Structure Functions at High x

"Quarks, Color Neutral Clusters, and Hadrons"

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DIS 2005, XIII International Workshop on Deep Inelastic Scattering
Madison, Wisconsin, USA
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There is an intrinsic, accepted *"Statement of Duality"* in our current view of high energy phenomena:

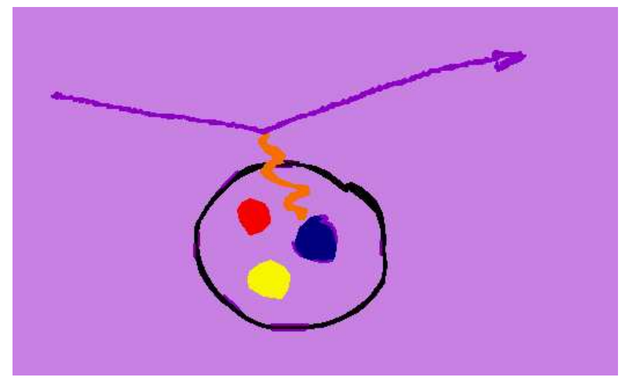
"The output of any high energy reaction is determined by the initial scattering process among elementary constituents.
The cross section factors out into a "short distance", perturbatively calculable part:

$\Rightarrow 1/Q << \textit{hadronic size}$

and a "large distance", measurable part,

$\Rightarrow 1/\Lambda_{QCD} \approx \textit{hadronic size}$

directly related to the quarks and gluons distribution inside the hadron."



The mechanism of transformation of partons into colorless hadrons, and vice versa modifies the final state

⇒ *partons get transformed, but not the cross section.*

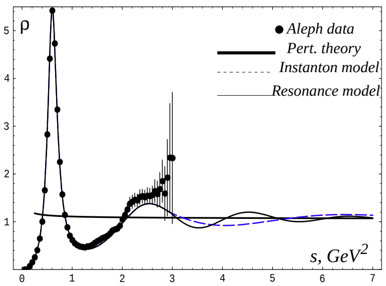
- $e^+e^- \to \text{hadrons} \equiv \sum_q (e^+e^- \to q\bar{q}) \Rightarrow$ $$\sigma_{hadrons} \equiv \sum_q \hat{\sigma}_q$$

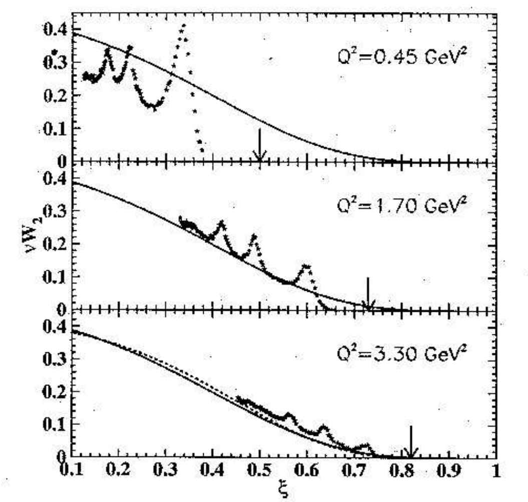
- $ep \to eX \Rightarrow$ $$d\sigma \approx \sum_q \int dx\, q(x, Q^2) d\hat{\sigma}_q$$

- $ep \to ehX \Rightarrow$ $$d\sigma \approx \sum_q \int dx\, q(x, Q^2) D_h(z, Q^2) d\hat{\sigma}_q$$

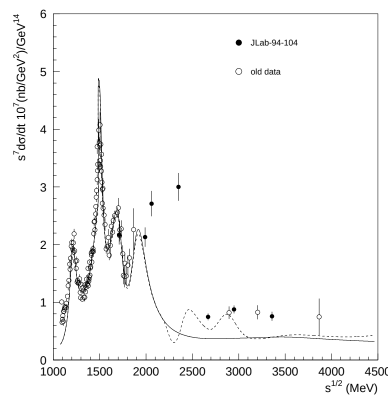
Overview of data

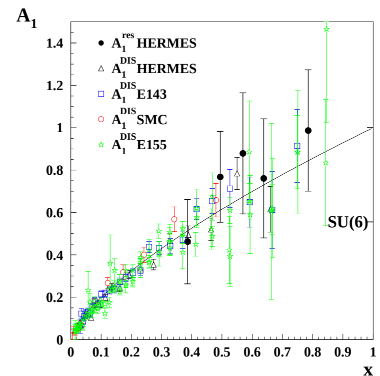
$\tau \rightarrow \nu + \text{hadrons}$

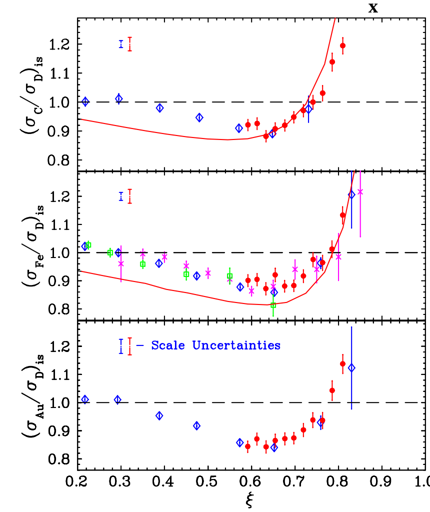




$\gamma p \rightarrow \pi^+ n$







The goal of parton-hadron duality studies

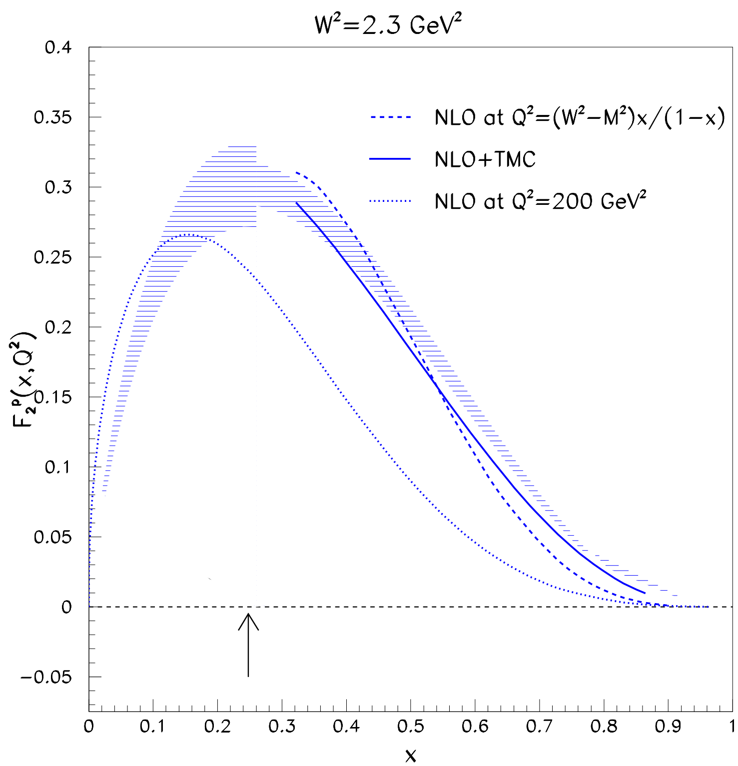
Duality a la' Bloom and Gilman was the observation that *qualitatively* the resonances are driven by a similar underlying picture

Modern studies of parton-hadron duality address the limits of validity of the factorization property of QCD, and its violations *(global and local)*

Passage from *qualitative* to *quantitative* picture

Quantitative Analysis of Bloom Gilman Duality in unpolarized ep scattering

S.L., R.Ent, C. Keppel and I. Niculescu, Phys. Rev. Lett. **89**, 162001 (2002).

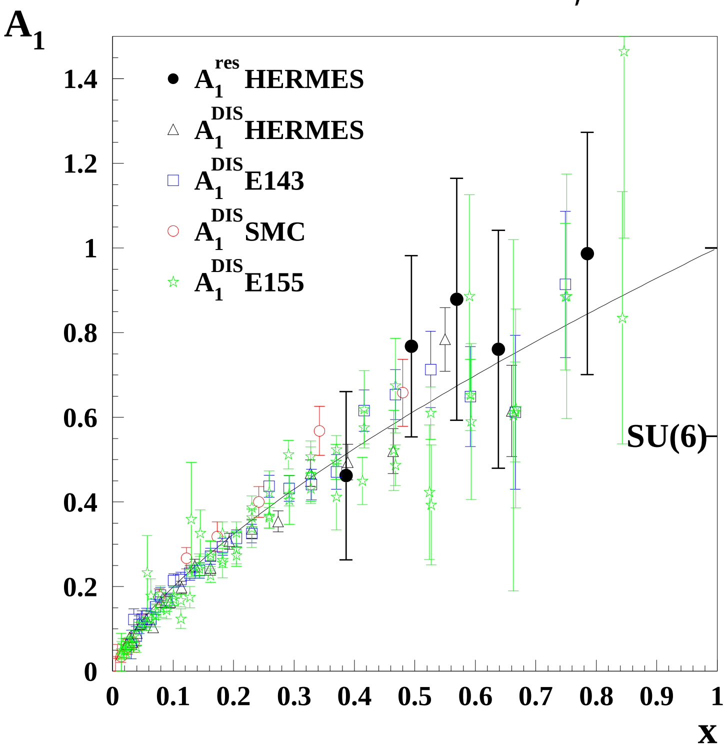


Continuing pQCD curve into the resonance region: a multi-step program

1. What theoretical curves are resonances dual to?
2. Is *factorization/dominance of partonic d.o.f.* still valid in the resonance region?
3. What accuracy is required for duality to be established?
4. $Practically$ – 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 Twists (HT) $\Rightarrow \mathcal{O}(1/Q^2)$
   - For the neutron: nuclear effects $\Rightarrow$ Leading Twist
   - Anything else ... ? $\Rightarrow$ beyond twist expansion
5. Important!! Corrections have to be applied consistently to *all* observables to guarantee universality.

New Analysis of Unpolarized & Polarized Data

N. Bianchi, A. Fantoni & S.L., Phys.Rev. **D69** 014505 (2004)



HERMES Coll., P.R.L. **90** (2003) 092002

$$g_1(x, Q^2) = \frac{F_1(x, Q^2)}{d'}\left[A_\parallel + \tan\theta/2 \cdot A_\perp\right]$$
$$\approx A_1(x) F_1(x, Q^2)$$

$$A_\parallel = D(A_1 + \eta A_2)$$

$$A_\perp = d(A_2 - \zeta A_1)$$

$$A_2 \approx 0.06$$

Average over the Resonances

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

$$F_2^{\mathrm{res}}\left(x, Q^2(x, W^2)\right) = F_2^{\mathrm{par}}(\xi, W^2)$$

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

Duality Ratios

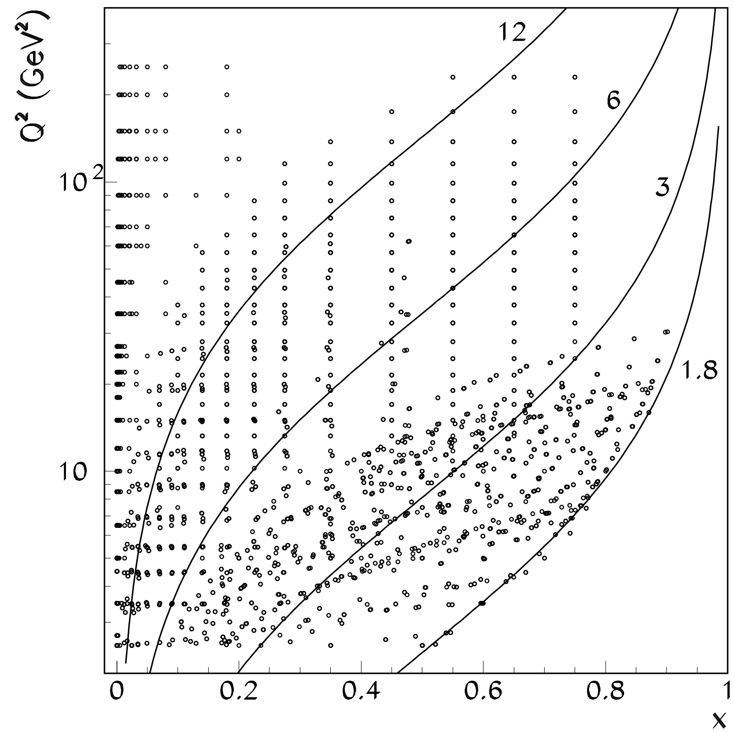
$$R_A(\langle x \rangle, Q^2) = \frac{I^{\rm res}(\langle x \rangle, Q^2)}{I^{\rm DIS}(\langle x \rangle, Q^2)}$$

$$R_B\left(x, Q^2(W^2)\right) = \frac{F_2^{\rm par}(\xi, W^2)}{F_2^{\rm DIS}(x, W^2)}$$

$$R_C(Q^2) = \frac{M_n^{\rm res}(Q^2)}{M_n^{\rm DIS}(Q^2)}$$

- $I^{\rm DIS}$, $F_2^{\rm DIS}(x, Q^2)$, and $M_n^{\rm DIS}(Q^2)$ are extrapolations of DIS data, based on global parametrizations, to the resonance region.

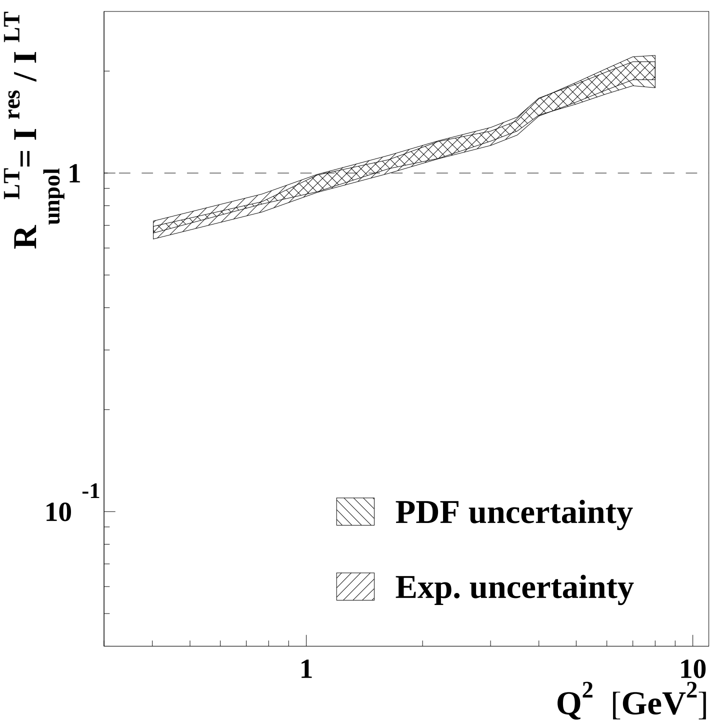
DIS Kinematical Coverage

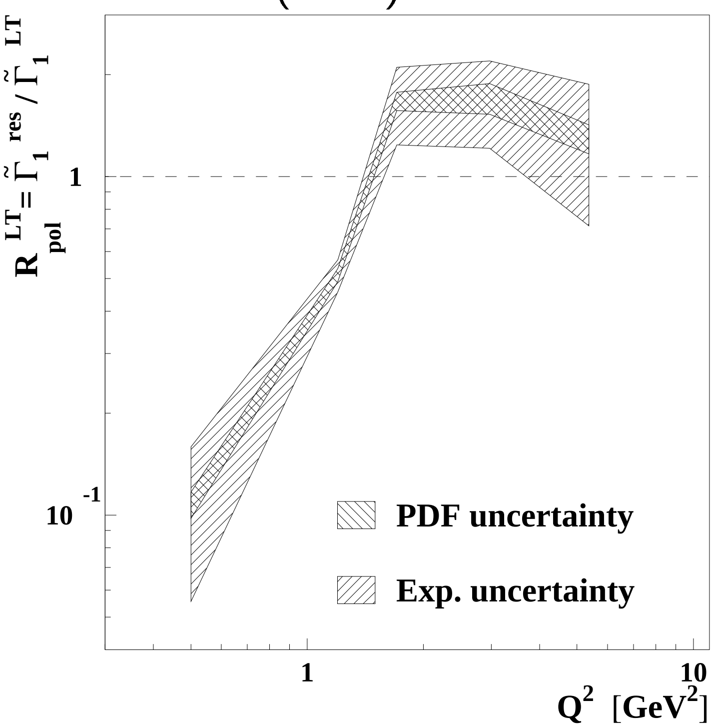


S. Alekhin, S. Kulagin, and S.L., Phys. Rev. **D69**, 114009 (2004)

Comparison with Extrapolations of NLO Parton Distribution Functions

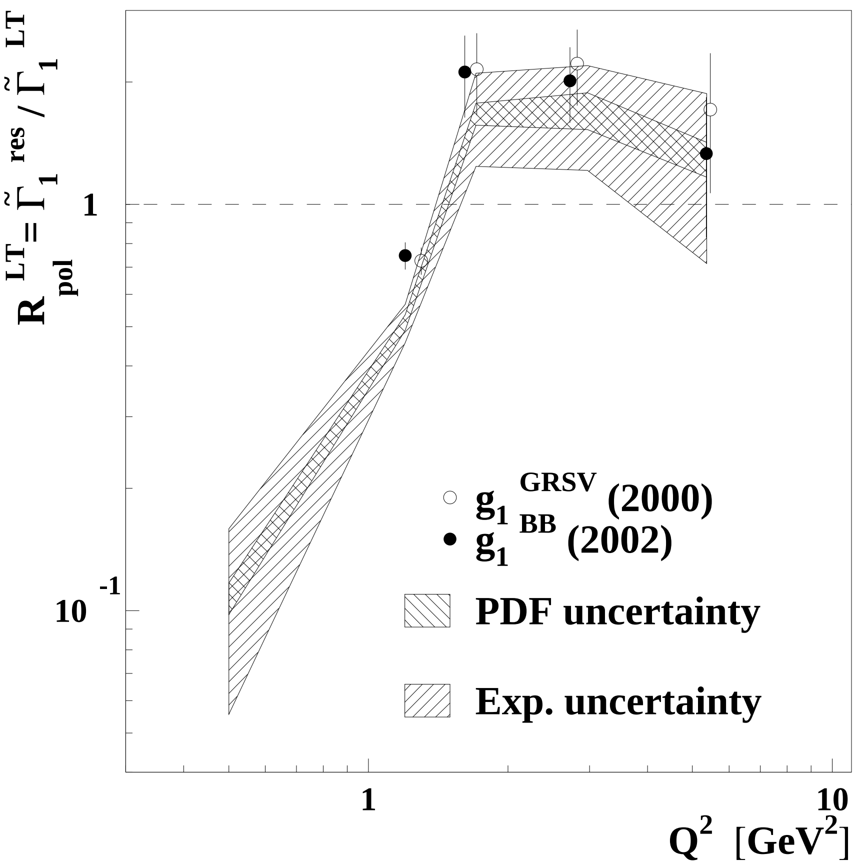
N. Bianchi, A. Fantoni & S.L., Phys.Rev. **D69** 014505 (2004)





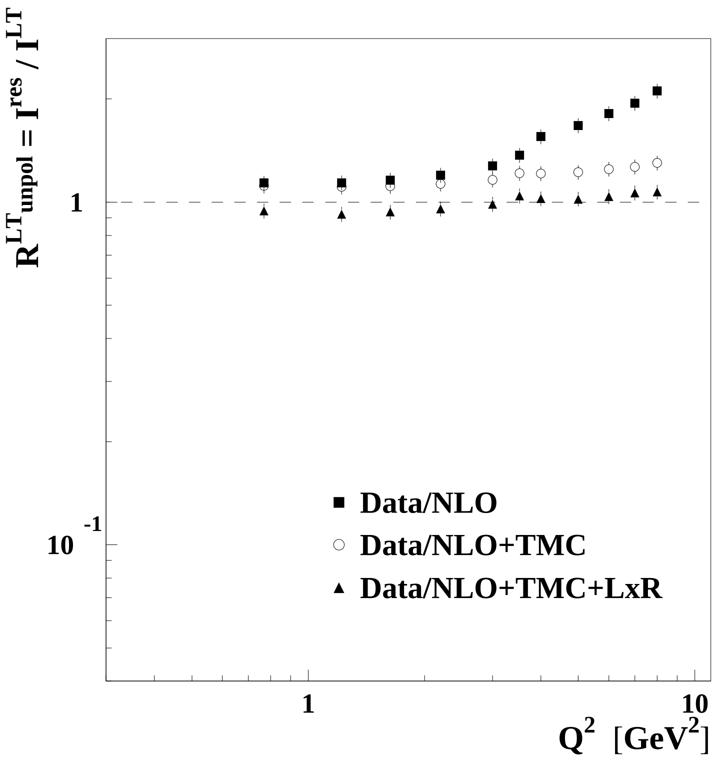
$$\frac{I^{res}}{I^{DIS}} = \frac{\int_{x_{\min}}^{x_{\max}} F_2^{res}(x,Q^2)\, dx}{\int_{x_{\min}}^{x_{\max}} F_2^{pQCD,NLO}(x,Q^2)\, dx}$$

$$\frac{\widetilde{\Gamma}^{res}}{\widetilde{\Gamma}^{DIS}} = \frac{\int_{x_{\min}}^{x_{\max}} g_1^{res}(x,Q^2)\, dx}{\int_{x_{\min}}^{x_{\max}} g_1^{pQCD,NLO}(x,Q^2)\, dx}$$

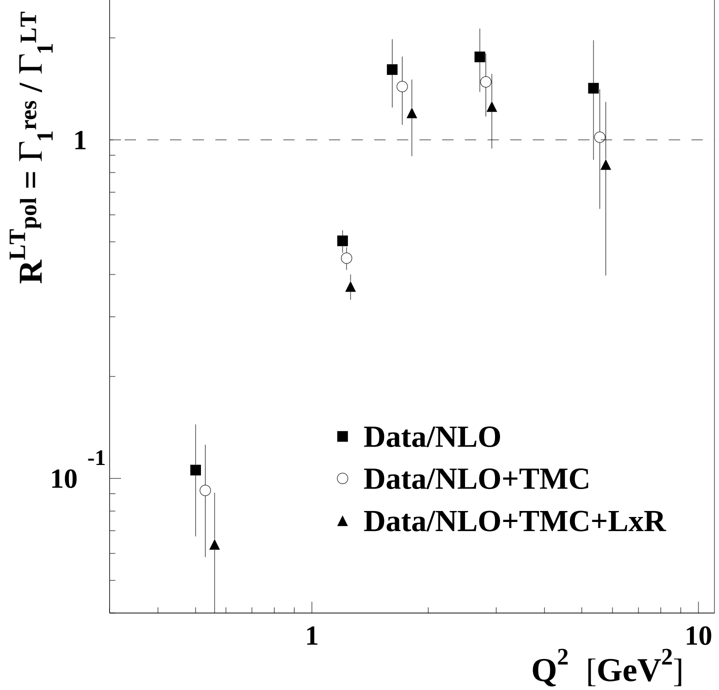


$R_{pol}^{LT} = \tilde{\Gamma}_1^{res} / \tilde{\Gamma}_1^{LT}$
1
10^{-1}
g_1^{GRSV} (2000)
g_1^{BB} (2002)
PDF uncertainty
Exp. uncertainty
1
10
Q^2 [GeV^2]

Breakdown of Contributions to Q^2 dependence

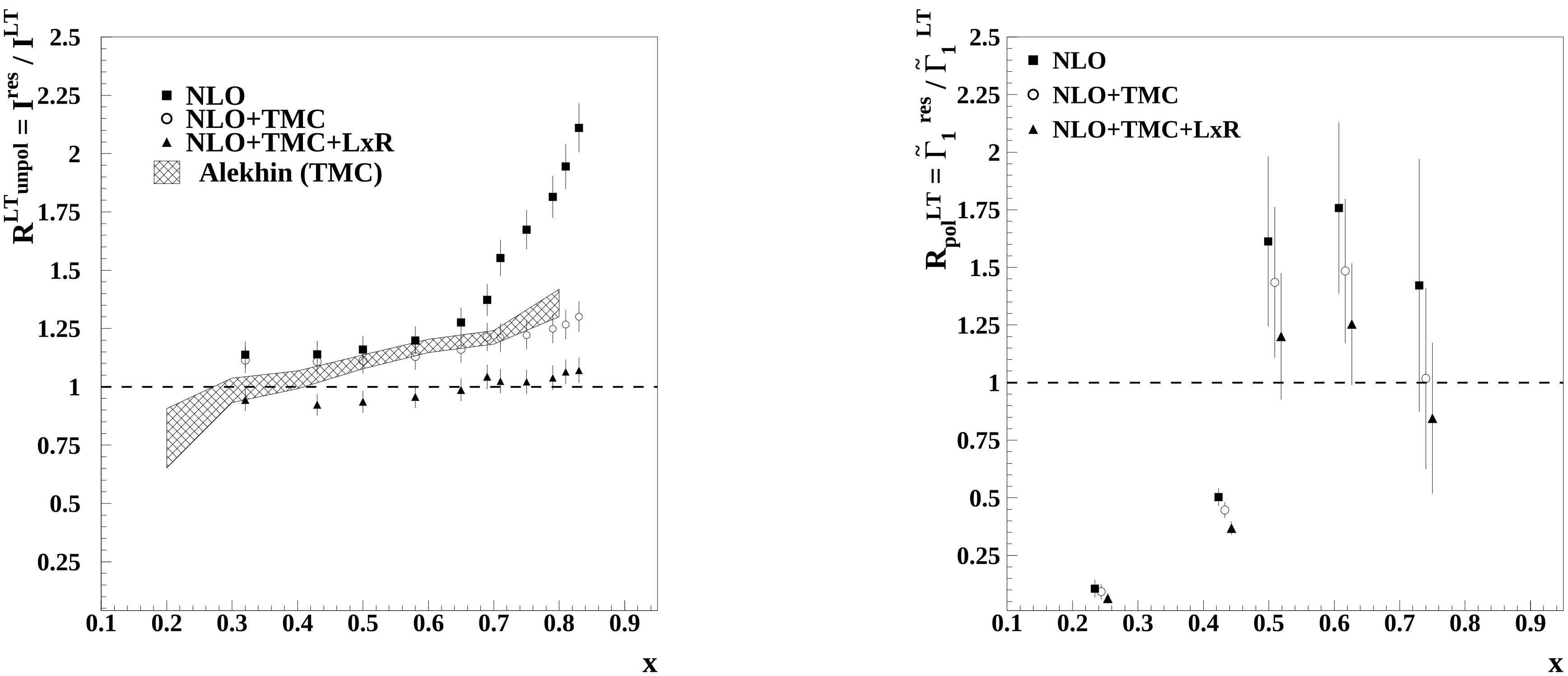


$$\frac{I^{res}}{I^{DIS}} = \frac{\int_{x_{\min}}^{x_{\max}} F_2^{res}(x,Q^2)\, dx}{\int_{x_{\min}}^{x_{\max}} F_2^{pQCD,NLO}(x,Q^2)\, dx}$$

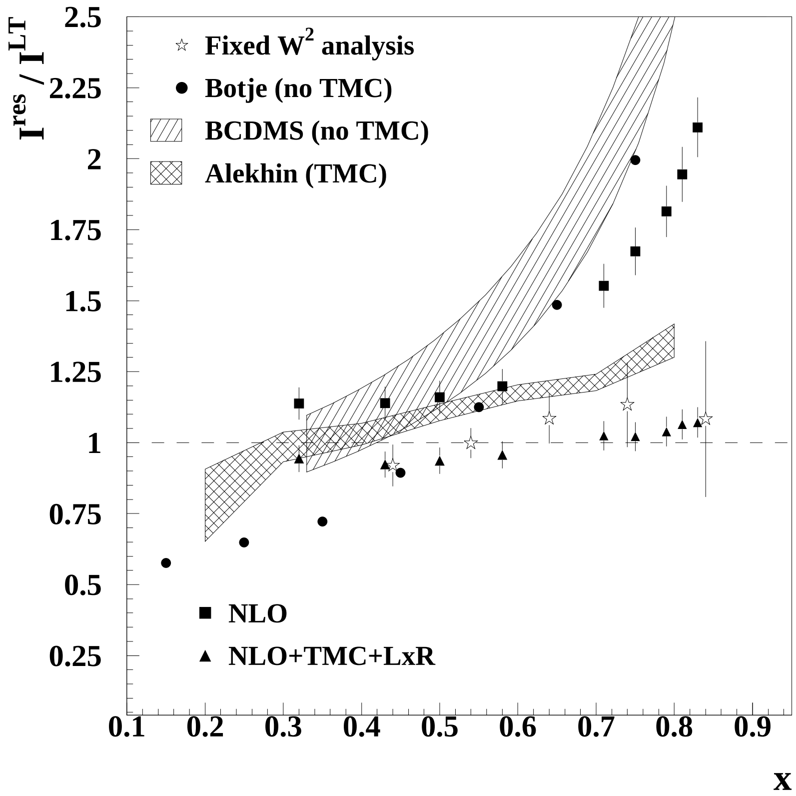


$$\frac{\widetilde{\Gamma}^{res}}{\widetilde{\Gamma}^{DIS}} = \frac{\int_{x_{\min}}^{x_{\max}} g_1^{res}(x,Q^2)\, dx}{\int_{x_{\min}}^{x_{\max}} g_1^{pQCD,NLO}(x,Q^2)\, dx}$$

Extraction of HTs, part 1



Comparison with other extractions of HT terms

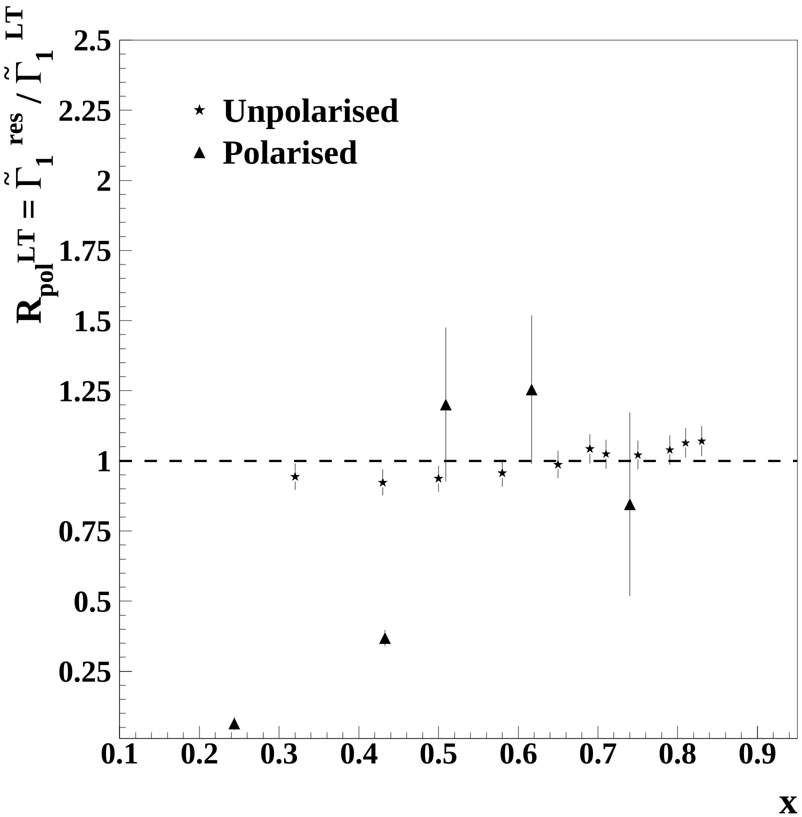


$$R(x,Q^2) = \frac{F_2^{exp}}{F_2^{LT}}$$

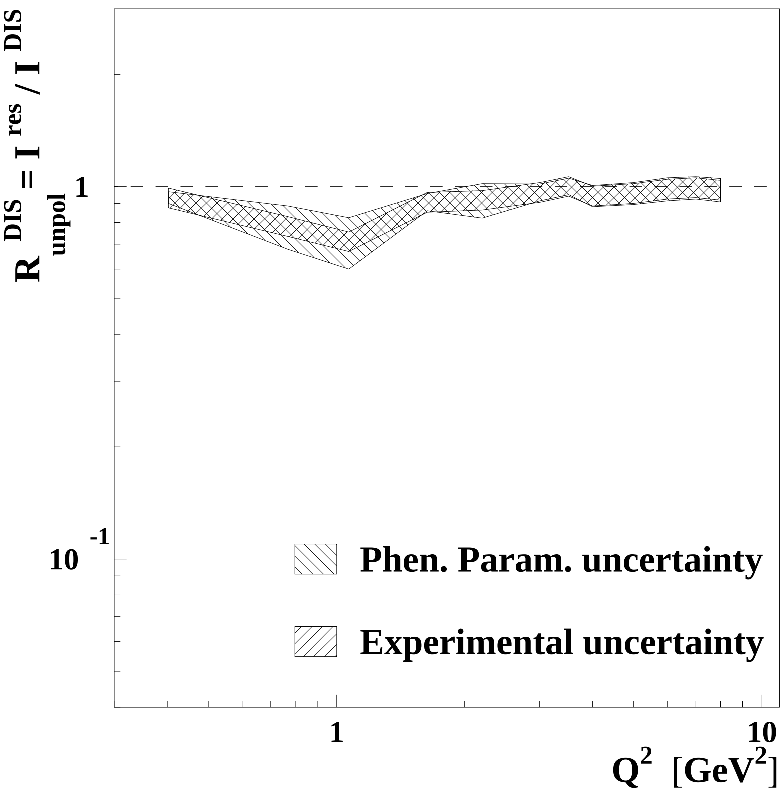
$$= \frac{F_2^{LT} + H/Q^2}{F_2^{LT}}$$

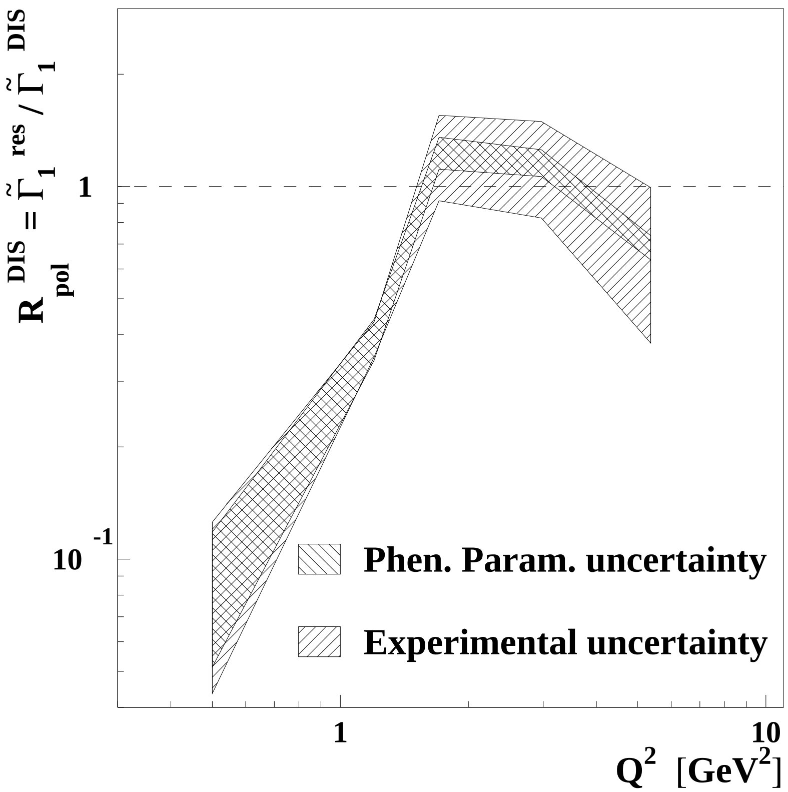
$$= 1 + \left[\frac{H}{F_2^{LT}}\right]\frac{1}{Q^2}$$

Comparison of HT terms in polarized and unpolarized

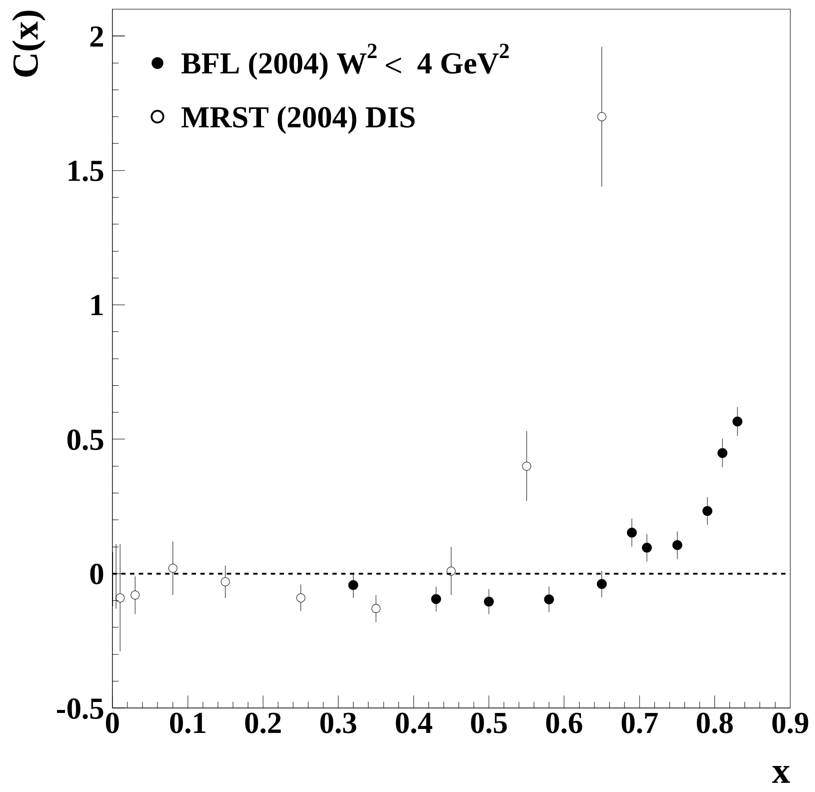


Comparison with Phenomenological Parton Distribution Functions including extra non – "pQCD-inspired" – Q^2 dependence





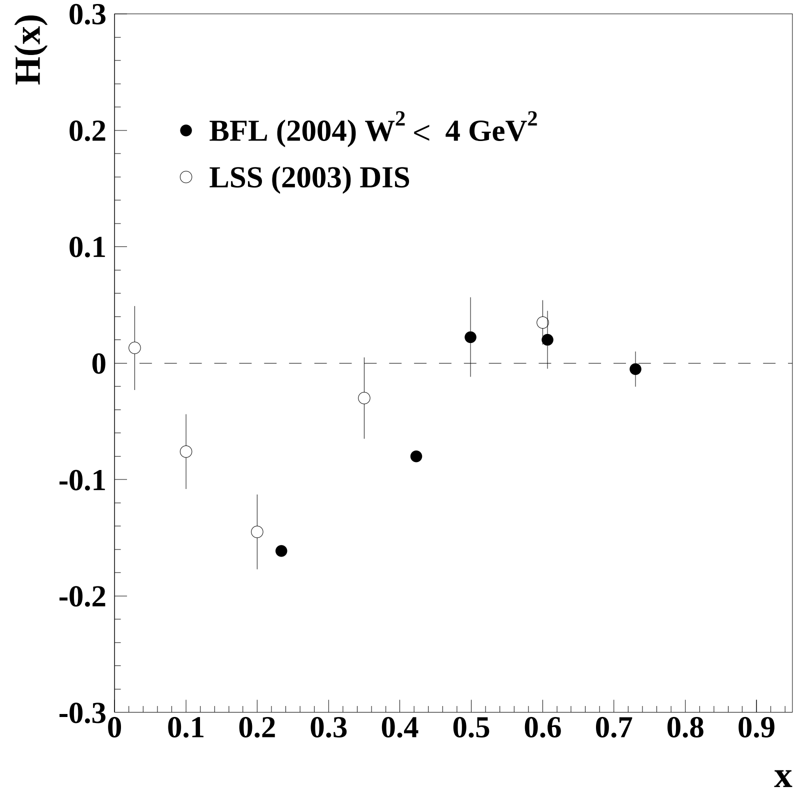
NEW WORK IN PROGRESS (BFL, 2005)
Comparison of HT terms in Resonance and DIS Regions



$$R(x, Q^2) = 1 + \frac{C(x)}{Q^2}$$

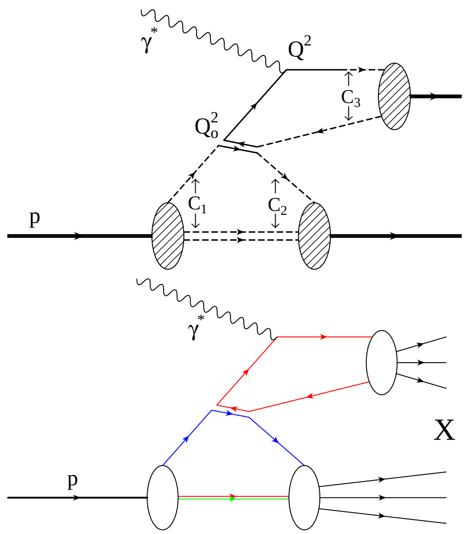
$$C(x) = H/F_2^{LT}$$

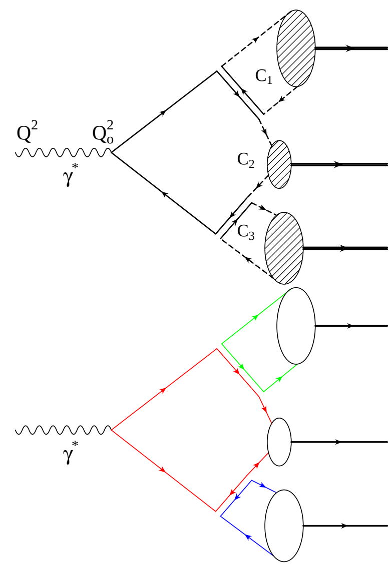
Polarized case



Quarks → Color Neutral Clusters → Hadrons

QCD at Large N_c



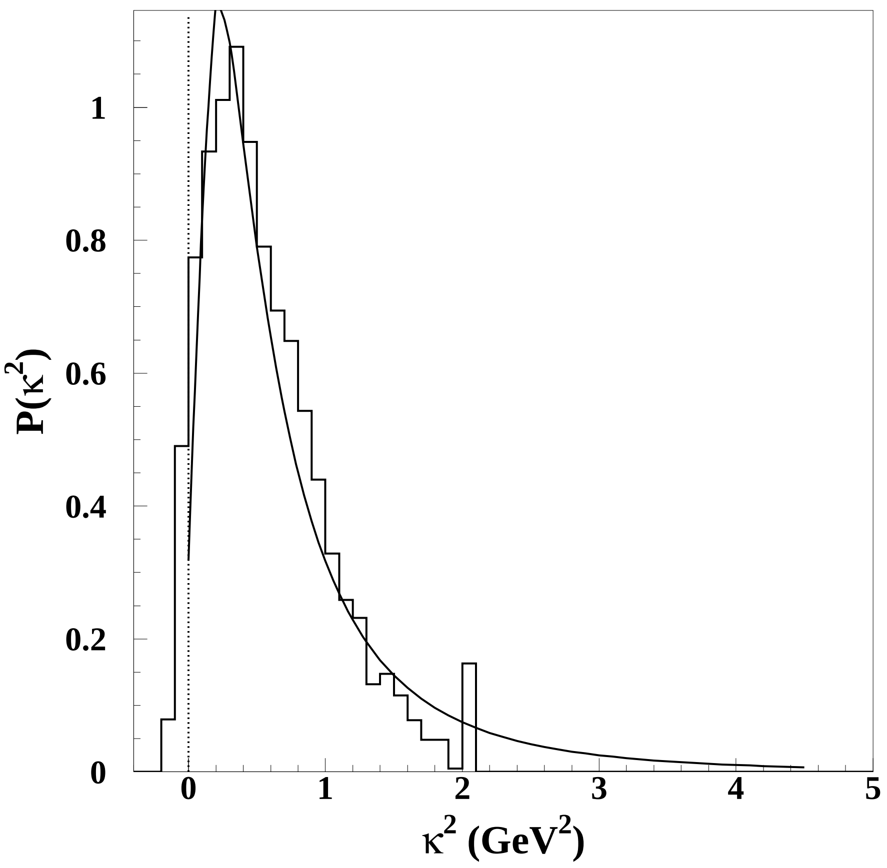


$$F_2^p(x,Q^2) = \sum_c \int d\kappa^2 \int_x^1 dz\, P_c(z,\kappa^2)\, F_2^c\left(\frac{x}{z}, Q^2, \kappa^2\right)$$

$$P_c(z,\kappa^2) = \widetilde{P}(\kappa^2) G_c(z)$$
$$G_c(z) = A_1 z^{A_2}(1-z)^{A_3}$$
$$F_2^c(x/z, Q_o^2) = \delta(1 - x/z)$$

$$F_2^p(x,Q^2) = \sum_c \int d\kappa^2 \int_x^1 dz\, G_c(z)\, F_2^c\left(\frac{x}{z}, Q^2\right)$$

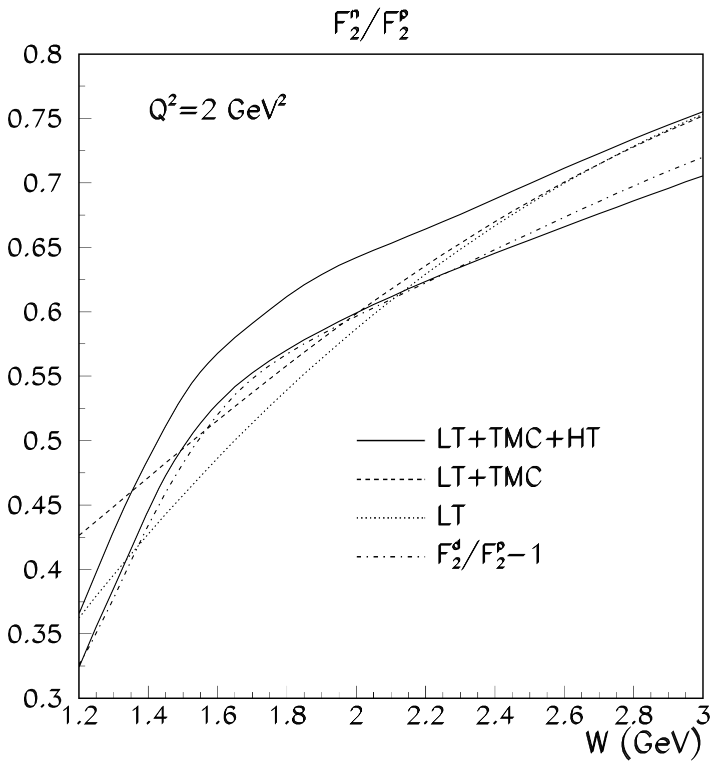
$$lim_{W^2>>\kappa^2} \rightarrow \widetilde{P}(\kappa^2) \approx \delta(\kappa^2 - \kappa_0^2)$$



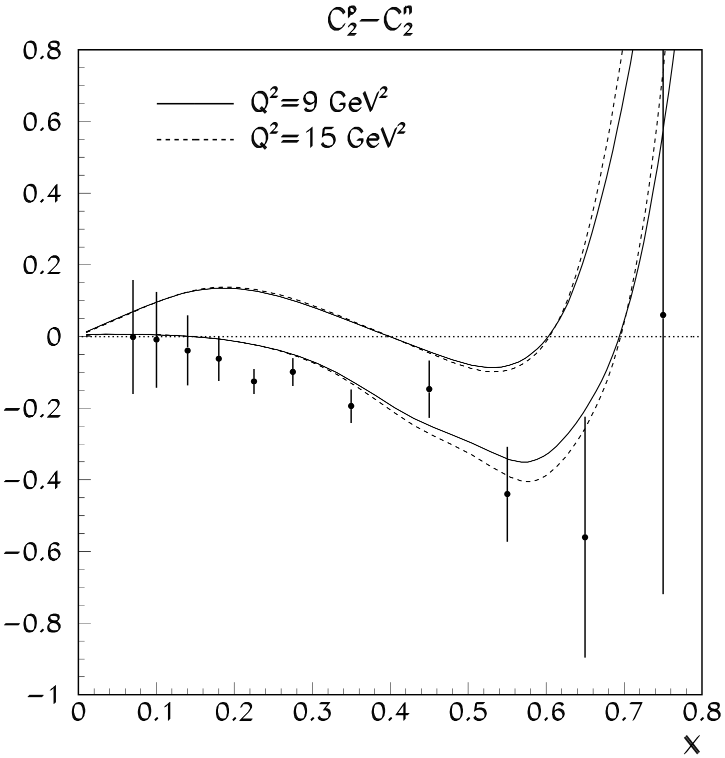
1
0.8
0.6
0.4
0.2
0
P(κ²)
0
1
2
3
4
5
κ² (GeV²)

Isospin Dependence of HTs

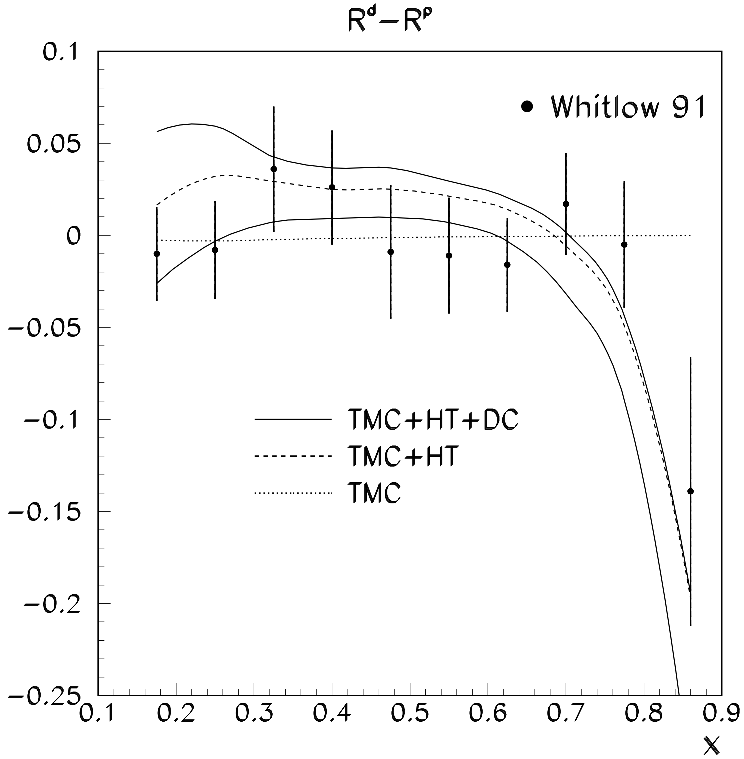
S. Alekhin, S. Kulagin, and S.L., Phys. Rev. **D69**, 114009 (2004)



Global Analysis +
Accurate Subtraction of Nuclear Effects in Deuteron



$C_2^p - C_2^n$
Q^2=9 GeV^2
Q^2=15 GeV^2
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
x



$R^d - R^p$
Whitlow 91
TMC+HT+DC
TMC+HT
TMC
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
−0.25
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
x

Conclusions, Open Questions, and Outlook

- Conclusions
  - All recent accurate measurements in the resonance region (Jlab, HERMES, COMPASS,...) are extremely interesting.
  - Ongoing investigations of duality and its violations – the exclusive inclusive connection – within a QCD context are an important addition to studies of the structure of hadrons (*transversity issue...*)
  - There are uncertainties in the extrapolations to the resonance region, that we quantify by means of a "discrepancy in the HT term".
  - Currenlty these uncertainties are too large to guarantee a meaningful extraction of PDFs at large x including resonant data.

- Open Questions
  - Are we unraveling new degrees of freedom more pertinent to the scale of the hadronization phase?
  - How do we go about to study this phase?
  - Do we understand the Q^2 dependence in terms of a “standard” pQCD based scheme?
  - Are we witnessing a breakdown on factorization?
  - How are the smooth curves compared to the data? What are the best statistical estimators to be used?

- Outlook
  - Many different observables, proton, neutron and GDH, nuclei, semi-inclusive reactions, need to be further studied to ascertain the universality and nature of the phenomenon.
  - **Jlab at 12 GeV !!!!**
  - More studies are certainly needed

  Workshop in Frascati, June, 6th-8th, 2005

  Will bring together researchers in different areas of hadronic physics, dealing with different manifestations of quark-hadron duality.

Duality 2005 - Microsoft Internet Explorer

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First Workshop on Quark-Hadron Duality and the Transition to pQCD

Laboratori Nazionali di Frascati, June 6-8 2005

Amor Sacro ed Amor Profano: oil on canvas (118 x 279 cm) by Tiziano Vecellio 1515-16 (Galleria Borghese, Roma).

Aim of the Workshop

The aim of this workshop is to discuss recent and existing results, and to foster current and future research, investigating the phenomenon of quark-hadron duality.
Whereas perturbative QCD methods fully describe experimental results at high energies, and chiral perturbation theory is the low energy effective theory of the strong interactions, a for of duality is observed transcending these two regimes. In these intermediate kinematics, a wide variety of reactions are observed which can be described simultaneously by single particle (quark) scattering, and by exclusive resonance (hadron) scattering. This dedicated workshop is aimed at bringing together for the first time researchers from different areas of hadronic physics, dealing with different manifestations of quark-hadron duality, to address as one group this exciting topic.

Scientific Program

- Recent Results on Bloom and Gilman's Quark-Hadron Duality: Unpolarized and Polarized electron-nucleus scattering
- Theoretical approaches: QCD Sum Rules, Large N_c, Constituent Quark Models, Other...