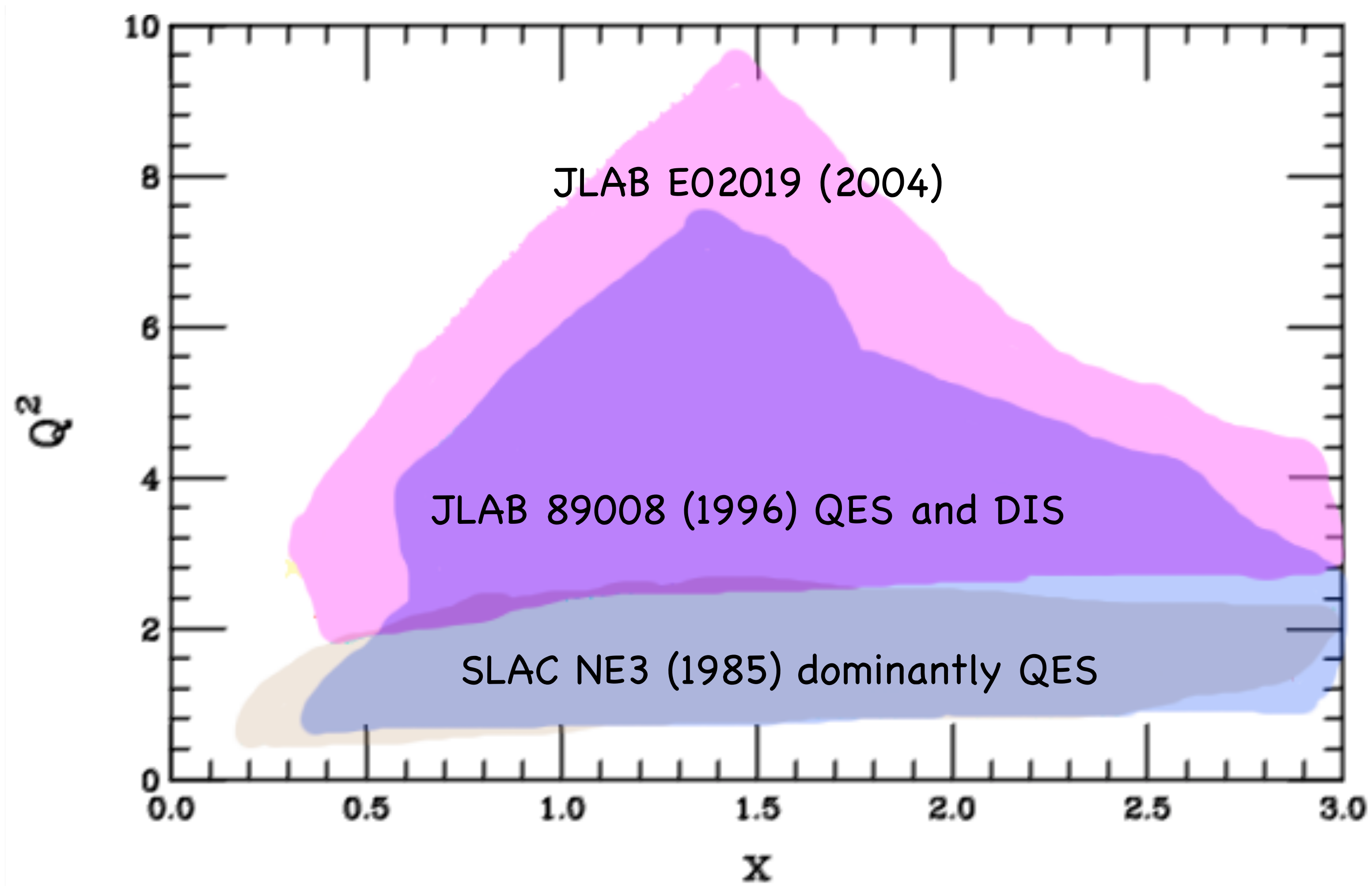
Duality in Nuclei



Donal Day, University of Virginia

Parton Hadron Duality Meeting Charlottesville, March 13, 2015

Proloque

Inclusive electron scattering from nuclei remains fertile

- Short Range Correlations
- Scaling (y, φ', x, ξ), and scale breaking
- Medium Modifications -- tests of EMC; 6-quark admixtures
- Application of duality to nuclei and over QEP
- Extraction of the structure functions and quark distributions at $x > 1$

Latest data is from from JLAB E02019

- E02019 finished in late 2004, E = 5.77 GeV , $I \leq 80uA$
- Cryogenic Targets: H, ^2H, ^3He, ^4He Solid Targets: Be, C, Cu, Au
- Provided greatest reach in x and Q^2 to date

Scaling of the F_2 structure function in nuclei and quark distributions at x>1

Fomin, Arrington, Day et al. Phys. Rev. Lett. 105, 212502 November 2010

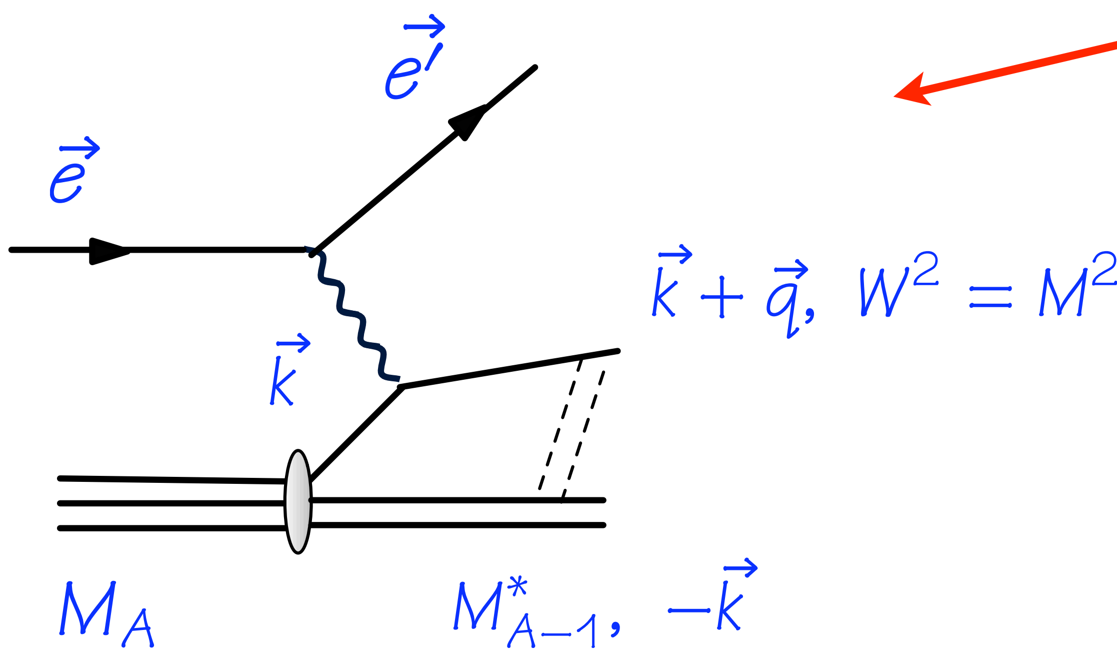
New measurements of high-momentum nucleons and short-range structures in nuclei

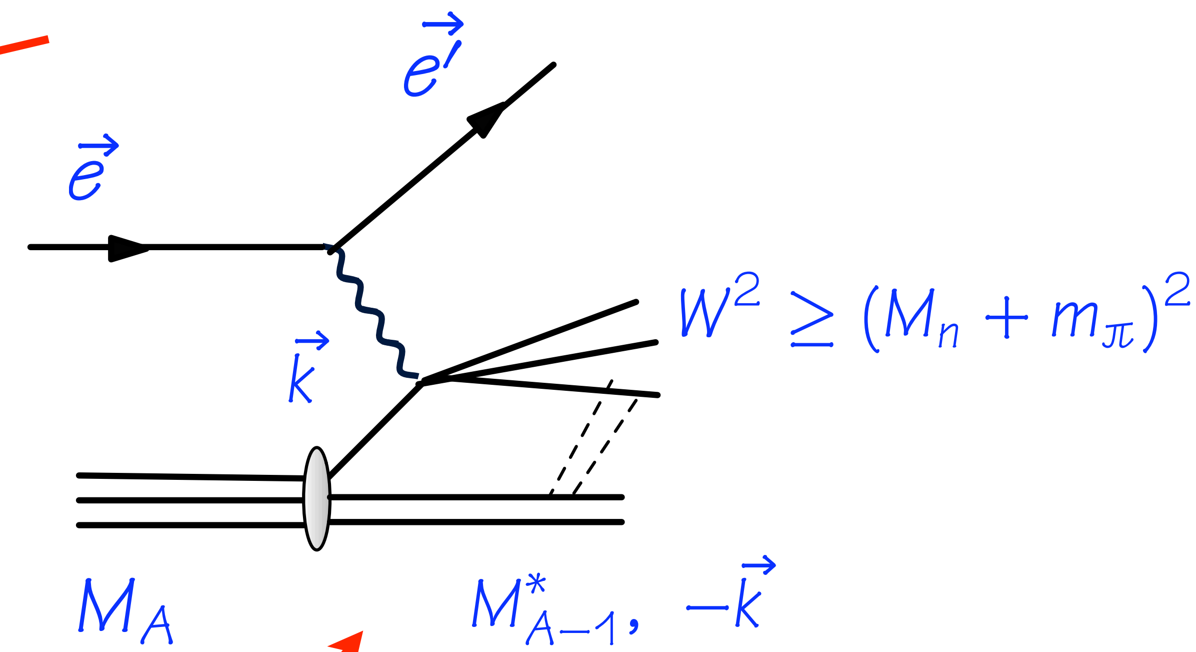
Fomin et al. Phys. Rev. Lett. 108 (2012) 092502

Inclusive Electron Scattering from Nuclei

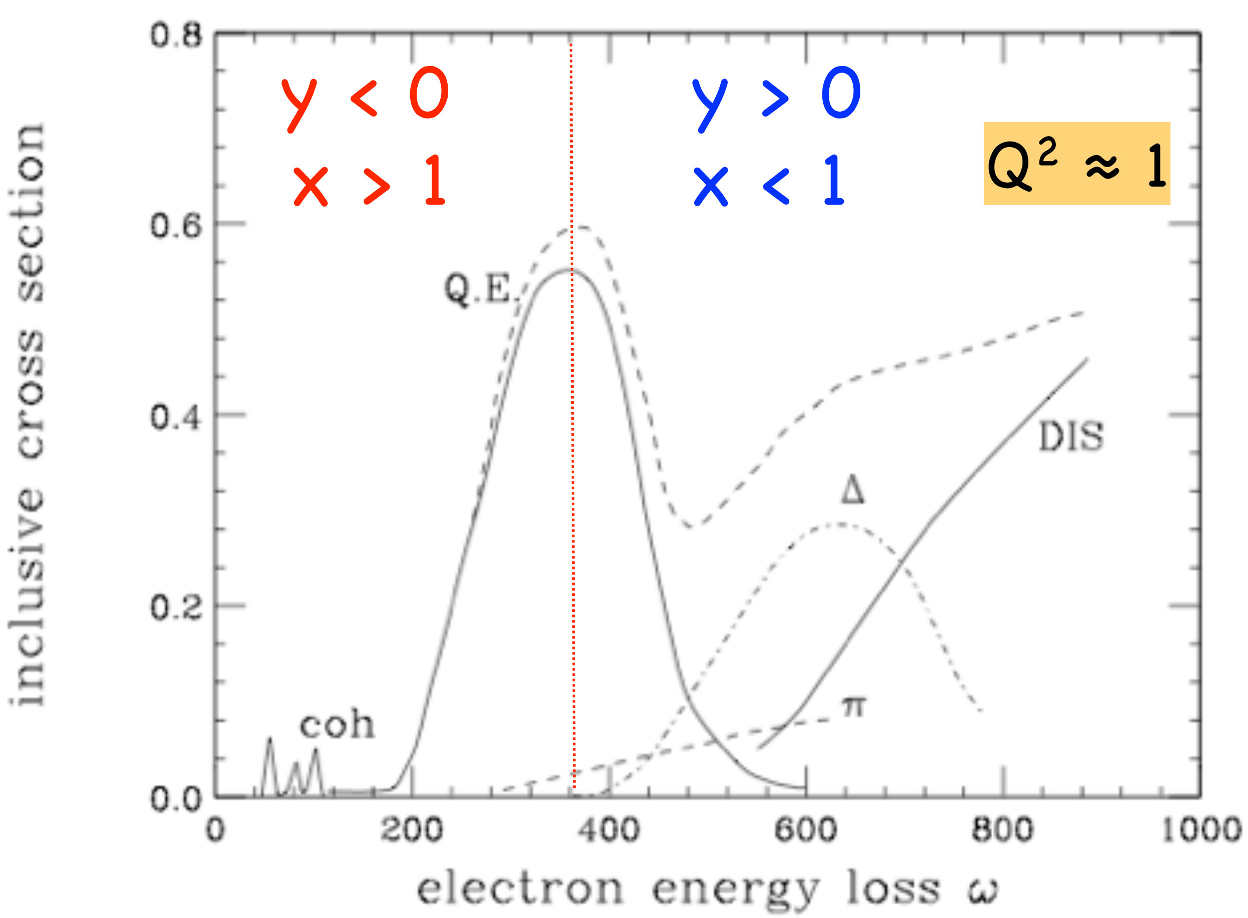
Two dominant and distinct processes

Quasielastic from the nucleons in the nucleus





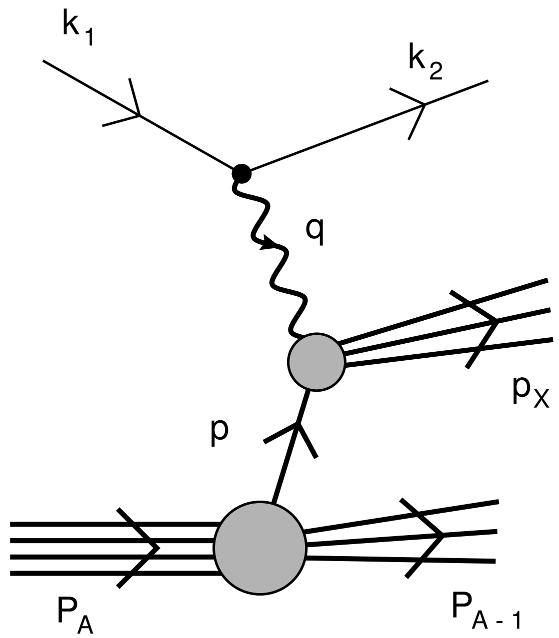
Inelastic (resonances) and DIS from the quark constituents of the nucleon.



Inclusive final state means no separation of two dominant processes

$x = Q^2/(2m\upsilon)$

υ,ω=energy loss



$$\frac{d\sigma^2}{dQ_{e'}dE_{e'}} = \frac{\alpha^2}{Q^4}\frac{E'_e}{E_e}L_{\mu\nu}W^{\mu\nu}$$

The two processes share the same initial state

QES in IA

$$\frac{d^2\sigma}{dQd\nu} \propto \int d\vec{k} \int dE \sigma_{ei} \underbrace{S_i(k,E)}_{\text{Spectral function}} \delta()$$

The limits on the integrals are determined by the kinematics. Specific (x, Q^2) select specific pieces of the spectral function.

DIS

$$\frac{d^2\sigma}{dQd\nu} \propto \int d\vec{k} \int dE\, W_{1,2}^{(p,n)} \underbrace{S_i(k,E)}_{\text{Spectral function}}$$

$$n(k) = \int dE\, S(k,E)$$

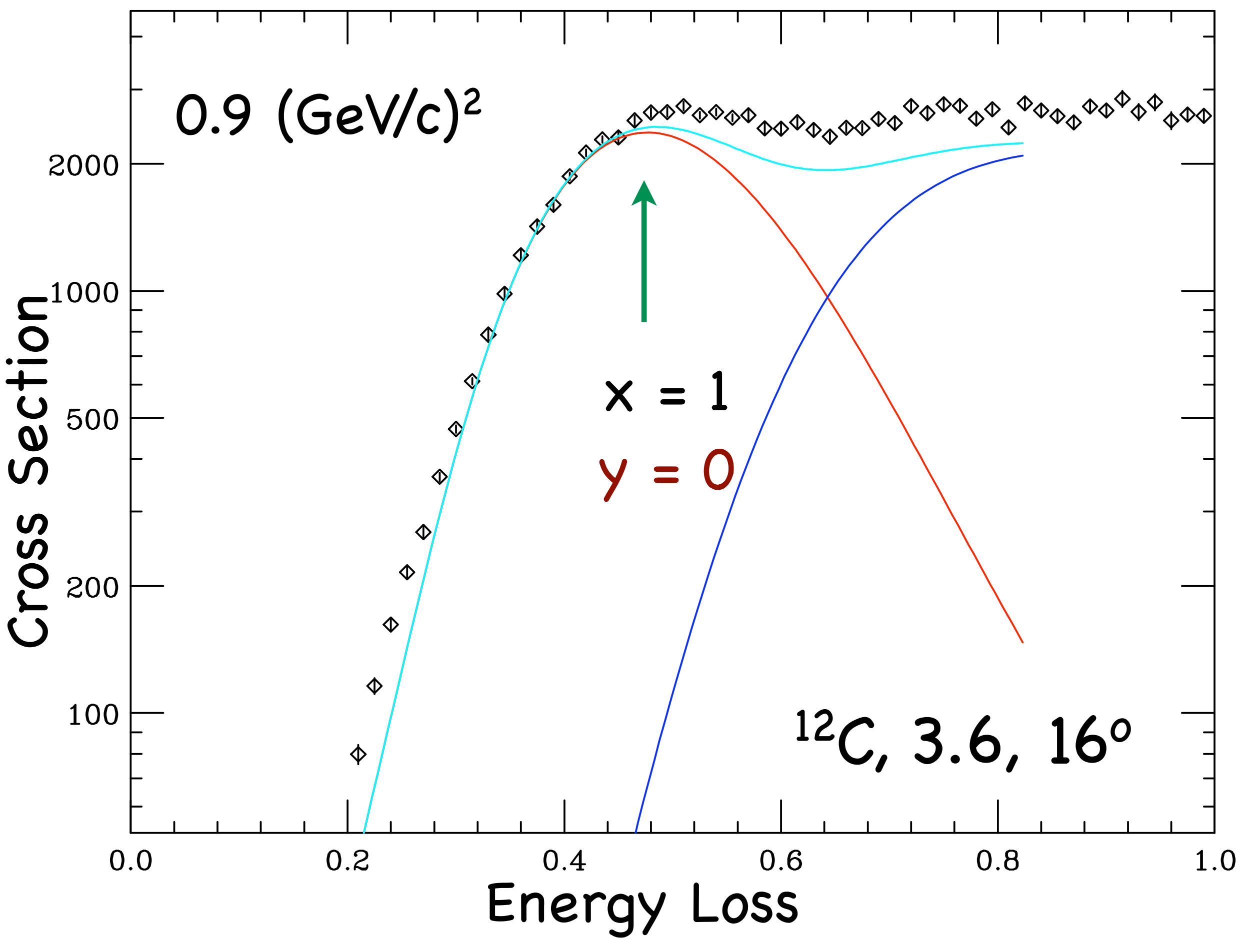
However they have very different Q^2 dependencies

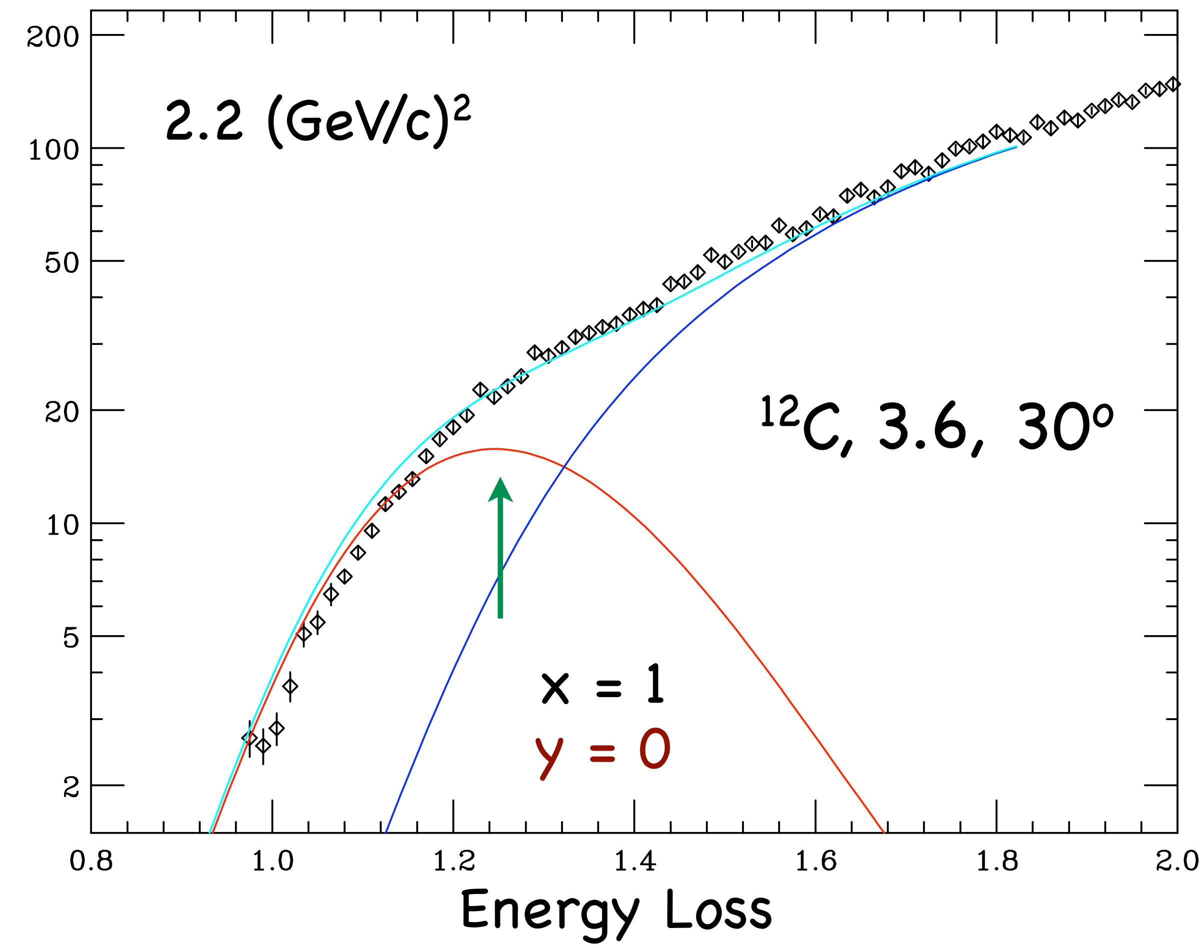
$\sigma_{ei} \propto$ elastic (form factor)$^2 \approx 1/Q^4$

$W_{1,2}$ scale with ln Q^2 dependence

Exploit this dissimilar Q^2 dependence

Inelastic contribution increases with Q^2

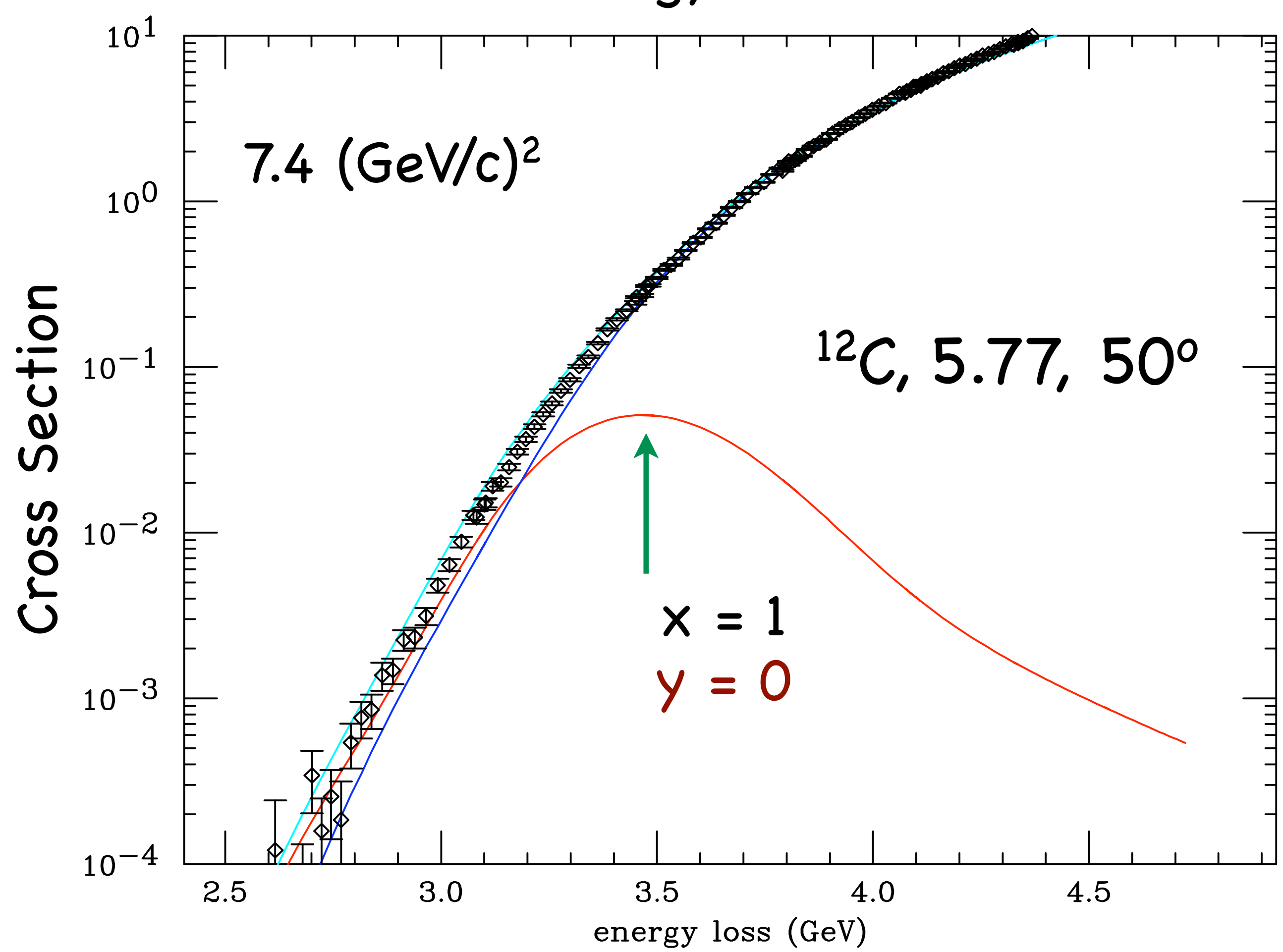




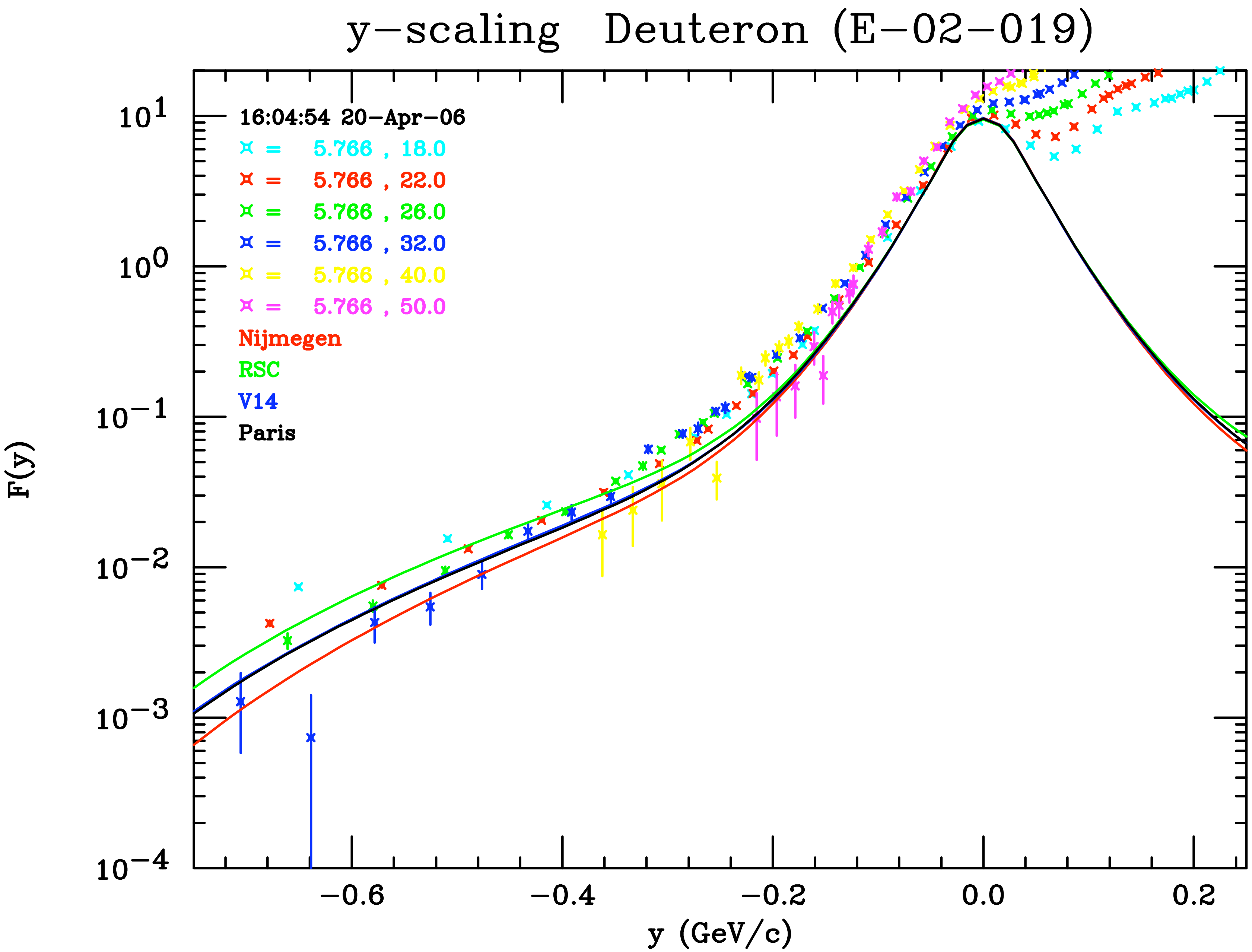
DIS begins to contribute at $x > 1$

Convolution model

We expect that as Q^2 increases to see evidence (x-scaling) that we are scattering from a quark at $x > 1$



Deuteron

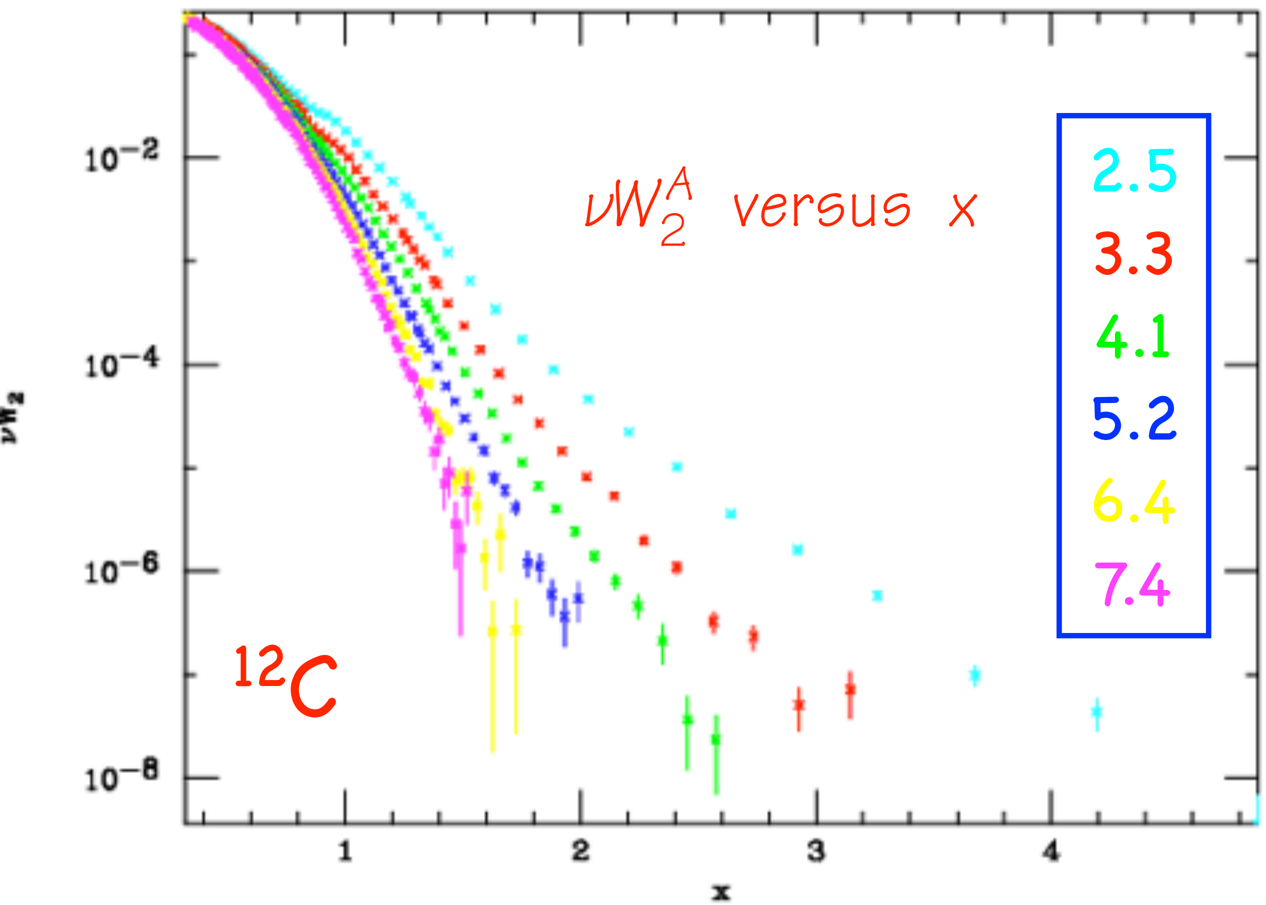


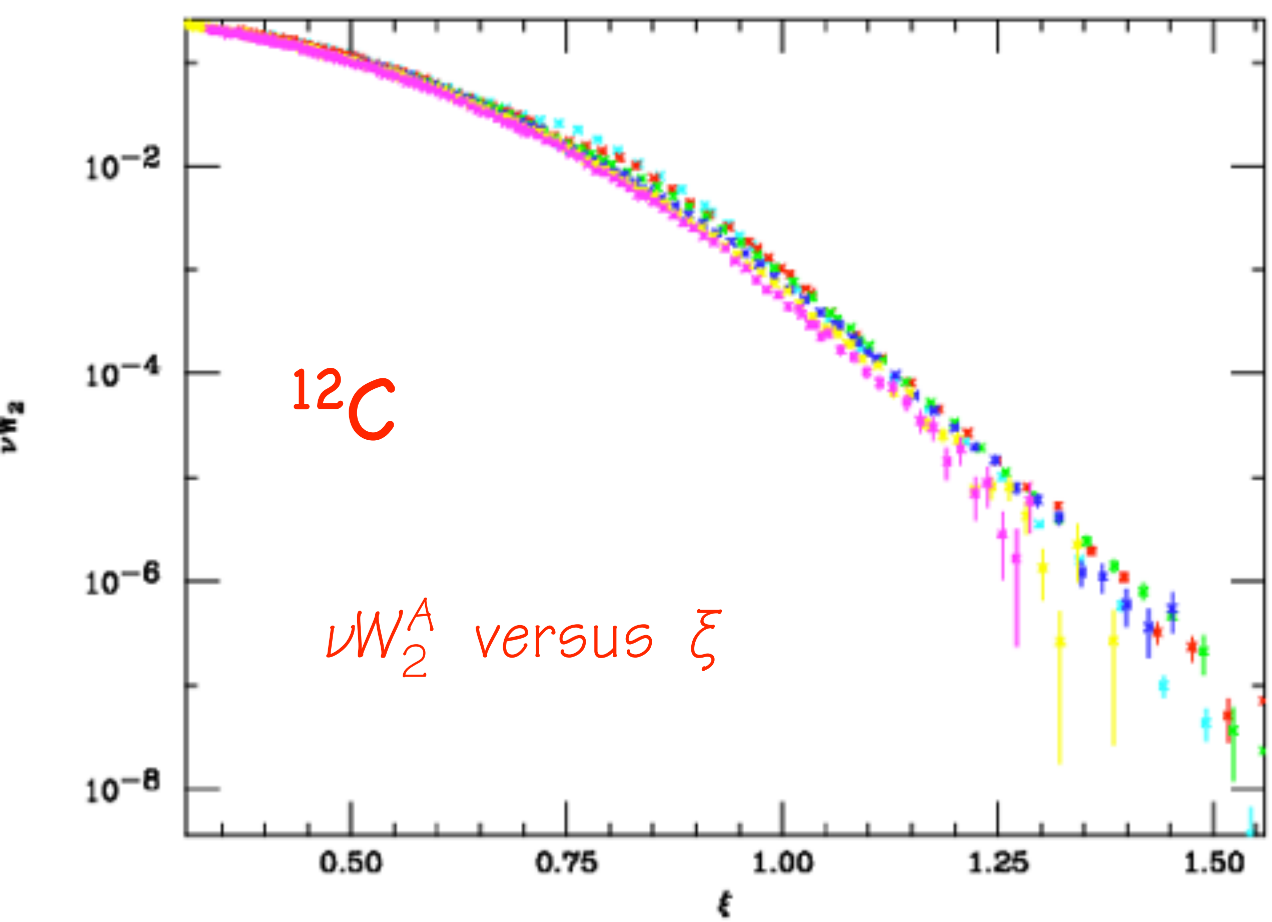
$$F(y) = \frac{\sigma^{exp}}{(Z\sigma_p + N\sigma_n)} \cdot K$$

$$n(k) = -\frac{1}{2\pi y}\frac{dF(y)}{dy}$$

Assumption: scattering takes place from a quasi-free proton or neutron in the nucleus.

y is the momentum of the struck nucleon parallel to the momentum transfer:
$y \approx -q/2 + m\nu/q$





Especially for the heavier nuclei

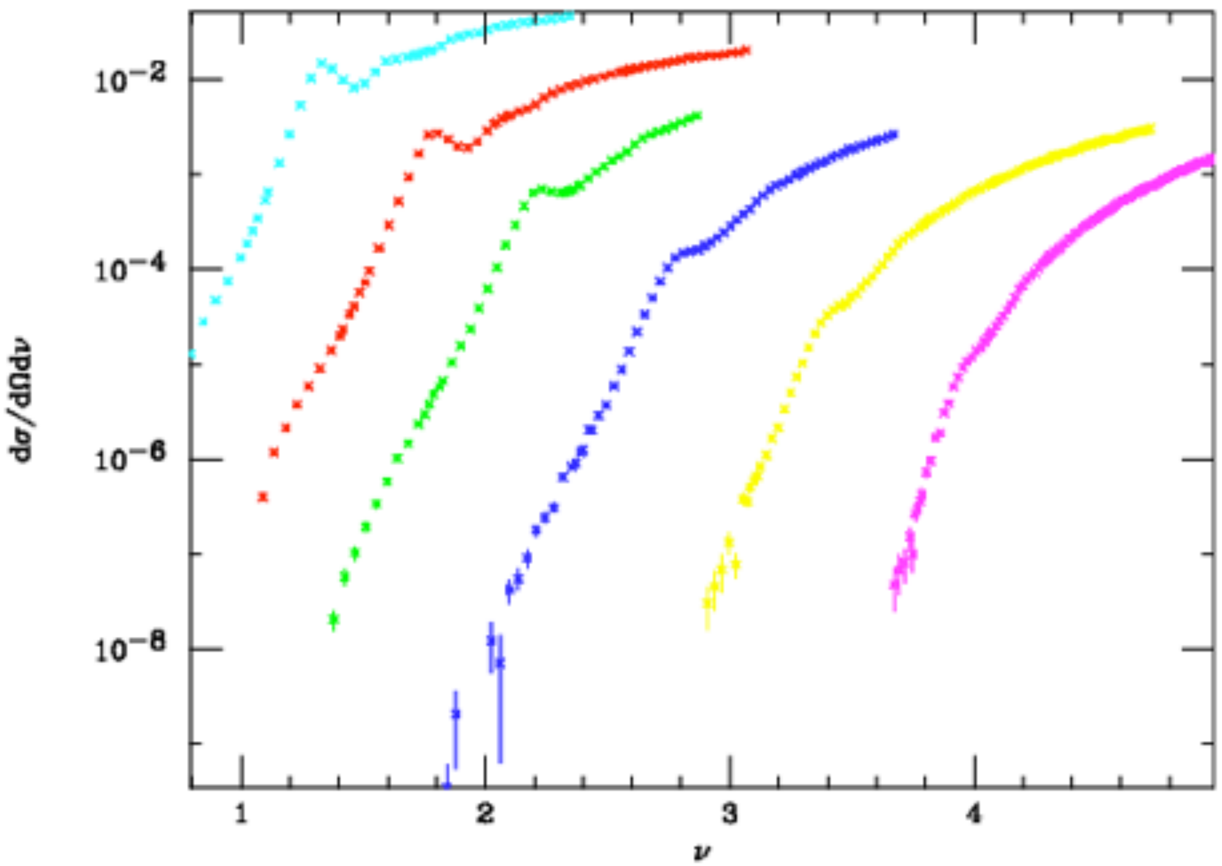
ξ (fraction of nucleon light cone momentum p^+) is proper variable in which logarithmic violations of scaling in DIS should be studied.

Local duality (averaging over finite range in x) should also be valid for elastic peak at x = 1 if analyzed in ξ

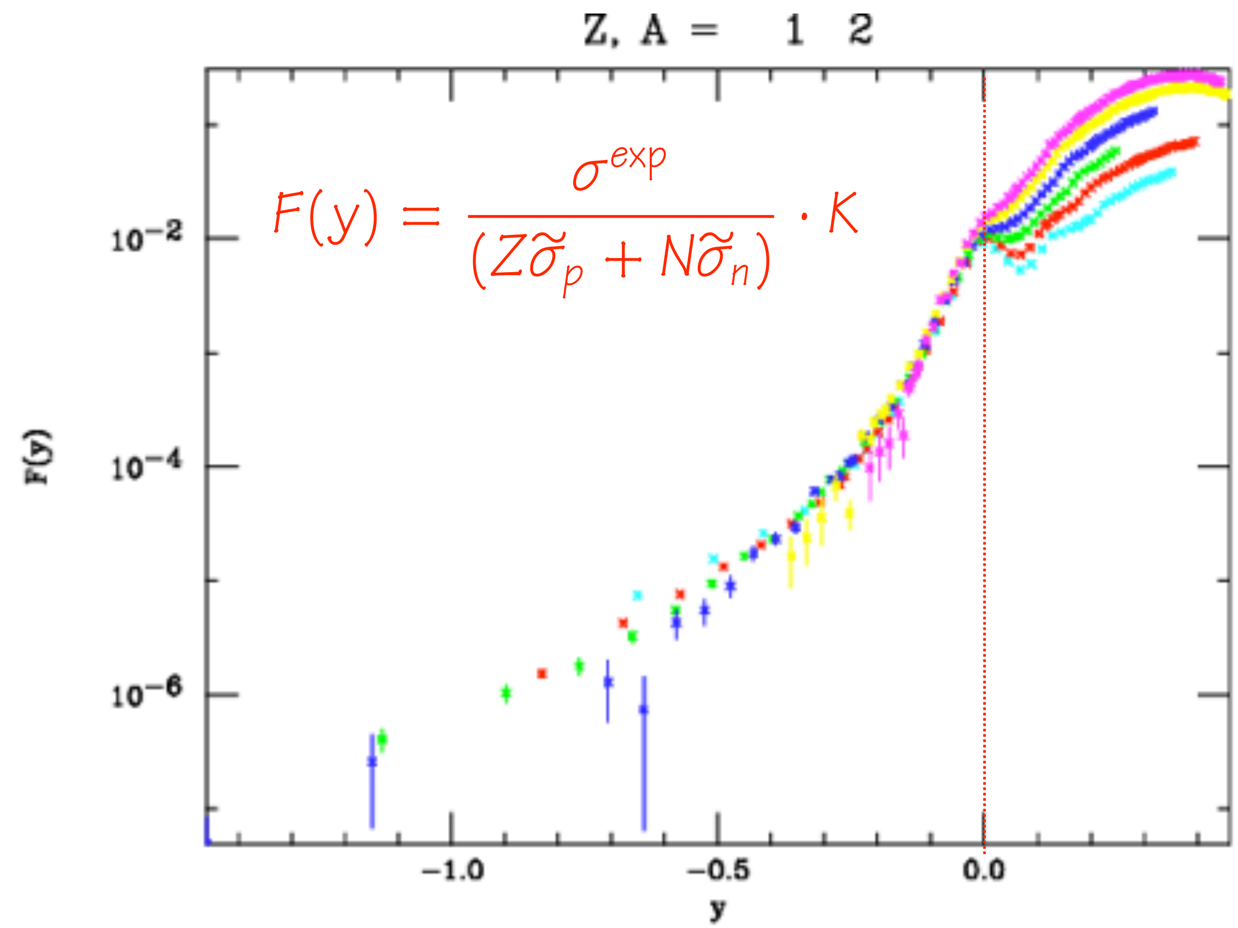
$$F_2^A(\xi) = \underbrace{\int_{\xi}^{A} dz F(z) F_2^n(\xi/z)}_{\text{averaging}}$$

Evidently the inelastic and quasielastic contributions cooperate to produce ξ scaling. Is this local duality?

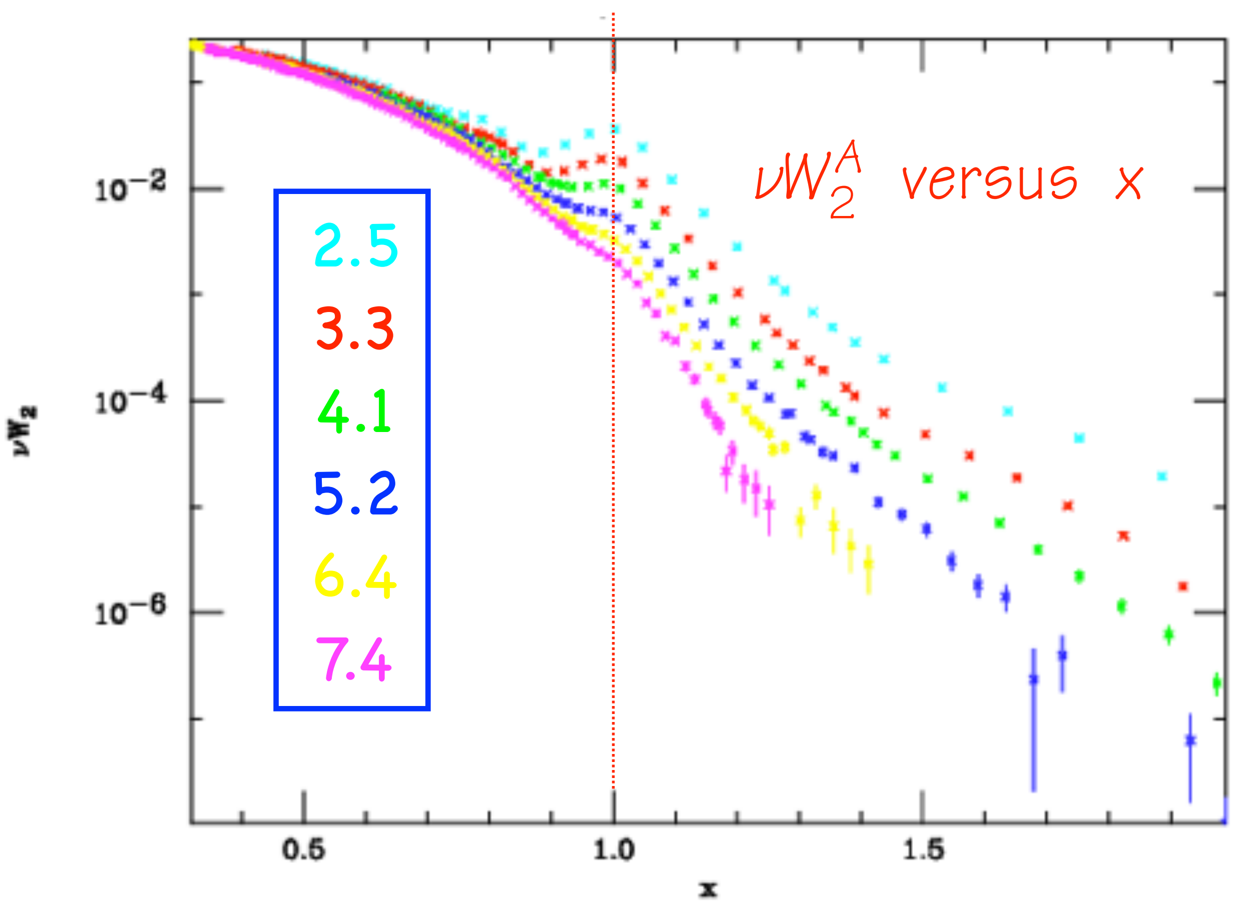
Deuteron



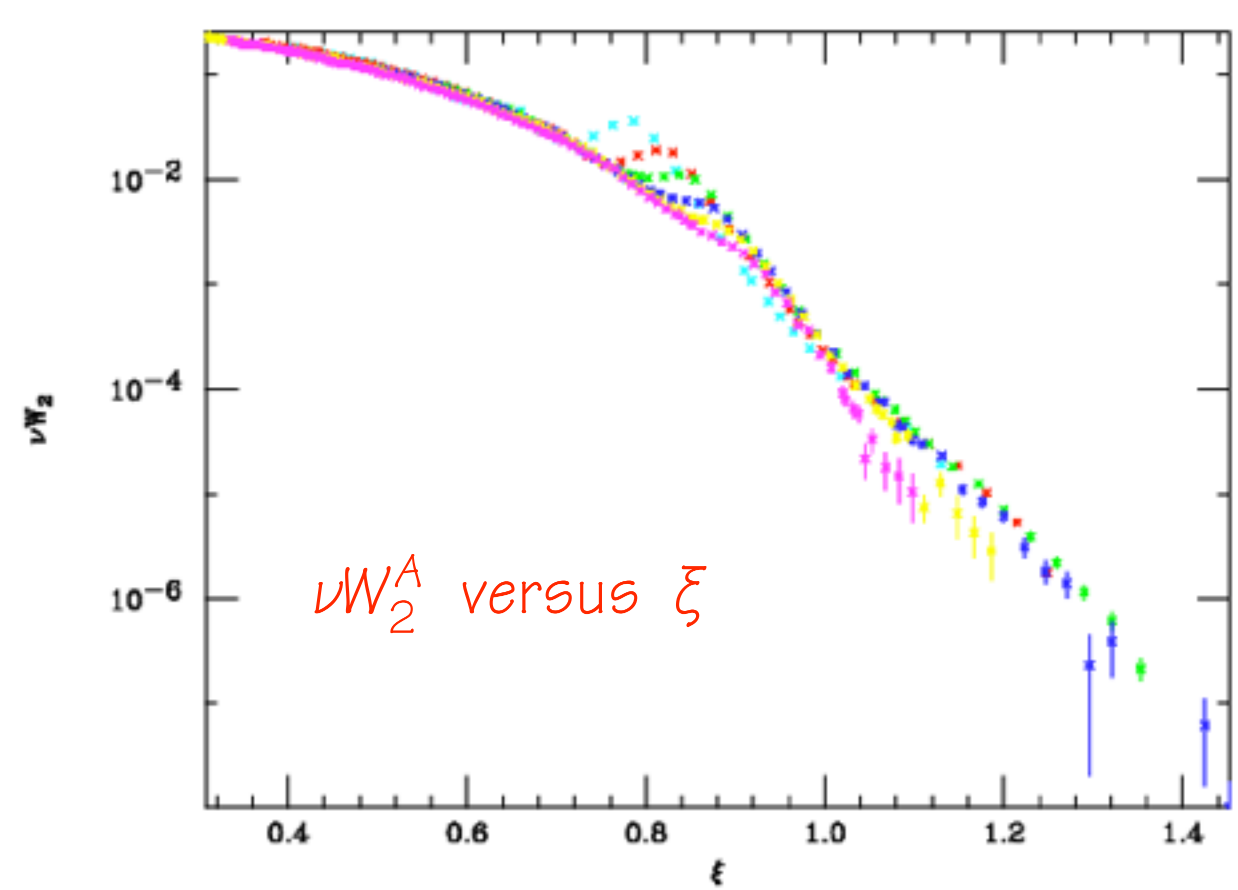
dσ/dΩdν
ν



Z, A = 1 2
$F(y) = \frac{\sigma^{exp}}{(Z\tilde{\sigma}_p + N\tilde{\sigma}_n)} \cdot K$
F(y)
y

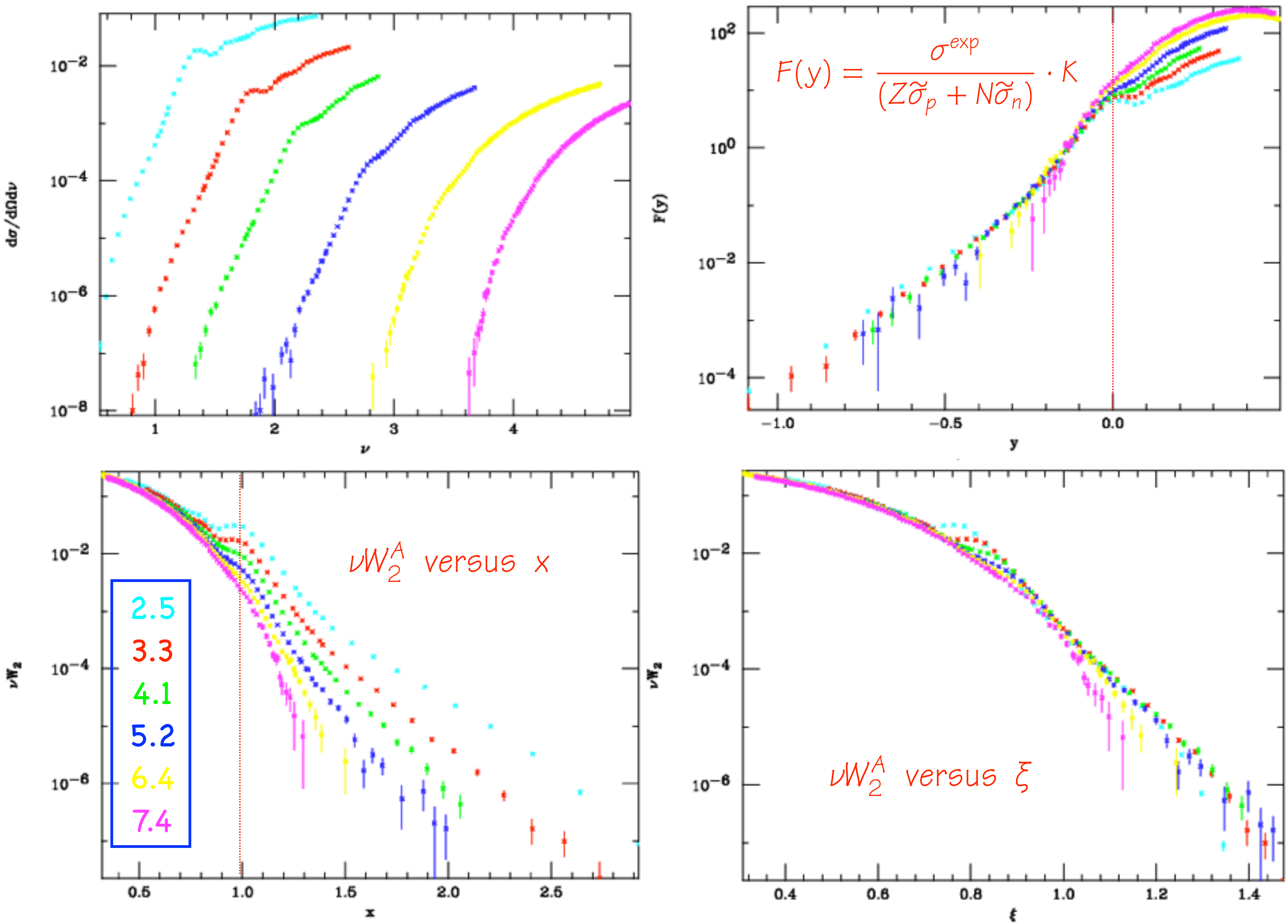


νW_2^A versus x
2.5
3.3
4.1
5.2
6.4
7.4
νW₂
x

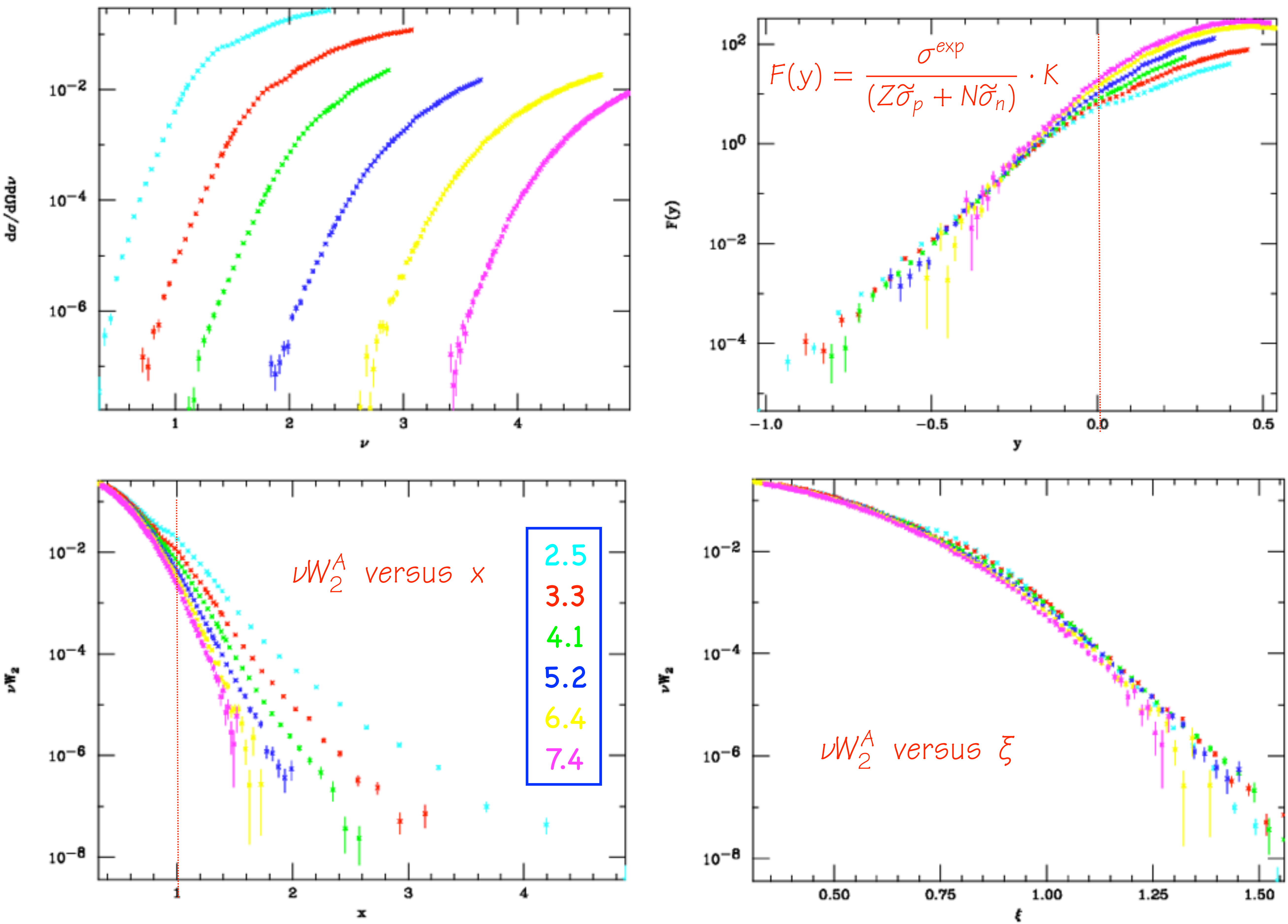


νW_2^A versus ξ
νW₂
ξ

^{3}He

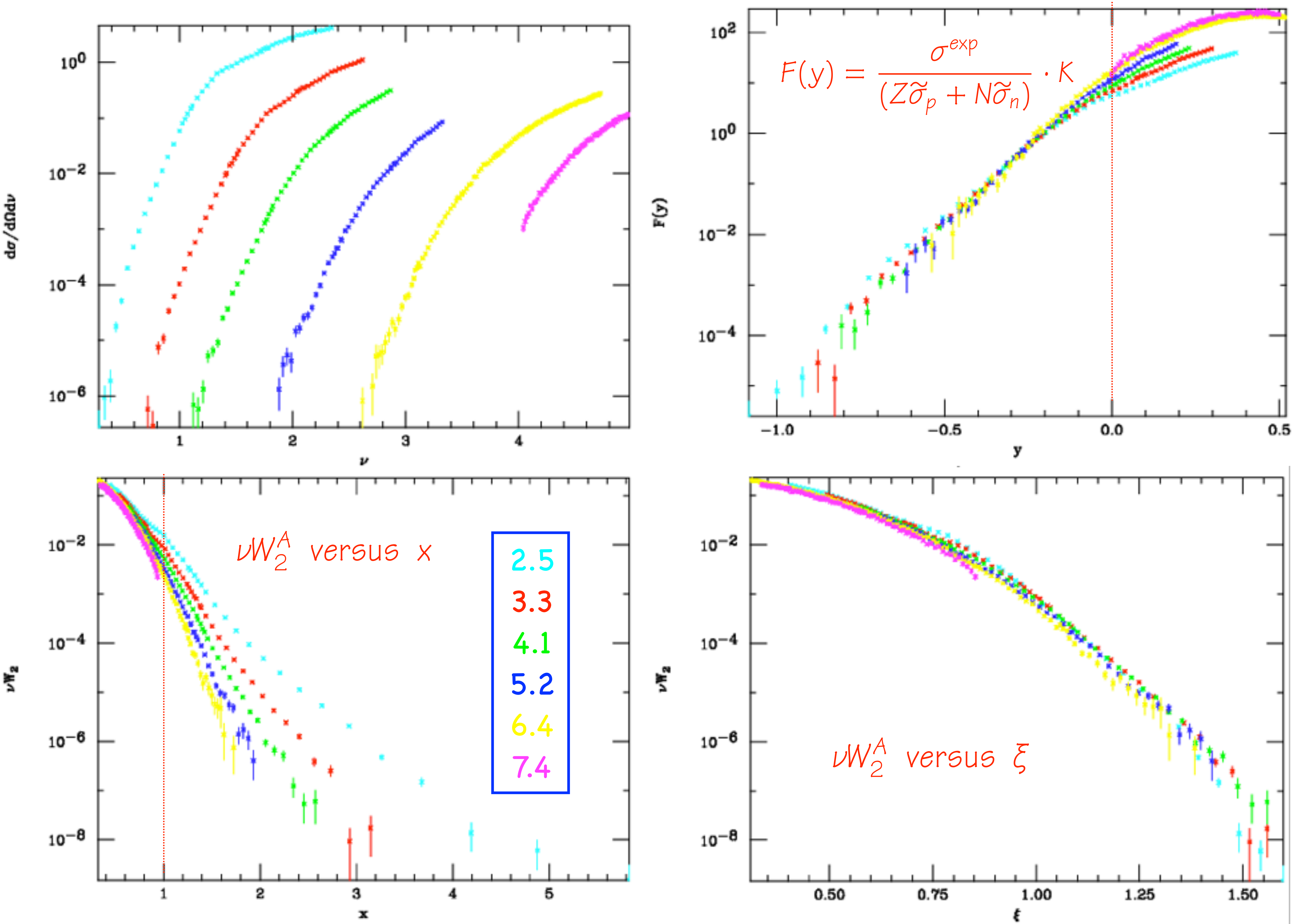

dσ/dΩdν
ν
$F(y) = \frac{\sigma^{exp}}{(Z\tilde{\sigma}_p + N\tilde{\sigma}_n)} \cdot K$
F(y)
y
νW₂
x
νW_2^A versus x
2.5
3.3
4.1
5.2
6.4
7.4
ξ
νW_2^A versus ξ

^{12}C



dσ/dΩdν
ν
F(y)
y
$F(y) = \frac{\sigma^{exp}}{(Z\tilde{\sigma}_p + N\tilde{\sigma}_n)} \cdot K$
νW₂
x
νW_2^A versus x
2.5
3.3
4.1
5.2
6.4
7.4
ξ
νW_2^A versus ξ

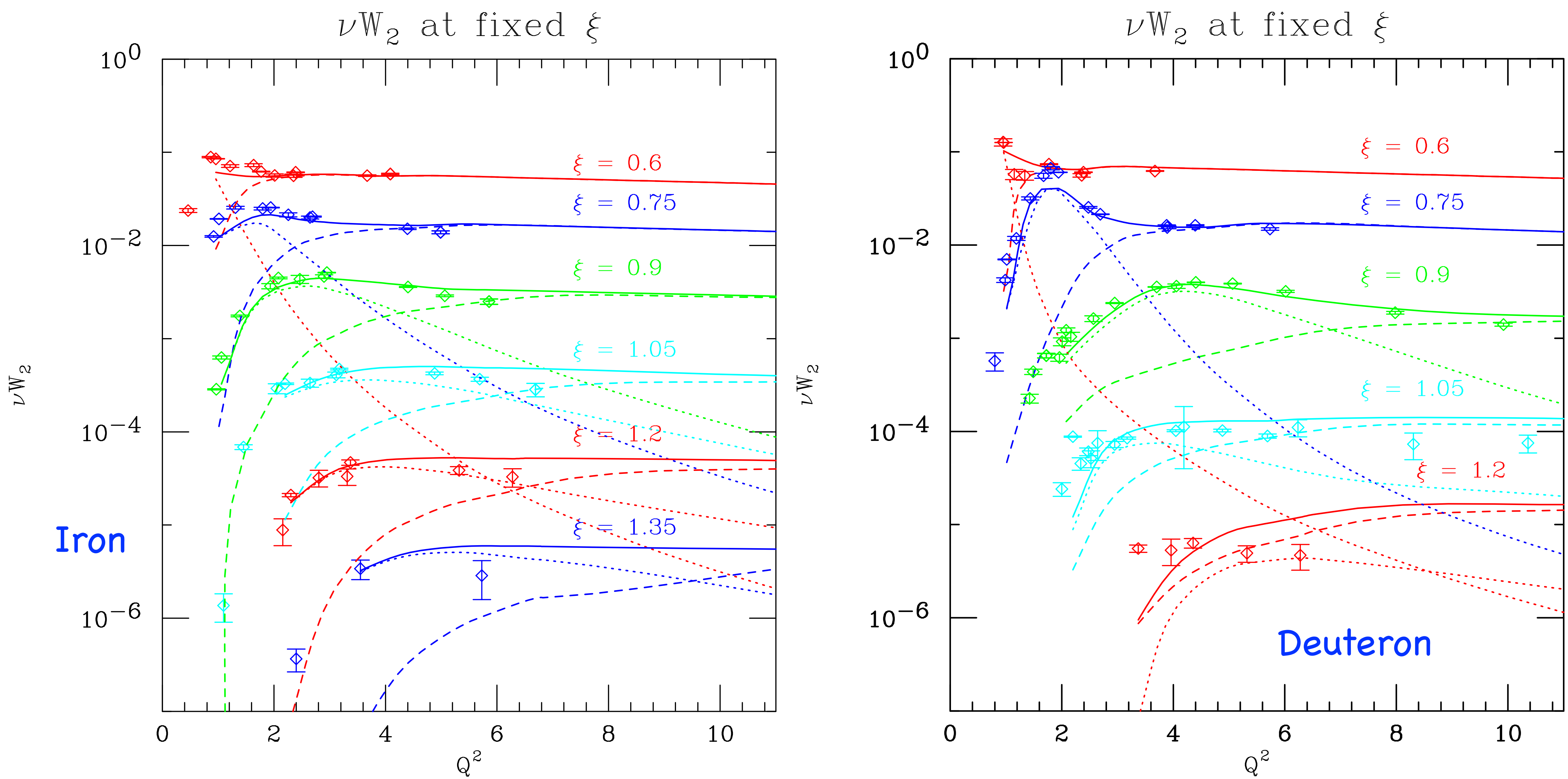
^{197}Au


$F(y) = \frac{\sigma^{exp}}{(Z\tilde{\sigma}_p + N\tilde{\sigma}_n)} \cdot K$
νW_2^A versus x
νW_2^A versus ξ
2.5
3.3
4.1
5.2
6.4
7.4
dσ/dΩdν
ν
F(y)
y
νW₂
x
ξ

Is simultaneous y and xi scaling in the quasielastic region accidental?

Day and Sick, PRC 69, 028501 (2004)

O. Benhar and S. Liuti, Phys. Lett. B 358, 173 (1995).



Convolution Model - QES (dotted), DIS (Dashed), Total (Solid)

Do QES and DIS conspire to produce xi scaling?

Can we make an connection to quark distributions at x > 1

125

Two measurements (very high Q^2) exist so far:

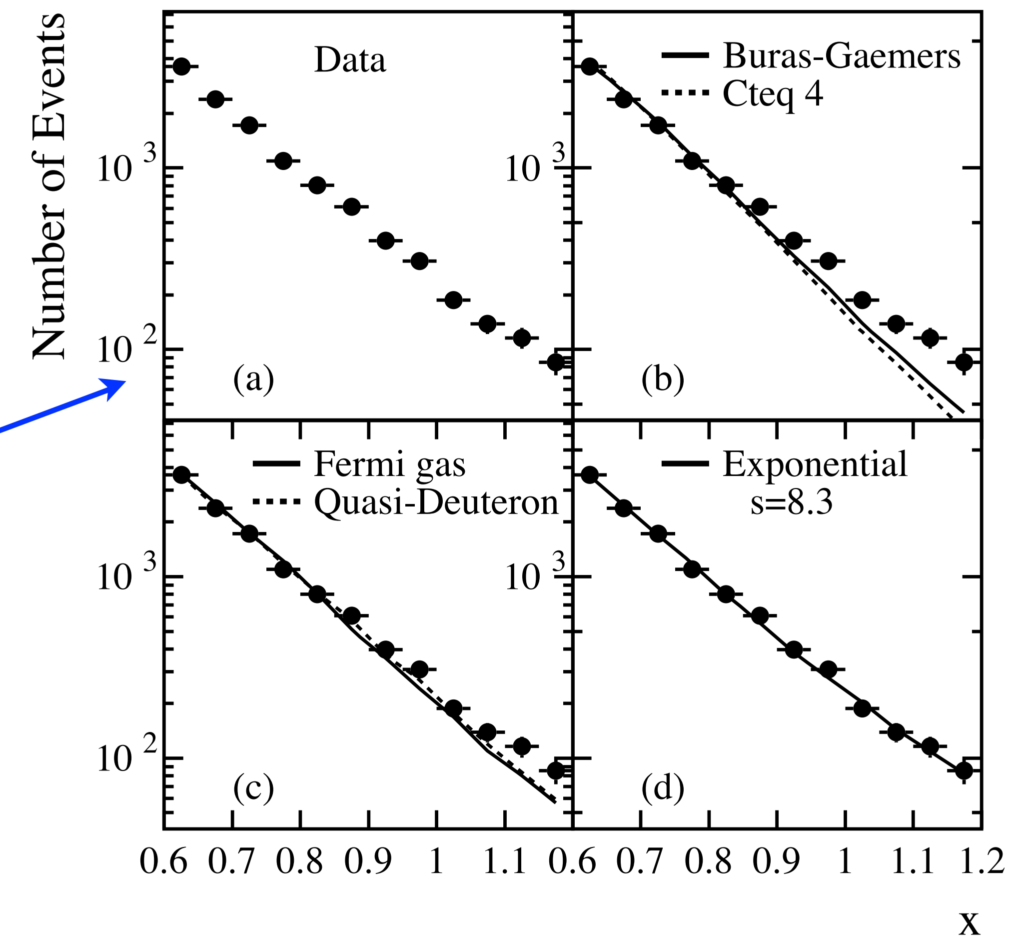
CCFR (ν-C): $F_2(x) \propto e^{-sx}$ s = 8

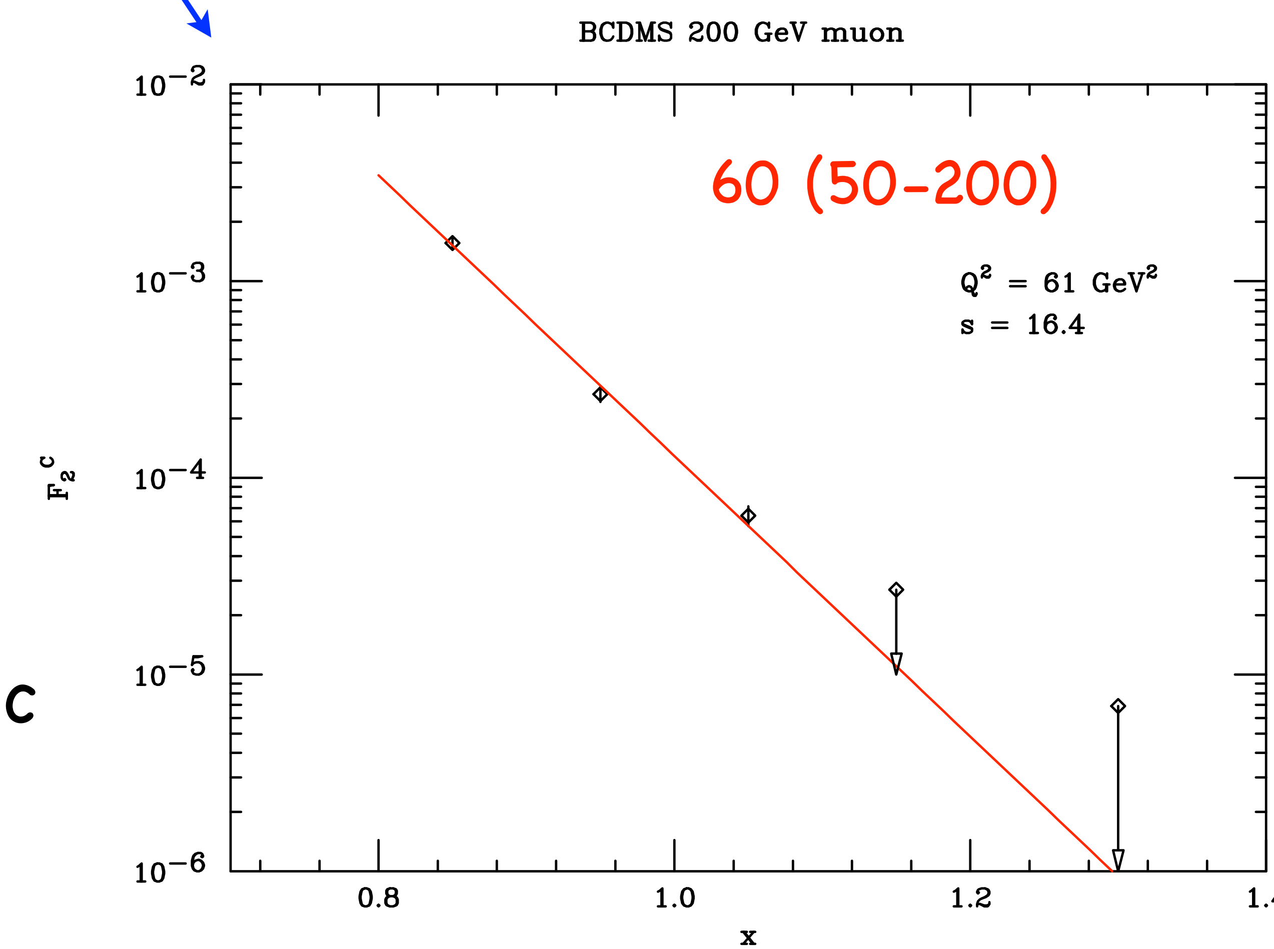
BCDMS (μ-Fe): $F_2(x) \propto e^{-sx}$ s = 16

Poor resolution, limited x range

Low statistics

CCFR results suggested large contribution from SRC or other exotic effects





We can, but first we must account for the fact that none of these measurements are at the asymptotic limit.

“Target Mass Corrections”

In OPE

$$F_2^{TMC}(x,Q^2) = \frac{x^2}{\xi^2 r^2} F_2^0(\xi,Q^2) + \frac{6M^2x^3}{Q^2r^4} h_2(\xi,Q^2) + \frac{12M^4x^4}{Q^4r^5} g_2(\xi,Q^2)$$

$$h_2(\xi,Q^2) = \int_\xi^1 du \frac{F_2^0(u,Q^2)}{u^2} \qquad g_2(\xi,Q^2) = \int_\xi^1 dv(v-\xi)\frac{F_2^0(v,Q^2)}{v^2}$$

where F_2^0 is structure function in Q^2 >> limit

Assuming leading twist, this can be turned around to extract F_2^0 from the data (F^{TMC}) -> F_2^0 has only QCD determined (evolution) Q^2 dependence

Georgi, Politzer; DuRujula, Georgi and Politzer
Schienbein et al. J.Phys. G. Part. Phys. 35 (2008)

$$r = \sqrt{1+\frac{4x^2M^2}{Q^2}} = \sqrt{1+\frac{Q^2}{\nu^2}}$$

Procedure

Assumption: data is entirely leading twist and we can factorize the ξ and Q^2 dependence

1. Take F_2^0 to be
$$F_2^0(\xi, Q^2) = \frac{\xi^2 r^2}{x^2} F_2^{TMC \equiv Data}(x, Q^2)$$

2. Fit the F_2^0 with some convenient form

3. Use this to calculate integrals

$$h_2(\xi, Q^2) = \int_\xi^1 du \frac{F_2^0(u, Q^2)}{u^2} \qquad g_2(\xi, Q^2) = \int_\xi^1 dv (v - \xi) \frac{F_2^0(v, Q^2)}{v^2}$$

4. Calculate F_2^0 again by

$$F_2^0(\xi, Q^2) = \frac{\xi^2 r^2}{x^2} \left[F_2^{TMC}(x, Q^2) - \frac{6M^2 x^3}{Q^2 r^4} h_2(\xi, Q^2) - \frac{12 M^4 x^4}{Q^4 r^5} g_2(\xi, Q^2) \right]$$

5. Go back to 2 until F_2^0 quits changing

6. Figure out Q^2 dependence of $F_2^{(0)}$

7. Fit the Q^2 evolution of the existing data for fixed values of ξ

Procedure, continued

- Evolve fit to data at Q_0^2 (up or down) to other Q^2 (using slopes of $d(\ln F_2)/d(\ln Q^2)$ extrapolated into the region $x > 1$)
- Apply target mass corrections (TMC) and compare with other (higher or lower) Q^2 data

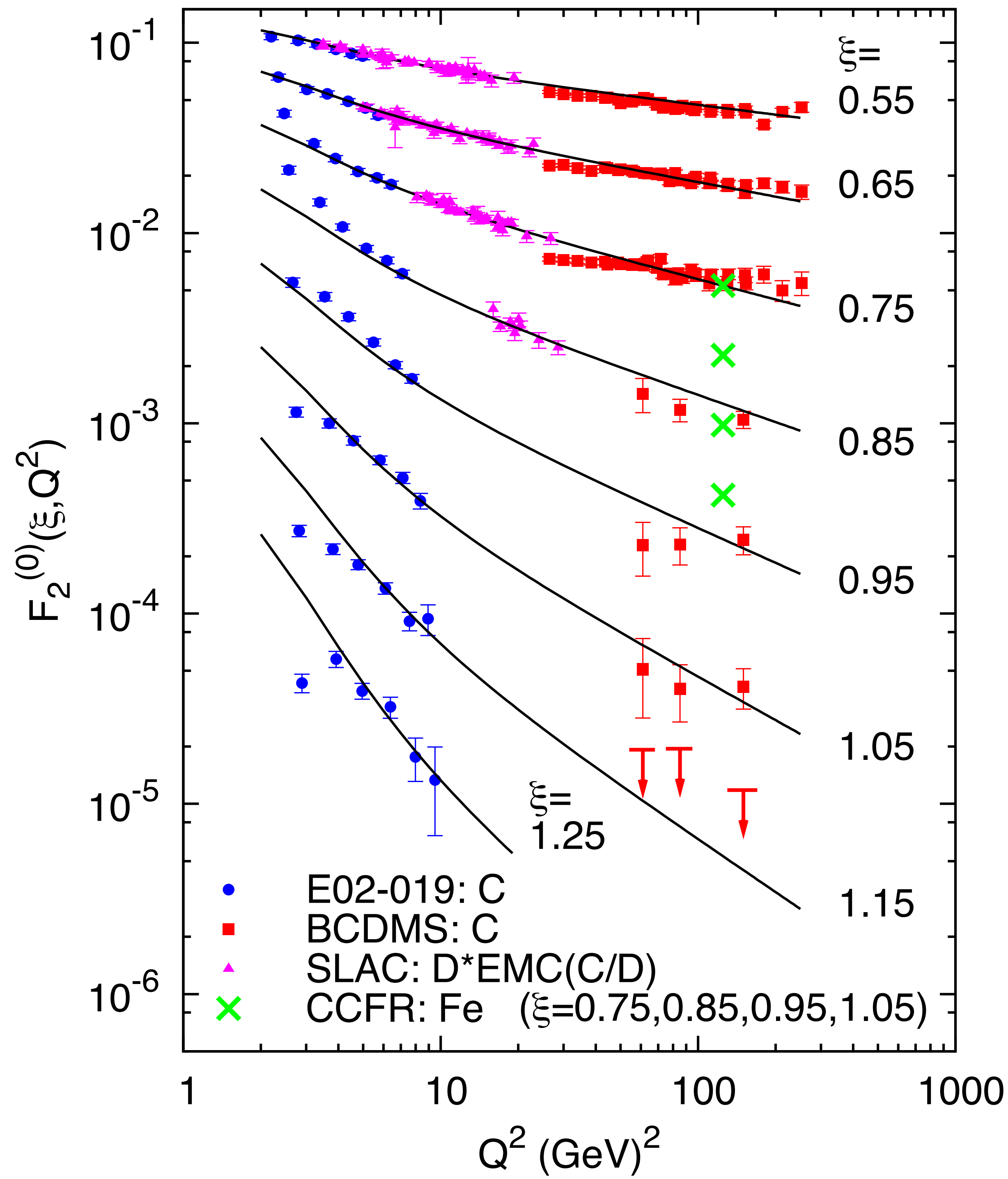
$$F_2^{TMC}(x, Q^2) = \frac{x^2}{\xi^2 r^2} F_2^0(\xi, Q^2) + \frac{6M^2 x^3}{Q^2 r^4} h_2(\xi, Q^2) + \frac{12M^4 x^4}{Q^4 r^5} g_2(\xi, Q^2)$$

$$h_2(\xi, Q^2) = \int_\xi^1 du \frac{F_2^0(u, Q^2)}{u^2} \qquad g_2(\xi, Q^2) = \int_\xi^1 dv (v - \xi) \frac{F_2^0(v, Q^2)}{v^2}$$

How well does this work?

The comparison to the world data set is good and can be used to extract the behavior of the SF at large x.

- At $\xi \leq 0.75$ where the high Q^2 data dominates our the agreement is good down to about $Q^2 = 3\ GeV^2$.
- As ξ increases the dependence on Q^2 grows continually.
- Agreement is still good except at low Q^2 where there is a QES contribution and HT must play a role
- Finally note that the BCDMS data fails to display a dependence on momentum transfer above ξ about 0.65



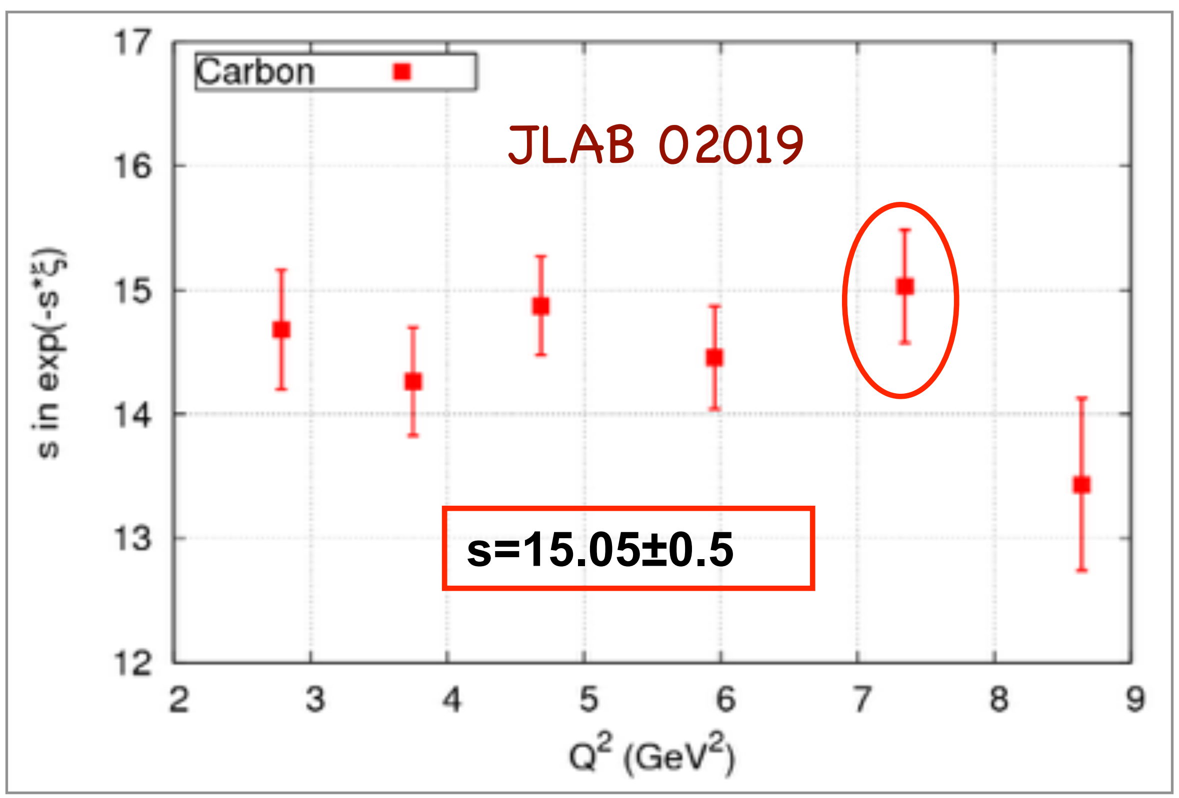
E02-019 carbon
SLAC deuterium
BCDMS carbon
× CCFR projection
(ξ=0.75,0.85,0.95,1.05)

Compare to the very high Q^2 BCDMS and CCFR data

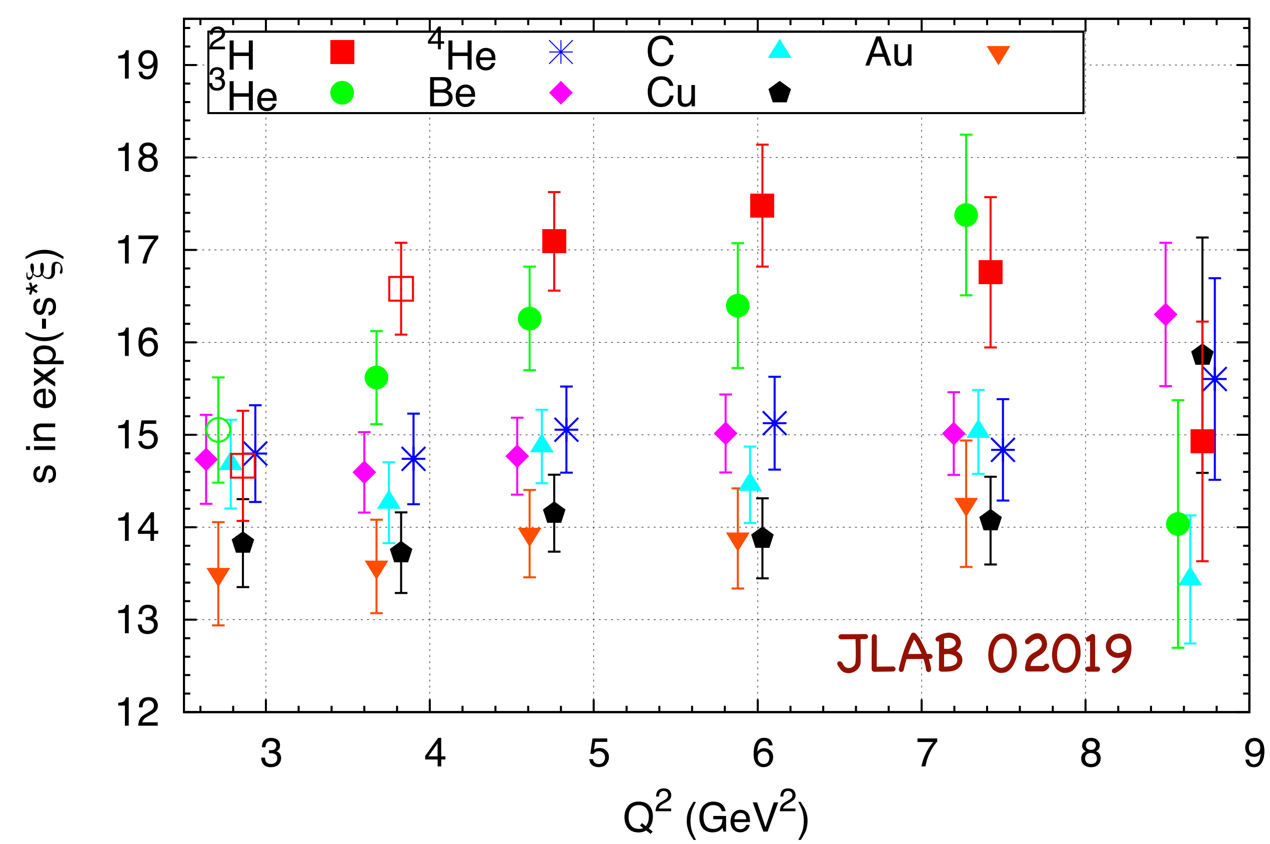
Fit our F_2^0 (over a limited range of ξ) with the functional form F_2^0 = Constant x $e^{(-s\xi)}$

CCFR – (Q^2 = 125 GeV^2) s=8.3±0.7

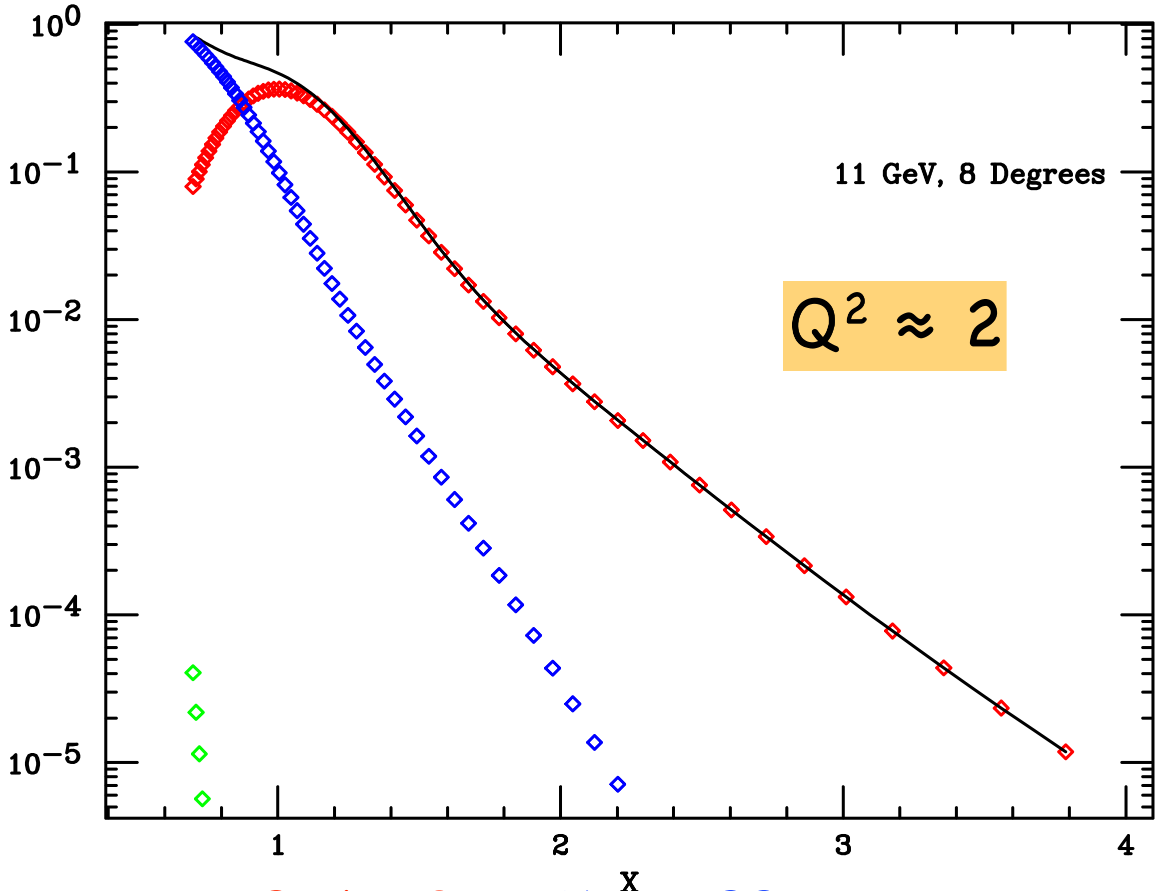
BCDMS – (Q^2: 52 - 200 GeV^2) s=16.5±0.5

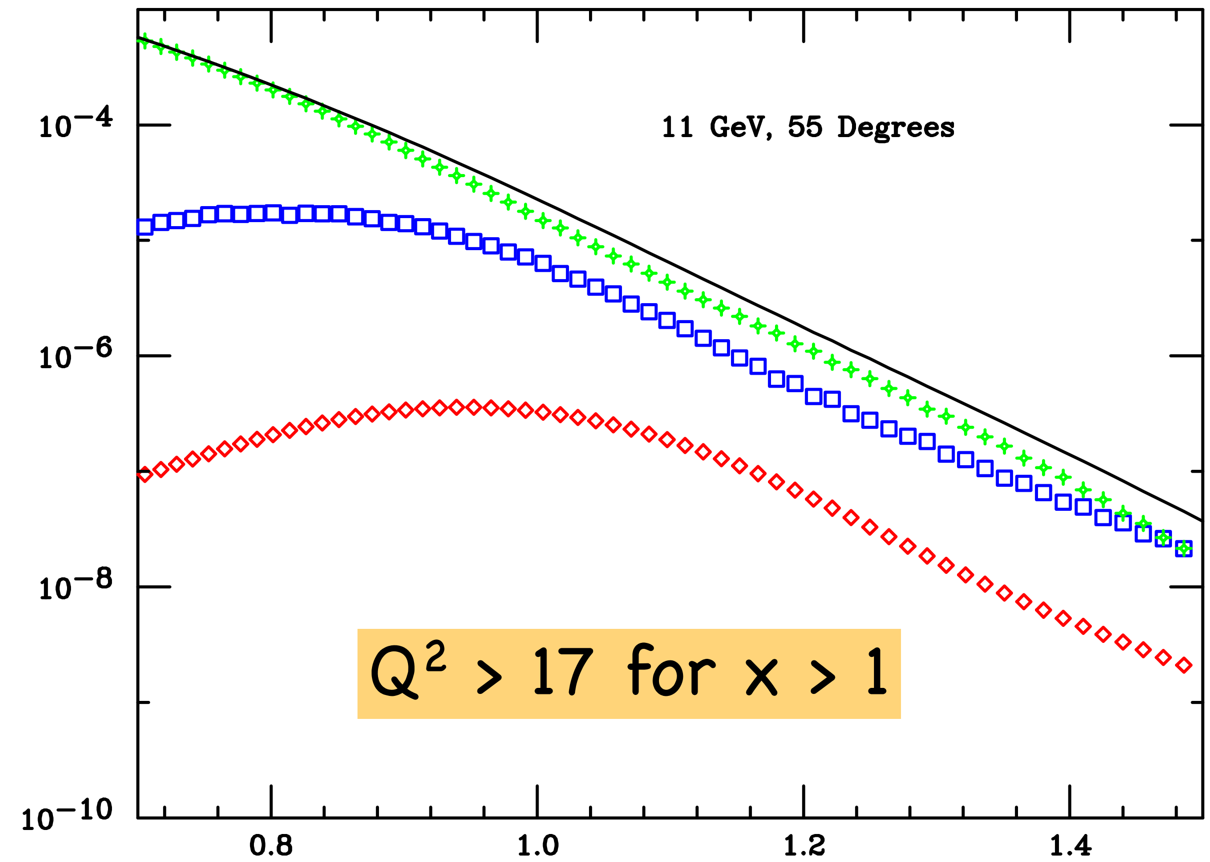


For all nuclei



Our results contradict those of CCFR and support BCDMS



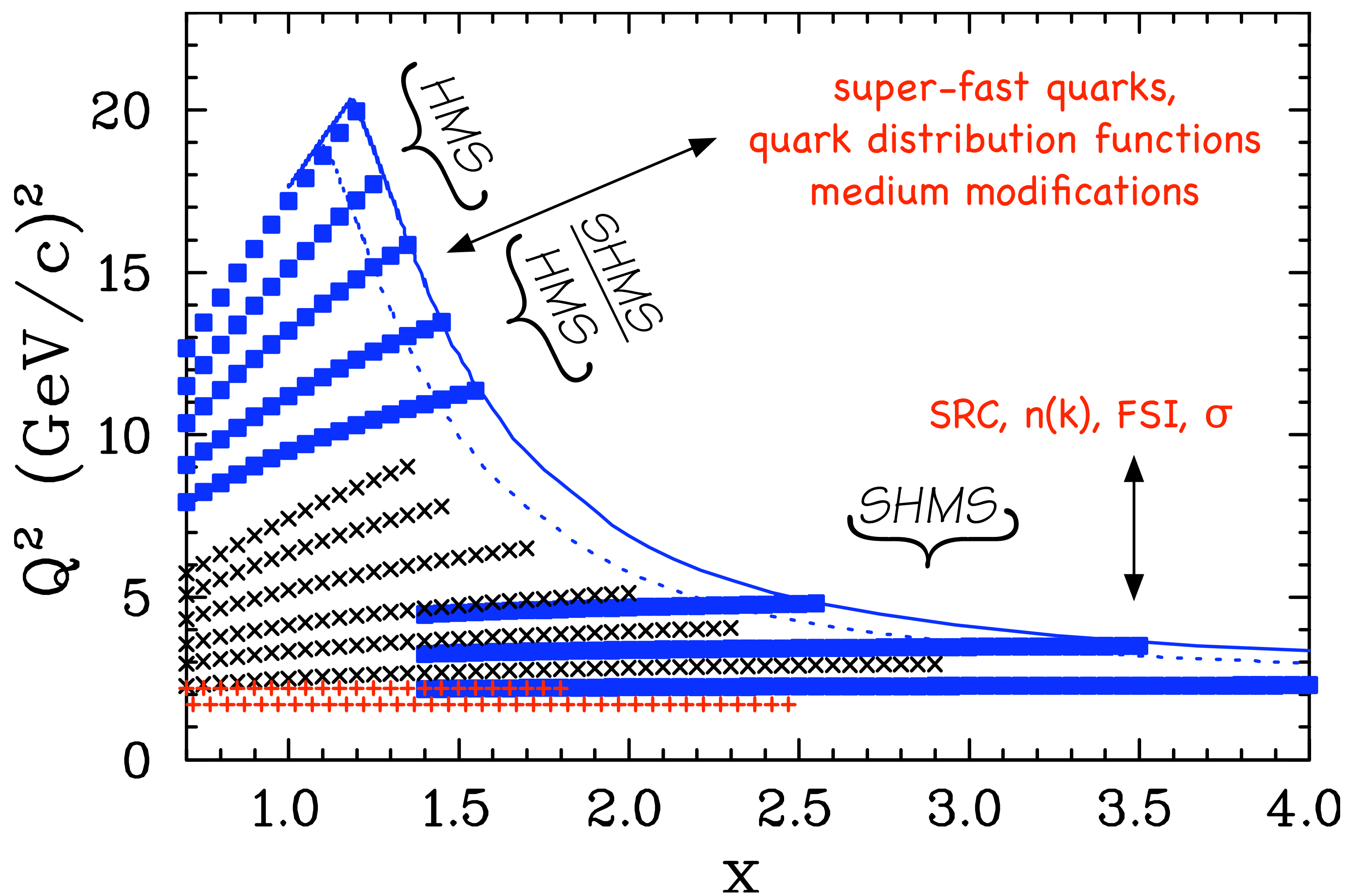


Red - QES, Blue - RR, Green - DIS, line total (convolution model)

E12-06-105

Data coverage

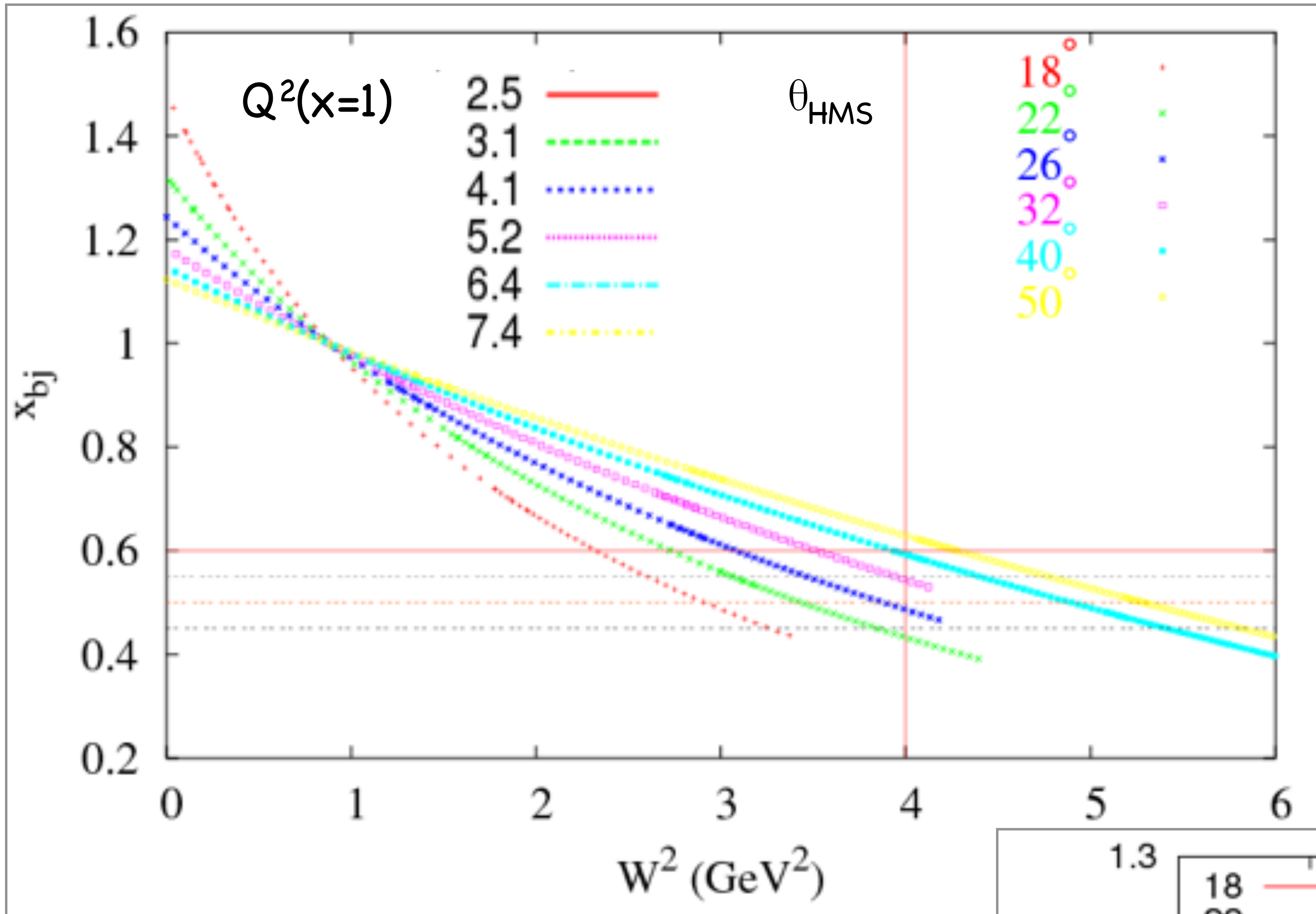
^{2}H, ^{3}He, ^{4}He, ^{6,7}Li, ^{10,11}Be, ^{12}C, ^{40,48}Ca, Cu, Au



Summary

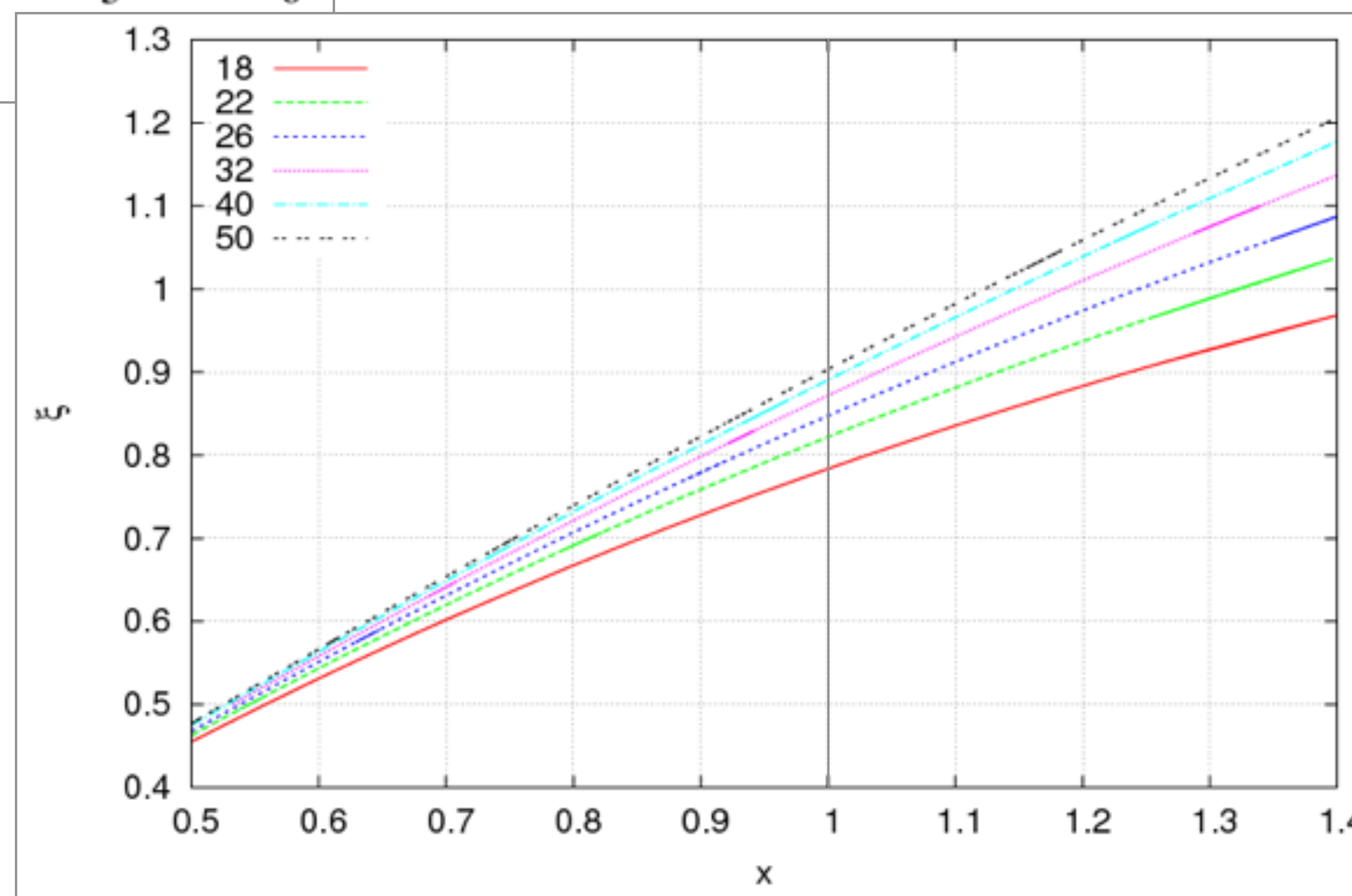
- We see evidence for the dominance of DIS at $x > 1$ from nuclear data at large Q^2
    - Application of "TMCs" allows us to extract F_2^0 (which retains a Q^2 dependence limited to QCD evolution) and allows the extraction of the quark distribution functions at $x > 1$
    - These new data have been compared to high Q^2 results of previous experiments
        - In doing so appears to support BCDMS results
    - Future work: compare and contrast our ad-hoc Q^2 dependence against bonafide pQCD evolution
    - Follow-up experiment approved with higher energy (E12-06-105)

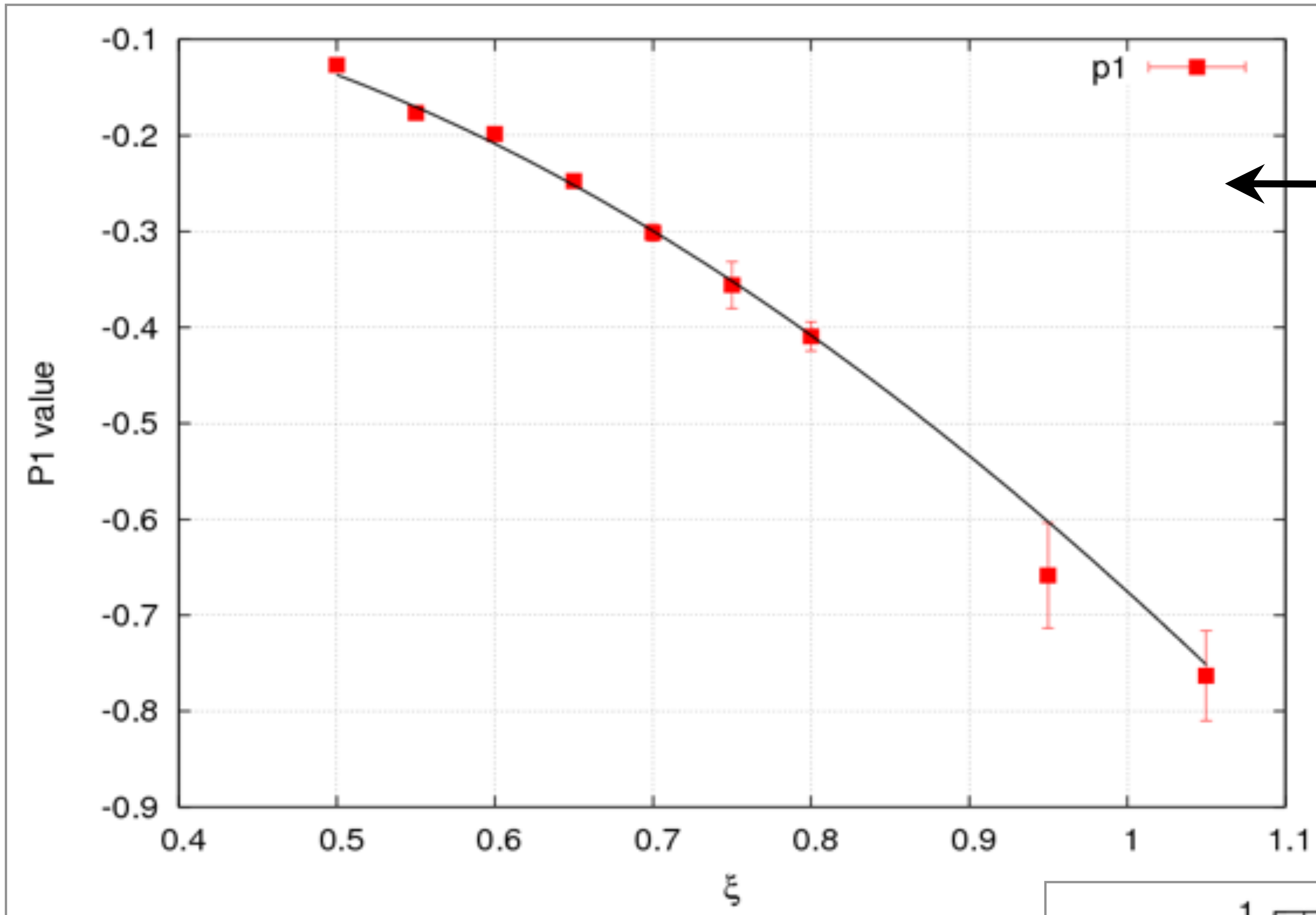
Also to come from E02019 - extraction of ratios of heavy to light nuclei at large x (SRCs)



Cannot use the traditional $W^2>4GeV/c^2$ cut to define the DIS region

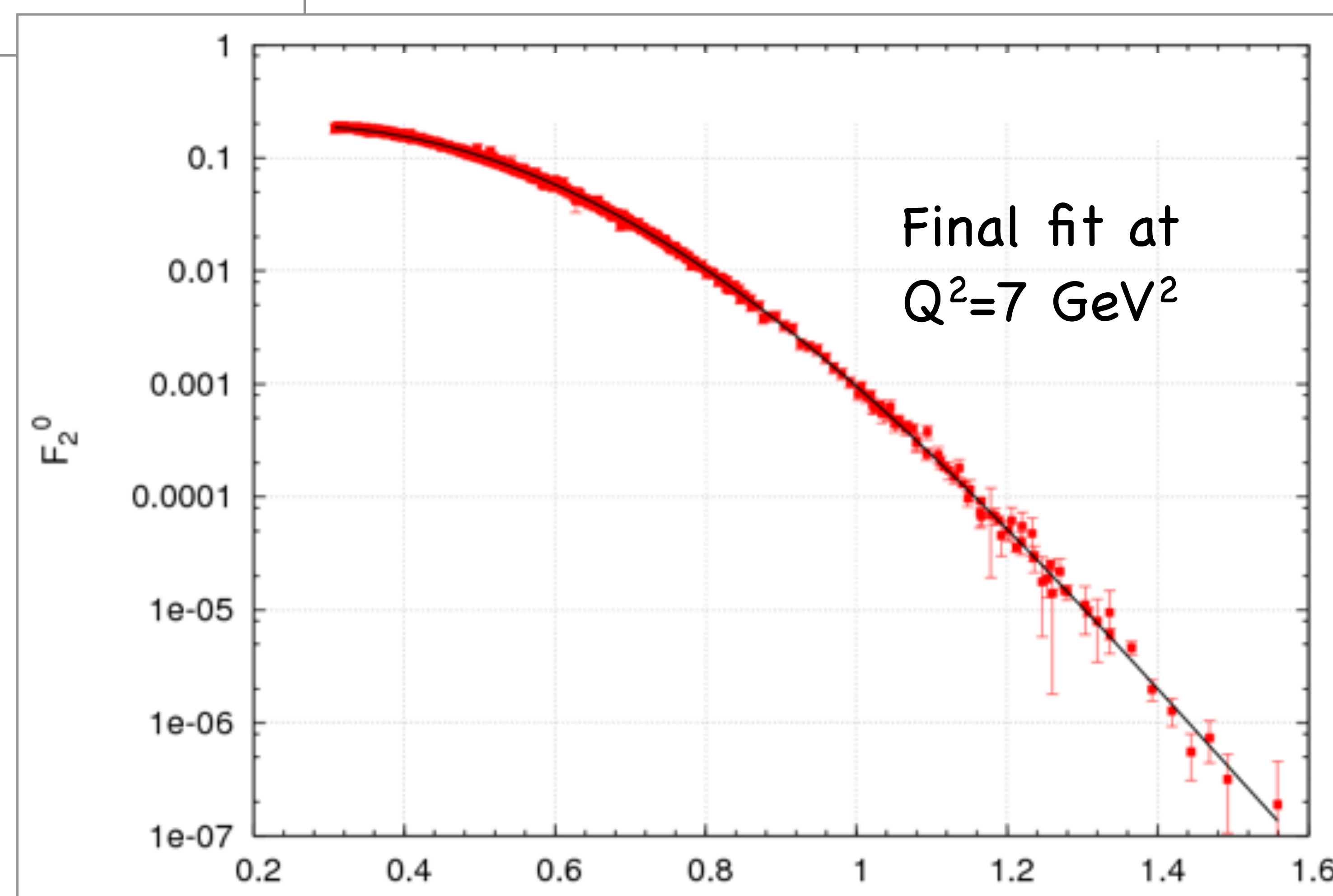
Don't expect scaling around the quasielastic peak (on either side of x=1)





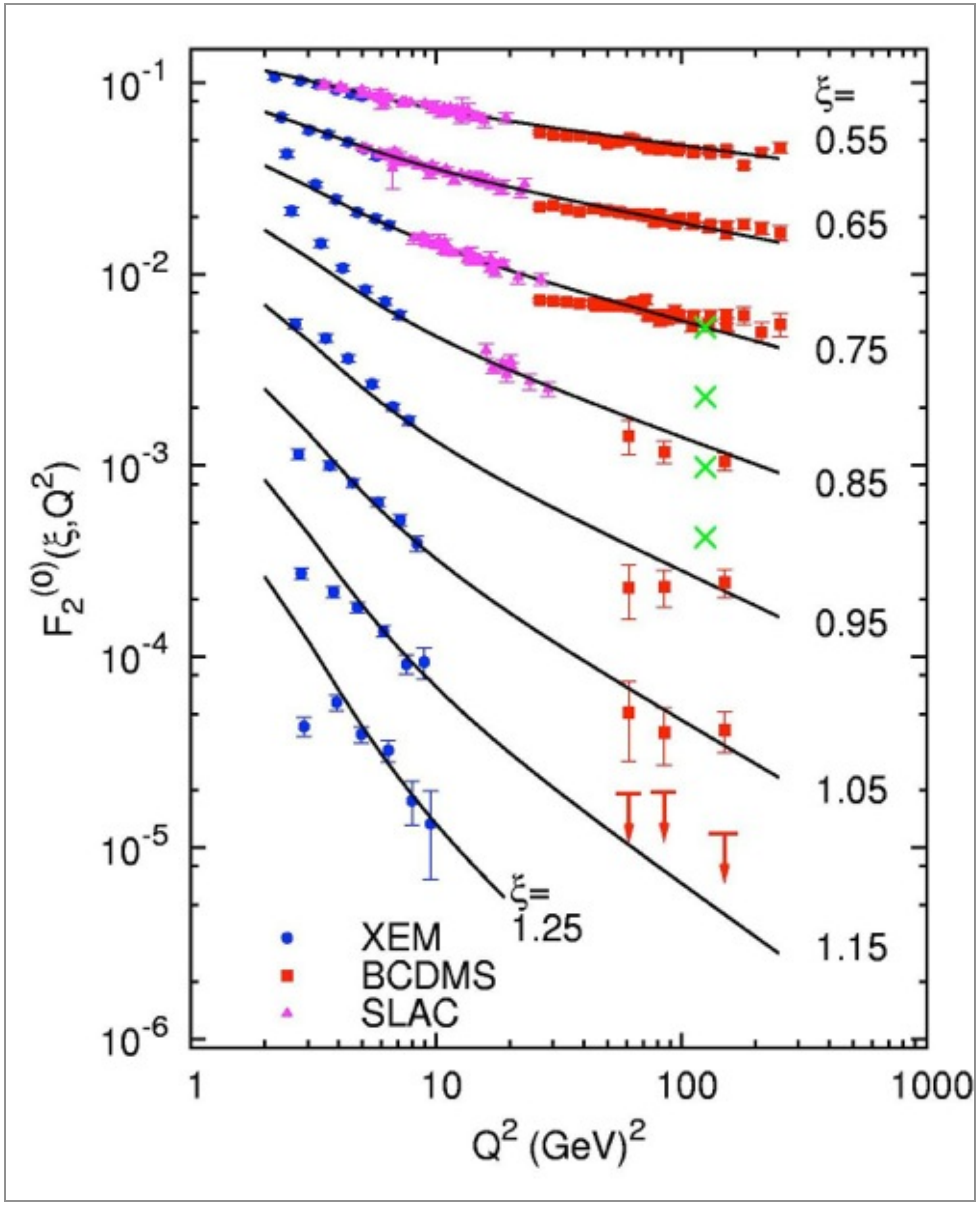
P_1 parameter vs ξ, i.e. the Q^2 dependence

F_2^0 fit with a subset of E02-019 and SLAC data



Putting it all Together

- With all the tools in hand, we apply target mass corrections to the available data sets
- With the exception of low Q^2 quasielastic data – E02-019 data can be used for SFQ distributions



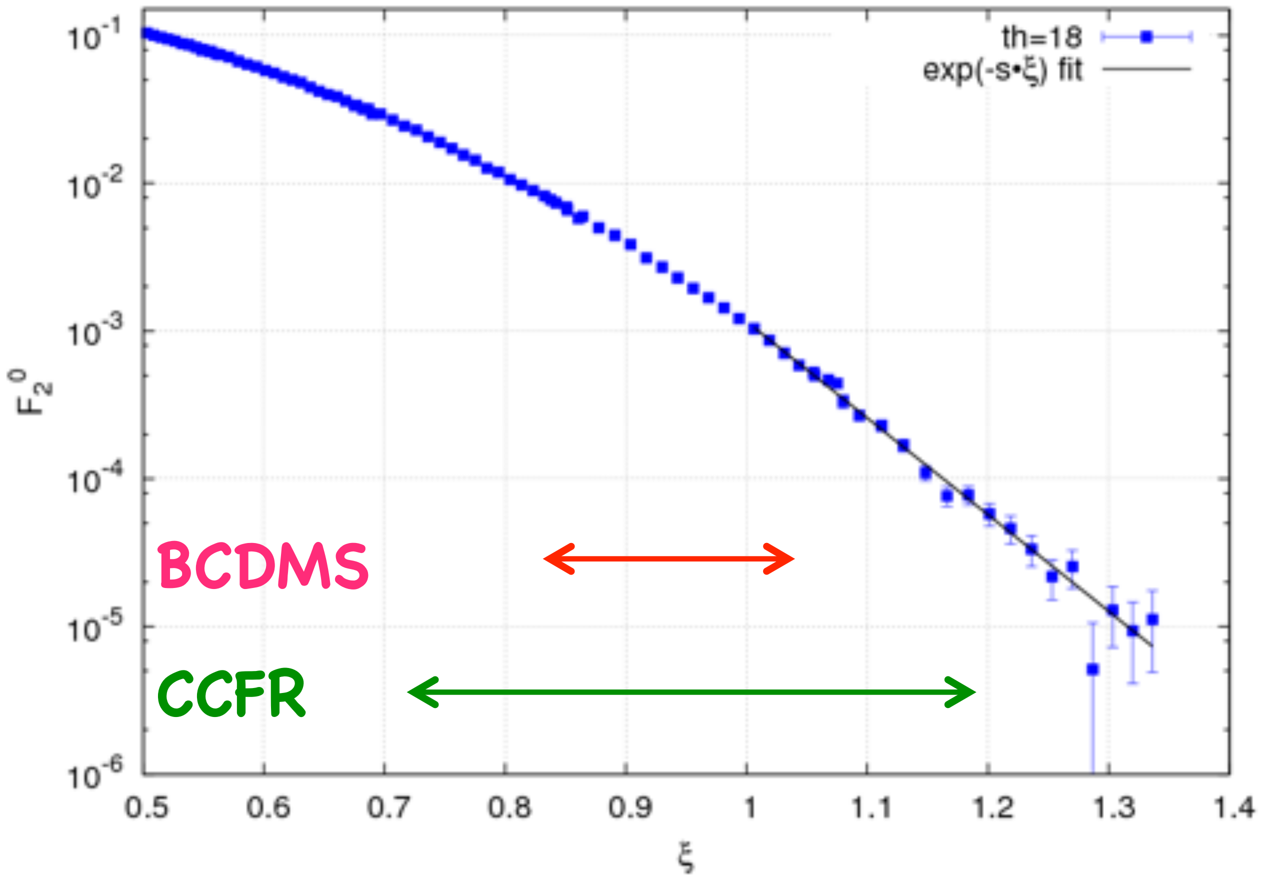
E02-019 carbon

SLAC deuterium

BCDMS carbon

x CCFR projection

(ξ=0.75,0.85,0.95,1.05)



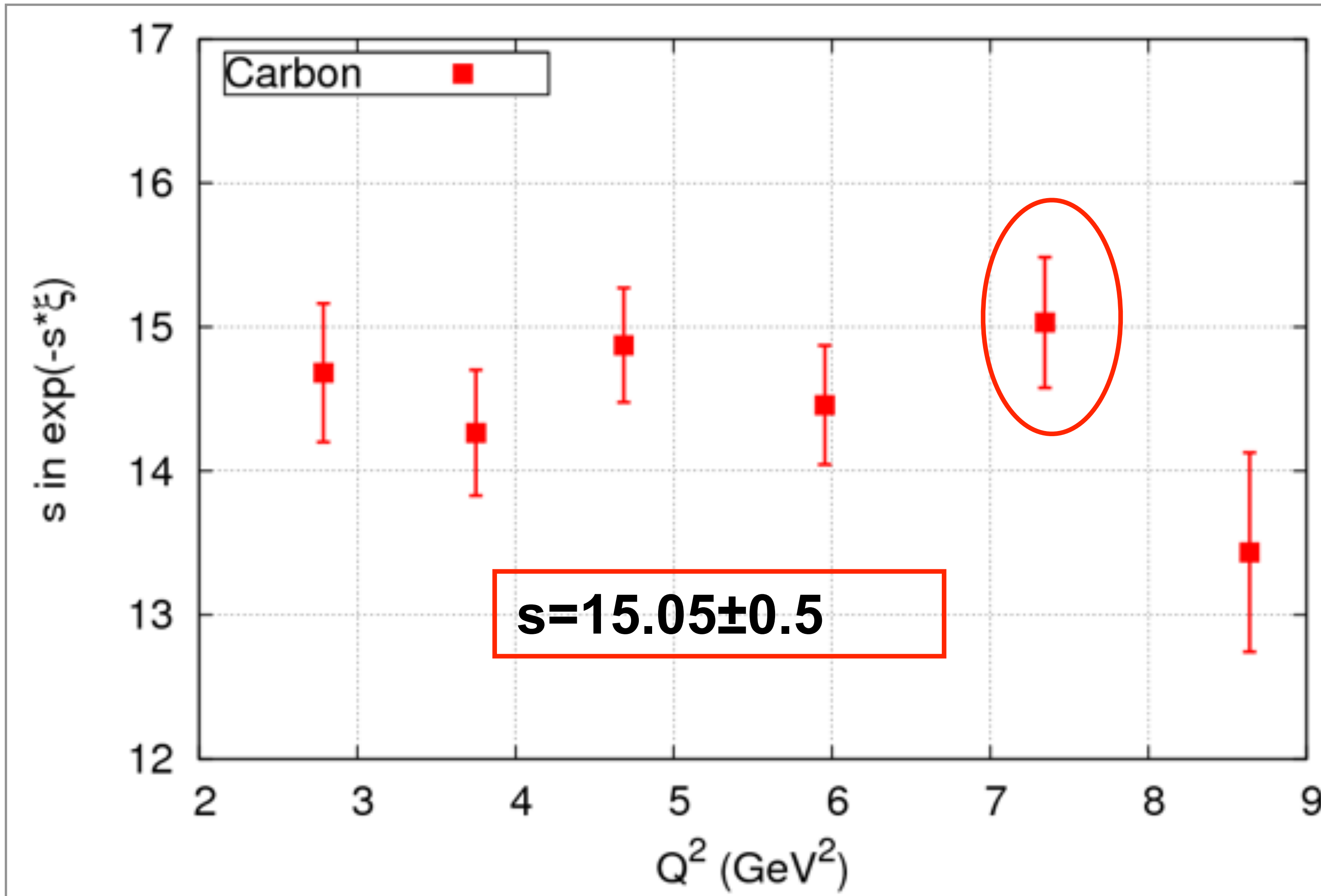
Final step: fit exp(-sξ) to F_2^0 and compare to BCDMS and CCFR

CCFR – (Q^2=125GeV^2)

s=8.3±0.7

BCDMS – (Q^2: 52-200 GeV^2)

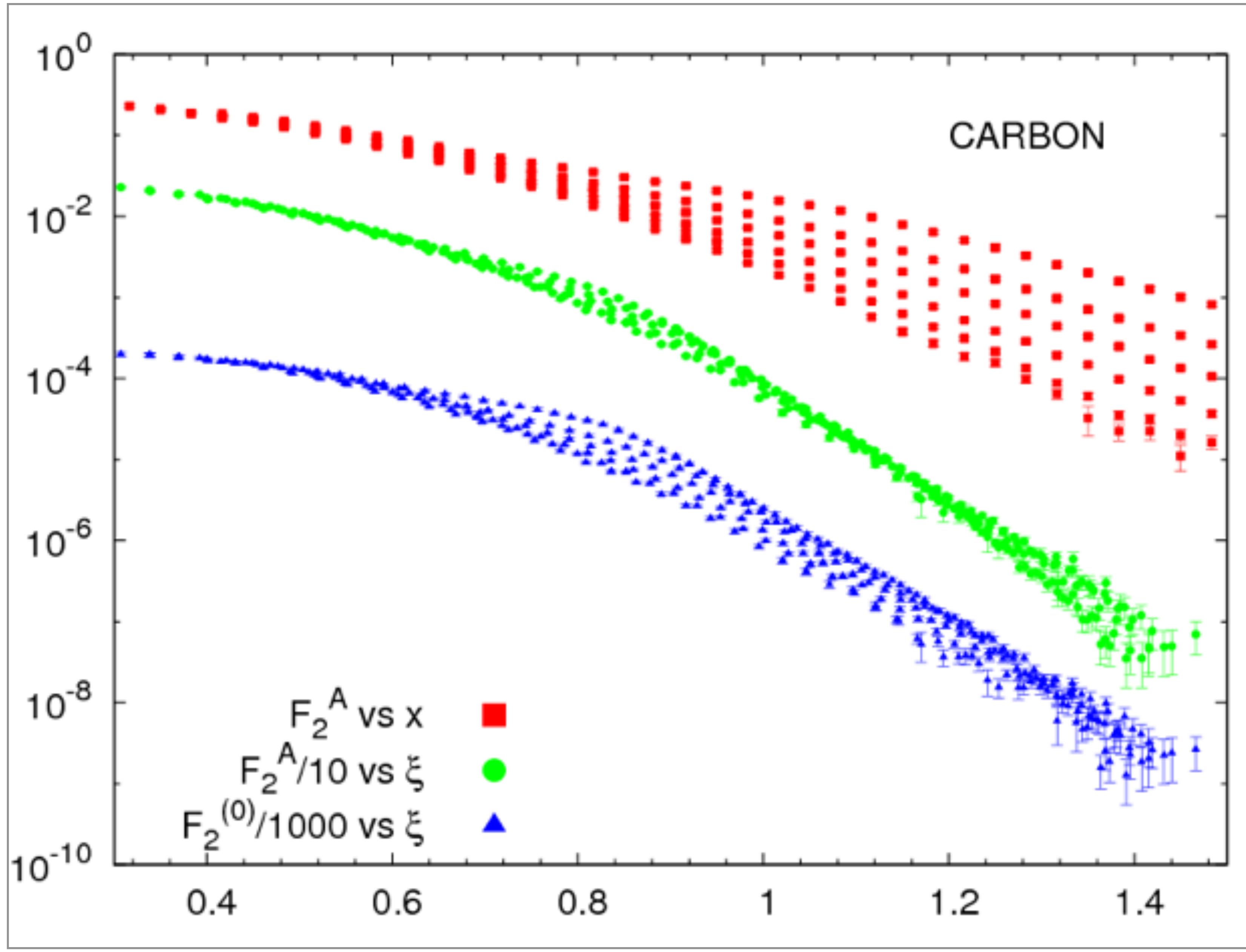
s=16.5±0.5

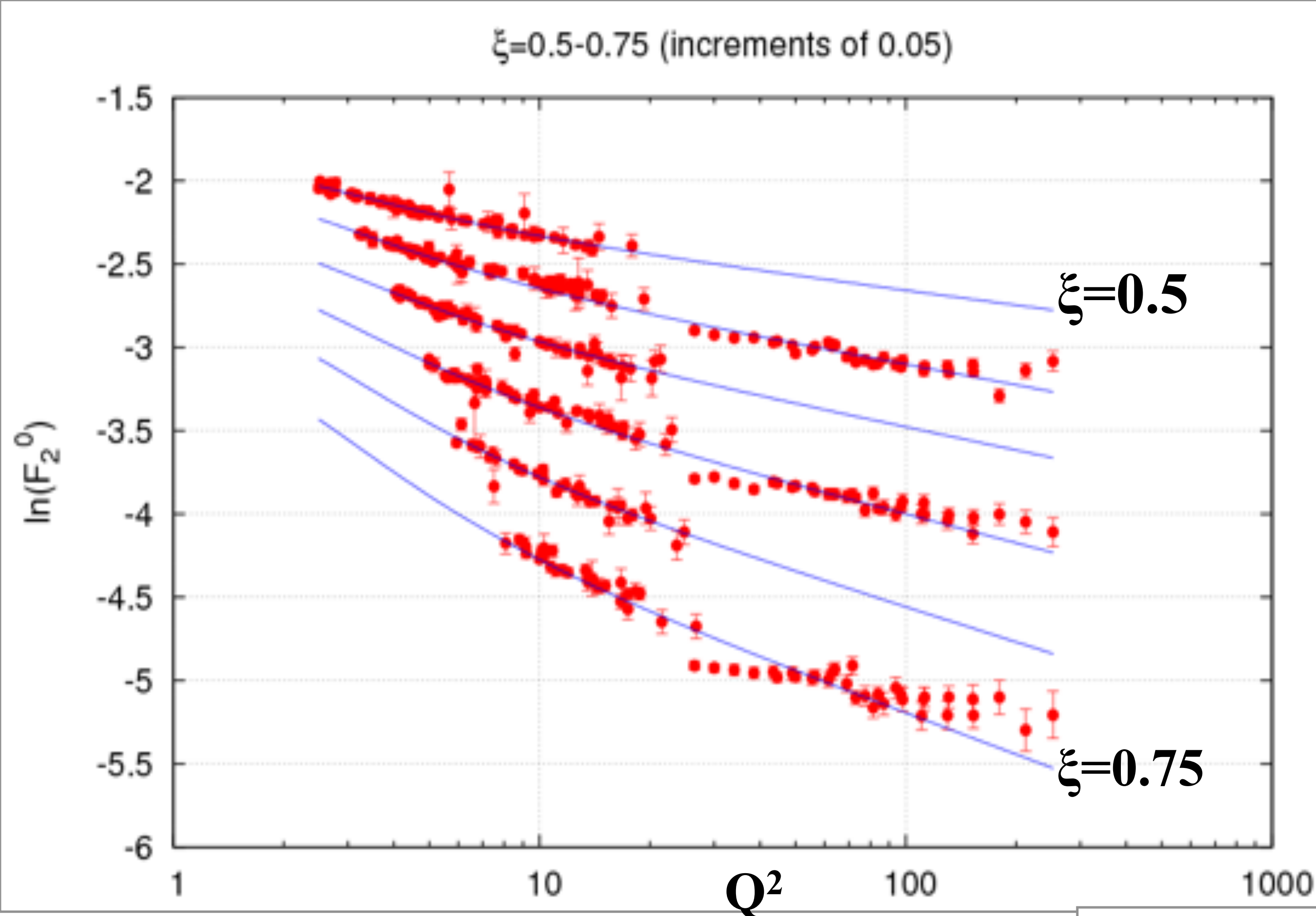


ξ-scaling: is it a coincidence or is there meaning behind it?

$$\xi = \frac{2x}{\left(1+\sqrt{1+\frac{4M^2x^2}{Q^2}}\right)}$$

- Interested in ξ-scaling since we want to make a connection to quark distributions at x>1
- Improved scaling with x->ξ, but the implementation of target mass corrections (TMCs) leads to worse scaling by reintroducing the Q^2 dependence
- TMCs – accounting for subleading $1/Q^2$ corrections to leading twist structure function

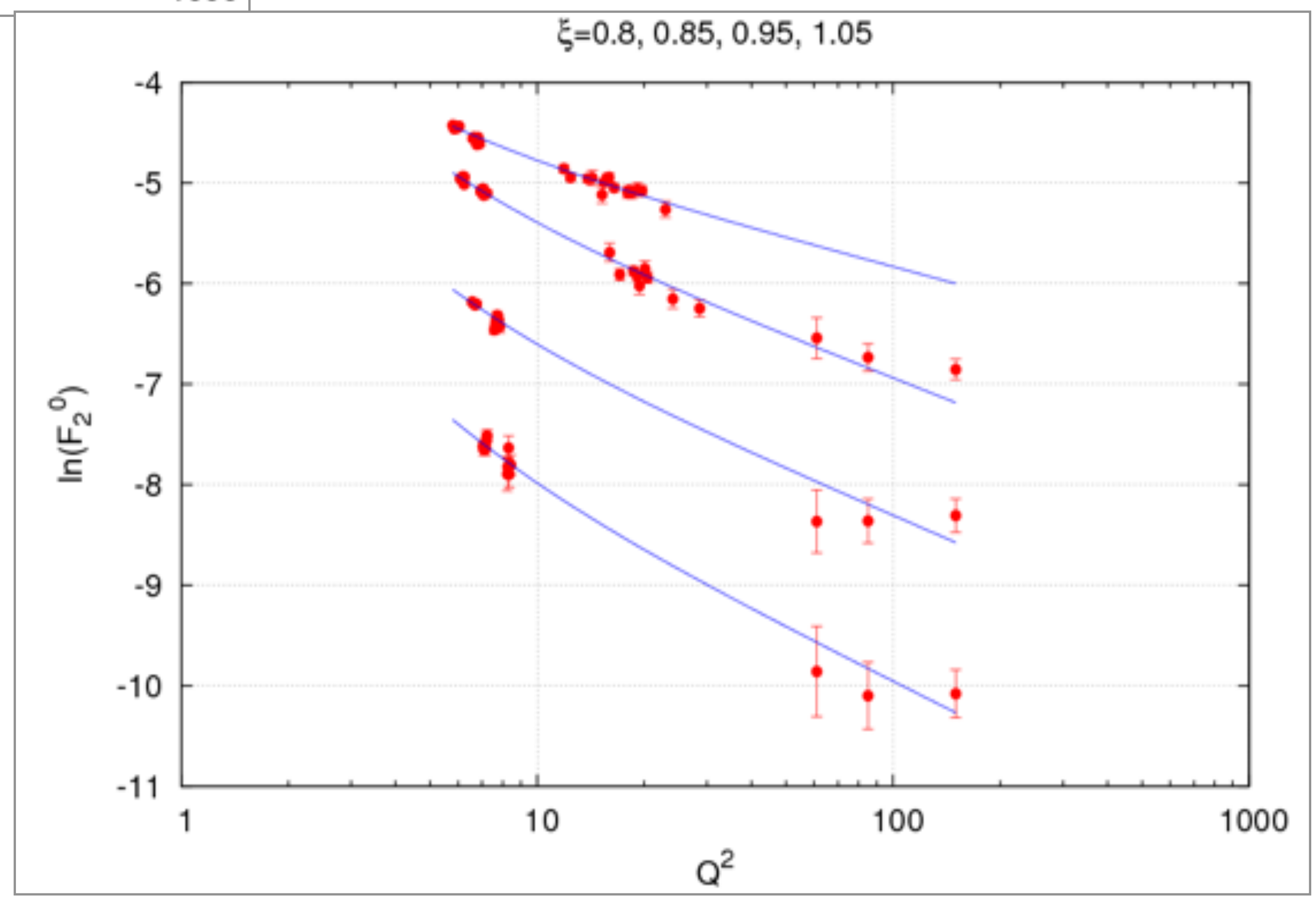




- Fit $\log(F_2^0)$ vs $\log(Q^2)$ for fixed values of ξ to

$$\ln(F_2^0) = p_0 + \log(Q^2)\, p_1 \left(1 + p_2\, e^{-\log(Q^2)/p_3}\right)$$

- p_2, p_3 fixed
- p_1 governs the "slope", or the QCD evolution.
- fit p_1 vs ξ



- Use the extracted Q^2 dependence to redo the F_2^0 fit at fixed Q^2 and to add more data (specifically SLAC)

- TMCs account for kinematical Q^2 dependence
- Ignore HT Q^2 by assuming that the data is leading twist
- Remaining Q^2 is evolution
- Factorize the ξ and Q^2 dependence of F_2^0
    - With a convenient parametrization of the ξ dependence of the data evaluate $F_2(\xi,Q^2)$ at a fixed set of ξ's.
    - Fit the Q^2 dependence for each of these ξs; $z_i(\xi_i,Q^2)$
    - Use to move all the data to a common $Q^2 = Q_0^2$ and fit the ξ dependence; $w(\xi,Q_0^2)$
- Use to determine the TMC to data via big equation
- Now compare the data $F_2^0\,(\xi,Q^2)$ to $F_2^{model} = w(\xi)z(Q^2)$