Status of nuclear parton distributions

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1. Fixed-target experiment constrains on nuclear parton distributions

2. Comparison of QCD fits and models

3. Leading twist model: HT effects in nuclear DIS data

4. Conclusions

Nuclear parton distributions from fixed-target experiments

- NMC (CERN)

  NP B 441 (1995) 3 and 12; NP B 481 (1996) 3 and 23

  Inclusive DIS on nuclei. Most accurate and high statistics. Measures F_2^A/F_2^D for He, Li, Be, C, Al, Ca, Fe, Sn, Pb for 0.0035 $< x <$ 0.65 and 0.7 $< Q^2 <$ 40 GeV^2 and $10^{-4} < x <$ 0.7 and 0.01 $< Q^2 <$ 70 GeV^2 in 1995; 0.01 $< x <$ 0.8 and 2$< Q^2 <$ 70 GeV^2 in 1996.

  Note that $Q^2 > 1$ GeV^2 corresponds to $x > 5 \times 10^{-3}$.

- E665 (Fermilab)

  PRL 68 (1992) 3266, Z. Phys. C 67 (1995) 403

  Inclusive DIS on nuclei. Less accurate, systematically above NMC data. Measures F_2^A/F_2^D for C, Ca, Xe, Pb for $2 \times 10^{-5}< x <$0.2 and 0.03$< Q^2 <$18 GeV^2 and $10^{-4}< x <$0.56 and 0.1$< Q^2 <$80 GeV^2.

  Same at NMC, $Q^2 > 1$ GeV^2 corresponds to $x > 5 \times 10^{-3}$.

- E772 and E866/NuSea (Fermilab)

  PRL 64 (1990) 2479, PRL 83 (1999) 2304

  Measures DY ratio in $pA \to \mu^+ \mu^- X$ (nuclear Drell-Yan) for C, Ca, Fe and W for 0.04$< x <$0.269 and $16 < Q^2 < 35$ GeV^2.

- NMC (CERN), NP B 481 (1996) 23
  From Q^2-dependence of F_2^{Sn}/F_2^C for $0.01 < x < 0.75$ and $1 < Q^2 < 140$ GeV^2, Gousset and Pirner PL B 375 (1996) 349 extracted g^{Sn}/g^C.

- NMC (CERN), NP B 371 (1992) 553
  Measures $\mu\, A \to \mu\, J/\Psi\, X$ for C and Sn. Result interpreted as $g^{Sn}/g^C = 1.13 \pm 0.08$ for $0.05 < x < 0.15$.

- E772 (Fermilab), PRL 66 (1991) 133
  Measures $p\, A \to J/\Psi\, X$ for D, C, Ca, Fe and W. Observes depletion of nuclear to nucleon yields for $0.01 < x < 0.04$.

- CCFRC and NuTeV (Fermilab)
  PL B 79 (1997) 1213; PRL 88 (2002) 091802
  Measures F_2 and xF_3 in neutrino-Fe DIS.

Constraints on nuclear parton distributions

- Inclusive DIS measurement of F_2^A (NMC, E665) determines mostly $q + \bar{q}$ nuclear parton distributions (nPDFs).

  Moreover, for fixed-target kinematics, the perturbative QCD requirement that $Q^2 > 1$ GeV^2 corresponds to $x > 5 \times 10^{-3}$ $\rightarrow$ small-x region (nuclear shadowing) is barely probed.

- Nuclear Drell-Yan (Fermilab) determines $\bar{q}$ nPDF for $x > 0.04$ and $Q^2 > 16$ GeV^2. Again, limited kinematics.

- The gluon distribution is studied indirectly via scaling violations of F_2^A or via J/Ψ muon or hadroproduction. Since the coverage in $x - Q^2$ is poor, the gluon nPDF is rather uncertain.

- The EIC will cover much wider kinematics: $Q^2 > 1$ GeV^2 will correspond to $x > 5 \times 10^{-5}$. Staying the perturbative domain, one will

  - probe much deeper in nuclear shadowing
  - determine gluon nPDFs from scaling violations more reliably
  - Measurement of other observables, such F_L^A, will probe gluon nPDFs directly

Limited experimental info allows for large uncertainties in nPDFs, especially at low x. This is reflected in large variety of models, which are all consistent with data but give rather different predictions at low x.

Three classes of models nPDFs:

- QCD fits to data
- models based on Gribov theorem connecting diffraction and shadowing; vector meson dominance motivated; dipole models
- colored glass condensate

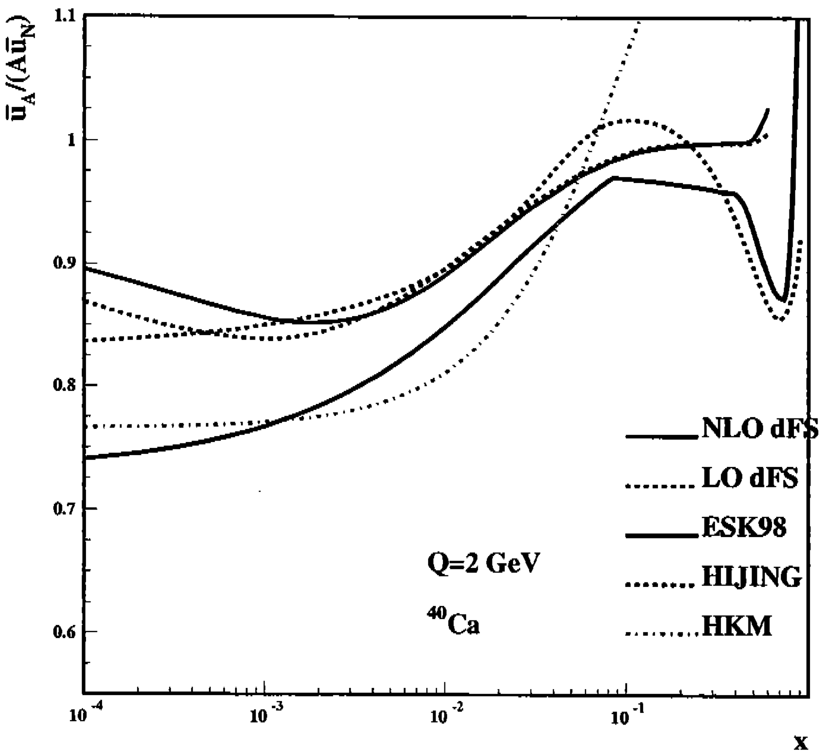
QCD fits to data

- Eskola, Kolhinen, Ruuskanen, Honkanen, Salgado NP B 535 (1998) 351, Eur. Phys. J C 9 (1999) 61, PL B 532 (2002) 222
  - The most comprehensive LO analysis
  - Assumes $R_G^A(x, Q_0^2) = R_{F_2}^A(x, Q_0^2)$ at small x
  - Assumes saturation of shadowing at small x

- Hirai, Kumano, Miyama, PRD 64 (2001) 034003
  - Ignores nuclear Drell-Yan data (constraints on $\bar{q}$ nPDF) and NMC scaling violation data (constraints on gluon nPDF)

- Li and Wang, PL B 527 (2002) 85
  - Rather arbitrary parameterization (momentum sum rule?) aimed to improve description of hadron production at RHIC
  - Comparison is made to NMC F_2^A data

- de Florian and Sassot hep-ph/0311227
  - The only NLO comprehensive analysis


$\bar{u}_A/(A\bar{u}_N)$
1.1
1
0.9
0.8
0.7
0.6
NLO dFS
LO dFS
ESK98
HIJING
HKM
Q=2 GeV
^{40}Ca
10^{-4}
10^{-3}
10^{-2}
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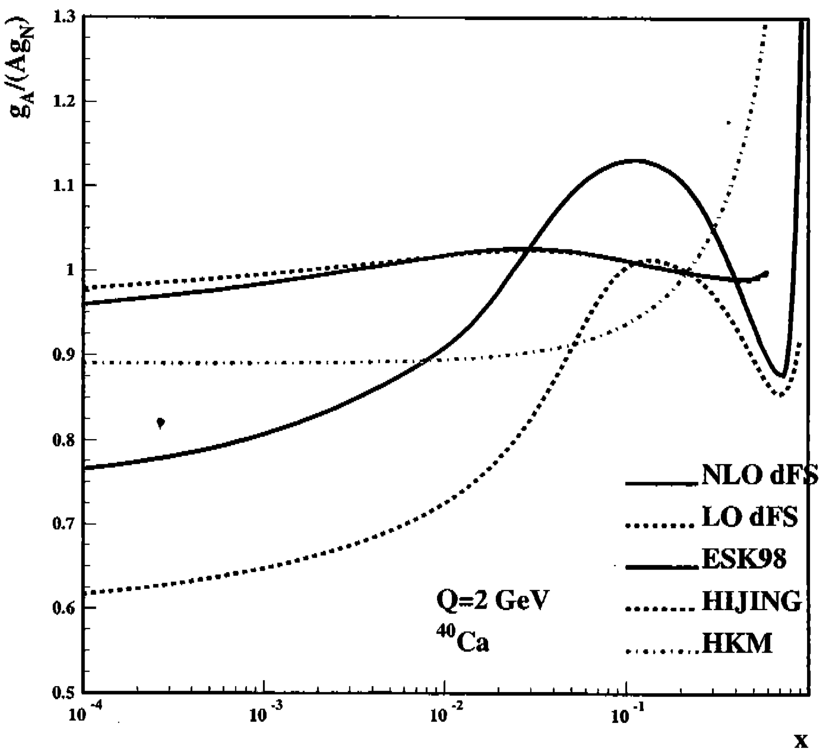
x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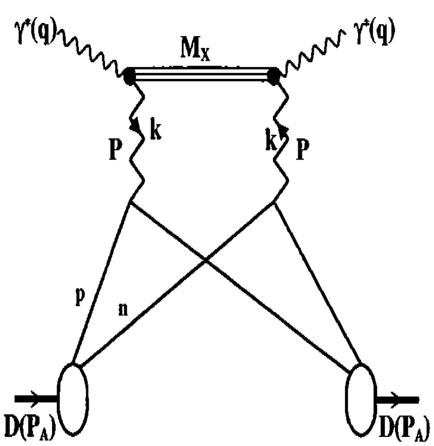
Models based on connection between shadowing and diffraction

- In high-energy hadron-deuteron scattering, Gribov showed that shadowing correction to total hD cross section is given in terms of hadron-nucleon diffraction, V.N. Gribov, Sov. Phys. JETP 29 (1959) 483

$$\sigma_{\rm tot}^{hD} = 2\sigma_{\rm tot}^{hN} - 2\int dk^2 \rho(4k^2) \frac{d\sigma_{\rm diff}^{hN}}{dk^2}$$

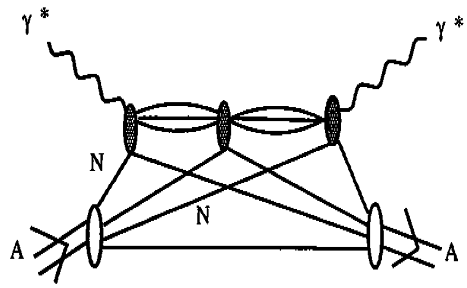
$\vec{k}$ is momentum transfer to the nucleon; ρ is the deuteron charge form factor.

- Same logic can be applied to DIS on deuterium, Frankfurt, Strikman, Eur. J. A 5 (1999) 293



$$\delta F_2^D = 2\frac{1-\eta^2}{1+\eta^2}\int dk_t^2 dx_{I\!P} F_2^{D(4)}(\beta, Q^2, x_{I\!P}, t)\rho(4k_t^2 + 4x_{I\!P}^2 m_N^2)$$

- Application to any nucleus other than D is model-dependent: need to model multiple interactions

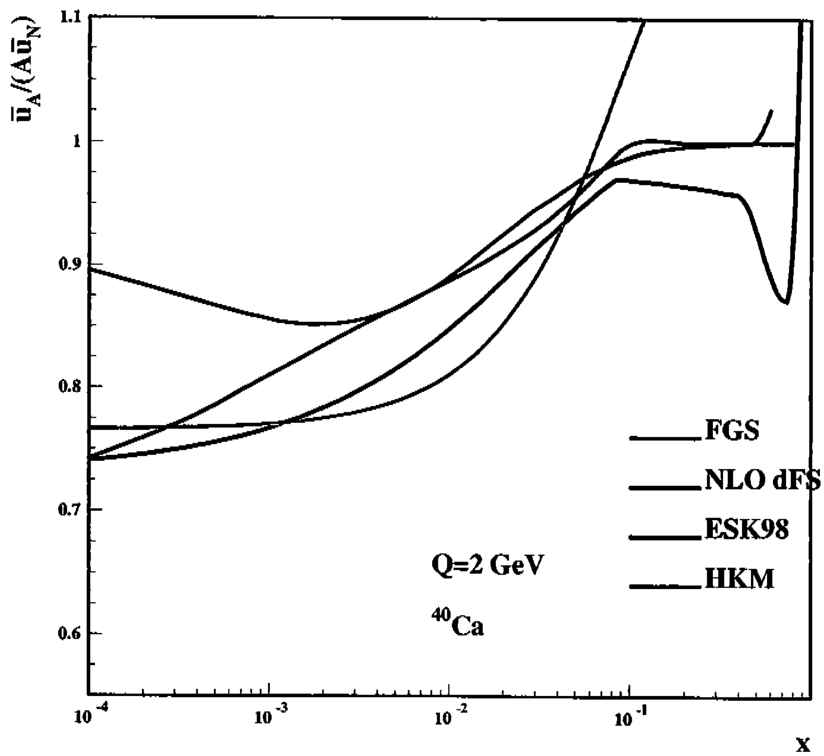


- Leading twist model, Frankfurt, Guzey, Strikman, hep-ph/0303022; +McDermott, JHEP 202 (2002) 27
  - Use QCD factorization theorem for hard diffraction → work in terms of nPDFs and proton diffractive parton distributions
  - Model multiple scattering using quasi-eikonal approximation
  - Model antishadowing to conserve baryon number and momentum sum rules
  - Use only as **input for QCD evolution** of $f_{j/A}$ → leading twist nuclear shadowing

$$\delta f_{j/A}(x,Q_0^2) = \frac{A(A-1)}{2} 16\pi Re\Bigg[\frac{(1-i\eta)^2}{1+\eta^2}\int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \times$$
$$\int_x^{x_{I\!P,0}} dx_{I\!P} f_{j/N}^D(\beta,Q_0^2,x_{I\!P},0)\,\rho_A(b,z_1)\,\rho_A(b,z_2) e^{ix_{I\!P} m_N (z_1-z_2)} \times$$
$$e^{-(A/2)(1-i\eta)\sigma_{eff}^j \int_{z_1}^{z_2} dz \rho_A(z)}\Bigg]$$

- Cappella, Kaidalov, Armesto, Salgado, Eur. Phys. J. C 5 (1998) 111; hep-ph/0304119
  - Do not use factorization theorem, maybe for gluons
  - Apply the final formula at all Q^2. Note that this limits applicability to $Q^2 < 10$ GeV^2
  - Contain both LT and HT contributions
  - Do not enforce momentum sum rule
  - Gluons are shadowed **less** than F_2, in contrast with leading twist model

- Two-component models, Melnitchouk and Thomas, PR D (1993) 3783; hep-ex/0208016
  - Contain both vector meson (HT) and Pomeron exchange (LT) contributions
  - Use old diffractive data → hard to compare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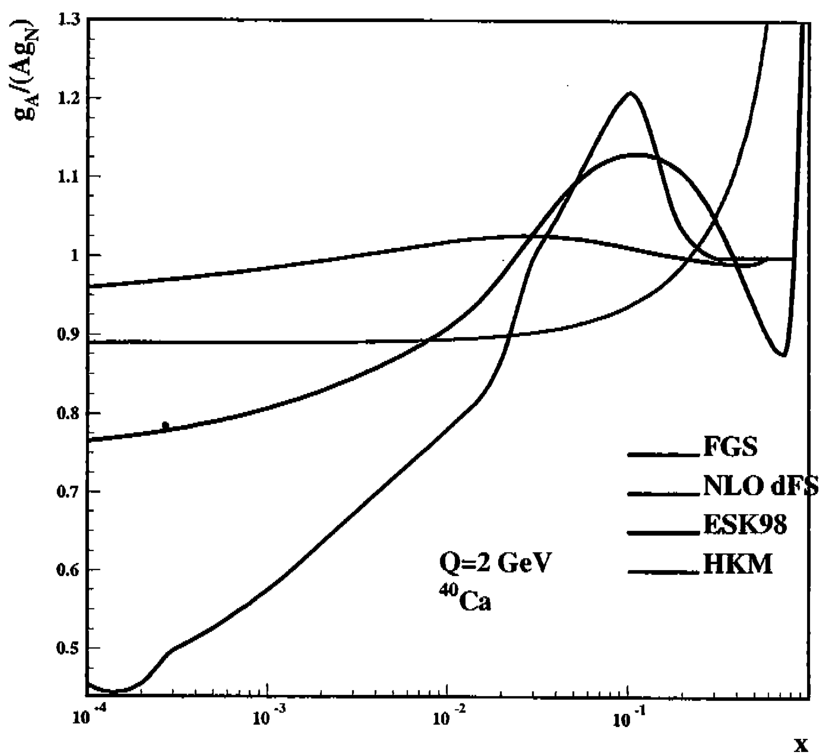
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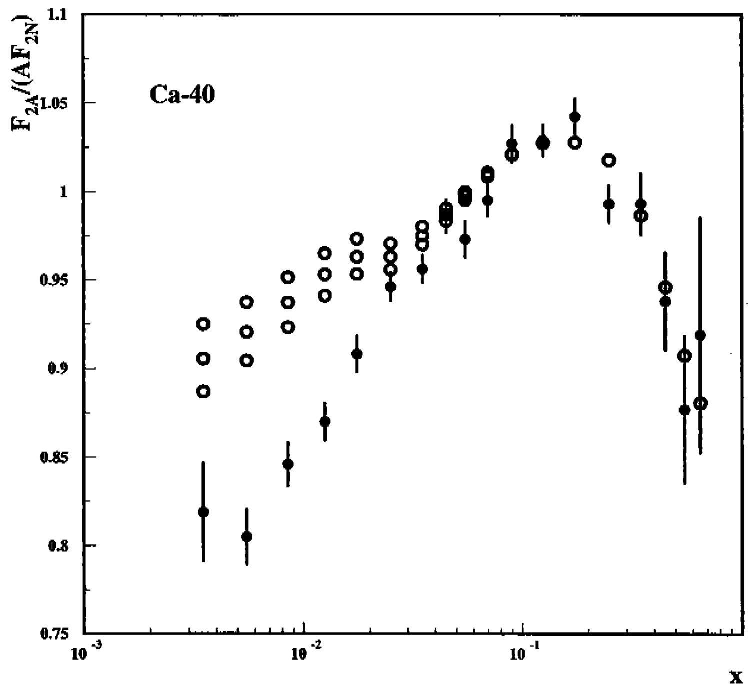
LT model comparison to NMC data on F_2^A for ^{40}Ca



- LT model (open circles) vs. NMC data at x and Q^2 of the data. For 5 left points, $Q^2 = Q_0^2 = 4$ GeV^2.

- LT model clearly underestimates data at low x. Our explanation: low x-data with small Q^2 contain significant higher twist effects which are absent in our LT approach.

- Important implication for QCD fit models: it is dangerous (incorrect) to use low-x data in fits. Low-x behavior of nPDFs is not known as good as one might think.

Conclusions

- Low-x ($x < 5 \times 10^{-3}$) nuclear parton distributions, especially gluons, are not constrained well enough by fixed-target data (insufficient $x - Q^2$ coverage, HT effects) $\rightarrow$ need eA collider

- As a result, different approaches give rather distinct predictions, especially at low x.

- LT model predicts significant leading twist nuclear shadowing. Moreover, gluons are shadowed more than quarks $\rightarrow$ in contrast with most other models.

- Inability to describe low-x NMC data on F_2 is interpreted as presence of HT effects in data $\rightarrow$ QCD fit methods maybe unreliable there $\rightarrow$ nPDFs are not known as good as one might imagine.

- Nuclear shadowing and saturation – discussed in context of EIC – at small x are related. Quantitative analysis of saturation requires gluon distribution in nuclei at small x.