Measurements of $F_2$ at large $x$

Simona Malace

Hampton University/Bucharest University

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Outline

- Quark-hadron duality
- Physics motivation for E00-116
- $F_2^p$ at high $x$ from E00-116 data
Bloom-Gilman duality

’70- Bloom and Gilman observed that the prominent resonances in e-p scattering do not disappear with increasing $Q^2$ relative to the “background” under them but follow the DIS scaling limit curve falling at roughly the same rate as any “background”.

Finite energy sum rule:

$$\frac{2M}{Q^2} \int_0^{\nu_m} \nu W_2(\nu, Q^2) d\nu = \int_1^{(2Mv_m+m^2)/Q^2} \nu W_2(\nu') d\nu'$$

’76- A QCD based explanation by de Rujula Georgi and Politzer: in the resonance regime the higher twist effects are small or cancel → duality
Duality in the $F_2$ Structure Function

Use Bjorken $x$ instead of Bloom-Gilman’s $ω'$. Empirically, DIS region is where logarithmic scaling is observed: $Q^2 > 5$ GeV$^2$, $W^2 > 4$ GeV$^2$

Duality: Averaged over $W$, logarithmic scaling observed to work also for $Q^2 > 0.5$ GeV$^2$, $W^2 < 4$ GeV$^2$, resonance regime (note: $x = Q^2/(W^2-M^2+Q^2)$)

JLab results: Works quantitatively to better than 10% at surprisingly low $Q^2$
Quantification: Resonance Region $F_2$ w.r.t. Alekhin NNLO Scaling Curve

$(Q^2 \sim 1.5 \text{ GeV}^2)$

Difference between Alekhin NNLO curve (formed from lepton-nucleon scattering only) and resonance data, integrated for many spectra

$E=4 \text{ GeV}, \theta=24 \text{ Deg}$

$\Delta F_2$

$I(\text{data-scaling curve})$

LT+TMC+HT

incomplete $W$ region

$\int_{Q^2 < 1 \text{ GeV}^2} (\text{data-extr}) \, dW$ (GeV)

$W$ (GeV)

$N$ of spectra

$f=-0.0012 \pm 0.0066$
With increasing $Q^2$ the resonances slide towards higher $x$ on *ALLM97* curve while pdf curve $\text{MRST+NNLO+TMC}$ starts undershooting the data.

*Higher $Q^2/x$ data needed to get more information ...*
**E00-116 physics motivation**

- **Resonance data**
- **High x**

Embeds higher moments

\[ M_n(Q^2) = \int_0^1 dx \ x^{n-2} F(x,Q^2) \]

- **Higher twist extraction**
- **High x pdf evolution**
- **\( F_2^d / F_2^p \) ratio at large x**
E00-116 kinematics

\[ Q^2 \in (3.88 - 5.25) \]
\[ x \in (0.54 - 0.87) \]

\[ Q^2 \in (4.32 - 5.85) \]
\[ x \in (0.59 - 0.94) \]

\[ Q^2 \in (4.63 - 6.27) \]
\[ x \in (0.61 - 0.94) \]

\[ Q^2 \in (4.88 - 6.59) \]
\[ x \in (0.61 - 0.92) \]

\[ Q^2 \in (5.43 - 6.91) \]
\[ x \in (0.67 - 0.92) \]

\[ Q^2 \in (4.89 - 7.21) \]
\[ x \in (0.56 - 0.92) \]

\[ Q^2 \in (5.83 - 6.62) \]
\[ x \in (0.66 - 0.77) \]
Background analysis

**Charge symmetric background:** These are electrons coming from $\gamma$ and $\pi^0$ produced in the target. $\gamma \rightarrow e^+e^-$ while $\pi^0 \rightarrow \gamma \gamma \rightarrow e^+e^-$

The background electrons are symmetrically produced in pairs with positrons that can be detected and used for background subtraction.

We used **SOS** for H,D (e, e+) measurement.

SOS has a larger acceptance than HMS. (e, e+) cross sections is varying strongly as a function of $\theta$ and $E'$. Therefore we need to disentangle $\theta$ and $E'$ dependence in order to do the subtraction.

For **positron cross section calculation**, spectrometer acceptance corrections were applied and **P. Bosted model** was used for **bin centering correction**.

The background was subtracted as difference on a theta/momentum grid.
Background analysis

Positron cross sections for e00-116 kinematics on $h_2$ target as a function of momentum.

An example of positron cross section across angular acceptance before / after corrections: acceptance and bin centering corrections.
\[ F_2 = \frac{d^3 \sigma}{d\Omega dE'} \begin{vmatrix} 1 + R \end{vmatrix} \frac{K\nu}{1 + R\epsilon} \frac{1}{4\pi^2 \alpha \Gamma} \frac{1}{1 + \nu^2 / Q^2} \]

E00-116 measures \( \frac{d^3 \sigma}{d\Omega dE'} \)

We wish to construct \( F_2 \) but have not measured \( R \).
Duality works well for $2x F_1(F_T)$, $F_L$ and works for $R$. 
For $F_2$ extraction R1998 was used.
F$_2$ sensitivity to R parameterization

R1998 was used to extract F$_2$ from the data. The relative difference in F$_2$ when using R94-110 or R1990 as opposed to R1998 is $\sim$ 2%. So the estimated uncertainty on F$_2$ originating from the R parameterization used is 2%.
F_{2}^{p} \text{ from E00-116 data}

As observed from E94-110, MRST pdf evolution curve undershoots the data at intermediate $Q^{2}$, high $x$.

ALLM97 fit behaves, to a certain degree, as a “scaling curve” for the resonance data.
ALLM97 (Abramowicz, Levin, Levy, Maor) is a fit to a wide range of $\gamma^*p$ scattering data (all existing data by 1997) with $W^2 > 3$ GeV$^2$ including also photoproduction data ($\gamma p$).

The fit form assumed for $F_2$ is the product of:

1. $Q^2/(Q^2+m_0^2)$
2. $c_{P,R}(t) * x_{P,R}^{a_{P,R}(t)} * (1-x)^{b_{P,R}(t)}$

where

$$t = \ln \left( \frac{\ln[(Q^2+Q_0^2)/\Lambda^2]}{\ln(Q_0^2/\Lambda^2)} \right)$$

$x_{P,R} =$ modified Bjorken $x$

$$1/x_{P,R} = 1 + (W^2-M^2)/(Q^2+m^2_{P,R})$$
Remaining spectra of $Q^2 = 5.0\text{ GeV}^2$, $Q^2 = 5.3\text{ GeV}^2$, $Q^2 = 6.0\text{ GeV}^2$, $Q^2 = 6.5\text{ GeV}^2$.
“Duality studies”

ALLM97 fit was used, at this stage, as scaling curve for “duality studies”.
“Duality studies”

Global duality: when integrating over the entire spectrum - resonance + DIS region – with ALLM97 as scaling curve, duality holds up to 2%.

Local duality: when integrating region by region the resonances seem 10% higher than ALLM97 fit, on average.

$W^2$ cuts:
- $\Delta \rightarrow (1.3 - 1.9) \text{ GeV}^2$
- $S \rightarrow (1.9 - 2.5) \text{ GeV}^2$
- $F \rightarrow (1.9 - 3.1) \text{ GeV}^2$
$F_2^P(x,Q^2)$ “kinematics”

$W^2$ cuts:

$\Delta \rightarrow (1.3 \text{ – } 1.9) \text{ GeV}^2$
$S \rightarrow (1.9 \text{ – } 2.5) \text{ GeV}^2$
$F \rightarrow (1.9 \text{ – } 3.1) \text{ GeV}^2$
$4^{th} \rightarrow (3.1 \text{ – } 3.9) \text{ GeV}^2$
$\text{DIS} \rightarrow (3.9 \text{ – } \ldots) \text{ GeV}^2$

These were used to average over each dis / resonance region, for a given scan, in order to obtain $F_2^P(x,Q^2)$.

Then…
\( F_2^p \) dependence of \( Q^2 \) \( \Longleftrightarrow F_2^p(Q^2) \mid_{x=\text{const}} \)

ALLM97 fit was used to bin-center \( F_2^p(x,Q^2) \) “points” at different kinematics where world data exist. 

**E00-116** data were compared to world data (where found) and they follow overall the same \( Q^2 \) behavior as ALLM97.
For a fixed $Q^2$, the $F_2$ dependence of $x$ goes like $(1-x)^b$.

E00-116 $F_2^p$ “points” were centered at a fixed $Q^2 = 5.5$ GeV$^2$ and the $x$ dependence of $F_2^p$ was fitted.

If compared to ALLM97...
E00-116 is in agreement with calculation of $F_2^p$ dependence of $Q^2$ using ALLM97. If fitting the $x$ dependence of $F_2^p$-ALLM97 for various $Q^2$, a ALLM parameterization for “b power” as a function of $Q^2$ is obtained.

E00-116 is in agreement with calculation of “b power” dependence of $Q^2$ using ALLM97.
Summary

- $F_2^p$ extracted from E00-116 resonance data were shown. With increasing $Q^2/x$ they slide on ALLM97 curve but are becoming systematically higher than MRST+NNLO+TMC curve.

- Global and local “duality studies” were shown with ALLM97 as scaling curve but a $W^2$ cut study needs to be done for an accurate quantitative estimation of local duality.

- $F_2^p$ dependence of $Q^2/x$ for E00-116 data were checked against world data, ALLM97 fit and MRST+NNLO+TMC. E00-116 data follow the $Q^2/x$ behavior of ALLM97 fit.

- All the studies are preliminary since iteration for both $H_2$ and $D_2$ (not shown here) data still needs to be done.

- $F_2^d$ extracted from E00-116 $D_2$ data will follow soon…
• Moments of the Structure Function \[ M_n(Q^2) = \int x^n x^{-2} F(x, Q^2) \] If \( n = 2 \), this is the Bloom-Gilman duality integral!

• Operator Product Expansion

\[ M_n(Q^2) = \sum (nM_0^2/Q^2)^k B_{nk}(Q^2) \]

higher twist logarithmic dependence

• Duality is described in the Operator Product Expansion as higher twist effects being small or canceling

DeRujula, Georgi, Politzer (1977)
In general, Next-to-Leading-Order (NLO) perturbative QCD (DGLAP) fits do a good job of reproducing the data over the full measurement range.