# Setting the Scale for DIS at Large Bjorken x

Simonetta Liuti
University of Virginia

HIx Workshop 2010
Jefferson Lab
October 11th-15th, 2010

# Outline

- Review DGLAP evolution at large Bjorken x
  - z-dependent scale gives rise to "large Bjorken x evolution"
- Interplay of TMCs, Large Bjorken x evolution,HigherTwists
- Nuclear corrections at large Bjorken x
- Conclusions/Outlook for the 12 GeV program and beyond…

# Interest in Large x Studies

→ Precise determination of PDFs (Jlab + CTEQ studies): extend the domain of validity of PDF global analyses (importance of large x gluons, …)

→ QCD predictions at $x_{Bj}$=1 (Ratio $F_2^n/F_2^p$,…)

→ Parton-Hadron Duality in DIS at large $x_{Bj}$ monitors the transition in QCD between the "perturbative" region, where factorization applies to the "non-perturbative" region: consequence of factorization theorems in QCD?
(J. Collins)

→ Possibility of extracting $\alpha_s$ at low scale (complementary to GDH sum rule analysis by S. Brodsky, J.P. Chen and A. Deur)

Large $x_{Bj}$ at fixed $Q^2$ implies the continuation of the pQCD curve into the resonance region

$$W^2 = Q^2\left(\frac{1}{x_{Bj}} - 1\right) + M^2$$

Main question: how to continue pQCD curve? What defines the pQCD curve?

Suggested approach

(S.L., R. Ent, C.Keppel, I. Niculescu, PRL 2000)

Fix the order of the analysis, e.g. NLO and extend curve ⇒

corrections arise that are more important than at low $x_{Bj}$ and that point at interesting physics (duality)

- TMC
- Large x structure of PQCD evolution equations
- NNLO and higher...
- Higher Twists
- Nuclear corrections (for neutron)

All effects need to be taken into account simultaneuosly.

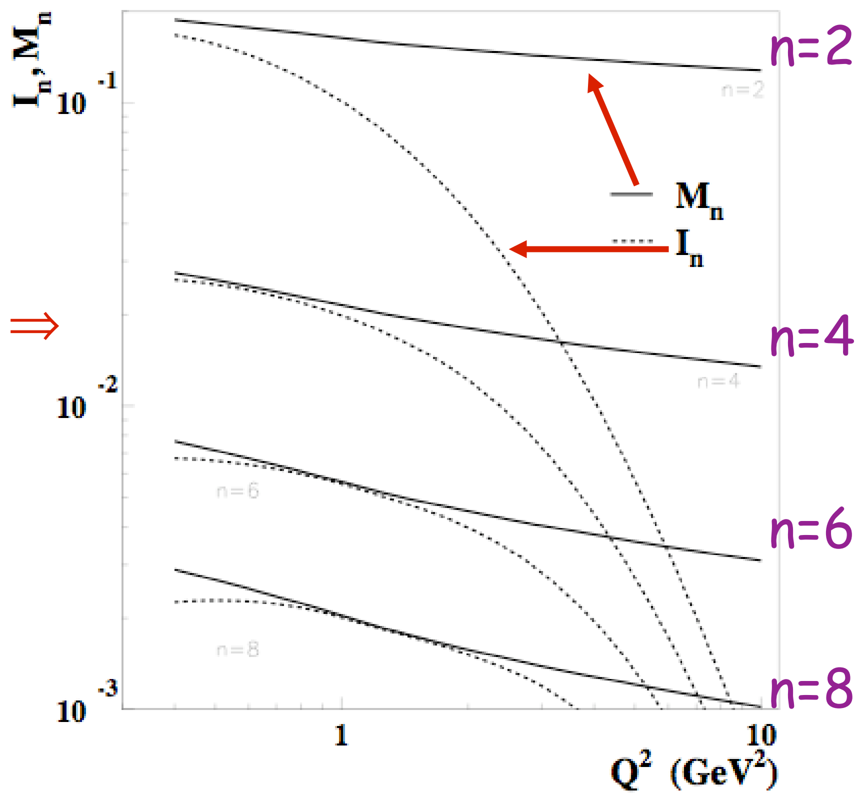
Some results from Bianchi, Fantoni, S.L. (PRD, 2003) and Fantoni, S.L. (2006)

$$I^{res}(Q^2) = \int_{x_{min}}^{x_{max}} F_2^{res}(x, Q^2)\, dx$$

$$M_n(Q^2) = \int_0^1 dx x^{n-2} F_2(x, Q^2),$$

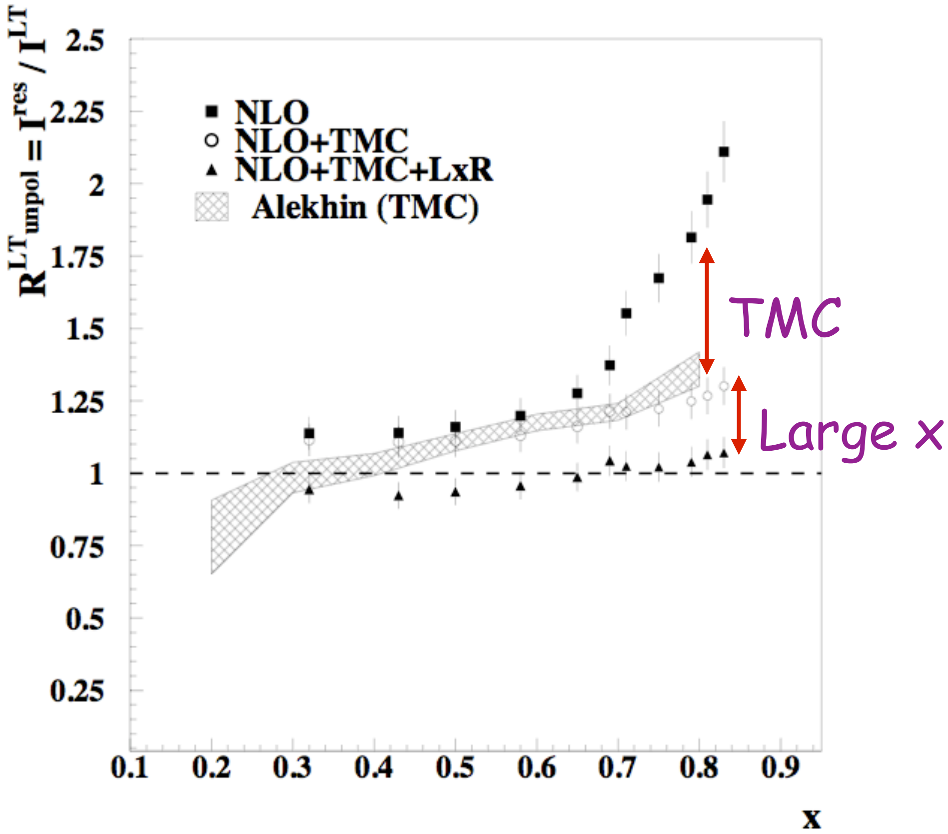
Precise pQCD prediction ⇒

$M_n \propto \ln Q^2$ + NLOrders...

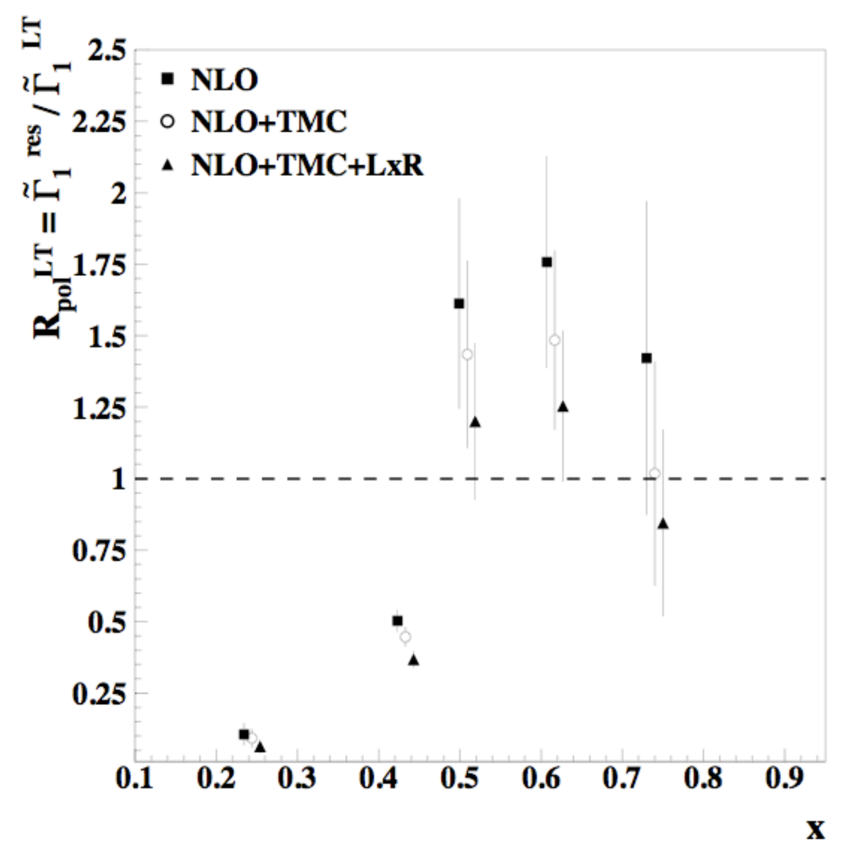



$I_n$ and $M_n$ calculated using CTEQ

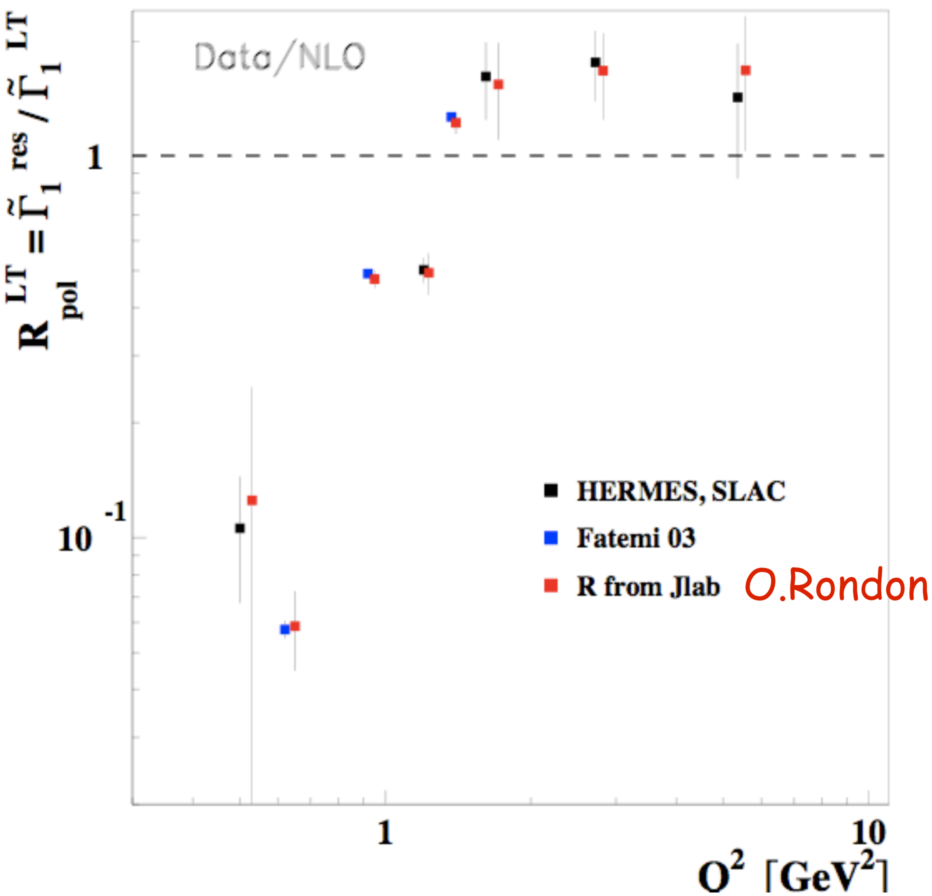
Unpolarized Jlab+SLAC data




Polarized HERMES+Jlab+SLAC data

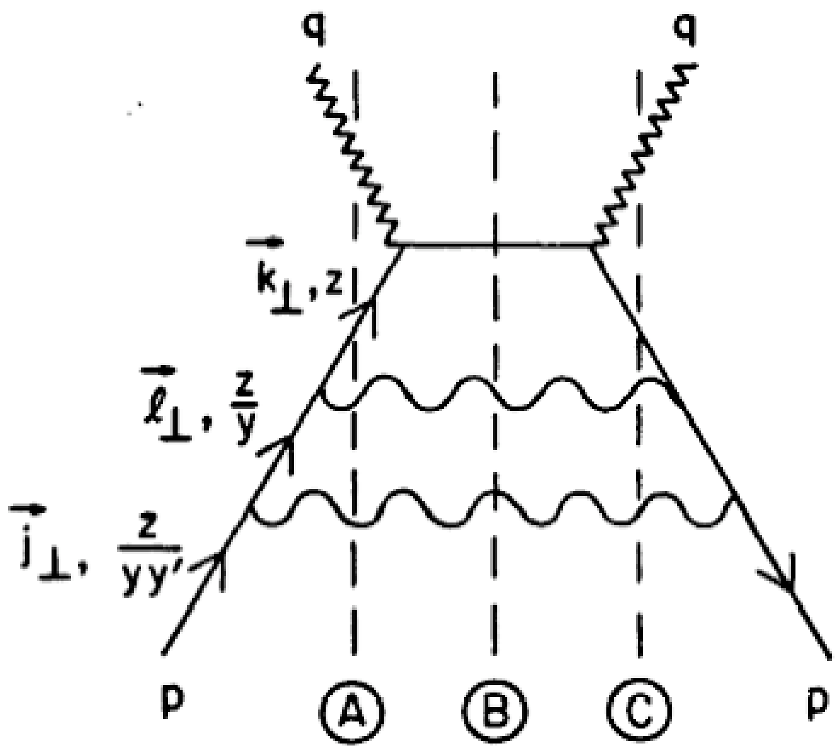


# More recent polarized data (O. Rondon et al.)



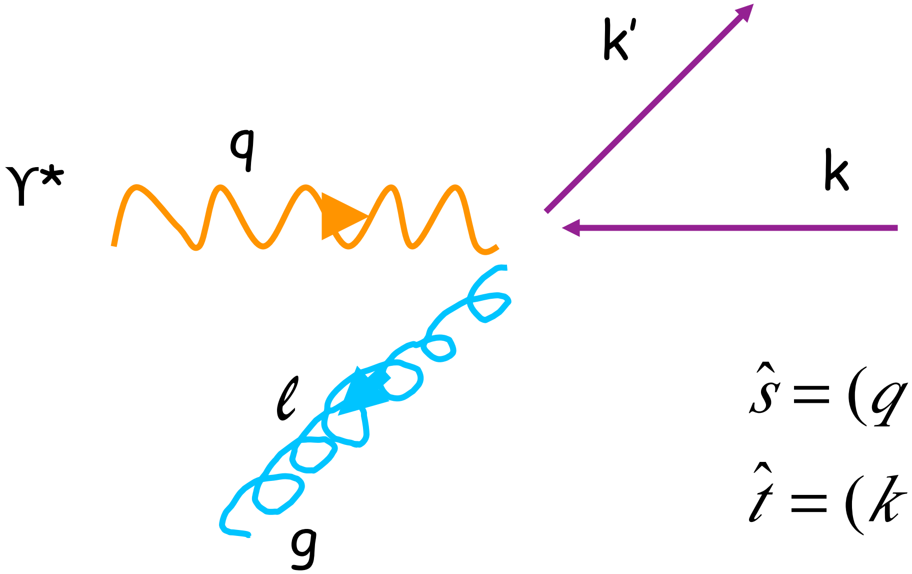
# Large $x_{Bj}$ evolution

(S. Brodsky, SLAC lectures (1979), D. Amati et al., NPB(1980), R. Roberts, "Structure of the Proton")




$\alpha_S = \alpha_S(k^2)$ at each vertex

$$\alpha_S(Q^2) = \frac{4\pi}{\beta_0 \ln(Q^2/\Lambda^2_{QCD})}$$




γ*q ➔ q' g

$$\hat{s} = (q+k)^2 = 4k'^2$$

$$\hat{t} = (k-k')^2 = -2qk'(1-\cos\theta)$$

$$\hat{u} = (q-k')^2 = -2qk'(1+\cos\theta)$$

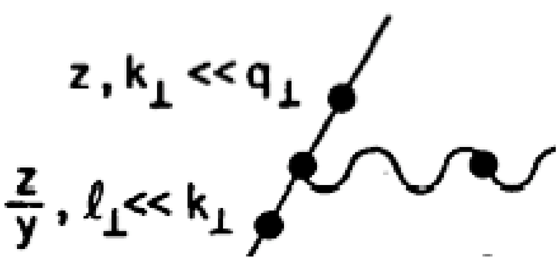
$$k_T^2 = \frac{\hat{s}(-\hat{t})\hat{u}}{\hat{s}(\hat{s}+Q^2)} = \frac{\hat{s}\sin^2\theta}{4}$$

$$(k_T^{MAX})^2 = \frac{\hat{s}}{4}$$

Invariant mass!

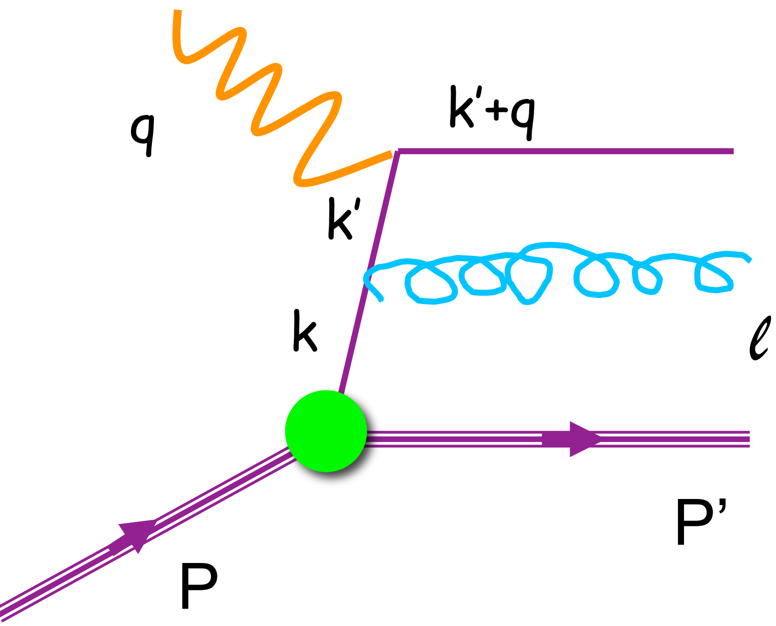
In terms of LC variables ➔ $(k_T^{MAX})^2 = \dfrac{Q^2(1-z)}{4z}$

$k = (k^+ = zP^+, k^- = P^- - \ell^-, k_T)$




Next, write amplitude for

γ*P ➔ (final quark) + g + X

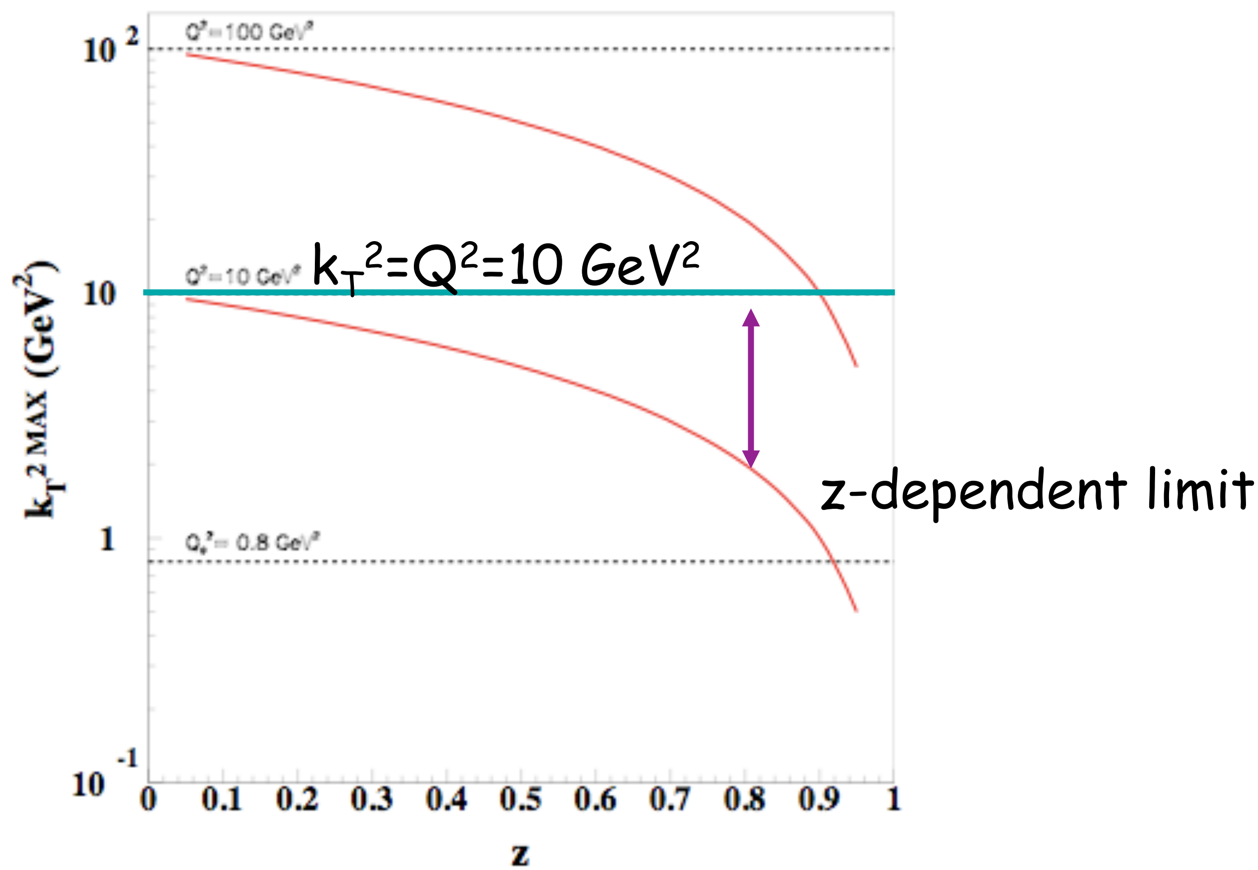



|Amplitude|² for γ*P ➔ (final quark) + g + X ∝

$$q(x,Q^2) = \int_x^1 \frac{dz}{z} \int_{\mu^2}^{Q^2 \frac{1-z}{4z}} dk_T^2\, \alpha_S(k_T^2)\, P_{qq}(z)\, q\left(\frac{x}{z}, k_T^2\right)$$

Disregarding z-dependence in $k_T$ integration limit

$$\frac{dq(x,Q^2)}{d\ln Q^2} = \frac{\alpha_S(Q^2)}{2\pi} \int_x^1 \frac{dz}{z} P_{qq}(z)\, q\left(\frac{x}{z}, Q^2\right)$$




It matters at large x!

As a consequence…

$$\alpha_S(Q^2) \rightarrow \alpha_S[Q^2(1-z)] \approx \alpha_S(Q^2) - \frac{1}{2}\beta_0 \underline{\ln(1-z)} \left(\alpha_S(Q^2)\right)^2$$

This takes care of the large log term in the Wilson coefficient f.
(NLO, MS-bar)

$$F_2^{NS}(x, Q^2) = \frac{\alpha_s}{2\pi} \sum_q \int_x^1 dz\, \underline{C_{NS}(z)}\, q_{NS}(x/z, Q^2), \tag{24}$$

$$C_{NS}(z) = \delta(1-z) + \left\{ C_F \left(\frac{1+z^2}{1-z}\right)_+ \left[\ln\left(\frac{1-z}{z}\right) - \frac{3}{2}\right] + \frac{1}{2}(9z+5) \right\}$$

The scale that allows one to annihilate the effect of the large ln(1-z) terms at large x at NLO is the invariant mass, $W^2$

Equivalent to a resummation of these terms up to NLO

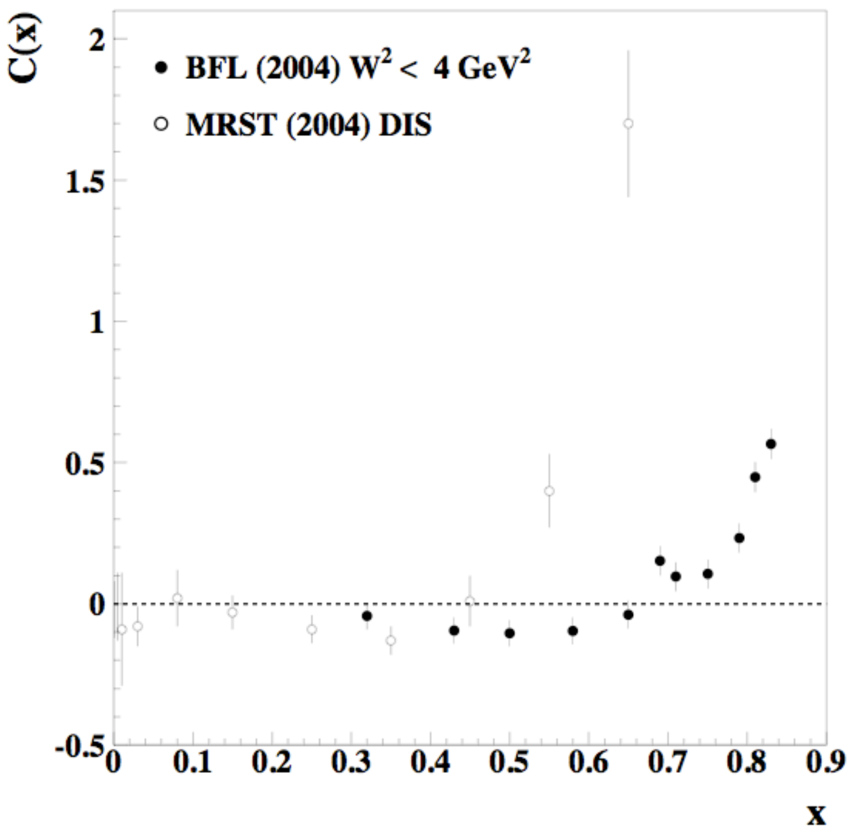
Work in progress based on recent analysis by A.Accardi, J.Qiu, JHEP (2008) that extends range of validity of TMCs approach without introducing mismatches between the x and ξ ranges

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

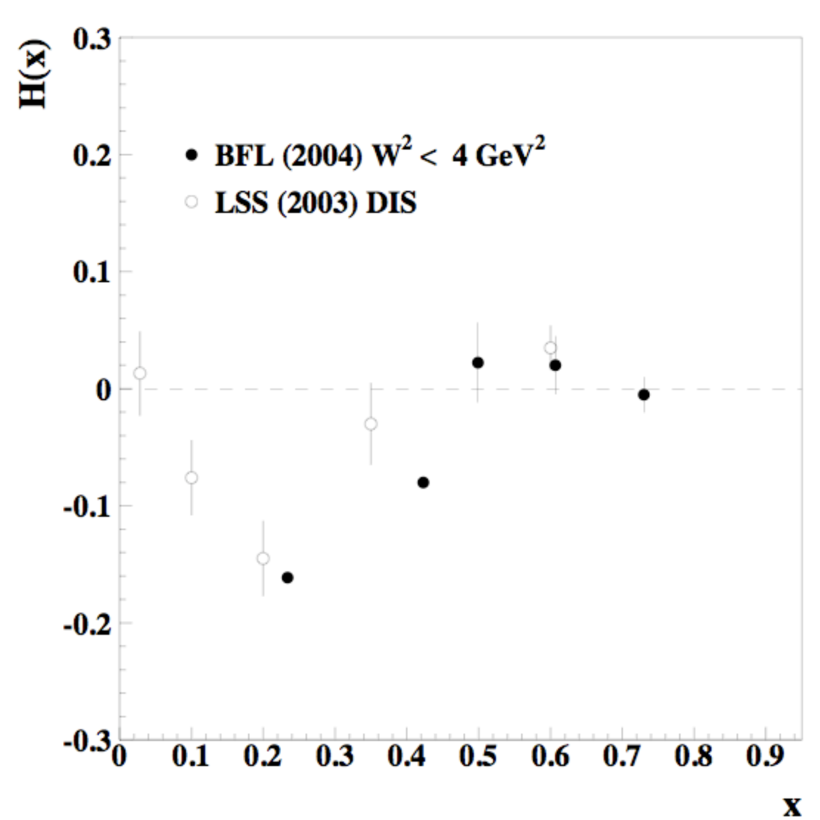
Instead of 1

Joint large x evolution and new TMCs approach

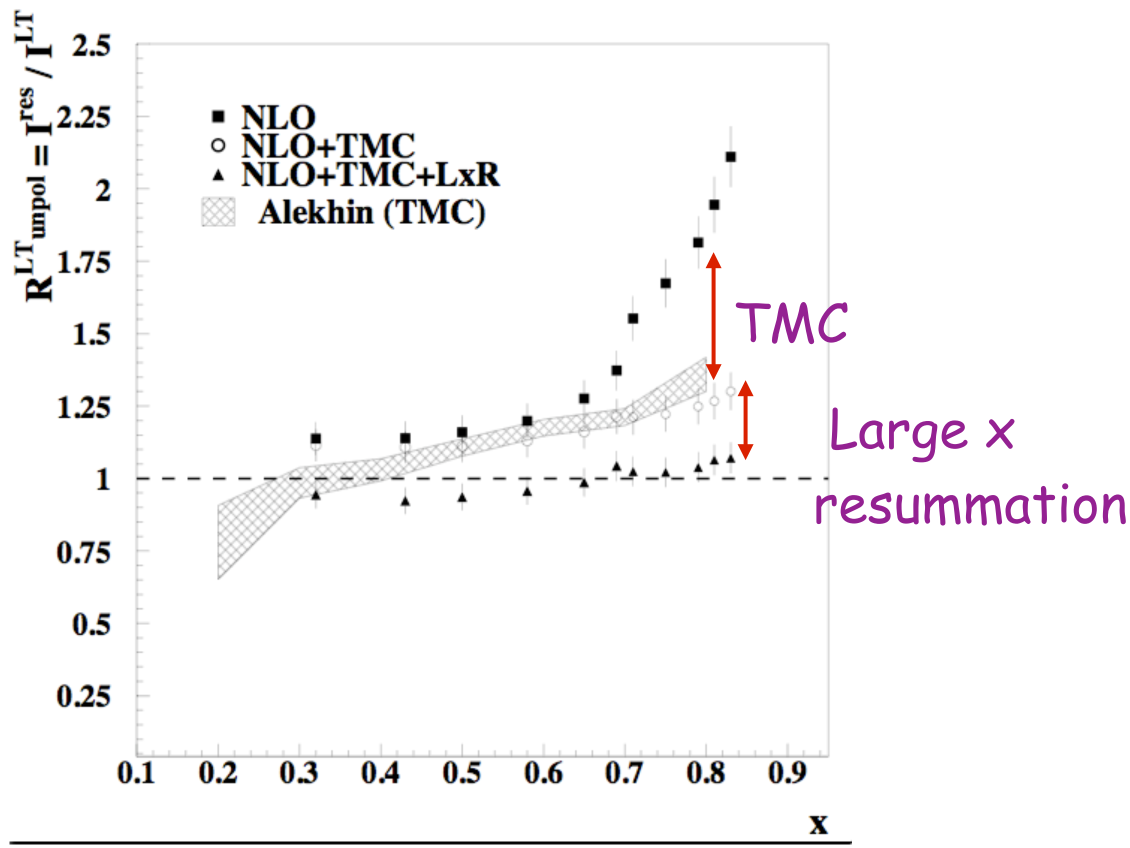
# Once PQCD is taken into account, extract HTs




$$H(x) = F^{LT}(x)C_{HT}(x)$$ → additive form




$$F_2^{exp} = F_{PQCD}(1 + C(x)/Q^2)$$

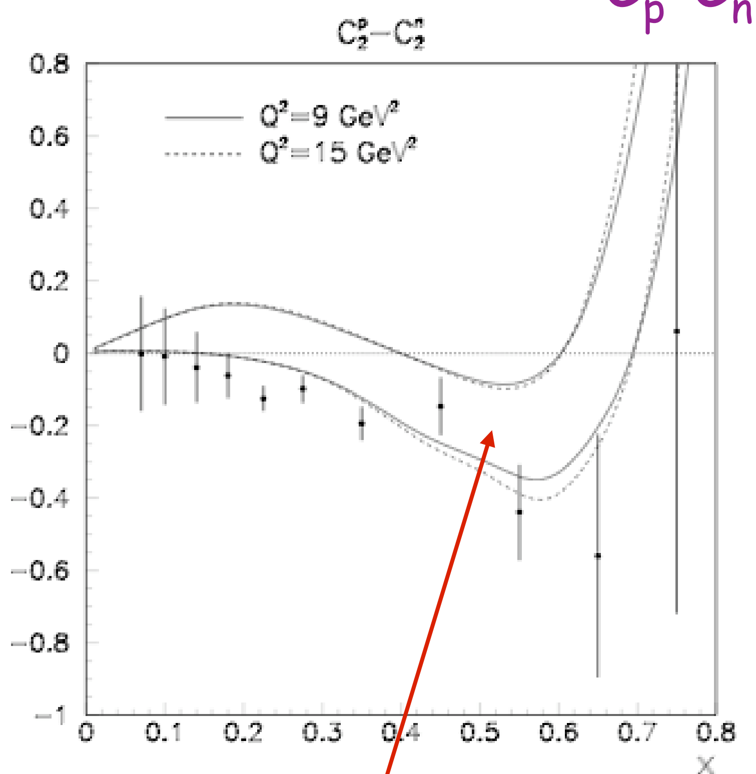


$R^{LT}_{unpol} = I^{res} / I^{LT}$
2.5
2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
x
NLO
NLO+TMC
NLO+TMC+LxR
Alekhin (TMC)
TMC
Large x resummation

## Nuclei

✔ Are HTs isospin dependent? Deviations from PQCD effects

$C_p$-$C_n$



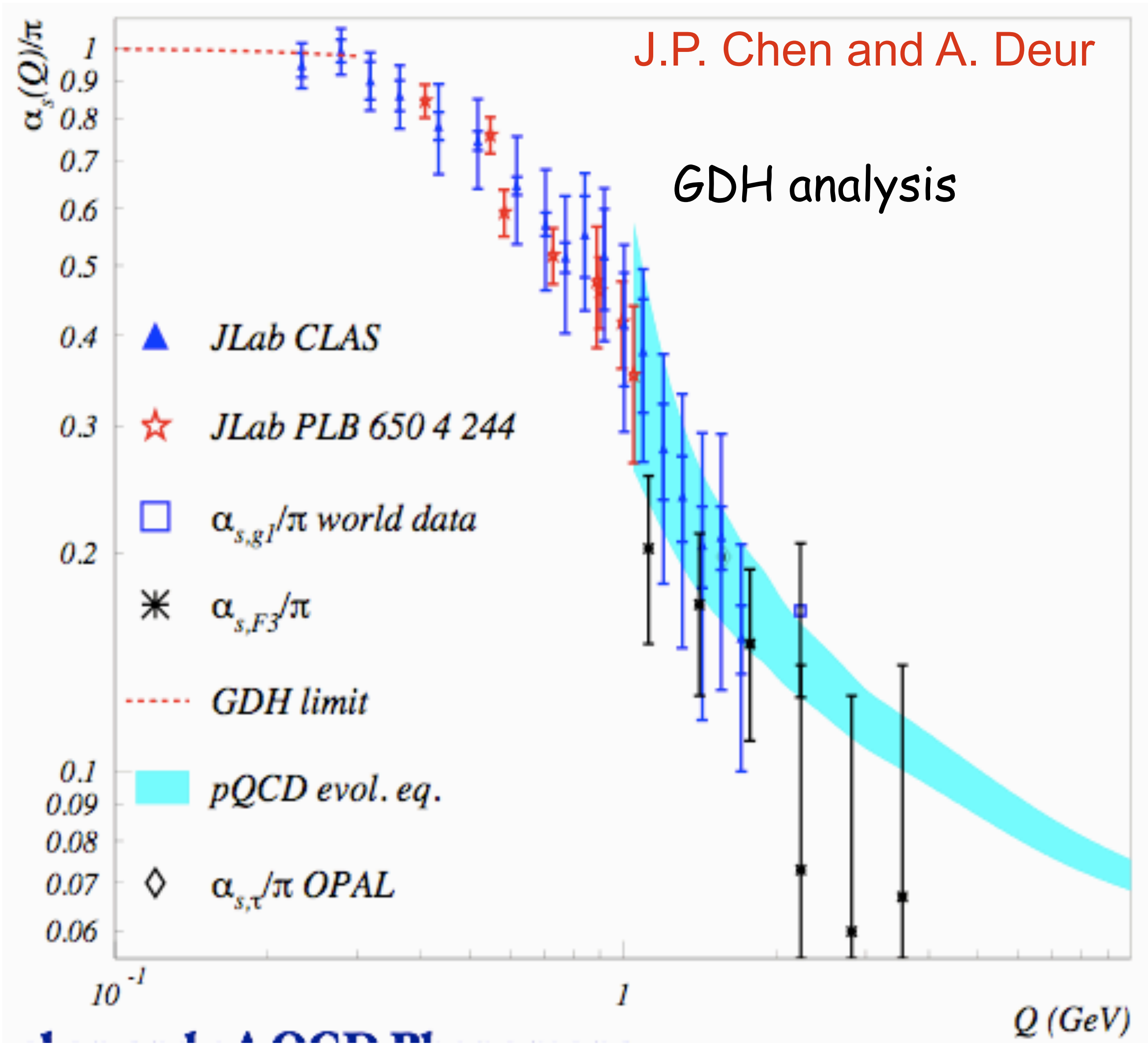

NMC data

Alekhin, Kulagin and S.L., PRD (2003)

In addition …. $\alpha_S$ needs to be continued at very low $Q^2$

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

S.L. work in progress
Use this "positively" to
Extract $\alpha_S$ at low scale



## Towards the Jlab 12 GeV program….

The very large and accurate Jlab Hall C set of data has shown that parton hadron duality can be studied in detail: $Q^2$,$W^2$ and longitudinal variables dependences have been analyzed thouroughly

⇒ Observation of similarity between "high" and "low" energy cross sections at the core of strong interaction theory

⇒ Theoretical background: starts from Finite Energy Sum Rules (FESR) Dolen, Horn and Schmid, PR166(1968)

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

⇒ Is there an interpretation within QCD? Shifman (2005), Bigi and Uraltsev (2004)

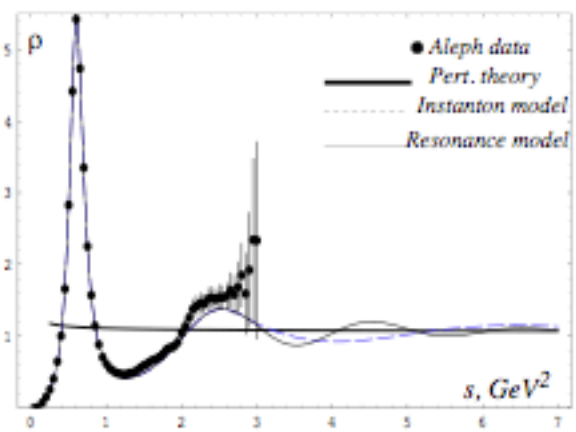
⇒ Is there a more general implication from factorization theorems of QCD? Interplay of ISI and FSI Frankfurt (this workshop)

All experimental measurements should be compared....

# Data (1)

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

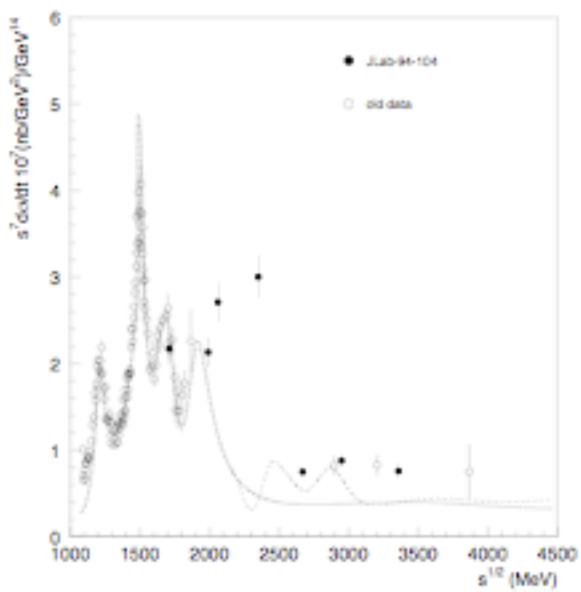
M. Shifman, hep-th/0009131




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

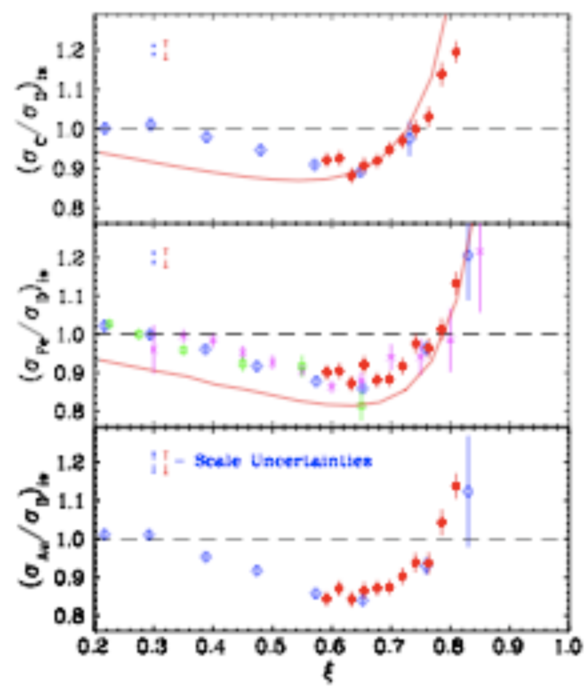
L.Y. Zhu *et al.*, PRL 91 (2003) 022003,

L.Y. Zhu *et al.*, PRC 71 (2005) 044603




$eA \to eX$

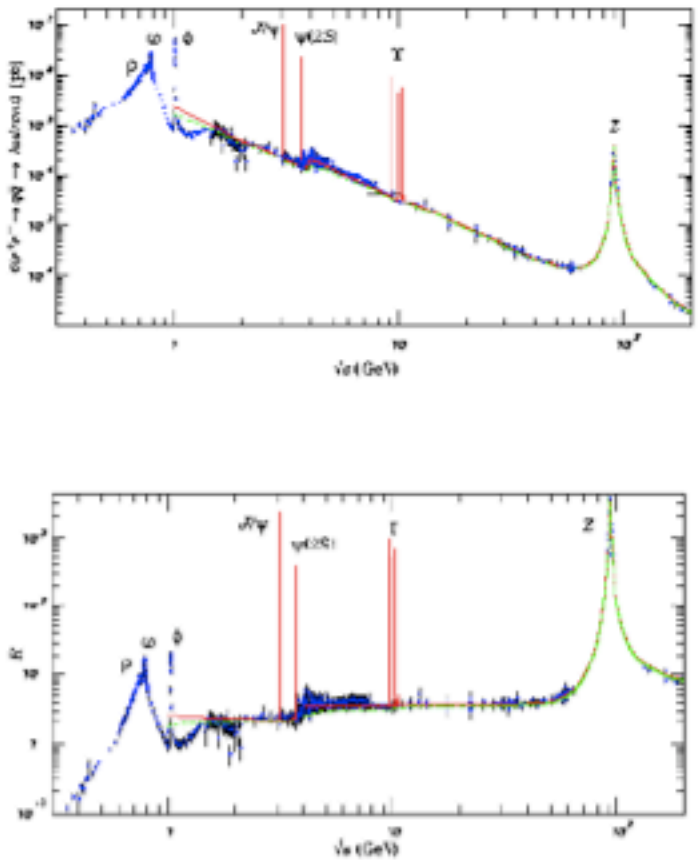
J. Arrington *et al.* (submitted)



# Data (2)

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

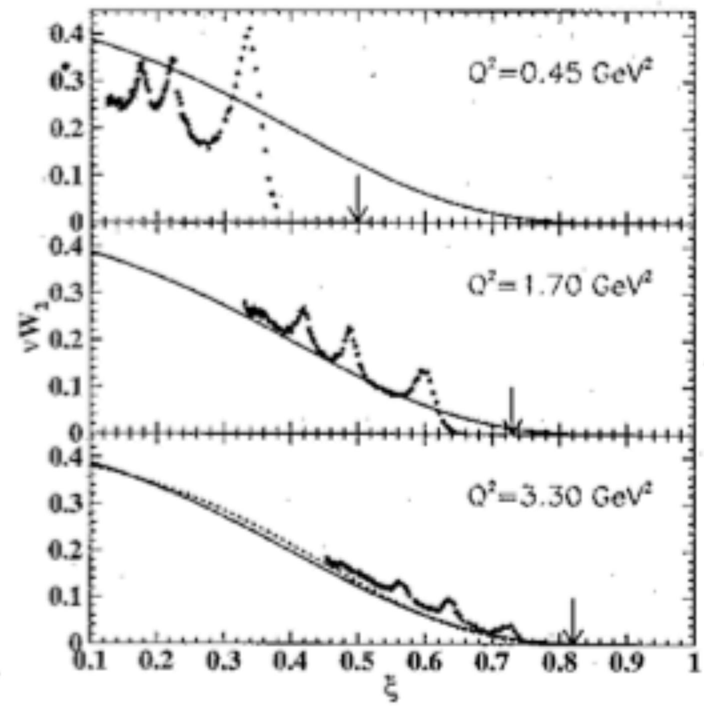
$\sigma$ and $R$ in $e^+e^-$ Collisions




$ep \rightarrow eX$

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

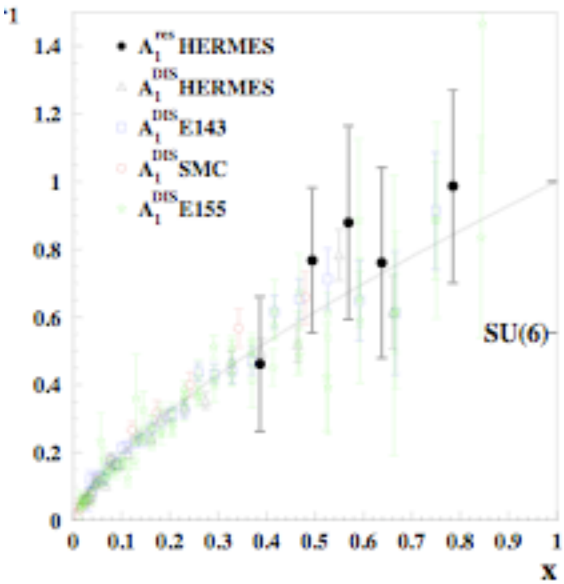
I. Niculescu *et al.*, PRL 85 (2000) 1186



# Data (3)

$e^{\rightarrow}p^{\rightleftarrows} \rightarrow e^{\rightarrow}X$

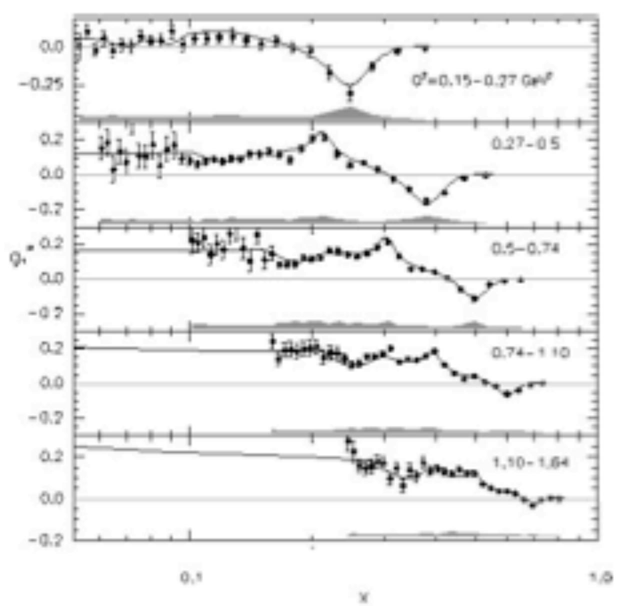
A. Airapetian *et al.*, PRL 90 (2003) 092002




$< A_1^{\rm res}/A_1^{\rm DIS} >=$
$1.11 \pm 0.16 \pm 0.18$
for $Q^2 > 1.6$ GeV$^2$

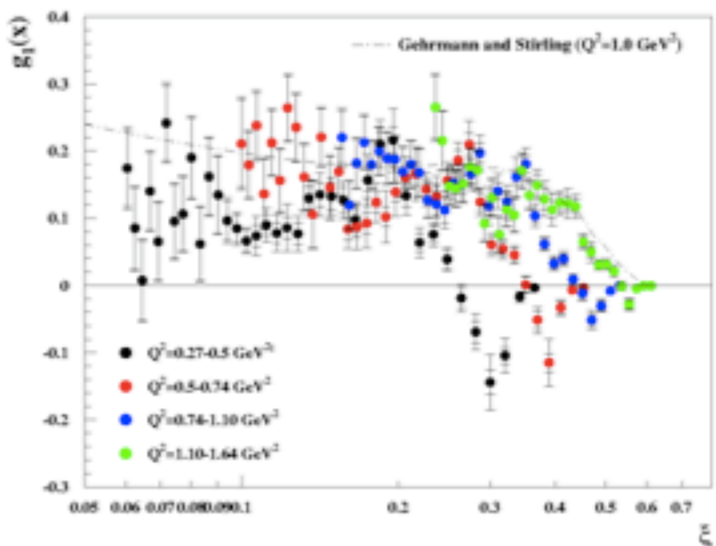
$e^{\rightarrow}p^{\rightleftarrows} \rightarrow e^{\rightarrow}X$

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




$e^{\rightarrow}p^{\rightleftarrows} \rightarrow e^{\rightarrow}X$

Preliminary Eg1 data




Strong violation of duality
for $Q^2$ <1.1 GeV$^2$

# Conclusions

- At $x \rightarrow 1$ we consider two independent scales, $W^2$ and $Q^2$
- PQCD evolution is governed by $W^2$
- This has consequences
  - Account of TMCs
  - Parton-Hadron Duality
  - Extraction of $\alpha_s$