PQCD Analysis of Parton-Hadron Duality

Simonetta Liuti
University of Virginia

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``QCD nowadays has a split personality. It embodies 'hard' and 'soft' physics, both being hard subjects and the softer the harder.''

Y. Dokshitzer

Outline

- Introduction
- Review DGLAP evolution at large Bjorken (z-dependent scale)
- Describe interplay of TMCs, Large Bjorken x evolution, HigherTwists
- Extract α_S → exploring interplay between perturbative and non perturbative effects (AdS/CFT ideas ?)

in collaboration with J.P Chen and A. Deur

- Briefly mention nuclear corrections at large Bjorken x
- Conclusions/Outlook for the 12 GeV program and beyond…

Parton-Hadron Duality ➔ an Important Element in Large x_{Bj} Studies

Practical Aspects:

✔ Precise determination of PDFs at large x_{Bj} needed to extend the domain of validity of PDF global analyses (importance of large x gluons, ...)

(Jlab + CTEQ studies, PRL 2011)

✔ Tests of QCD predictions at $x_{Bj}=1$

(Ratio F_2^n/F_2^p, W. Melnitchouk et al....)

Theoretical Aspects:

- ✔ Monitoring the transition in QCD between the "perturbative" region, where factorization applies to the "non-perturbative" region: interpretation within factorization theorems in QCD?

  (J. Collins)

- ✔ Possibility of extracting α_s at low scale

  (GDH sum rule analyses by J.P. Chen, A. Deur)

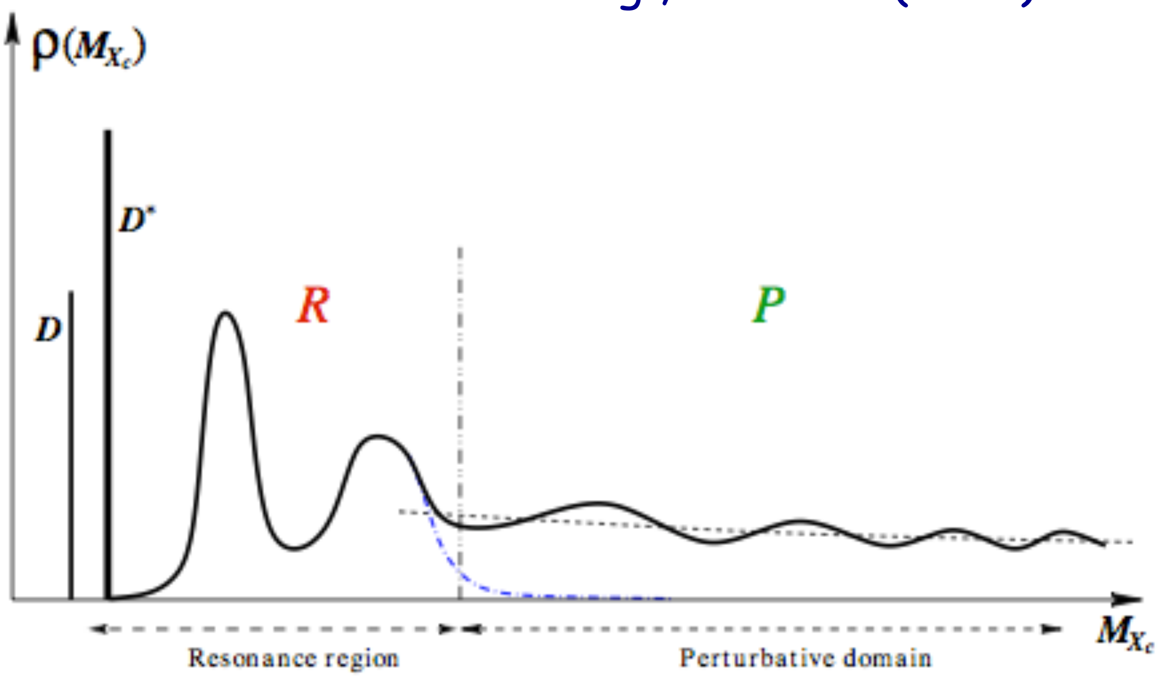
- ✔ Understanding the mechanism of hadron formation

In a nutshell

A Vademecum on Quark–Hadron Duality 5219

Bigi, Uraltsev (2001)

Observable "X"



FS Invariant Mass

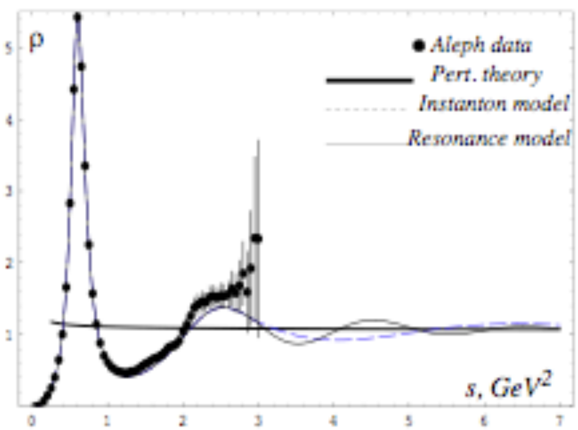
Duality is Ubiquitous

(from A. Fantoni's talks)

Data (1)

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

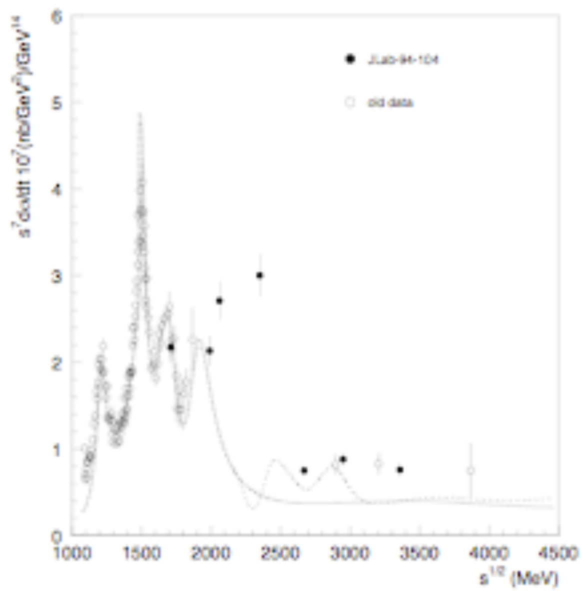
M. Shifman, hep-th/0009131



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

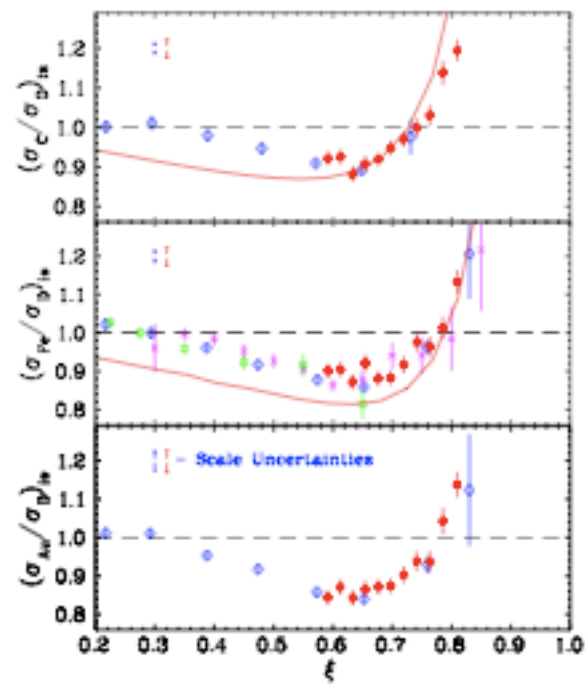
L.Y. Zhu *et al.*, PRL 91 (2003) 022003,

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



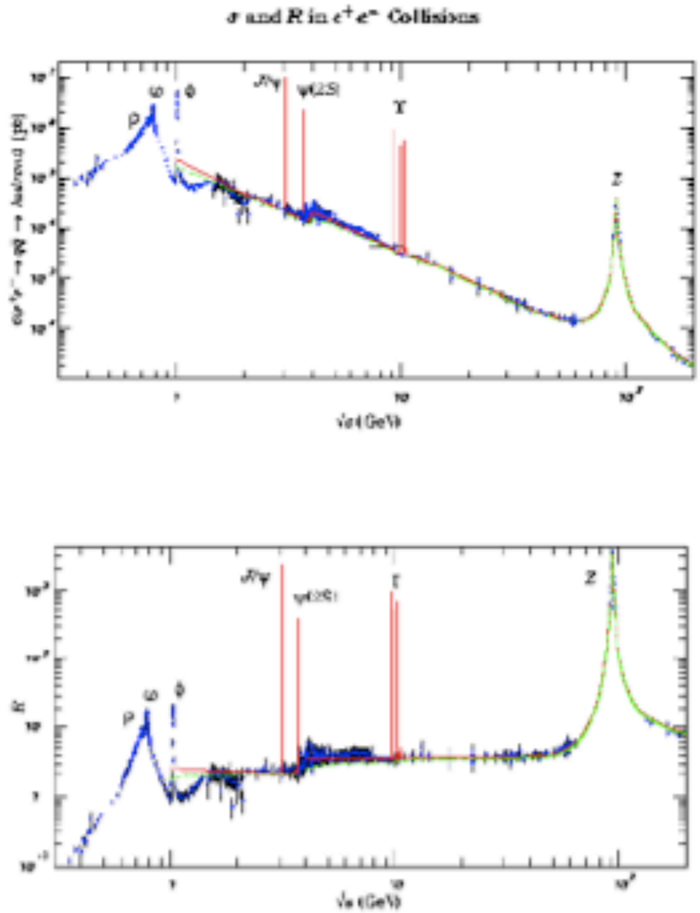
$eA \to eX$

J. Arrington *et al.* (submitted)



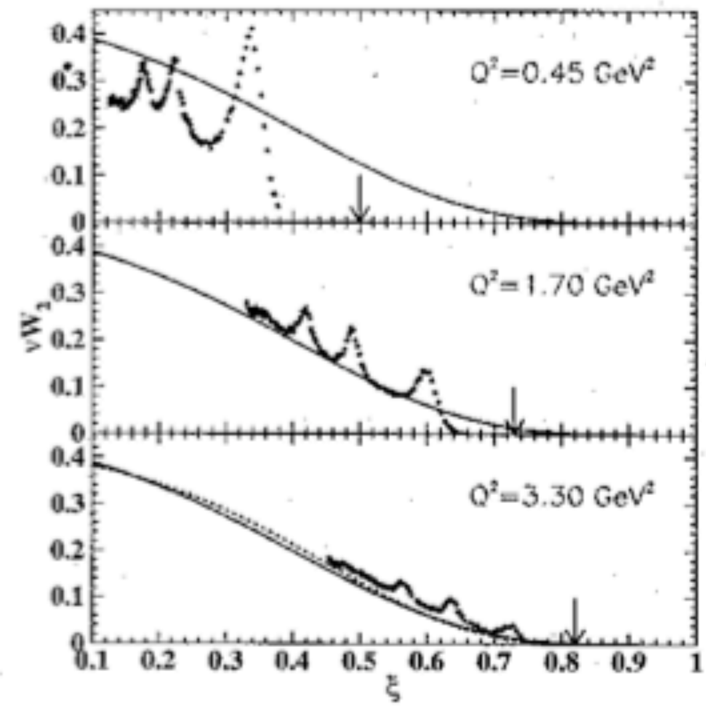
Data (2)

e+ - e− → hadrons



$ep \to eX$

I. Niculescu *et al.*, PRL 85 (2000) 1182,
I. Niculescu *et al.*, PRL 85 (2000) 1186

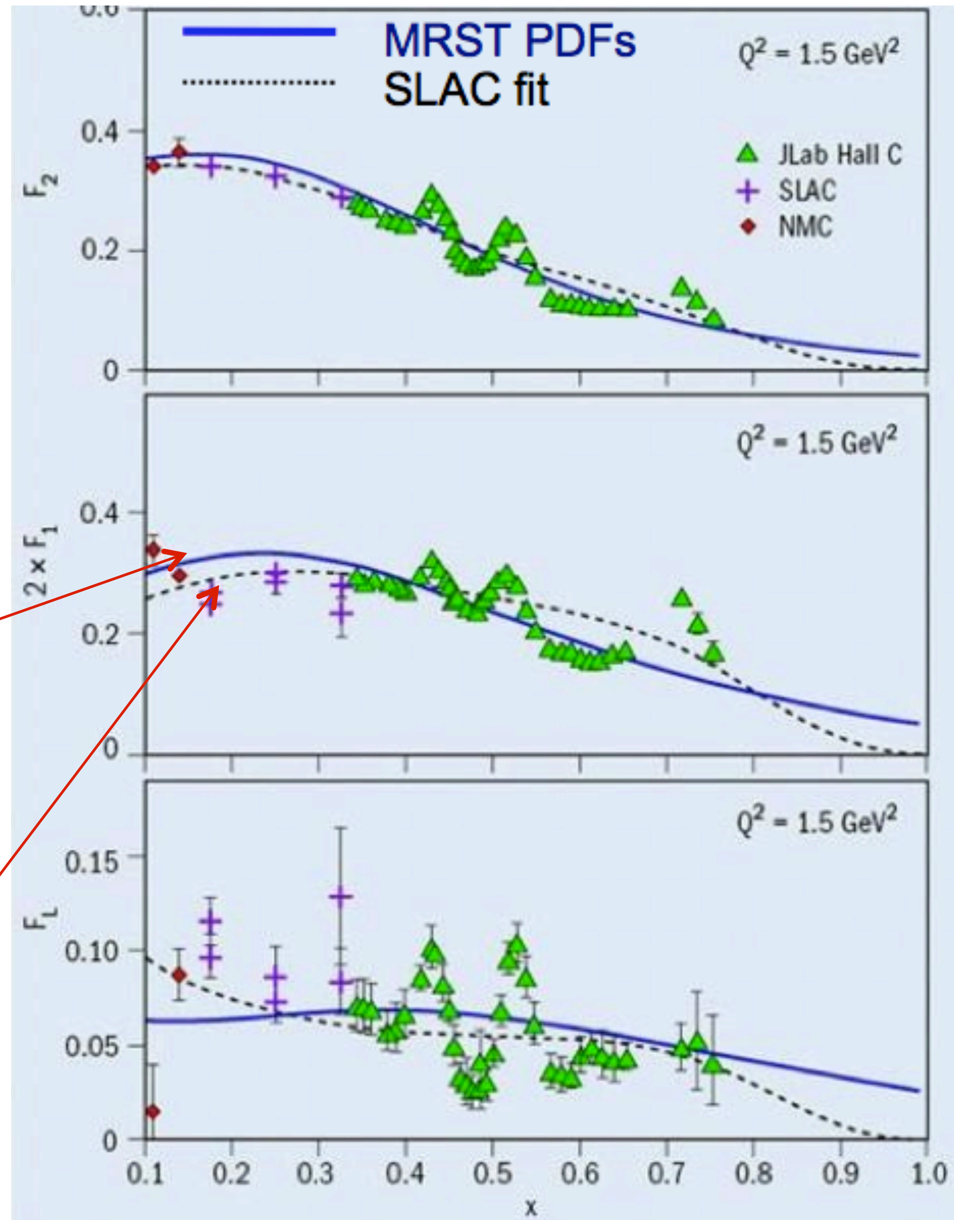


Focus on DIS: What defines the smooth curve that fits the data?

Large x_{Bj} at fixed Q^2 implies a continuation of the "PQCD curve" into the resonance region

Hall C data

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



PQCD

Data fit

Two Complementary Approaches

Quantum Mechanics based Model of Resonances Excitation

Duality arises from Quantum Mechanical properties of quarks confined in "empirically inspired" linear potential: excitation of resonances of opposite parity interfere in all but the leading twist.

(Close,Isgur, Melnitchouk,Jeschonnek,VanOrden…)

QCD-based phenomenological analyses

OPE-treatable reactions are two step processes:

(1) Hard dynamics scattering at large momentum/small distance scale ($1/Q^2$).

(2) Soft dynamics process turns the partons into hadrons at much larger distance scalesin ($1/\Lambda_{QCD}$).

First step → Gross features (total cross sections, jet directions, …)

Second step → Detailed structure of the final state,

In a phenomenological context, duality studies how a number of properties defined from the beginning of the hard scattering process,
are predetermined and persist in the non-perturbative stage.

Where does the separation start?

The separation and yet coexistence of long distance and short distance structure in QCD has become naturally accepted as part of a ``common wisdom framework'' underlying the interpretation of most experiments

Systematic Analysis

-- S.L., R. Ent, C.Keppel, I. Niculescu, PRL 2000
-- N. Bianchi, A. Fantoni, S.L., PRD2003
-- A. Fantoni, S.L. 2005
-- J.P. Chen, A. Deur, S.L., in preparation 2011

1) Fix the order of the analysis to NLO and extend curve to low W^2

2) 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.

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

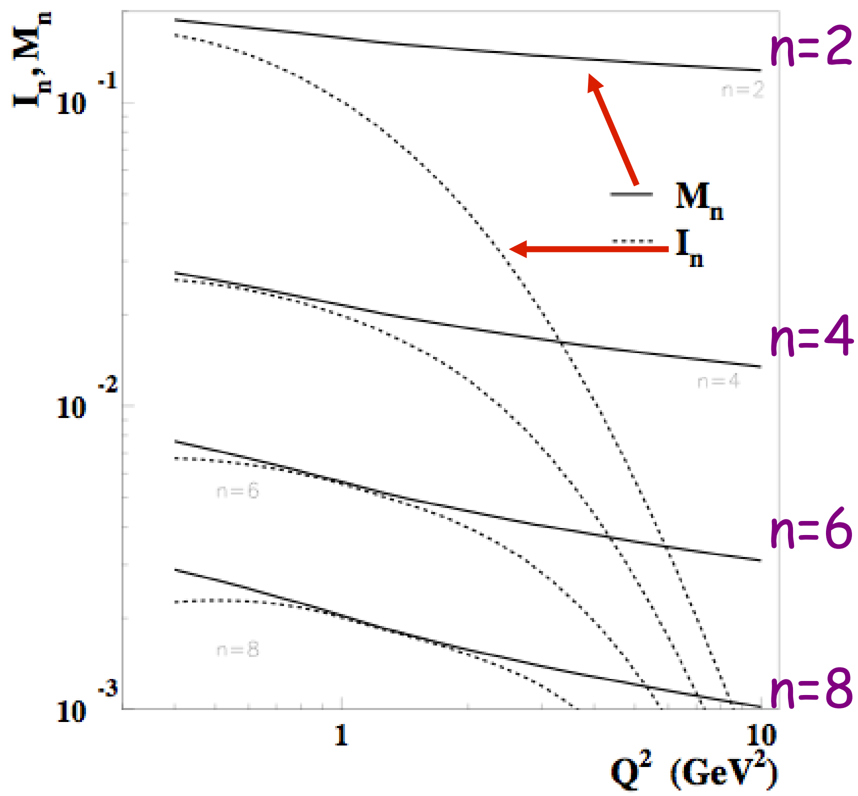
$$I^{res}(Q^2) = \int_{x_{min}}^{x_{max}} F_2^{res}(x, Q^2)\, dx$$

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

$$x_{min} = \frac{Q^2}{Q^2 + W_{max}^2 - M^2}$$

pQCD prediction

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

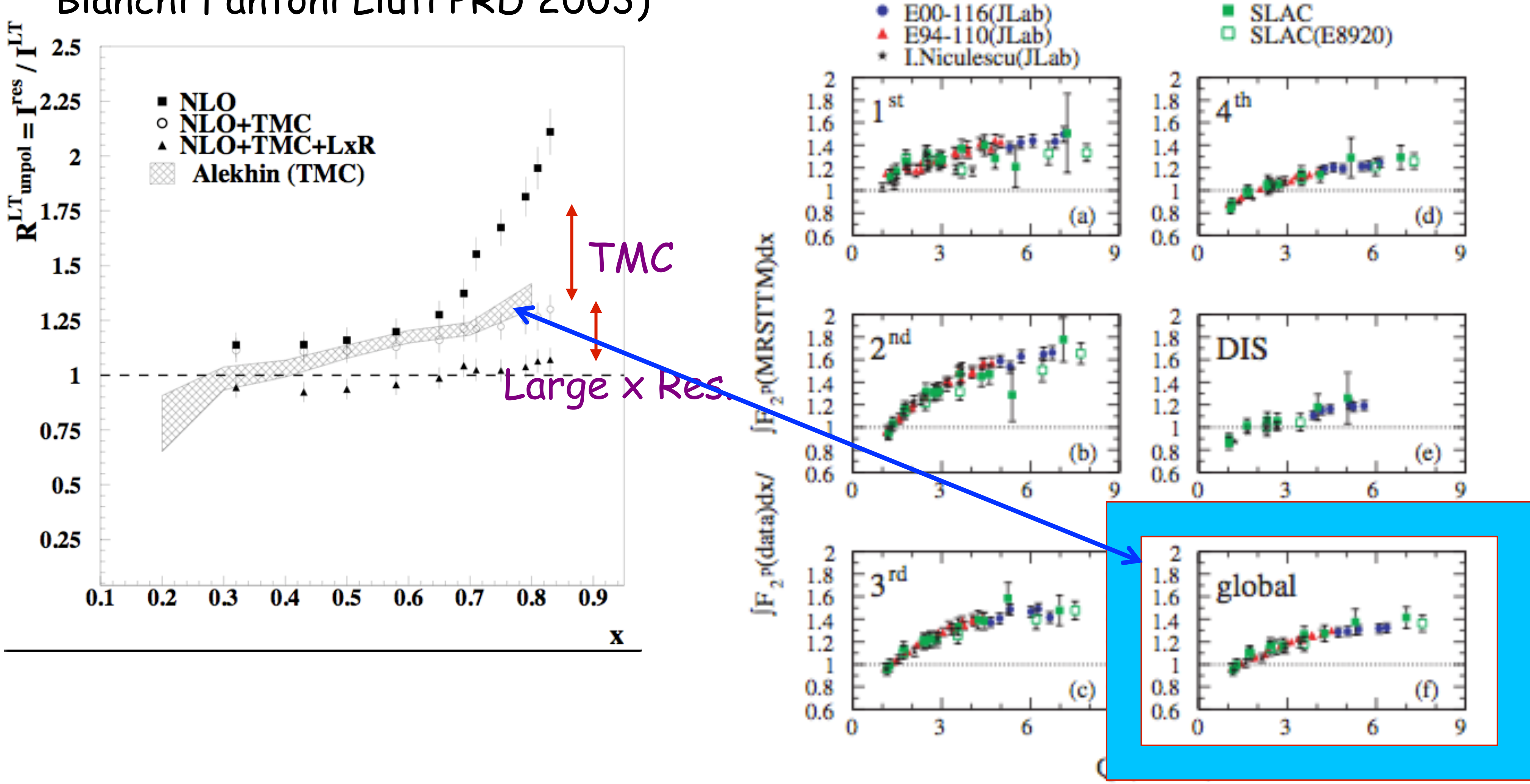


I_n and M_n calculated using CTEQ

Unpolarized Jlab+SLAC data

Bianchi Fantoni Liuti PRD 2003)

S. P. MALACE *et al.* PRC 2010

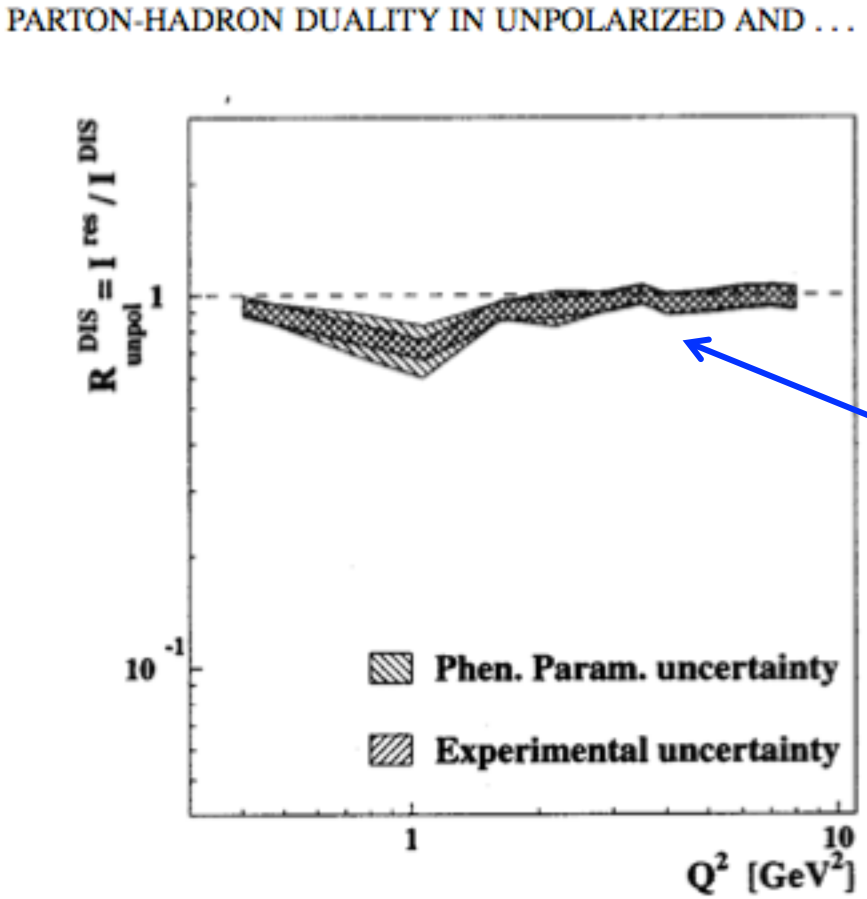


$$R = \frac{\int_{x_{\min}}^{x_{\max}} F_2^{res}(x,Q^2)\,dx}{\int_{x_{\min}}^{x_{\max}} F_2^{LT,param}(x,Q^2)\,dx}$$

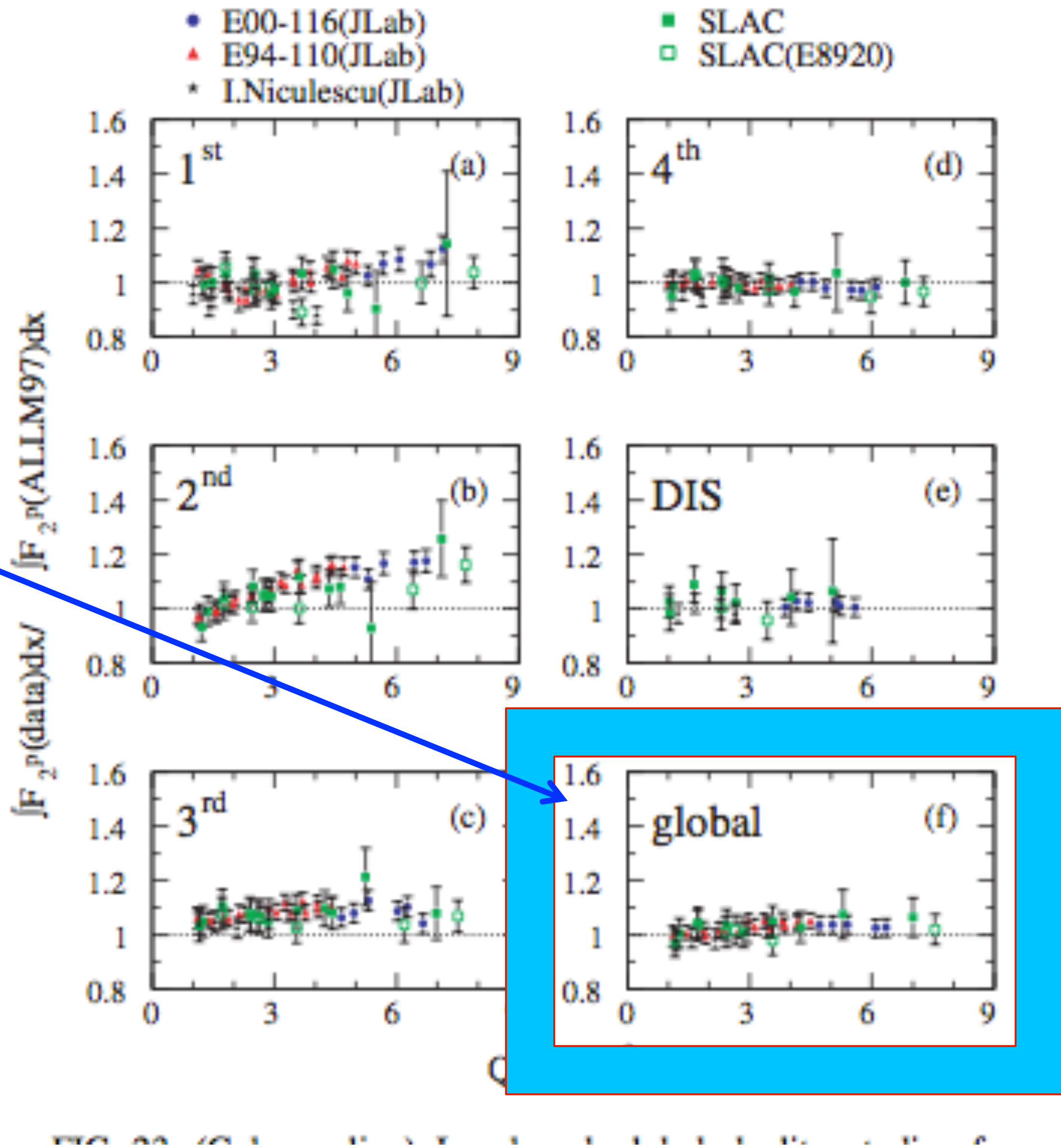
Using ALLM ➔ extra NP Q^2 dependence

Unpolarized Jlab+SLAC data

Bianchi Fantoni Liuti PRD 2003)

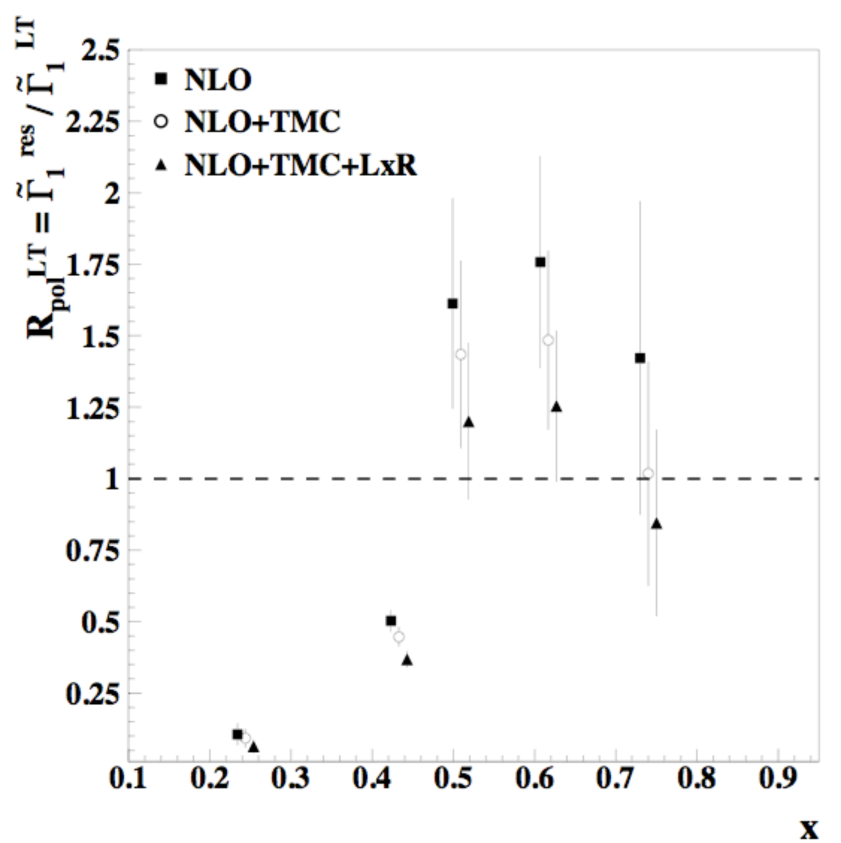


S. Malace et al., PRC 2010

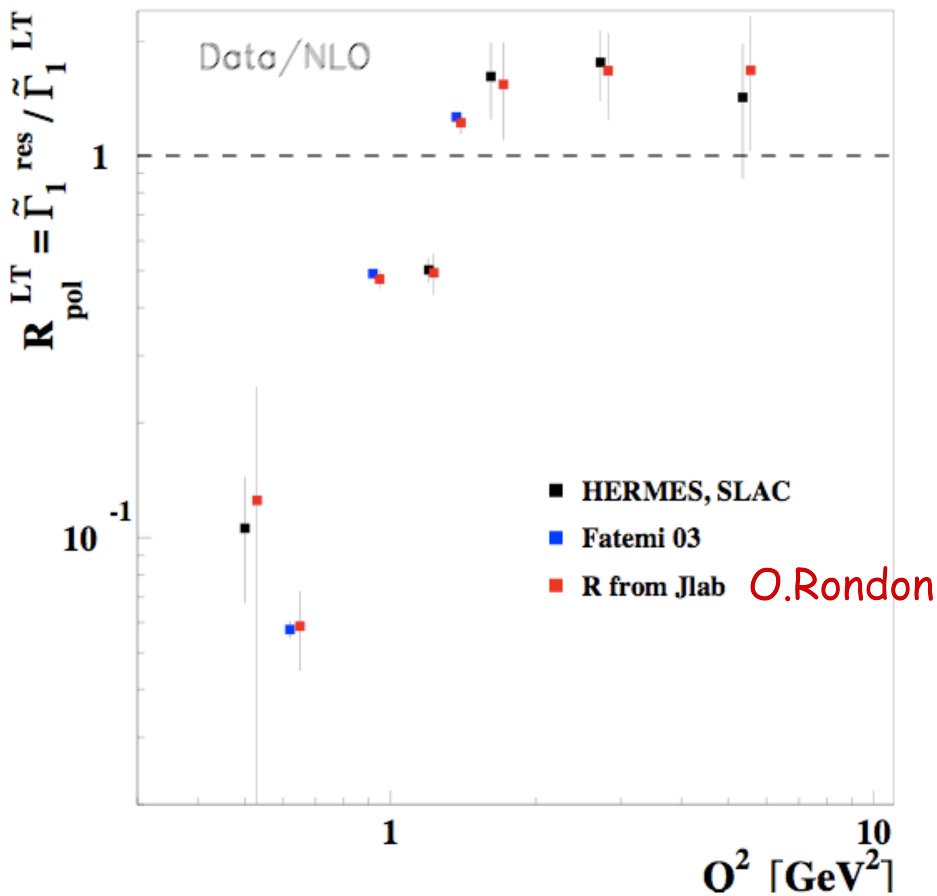


$$R = \frac{\int_{x_{\min}}^{x_{\max}} F_2^{res}(x,Q^2)\,dx}{\int_{x_{\min}}^{x_{\max}} F_2^{LT,param}(x,Q^2)\,dx}$$

Polarized HERMES+Jlab+SLAC data

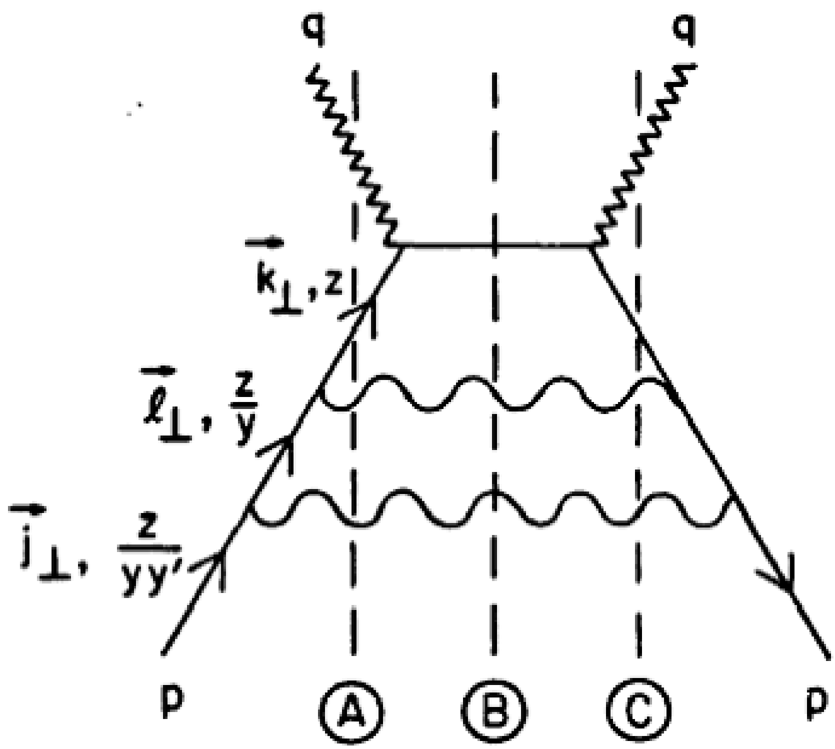


More recent polarized data (O. Rondon et al.)



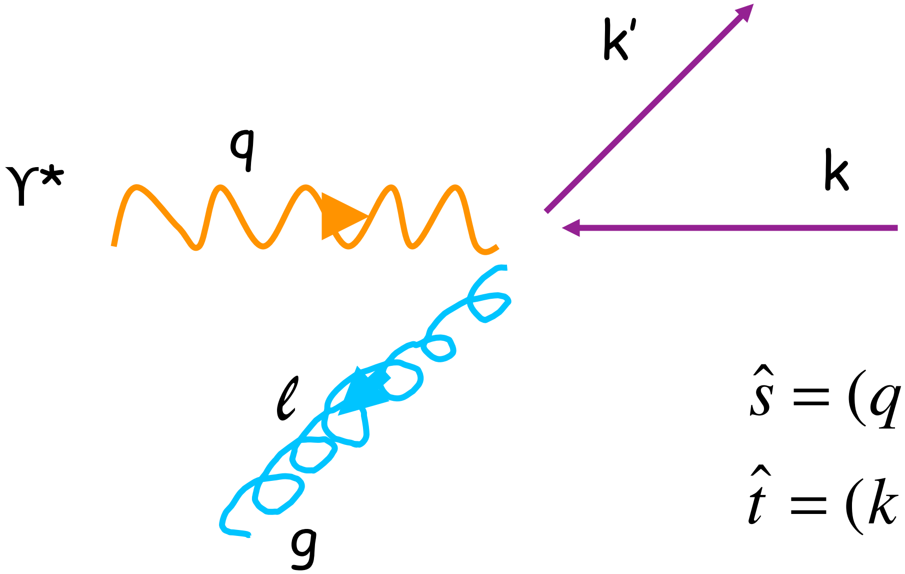
Large x_{Bj} evolution

(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

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



$\gamma^* q \rightarrow q' g$

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

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

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

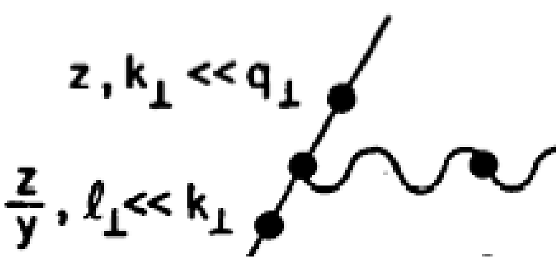
$$k_T^2 = \frac{\hat{s}\,(-\hat{t})\,\hat{u}}{\hat{s}\,(\hat{s}+Q^2)} = \frac{\hat{s}\sin^2\theta}{4} \qquad (k_T^{MAX})^2 = \frac{\hat{s}}{4}$$

Invariant mass!

In terms of LC variables

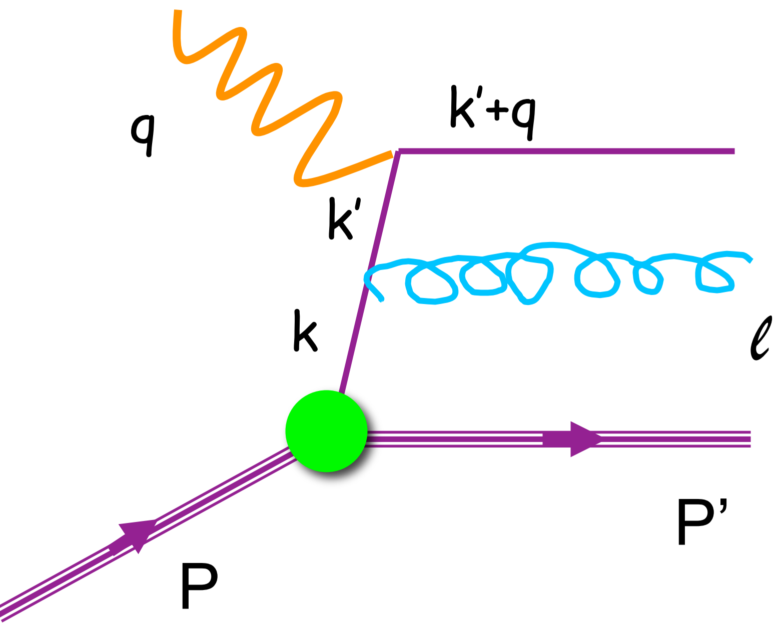
$k = (k^+ = zP^+, k^- = P^- - \ell^-, k_T)$

$$\rightarrow \quad (k_T^{MAX})^2 = \frac{Q^2(1-z)}{4z}$$



Next, write amplitude for

$\gamma^* P \rightarrow$ (final quark) + g + X

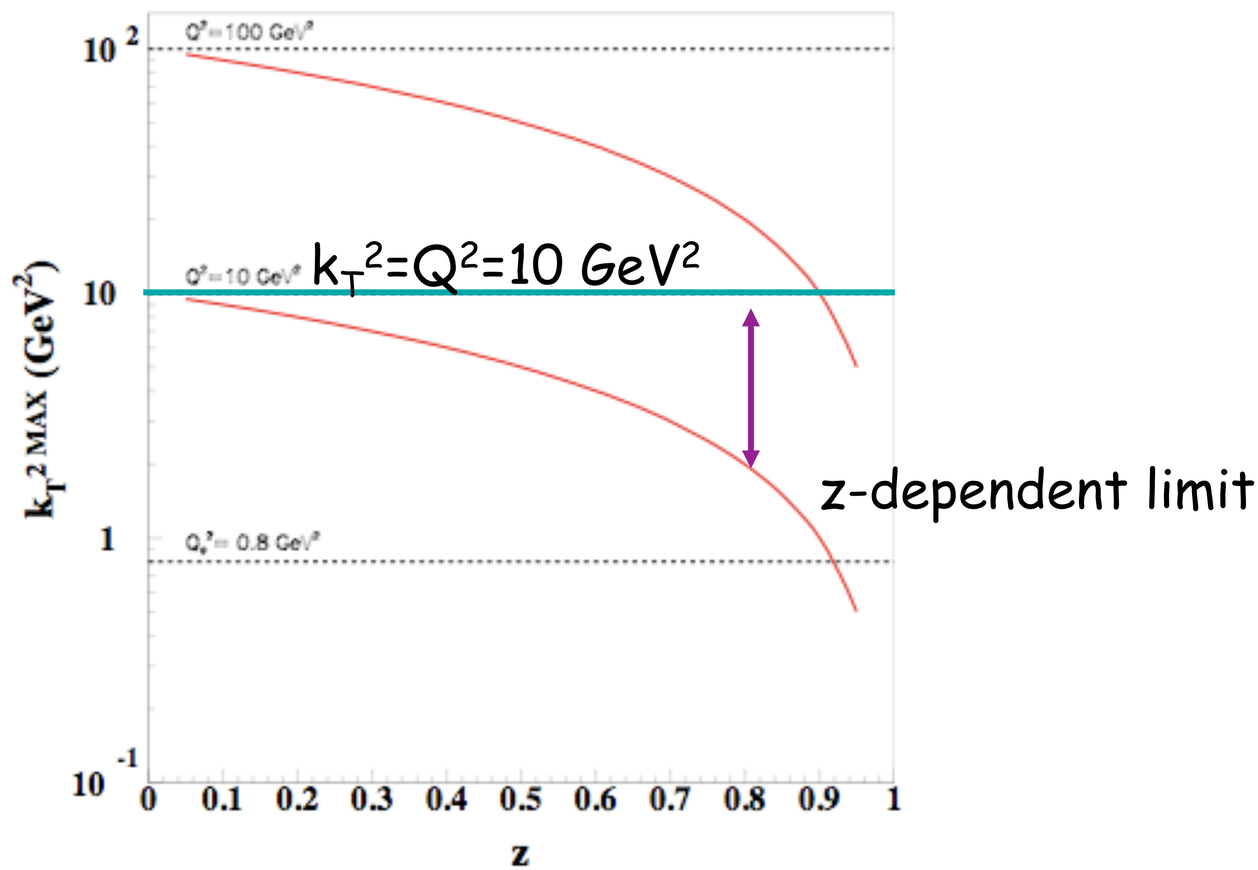


$|\text{Amplitude}|^2$ for $\gamma^* P \rightarrow$ (final quark) + g + X

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

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…

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

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

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

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

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

Target Mass Corrections (TMC)

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

Target Mass Corrections (TMC)

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

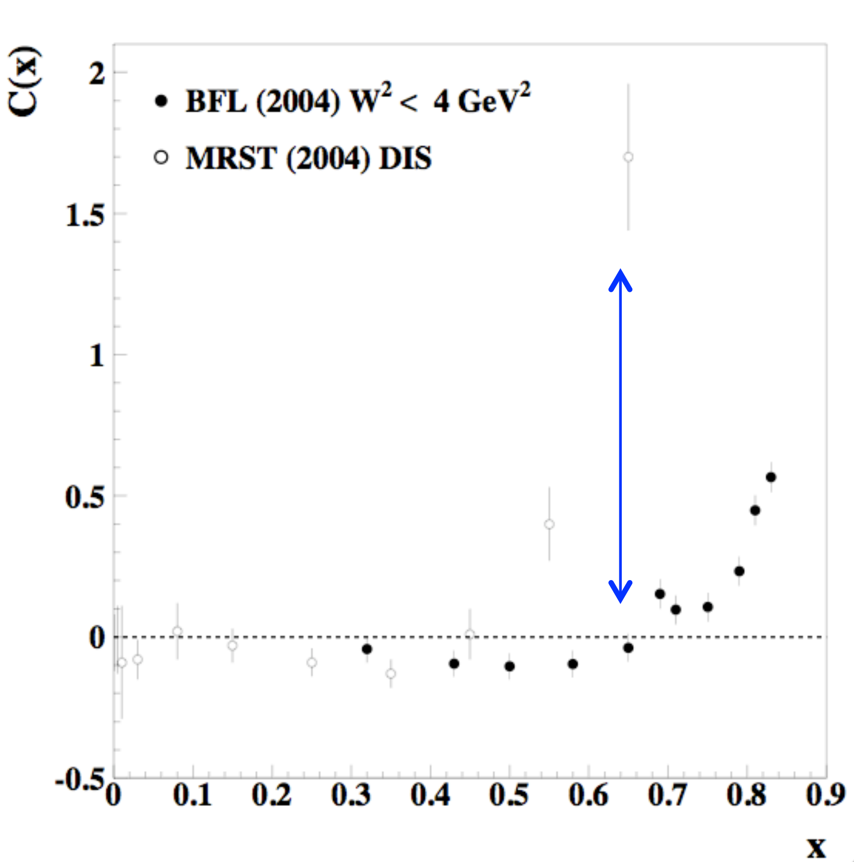
$$F_{T,L}(x_B, Q^2, m_N^2) = \int_{\xi}^{\xi/x_B} \frac{dx}{x} h_{f|T,L}(\tilde{x}_f, Q^2)\varphi_f(x, Q^2) \; . \qquad (18)$$

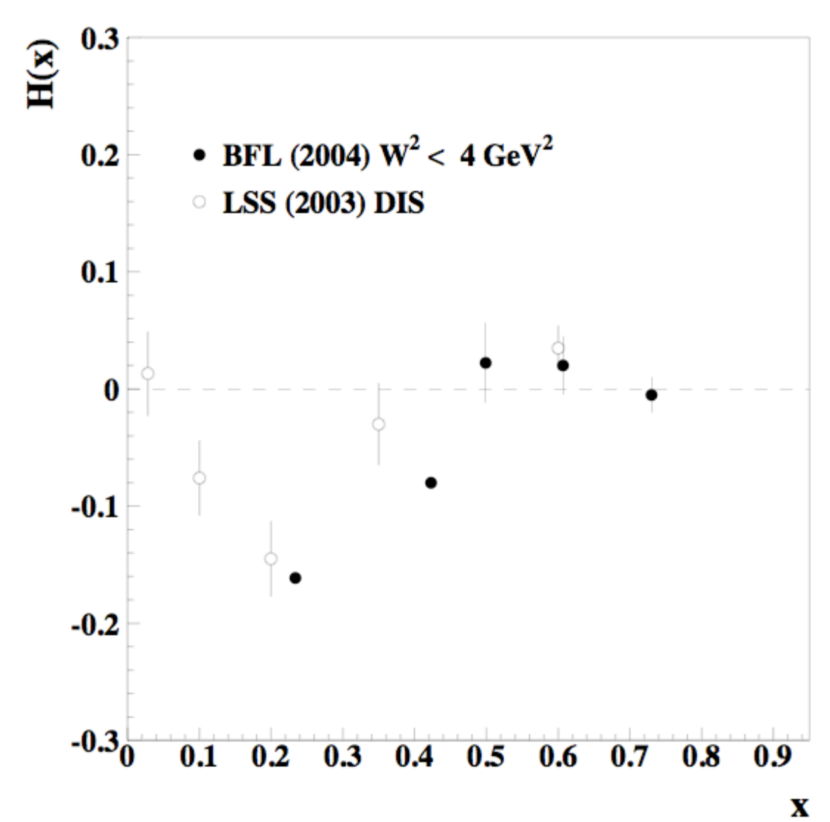
Instead of 1

Joint large x evolution and new TMCs approach

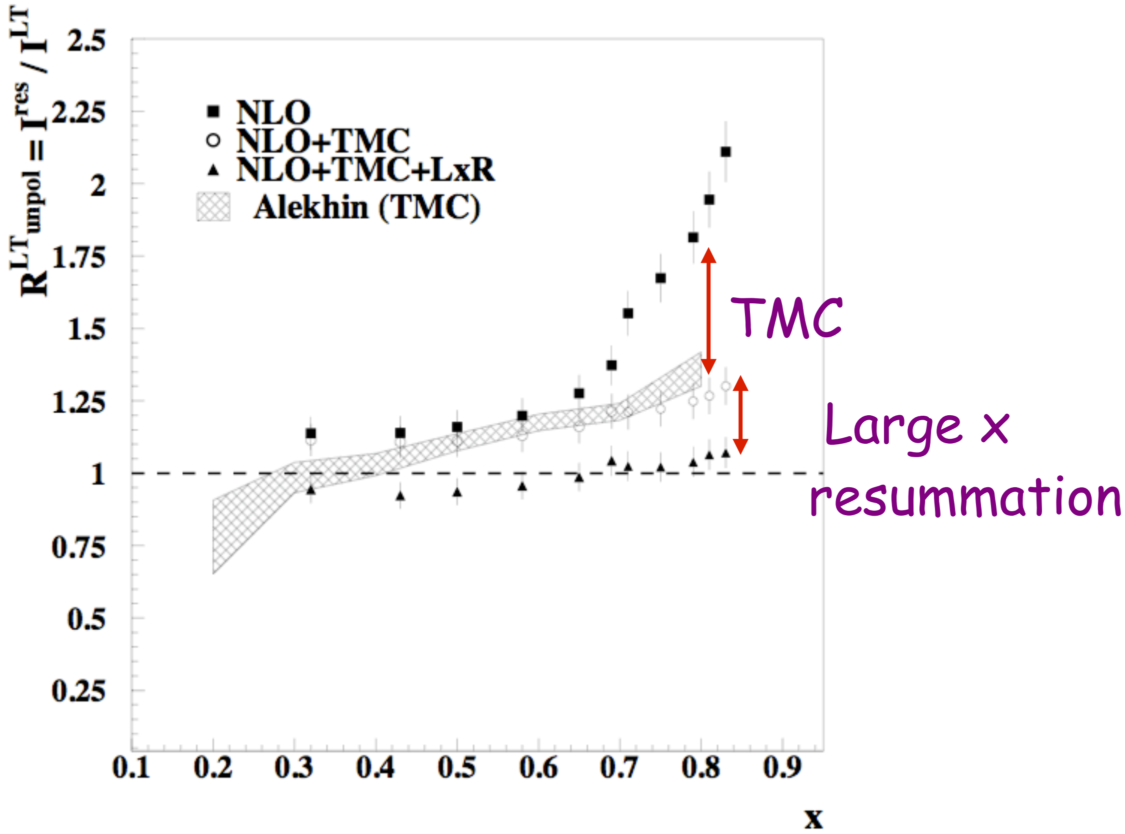
All of these effects can be taken into account using "reasonable" Parameters ➔ No need to introduce large HT component at Large x

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





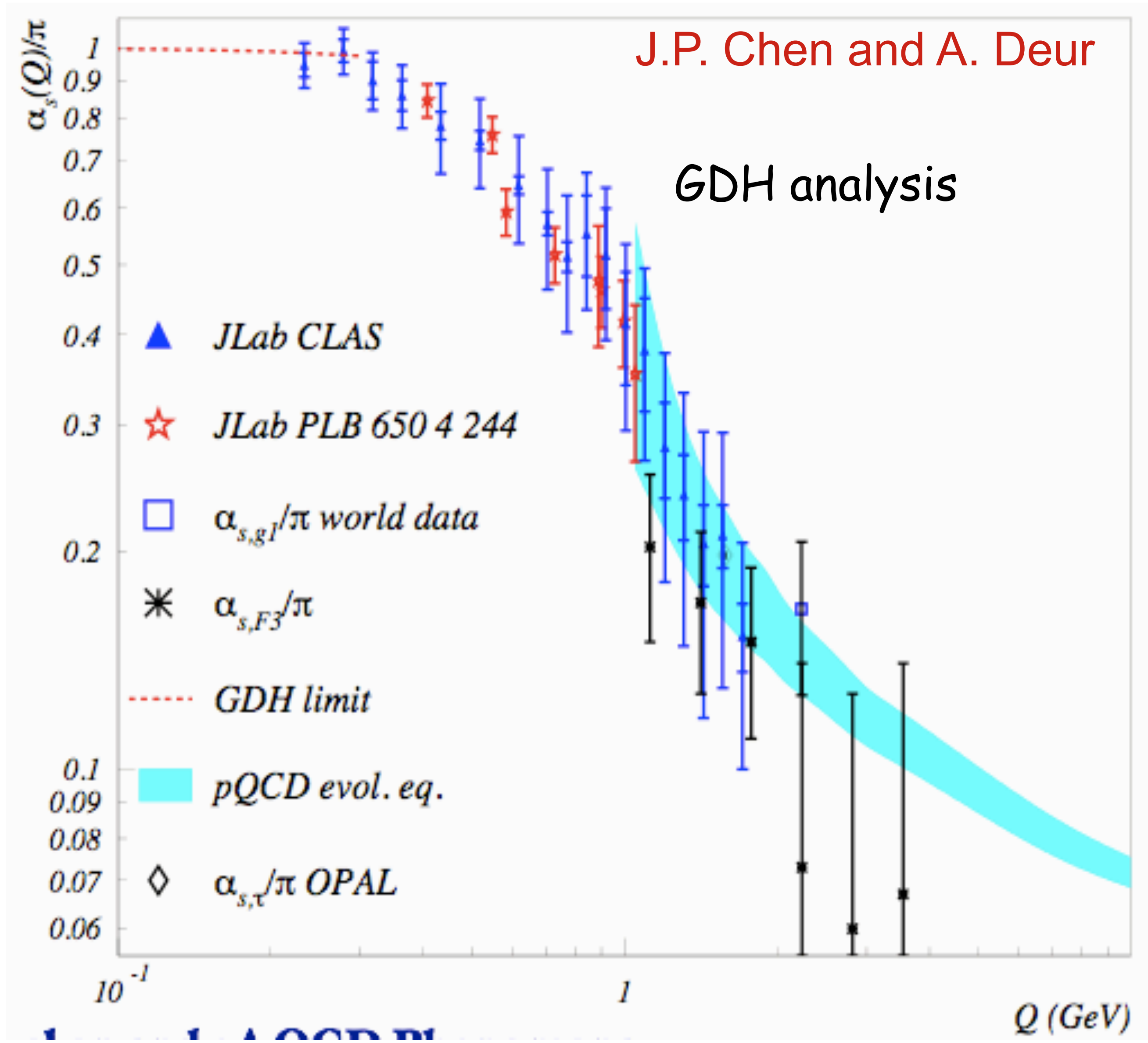
$$F_2^{exp} = F_{PQCD}(1 + C(x)/Q^2)$$



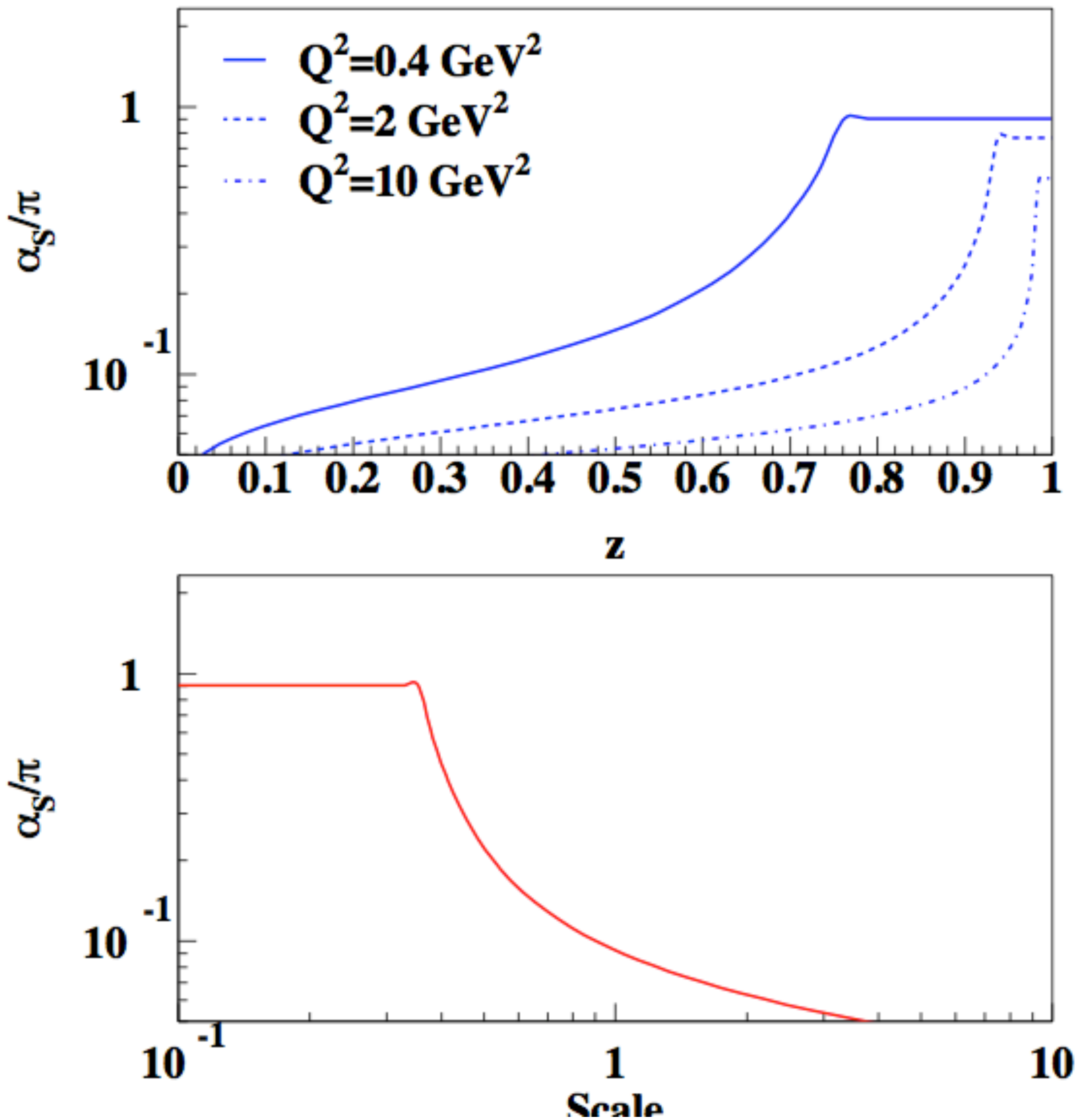
What is happening is that (part) of the HTs contributions have been absorbed in α_S

This is correlated with the fact that at large x, α_S needs to be continued at very low Q^2

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



Work in progress:
Use this "positively" to
Extract α_S at low scale



Q^2=0.4 GeV^2
Q^2=2 GeV^2
Q^2=10 GeV^2
α_S/π
1
10^{-1}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
z
α_S/π
1
10^{-1}
10^{-1}
1
10
Scale

What is the physics behind this?

Pioneering Work

Pennington, Roberts, Ross 80's

+ far reaching extensions

related to discussion at this W'shop

Extension of α_S in timelike region:
going through the Landau pole

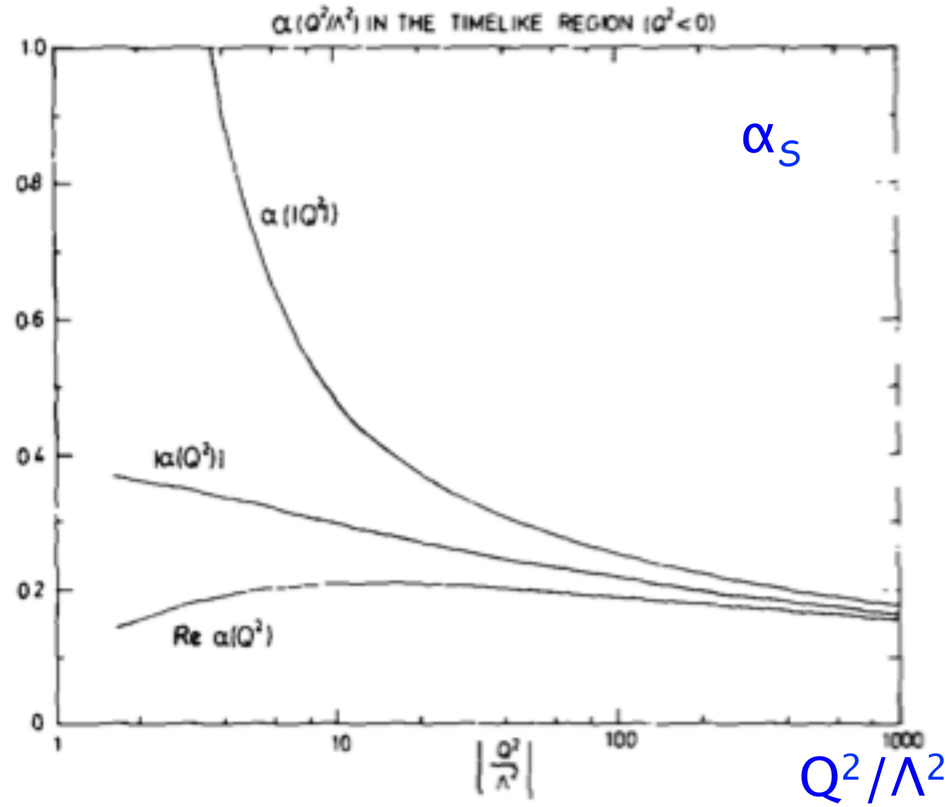


Fig. 1. The three expansion parameters $\alpha(|Q^2|)$, $|\alpha(Q^2)|$ and Re $\alpha(Q^2)$ in the timelike region ($Q^2 < 0$) are shown as functions of $|Q^2|/\Lambda^2$. $\alpha(Q^2)$ is defined by eq. (2) with β_0, β_1 evaluated for $n_f = 4$, but with all higher coefficients zero. $\alpha(|Q^2|)$ is given by its commonly used, next-to-leading order, expression

$$\frac{\alpha(|Q^2|)}{4\pi} = \frac{1}{\beta_0 \ln|Q^2/\Lambda^2|} - \frac{\beta_1 \ln\ln|Q^2/\Lambda^2|}{\beta_0^3 \ln^2|Q^2/\Lambda^2|} .$$

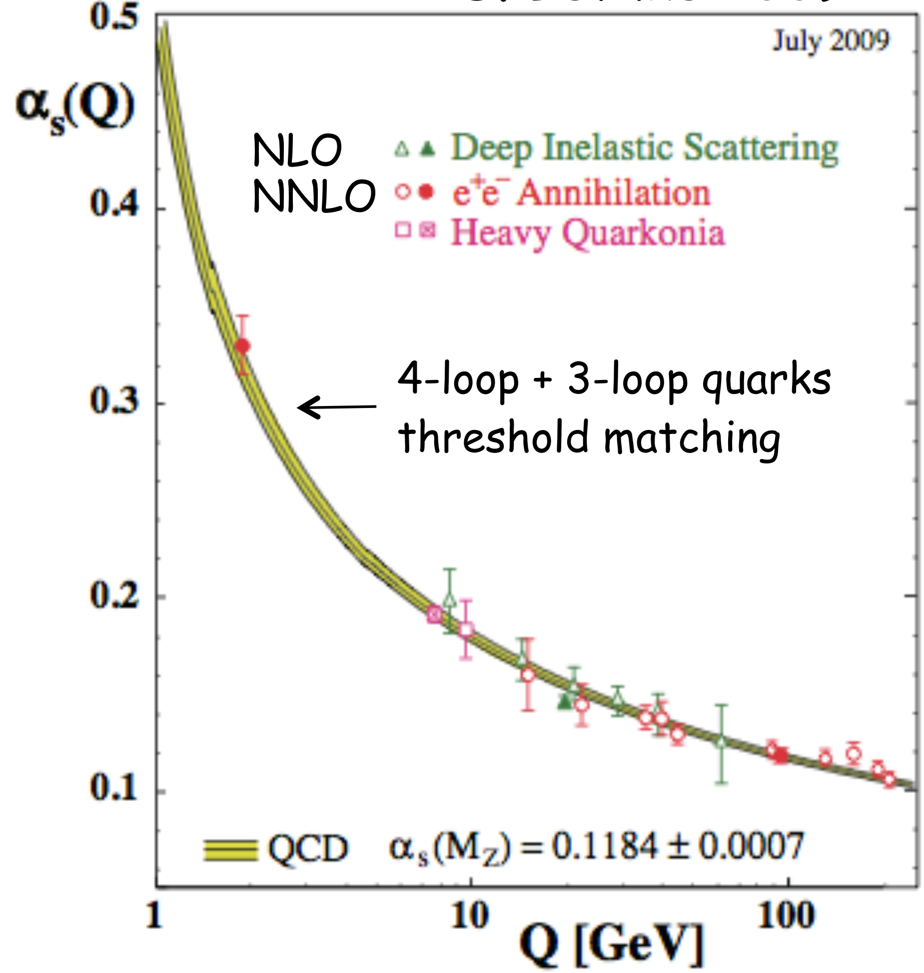
Note, however, that, for $|Q^2/\Lambda^2| < 100$, representing $|\alpha(Q^2)|$, Re $\alpha(Q^2)$ by similar power series in $(\ln|Q^2/\Lambda^2|)^{-1}$ is very inaccurate, unless many terms are included. $|\alpha(Q^2)|$, Re $\alpha(Q^2)$ have therefore been evaluated from eq. (2) by expressing ln Q^2 as a series in α. The curves shown reflect terms up to $O(|\alpha|^6)$ in Im α, eq. (5), and so are accurate even at low $|Q^2|$.

Two Points of Interest for Jlab Community

1) The coupling's behavior as one approaches the Landau pole, matters for predictions at the LHC

S. Bethke 2009

Long known systematic difference between e+ e- (smaller α) and structure functions (larger α)



2) Study of the interplay between perturbative and non-perturbative effects is important: formulate it in a way where comparison with lattice results is easier and attack the question of process dependent α_S predictions

Outline of a Phenomenology Study

Start from the point that the Landau pole in α_S is unphysical

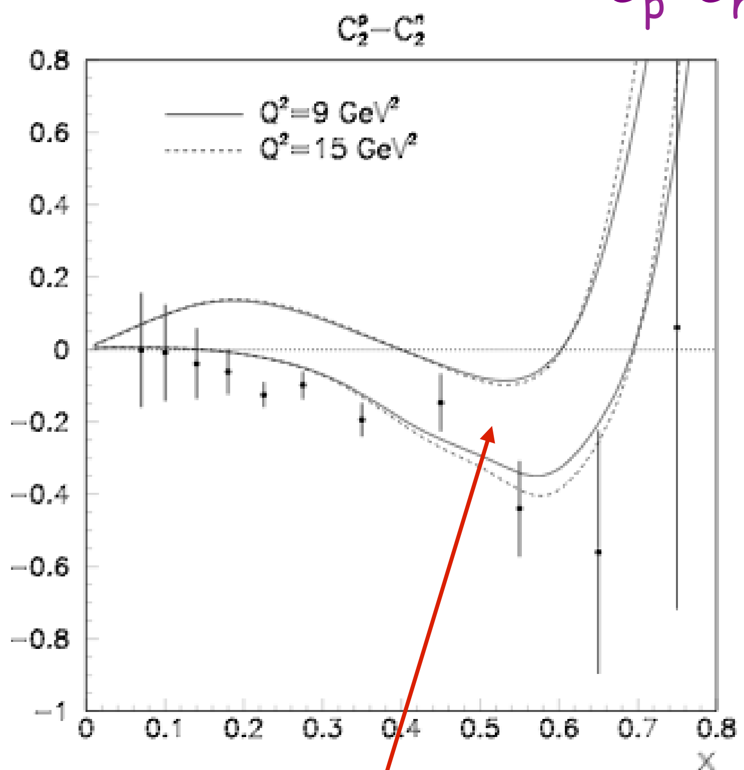
Introduce effective couplings/charges that can be extracted directly from data

Define scheme to connect and compare different extractions
(commensurate scale relations, Brodsky, Deur, deTeramond)

Nuclei

✔ Are HTs isospin dependent? Deviations from PQCD effects

C_p-C_n



NMC data

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

Towards the Jlab 12 GeV/EIC 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: would love to see study of large x and larger W^2 to see how HTs behave

⟹ Theoretical background: starts from Finite Energy Sum Rules

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, Collins

Conclusions

PQCD analyis of highly precise large x_{Bj} Jefferson Lab data in resonance region is interesting for both studying the transition of partons into hadrons and for studies of α_S