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Linear relation between the gluon EMC effect and short-range correlation

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Based on W. Wang, J. Xu, X. H. Yang and **SZ**, 2401.16662

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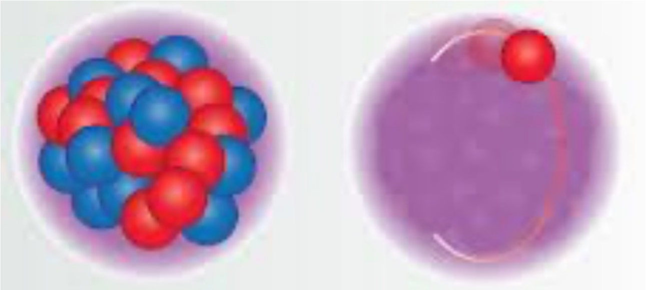
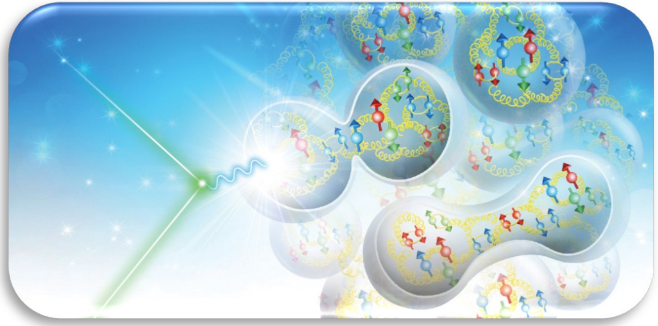
The EMC effect

- Nucleus: a collection of unmodified nucleons, moving non-relativistically, under the influence of 2- and 3- nucleon forces.
  Many-body problem
  Mean field, Shell model



- Deep Inelastic Scattering (DIS): to probe the partonic structures



- Proton's inelastic structure function $F_2^p(x, Q^2)$

$$F_2^p\left(x_p, Q^2\right) = x_p \sum_q e_q^2 \cdot \left(q^p\left(x_p\right) + \bar{q}^p\left(x_p\right)\right) .$$

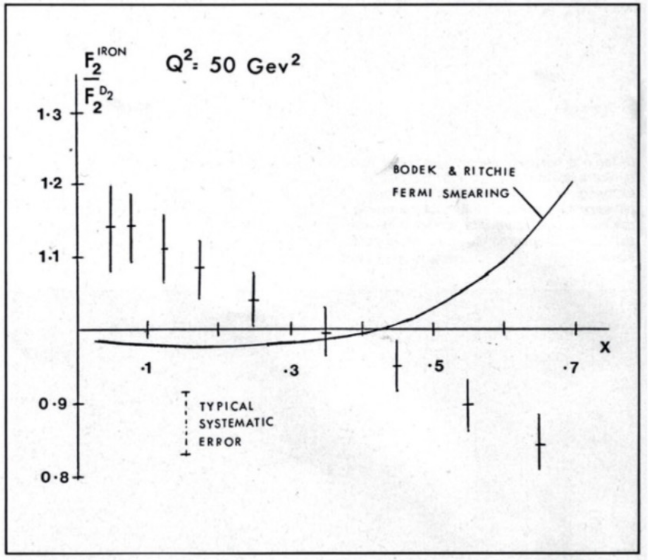
The EMC effect

- Nucleon binding energy ~MeV

  Momentum transfer in DIS ~GeV

- The partonic structure functions of bound and free nucleons should be identical

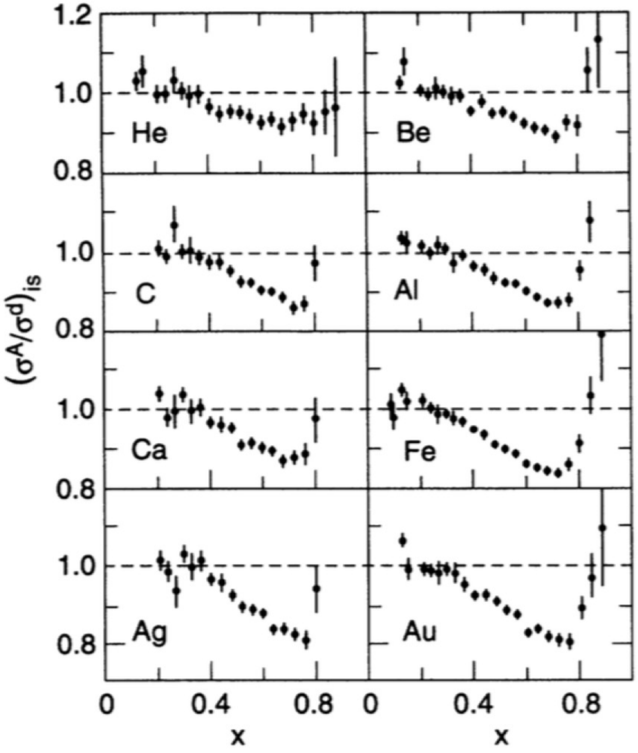
- Deep inelastic scattering should give the same structure functions for all nuclei



European Muon Collaboration (EMC), 1983

The EMC effect

- Confirmed by many groups: SLAC, FermiLab, NMC@CERN, JLab,…
- Universal shape. Independent of Q^2
- Strength is characterized by the slope
- Increased with mass number A and average nuclear density
- Lesson from ^{9}Be: local density is more relevant
- No fully accepted theoretical explanation.
  Everyone's Model is Cool (Miller, 1988)



Short Range Nucleon-Nucleon correlations

- The two-nucleon short-range correlations (2N-SRC) are defined operationally in experiments as having small center-of-mass (c.m.) momentum and large relative momentum

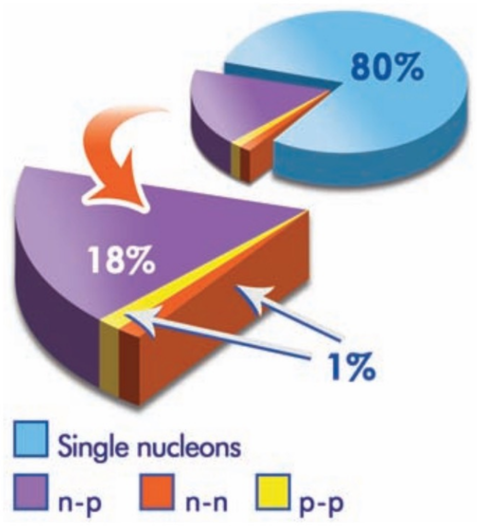
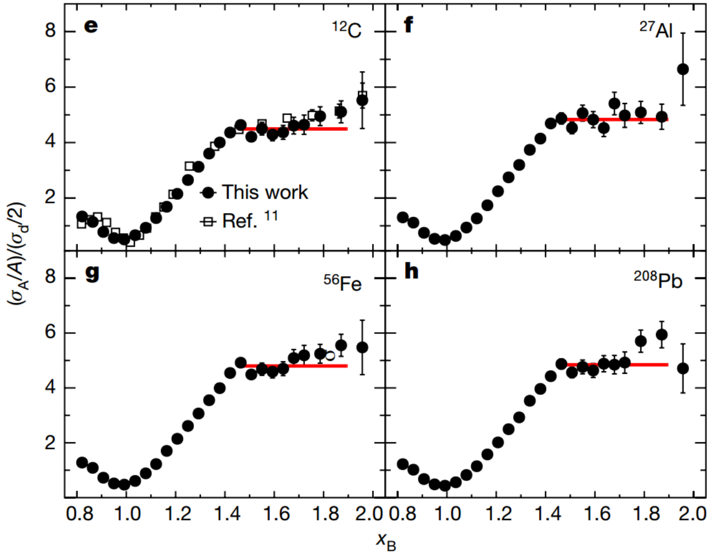


Fig. 3. The average fraction of nucleons in the various initial-state configurations of ^{12}C.

CLAS Collaboration, Science 320 (2008)



CLAS Collaboration, Nature 566 (2019)

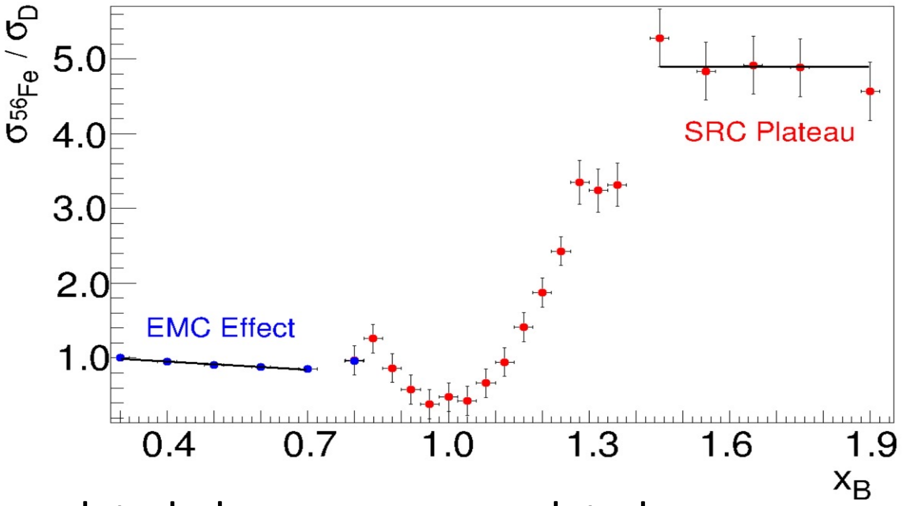
EMC and SRC

- EMC: characterized by the slope dR_{EMC}/dx $(0.35 \leq x \leq 0.7)$

$$R_{\rm EMC}(A,x) = \frac{2F_2^A(x,Q^2)}{AF_2^d(x,Q^2)}$$

- SRC scale factor: ratio of cross section in plateau region

$$a_2(A/d) = \frac{2}{A}[\sigma_A/\sigma_d]\ (1.5 \leq x \leq 2.0).$$



- Two seemly unrelated phenomena are related

Linear Relation Between EMC and SRC

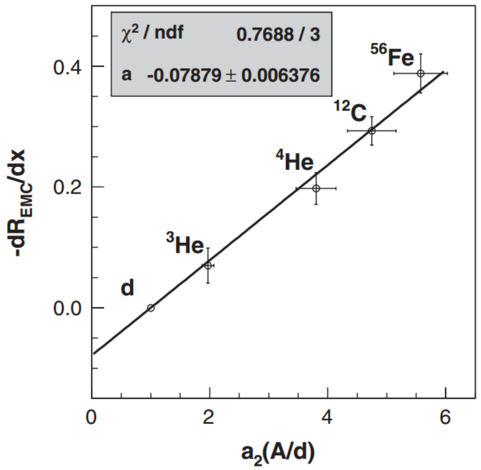
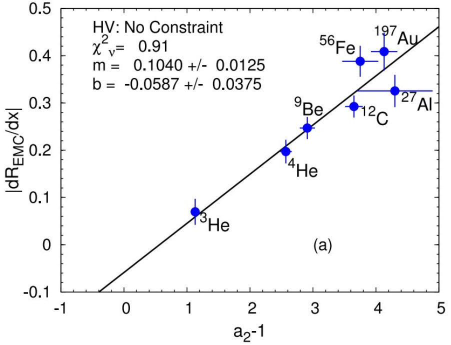
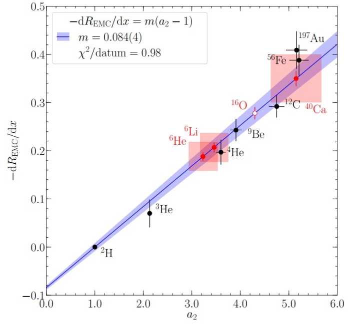


FIG. 1. The EMC slopes versus the SRC scale factors. The uncertainties include both statistical and systematic errors added in quadrature. The fit parameter is the intercept of the line and also the negative of the slope of the line.

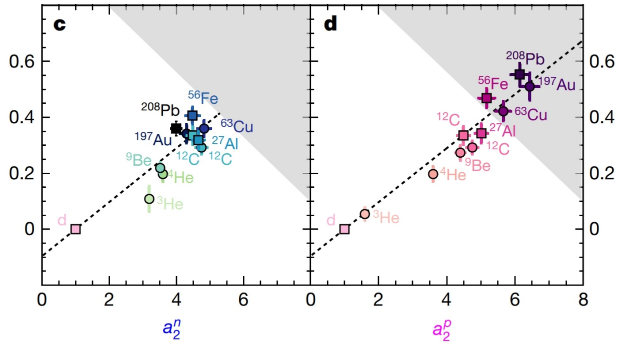
Phys. Rev. Lett. 106 (2011)



Phys. Rev. C 86 (2012)



J. Phys. G 47 (2020)



CLAS Collaboration, Nature 566 (2019)

- Other explanation: no connection between SRC and EMC

  Wang, Thomas, Melnitchouk, PRL 125, 262002

Linear Relation from EFT

- It was demonstrated that the linear relation follows from EFT description of EMC effect   Chen et al, Phys.Rev.Lett. 119 (2017) 26, 262502

- The leading twist PDFs are determined by target matrix element of bilocal light-cone operators

$$\langle x^n \rangle_A(Q) = \int_{-A}^{A} x^n q_A(x,Q)dx,$$

$$\langle A;p|\mathcal{O}^{\mu_0\cdots\mu_n}|A;p\rangle = \langle x^n\rangle_A(Q)\, p^{(\mu_0}\dots p^{\mu_n)} \qquad \mathcal{O}^{\mu_0\cdots\mu_n} = \bar{q}\gamma^{(\mu_0} iD^{\mu_1}\cdots iD^{\mu_n)}q$$

- Matching onto EFT operators

$$\mathcal{O}^{\mu_0\dots\mu_n} \to : \langle x^n\rangle_N M^n v^{(\mu_0}\cdots v^{\mu_n)} N^\dagger N\left[1+\alpha_n N^\dagger N\right] + \langle x^n\rangle_\pi \pi^\alpha i\partial^{(\mu_0}\cdots i\partial^{\mu_n)}\pi^\alpha + \dots :$$

- Relation for quark PDFs and then structure functions

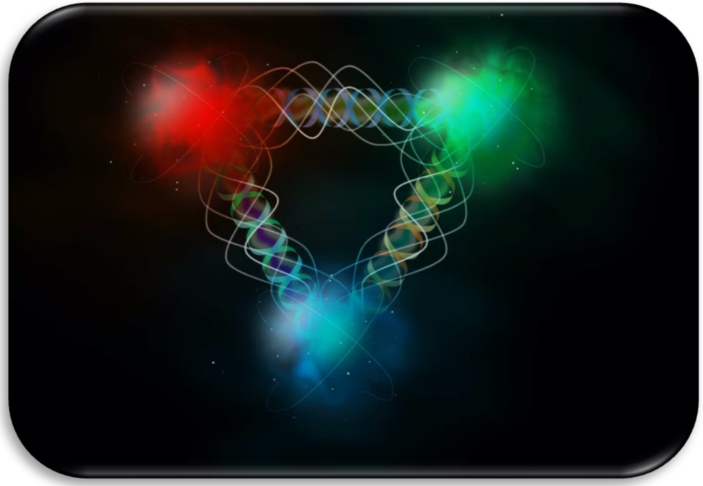
$$F_2^A(x,Q^2)/A \simeq F_2^N(x,Q^2) + g_2(A,\Lambda) f_2(x,Q^2,\Lambda). \qquad g_2(A,\Lambda) = \frac{1}{2A}\langle A| : (N^\dagger N)^2 : |A\rangle_\Lambda$$

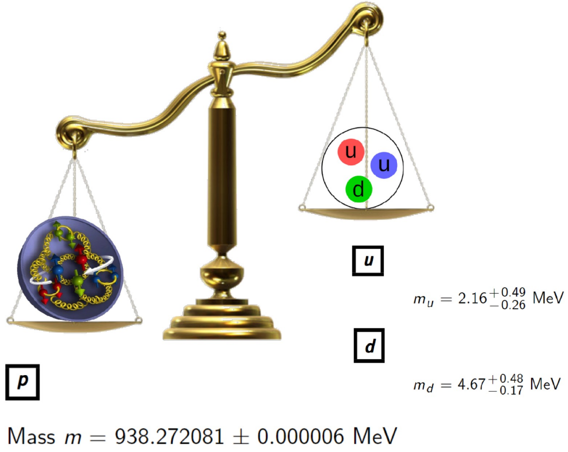
- Linear relation

$$\frac{dR_{\mathrm{EMC}}(A,x)}{dx} \simeq C(x)\left[a_2(A) - 1\right]$$

The gluons

- A proton is made up of three quarks that are tightly held together by the strong force.





- What about gluons in nuclei?
- Does the EFT analysis work for gluon PDF?
- Important for testing the universality

Gluon EMC and reduced cross section

- A direct approach to constrain the gluon nPDF is to measure the production cross section of heavy quark pair in electron ion collision

$$\sigma^{c\bar{c}}_{A,red}(x,Q^2) \equiv \left(\frac{d\sigma^{c\bar{c}}_A}{dxdQ^2}\right)\frac{xQ^4}{2\pi\alpha^2[1+(1-y)^2]} .$$

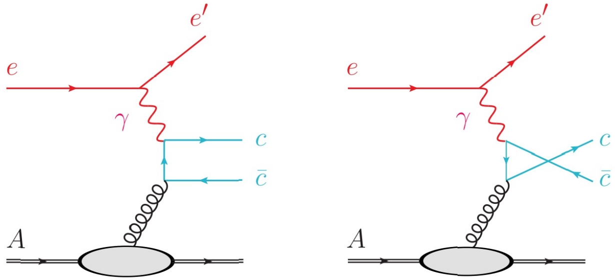


FIG. 1: Photoproduction of the heavy quark pair $c\bar{c}$ through photon-gluon fusion at leading order.

- An EIC will offer possibilities to constrain the gluon density in nuclei via measurements of the charm structure function

Gluon EMC and reduced cross section

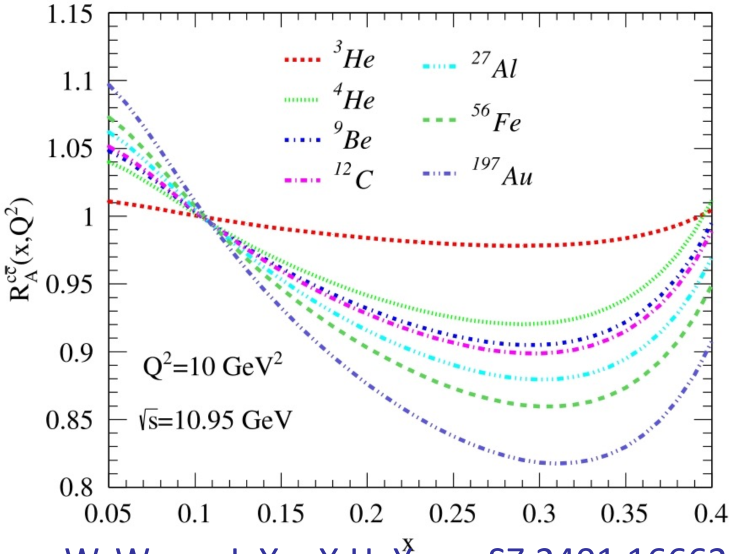
- The gluon nuclear PDF (nPDF) can be parameterized through the gluon PDF in a free proton Eskola et al Eur.Phys.J.C 82 (2022)

$$g_A(x, Q^2) = AR_g^A(x, Q^2)g(x, Q^2)\,.$$

- Define the nuclear modification

$$R_A^{c\bar{c}}\left(x, Q^2\right) = \frac{\sigma_{A,red}^{c\bar{c}}\left(x, Q^2\right)}{A\sigma_{N,red}^{c\bar{c}}\left(x, Q^2\right)}\,.$$

- The slope is obtained through a fit of the reduced cross-section in $0.1 \leq x \leq 0.25$



Based on EPPS21 data

W. Wang, J. Xu, X.H. Yang, SZ,2401.16662

SRC and sub-threshold J/Ψ production

- One can impose kinematics constrains to isolate the SRC effects in heavy quark pair generation.
- For a free nucleon target, the threshold photon energy to generate a J/ψ is $E_\gamma \sim 8.2$ GeV.
- If the nucleon is bound in nucleus, the production of J/ψ can occur at lower photon energy.

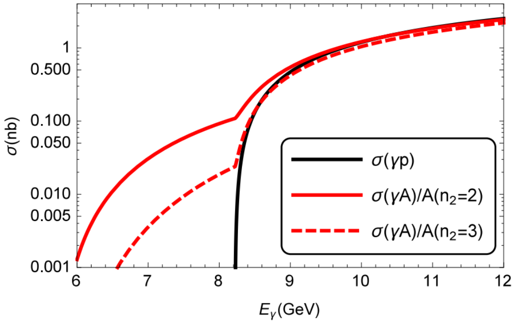


FIG. 2. Threshold and sub-threshold J/ψ production in γp and γA collisions.

J.Xu, F. Yuan, PLB 801 (2020) 135187

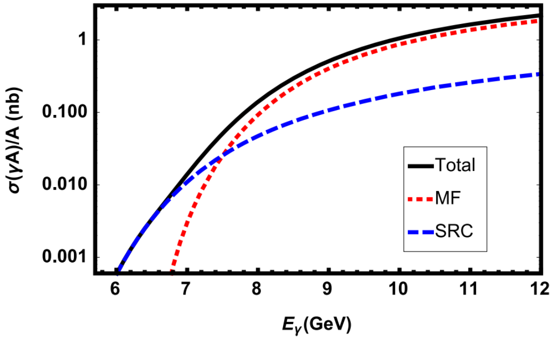


Fig. 3. Sub-threshold J/ψ production in photon-Carbon collisions as a function of incoming photon energy E_γ. We have estimated $P_{MF} = 0.84$ for the mean field normalization in Eq. (12).

Hatta et al, PLB 803 (2020), 135321

EFT analysis for gluon nPDF

- We analyze the gluon nPDF with EFT as the analysis in Phys.Rev.Lett. 119 (2017)

- Relevant momentum scales: $Q \gg \Lambda \gg P$
    - Momentum transfer Q in DIS
    - Typical EFT scale $\Lambda \sim 0.5$ GeV
    - Typical momentum inside the nucleus $P \sim m_\pi$

- Two small expansion parameter: Λ/Q, P/Λ.

collinear expansion

chiral expansion

EFT analysis for gluon nPDF

- Mellin moments of gluon PDF

$$\langle A;p|\mathcal{O}_g^{\mu_0\cdots\mu_n}|A;p\rangle = \langle x_g^n\rangle_A(Q^2)p^{(\mu_0}\cdots p^{\mu_n)} \qquad \mathcal{O}_g^{\mu_0\cdots\mu_n} = G_a^{\alpha(\mu_0}iD^{\mu_1}\cdots iD^{\mu_{n-1}}G_{a,\alpha}^{\ \ \mu_n)}$$

- Matching QCD operator onto EFT operator (with the same chiral transform properties)

$$\mathcal{O}_g^{\mu_0\cdots\mu_n} \to \langle x^n\rangle_{g,N}M^n v^{(\mu_0}\cdots v^{\mu_n)} : N^\dagger N[1+\delta_n N^\dagger N] + \langle x\rangle_\pi \pi^\alpha i\partial^{(\mu_0}\cdots i\partial^{\mu_n)}\pi^\alpha + \ldots :$$

- Matching relation for Mellin moments

$$\langle x^n\rangle_{g,A} = A\langle x^n\rangle_{g,N} + \langle x^n\rangle_{g,N}\delta_n(\Lambda,Q)\langle A|(:N^\dagger N:)^2|A\rangle$$

- Matching relation for gluon PDFs

$$g_A(x,Q^2)/A \simeq g(x,Q^2) + g_2(A,\Lambda)\,\tilde{f}_g(x,Q^2,\Lambda)\,, \qquad g_2(A,\Lambda) = \frac{1}{2A}\langle A|(:N^\dagger N:)^2|A\rangle$$

Linear relation between gluon EMC and SRC

- Relation for structure functions

$$F_{2,A}^{c\bar{c}}(x,Q^2) = \int_{ax}^{1} \frac{dz}{z} z\, g_A(z,\hat{s}) f_2(\frac{x}{z},Q^2)$$

$$\frac{F_{2,A}^{c\bar{c}}(x,Q^2)}{A} = F_{2,N}^{c\bar{c}}(x,Q^2) + g_2(A,\Lambda)\tilde{F}_2(x,Q,\Lambda)$$

- Relation for the reduced cross-section

$$\sigma_{A,red}^{c\bar{c}}(x,Q^2)/A = \sigma_{N,red}^{c\bar{c}}(x,Q^2) + g_2(A,\Lambda)\tilde{\sigma}(x,Q^2,\Lambda)\,.$$

- Linear relation between $\left|dR_A^{c\bar{c}}/dx\right|$ and $g_2(A,\Lambda)$

$$R_A^{c\bar{c}}(x,Q^2) = \frac{\sigma_{red,A}^{c\bar{c}}(x,Q^2)}{A\sigma_{red,N}^{c\bar{c}}(x,Q^2)} \qquad \left|\frac{dR_A^{c\bar{c}}(x,Q^2)}{dx}\right| = C(x,Q^2)\, g_2(A,\Lambda)\,,$$

with $C(x,Q^2) = |d(\tilde{\sigma}(x,Q^2,\Lambda)/\sigma_{N,red}^{c\bar{c}}(x,Q^2,\Lambda))/dx|$.

Linear relation between gluon EMC and SRC

- The subthreshold J/Ψ production is dominated by $g_2(A, \Lambda)\, \tilde{q}_2(x, Q, \Lambda)$ term

- Ratio of the cross section of the subthreshold J/Ψ production for different nuclei is determined by the ratio of $g_2(A, \Lambda)$

$$\frac{g_2(A, \Lambda)}{g_2(A', \Lambda)} \simeq \left. \frac{\sigma_A^{sub}/A}{\sigma_{A'}^{sub}/A'} \right|_{E_\gamma \sim 7\,\mathrm{GeV}} .$$

- A non-trivial prediction from chiral EFT on gluon nPDF

$$\left| \frac{dR_A^{c\bar{c}}(x, Q^2)}{dx} \right| = \left. \frac{C(x, Q^2) g_2(d, \Lambda)}{(\sigma_d^{sub}/2)} \, (\sigma_A^{sub}/A) \right|_{E_\gamma \sim 7\,\mathrm{GeV}} .$$

- One can examine the linear relation from the future experimental data.

Linear gluon EMC-SRC relation

- Hints from existing data
- The sub-threshold cross section is calculated $\left(\sigma_d^{sub}/2\right) = 3.2\ \mathrm{pb}.$

  Phys.Lett.B 803 (2020)

- Two ways to estimate (σ_A^{sub}/A) for different nuclei.
  - I: Making use of the SRC scaling factor a_2 in Nature 566 (2019) and Phys.Rev.C 85 (2012).

    It is likely that a_2 is roughly equals to $g_2(A)/g_2(d)$ if the gluon nPDF is affected by the SRCs in about the same way as quarks.

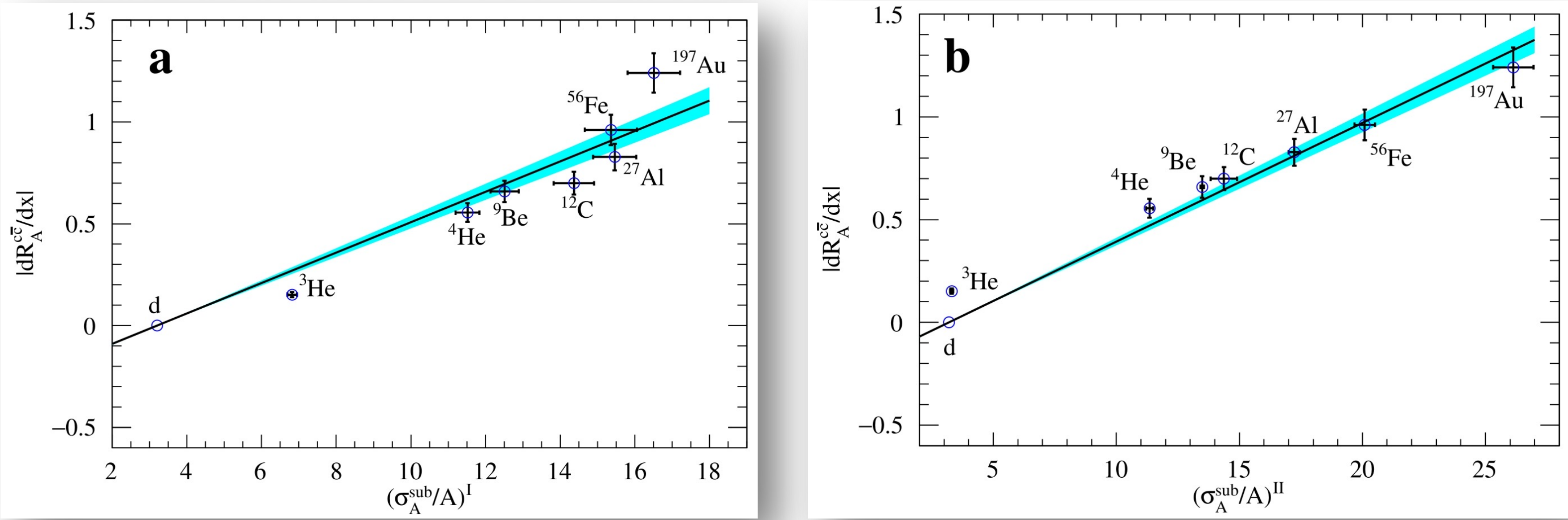
  - II: Making use of the parameterization in EPPS21

Linear gluon EMC-SRC relation

- The cross sections (picobarn) per nucleon for sub-threshold J/ψ production.

Nucleus	$\lvert dR_A^{c\bar{c}}/dx \rvert$	$(\sigma_A^{sub}/A)^{\mathrm{I}}$	$(\sigma_A^{sub}/A)^{\mathrm{II}}$
^{3}He	0.152 ± 0.013	6.82 ± 0.13	3.31 ± 0.06
^{4}He	0.555 ± 0.046	11.52 ± 0.32	11.35 ± 0.14
^{9}Be	0.659 ± 0.053	12.51 ± 0.38	13.49 ± 0.07
^{12}C	0.699 ± 0.056	14.37 ± 0.54	14.37 ± 0.54
^{27}Al	0.828 ± 0.065	15.46 ± 0.58	17.23 ± 0.23
^{56}Fe	0.961 ± 0.075	15.36 ± 0.70	20.09 ± 0.42
^{197}Au	1.241 ± 0.097	16.51 ± 0.70	26.13 ± 0.82

Linear gluon EMC-SRC relation



$$|dR_A^{c\bar{c}}/dx| = (0.0747 \pm 0.0045) \times \left[(\sigma_A^{sub}/A)^{\mathrm{I}} - (\sigma_d^{sub}/2) \right] .$$

$$|dR_A^{c\bar{c}}/dx| = (0.0578 \pm 0.0027) \times \left[(\sigma_A^{sub}/A)^{\mathrm{II}} - (\sigma_d^{sub}/2) \right] .$$

Wang, Xu, Yang, SZ, 2401.16662

Summary

- The investigation of nuclear modification in gluon nPDFs can be carried out through the study of heavy flavor production.

- We suggest a linear relation between the magnitude of the gluon EMC effect and the sub-threshold J/ψ production cross section based on EFT analysis.

- Future measurements should be significant for an independent test of the nuclear modification of the gluon distribution function and the universal influence of SRCs on parton distributions in nucleon.

Thank you!