Nuclear effects in high energy lepton-nucleus scattering

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Outline

- Introduction: Deep Inelastic Scattering and microscopic structure of hadrons

- Deep Inelastic Scattering with nuclear targets

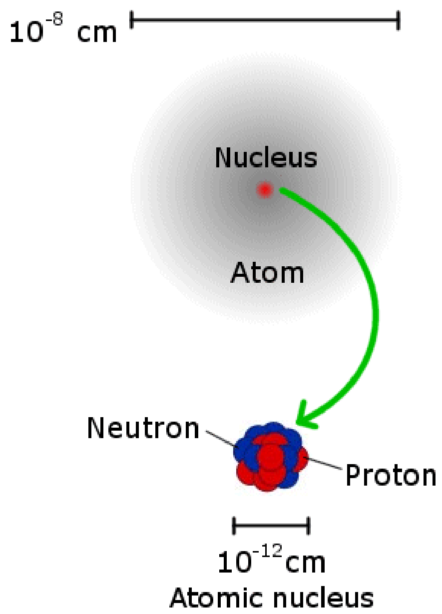
  – EMC effect (lecture 1)
  – nuclear shadowing (lecture 2)

- Summary

Introduction: Strong Interaction

Protons and neutrons (nucleons) are basic building blocks of atomic nuclei.

The *strong interaction* between protons and neutrons determines the properties of atomic nuclei, which form all the variety of Matter around us.

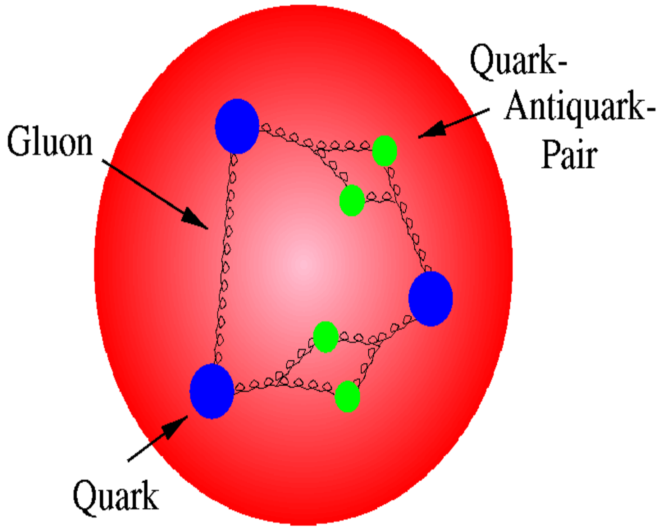


The strong interaction also governs nuclear reactions, such as those which shaped the early Universe, fuel suns and take place in nuclear reactors.

Introduction: QCD

The modern theory of the strong interactions is Quantum Chromodynamics (QCD), a quantum field theory whose fundamental d.o.f. are *quarks* and *gluons*.

It is a key objective of nuclear physics to understand the structure of the nucleon and nuclei in terms of quarks and gluons.



Nucleon in QCD

Introduction: Electron scattering

One of the most powerful tools in unraveling the hadron structure is high-energy electron scattering.

Historically, such experiments provided two crucial insights.

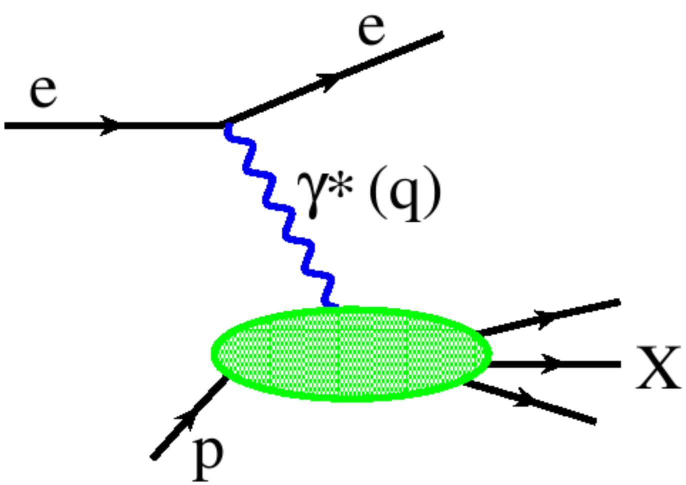
1) Elastic electron scattering established the extended nature of the proton, proton size ~ 10^{-13} cm.

R. Hofstadter, Nobel Prize 1961

2) Deep-Inelastic scattering (DIS) discovered the existence of quasi-free point-like objects (quarks) inside the nucleon, which eventually paved the way to establish QCD.

Friedman, Kendall, Taylor, Nobel Prize 1990
Gross, Politzer, Wilczek, Nobel Prize 2004

Deep Inelastic Scattering (DIS)



$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{4\pi\alpha_{\mathrm{em}}^2}{xQ^4}\left[(1-y)F_2(x,Q^2) + y^2 x\,F_1(x,Q^2)\right]$$

Unpolarized structure functions

$$\left.\begin{array}{l} \left.\begin{array}{l} q^2 = -Q^2 \\ W^2 = (p+q)^2 \end{array}\right\} \text{large} \\ x_B = \dfrac{Q^2}{2p\cdot q} \qquad \text{fixed} \end{array}\right\}$$

Bjorken limit

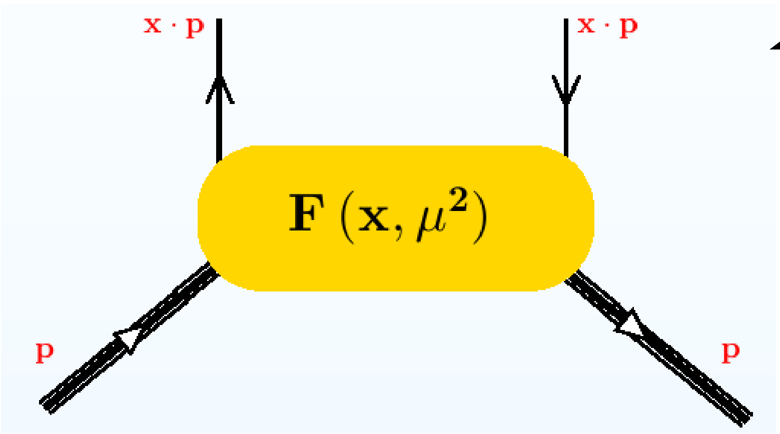
Parton distributions

In the Bjorken limit, $\alpha_S(Q^2)$ is small (asymptotic freedom) and one can use the perturbation theory to prove the *factorization theorem*:

$$F_2(x,Q^2) = \sum_{i=q,\bar{q},g} \int_0^1 \frac{dz}{z} C^i\left(\frac{x}{z}, \frac{Q^2}{\mu^2}\right) \phi_i(z,\mu^2)$$

Perturbative coefficient function

Non-perturbative parton distribution functions (PDFs) defined via matrix elements of parton operators between nucleon states with equal momenta



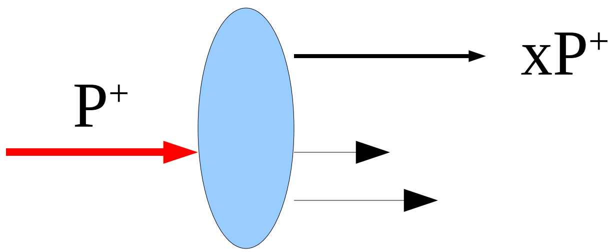
p -- nucleon momentum

x -- longit. momentum fraction

μ^2 -- factorization scale

Parton distributions: Interpretation

Interpretation in the infinite momentum frame:



Parton distributions are probabilities to find a parton with the light-cone fraction x of the nucleon P^+ momentum.

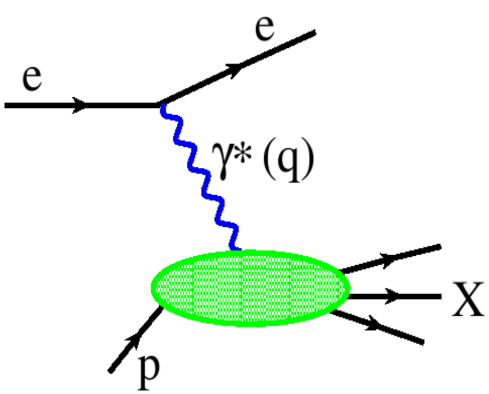
Fast moving nucleon with $P^+=E+p_z$

Q^2 is the resolution of the "microscope"

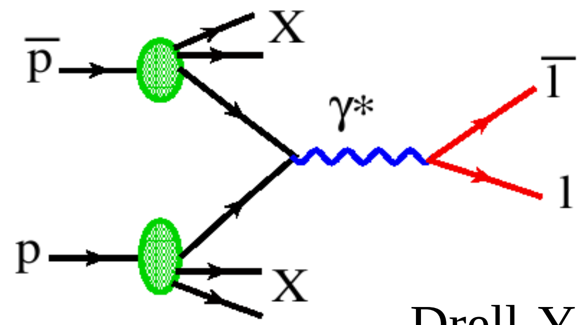
Information about the transverse position of the parton is integrated out.

Factorization

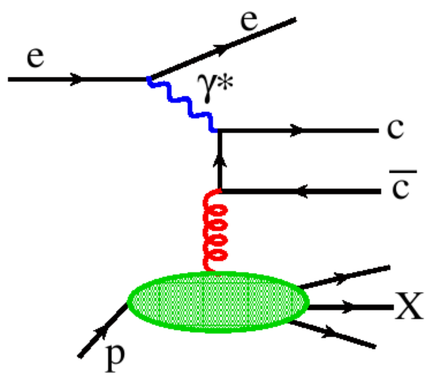
The power of the *factorization theorem* is that the same quark and gluon PDFs can be accessed in different processes as long as there is large scale, which guarantees validity of factorization.



Inclusive DIS



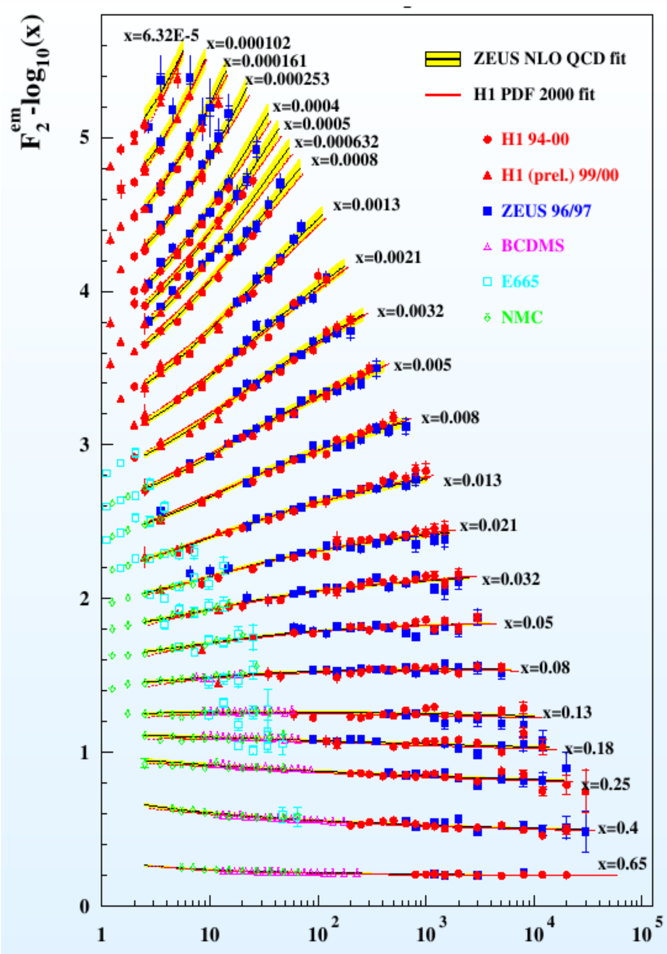
Drell-Yan process

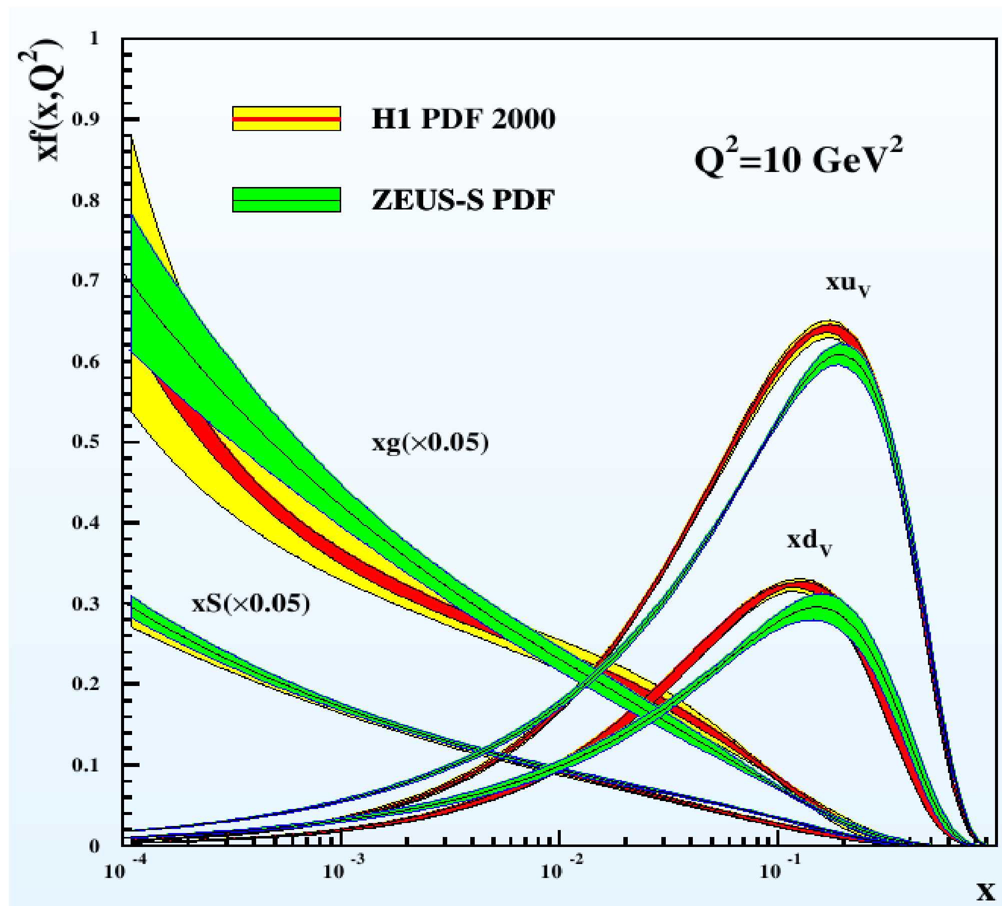


Inclusive charm production, sensitive to gluons

PDFs from DIS

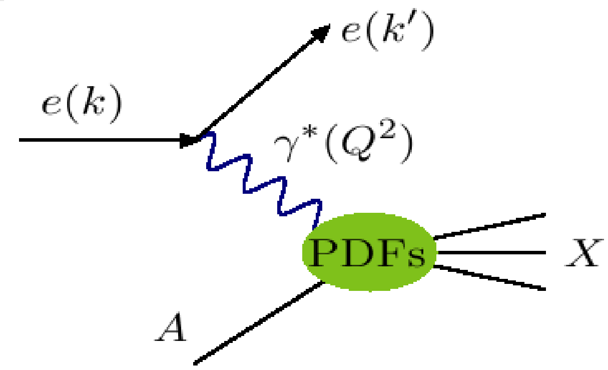
A huge amount of data on DIS off nucleons and nuclei have been collected and analyzed in terms of PDFs:





DIS with nuclear targets

Inclusive DIS with nuclear targets measures nuclear structure function $F_{2A}(x,Q^2)$



Ratio of nuclear to deuteron structure functions

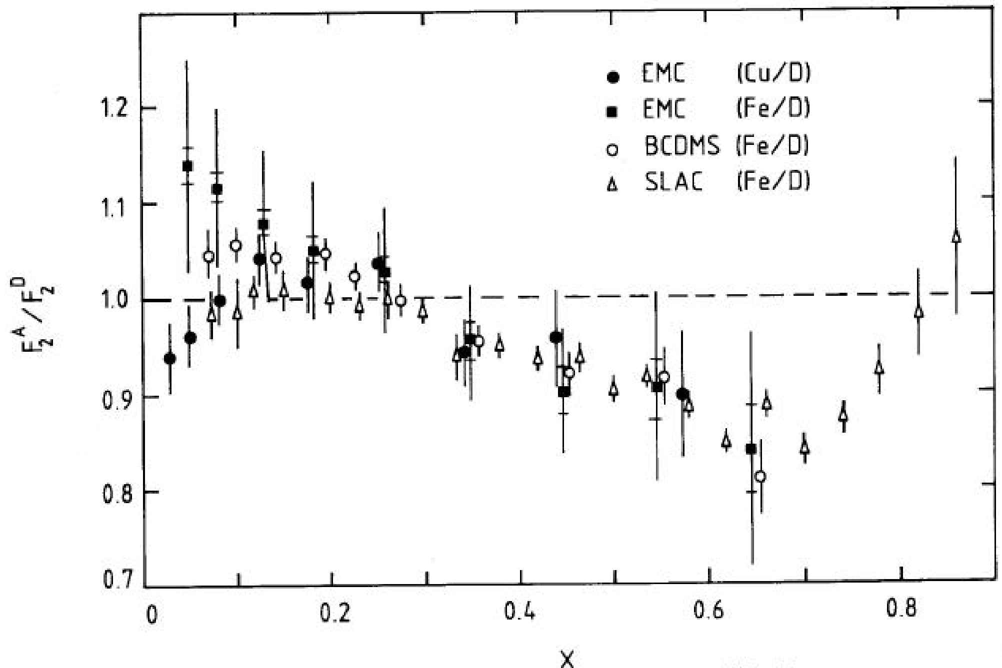
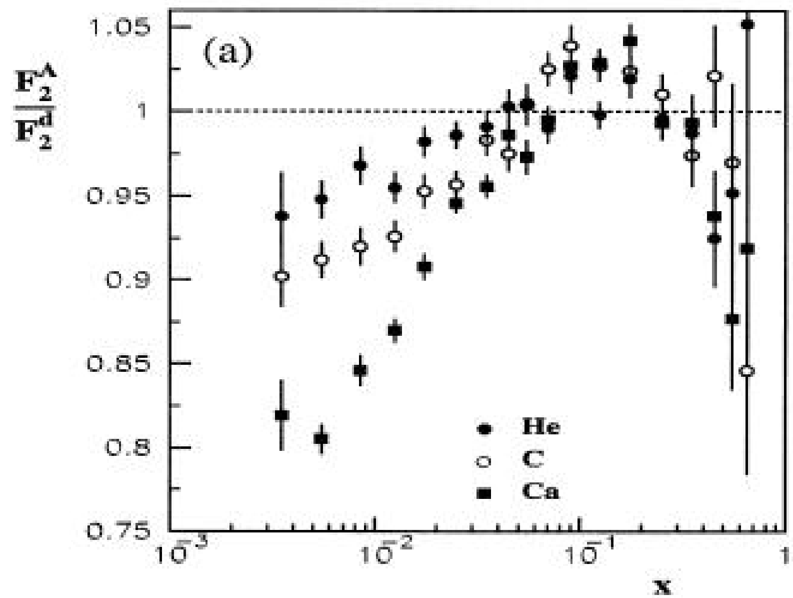


FIG. 3



shadowing EMC shadowing EMC

Nuclear parton distributions

Using factorization theorem and QCD evolution equations, one can determine nuclear PDFs from data on nuclear $F_{2A}(x,Q^2)$

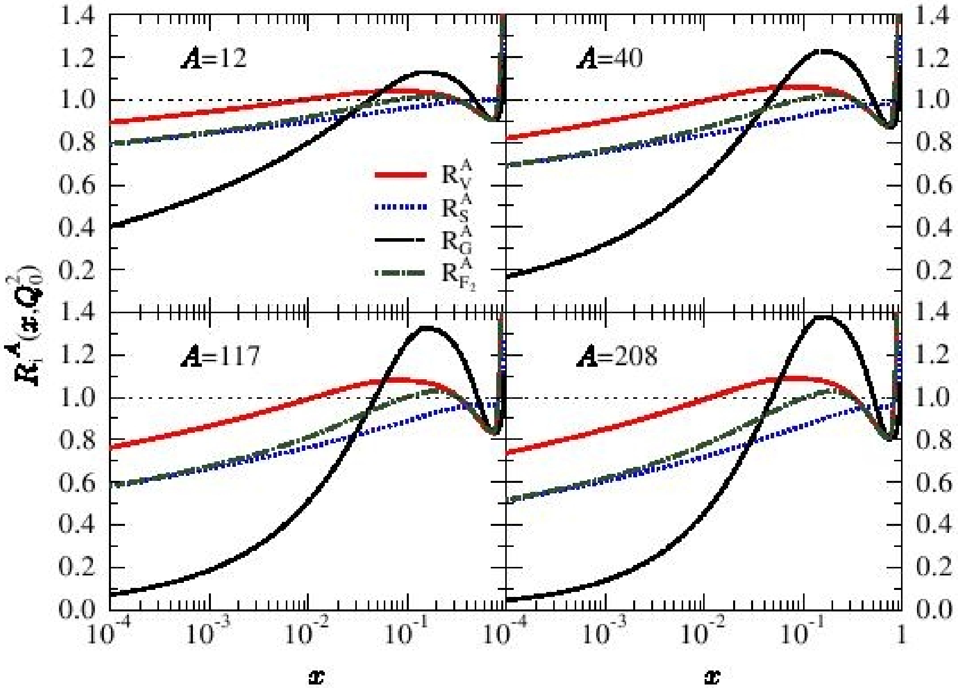


Figure 2: The nuclear modification factors R_V^A, R_S^A and R_G^A for C, Ca, Sn, and Pb at $Q_0^2 = 1.69\,\mathrm{GeV}^2$. The DIS ratio $R_{F_2}^A$ is shown for comparison.

Eskola et al. '08

EMC effect: discovery

The EMC effect: $F_{2A}(x,Q^2)<AF_{2N}(x,Q^2)$ for $0.7 > x > 0.2$

European Muon Collaboration (EMC), CERN
J.J. Aubert et al. Phys. Lett. B123, 275 (1983)

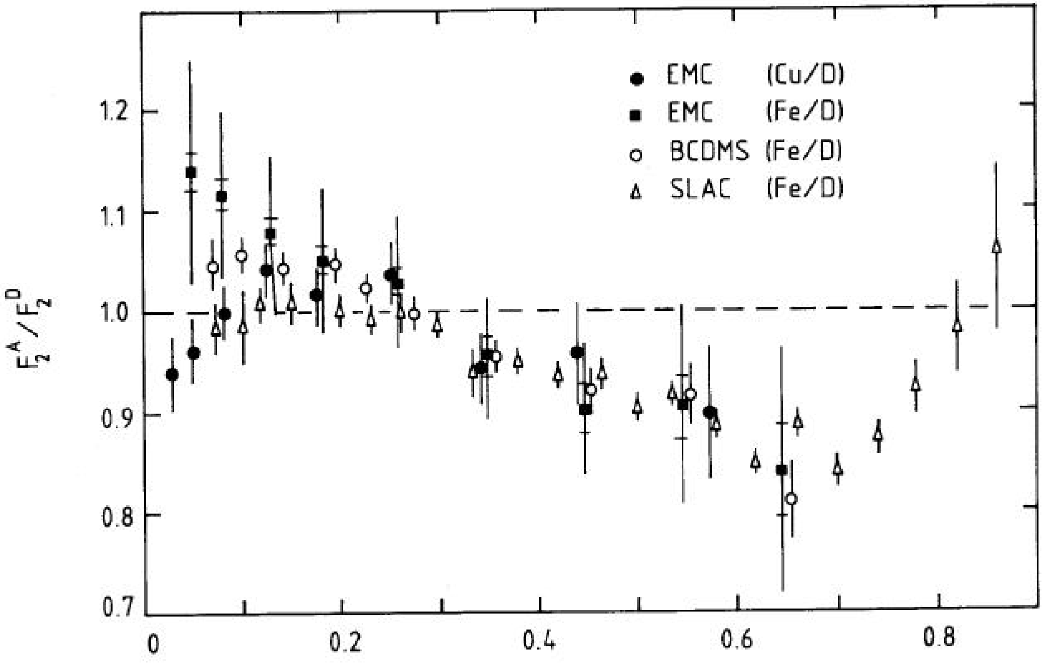
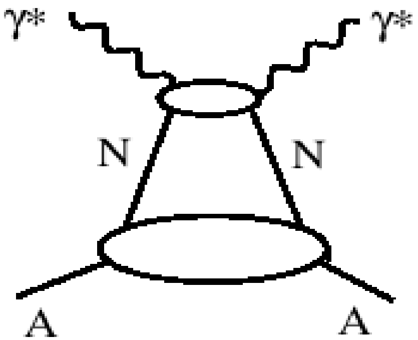


FIG. 3

Naive expectation: $F_{2A}(x,Q^2)\approx AF_{2N}(x,Q^2)$ since $Q^2 \gg$ nuclear scales

EMC effect: Interpretation

The EMC effect *cannot* be explained by assuming that the nucleus consists of unmodified nucleons



$$\frac{1}{A}F_{2A}(x) = \int_x^A dy f_N(y) F_{2N}^*\left(\frac{x}{y}\right)$$

$y = A\frac{k^+}{p_A^+}$ is the light-cone fraction of the nucleus carried by the nucleon

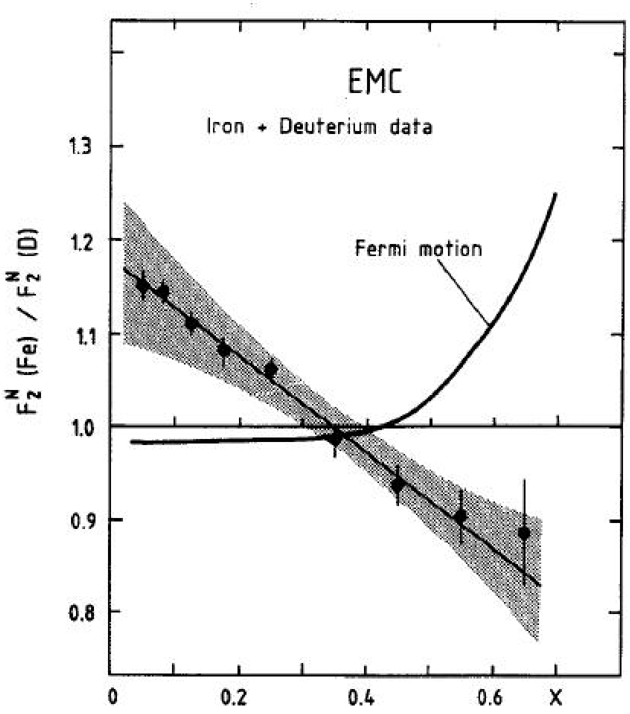
$f_N(y)$ is the probability to find the nucleon with given y

EMC effect: Interpretation

$f_N(y)$ is peaked around y≈1

$$\frac{1}{A}F_{2A}(x) = F^{*}_{2N}(x) + \frac{\langle T\rangle}{3m_N}\left(2xF^{*\prime}_{2N}(x) + x^2F^{*\prime\prime}_{2N}\right)$$

Assuming that $F_{2N}^{*}(x)=F_{2N}(x)$



Conventional nuclear binding cannot reproduce EMC effect!

EMC effect: models

There is no universally accepted explanation of the EMC effect

Two classes of models of the EMC effect:

1) **medium modifications**, $F_{2N}^{*}(x,Q^2) \neq F_{2N}(x,Q^2)$,

-- decrease of the mass of the bound nucleon (nucleon bag models, Quantum Hadrodynamics, Quark-Meson Coupling model)

-- increase of the confinement size of the bound nucleon

2) **explicit non-nucleonic degrees of freedom**

-- pion excess models

-- other non-nucleon dof's (Delta)

Example of medium modifications: QMC model

A particular realization of $F_{2N}^{*}(x,Q^2) \neq F_{2N}(x,Q^2)$ is the Quark-Meson coupling (QMC) model,

K. Saito, K. Tsushima, A.W. Thomas, Prog. Part. Nucl. Phys. 58, 1 (2007)

QMC model:

- nucleus=collection of non-overlapping nucleon bags
- quarks in the bags interact with the scalar and vector fields, which provide nuclear binding
- coupling constants tuned to reproduce properties of nuclear matter

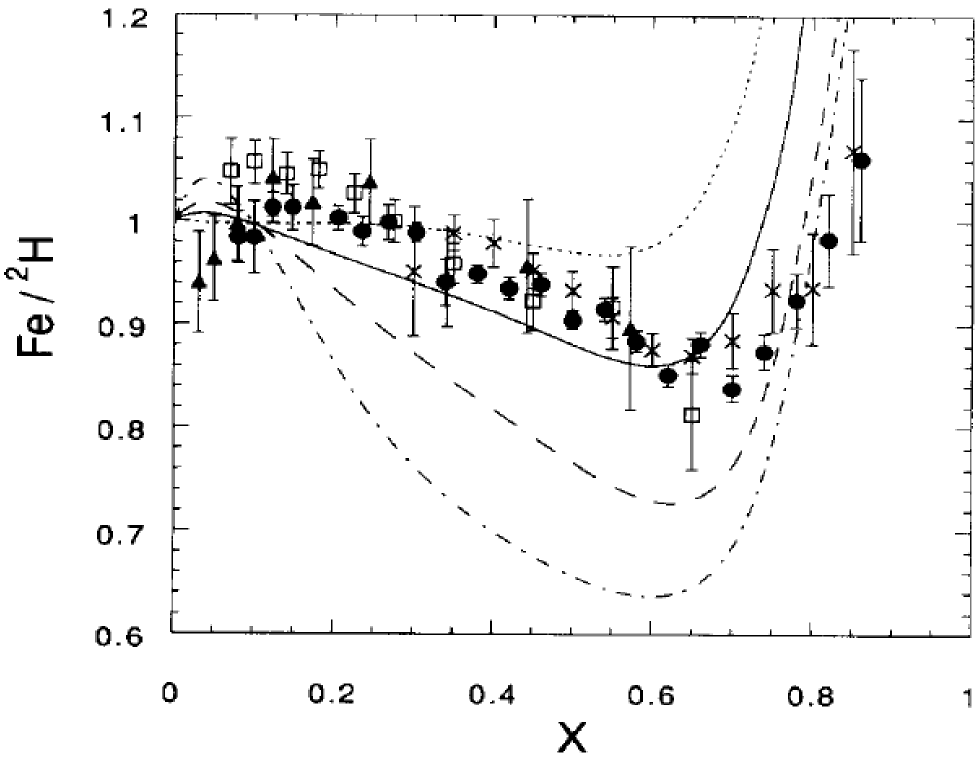
↓

Successful description of nuclear structure (level structure, charge form factors, binding energies, etc.)

Example of medium modifications: QMC model

Calculation in Quark-Meson coupling model:

K. Saito, A.W.Thomas, Nucl. Phys.A 574, 659 (1994)



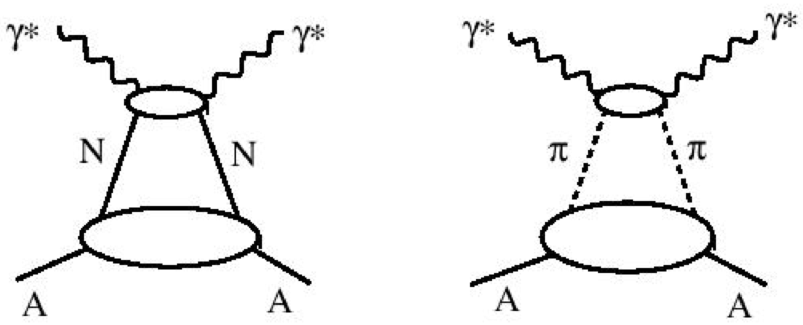
Example: pion excess model

- Pions in a nucleus provide long-distance part of nuclear force.

- Virtual photon can scatter not only on a quark in a bound nucleon, but also on a quark (antiquark) in a pion

$$y = A\frac{k^+}{p_A^+}$$

$$x = A\frac{Q^2}{2(qp_A)}$$



$$\frac{1}{A}F_{2A}(x) = \int_x^A dy\, f_N(y) F_{2N}\left(\frac{x}{y}\right) + \int_x^A dy\, f_\pi(y) F_{2\pi}\left(\frac{x}{y}\right)$$

Example: pion excess model

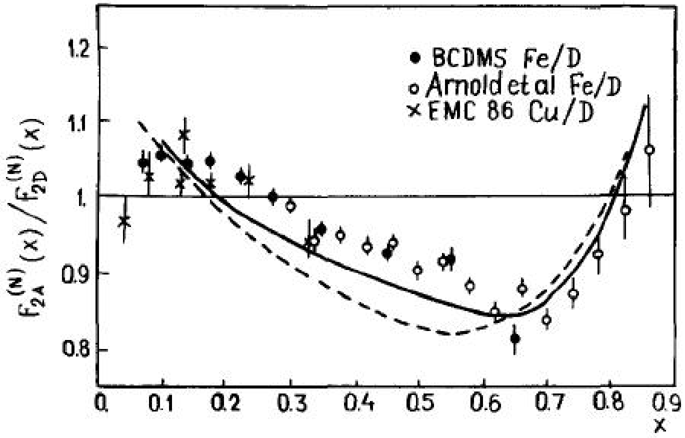
- $f_N(y)$ is peaked around $y \approx 1 \rightarrow$ Taylor expansion

$$\frac{1}{A}F_{2A}(x) = F_{2N}(x) + \eta_\pi x F'_{2N}(x) + \frac{\langle T \rangle}{3m_N}(2xF'_{2N} + x^2 F''_{2N})$$
$$+ \int_x^A dy\, f_\pi(y) F_{2\pi}\left(\frac{x}{y}\right)$$

- η_π is the momentum fraction carried by pions;
  $\langle T \rangle$ is the average kinetic energy of the nucleon.

The EMC effect requires eta=0.04 for Fe

M. Ericson, A.W. Thomas, PL B 128, 112 (1983)

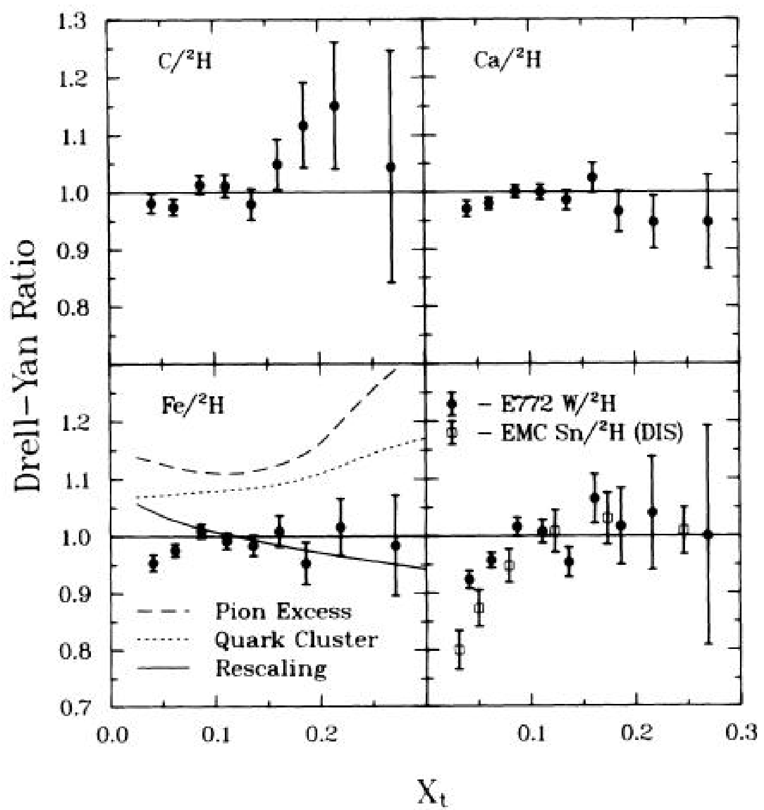


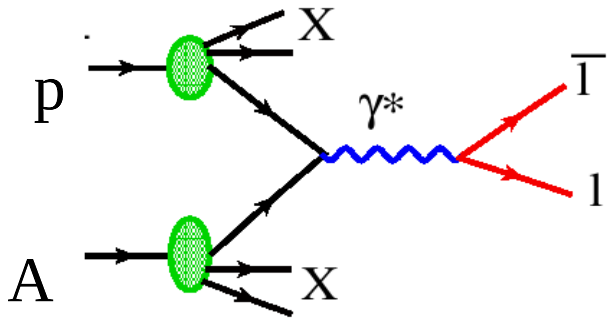
Problem with pion excess model

The pion excess explanation of the EMC effect **contradicts***

Fermilab E772 data on nuclear Drell-Yan

$$pA \rightarrow \mu^+\mu^- X$$

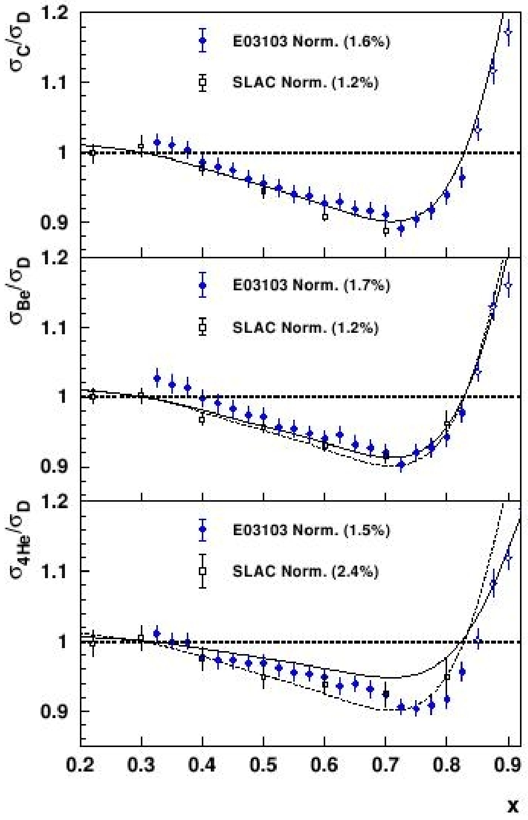




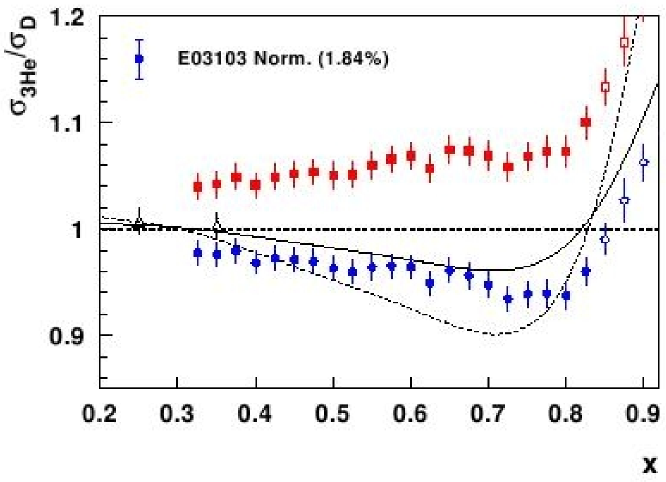
*Has recently been challenged

New JLab data

New Jefferson Lab data on EMC effect for light nuclei:



J. Seely et al, arXiv:0904:4448



The new data is very interesting:

- first measurement for He-3
- does not support A- or density- dependence of previous fits

Summary of lecture 1

- Parton structure of the nucleon and nuclei is studied in deep inelastic scattering with large momentum transfers
- Main theoretical tool is factorization theorems which allow to determine universal quark and gluon parton distributions
- Nuclear parton distributions differ from those of the free nucleon
- In the region $0.7 > x > 0.2$, $F_{2A}(x,Q^2) < AF_{2N}(x,Q^2)$: EMC effect
- While there is no universally accepted explanation of the EMC effect, it unambiguously indicates that conventional nuclear binding cannot explain it, and favors medium modifications of properties of bound nucleons.

Literature for lecture 1

- EMC effect

  -- M. Arneodo, Phys. Rept. 240: 301-393 (1994)

  -- D.F. Geesaman, K. Saito, A.W. Thomas,
  Ann. Rev. Nucl. Part. Part. Sci, 45: 337-390 (1995)

- Quark Meson Coupling model

  -- K. Saito, K. Tsushima, A.W. Thomas,
  Prog. Part. Nucl. Phys. 58: 1-167 (2007)

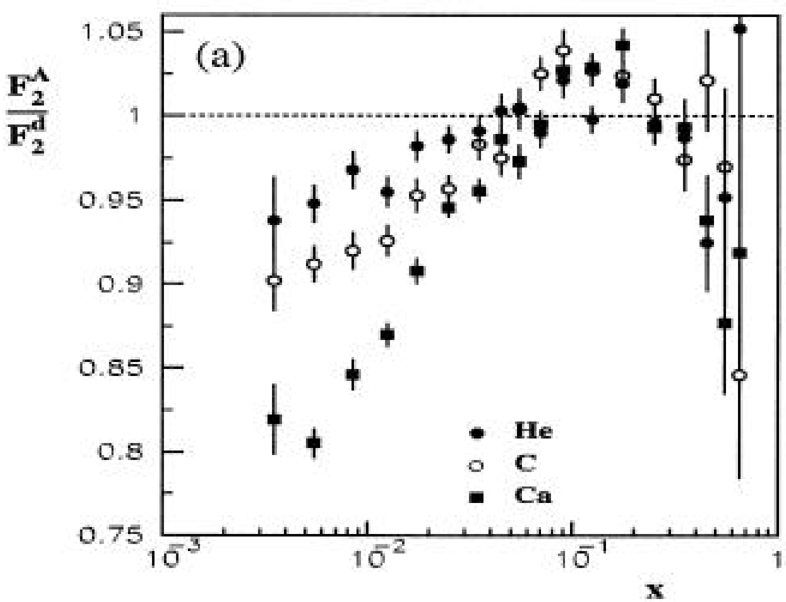
Lecture 2: **Nuclear shadowing in lepton-nucleus scattering**

Outline:

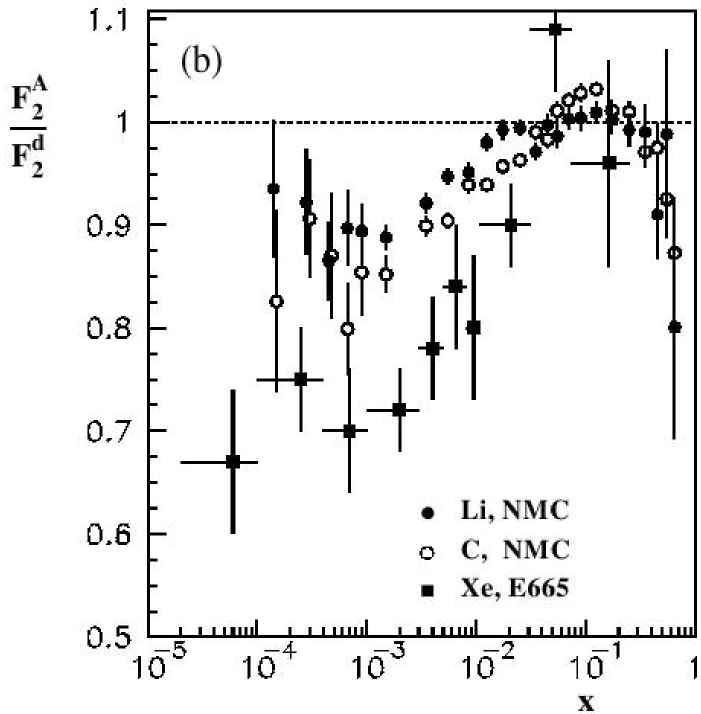
- Deep Inelastic scattering on fixed nuclear targets
- Global fits and their limitations
- Dynamical models of nuclear shadowing
- Future perspective to study nuclear shadowing

Nuclear shadowing

Nuclear shadowing is modification (depletion) of cross sections, structure functions and, hence, the distributions of *quarks* and *gluons* in nuclei relative to free nucleons at small values of Bjorken x, $x < 0.05$.



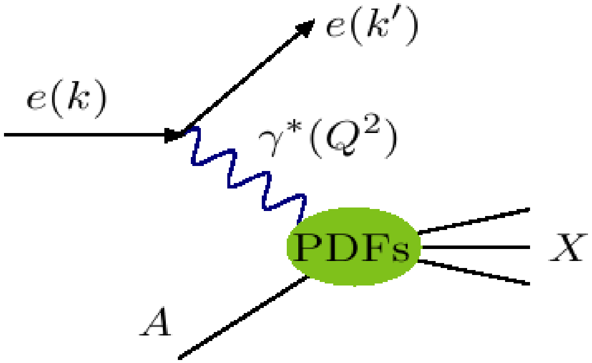
NMC Collaboration (CERN)



E665 (Fermilab)

Summary of experiments

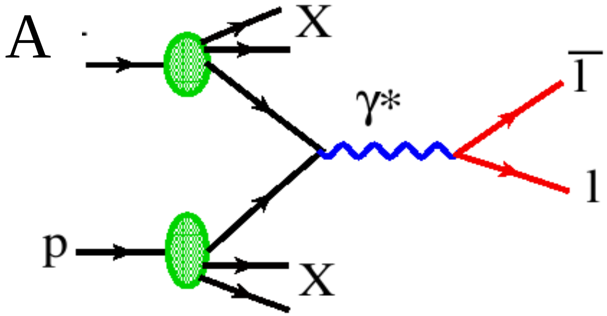
Most of information on nuclear shadowing came from experiments on inclusive DIS on fixed nuclear targets:



- New Muon Collaboration (NMC), CERN
  F_{2A}/F_{2D} for He, Li, C, Be, Al, Ca, Fe, Sn, Pb

- E665 (Fermilab)
  F_{2A}/F_{2D} for C, Ca, Xe, Pb

Additional info from nuclear Drell-Yan:



- E772 (Fermilab)
  DY ratio for C, Ca, Fe, W

How well do the data constrain nuclear parton distributions?

- In fixed-target experiments, the values of x and Q^2 are correlated: small Bjorken x correspond to small virtualities Q^2.

For instance, the requirement $Q^2 > 1$ GeV^2 means that $x > 0.005$

→ The most interesting and important region of the data where nuclear shadowing is large is excluded

- The measurement of $F_{2A}(x,Q^2)$ probes directly only *quark* distributions.

The gluon distribution is studied indirectly via scaling violations (next slide)

Since the coverage in x-Q^2 is poor, the gluon PDF is uncertain.

Answer: Not too well!

Global fits to nuclear DIS

- Assume the form of nuclear PDFs $q(x,Q_0)$ and $g(x,Q_0)$ at some initial input scale Q_0
- Use Dokshitzer-Gribov-Lipatov-Altarelly-Parisi (DGLAP) equations to evaluate nuclear PDFs at any given x and Q^2:

$$\frac{d\, f^{ns}_{j/A}(x,Q^2)}{d\log Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dx'}{x'} P_{qq}\left(\frac{x}{x'}\right) f^{ns}_{j/A}(x',Q^2)\,,$$

$$\frac{d}{d\log Q^2}\begin{pmatrix} f^s_A(x,Q^2) \\ f_{g/A}(x,Q^2)\end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dx'}{x'}\begin{pmatrix} P_{qq}\left(\frac{x}{x'}\right) & P_{qg}\left(\frac{x}{x'}\right) \\ P_{gq}\left(\frac{x}{x'}\right) & P_{gg}\left(\frac{x}{x'}\right)\end{pmatrix}\begin{pmatrix} f^s_A(x',Q^2) \\ f_{g/A}(x',Q^2)\end{pmatrix}$$

- Calculate observables $$F_2(x,Q^2) = \sum_{q,\bar{q}} e_q x q(x,Q^2)$$

- Compare to the data and adjust the assumed form to obtain the best description of the data.

Results of global fits

The result of such global fits is nuclear parton distributions at chosen low input $Q_{0.}$

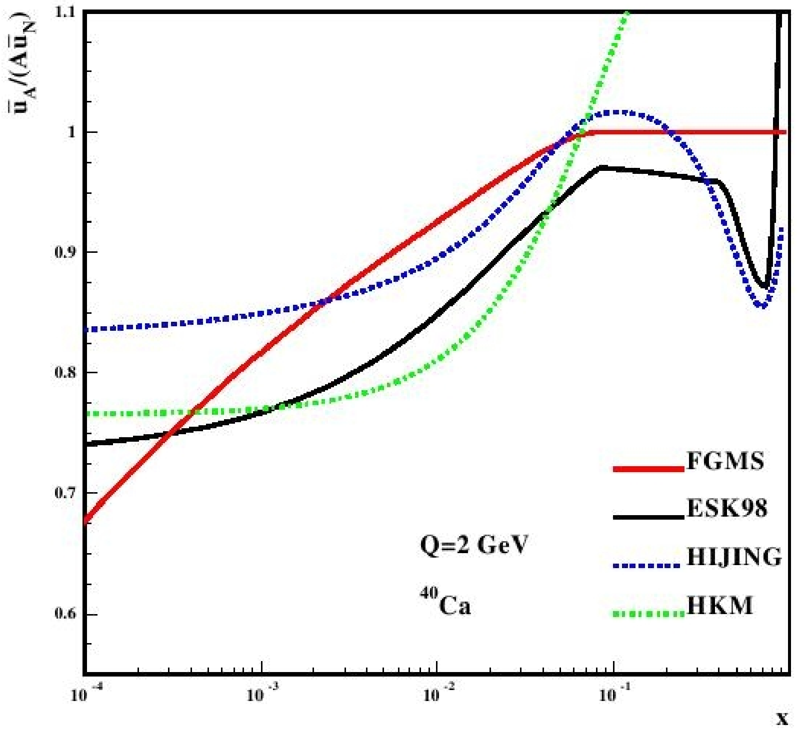
The results depend on the assumed initial shape of nuclear PDFs and the data used in the fit -> different groups obtain different results

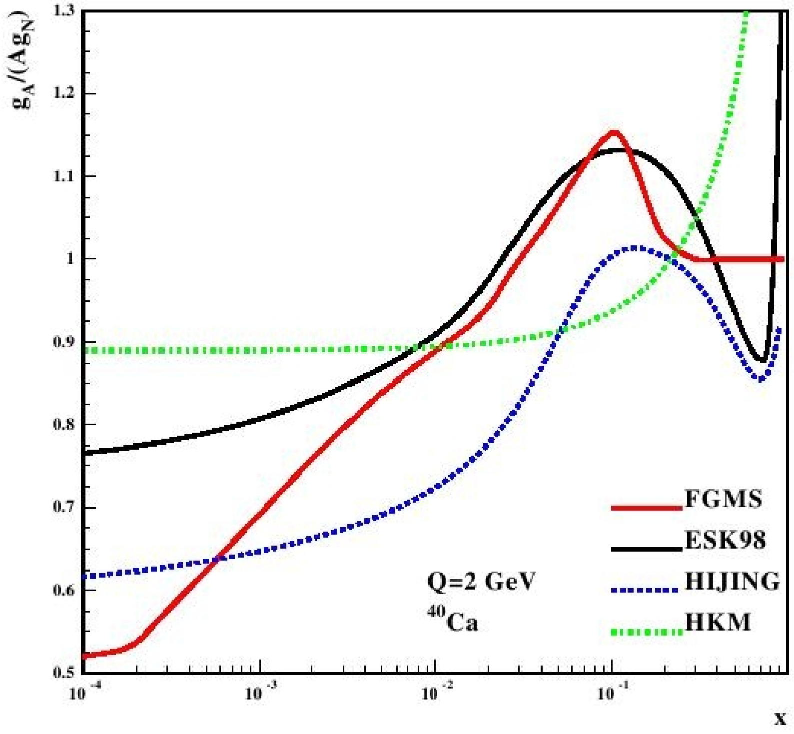
Compared in next slide:

- Eskola, Kolhinen, Ruuskanen (ESK98), 1998
- Li, Wang (HIJING), 2002
- Hirai, Kumano, Miyama (HKM), 2001

- Frankfurt, Guzey, McDermott, Strikman (FGMS), 2002 **(model, not fit)**

Results of global fits





- Different fits give very different results
- Especially at very small x where there is no data -> pure guess!
- Gluons are generally more uncertain than quarks

Models of nuclear shadowing

Alternative to global fits: use theoretical (dynamical) models of nuclear shadowing.

I will use the *leading twist model of nuclear shadowing* which predicts nuclear PDFs at low Q_0.

Nuclear PDFs at any Q^2 is obtained using DGLAP eqs.

The LT model of NS is based on:

- generalization by Strikman and Frankfurt (1998) of the theory of NS developed by Gribov (1970), which in turn was a generalization of Glauber theory of nuclear shadowing (1955)
- application of *factorization theorem*
- HERA data on diffraction in Deep Inelastic scattering

Glauber theory of nuclear shadowing

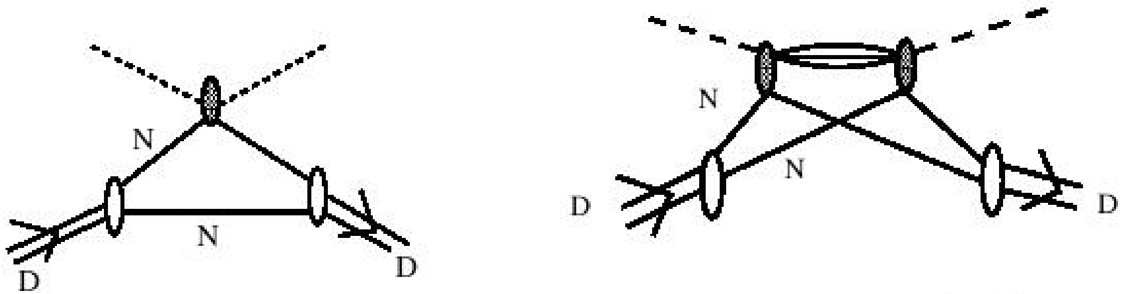
- Nuclear shadowing in hadron-deuteron scattering at high energies ($E > 0.8$ GeV): $\sigma_{\mathrm{tot}}^{hD} < 2\sigma_{\mathrm{tot}}^{hN}$
- Explanation: Contribution of the rescattering diagram due to successive interactions with nucleons

Glauber '55

$$\sigma_{\mathrm{tot}}^{hD} = 2\sigma_{\mathrm{tot}}^{hN} - \frac{\sigma_{\mathrm{tot}}^{hN}}{4\pi}\langle\frac{1}{r^2}\rangle_D$$

Gribov theory of nuclear shadowing

- Based on a different space-time picture of strong interactions: Incident hadron is a cohent sum of its long-lived fluctuations
- At high energies ($E > 5$ GeV), the incident hadron (its fluctuations) interacts simultaneously with all nucleons, Gribov '69



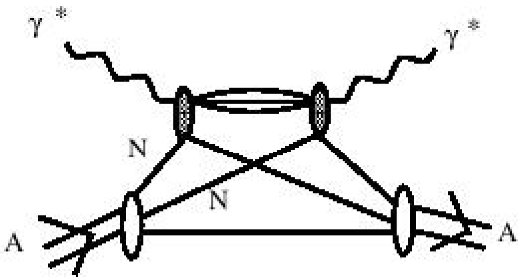
$$\sigma_{\rm tot}^{hD} = 2\sigma_{\rm tot}^{hN} - 2\int dk^2 \rho(4k^2)\frac{d\sigma_{\rm diff}^{hN}}{dt}$$

- Key result: Shadowing correction to nuclear cross section is given in terms of elementary diffractive cross section

Leading twist theory of nuclear shadowing

- Generalization to DIS on any nucleus

- $F_{2A} = AF_{2N} - \delta F_{2A}$



$$\delta F_{2A}^{(2)}(x, Q_0^2) = \frac{A(A-1)}{2} 16\pi \mathcal{R}e \left[\frac{(1-i\eta)^2}{1+\eta^2} \int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \int_x^{x_{I\!P,0}} dx_{I\!P} \right.$$

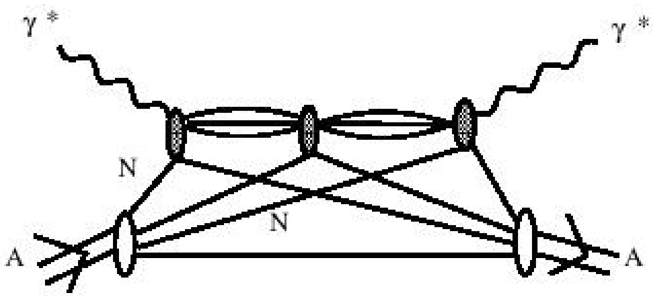
$$\left. \times F_2^{D(4)}(\beta, Q_0^2, x_{I\!P}, t)\Big|_{t=t_{\min}} \rho_A(b, z_1)\rho_A(b, z_2) e^{ix_{I\!P} m_N (z_1 - z_2)} \right]$$

Leading twist theory of nuclear shadowing (Cont.)

- QCD factorization theorems for inclusive and diffractive DIS

$$\delta x f^{(2)}_{j/A}(x,Q_0^2) = \frac{A(A-1)}{2} 16\pi \mathcal{R}e\left[\frac{(1-i\eta)^2}{1+\eta^2}\int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \int_x^{x_{I\!P,0}} dx_{I\!P} \right.$$
$$\left. \times \beta f^{D(4)}_{j/N}(\beta, Q_0^2, x_{I\!P}, t)\big|_{t=t_{\min}} \rho_A(b,z_1)\rho_A(b,z_2) e^{i x_{I\!P} m_N (z_1 - z_2)}\right]$$

- Take into account the rest of interactions: quasi-eikonal approximation
- The intermediate state rescatters with σ_{eff}



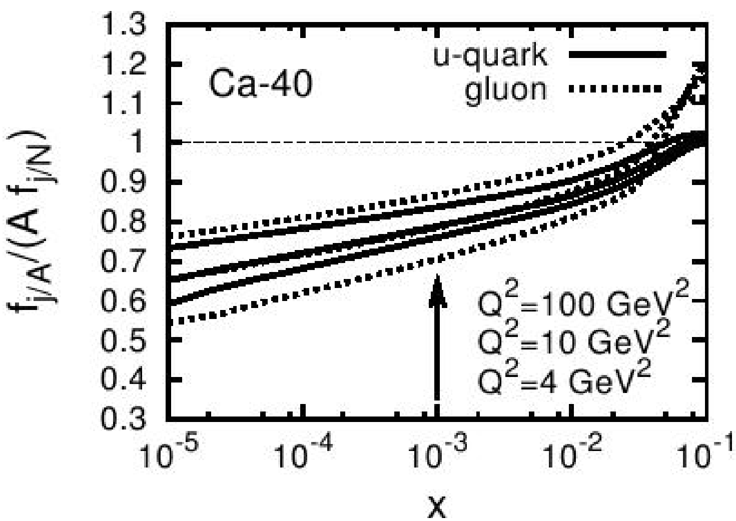
$$\sigma^j_{\text{eff}}(x,Q_0^2) = \frac{16\pi}{x f_{j/N}(x,Q_0^2)} \int_x^{x_0} dx_{I\!P}\, \beta f^{D(4)}_{j/N}(\beta, Q_0^2, x_{I\!P}, t=0)$$

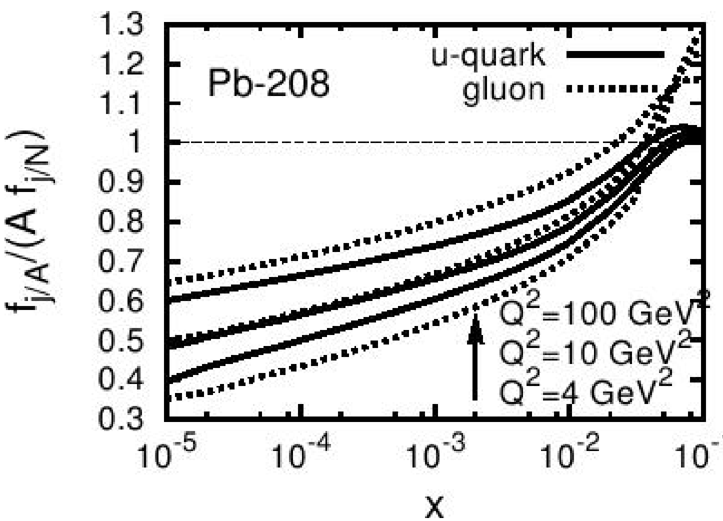
LT theory of nuclear shadowing: Predictions

- Master equation for $\delta f_{j/A} = A f_{j/N} - f_{j/A}$

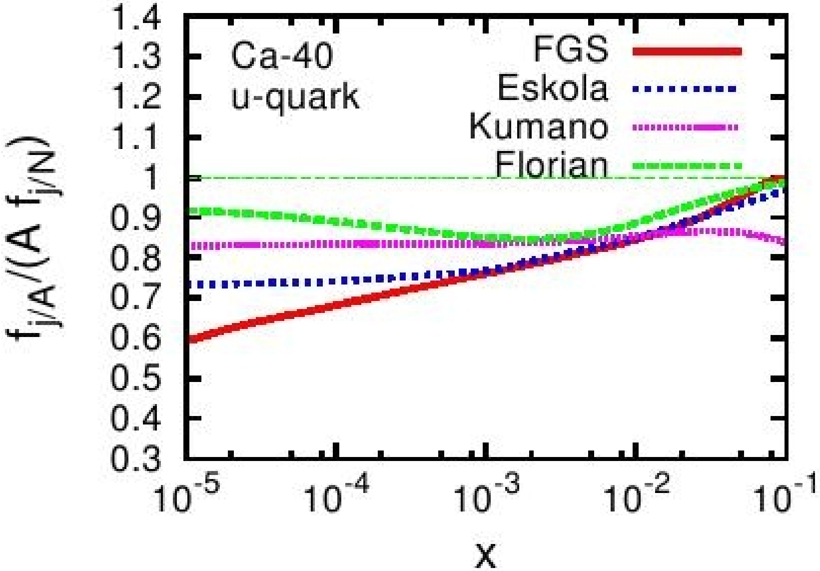
$$\delta x f_{j/A}(x, Q_0^2) = \frac{A(A-1)}{2} 16\pi \mathcal{R}e \left[\frac{(1-i\eta)^2}{1+\eta^2} \int d^2 b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \int_x^{x_{I\!P,0}} dx_{I\!P} \right.$$

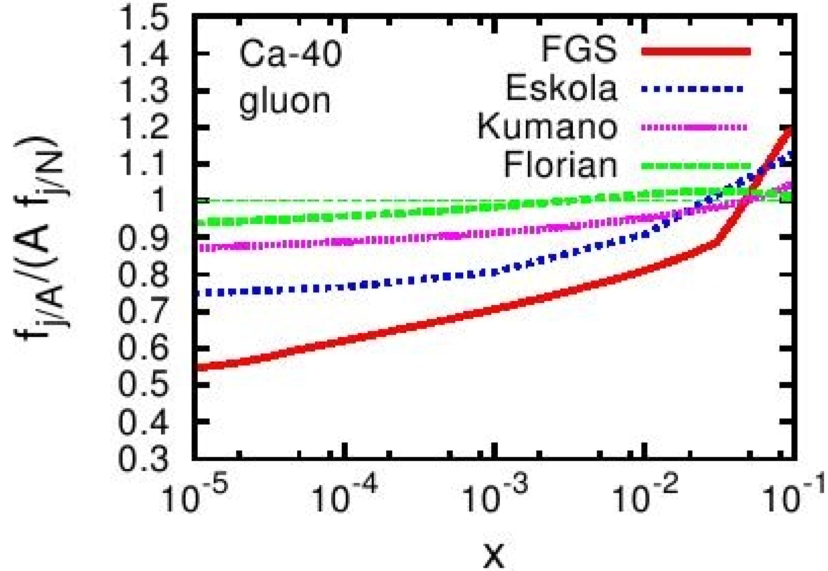
$$\left. \times \beta f_{j/N}^{D(4)}(\beta, Q_0^2, x_{I\!P}, t)\Big|_{t=t_{\min}} \rho_A(b, z_1) \rho_A(b, z_2) e^{i x_{I\!P} m_N (z_1 - z_2)} e^{-A \frac{1-i\eta}{2} \sigma_{\rm eff}^{j} \int_{z_1}^{z_2} dz' \rho_A(b, z')} \right]$$





LT theory of NS vs. global fits

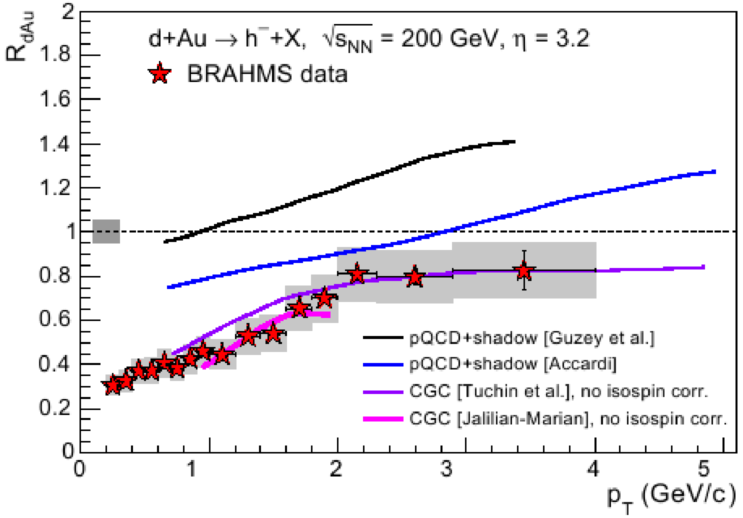




- Predicted nuclear shadowing is different for quarks and gluons
- Nuclear shadowing is larger for gluons than for quarks

Why do we study nuclear distributions?

- Fundamental characteristics of nuclei in terms of quarks and gluons
- Nuclear PDFs test theoretical models of nuclear shadowing and saturation
- Essential for pQCD analysis and interpretation of RHIC and LHC data



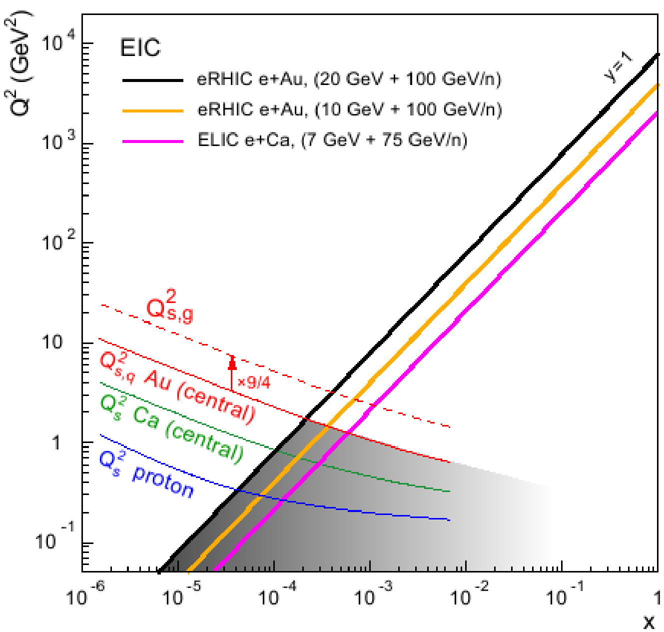
Note that saturation effects at forward rapidities at RHIC (rare) will appear at midrapidities at the LHC (very common)

- Energy loss and hadronization in hot nuclear matter: precise nuclear PDFs are needed to separate the initial state effects from final state effects (parton energy loss) and test different models of fragmentation.

Future measurements of nuclear PDFs

The future Electron-Ion Collider (EIC) with a wide kinematic coverage will allow to determine nuclear PDFs at small x using several complimentary measurements:

- $F_2(x,Q^2)$ and scaling violations of $F_2(x,Q^2)$ ... quarks and gluons
- longitudinal structure function $F_L(x,Q^2)$ ... gluons
- charm and jets ... gluons



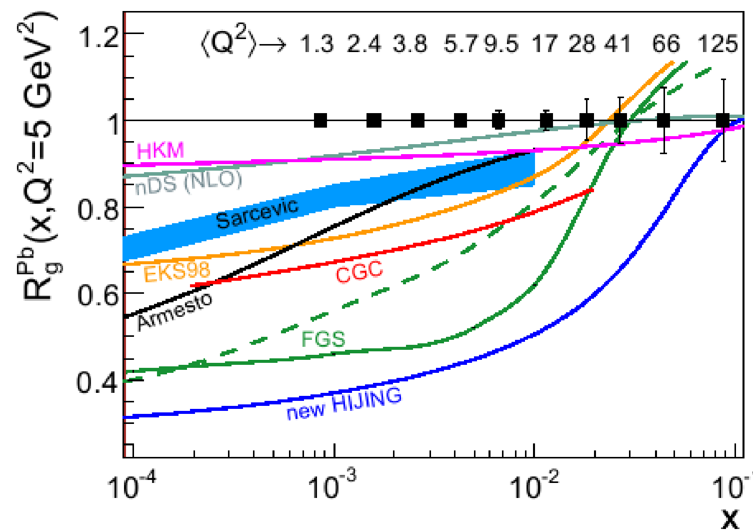


Figure 5: *The ratio of gluon distributions in Pb nuclei to those in deuterium extracted from the ratio of the respective longitudinal structure functions F_L. The filled squares and error bars correspond respectively to the projected kinematic reach and statistical uncertainties for this measurement (for $10/A\,fb^{-1}$) with the EIC. A large range of model predictions are shown which differ widely in this kinematic region.*

Concepts of Electron-Ion Collider

eRHIC (BNL): Add energy recovery linac to RHIC

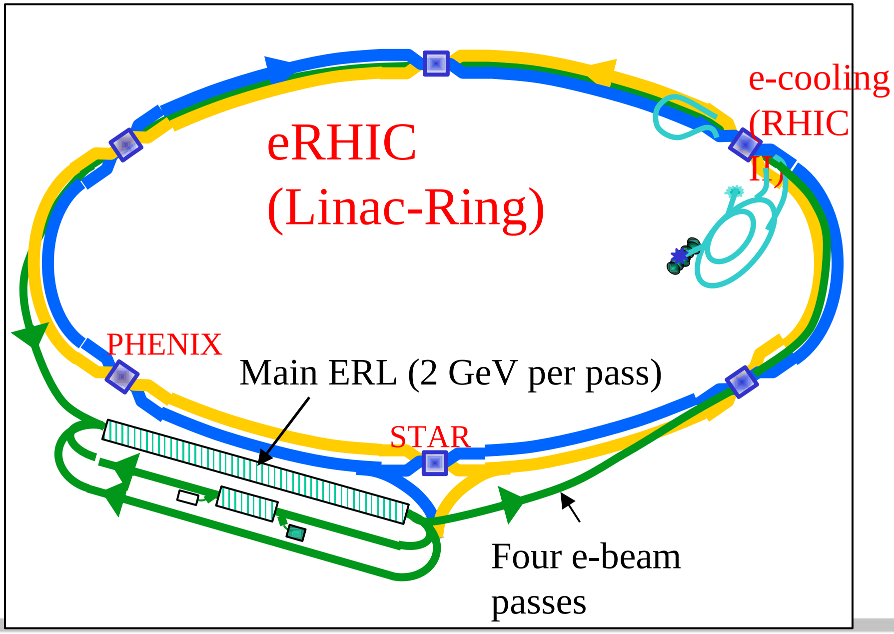
- higher energy, lower luminosity

E_e=10 (20) GeV

E_A=100 GeV (up to U)

$\sqrt{s_{eN}}$=63 (90) GeV

L_{eAu}(peak)/n=$2.9 \bullet 10^{33}$ $cm^{-2}\,s^{-1}$



ELIC (JLab): Add hadron beam facility to existing CEBAF

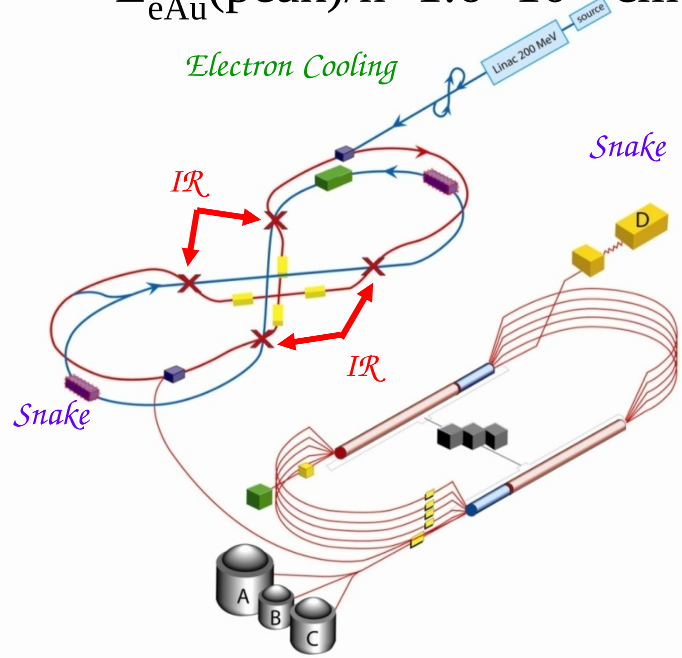
- lower energy, higher luminosity

E_e=9 GeV

E_A=90 GeV (up to Au)

$\sqrt{s_{eN}}$=57 GeV

L_{eAu}(peak)/n=$1.6 \bullet 10^{35}$ $cm^{-2}\,s^{-1}$



Summary of lecture 2

- Nuclear parton distributions are not constrained well enough by available fixed-target data at small x.

- Different global fits predict very different amount of nuclear shadowing, especially for gluons.

- An alternative to global fits is dynamical models of nuclear shadowing. I discussed the leading twist model of nuclear shadowing based on factorization theorem and HERA diffractive data.

- Nuclear parton distributions will be constrained much better by the future Electron-Ion collider with much larger energy, kinematics coverage and measurement of longitudinal structure function $F_L(x,Q^2)$.

Literature for lecture 2

- Review on nuclear shadowing

  -- G. Piller and W. Weise, Physics Reports 330:1 (2000)

- Leading twist model of nuclear shadowing

  -- L. Frankfurt, V. Guzey, M. McDermott, M. Strikman, JHEP 202: 27 (2002)

- Electron-Ion Collider project

  http:web.mit.edu/eicc (general info)
  http://www.eic.bnl.gov (eA Working Group)