Gluonic Probe for the Short Range Correlations in Nucleus

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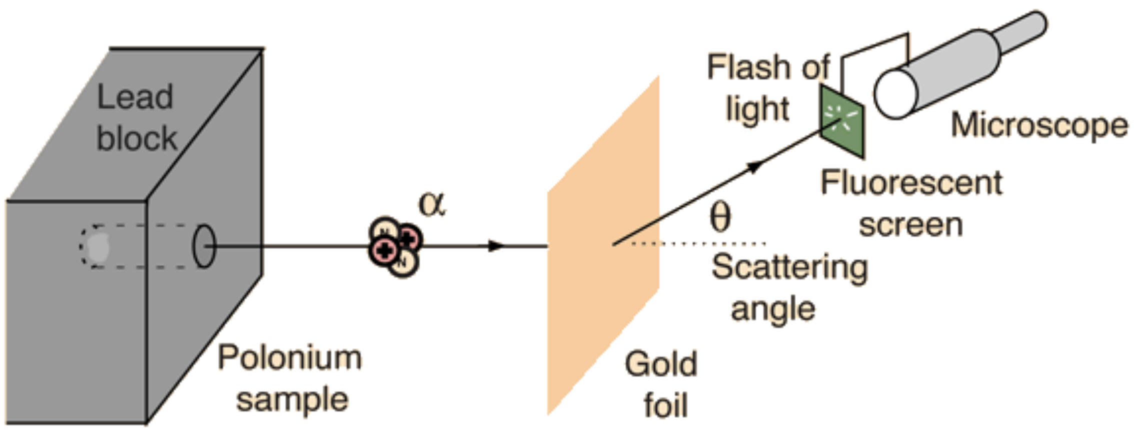
Xu, Yuan, PLB 801, 135187 (2020)

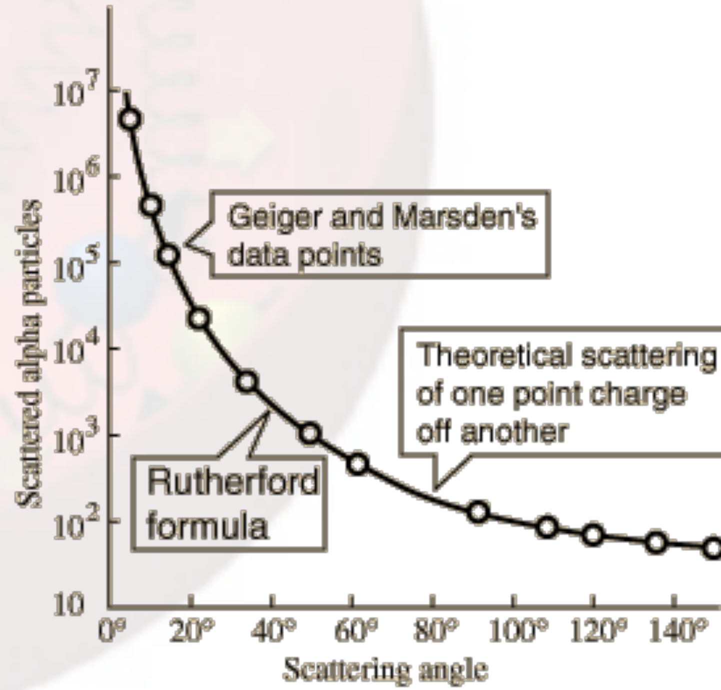
Hatta, Strikman, Xu, Yuan, PLB 803, 135321 (2020)

Rutherford scattering

The Scattering of α and β Particles by Matter and the Structure of the Atom

E. Rutherford, F.R.S.*
Philosophical Magazine
Series 6, vol. 21
May 1911, p. 669-688



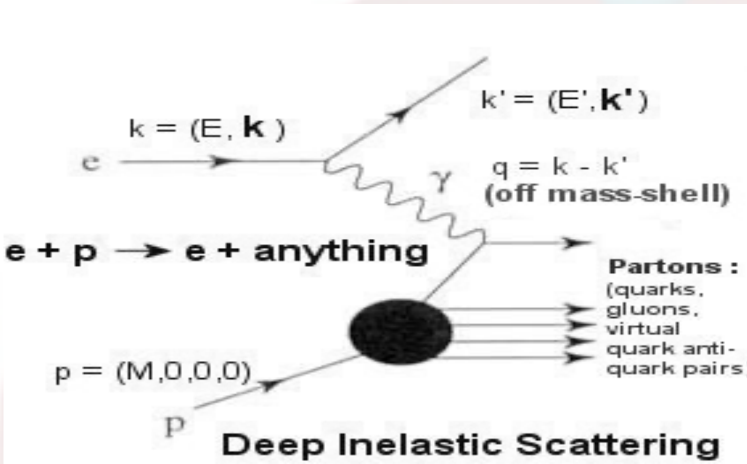


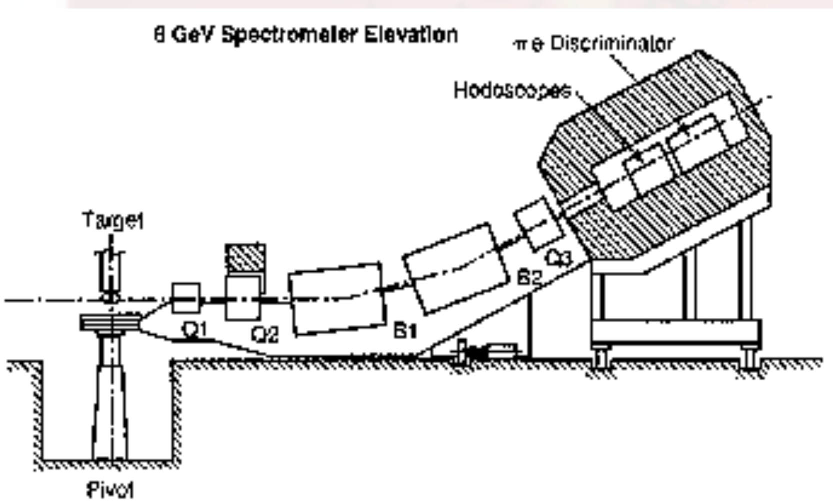
Discovery of Nuclei

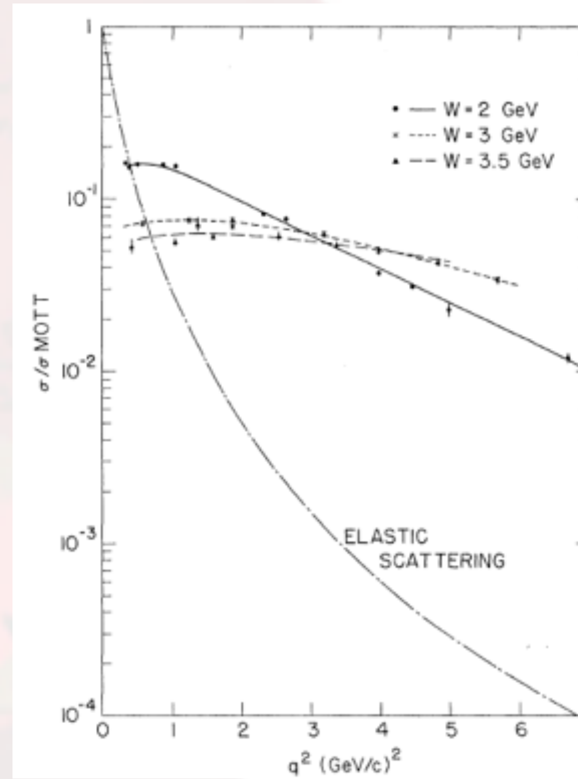
Deep Inelastic Scattering

Discovery of Quarks

Friedman Kendall Taylor







Bjorken Scaling: $Q^2 \rightarrow$ Infinity

Feynman Parton Model:

Point-like structure in Nucleon

Quantum Chromodynamics

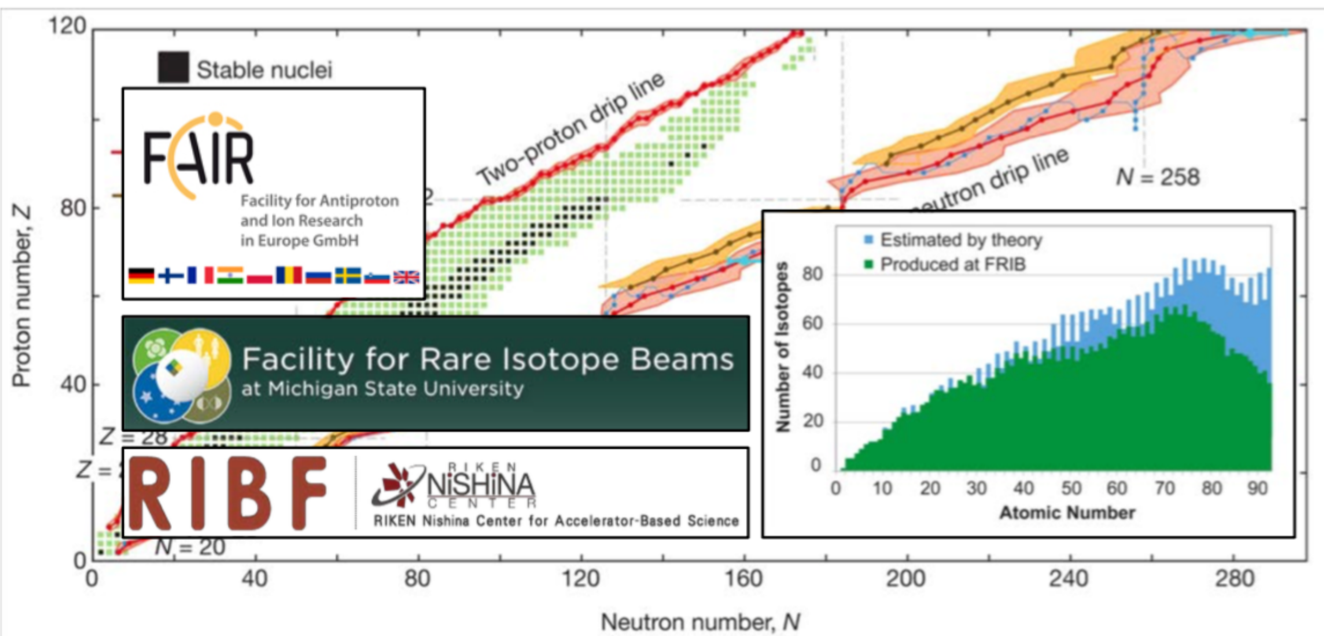
- There is no doubt that QCD is the right theory for hadron physics
- However, many fundamental questions…
- How does the **nucleon mass** emerge from the light quarks dynamically?
- Why quarks and gluons are **confined** inside the nucleon?
- How do the fundamental **nuclear forces** arise from QCD?
- We don't have a **comprehensive picture** of the nucleon structure as we don't have an approximate QCD nucleon wave function
- …

Central questions for nuclear structure physics

Where do heavy elements come from?

How does the nuclear chart emerge from QCD?

How to predict properties of nuclei?



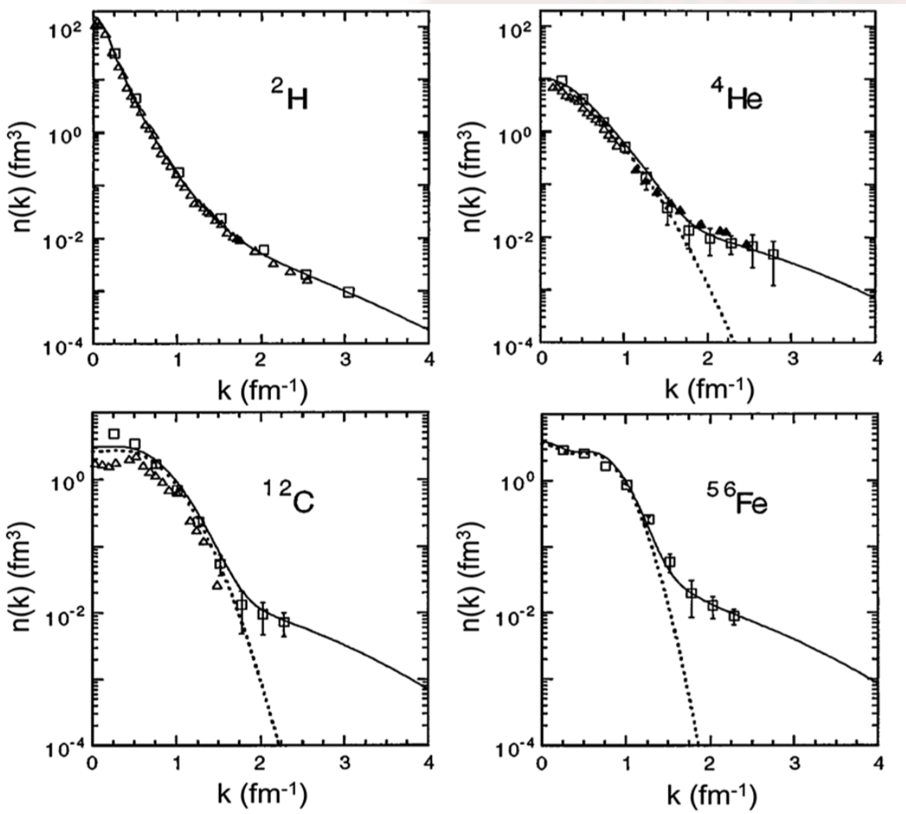
observables

many-body framework

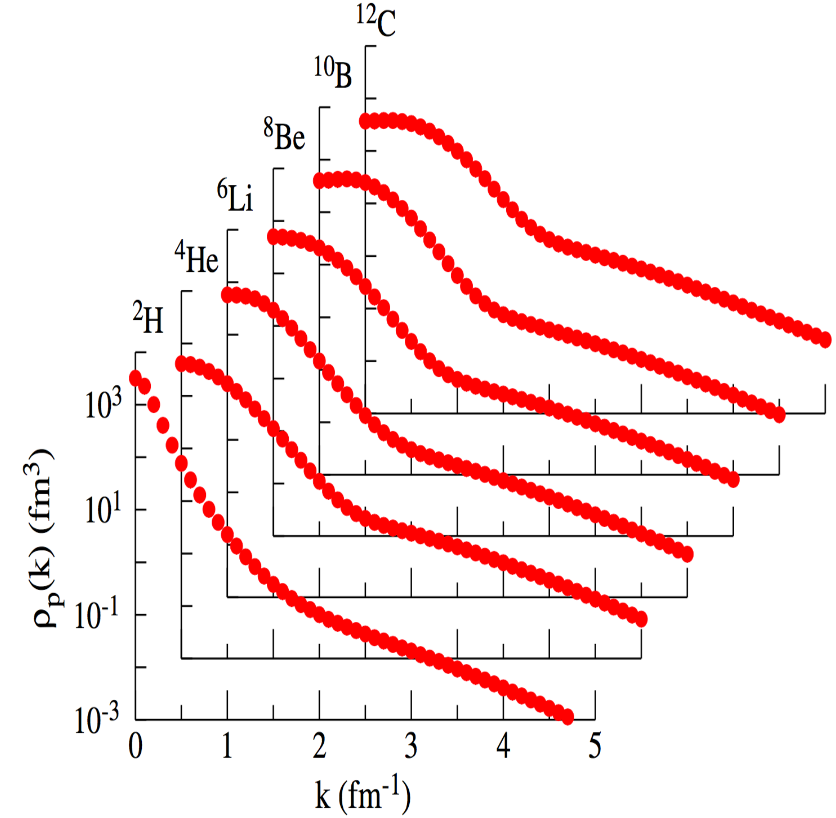
effective field theory

quantum chromodynamics

Nucleon momentum distribution inside nucleus

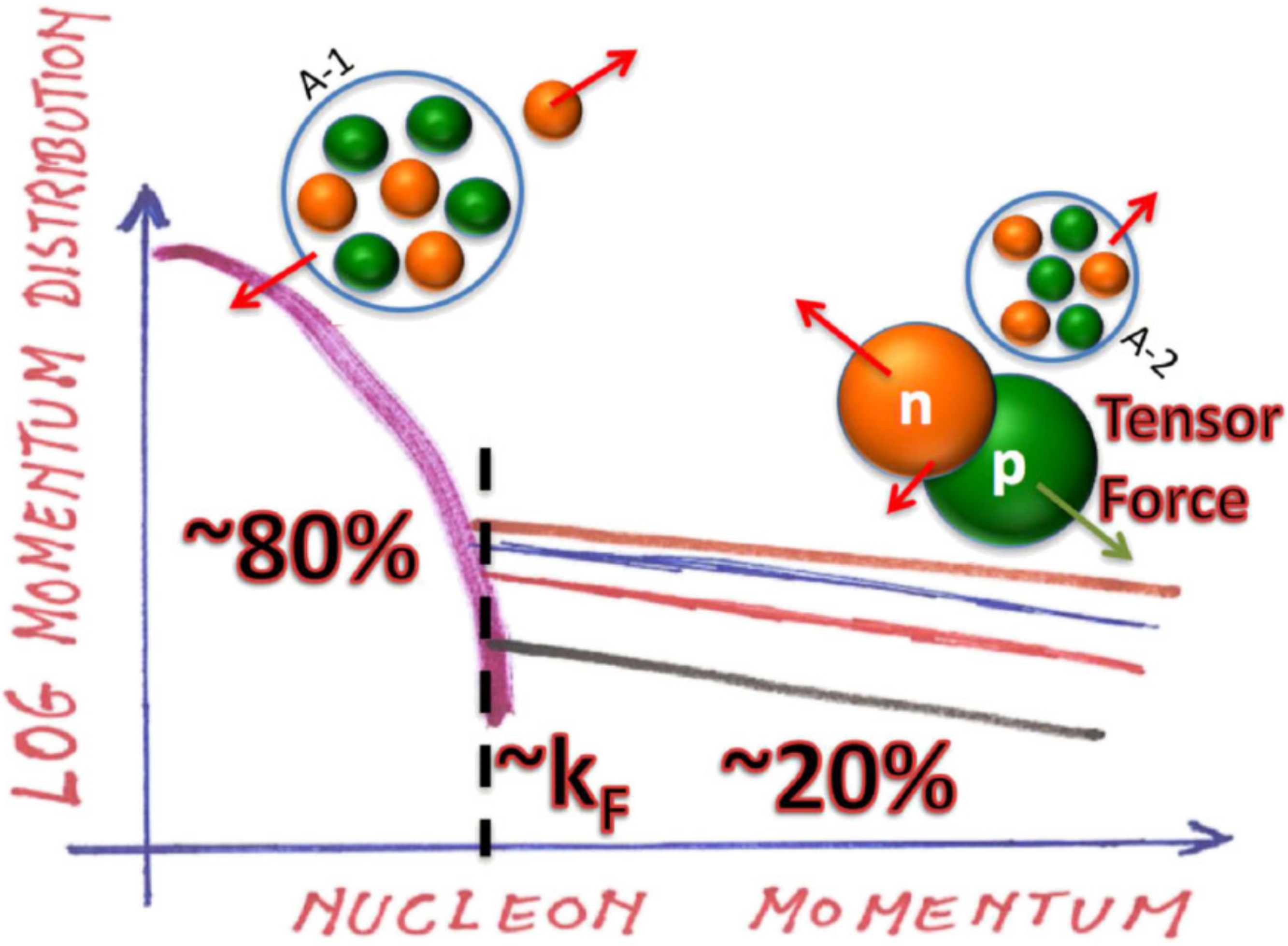


Electron scattering exp.



Carlson et al, RMP, 2015

Basic Picture



Hen et al, RMP 2017

What is short-range correlation

- Neutron-proton close in coordinate space
- Momentum space
  - Low total momentum
  - High relative momentum

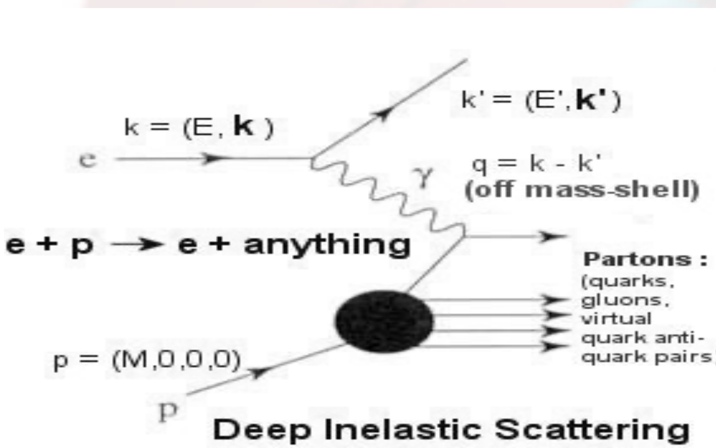
Three Different Ways to Probe the SRC

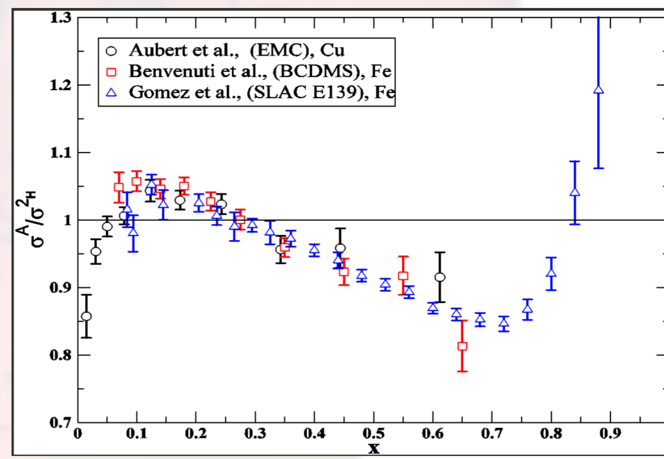
- Momentum distribution of nucleons
  - Limited to low momentum region
- Knock out experiments
- Hard partonic processes: structure function modifications
  - EMC effects
  - Fast moving partons
    - (Structure function at $x_B>1$)

JLab's major Activities: Quark

EMC: nuclear modification of structure functions

- DIS structure function measures the parton distribution in nucleon/nucleus

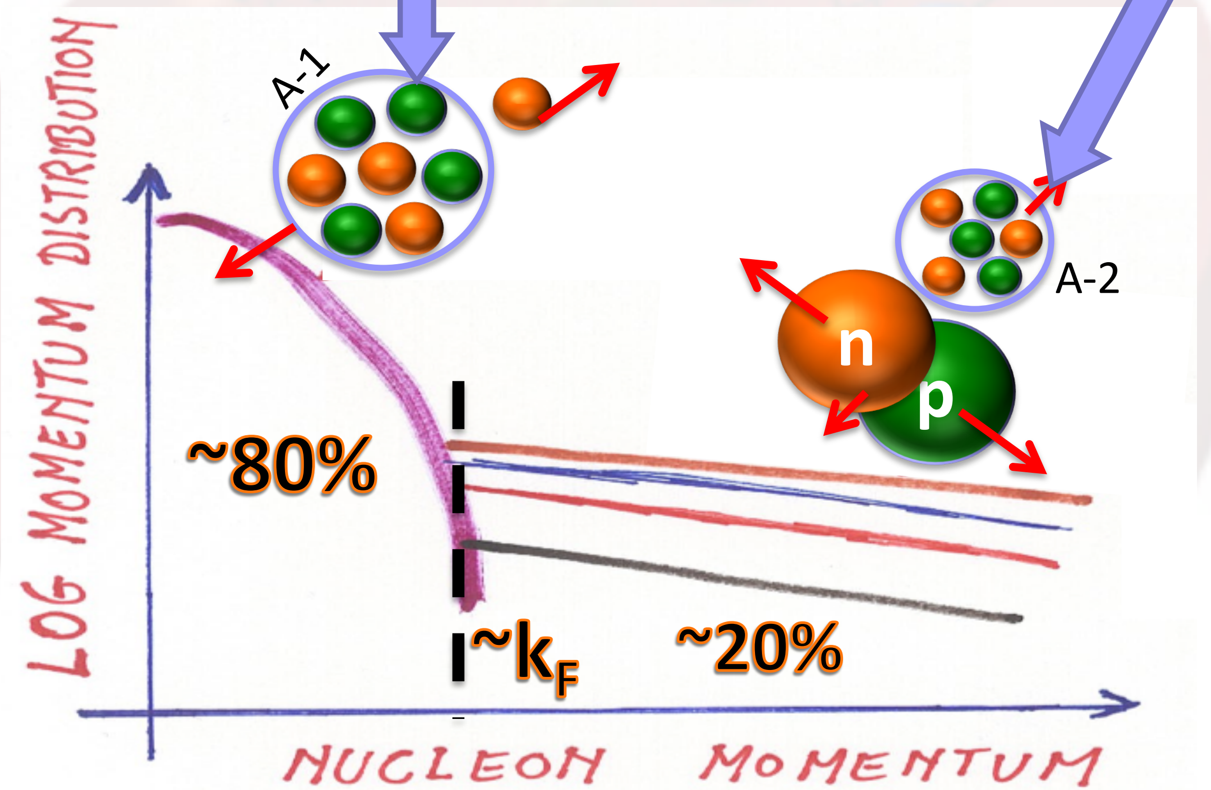




$$F_2^A = Z\,F_2^p + N\,F_2^n \longrightarrow \frac{\sigma_A/A}{\sigma_D/2} \approx 1$$

Bound = 'quasi Free' + Modified SRCs

$$\sigma_A = n_p\sigma_p + n_n\sigma_n + n_{np}(\Delta\sigma_p + \Delta\sigma_n)$$

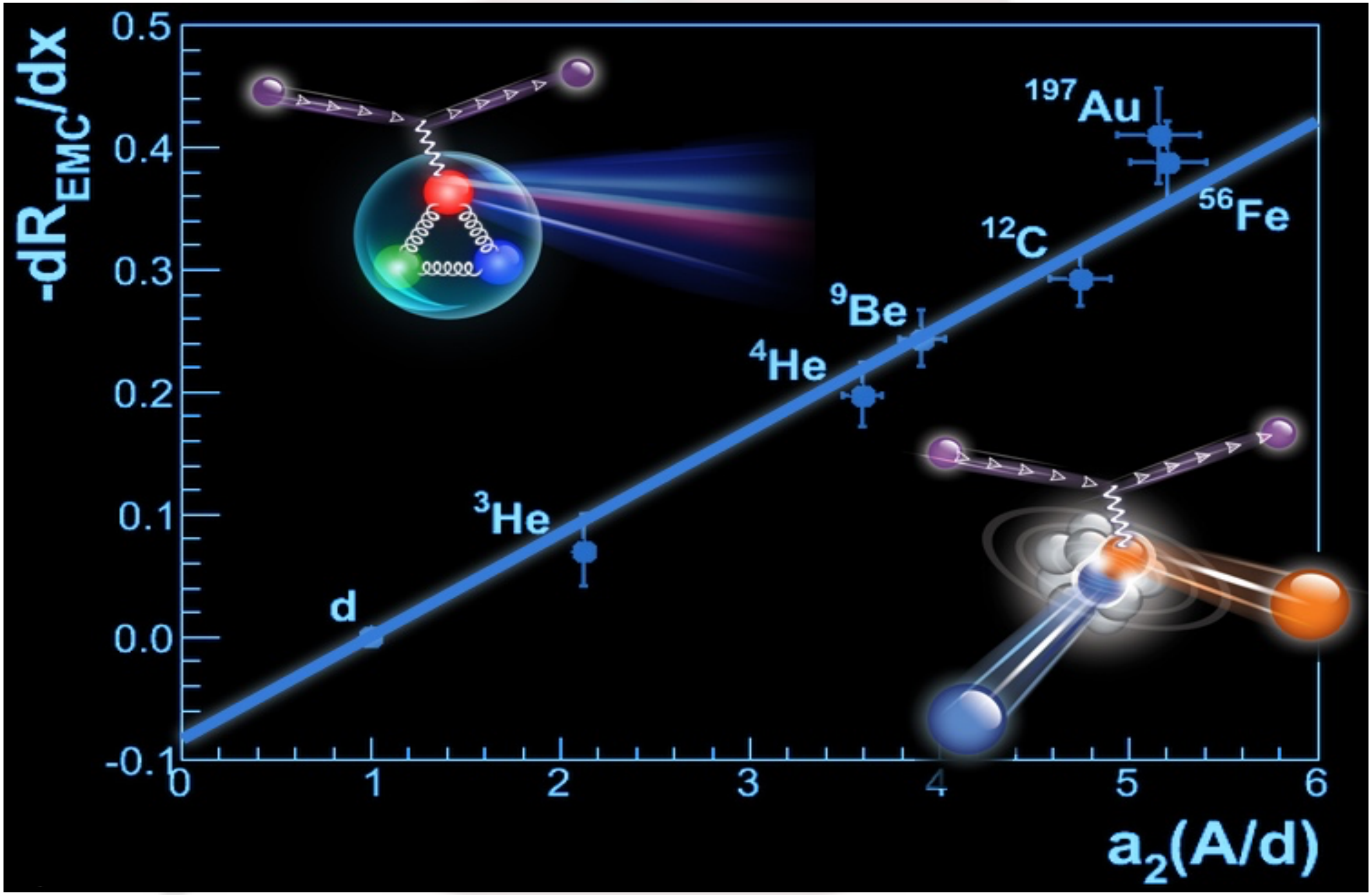


Universality is the key to establish the physics associated with SRC!!

Universality of SRC Contributions

- Different processes
  - Same SRC pair contribute to different hard processes
  - Universal partonic structure
- Different nuclei
  - Only depend on the probability of the SRC pair, nuclear dependence same for different processes
  - Link different nuclei by the SRC factors

Universality: Quark Sector



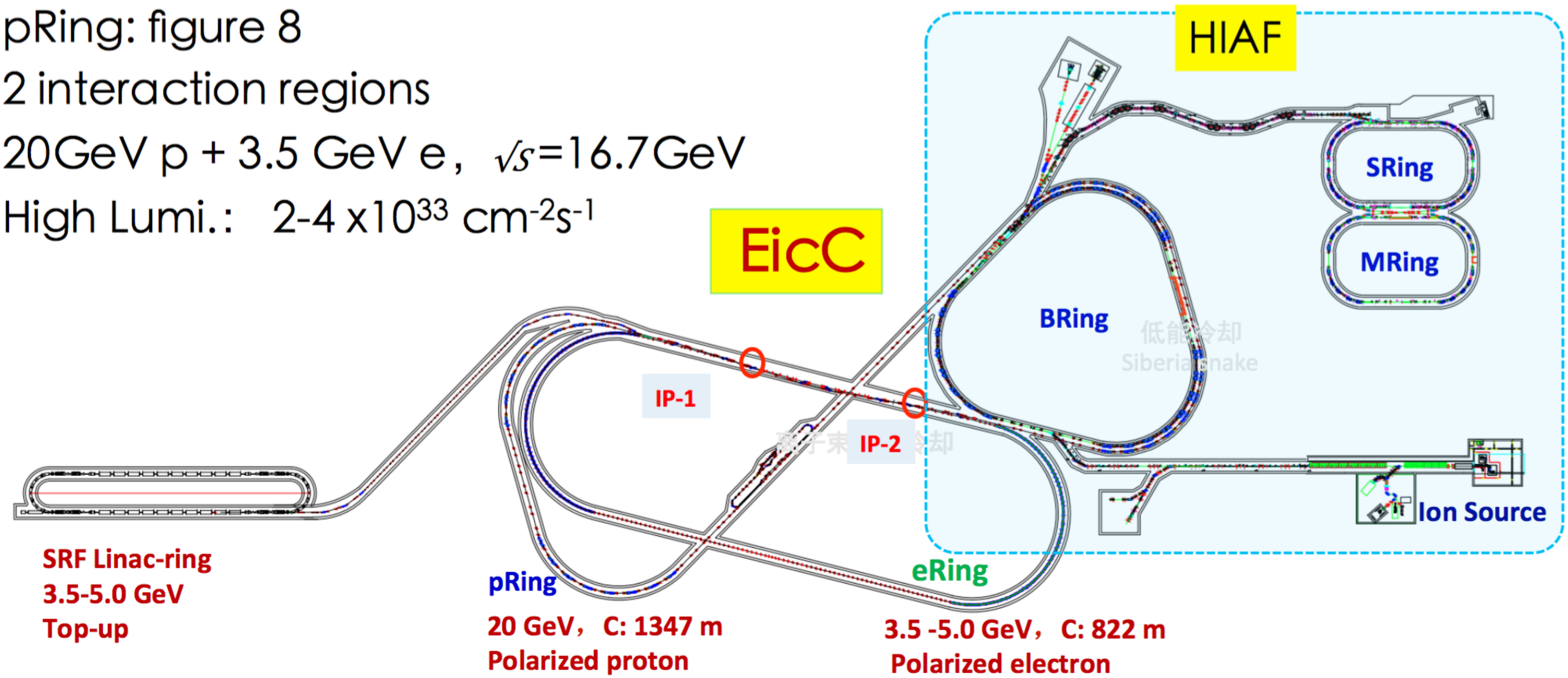
Gluonic probe for SRC at an Intermediate Energy EIC

- Kinematic focus will be in the EMC region
- Energy is high enough to study heavy flavor production
  - Charm Structure Function
  - Sub-threshold production of open Charm and Charmonium

Polarized Electron-Ion Collider in China EicC

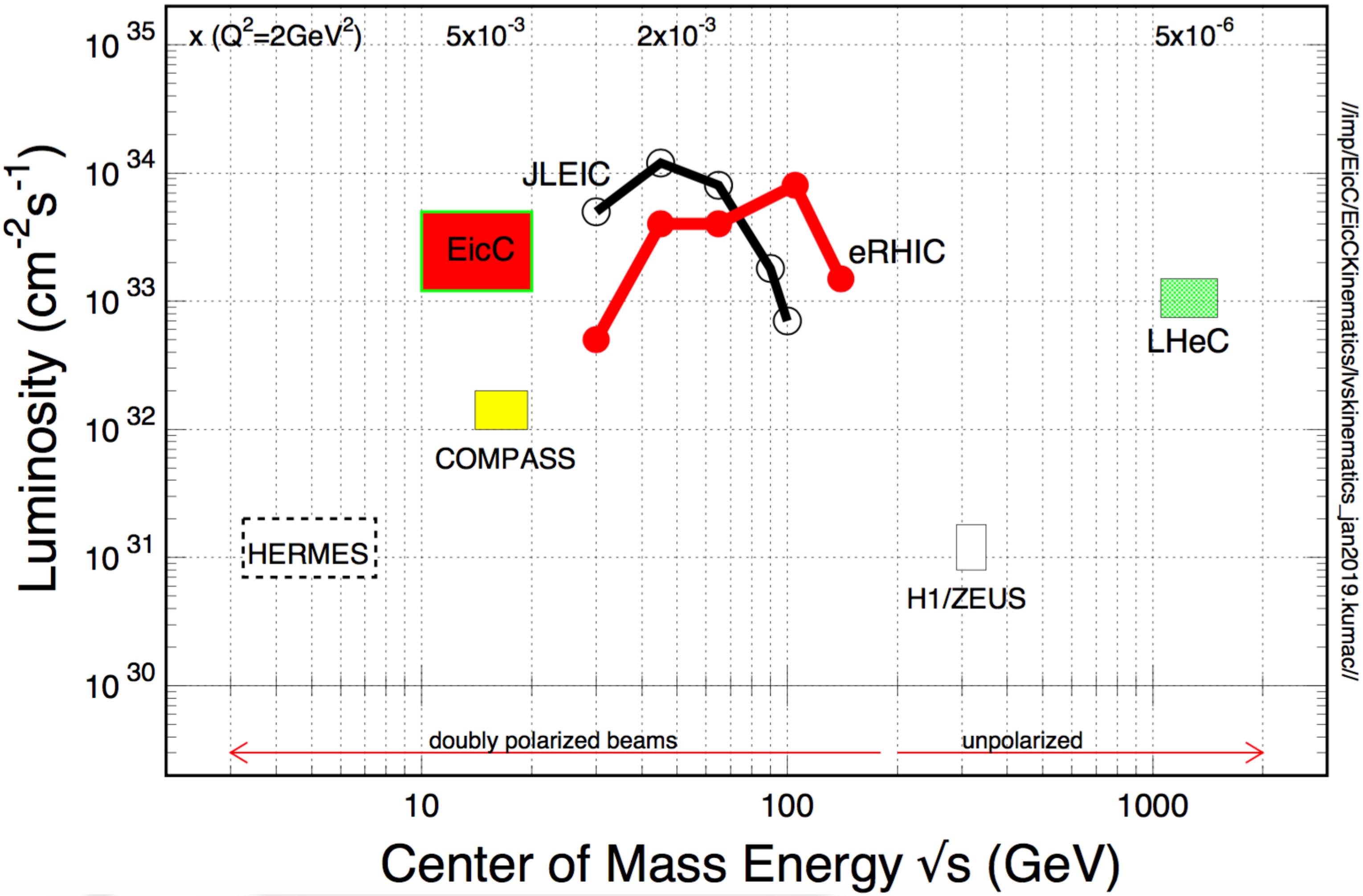
EicC Accelerator Complex

- pRing: figure 8
- 2 interaction regions
- 20GeV p + 3.5 GeV e, $\sqrt{s}$=16.7GeV
- High Lumi.: 2-4 x10^{33} $cm^{-2}s^{-1}$



Nu Xu@QCD Workshop, Weihai, July 2019

Designed Energy and Luminosity



Nu Xu@QCD Workshop, Weihai, July 2019

Gluon distribution in nucleus: SRC contributions

- Because of isospin symmetry:

$$g_A(x,Q^2) = Ag_p(x,Q^2) + 2n^A_{src}\delta\tilde{g}(x,Q^2)$$

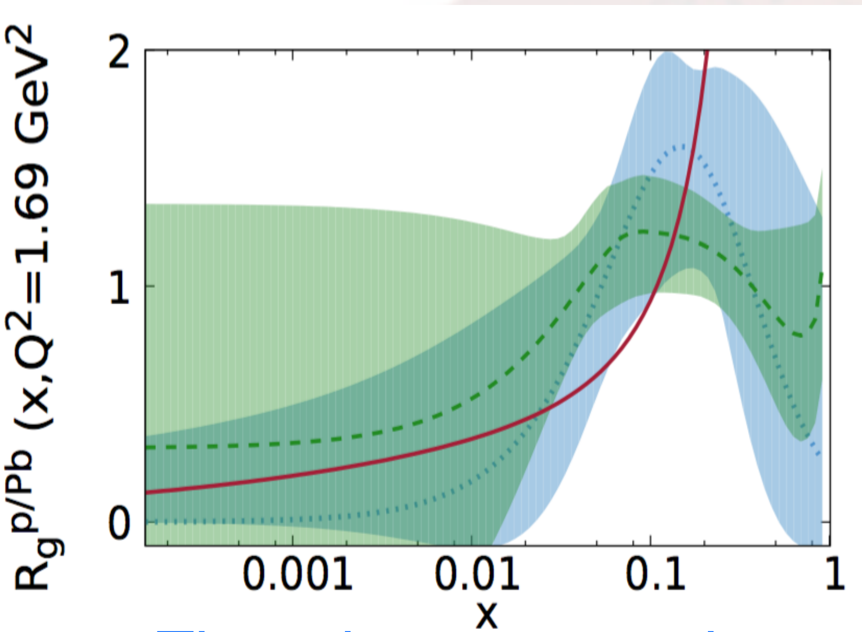
  - Compare to the quark sector

$$F_2^A = (Z - n^A_{SRC})F_2^p + (N - n^A_{SRC})F_2^n + n^A_{SRC}(F_2^{p*} + F_2^{n*})$$

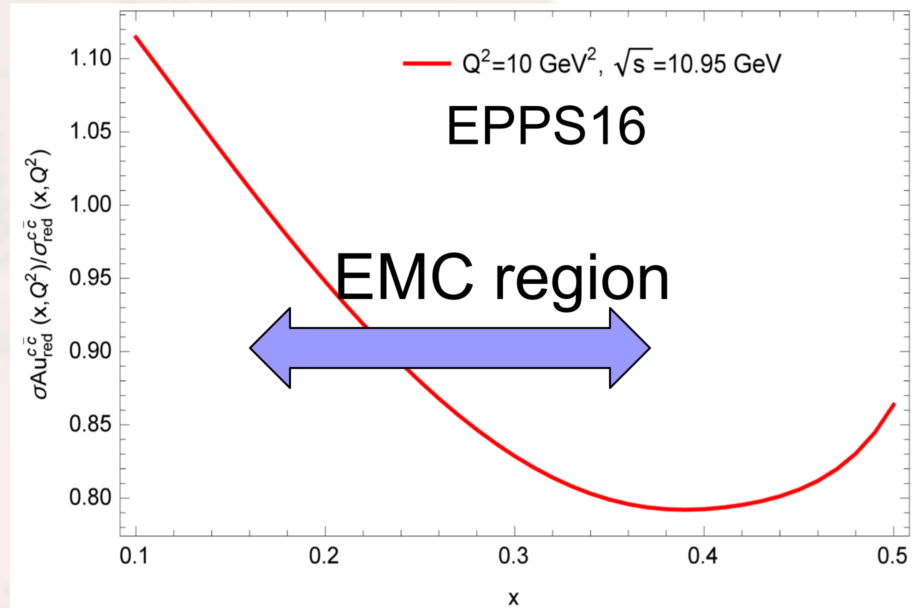
$$= ZF_2^p + NF_2^n + n^A_{SRC}(\Delta F_2^p + \Delta F_2^n)$$

SRC Factor: n^A_{src}

EMC Effects in Charm F_2 at EicC

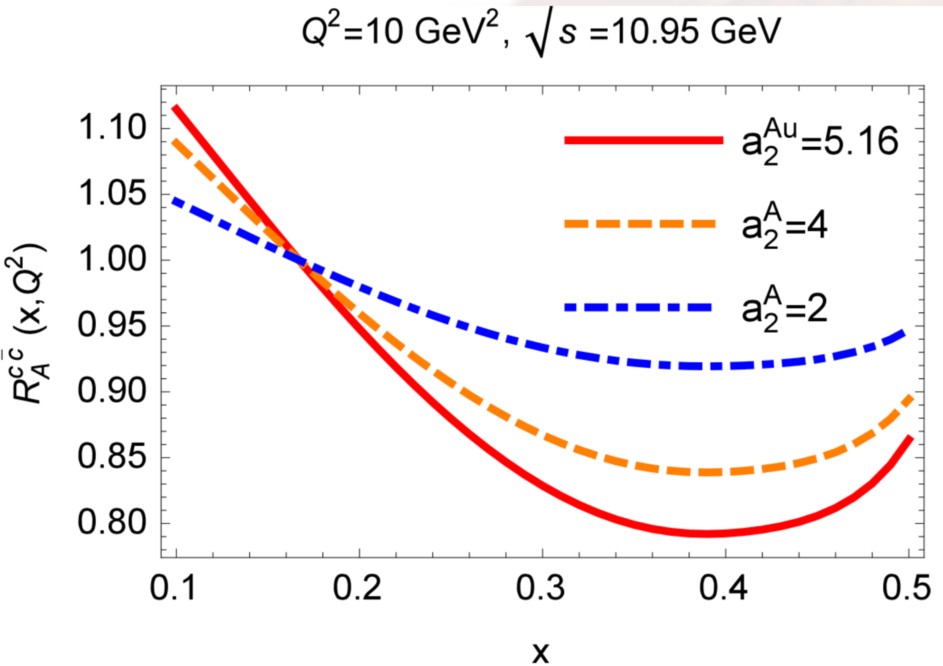


There is no constraint for the gluon EMC:
EPPS16, 1612.05741
nCTEQ, 1509.00792
TUJU19, 1908.03355



Gluon momentum fraction= $x(1+4m_c^2/Q^2)$

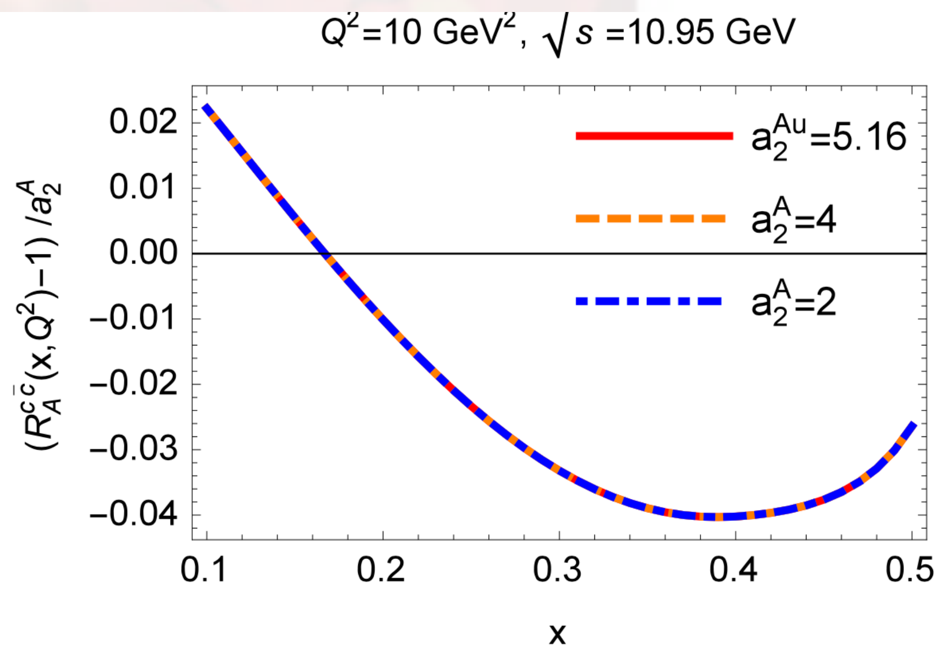
Universality of the nuclear modifications



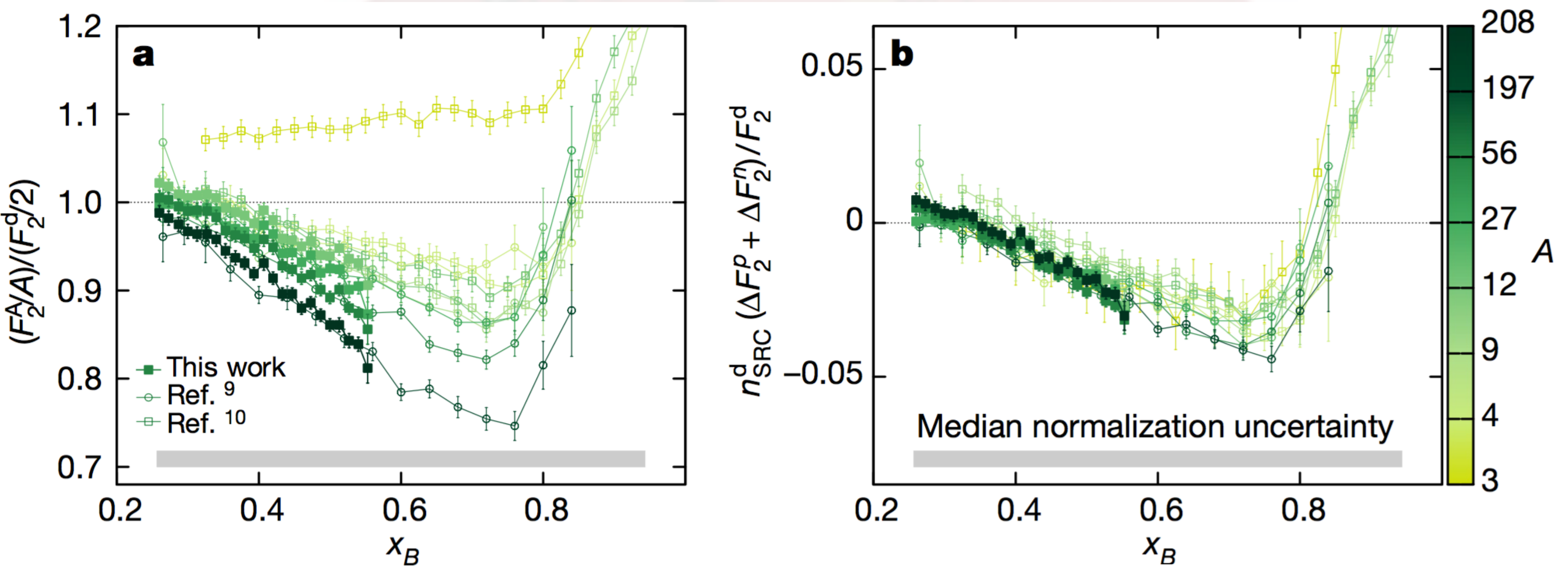
Au: EPPS16; others follow the universal behavior

Divide by the SRC Factor

$$a_2^A = (n_{src}^A/A)/(n_{src}^d/2)$$



Quark sector: Isospin dependence



CLAS Coll., Nature 2019
See also, Hen et al,1908.02223

$$\frac{n_{\mathrm{SRC}}^{\mathrm{d}}(\Delta F_2^p + \Delta F_2^n)}{F_2^{\mathrm{d}}} = \frac{\frac{F_2^{\mathrm{A}}}{F_2^{\mathrm{d}}} - (Z-N)\frac{F_2^p}{F_2^{\mathrm{d}}} - N}{(A/2)a_2 - N}$$

Universality of SRC: two facts

- EMC effects for different nuclei can be described by the same universal SRC contributions
  - Quark/gluon shall differ
- The same SRC factor for both quark and gluon sectors

Jpsi production: build a model for SRC contributions

- Jpsi production in photo-nuclear collisions

$$\sigma_{\gamma A\to J/\psi}(\sqrt{s_{\gamma p}}) = A\sigma_{\gamma p\to J/\psi}(\sqrt{s_{\gamma p}}) \\ + n^A_{src}(\sigma_{\gamma(pn)\to J/\psi}(\sqrt{s_{\gamma p}}) - 2\sigma_{\gamma p\to J/\psi}(\sqrt{s_{\gamma p}}))$$

- Below the photon-proton threshold

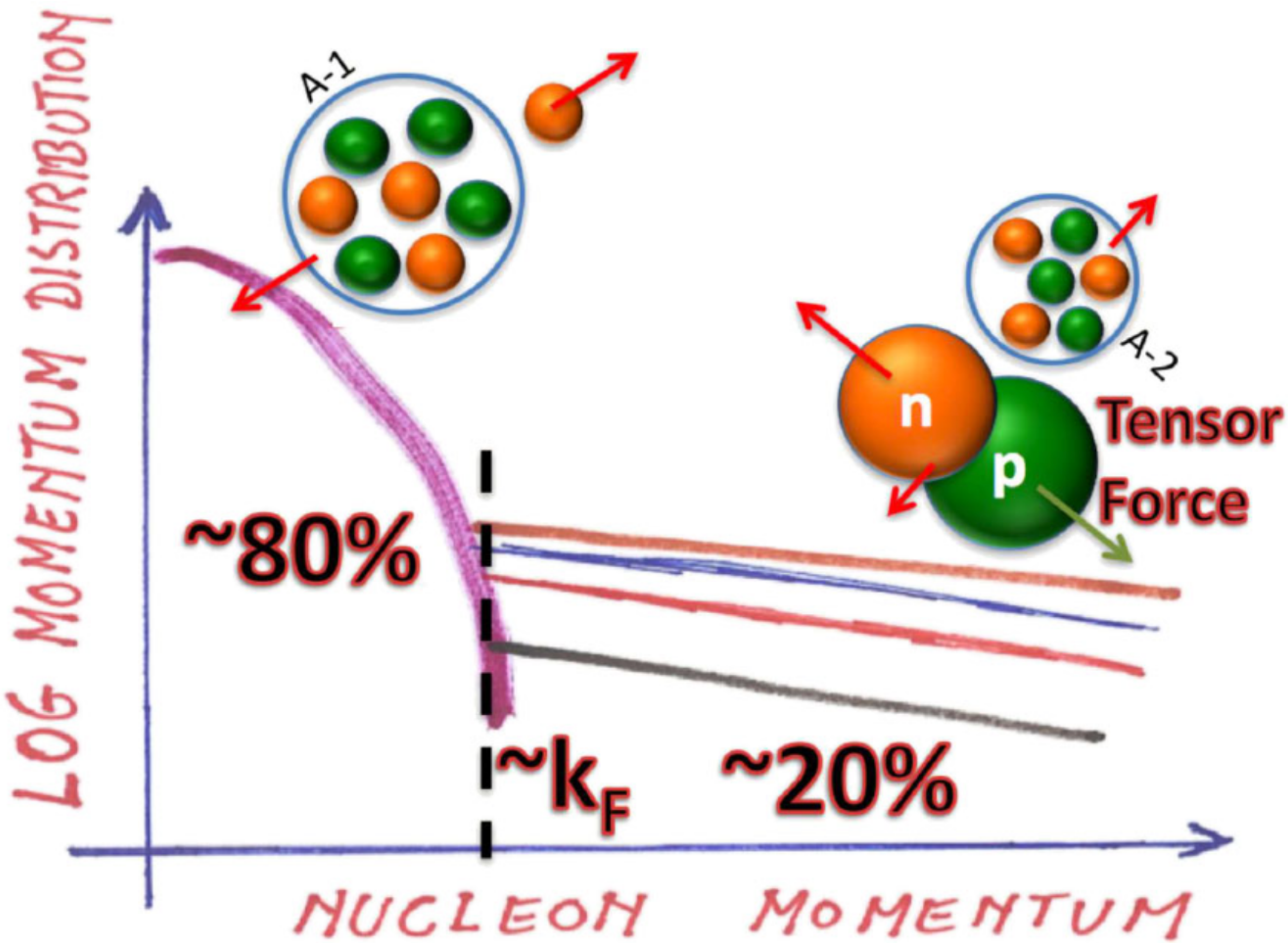
$$\sigma_{\gamma A\to J/\psi}(\sqrt{s_{\gamma p}} < M_p + M_{J/\psi}) = n^A_{src}\sigma_{\gamma(pn)\to J/\psi}(\sqrt{s_{\gamma p}})$$

- Universality

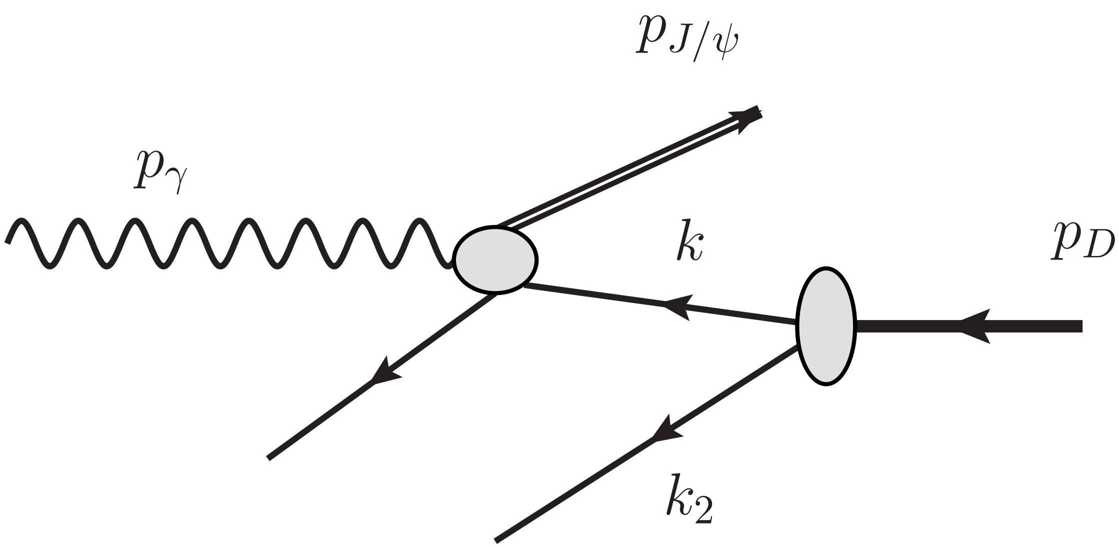
$$\boxed{\frac{\sigma_{\gamma A\to J/\psi}(\sqrt{s_{\gamma p}} < M_p + M_{J/\psi})}{\sigma_{\gamma d\to J/\psi}(\sqrt{s_{\gamma p}} < M_p + M_{J/\psi})} = \frac{n^A_{src}}{n^d_{src}} = \frac{F^A_2(x_B)}{F^d_2(x_B)}\Big|_{1.5<x_B<2.0}}$$

(See also: Paryev, 1510.00155)

However: Mean Field Contributions



Example: Deuteron Case



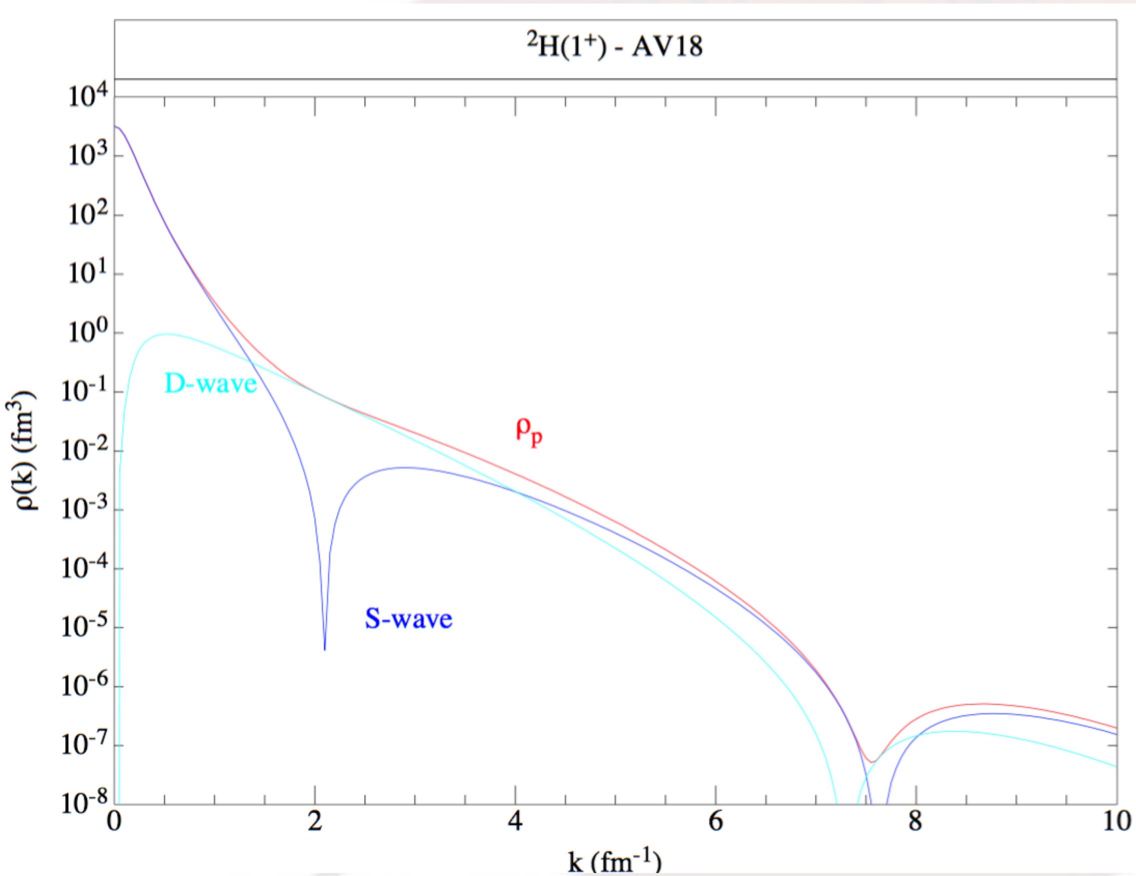
$$\sigma_{\gamma D}(W_{\gamma p}) = 2\int d^3k\,\rho_n(k)\widetilde{\mathcal{F}}(k)\sigma_{\gamma p}(W_{\gamma p'})$$

Nucleon's

Momentum distribution

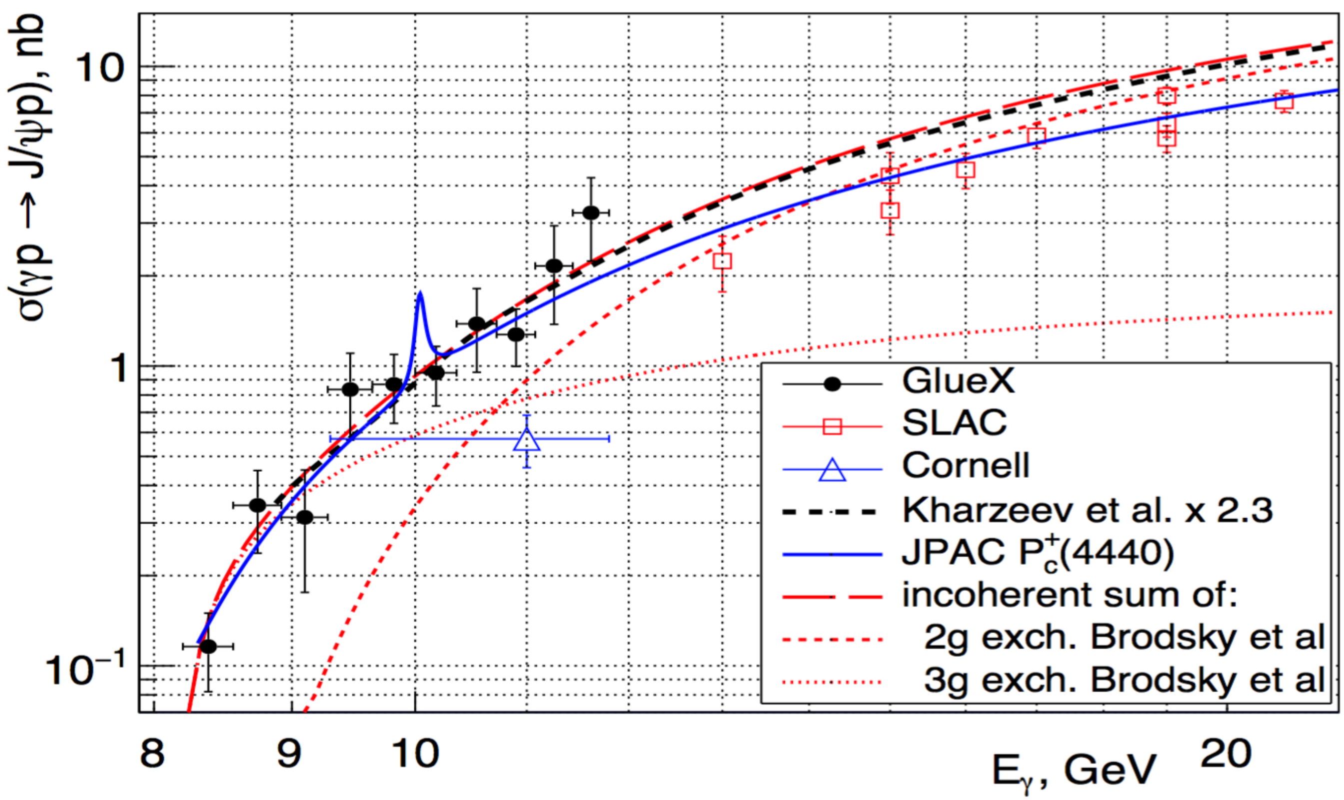
$$\int d^3k\,\rho_n(k) = 1$$

Nucleon momentum distribution in deuteron



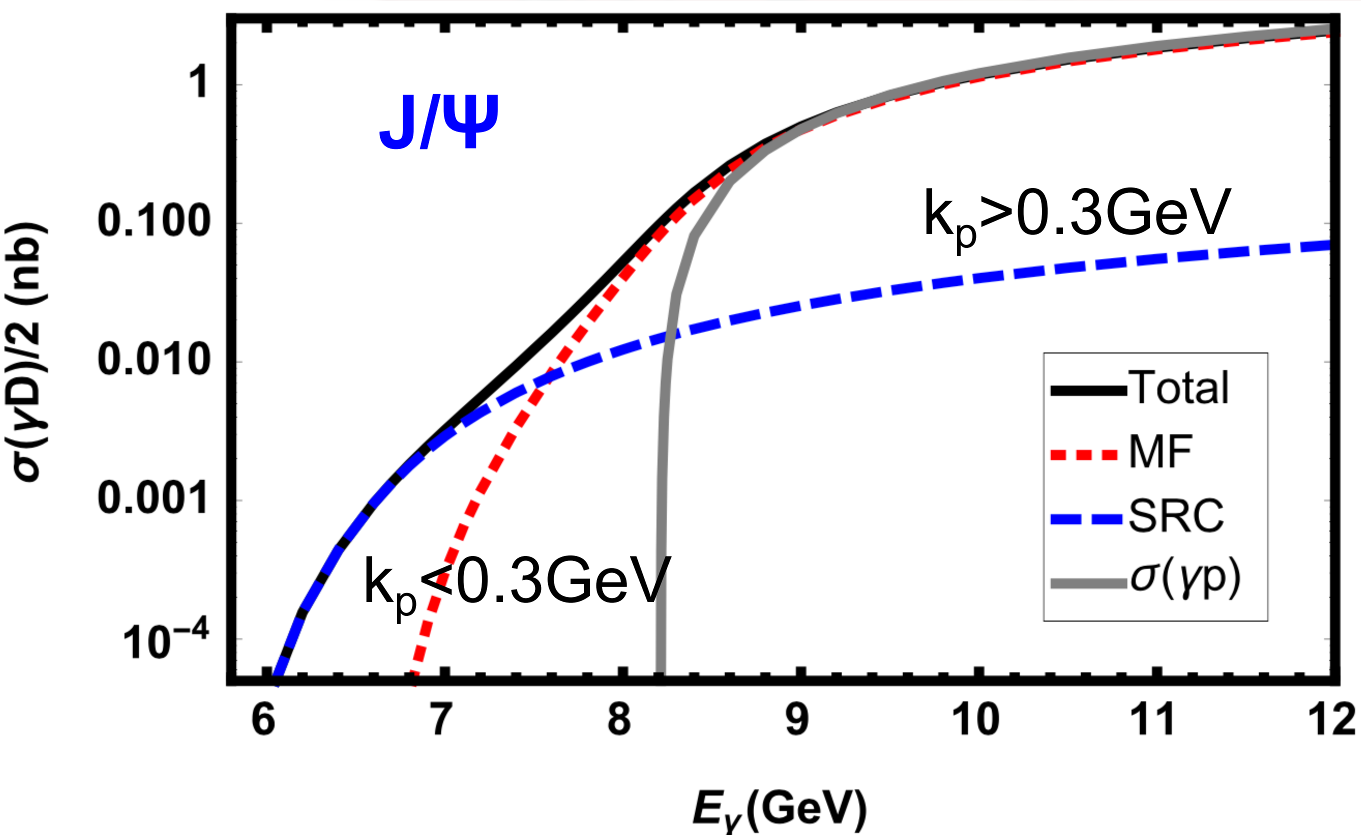
- Argonne potential: Wiringa et al., PRC 89, 024305 (2014)

Photon-proton cross sections: Recent JLab Measurement



GlueX Coll., PRL 2019, 1905.10811

Sub-threshold Jpsi production in photon-deuteron collisions



around 7GeV dominated by SRC

Hatta, Strikman, Xu, Yuan, 1911.11706

Generic nucleus: spectral function

$$\sigma_{\gamma A} = A \int d^3k d\epsilon \rho_A(k,\epsilon) \widetilde{\mathcal{F}}(k,\epsilon) \sigma_{\gamma p}(W_{\gamma p'})$$

- Spectral function describes nucleon momentum and energy distribution
  - Mean field: Gaussian distribution with width $k_F/2$
  - SRC contribution has to be calculated

$$\bar{\sigma}_{\gamma A} = \frac{\sigma_{\gamma A}}{A} \equiv \int_{k<k_F} \bar{\sigma}_{MF}(k) + \int_{k>k_F} \bar{\sigma}_{SRC}(k)$$

Spectral function from SRC

- Proton: (pn) and (pp) pair

$$\rho_A^{(SRC)p}(k,\epsilon) = C_{pn}^1 S_{pn}^1(k,\epsilon) + C_{pn}^0 S_{pn}^0(k,\epsilon) + 2C_{pp}^0 S_{pp}^0(k,\epsilon) \ ,$$

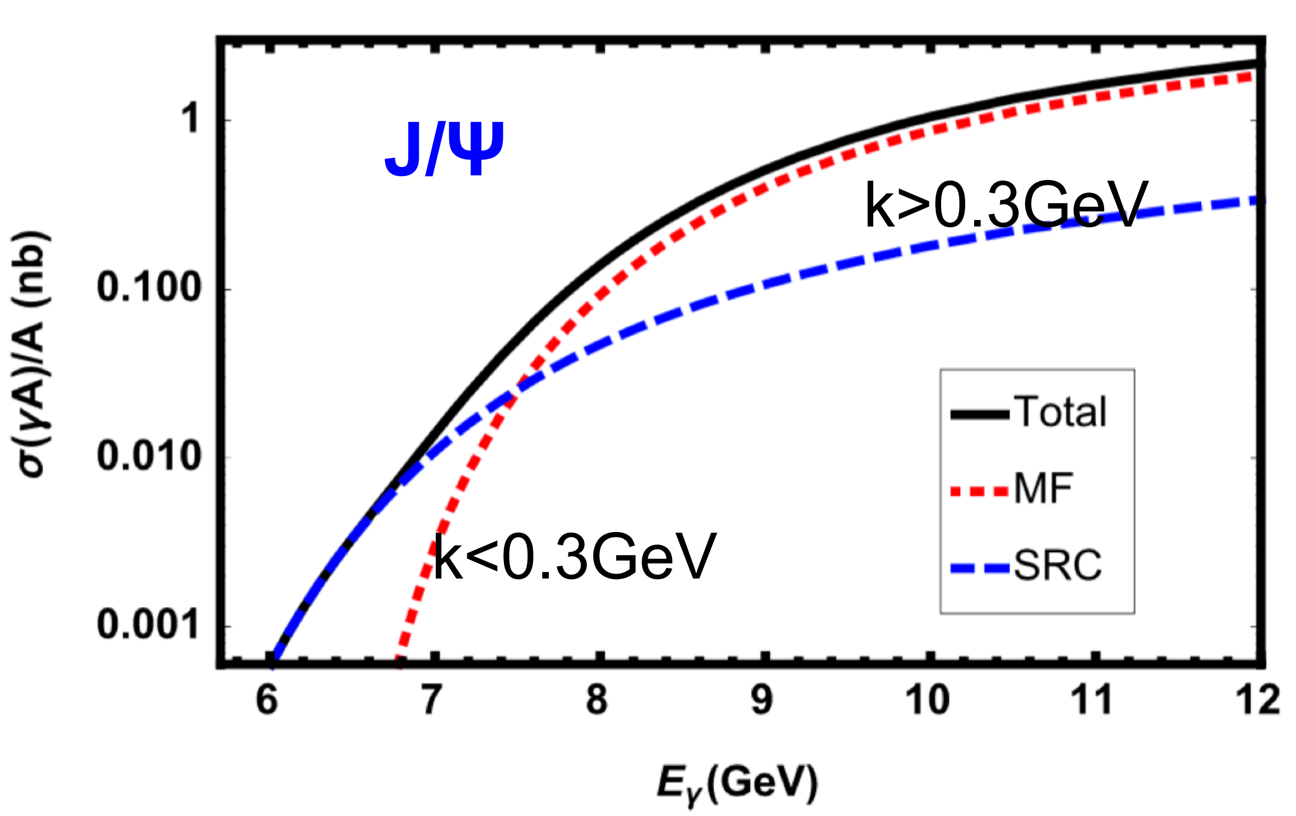
- Contacts:

$$C_{pp}^0 = C_{nn}^0 = 1.140\% \ ,$$
$$C_{pn}^0 = 1.244\% \ ,$$
$$C_{pn}^1 = 15.876\% \ .$$

Carbon-12

Duer et al., PRL 122, 172502 (2019)

Sub-threshold production in photon-Carbon collisions



- 16% SRC
- 84% MF

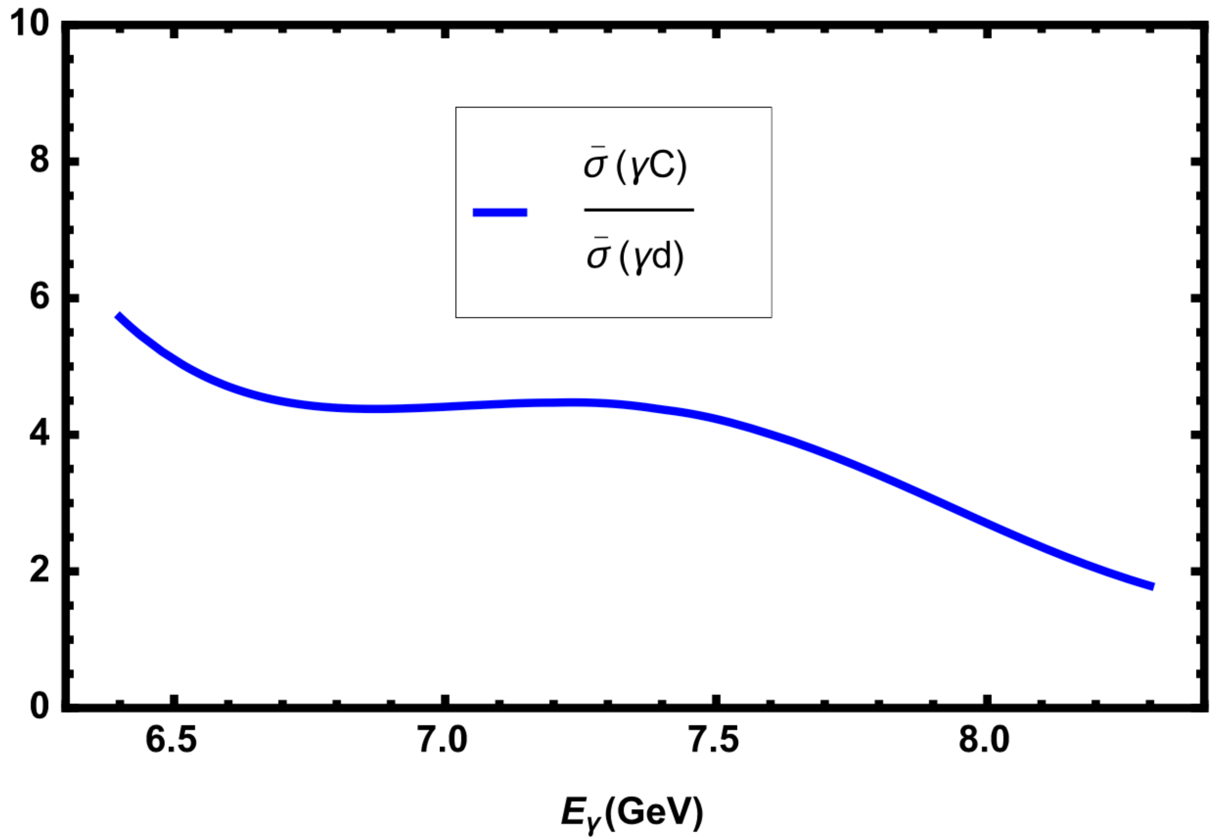
SRC Universality

- Cross section ratios only depend on the probability of SRC pair

$$\frac{\tilde{\sigma}_{\gamma A\to J/\psi}}{\sigma_{\gamma d\to J/\psi}}\Big|_{E_\gamma\sim 7\mathrm{GeV}} = \frac{n^A_{src}}{n^d_{src}} = \frac{F_2^A(x_B)}{F_2^d(x_B)}\Big|_{1.5<x_B<2.0}$$

- The same ratios measured from structure functions beyond x_B~1 at JLab

Example: Carbon-12



- Cross section per nucleon

$\boxed{a_2^C \approx 4.5}$

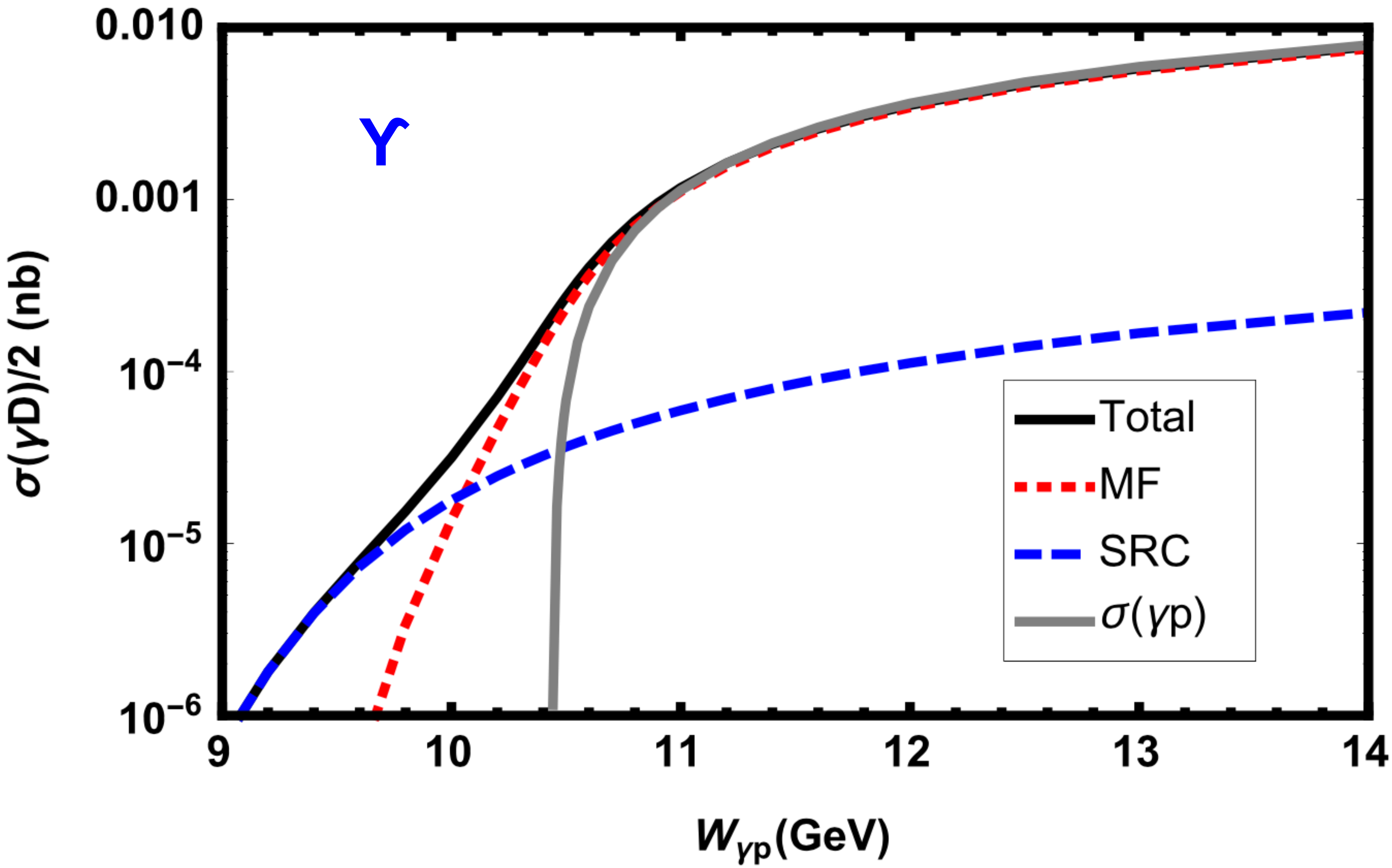
$$\boxed{a_2^A = (n_{src}^A/A)/(n_{src}^d/2)}$$

Corrections: Nuclear Absorption

$$\frac{1}{A}\int d^2\vec{b}\,dz\,\rho_A(\vec{b},z)\exp\left(-\int_z^{\infty}dz'\sigma_{eff}\,\rho_A(\vec{b},z')\right)$$

- Effective Abs. cross section ~ 4mb
- Modification is proportional to $A^{1/3}$
  - For Carbon-12, less than 10%
  - For heavy nucleus, like Pb, about 30%

Extend to Bottomonium



SRC Scaling

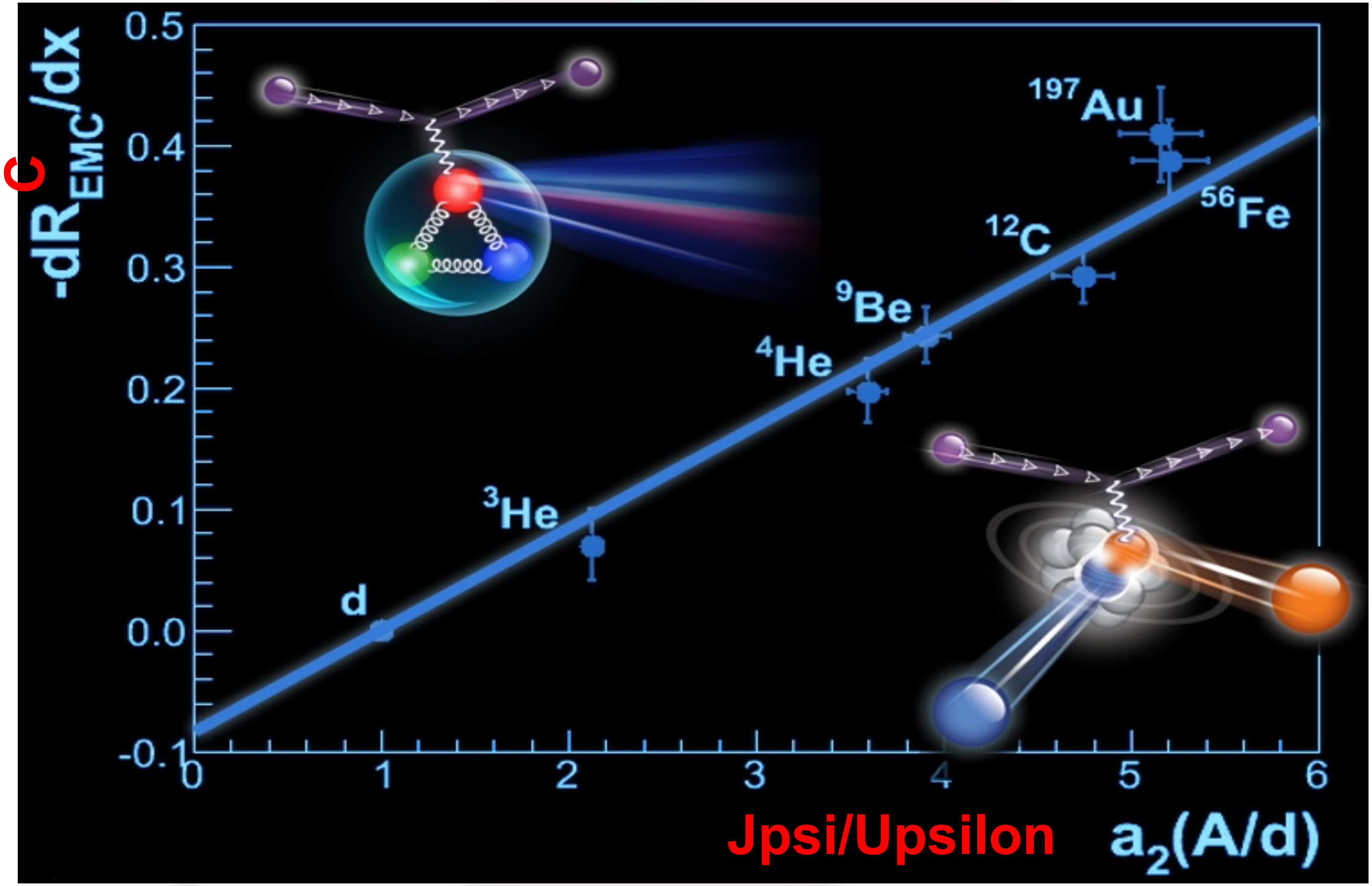
- Sub-threshold Charm and Bottom Quarkonium production

$$\left.\frac{\bar{\sigma}_{\gamma A\to J/\psi}}{\bar{\sigma}_{\gamma d\to J/\psi}}\right|_{E_\gamma\sim 7\mathrm{GeV}} = \left.\frac{\bar{\sigma}_{\gamma A\to \Upsilon}}{\bar{\sigma}_{\gamma d\to \Upsilon}}\right|_{W_{\gamma p}\sim 9.7\mathrm{GeV}}$$

$$= \frac{n^A_{src}/A}{n^d_{src}/2} = \left.\frac{F^A_2(x_B,Q^2)/A}{F^d_2(x_B,Q^2)/2}\right|_{1.4<x_B<1.8},$$

*Cross section per nucleon

Universality: Gluon Sector



Summary

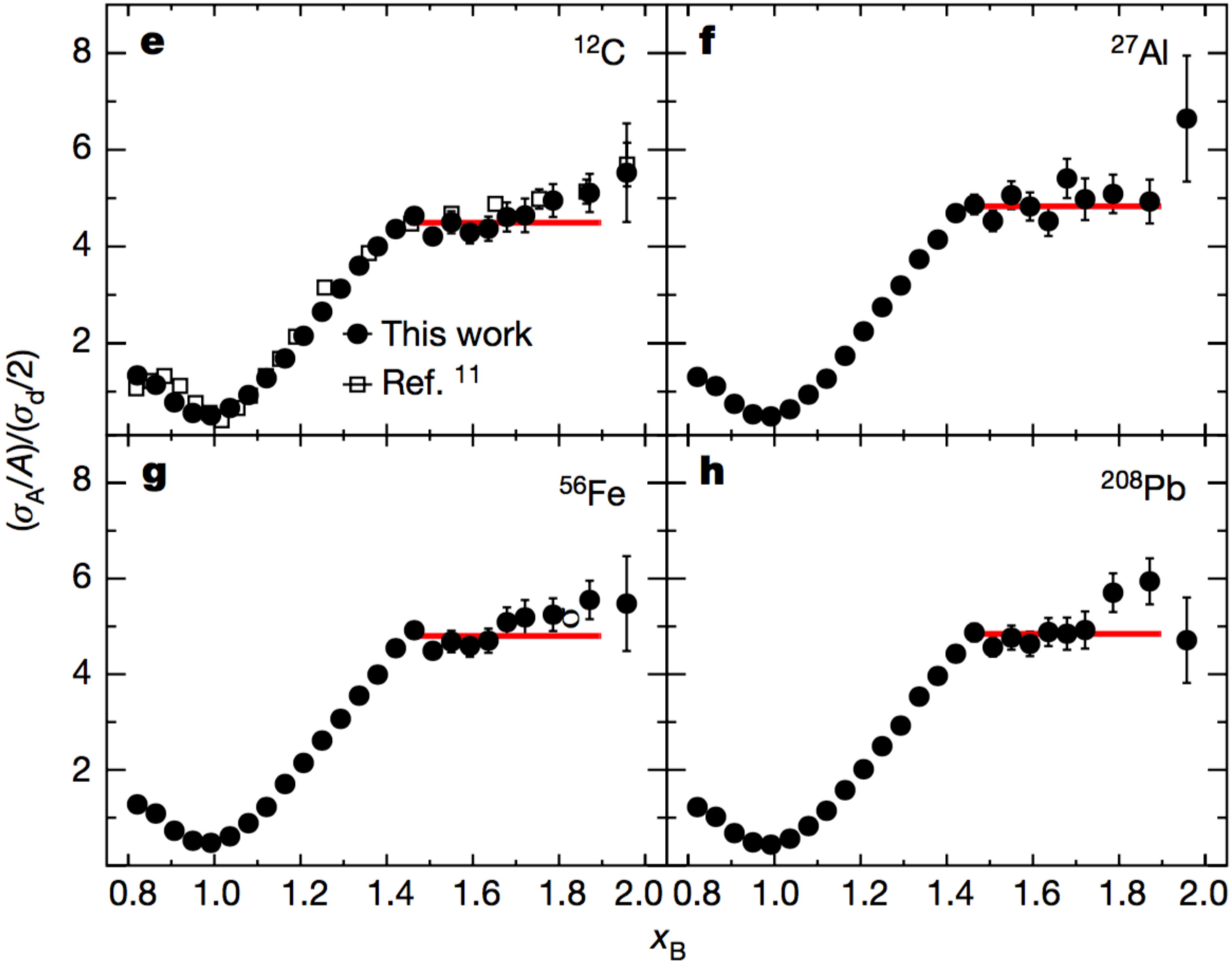
- Heavy flavor production in eA collisions provide the gluonic probe of the nucleon-nucleon short range correlation in nucleus
- Charmonium (Jpsi) can be easily measured at Jlab
- Charm structure function and Upsilon can be studied at EIC in China

Back-ups

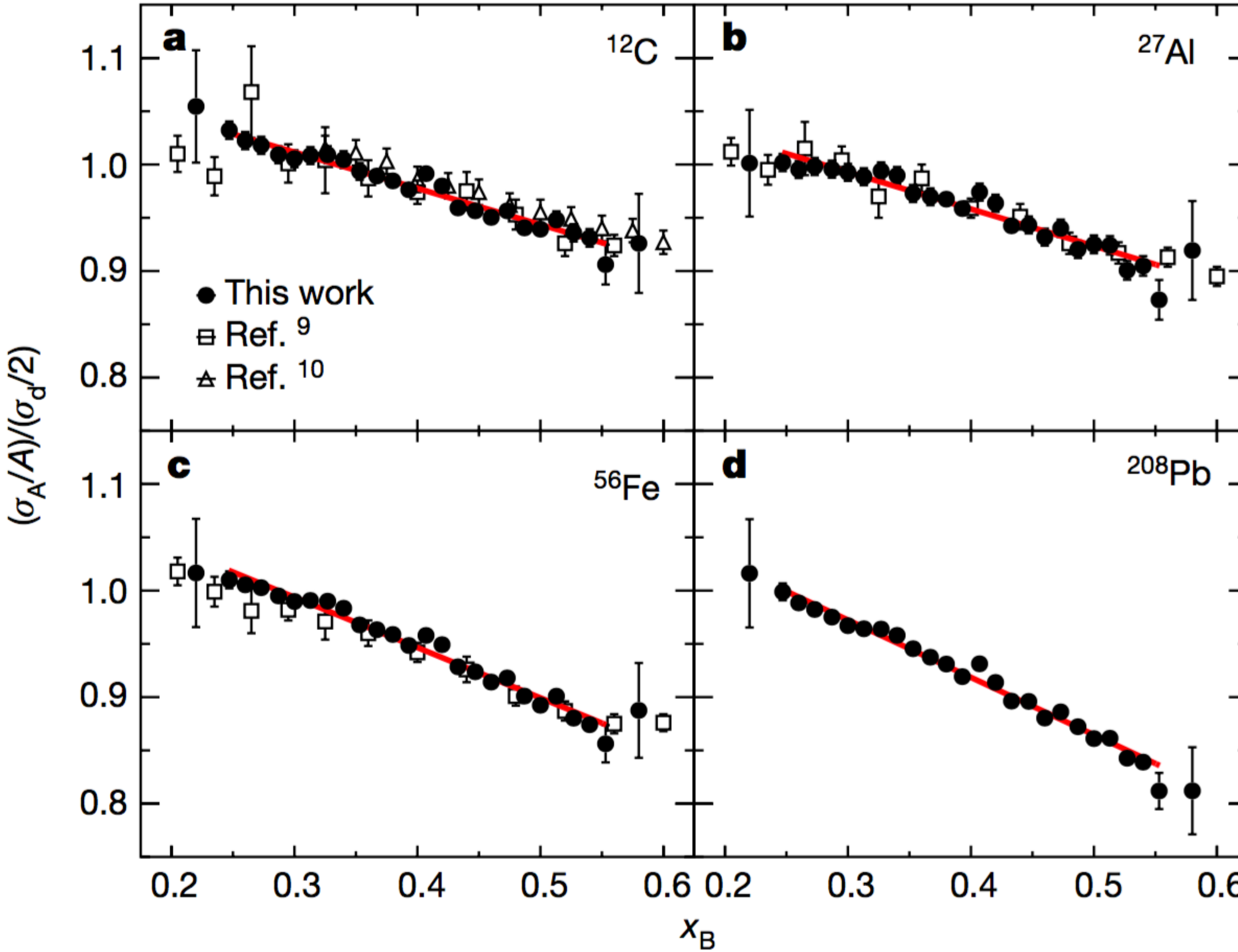
SRC Scale Factor

Nucleus	This work		
	a_2	a_2^p	a_2^n
^{3}He			
^{4}He			
^{9}Be			
^{12}C	4.49±0.17	4.49±0.17	4.49±0.17
^{27}Al	4.83±0.18	5.02±0.19	4.66±0.17
^{56}Fe	4.80±0.22	5.17±0.24	4.48±0.21
^{63}Cu			
^{197}Au			
^{208}Pb	4.84±0.20	6.14±0.25	3.99±0.17

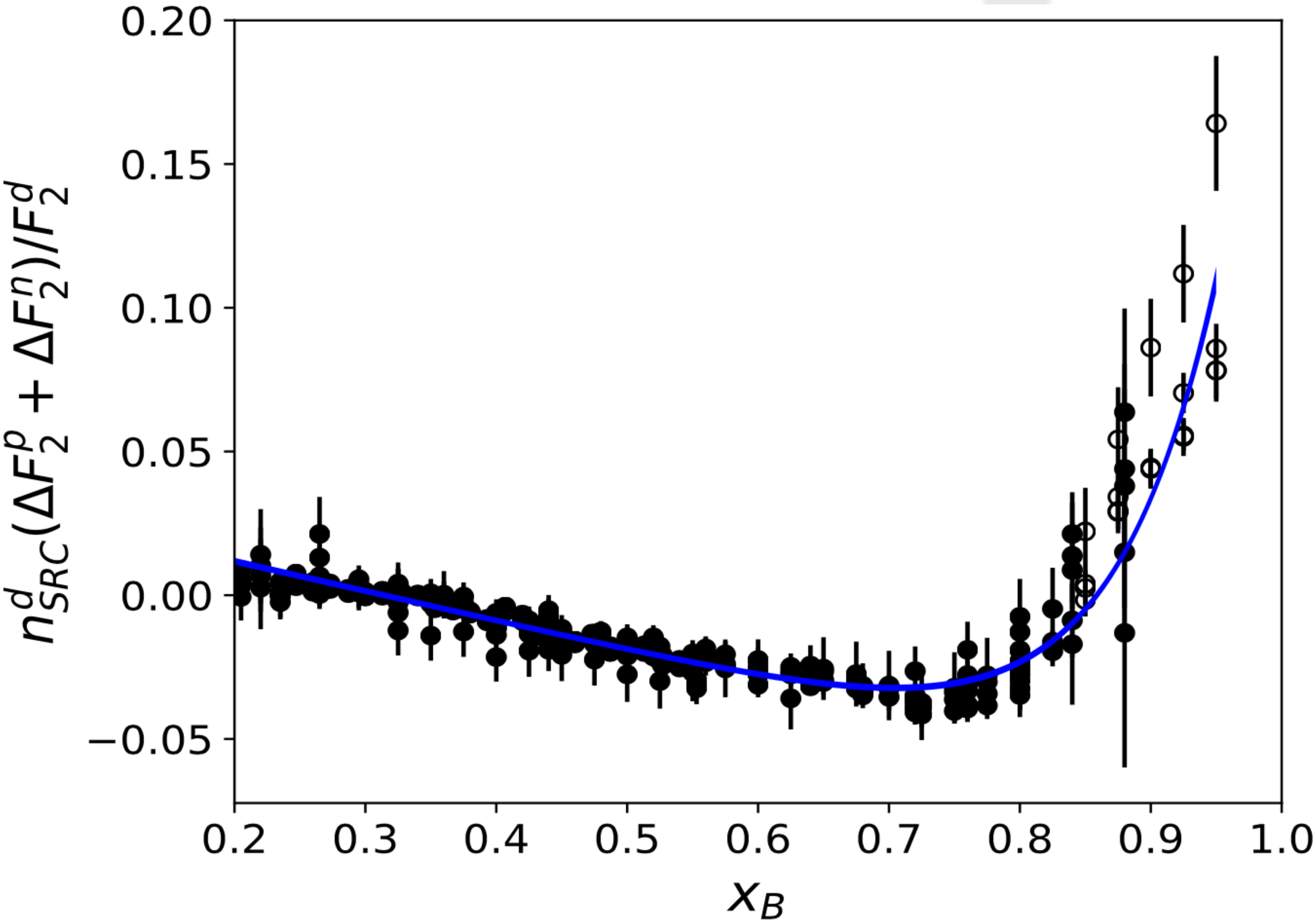
CLAS Coll., Nature 2019



CLAS Coll., Nature 2019

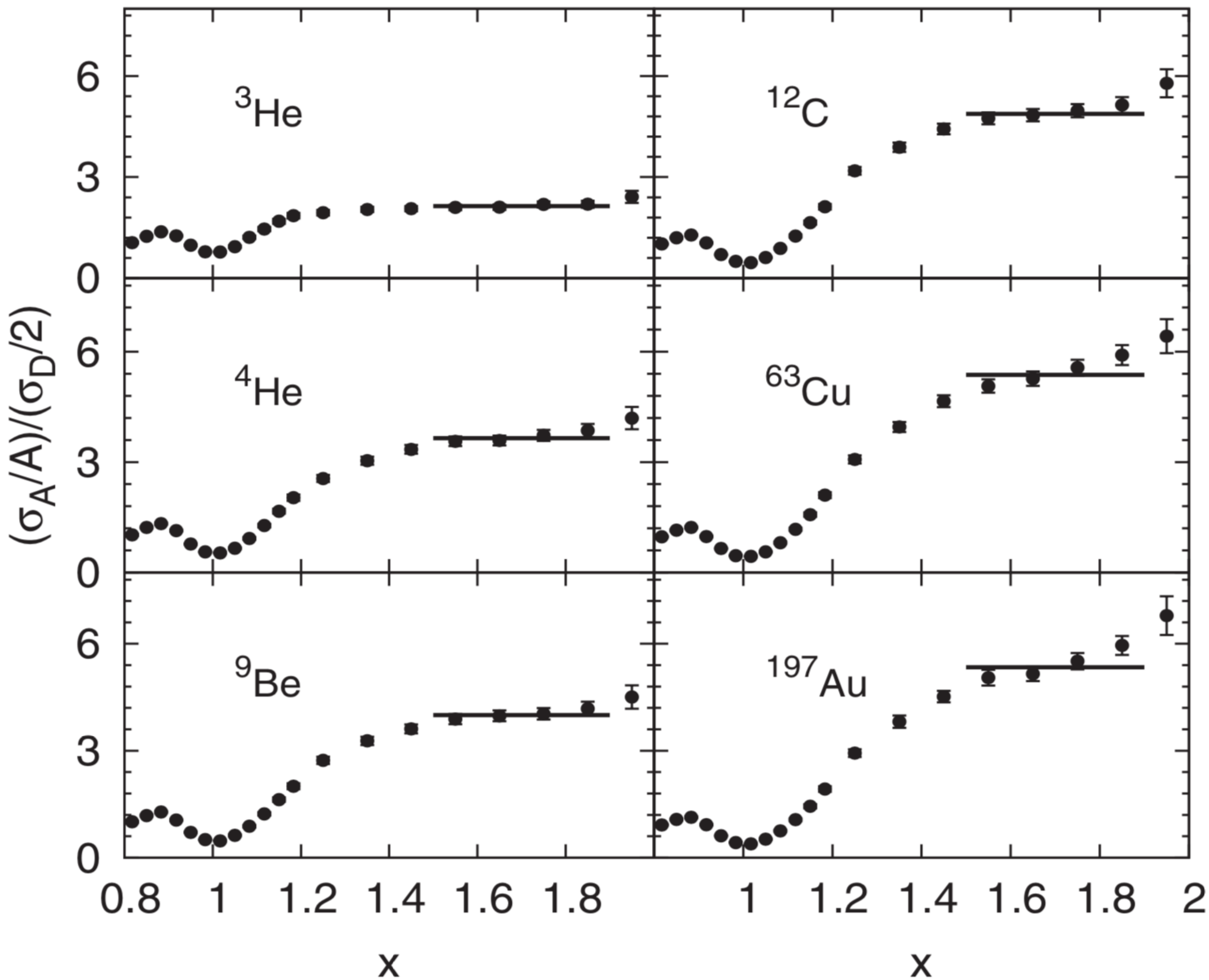


CLAS Coll., Nature 2019



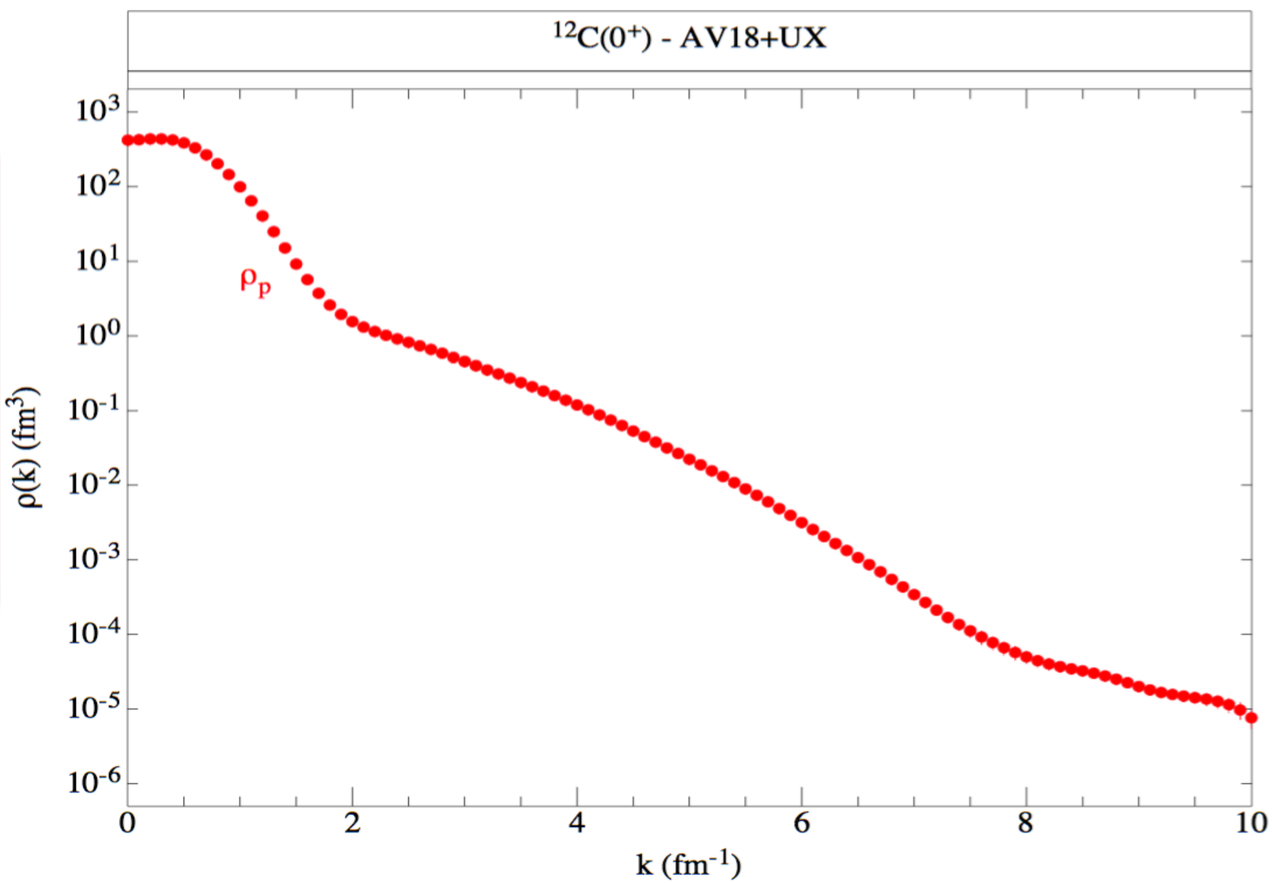
Hen et al., 1908.02223: fit SRC function and F_p/F_n both

2012 High-Momentum Scaling



Fomin, PRL (2012)

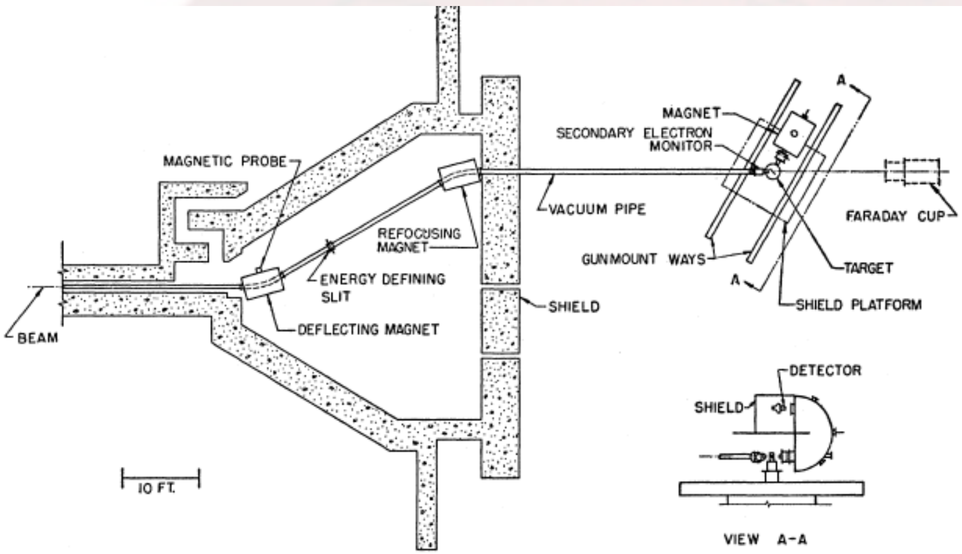
Nucleon momentum distribution in Carbon

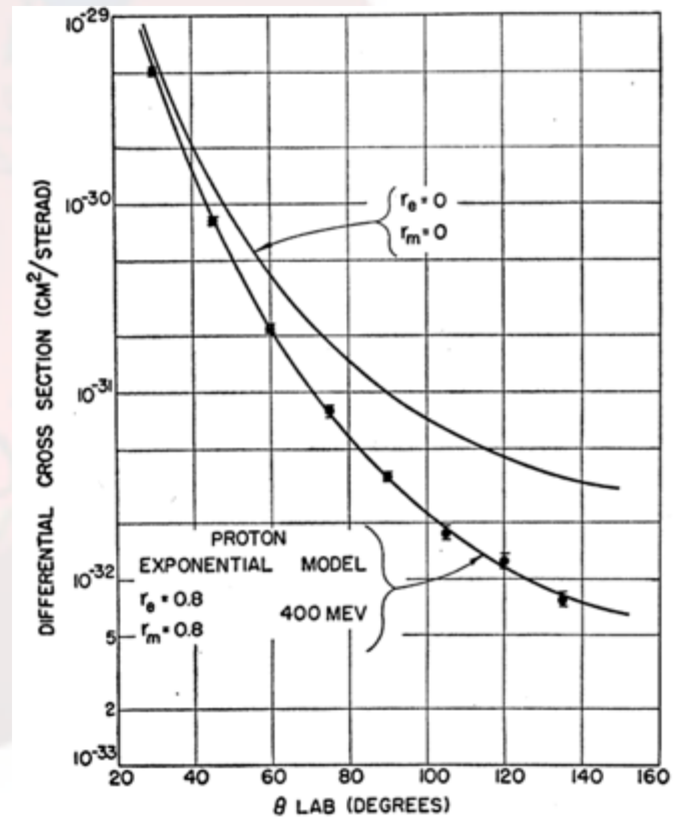


Finite size of nucleon (charge radius)

Hofstadter

- Rutherford scattering with electron





Renewed interest on proton radius:

RevModPhys.28.214