Modelling Nuclear Parton Distributions

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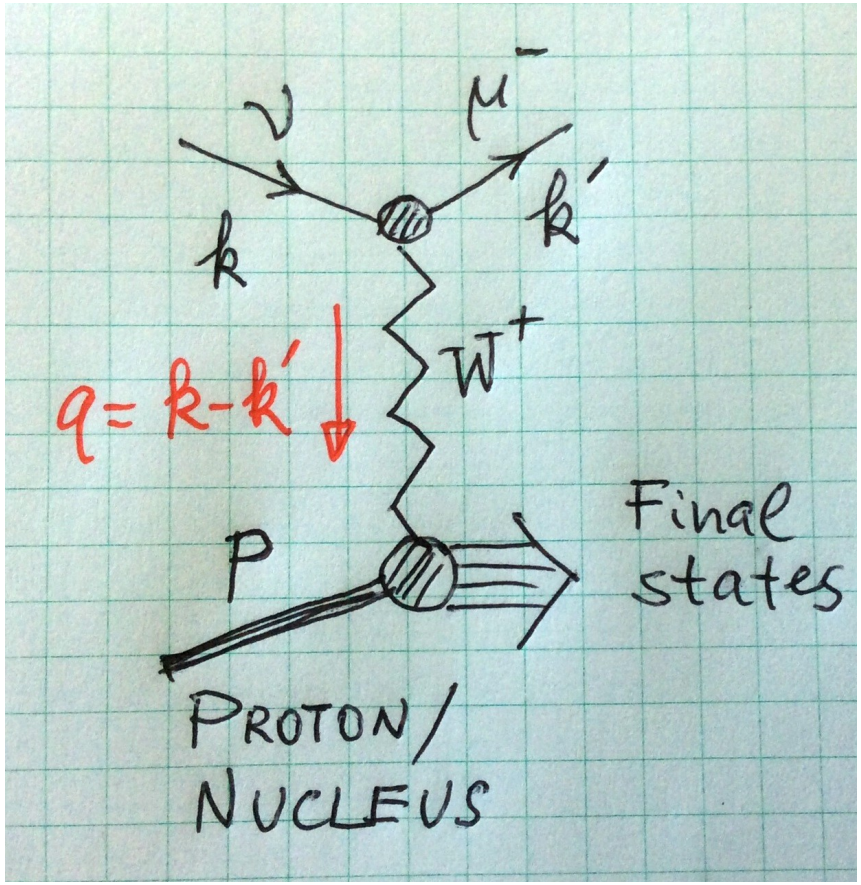
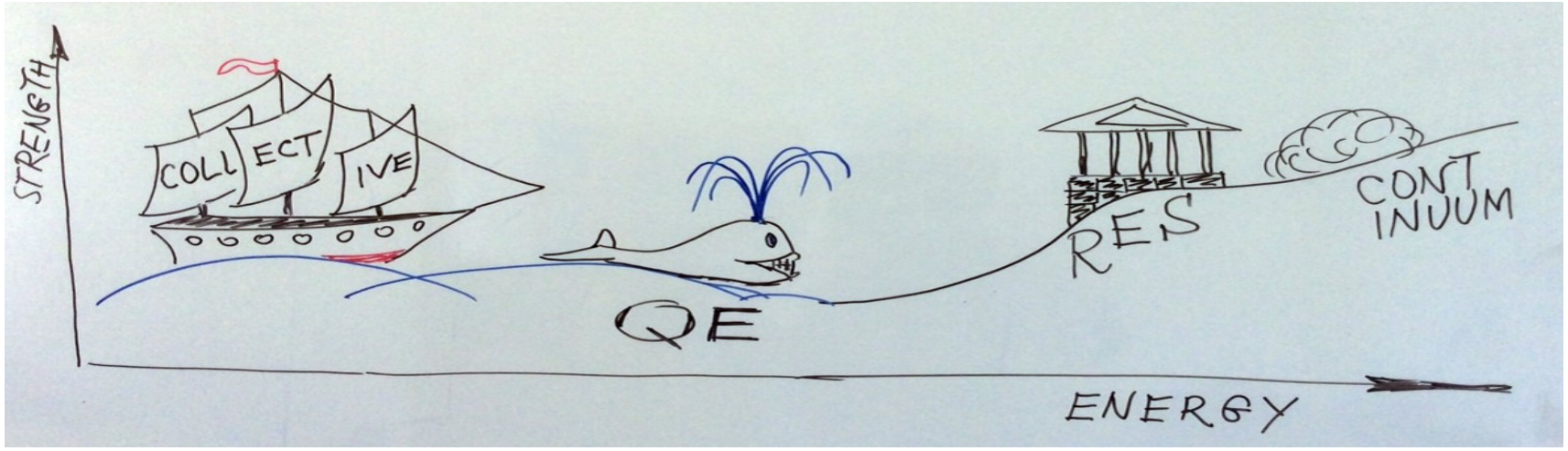
Inelastic neutrino scattering as example

- The cross section can be described by 3 structure functions: F_1, F_2, F_3
- Traditional variables (low-energy quantum mechanics): energy and momentum transfer
- Relativistic variables: invariant momentum transfer $Q^2 = (k - k')^2$ and the scaling (Bjorken) variable $x = Q^2/2p \cdot q$
- Global variable: neutrino energy E or invariant mass of the initial state $s = (k + p)^2 \approx 2ME$

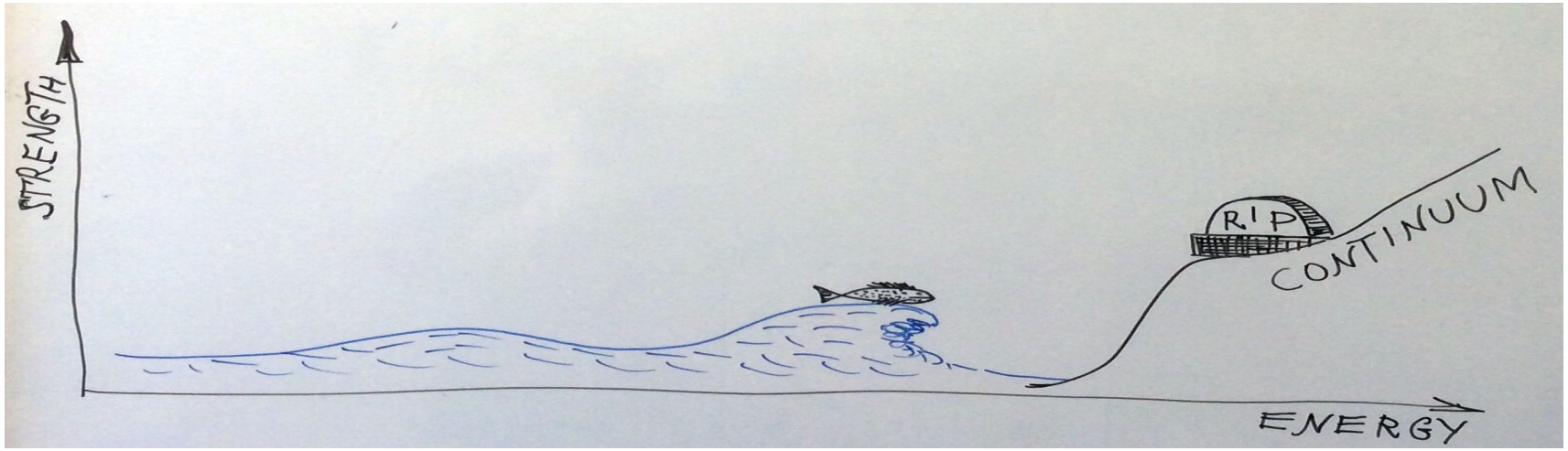


Seascape of cross section strength

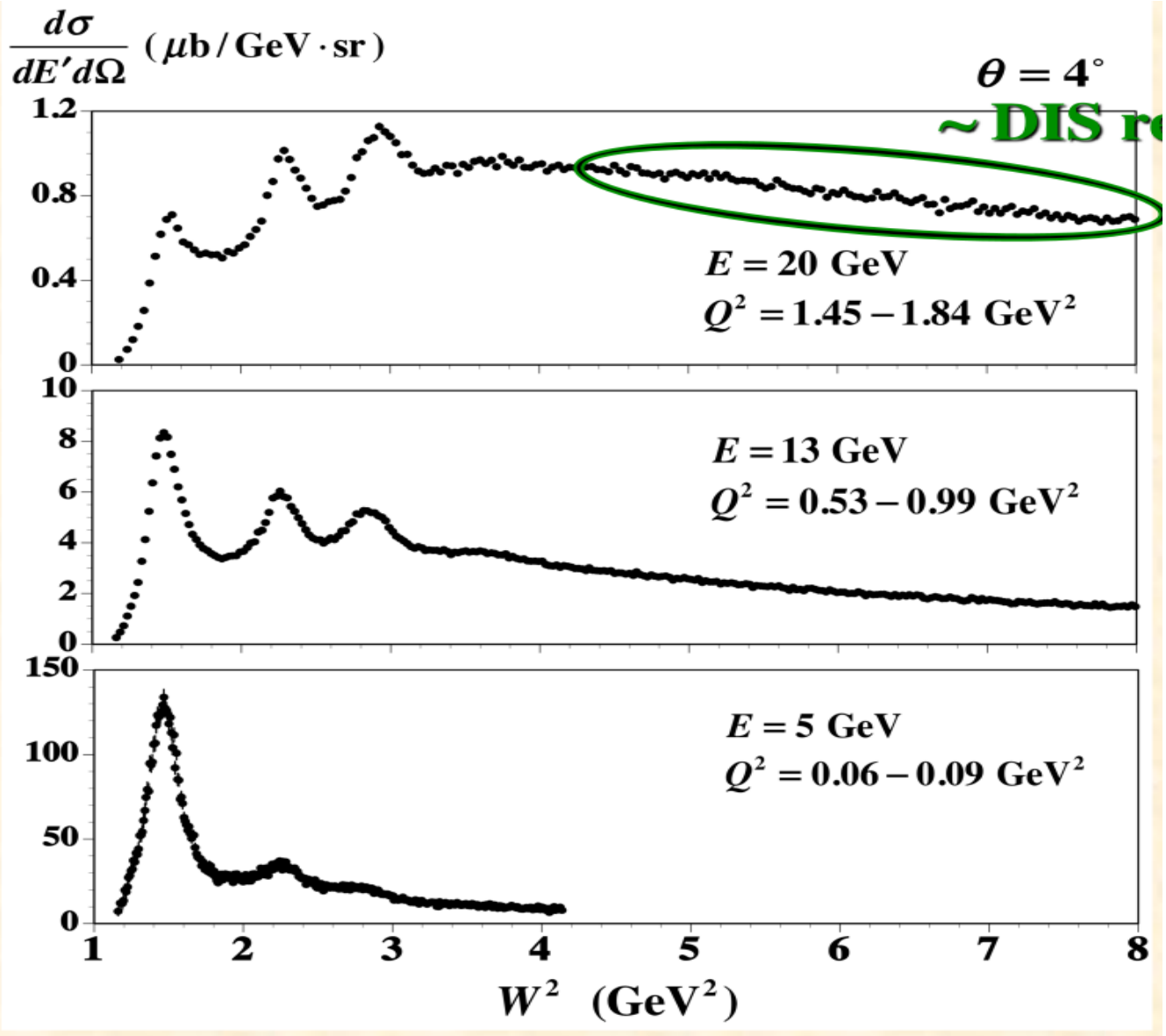
Nuclear cross section life at low $Q \ll 1$ GeV



Nuclear cross section life at high $Q \gg 1$ GeV



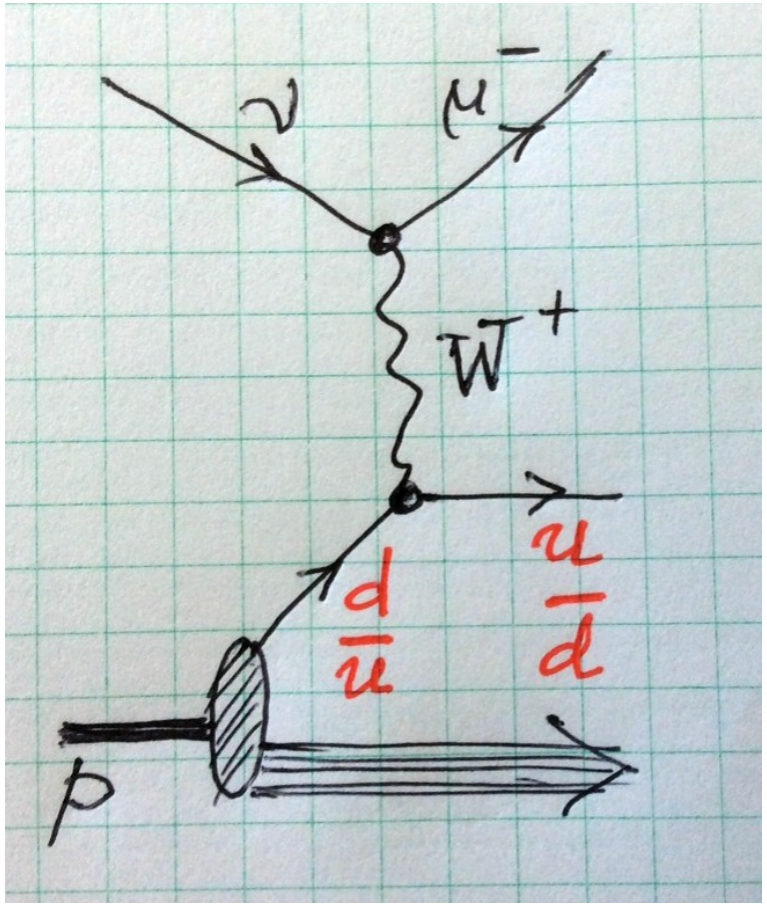
Inelastic cross section (in a somewhat more scientific form)



Inelastic scattering at high Q (deeply-inelastic scattering)

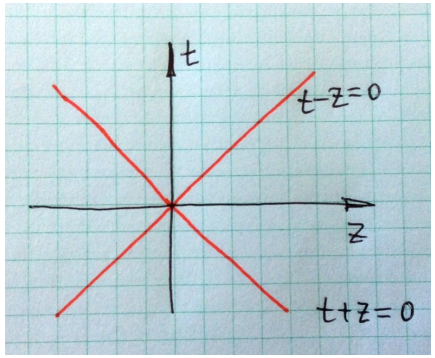
In QCD the leading contribution to the cross sections/structure functions can be given in terms of parton distributions (PDFs)

$$F_2(x,Q^2) = x\,(d + \bar{u} + s) + \mathcal{O}(\alpha_S) + \mathcal{O}(Q^{-2})$$
$$xF_3(x,Q^2) = x\,(d - \bar{u} + s) + \mathcal{O}(\alpha_S) + \mathcal{O}(Q^{-2})$$
$$\bar{u} = \bar{u}(x,Q^2) \quad u \text{ antiquarks}$$
$$d = d(x,Q^2) \quad d \text{ quarks}$$
$$s = s(x,Q^2) \quad s \text{ quarks}$$
$$\ldots$$



Parton distributions in a nutshell

- PDFs are the distributions of partons (quarks and gluons) over the ligh-cone momentum



$$q(x,\mu^2) = \int \frac{\mathrm{d}z}{2\pi} e^{2iMxz} \langle p|\bar{\psi}_q(t=-z,z,\mathbf{0}_T)\gamma_+\psi_q(0)|p\rangle_{\mu^2}$$

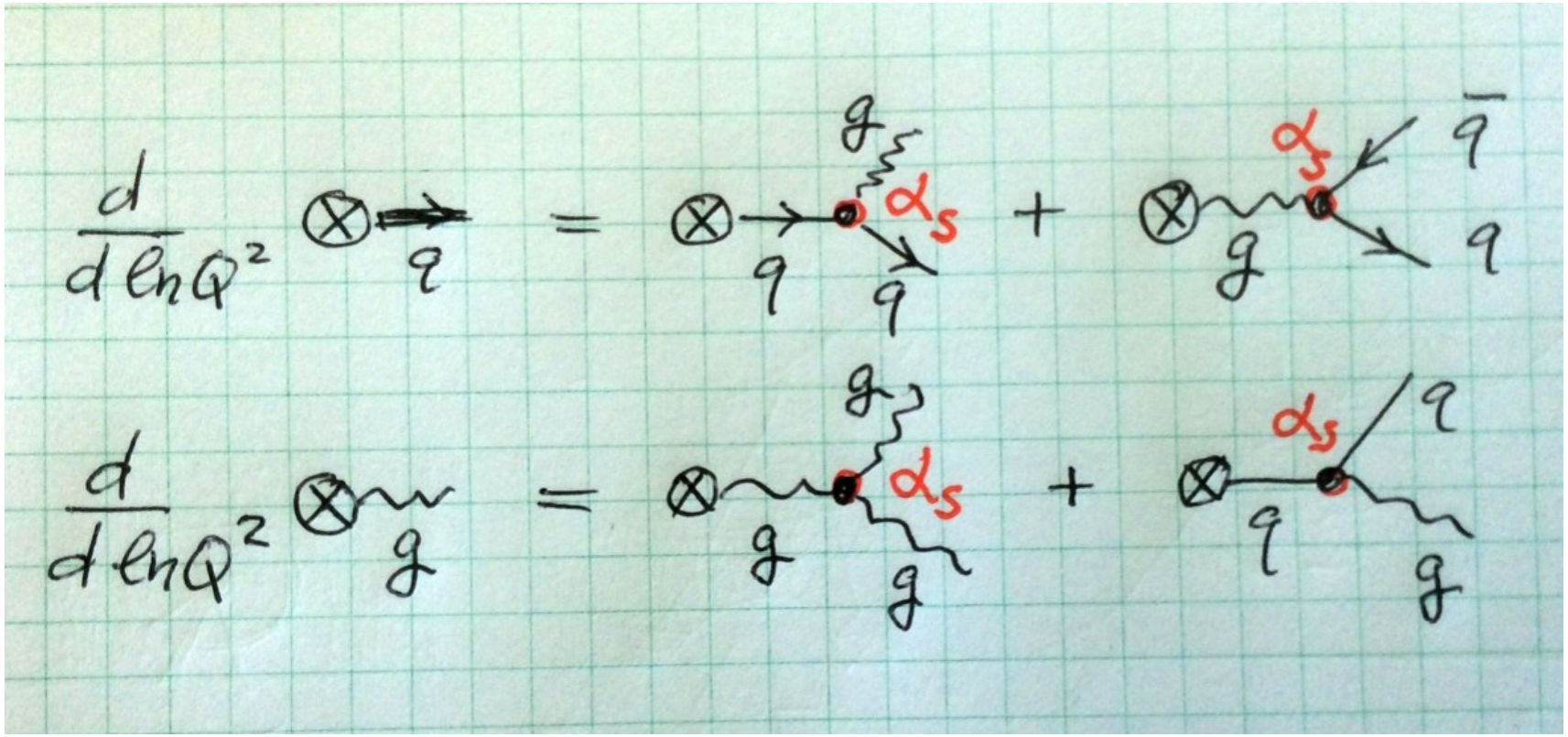
- PDFs are positively defined. The difference of Quark−Antiquark distributions is normalized to the number of valence quarks:

$$\int_0^1 \mathrm{d}x \left(u^p(x,Q^2) - \bar{u}^p(x,Q^2)\right) = 2, \quad \int_0^1 \mathrm{d}x \left(d^p(x,Q^2) - \bar{d}^p(x,Q^2)\right) = 1$$

- PDFs are universal, i.e. in the leading order same PDF drives cross sections of different processes [DIS induced by electron and neutrino, production of muon pair in hadron collisions (Drell-Yan process), etc]
- PDFs are hard to calculate in QCD since it requires solving QCD in a strong coupling regime. The Q^2 dependence can though be calculated if PDF is known at some scale Q_0^2.

Q^2 evolution

Partons can emit and absorb gluons with the coupling $\alpha_S(Q^2) \Longrightarrow$ PDFs evolve with Q^2 *Dokshitser-Gribov-Lipatov-Altareli-Parisi, 1970s*



Kernels of evolution equations are known to N^{3}LO order in α_S.

How do we know PDFs?

- *Proton* PDFs are obtained from global fits to high-energy data

$$\text{DIS:} \quad \mu + P \to \mu + X \quad \text{and} \quad \nu_\mu + P \to \mu + X$$
$$\text{DY:} \quad P + P \to \mu^+\mu^- + X$$

  assuming some functional form of PDFs at a fixed scale $Q^2 = Q_0^2$

$$f_i(x, Q_0^2) = A_i x^{a_i}(1-x)^{b_i}\,(1 + c_i x + \cdots) \quad i = u_V,\ d_V,\ \bar{u},\ \bar{d},\ \bar{s},\ g$$

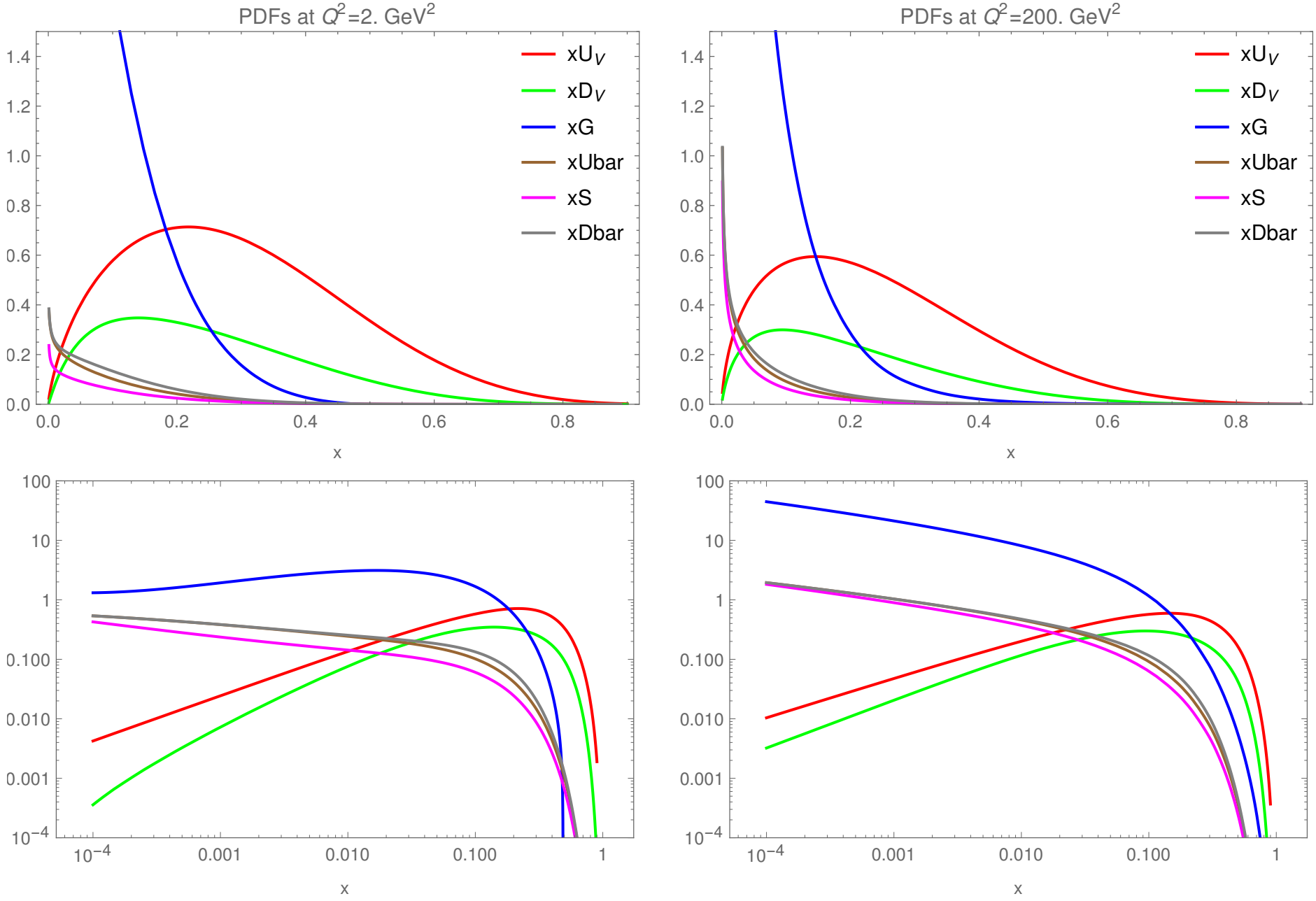
  and calculating observables and minimizing χ^2 between data and predictions.
- A few analyses are available which are regularly updated

  ABM = Alekhin + Blümlein + Moch + ...

  CTEQ = Coordinated Theoretical-Experimental project on QCD

  HERAPDF = H1 and ZEUS Collaborations from HERA

  MRST = Martin + Stirling + Thorn + Watt + ...
- Note that a direct measurement of the *neutron* PDFs is difficult as the free neutron is unstable particle ($n \to p + e + \bar{\nu}_e$ with the life time ~ 15 minutes). Neutron is stable in abound state in nuclei. Measurement of neutron observables requires to combine the proton and *nuclear* (usually deuteron) data. Thus a precision measurement of neutron parameters requires the understanding nuclear effects.


PDFs at Q^2=2. GeV^2
PDFs at Q^2=200. GeV^2
xU$_V$
xD$_V$
xG
xUbar
xS
xDbar
x

Do we know the nuclear PDFs if we know those of the proton and the neutron?

The answer depends on the accuracy we require...

- Nucleus $= Z$ protons $+N$ neutrons; ($A = Z + N$ the total number of bound nucleons).
- Nucleus is a loosely bound system with binding energy $E_B \ll M$ the nucleon mass.
- A naive expectation for nuclear PDF:

$$q_{i/A}(x, Q^2) = Zq_{i/p}(x, Q^2) + Nq_{i/n}(x, Q^2)$$

  This hypothesis was tested experimentally. The experiment shows violation of this relation up to $30 - 50\%$ depending on kinematical region.

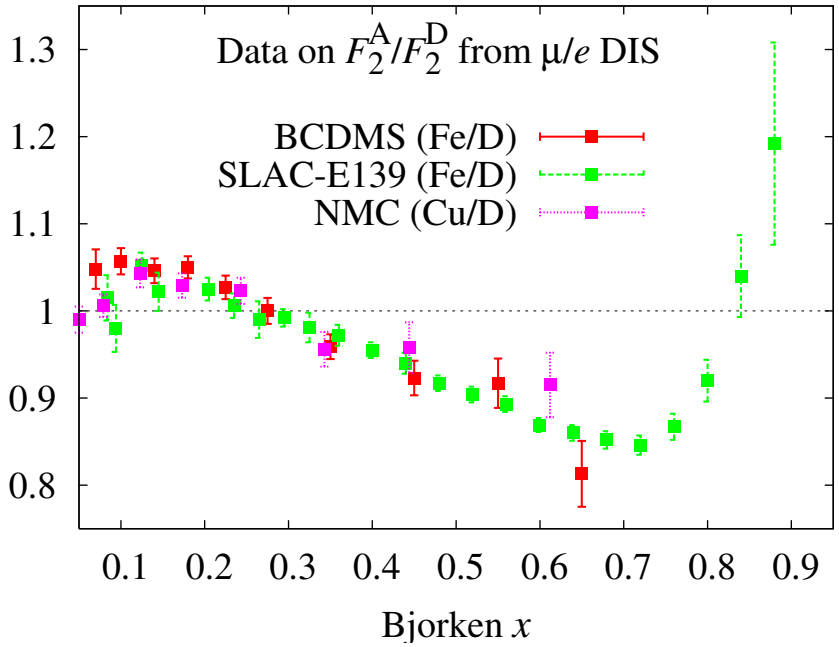
Data on nuclear effects in DIS

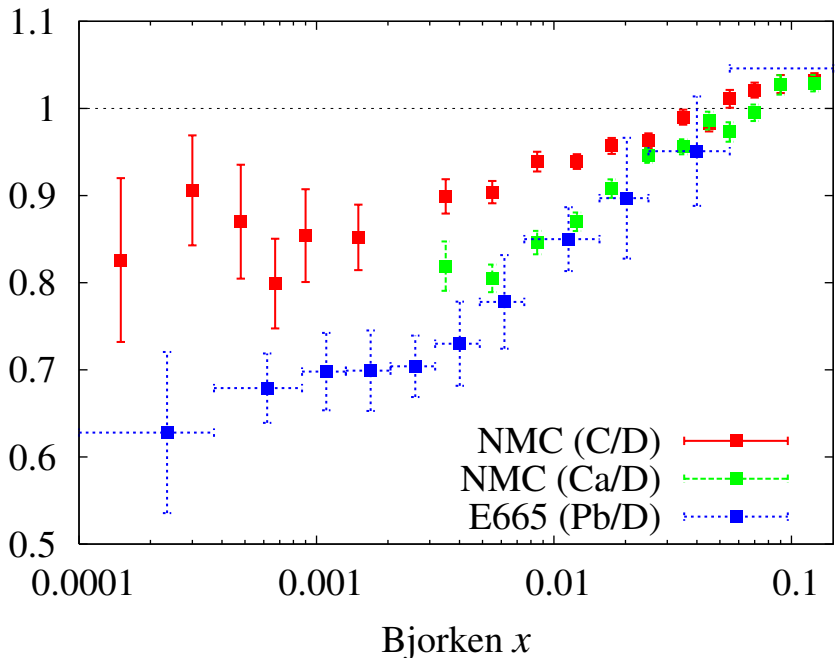
- Data on nuclear effects in DIS are available in the form of the ratio $\mathcal{R}(A/B) = \sigma_A(x, Q^2)/\sigma_B(x, Q^2)$ or F_2^A/F_2^B.
- Data for nuclear targets from ^{2}H to ^{208}Pb
- Fixed-target experiments with e/μ:
  - Muon beam at CERN (EMC, BCDMS, NMC) and FNAL (E665).
  - Electron beam at SLAC (E139, E140), HERA (HERMES), JLab (E03-103).
- Kinematics and statistics:

  Data covers the region $10^{-4} < x < 1.5$ and $0 < Q^2 < 150$ GeV^2. About 800 data points for the nuclear ratios $\mathcal{R}(A/B)$ with $Q^2 > 1$ GeV^2.
- Nuclear effects for antiquarks comes have been probed by Drell-Yan experiments at FNAL (E772, E866).
- Neutrino data on DIS cross sections on nuclear targets ^{2}H, ^{20}Ne, ^{12}C, ^{56}Fe, ^{207}Pb from CERN (BEBC, CDHS, CHORUS, NOMAD) and FNAL (CCFR, NuTeV).
- A direct measurement of the nuclear ratios from neutrino experiment MINERvA in the region of low Q^2.

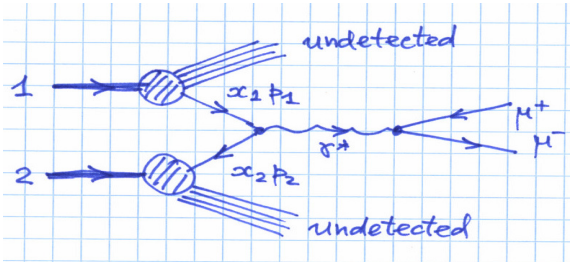
Data on the nuclear ratios $\mathcal{R}(A/D)$ show a pronounced x dependence and a weak Q^2 dependence. The ratios have *oscillating* shape vs. the Bjorken x

- Suppression (shadowing) at small x ($x < 0.05$).
- Enhancement (antishadowing) at $0.1 < x < 0.25$.
- A well with a minimum at $x \sim 0.6 \div 0.75$ (EMC effect).
- Enhancement at large values of $x > 0.75 \div 0.8$ (Fermi motion region).





Drell–Yan reaction



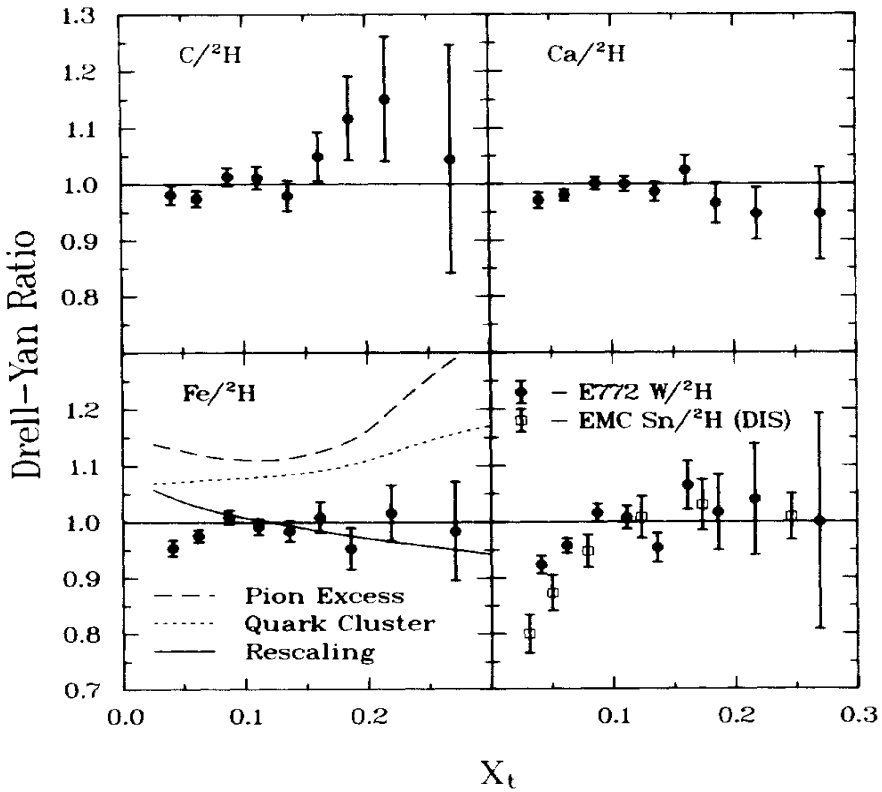


FIG. 3. Ratios of the Drell-Yan dimuon yield per nucleon, $Y_A/Y_{^2\mathrm{H}}$, for positive x_F. The curves shown for Fe/^{2}H are predictions of various models of the EMC effect. Also shown are the DIS data for Sn/^{2}H from the EMC (Ref. 4).

Production of a lepton pair in hadron collisions (Drell-Yan process)

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_B\mathrm{d}x_T} = \frac{4\pi\alpha^2}{9Q^2} K \sum_a e_a^2 \left[q_a^B(x_B)\bar{q}_a^T(x_T) + \bar{q}_a^B(x_B) q_a^T(x_T)\right]$$

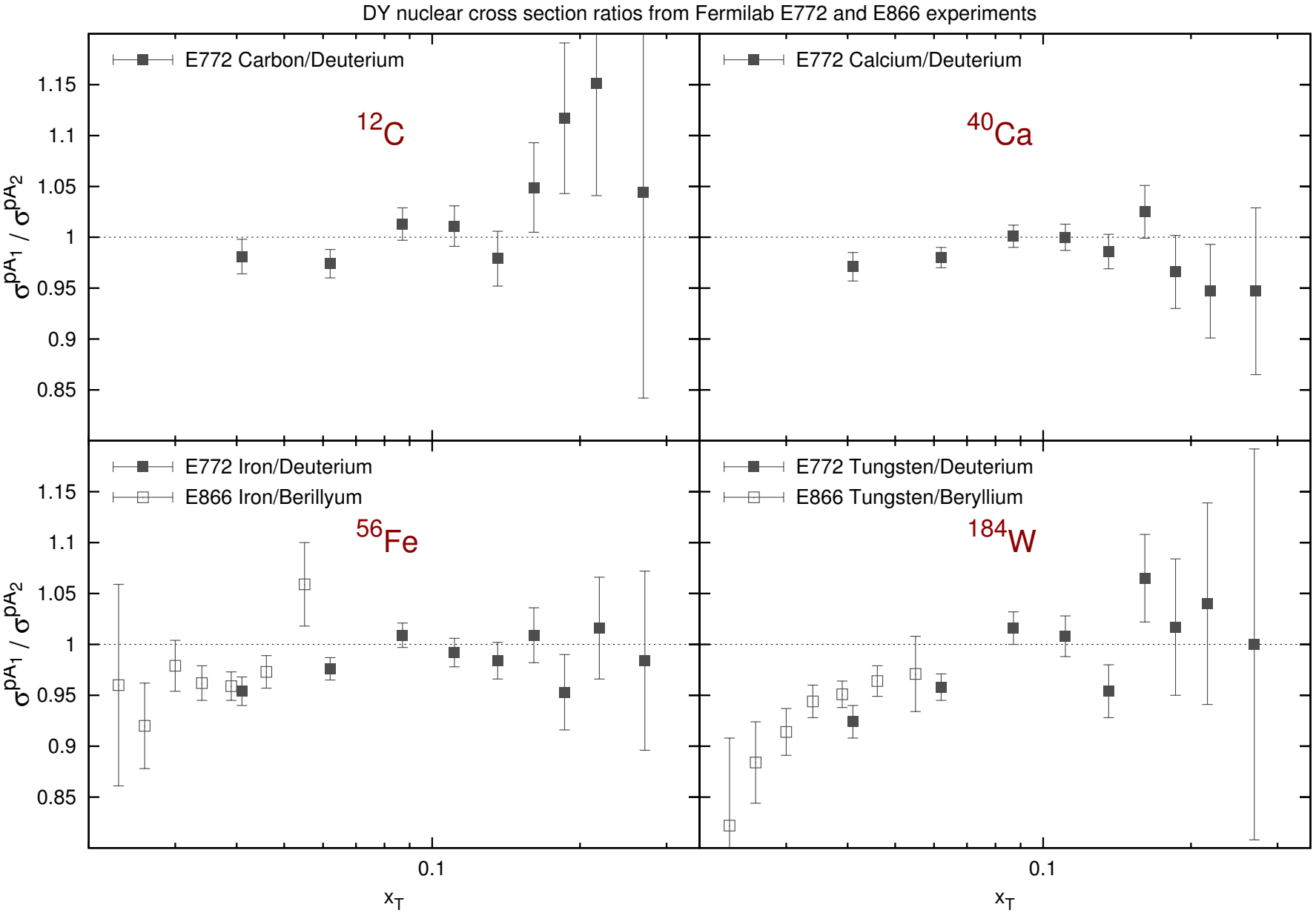
$$x_T x_B = Q^2/s,$$

$$x_B - x_T = 2q_L/\sqrt{s} = x_F$$

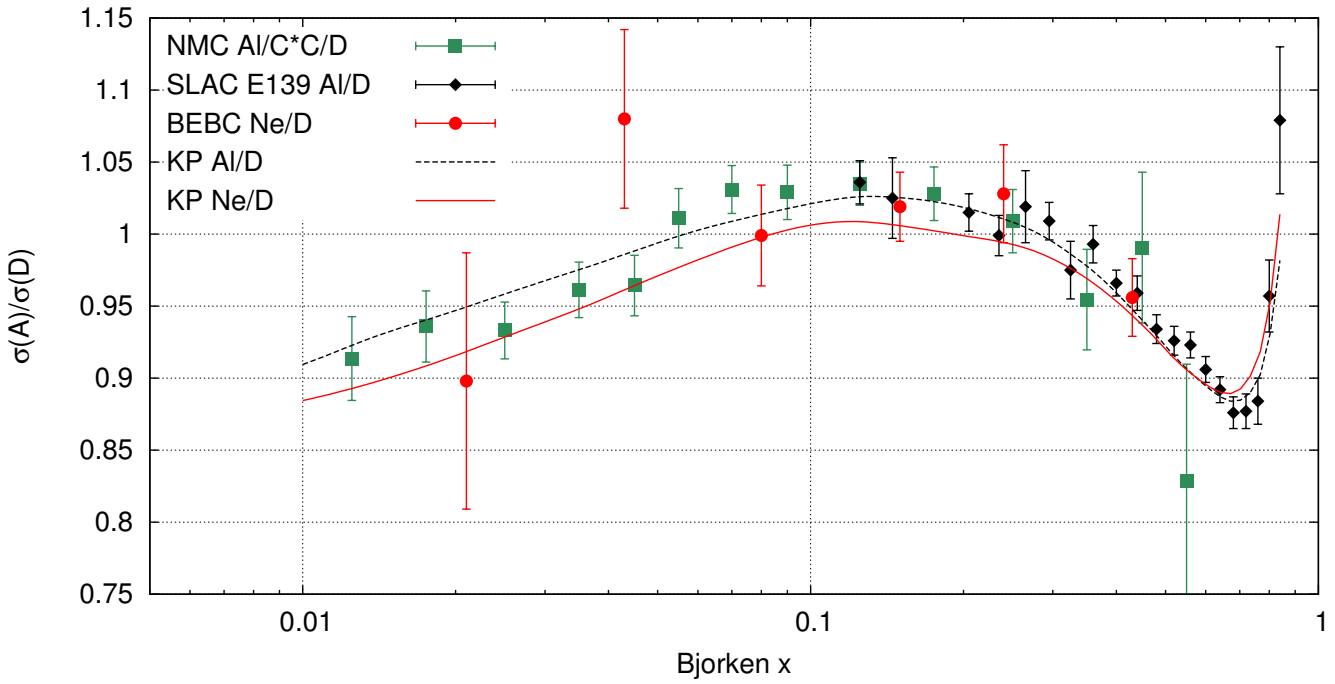
Small Q^2/s and large $x_F \Longrightarrow$ probe the target's antiquarks.
In Fermilab E772 experiment $s = 1600$ GeV^2. At $x_F = x_B - x_T > 0.2$ the process is dominated by $q^B\bar{q}^T$ annihillation.

$$\frac{\sigma_A^{\mathrm{DY}}}{\sigma_B^{\mathrm{DY}}} \approx \frac{\bar{q}_A(x_T)}{\bar{q}_B(x_T)}$$

DY nuclear data from E772 and E866 experiments

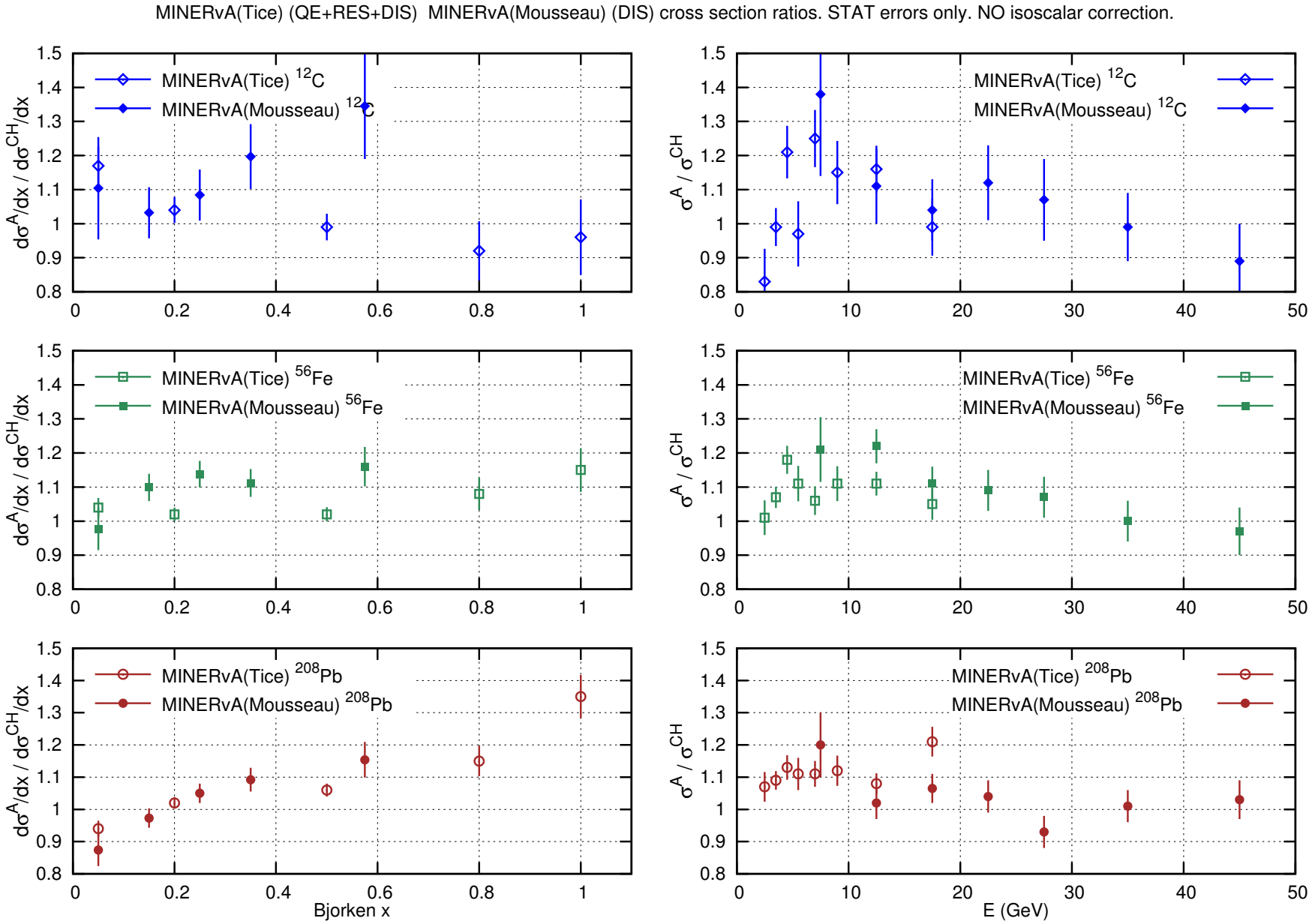


BEBC measurement of nuclear efects with neutrino



- For a long time was the only DIRECT measurement of nuclear effects in $\nu(\bar{\nu})$ DIS from ratio ^{20}Ne/D by *BEBC Coll., ZPC 36 (1987) 337; PLB 232 (1989) 417*. Consistent with nuclear effects measured from e, μ DIS but large uncertainties.
- Differences with respect to e, μ DIS at small x mainly due to the axial-vector current.

New measurement of nuclear effects with ν from MINERvA



Nuclear PDF fits

Nuclear PDFs (nPDF) are phenomenologically extracted from data in a way similar to the proton analyses. Basic steps:

- Assume $f_{i/A}(x, Q^2) = Z f_{i/p}(x, Q^2) + N f_{i/n}(x, Q^2)$ with $f_{i/p}$ and $f_{i/n}$ the *bound* proton and neutron PDF.
- Assume isospin symmetry relations $u_p = d_n$, $d_p = u_n$, $s_p = s_n$.
- Assume a functional form for $f_{i/A}$ or for the ratio $R_i^A = f_{i/A}/(Z f_{i/p}^0 + N f_{i/n}^0)$ where $f_{i/p}^0$ and $f_{i/n}^0$ are *free* proton and neutron PDFs.
- Fit R_i^A to nuclear DIS and DY data by minimizing χ^2.

A few analyses are available which differ by functional form (parameterization) of x and A dependencies.

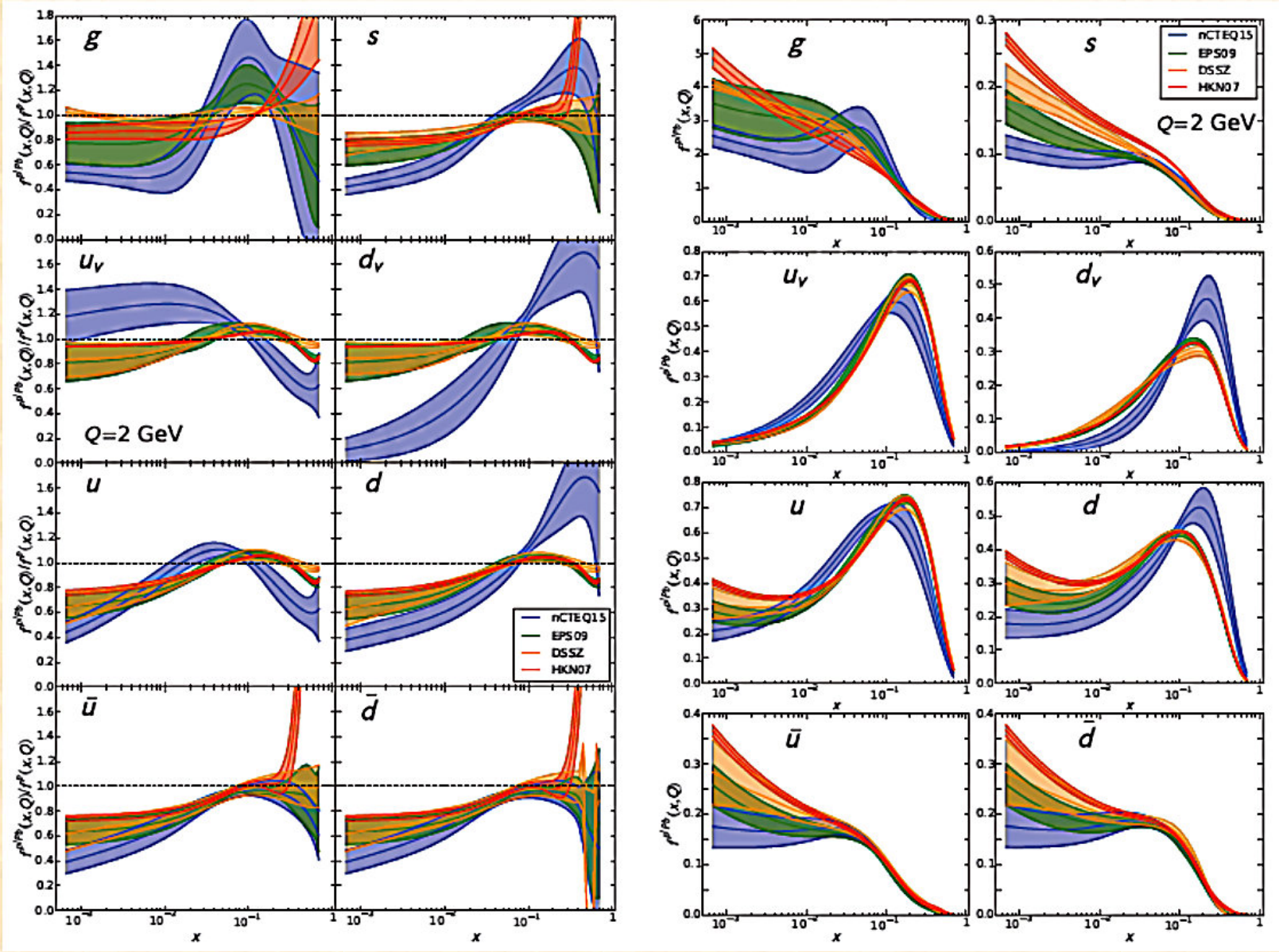
DSZS = de Florian + Sassot + Zurita + Stratmann

EPS = Eskola + Paukkunen + Salgado

HKN = Hirai + Kumano + Nagai

nCTEQ = Kovarik + Kusina + Jezo + . . .

Comparison of different nPDF fit results



Physics mechanisms of nuclear effects in the PDFs

Why nuclear corrections survive at high energy?

In the lab frame it is useful to think of PDFs as scattering amplitudes. Typical DIS space-time regions in the target rest frame as derived from uncertainty principle:

- DIS proceeds near the light cone: $t^2 - z^2 \sim Q^{-2}$ and $r_\perp \sim Q^{-1}$.
- Characteristic DIS time and longitudinal distance $t \sim z \sim L = (Mx)^{-1}$ NOT small in hadronic scale (in the target rest frame) $\Rightarrow$ the reason for nuclear effects to survive even at high Q^2.

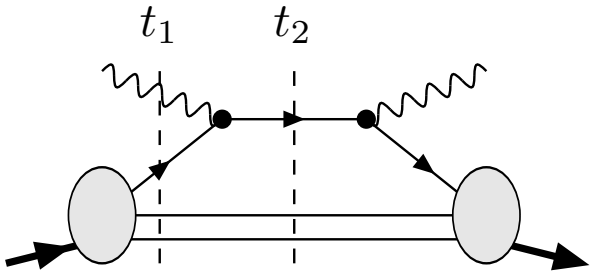
L has to be compared with average distance between bound nucleons r_{NN} $\Rightarrow$ two different kinematical regions:

- $L < r_{\mathsf{NN}}$ (or $x > 0.2$) $\Rightarrow$ Nuclear DIS $\approx$ incoherent sum of contributions from bound nucleons.
- $L \gg r_{\mathsf{NN}}$ (or $x \ll 0.2$) $\Rightarrow$ Coherent effects of interactions with a few nucleons are important.

Understanding the nuclear corrections

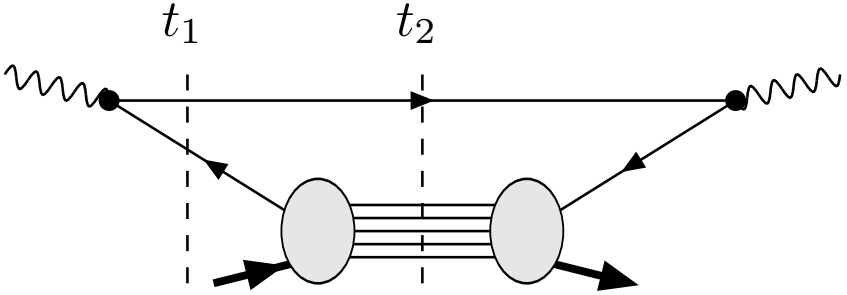
In the lab frame it is useful to think of PDFs as scattering amplitudes.
Two different mechanisms of DIS:

(I) Quasielastic scattering off bound quark. This process dominates at intermediate and large values of x and the structure functions are determined by the quark wave (spectral) functions.



Nuclear effects are due to averaging with nucleon distributions in a nucleus.

(II) Conversion $\gamma^* \to q\bar{q}$ with subsequent propagation of a $q\bar{q}$ state dominates at small x since the life time of a $q\bar{q}$ state grows as $(Mx)^{-1}$. The structure functions are determined by quark scattering amplitudes.



Nuclear effects are due to propagation of $q\bar{q}$ state in nuclear environment.

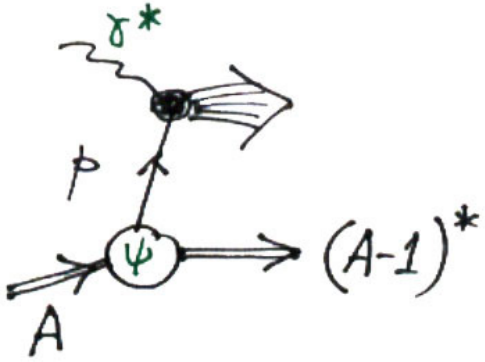
Note that (II) will dominate at small values of Bjorken x while (I) will be relevant at large x.

Incoherent scattering from bound nucleons (Impulse Approximation)

A good starting point is approximation of incoherent scattering off bound protons and neutrons

$$xq^A(x,Q^2) = \int \mathrm{d}^4p\,\mathcal{P}_A(p)\left(1+\frac{p_z}{M}\right)x'q^N(x',Q^2,p^2),$$

$$x = \frac{Q^2}{2Mq_0}, \quad x' = \frac{Q^2}{2p\cdot q} = \frac{M\,x}{p_0+p_z}$$



In this approx the basic corrections are due to the nucleon momentum distribution (Fermi motion) and its energy spectrum. Both effects are driven by nuclear spectral function, which describes probability to find a bound nucleon with momentum $\boldsymbol{p}$ and energy $p_0 = M + \varepsilon$:

$$\mathcal{P}_A(p) = \sum_n |\psi_n(\boldsymbol{p})|^2(2\pi)^4\delta(\varepsilon + E_n(A-1) - E_0(A)).$$

Nuclear spectral function

- The nuclear spectral function describes probability to find a bound nucleon with momentum $\boldsymbol{p}$ and energy $p_0 = M + \varepsilon$:

$$\mathcal{P}(\varepsilon, \boldsymbol{p}) = \int \mathrm{d}t\, e^{-i\varepsilon t} \left\langle \psi^\dagger(\boldsymbol{p}, t)\psi(\boldsymbol{p}, 0)\right\rangle$$

- At low energy and momentum, $|\varepsilon| < 50\,\text{MeV}$, $p < 300\,\text{MeV/c}$, the nuclear spectrum is described by a mean-field model. The spectral function is given in terms of the wave functions and energies of the occupied levels in a selconsistent mean field:

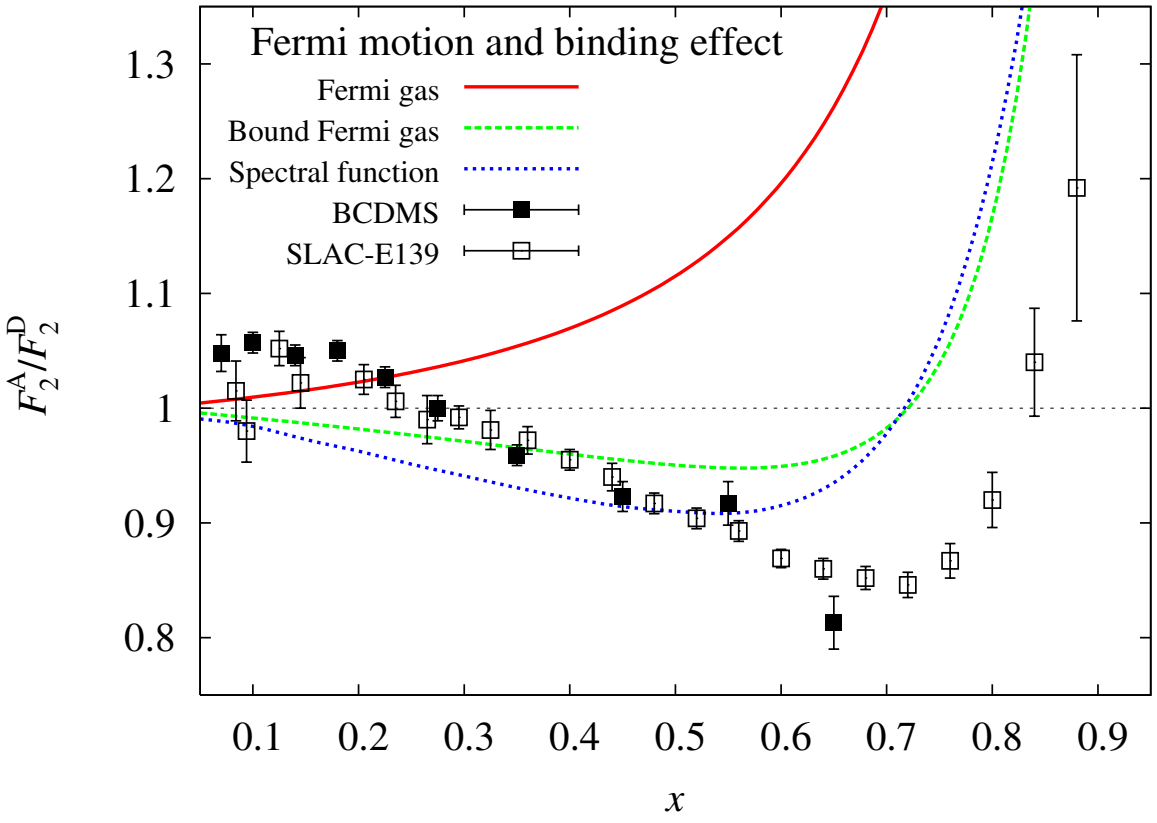
$$\mathcal{P}_{\mathrm{MF}}(\varepsilon, \boldsymbol{p}) = \sum_{\lambda<\lambda_F} n_\lambda |\phi_\lambda(\boldsymbol{p})|^2 \delta(\varepsilon - \varepsilon_\lambda)$$

- At high-energy and momentum $p < 300\,\text{MeV/c}$ the mean field fails. The spectrum is driven by $(A-1)^*$ excited states with one or more nucleons in the continuum, which are due to correlation effects in nuclear ground state as witnessed by numerous studies.

EMC effect in impulse approximation

Impulse approximation: $q(x', Q^2, p^2) = q(x', Q^2)$

- Fermi motion qualitatively describes data at $x > 0.7$
- Binding correction is important and brings the calculation closer to data in the dip region.
- However, even realistic nuclear spectral function fails to explain the slope and the position of the minimum.



Nucleon off-shell effect

Bound nucleons are off-mass-shell $p^2 = (M+\varepsilon)^2 - \boldsymbol{p}^2 < M^2$. In off-shell region the nucleon PDFs depend on additional variable $q(x, Q^2, p^2)$.
The nucleon virtuality parameter $v = (p^2 - M^2)/M^2$ is small (average virtuality $v \sim -0.15$ for ^{56}Fe). Expand $q(x, Q^2, p^2)$ in series in v:

$$q^N(x, Q^2, p^2) = q^N(x, Q^2)\big(1 + \delta f(x, Q^2)(p^2 - M^2)/M^2\big)$$

- $\delta f(x, Q^2)$ is a new structure function that describes modification of the off-shell nucleon PDFs in the vicinity of the mass shell.
- Off-shell correction is closely related to modification of the nucleon PDFs in nuclear environment *S.K. & R.Petti, 2004*. In fact this is another way to describe this effect.

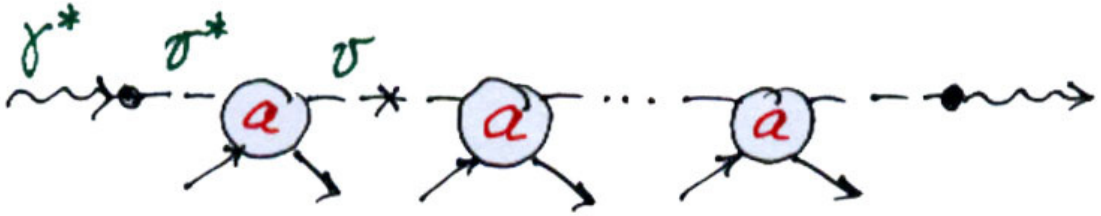
Nuclear meson-exchange current effect (MEC)

Leptons can scatter on nuclear meson field which mediate interaction between bound nucleons. This process generate a MEC correction to nuclear sea quark distribution

$$\delta q_{\mathsf{MEC}}(x, Q^2) = \int_x \frac{\mathrm{d}y}{y} f_{\pi/A}(y) q^{\pi}(\frac{x}{y}, Q^2)$$

- Contribution from nuclear pions (mesons) is important to balance nuclear light-cone momentum $\langle y \rangle_\pi + \langle y \rangle_N = 1$.
- The nuclear pion distribution function is localized in a region $y < p_F/M \sim 0.3$. For this reason the MEC correction to nuclear (anti)quark distributions is localized at $x < 0.3$.
- The magnitude of the correction is driven by average number of "nuclear pion excess" $n_\pi = \int \mathrm{d}y\, f_{\pi/A}(y)$ and $n_\pi/A \sim 0.1$ for a heavy nucleus like 56Fe.

Nuclear shadowing



Coherent nuclear corrections are due to multiple scattering series which can be described in the Glauber-Gribov approach.

$$\delta\mathcal{R} = \frac{\delta q^{\text{coh}}}{q^N} \approx \frac{\delta\sigma^{\text{coh}}}{\sigma} = \mathrm{Im}\left[ia^2\mathcal{C}_2^A(a)\right] / \mathrm{Im}\, a,$$

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

where $\rho_A(\boldsymbol{r})$ is the nuclear number density and $a = \sigma(i+\alpha)/2$ is a scattering amplitude in forward direction, $k_L = Mx(1+m_v^2/Q^2)$ is longitudinal momentum transfer in the process $v^* \to v$ which accounts for the life time of intermediate $q\bar{q}$ (hadronic) state. The presence of k_L suppresses nuclear mult. scat. effect as x increases.

Modelling the nuclear PDFs

S.K. & R.Petti, NPA765 (2006) 126; PRD76(2007)094023; PRC82(2010)054614; PRC90(2014)045204

$$q_{i/A} = \langle q_{i/p} \rangle + \langle q_{i/n} \rangle + \delta_{\mathsf{MEC}} q_i + \delta_{\mathsf{coh}} q_i$$

Input:

- Free proton and neutron PDFs from analysis by *S.Alekhin*. Phenomenological higher-twist terms and target mass correction (to compute proton and neutron structure functions).
- Realistic nuclear spectral function which includes the mean-field contribution as well as the correlated part, which is responsible for high-momentum component.
- Various contributions to nuclear PDFs are correlated by normalizations and DIS sum rules.

Analysis of nuclear ratios (EMC effect)

Strategy: Parameterize unknown off-shell function $\delta f(x)$ and effective scattering amplitude a_T. Calculate nuclear structure functions, test with data and extract parameters from data.

- We study the data from e/μ DIS in the form of ratios $R_2(A/B) = F_2^A/F_2^B$ for a variaty of targets. The data are available for $A/^2H$ and $A/^{12}C$ ratios.
- We perform a fit to minimize $\chi^2 = \sum_{\text{data}}(\mathcal{R}_2^{exp} - \mathcal{R}_2^{th})^2/\sigma^2(\mathcal{R}_2^{exp})$ with σ the experimental uncertainty of $\mathcal{R}_2^{exp}$. We use data with $Q^2 > 1$ GeV^2. The nuclear ratios used in our analysis (overall about 560 points available before 1996):

^{4}He/D	^{7}Li/D	^{9}Be/D
^{12}C/D	^{27}Al/D	^{27}Al/^{12}C
^{40}Ca/D	^{40}Ca/^{12}C	
^{56}Fe/D	^{63}Cu/D	^{56}Fe/^{12}C
^{108}Ag/D	^{119}Sn/^{12}C	
^{197}Au/D	^{207}Pb/D	^{207}Pb/^{12}C

- Verify the model by comparing the calculations with data not used in analysis.

Parameters of the model

- Off-shell structure function $\delta f_2(x) = C_N(x - x_1)(x - x_0)(h - x)$
  - From preliminary studies we observe that h is fully correlated with x_0, i.e. $h = 1 + x_0$.
  - C_N, x_0, x_1 are independent ajustable parameters.
- Effective amplitude

$$\bar{a}_T = \bar{\sigma}_T(i + \alpha)/2, \quad \bar{\sigma}_T = \sigma_1 + \frac{\sigma_0 - \sigma_1}{1 + Q^2/Q_0^2}$$

  - Parameters $\sigma_0 = 27\,\text{mb}$ and $\alpha = -0.2$ were fixed in order to match the vector meson dominance model predictions at low Q.
  - Parameter $\sigma_1 = 0$ fixed (preferred by preliminary fits and fixed in the final studies).
  - Q_0^2 is adjustable scale parameter controlling transition between low and high Q regimes.

Results

- The x, Q^2 and A dependencies of the nuclear ratios are reproduced for all studied nuclei (^{4}He to ^{208}Pb) in a 4-parameter fit with $\chi^2/\text{d.o.f.} = 459/556$.
- Global fit to all data is consistent with the fits to different subsets of nuclei (light, medium, heavy nuclei).
- Parameters of the off-shell function δf and effective amplitude a_T are determined with a good accuracy.

For detailed discussion and comparison with data see *S.K. & R. Petti, Nucl.Phys. A765(2006)126*.

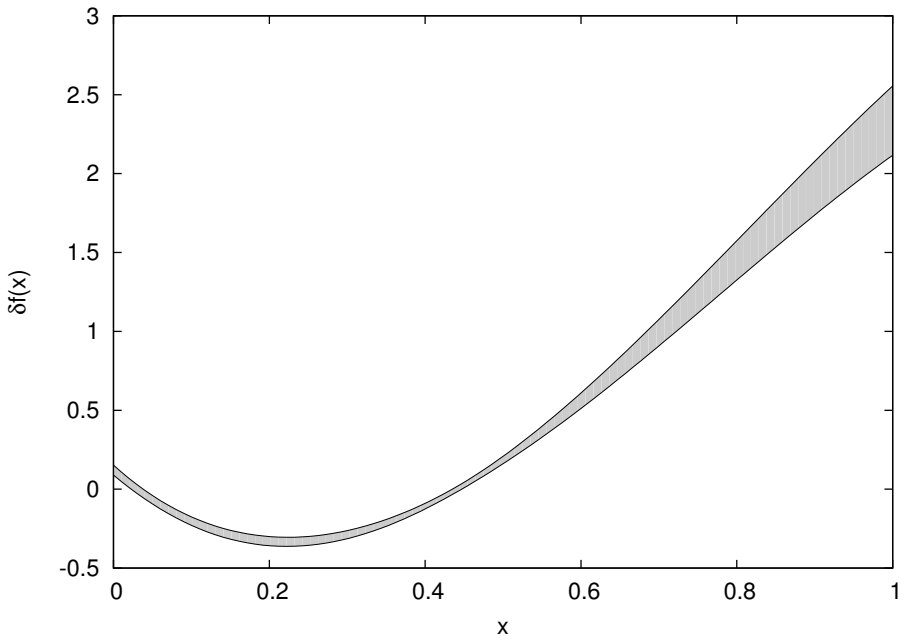
Off-shell function δf

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

$$C_N = 8.1 \pm 0.3 \pm 0.5$$

$$x_0 = 0.448 \pm 0.005 \pm 0.007$$

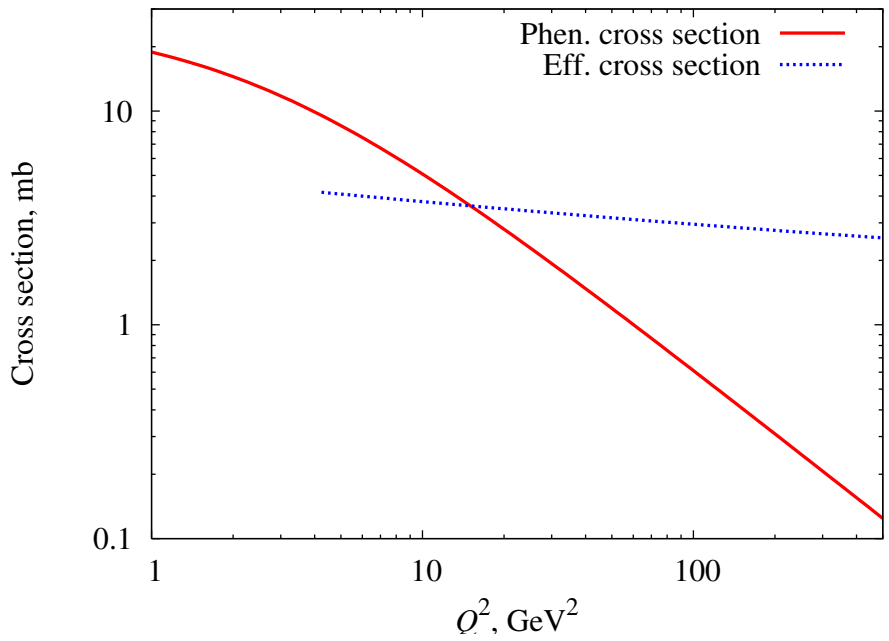
$$x_1 = 0.05$$



- The function $\delta f(x)$ provides a measure of the modification of the quark distributions in a bound nucleon.
- The slope of $\delta f(x)$ in a single-scale nucleon model is related to $\mathrm{d}\log\Lambda/\mathrm{d}\log p^2$. The observed slope suggests an increase in the bound nucleon radius in Iron by about 10% and in the deuteron by about 2%.

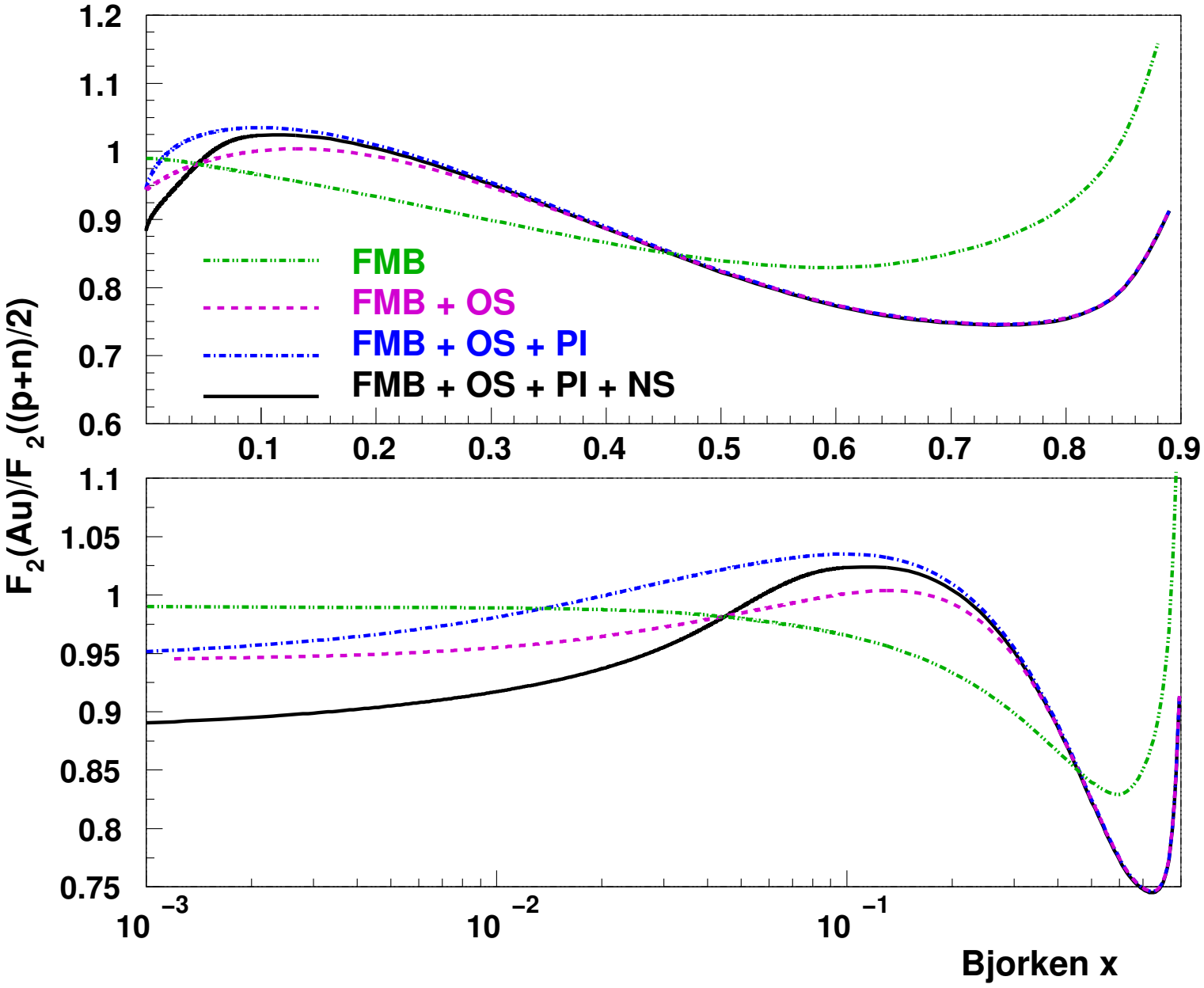
Effective cross section

- The monopole form $\sigma_T = \sigma_0/(1+Q^2/Q_0^2)$ with $\sigma_0 = 27$ mb and $Q_0^2 = 1.43 \pm 0.06 \pm 0.195$ GeV^2 provides a good fit to existing DIS data on nuclear shadowing for $Q^2 < 20$ GeV^2.
- The cross section at high Q^2 is not constrained by data. However, it is possible to evaluate using the results on the off-shell function and normalization condition.



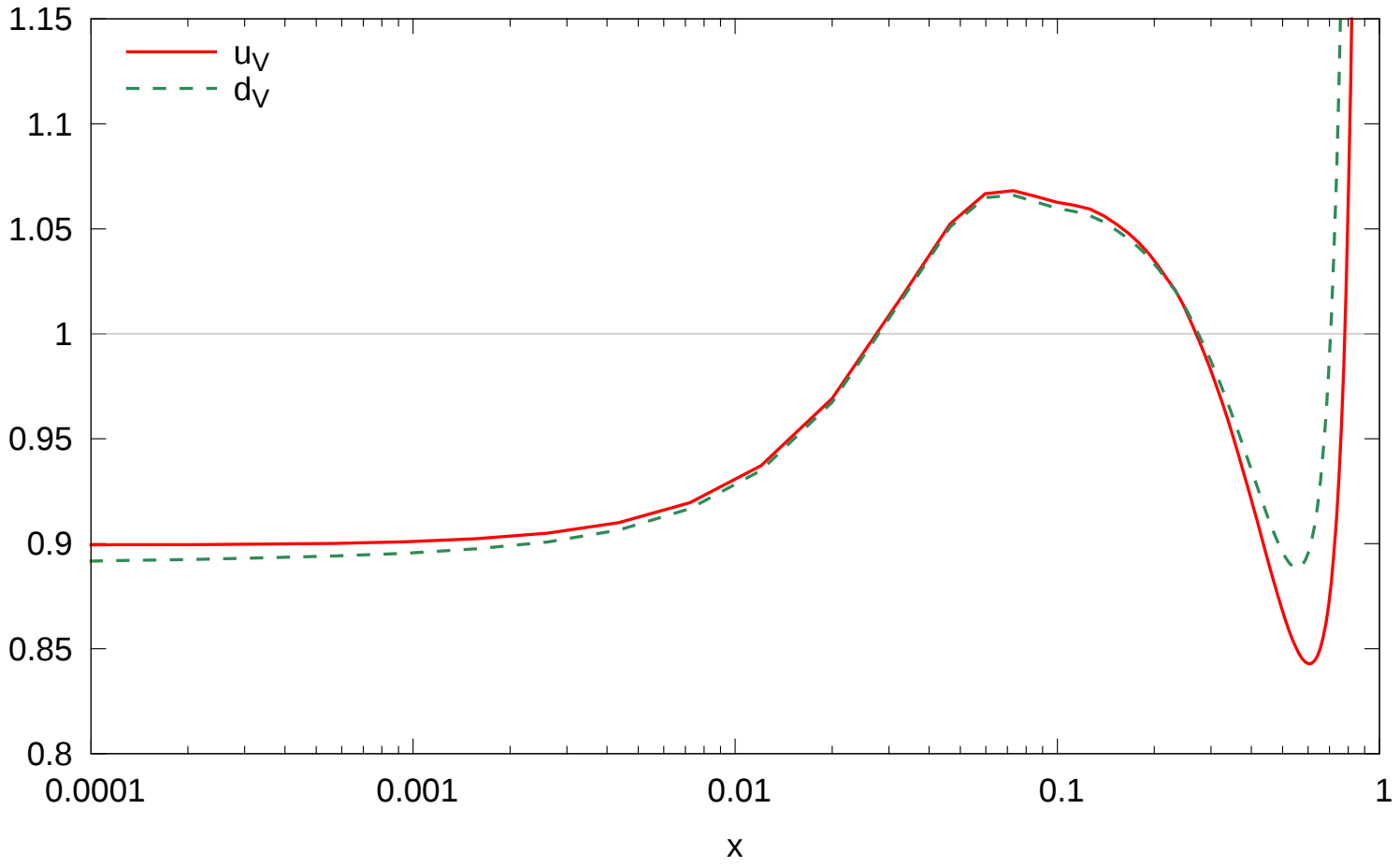
We require exact cancellation between off-shell (OS) and shadowing (NS) contributions to normalization: $\delta N_{\rm val}^{\rm OS} + \delta N_{\rm val}^{\rm NS} = 0$. Numeric solution to this equation is shown by blue curve.

Different nuclear effects for $^{197}\mathrm{Au}$ at $Q^2 = 10\,\mathrm{GeV}^2$



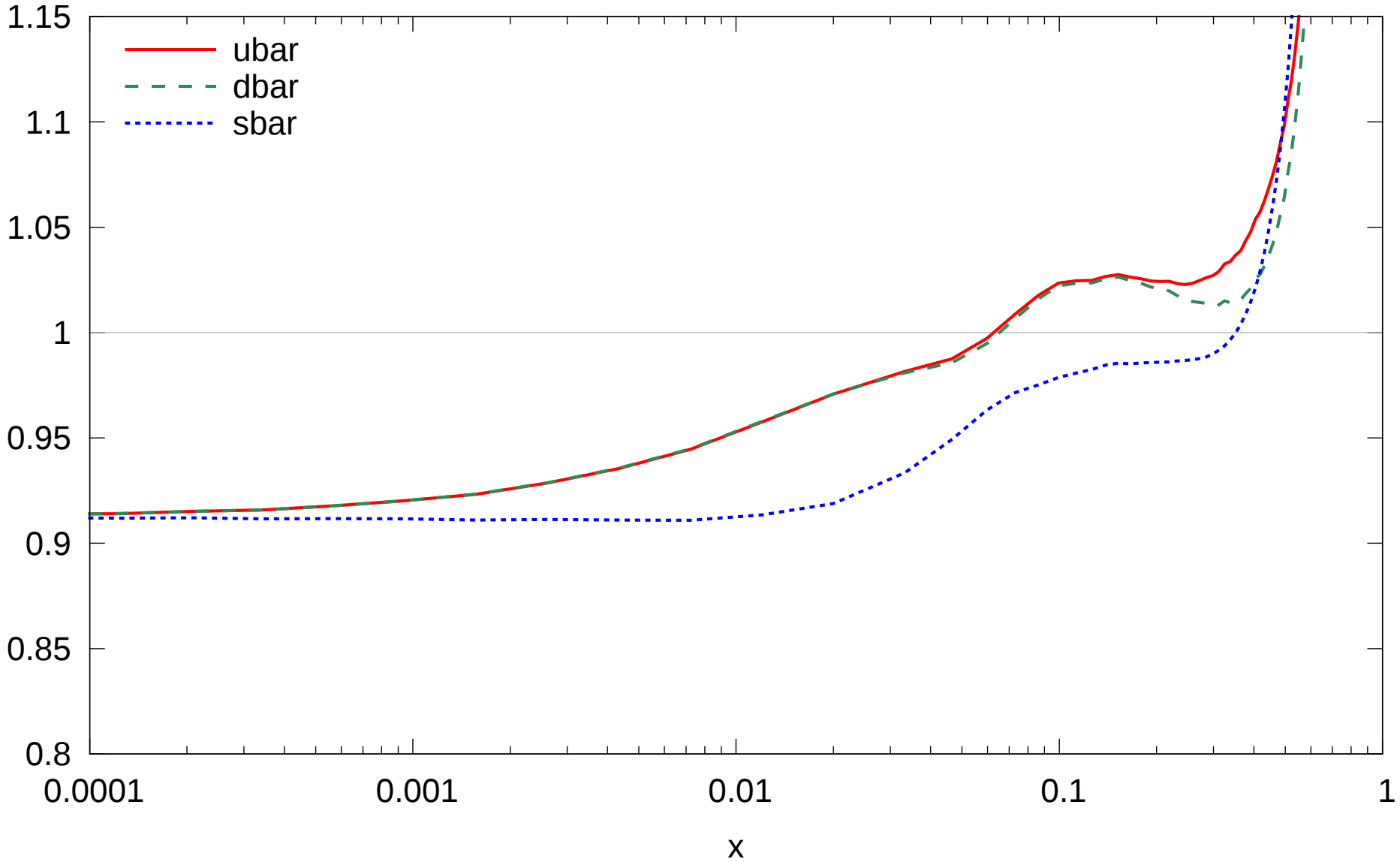
Results for nuclear valence quarks

Ratio $q_{\text{val}/A}/(Zq_{\text{val}/p} + Nq_{\text{val}/n})$ calculated for ^{208}Pb at $Q^2 = 25$ GeV^2



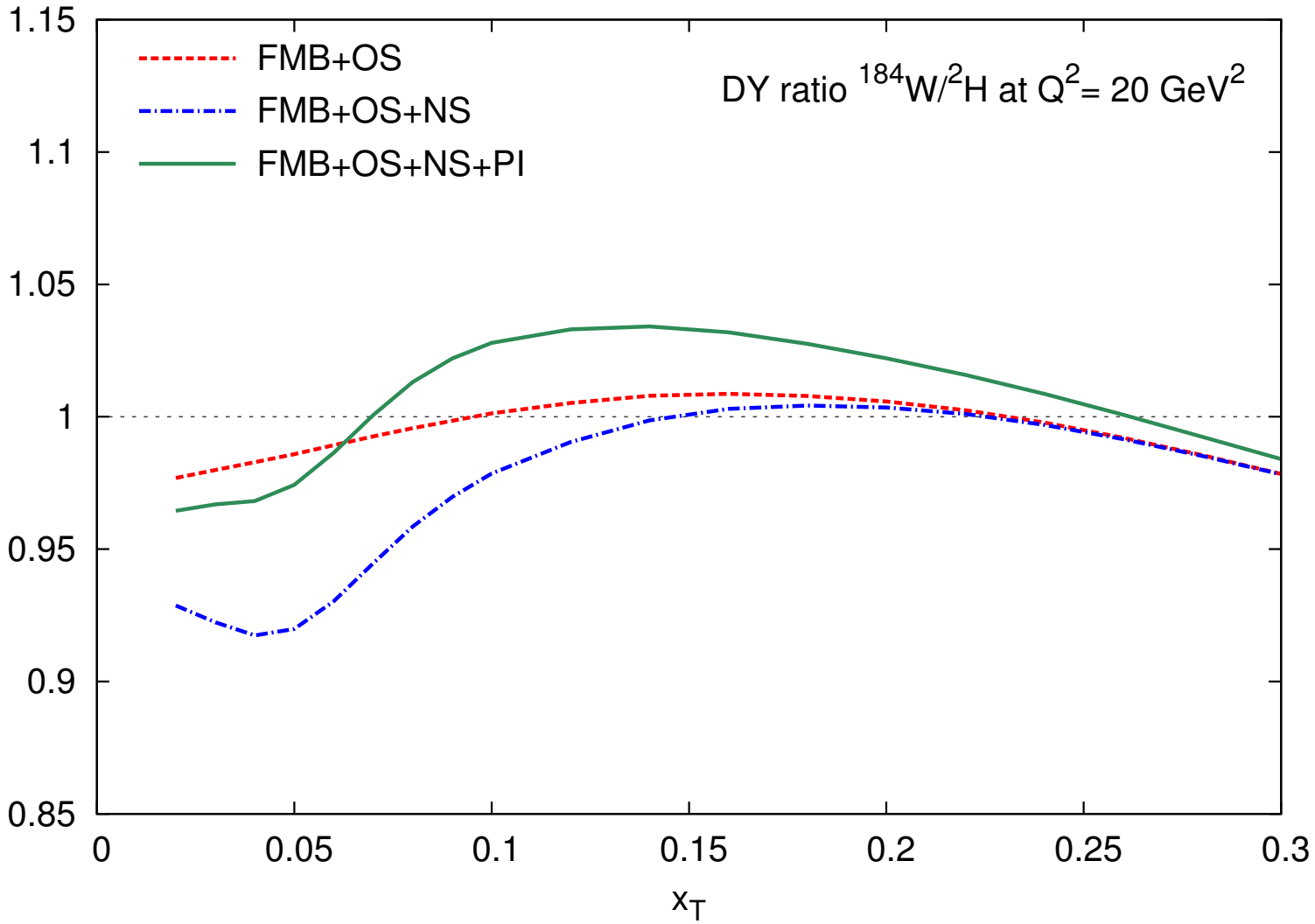
Results for nuclear antiquarks

Ratio $\bar{q}_A/(Z\bar{q}_p + N\bar{q}_n)$ calculated for ^{208}Pb at $Q^2 = 25$ GeV^2

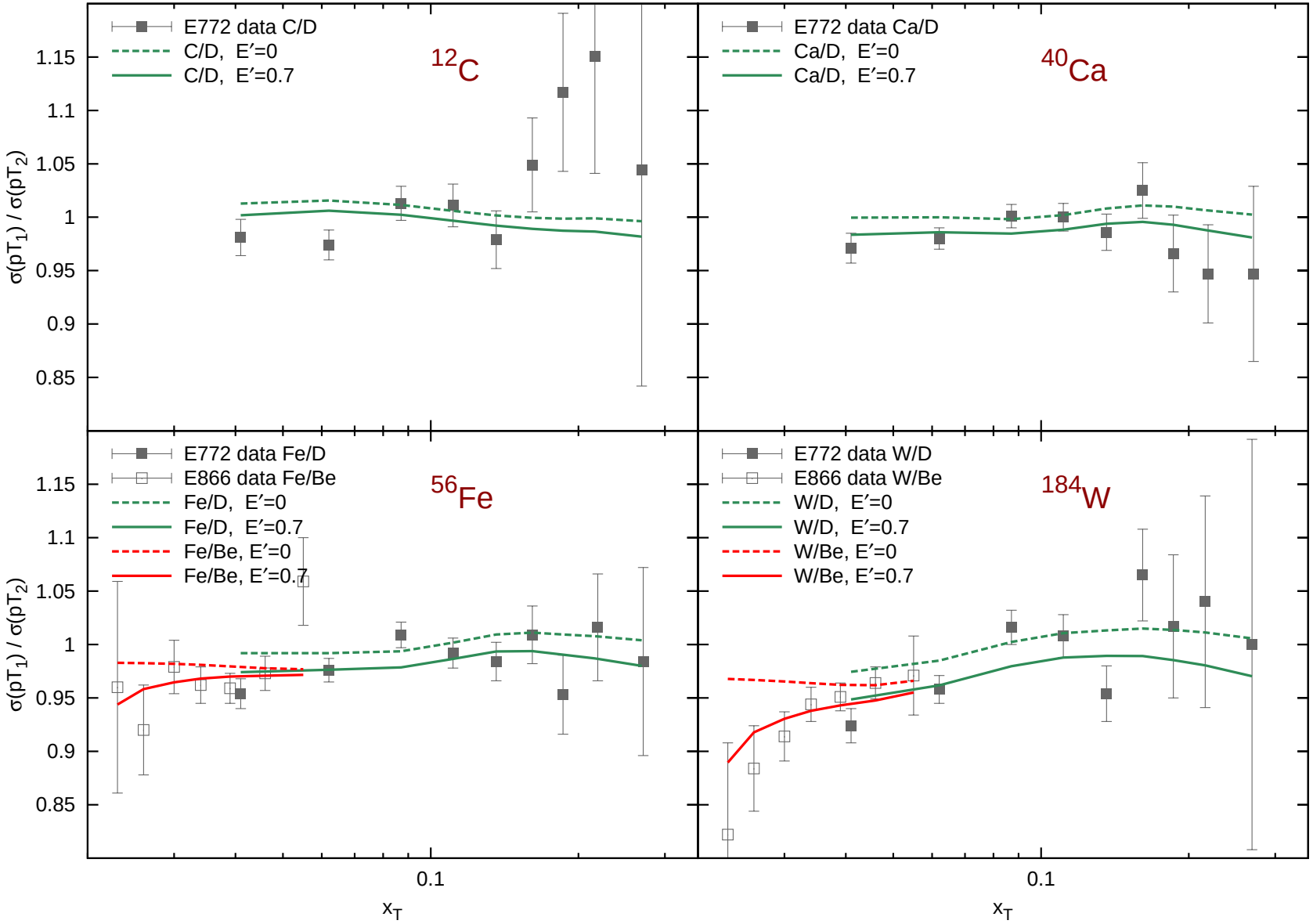


Nuclear corrections for Drell-Yan production cross sections

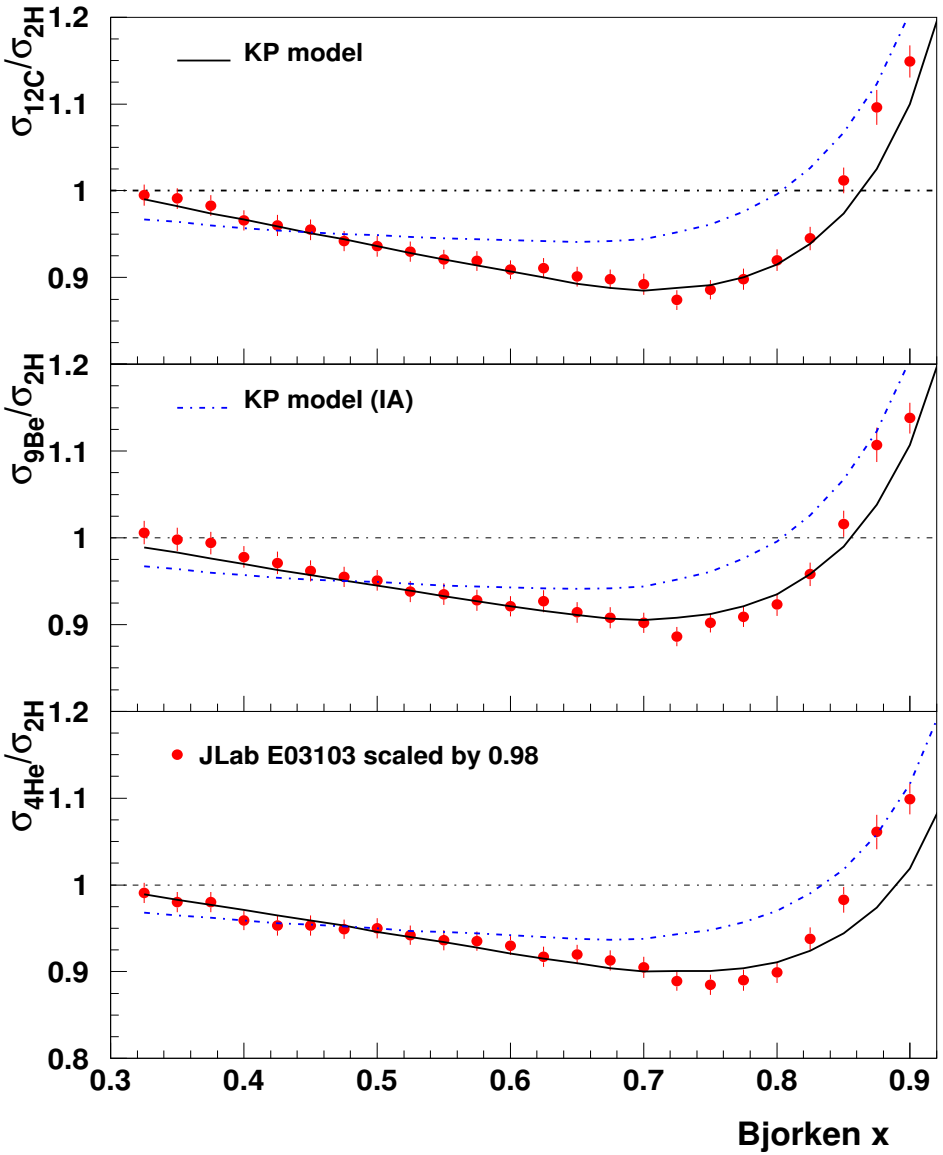
DY process cross section $\propto \sum e_q^2 \left[q^B(x_B)\bar{q}^T(x_T) + \bar{q}^B(x_B)q^T(x_T)\right]$. The kinematic variables are related as $Q^2 = sx_Bx_T$. For E772 kinematics $s \approx 1600$ GeV^2.



Comparison with E772 and E866 experiments

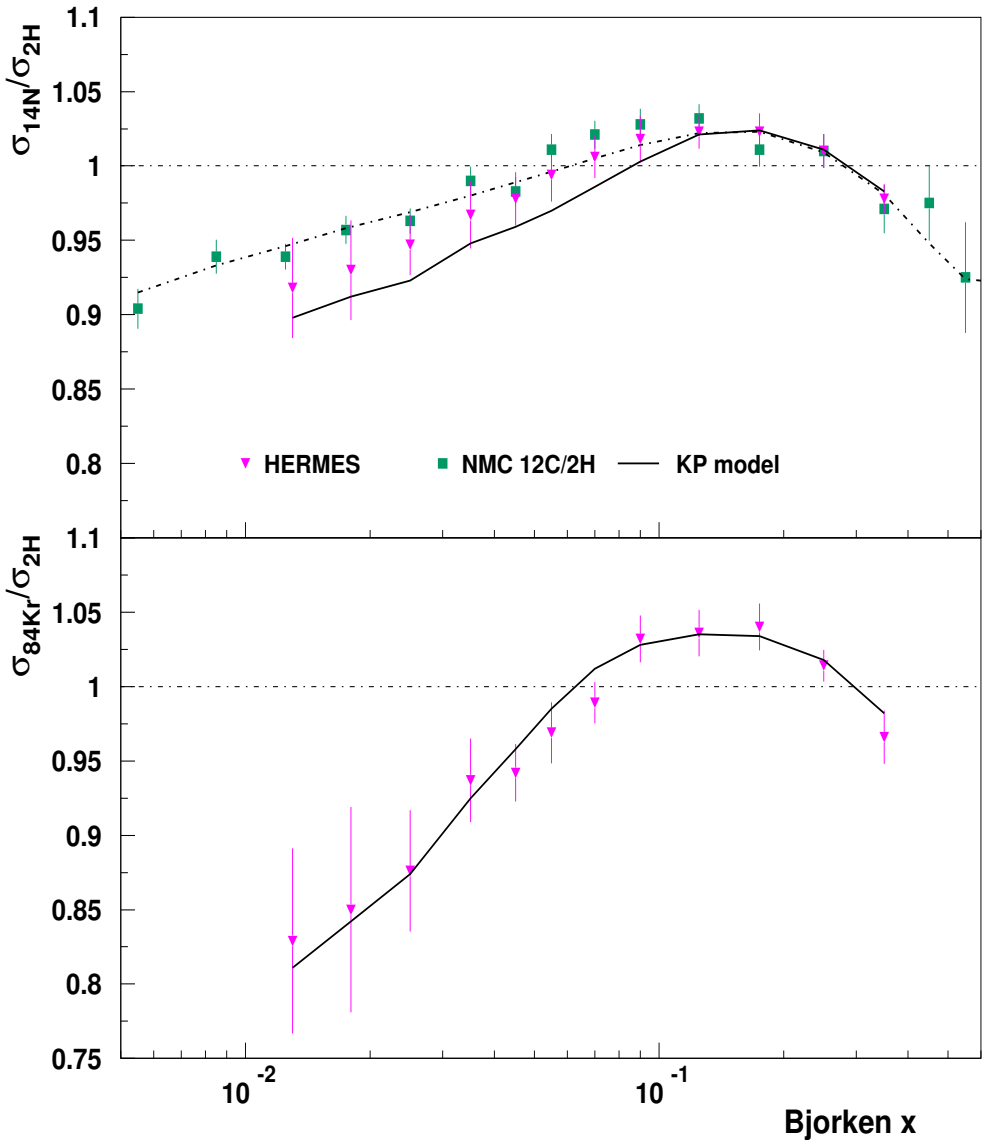


Comparison with E03-103 (not a fit) *S.K. & R.Petti, 2010*



- Very good agreement of our predictions with JLab E03-103 for all nuclear targets: $\chi^2/d.o.f. = 26.3/60$ for $W^2 > 2$ GeV^2
- Nuclear corrections at large x is driven by nuclear spectral function, the off-shell function $\delta f(x)$ was fixed from previous studies.
- A comparison with the Impulse Approximation (shown in blue) demonstrates that the off-shell correction is crucial to describe the data leading to both modification of the slope and position of the minimum of the EMC ratios.

Comparison with HERMES (not a fit) *S.K. & R.Petti, 2010*



- A good agreement of our predictions with HERMES data for $^{14}\mathrm{N/D}$ and $^{84}\mathrm{Kr/D}$ with $\chi^2/d.o.f. = 14.7/24$
- A comparison with NMC data for $^{12}\mathrm{C/D}$ shows a significant Q^2 dependence at small x in the shadowing region related to the cross-section for scattering of hadronic states off the bound nucleons nucleons.

  The model correctly describes the observed x and Q^2 dependence.

Summary

- A detailed semi-microscopic model of nuclear PDFs was developed which includes the QCD treatment of nucleon structure function and addresses a number of nuclear effects such as shadowing, Fermi motion and nuclear binding, nuclear pion and off-shell corrections to bound nucleon structure functions
- A quantitative study of existing data from charged lepton-nucleus DIS has been performed in a wide kinematic region of x and Q^2.
- Note the importance of the nuclear binding along with the off-shell corrections to the bound nucleon structure function. The off-shell correction was extracted from data and responsible for a large fraction of nuclear effects at intermediate and large Bjorken x.
- The nuclear effects are not universal and differ for the valence and the sea-quark distributions.
- Good agreement of our predictions with the DIS data from JLab and HERMES experiments. Good agreement with the Drell-Yan data from E772 and E866 experiments. Here we note a cancellation between different nuclear effects.