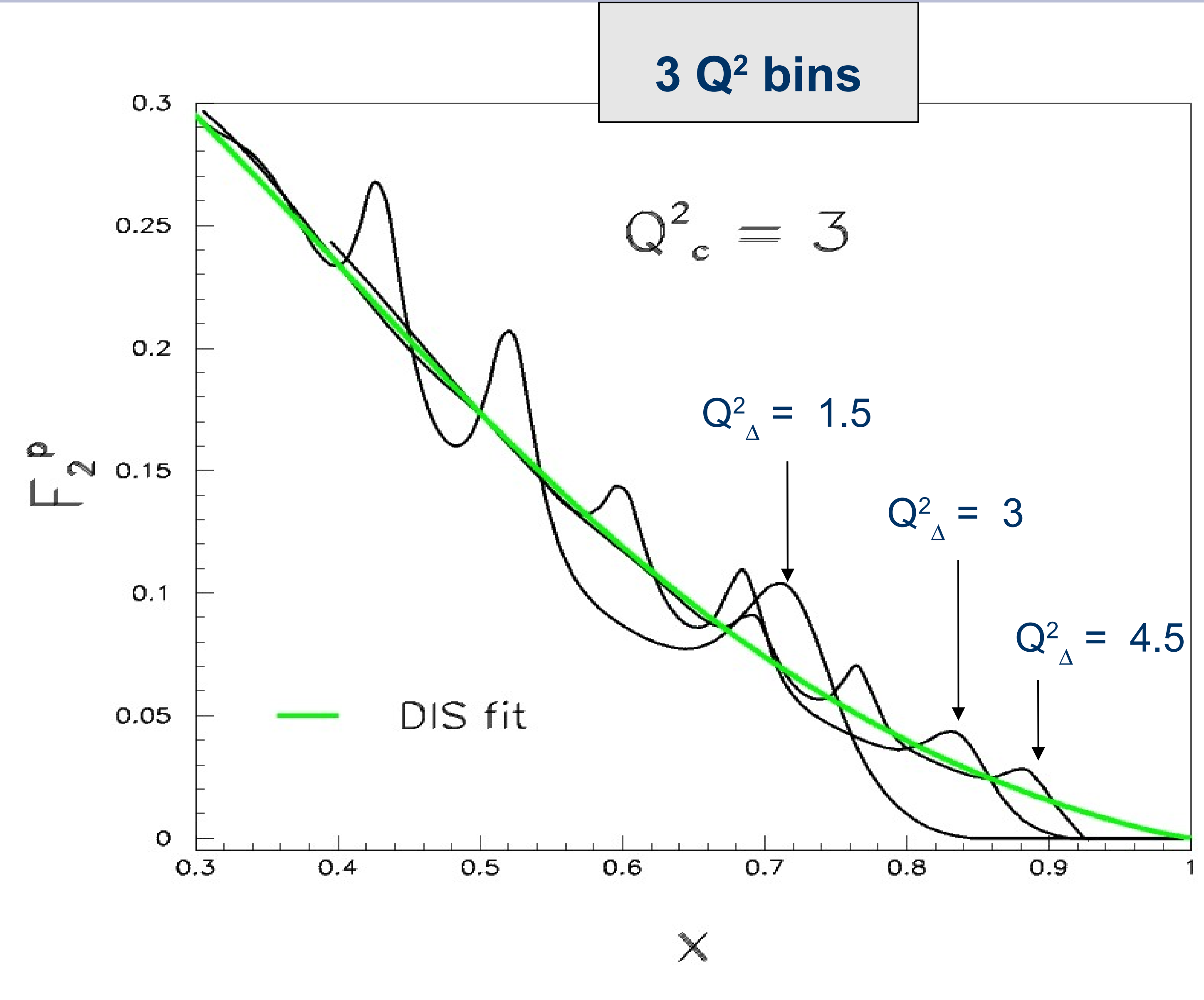
But what scaling curve?

A pure pQCD curve or that defined by data (LT + TM + HT)?

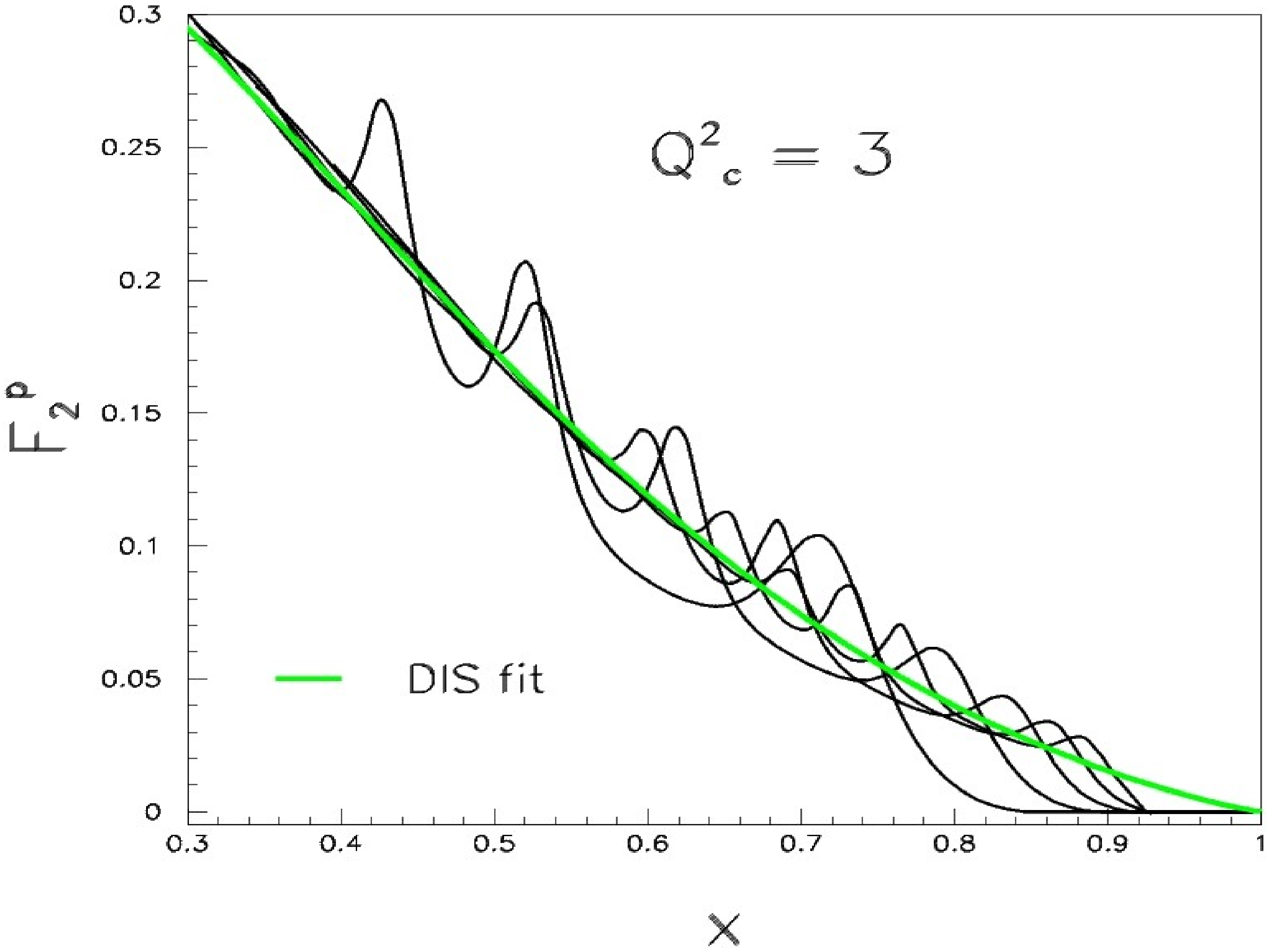
Can we use resonance region data and Duality to constrain high-x DIS SFs?

What do we average over to be less sensitive to local (W regions) variations?

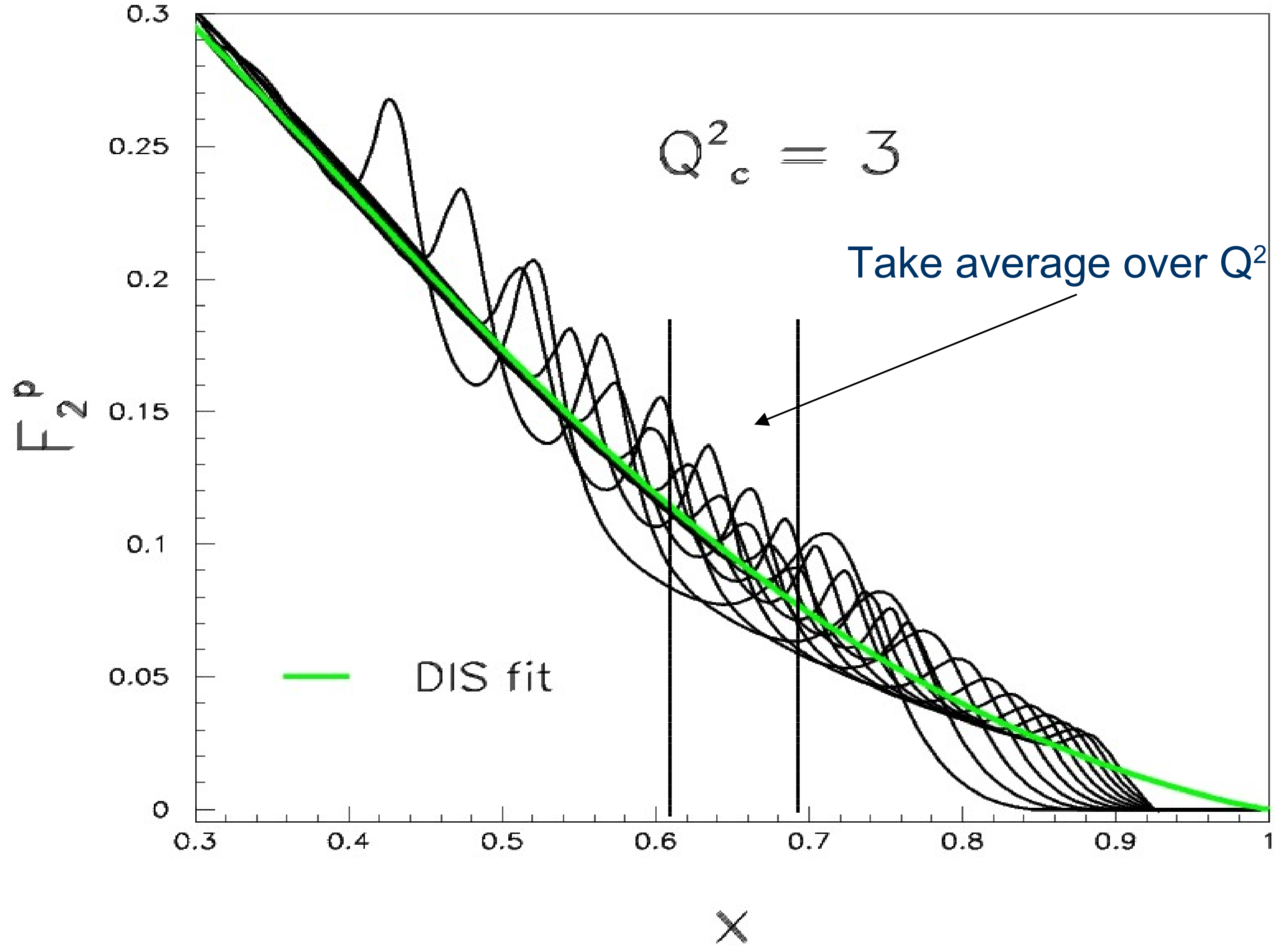
'DIS-like' duality averaging procedure



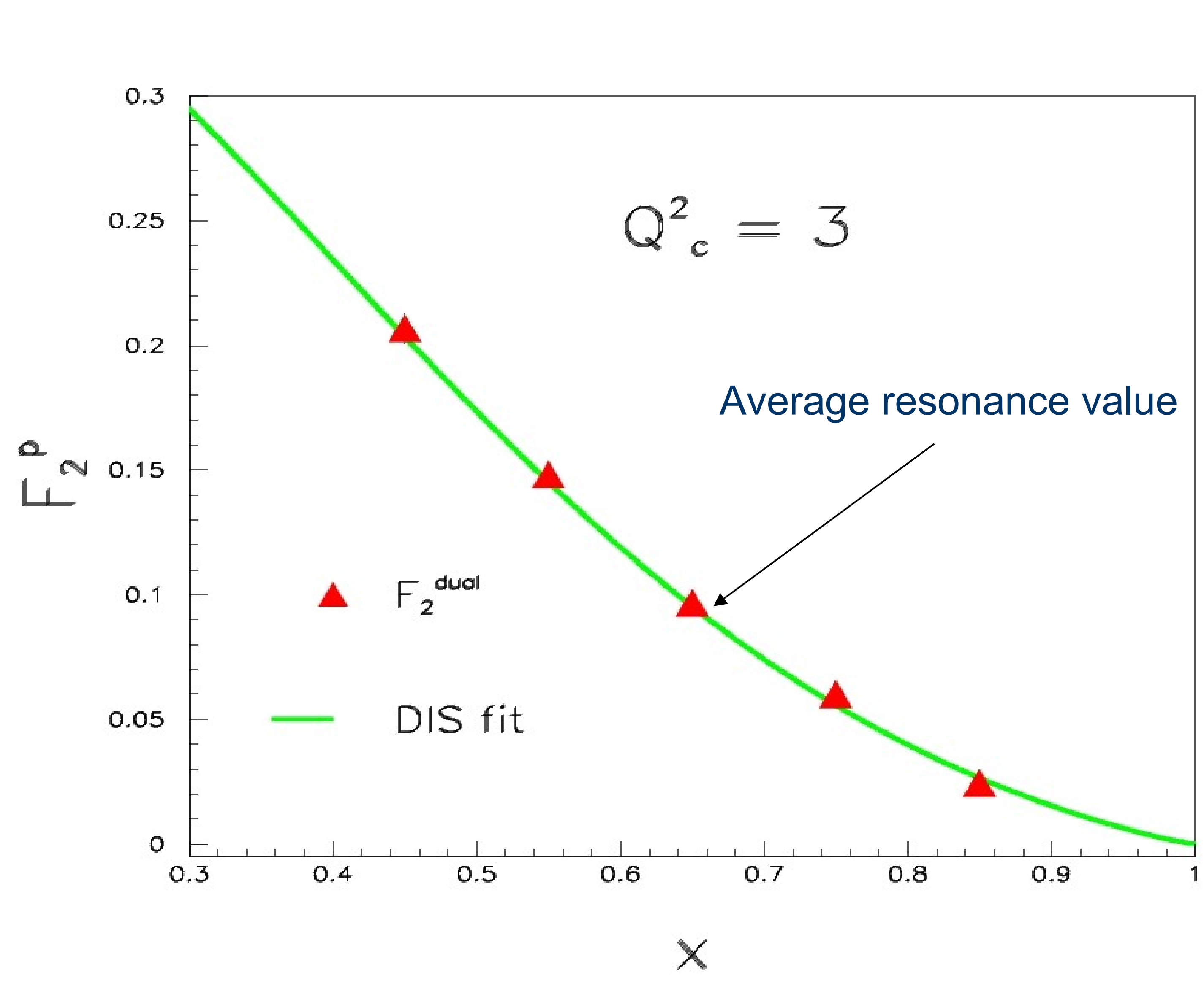
5 Q^2 bins



9 Q^2 bins

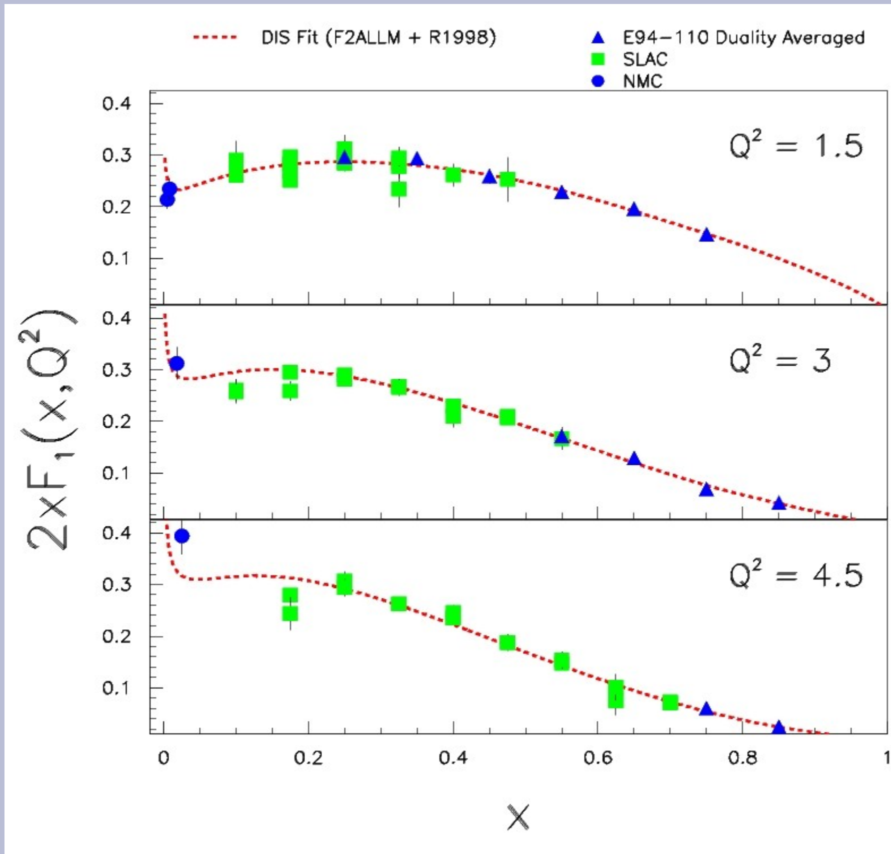


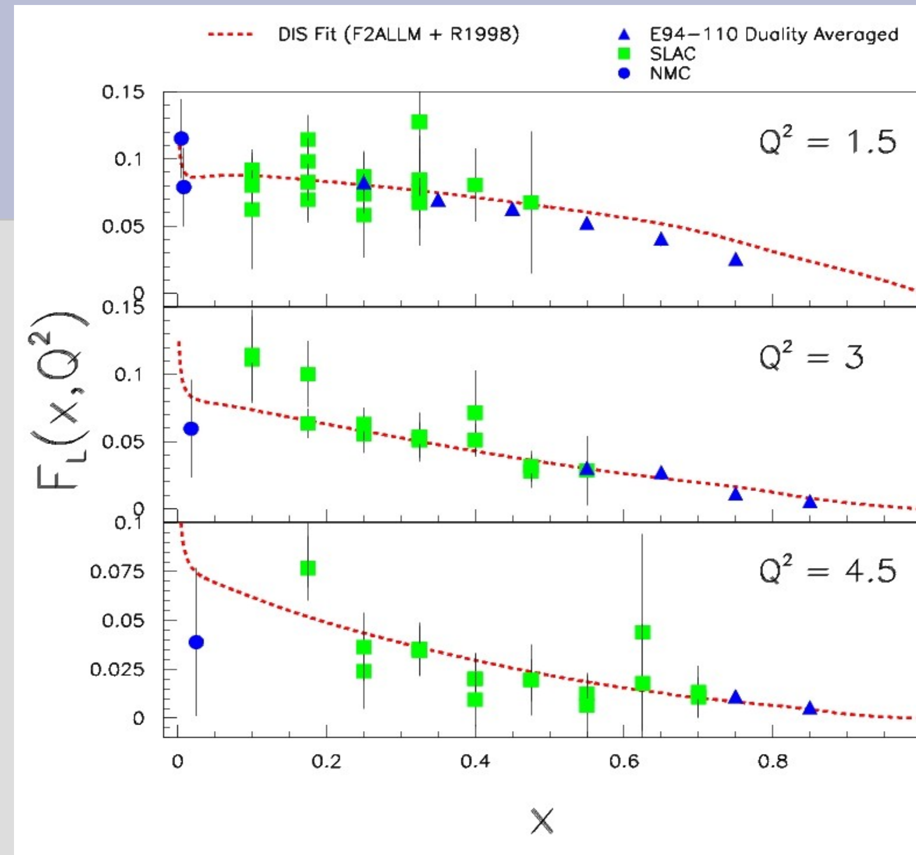
$Q^2_c = 3$
Take average over Q^2
DIS fit
F_2^p
x
0.3
0.25
0.2
0.15
0.1
0.05
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1



0.3
0.25
0.2
0.15
0.1
0.05
0
F_2^p
$Q^2_c = 3$
Average resonance value
F_2^{dual}
DIS fit
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
X

Duality averaging results for low Q^2 proton data





- Good consistency with DIS and relatively smooth *x* dependence.
- Note different Q^2 dependence in averaged F_L from fit at lowest Q^2.

Issues in modeling inclusive ν-A cross sections

1. Separation of non-resonant and resonant strength
2. How to apply measured EMC factors?
3. Are we including all high-x effects?

 (Bodek-Yang absorbs these into effective LO PDFs)

4. How to properly account for non-isoscalar targets?

Critical need for inclusive nuclear target data, eg. MINERνA

(see Joel Mousseau's talk from yesterday)

Summary

→ Jlab 6 GeV data has provided wealth of inclusive structure function Measurements at large x and low Q^2 from charged lepton scattering.

→ Data provides critical insight into:

I) Quark-hadron duality

II) d-quark distribution and neutron structure

III) Isoscalar corrections

IV) EMC effect

V) …

which provides input and guidance for νA model building

Thank You!

Backup Slides

Scattering with longitudinal photons

Polarization
(Relative flux of longitudinal photons)

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

Flux of transverse photons

Transverse cross section

Longitudinal cross section

	$\sigma_T \propto$	$\sigma_L \propto$
Elastic scattering:	$G_M^2(Q^2)$	$G_E^2(Q^2)$
Inelastic scattering:	$F_1(x,Q^2)$	$F_L(x,Q^2)$

$Q^2 \to \infty$, $F_L \to 0$ (helicity conservation – spin ½ quarks, no transverse momentum)
$Q^2 \to 0$, $F_L \to Q^4$ (current conservation)

How to separate transverse from longitudinal?

Reduced cross-section:

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

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

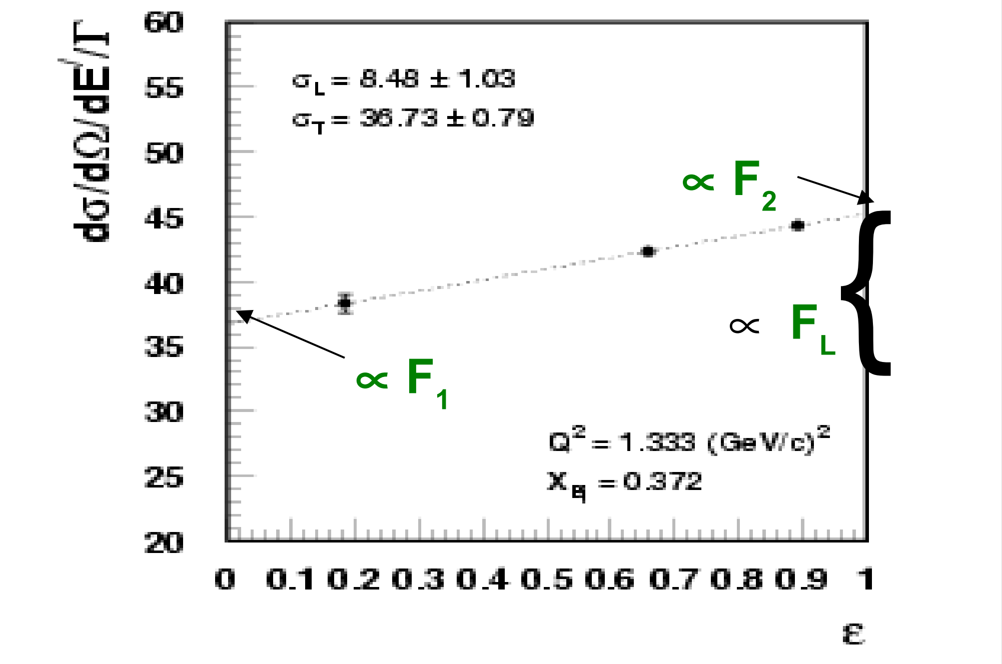
σ_L = Slope

σ_T = Intercept

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

Extraction of F_2 depends on F_L and ε !

Important for Jlab kinematics



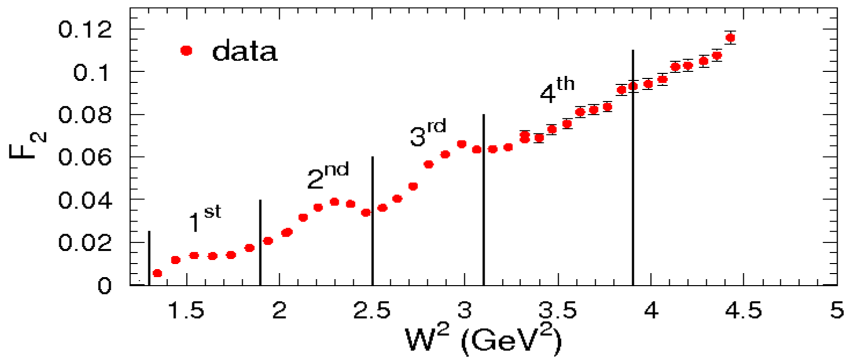
→ need 1-2% uncertainties pt-pt in **ε** to provide 15-20% **δR** ($\delta F_L/F_L$)

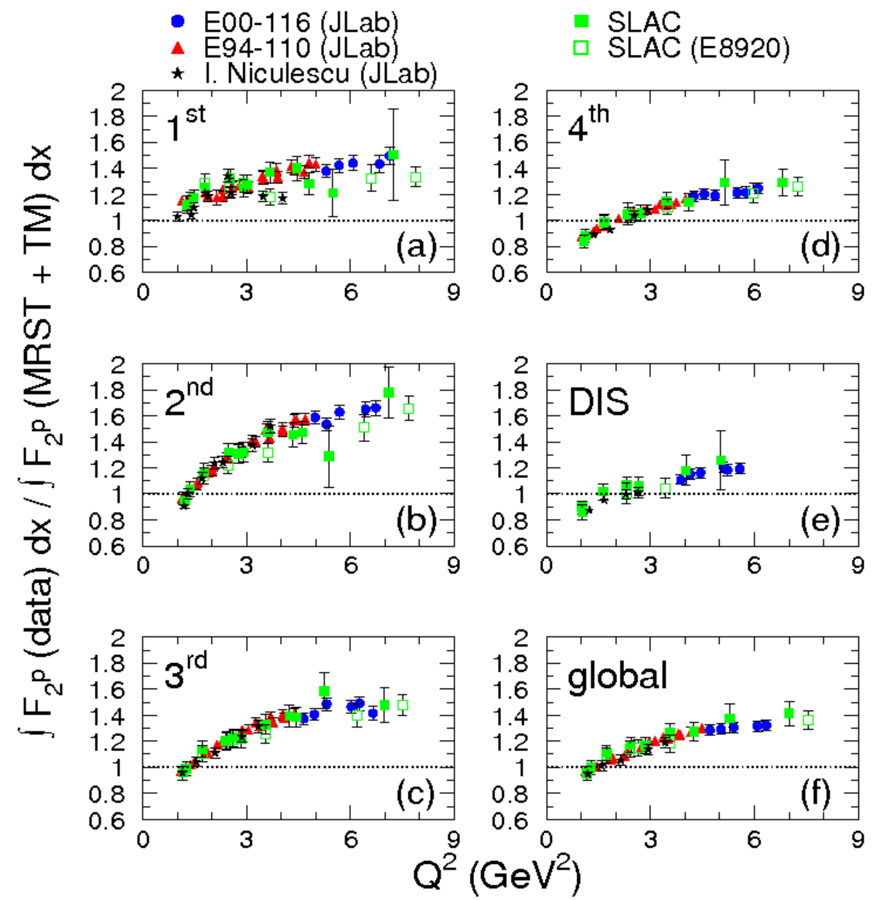
→ also requires multiple beam energies and spectrometer settings for multiple **ε**.

Very challenging experimentally!

Local Duality Quantification - I

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



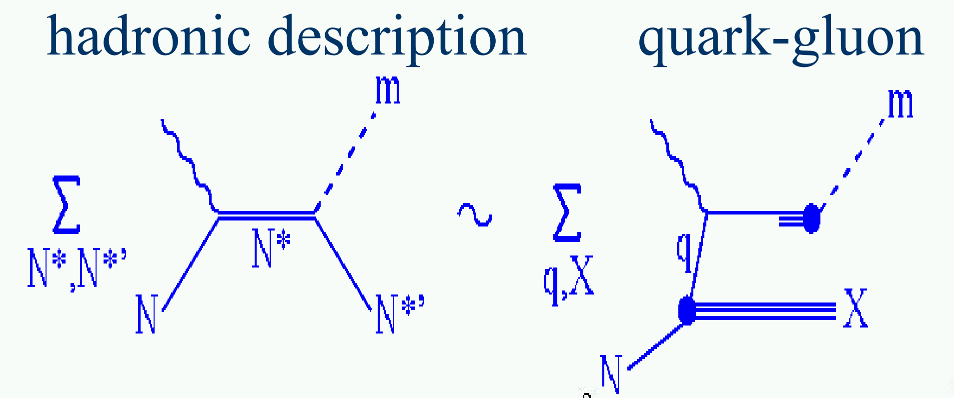


$$I = \frac{\int_{x_{min}}^{x_{max}} F_2^{data}(x,Q^2)dx}{\int_{x_{min}}^{x_{max}} F_2^{param.}(x,Q^2)dx}$$

→ Data in all regions rise above PDF curve for $Q^2 > \sim 2$

→ largest for lower resonances which are at large *x*, where PDFs are less well constrained.

Duality in semi-inclusive pion producton

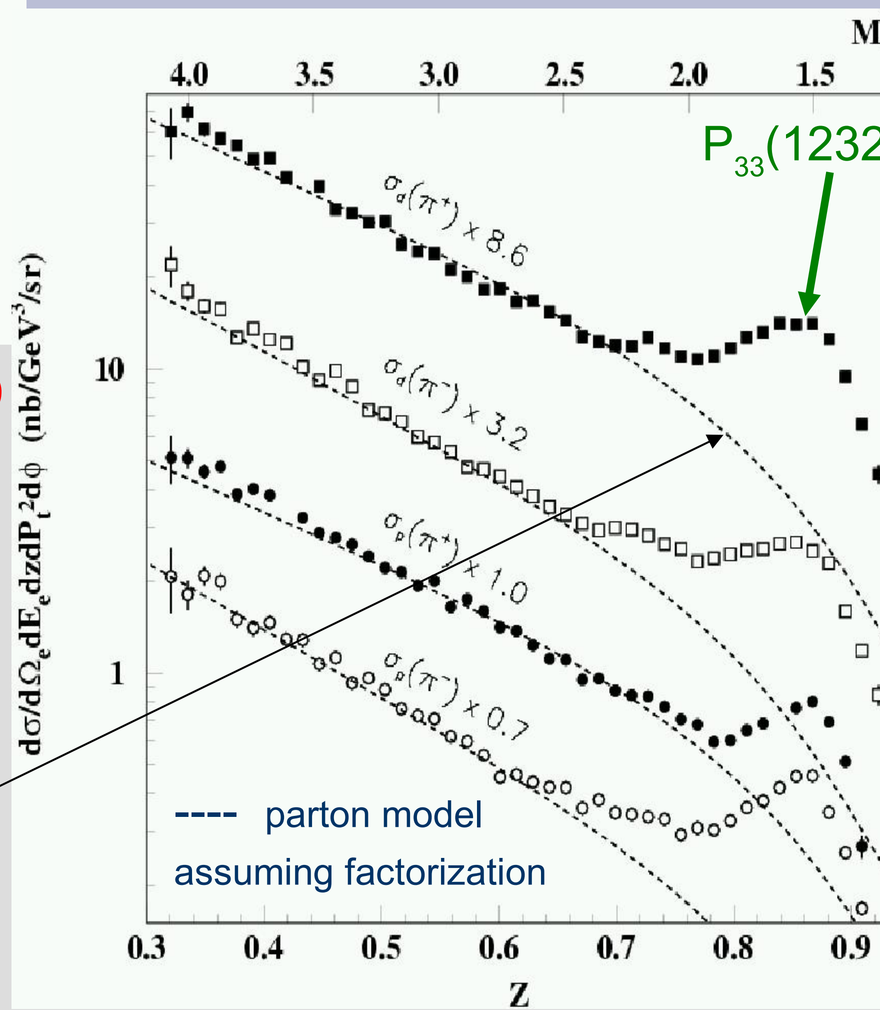


$$\sum_{N'^*}\left|\sum_{N^*} F_{\gamma^* N\to N^*}(Q^2,W^2)\, \mathcal{D}_{N^*\to N'^* M}(W^2,W'^2)\right|^2 = \sum_q e_q^2\, q(x)\, D_{q\to M}(z)$$

Transition Form Factor   Decay Amplitude   Quark distribution q(x) X Fragmentation Function. D(z)

$z = E_\pi / \nu$ is fractional energy carried by pion

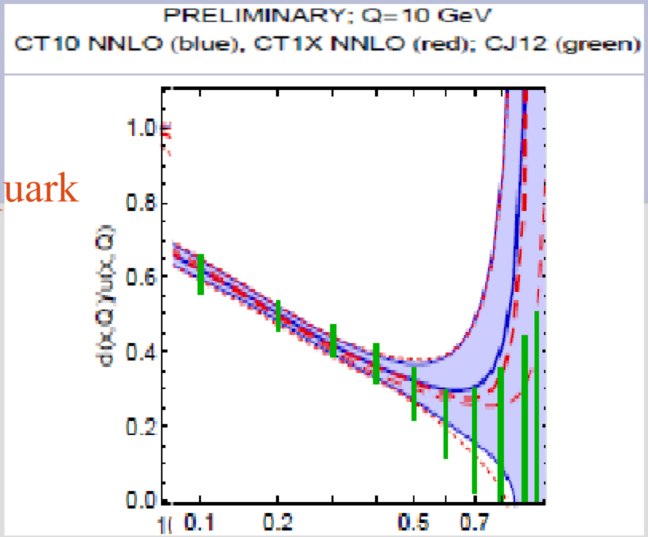
Parton model using fragmentation functions from DIS generally describes data well.



Large-x *d*/*u* quark ratio: state-of-the-art

- Large *d*-quark suppression ← nuclear corr.
- Meaningful extrapolation to $x \to 1$ ← Extended d-quark

$$d/u \xrightarrow[x\to 1]{} 0.22 \pm 0.20\,(\mathrm{PDF}) \pm 0.10\,(\mathrm{nucl})$$

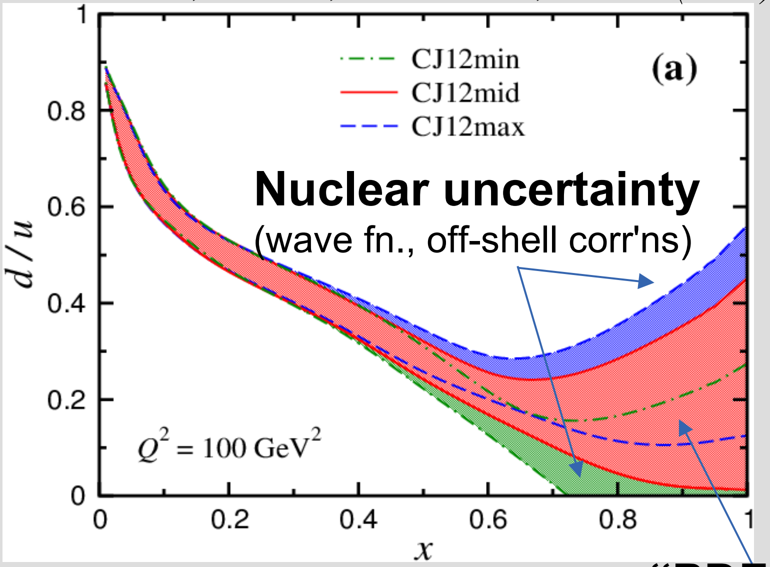


x

- Can almost constrain proton models

-Need more data, constraints on nuclear uncertainty

Owens, Accardi, Melnitchouk, PRD87 (2013) 094012



Non-perturbative proton models

← SU(6) spin-flavor

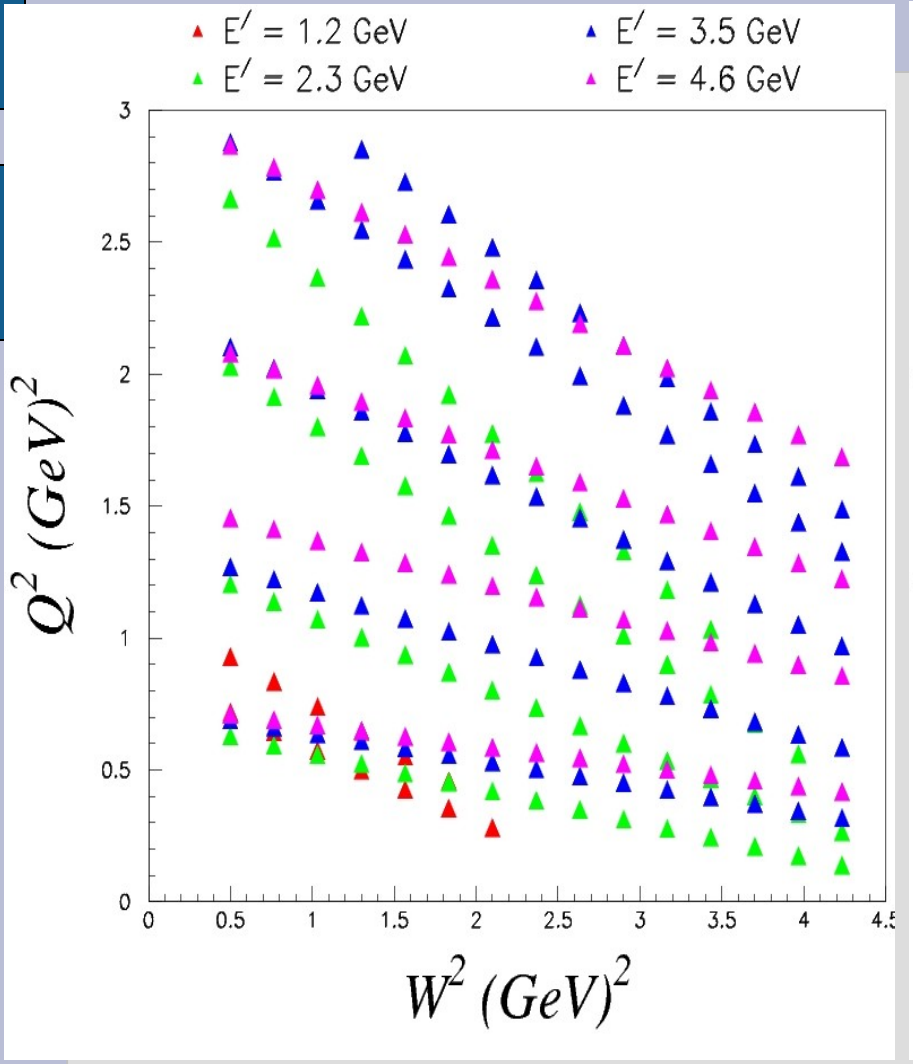
← hard gluon exchange

← *S*=0 diquark dominance

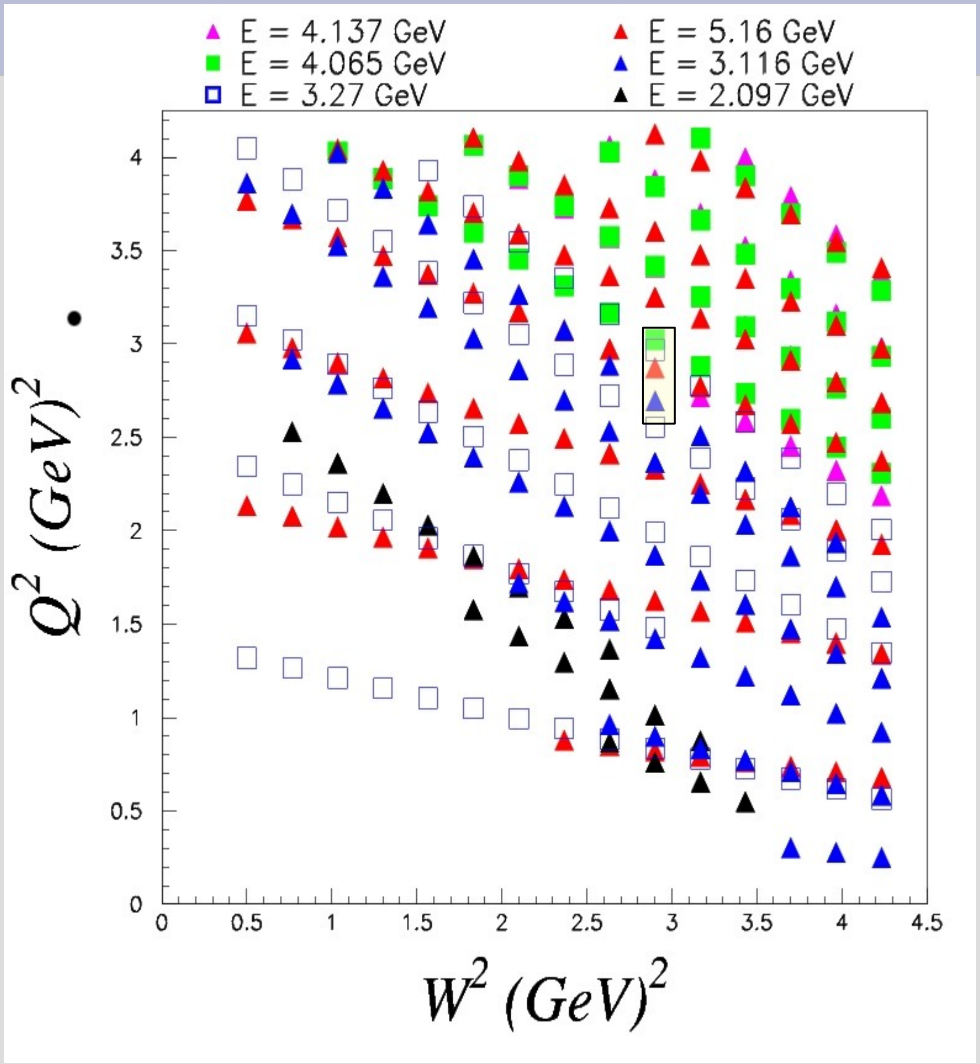
Deuteron F_L and Moments (E02-109, E06-009)

L/T Separations on d, C, Al, Cu, Fe

2005



2007



Lots of new L/T data from Jlab Hall C

Experiment	target(s)	W range	Q^2 range	Status
E94-110	p	RR	0.3 - 4.5	nucl-ex/0410027
E99-118	p,d	DIS+RR	0.1 - 1.7	PRL98:14301
E00-002	p,d	DIS+RR	0.25 - 1.5	Publication in progress
E02-109	d	RR+QE	0.2 - 2.5	Finalizing analysis
E06-009	d	RR+QE	0.7 - 4.0	Publication in progress
E04-001 - I	C,Al,Fe	RR+QE	0.2 - 2.5	Finalizing analysis
E04-001 - II	C,Al,Fe	RR+QE	0.7 - 4.0	Publication in progress

Lots of results expected soon!

What if $R_A = R_D$?

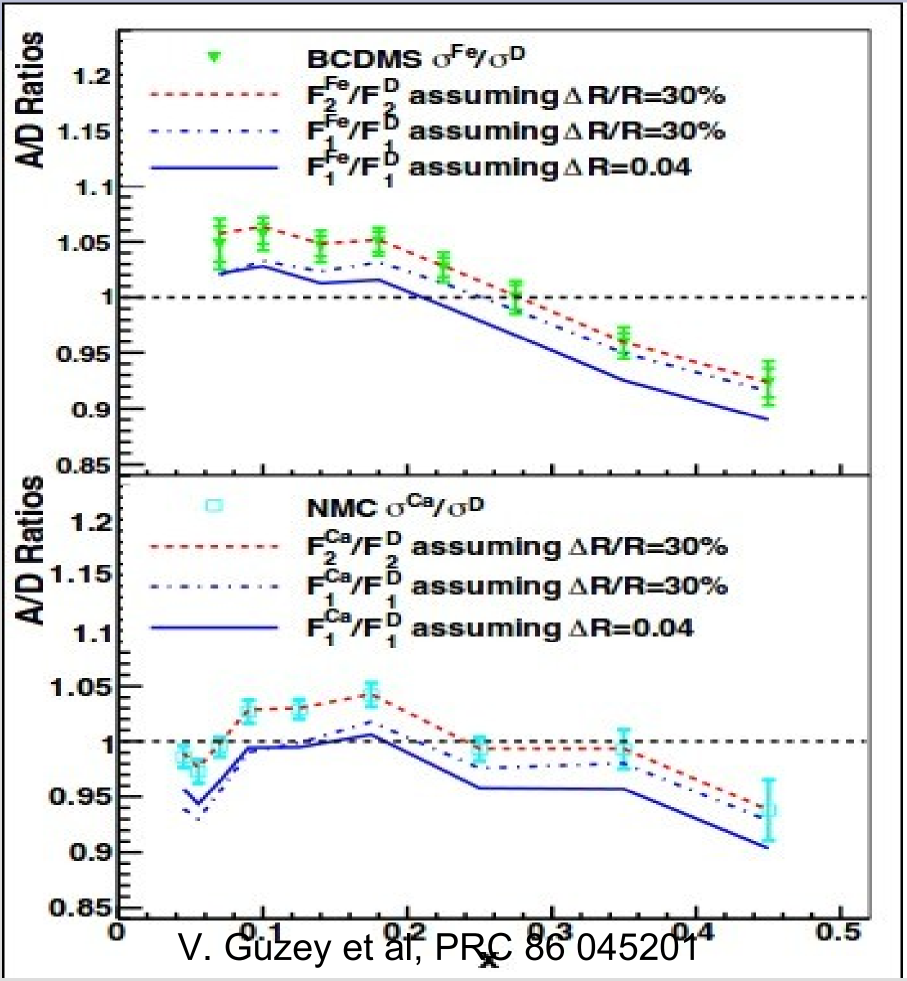
Must mean that $F_2^A/F_2^d \neq F_L^A/F_L^d \neq F_1^A/F_1^d$

$$\frac{\sigma_A}{\sigma_D} = \frac{F_1^A(x)}{F_1^D(x)}\left[1 + \frac{\epsilon(R_A - R_D)}{1+\epsilon R_D}\right]$$

Using measured Cross section Ratios, different assumptions for

$\Delta R = R_A - R_D$

yields different structure function Ratios.

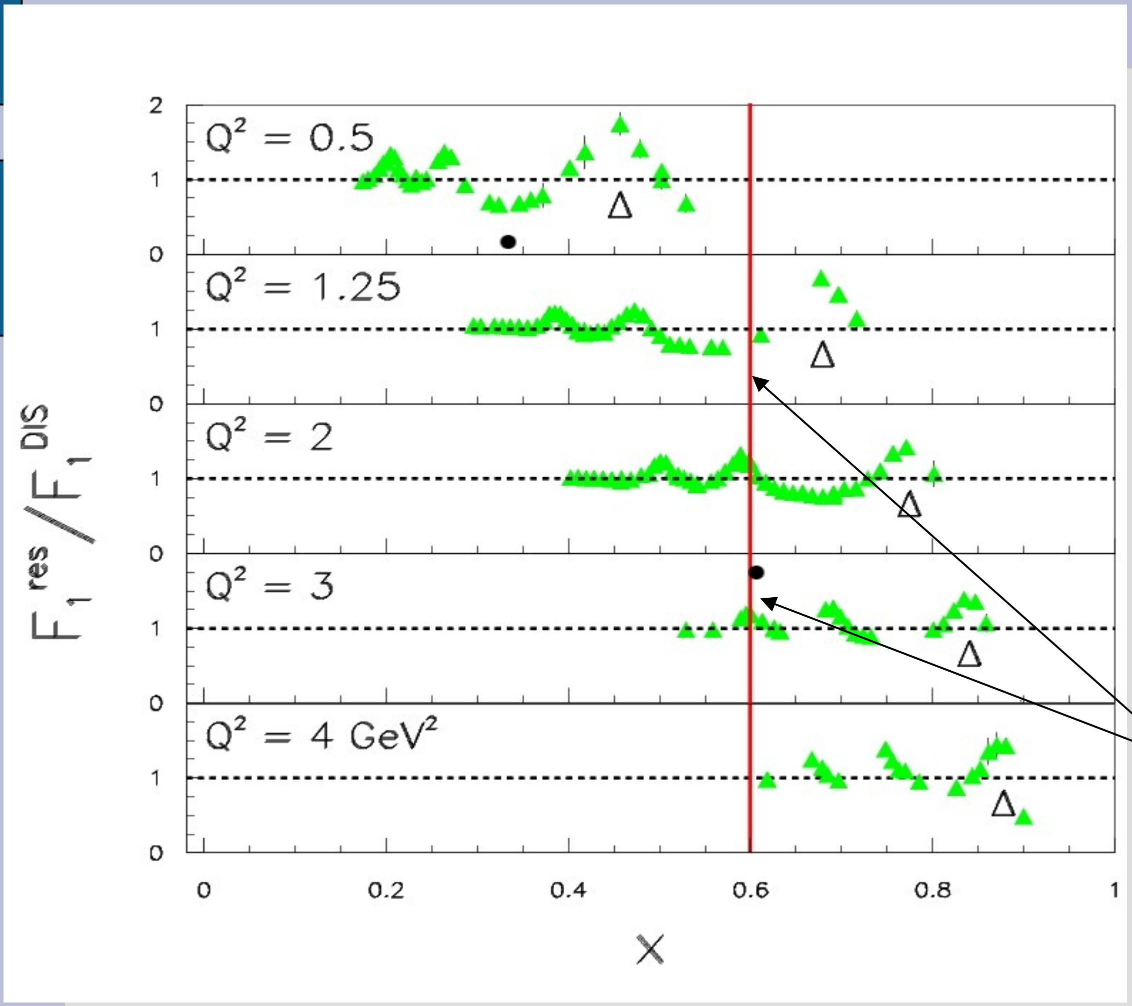


V. Guzey et al, PRC 86 045201 (2012)

Perhaps anti-shadowing due to absorption of longitudinal photons?

Comparison L/T separated data to empirical fits

Comparison of Rosenbluth separated F_1



DIS fit:

F_2ALLM fit to F_2

H.Abramowicz and A.Levy, hep-ph/9712415

+

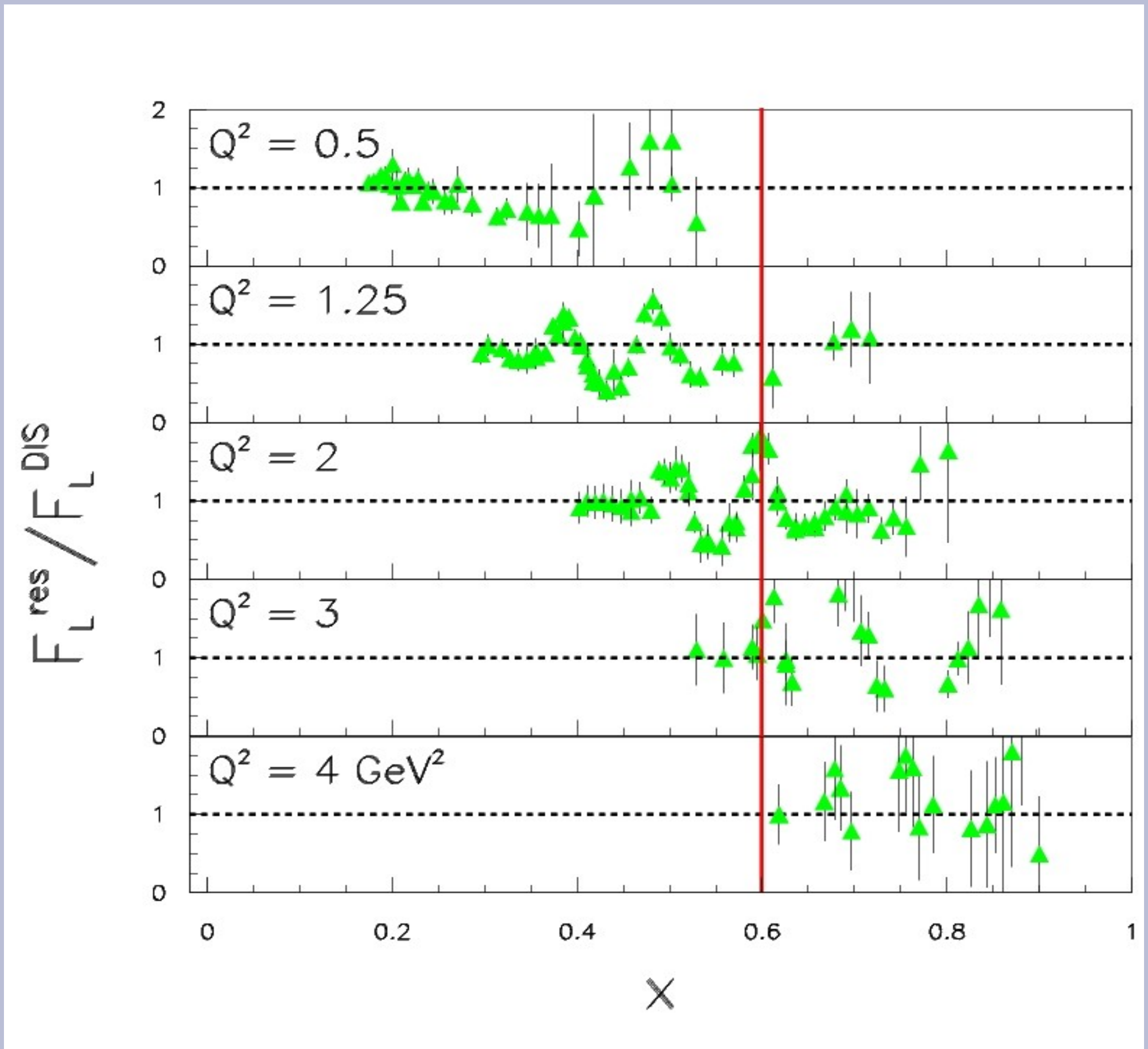
$R = \sigma_L / \sigma_T$

K. Abe et.al Phys.Lett.B452:194-200,1999

→ In principle these fits contain Contributions from L-T and H-T

→ Ratio of data to DIS fit oscillates about unity => duality well obeyed

Similar results for F_L



Observation

As Q^2 increases, different resonance peak and valleys pass through x=0.6

=> Averaging over a range in Q^2 at fixed x effectively averages out the variations due to the resonance contribution to the structure function.

Can we use this to provide DIS-like data?

E94-110: proton F_L in resonance region

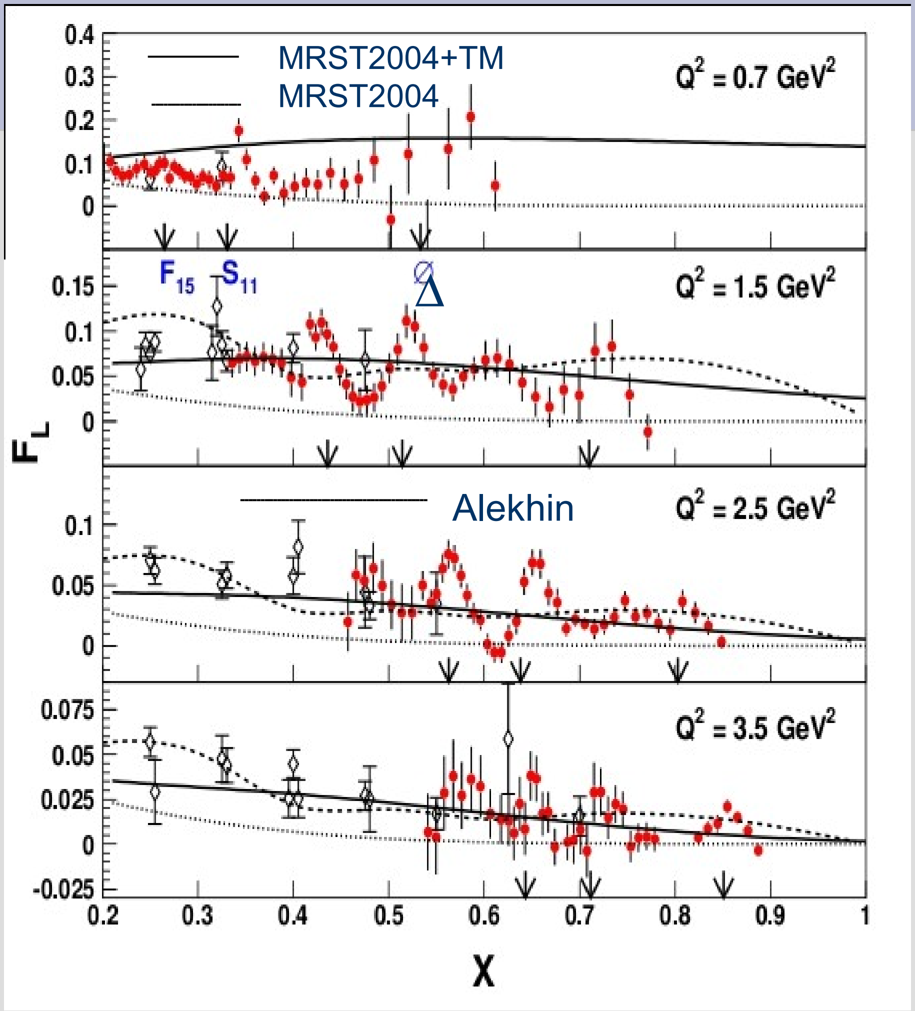
→ ~200 individual L/T separations.

→ Among most precise ever performed.

→ First observation of quark-hadron duality in F_L.

While resonance structure is clearly observed, resonance dips and peaks oscillate about scaling curve describing DIS.

- pQCD curves from MRST2004 and Alekhin parton distribution function (PDF) fits +TM.



Inclusive cross section modeling formalism:

Fit reduced cross section in Rosenbluth form:

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

Cross section is sum of Resonant + non-resonant contributions.

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

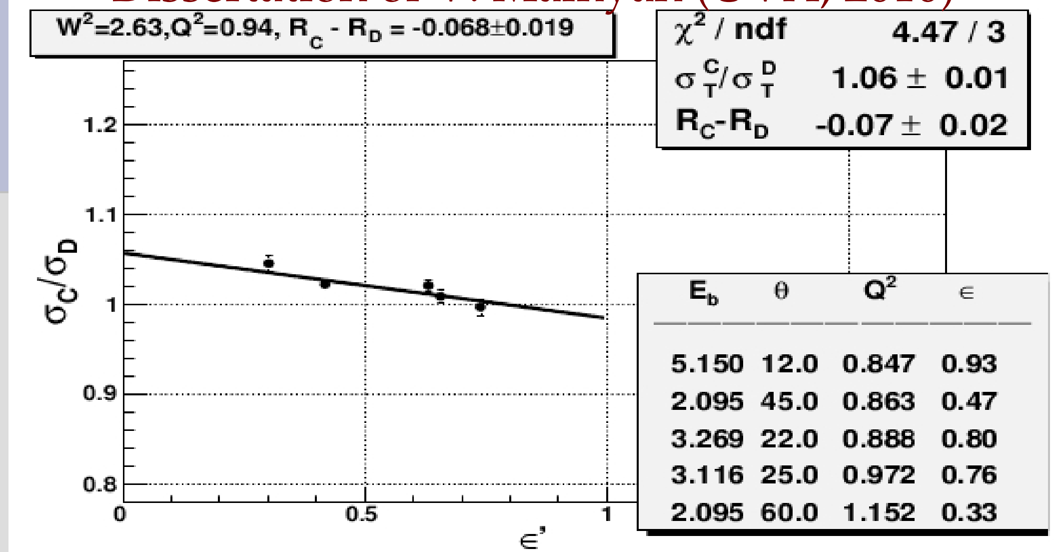
$$\sigma_L\left(W^2, Q^2\right) = \sigma_L^R\left(W^2, Q^2\right) + \sigma_L^{NR}\left(W^2, Q^2\right)$$

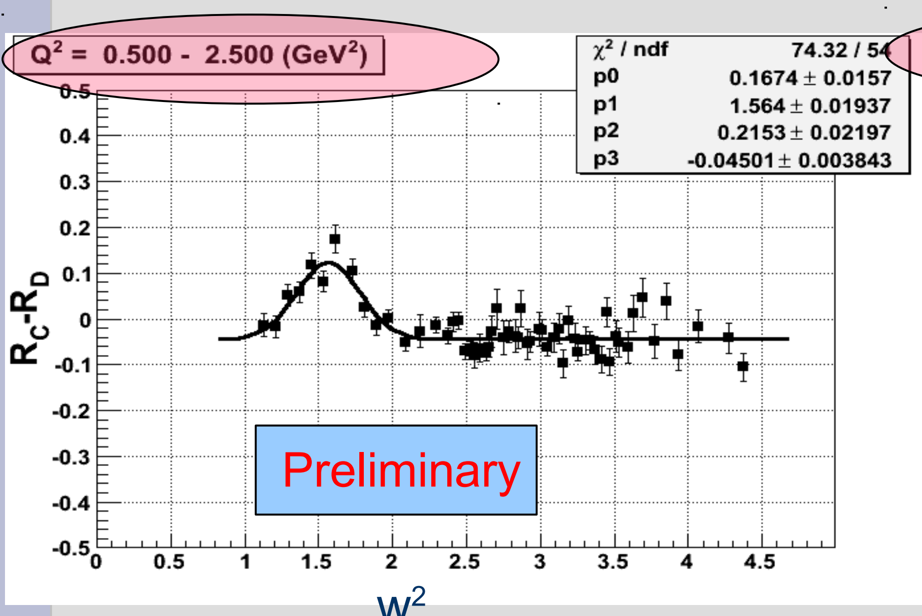
** It is assumed that all sums are incoherent.*

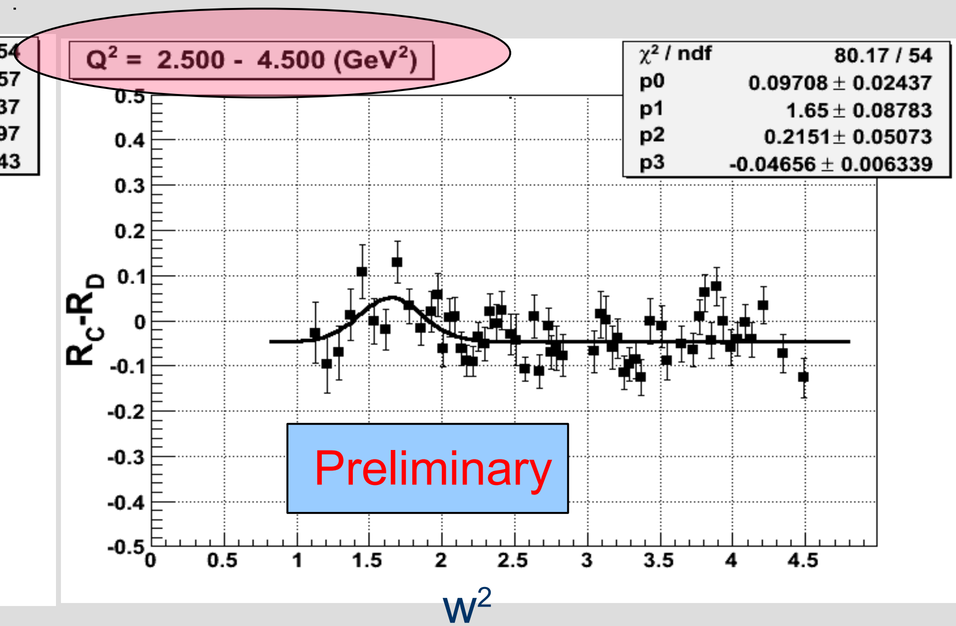
=> no interference between resonance and non-resonance states

Preliminary results from JLab E06-109(D), E04-001 (A)

Dissertation of V. Mamyan (UVA, 2010)







A consistent Picture seems to be emerging...

Evidence that $R_A < R_d$ for $1 < Q^2 < 5$ and moderate to large *x*.

Further investigation forthcoming

→ Anticipate publication of R (F_L) results from 2007 data this year focusing on $2 < Q^2 < 4$.

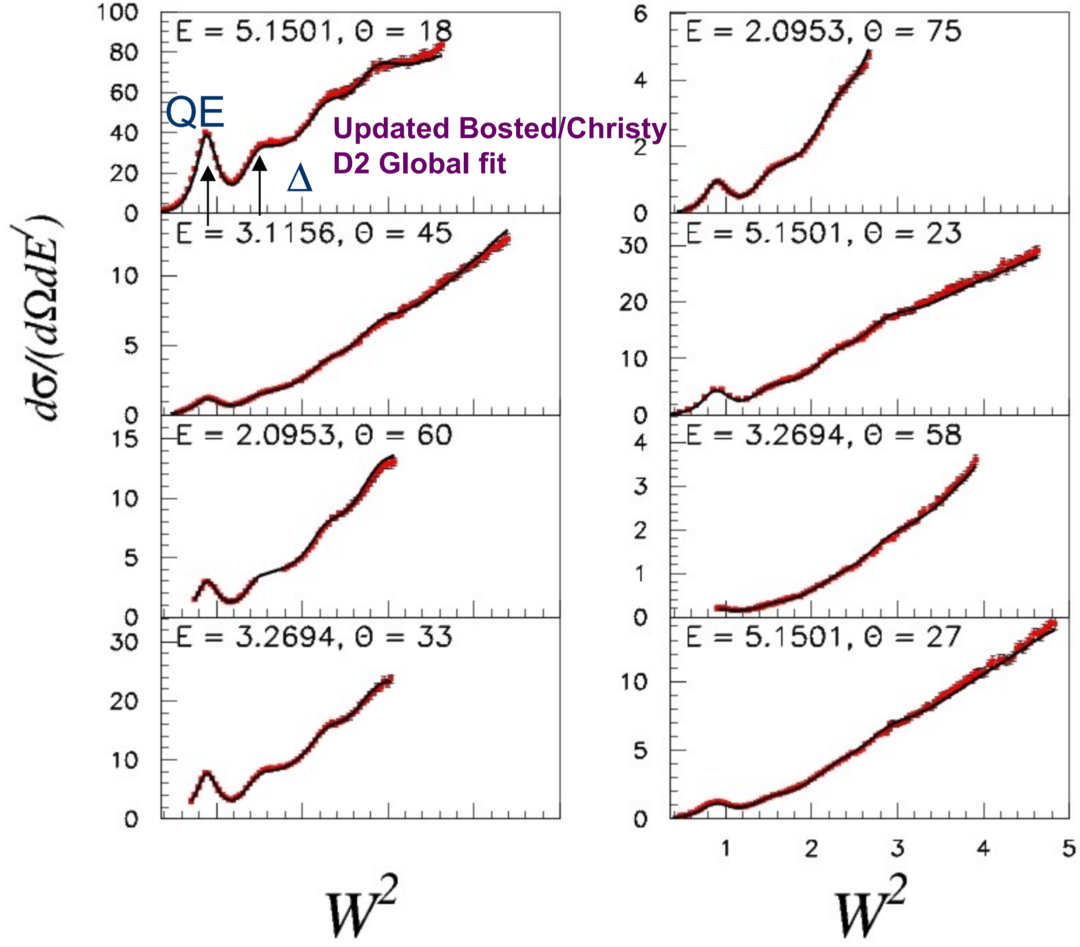
→ Anticipate publication of full data set including 2005 low Q^2 data early 2013 for $0.25 < Q^2 < 4$.

Study of deuteron F_L, and separation of singlet and non-singlet (p-n) moments – E02-109, E06-009

Dissertation of I. Albayrak (Hampton, 2011)

- **Extend resonance L/T separations to deuteron.**
- **Allow study quark-hadron duality for neutron in both transverse and longitudinal structure.**
- **Allow higher precision non-singlet moment extractions for F_2, F_1 (compare to lattice predictions at Q^2 = 4 GeV²).**
- **Comparisons of F_L^p and F_L^d (F_l^n) and moments.**

Sample E06-009 cross sections

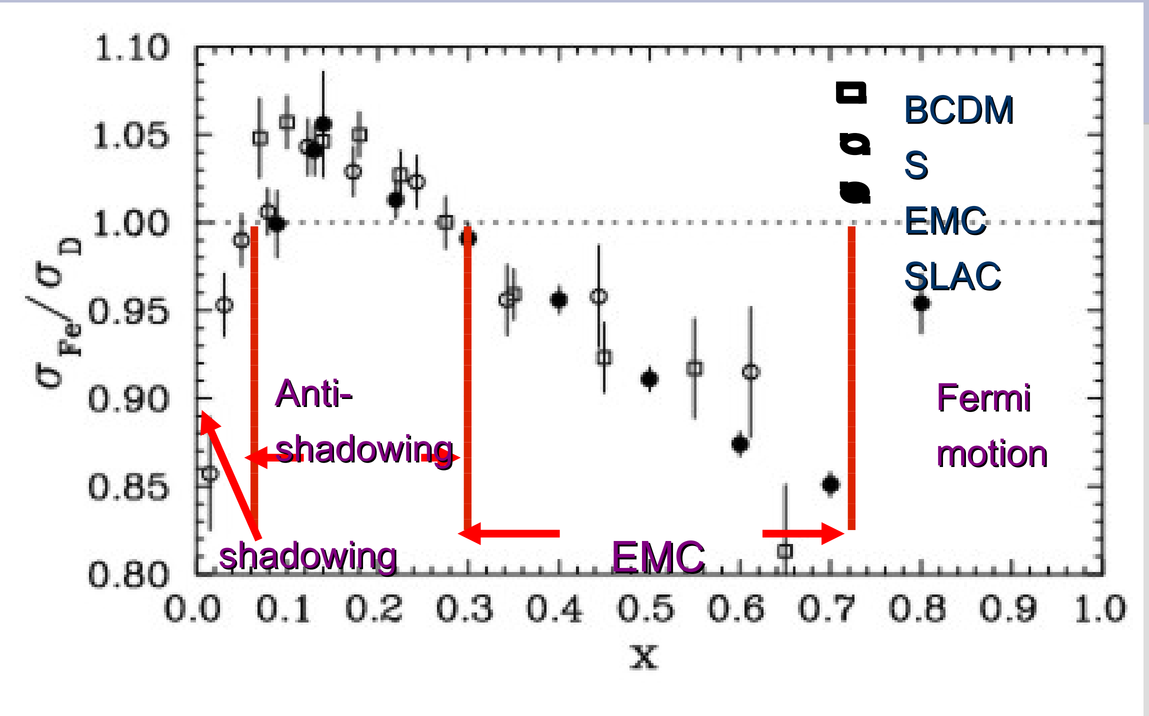


F_L (R) in Nuclei

*Well known since the EMC experiment that the nuclear medium modifies nucleon structure functions.

→ However, after 25 years the mechanism is *still* not fully understood.

→ Is the effect different in F_1 and F_2?



* The latter => nuclear dependence of R and F_L !

Important to know if *A* dependence exists in F_L for full understanding of EMC effect.

Highest precision data on R_A comes from SLAC E139/E140

→ SLAC analysis showed *no clear evidence* for $R_A \neq R_d$ ... However

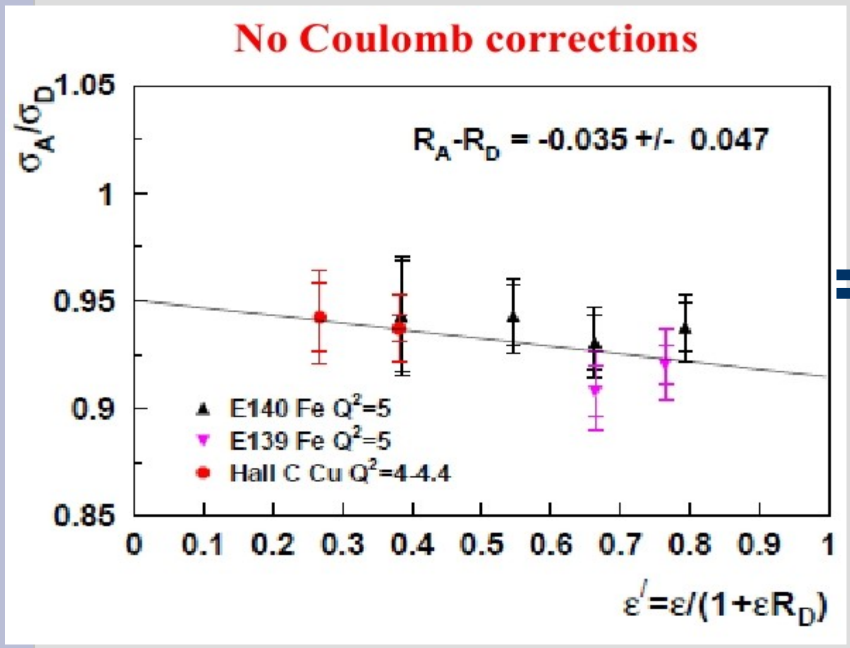
Re-analysis of L/T separations (P. Solvignon, J. Arrington, D. Gaskell, ArXiv:0906.0512) including neglected Coulomb effects for electron entering and exiting nucleus

Following Dasu *et.al Analysis of SLAC* (PRD.49.5641)

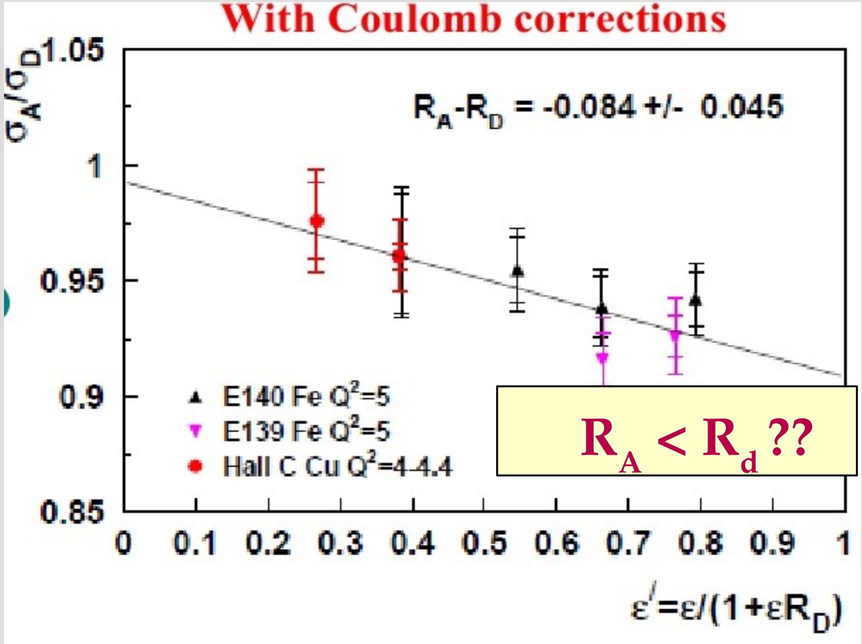
$$\frac{\sigma_A}{\sigma_D} = \frac{\sigma_A^T}{\sigma_D^T}\left(1 + r \cdot \varepsilon'\right)$$

$r = R_A - R_d$, $\varepsilon' = \varepsilon/(1 + \varepsilon R_d)$

→ **Much of systematics cancel!**



=>



$R_A < R_d$??

D_2 (n) fit

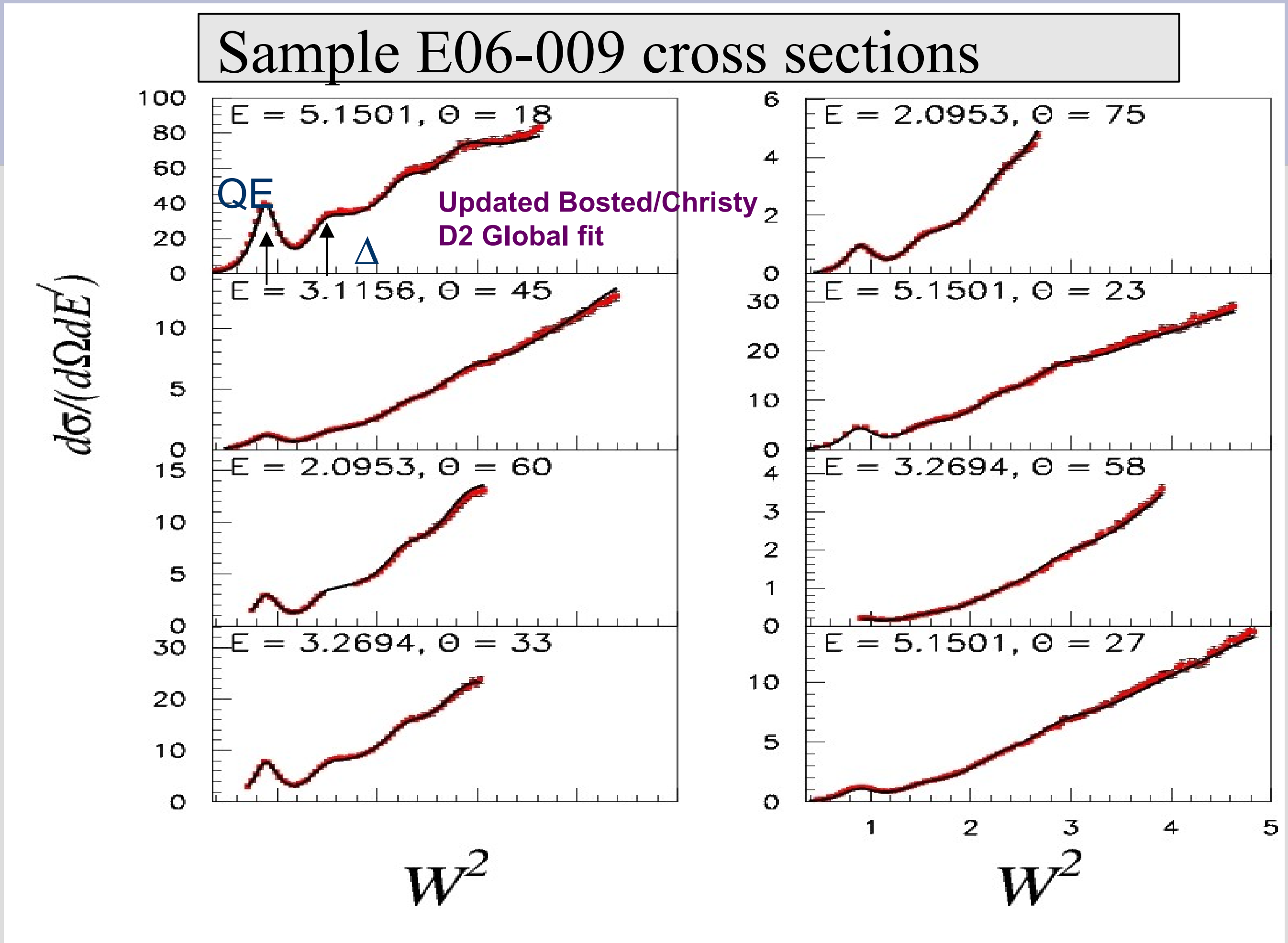
→ In published version Rd = Rp is assumed.

→ Only F1n is parameterized.

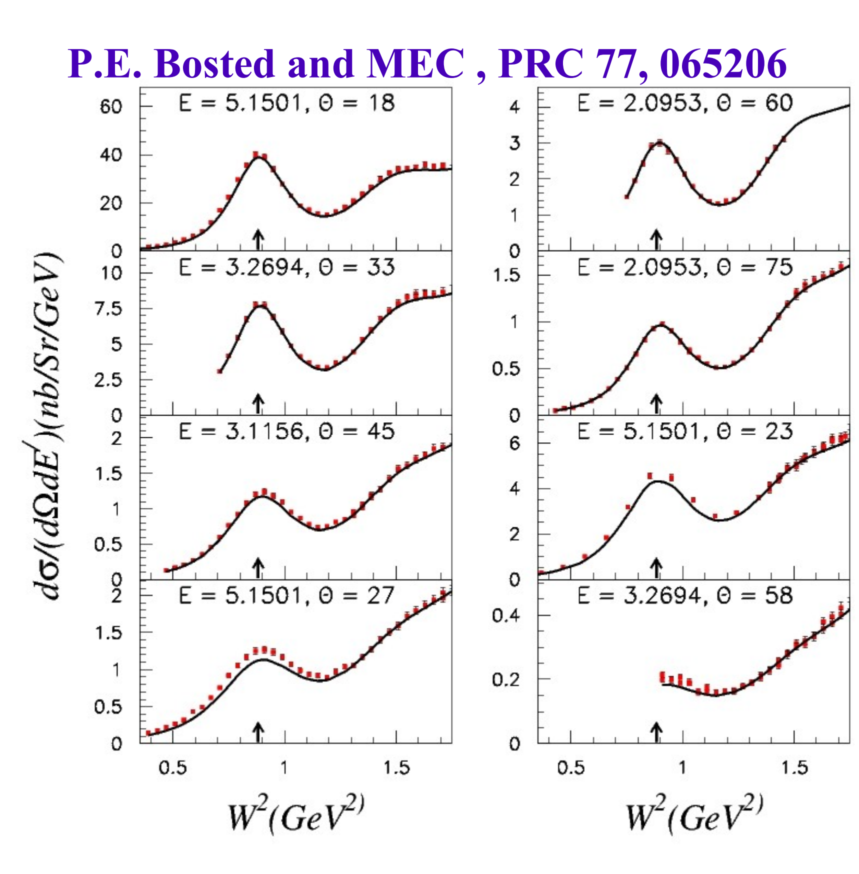
→ Both proton and neutron elastic form factors are taken from fit by P. Bosted. New fits to larger data set are now available.

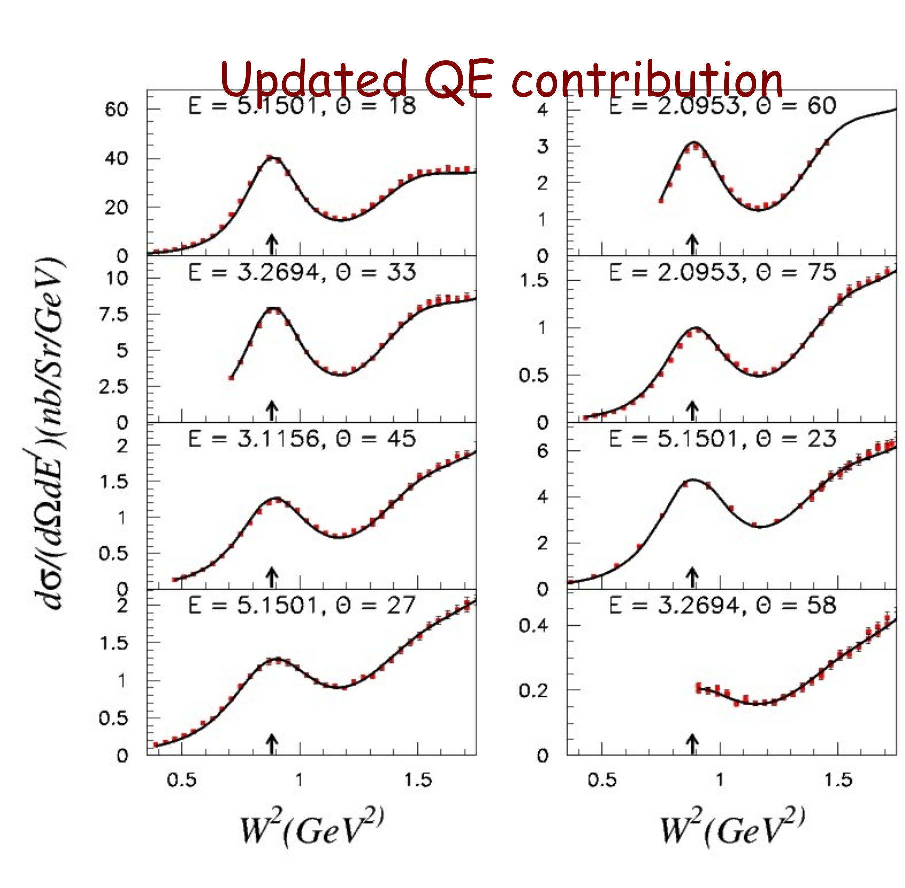
→ Smearing is done by sampling momentum distribution from Paris wf

D_2 (n) fit comparison to E06-009



D_2 (n) fit QE comparison to E06-009





→ Replaced QE smearing with convolution model of W. Melnitchouk.

→ Will study with different potentials & off-shell effects, including BONUS n

→ Replaced p,n form factors with modern parameterizations including new GMN data from CLAS. (biggest contribution to difference)

A>2 fit

→ For QE use superscaling formalism of Sick, Donnelly, Maieron (nucl--th/0109032)

$$\frac{d^2\sigma}{d\Omega d\omega}\frac{1}{\sigma_{Mott}}\epsilon\left(\frac{q}{Q}\right)^4 = \epsilon R_L(q,\omega) + \frac{1}{2}\left(\frac{q}{Q}\right)^2 R_T(q,\omega)$$

$$f_{L,T} \equiv k_F \frac{R_{L,T}}{G_{L,T}}$$

→ Developed by Peter Bosted and tuned by Vahe Mamyan for E04-001.

→ uses nucleon fits by by Bosted and Christy as input and Fermi smears for nuclear targets using FG.

→ nuclear modifications to inelastic structure functions are determined from fit parameters.

→ Uses existing world data.

”

Measurements of the Transverse and Longitudinal Structure Functions in Electron Scattering on Nuclear Targets

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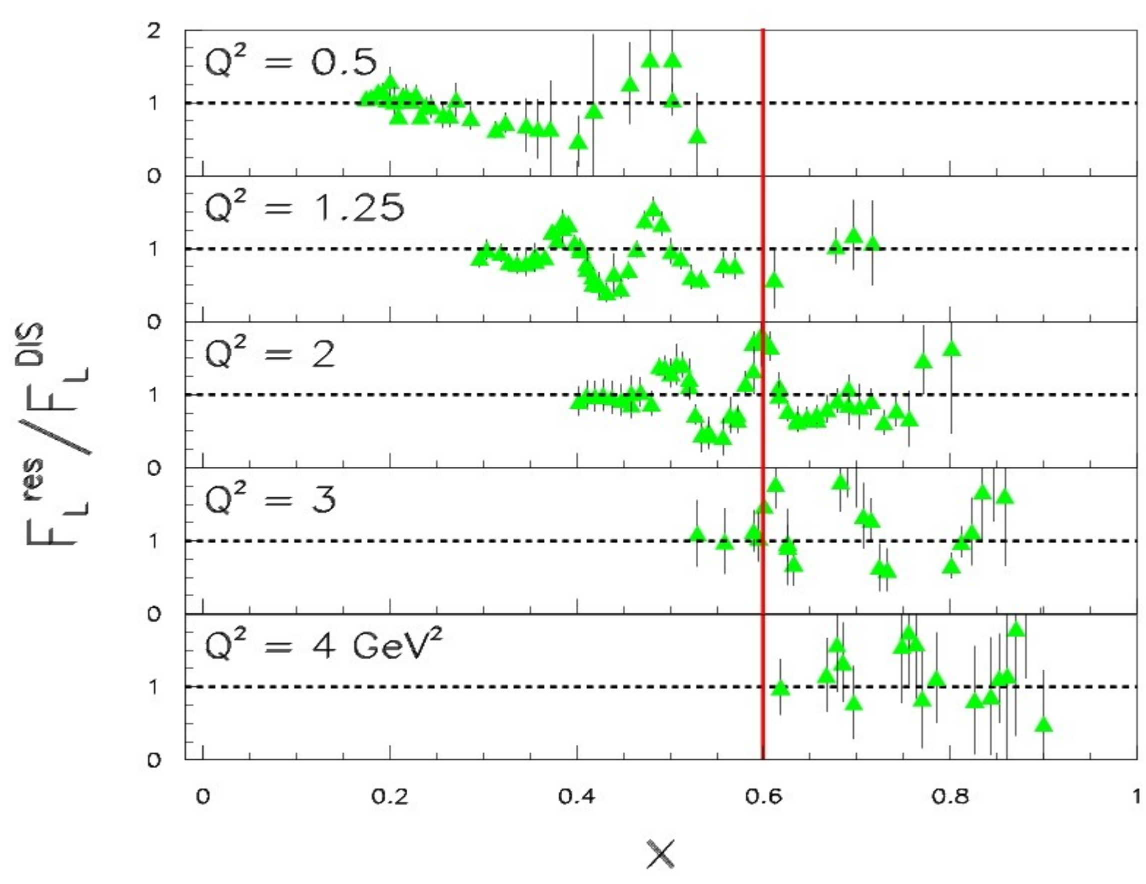
(The JUPITER Collaboration Jlab E02-109, E04-001, E06-009)

A number of neutrino physicists involved in these measurements

Q-H duality: comparisons to empirical DIS fits

- F_2ALLM fit to F_2 H.Abramowicz and A.Levy, et.all., hep-ph/9712415
- R_{1998} to $R = \sigma_L / \sigma_T$ K. Abe et.al Phys.Lett.B452:194-200,1999



Observations

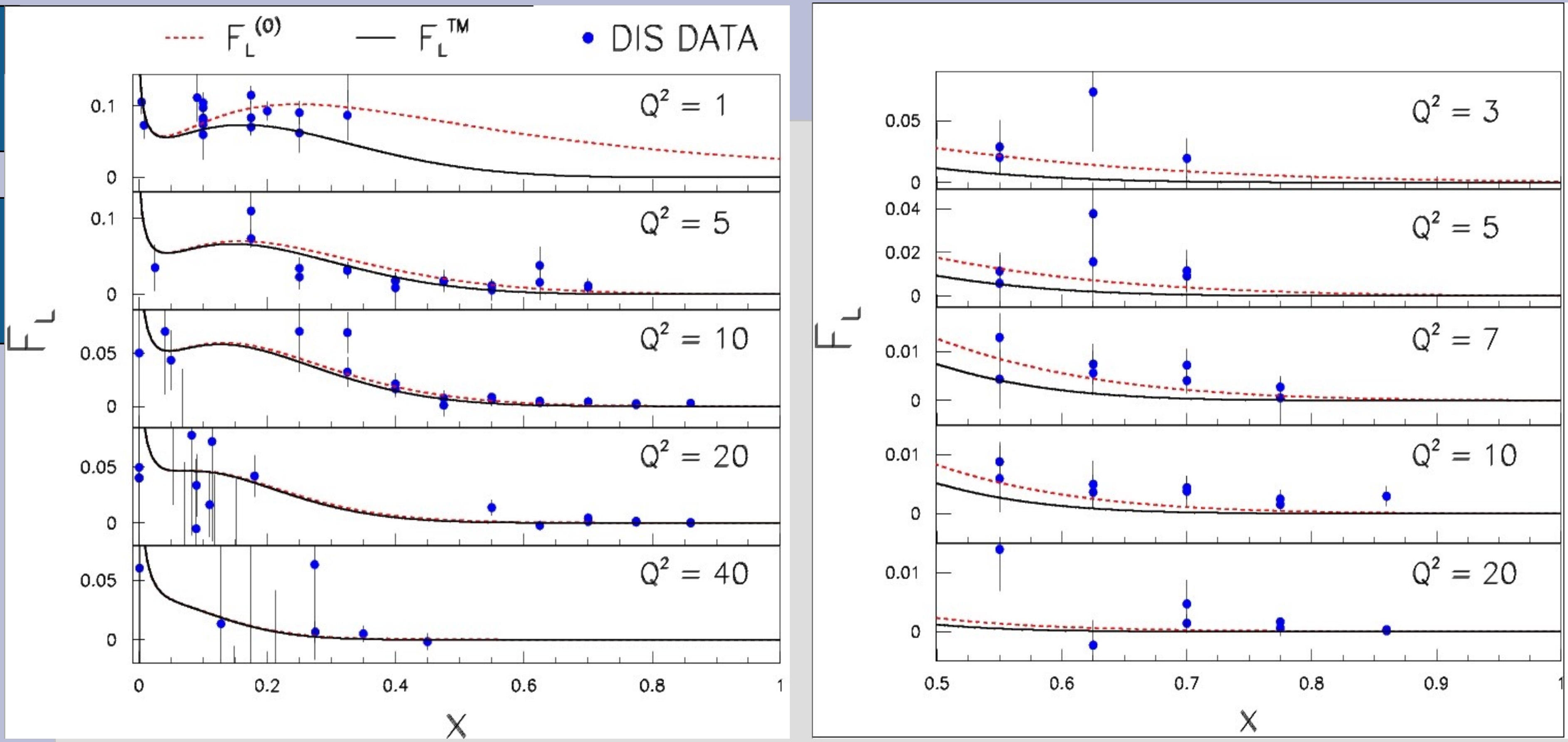
As Q^2 increases, different resonance peak and valleys pass through x=0.6

=> Averaging over a range in Q^2 at fixed x effectively averages out the variations due to the resonance contribution to the structure function.

Can we use this to provide DIS-like data?

F_L^p results from TMC unfolding procedure

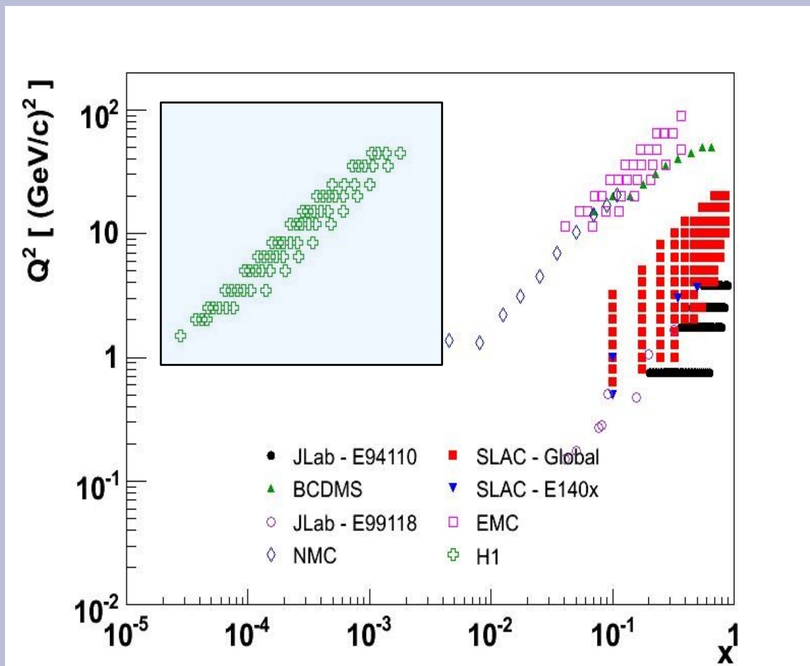
(MEC, J. Blumlein, H. Bottcher – in preparation)

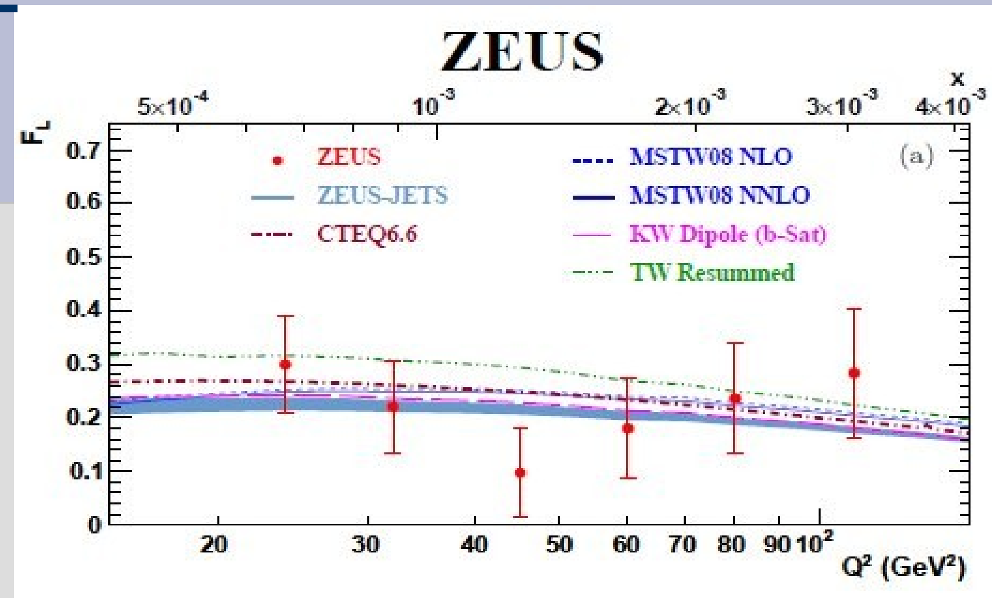


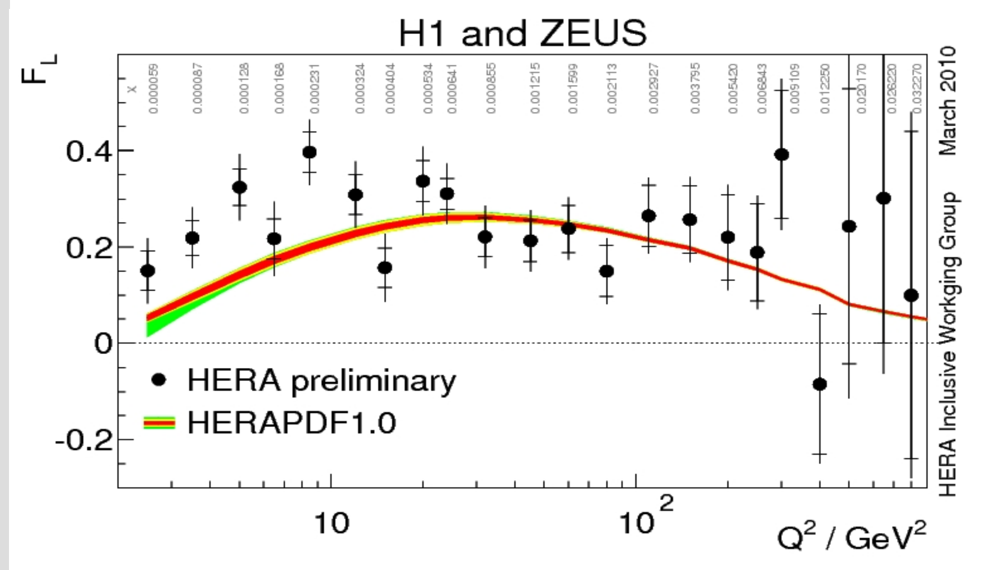
Use to → test pQCD evolution of extracted $F_{L,2}^{(o)}$

→ Further duality studies using as 'scaling' curve

New HERA F_L data at low x



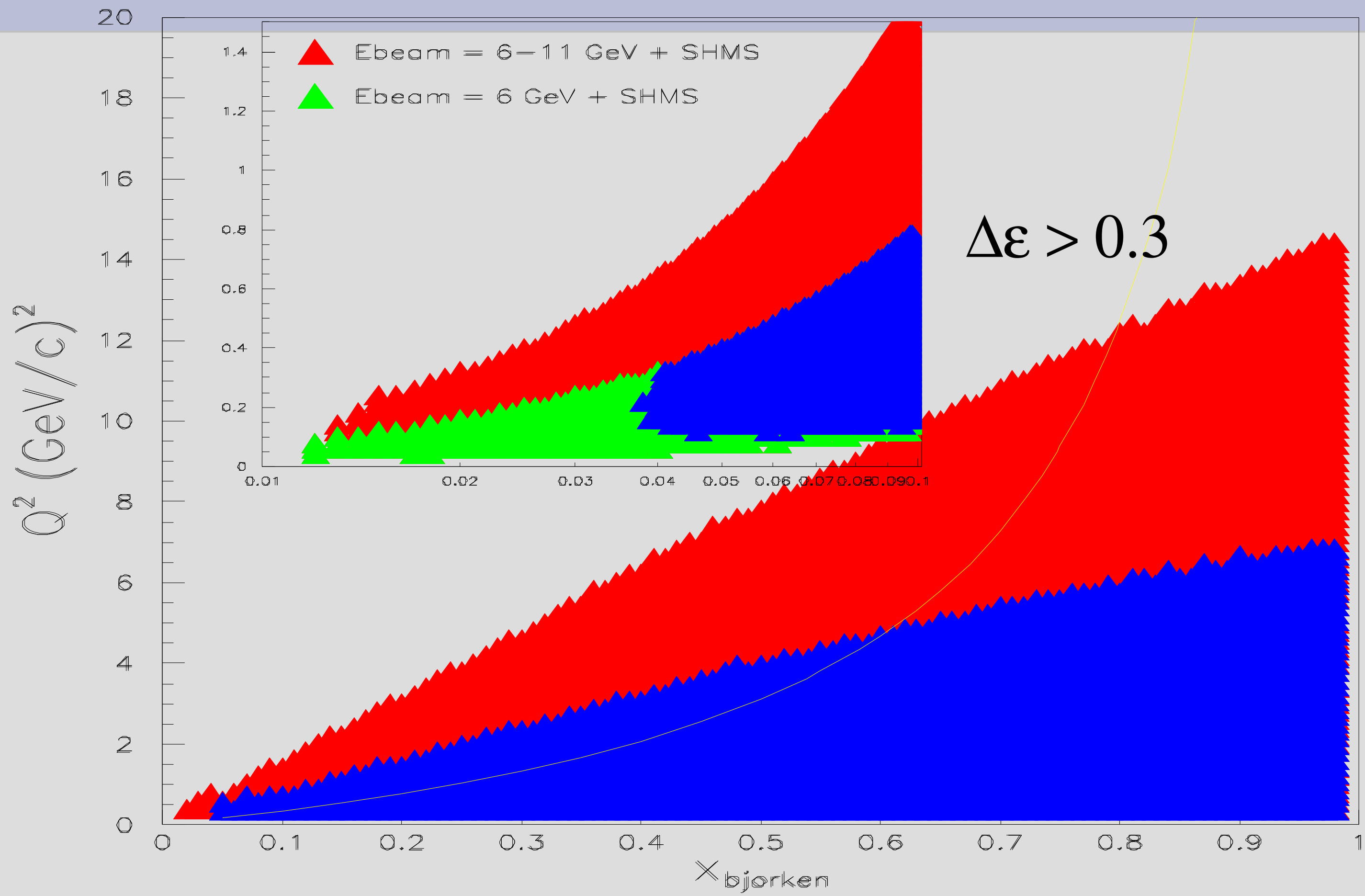




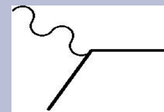
→ Lowering of beam energy during Last years of HERA allowed L/T separations to be performed by both H1 and ZEUS.

→ provides important constraint on $g(x)$.

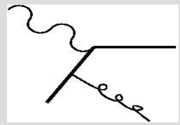
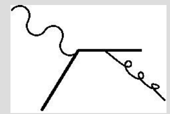
Can significantly increase Q^2 Accessible for F_L at 11 GeV JLab

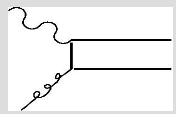
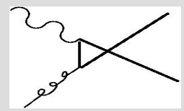


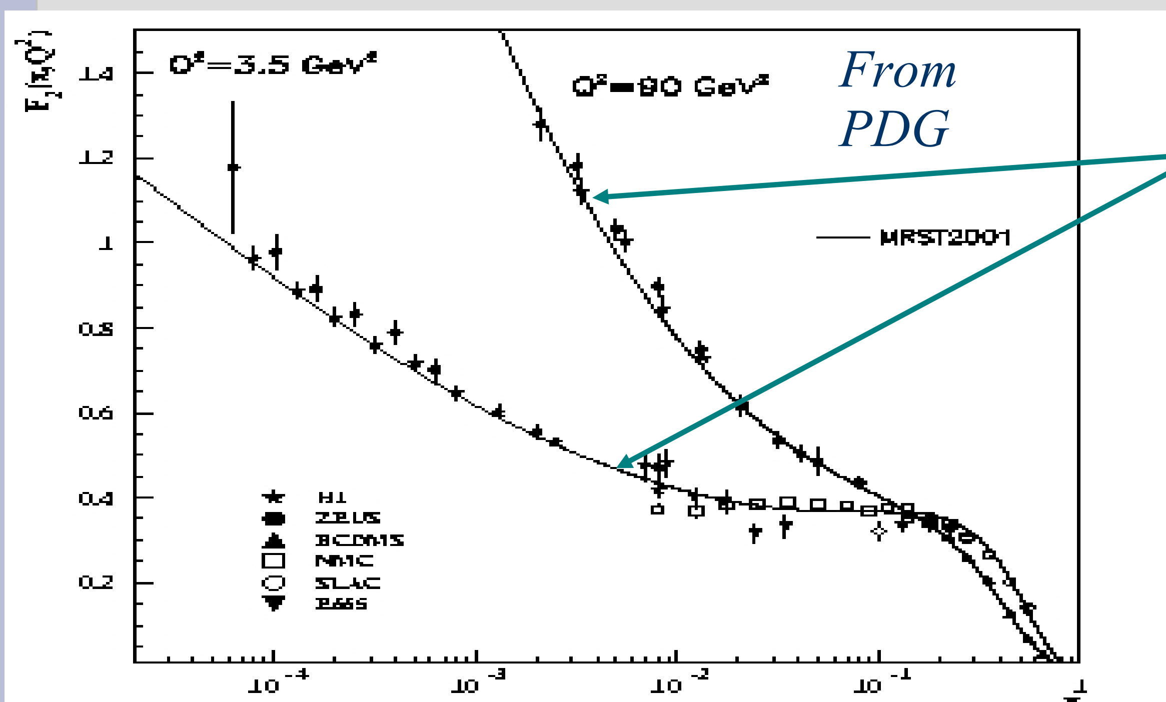
F_2 Structure Function allows study of *pQCD*

$F_2(x) = x \int e_q^2 \, \mathbf{q}(x) \; : \; x \,\Big|$  $\Big|^2$ *(parton model prediction of x scaling)*

Order $\alpha_s(Q^2)$ corrections look like:

(1) + (   ) : $x\,\Big|$  +  $\Big|^2$ $\alpha_s(Q^2)\log(Q^2/m^2)$ $\mathbf{q}(y)\,P_{qq}(x/y)$

(2) + (   ) : $x\,\Big|$  +  $\Big|^2$ $\alpha_s(Q^2)\log(Q^2/m^2)$ $\mathbf{g}(y)\,P_{qg}(x/y)$



From PDG

Sea quarks mix with glue!

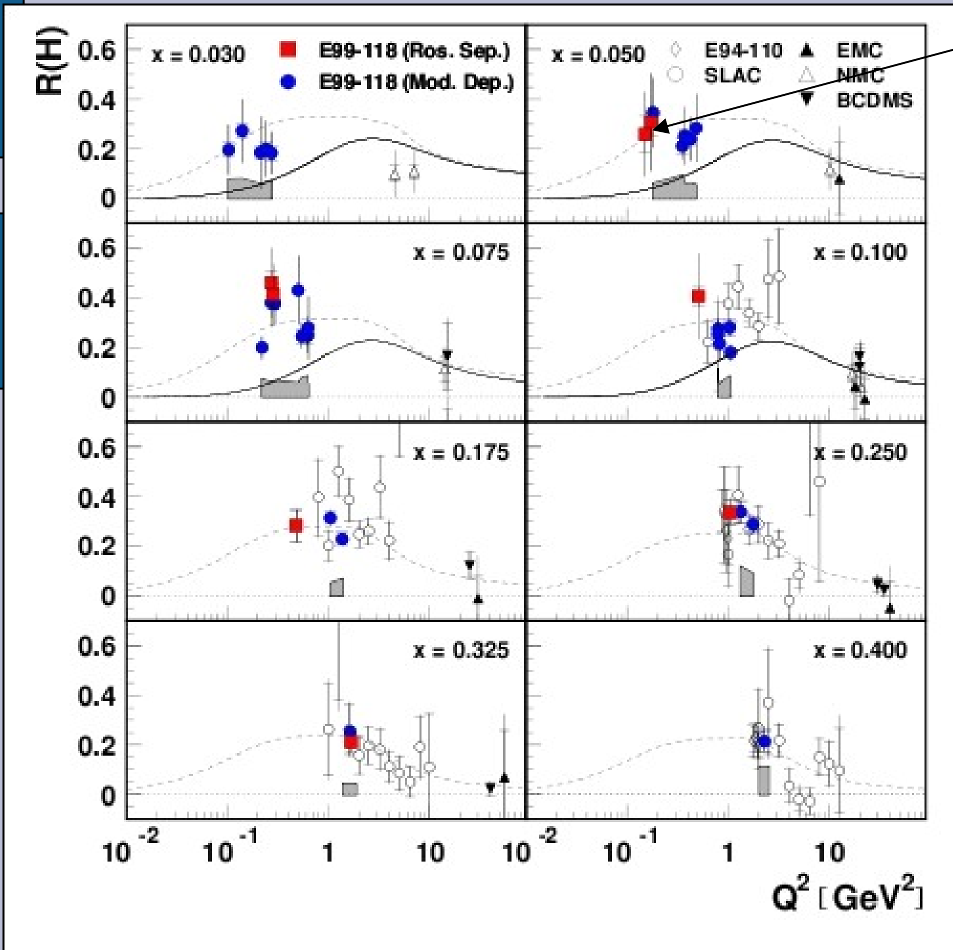
pQCD evolution given by logarithmic scaling violations from (1) and (2)!

(1) introduces transverse quark momentum

(2) Sensitive to the gluon density g(*x*)

Proton F_L and R_d-R_p small $Q^2 \rightarrow 0$ and x

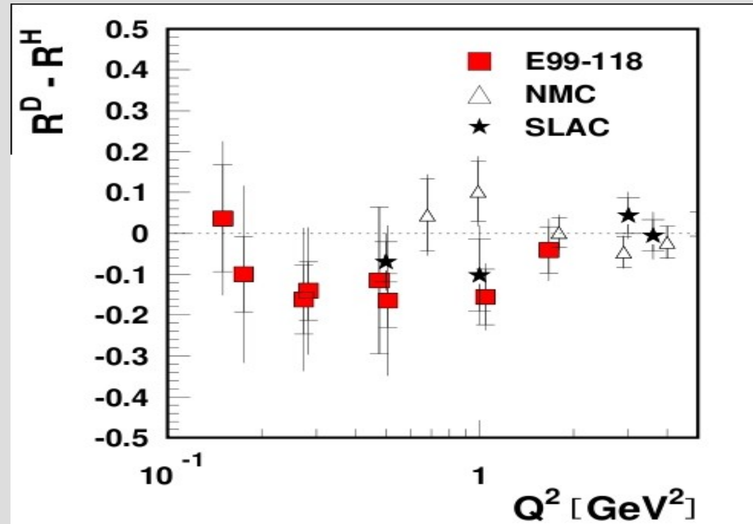
E99-118



From current conservation

R → Q^2 for **Q^2 → 0**

But this behavior is not yet observed.



For first time, intriguing hint that

$R_d < R_p$

Difference in neutron?

New data from E02-109, E06-009, and E00-002 will help resolve these open questions.

Estimate of σ_ν uncertainty on R

(from Arie Bodek, based on quark-parton model)

With $\langle \mathcal{R} \rangle = 0.2$ and $\langle f_{\bar{q}} \rangle = 0.1725$, we obtain $\langle \sigma_{\bar{\nu}}/\sigma_\nu \rangle = 0.487$, which is the world's experimental average value in the 30-50 GeV energy range. The above expressions are used to estimate the systematic error in the cross section originating from uncertainties in $\mathcal{R}$ and $f_{\bar{q}}$ (as shown in Table 3).

Want to know R to +- 0.025 to reduce error to 1%

source	change (error)	change in σ_ν	change in $\sigma_{\bar{\nu}}$	change in $\sigma_{\bar{\nu}}/\sigma_\nu$	
R	+0.10	-2.0%	-4.0%	-2.1%	<---- R
$f_{\bar{q}}$	+10%	-1.4%	+2.8%	+4.2$	<-----Sea antiquarks
P (K^{axial}_{sea})	+ 0.3	+1%	+2%	+1.0%	<----Axial sea
N	+3%	+3%	+3%	0	--PDF normalization quark versus gluon
Total		±4.0%	±6.1%	±4.8%	

Error in R leads to large error in the antineutrino cross sections from the inelastic part.

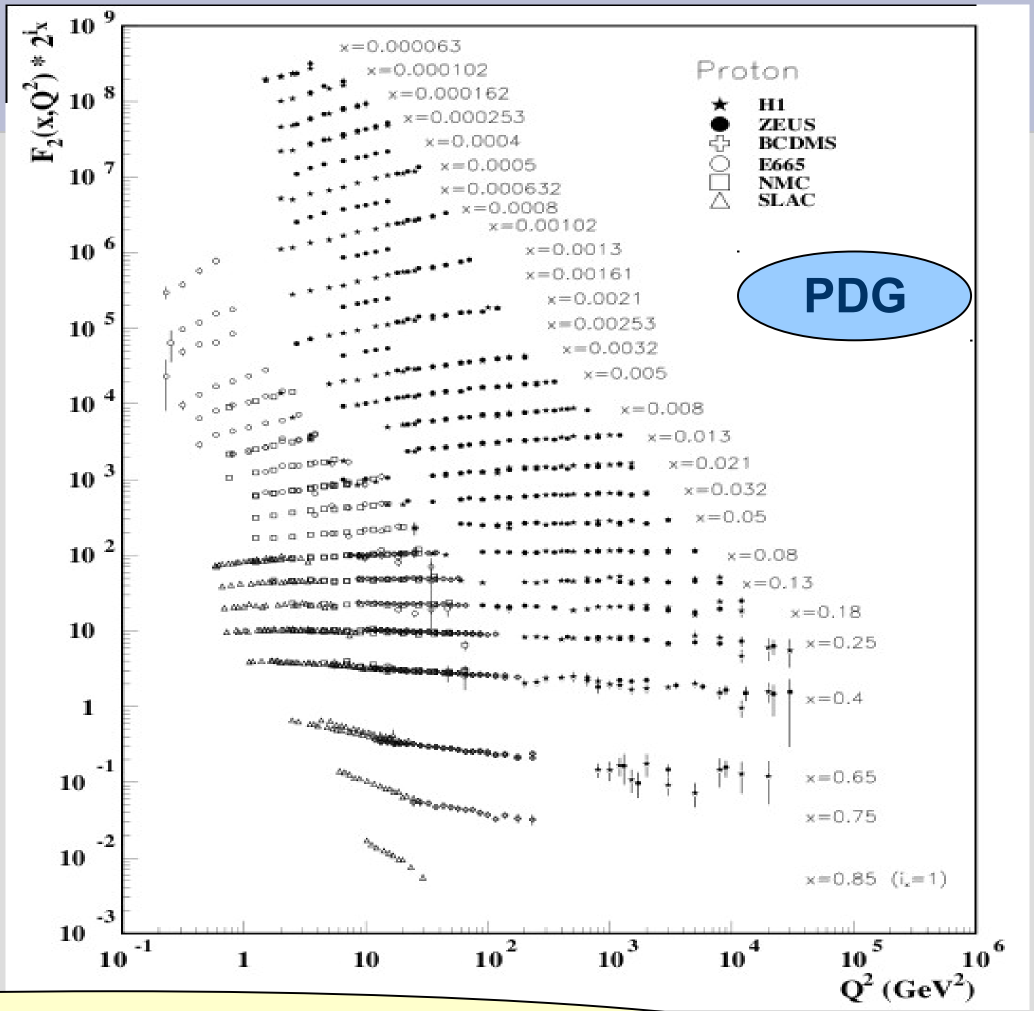
Above does not include error from EMC effect/shadowing, or axial valence. Or resonances and QE components of F2.

Measurements of Structure functions are Critical for a full understanding of QCD

→ Approximate scaling of F_2 with Q^2 provided verification of proton constituents, carrying longitudinal Momentum fraction x.

→ $R = \sigma_L/\sigma_T < 1$
provided evidence that charged constituents were spin 1/2.

→ Scaling violations measured over orders of magnitude in x and Q^2 well described by universal set of parton distribution functions (PDFs) within pQCD.



F_L data is relatively sparse and much less precise.

Outline

1. Status of proton and deuteron structure functions at large x and low Q^2

2. Quark-Hadron duality:
   the transition from perturbative to non-perturbative QCD

3. Extracting neutron structure functions
   => minimizing uncertainties on the d-quark (CJ PDFs)

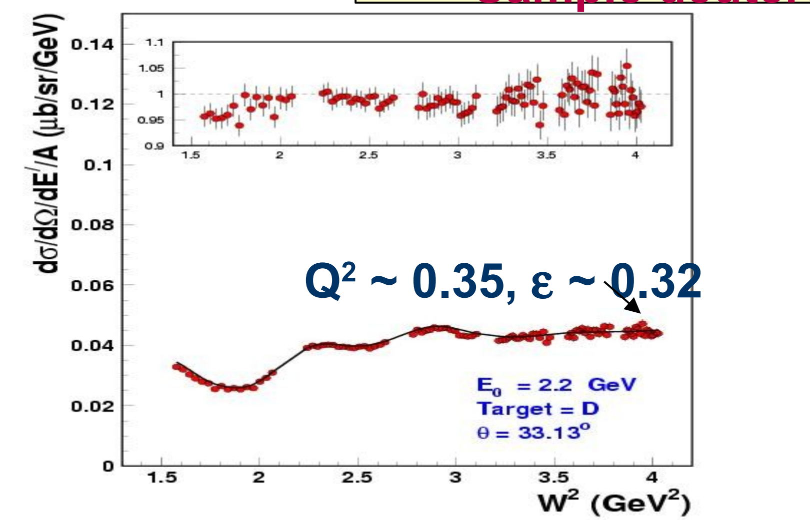
4. How to build deuteron from p+n?

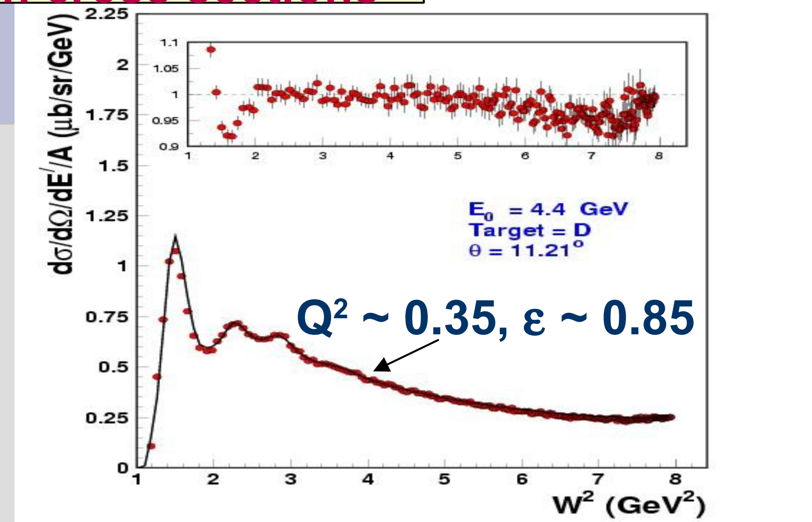
5. Structure functions in nuclei

6. Open issues in modeling ν-A scattering at large x

E00-002 Results

Sample deuteron cross sections

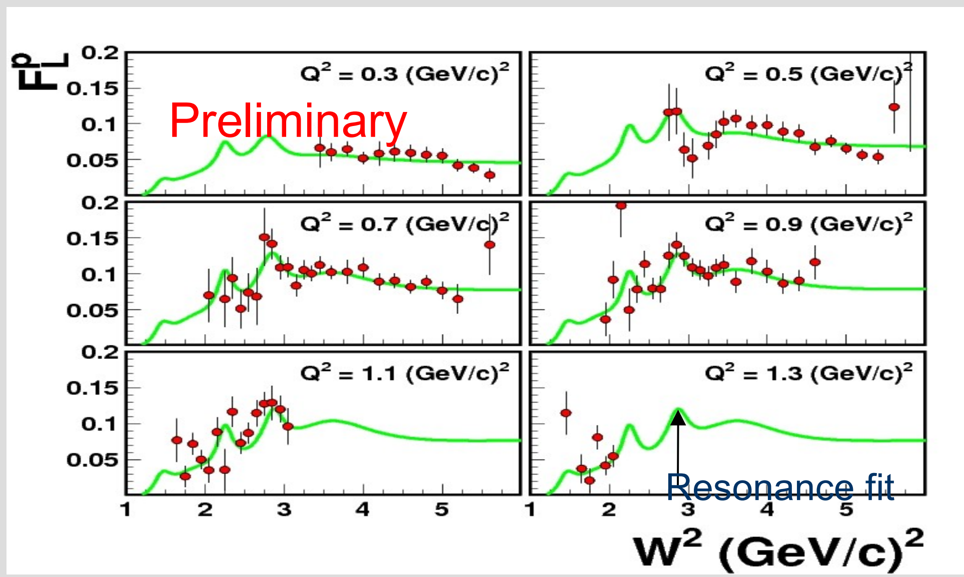




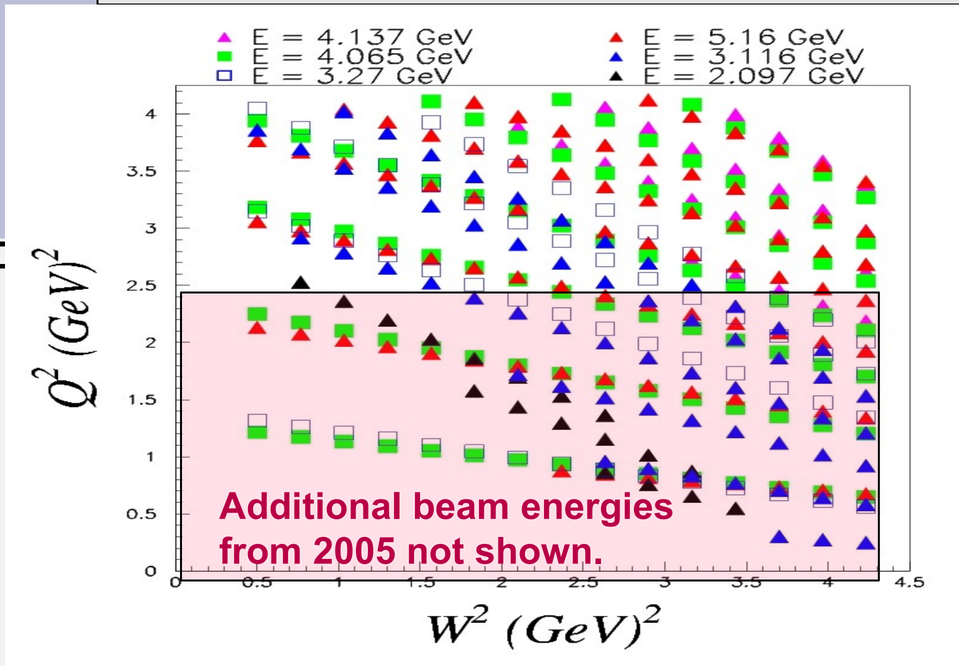
Preliminary results for F_L^p

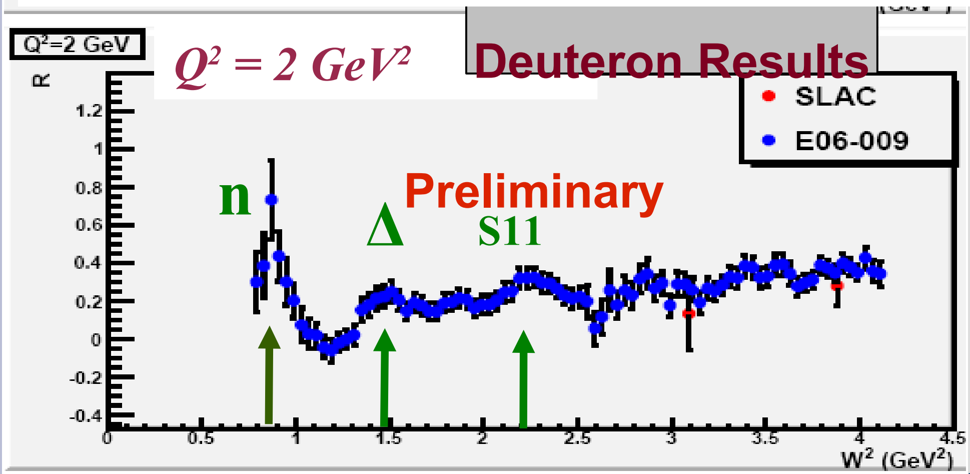
Consistent with resonance global fit.

Results for deuteron and R_d - R_p coming soon.



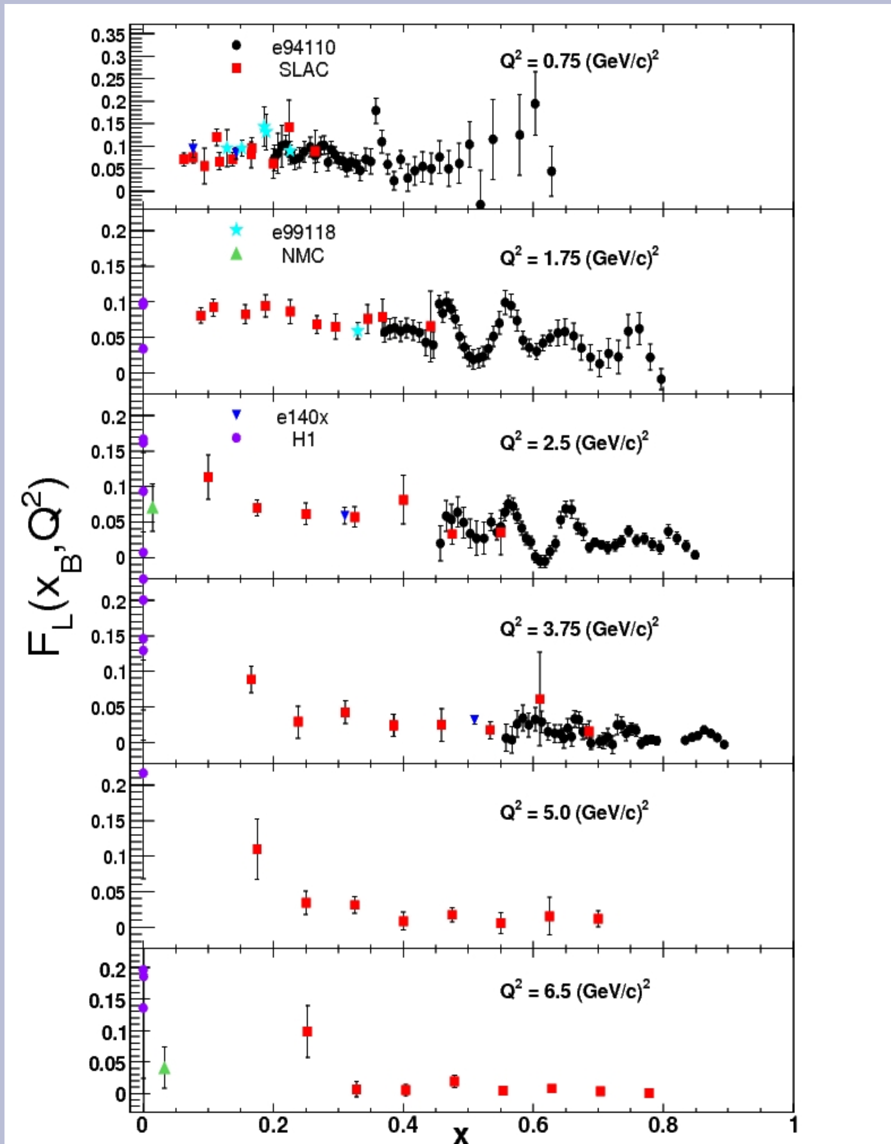
$F_{L,}$ R on Deuterium and heavier targets
JLab Hall C: E02-109, E04-001, E06-009

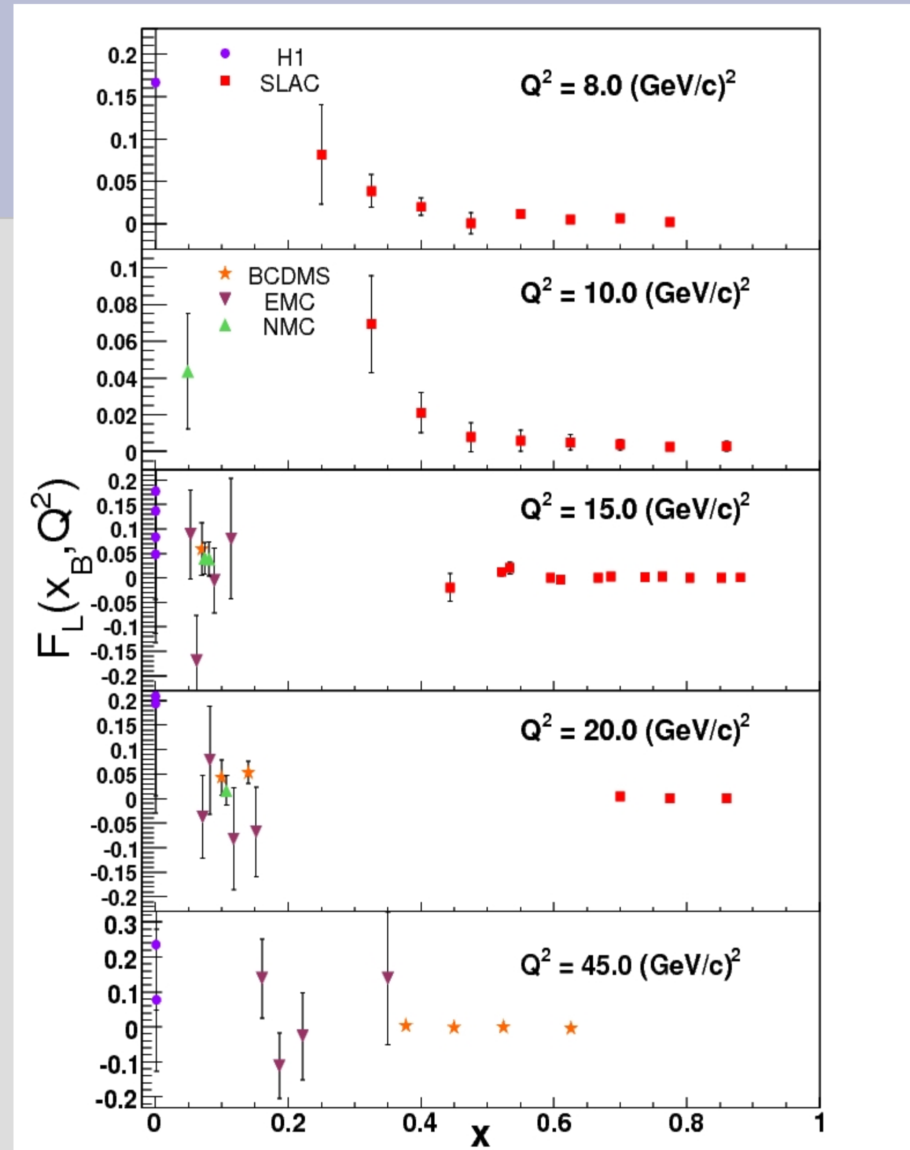




- Precision extraction separated structure functions on D, Al, C, Fe/Cu
- Search for nuclear effects in F_L, R.
- Neutron and p-n moment extractions (non-singlet / singlet).
- Allow study quark-hadron duality for neutron, nuclei separated structure function.

Global status of the Proton F_L data





Unfolding TM Contributions from data

In the OPE

$$F_2^{TM}(x,Q^2) = \frac{x^2}{r^3}\frac{F_2^{(0)}(\xi,Q^2)}{\xi^2} + 6\frac{M^2}{Q^2}\frac{x^3}{r^4}\int_\xi^1 dx' \frac{F_2^{(0)}(x',Q^2)}{x'^2} + 12\frac{M^4}{Q^4}\frac{x^4}{r^5}\int_\xi^1 dx' \int_{x'}^1 dx'' \frac{F_2^{(0)}(x'',Q^2)}{x''^2}$$

$$F_1^{TM}(x,Q^2) = \frac{x}{r}\frac{F_1^{(0)}(\xi,Q^2)}{\xi} + \frac{M^2}{Q^2}\frac{x^2}{r^2}\int_\xi^1 dx' \frac{F_2^{(0)}(x',Q^2)}{x'^2} + \frac{2M^4}{Q^4}\frac{x^3}{r^3}\int_\xi^1 dx' \int_{x'}^1 dx'' \frac{F_2^{(0)}(x'',Q^2)}{x''^2}$$

$$2xF_1^{TM} = \frac{F_2^{TM} - F_L^{TM}}{r^2}$$

$$2xF_1^{(0)} = F_2^{(0)} - F_L^{(0)}$$

$$r = 1 + \nu^2/Q^2 = \sqrt{1 + \frac{4M^2x^2}{Q^2}}$$

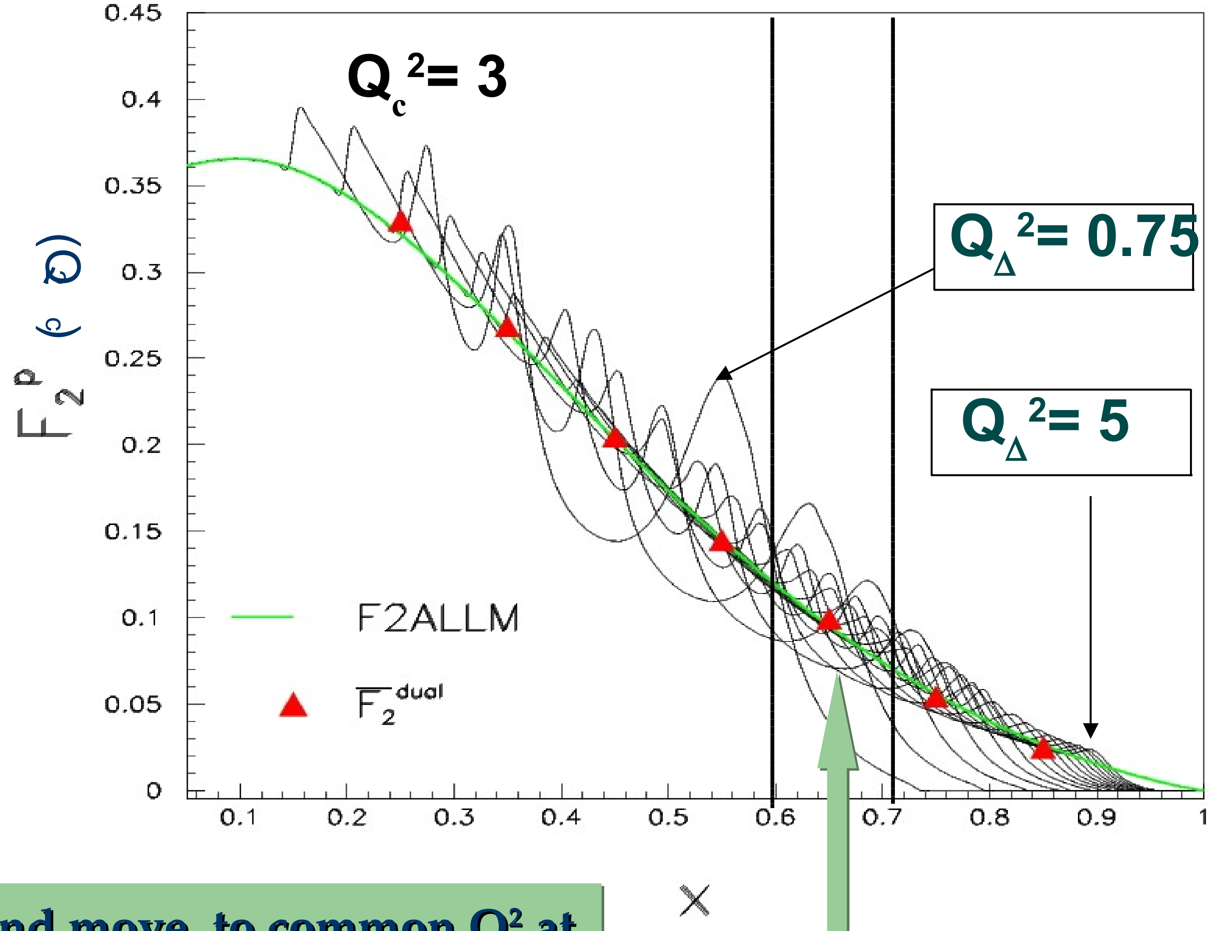
$$\xi = 2x/(1+r)$$

Parameterize $F_{2,L}^{M=0}$ (x,Q²) and fit $F^{TM}_{2,L}$(*x*,Q²) to world data set => determine TMCs directly from data.

- ***Not* a perturbative expansion**
- ***Assume that higher twist operators obey same formalism.***

*Proton charged lepton data on F_2 and F_L fit for **$0.3 < Q^2 < 250$** and **$x > 1\mathrm{x}10^{-4}$***

Duality Averaging Procedure for proton F_2



Averaging over bite in Q^2 effectively averages over resonances.

Can use fit to do averaging and correct with data where available.

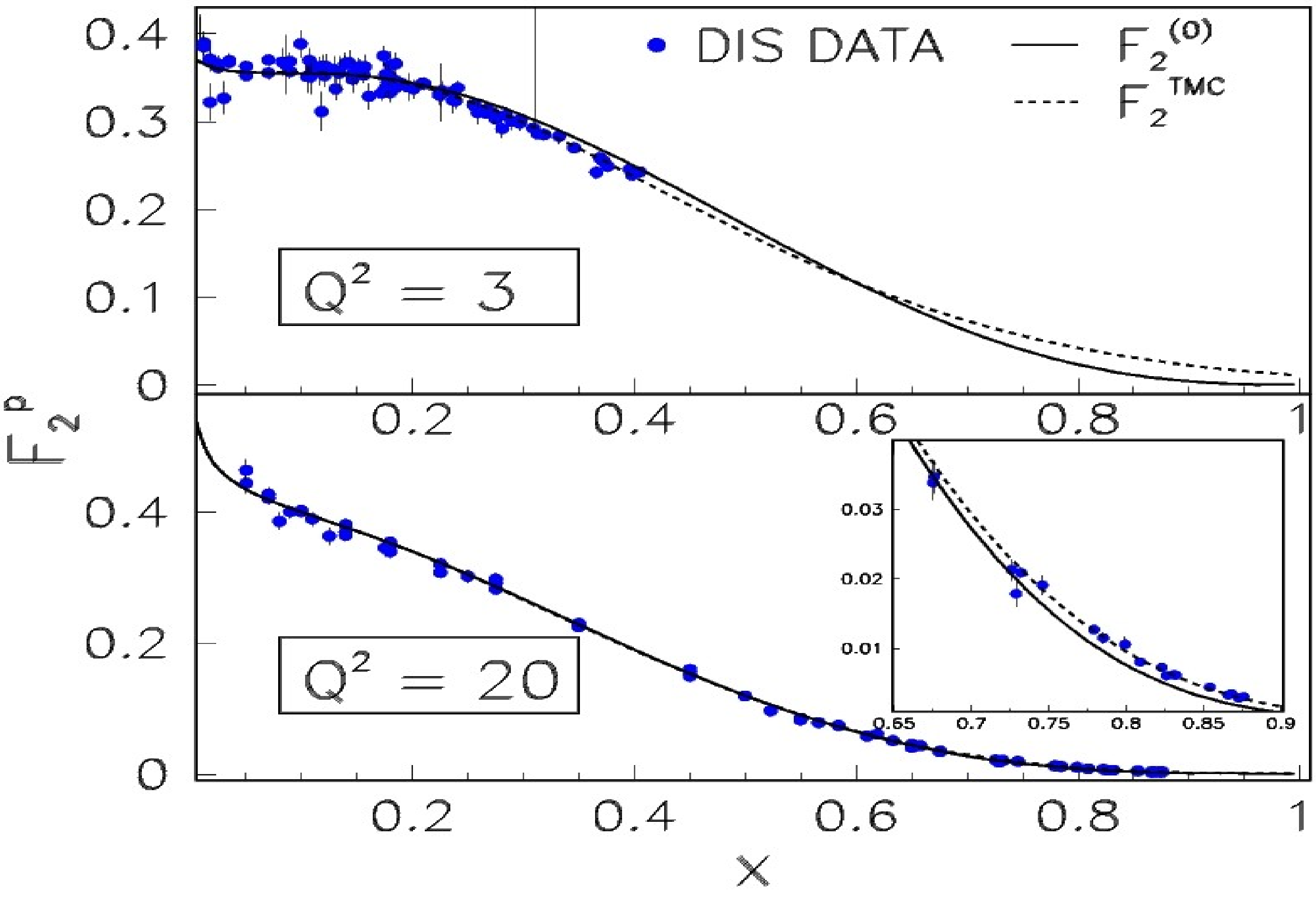
For F_2 resonance average is very close to DIS fit!

Fix x and move to common Q^2 at using Q^2 dependence of DIS fits. (Can iterate to get new fit)

Then average fit/data over this x bin

=> 'DIS-like' data

F_2 fit results



Are the CN moments of data what should be compared to pQCD?

In pQCD

$$M_2^{(n)}(Q^2) = \int dx\, x^{n-2} F_2^{(0)}(x)$$

This is not true for finite M^2/Q^2 due to TMCs. However, *Nachtmann (1973)* found a way to project out the massless limit contribution via

$$M_L^{(n)}(Q^2) = \int_0^1 dx\, \frac{\xi^{n+1}}{x^3} \{ F_L(x,Q^2) + \frac{4M^2x^2}{Q^2} \frac{(n+1)\xi/x - 2(n+2)}{(n+2)(n+3)} F_2(x,Q^2) \} \quad (1)$$

→ Here F_2, F_L are the *experimental* structure functions.

→ Nachtmann moment effectively removes the TM contributions.

How do we determine the Proton F_L Nachtmann Moments?

- Bin data in fine x bins over ($0.01 < x < 1$).

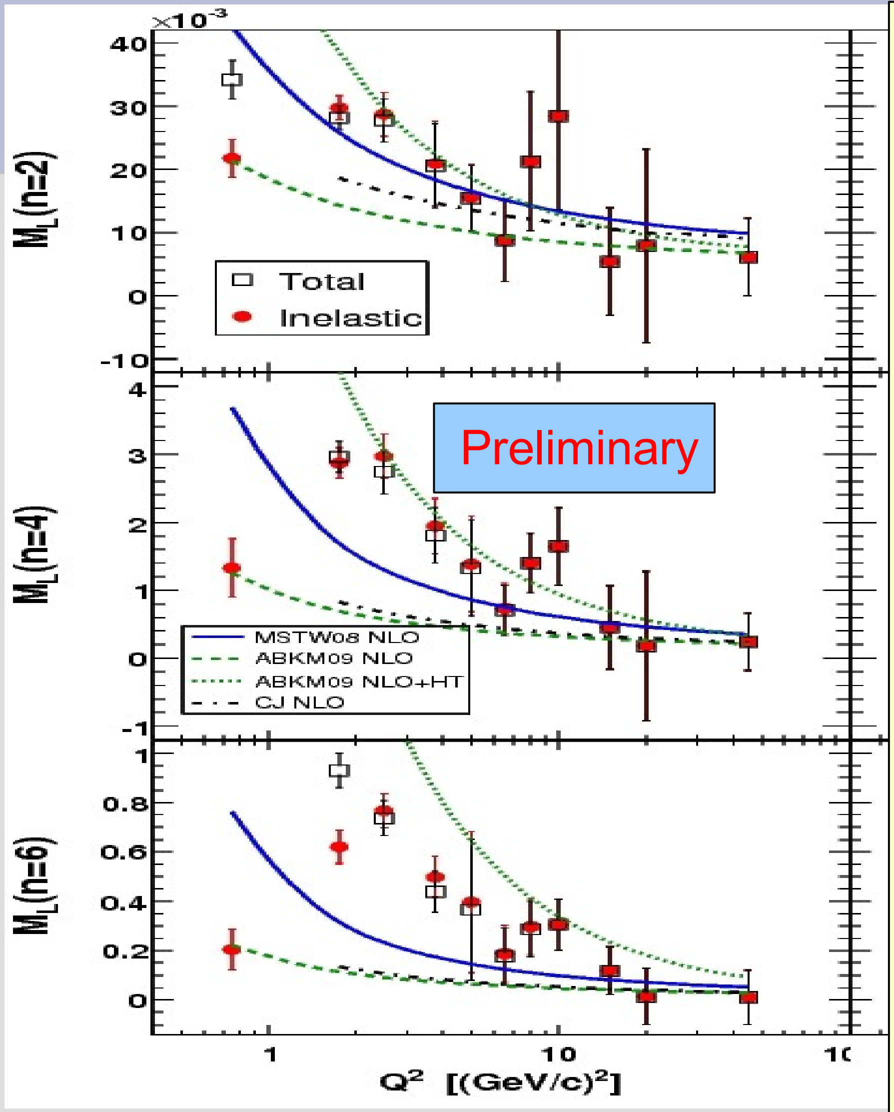
- Utilize resonance and DIS fits to interpolate between data points, where necessary.

- Determine uncertainties in moments from uncorrelated uncertainties by generating 1000 'pseudo' data sets with individual F_L values randomly sampled within uncorrelated uncertainties.
  → produces set of 1000 moment values with uncorrelated uncertainty given width of distribution.

* Nachtmann F_L moment requires F_2 moments be determined.

Results for Proton F_L Nachtmann Moments

P. Monaghan, A. Accardi, M.E.C, C.E. Keppel, W. Melnitchouk, L. Zhu



→ Inclusion of precision JLab data results in small uncertainties at $Q^2 < 4$.

→ Contribution at x=1 ($\xi < 1$) from elastic form factors is increasingly large for small Q^2, but small above $Q^2 = 2$.

→ Turn over at low Q^2 due to pion production threshold appearing at smaller x for small Q^2.

→ Different PDF NLO results are similar at $Q^2 > 20$, but are significantly different at Low Q^2.

→ Note that only ABKM includes H-T terms in fit. Contribution partially absorbed in MRST gluon?

→ Differences in higher moments likely due to underestimated Gluon strength at high x and/or H-T contributions.

Cornwall-Norton Moments of F_L

Moments of the Structure Function

- $$M_n^{2,L}(Q^2) \equiv \int_0^1 dx \;\; x^{n-2} \; F_{2,L}(x,Q^2)$$

  $$M_n^1(Q^2) \equiv \int_0^1 dx \;\; x^{n-1} \; F_1(x,Q^2).$$

If $n = 2$ → Bloom-Gilman duality integral!

(integral of DIS or resonance curve is the same)

Operator Product Expansion

$M_n(Q^2) = \Sigma \; (nM_0{}^2/\,Q^2)^{k-1}\, B_{nk}(Q^2)$ K=1 term is twist-2, eg *free* partons

higher twist pQCD

→ Duality is described in the Operator Product Expansion *as higher twist effects being small or cancelling* - **DeRujula, Georgi, Politzer (1977)**

→ The determination of structure function moments allow us to study the transition of QCD from asymptotic to confinement scales..