Nuclear modifications of Structure Functions

Sergey Kulagin
INR Moscow

Roberto Petti
University of South Carolina
CERN

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MOTIVATIONS AND OUTLINE

- *Main motivation of our studies was the development of a quantitative model providing predictions and corresponding uncertainties to be used in the analysis of present and future data from nuclear targets in a wide kinematic range of x and Q^2*

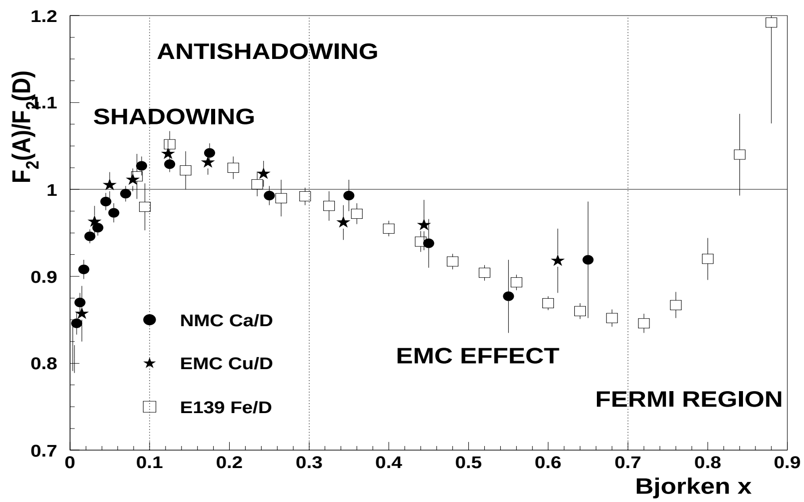
- *Analysis of nuclear structure functions (SF)*
  - *Data and basic mechanisms of nuclear DIS*
  - *Description of the approach*
  - *Results and interpretation*

- *Applications of the model*
  - *Nuclear parton distribution functions (nPDF)*
  - *Drell-Yan pA cross-sections*
  - *(Anti)neutrino-nucleus inelastic cross-sections*

NUCLEAR STRUCTURE FUNCTIONS

- GLOBAL APPROACH *aiming to obtain quantitative calculations covering the complete range of x and Q^2 available (S. Kulagin and R.P., NPA 765 (2006) 126-187):*

  - *Scale controlling nuclear processes $L_I = (Mx)^{-1}$*
    Distance between nucleons $d = (3/4\pi\rho)^{1/3} \sim 1.2 Fm$
  - $L_I < d$
    For $x > 0.2$ nuclear DIS $\sim$ incoherent sum of contributions from bound nucleons
  - $L_I \gg d$
    For $x \ll 0.2$ coherent effects of interactions with few nucleons are important



- DIFFERENT EFFECTS *on structure functions (SF) are taken into account:*

$$F_i^A = F_i^{p/A} + F_i^{n/A} + F_i^{\pi/A} + \delta F_i^{\rm coh}$$

- $F_i^{p(n)/A}$ *bound proton(neutron) SF with Fermi Motion, Binding (FMB) and Off-Shell effect (OS)*
- $F_i^{\pi/A}$ *nuclear Pion excess correction (PI)*
- $\delta F_i^{\rm coh}$ *contribution from coherent nuclear interactions: Nuclear Shadowing (NS)*

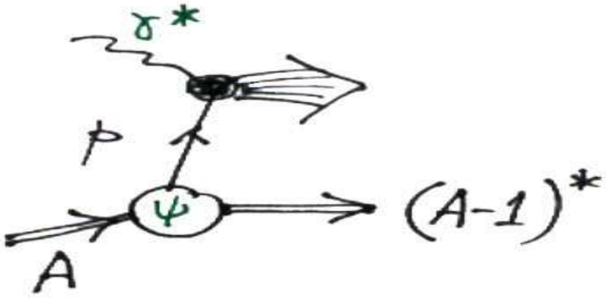
INCOHERENT NUCLEAR SCATTERING

- **FERMI MOTION AND BINDING** *in nuclear structure functions can be calculated from the convolution of nuclear spectral function and (bound) nucleon SFs:*

$$F_2^A(x,Q^2) = F_2^{p/A} + F_2^{n/A}$$

$$F_2^{p/A} = \int d\varepsilon\, d^3\mathbf{k}\, \mathcal{P}_p(\varepsilon,\mathbf{k}) \left(1+\frac{k_z}{M}\right) F_2^p(x',Q^2,k^2)$$

where $x' = Q^2/(2k\cdot q)$ *and* $k = (M+\varepsilon,\mathbf{k})$.



- *Since bound nucleons are* **OFF-MASS-SHELL** *there appears dependence on the nucleon virtuality* $k^2 = (M+\varepsilon)^2 - \mathbf{k}^2$*:*

$$F_2(x,Q^2,k^2) = F_2(x,Q^2)\left(1+\delta f_2(x)(k^2-M^2)/M^2\right).$$

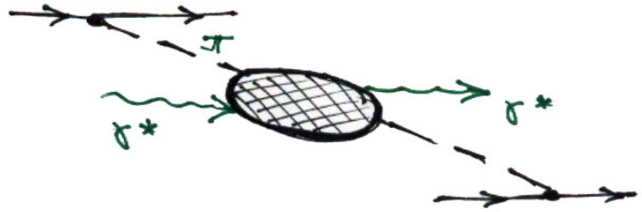
where we have introduced an off-shell structure function $\delta f_2(x)$

- *Hadronic/nuclear input:*
  - *Proton/neutron SFs computed in NNLO pQCD + TMC + HT from fits to DIS data*
  - *Two-component nuclear spectral function (mean-field + correlated part) based on Ciofi & Simula*

NUCLEAR PION CORRECTION

- *Leptons can scatter off mesons which mediate interactions among bound nucleons:*

$$F_i^{\pi/A}(x,Q^2) = \int_x \mathrm{d}y\, f_{\pi/A}(y) F_i^{\pi}(x/y,Q^2)$$

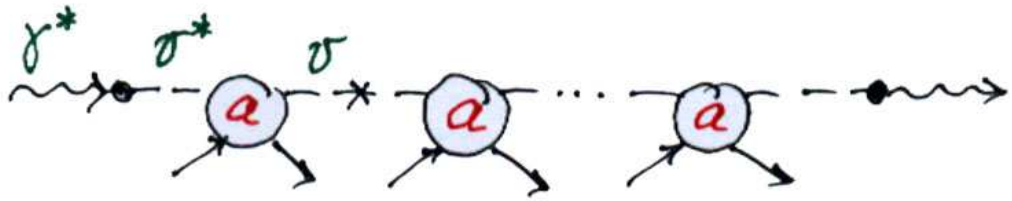


- *Contribution from nuclear pions (mesons) to balance nuclear light cone momentum* $\langle y\rangle_\pi + \langle y\rangle_N = M_A/(A\,M)$. *The pion distribution function is localized at* $y \leq p_F/M \sim 0.3$ *so that the pion contribution is at* $x < 0.3$. *The correction is driven by the average number of "pion excess"* $n_\pi = \int \mathrm{d}y\, f_\pi(y)$ *and* $n_\pi/A \sim 0.1$ *for heavy nuclei. It modifies the nuclear sea quark distributions, but not the valence quarks.*

- *Hadronic/nuclear input:*
  - *Pion Parton Density Functions from fits to Drell-Yan data by Gluck, Reya & Schienbein*
  - $f_{\pi/A}(y)$ *calculated using constraints of light-cone momentum conservation and equations of motion for pion-nucleon system*

COHERENT NUCLEAR EFFECTS

- **SHADOWING** *correction comes from multiple interactions of the hadronic component of virtual photon during the propagation through matter. This is described following the Glauber-Gribov approach:*



$$\delta\mathcal{R} = \frac{\delta F_2^{\rm coh}}{F_2^N} \approx \frac{\delta\sigma^{\rm coh}}{\sigma}; \quad \delta\sigma^{\rm coh} = 2\,{\rm Im}\left(ia^2\mathcal{C}_2^A(a)\right)$$

$$\mathcal{C}_2^A(a) = \int_{z_1<z_2} {\rm d}^2\mathbf{b}\,{\rm d}z_1{\rm d}z_2\,\rho_A(\mathbf{b},z_1)\rho_A(\mathbf{b},z_2)\exp\left[i\int_{z_1}^{z_2}{\rm d}z'\left(a\,\rho_A(\mathbf{b},z') - k_L\right)\right]$$

$a = \sigma(i+\alpha)/2$ *is the (effective) scattering amplitude* ($\alpha = {\rm Re}\,a/{\rm Im}\,a$) *in forward direction,* $k_L = Mx(1+m_v^2/Q^2)$ *is longitudinal momentum transfer in the process* $v^* \to v$ *(accounts for finite life time of virtual hadronic configuration).*

- *Hadronic/nuclear input:*
  - *Nuclear number densities* $\rho_A(r)$ *from parameterizations based on elastic electron scattering data*

PARAMETERS OF THE MODEL

- **EFFECTIVE CROSS-SECTION** *and amplitude which are used to describe the weighted sum of hadronic components of virtual photon:*

$$\bar{a}_T = \bar{\sigma}_T(i+\alpha)/2$$

$$\bar{\sigma}_T = \sigma_1 + \frac{\sigma_0 - \sigma_1}{1 + Q^2/Q_0^2}$$

where $\sigma_1 = 0$ fixed and $\sigma_0 \equiv 27$ mb, $\alpha \equiv -0.2$ in order to match VMD model at low Q^2. The parameter Q_0^2 controlling the transition to partonic regime is free.

- **OFF-SHELL FUNCTION**:

$$\delta f_2(x) = C_N(x-x_1)(x-x_0)(1+x_0-x)$$

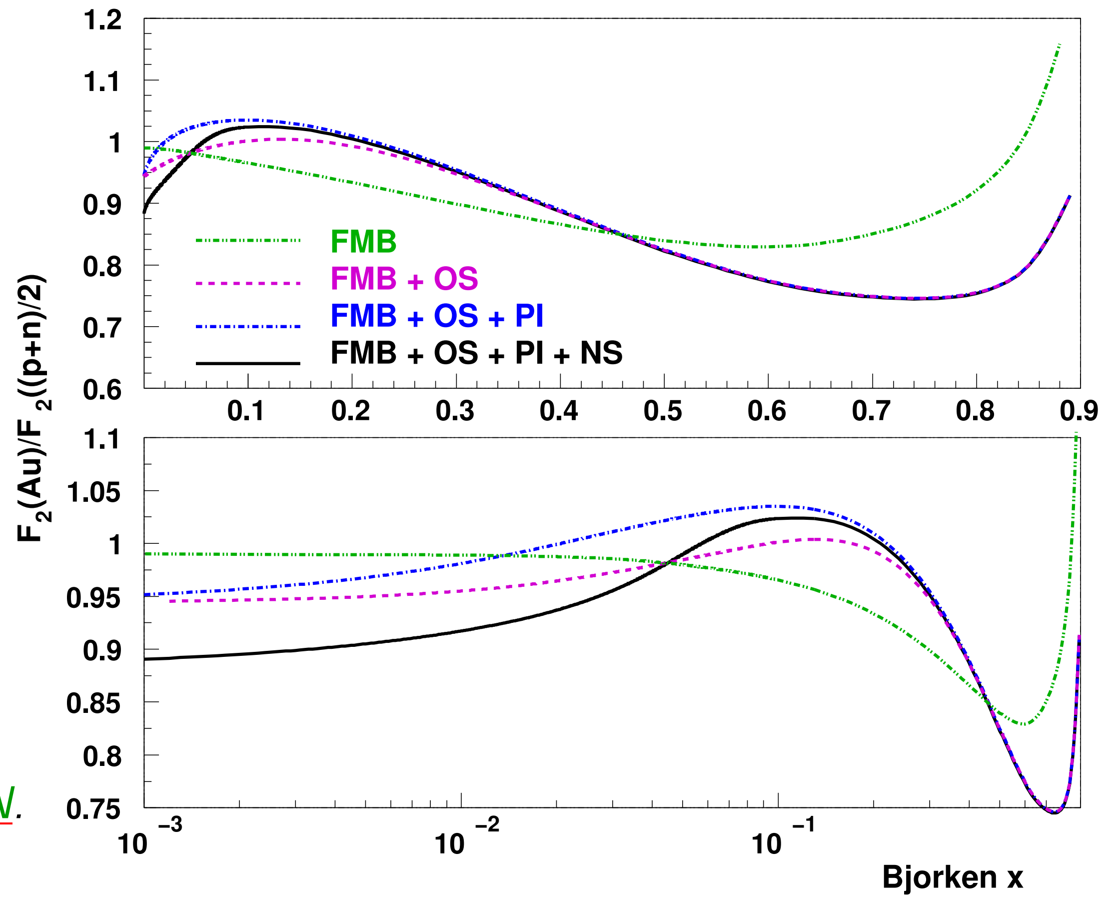
where $x_1 \equiv 0.05$ from conservation of nuclear valence number, C_N and x_0 free par's.

- *C_N, x_0 and Q_0^2 describe the modification of bound (off-shell) nucleon and are extracted phenomenologically from nuclear DIS data on ratios $\mathcal{R}_2(A,B) = F_2^A/F_2^B$:*
  - *Electron and muon scattering from BCDMS, EMC,E139,E140,E665 and NMC*
  - *Wide range of targets He,Li,Be,C,Al,Ca,Fe,Cu,Ag,Sn,Au,Pb*

RESULTS FROM NUCLEAR DIS

- *Excellent agreement with existing data for the entire kinematics:*

$$\chi^2/d.o.f. = 459/556$$



- *Independent fits to different sub-sets of nuclei provide parameters consistent with the global fit:*

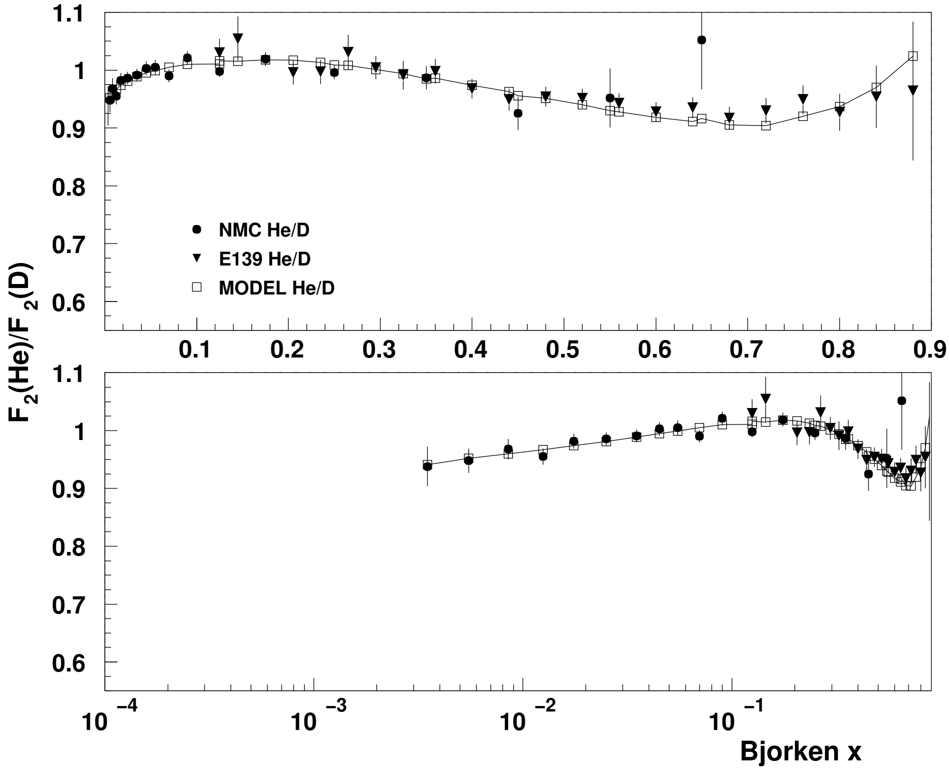
$$C_N = 8.10 \pm 0.30$$
$$x_0 = 0.448 \pm 0.005$$
$$Q_0^2 = 1.43 \pm 0.06 \; GeV^2$$

$\Longrightarrow$ *Common par's related to structure of BOUND NUCLEON.*

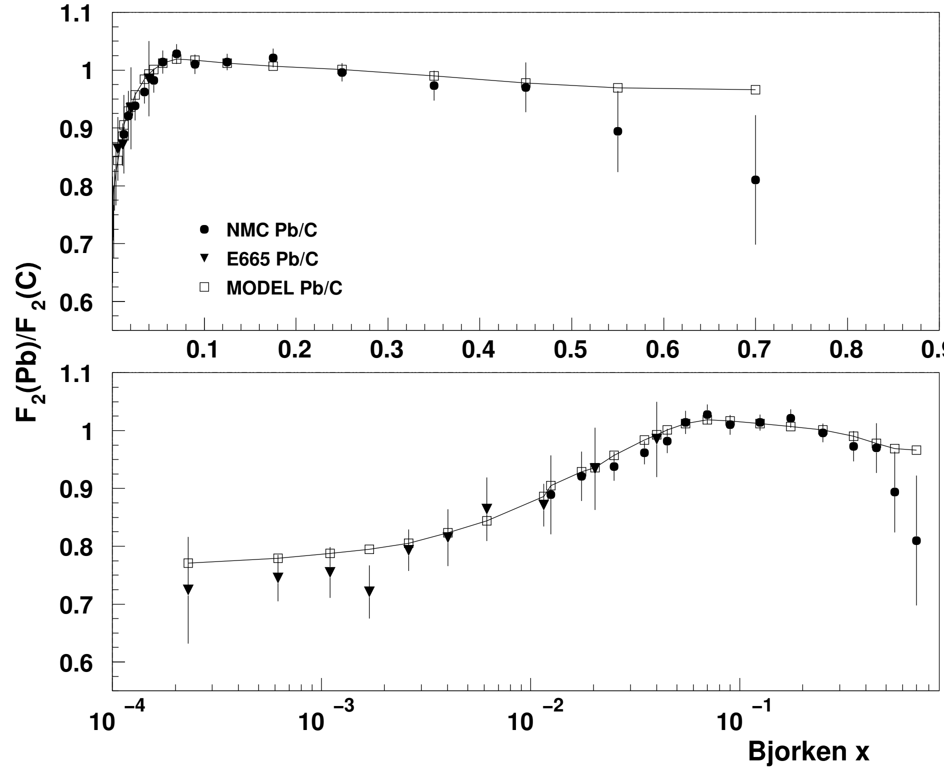
- *Detailed study of systematic uncertainties:* δC_N=0.5, δx_0=0.007, δQ_0^2=0.2 GeV^2

COMPARISON WITH NUCLEAR DIS DATA

- ^{4}He/D

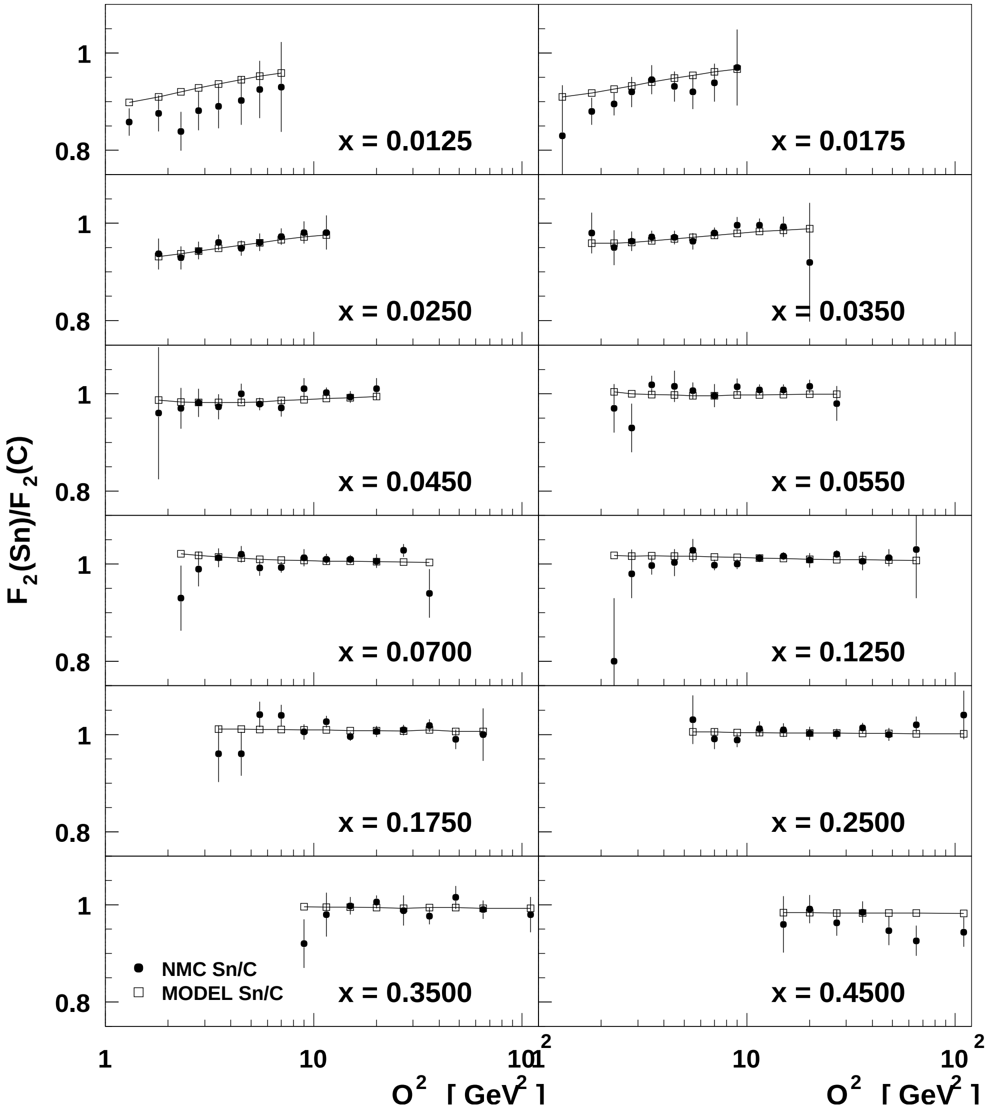


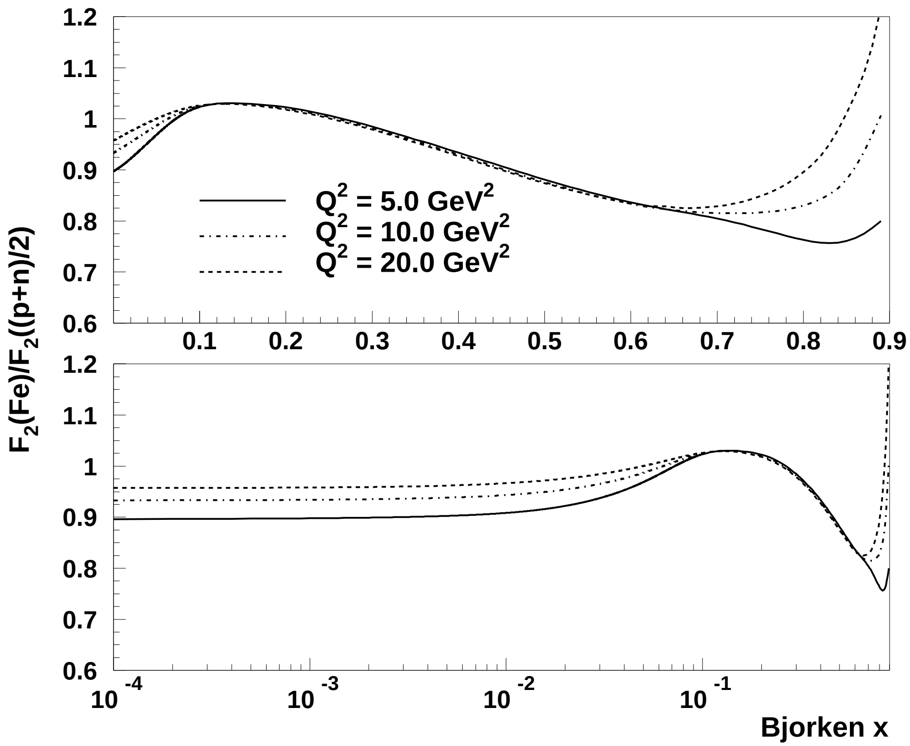
- ^{207}Pb/^{12}C



Good agreement for all measured nuclei from ^{4}He to ^{207}Pb
(for details see hep-ph/0412425)

ANALYSIS OF Q^2 DEPENDENCE OF $\mathcal{R}_2$





Significant Q^2 dependence only for $x < 0.1$ (shadowing) and $x > 0.65$ (TMC expansion)

OFF-SHELL FUNCTION

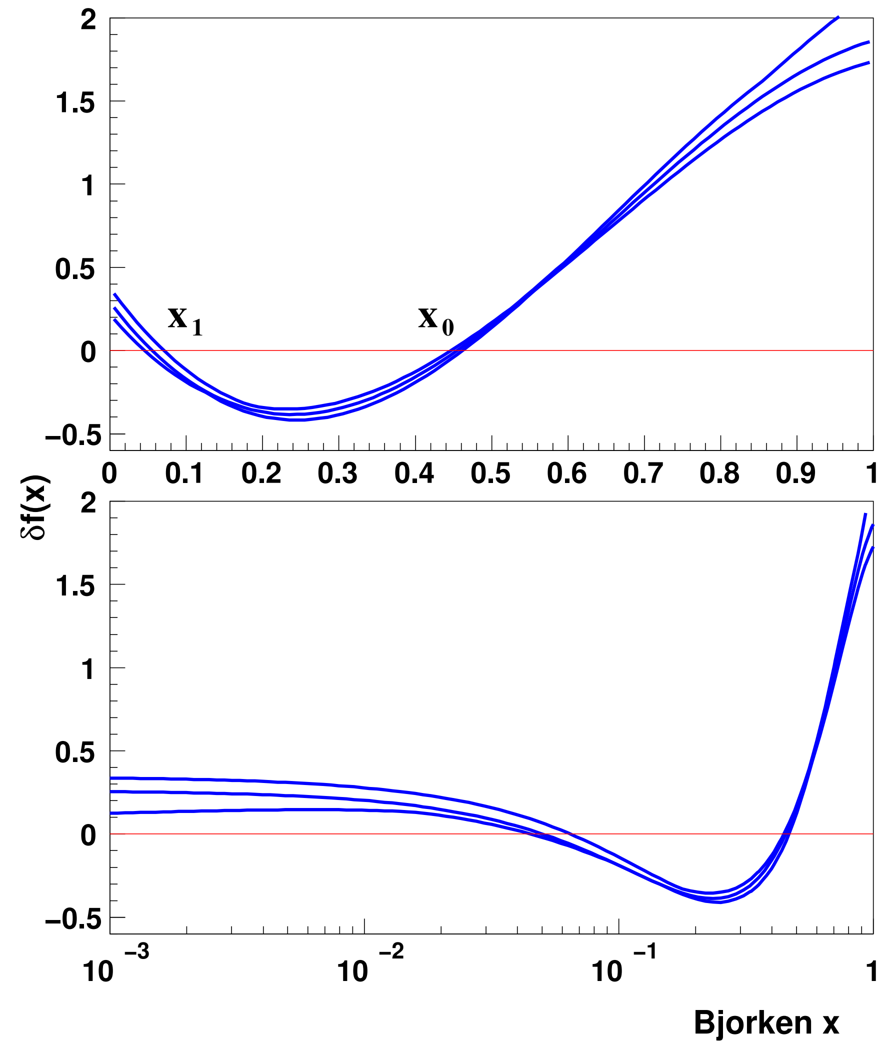
- *The Off-Shell structure function provides an estimate of the modification of the bound nucleon radius in nuclear medium*

  $\Longrightarrow$ *x_0 and the slope $\delta f'(x_0)$ suggest an increase of the radius of nucleon valence region by $\sim 10\%$ in Fe*

- *Inclusive nuclear DIS can be used to probe the off-shell function $\delta f(x)$*

  $\Longrightarrow$ *Additional information could be provided by semi-inclusive DIS data*

- *Interesting to check the universality of δf for all partons, which was suggested by normalization of nuclear valence number*



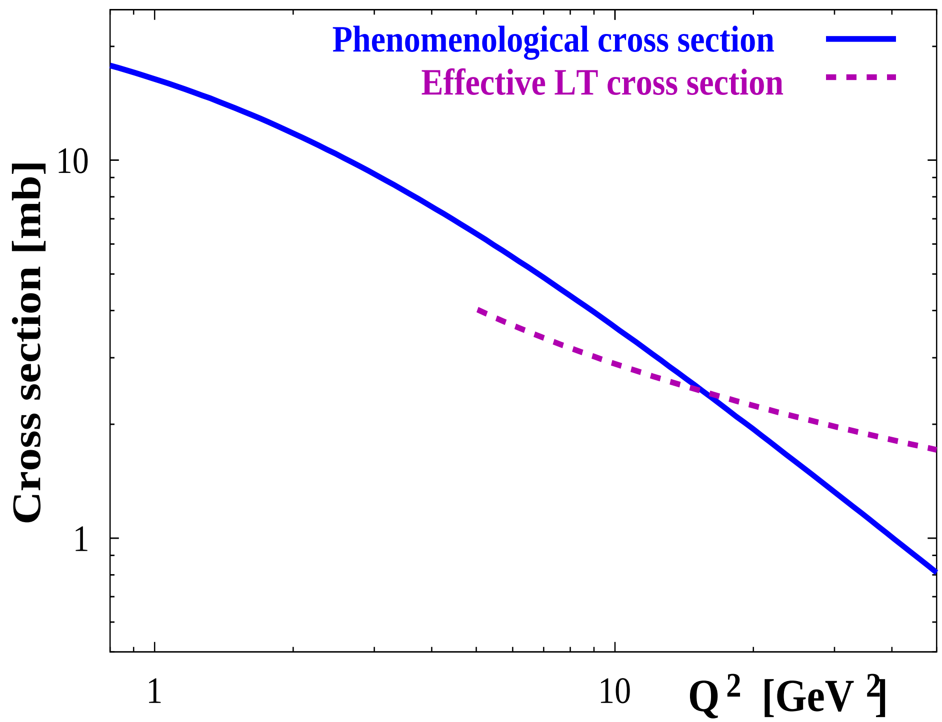
EFFECTIVE CROSS-SECTION

- *The monopole form* $\bar{\sigma} = \sigma_0/(1 + Q^2/Q_0^2)$ *describes well the existing data on nuclear shadowing for* $Q^2 < 20$ *GeV*^{2}

  $\Longrightarrow$ *No constraint from current data on* $\bar{\sigma}$ *at* $Q^2 > 20$ *GeV*^{2}

- *An effective cross-section at high* Q^2 *can be calculated by imposing the conservation of the nuclear valence quark number (baryon number):*

$$\delta N_{\rm val}^{\rm off-shell} + \delta N_{\rm val}^{\rm shadowing} = 0$$



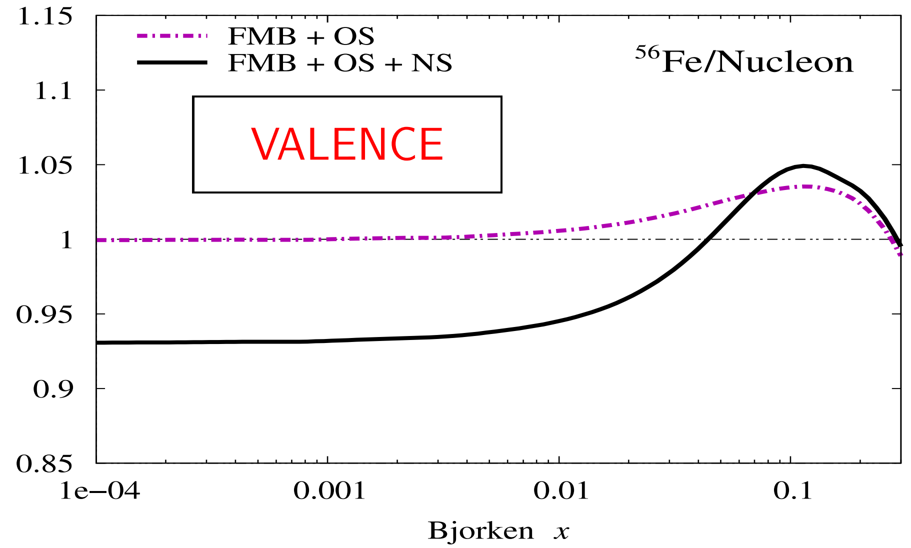
$\Longrightarrow$ *Nuclear data indicate substantial High Twist contributions at* $Q^2 < 10$ *GeV*^{2}
$\Longrightarrow$ *Effective Leading Twist cross-section allows the calculation of nuclear PDFs*

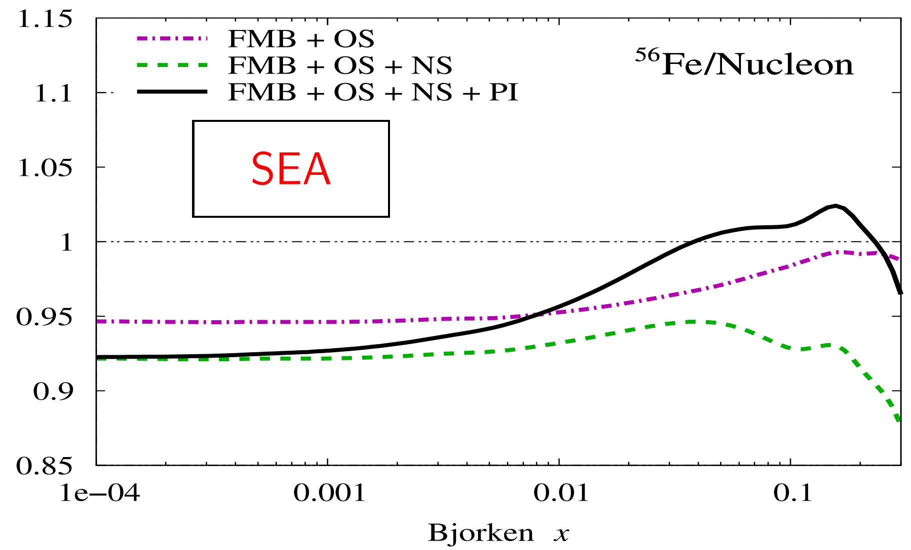
CORRECTION TO VALENCE AND SEA QUARKS

- *Nuclear corrections to parton distributions (nuclear PDFs) can be derived naturally from our analysis of SFs*
- *Universality of off-shell function implies an universal nuclear convolution for all partons*
- *For isoscalar targets the nuclear pion (meson) correction to valence dist. cancels out*
- *Nuclear shadowing depends on C-parity* $q^{\pm} = q \pm \bar{q}$. *Multiple scattering correction is enhanced for valence, however total relative effect is similar for valence and sea.*

$$\frac{\delta\bar{q}_A(x)}{\bar{q}_N(x)} = \delta\mathcal{R}^+ + \frac{q_{\mathrm{val}/N}(x)}{2\bar{q}_N(x)}\left(\delta\mathcal{R}^+ - \delta\mathcal{R}^-\right)$$

$\Longrightarrow$ *Remarkable cancellation between pion and shadowing effects for* $\bar{q}$





ISOSPIN DEPENDENCE OF NUCLEAR PDFs

- *Different Fermi motion and binding corrections for isoscalar $q_0 = u + d$ and isovector $q_1 = u - d$ quark distributions:*

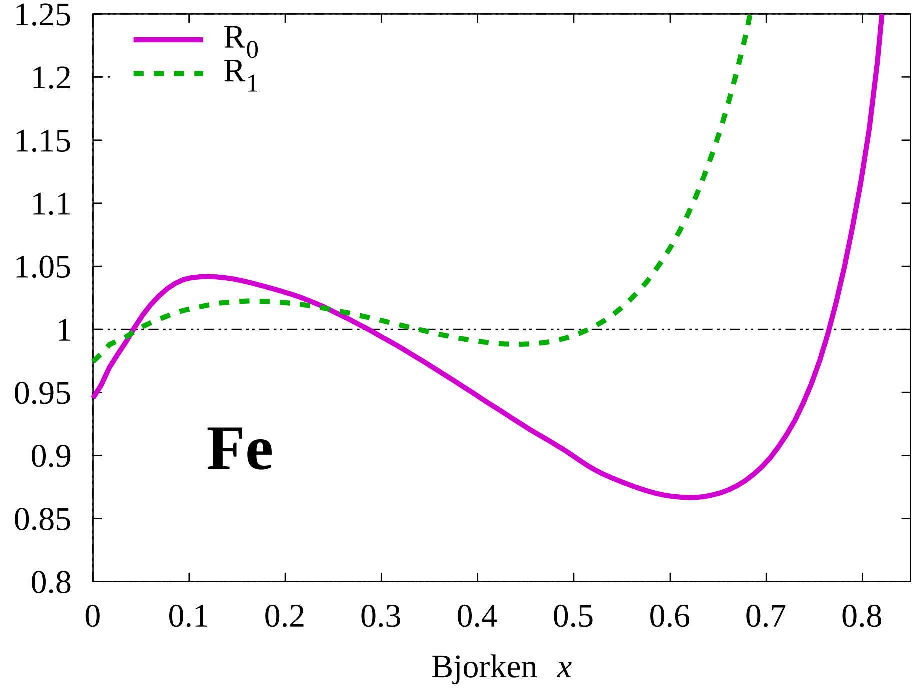
$$\mathcal{P}^{p+n} = A\mathcal{P}_0; \quad \mathcal{P}^{p-n} = (Z - N)\mathcal{P}_1$$

isoscalar and isovector spectral functions $\mathcal{P}_1$ and $\mathcal{P}_1$ are different distributions

$\Longrightarrow$ *Isospin effect in the FMB correction*
$\Longrightarrow$ *Flavour-dependent nuclear correction*

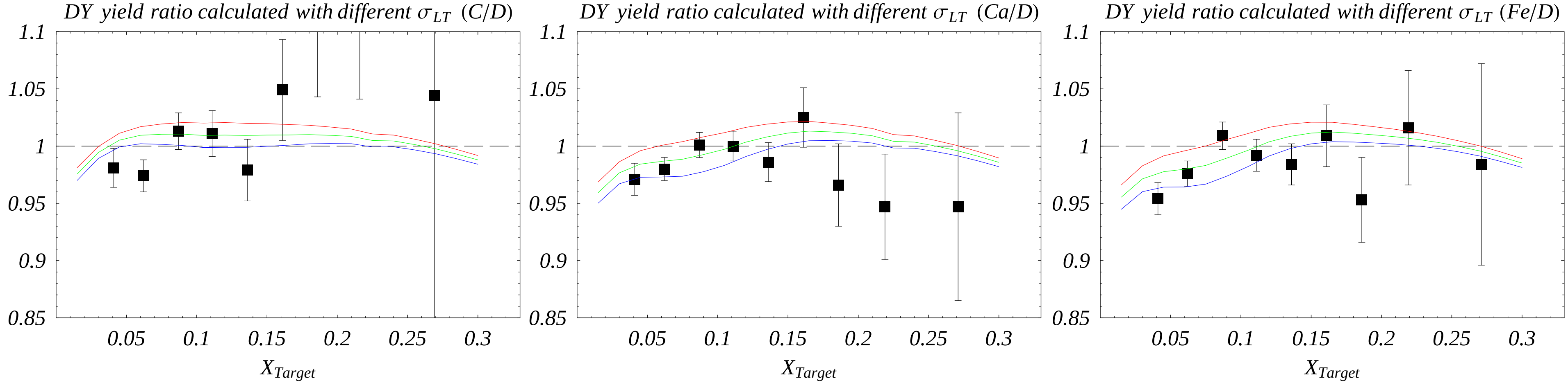
- *Convolution of q_0 and q_1 quark distributions with isoscalar f_0 and isovector f_1 nucleon distributions in nucleus*

$$q_{0/A} = Af_0 \otimes q_{0/p}; \quad q_{1/A} = (Z-N) f_1 \otimes q_{1/p}$$



- *Implementation of isospin (quark flavour) effects for nuclear shadowing is in progress*

APPLICATION TO DRELL-YAN pA CROSS-SECTIONS



- *Extraction of Leading Twist and calculation of nuclear parton distributions can be checked against Drell-Yan data from E772 experiment:*
  - *Different process and kinematics with respect to DIS data ($Q^2 \geq 16$ GeV^2);*
  - *As a first test, calculate Drell-Yan cross-sections in the LO approximation (with NNLO PDFs);*
  - *Exact kinematics (mass) of points not available from paper.*

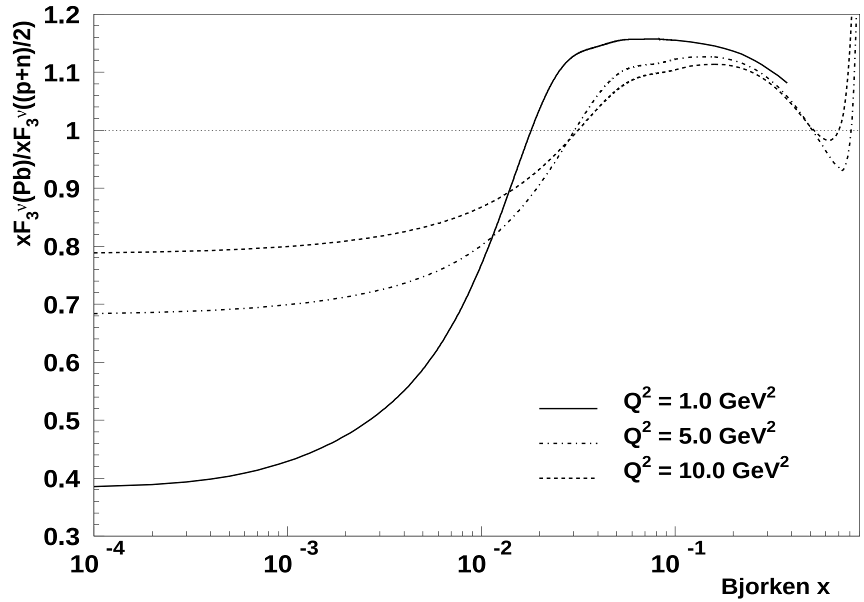
$\Longrightarrow$ *Predictions are in reasonable agreement with C/D, Ca/D and Fe/D ratios.*

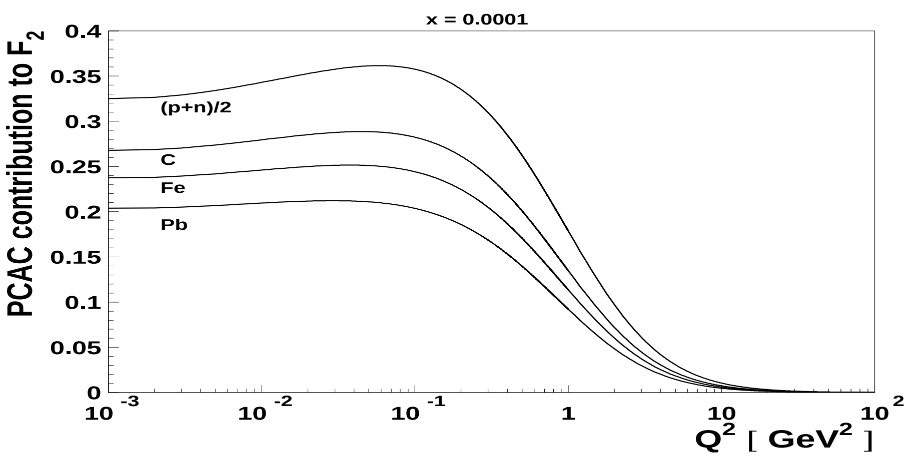
- *Cancellation from shadowing reconciles nuclear pion excess with Drell-Yan data*

APPLICATION TO $\nu(\bar{\nu})A$ CROSS-SECTIONS

- *Similarities between neutrino and charged lepton scattering for Leading Twist (high Q^2) are based on description in terms of universal process-independent PDFs. Nuclear corrections to PDFs (nuclear PDFs) are also process-independent.*

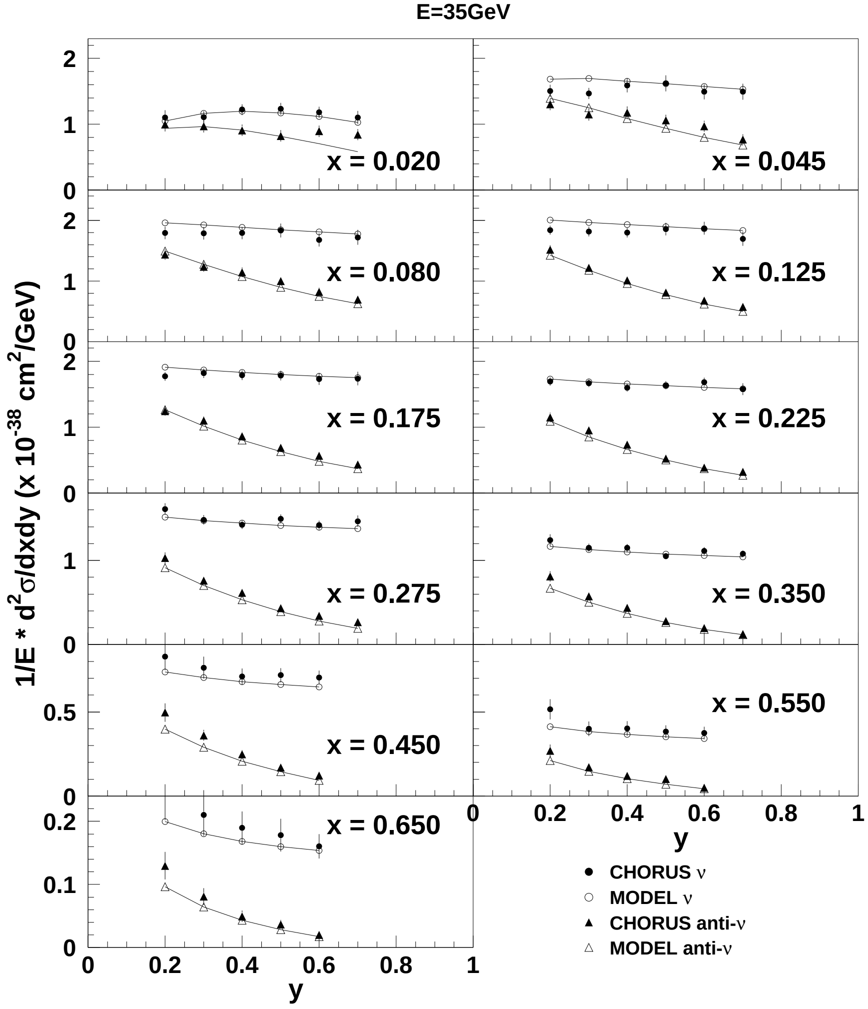
- *High Twist contributions are generally process-dependent and differ for neutrino and charged lepton scattering (low Q^2):*
  - *The axial current dominates neutrino cross-sections at $Q^2 \ll 1 GeV^2$. The PCAC relation links structure functions to virtual pion cross section (Adler). Coherent nuclear corrections are driven by multiple scattering effects in the virtual pion cross section.*
  - *Non PCAC contributions (e.g. axial-vector states $a_1, \rho\pi$) are relevant in the transition region of $Q^2 \sim 1 GeV^2$ and $x \sim (1-5)10^{-2}$.*



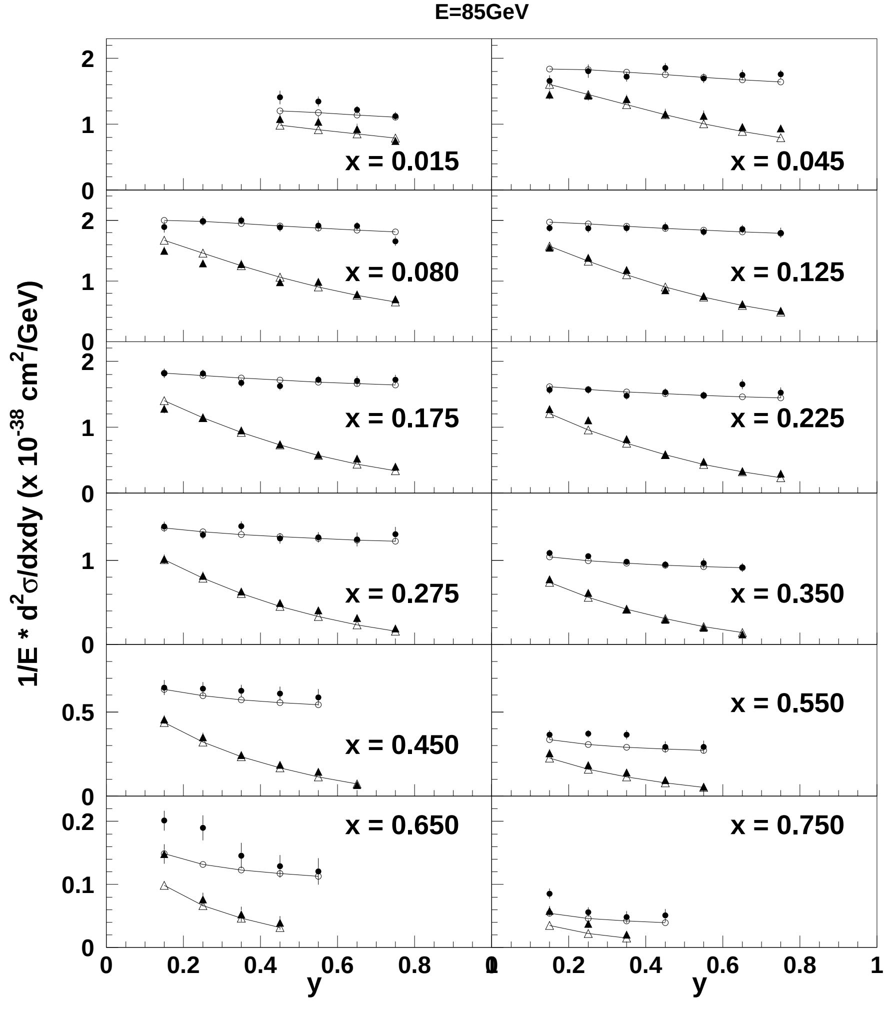


COMPARISON WITH $\nu(\bar{\nu})A$ DATA

CHORUS $\nu(\bar{\nu})$ Pb



NuTeV $\nu(\bar{\nu})$ Fe



Predictions of our model for differential cross sections

SUMMARY

- *A detailed and quantitative study of existing data from charged lepton-nucleus scattering has been performed in a wide kinematic region of x and Q^2*

- *A model was developed which includes the QCD treatment of nucleon structure functions as well as major nuclear effects like shadowing, Fermi motion and nuclear binding, nuclear pion and off-shell corrections to bound nucleon structure functions*

- *Nuclear parton distribution functions (nPDFs) can be derived naturally from our treatment of nuclear structure functions, by extracting the Leading Twist contribution*

- *Applications to Drell-Yan pA cross-sections and to (anti)neutrino-nucleus cross-sections are in agreement with existing experimental data*