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Resonance-DIS transition and low Q^2 phenomena

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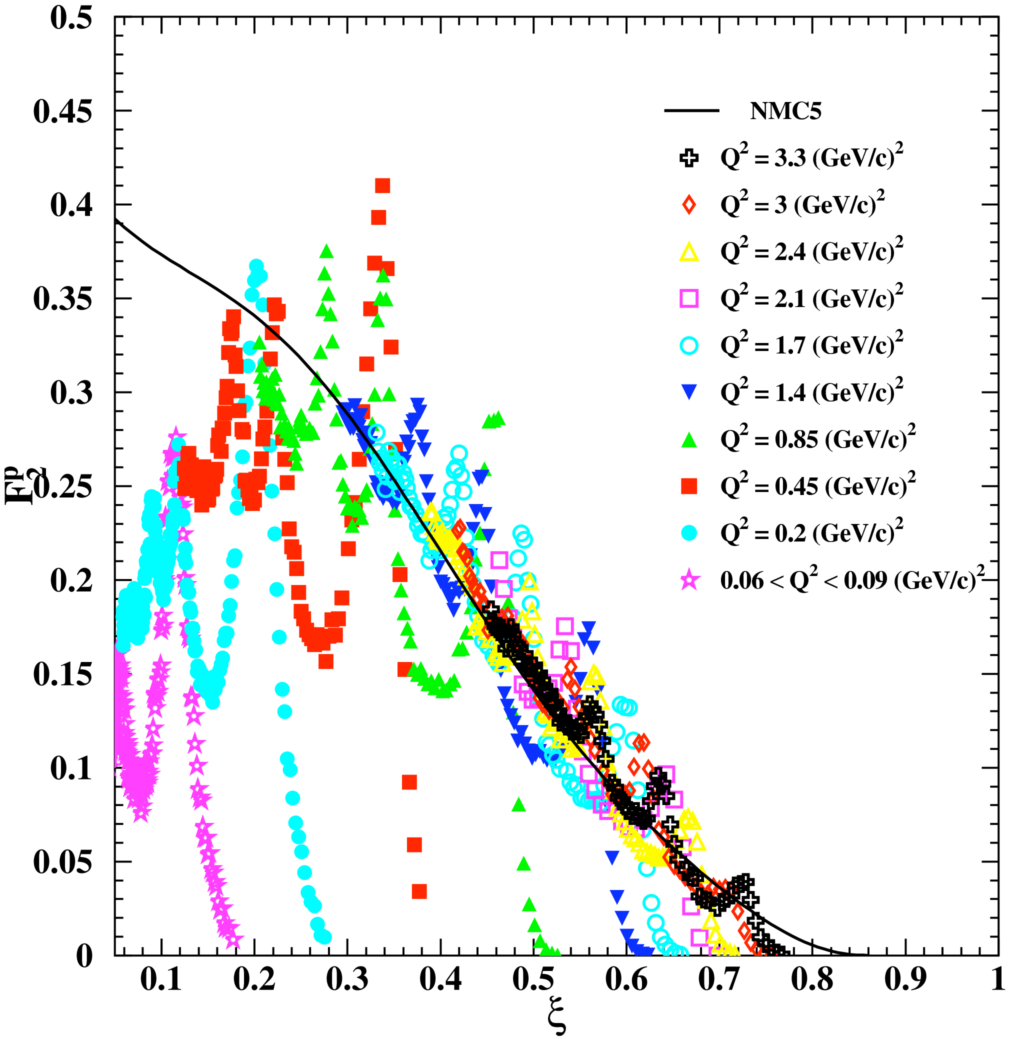
Outline

1. Introduction:
   resonance-DIS transition & Bloom-Gilman duality
2. Duality in QCD:
   moments & higher twists
3. Local duality in dynamical quark models
4. Phenomenological models
5. DIS at low Q^2
6. Summary

1.
Introduction

Resonance-DIS transition characterized by Bloom-Gilman duality



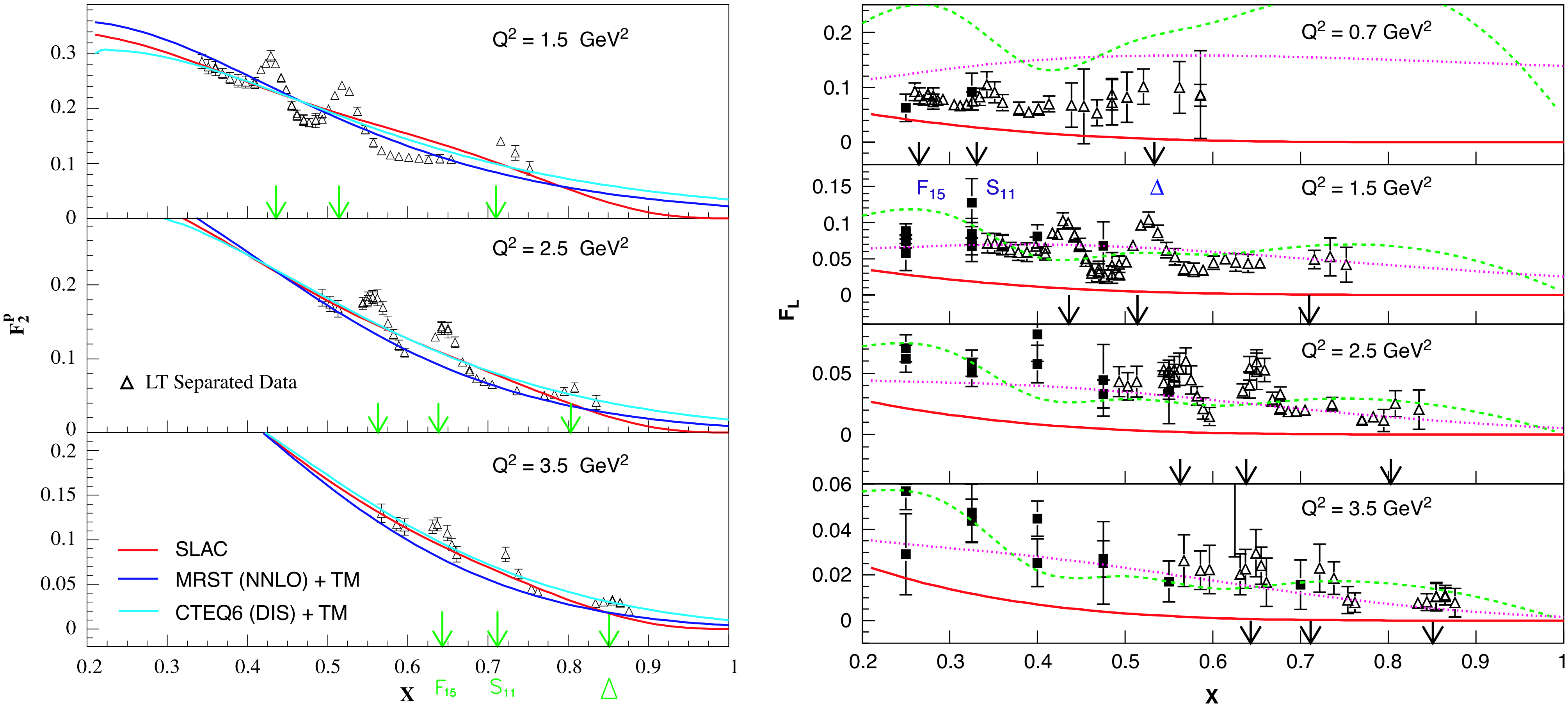
Jefferson Lab (Hall C)

Niculescu et al., Phys. Rev. Lett. 85 (2000) 1182

Average over (strongly Q^2 dependent) resonances

$\approx Q^2$ independent scaling function

Bloom-Gilman duality

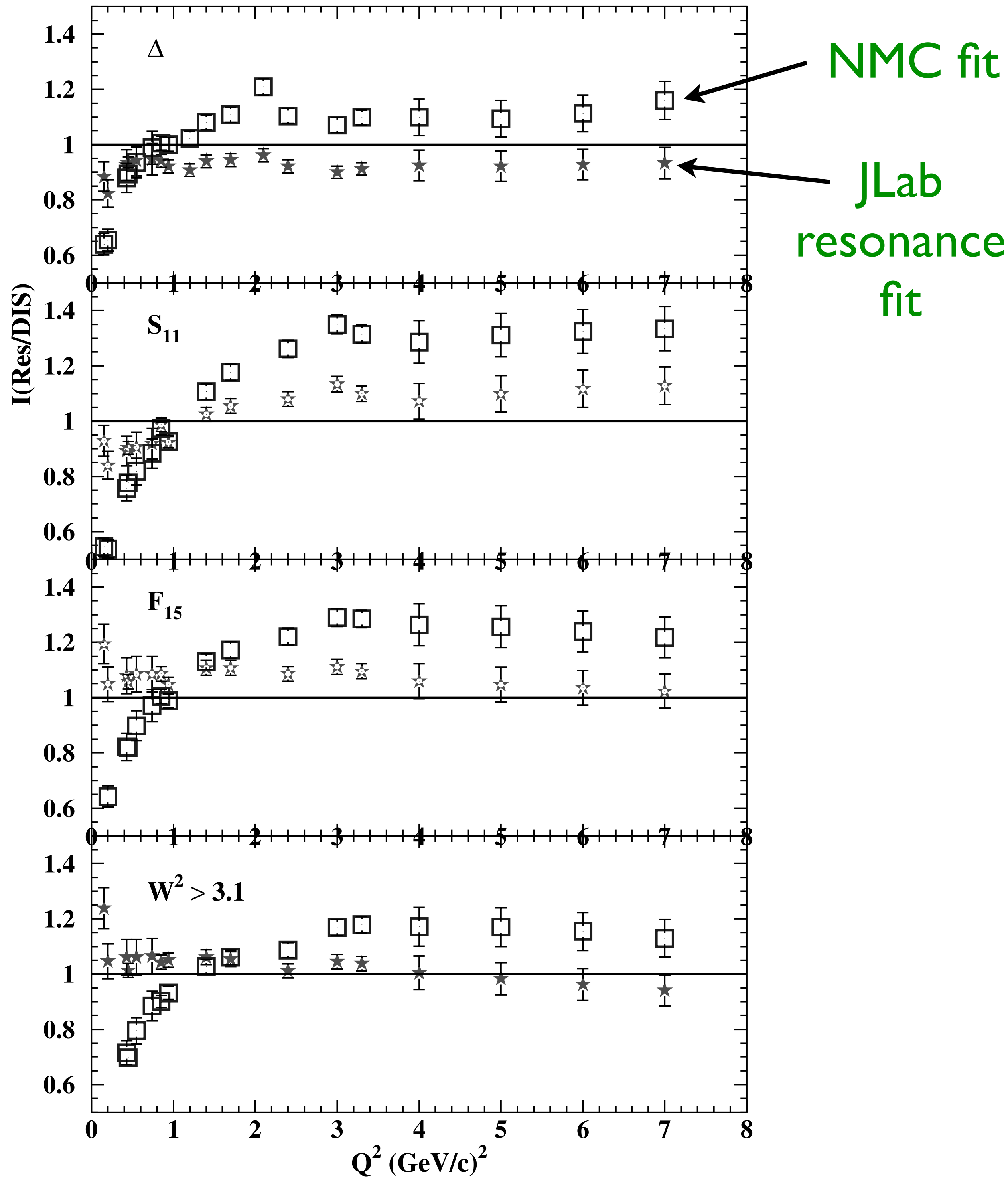


Christy et al. (2005)

duality in F_2 and F_L structure functions

(from longitudinal-transverse separation)

Integrated strength

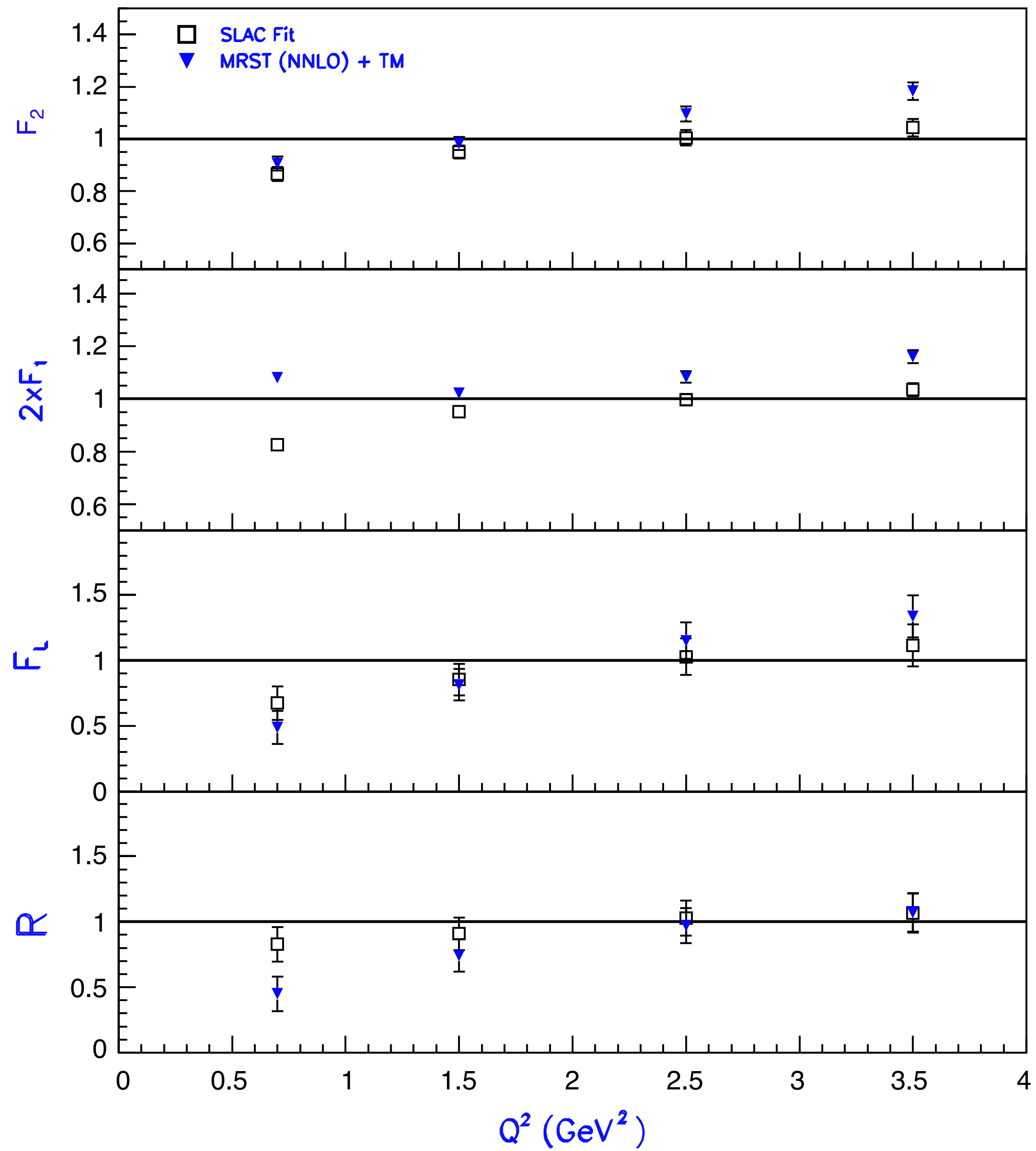


~10% agreement for $Q^2 > 1$ GeV^2

Niculescu et al, Phys. Rev. Lett. 85 (2000) 1186

Moments

data from longitudinal-transverse separation !



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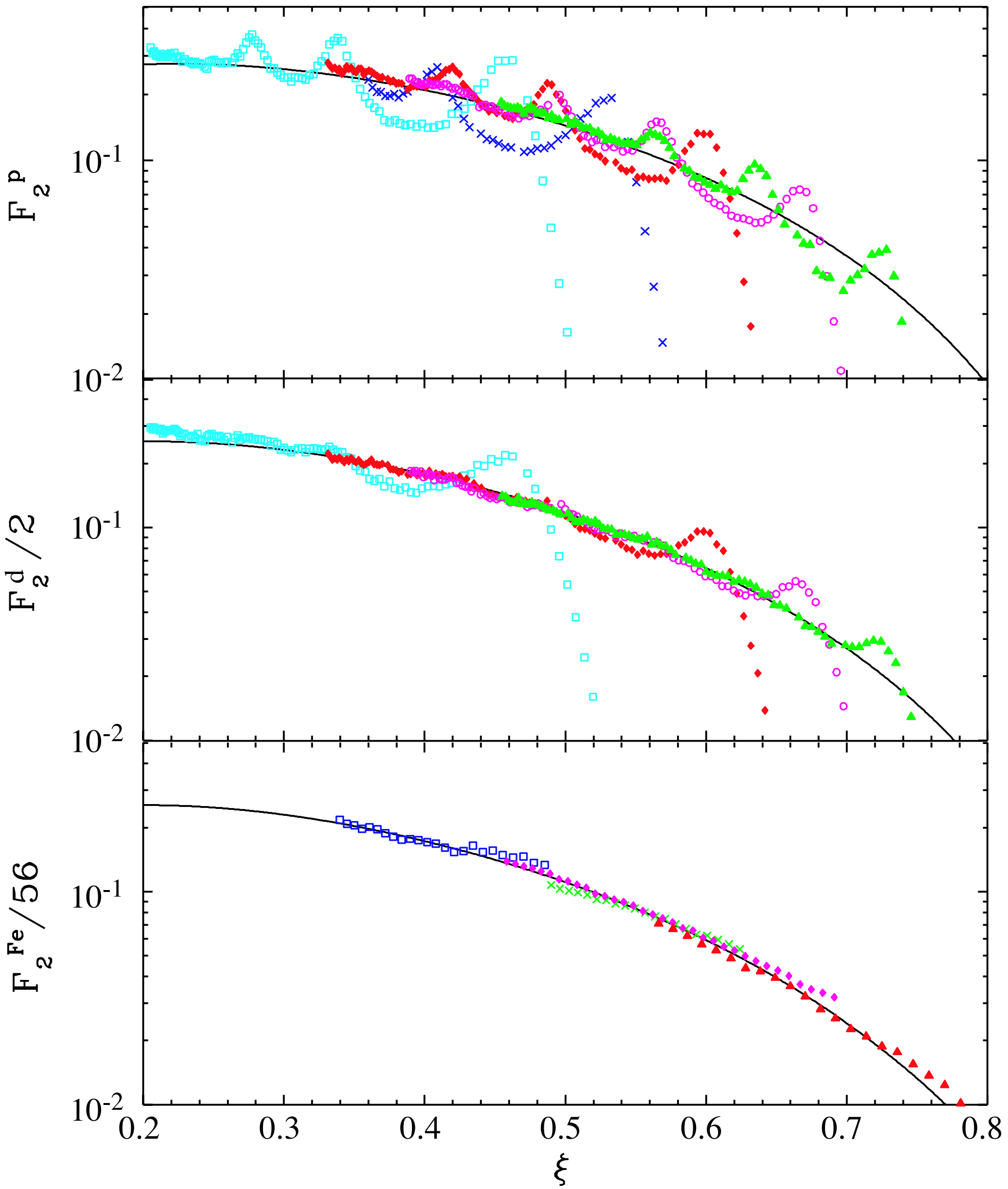
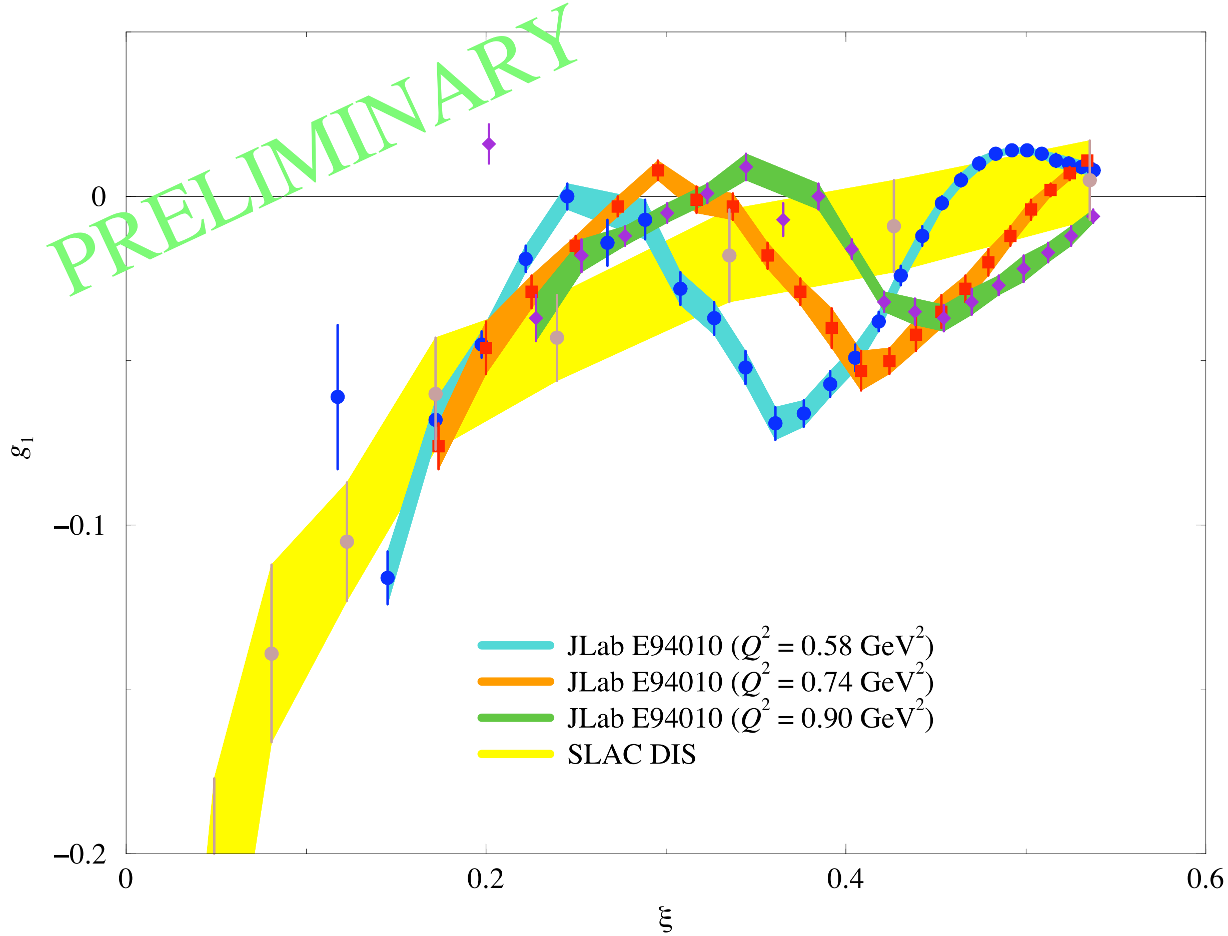
Nuclear structure functions



for larger nuclei, Fermi motion does resonance averaging automatically !

Jefferson Lab (Hall C)

Neutron (^{3}He) g_1 structure function



Liyanage et al. (JLab Hall A)

2.
Duality in QCD

Duality and the OPE

Operator product expansion

→ expand moments of structure functions in powers of $1/Q^2$

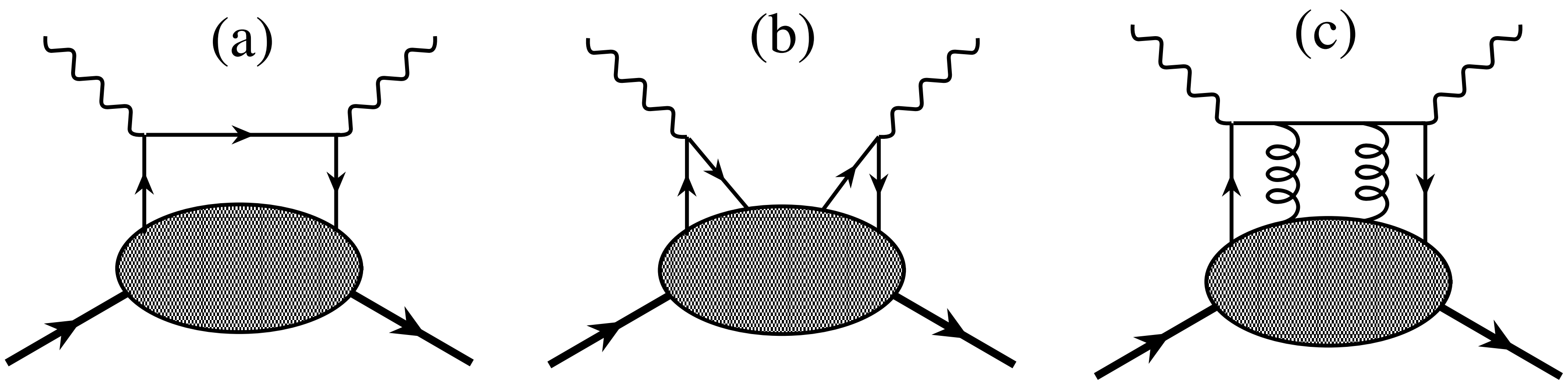
$$M_n(Q^2) = \int_0^1 dx\; x^{n-2}\; F_2(x, Q^2)$$

$$= A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \cdots$$

matrix elements of operators with specific "twist" τ

$$\tau = \mathrm{dimension} - \mathrm{spin}$$

Higher twists



$\tau = 2$

single quark scattering

$\tau > 2$

nonperturbative qq and qg correlations

($\longrightarrow$ confinement)

Duality and the OPE

Operator product expansion

➡ expand moments of structure functions in powers of $1/Q^2$

$$M_n(Q^2) = \int_0^1 dx\ x^{n-2}\ F_2(x, Q^2)$$
$$= A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \cdots$$

If moment $\approx$ independent of Q^2

➡ higher twist terms $A_n^{(\tau>2)}$ small

Duality and the OPE

Operator product expansion

→ expand moments of structure functions in powers of $1/Q^2$

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

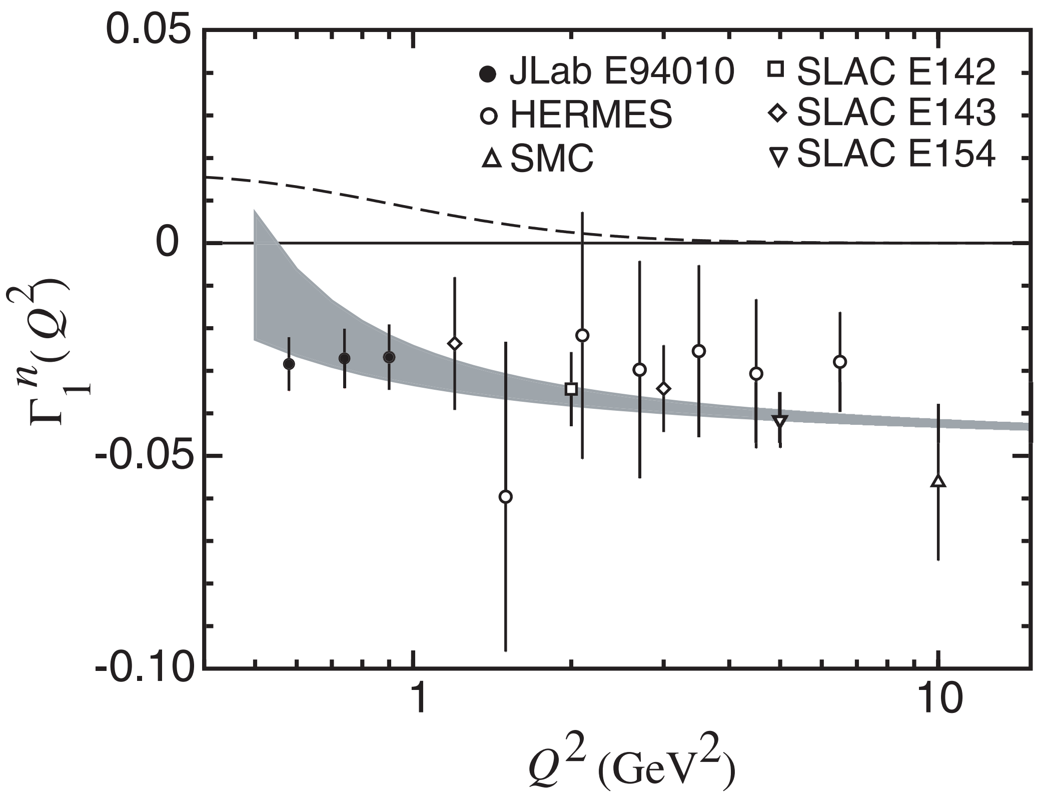
$$= A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \cdots$$

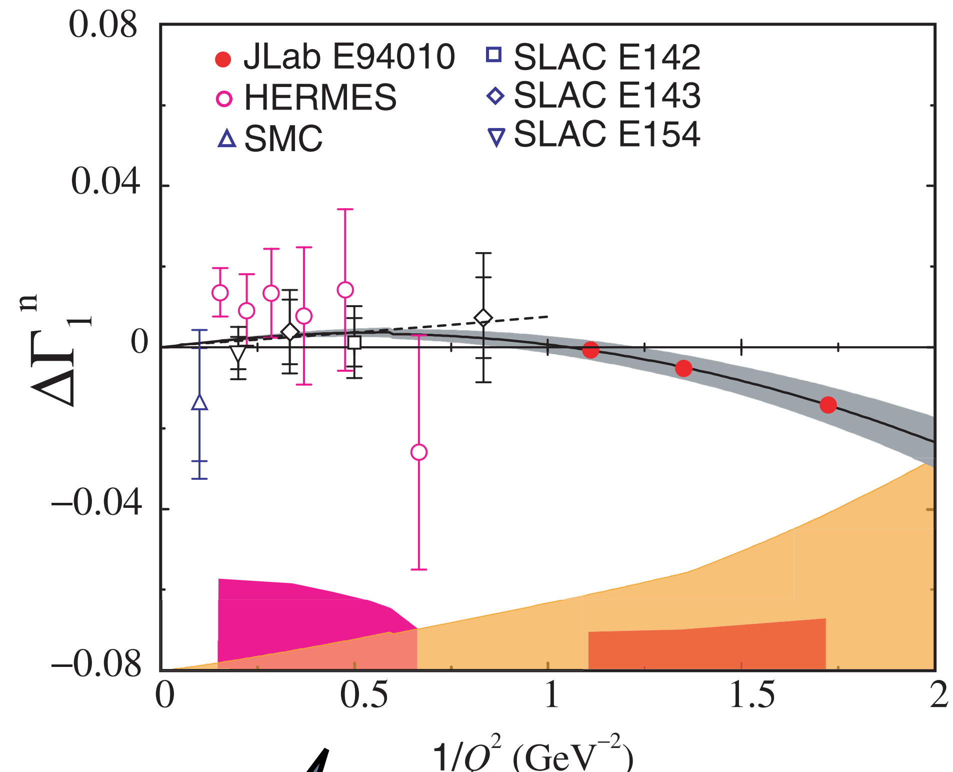
Duality $\Longleftrightarrow$ suppression of higher twists

de Rujula, Georgi, Politzer, Ann. Phys. 103 (1975) 315

Moment of neutron g_1 structure function

Meziani, WM, et al., Phys. Lett. B613, 148 (2005)





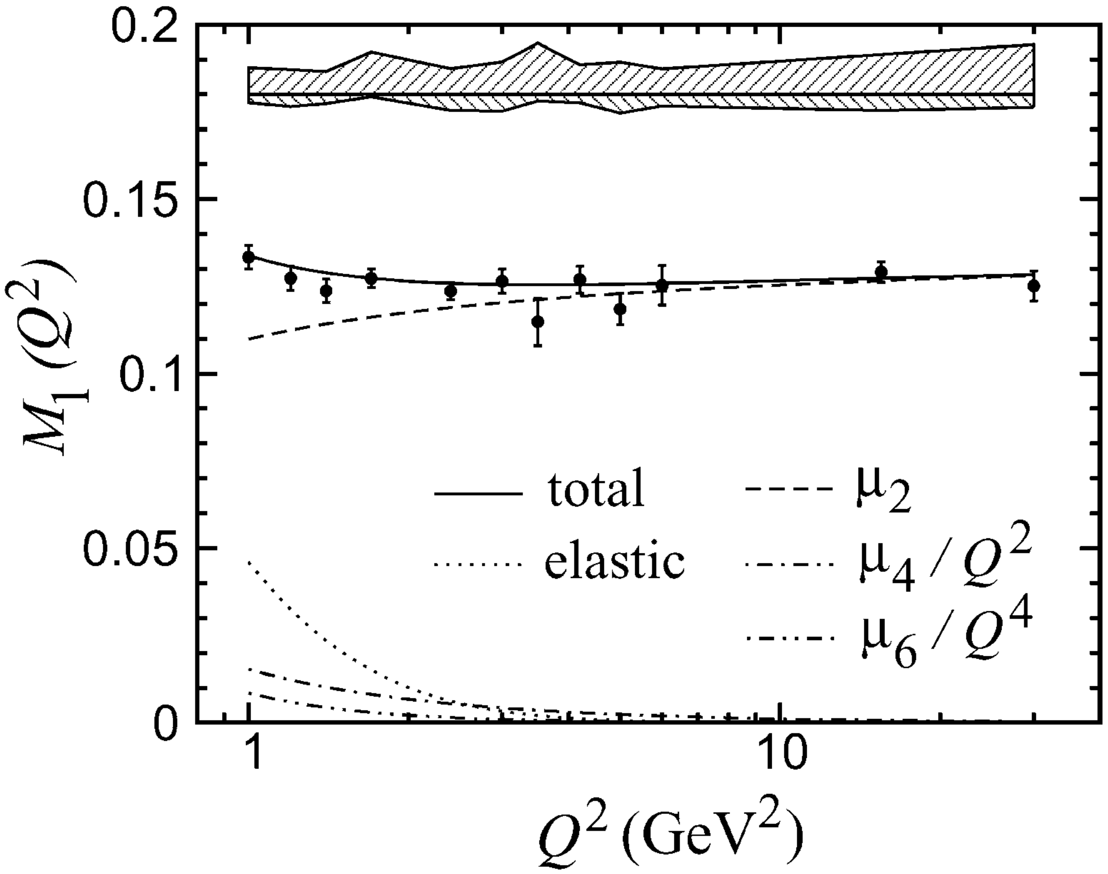
$$\Gamma_1(Q^2) = \int_0^1 dx\ g_1(x, Q^2)$$

$$= \Gamma_1^{(\tau=2)}(Q^2) + \Delta\Gamma_1(Q^2)$$

higher twist small down to $Q^2 \sim 1$ GeV^2

Moment of proton g_1 structure function

Osipenko, WM et al., Phys. Lett. B609, 259 (2005)



⇨ higher twist small down to $Q^2 \sim 2$ GeV^2

Total higher twist small at $Q^2 \sim 1 - 2\ \mathrm{GeV}^2$

- ⇒ nonperturbative interactions between quarks and gluons not dominant at these scales

- ⇒ suggests *strong cancellations* between resonances, resulting in dominance of *leading twist*

- ⇒ OPE does not tell us *why* higher twists are small !

- ⇒ need dynamical models to understand *how* cancellations between *coherent* resonances produce *incoherent* scaling function

3.
Local duality in dynamical quark models

Coherence vs. incoherence

Exclusive form factors

⟹ *coherent* scattering from quarks

$$d\sigma \sim \left(\sum_i e_i\right)^2$$

Inclusive structure functions

⟹ *incoherent* scattering from quarks

$$d\sigma \sim \sum_i e_i^2$$

⟹ how can the *square of a sum*
become the *sum of squares?*

Pedagogical model

Two quarks bound in a harmonic oscillator potential

⟹ exactly solvable spectrum

Structure function given by sum of squares of transition form factors

$$F(\nu, \mathbf{q}^2) \ \sim \ \sum_n \left| G_{0,n}(\mathbf{q}^2) \right|^2 \ \delta(E_n - E_0 - \nu)$$

Charge operator $\Sigma_i \ e_i \exp(i\mathbf{q} \cdot \mathbf{r}_i)$ excites

even partial waves with strength $\propto (e_1 + e_2)^2$

odd partial waves with strength $\propto (e_1 - e_2)^2$

Pedagogical model

Resulting structure function

$$F(\nu, \mathbf{q}^2) \;\sim\; \sum_n \left\{ (e_1 + e_2)^2 \; G^2_{0,2n} + (e_1 - e_2)^2 \; G^2_{0,2n+1} \right\}$$

If states degenerate, cross terms $(\sim e_1 e_2)$ cancel when averaged over nearby even and odd parity states

Minimum condition for duality:

⟹ *at least one complete set of <u>even</u> and <u>odd</u> parity resonances must be summed over*

Close, Isgur, Phys. Lett. B509 (2001) 81

Quark model

Even and odd parity states generalize to $\mathbf{56}^+$ ($L=0$) and $\mathbf{70}^-$ ($L=1$) multiplets of spin-flavor SU(6)

⟹ scaling occurs if contributions from $\mathbf{56}^+$ and $\mathbf{70}^-$ have equal overall strengths

Simplified case: magnetic coupling of γ^* to quark

⟹ expect dominance over electric at large Q^2

Quark model

Even and odd parity states generalize to **56**$^+$ ($L=0$) and **70**$^-$ ($L=1$) multiplets of spin-flavor SU(6)

⟹ scaling occurs if contributions from **56**$^+$ and **70**$^-$ have equal overall strengths

representation	$^2\mathbf{8}[\mathbf{56}^+]$	$^4\mathbf{10}[\mathbf{56}^+]$	$^2\mathbf{8}[\mathbf{70}^-]$	$^4\mathbf{8}[\mathbf{70}^-]$	$^2\mathbf{10}[\mathbf{70}^-]$	Total
F_1^p	$9\rho^2$	$8\lambda^2$	$9\rho^2$	0	λ^2	$18\rho^2+9\lambda^2$
F_1^n	$(3\rho+\lambda)^2/4$	$8\lambda^2$	$(3\rho-\lambda)^2/4$	$4\lambda^2$	λ^2	$(9\rho^2+27\lambda^2)/2$
g_1^p	$9\rho^2$	$-4\lambda^2$	$9\rho^2$	0	λ^2	$18\rho^2-3\lambda^2$
g_1^n	$(3\rho+\lambda)^2/4$	$-4\lambda^2$	$(3\rho-\lambda)^2/4$	$-2\lambda^2$	λ^2	$(9\rho^2-9\lambda^2)/2$

$\lambda\ (\rho) =$ (anti) symmetric component of ground state wfn.

$$|N\rangle = \lambda\ |\varphi\otimes\chi\rangle_{\rm sym} + \rho\ |\varphi\otimes\chi\rangle_{\rm antisym}$$

Quark model

Even and odd parity states generalize to $\mathbf{56}^+$ $(L=0)$ and $\mathbf{70}^-$ $(L=1)$ multiplets of spin-flavor SU(6)

⟹ scaling occurs if contributions from $\mathbf{56}^+$ and $\mathbf{70}^-$ have equal overall strengths

Similarly for neutrinos ...

representation	${}^2\mathbf{8}[\mathbf{56}^+]$	${}^4\mathbf{10}[\mathbf{56}^+]$	${}^2\mathbf{8}[\mathbf{70}^-]$	${}^4\mathbf{8}[\mathbf{70}^-]$	${}^2\mathbf{10}[\mathbf{70}^-]$	Total
$F_1^{\nu p}$	0	$24\lambda^2$	0	0	$3\lambda^2$	$27\lambda^2$
$F_1^{\nu n}$	$(9\rho+\lambda)^2/4$	$8\lambda^2$	$(9\rho-\lambda)^2/4$	$4\lambda^2$	λ^2	$(81\rho^2+27\lambda^2)/2$
$g_1^{\nu p}$	0	$-12\lambda^2$	0	0	$3\lambda^2$	$-9\lambda^2$
$g_1^{\nu n}$	$(9\rho+\lambda)^2/4$	$-4\lambda^2$	$(9\rho-\lambda)^2/4$	$-2\lambda^2$	λ^2	$(81\rho^2-9\lambda^2)/2$

$\lambda\ (\rho) =$ (anti) symmetric component of ground state wfn.

Close, WM, Phys. Rev. C68 (2003) 035210

Quark model

SU(6) limit ⟹ $\lambda = \rho$

$SU(6)$:	$[\mathbf{56},\mathbf{0}^+]^{\mathbf{2}}\mathbf{8}$	$[\mathbf{56},\mathbf{0}^+]^{\mathbf{4}}\mathbf{10}$	$[\mathbf{70},\mathbf{1}^-]^{\mathbf{2}}\mathbf{8}$	$[\mathbf{70},\mathbf{1}^-]^{\mathbf{4}}\mathbf{8}$	$[\mathbf{70},\mathbf{1}^-]^{\mathbf{2}}\mathbf{10}$	*total*
F_1^p	9	8	9	0	1	27
F_1^n	4	8	1	4	1	18
g_1^p	9	-4	9	0	1	15
g_1^n	4	-4	1	-2	1	0

Summing over all resonances in $\mathbf{56}^+$ and $\mathbf{70}^-$ multiplets

⟹ $R^{np} = \frac{F_1^n}{F_1^p} = \frac{2}{3}$ $A_1^p = \frac{g_1^p}{F_1^p} = \frac{5}{9}$ $A_1^n = \frac{g_1^n}{F_1^n} = 0$

⟹ as in quark-parton model !

Quark model

SU(6) limit ⟹ $\lambda = \rho$

$SU(6)$:	$[\mathbf{56}, 0^+]^{\mathbf{2}}\mathbf{8}$	$[\mathbf{56}, 0^+]^{\mathbf{4}}\mathbf{10}$	$[\mathbf{70}, 1^-]^{\mathbf{2}}\mathbf{8}$	$[\mathbf{70}, 1^-]^{\mathbf{4}}\mathbf{8}$	$[\mathbf{70}, 1^-]^{\mathbf{2}}\mathbf{10}$	*total*
F_1^p	9	8	9	0	1	27
F_1^n	4	8	1	4	1	18
g_1^p	9	-4	9	0	1	15
g_1^n	4	-4	1	-2	1	0

⟹ expect duality to appear earlier for F_1^p than F_1^n

⟹ earlier onset for g_1^n than g_1^p

⟹ cancellations *within* multiplets for g_1^n

Quark model

Similarly for neutrinos ...

SU(6) limit $(\lambda = \rho)$

$SU(6):$	$[\mathbf{56},\mathbf{0}^+]^{\mathbf{2}}\mathbf{8}$	$[\mathbf{56},\mathbf{0}^+]^{\mathbf{4}}\mathbf{10}$	$[\mathbf{70},\mathbf{1}^-]^{\mathbf{2}}\mathbf{8}$	$[\mathbf{70},\mathbf{1}^-]^{\mathbf{4}}\mathbf{8}$	$[\mathbf{70},\mathbf{1}^-]^{\mathbf{2}}\mathbf{10}$	*total*
$F_1^{\nu p}$	0	24	0	0	3	27
$F_1^{\nu n}$	25	8	16	4	1	54
$g_1^{\nu p}$	0	−12	0	0	3	−9
$g_1^{\nu n}$	25	−4	16	−2	1	36

Summing over all resonances in $\mathbf{56}^+$ and $\mathbf{70}^-$ multiplets

⟹ $$R^\nu = \frac{F_1^{\nu p}}{F_1^{\nu n}} = \frac{1}{2} \left(= \frac{d}{u} \right)$$

$$A_1^{\nu p} = -\frac{1}{3} \left(= \frac{\Delta d}{d} \right)$$

$$A_1^{\nu n} = \frac{2}{3} \left(= \frac{\Delta u}{u} \right)$$

⟹ as in parton model !

Quark model

SU(6) may be ≈ valid at $x \sim 1/3$

But significant deviations at large x

⟹ which combinations of resonances reproduce behavior of structure functions at large x?

Model	SU(6)	No $^4\mathbf{10}$	No $^2\mathbf{10}$, $^4\mathbf{10}$	No $S_{3/2}$	No $\sigma_{3/2}$	No ψ_λ
R^{np}	2/3	10/19	1/2	6/19	3/7	1/4
A_1^p	5/9	1	1	1	1	1
A_1^n	0	2/5	1/3	1	1	1

Quark model

SU(6) may be $\approx$ valid at $x \sim 1/3$

But significant deviations at large x

$\Longrightarrow$ which combinations of resonances reproduce behavior of structure functions at large x?

Model	SU(6)	No $^4\mathbf{10}$	No $^2\mathbf{10}$, $^4\mathbf{10}$	No $S_{3/2}$	No $\sigma_{3/2}$	No ψ_λ
R^{np}	2/3	10/19	1/2	6/19	3/7	1/4
A_1^p	5/9	1	1	1	1	1
A_1^n	0	2/5	1/3	1	1	1

gives $\Delta u/u > 1$ $\Longrightarrow$ *inconsistent with duality*

Quark model

SU(6) may be ≈ valid at $x \sim 1/3$

But significant deviations at large x

→ which combinations of resonances reproduce behavior of structure functions at large x?

Model	SU(6)	No $^4\mathbf{10}$	No $^2\mathbf{10}$, $^4\mathbf{10}$	No $S_{3/2}$	No $\sigma_{3/2}$	No ψ_λ
R^{np}	2/3	10/19	1/2	6/19	3/7	1/4
A_1^p	5/9	1	1	1	1	1
A_1^n	0	2/5	1/3	1	1	1

$^4\mathbf{10}\ [\mathbf{56}^+]$ and $^4\mathbf{8}\ [\mathbf{70}^-]$ suppressed

Quark model

SU(6) may be $\approx$ valid at $x \sim 1/3$

But significant deviations at large x

→ which combinations of resonances reproduce behavior of structure functions at large x?

Model	SU(6)	No $^4\mathbf{10}$	No $^2\mathbf{10}$, $^4\mathbf{10}$	No $S_{3/2}$	No $\sigma_{3/2}$	No ψ_λ
R^{np}	2/3	10/19	1/2	6/19	3/7	1/4
A_1^p	5/9	1	1	1	1	1
A_1^n	0	2/5	1/3	1	1	1

helicity 3/2 suppression

Quark model

SU(6) may be $\approx$ valid at $x \sim 1/3$

But significant deviations at large x

$\Longrightarrow$ which combinations of resonances reproduce behavior of structure functions at large x?

Model	SU(6)	No $^4\mathbf{10}$	No $^2\mathbf{10}$, $^4\mathbf{10}$	No $S_{3/2}$	No $\sigma_{3/2}$	No ψ_λ
R^{np}	2/3	10/19	1/2	6/19	3/7	1/4
A_1^p	5/9	1	1	1	1	1
A_1^n	0	2/5	1/3	1	1	1

e.g. through $\vec{S}_i \cdot \vec{S}_j$ interaction between quarks $\Longleftarrow$ suppression of symmetric part of spin-flavor wfn.

Quark model

SU(6) may be $\approx$ valid at $x \sim 1/3$

But significant deviations at large x

$\Longrightarrow$ which combinations of resonances reproduce behavior of structure functions at large x?

Model	SU(6)	No $^4\mathbf{10}$	No $^2\mathbf{10}$, $^4\mathbf{10}$	No $S_{3/2}$	No $\sigma_{3/2}$	No ψ_λ
R^ν	1/2	3/46	0	1/14	1/5	0
$A_1^{\nu p}$	−1/3	1		1		−1/3
$A_1^{\nu n}$	2/3	20/23	13/15	1	1	1

gives d/u, $\Delta u/u$, $\Delta d/d$ inconsistent with e scattering

Quark model

SU(6) may be $\approx$ valid at $x \sim 1/3$

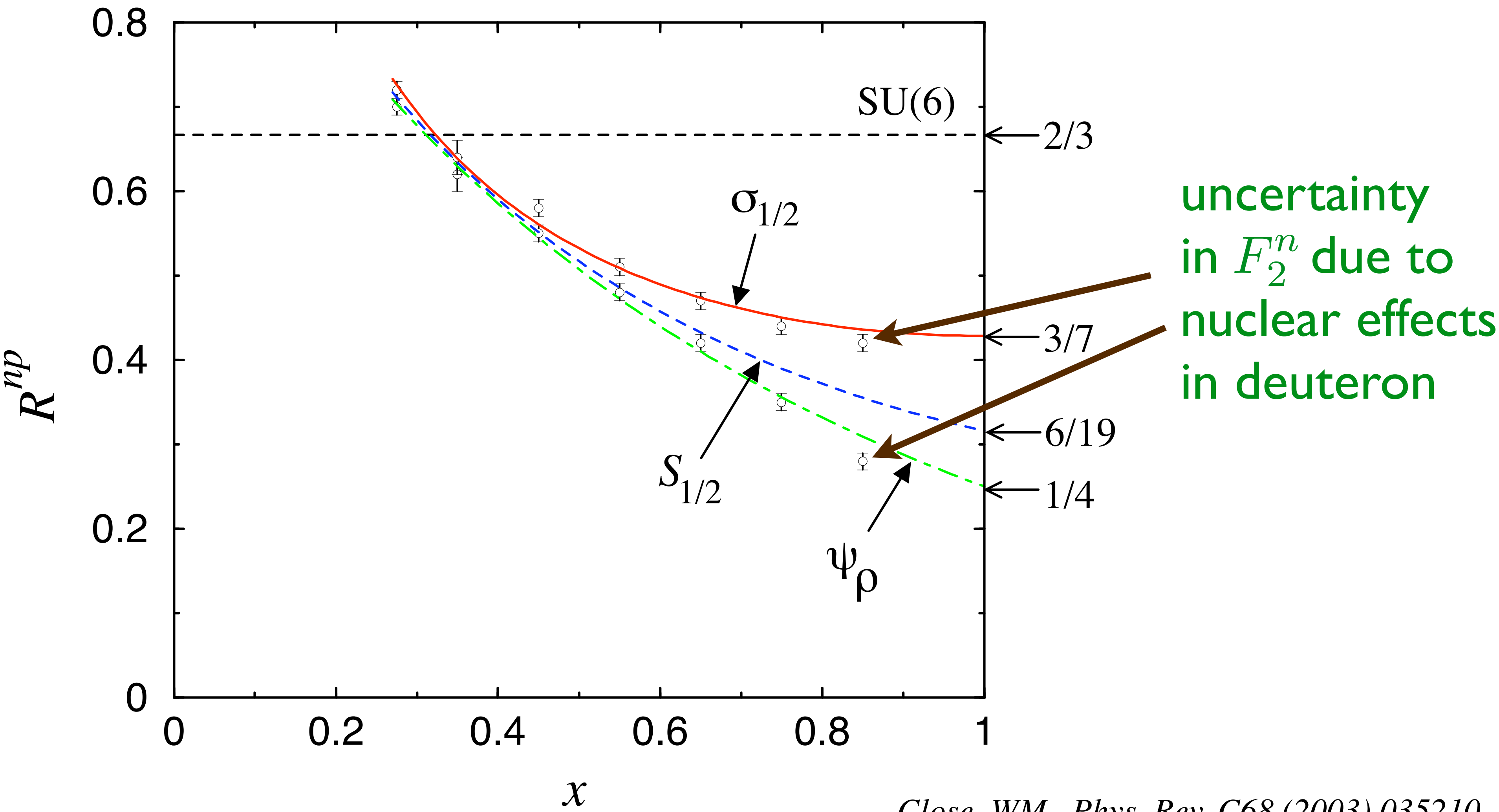
But significant deviations at large x

→ which combinations of resonances reproduce behavior of structure functions at large x?

Model	SU(6)	No $^4\mathbf{10}$	No $^2\mathbf{10}$, $^4\mathbf{10}$	No $S_{3/2}$	No $\sigma_{3/2}$	No ψ_λ
R^ν	1/2	3/46	0	1/14	1/5	0
$A_1^{\nu p}$	−1/3	1		1		−1/3
$A_1^{\nu n}$	2/3	20/23	13/15	1	1	1

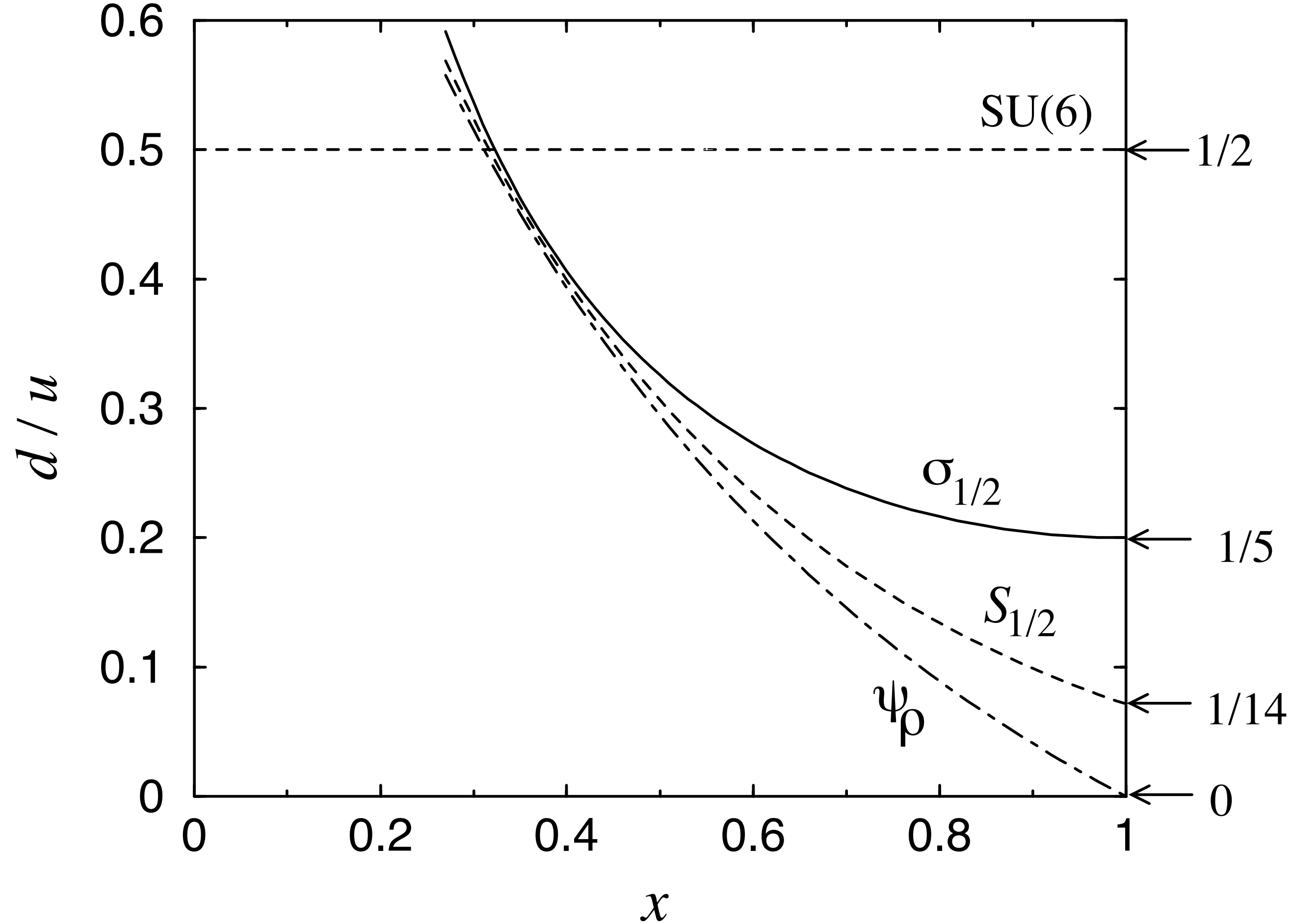
consistent with duality in e scattering

Fit to $\begin{cases} \text{SU(6) symmetry at } x \sim 1/3 \\ \text{SU(6) breaking at } x \sim 1 \end{cases}$

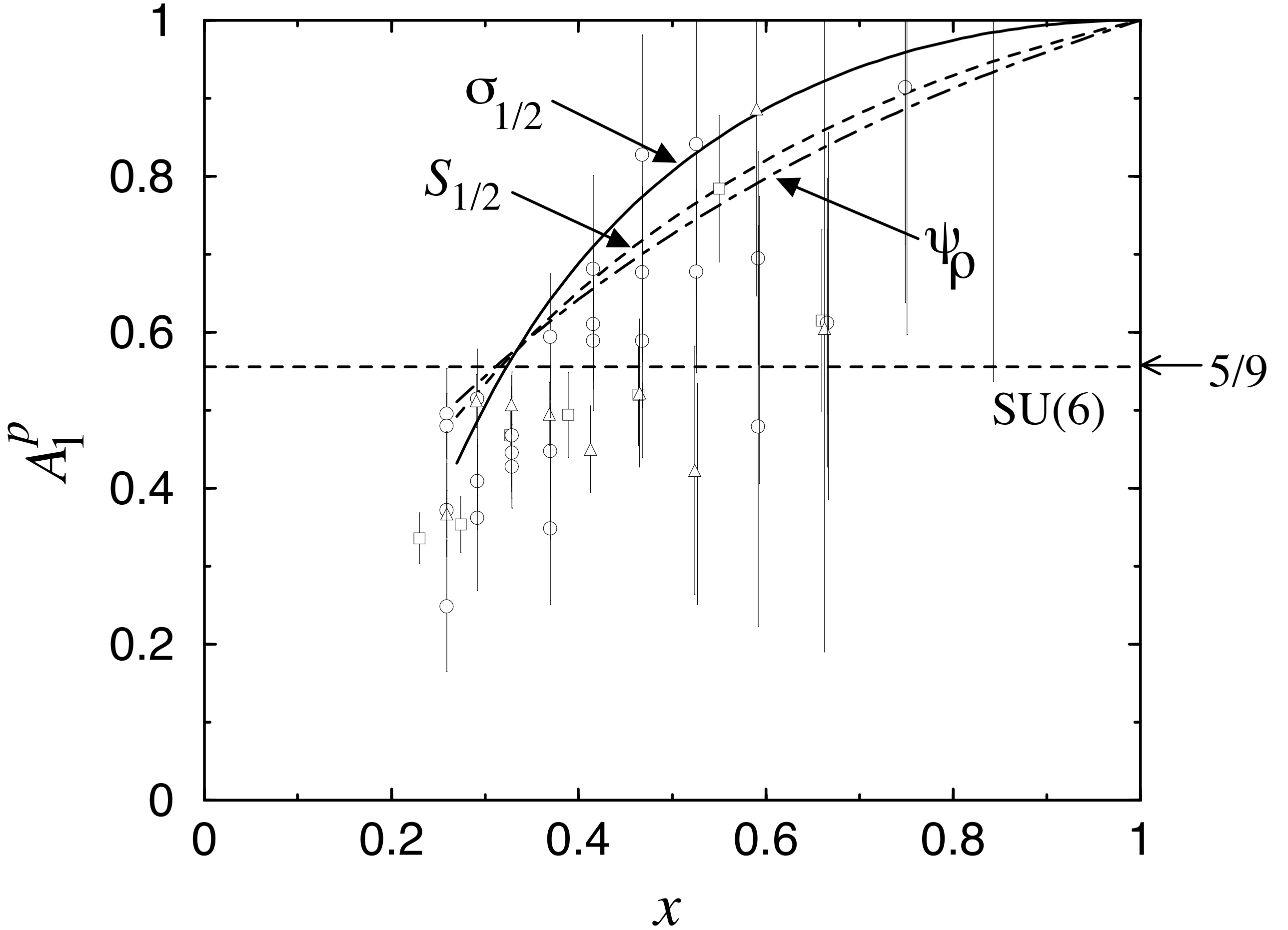


Close, WM, Phys. Rev. C68 (2003) 035210

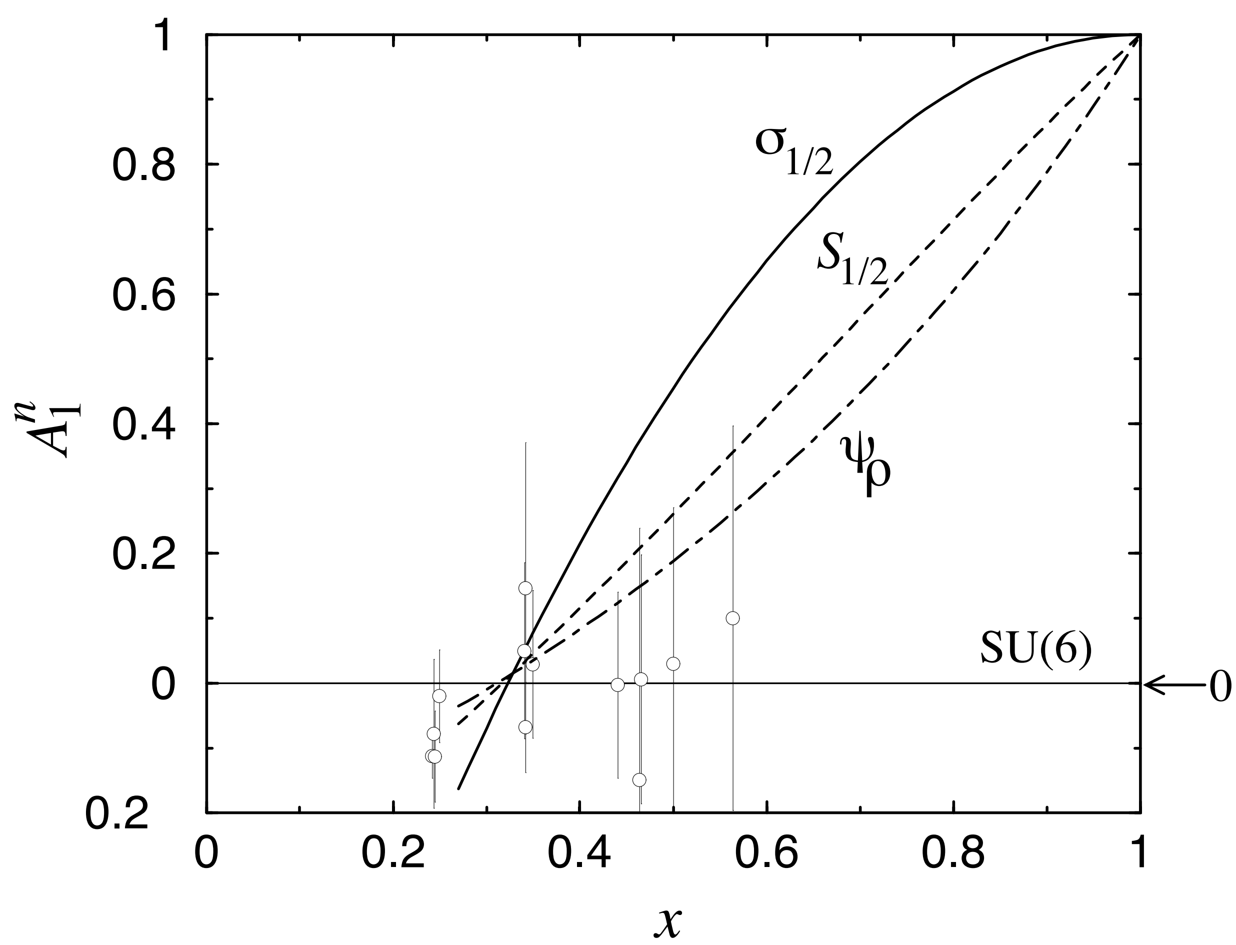
R^{ν} $(= d/u)$



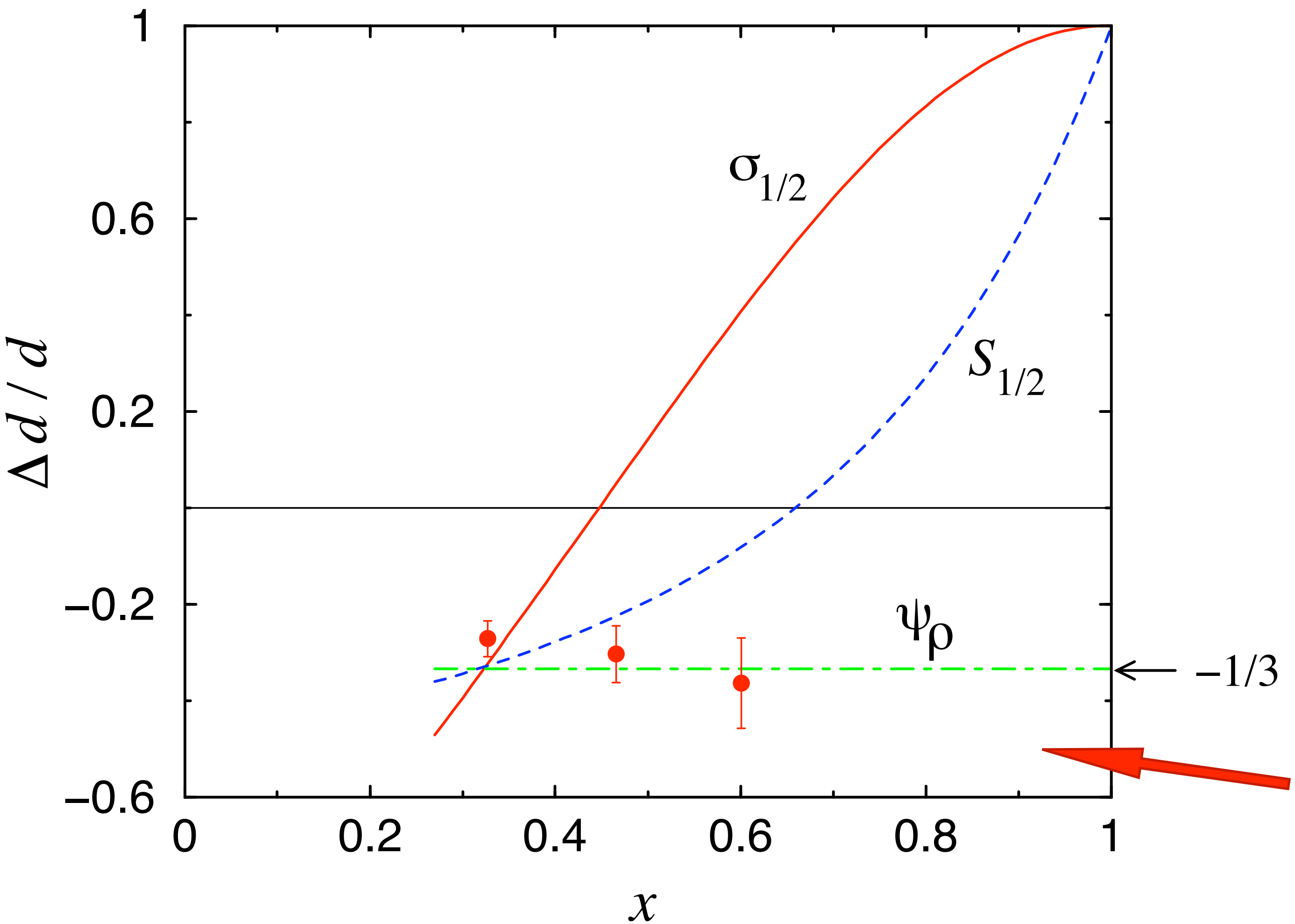
Polarization asymmetry A_1^p



Polarization asymmetry A_1^n



$$\frac{\Delta d}{d} = \frac{4}{15} A_1^n \left(4 + \frac{u}{d}\right) - \frac{1}{15} A_1^p \left(1 + 4\frac{u}{d}\right) \quad (= A_1^{\nu p})$$



$$\frac{u}{d} = \frac{4 - R^{np}}{4R^{np} - 1}$$

$$(= 1/R^{\nu})$$

no sign of pQCD behavior

Zheng et al. [JLab Hall A], Phys. Rev. Lett. (2004) 012004

λ suppression model ⟹ identical production rates in $\mathbf{56}^+$ and $\mathbf{70}^-$ channels

representation	$^2\mathbf{8}[\mathbf{56}^+]$	$^4\mathbf{10}[\mathbf{56}^+]$	$^2\mathbf{8}[\mathbf{70}^-]$	$^4\mathbf{8}[\mathbf{70}^-]$	$^2\mathbf{10}[\mathbf{70}^-]$	Total
F_1^p	$9\rho^2$	$8\lambda^2$	$9\rho^2$	0	λ^2	$18\rho^2+9\lambda^2$
F_1^n	$(3\rho+\lambda)^2/4$	$8\lambda^2$	$(3\rho-\lambda)^2/4$	$4\lambda^2$	λ^2	$(9\rho^2+27\lambda^2)/2$
g_1^p	$9\rho^2$	$-4\lambda^2$	$9\rho^2$	0	λ^2	$18\rho^2-3\lambda^2$
g_1^n	$(3\rho+\lambda)^2/4$	$-4\lambda^2$	$(3\rho-\lambda)^2/4$	$-2\lambda^2$	λ^2	$(9\rho^2-9\lambda^2)/2$

representation	$^2\mathbf{8}[\mathbf{56}^+]$	$^4\mathbf{10}[\mathbf{56}^+]$	$^2\mathbf{8}[\mathbf{70}^-]$	$^4\mathbf{8}[\mathbf{70}^-]$	$^2\mathbf{10}[\mathbf{70}^-]$	Total
$F_1^{\nu p}$	0	$24\lambda^2$	0	0	$3\lambda^2$	$27\lambda^2$
$F_1^{\nu n}$	$(9\rho+\lambda)^2/4$	$8\lambda^2$	$(9\rho-\lambda)^2/4$	$4\lambda^2$	λ^2	$(81\rho^2+27\lambda^2)/2$
$g_1^{\nu p}$	0	$-12\lambda^2$	0	0	$3\lambda^2$	$-9\lambda^2$
$g_1^{\nu n}$	$(9\rho+\lambda)^2/4$	$-4\lambda^2$	$(9\rho-\lambda)^2/4$	$-2\lambda^2$	λ^2	$(81\rho^2-9\lambda^2)/2$

λ suppression model ⟹ identical production rates in $\mathbf{56}^+$ and $\mathbf{70}^-$ channels

representation	$^2\mathbf{8}[\mathbf{56}^+]$	$^4\mathbf{10}[\mathbf{56}^+]$	$^2\mathbf{8}[\mathbf{70}^-]$	$^4\mathbf{8}[\mathbf{70}^-]$	$^2\mathbf{10}[\mathbf{70}^-]$	Total
F_1^p	$9\rho^2$	~~$8\lambda^2$~~	$9\rho^2$	0	~~λ^2~~	$18\rho^2+9\lambda^2$
F_1^n	$(3\rho+$~~λ~~$)^2/4$	~~$8\lambda^2$~~	$(3\rho-$~~λ~~$)^2/4$	~~$4\lambda^2$~~	~~λ^2~~	$(9\rho^2+27\lambda^2)/2$
g_1^p	$9\rho^2$	~~$-4\lambda^2$~~	$9\rho^2$	0	~~λ^2~~	$18\rho^2-3\lambda^2$
g_1^n	$(3\rho+$~~λ~~$)^2/4$	~~$-4\lambda^2$~~	$(3\rho-$~~λ~~$)^2/4$	~~$-2\lambda^2$~~	~~λ^2~~	$(9\rho^2-9\lambda^2)/2$

representation	$^2\mathbf{8}[\mathbf{56}^+]$	$^4\mathbf{10}[\mathbf{56}^+]$	$^2\mathbf{8}[\mathbf{70}^-]$	$^4\mathbf{8}[\mathbf{70}^-]$	$^2\mathbf{10}[\mathbf{70}^-]$	Total
$F_1^{\nu p}$	0	~~$24\lambda^2$~~	0	0	~~$3\lambda^2$~~	$27\lambda^2$
$F_1^{\nu n}$	$(9\rho+$~~λ~~$)^2/4$	~~$8\lambda^2$~~	$(9\rho-$~~λ~~$)^2/4$	~~$4\lambda^2$~~	~~λ^2~~	$(81\rho^2+27\lambda^2)/2$
$g_1^{\nu p}$	0	~~$-12\lambda^2$~~	0	0	~~$3\lambda^2$~~	$-9\lambda^2$
$g_1^{\nu n}$	$(9\rho+$~~λ~~$)^2/4$	~~$-4\lambda^2$~~	$(9\rho-$~~λ~~$)^2/4$	~~$-2\lambda^2$~~	~~λ^2~~	$(81\rho^2-9\lambda^2)/2$

for both e and ν scattering

⟹ important test for future ν experiments

4.
Phenomenological models

- Rein, Sehgal (1981): early model of π production in ν scattering
  - → based on relativistic HO model of Feynman, Kislinger & Ravndal (1971)

Rein, Sehgal, Ann. Phys.133, 79 (1981)

- extended by Bodek, Yang to include DIS region

Bodek, Yang, hep-ph/0411202

- Matsui, Sato, Lee (2005): CC and NC π production in Δ region

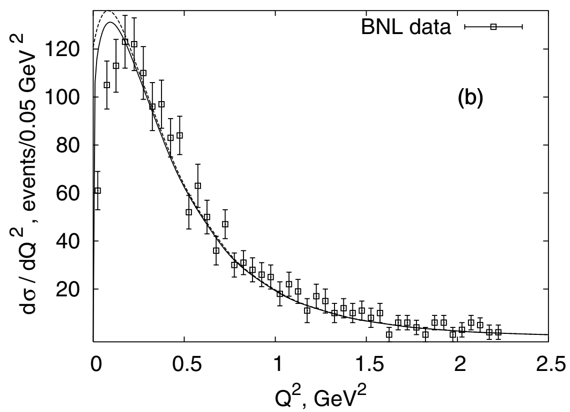
Matsui, Sato, Lee, Phys. Rev. C72, 025204 (2005)

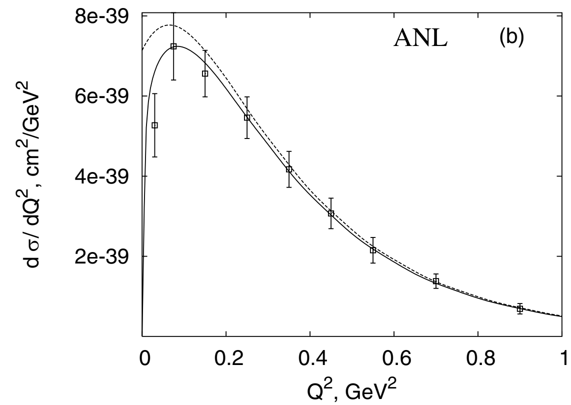
- Parameterize $\nu N N^*$ vertex function with phenomenological form factors

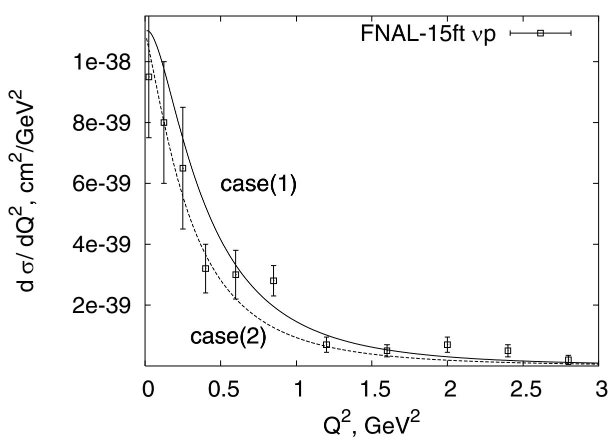
Lalakulich, Paschos, Phys. Rev. D71, 074003 (2005)

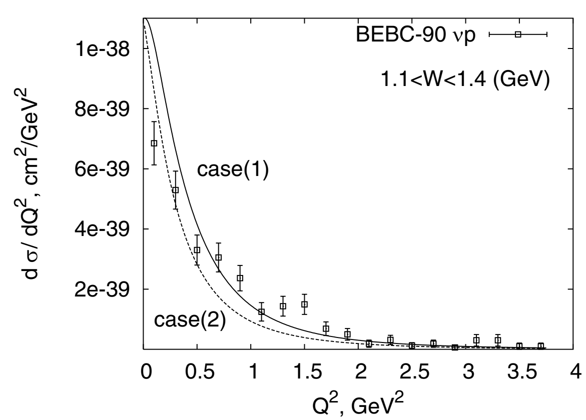
Phenomenological model

Neutrino form factors fitted to neutrino cross section data from BNL, ANL, BEBC, FNAL (more to come with MINERνA)





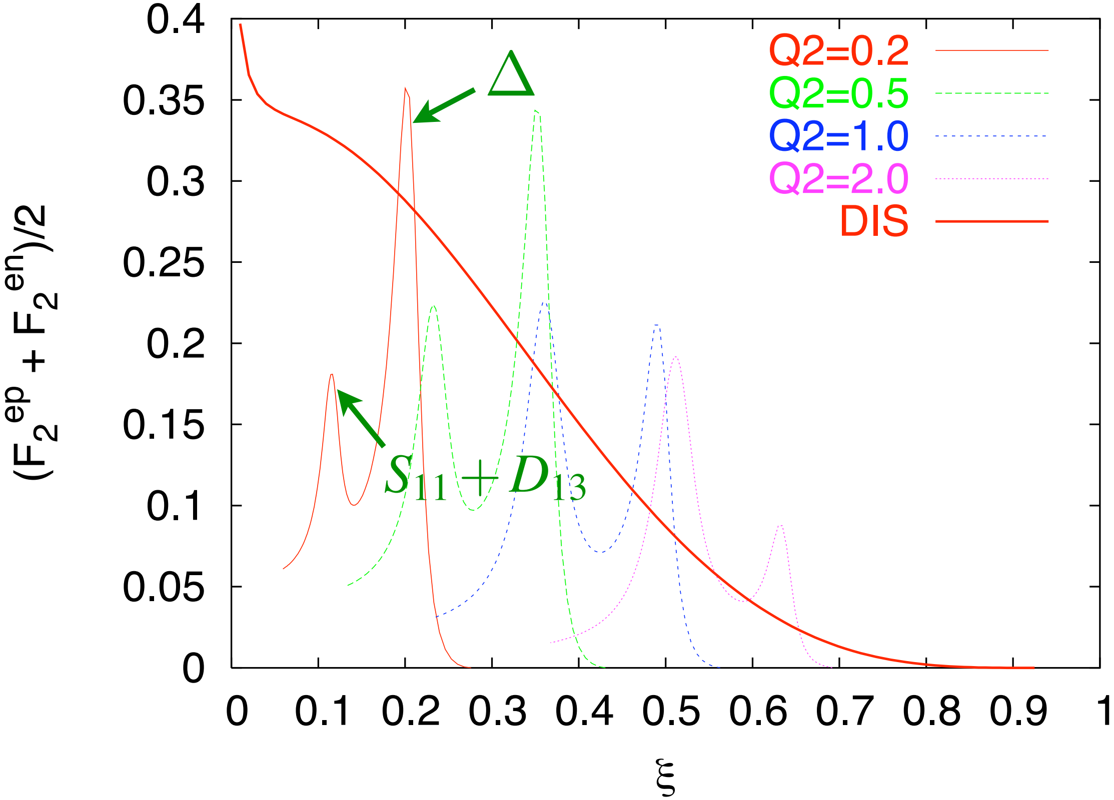




Lalakulich, Paschos,
Phys. Rev. D71 (2005) 074003

Electromagnetic structure functions

Construct structure function from phenomenological $N \to N^*$ transition form factors

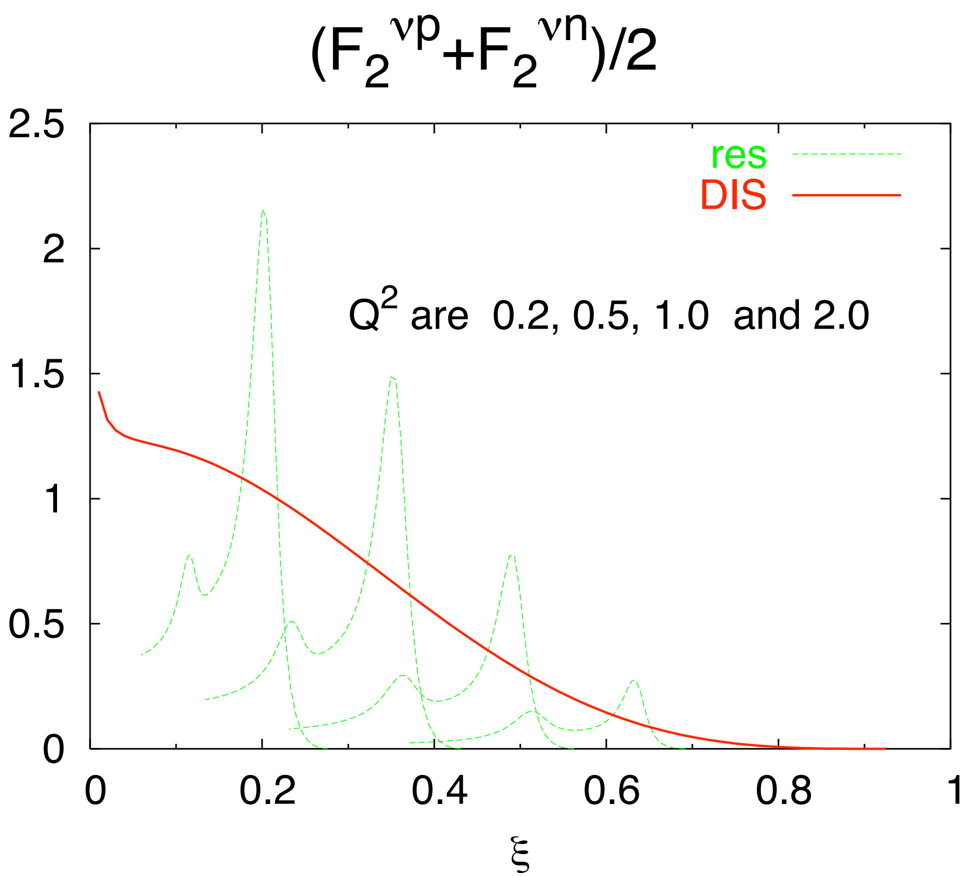


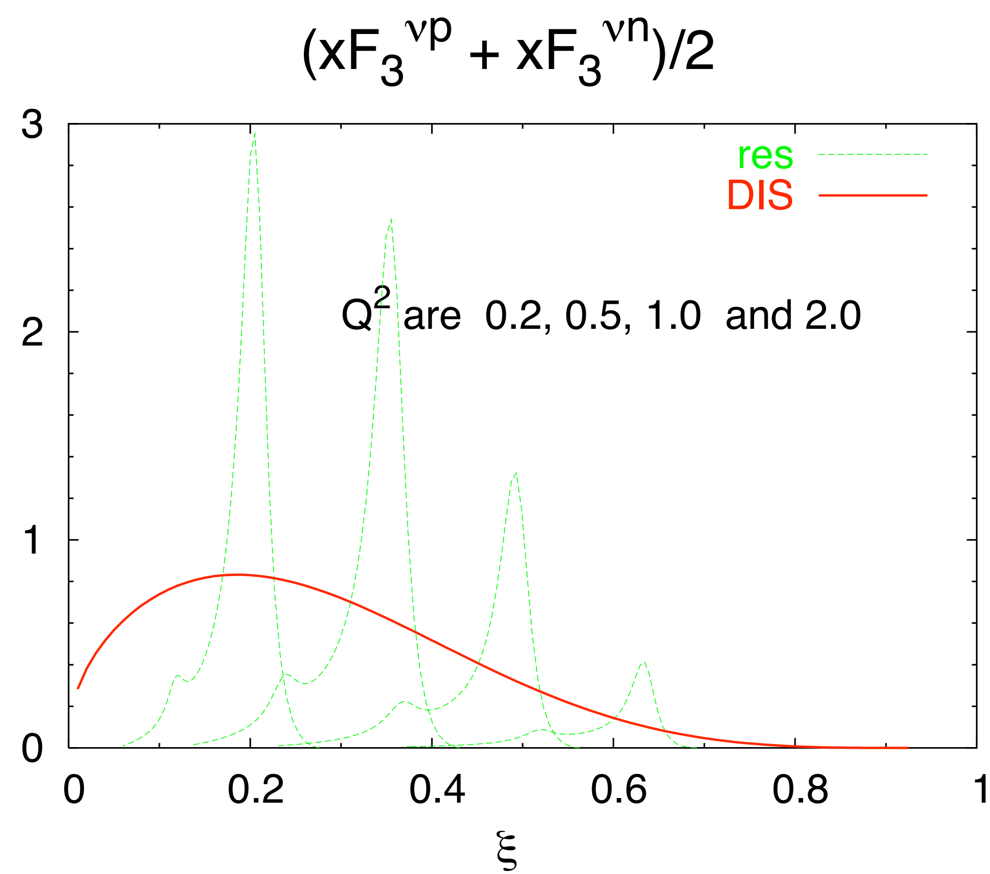
Lalakulich,WM, Paschos (2005)

Resonance widths

$$\delta(W^2 - M_R^2) \longrightarrow \frac{M_R \Gamma_R}{\pi} \frac{1}{(W^2 - M_R^2)^2 + M_R^2 \Gamma_R^2}$$

Neutrino structure functions

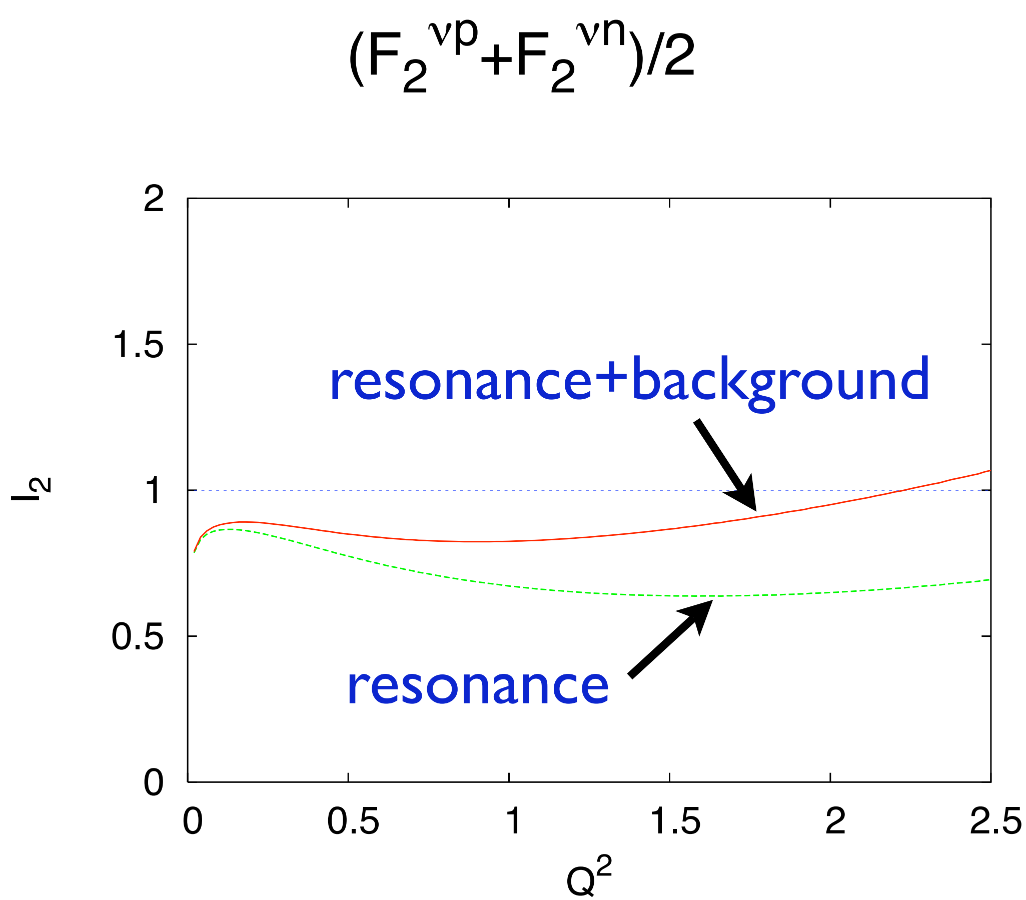


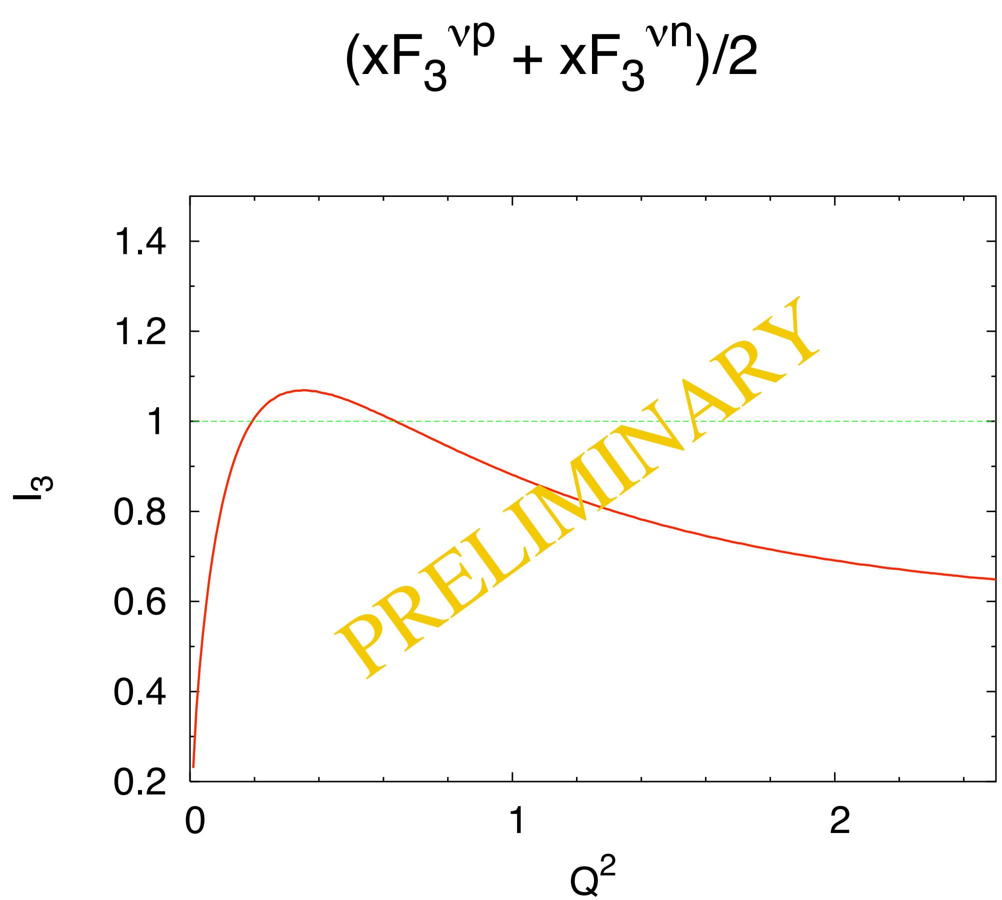


Lalakulich, WM, Paschos (2005)

→ Important to understand systematics of duality in ν scattering cf. e scattering

Integrated structure functions



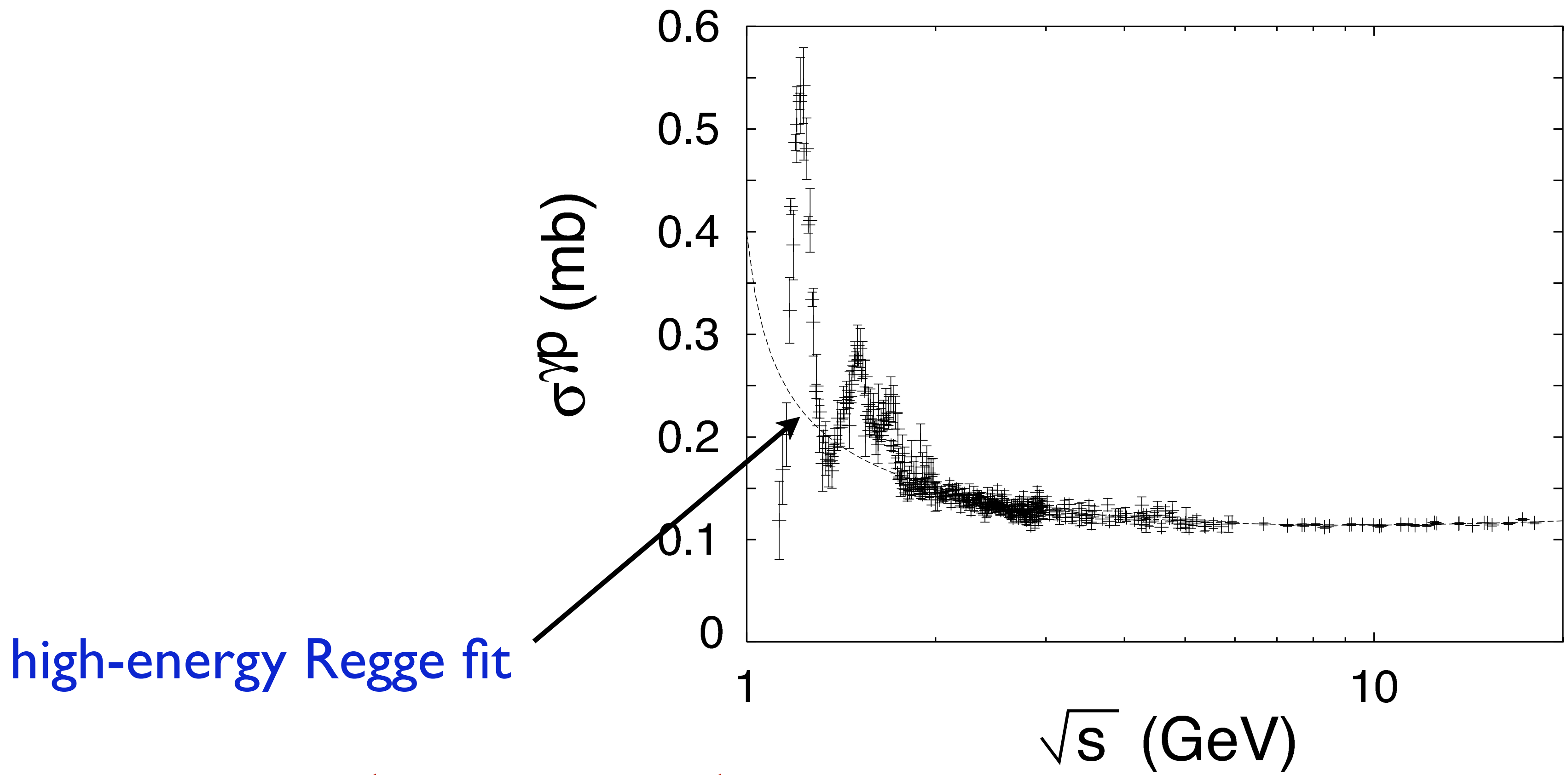


Lalakulich,WM, Paschos (2005)

- integrated from W=1.1 GeV to 1.6 GeV
  $P_{33}(1232) + D_{13}(1520)$
- importance of background contribution

5.
DIS at low Q^2

- as Q^2 decreases, pQCD description (twist expansion) breaks down
  - → near real photon point expand in Q^2 rather than $1/Q^2$
  - → intriguing indications of duality even at $Q^2 = 0$



$$\sigma^{\gamma p} = X(2M\nu)^{\alpha_P - 1} + Y(2M\nu)^{\alpha_R - 1}$$

Donnachie, Landshoff (1992)

- low Q^2 behavior constrained by (electromagnetic) gauge invariance

$$\left.\begin{array}{l} F_2(x,Q^2) \to Q^2 \\ F_L(x,Q^2) \to Q^4 \end{array}\right\} \quad as \;\; Q^2 \to 0$$

- since axial current only partially conserved

$$F_2^{\nu}(x,Q^2) \to f_{\pi}^2 \, \sigma^{\pi N} \;\; as \; Q^2 \to 0$$

→ model for F_2^{ν} at low Q^2

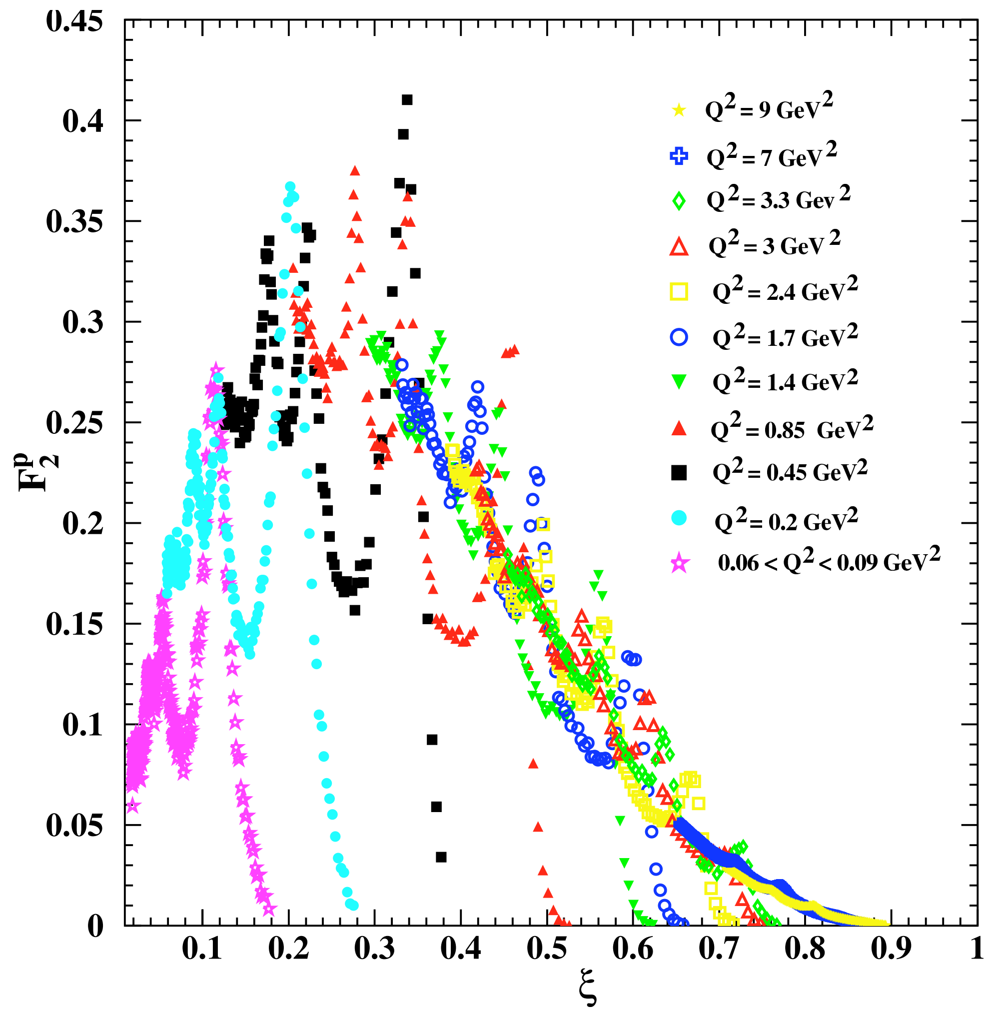
$$F_2^{\nu} = Q^2 \left(\frac{f_{\rho}}{1+Q^2/m_{\rho}^2} \right)^2 \sigma^{\rho N} + f_{\pi}^2 \left(\frac{1}{1+Q^2/m_{A_1}^2} \right)^2 \sigma^{\pi N}$$

VMD PCAC

gauge invariance or dynamics?

F_2 valence-like at low Q^2 ?

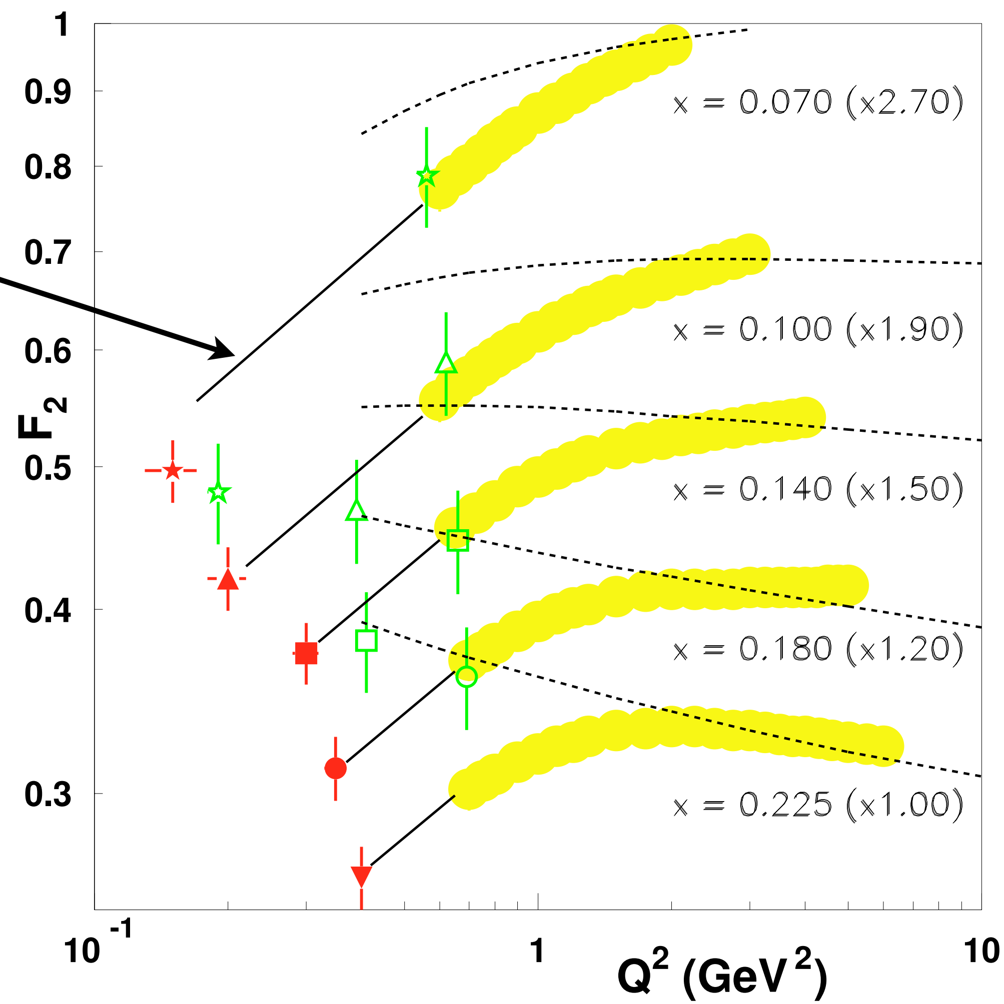
→ cf. xF_3



Niculescu et al., Phys. Rev. Lett. 85 (2000) 1182

gauge invariance or dynamics?

$F_2 \sim Q^{0.5}$



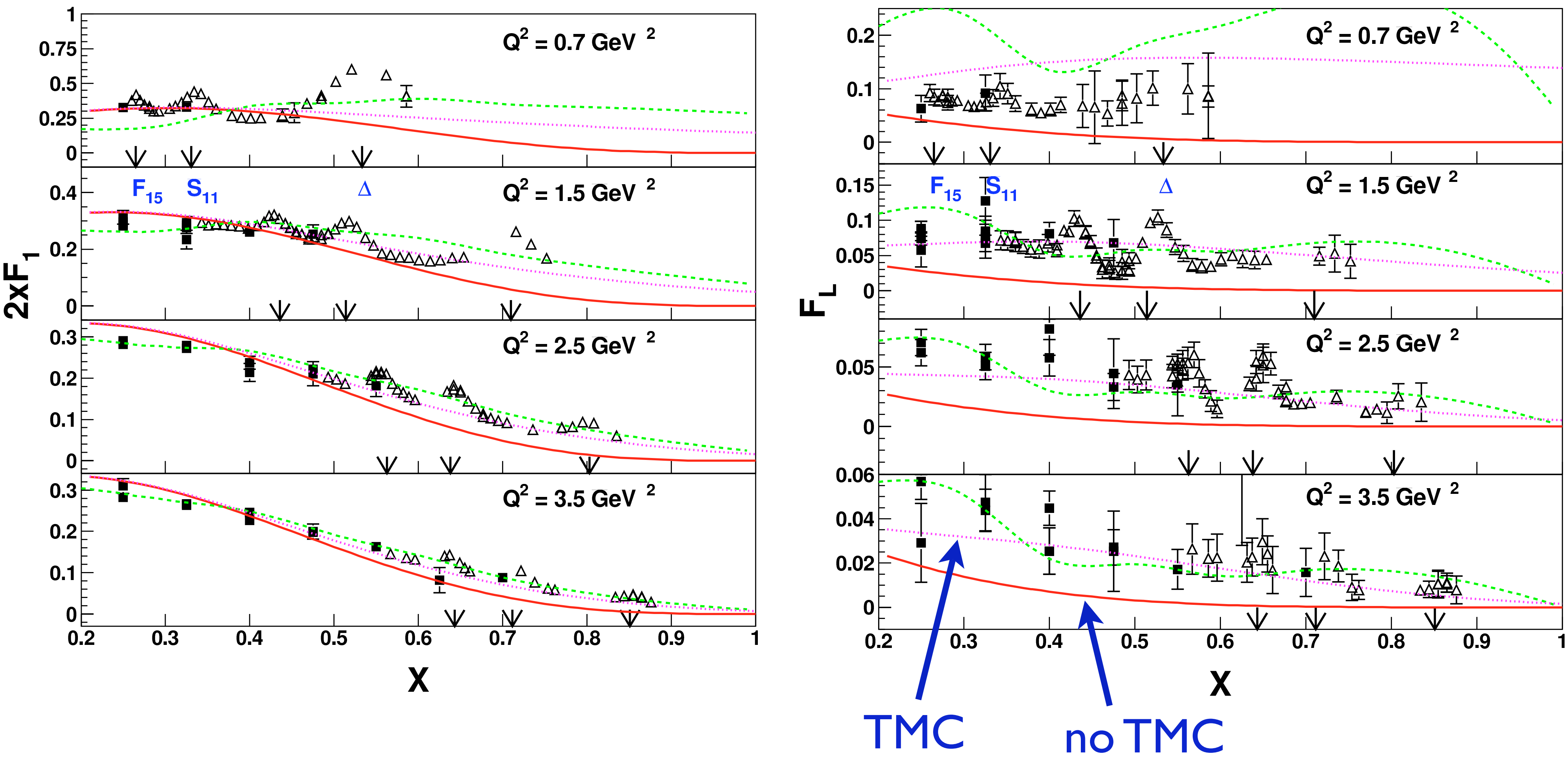
Niculescu et al., Phys. Rev. Lett. 85 (2000) 1182

→ need lower Q^2 before behavior driven by gauge inv.

Target mass corrections

- kinematical $1/Q^2$ corrections (twist-2) associated with finite value of M/Q
- important at large x^2M^2/Q^2

Christy et al. (2005)



Target mass corrections

- TMCs for weak structure functions calculated by Kretzer & Reno (2004)

- difficulty with (well-known) threshold problem

$$F_T^{\rm TMC}(x,Q^2) = \frac{x^2}{\xi^2\gamma} F_T^{\rm LT}(\xi,Q^2) + \frac{2x^3M^2}{Q^2\gamma^2}\int_\xi^1 \frac{{\rm d}z}{z^2} F_2^{\rm LT}(z,Q^2),$$

$$F_2^{\rm TMC}(x,Q^2) = \frac{x^2}{\xi^2\gamma^3} F_2^{\rm LT}(\xi,Q^2) + \frac{6x^3M^2}{Q^2\gamma^4}\int_\xi^1 \frac{{\rm d}z}{z^2} F_2^{\rm LT}(z,Q^2), \qquad +O(1/Q^4)$$

$$xF_3^{\rm TMC}(x,Q^2) = \frac{x^2}{\xi^2\gamma^2} \xi F_3^{\rm LT}(\xi,Q^2) + \frac{2x^3M^2}{Q^2\gamma^3}\int_\xi^1 \frac{{\rm d}z}{z^2} z F_3^{\rm LT}(z,Q^2).$$

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

since $\xi(x=1) < 1$ ➡ $F_i^{LT}(\xi,Q^2) > 0$

➡ $F_i^{TMC}(x \to 1, Q^2) \neq 0$

Target mass corrections

- one solution (Kulagin/Petti) - expand in $1/Q^2$

$$
\begin{aligned}
F_T^{\mathrm{TMC}}(x,Q^2) &= F_T^{\mathrm{LT}}(x,Q^2) + \\
&\quad \frac{x^3 M^2}{Q^2}\left(2\int_x^1 \frac{\mathrm{d}z}{z^2} F_2^{\mathrm{LT}}(z,Q^2) - \frac{\partial}{\partial x} F_T^{\mathrm{LT}}(x,Q^2)\right), \\
F_2^{\mathrm{TMC}}(x,Q^2) &= \left(1 - \frac{4x^2 M^2}{Q^2}\right) F_2^{\mathrm{LT}}(x,Q^2) + \\
&\quad \frac{x^3 M^2}{Q^2}\left(6\int_x^1 \frac{\mathrm{d}z}{z^2} F_2^{\mathrm{LT}}(z,Q^2) - \frac{\partial}{\partial x} F_2^{\mathrm{LT}}(x,Q^2)\right), \\
xF_3^{\mathrm{TMC}}(x,Q^2) &= \left(1 - \frac{2x^2 M^2}{Q^2}\right) xF_3^{\mathrm{LT}}(x,Q^2) + \\
&\quad \frac{x^3 M^2}{Q^2}\left(2\int_x^1 \frac{\mathrm{d}z}{z^2} zF_3^{\mathrm{LT}}(z,Q^2) - \frac{\partial}{\partial x} xF_3^{\mathrm{LT}}(x,Q^2)\right)
\end{aligned}
$$

Kulagin, Petti
hep-ph/0412425

→ has correct threshold behavior

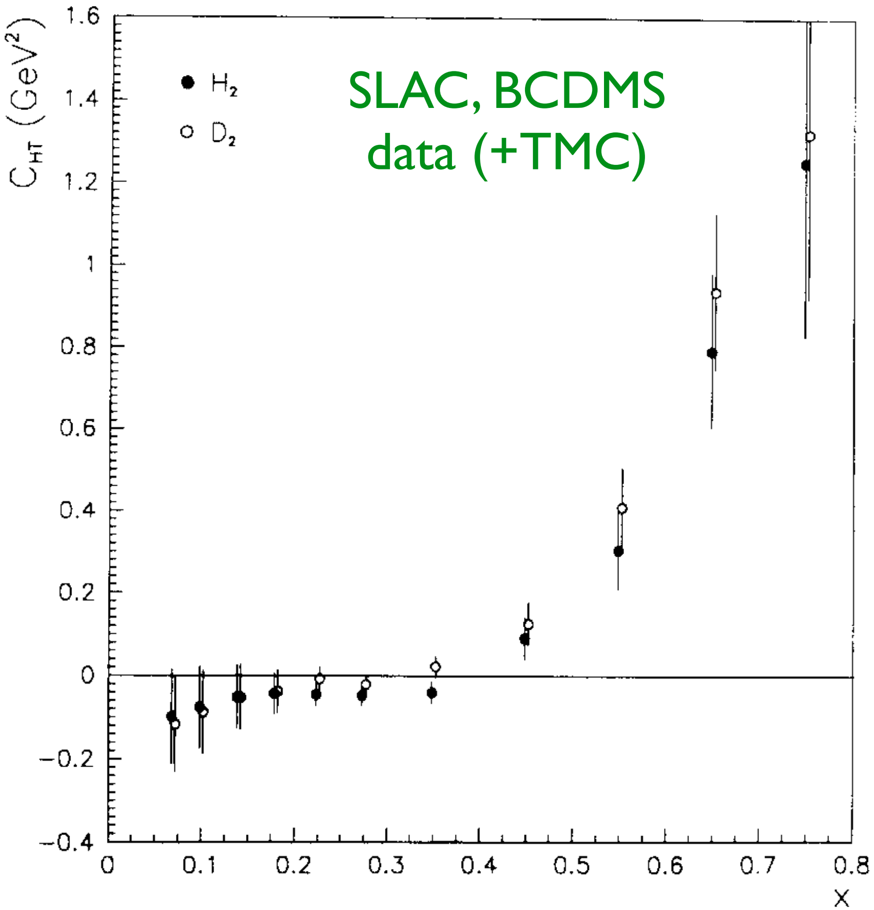
- alternatively, work with $\xi_0 = \xi(x=1)$ dependent PDFs

Steffens, WM 2005

Phenomenological higher twists

- usually parameterized as

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



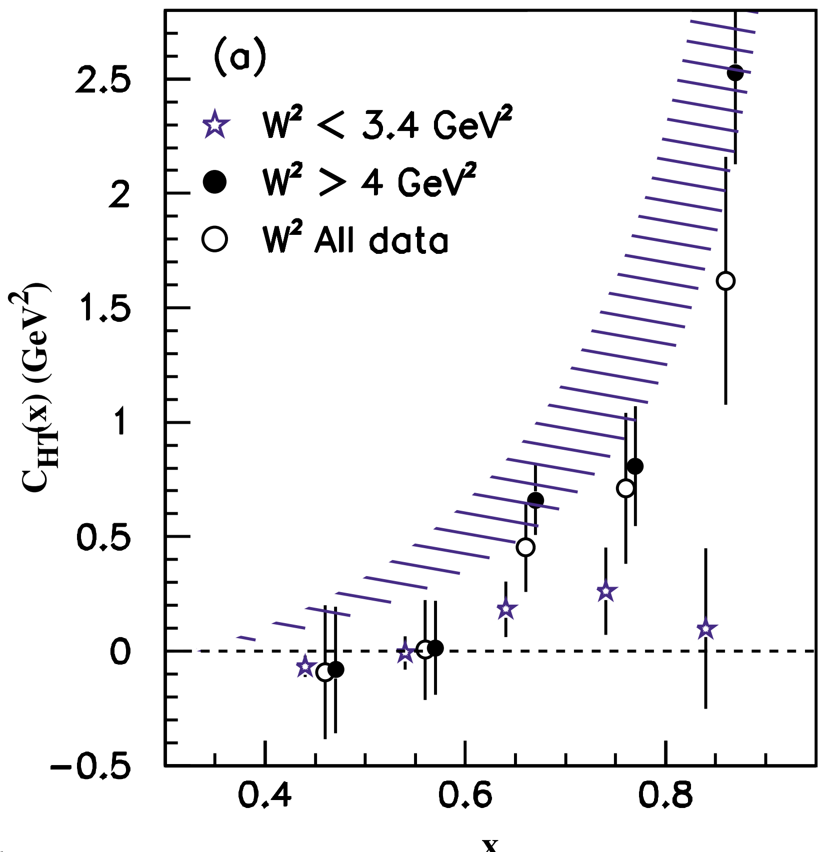
Virchaux, Milsztajn,
Phys. Lett. B274 (1992) 221

Phenomenological higher twists

- more recent JLab data analysis

$$F_2(x,Q^2) = F_2^{LT}(x,Q^2)\left(1+\frac{C_{HT}(x)}{Q^2}+\Delta H(x,Q^2)\right)$$

+ TMC
+ large-x resummation



→ large-x resummation reduces C_{HT}

→ lower-W data require negative $1/Q^4$ term

Liuti, Ent, Keppel, Niculescu, Phys. Rev. Lett. 89 (2002) 162001

Phenomenological higher twists

- more recent JLab data analysis

$$F_2(x,Q^2) = F_2^{LT}(x,Q^2)\left(1+\frac{C_{HT}(x)}{Q^2}+\Delta H(x,Q^2)\right)$$

+ TMC
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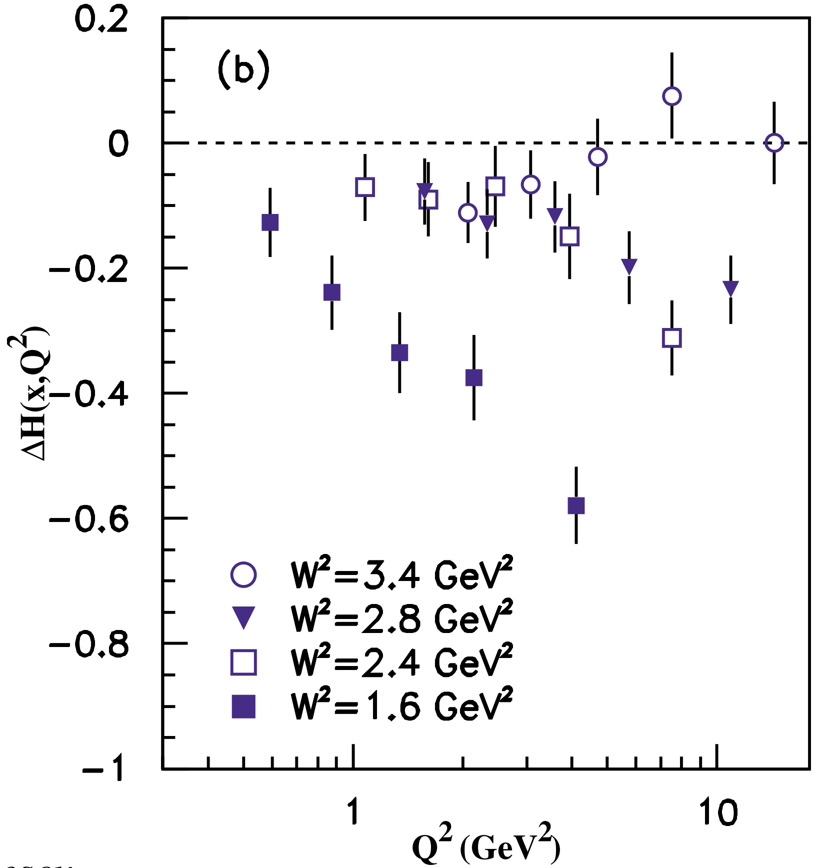

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Liuti, Ent, Keppel, Niculescu, Phys. Rev. Lett. 89 (2002) 162001

Phenomenological higher twists

extrapolation to low Q^2

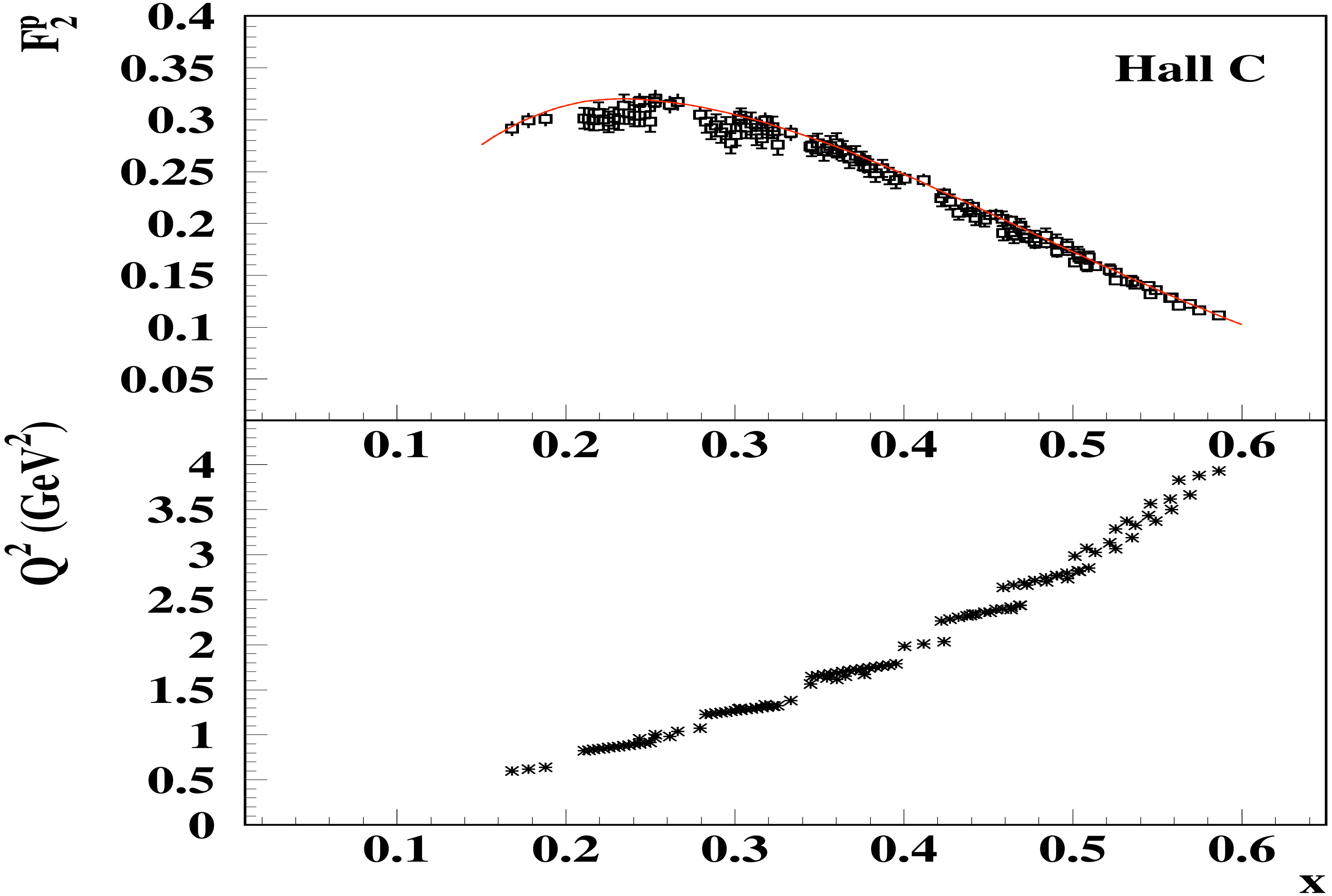
(Alekhin, Kulagin, Petti 2005) ($\longrightarrow$ talk of R. Petti)

- The leading-twist terms with the NNLO QCD evolution up to $Q^2 = 1\ \mathrm{GeV}^2$ (dominate structure functions for $Q^2 \gtrsim 10\ \mathrm{GeV}^2$).
- Phenomenological higher-twist terms are parameterized as additive corrections $H^{(t)}(x)/Q^{t-2}$. No $Q-$dependence of $H^{(t)}$ is assumed. The $t = 4$ terms are important for $Q^2 \lesssim 10\ \mathrm{GeV}^2$ and the $t = 6$ terms – at $Q^2 \lesssim 3\ \mathrm{GeV}^2$.
- The QCD structure functions are interpolated between $Q^2 = 1\,\mathrm{GeV}^2$ and $Q^2 = 0$ using cubic spline at fixed x and the constraints due to current conservation $F_2 \sim Q^2$ and $F_L \sim Q^4$ as $Q^2 \to 0$.

Phenomenological higher twists

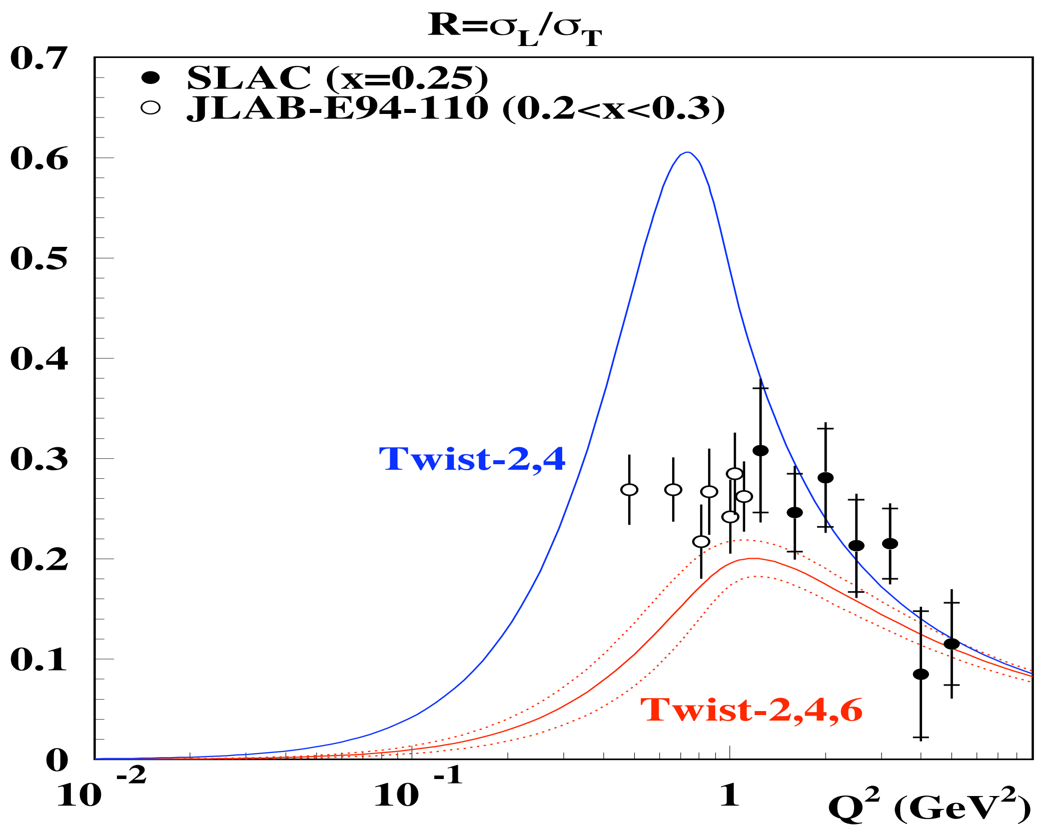
- extrapolation to low Q^2
  (Alekhin, Kulagin, Petti 2005)

Comparison with JLAB data beyond resonance region
($W = 1.9 \div 2$ GeV)



Phenomenological higher twists

- extrapolation to low Q^2
  (Alekhin, Kulagin, Petti 2005)



large twist 6!
convergence?

NB: $R^{\nu} \not\to 0 \quad as \quad Q^2 \to 0$

Summary

- Remarkable confirmation of quark-hadron duality in structure functions
  - → higher twists "small" down to low Q^2 (~ 1 GeV^2)
  - → provides quantitative handle on resonance-DIS transition

- Quark models provide clues to origin of resonance cancellations
  - → study systematics of local duality in ν vs. e scattering
  - → detailed phenomenological study underway

- Intriguing low-Q^2 behavior
  - → phenomenological extraction of higher twists
  - → $Q^2 \to 0$ constraints for e.m. but *different* for ν
  - → TMCs not completely understood for large x^2M^2/Q^2

THE END