The transition from pQCD to npQCD: Duality and Higher Twists

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- Introduction
- Overview of Data
- Different approaches for duality and choice of the method
- Transition from pQCD to npQCD
- Studies of Higher Twists
- Conclusions & Outlook

Introduction (1)

High energy reaction: cross section factors into

Long distance: measurable part

$1/\Lambda_{\mathrm{QCD}} \approx$ hadronic size

Related to quarks and gluons distribution inside the nucleon: hadronic observables

Low energy: confinement, npQCD

Short distance: pert. calculable part

$1/Q \ll$ hadronic size

Parton interaction negligible: asymptotically free quarks

High energy: regime of perturbative QCD

$\Longrightarrow$ **Transition from soft to hard QCD**

The mechanism of transformation of parton into hadron (and viceversa) modifies the final state: partons get transformed but not the cross section

Hadronic cross sections (averaged over appropriate energy range)

Partonic cross sections (from perturbative quark-gluon theory)

$$\Sigma_{\text{hadrons}} = \Sigma_{\text{quarks+gluons}}$$

Complementarity between Parton and Hadron description of observables

Relation to nature and transition from non-perturbative to pQCD

Introduction (2)

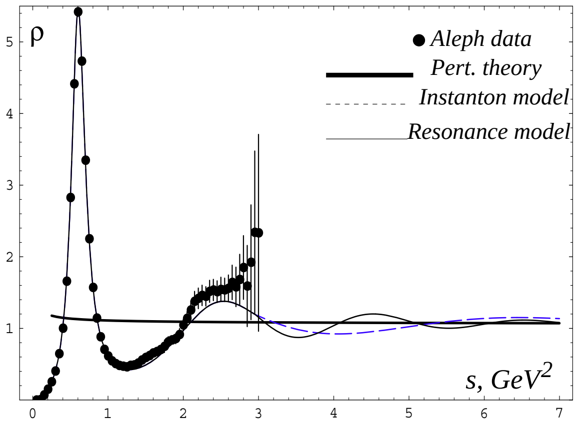
Present in Nature in different aspects:

- e^+ - e^- $\longrightarrow$ hadrons $\equiv \sum_q (e^+e^- \longrightarrow q\bar{q}) \Rightarrow$ $\sigma_{hadrons} \equiv \sum_q \hat{\sigma}_q$
- $ep \longrightarrow eX \Rightarrow$ $d\sigma \approx \sum_q \int dx\, q(x, Q^2) d\hat{\sigma}_q$
- $ep \longrightarrow ehX \Rightarrow$ $d\sigma \approx \sum_q \int dx\, q(x, Q^2) D_h(z, Q^2) d\hat{\sigma}_q$
- $e^{\rightarrow} p^{\rightleftarrows} \longrightarrow e^{\rightarrow} X$
- $eA \longrightarrow eX$
- $\tau \longrightarrow \nu +$ hadrons
- semi-leptonic decay of heavy quarks
- $\gamma p \longrightarrow \pi^+ + n$

Data (1)

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

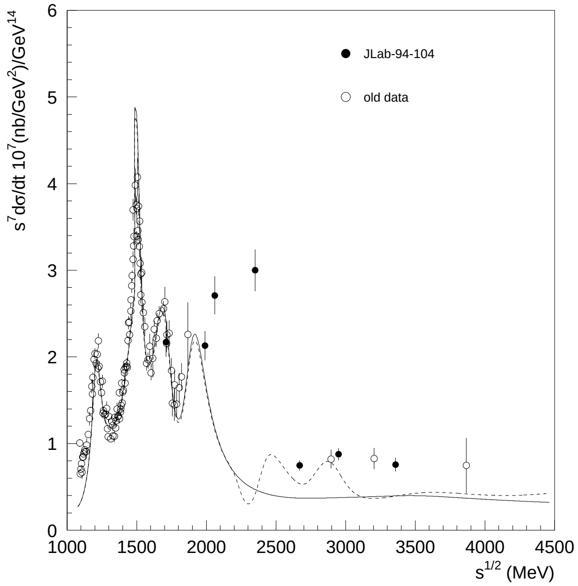
M. Shifman, hep-th/0009131



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

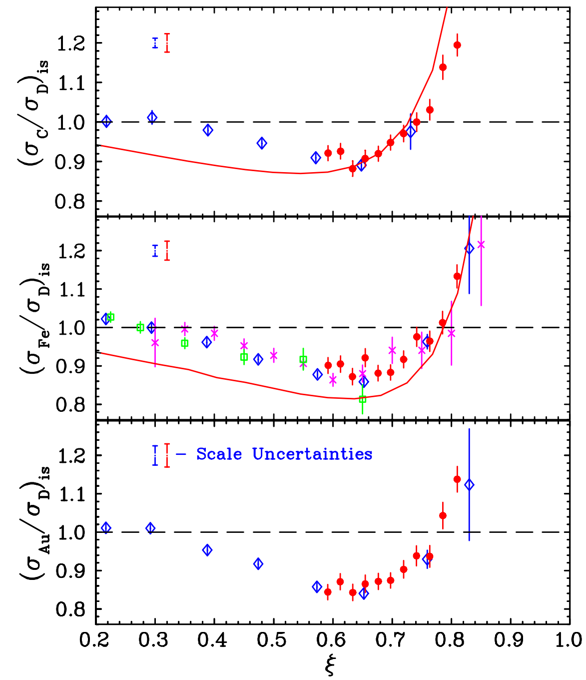
L.Y. Zhu *et al.*, PRL 91 (2003) 022003,

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



$eA \to eX$

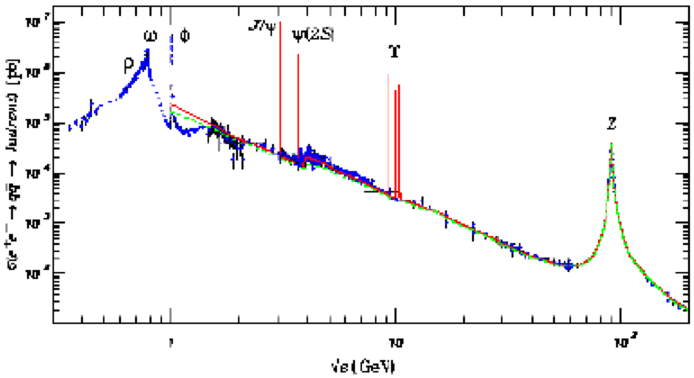
J. Arrington *et al.* (submitted)

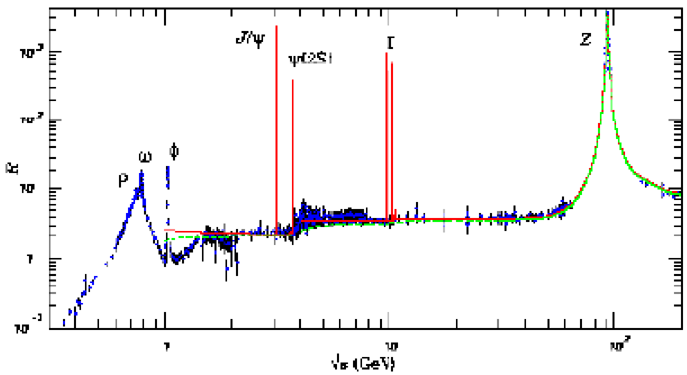


Data (2)

$e^+ - e^- \longrightarrow$ hadrons

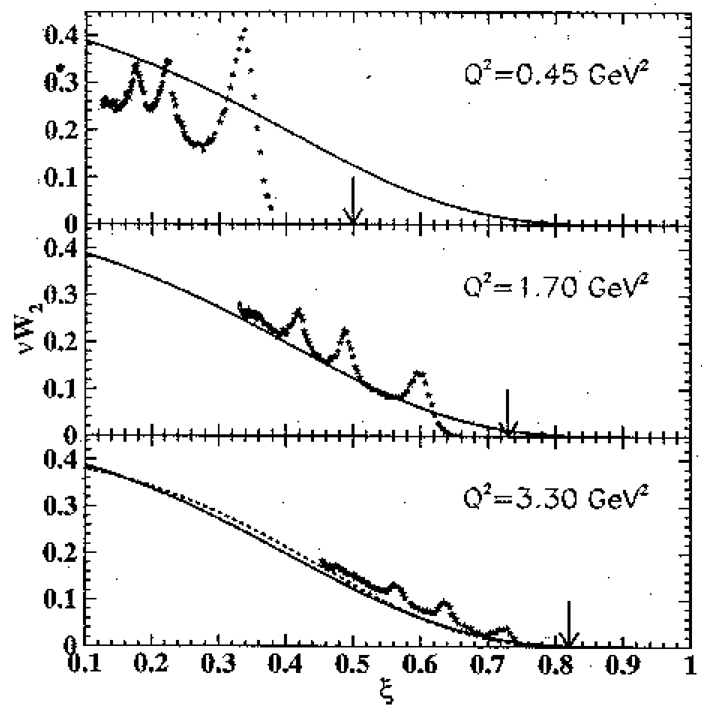
σ and R in e^+e^- Collisions





$ep \longrightarrow eX$

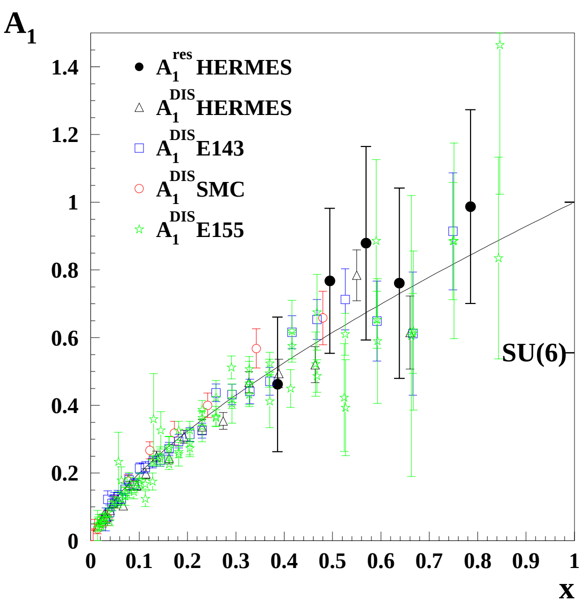
I. Niculescu *et al.*, PRL 85 (2000) 1182,
I. Niculescu *et al.*, PRL 85 (2000) 1186



Data (3)

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

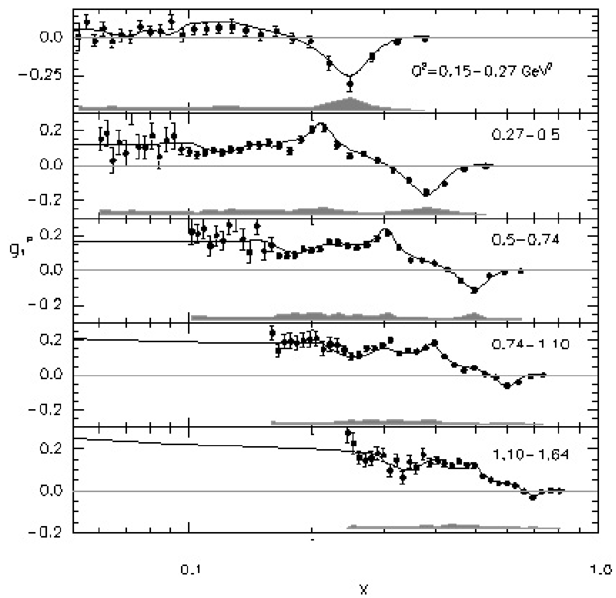
A. Airapetian *et al.*, PRL 90 (2003) 092002



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

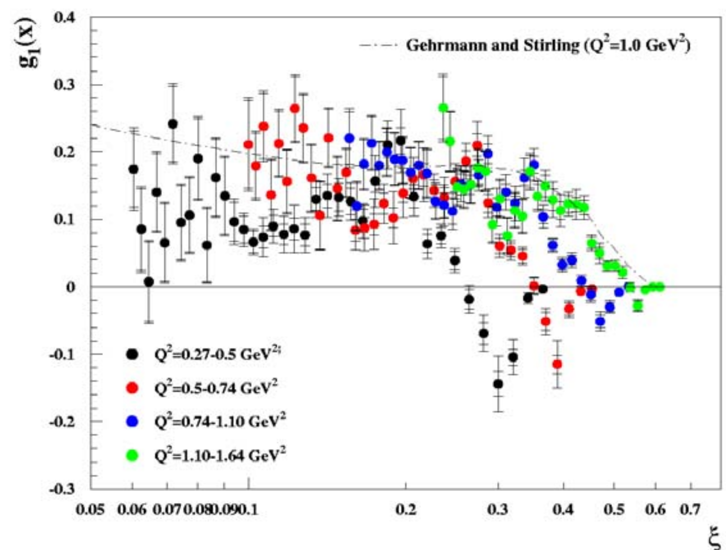
$e^{\rightarrow} p^{\rightleftarrows} \rightarrow e^{\rightarrow} X$

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

Remarks and Questions

- Breakdown of Duality at sufficiently low Q^2:
  1. Which value of Q^2 ?
  2. Same value for unpolarised and polarised structure functions?

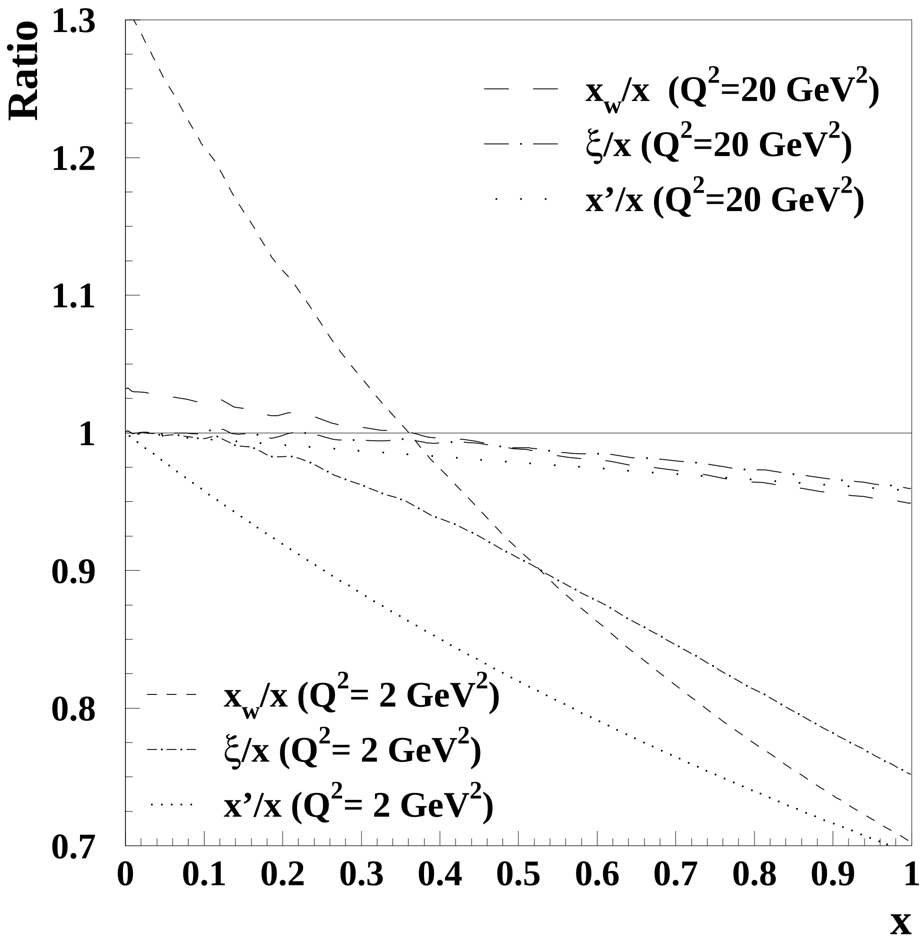
- Duality expected to be isospin dependent:
  1. p behavior
  2. n behavior

Close & Isgur, PL B509 (2001) 81; Isgur *et al.*, PRD 64 (2001) 054005

Global duality $\Longrightarrow$ average over large W^2 range (whole resonance region)
Local duality $\Longrightarrow$ average over small W^2 range (single resonances)

Important: passage from **qualitatively** to **quantitatively** picture

Kinematical variables



$x' = 1/\omega' \qquad \omega' = 1/x + M^2/Q^2$ B.G.

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

$x_w = Q^2 + B/(Q^2 + W^2 - M^2 + A)$ B.Y.

x', ξ rescale S.F. to lower x with Q^2 dep.

Rescaling larger at lower Q^2

Use of x to avoid ambiguities associated to usage other variables

3 approaches (1)

a) Mellin moments:

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

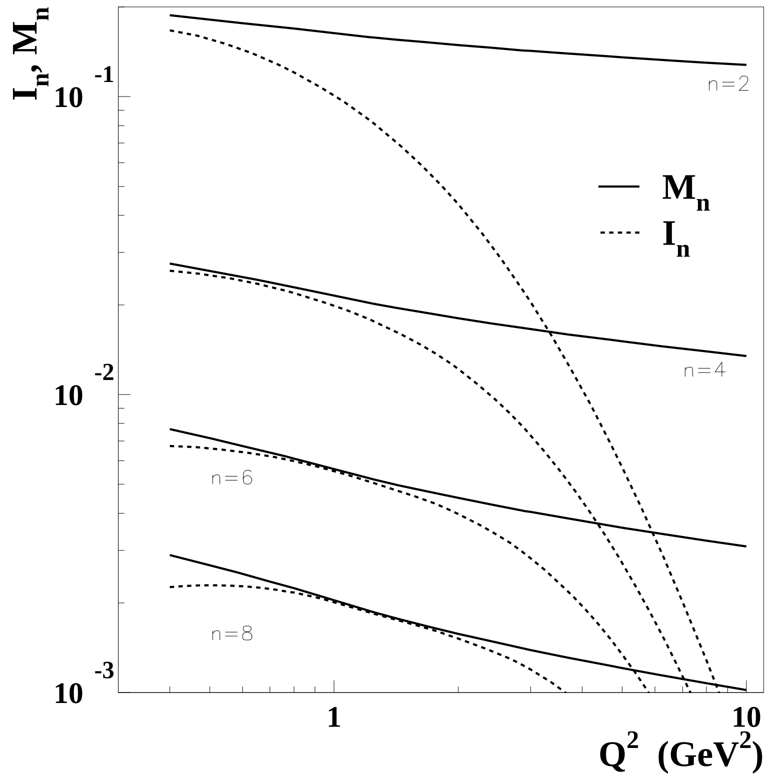
elastic contribution should be included
elastic contribution dominant for $Q^2 \leq 1$ GeV^2
need of experimental values of SF outside resonance region

b) Point by point comparison: SF vs Q^2 at specific x values
elastic contribution excluded by kinematic
ok for unpolarised SF because lot of data, NOT ok for polarised SF

c) Comparison between SF integrals in RES & DIS regions, in the same x interval
elastic contribution excluded by kinematic

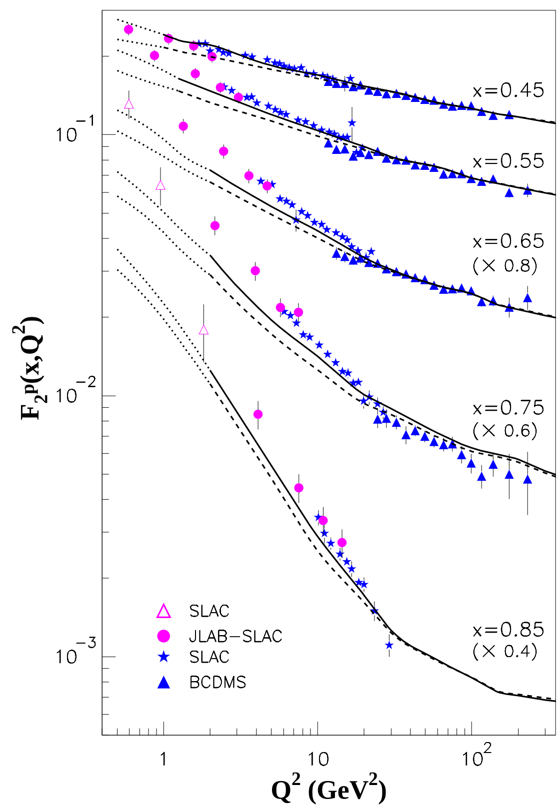
3 approaches (2)

a) Mellin moments



b) Point by point comparison

S. Liuti *et. al*, PRL 89 (2002) 162001



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

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

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

$$\tilde{\Gamma}_1^{\text{res}}(Q^2) = \int_{x_m}^{x_M} g_1^{\text{Res}}(x, Q^2)\, dx$$

$$\tilde{\Gamma}_1^{\text{DIS}}(Q^2) = \int_{x_m}^{x_M} g_1^{\text{DIS}}(x, Q^2)\, dx$$

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

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

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

- Resonance region can be described in terms of quark degrees of freedom
- Distinction between resonance & DIS region is somehow artificial

$\Longrightarrow$ Duality provides access to large x where DIS data suffer for low statistic

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

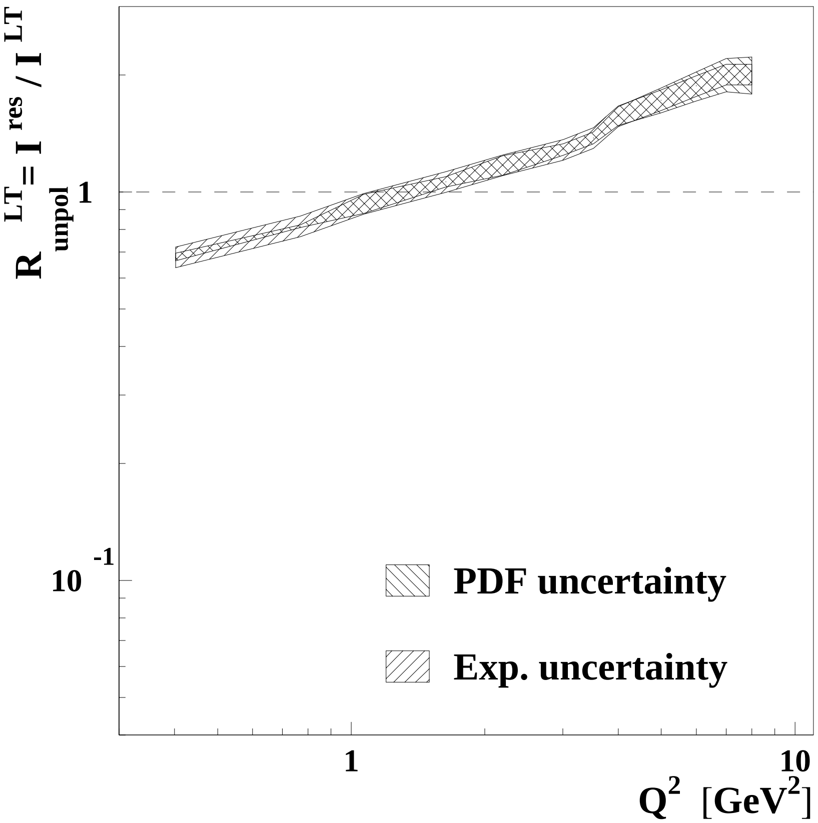
Starting point: NLO PDF for the unpolarised structure function F_2

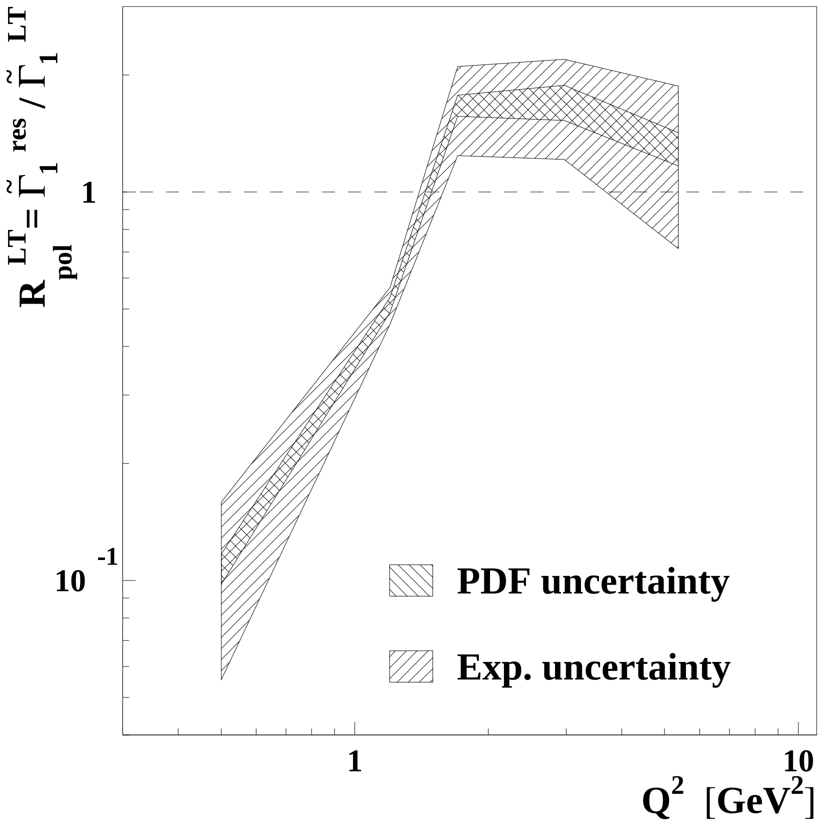
Practically - even under this assumption - corrections to the NLO analysis arise from:

- 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

F_2^{DIS} from PDF (LO & NLO)



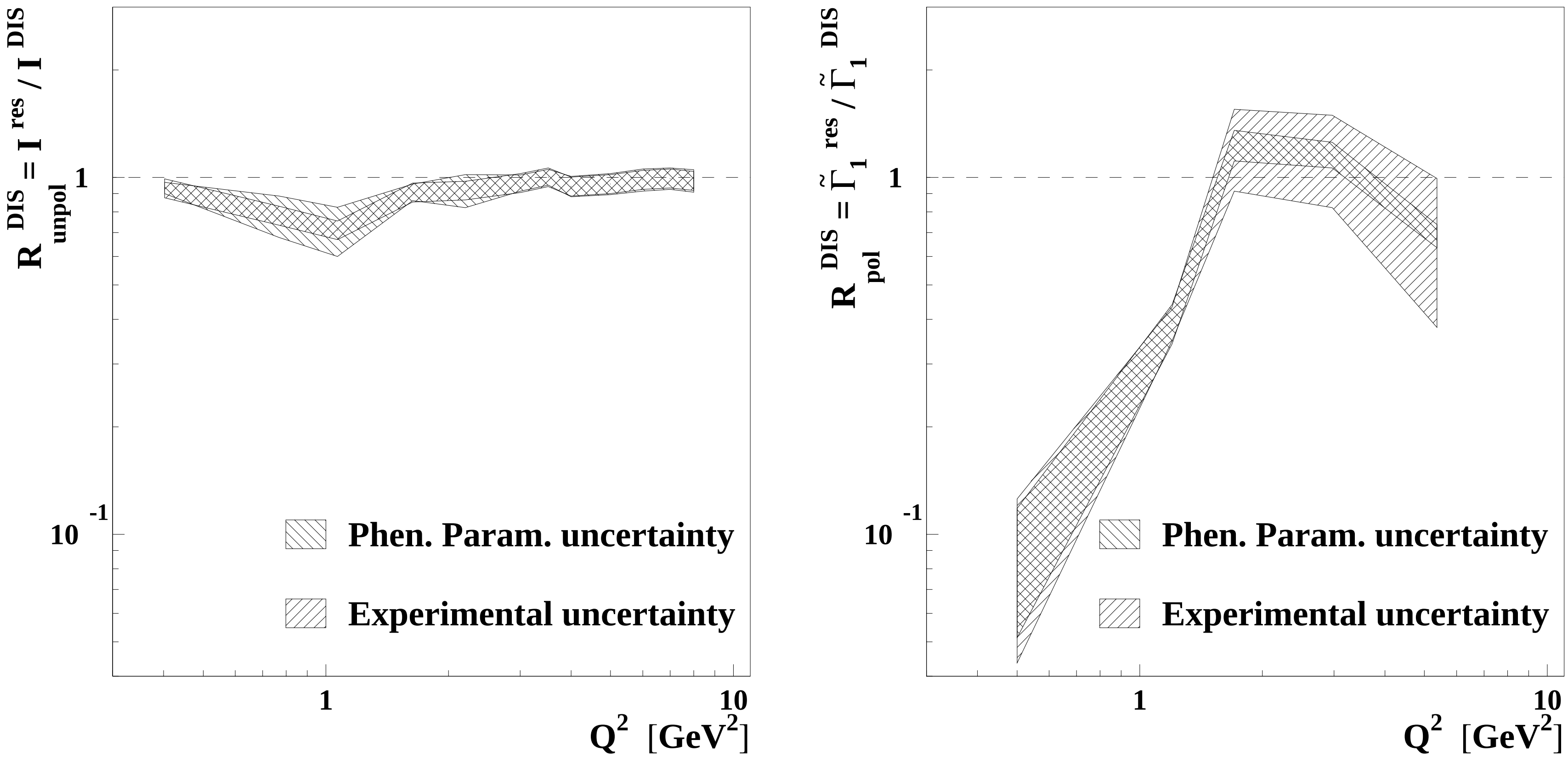


PDFs: MRST99, CTEQ5, GRV94 (LO & NLO), GRV98 (LO & NLO)

Quark-Hadron Duality NOT fulfilled by PDFs at LO or NLO

NLO PDF unable to reproduce large x region

$F_2^{\rm DIS}$ from Phenomenological Parameterisations



Phen. Parameterisations: ALLM97, NMC95, BY (GRV94mod)

Obtained by fitting DIS data even at low Q^2

$\Longrightarrow$ implicitely include non-perturbative effects

Non-perturbative Contributions

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

Quantitative analysis:

$\Rightarrow$ Disentangle Non Perturbative Contributions

Target Mass Corrections (TMC)

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

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

$F_2^{\infty}=F_2$ without TMC

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

Applied in a similar way to $g_1 = A_1 \cdot \frac{F_2}{2x(1+R)}$

Large x Resummation (1)

- First observed by Brodsky and Lepage, SLAC-REP224 (1979)
- Recently reconsidered by:
  1. R.G. Roberts Eur. Phys. Journal C 10 (1999) 697
  2. S. Liuti *et al.* PRL 89 (2002) 162001
  3. N. Bianchi, AF, S. Liuti PRD 69 (2004) 014505

Scattering from *off-shell* quark:

$$k_\mu^2 = x\left[M^2 - \frac{k_\perp^2 + M_X^2}{1-x} - \frac{k_\perp^2}{x}\right] \neq m^2$$

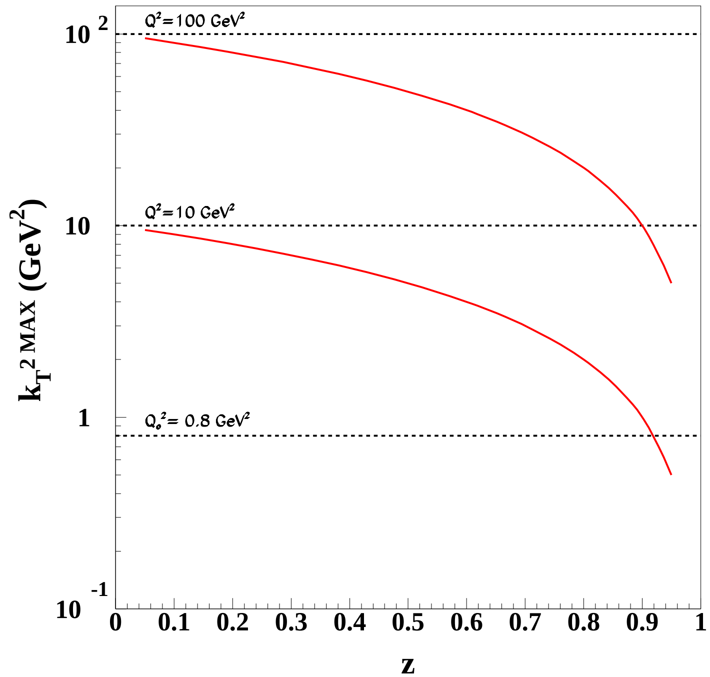
Large x Resummation (2)

Consequence:

Phase space for the parton's k_T

limited by $k^2_{T(MAX)} = Q^2(1-z)/z$

instead of $k^2_{T(MAX)} \approx Q^2$



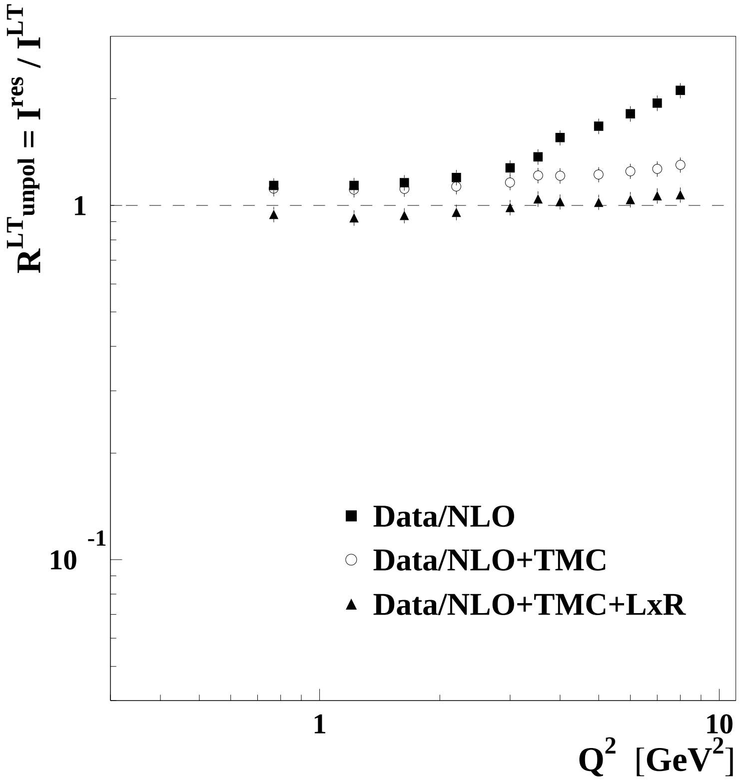
LxR terms arise from terms containing power of ln(1-z) terms in $C_{NS}(z)$

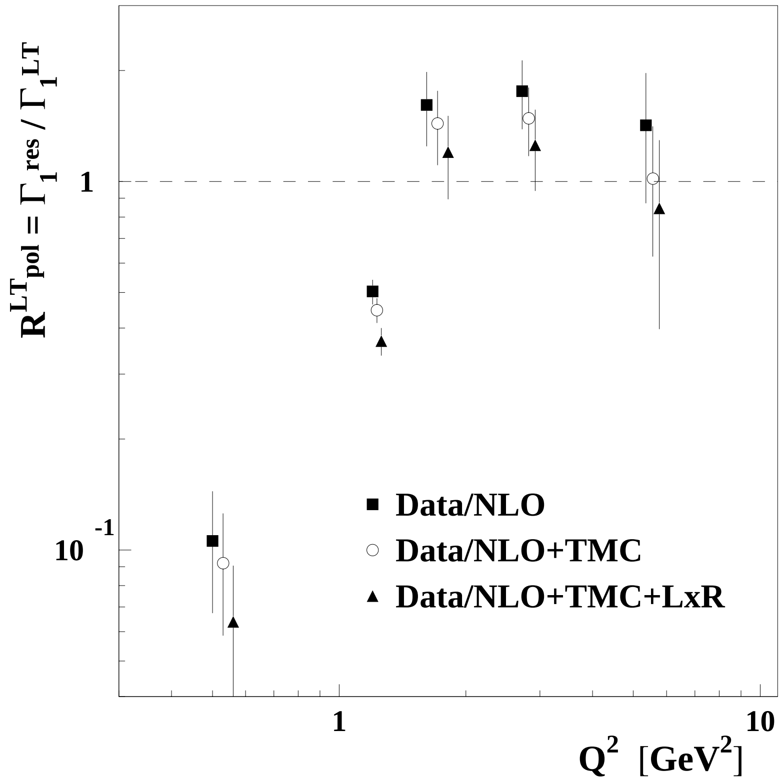
$$F_2^{NS}(x,Q^2) = \frac{\alpha_s}{2\pi} \sum_q \int_x^1 dz\, C_{NS}(z)\, q_{NS}(x/z,Q^2)$$

- z longitudinal variable in evolution equations; $C(z)$ Wilson coefficient functions
- only valence quark distributions relevant in this kinematic $\rightarrow F_2^{NS}$

$x \gg \Rightarrow C_{NS} \gg \Rightarrow$ $Q^2 \rightarrow Q^2(1-z)/z$ and $\alpha_S(Q^2) \rightarrow \alpha_S(Q^2(1-z)/z)$

Size of Non-perturbative Contributions

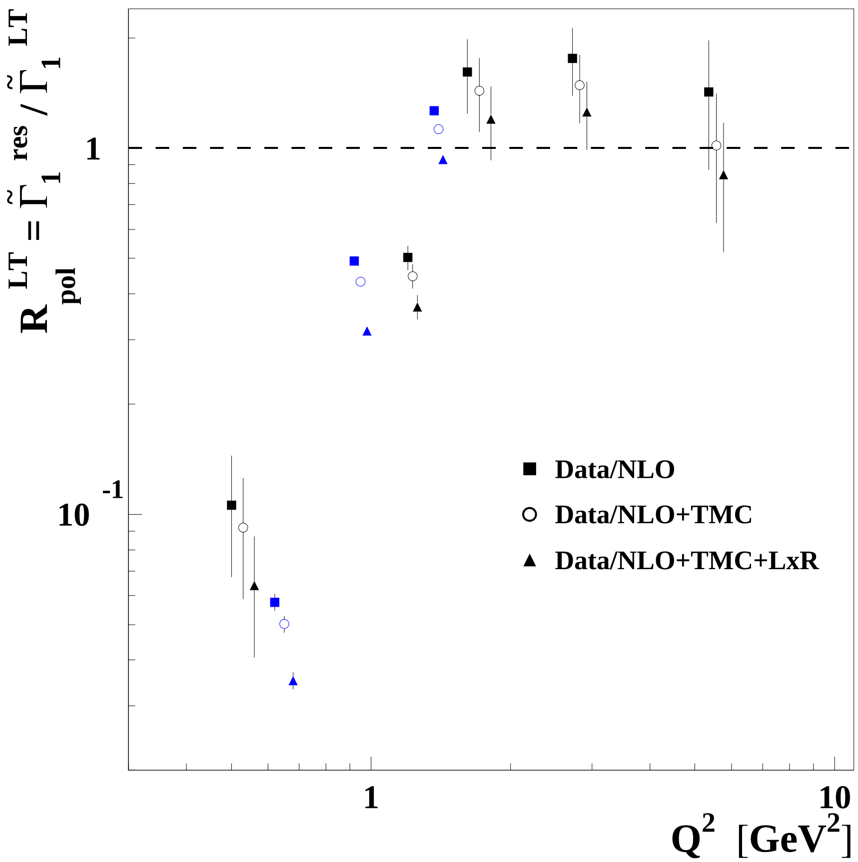


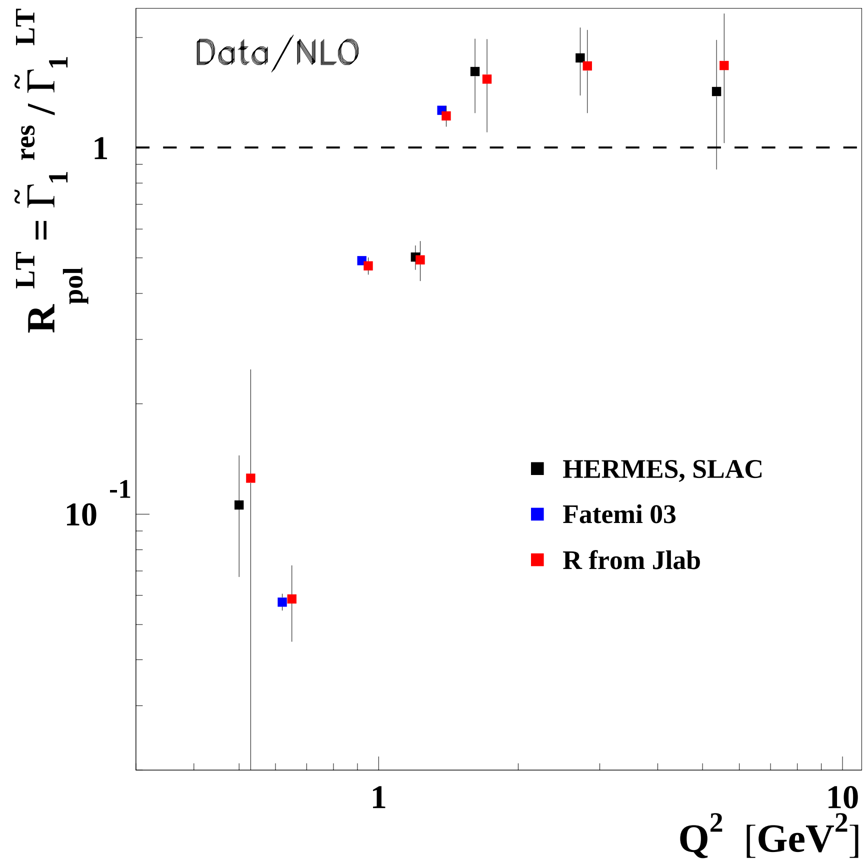


- Effects of Target Mass Correction (TMC) and Large x Resummation (LxR)
- Duality seems satisfied within ≈10% for $Q^2 \geq$1.5 GeV^2

⇒ Investigation of this 10% effect

Polarised case and data from Jlab

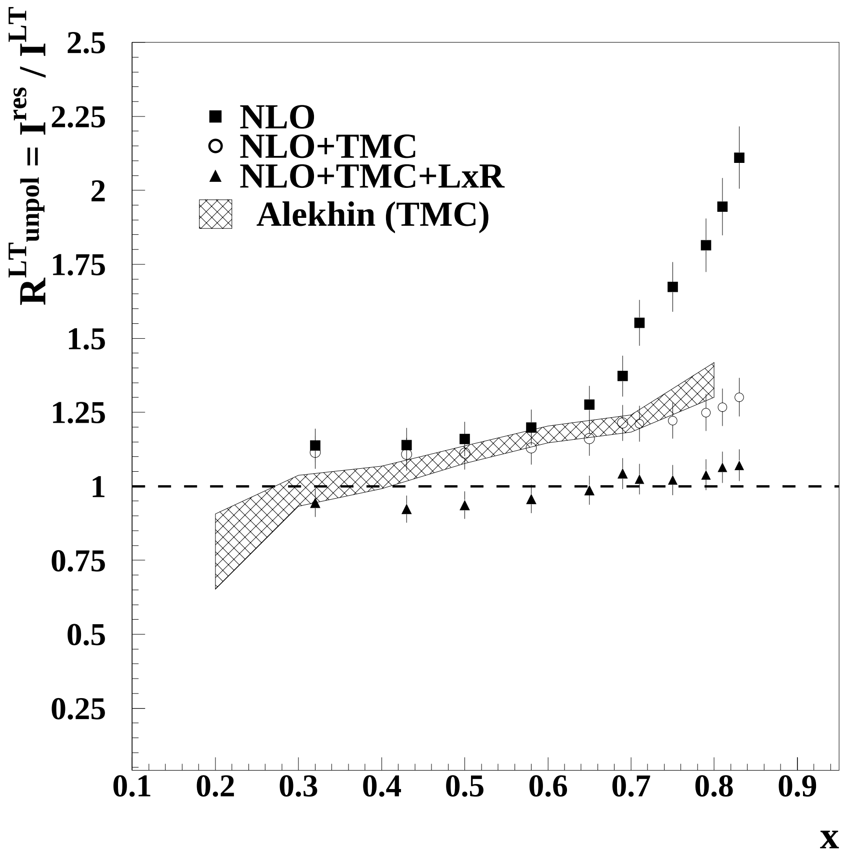


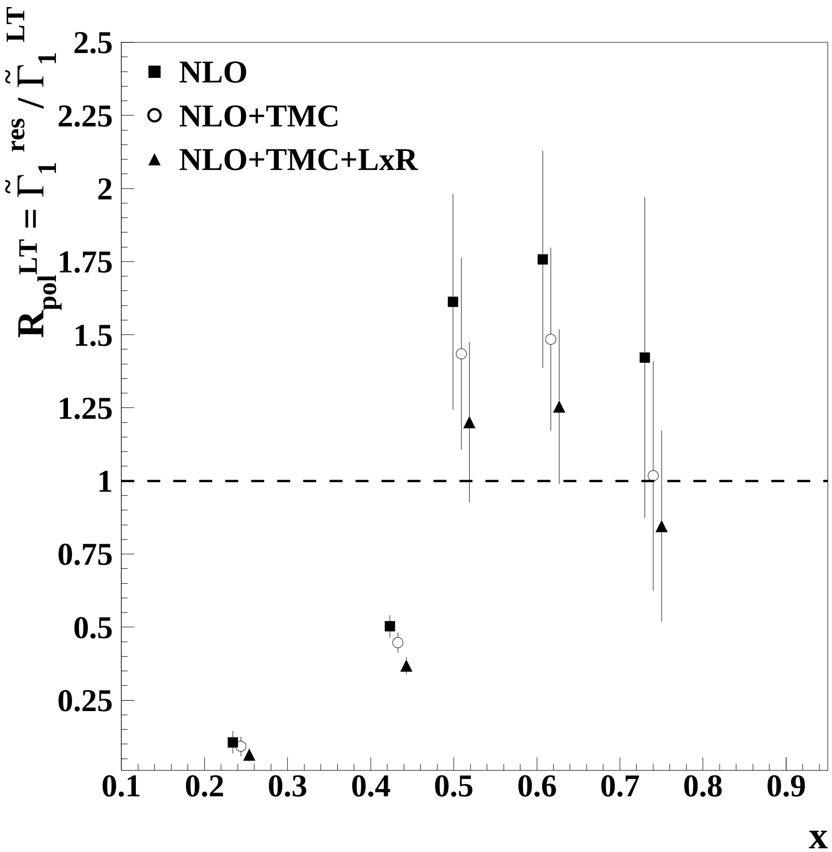


R. Fatemi *et al.*, PRL 91 (2003) 222002

E94110-data supplied by V. Tvaskis

x dependence of HT

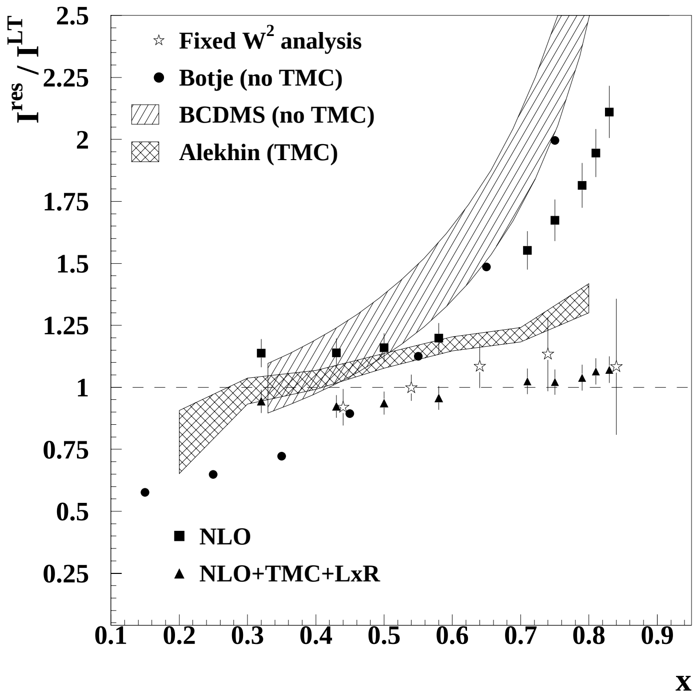


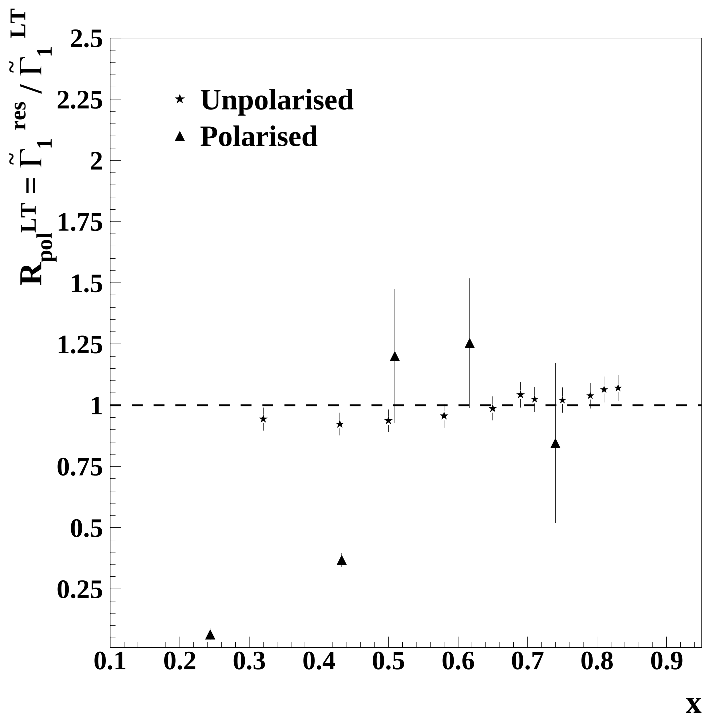


- NLO + TMC + LxR analysis → very small HT in whole x region
- Extracted values consistent with different method & more precise
- Different behaviour for HT at low Q^2

HT contributions

$$H(x,Q^2) = Q^2(F_2^{res}(x,Q^2) - F_2^{LT}); \qquad C_{HT} = \frac{H(x,Q^2)}{F_2^{pQCD}} \equiv Q^2 \frac{F_2^{res}(x,Q^2) - F_2^{LT}}{F_2^{LT}}$$

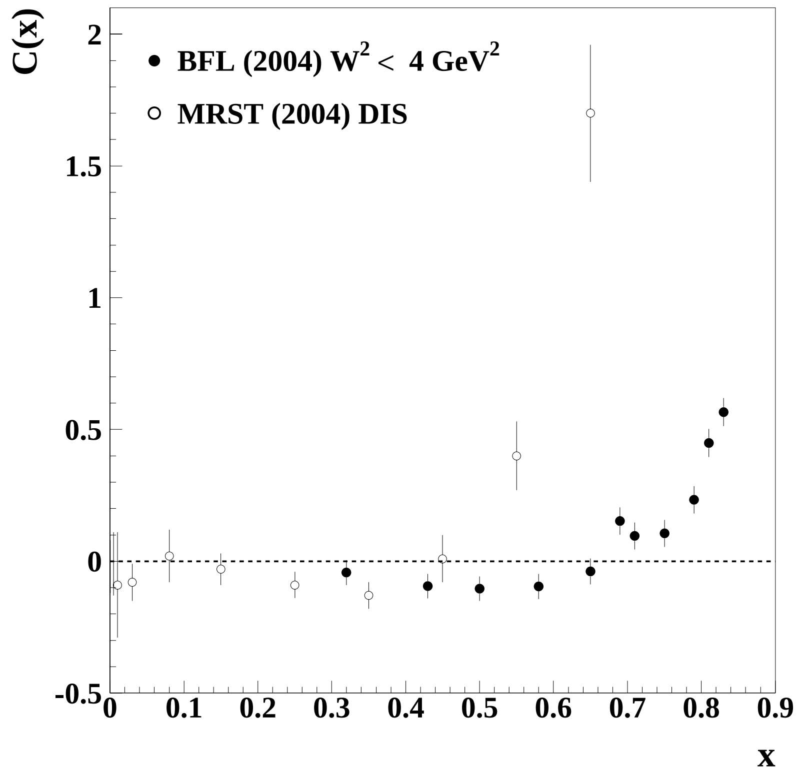


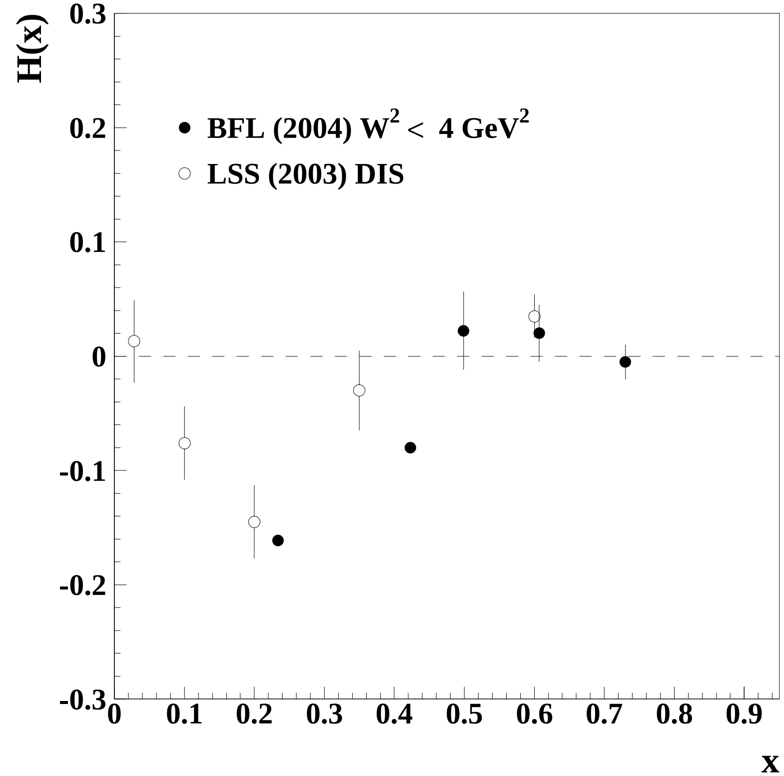


Comparison of HT from RES and from DIS (old analyses) at same x values

Low Q^2: $\mathrm{HT_{pol}}$ large and negative

HT contribution





$$F_2^{LT+HT} = F_2^{LT} \cdot \left(1 + \frac{C}{Q^2}\right)$$

high x: $C_{res}(x) \neq C_{DIS}(x)$

$$F_2^{LT+HT} = F_2^{LT} + \frac{H}{Q^2}$$

high x: few $H_{res}(x)$, no $H_{DIS}(x)$

$$C(x) = H(x)/F_2^{LT}$$

No Q^2 dependence in $C(x)$ and $H(x)$

Different behavior for unpolarised and polarised HT

Conclusions

- Quantitative analysis of Unpolarised and Polarised data compared with:
  - pQCD analyses using global PDF (GRV94, GRV98, CTEQ5, MRST99)
  - phenomenological fits with non-perturbative contributions (ALLM97, NMC95, BY (GRV94mod))

- Non perturbative contributions, TMC and LxR disentangled

- Duality seems satisfied within 10%

- Extraction of HT:

  1. Polarised $\neq$ Unpolarised
  2. RES $\neq$ DIS

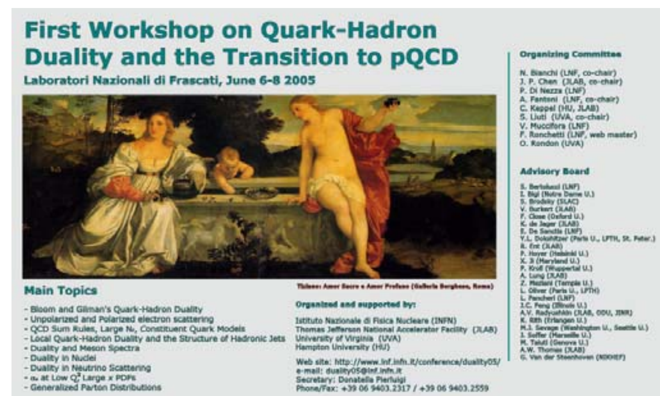
Outlook

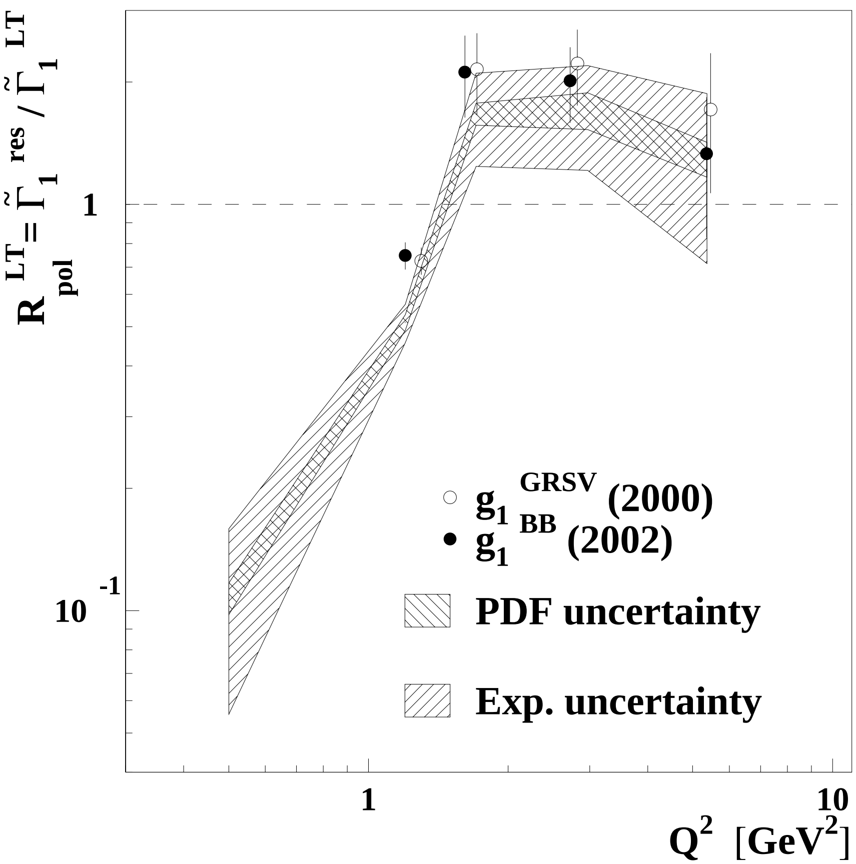
- Open questions:
  1. Are we unraveling new degrees of freedom more pertinent to the scale of the hadronization phase?
  2. Do we understand the Q^2 dep. in terms of a "standard" pQCD based scheme?
  3. Are we witnessing a breakdown on factorization?
  4. How are the smooth curves compared to the data? What are the best statistical estimators to be used?

- Many data from different reactions on proton, neutron, GDH, nuclei, semi-inclusive, photoproduction ... are available

- More e^+e^-, τ decays...to be explored

- Many new and promising results and theoretical approaches seen in the first dedicated workshop in June 2005




$R_{pol}^{LT} = \tilde{\Gamma}_1^{res} / \tilde{\Gamma}_1^{LT}$
1
10^{-1}
1
10
Q^2 [GeV^2]
g_1^{GRSV} (2000)
g_1^{BB} (2002)
PDF uncertainty
Exp. uncertainty