Quark-Hadron Duality: New studies from JLab

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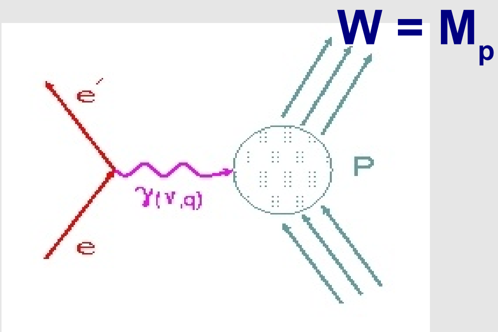
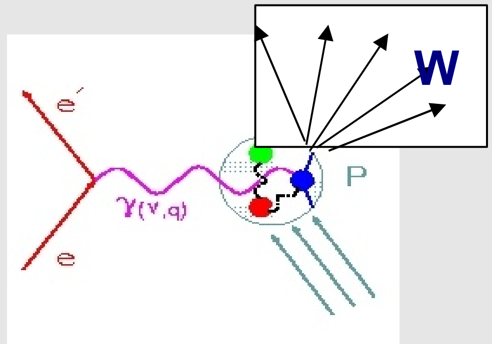
Outline

- Brief history of quark-hadron duality in electroproduction.
- JLab data
- Models of duality
- Quantifying global and local duality
- Testing models
- Summary

Inclusive Charged-Lepton Scattering

Elastic | **Inelastic**





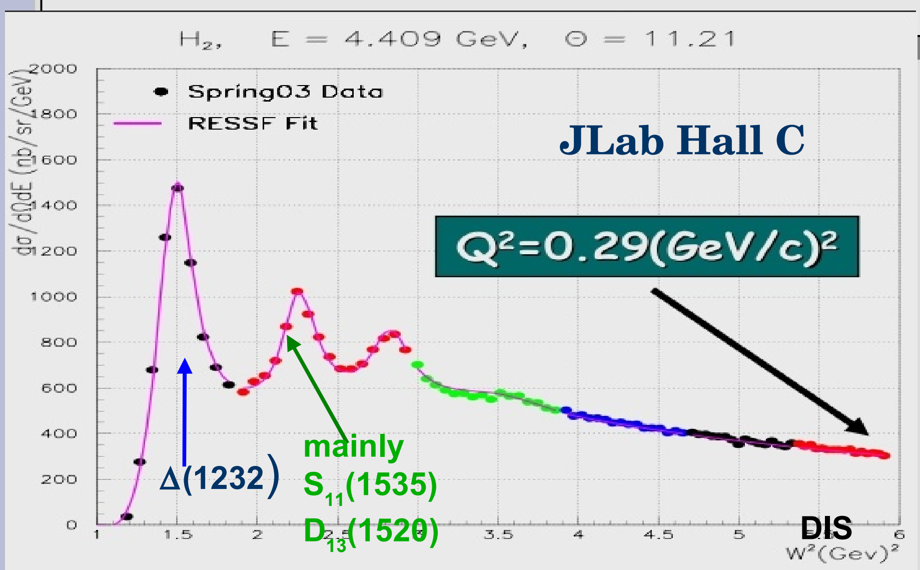
Q^2 : photon 4-momentum

ν: photon energy

W: Final state hadron mass

x: Bjorken variable

$$\frac{d\sigma}{d\Omega\, dE'} \propto \Gamma\, [2xF_1(x,Q^2) + \varepsilon\ F_L(x,Q^2)] \qquad F_2 = (2xF_1+F_L)/(1+\nu^2/Q^2)$$



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

Elastic → resonance → Continuum

The Beginning: Bloom-Gilman duality

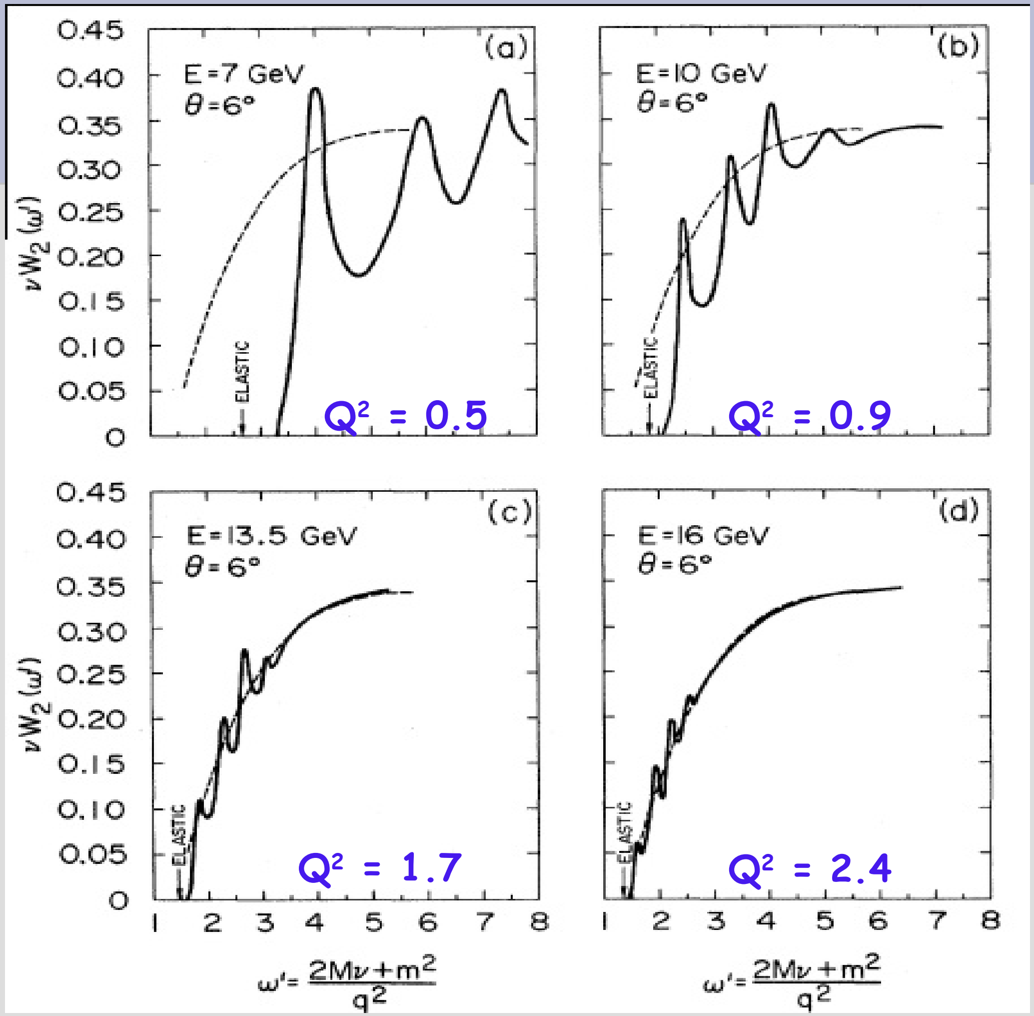
- Inclusive e-P scattering.

-Resonance excitation at low W,Q^2
-Continuum at larger W,Q^2

- First observed by Bloom and Gilman at SLAC *prior* to the development of QCD.
  Phys.Rev.Lett.25:1140,1970.

- Noted that resonances oscillate around a 'scaling' curve at all Q^2.

- hadrons excitations follow the DIS scaling behavior.



Bloom-Gilman Conclusions

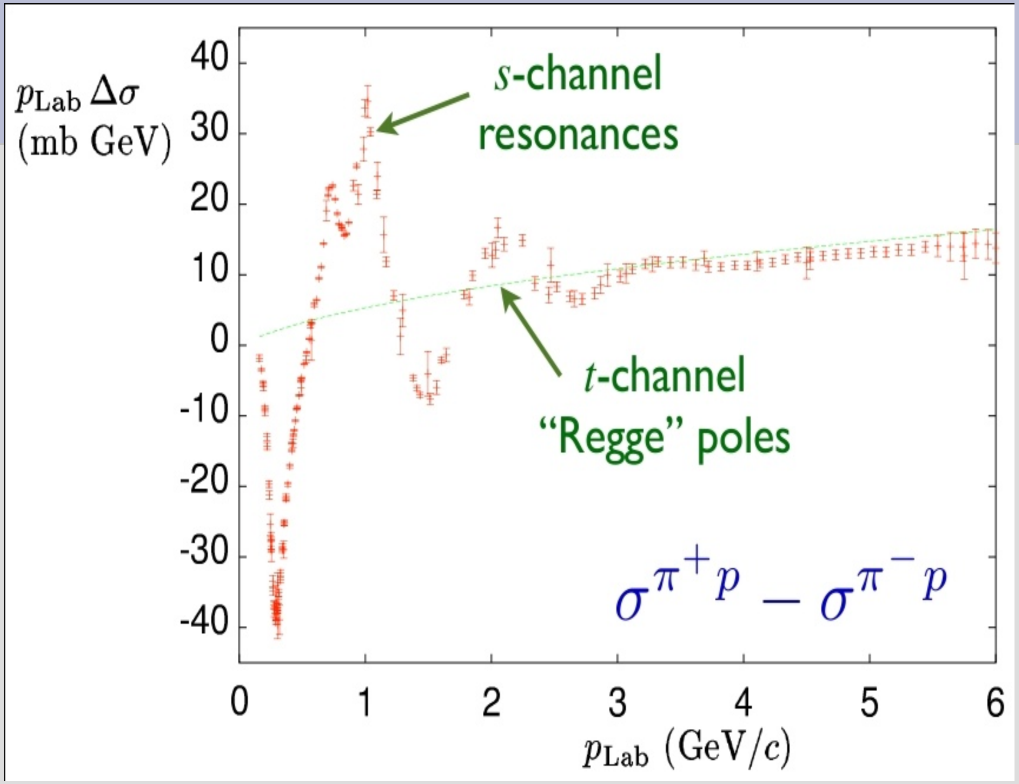
- ✓ As Q^2 increased then resonances move toward $\omega' = 1$, ***each*** clearly following the smooth scaling-limit curve.

- ✓ The resonances are not a separate entity but are an intrinsic part of the scaling behavior.

- ✓ This connection between the behavior of resonances and scaling hints at a common origin in terms of a point-like substructure.

Novel observation that was generally left unstudied for next 30 years.

Prior to Bloom-Gilman, a 'duality' was known from hadron-hadron scattering



→ Partial theoretical description provided by Finite Energy Sum Rules (FESR).

→ Provided relationship between t-channel Regge trajectories (high E) and s-channel resonance production (low E).

→ Developed in 1962 (Igi) and applied to charged pion-proton scattering in 1968 (Dolen, Horn,Schmidt).

→ Electroproduction is unique in that points at the same Bjorken x (ω') arising from different Q^2 at the same $s=W^2$, both in and outside the resonance region.

Local Duality allows us to relate structure Functions to Form Factors

For resonances, $F_2(W_{res} = M_{res}) \sim 2M\nu\, G^2(Q^2)$, where G is the resonance form factor

With $x_{res} = Q^2/(W^2_{res} - M^2 + Q^2) = Q^2/2M\nu_{res}$

If resonances slide down Q^2 independent F_2 scaling curve with

(1) $\boxed{F_2 \sim (1-x)^{2n-1}}$ for $x \rightarrow 1$

Then $G^2 \sim (1-x_{res})^{2n-1}/2M\nu_{res} = (1-x_{res})^{2n}$

And for $Q^2 \gg W^2_{res} - M^2$

(2) $\boxed{G \sim (1/Q^2)^n}$

Relationship between (1) and (2) for elastic is the **Drell-Yan-West** relation
With 'n' the minimum # of gluons exchanged => pQCD counting rules.

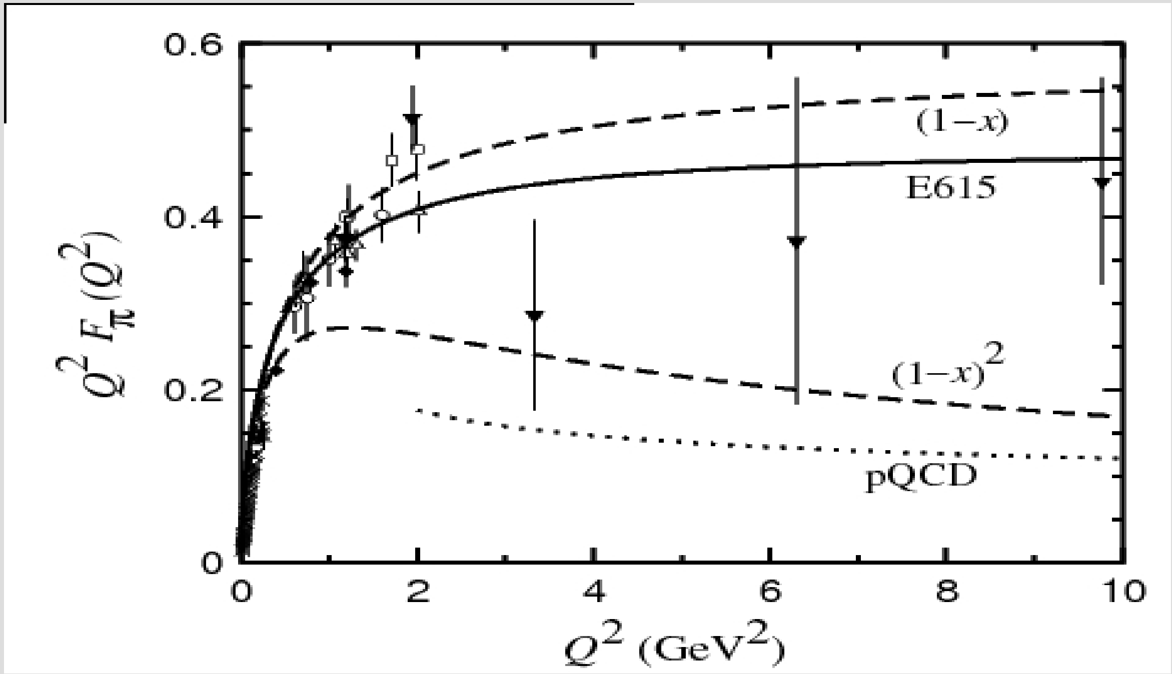
Conversely, DYW => 'local' duality for well isolated resonances.

Applicaton to pion structure function

$F_2^\pi \sim (1\text{-}x)^a$, with *a* from Drell-Yan **E615** data

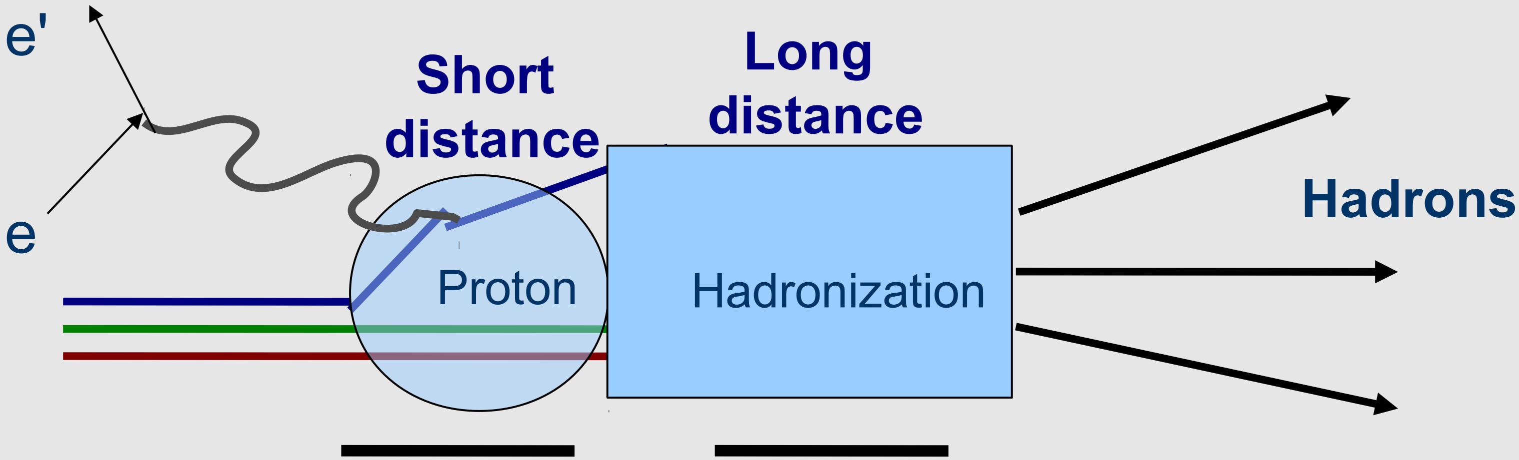
Assuming **local duality**, predict F_π form factor:

W. Melnitchouk, Eur.Phys.J.A. 17 (2003) 233.



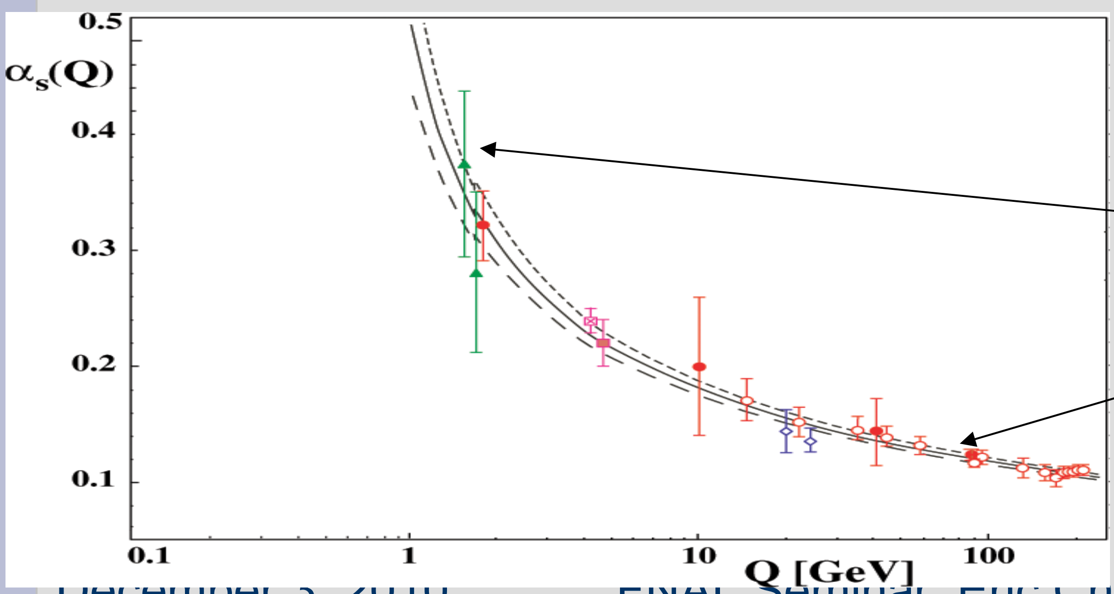
* Remarkable agreement with data

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

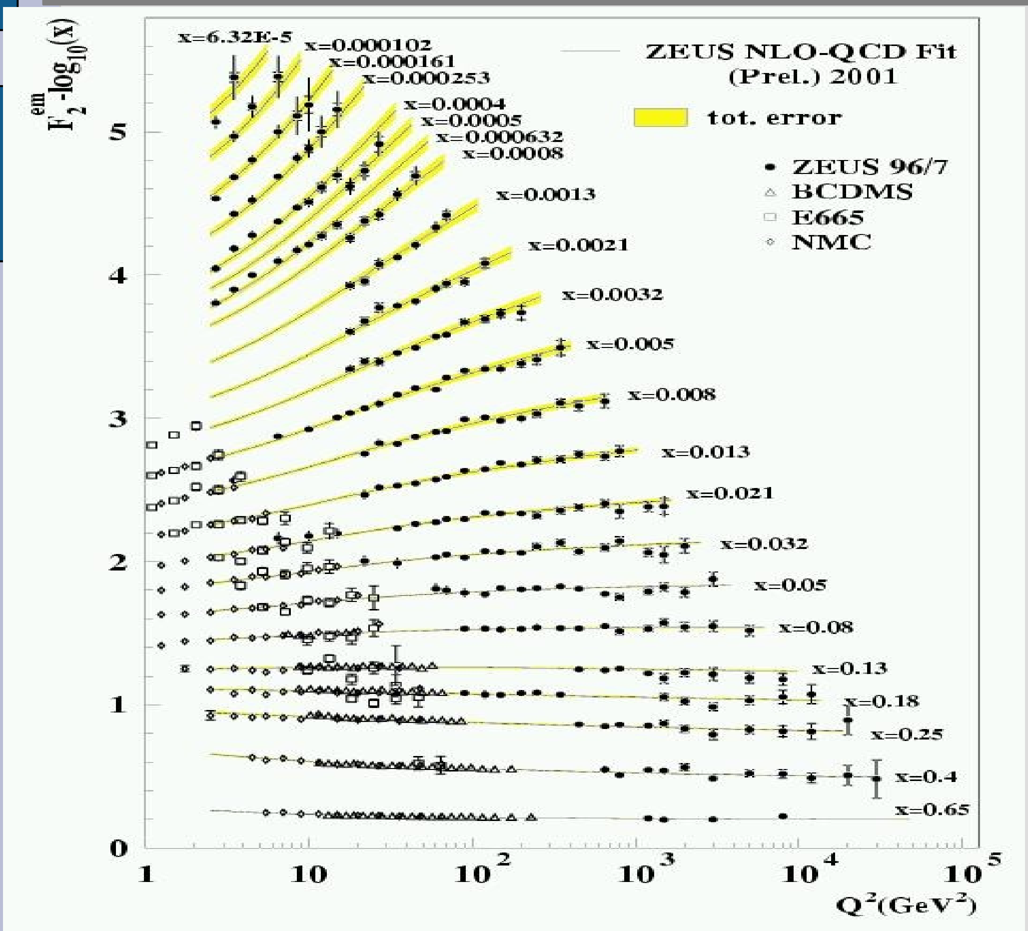
=> restoring force is large enough to pull q qbar pairs from vacuum.

quarks are close (~< 1fm)

=> strong coupling is small

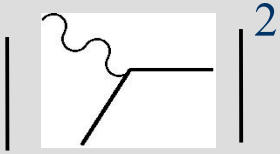
Separation of scale => Q^2 dependence of DIS structure functions governed by perturbative QCD

Scaling in F_2 measured to high precision over many orders of magnitude in *x* and Q^2,

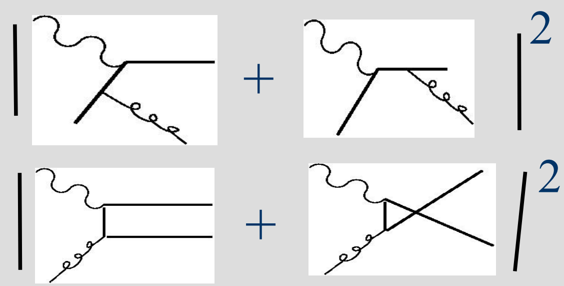


Single quark scattering (leading twist)

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



Where the $\mathbf{q}(x,Q^2)$ evolve via pQCD.
Order $\alpha_s(Q^2)$ corrections



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

$$\xi = 2x/(1+r) \qquad \text{With} \qquad r = 1 + \nu^2/Q^2 = \sqrt{1 + \frac{4M^2x^2}{Q^2}}$$

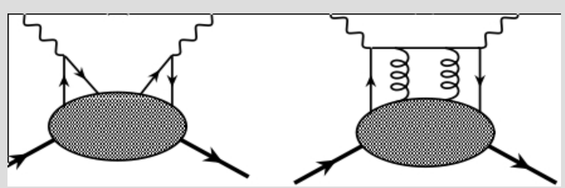
Note that $\xi \to x$ for $Q^2 \to \infty$ (or $M \to 0$) at fixed x

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

'Massless' limit

Higher Twist contributions (H-T)':

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



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)

$\Sigma_{hadrons}$ Σ_{quarks}

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

Duality and scaling

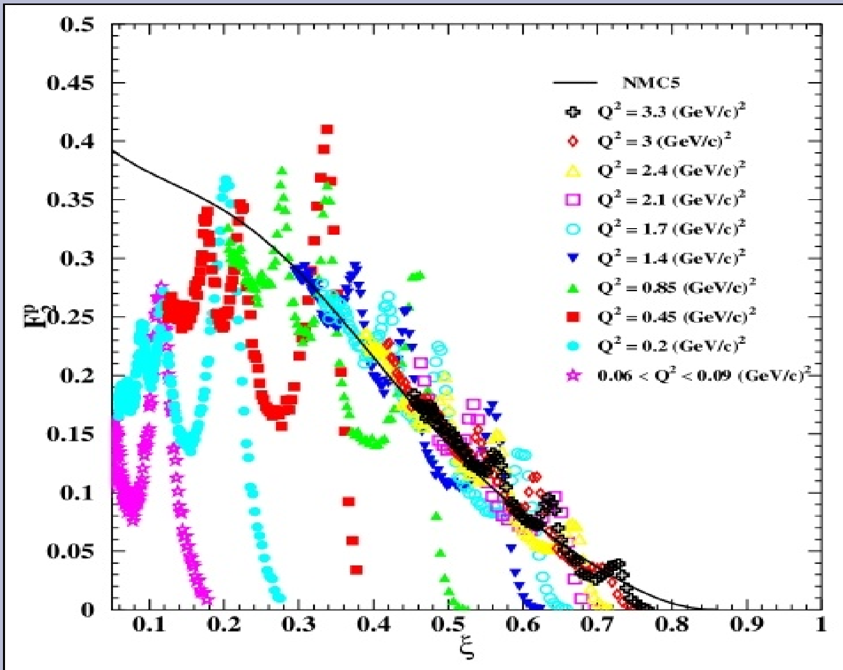
What does it mean?

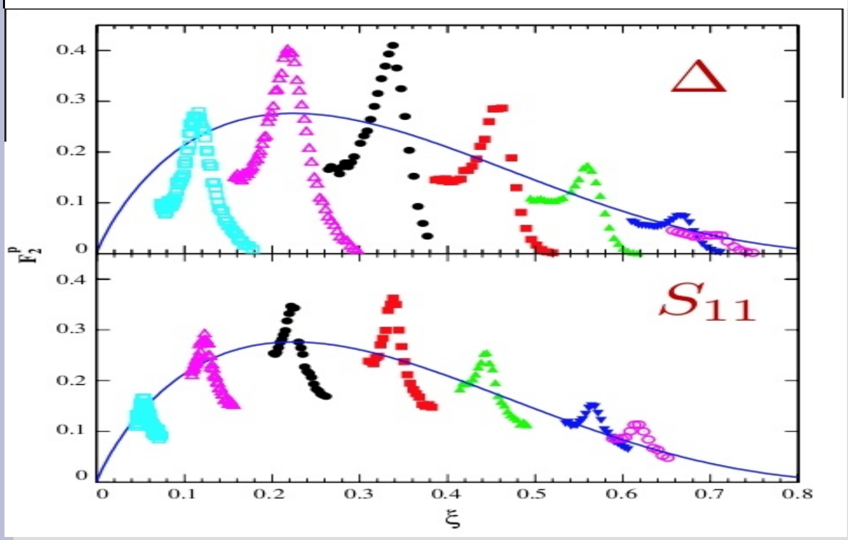
Resonances have same Q^2 dependence as scaling curve.

But what scaling curve?

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

First Hall C data



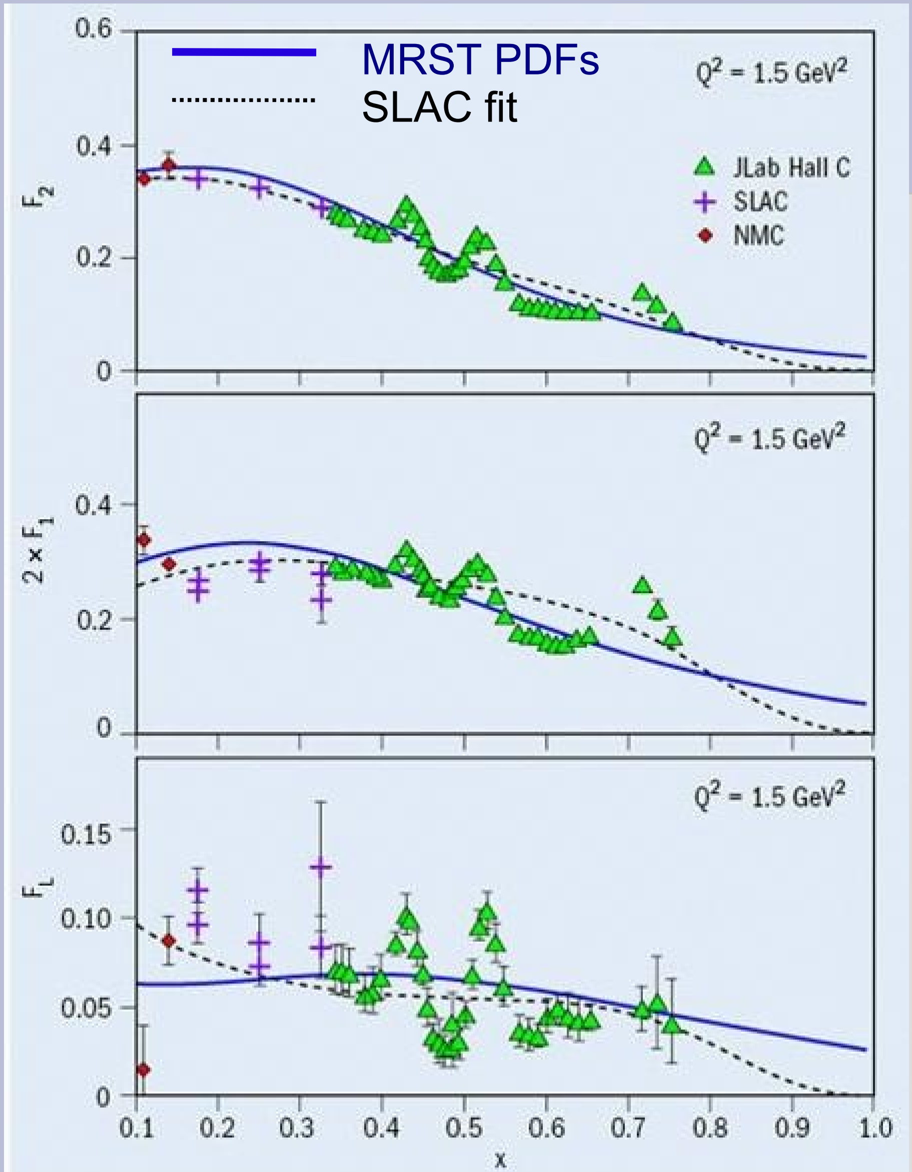


→ Confirmed Bloom-Gilman observation in spectacular fashion.

→ Observed that data trace out a *valence-like* curve when $Q^2 < 0.5$

→ *local* duality is observed.

Later duality observed in separated F_1 and F_L



Observed now in separated transverse (F_1) and longitudinal (F_L) structure functions.

Fascinating link between hadron and quark phenomenology- challenges our understanding of strong interaction dynamics.

"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, December 2004)

Tool to access large x regime?

Rosenbluth (L/T) Separations

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 reduced cross section linearly with ε at fixed W^2 and Q^2 (or x, Q^2).**
- **Linear fit yields:**

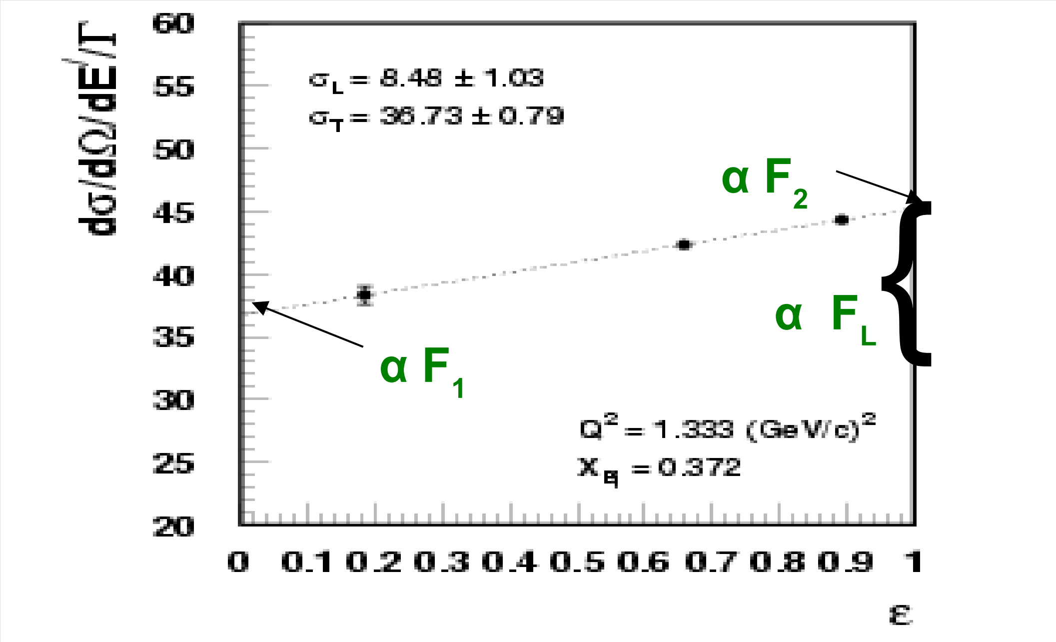
  σ_L = Slope

  σ_T = Intercept

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

Extraction of F_2 depends on R and ε !

Important for Jlab kinematics



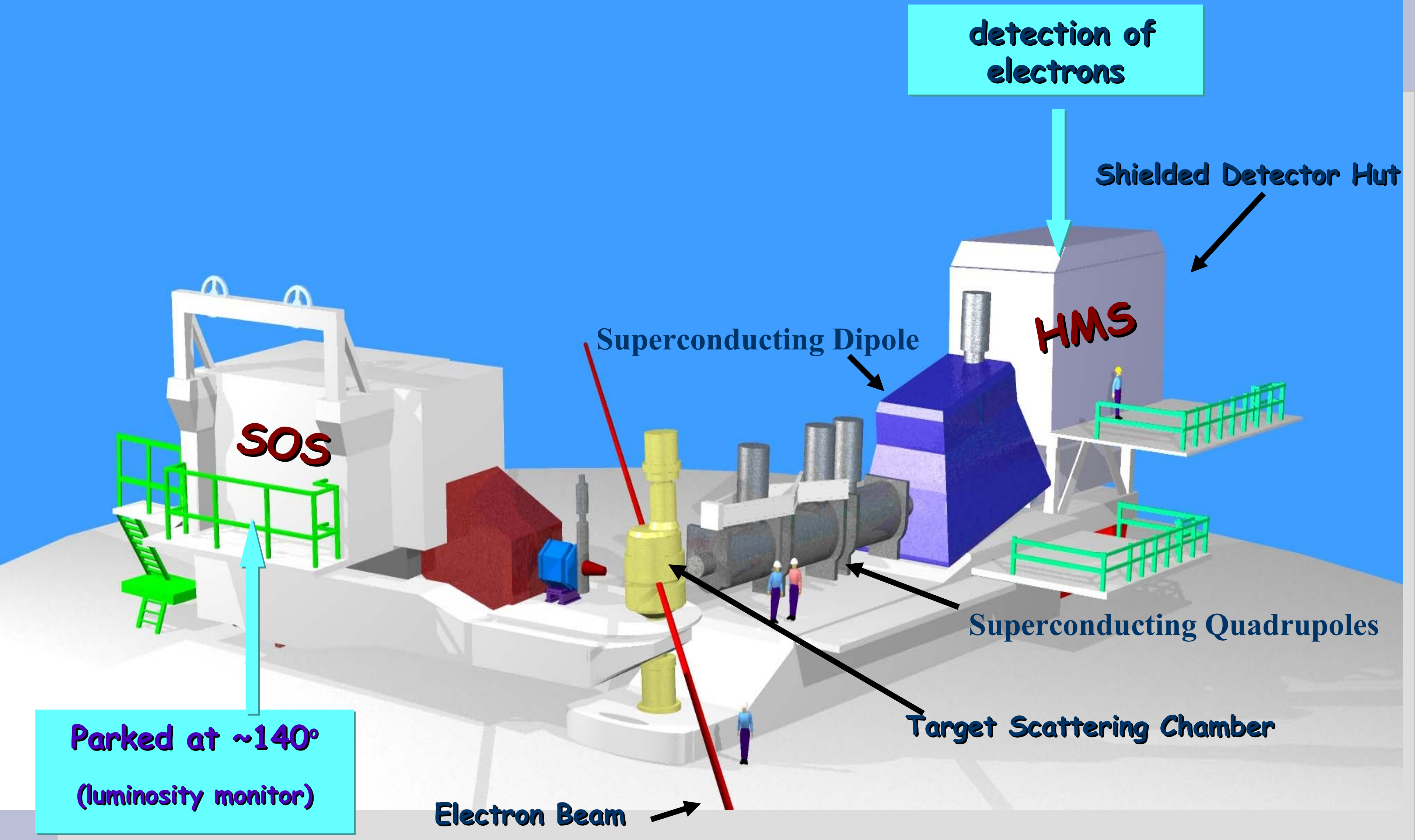
$R = \sigma_L/\sigma_T = F_L/2xF_1$ ~ 0.25 for much of Jlab kinematics

→ need 1.5-2% uncertainties pt-pt in ε to provide 15-20% δR ($\delta F_L/F_L$)

→ Requires multiple beam energies and spectrometer settings for multiple ε.

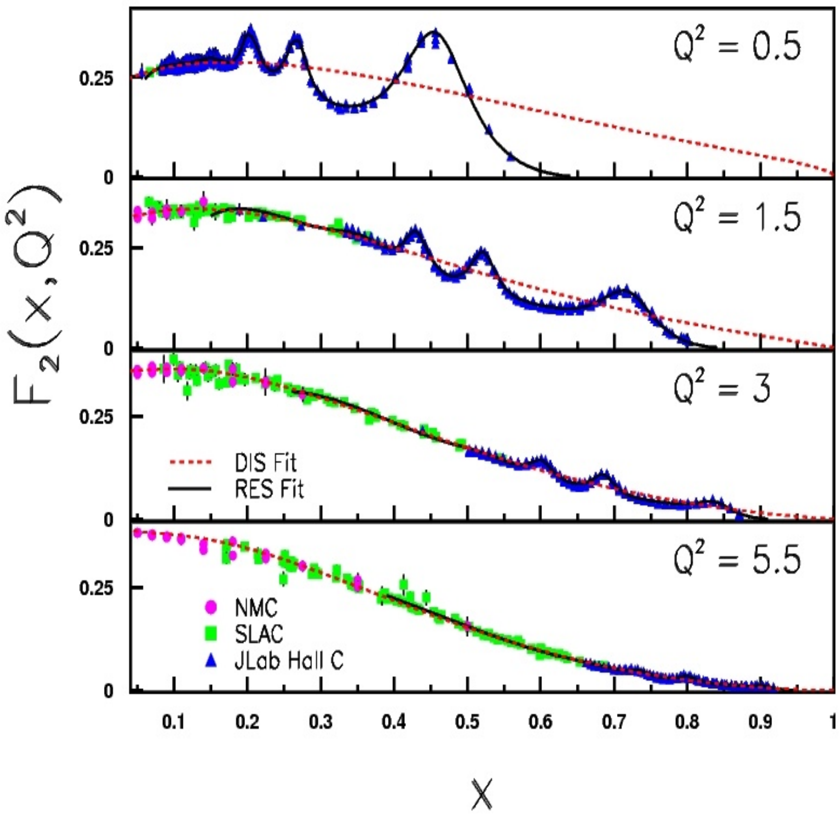
Very challenging experimentally!

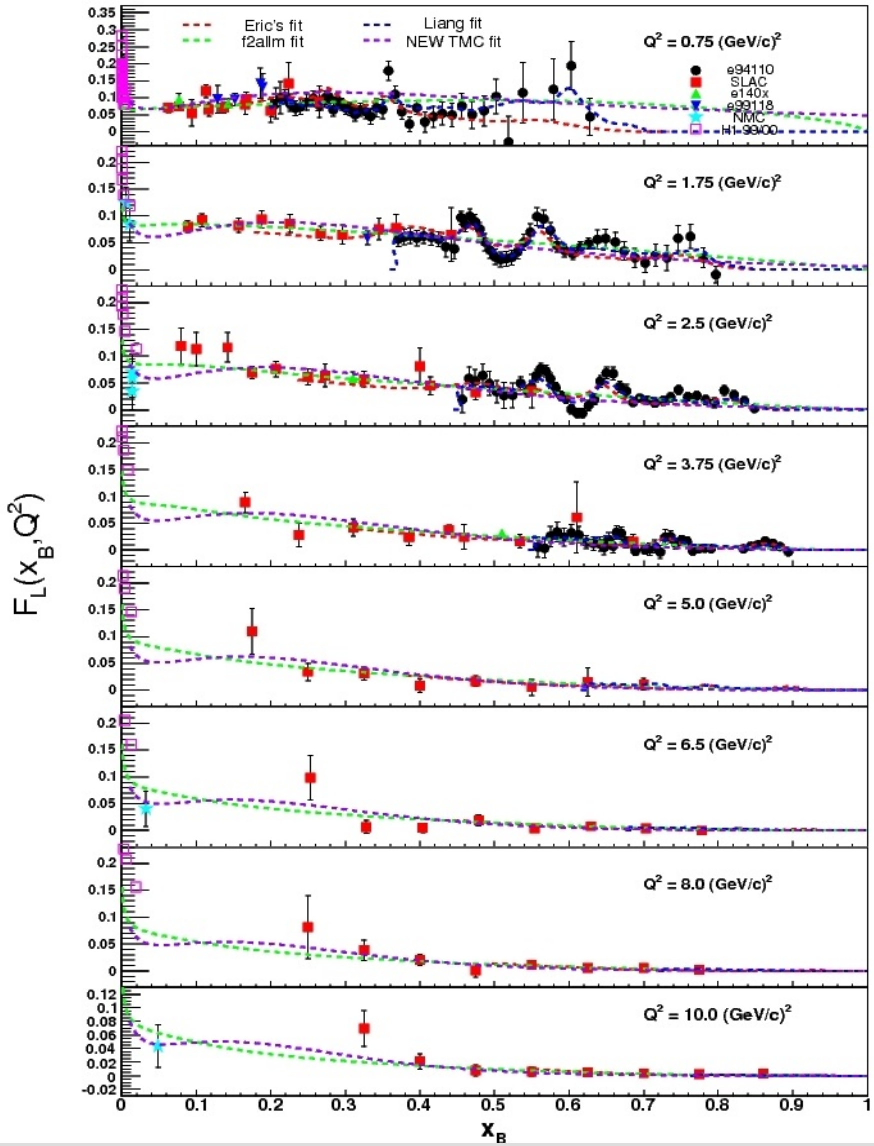
Precision cross sections in JLab Hall C



Status of unpolarized proton

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

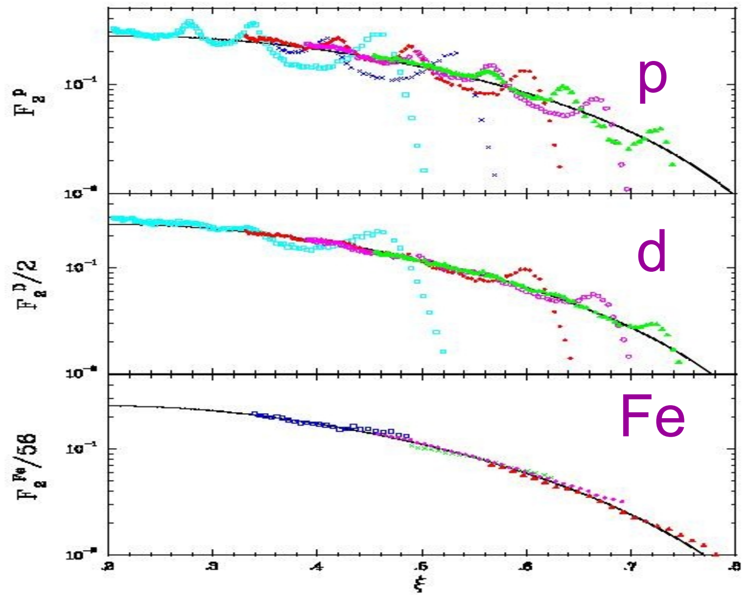


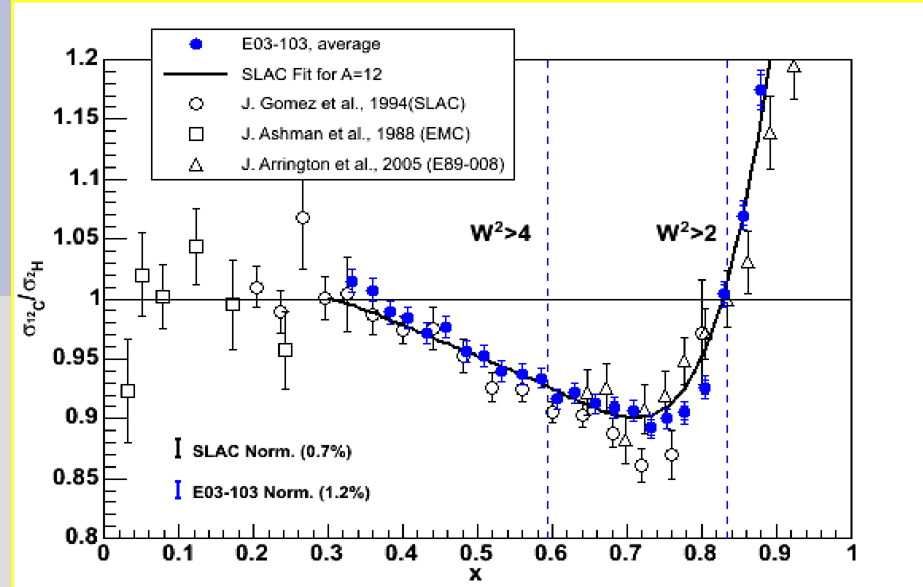


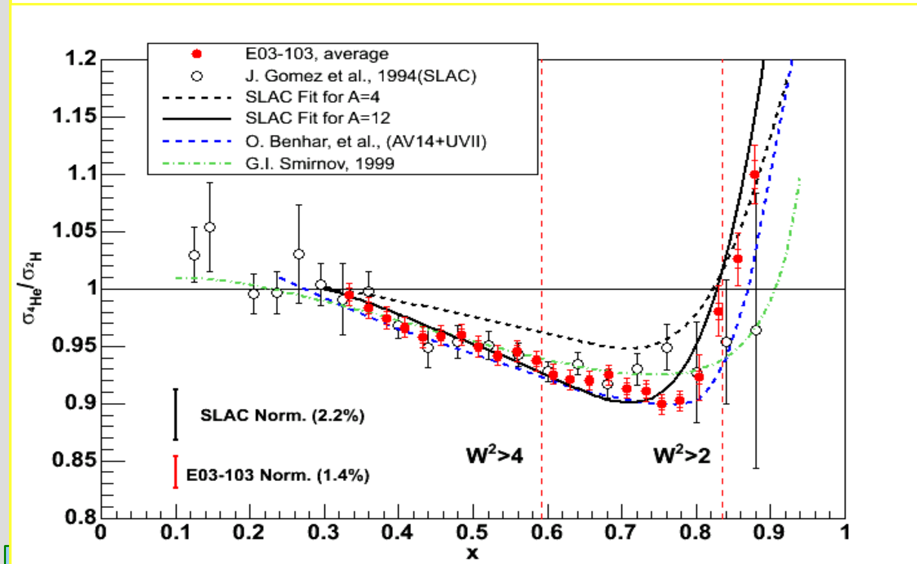
→ Duality observed in ALL unpolarized structure functions

Duality in Nuclei

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







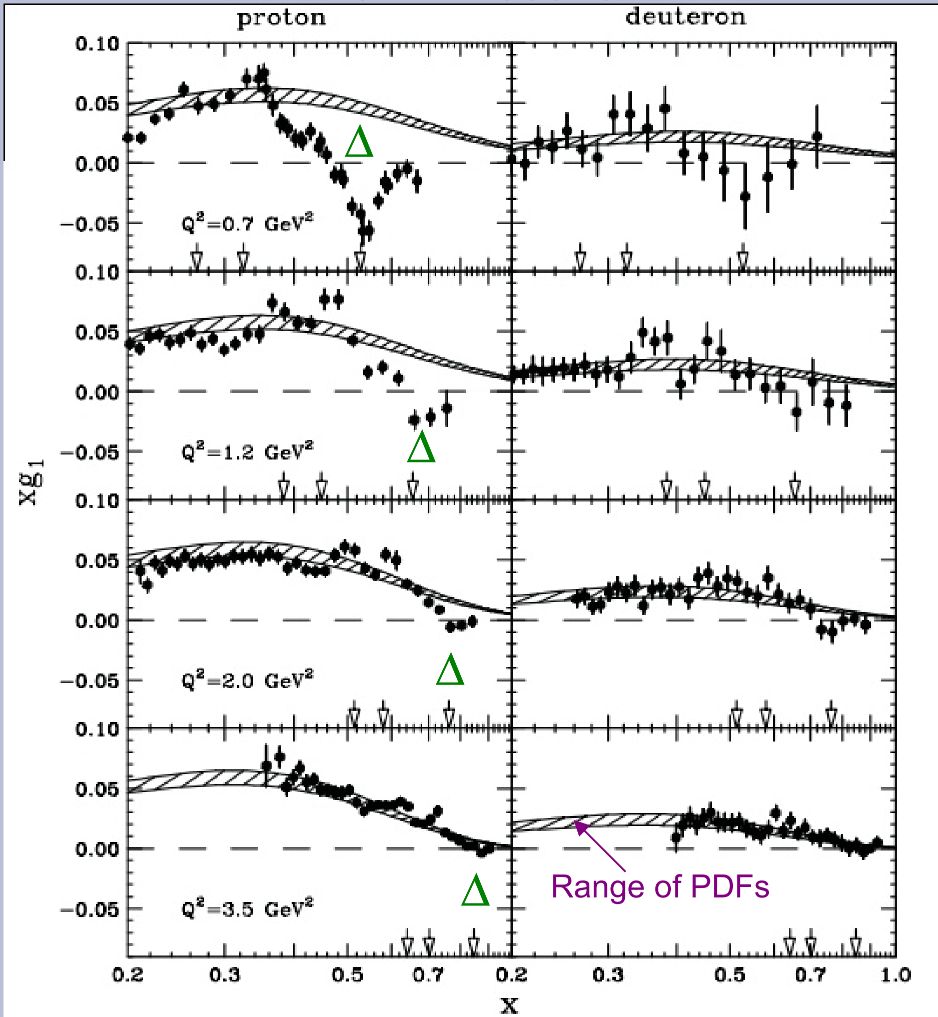
•Fermi motion in the nucleus accomplishes averaging in x, ξ.

=> Duality works even better in nuclei.

Duality is also observed in the EMC effect!

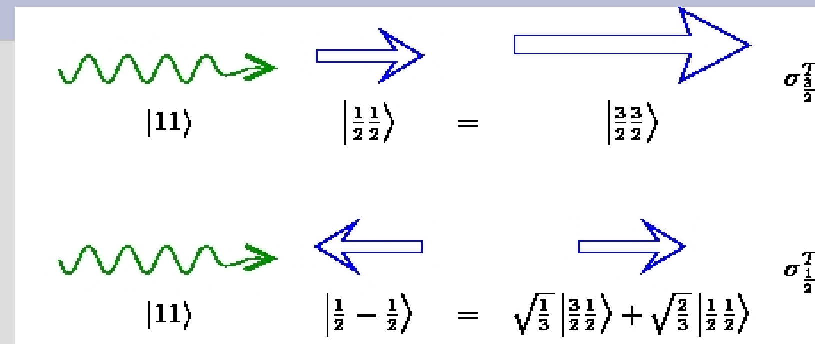
Duality in Spin Structure Functions

Hall B Results



P.E. Bosted, *et.al.* PRC 75, 035203 (2007)

Helicity asymmetries from polarized target



$g_1 \;\alpha\; (\sigma_{1/2} - \sigma_{3/2})$

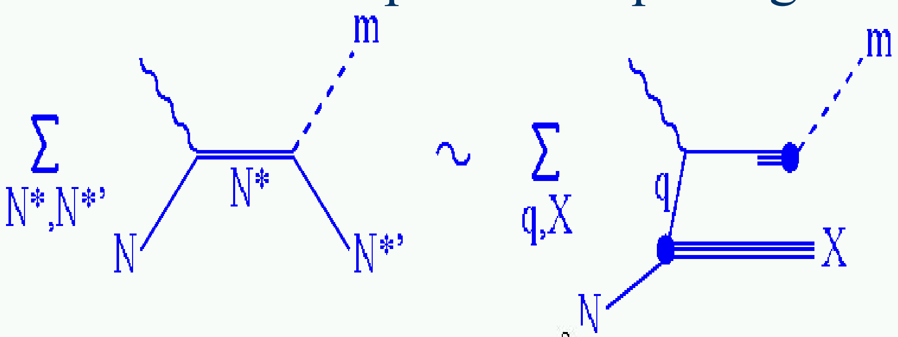
Sensitive to helicity of target particle

$F_1 \;\alpha\; (\sigma_{1/2} + \sigma_{3/2})$

Duality in both => duality in ***each*** Helicity state.

Duality in semi-inclusive pion producton

hadronic description   quark-gluon

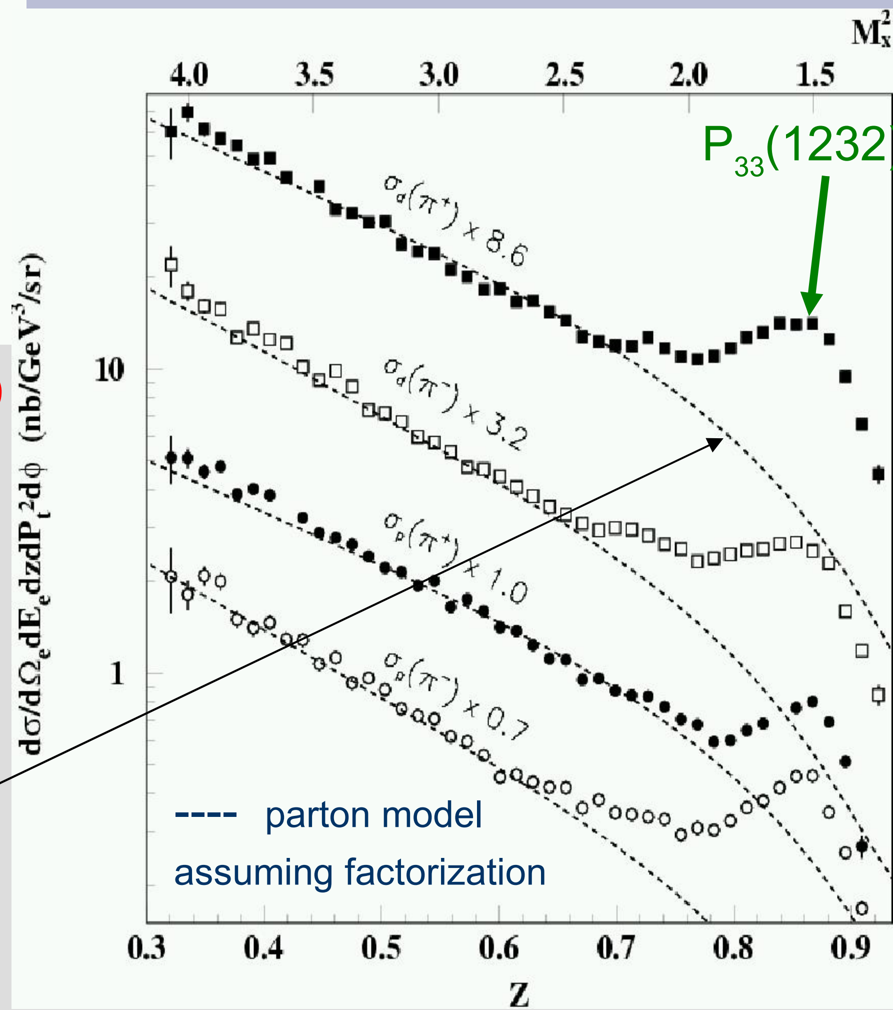


$$\sum_{N'^*}\left|\sum_{N^*} F_{\gamma^* N\to N^*}(Q^2,W^2)\, \mathcal{D}_{N^*\to N'^* M}(W^2,W'^2)\right|^2 = \sum_q e_q^2\, q(x)\, D_{q\to M}(z)$$

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.



Duality looks like it might be fundamental to QCD

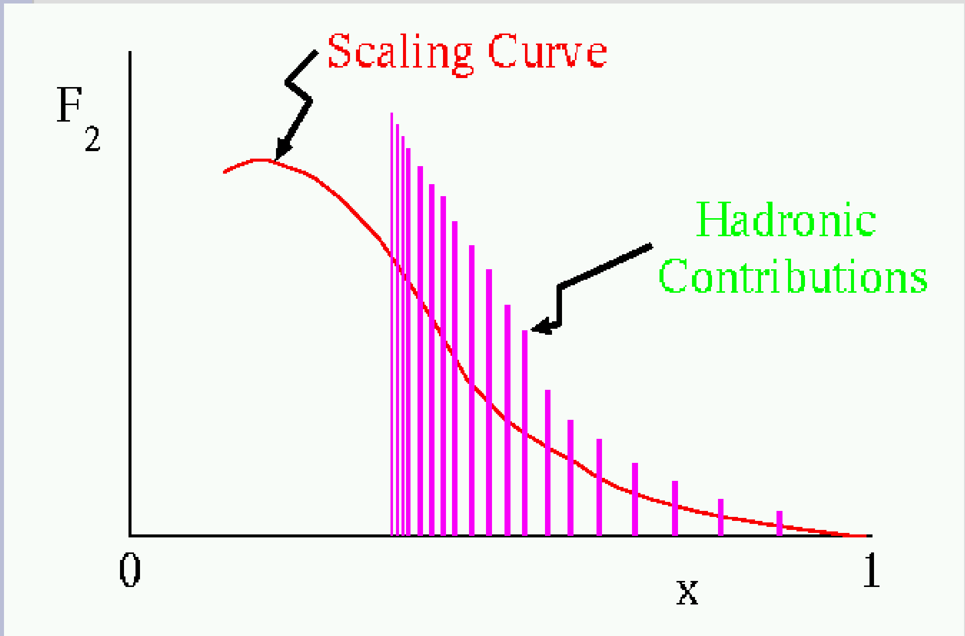
… but how do we understand it?

Theoretical progress has been made based on constituent quark models.

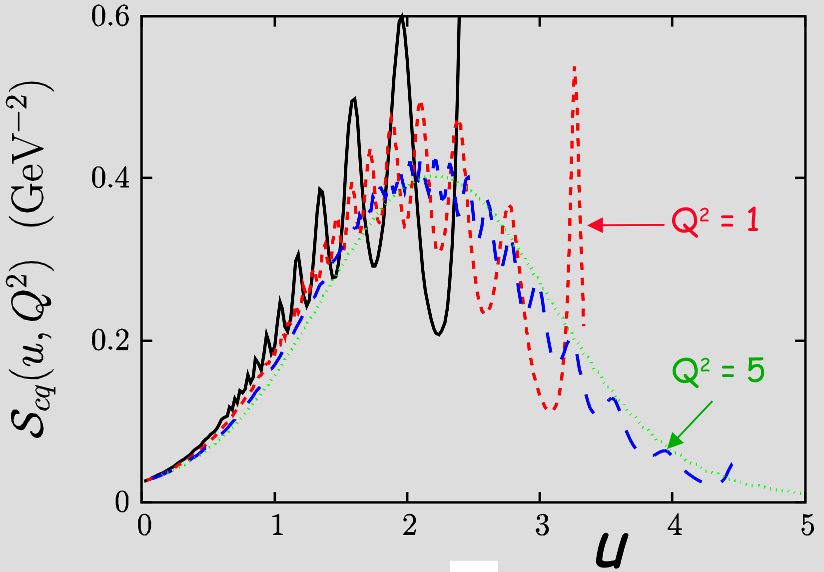
Close-Isgur Model: General observations

N. Isgur et al : $N_c \rightarrow \infty$

$q\bar{q}$ infinitely narrow resonances



One heavy quark, Relativistic HO



Scaling occurs rapidly!

- Illustrates how sum of resonance states can lead to scaling curve based on general properties of QCD
- Quark -Hadron Duality must be invoked even in the Bjorken Scaling region

Dynamical model of Close/Isgur PLB 509, 81 (2001)

→ Coupling to single quarks in baryon states in spin-flavor SU(6) model.

→ $F_2 \sim \Sigma\, e^2_q$ but Form factors ~ $(\Sigma\, e_q)^2$ How does square of sum become sum of squares?

→ Need enough even and odd parity states for ~$e_i e_j$ terms to cancel

N,Δ 2nd

$SU(6):$	$[\mathbf{56},0^+]^2\mathbf{8}$	$[\mathbf{56},0^+]^4\mathbf{10}$	$[\mathbf{70},1^-]^2\mathbf{8}$	$[\mathbf{70},1^-]^4\mathbf{8}$	$[\mathbf{70},1^-]^2\mathbf{10}$	*total*
F_1^p	9	8	9	0	1	27
F_1^n	4	8	1	4	1	18

→ Similar calculations now available for semi-inclusive

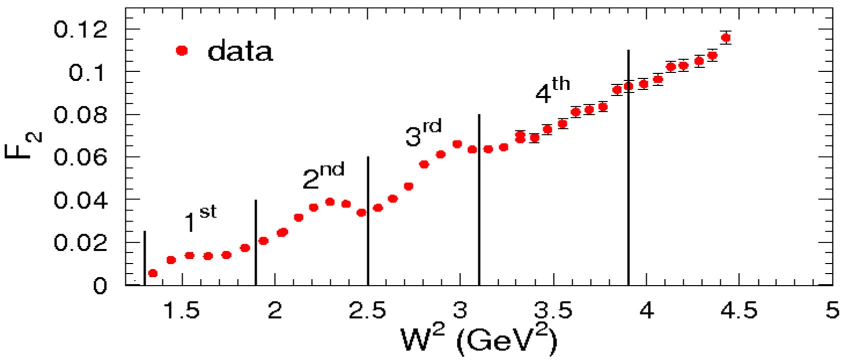
→ Duality is due to fortuitous cancellations in this model !!!

→ Duality obtained by end of second resonance region for proton, later for neutron => local duality different in neutron.

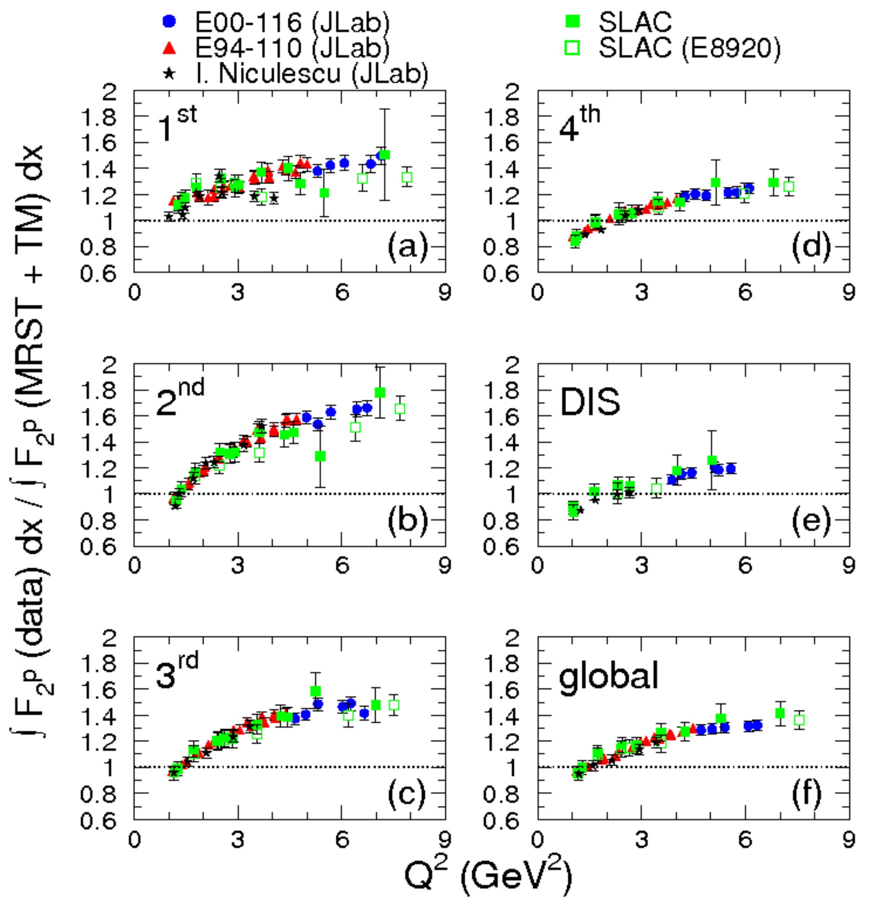
** Would like to test this with data **

Local Duality Quantification - I

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



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

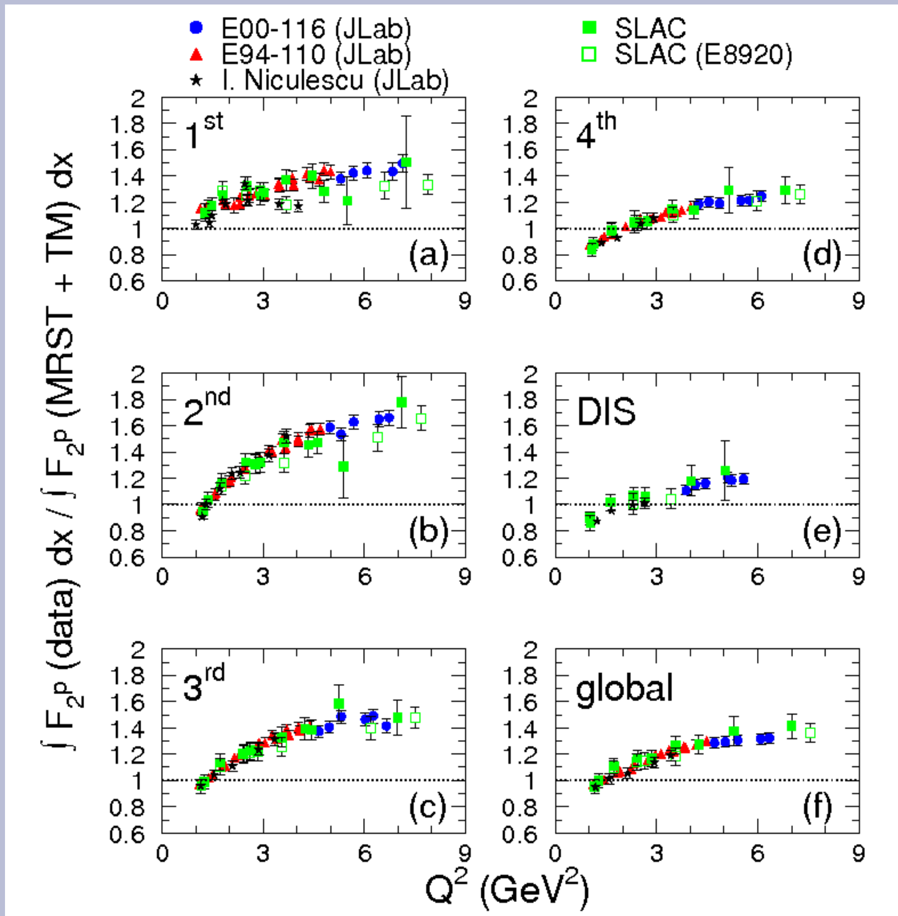


→ Data in all regions rise above PDF curve for Q^2 > ~2

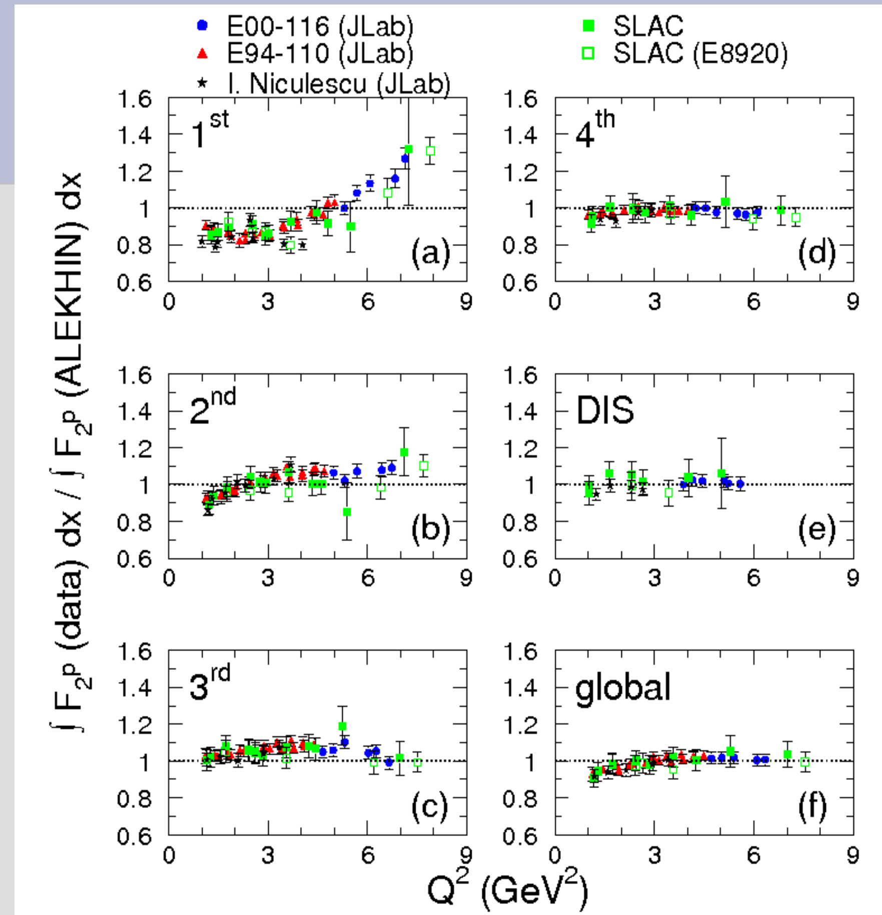
→ largest for lower resonances which are at large *x*, where PDFs are less well constrained.

Quantification - II

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



MRST2004



Alehkin

→ tighter kinematic cuts excludes much large x

→ No TMC or HT included in fit.

→ looser kinematic cuts

→ TMC and HT included in fits.

→ **Older PDFs not enough strength at large *x***

=> *looks* like larger duality violations (20-30%).

→ **Not as much a failure of duality, but unconstrained PDFs at large *x***

→ **New efforts to relax kinematic constraints and include TMCs and HTs in PDF fits result in much smaller duality violations observed (< 10%, except at Δ(1232)).**

=> telling us that *on average* resonance region H-T are the same as the DIS.

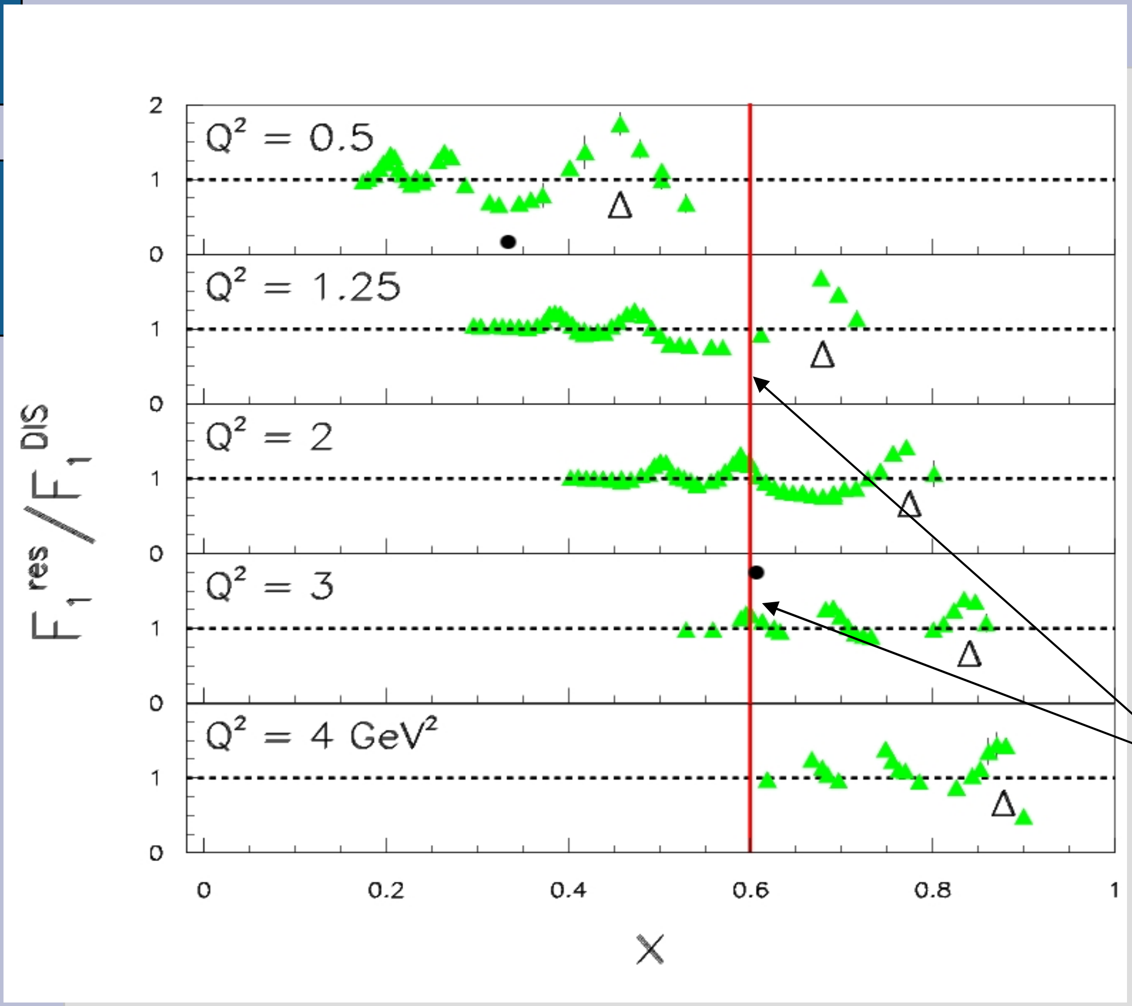
S. Alekhin, J. Blumlein, S. Klein, S. Moch, Phys. Rev. D 81, 014032 (2010).

CTEQ6x

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

Comparison L/T separated data to empirical fits

Comparison of Rosenbluth separated F_1



DIS fit:

F_2 ALLM fit to F_2

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

+

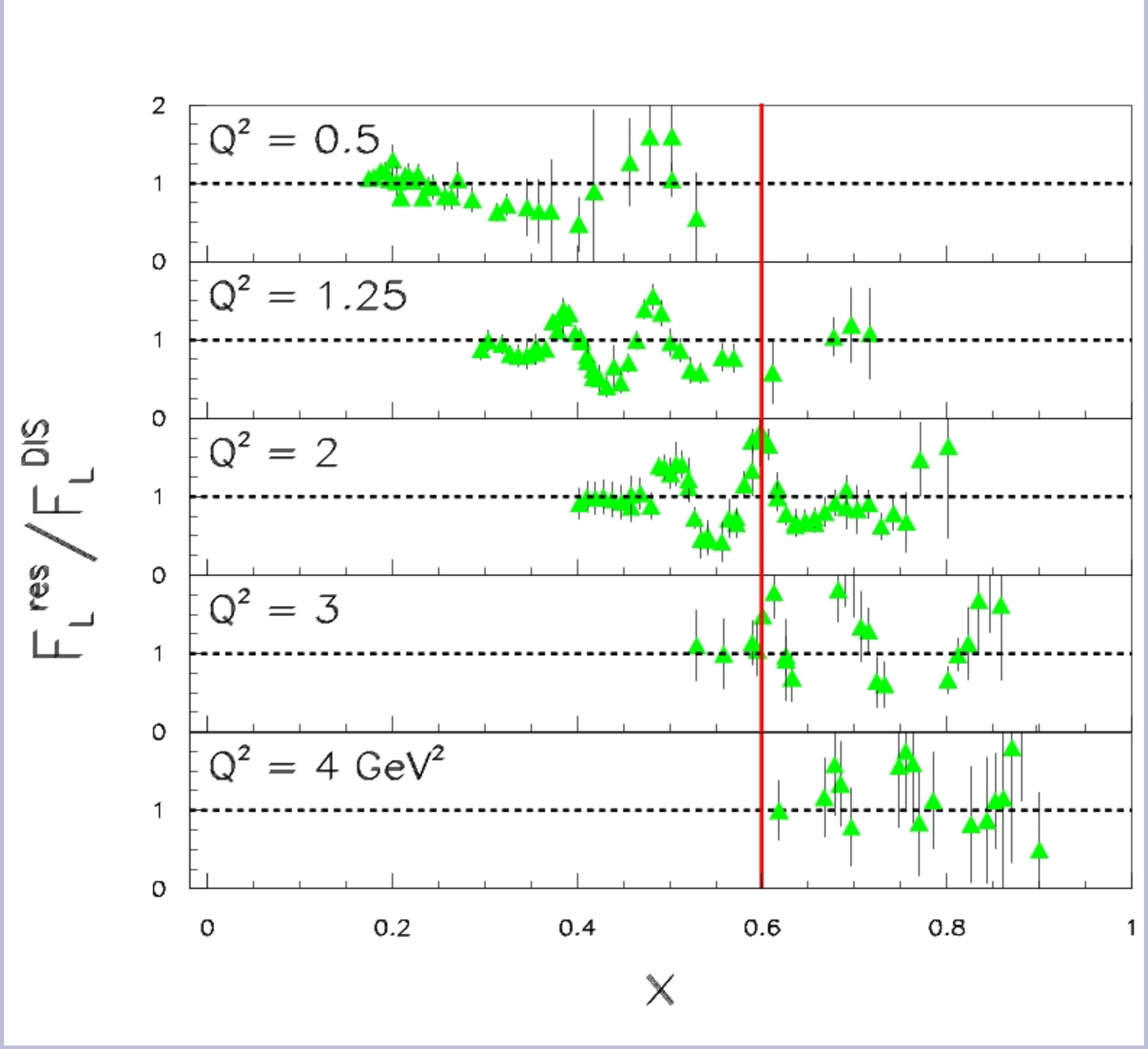
$R = \sigma_L / \sigma_T$

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



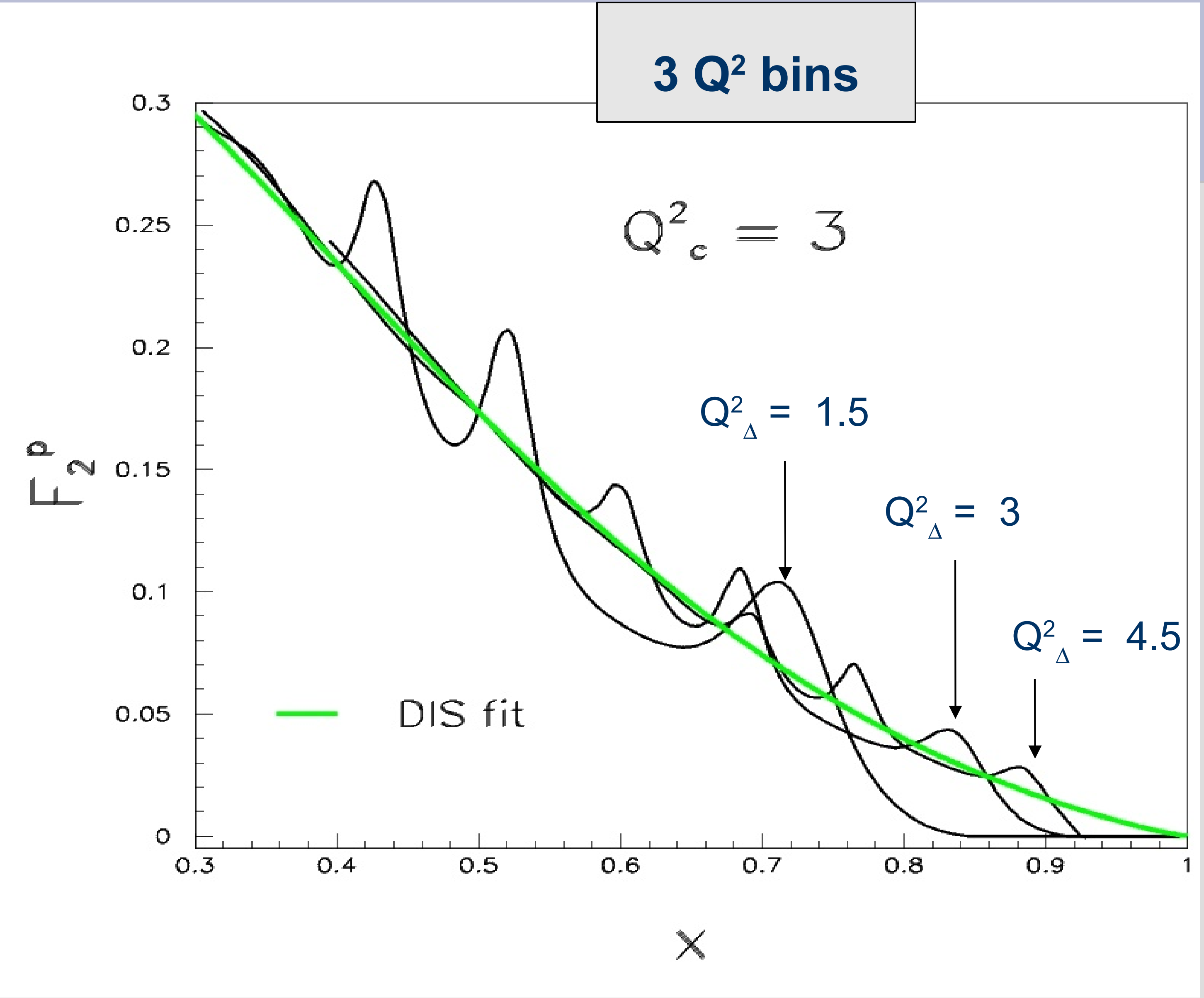
Observation

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

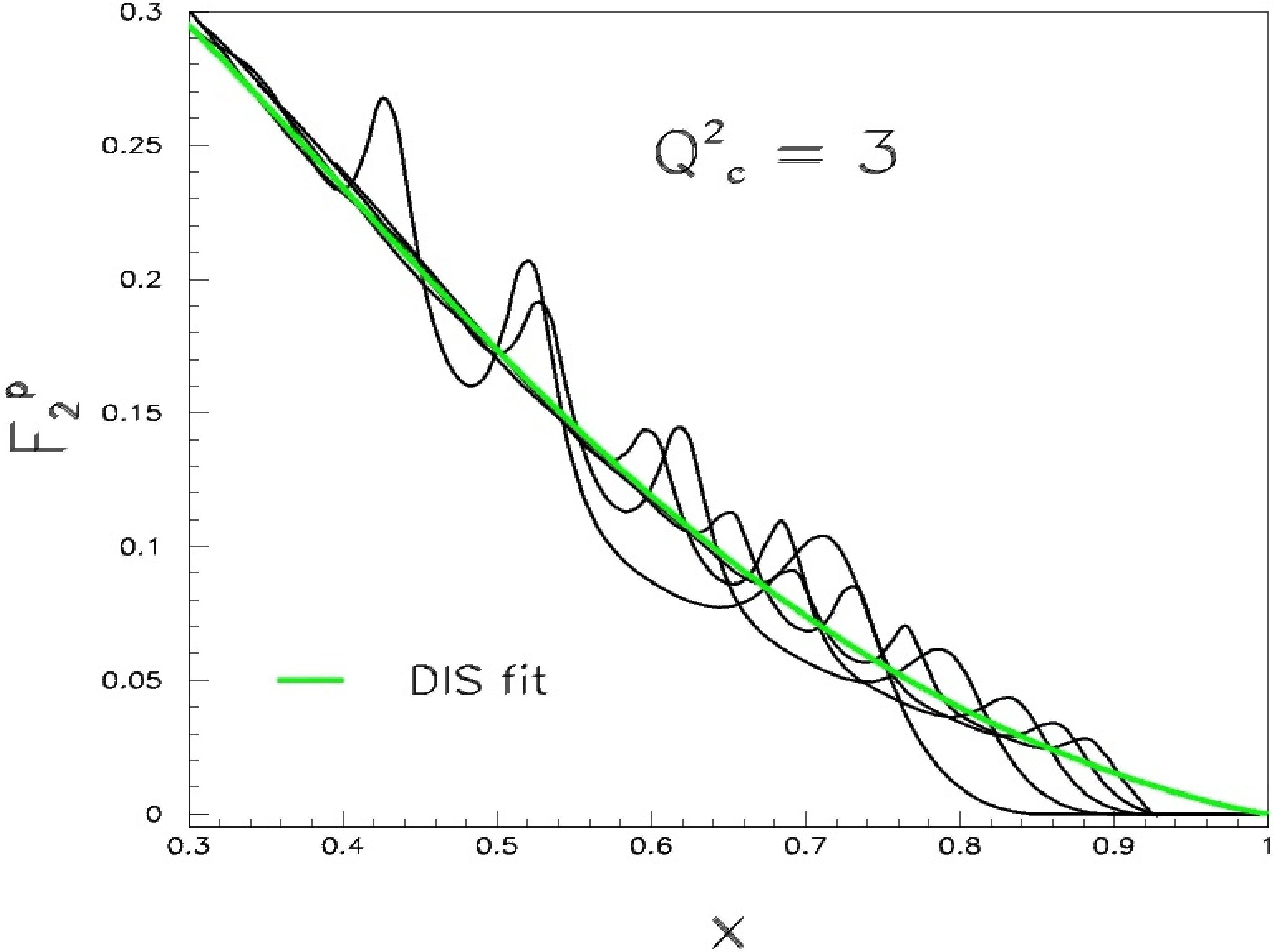
=> Averaging over a range in Q^2 at fixed x effectively averages out the variations due to the resonance contribution to the structure function.

Can we use this to provide DIS-like data?

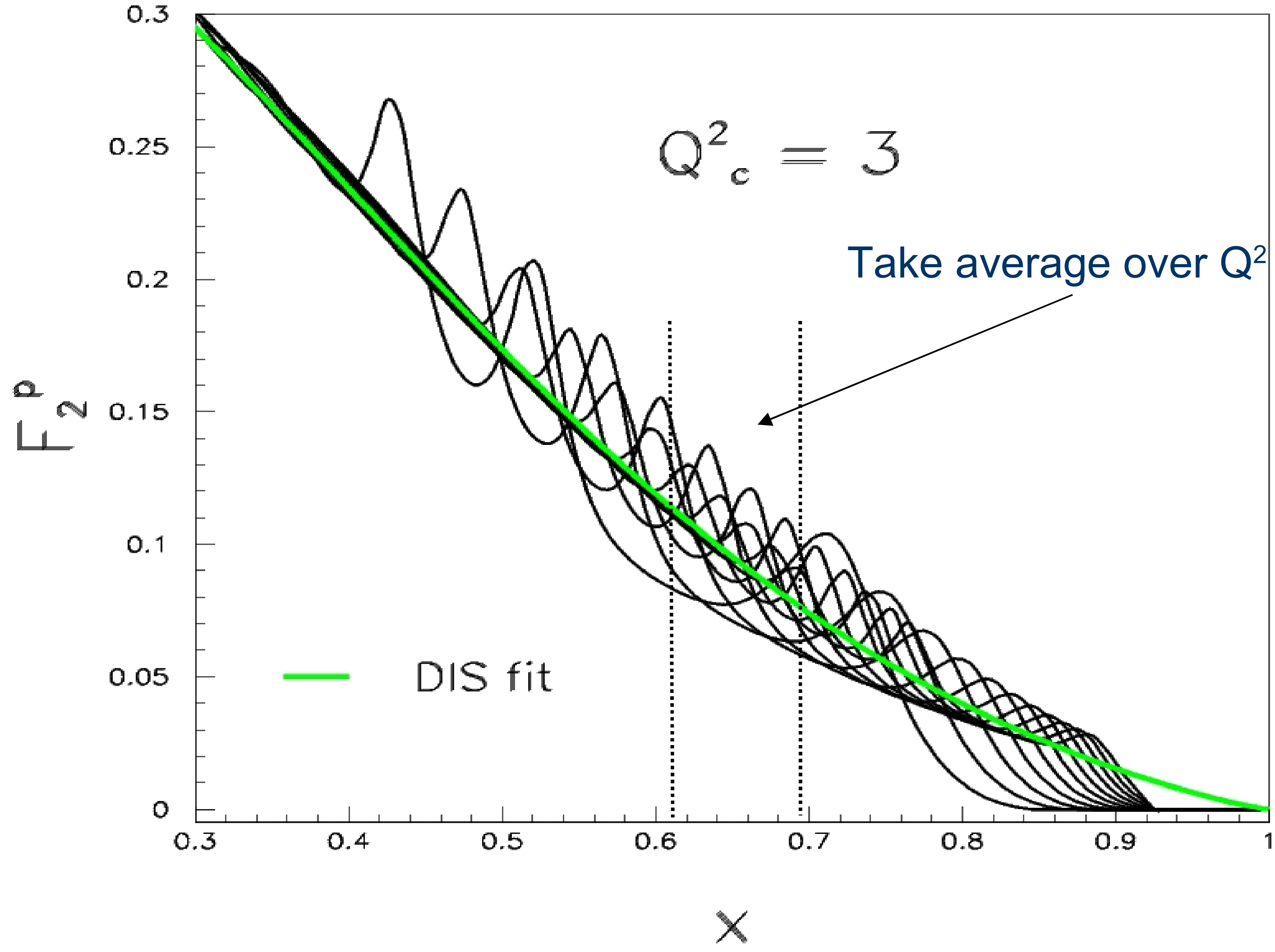
'DIS-like' duality averaging procedure



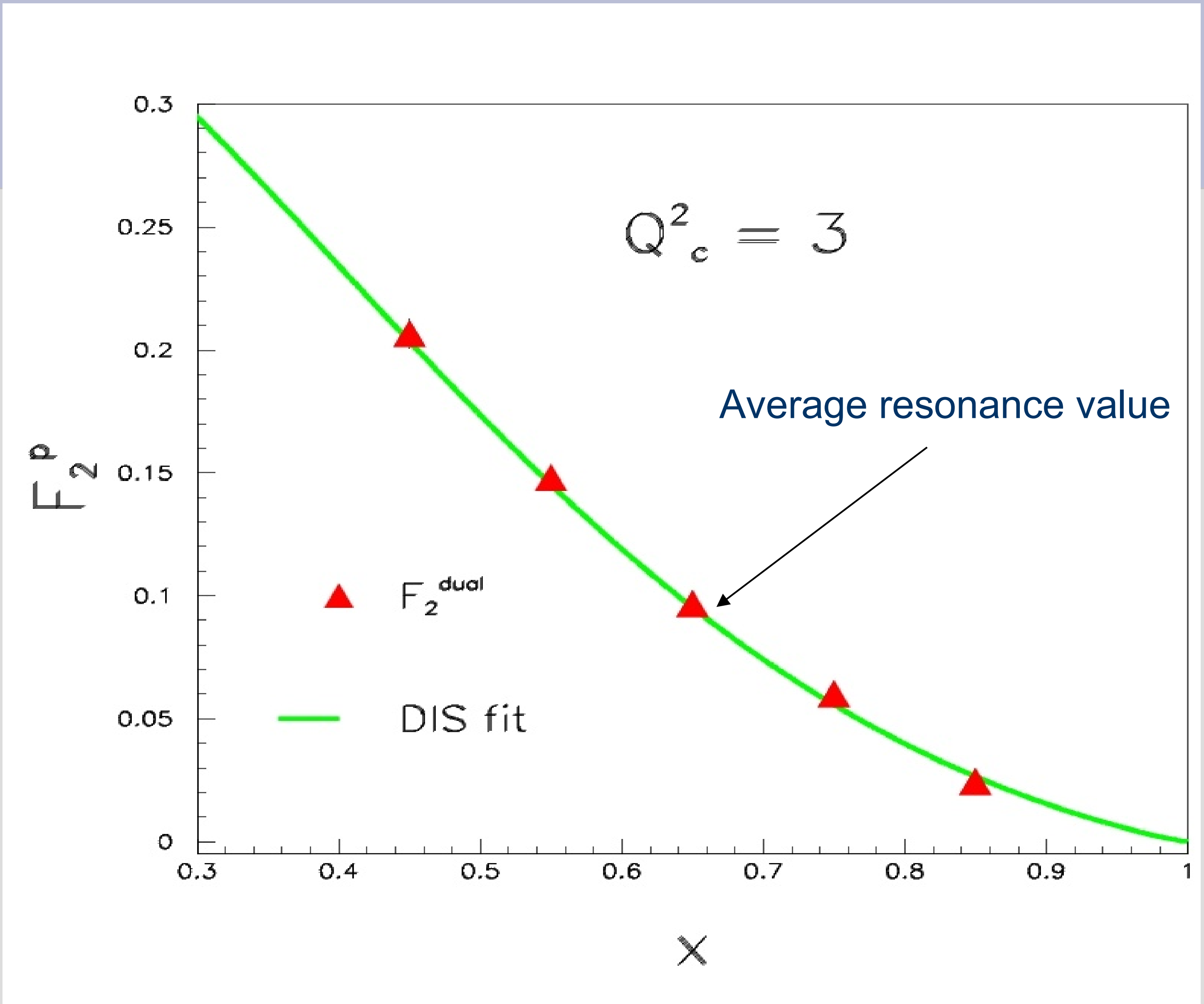
5 Q^2 bins



9 Q^2 bins

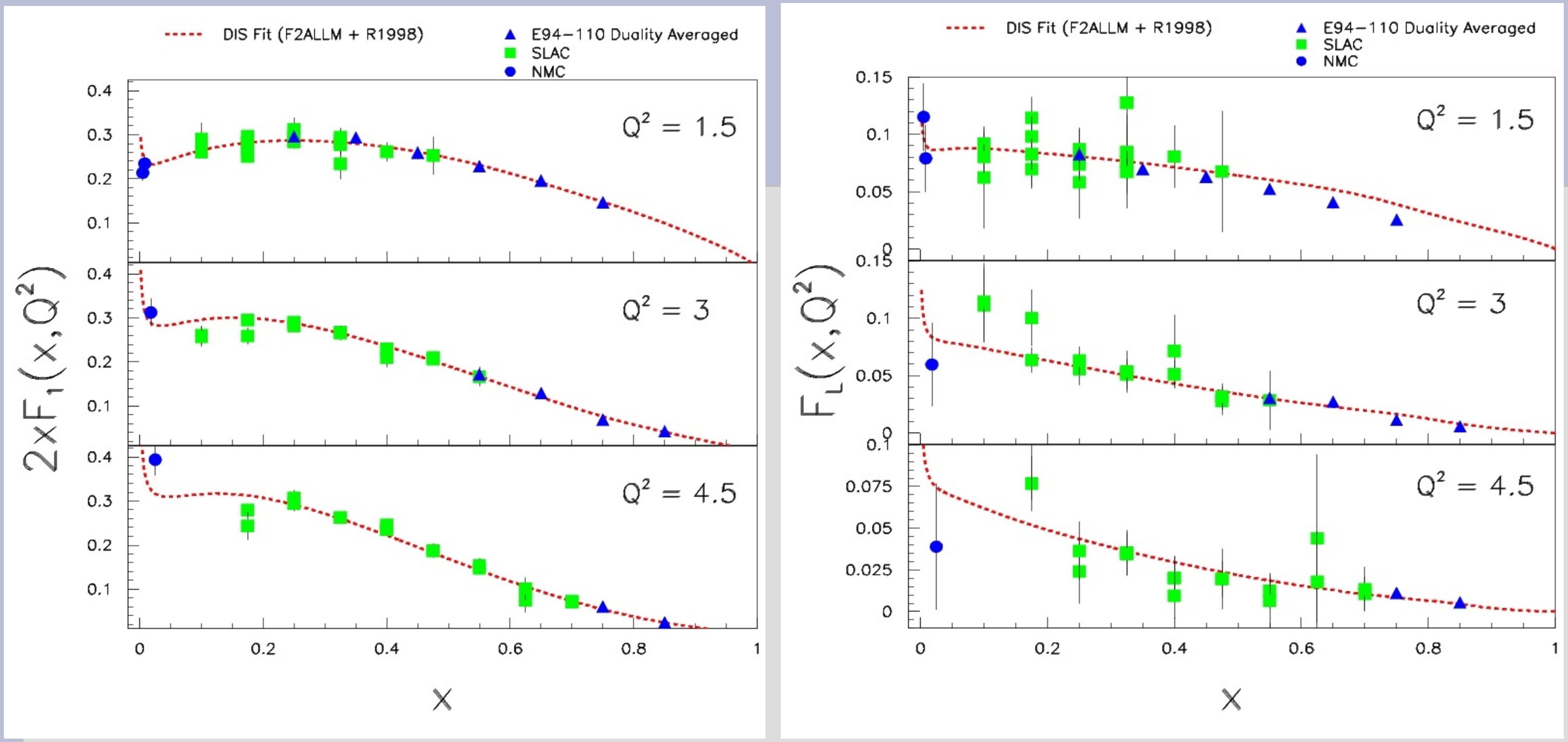


0.3
0.25
0.2
0.15
0.1
0.05
0
F_2^p
$Q^2_c = 3$
Take average over Q^2
DIS fit
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x



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.

Can we use duality data to constrain large x parton distributions?

Perhaps... must test if duality averaged data can be fit consistently with higher W data when including TM / H-T.

In principle this is no different then how H-T is handled in the fits to scattering data with relaxed kinematics.

Important to constrain standard model physics as much as possible for cleanest interpretation of new physics at LHC and Tevatron.

Since uncertainties on large x PDFs at small Q^2 evolve to smaller x at large Q^2.

Alternative tests: Moments in pQCD

- Moments of Structure Functions

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

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

Mellin Transforms

If n = 2 → Bloom-Gilman duality integral!

- Operator Product Expansion (OPE)

$M_n(Q^2) = \Sigma \; (nM_0^2/ Q^2)^{k-1} B_{nk}(Q^2)$

higher twist pQCD

N = 2, 4, 6, ...

→ Global duality is assured if H-T are *canceling*. **DeRujula, Georgi, Politzer (1977)**

=> pQCD is *the* scaling curve

Note: doesn't tell us why this might be the case!

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

Results for Proton F_2 Moments

(elastic contribution at x=1 is not included)

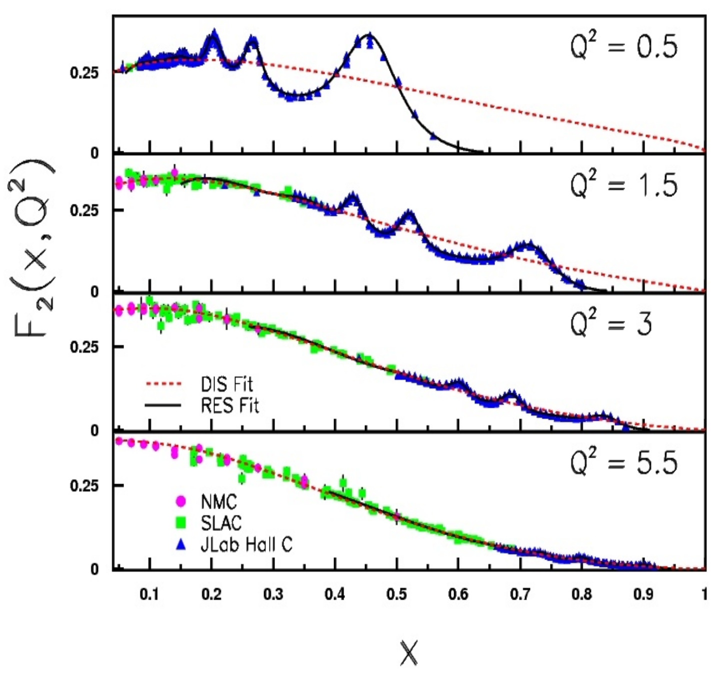
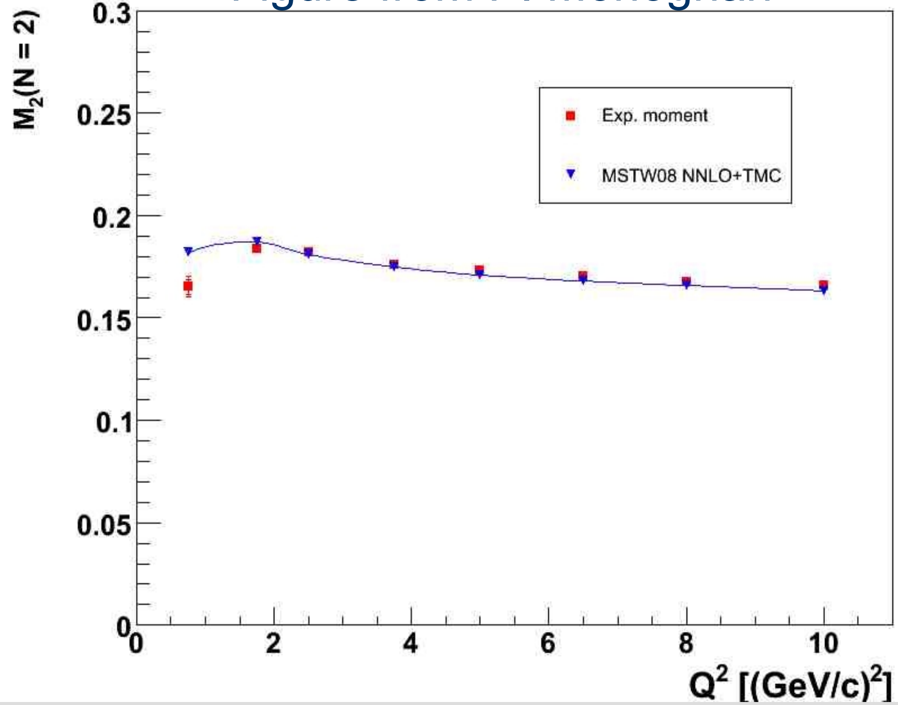


Figure from P. Monoghan

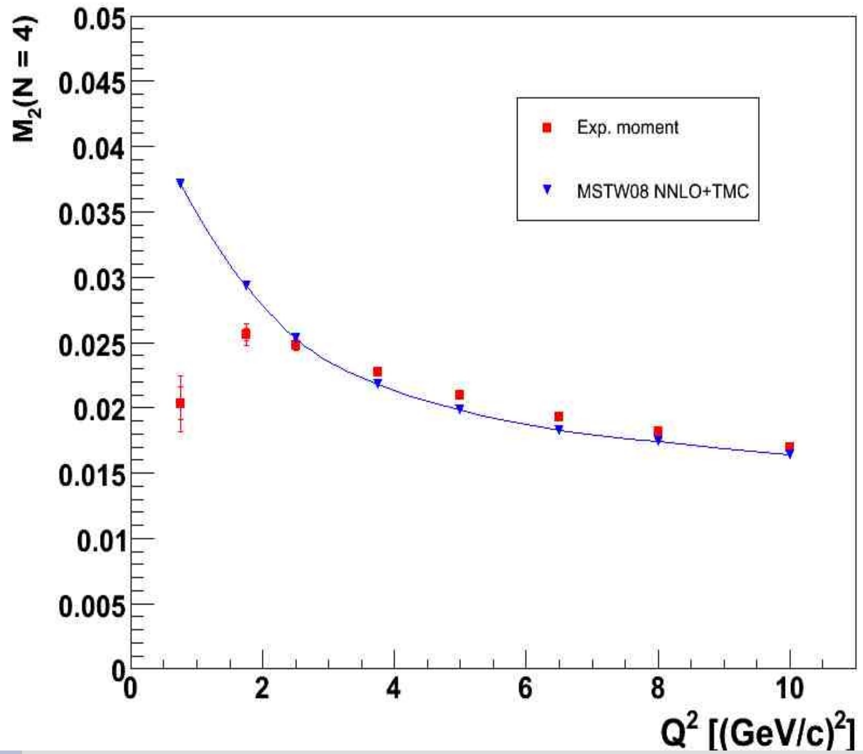


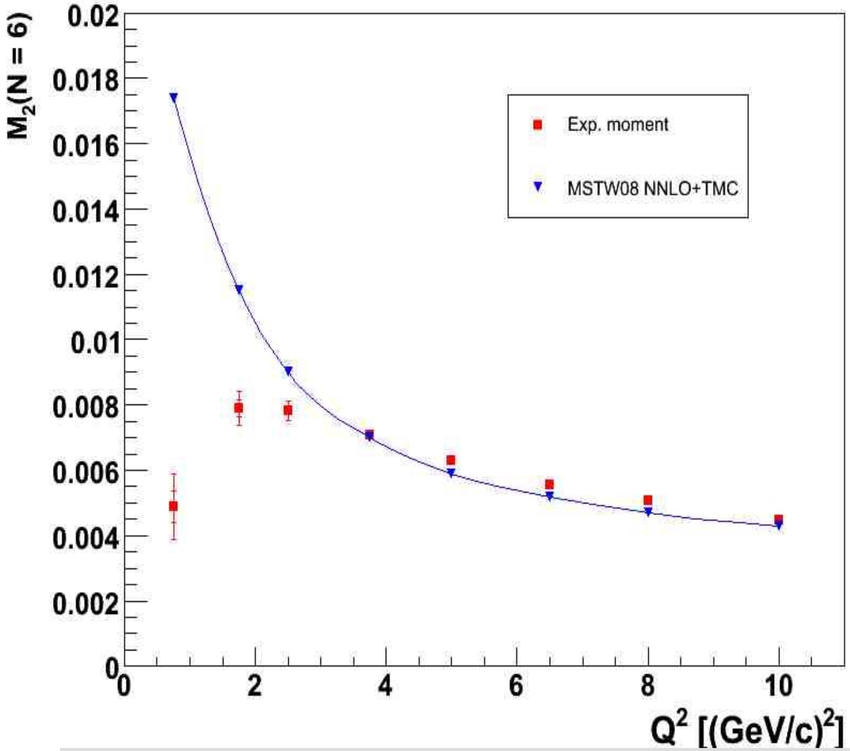
→ **Very precise determination from data. (consistent with previous determination)**

→ **NNLO pQCD curve from MSTW PDFs describes data *very* well to $Q^2 \sim 1$**
(where resonance region contributes more than 50% to the integral).

F_2 higher Moments

(elastic contribution not included)



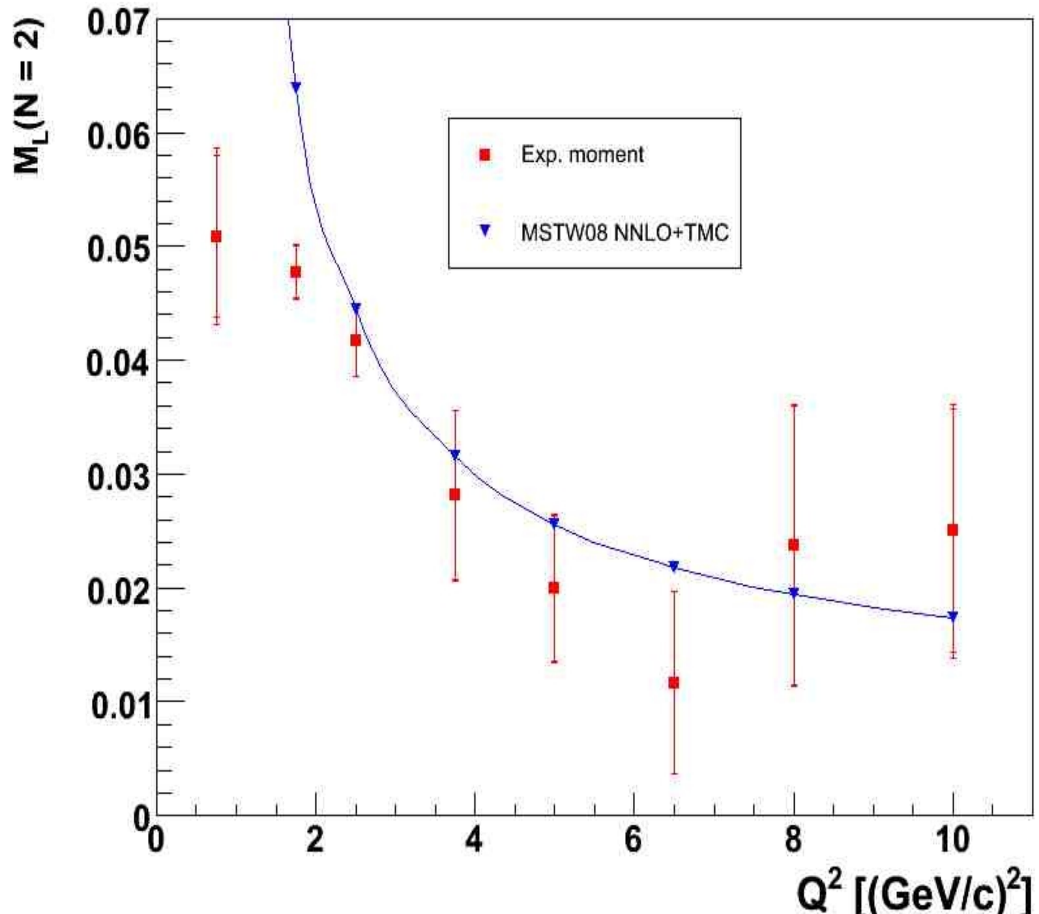


$$M_n^{2,L}(Q^2) \equiv \int_0^1 dx \ x^{n-2} \ F_{2,L}(x, Q^2)$$

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

Results for Proton F_L Moments

(elastic contribution not included)

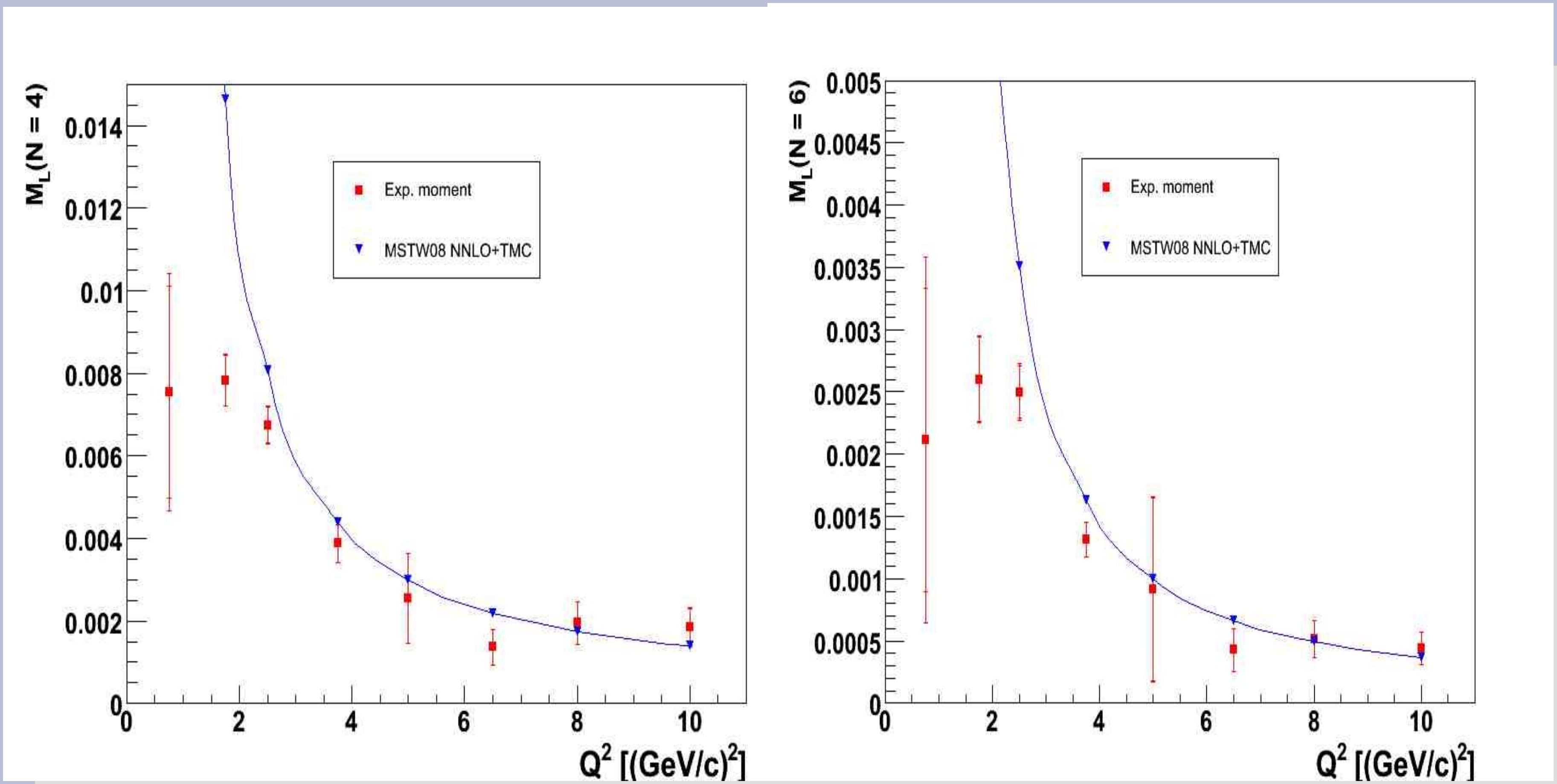


→ Inclusion of precision Jlab data results in small uncertainties at $Q^2 < 3$.

→ Comparison to PDF fit is fairly good for $Q^2 > 2$, once TM contribution is included.

Similar results for F_L higher Moments

(elastic contribution not included)



Moment analysis allows for analysis of global duality within context of pQCD.

What about locally?

Truncated Moments

Originally developed to address lack of <u>low</u> x data

Forte and Magnea, PLB 448, 295 (1999); Forte, Magnea, Piccione, and Ridolfi, NPB 594, 46 (2001); Piccione PLB 518, 207 (2001); Kotlorz and Kotlorz, PLB 644, 284 (2007).

Idea: construct doubly truncated moments from

$$\overline{M}_n(\Delta x, Q^2) = \int_{\Delta x} dx\ x^{n-2}\ F_2(x, Q^2)$$

Truncated moments follow ***DGLAP-like evolution*** equations.

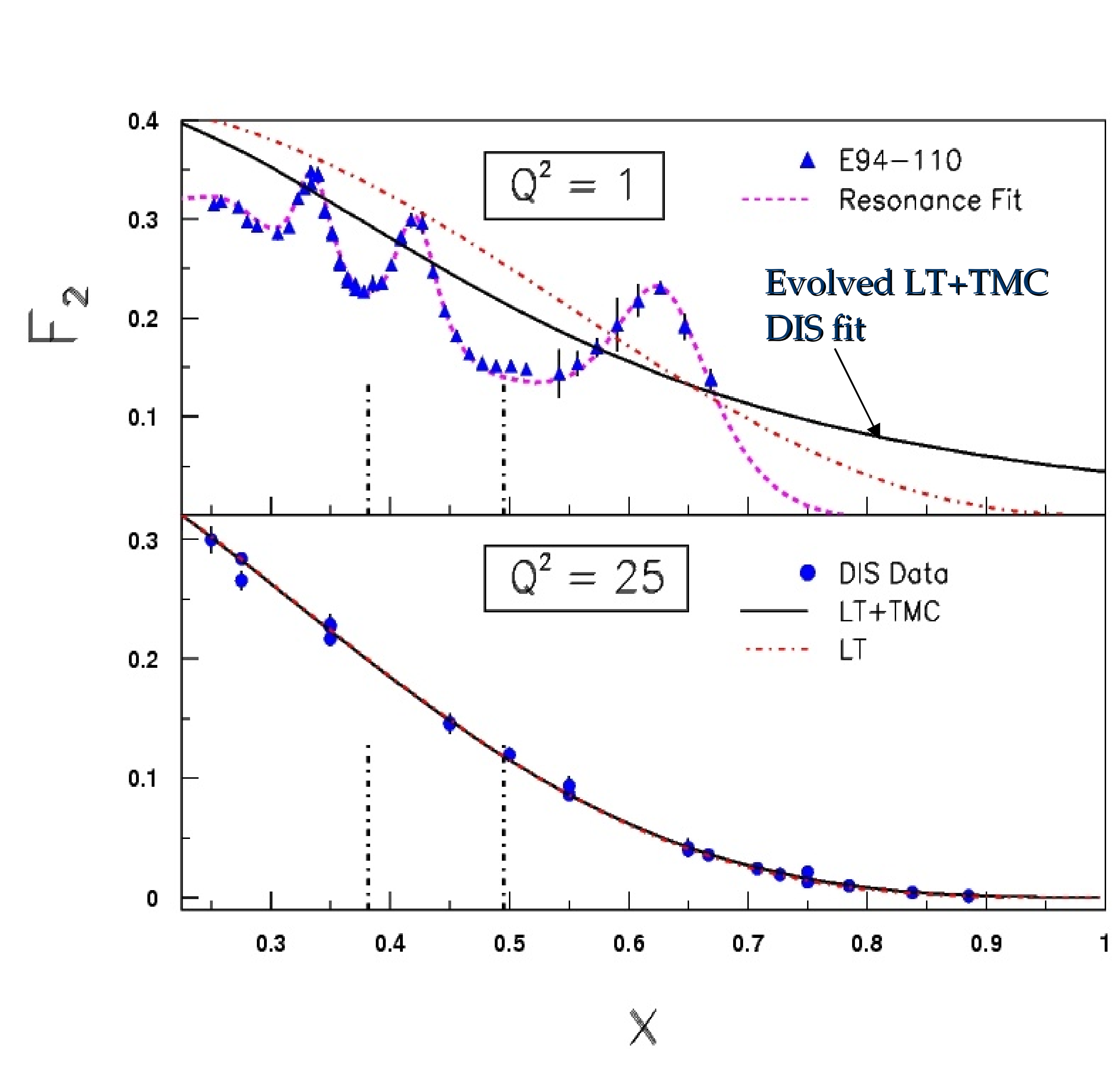
$$\frac{d\overline{M}_n(\Delta x, Q^2)}{d \log Q^2} = \frac{\alpha_s}{2\pi}\left(P'_{(n)} \otimes \overline{M}_n\right)(\Delta x, Q^2)$$

With modified splitting functions given by

$$P'_n(z, \alpha_S(Q^2)) = z^n P(z, \alpha_S(Q^2))$$

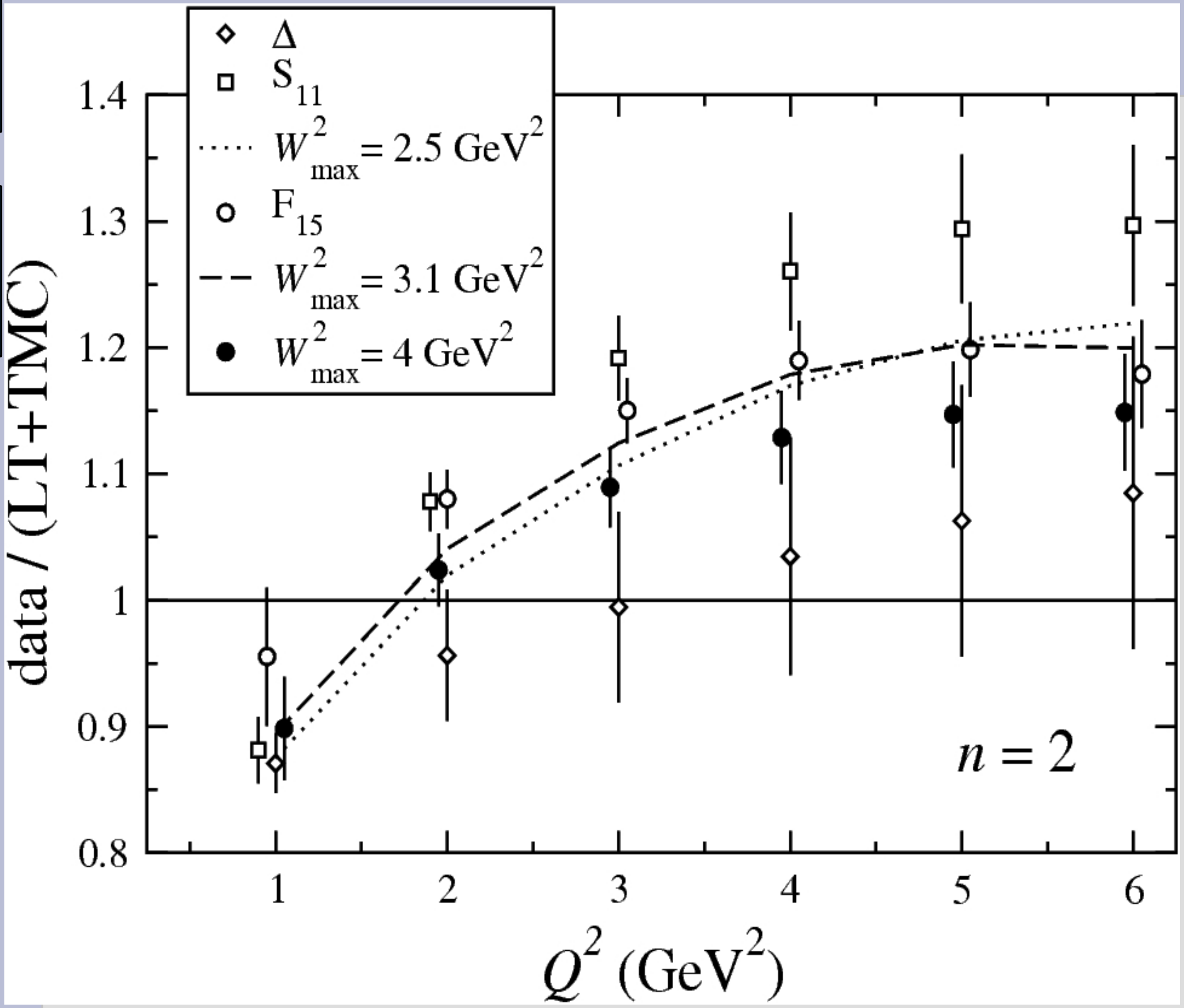
Allows study of ***regions in W*** within pQCD in well-defined, systematic way.

Truncated Moments - the basic idea



→ Compare integral over Select resonance regions to Evolved scaling curve + TM

Q^2 Dependence of Truncated Moments, x Regions Defined by Resonances



- Consider now individual and total resonance region
- Large Q^2 dependence below ~3 GeV^2 - decreases at higher Q^2
- Below $Q^2 = 0.75\ GeV^2$ the applicability of pQCD analysis doubtful
- Facilitates careful Higher Twist analysis….

Testing Models: the Neutron

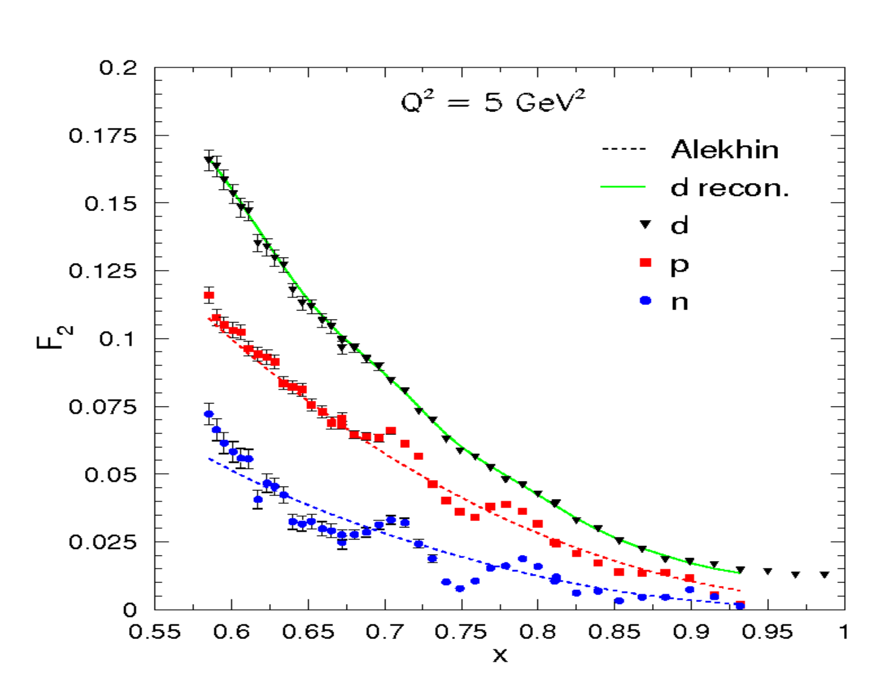
Problem: no free neutron targets

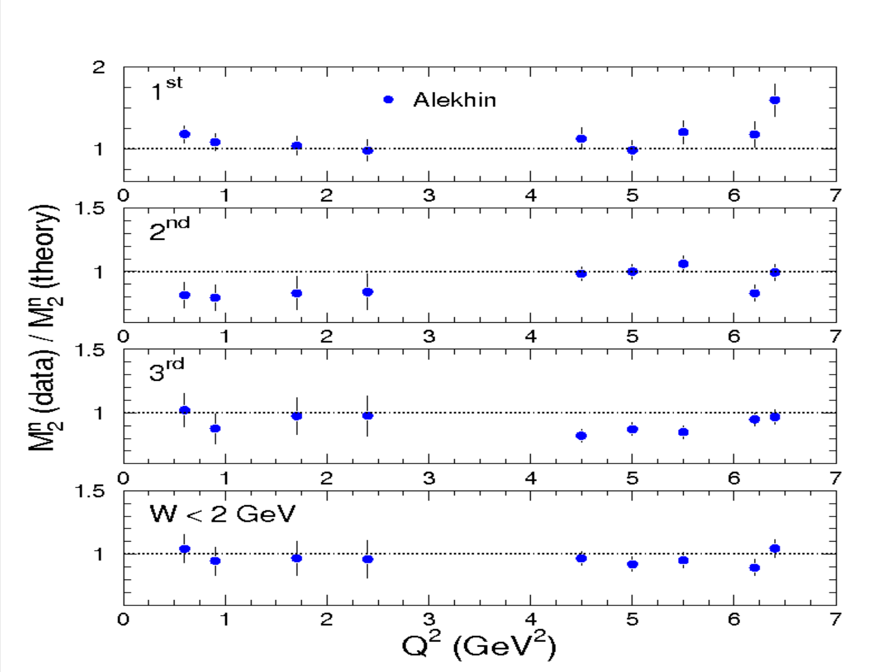
Model dependent method

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

→ Apply nuclear correctons including Fermi motion and off-shell corrections to get F2n = F2d –F2p.

→ Initial guess F2n = F2p to correct F2d then iterate twice.





→ Duality looks to be observed well locally in the neutron.

→ **NOT** just a chance cancellation as suggested by SU6 model!

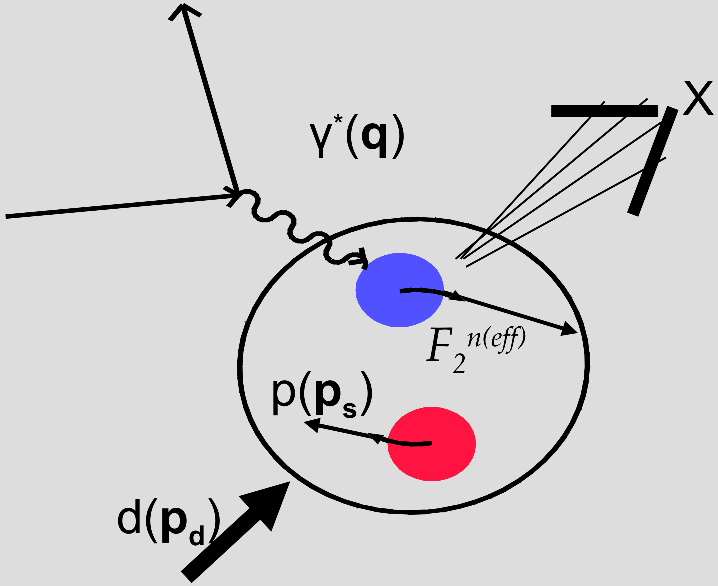
* Want to test in a completely model independent way with *free* neutron.

Method of Spectator Tagging

nuclear impulse approximation => the proton is a pure spectator and recoils with momentum $\mathbf{p}_s$ = -**p**

$$\frac{d\sigma}{dx dW^2 d\alpha d^2 p_T} \approx \frac{2\alpha_{em}^2(1-\nu/E)}{Q^4} \alpha \, \mathcal{S}(\alpha, p_T) \; F_2^{n(eff)}(W^2, p^2, Q^2)$$

With S the nucleon spectral function in the deuteron
and $F_2^{n(eff)}$ the effective off-shell neutron structure function



The spectator proton's four momentum:

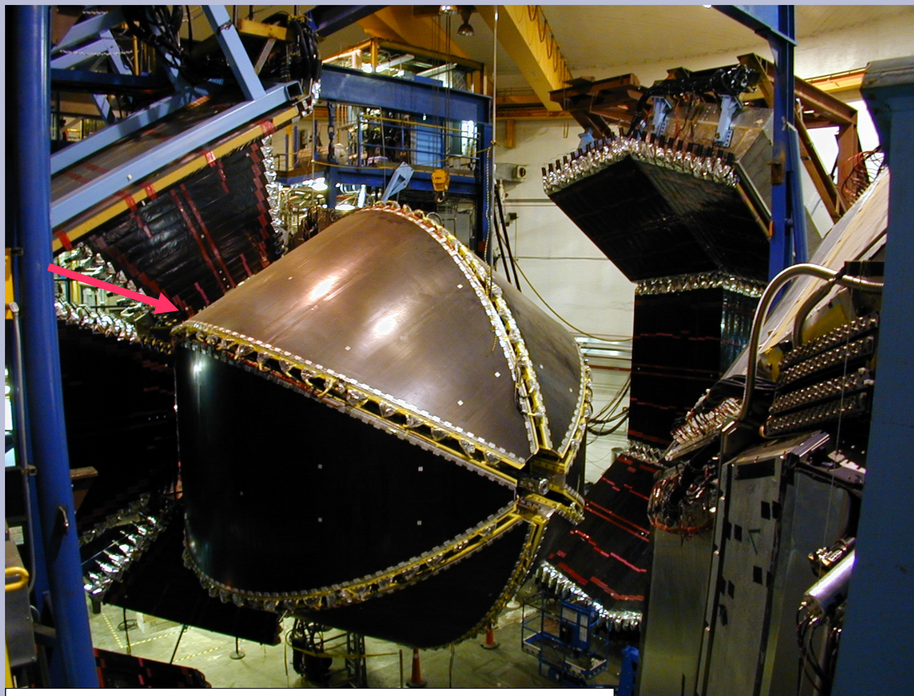
$$p^\mu = -(E_s - M_D, \mathbf{p}_s)$$

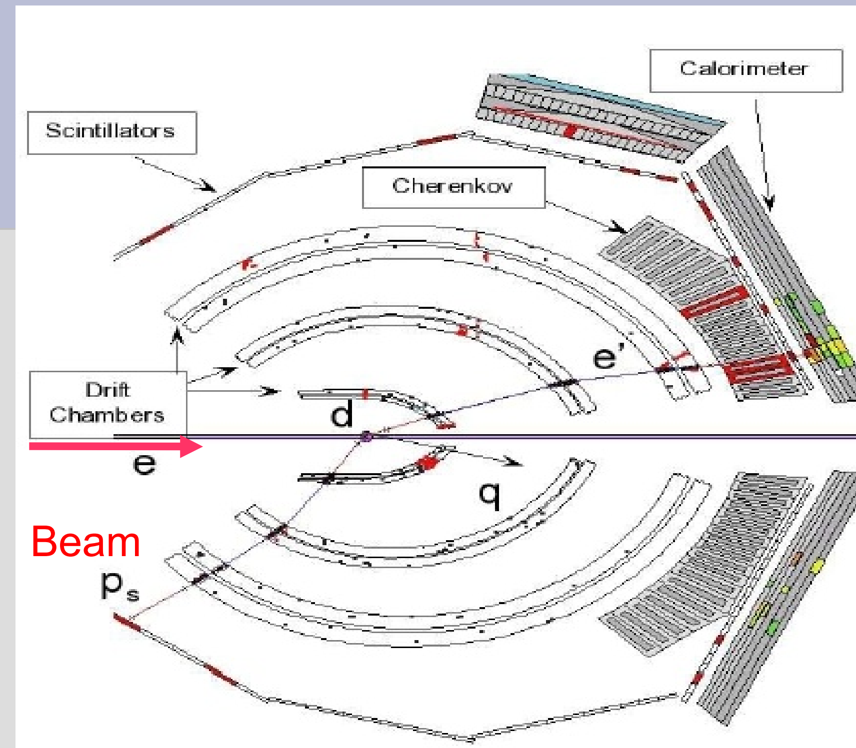
Light-cone momentum fraction:

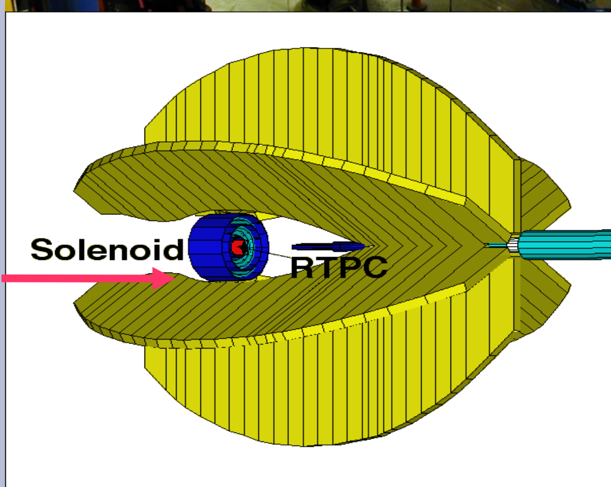
$$\alpha_s = (E_s - p_s^z)/M$$

Tag at small p_s and backward angles => 'nearly' free neutron

BoNuS Experiment

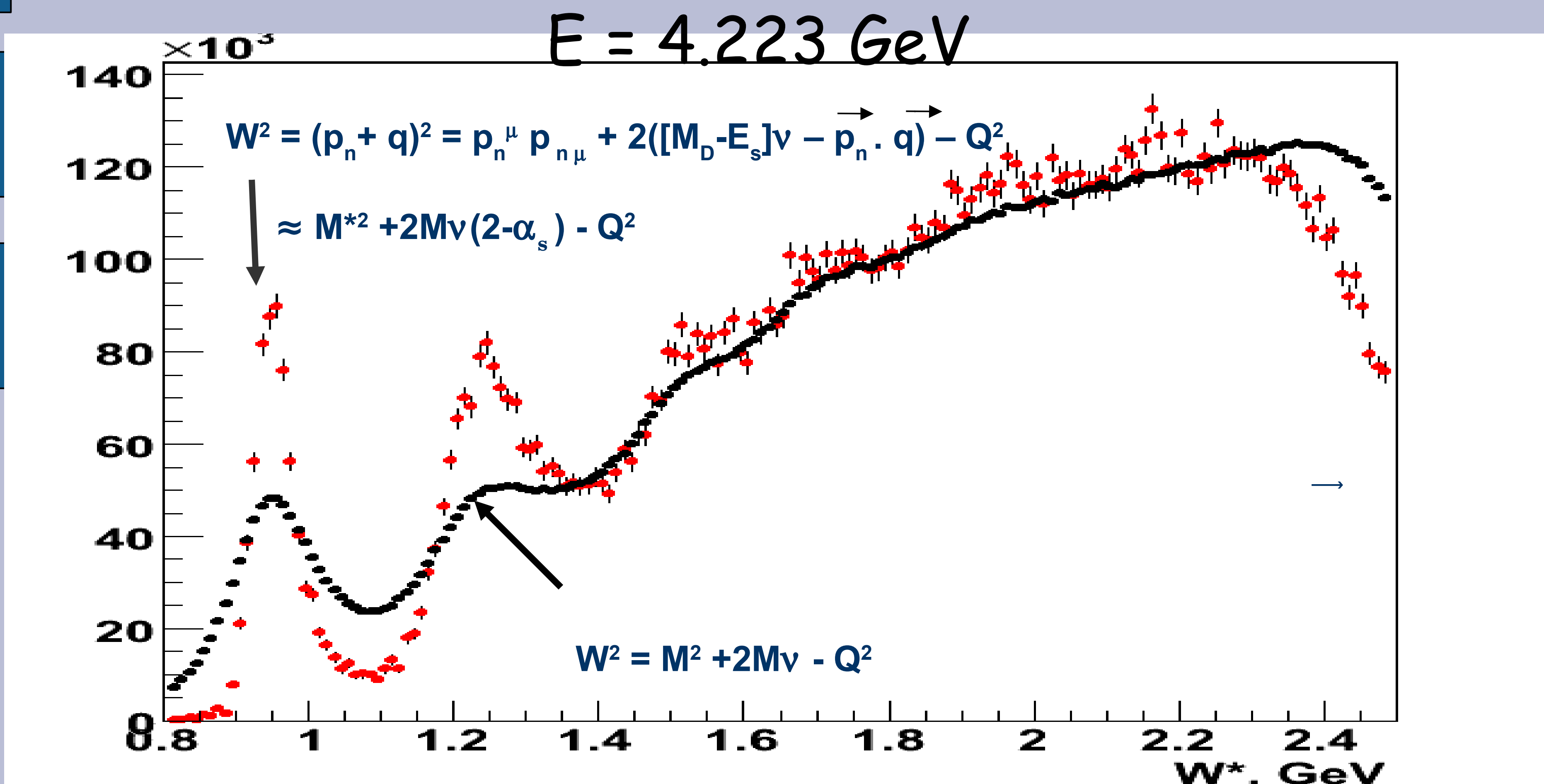






- Detect electrons in CLAS Spectrometer in Hall B
- Detect slow protons in radial time projection chamber (RTPC)
- Moller electrons bottled up by Solenoid field around target
- Solenoid field allows momentum determination

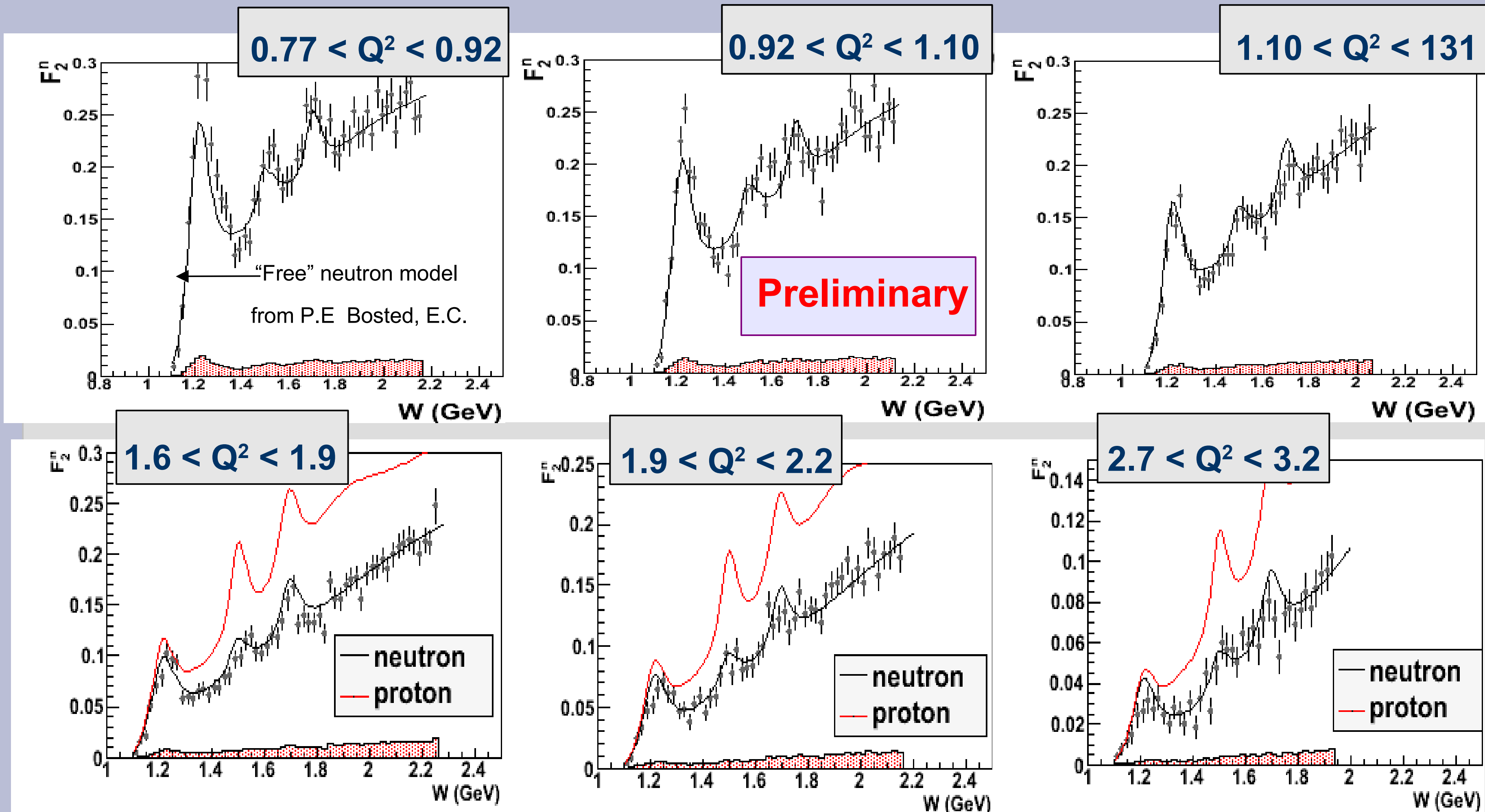
Kinematic reconstruction



The spectator proton's four momentum: $p_n^{\mu} = -(E_s - M_D, \mathbf{p}_s)$

Light-cone momentum fraction: $\alpha_s = (E_s - p_s^z)/M$

Extracted resonance F_2^n from BoNuS



→ ***First*** experimental determination of 'free' neutron resonance structure function.

→ Will be invaluable for future quantitative tests of duality.

Summary

- Quark-hadron duality is a non-trivial property of QCD

  → Soft-Hard Transition!
- Duality has been shown to hold in many observables thus far, including:

  1. All unpolarized structure functions (including Nuclei)
  2. Polarized structure functions
  3. Semi-inclusive

- Models are being confronted with new data, including ***free neutron***

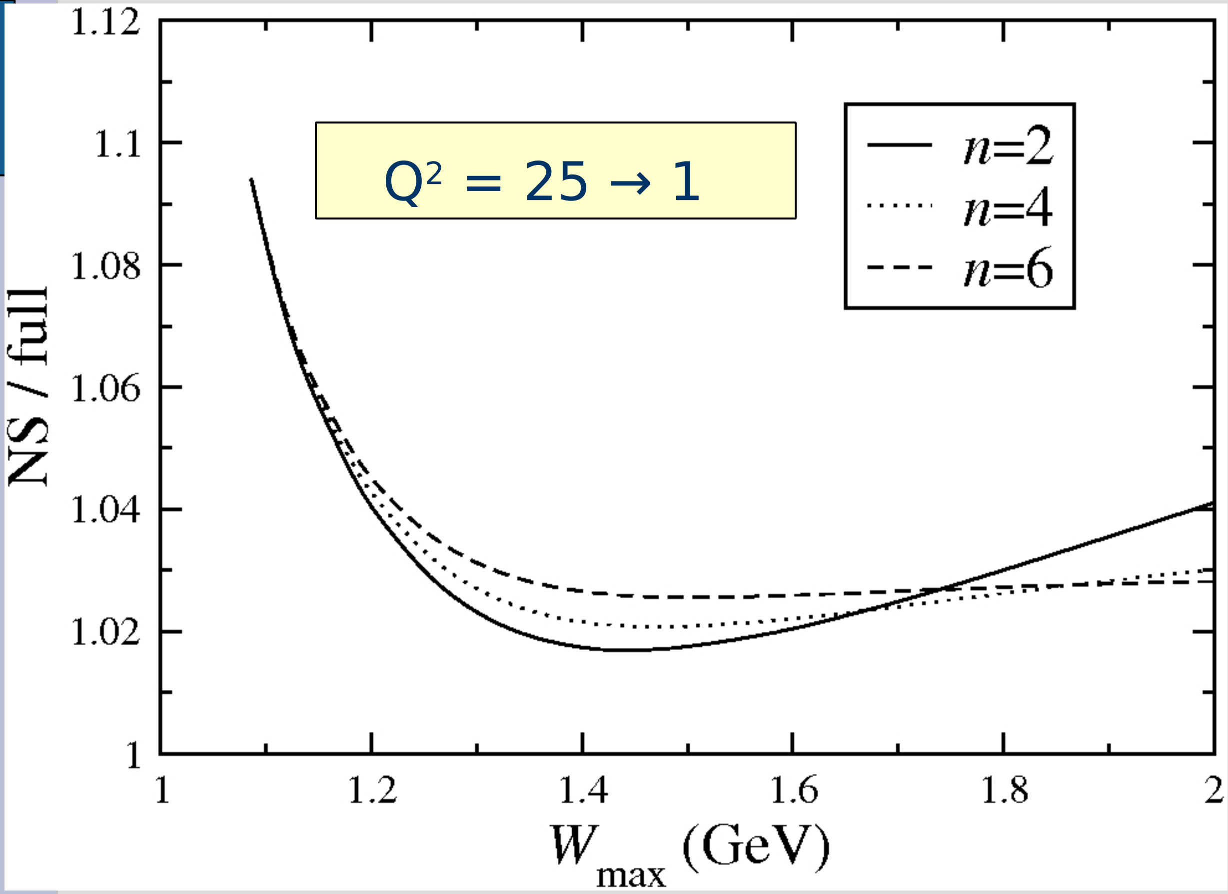
- More experimental results are coming:

  1. ***First*** **studies with neutrino scattering (MINERvA)!**
     Unique information on F_3 and flavor sensitive probe.
  2. Higher Q^2 and x with Jlab upgrade.

Backup Slides

First check Non-Singlet vs full evolution.

Evolve F_2 from MRST PDFs from Q^2 = 25 to 1 GeV^2 using both **N-S** and full (**N-S** + **Singlet**).



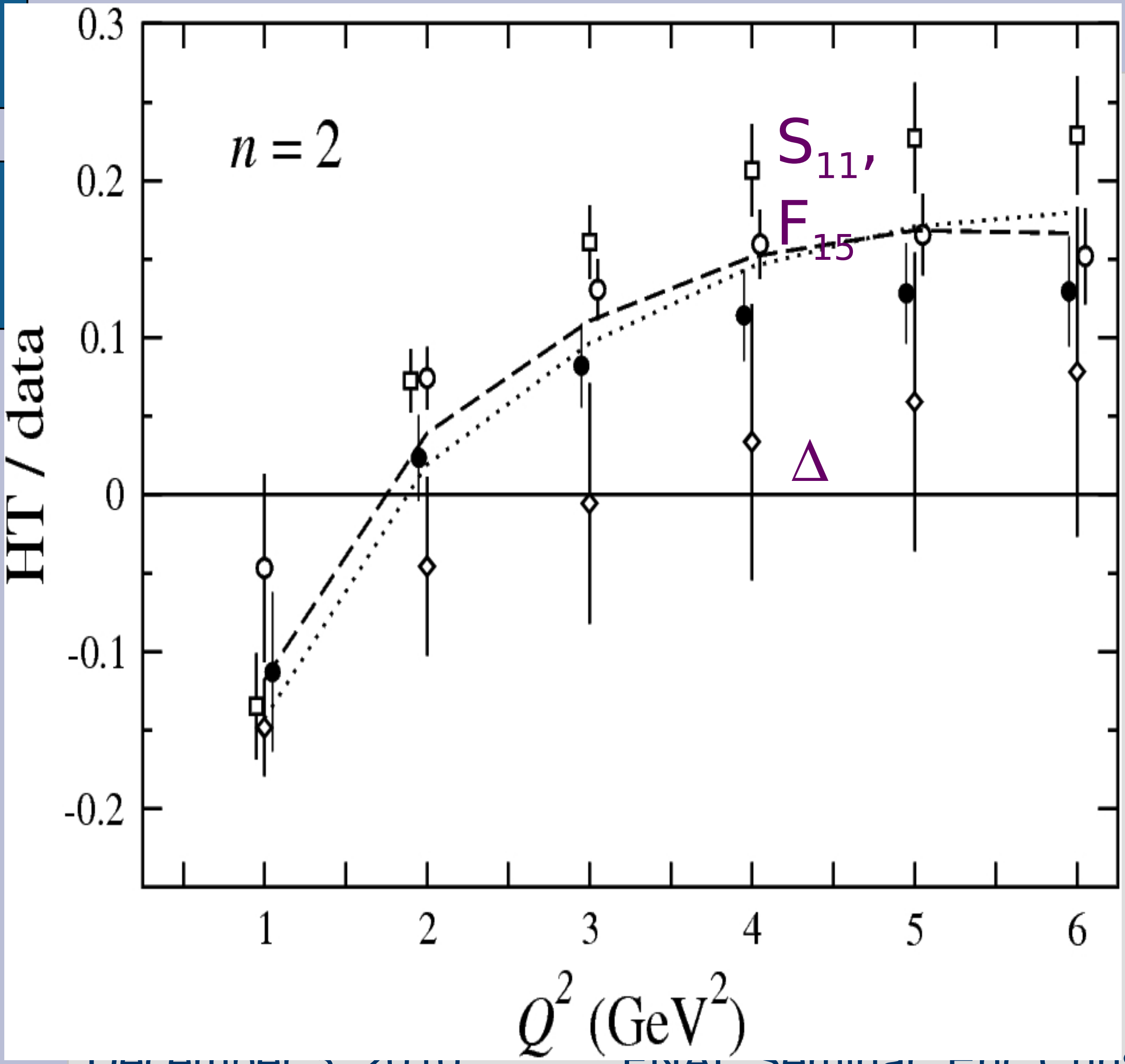
Largest difference for n=2 ***moments***

~4% effect

Higher order (higher n) moments dominated by larger *x* (smaller W) regime

Recall - high W corresponds to low x - glue increasingly more important. ***Becomes dominant uncertainty.***

Q^2 Dependence of Truncated Moments, x Regions Defined by Resonances



- Above Q^2 = 2 GeV^2, Δ about -10%, S_{11} and F_{15} less than +15% higher twist contribution
- First two resonances combined higher twist is about 10% (dotted line)
- All three resonances slightly higher (dashed line)
- *Less than 10%* for full region (black circles)
- Duality better with more resonances included - bears out quark model predictions

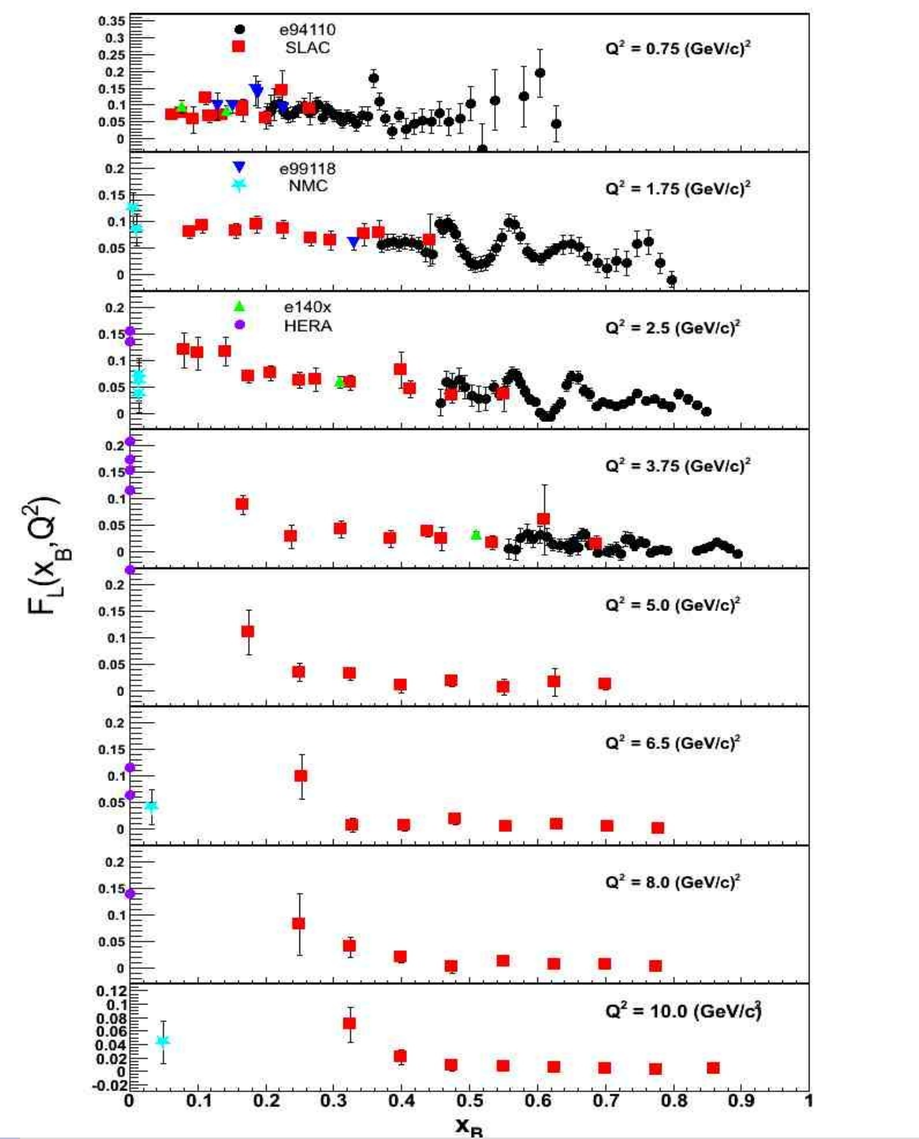
Truncated Moments Summary

- Truncated moments provide firm foundation for quantitative study of duality in QCD
- Higher twists both “small” and do tend to cancel on average
- This analysis also provides uncertainty on singlet evolution contribution

Still to do.

Quantify region dependence (choice of W, x range)
Longitudinal structure function, spin structure functions,...

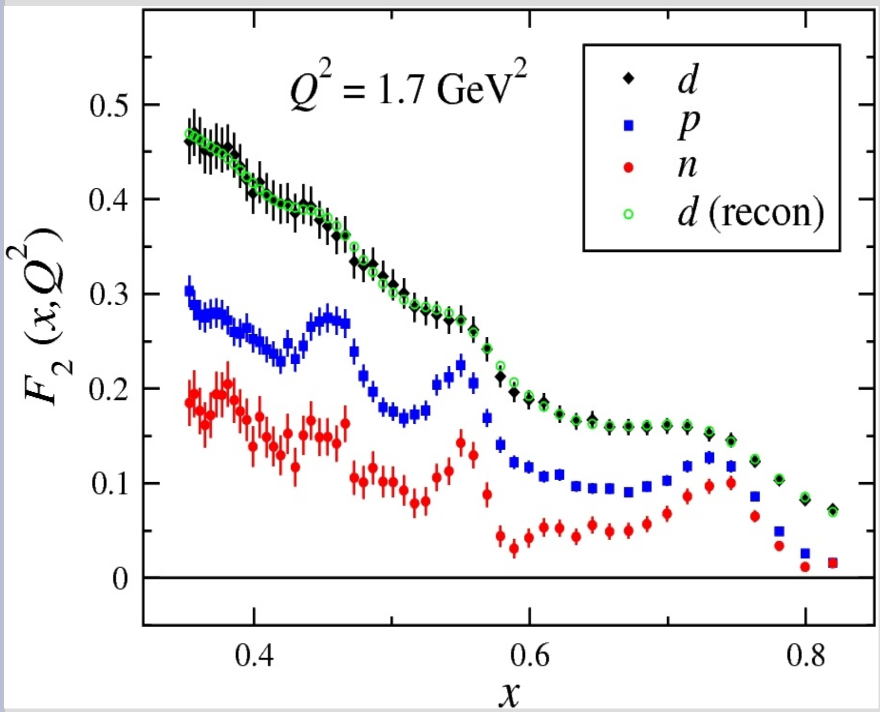
Status of the Proton F_L data



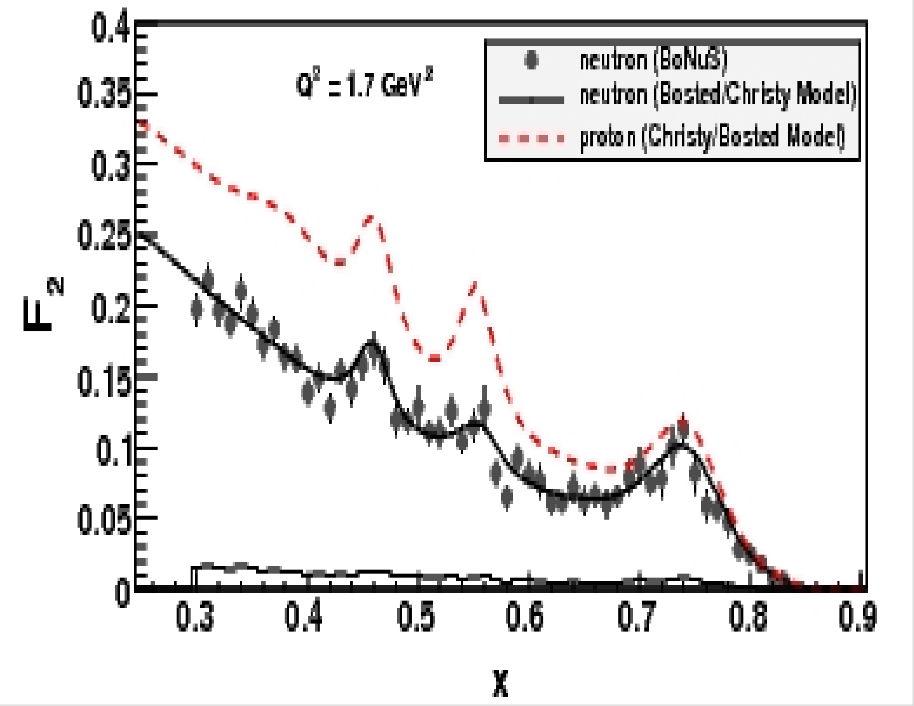
Will soon have comparable data For A = d, C, Al, Fe/Cu

F_2^n Method Comparison

Inclusive, model dependent



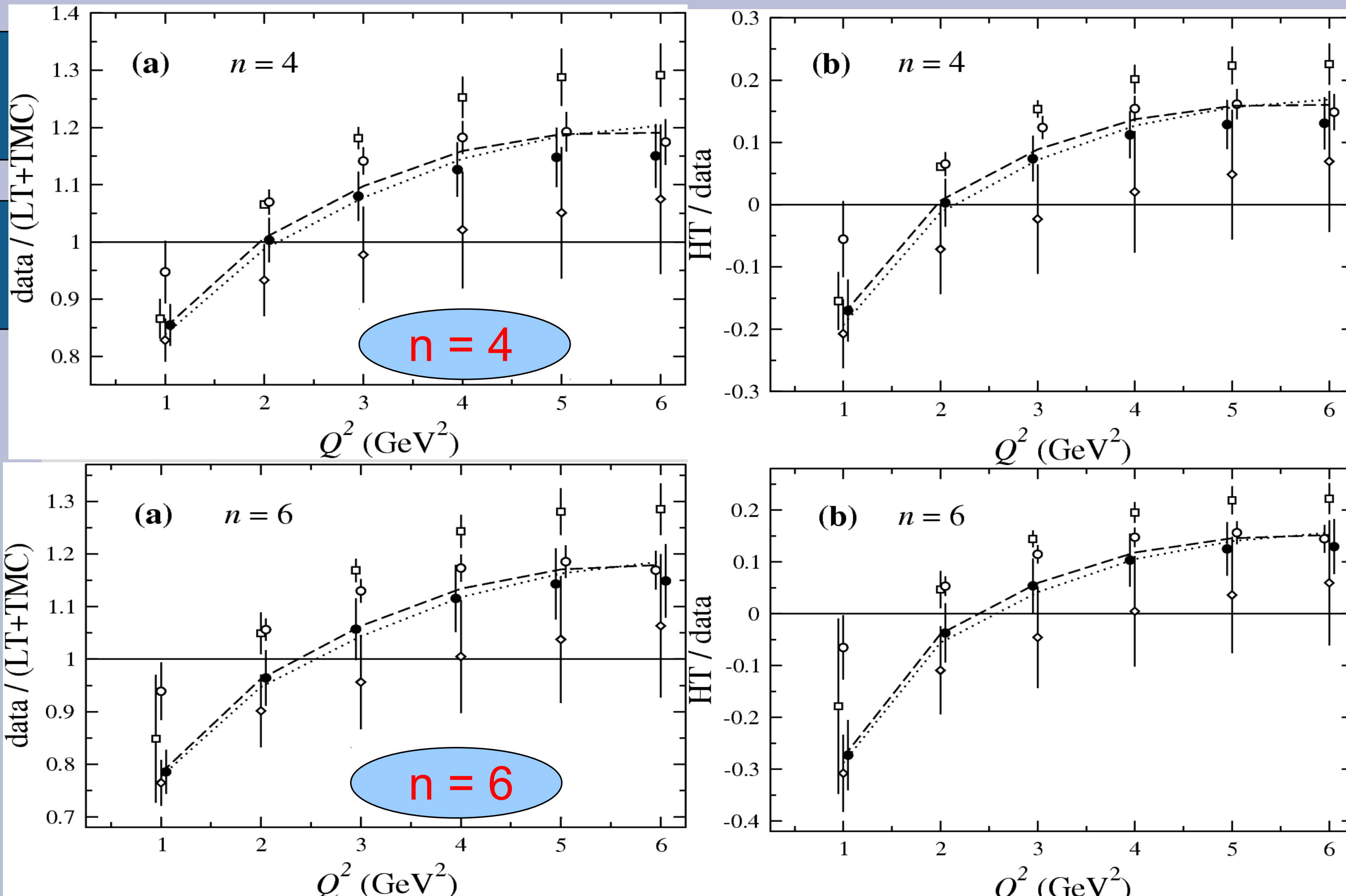
BoNuS, Tagged



→ Fairly consistent results.

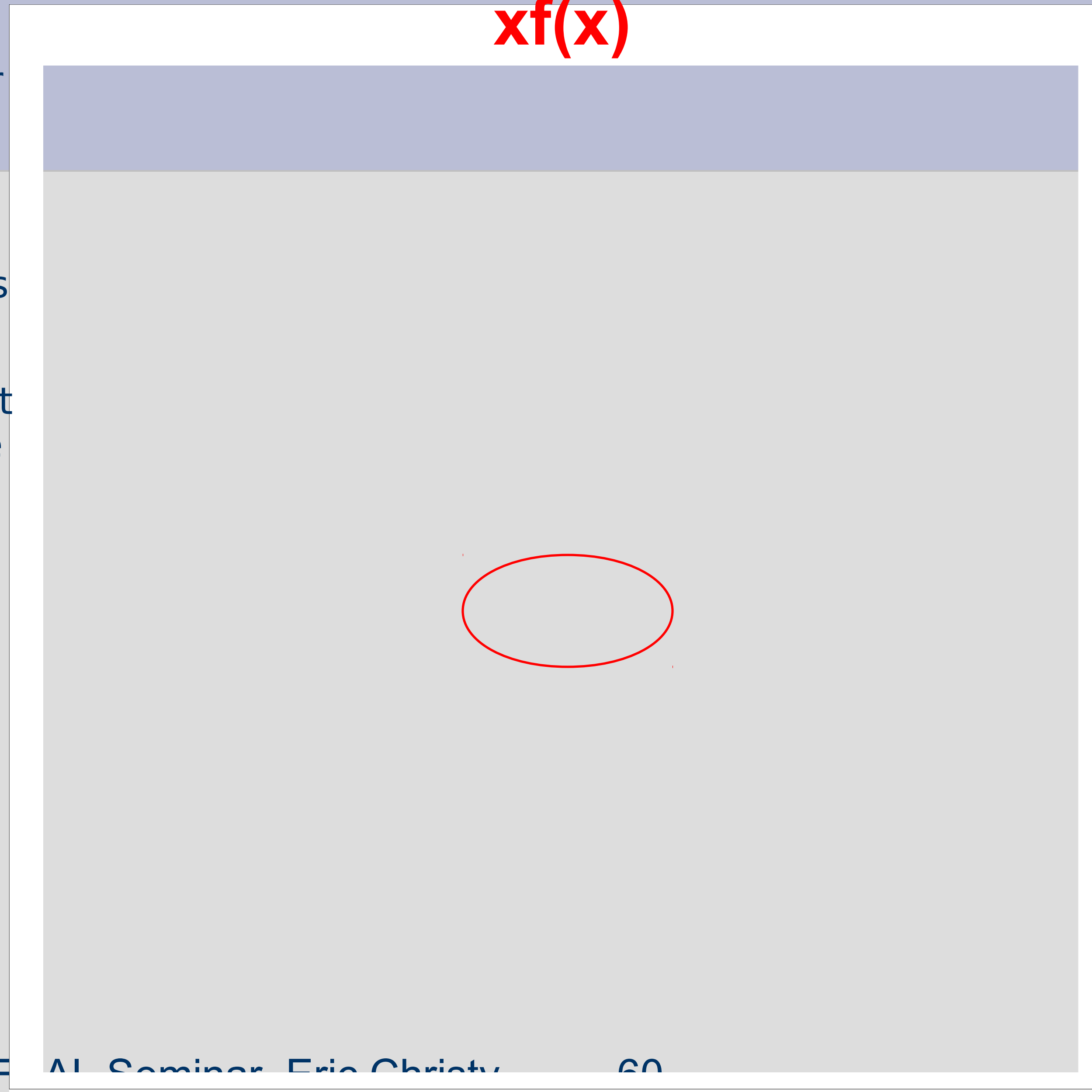
→ More comparisons to come.

Similar for Higher Order Moments

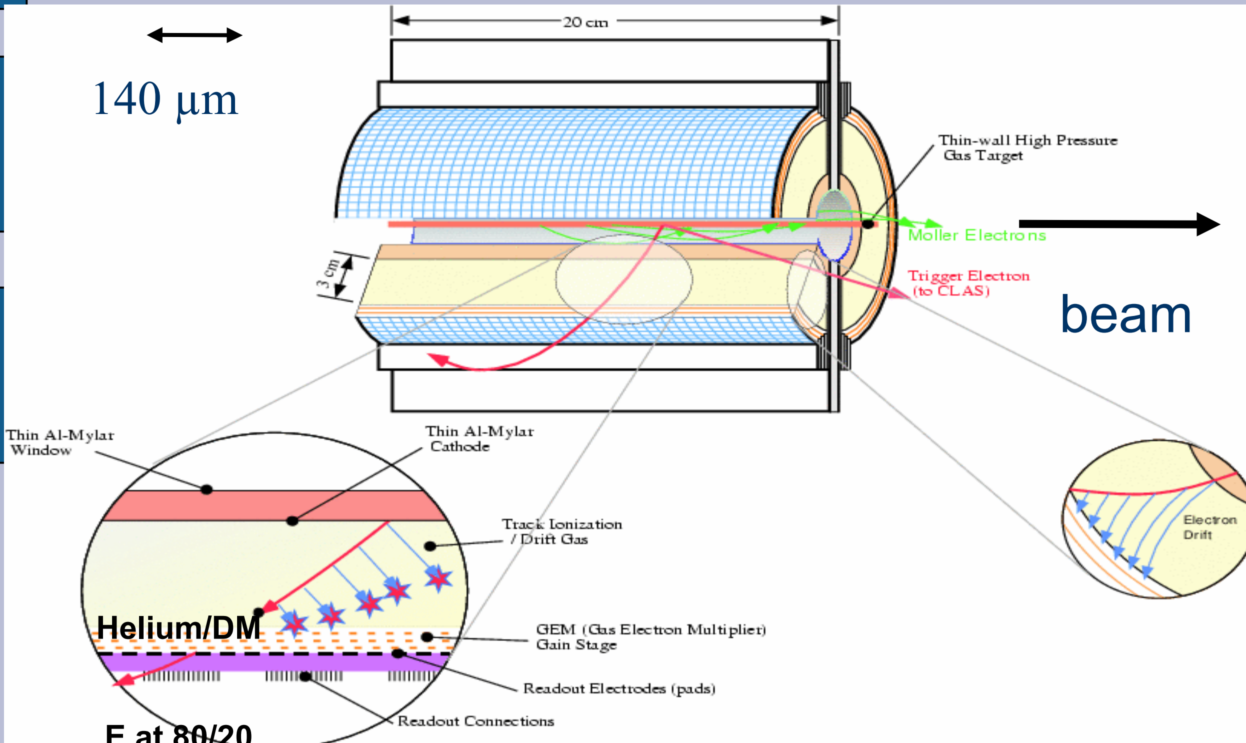


One important issue first....

- Trucated moment evolution equations exist for singlet (S) and non-singlet (NS) equations separately
- Note: g(x) comparable to d(x) at large x - issue always existed
- For analysis of data, do not know how much of structure function is S, and how much is NS.
- Test by evolving trial structure function with known S, NS components
- Compare full evolution to NS alone to determine accuracy



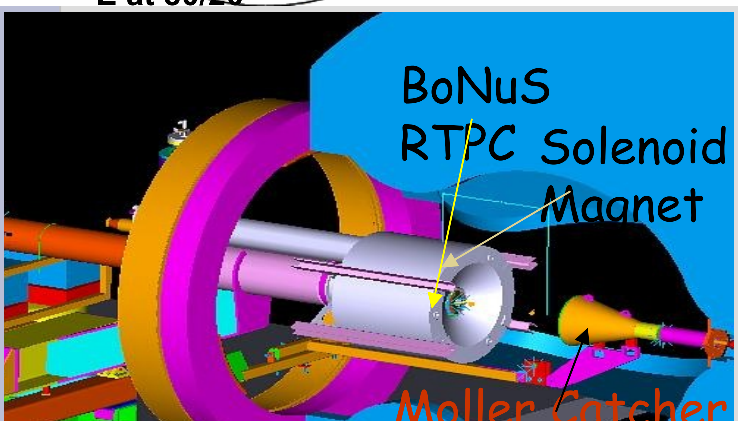
Experimental Setup II: BoNuS RTPC

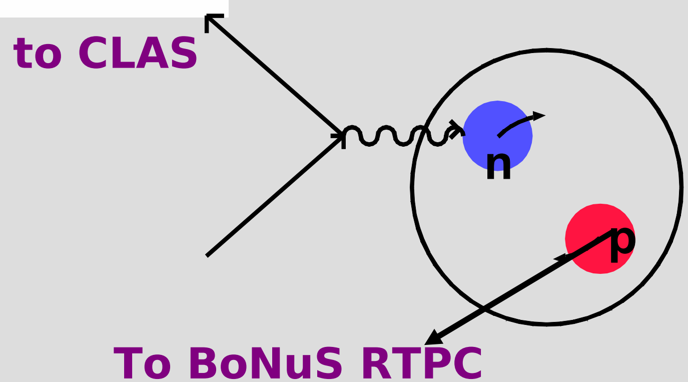


Fit RTPC points to determine helix of proton trajectory.

Momentum determined from track curvature in solenoid field.

dE/dx along track in RTPC also provides momentum and PID information.





Lots of new L/T data from Jlab Hall C

Experiment	target(s)	W range	Q^2 range	Status
E94-110	p	Res	0.3 - 4.5	nucl-ex/0410027
E99-118	p,d	DIS+RR	0.1 - 1.7	PRL98:14301
	C,Al,Cu,			Finalizing analysis
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	Finalizing analysis
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	Finalizing analysis

Lots of results expected in coming year!

Dynamical model of Close/Isgur : Semi-inclusive

$SU(6)$ and $SU(3) \times SU(2)$ Multiplet Contributions to $\pi^{\pm}$ Photoproduction

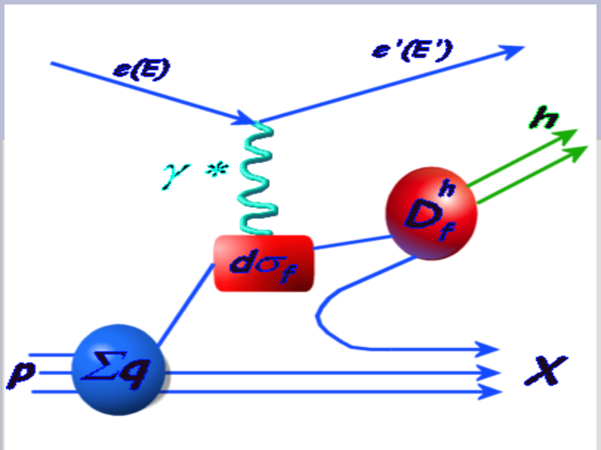
W'	$p(\gamma,\pi^+)W'$	$p(\gamma,\pi^-)W'$	$n(\gamma,\pi^+)W'$	$n(\gamma,\pi^-)W'$
56;8	100	0	0	25
56;10	32	24	96	8
70;^{2}8	64	0	0	16
70;^{4}8	16	0	0	4
70;^{2}10	4	3	12	1
Total	216	27	108	54

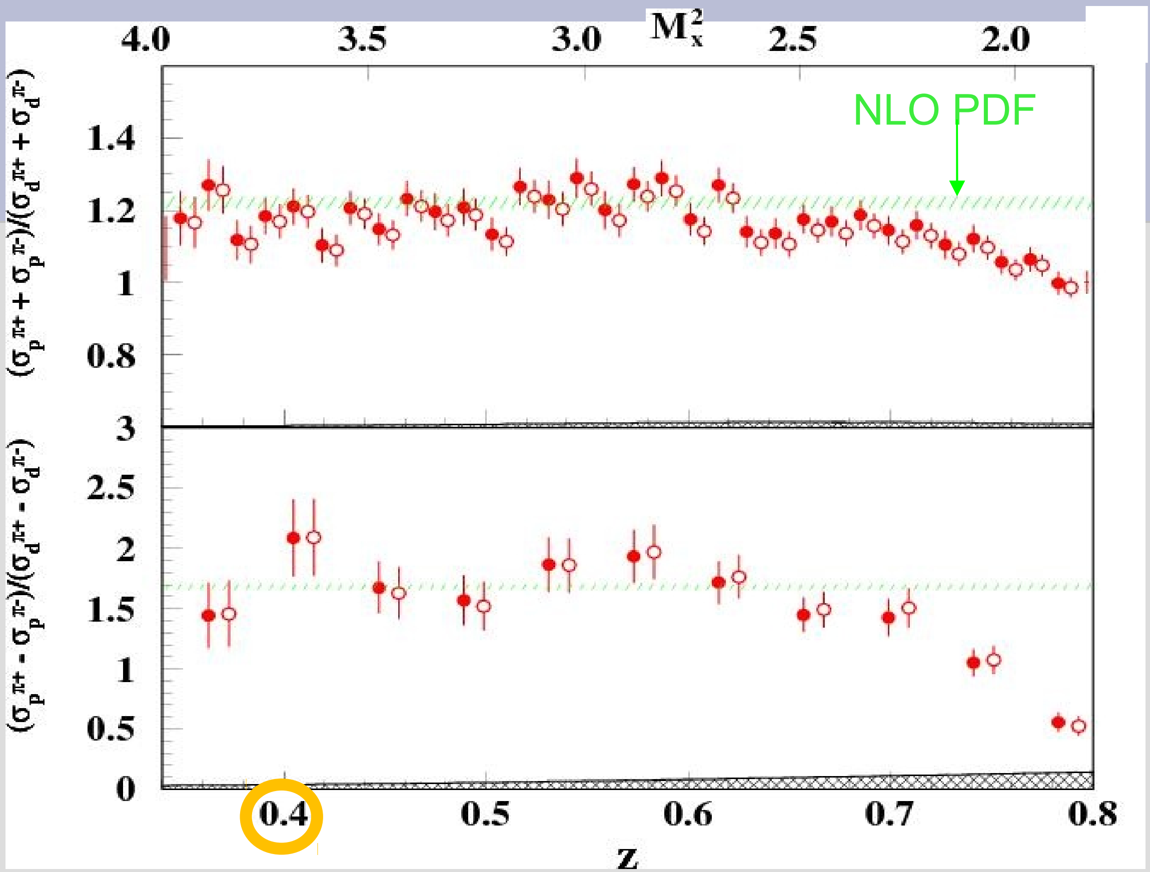
Destructive interference leads to factorization and duality

Predictions: Duality obtained by end of second resonance region

Factorization and approximate duality for $Q^2, W^2 < 3$ GeV^2

Duality in Semi-Inclusive π^+/π^- (E00-108)



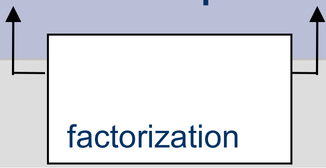


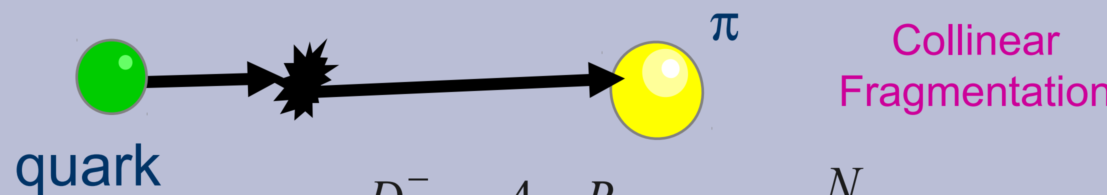
Good description for p and d targets for 0.4 < z < 0.65

(Note: $z = 0.65 \sim M_x^2 = 2.5$ GeV^2)

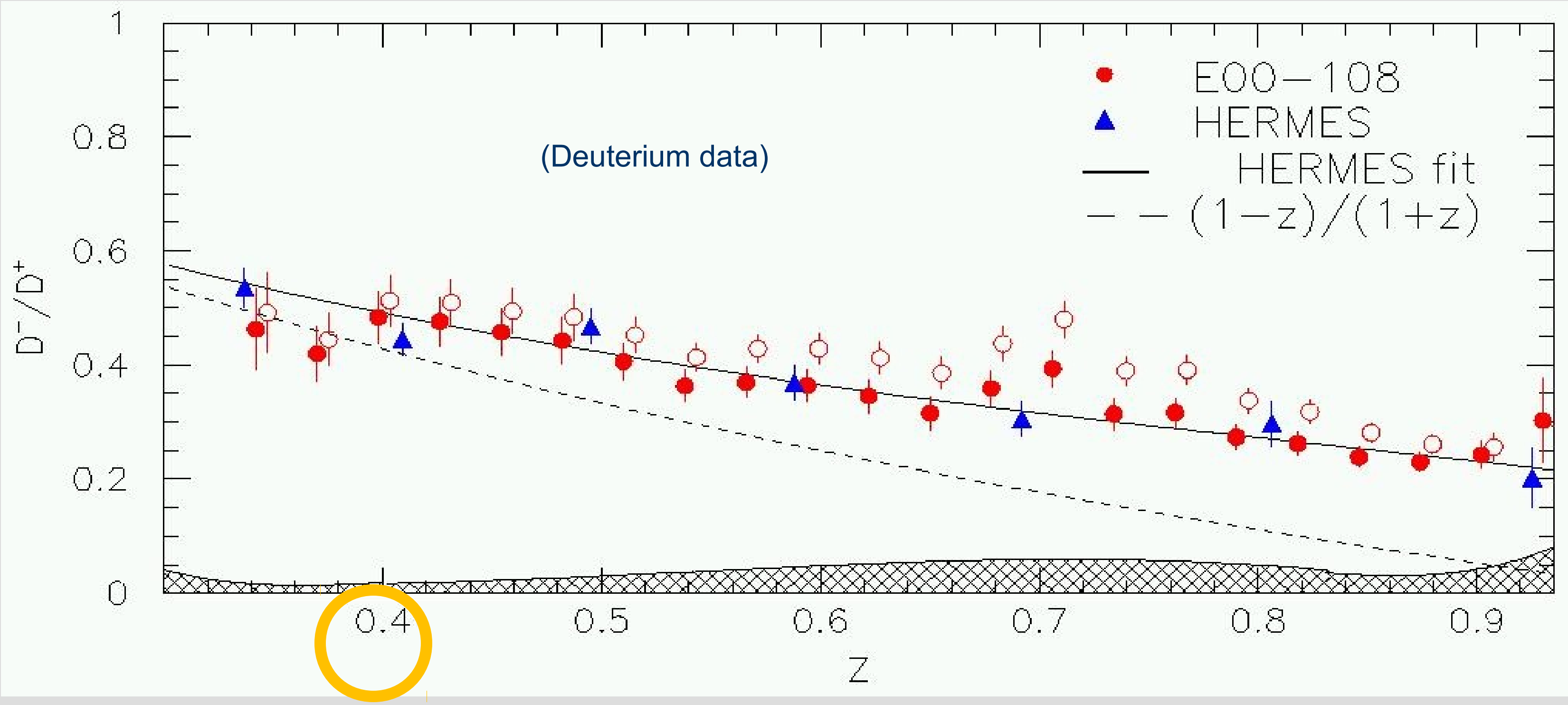
E00-108: Onset of the Parton Model

$\Sigma e_q^{\,2} q(x)\, D_q^{\pi}(z)$





$$\frac{D^-}{D^+} = \frac{4-R}{4*R-1} \qquad R = \frac{N_{\pi^+}}{N_{\pi^-}}$$

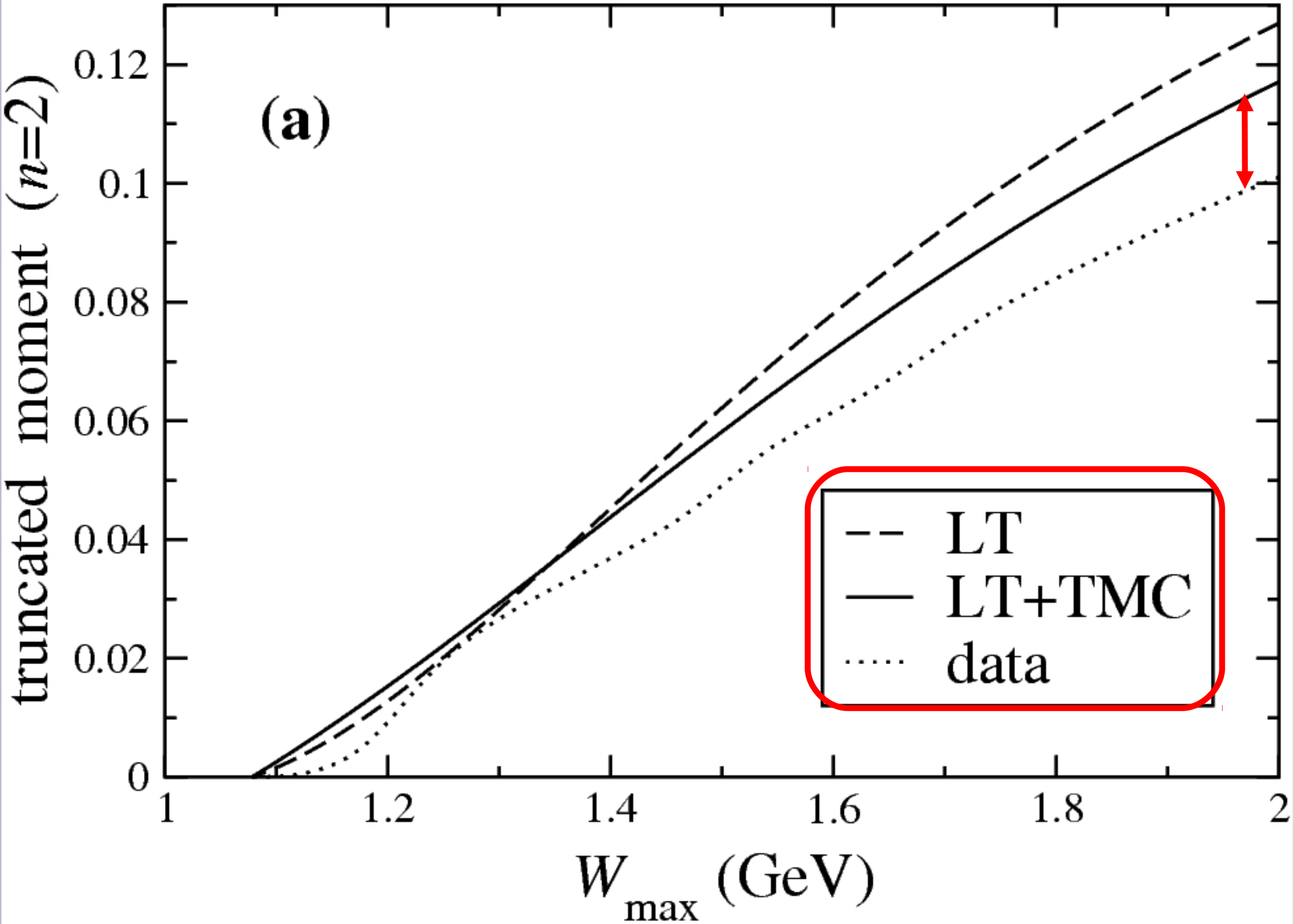


(Resonances cancel (in SU(6)) in D^-/D^+ ratio extracted from deuterium data)

Slide courtesy of R. Ent

Truncated Moment Analysis (NLO) of Hall C F_2 Data

- *Assume* data at highest Q^2 (25 GeV^2) is entirely leading twist
- Evolve (target mass corrected fit) as **NS**, with uncertainty evaluated, from Q^2 = 25 GeV^2 down to lower Q^2

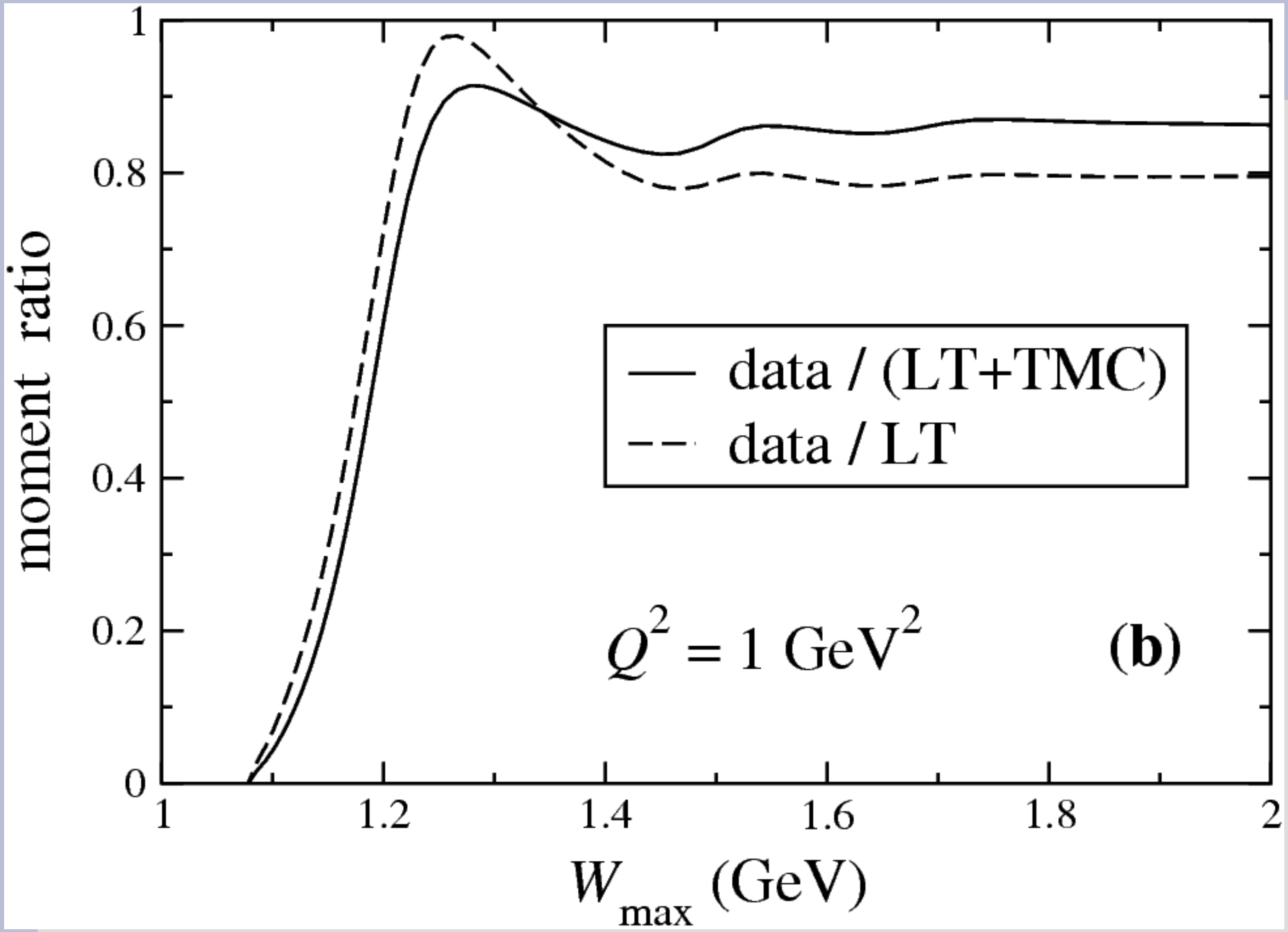


This difference quantifies the higher twist.

smallest x (low x = high W), largest integration range

highest x, smallest integration range

Quantified Higher Twist - ratio of curves on last plot



about 12% at $Q^2 = 1$ GeV^2

target mass corrections crucial

What about the Q^2 dependence?....

Unfolding TM Contributions from data

In the OPE

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

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

Scaling limit ($\nu^2/Q^2 \rightarrow 0$)

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

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

Parameterize $F_{2,L}^{M=0}$ (x,Q^2) and fit $F^{TM}_{2,L}(x,Q^2)$ 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 **$x > 1x10^{-4}$***

F_L^p Data Sets

Data Set	Q^2_{Min} (GeV^2)	x_{min}	Q^2_{Max} (GeV^2)	x_{max}	# Data Points
BCDMS [1]	15	0.07	50	0.65	10
EMC [2]	15	0.041	90	0.369	28
NMC [3]	1.31	0.0045	20.6	0.11	10
SLAC (Whitlow [18])	0.63	0.1	20	0.86	90
SLAC (E140x [19])	0.5	0.1	3.6	0.50	4
H1 [?]	25	0.00062	90	0.0036	5
E99-118 [20]	0.273	0.077	1.67	0.320	7

Fit Form

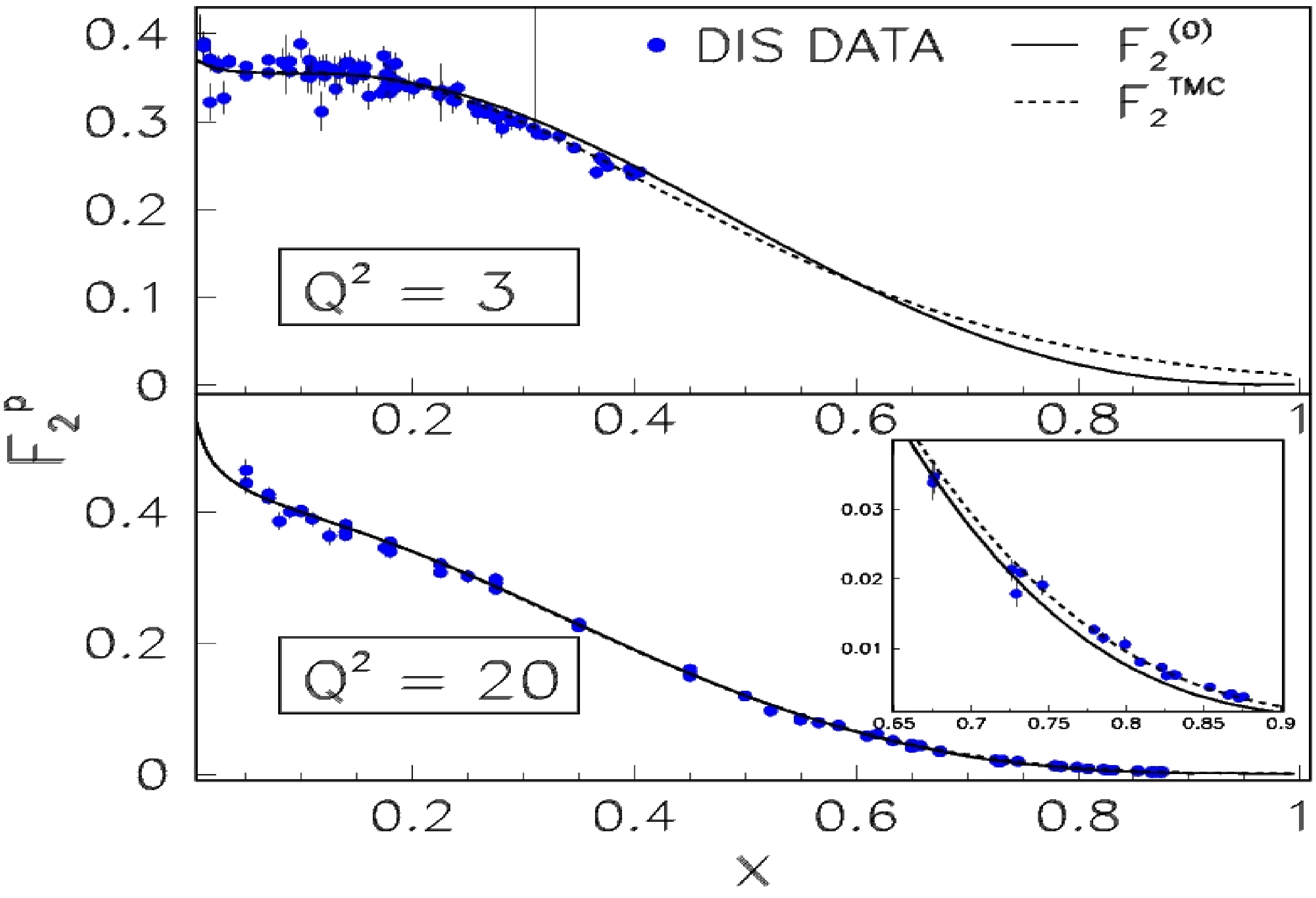
$$F^{(0)}_{2,L}(x) = Ax^B(1-x)^C(1+D\sqrt{x}+Ex),$$

F_2 parameter Q^2 dependence

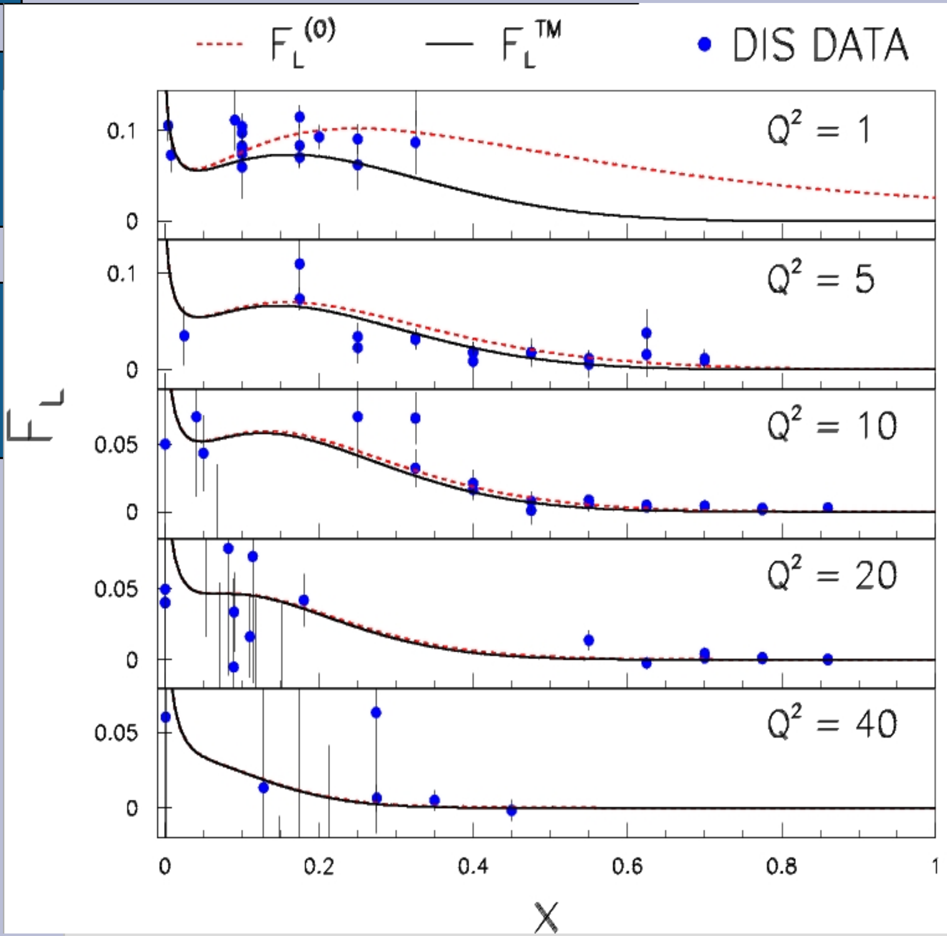
$$A(Q^2) = A_1 + A_2 e^{-Q^2/A_3} + A_4 \log(0.3^2 + Q^2)$$

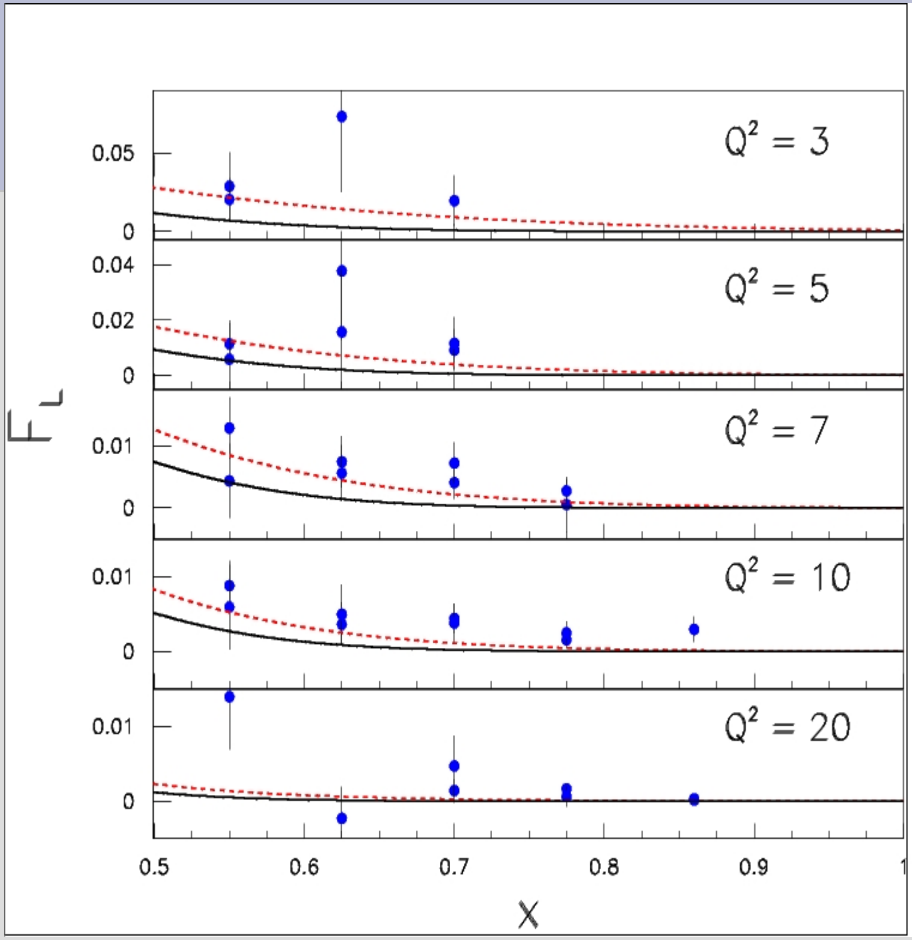
*Same form for **A**, **B**, **C**, **D**, and **E***

F_2 fit results (MEC, J. Blumlein, H. Bottcher)



F_L fit results



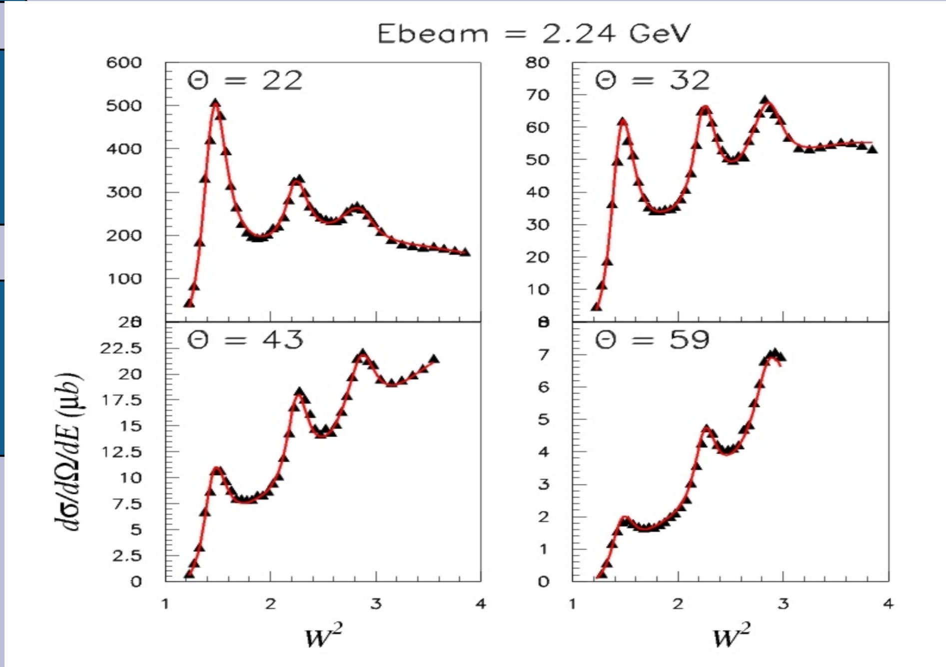


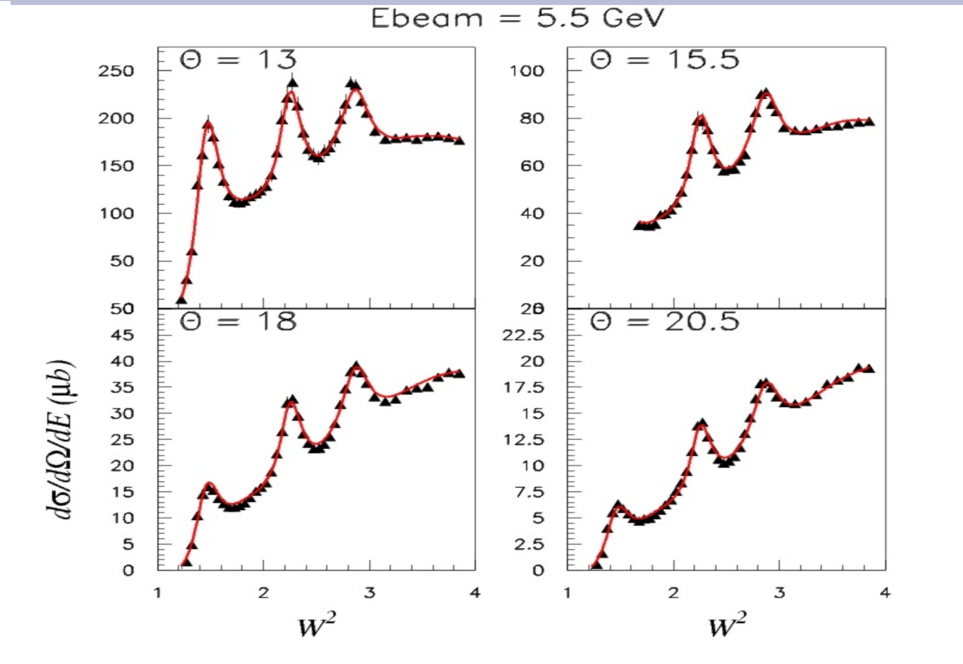
Can utilize for → test pQCD evolution of extracted $F_{L,2}^{(o)}$

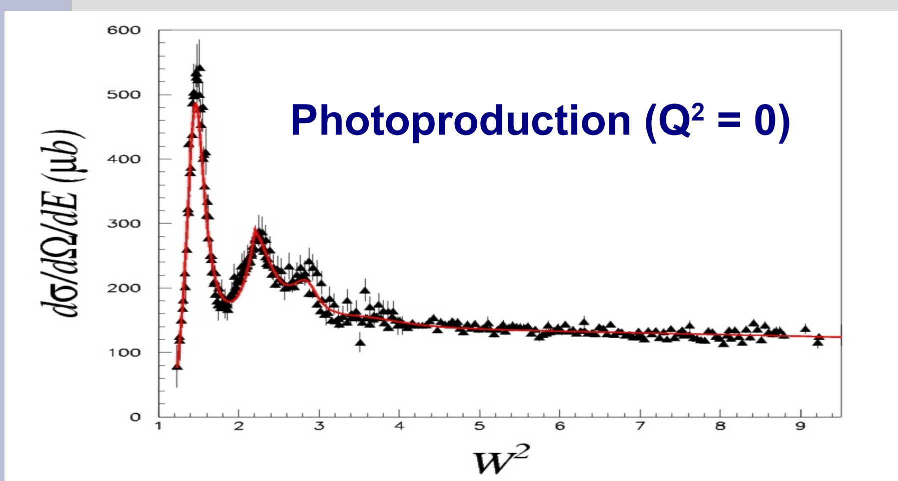
→ Further duality studies using as 'scaling' curve

Resonance Proton fit

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





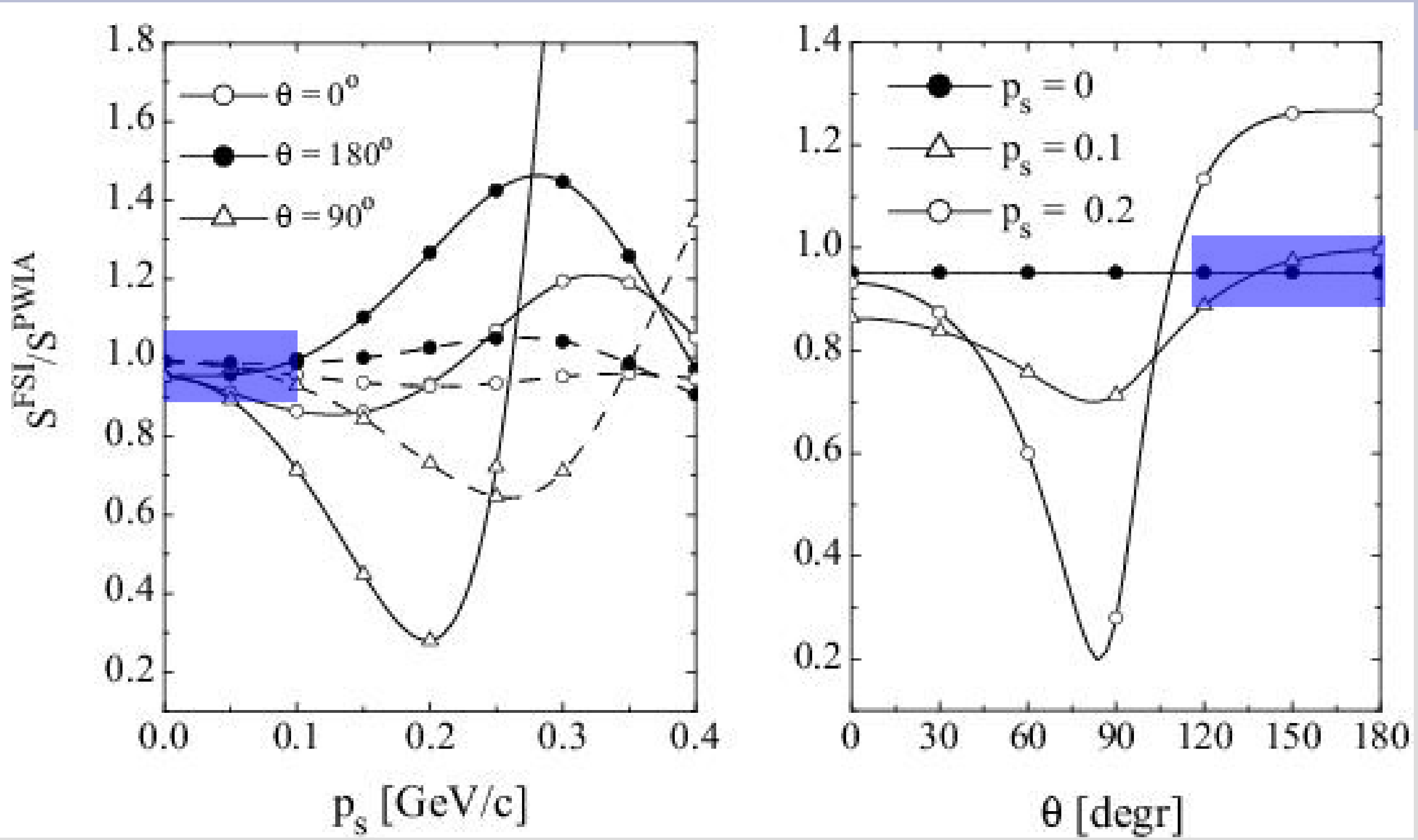


Kinematic range of fit: 0 < Q^2 < 9 and W < 3

- **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

“Rules” for the spectator.
Final state interactions.

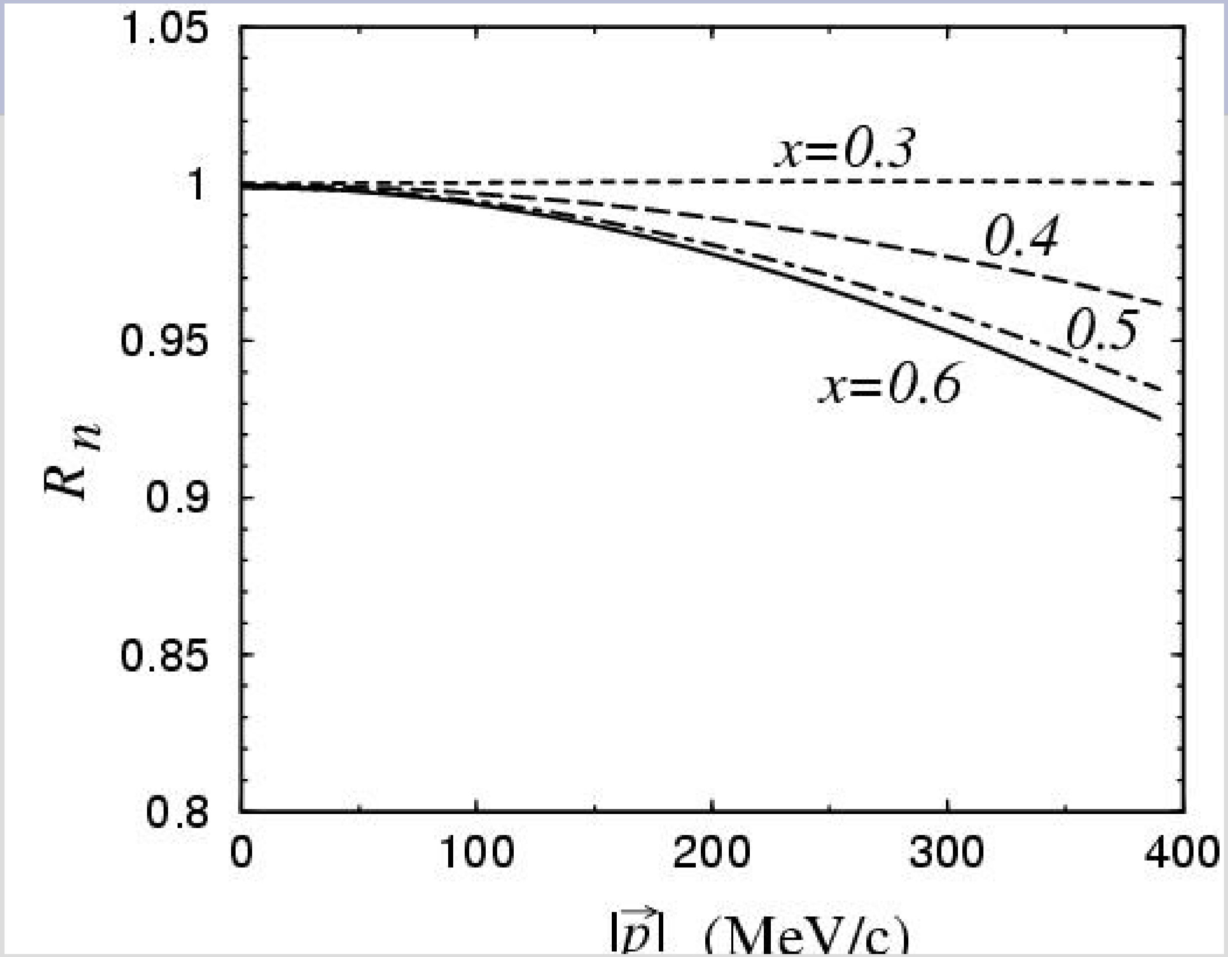


Ciofi degli Atti and Kopeliovich, Eur. Phys. J. A17(2003)133

The momentum and angular dependence of the ratio of spectral functions with and without FSI effects. Blue boxes mark preferred kinematics – regions where FSI have smaller effect.

"Rules" for the spectator.

"Off-shellness" depends on the spectator momentum magnitude.

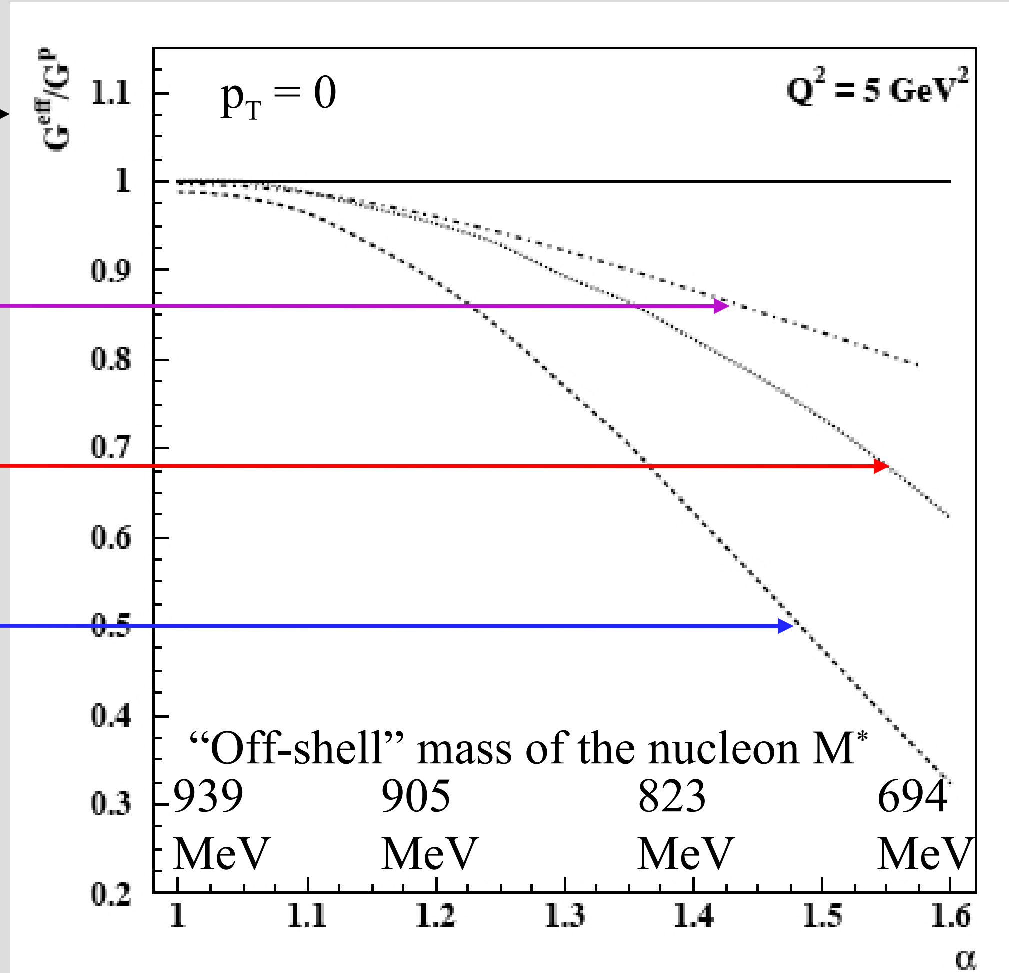


Ratio of the bound to free F_2 neutron structure functions vs spectator momentum.

Deviations from free structure function:

Off-shell Effects [should depend on α (p_s), x, Q^2]

$$\frac{F^{eff}_{2N}(x=0.6,Q^2,\alpha)}{F^{eff}_{2N}(x=0.2,Q^2,\alpha)}$$



P_s = 0 0.09 0.17 0.25 0.32 0.39 GeV/c

Modification of the off-shell scattering amplitude (Thomas, Melnitchouk et al.)

Color delocalization Close et al.

Suppression of "point-like configurations" Frankfurt, Strikman et al.

… plus 6-quark bags, ΔΔ, MEC…

And of course FSI!

Rules for the spectator.
Summary.

Low momentum spectators $\longrightarrow$ Minimize uncertainty due to the deuteron wave function and on-shell extrapolation.

$P_s < 100$ MeV/c

***O* (1%) correction.**

Backward kinematics $\longrightarrow$ Minimize effects from FSI and target fragmentation.

$\theta_{qp} > 110^o$

***O* (5%) correction.**