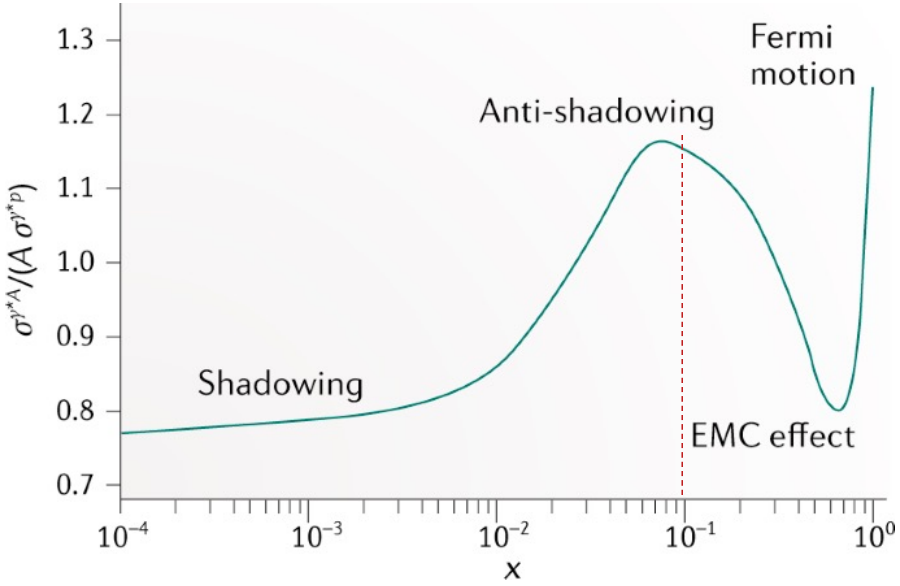
Theory Overview

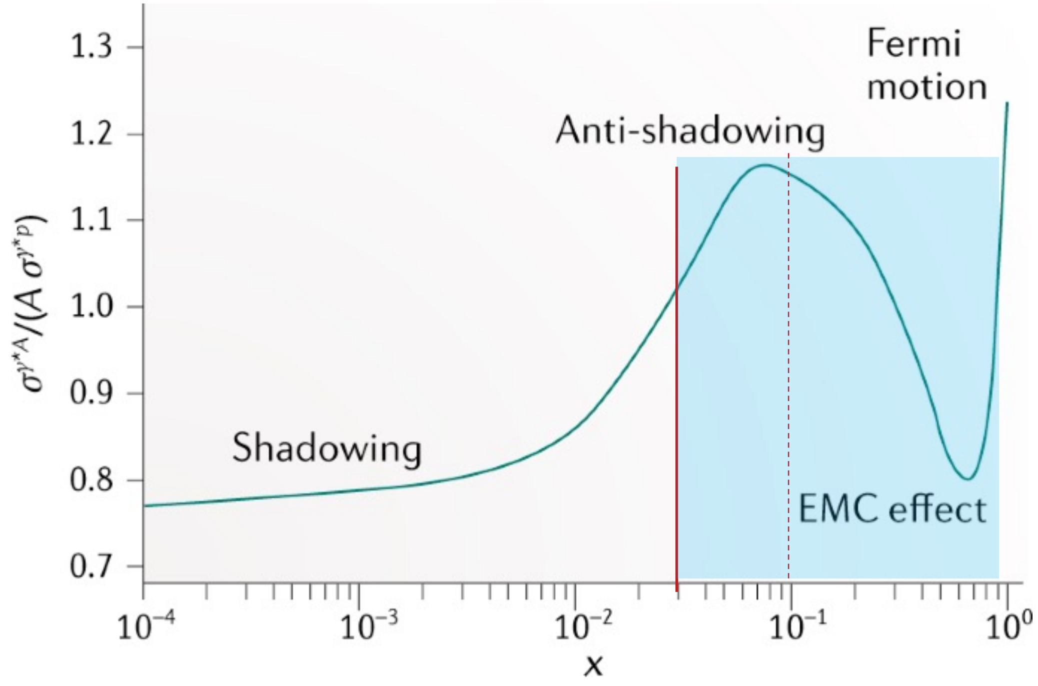
- What is so special at x = 0.1?
- Do we understand the physics behind the anti-shadowing?
- Transition between the valence and sea?
- Emergence of hadrons?
- …

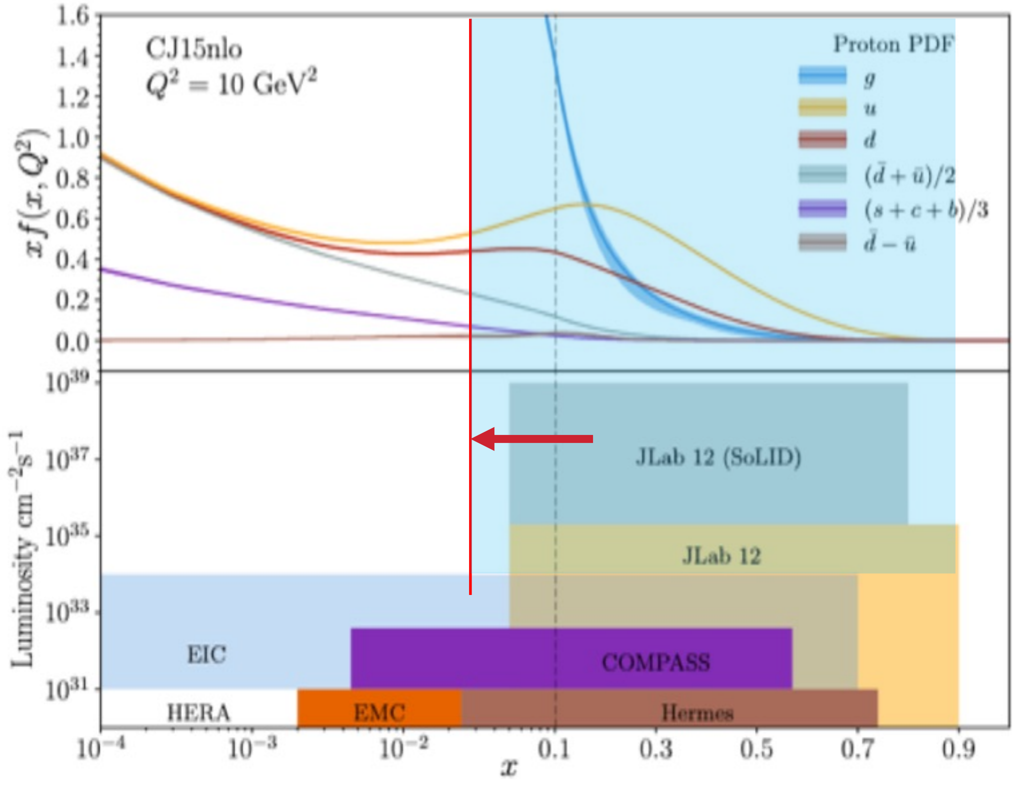


Jianwei Qiu
Theory Center, Jefferson Lab
July 22, 2022

CEBAF at a higher energy

- Kinematic reach along with a high luminosity:



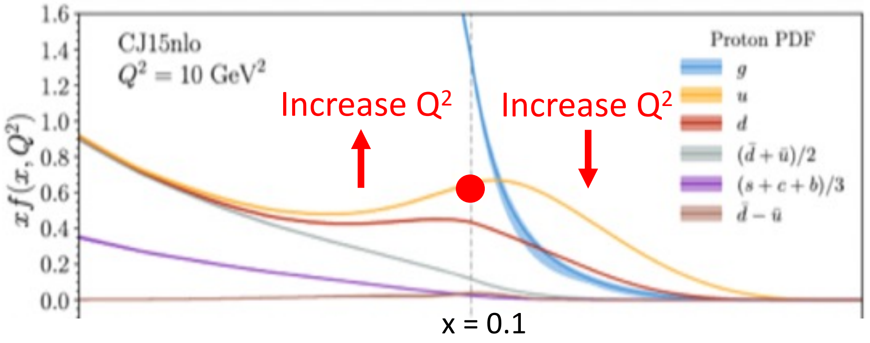


This is a most dynamical rich regime of partonic structure in nucleon and nuclei

- Emergence of the gluon dominance
- Interface between the sea and the valence, role of strange sea, …
- Nuclear structure at the parton level, …
- …

What is so special at x ~ 0.1?

❑ **Scaling and scaling violation:**



❑ **Hard probe and its probing distance:**

- Hard probe – process with a large momentum transfer

$$q^\mu \quad \text{with} \quad Q \equiv \sqrt{|q^2|} \gg \Lambda_{\text{QCD}}$$

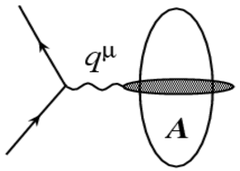
- Hard probe is much smaller than a typical hadron at rest

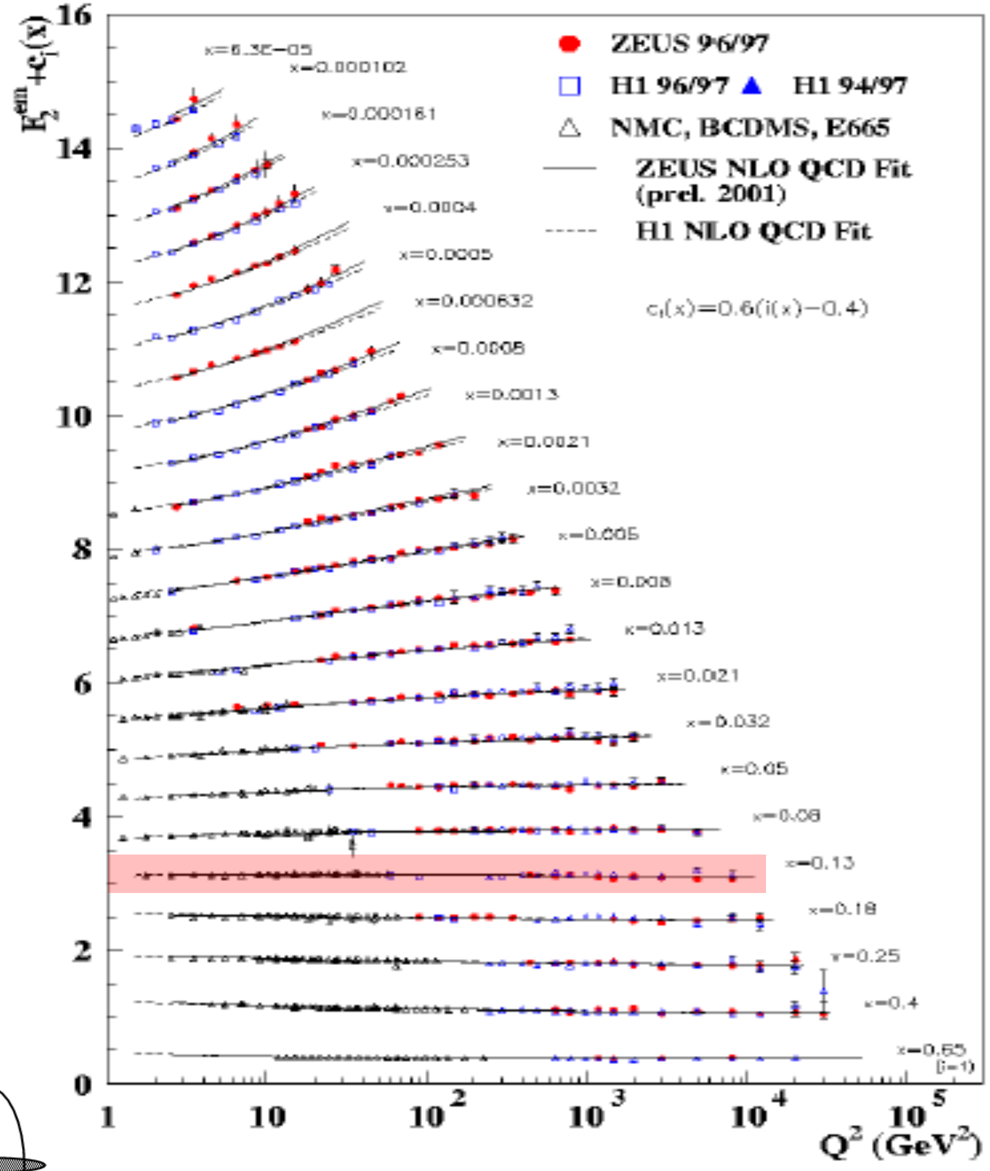
$$\frac{1}{Q} \ll 2R \sim \text{fm}$$

- But, it might be larger than a Lorentz contracted hadron

$$\frac{1}{Q} \sim \frac{1}{xp} \gg 2R\left(\frac{m}{p}\right) \quad \text{or equivalently} \quad x \ll x_c \equiv \frac{1}{2mR} \sim 0.1$$

If x is small enough, the probe could cover several nucleons in a Lorentz contracted large nucleus!





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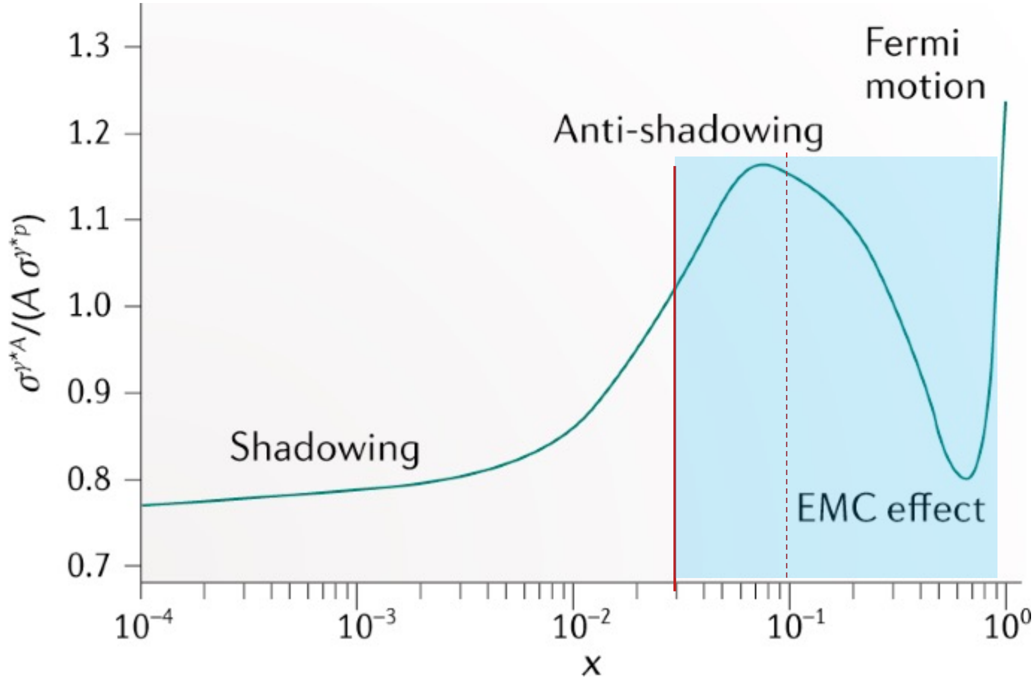
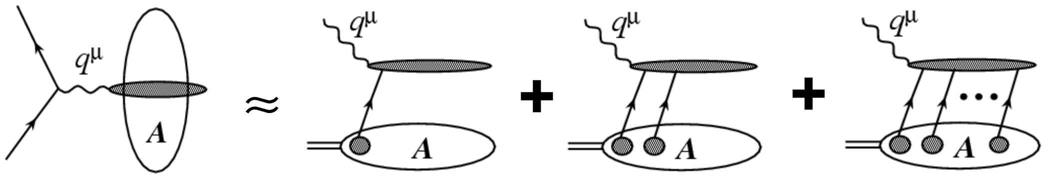
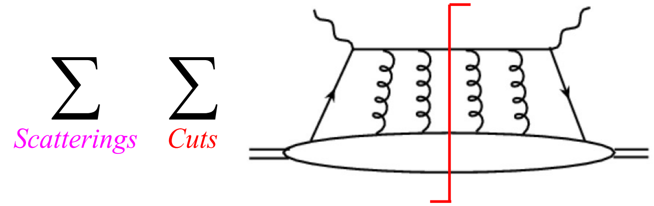
What is so special at x ~ 0.1?

❑ Physics at x < 0.1:



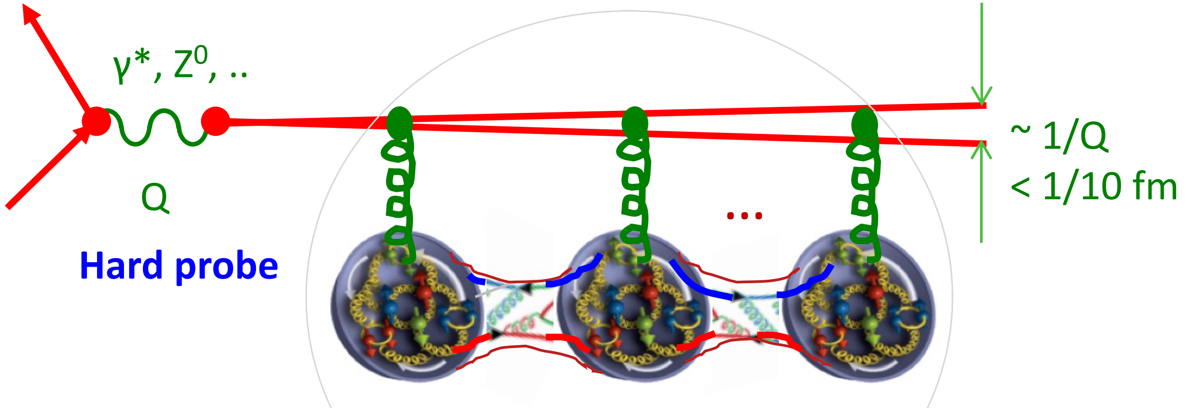




- Coherent multiple scattering:

Qiu and Vitev, PRL (2004)

$$\sigma^{\gamma^* A} \propto \langle P_A, A|\mathcal{O}_A(\{y_A\},\{y'_A\})|P_A, A|\rangle$$

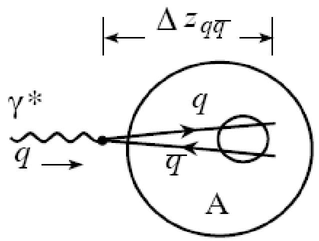


- Coherent length is frame independent:
  - Lifetime of the $q\bar{q}$ state:

$$\Delta E_{q\bar{q}} \sim \nu - E_{q\bar{q}} \sim \frac{Q^2}{2\nu}\left[1+\mathcal{O}\left(\frac{m_{q\bar{q}}^2}{Q^2}\right)\right]$$

$$\Delta z_{q\bar{q}} \sim \frac{1}{\Delta E_{q\bar{q}}} \sim \frac{2\nu}{Q^2} = \frac{1}{m x_B}$$

  - $\Delta z_{q\bar{q}} \gg 2$ fm, inter-nuclear distance, if $x_B \ll 0.1$



If $x_B \ll 0.1$, the probe (the $q\bar{q}$ state of the virtual photon) can interact with whole hadron/nucleus coherently

What is so special at x ~ 0.1?

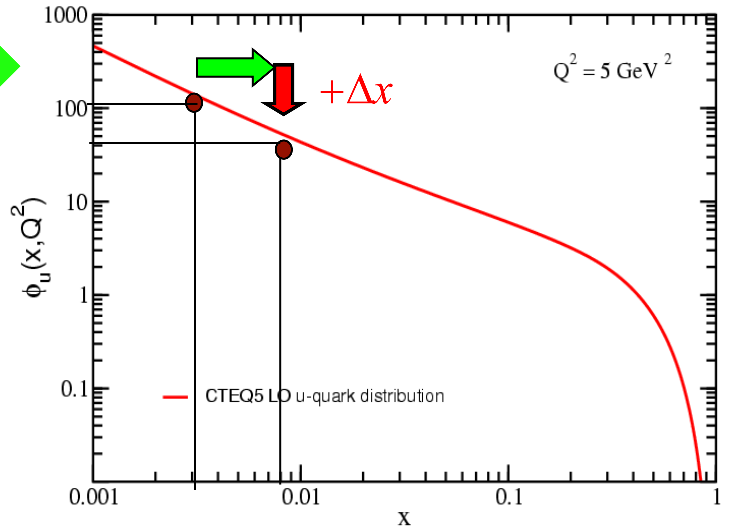
❑ Physics at x < 0.1:

$$F_T(x_B, Q^2) = \sum_{n=0}^{N} \frac{1}{n!}\left[\frac{\xi^2}{Q^2}\left(A^{1/3}-1\right)\right]^n x_B^n \frac{d^n}{dx_B^n} F_T^{(0)}(x_B, Q^2)$$

$$\approx F_T^{(0)}(x_B(1+\Delta), Q^2)$$

$$\Delta \equiv \frac{\xi^2}{Q^2}\left(A^{1/3}-1\right)$$

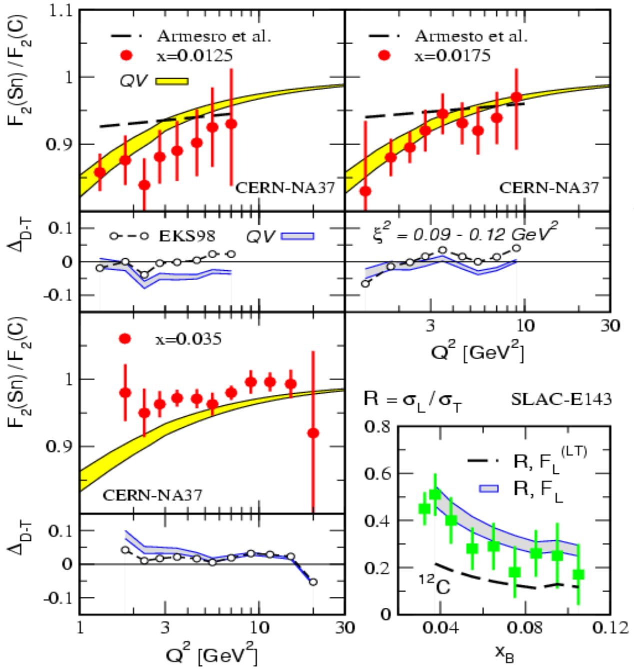
$$\xi^2 = \frac{3\pi\alpha_s}{8R^2}\langle F^{+\alpha} F_\alpha{}^+ \rangle$$

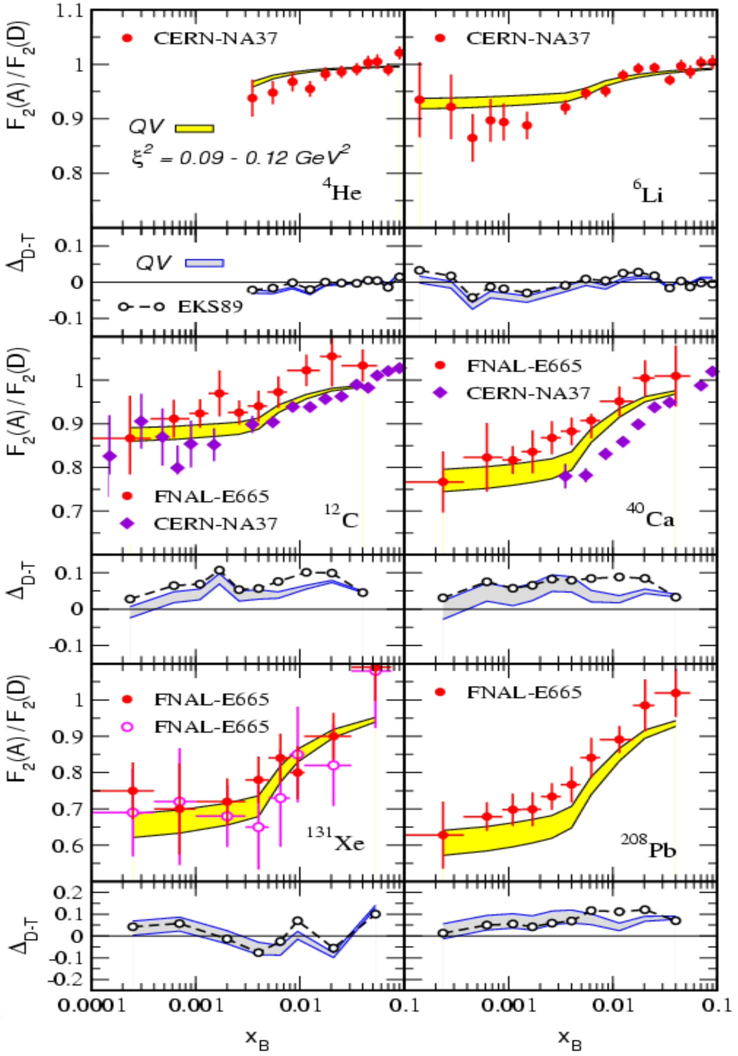


Qiu and Vitev, PRL (2004)

Single parameter for all x and Q^2 dependence

$\xi^2 \sim 0.09 - 0.12$ GeV^2





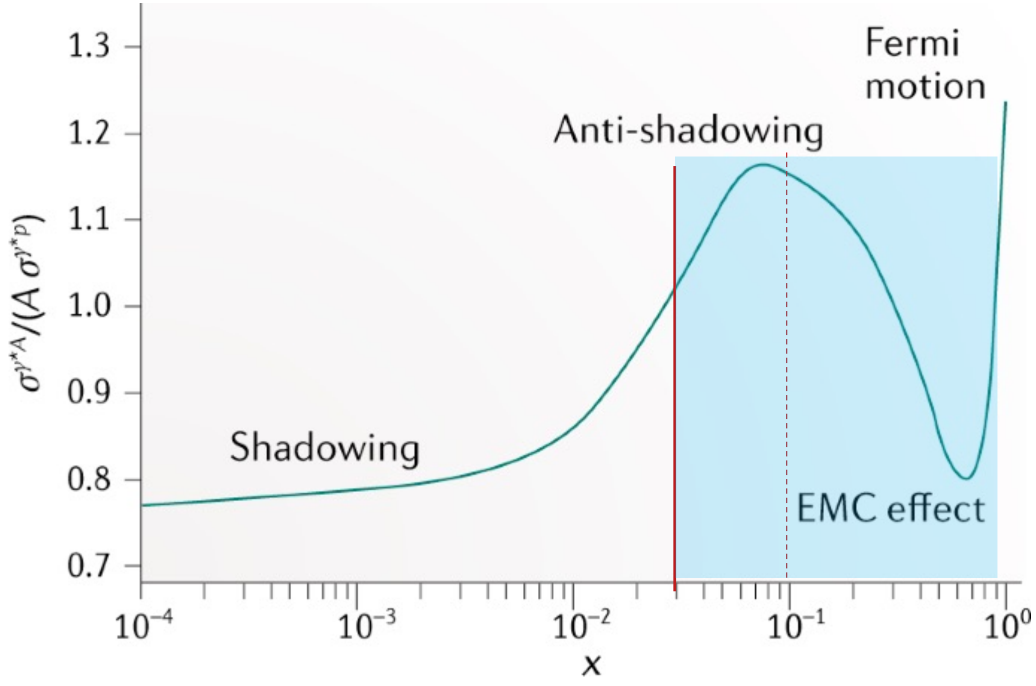
The suppression in small-x can be caused by "coherent multiple scattering" (collision effect)

+ "modification of nuclear parton density" due to inter-nucleon interaction (nuclear effect)

– how to separate these two (EIC WP)? *Nuclear gluon density at "large" x*

What is so special at x ~ 0.1?

❑ **Physics at x > 0.1:**

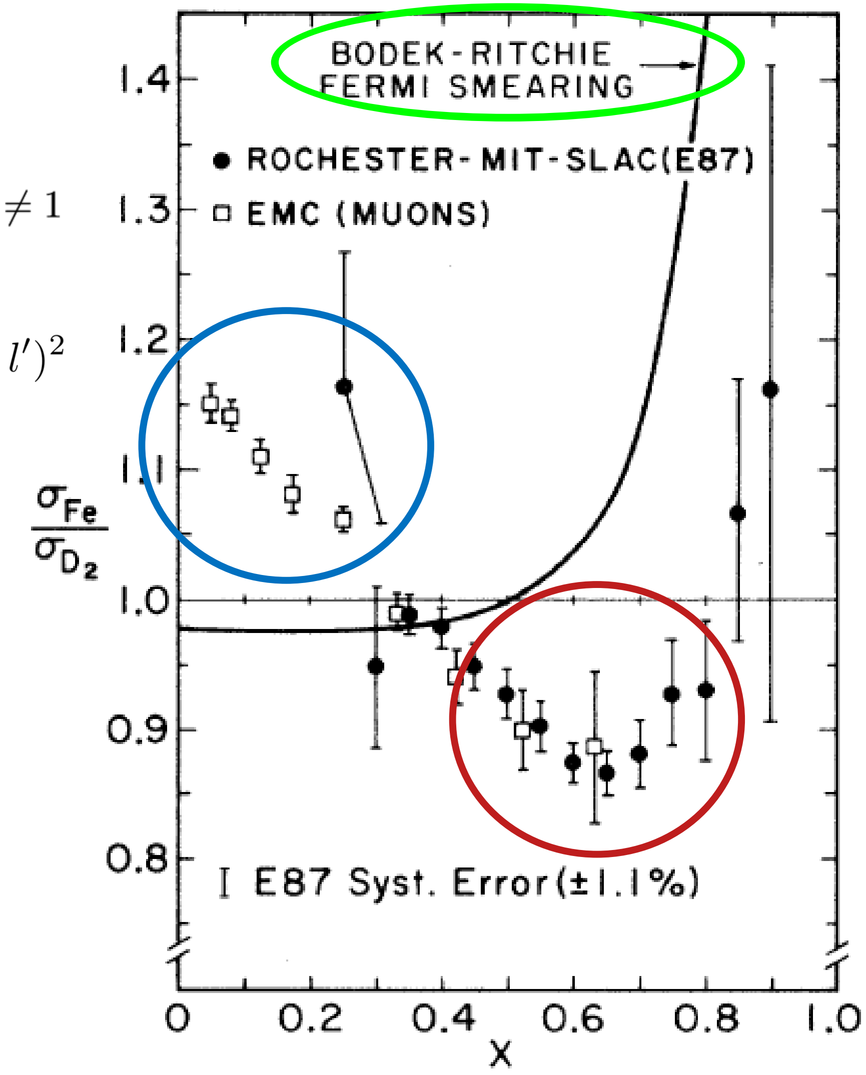


- EMC Effect:

$$R_{F_2} = \frac{\frac{1}{A} F_2^A(x, Q^2)}{\frac{1}{2} F_2^D(x, Q^2)} \neq 1$$

$$Q^2 = -q^2 = -(l - l')^2$$

$$x = \frac{Q^2}{2(p_A/A) \cdot q}$$



- The detailed study of "Tagged" structure functions can help explore internal structure of SRC nucleons
- The "breakup" of strongly correlated nucleons

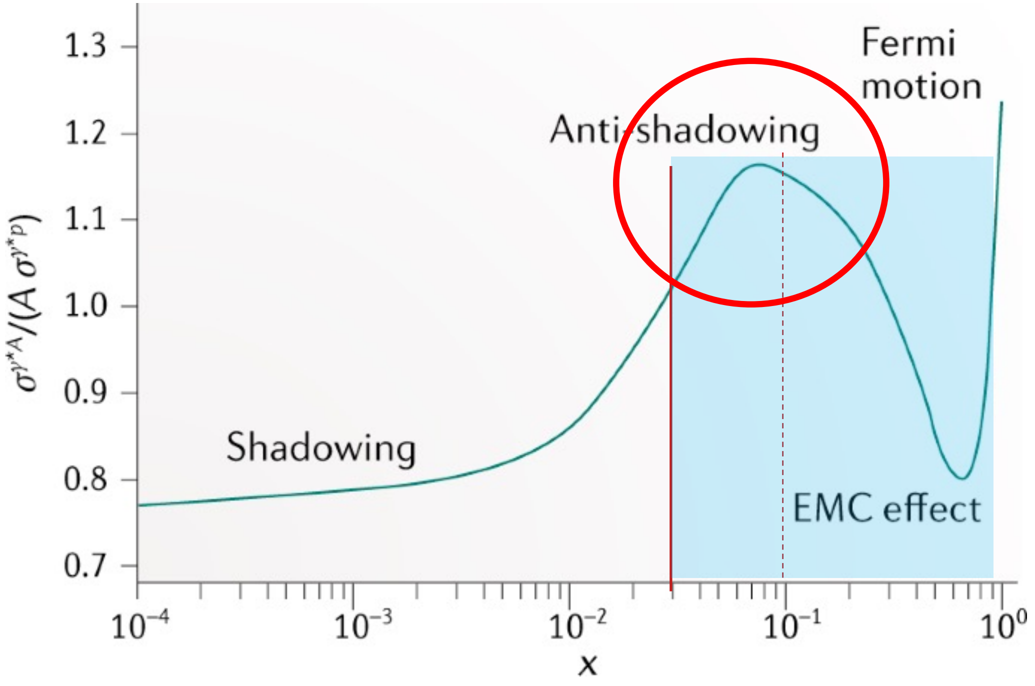
…

It is not the focus of this workshop

Short-range correlation (SRC) + other interpretations

What is so special at x ~ 0.1?

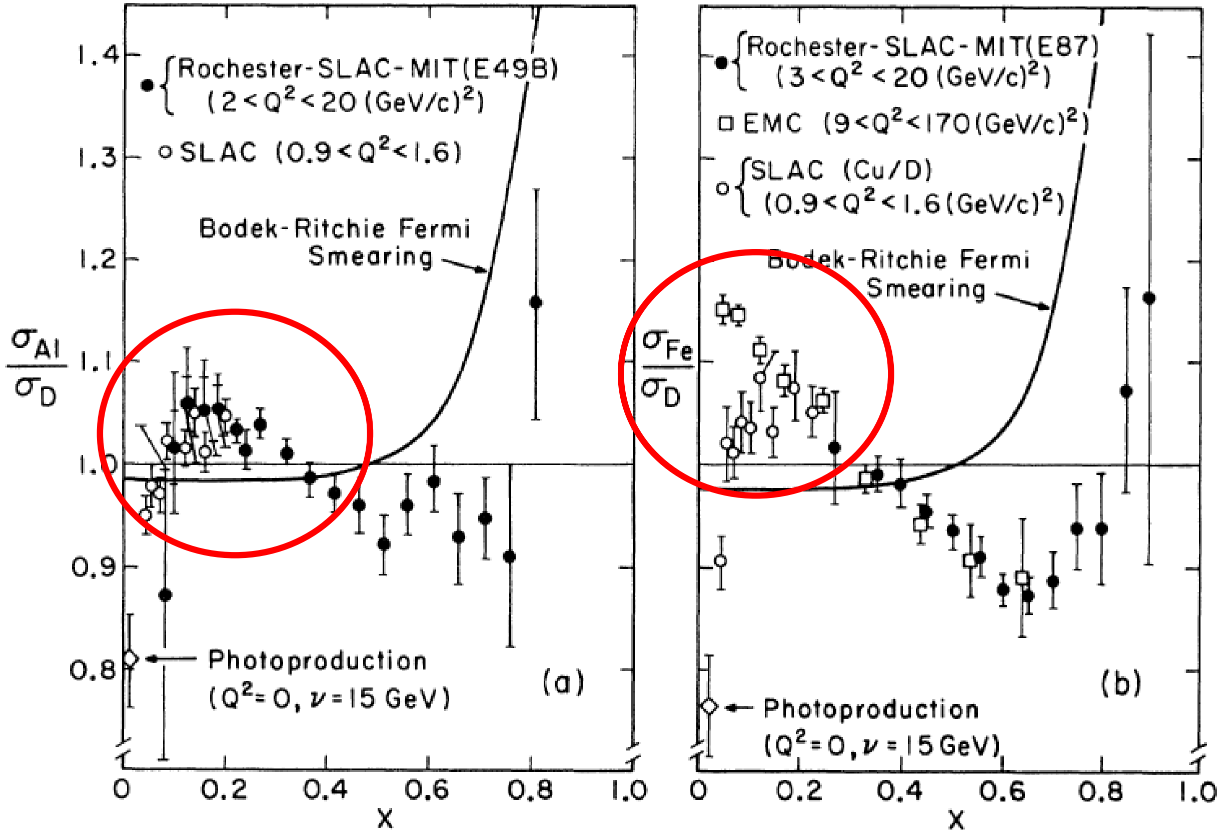
- **Physics at x ~ 0.1:**



What happened to all those calculations that were successful to explain the EMC data?

What is the physics behind the antishadowing?

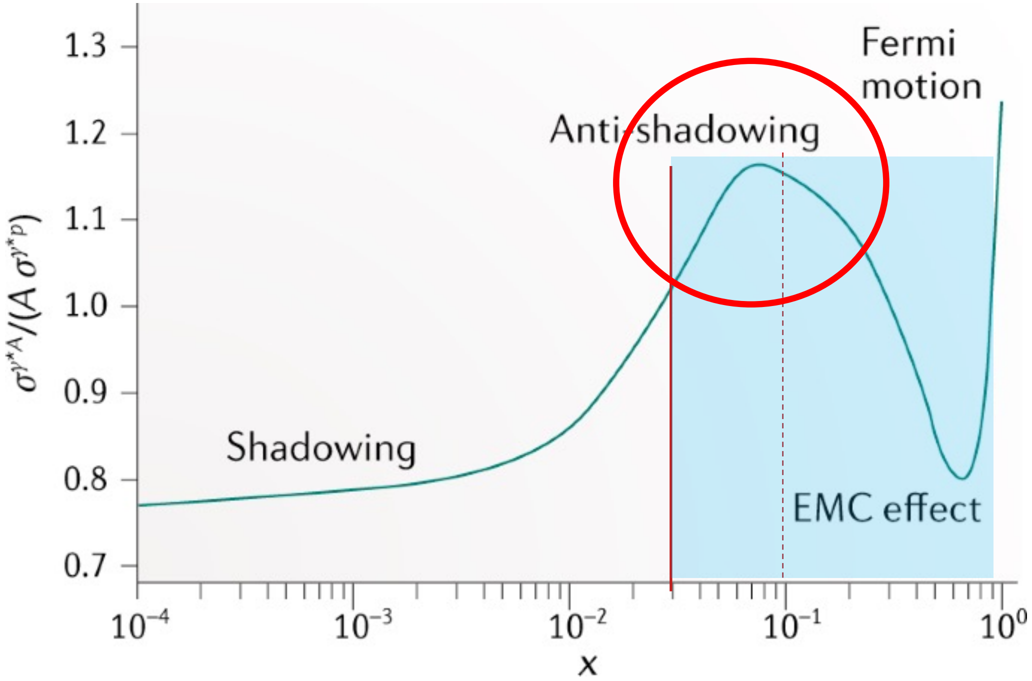
- Anti-shadowing:



At small x, SLAC and EMC data show an opposite effect

What is so special at x ~ 0.1?

❑ Physics at x ~ 0.1:

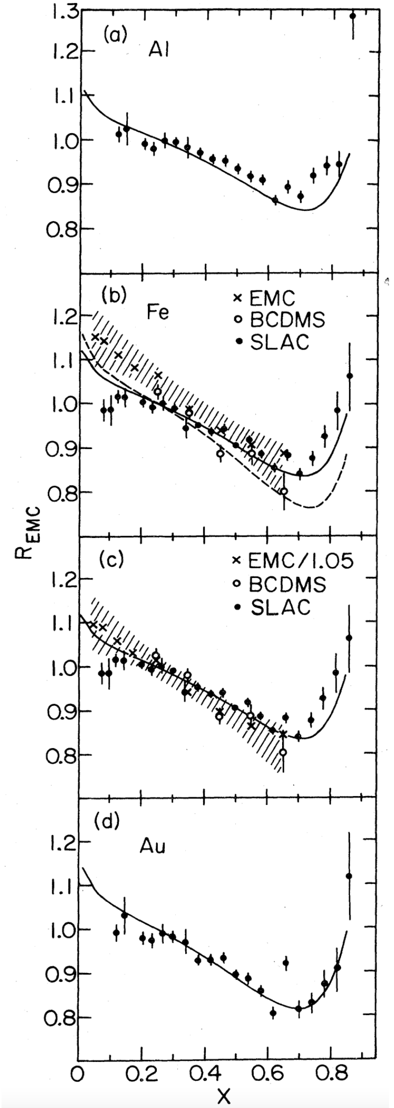


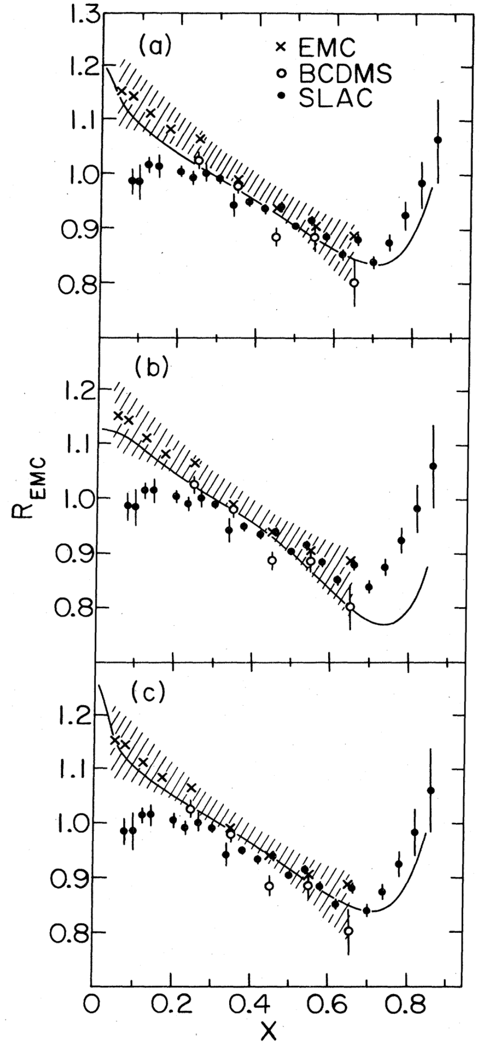
$$F_2^A(x,Q^2) = \int_{z \geq x} dz\, f_N(z) F_2^N\left[\frac{x}{z}, Q^2\right] + \int_{y \geq x} dy\, f_\pi(y) F_2^\pi\left[\frac{x}{y}, Q^2\right] + \int_{z \geq x} dz\, f_B(z) F_2^B\left[\frac{x}{z}, Q^2\right]$$

f_N, f_π, f_B Given by known nuclear model

- Pion Exchange Model:

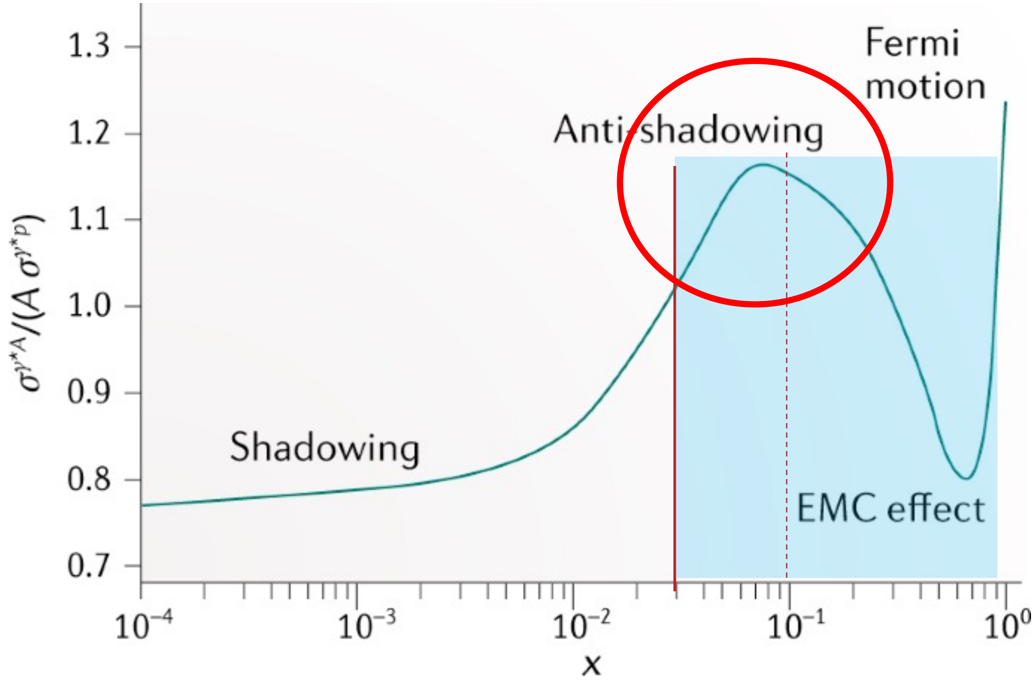
Berger, Coester, PRD, 1985





What is so special at x ~ 0.1?

- **Physics at x ~ 0.1:**



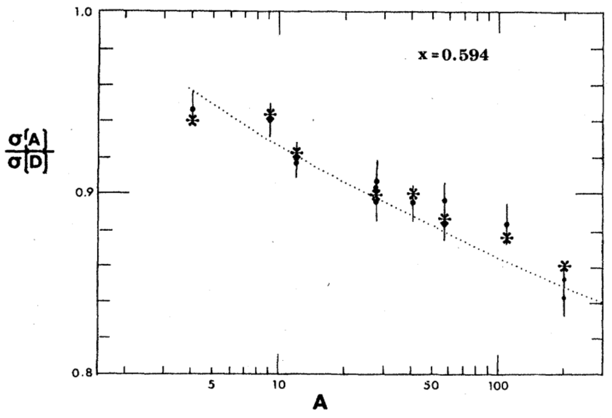
$$\frac{1}{A}F_2^A(x,Q^2)=F_2^N(x,\xi_A(Q^2)Q^2)$$

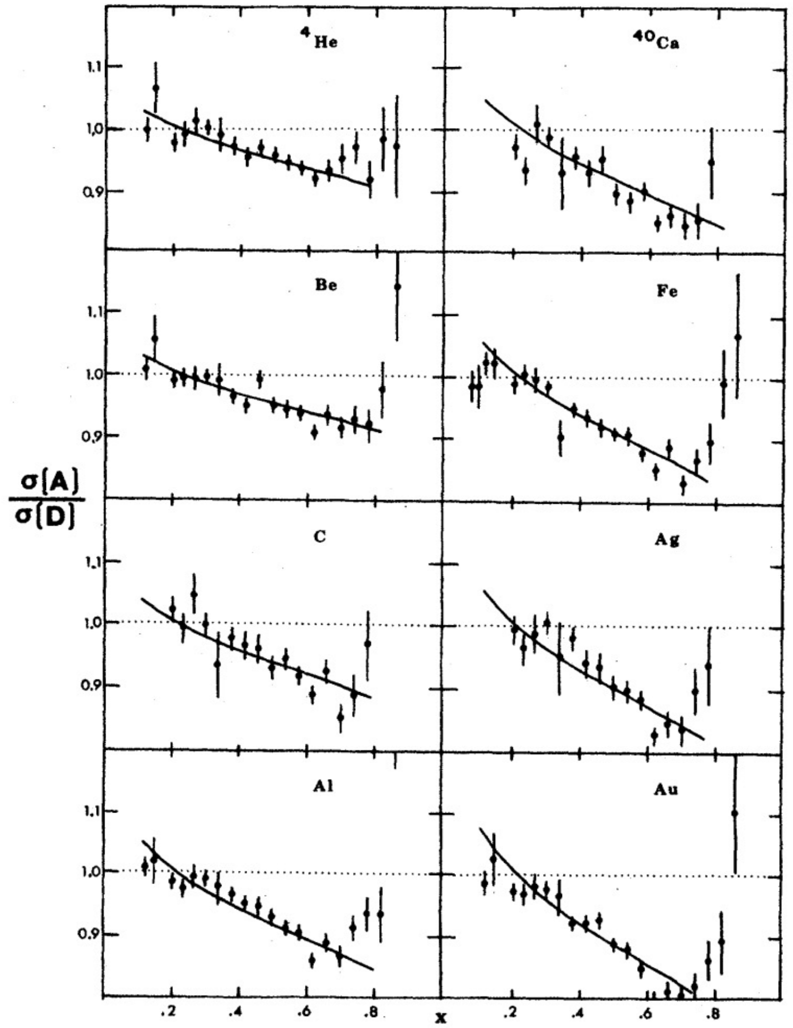
"rescaling parameter" $\xi_A(Q^2)$

Sensitive to nuclear model

Close, Jaffe, Roberts, Ross, PRD, 1985

- Change of confining scale:





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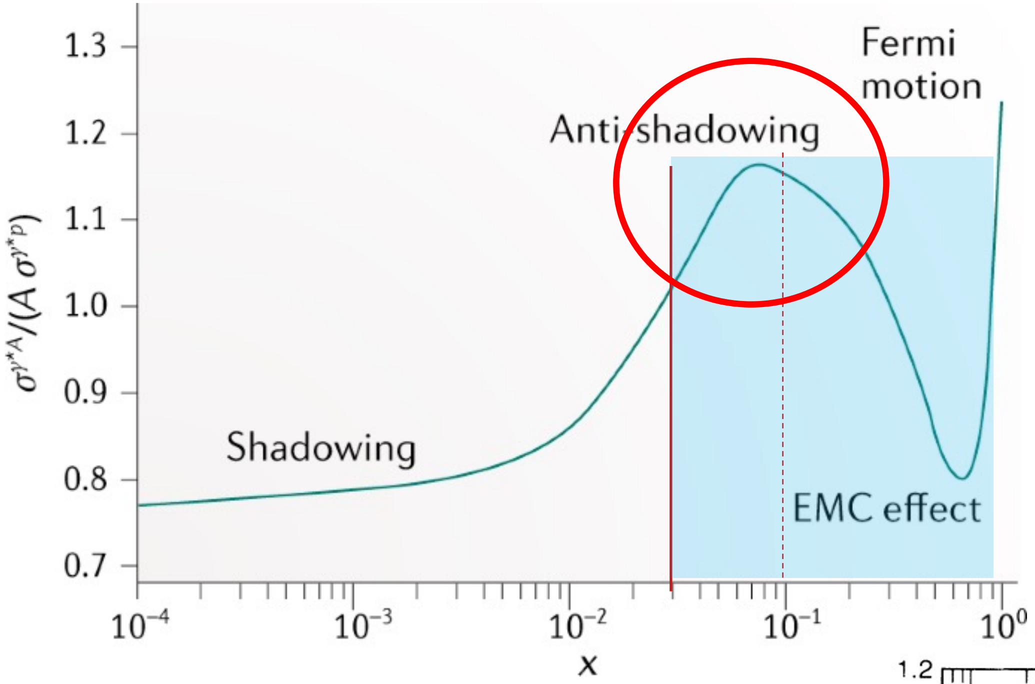
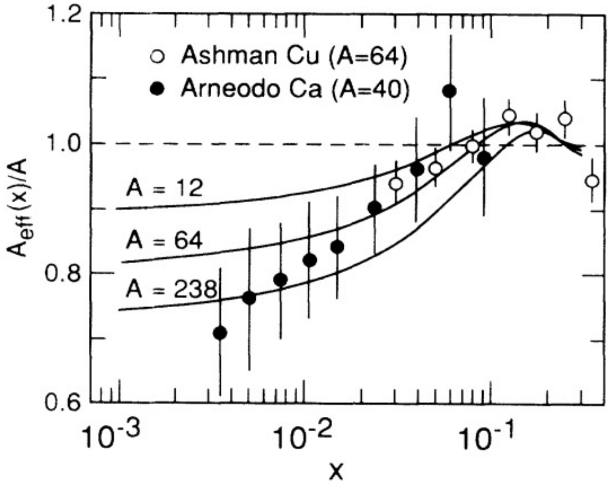
What is so special at x ~ 0.1?

❑ **Physics at x ~ 0.1:**



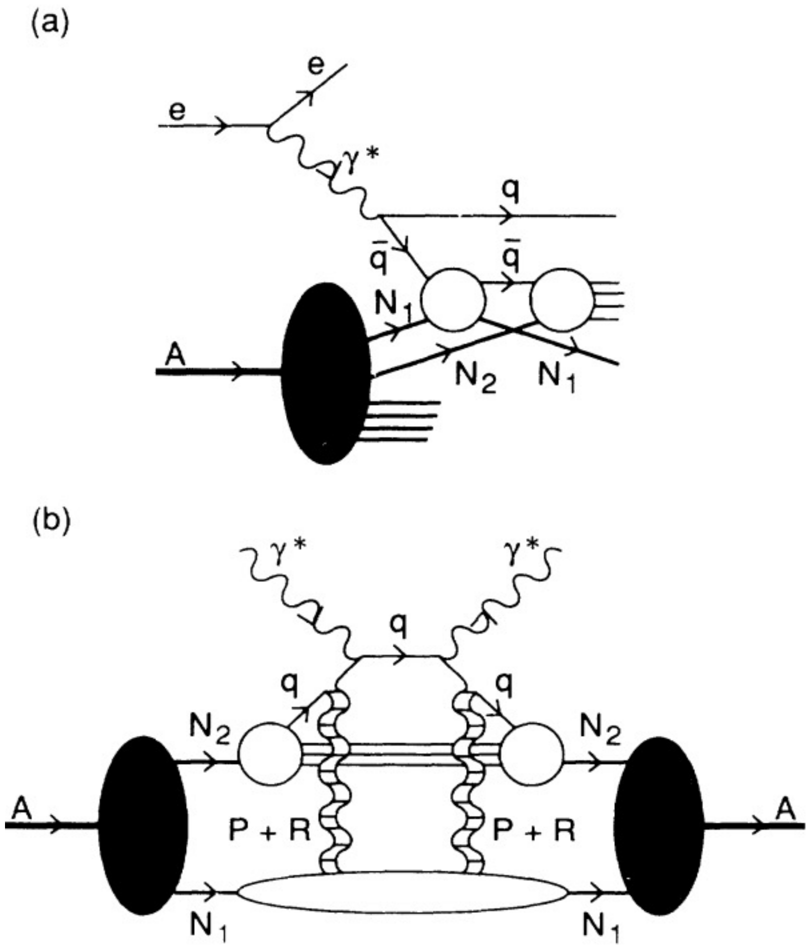
$$\frac{A_{\rm eff}(x)}{A} = \frac{F_2^A(x)}{AF_2^N(x)} = \frac{xf^A(x)}{Axf^N(x)}$$

$$= \frac{\int ds\, d^2k_\perp \,{\rm Im}T_R^A(s,v^2)}{A\int ds\, d^2k_\perp \,{\rm Im}T_R^N(s,v^2)}$$



- Multiple scattering:

Brodsky, Lu, PRL, 1990



Jefferson Lab

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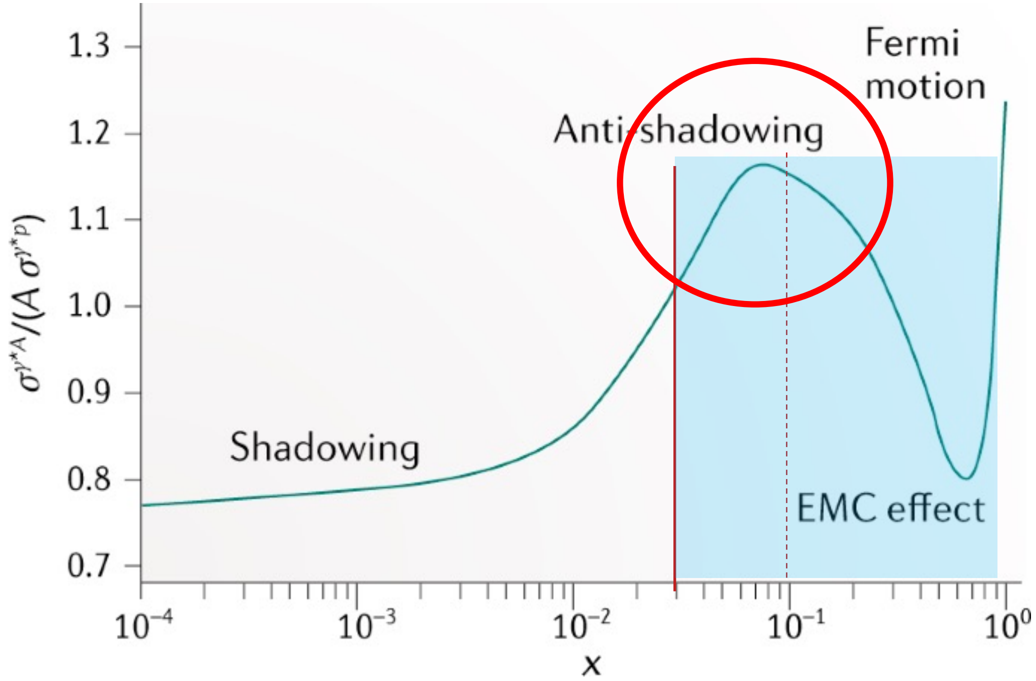
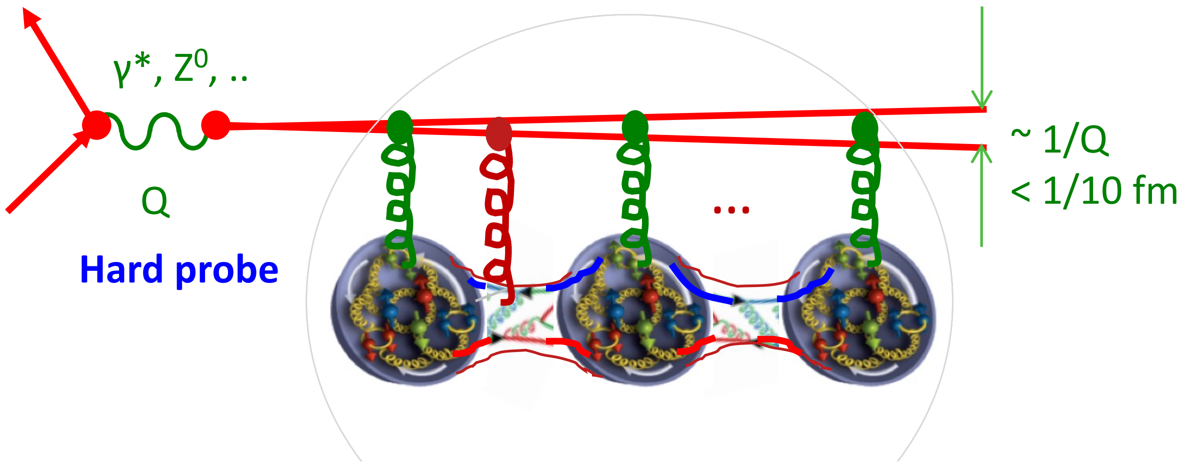


- Multiple scattering with nuclear enhanced DPFs?

$$\sigma^{\gamma * A} \propto \langle P_A, A|\mathcal{O}_A(\{y_A\},\{y'_A\})|P_A, A|\rangle$$



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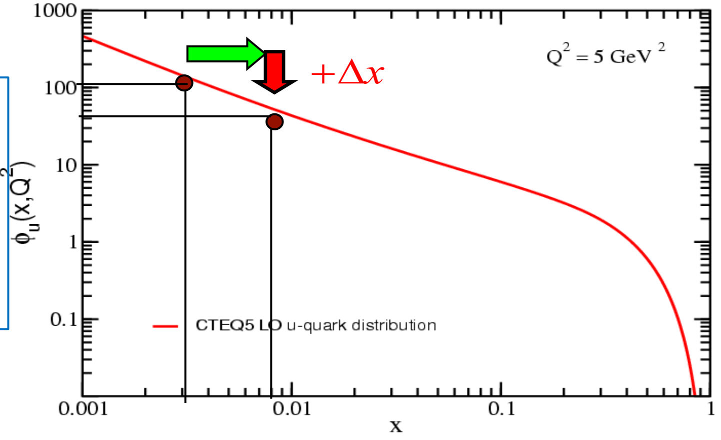
$$\approx F_T^{(0)}(x_B(1+\Delta),Q^2)$$

$$\Delta \equiv \frac{\xi^2}{Q^2}\left(A^{1/3}-1\right)$$

$$\xi^2 = \frac{3\pi\alpha_s}{8R^2}\langle F^{+\alpha}F_\alpha{}^{+}\rangle$$

Nuclear enhanced distributions

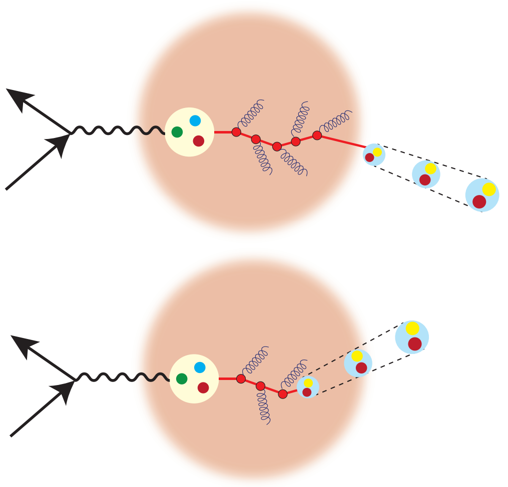
A shift in x on an enhanced "nuclear" structure functions could lead to the antishadowing phenomenon



Emergence of a hadron

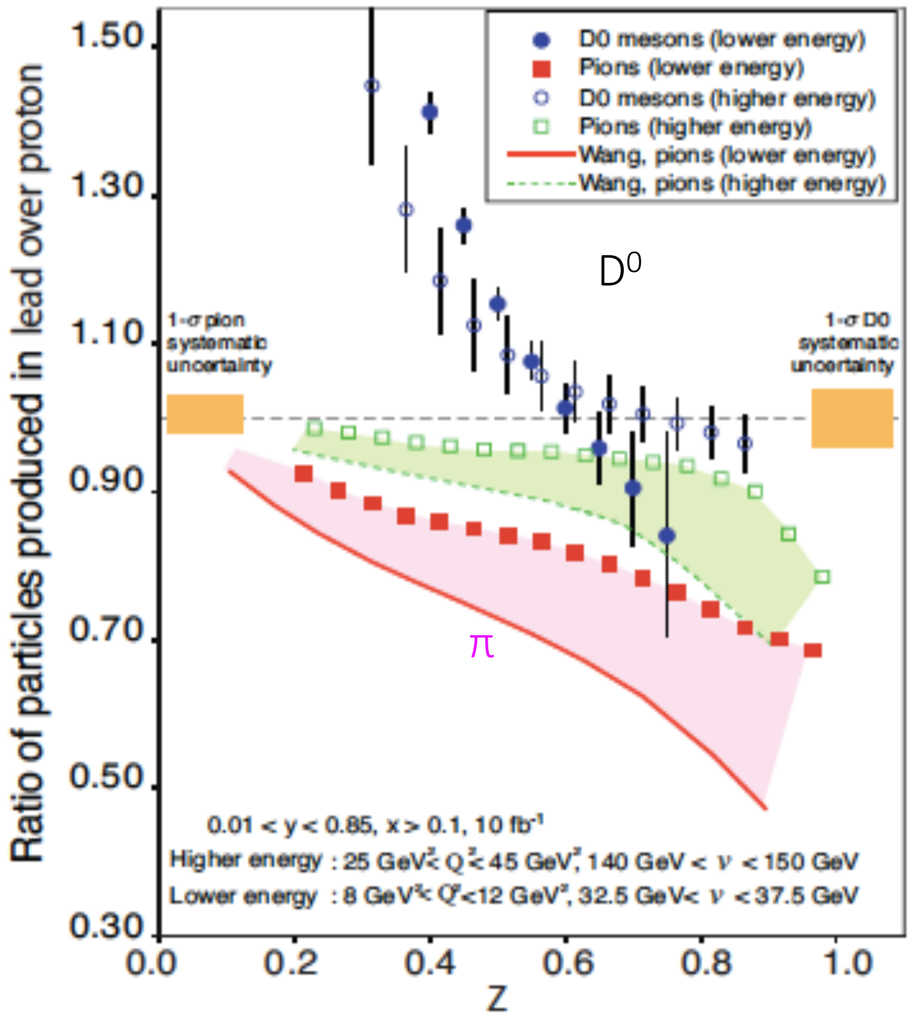
❑ Nuclei as femtometer sized detectors:

W.K. Brooks



$$\nu = \frac{Q^2}{2mx}$$

At JLab 20+GeV, better range of ν than JLab 6!



SIDIS in eA:

Propagation of a color charge, and multiple scattering

Color neutralization and the lifetime of a color state

A-dependence of production rate – 0^{th} moment
A-dependence of transverse momentum broadening – 1^{st} moment
…

EIC WP

Simulation is needed!

Summary

We have many excellent talks in this short and focused workshop

With a higher energy electron beam (~20-24 GeV) at JLab, we could explore

- the long-standing mystery of anti-shadowing for the first time in decades

  CTEQ found that nuclear dependence in this region seems different for neutrino beam

- novel tagged measurements to provide access to meson structure and the role of mesons in nuclei
- how to better extract the meson distributions
- the strange sea with minimal theoretical bias by using parity-violating electron scattering
- the interplay of the valence and sea regimes by studying in this transition region
- emergence of hadron and color propagation
- Impact on our theory perspectives for strong interaction at Fermi-scale

……

Backup slides