

***Highlights of DIS related theory for the  
Jlab 12 GeV program***

**Simonetta Liuti  
University of Virginia  
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Madrid**

Working towards Jefferson Lab @ 12 GeV:  
"strong" interactions between theorists and experimenters !!

- ⇒ Many theorists on experimental proposals
- ⇒ ... Some experimenters on theory papers 😊

Common "ultimate" hadronic physics goals:

- ⇒ To understand what gives mass and spin to hadrons
- ⇒ To understand how quarks and gluons form nucleons and nuclei

"Extended" DIS program (including deeply virtual exclusive experiments and connection to  $\nu$ -scattering in MultiGeV region) in Hall A, Hall B and Hall C plays a major role

# Exploring the border of the perturbative and non-perturbative regimes: The inclusive-exclusive connection

✓ From partons to hadrons and around

## Long standing problem

⇒ '70s -- connecting Regge theory with partonic ideas: Harari, Brodsky, Close, Gunion, Landshoff...)

⇒ '90s -- big hiatus in "innovative" phenomenology (in the meantime theoretical progress separately on n.p. and pert. QCD...)

⇒ Present -- new life, ideas, measurements,... nurtured within ideal environments at both Jefferson Lab and DESY (Hermes)

✓ Accent on spin/transverse d.o.f through semi-inclusive experiments → HERMES

✓ High precision exclusive experiments (large  $x_{Bj}$ ) → Jlab

## Three major themes to develop @ 12 GeV JLab

### Hall A

- ✓ Surprising results in elastic scattering: nucleon form factors, Strangeness form factors, in medium form factors, ...

### Hall B

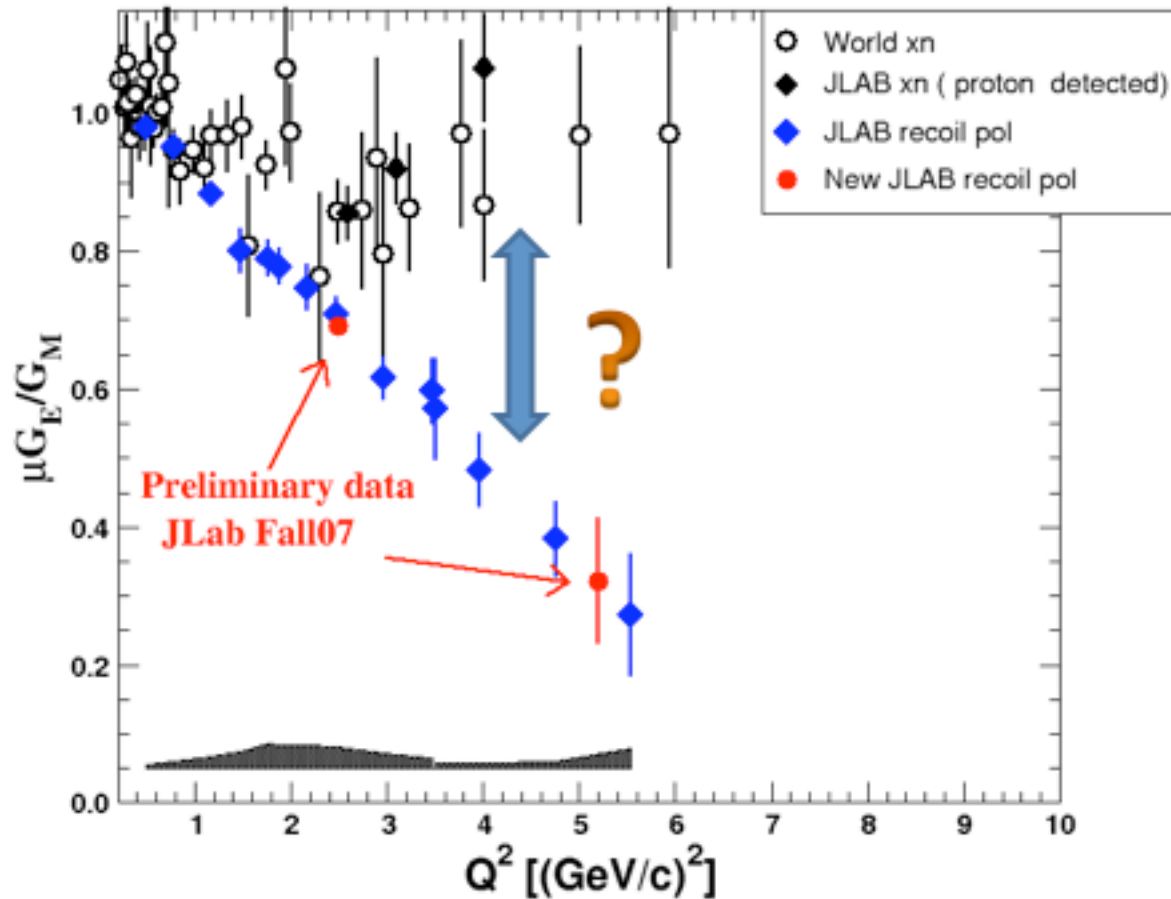
- ✓ Merging information from exclusive and inclusive processes → Generalized Parton Distributions, Hadrons Holography, transversity studies ...

### Hall C

- ✓ Connecting resonance formation and quark jets configurations → study of large  $x_{Bj}$

All of the above involve exclusivity and/or exclusive-inclusive connection!  
This turns out to be crucial for determinations of many related observables (even not directly related like  $\Delta G$ , ...)

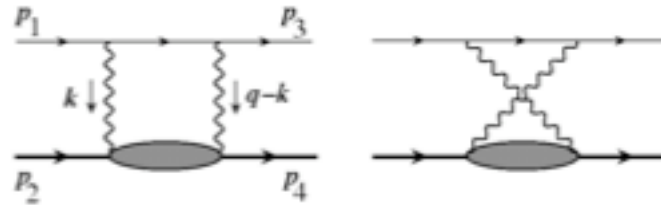
Replace old paradigms on charge and current distributions in the nucleon



What is the origin of this discrepancy?

## Different theoretical scenarios

- 1) Two photon effects might affect differently the two processes used to extract the form factors



Situation is unclear:

- ✓ Initial calculations by Blunden, Melnitchouk, Tjon (hadronic model) and Chen, Afanasev, Brodsky, Carlson and Vanderhaeghen (GPDs) predicted changes in cross section but small changes in polarization observable
- ✓ Bystritskiy, Kuraev, Tomasi-Gustafsson predict no significant two photon effects in cross section
- ✓ Jain, Joglekar and Mitra predict significant changes in two photon effects in polarization observables

⇒ Reason of all these possible discrepancies is in the model dependence of hadronic part

2) Difference in  $G_E/G_M$  translates into that in  $F_1/F_2$ .

PQCD explanation: spin flip FF involves OAM! (Belitsky, Ji, Yuan)

Different mechanisms be tested in a wide range in  $Q^2$ .

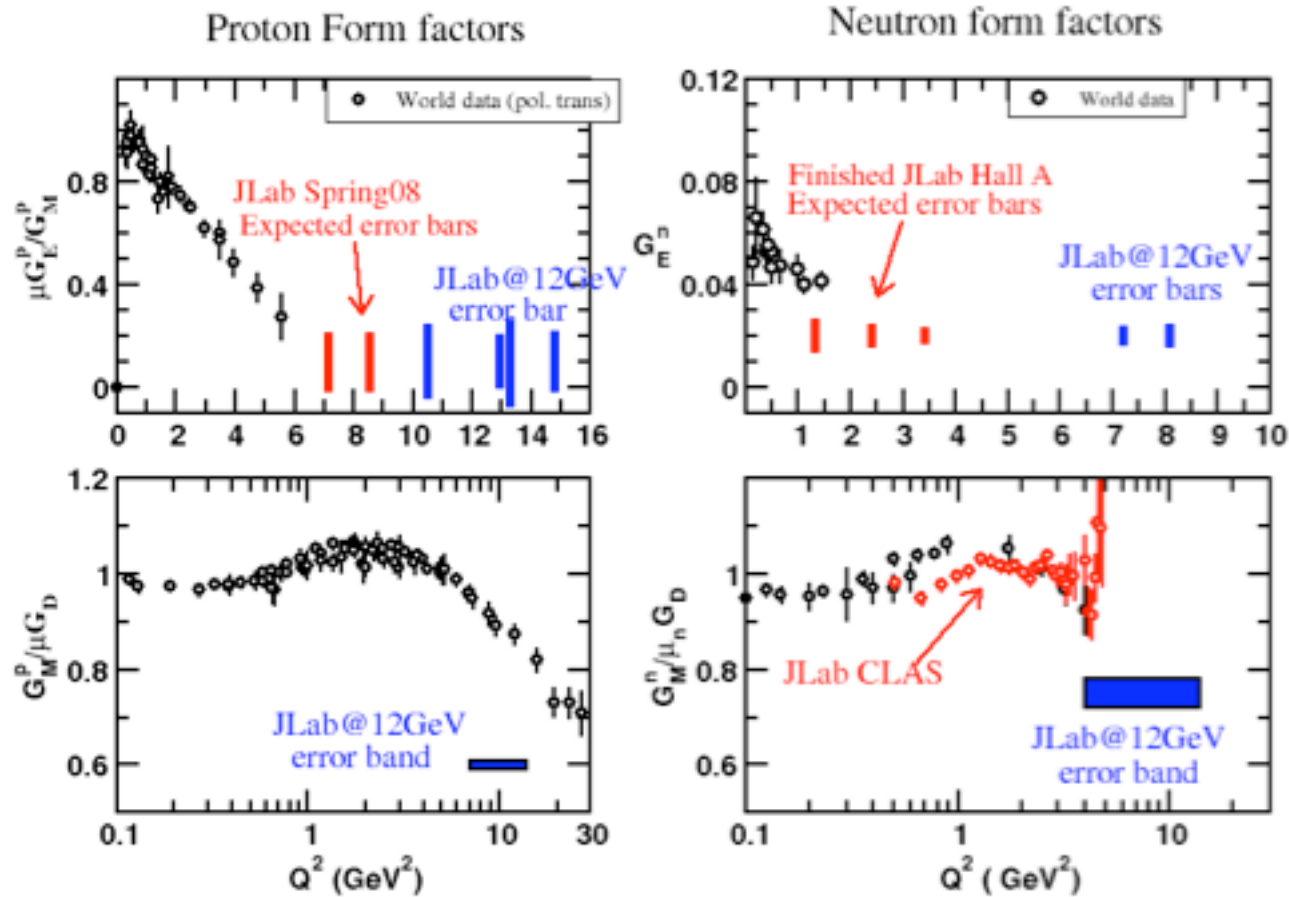
Interesting to explore this in terms of GPDs

Initial work by G. Miller ('07) and by C. Carlson and M. Vanderhaeghen ('08)

$$\begin{aligned}\rho_0^N(\vec{b}) &\equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2} e^{-i\vec{q}_\perp \cdot \vec{b}} \frac{1}{2P^+} \langle P^+, \frac{\vec{q}_\perp}{2}, \lambda | J^+(0) | P^+, -\frac{\vec{q}_\perp}{2}, \lambda \rangle && \text{Longitudinal Pol.} \\ &= \int_0^\infty \frac{dQ}{2\pi} Q J_0(bQ) F_1(Q^2)\end{aligned}$$

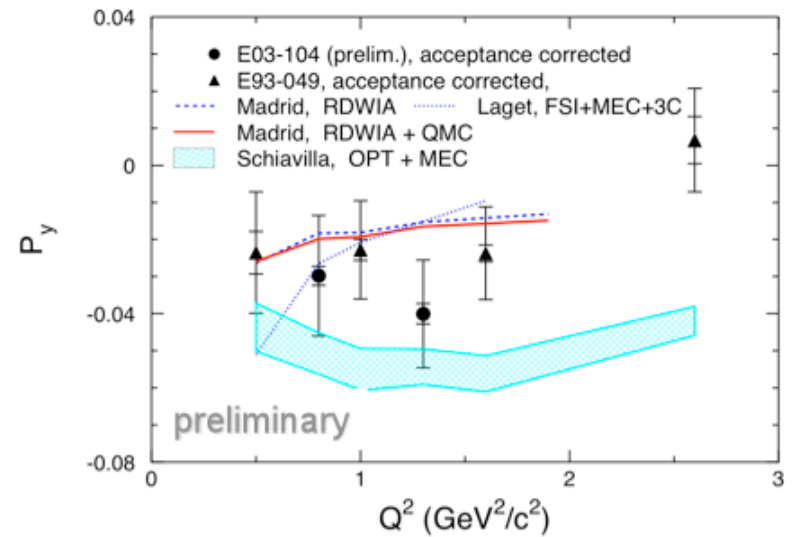
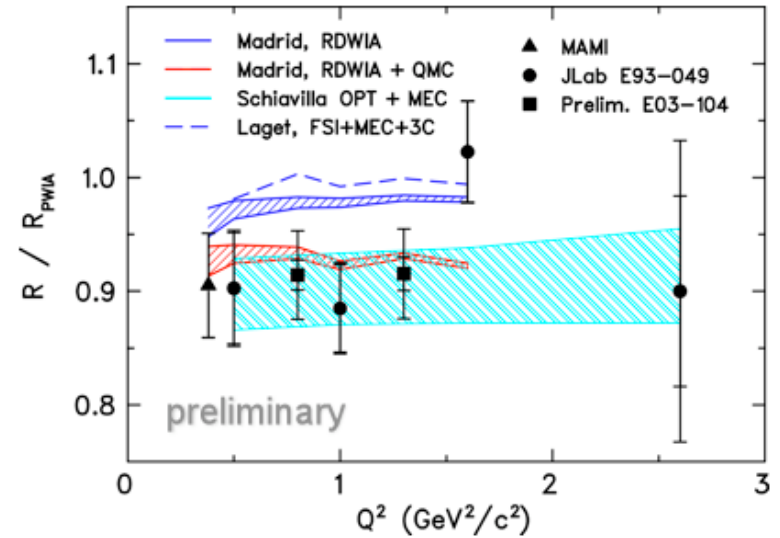
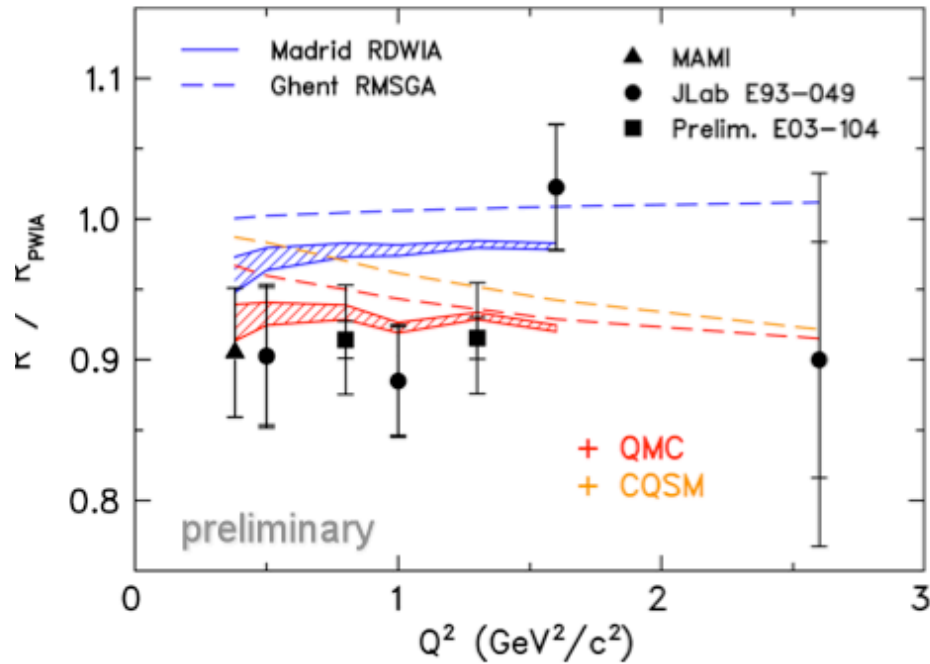
$$\begin{aligned}\rho_T^N(\vec{b}) &\equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2} e^{-i\vec{q}_\perp \cdot \vec{b}} \frac{1}{2P^+} \langle P^+, \frac{\vec{q}_\perp}{2}, s_\perp = +\frac{1}{2} | J^+(0) | P^+, -\frac{\vec{q}_\perp}{2}, s_\perp = +\frac{1}{2} \rangle \\ &= \rho_0^N(b) + \sin(\phi_b - \phi_S) \int_0^\infty \frac{dQ}{2\pi} \frac{Q^2}{2M_N} J_1(bQ) F_2(Q^2) && \text{Transverse Pol.}\end{aligned}$$

Jlab at 12 GeV will allow to extend  $Q^2$  range

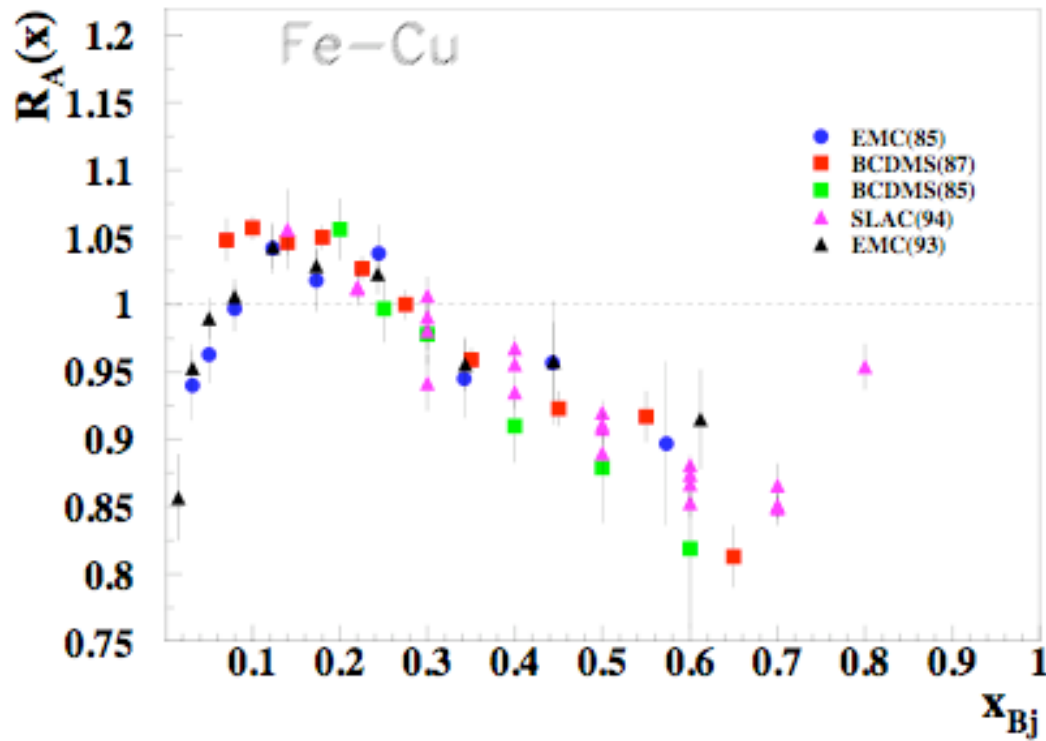


# In medium form factors (S. Strauch et al.)

$$G(Q^2, \rho) = G(Q^2) \frac{G_{\text{QMC}}(Q^2, \rho)}{G_{\text{QMC}}(Q^2)}$$

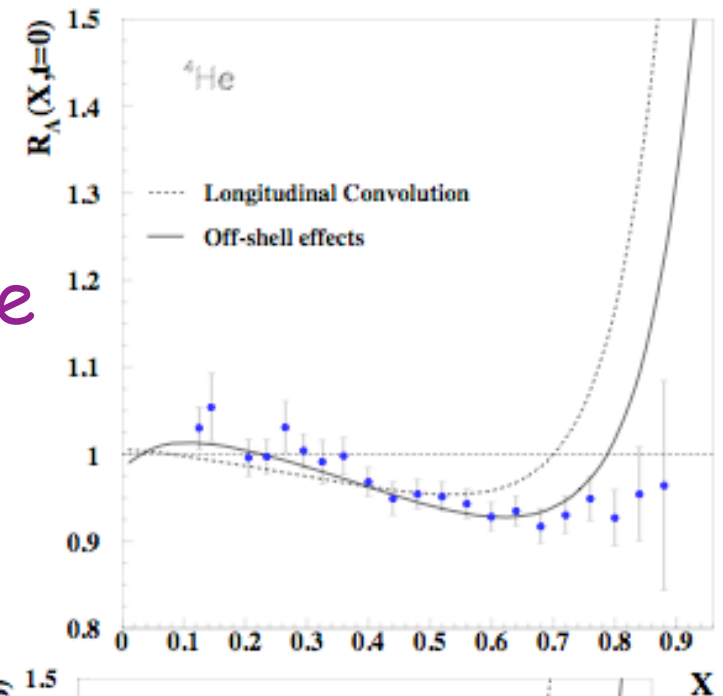


## The “EMC” effect

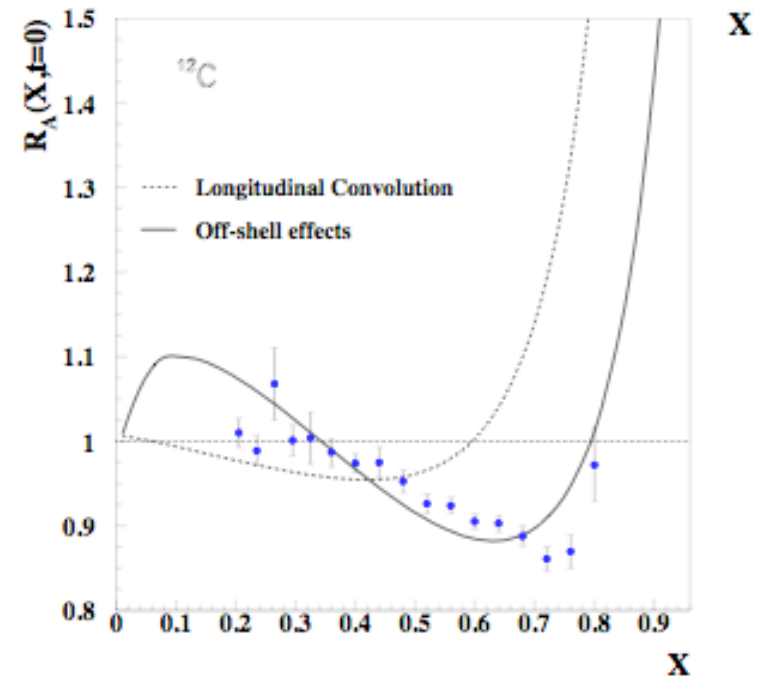


“Standard” treatment:  
trivial integration over  
transverse d.o.f.

$^4\text{He}$

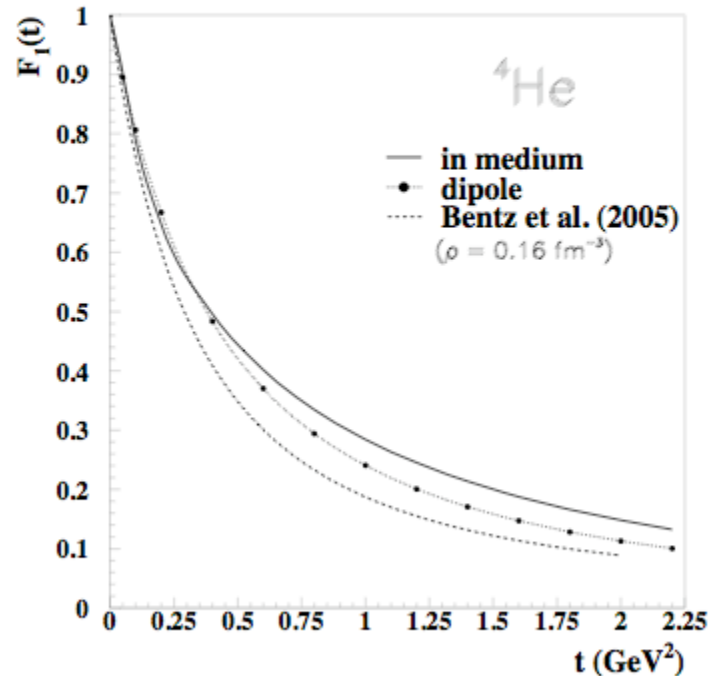


$^{12}\text{C}$



# GPDs bridge (quasi)elastic and (deeply) inelastic...

Form Factor in Nuclei *S.L., hep-ph/0601125*



$$F_A(t) = \int_0^A dx H_A(x, t)$$

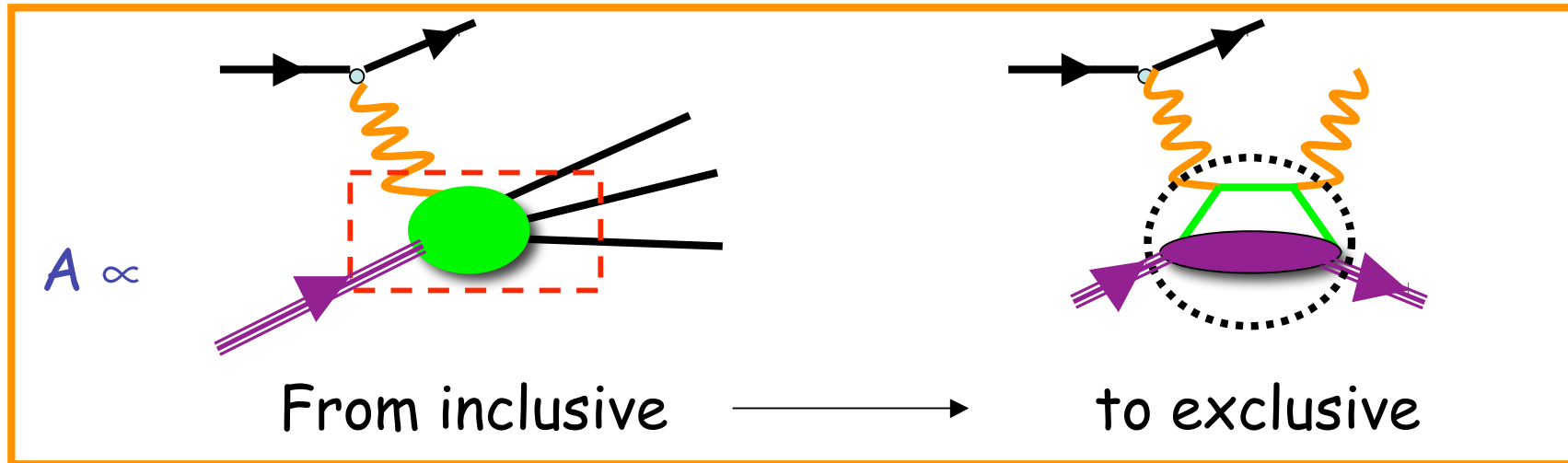
$$F_A^{LC}(t) = F_A^{point}(t) F_N(t)$$

$$F_A(t) = \int_X^A dY \int dP^2 \rho_A(Y, t; P^2) H_N\left(\frac{X}{Y}, t; P^2\right)$$

$$\hat{F}_1^N(t) = \left[ \frac{F^A(t)}{F_{LC}^A(t)} \right] F_1^N(t)$$

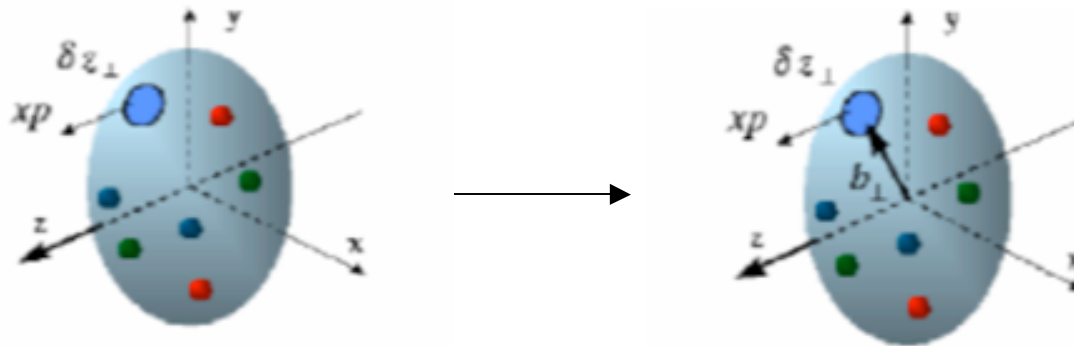
↑ Medium Modified Form Factor ↑

Generalized parton distributions: accessing the “unthinkable”  
both spatial and momentum distributions of partons



Spatial d.o.f.

+



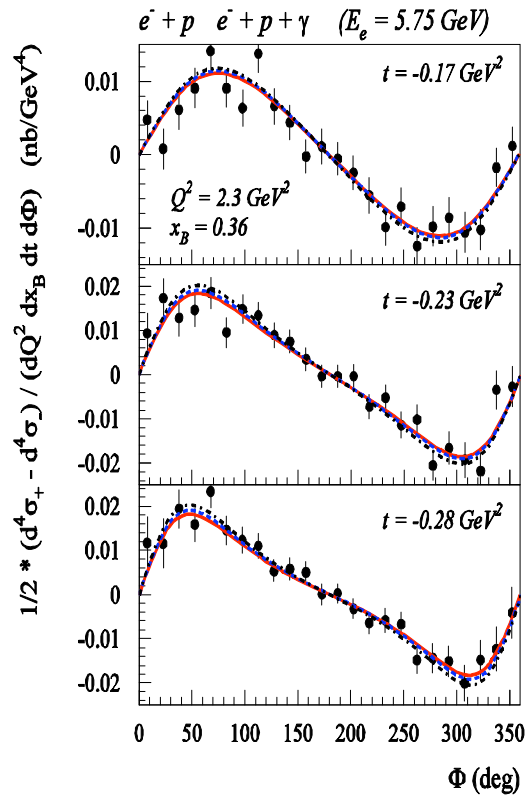
Quark Angular Momentum

$$\int dx x [H_q(x, \zeta, t=0) + E_q(x, \zeta, t=0)] = 2J_q \quad \text{X.Ji}$$

## What was accomplished

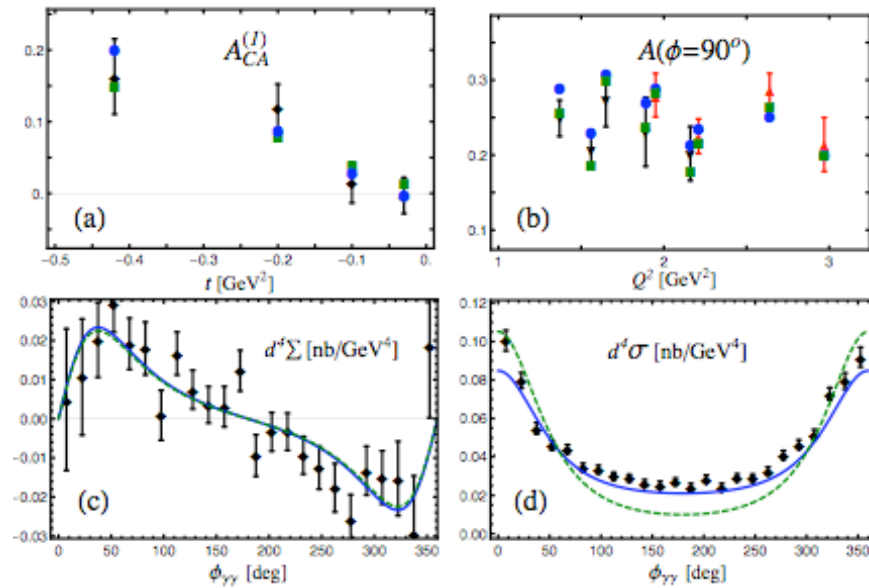
Initial data stimulated many predictions  $\Rightarrow$  important theoretical input for extracting GPDs from DVCS data at finite  $Q^2$  and different ranges in skewness parameter and  $t$

Puzzles in the outcome of DVMP data  $\Rightarrow Q^2$  dependence in L and T channels? What GPDs are involved?



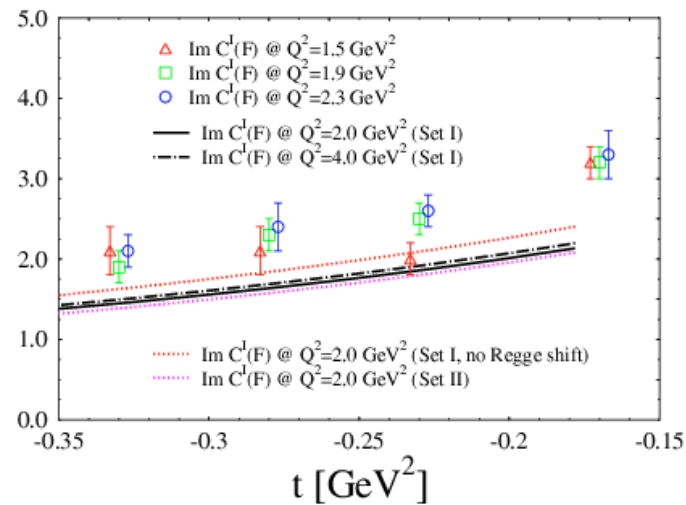
Dual Model with DR

Polyakov and Vanderhaghen, '08



Global analysis

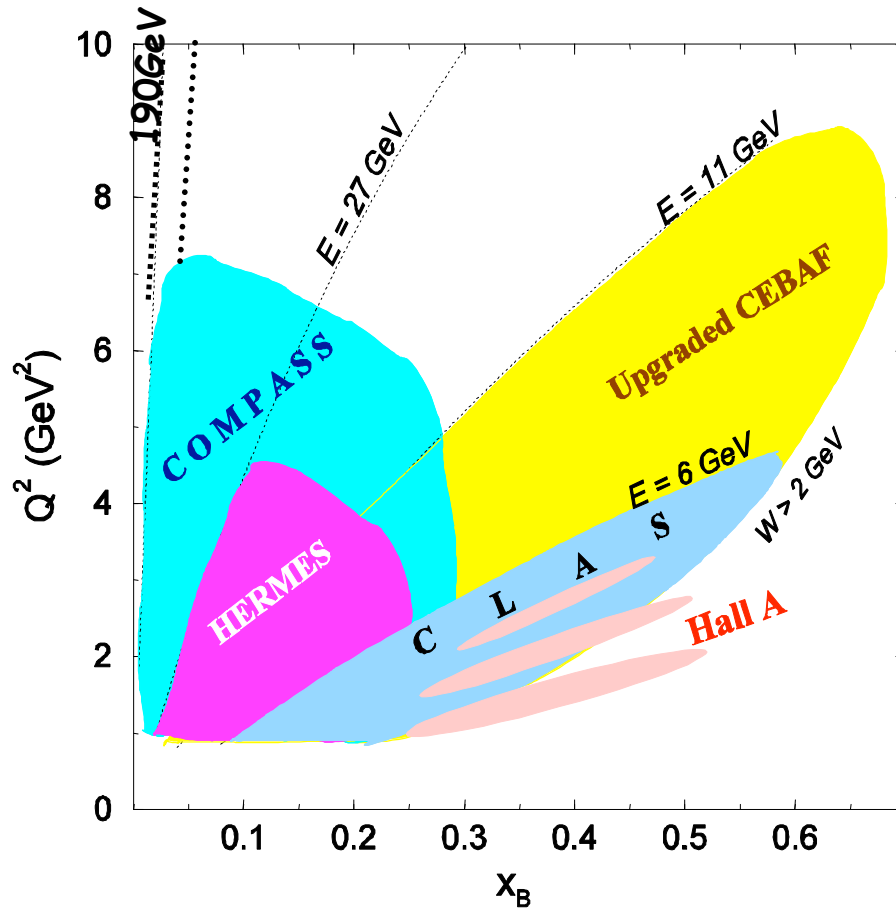
Kumericki and Mueller, '09



Other Global analysis

Ahmad et al., '08

## What we are aiming at...



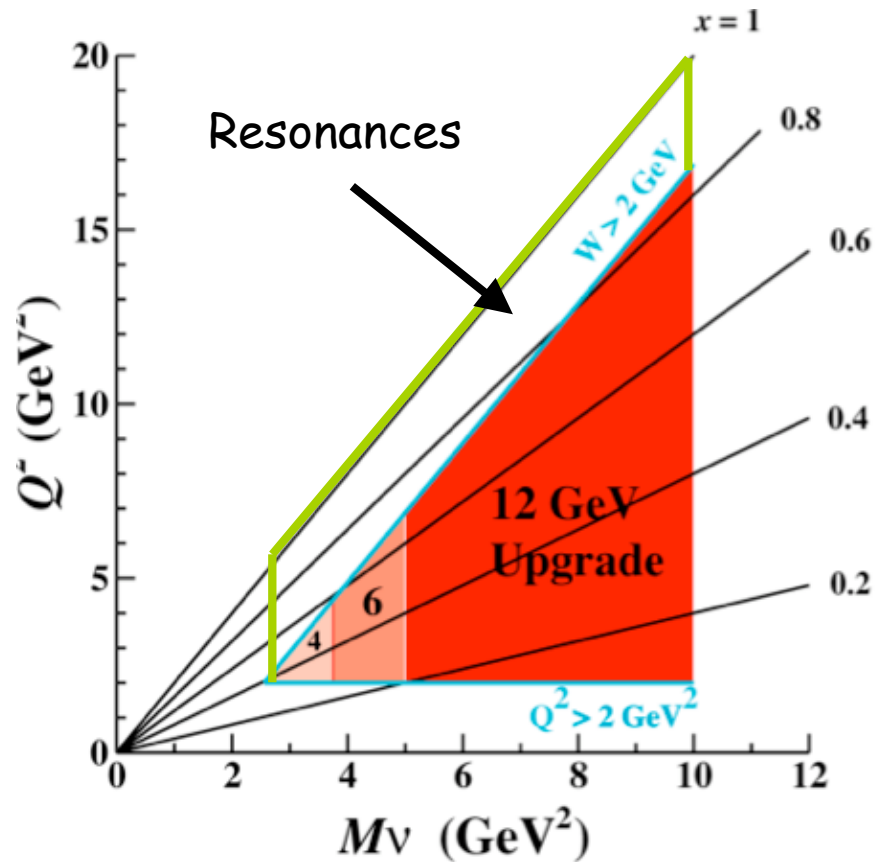
Improved GPD  
parametrizations: extraction  
of proton images

12 GeV program will allow for  
measurements of:

- ✓ Beam spin asymmetry
- ✓ Longitudinal and Transverse  
Target Spin asymmetries
- ✓ Beam charge asymmetry (?)

Increased  $x$  and  $Q^2$  coverage

## Duality: tracking the conversion of partons into hadrons



## What is parton-hadron duality?

Observation of similarity between “high” and “low” energy cross sections

⇒ Resonances follow “smooth” parton model curve

⇒ Theoretical background: Finite Energy Sum Rules (FESR)

Dolen, Horn and Schmid, PR166(1968)

$$S_n \equiv \frac{1}{N^{n+1}} \int_0^N \nu^n \text{Im} F d\nu = \sum \frac{\beta N^\alpha}{(\alpha + n + 1) \Gamma(\alpha + 1)}.$$

⇒ Is there an interpretation within QCD?

Shifman (2005), Bigi and Uraltsev (2004)

## Why is it important to study parton hadron duality?

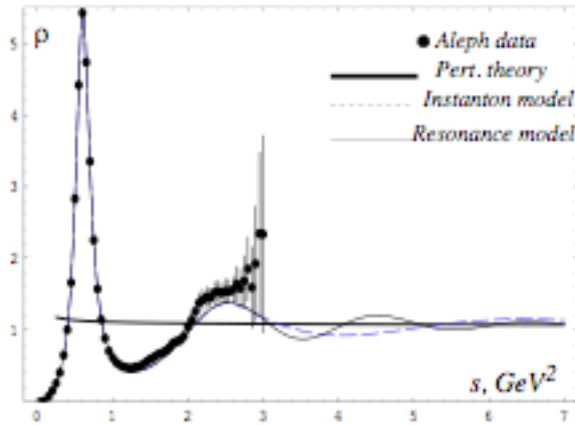
- To monitor the transition between the “perturbative QCD” region, where factorization applies to the “non-perturbative QCD region ( $\alpha$  strong? Brodsky, Deur,...)
- To understand mechanisms of hadron formation
- Practical reason (Jlab studies): to properly extend the domain of validity of PDF global analyses (example of large  $x$  gluons)

# Experimental observations of duality encompass several processes

## Data (1)

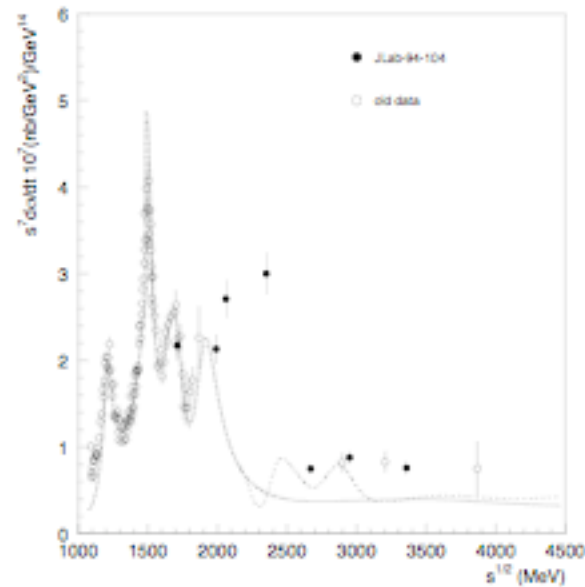
$$\tau \rightarrow \nu + \text{hadrons}$$

M. Shifman, hep-th/0009131



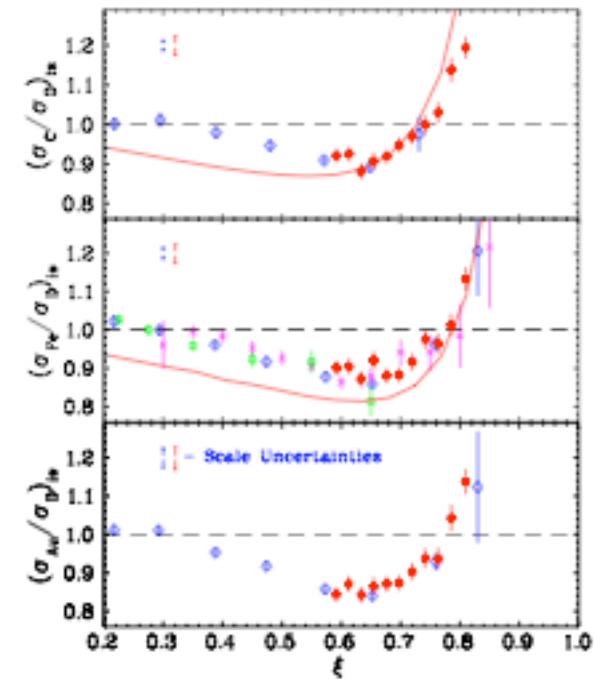
$$\gamma p \rightarrow \pi^+ n$$

L.Y. Zhu *et al.*, PRL 91 (2003) 022003,  
L.Y. Zhu *et al.*, PRC 71 (2005) 044603



$$eA \rightarrow eX$$

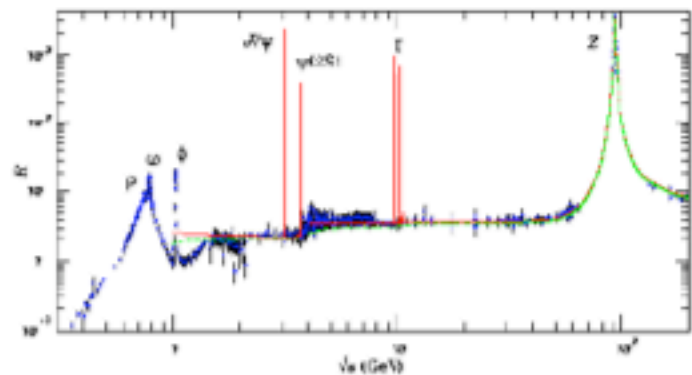
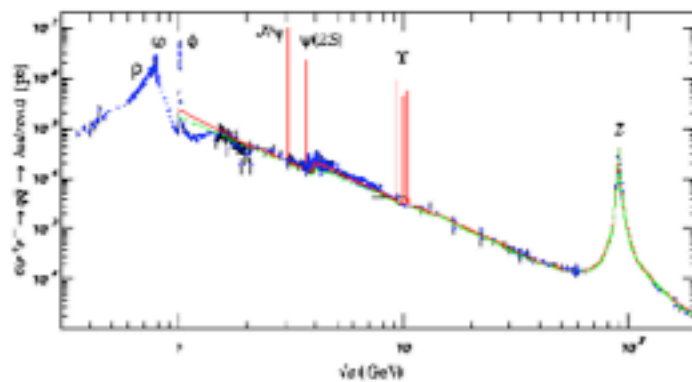
J. Arrington *et al.* (submitted)



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$$e^+ - e^- \rightarrow \text{hadrons}$$

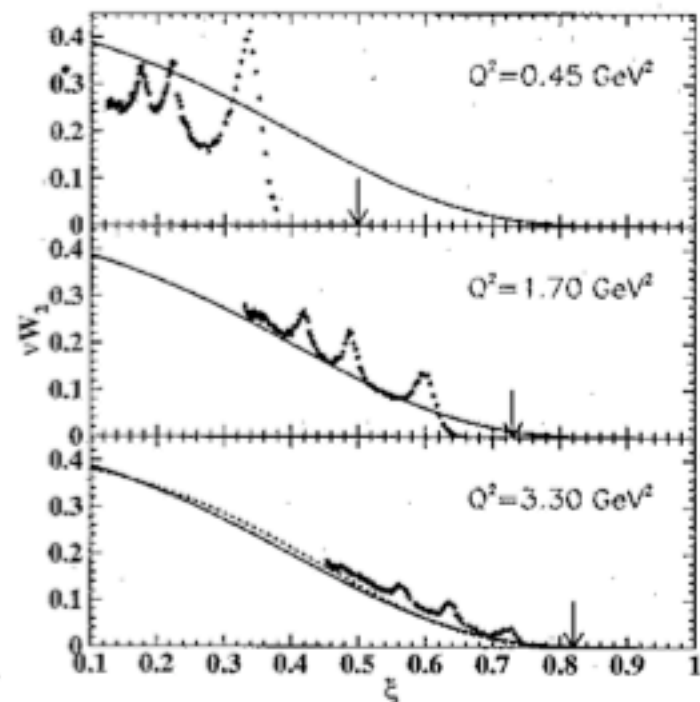
$\sigma$  and  $R$  in  $e^+e^-$  Collisions



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I. Niculescu *et al.*, PRL 85 (2000) 1182,

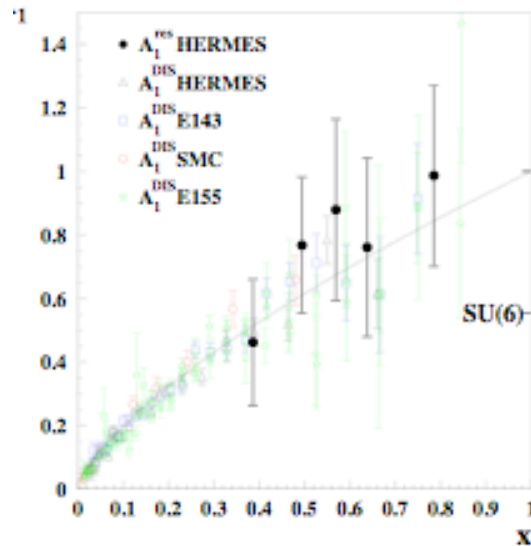
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$$e^- p^{\Rightarrow} \rightarrow e^- X$$

\. Airapetian *et al.*, PRL 90 (2003) 092002



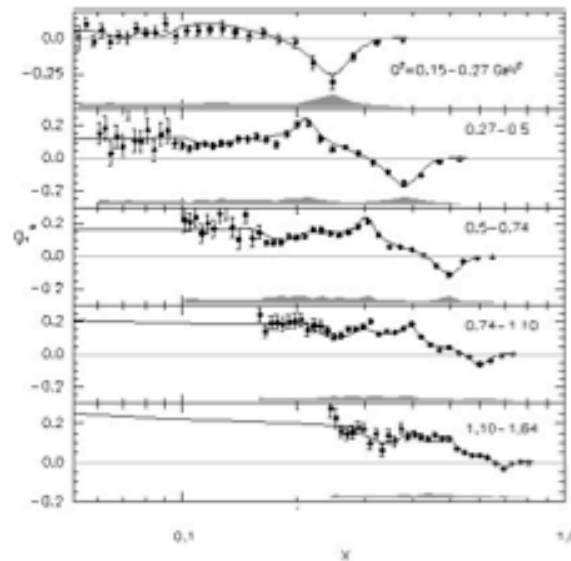
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for  $Q^2 > 1.6 \text{ GeV}^2$

See also K. Slifer, this workshop

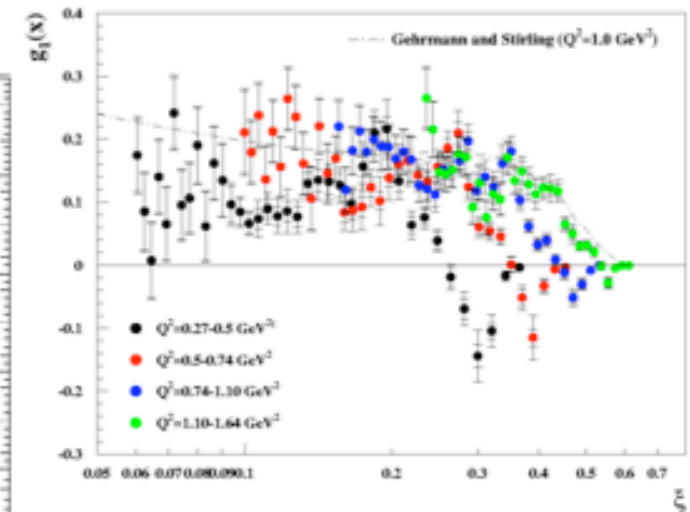
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R. Fatemi *et al.*, PRL 91 (2003) 222002



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Preliminary Eg1 data



Strong violation of duality  
for  $Q^2 < 1.1 \text{ GeV}^2$

c) Comparison between SF integrals in RES & DIS regions, in the same  $x$  interval

$$I^{\text{res}}(Q^2) = \int_{x_m}^{x_M} F_2^{\text{Res}}(x, Q^2) dx$$

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$$g_1 = A_1 \cdot \frac{F_2}{2x(1+R)}$$

$$(x_M \div x_m) \iff W_m^2 \div W_M^2 \simeq 1 \div 4 \text{ GeV}^2 \forall Q^2$$

$$R = I^{\text{Res}}/I^{\text{DIS}} = 1 \iff \text{Duality fulfilled} \implies R = \tilde{\Gamma}_1^{\text{Res}}/\tilde{\Gamma}_1^{\text{DIS}} = 1$$

- Resonance region can be described in terms of quark degrees of freedom
  - Distinction between resonance & DIS region is somehow artificial
- $\implies$  Duality provides access to large  $x$  where DIS data suffer for low statistic

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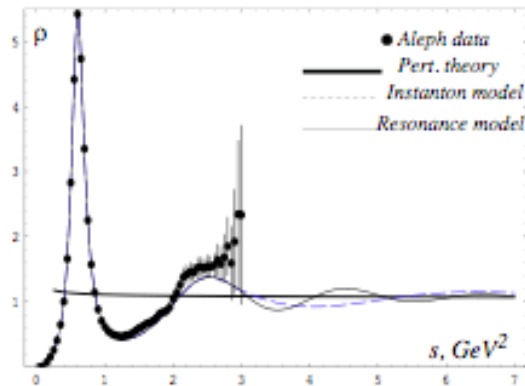
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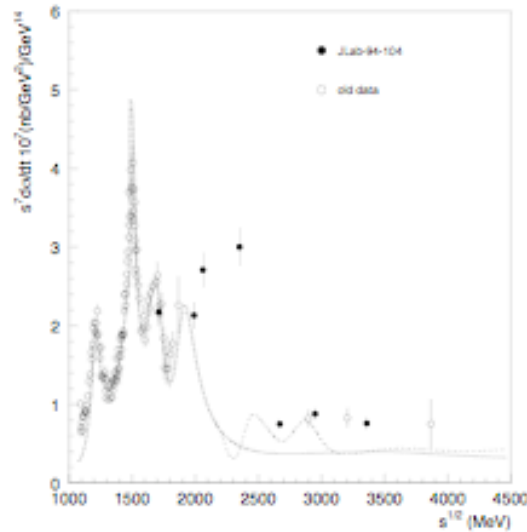
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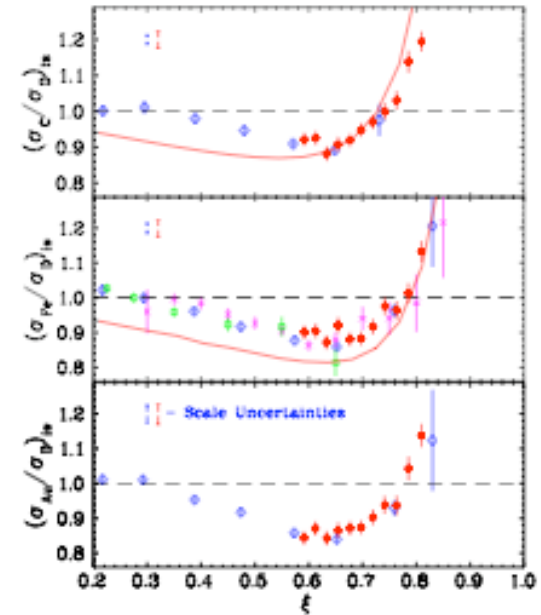
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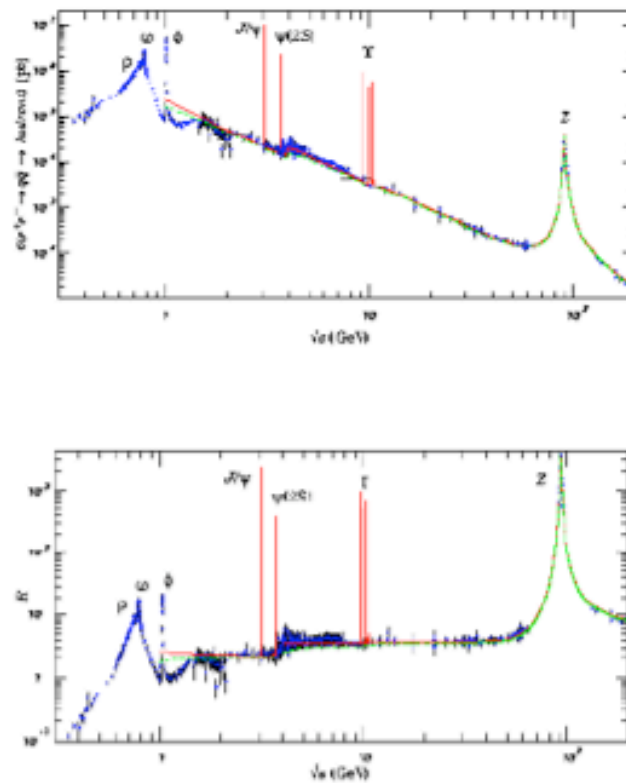
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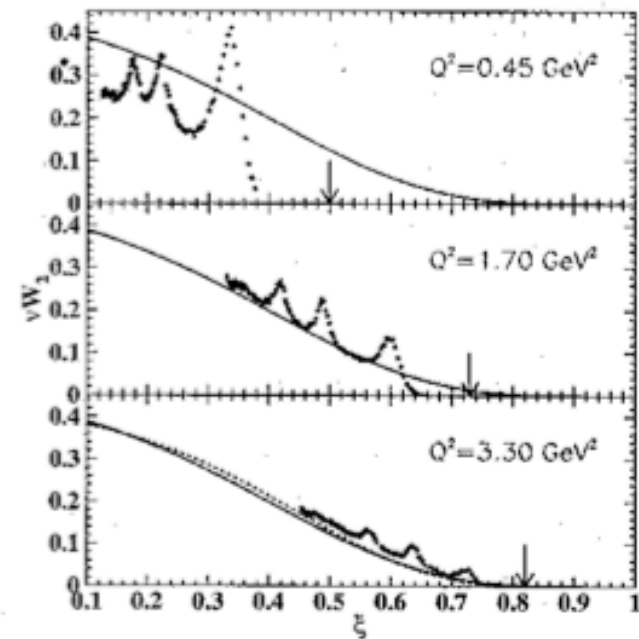
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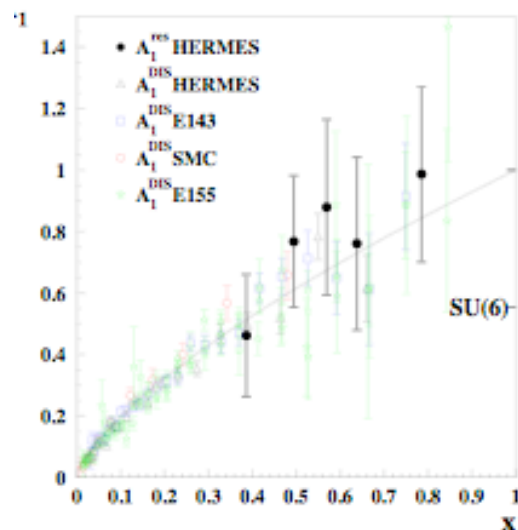
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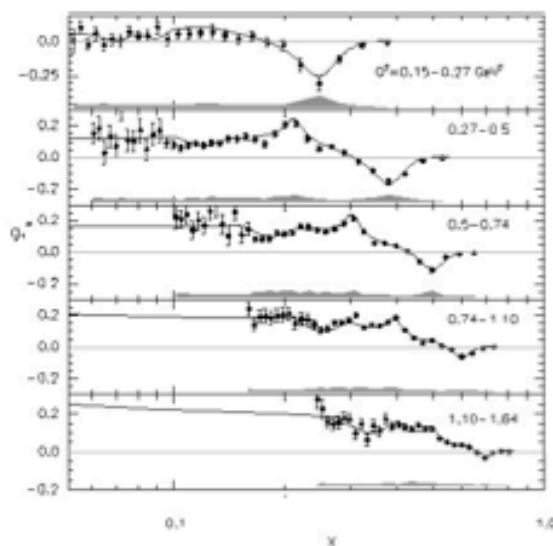


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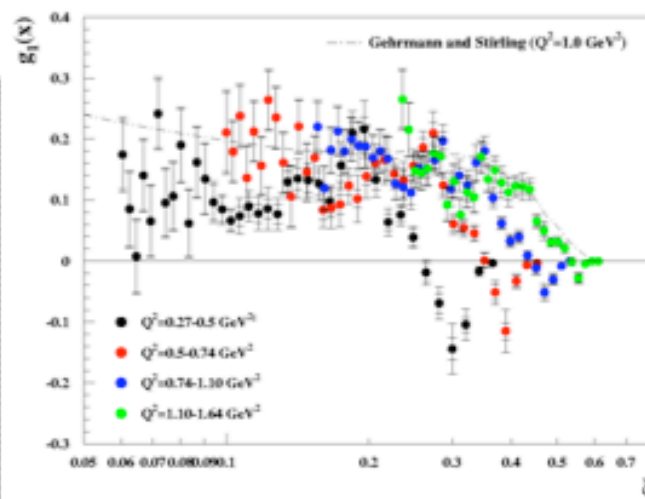
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## Transition from pQCD to npQCD

Problem of continuation of the pQCD curve into the resonance region

*Theoretically* based on the idea that partonic d.o.f are dominant in the RES region

Starting point: NLO PDF for the unpolarised structure function  $F_2$

*Practically* - even under this assumption - corrections to the NLO analysis arise from:

- Target Mass Corrections (TMC)  $\Rightarrow \mathcal{O}(1/Q^2)$
- Large  $x$  Resummation effects (LxR)  $\Rightarrow$  Leading Twist
- NNLO  $\Rightarrow$  Leading Twist
- Dynamical Higher Twist (HT)  $\Rightarrow \mathcal{O}(1/Q^2)$
- For the neutron: nuclear effects  $\Rightarrow$  Leading Twist
- Anything else  $\Rightarrow$  beyond twist expansion

Corrections have to be applied consistently to ALL observables to guarantee universality

- Starting point: NLO PDF at  $Q^2 = Q_0^2$
- Evaluation of Target Mass Correction
- Evaluation of Large  $x$  Resummation

What remains is “Higher Twist”, not predicted within the “standard” perturbative series

$$F_2(x, Q^2) = F_2^{LT}(x, Q^2) + \frac{H(x, Q^2)}{Q^2} + \mathcal{O}(1/Q^4)$$

# Target Mass Corrections (TMC)

Georgi, Politzer, '70s

$$F_2^{\text{LT,TMC}}(x, Q^2) = \frac{x^2}{\xi^2 \gamma^3} F_2^\infty(\xi, Q^2) + 6 \frac{x^3 M^2}{Q^2 \gamma^4} \int_\xi^1 \frac{d\xi'}{\xi'^2} F_2(\xi', Q^2)$$

$$\frac{2x}{1 + \sqrt{1 + \frac{4M^2 x^2}{Q^2}}}$$

$F_2^\infty = F_2$  without TMC

Limit of validity:  $x^2 M^2 / Q^2 < 1$

Applied in a similar way to

$$g_1 = A_1 \cdot \frac{F_2}{2x(1+R)}$$

## Recent development!

Accardi, Qiu, JHEP (2008)

It is possible to extend range of validity without introducing mismatches between the  $x$  and  $\xi$  range

$$F_{T,L}(x_B, Q^2, m_N^2) = \int_{\xi}^{\xi/x_B} \frac{dx}{x} h_{f|T,L}(\tilde{x}_f, Q^2) \varphi_f(x, Q^2) . \quad (18)$$



Instead of 1

## Large x resummation

(D. Amati et al. (1980), S. Brodsky (1980), R. Roberts, Z. Phys. (1999) ...)

Phase space for the parton's  $k_T$

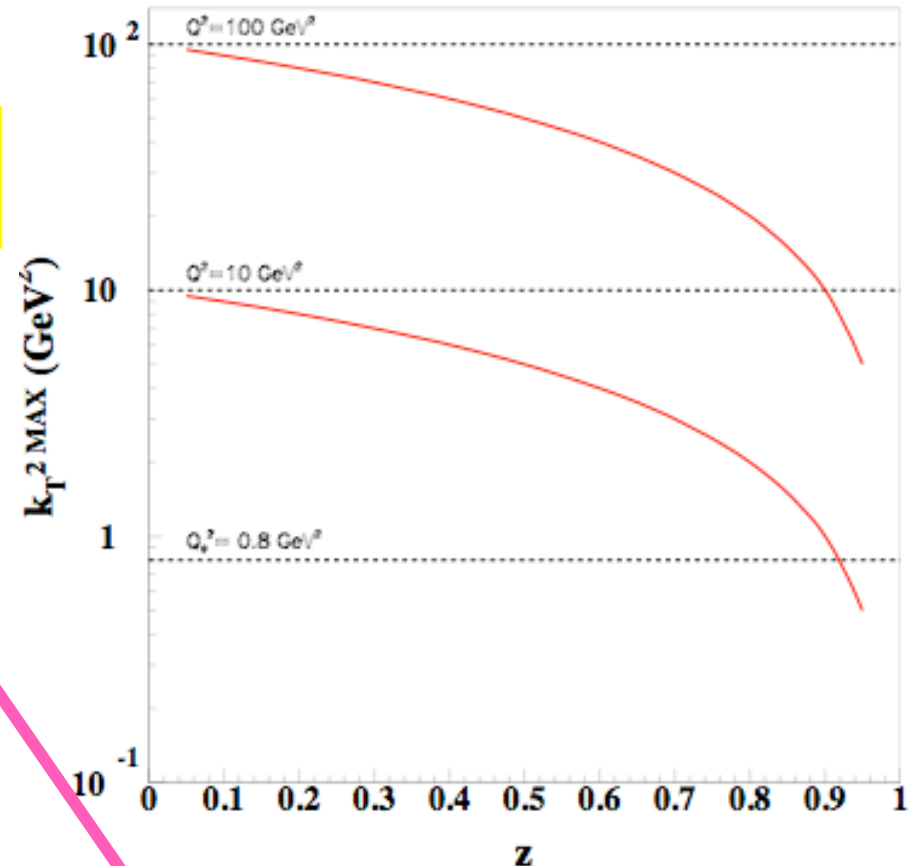
limited by

$$k_{T(MAX)}^2 = Q^2(1-z)/z$$

instead of

$$k_{T(MAX)}^2 \approx Q^2$$

This modifies Wilson Coefficient:  
Divergent  $\ln(1-z)$  are effectively  
“resummed”

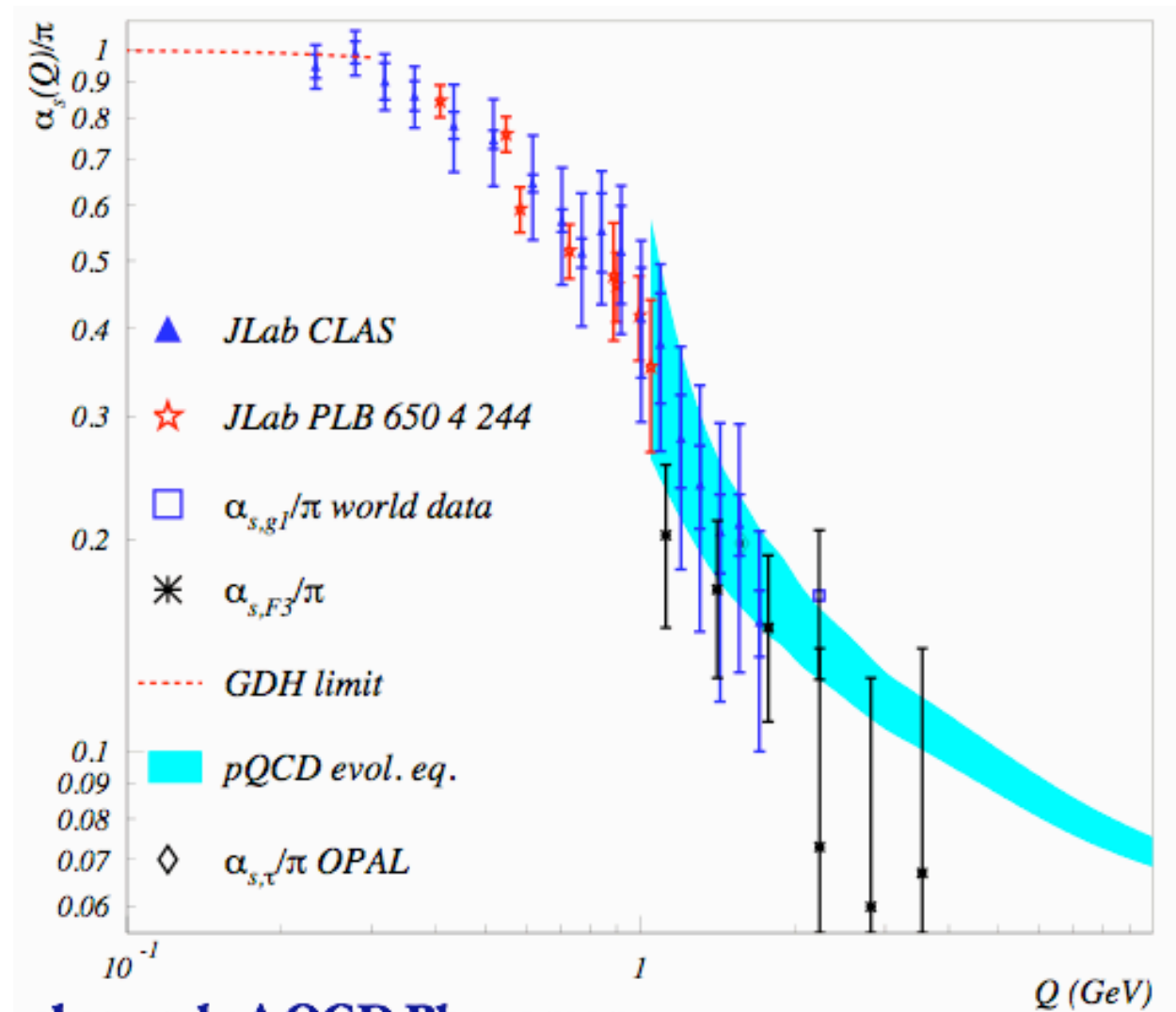


$$F_2^{NS}(x, Q^2) = \frac{\alpha_s}{2\pi} \sum_q \int_x^1 dz C_{NS}(z) q_{NS}(x/z, Q^2)$$

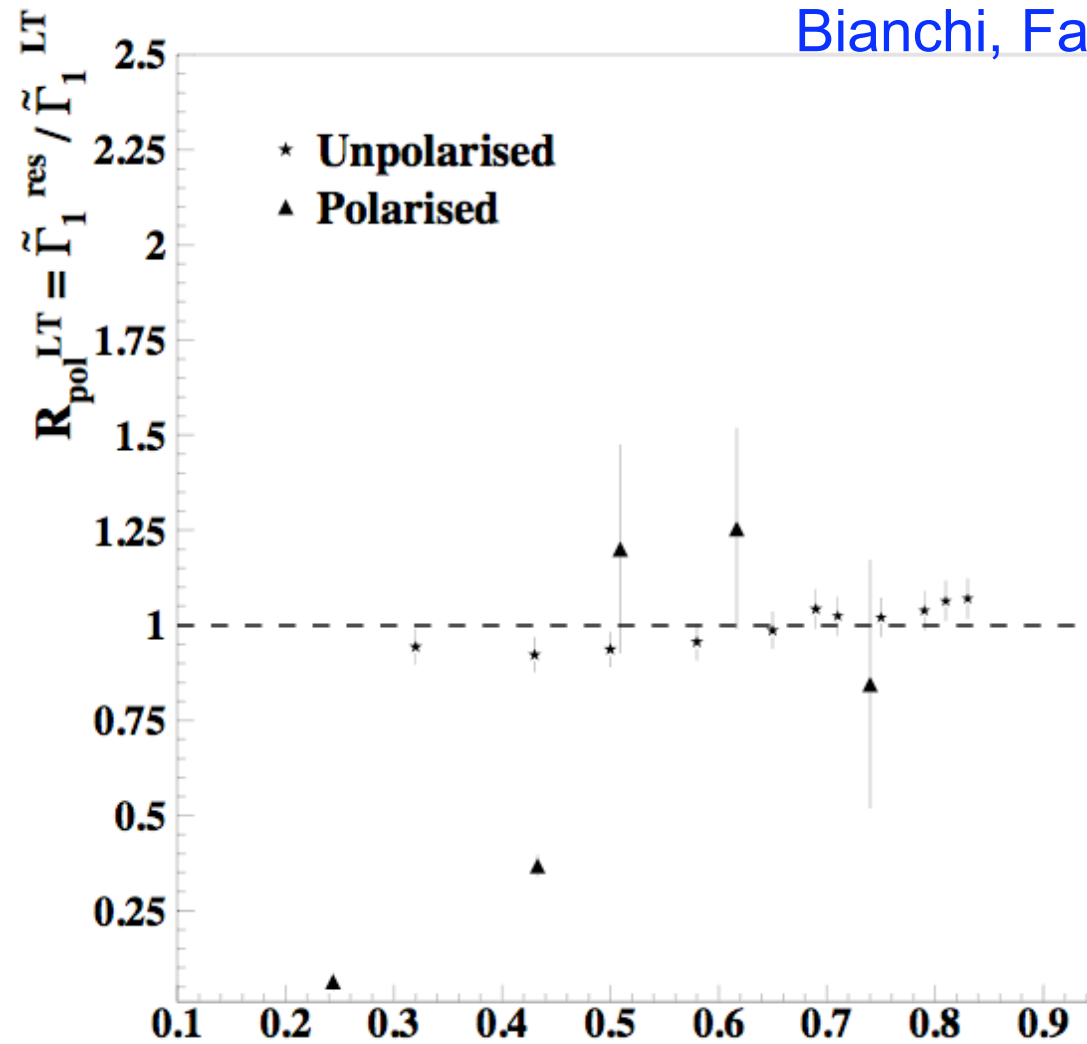
Approach valid at NLO!

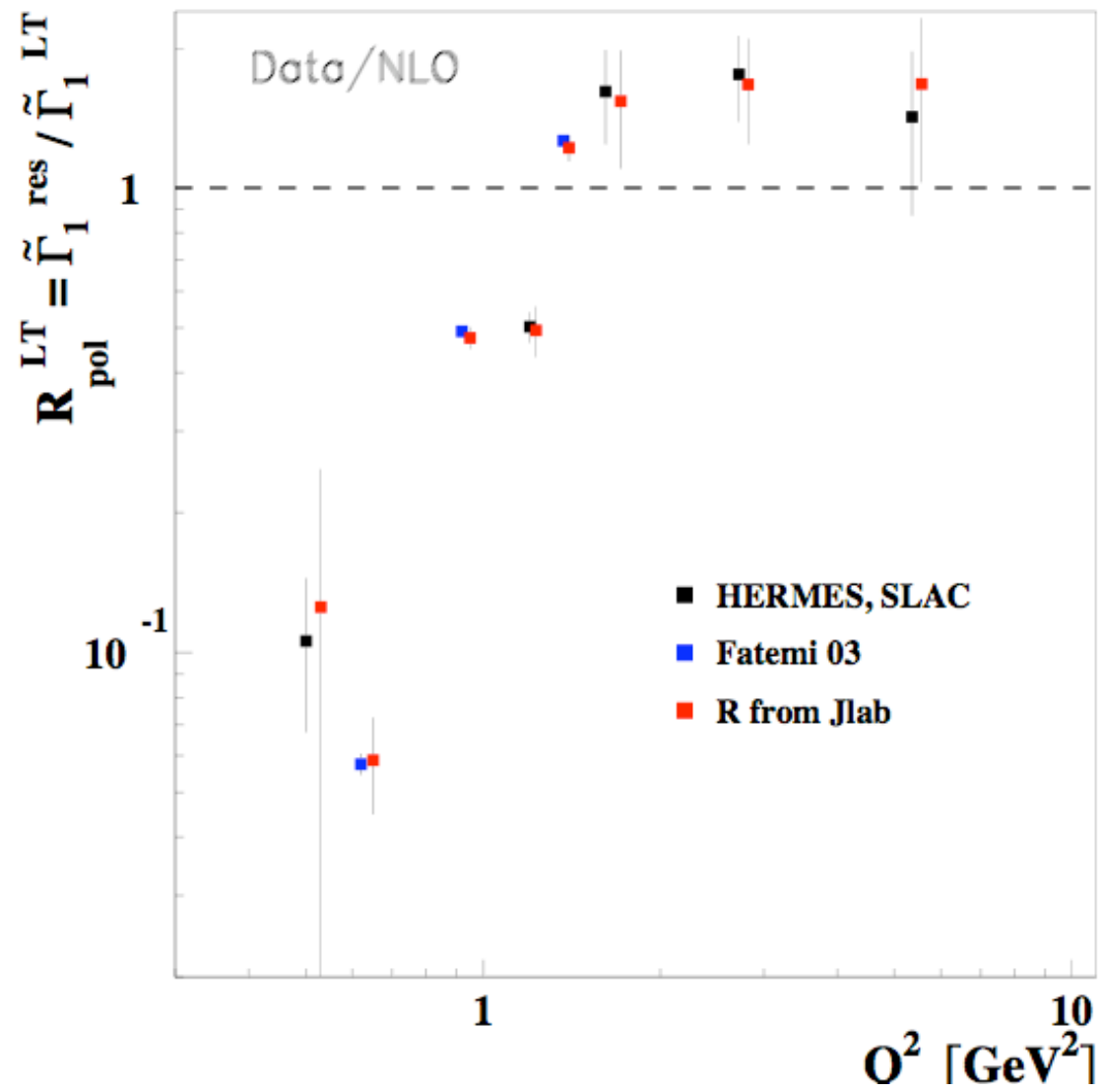
But  $\alpha_s$  needs to be continued at very low  $Q^2$

$$\alpha_s(Q^2) \rightarrow \alpha_s \left( Q^2 \frac{1-z}{z} \right)$$



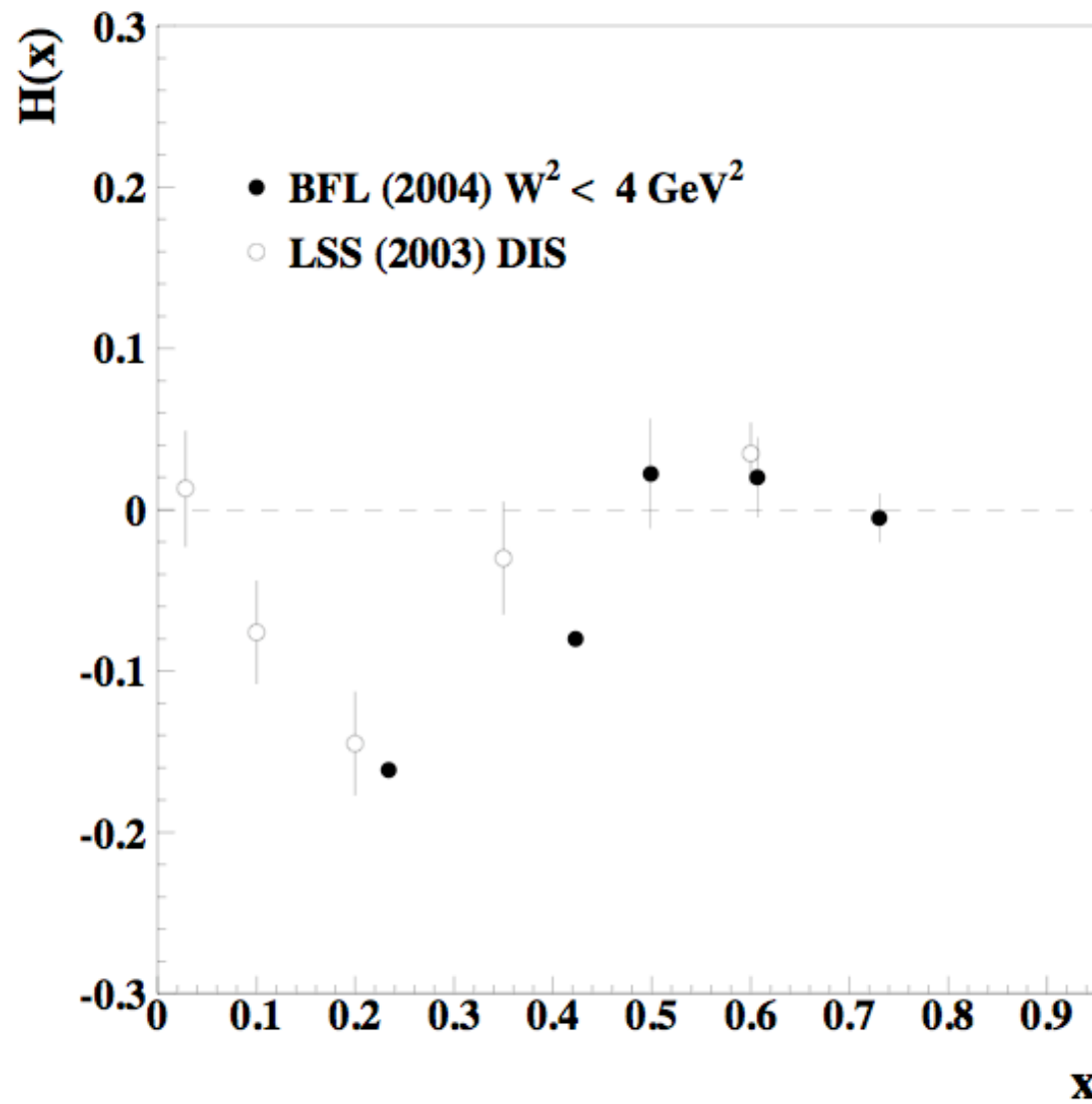
Bianchi, Fantoni, Liuti (2003)

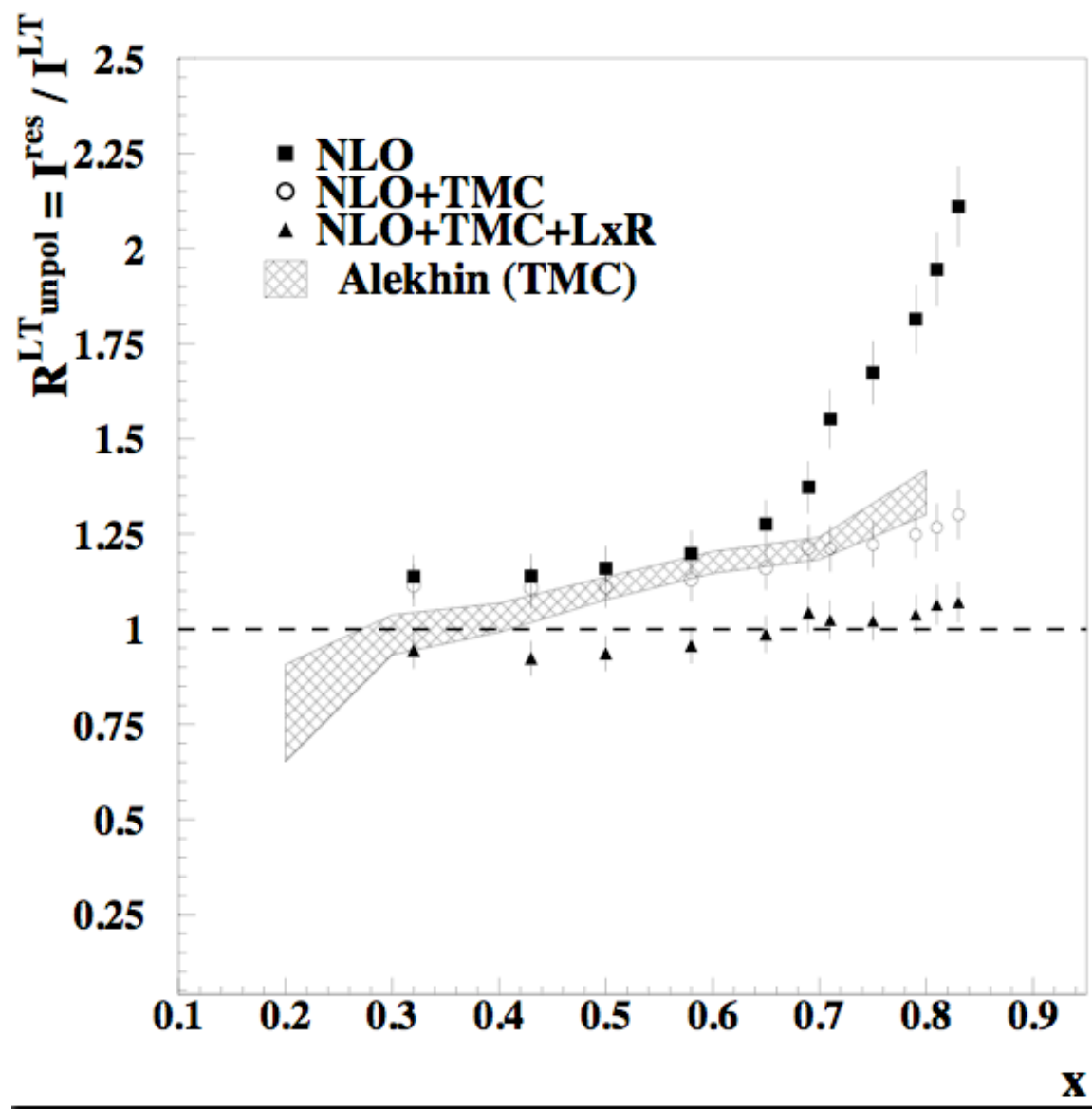


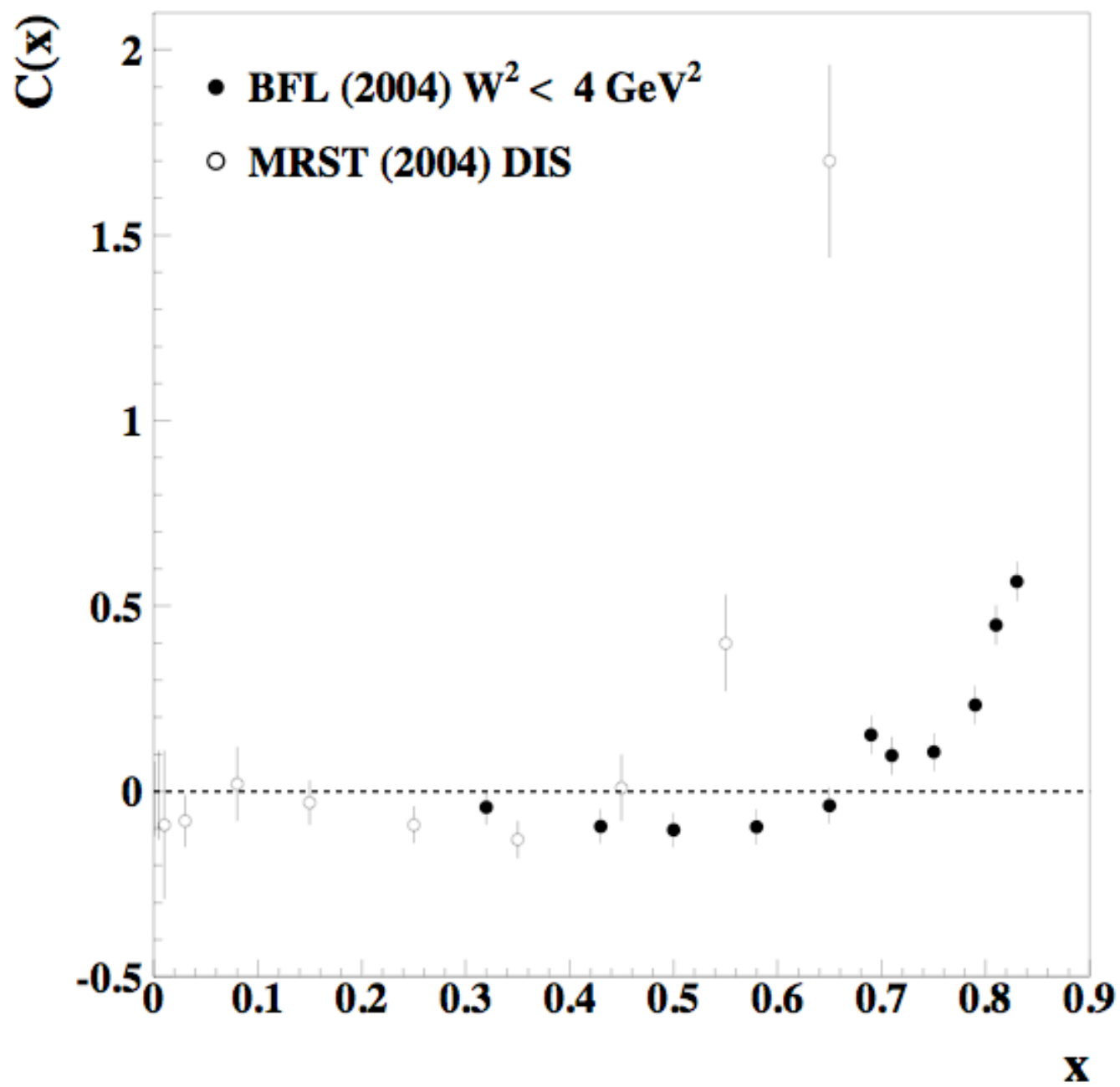


...up to 2006

$$H(x) = F^{LT}(x)C_{HT}(x) \rightarrow \text{additive form}$$





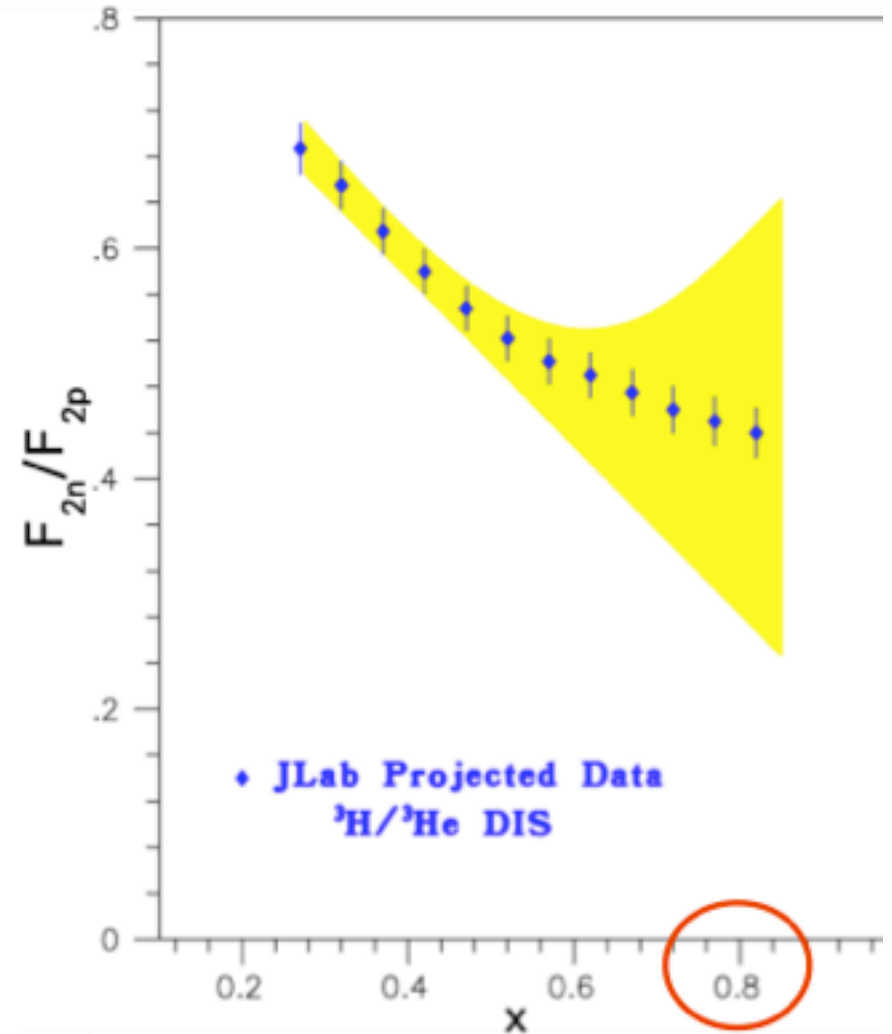
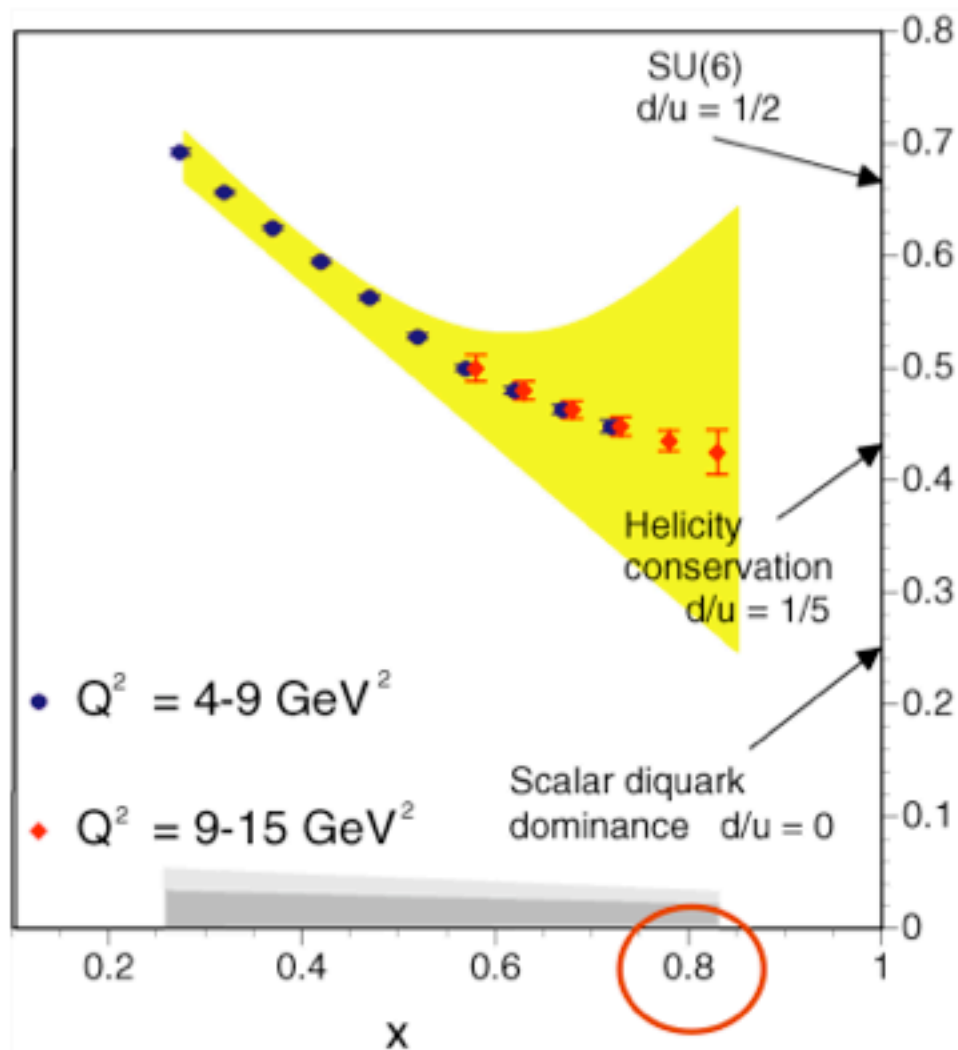


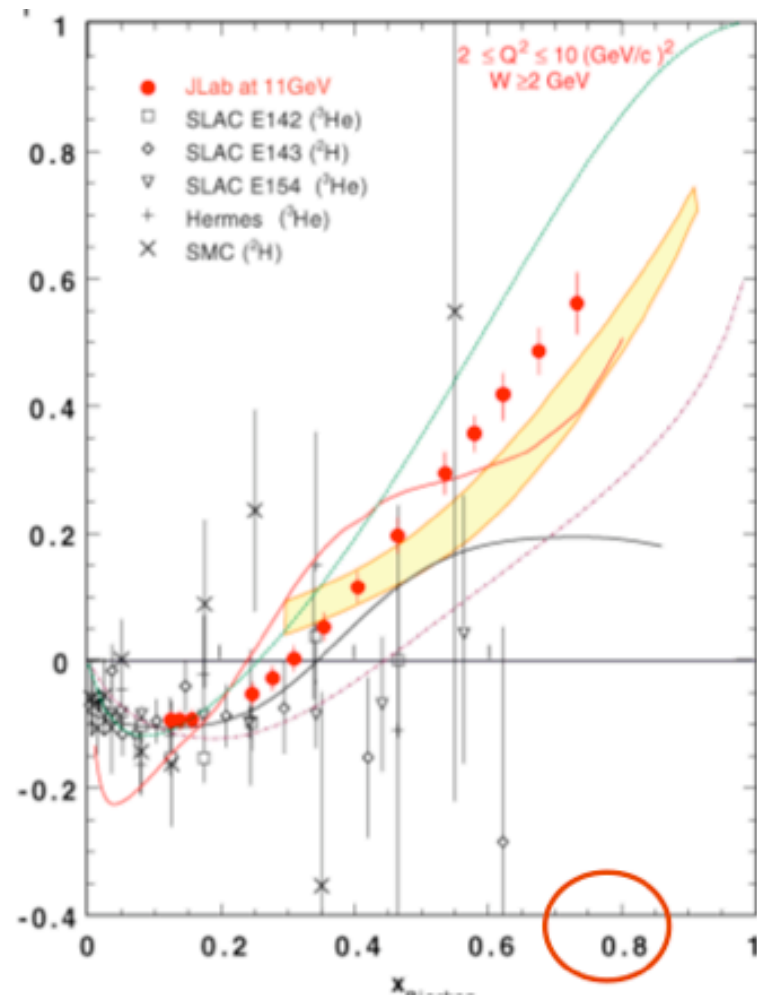
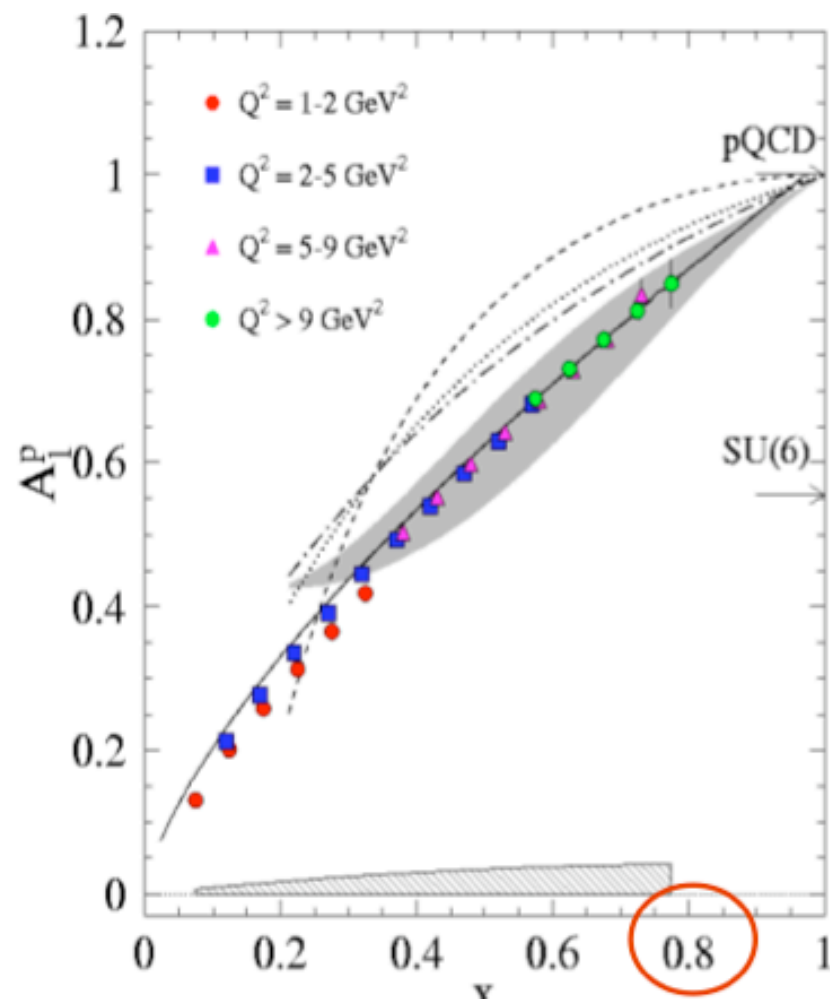
- Parton-hadron duality is interesting theoretically: low to high energy connection...
- Quantitative studies of parton-hadron duality are important in “Global Analyses” but... all aspects including TMCs, LxR, and dynamical HTs need to be included\
- Interesting to compare unpolarized and polarized results

# F<sub>2n</sub>/F<sub>2p</sub>

BONUS in Hall B 11 GeV with CLAS12

Hall A 11 GeV with HRS



$A_1^n$  $A_1^p$ 

Topics left out....

✓ Strangeness: global analyses of Parity Violating Experiments (PVES)

✓  $e^+e^-$

## Conclusions

All the discoveries, surprises, new insights, precise determinations, connections with neutrino reactions, achieved within the 6 GeV program in Halls A, B and C at Jefferson Lab will be further investigated with a wider leverage in the 12 GeV program

- Validation of results
- New discoveries are around the corner...
- Tip of the iceberg in nucleon holography... vast territory to explore with a variety of probes and targets