郑州大学
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Linear relation between SRC and EMC effect of gluons in nuclei

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Workshop on near-threshold J/ψ photoproduction

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In collaboration with:

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Outline

- **The relation of EMC and SRC on quark sector**
  1. Introduction to EMC and SRC
  2. Linear relation between EMC and SRC on quark sector
- **Linear relation of gluons in nuclei**
  1. EMC and reduced cross section
  2. SRC and sub-threshold J/ψ production
  3. Linear gluon EMC-SRC relation
- **Summary**

The EMC effect

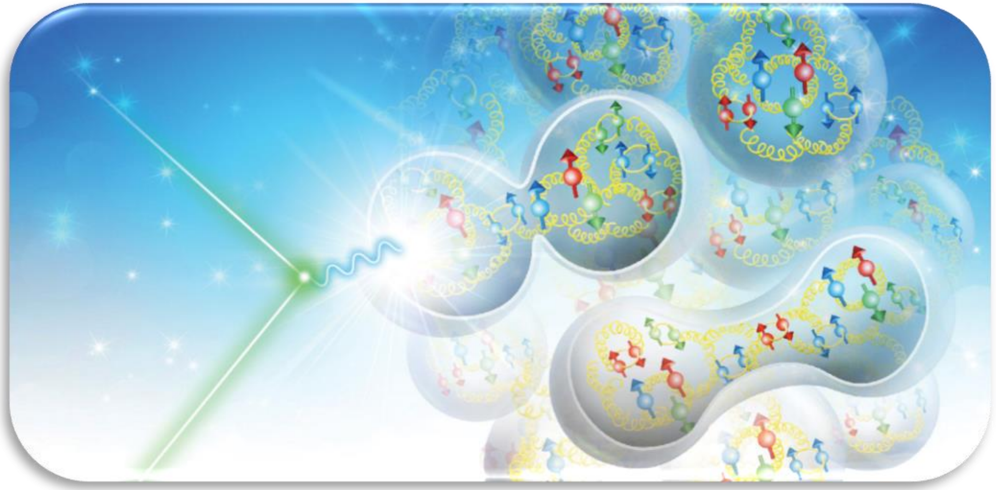
- Basic models of nuclear physics describe the nucleus as a collection of free nucleons under the influence of the sum of two-nucleon forces, which can be treated approximately as a mean field.

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

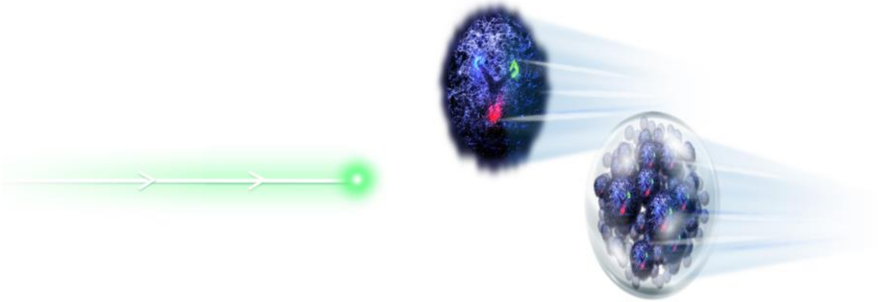
$$F_2^p\left(x_p, Q^2\right) = x_p \sum_q e_q^2 \cdot \left(q^p\left(x_p\right) + \bar{q}^p\left(x_p\right)\right) \, .$$

- At that time, people believed that Deep Inelastic Scattering (DIS) experiments which are sensitive to the partonic structure function of the nucleon would give the same result for all nuclei.

The EMC effect

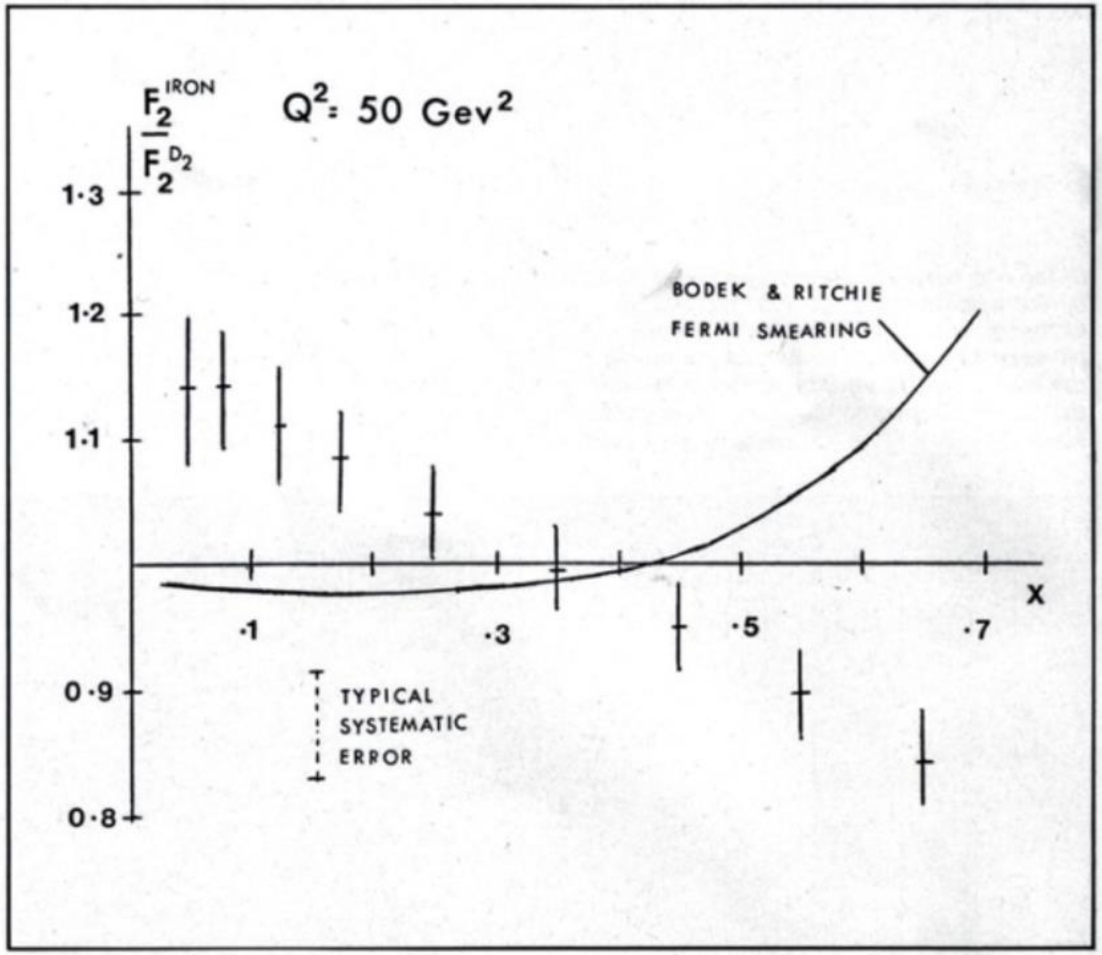


EIC Yellow Report, Nucl.Phys.A 1026 (2022)



The Present and Future of QCD, arXiv:2303.02579

But, things are not this simple !



European Muon Collaboration (EMC)

The EMC effect

- Soon confirmed by other groups.

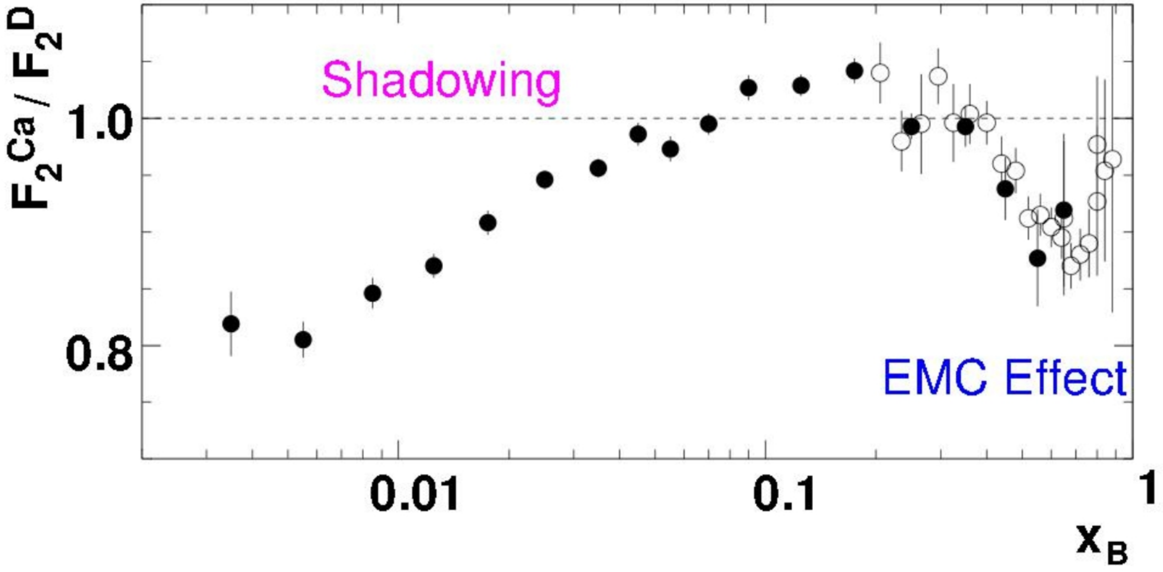


Fig. 2: The image shows the ratio of deep-inelastic cross sections of Ca to D from NMC (solid circles) and SLAC (open circles). The downward slope from 0.3 < x < 0.7 and subsequent rise from x_B > 0.7 is a universal characteristic of EMC data and has became known as the EMC effect. The reduction of the ratio at lower values of x_B, where valence quarks should no longer be playing a significant role, is known as the shadowing region.

30th Anniversary of the EMC Effect

- Recent results from CLAS Collaboration

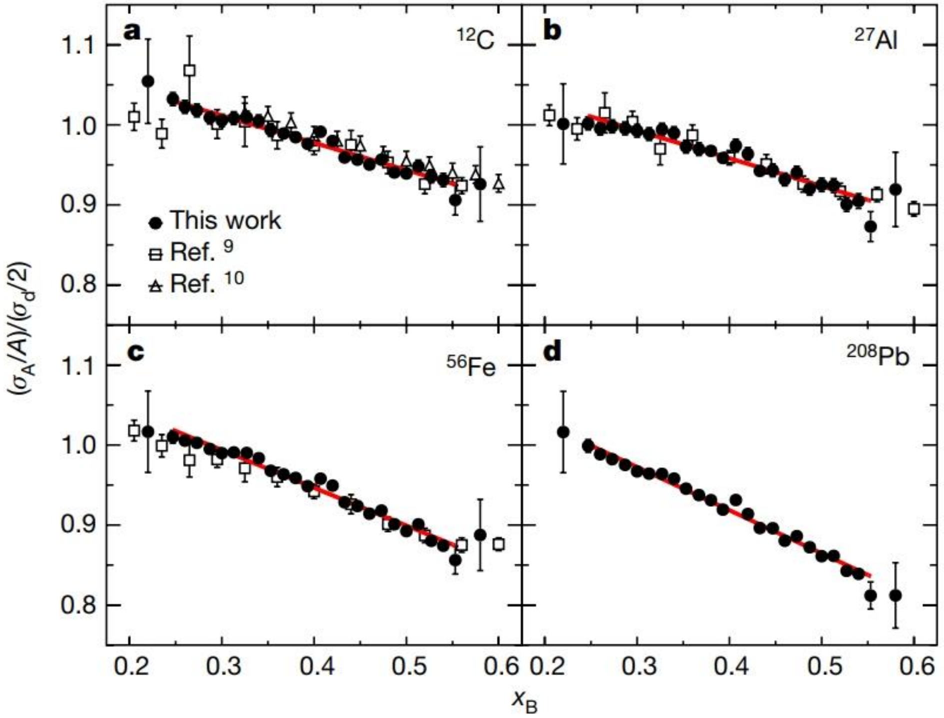


Fig. 1 | DIS and quasi-elastic (e,e') cross-section ratios. a–d, Ratio of the per-nucleon electron scattering cross-section of nucleus A (A = ^{12}C (**a**), ^{27}Al (**b**), ^{56}Fe (**c**) and ^{208}Pb (**d**)) to that of deuterium for DIS kinematics ($0.2 \leq x_B \leq 0.6$ and $W \geq 1.8$ GeV). The solid points show the data obtained in this work, the open squares show SLAC (Stanford Linear Accelerator Center) data[9] and the open triangles show Jefferson

CLAS Collaboration, Nature 566 (2019)

The EMC effect

EMC effect is very important ! *Rev. Mod. Phys. 89 (2017)*

There are a number of fundamental unanswered questions about nuclear physics.

- Is the nucleus really made of nucleons and mesons only?
- How does the nucleus emerge from QCD, a theory of quarks and gluons?
- How does the partonic content of the nucleus differ from that of N free neutrons plus Z free protons?

No one asked such questions before the discovery of the EMC effect.

The 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.

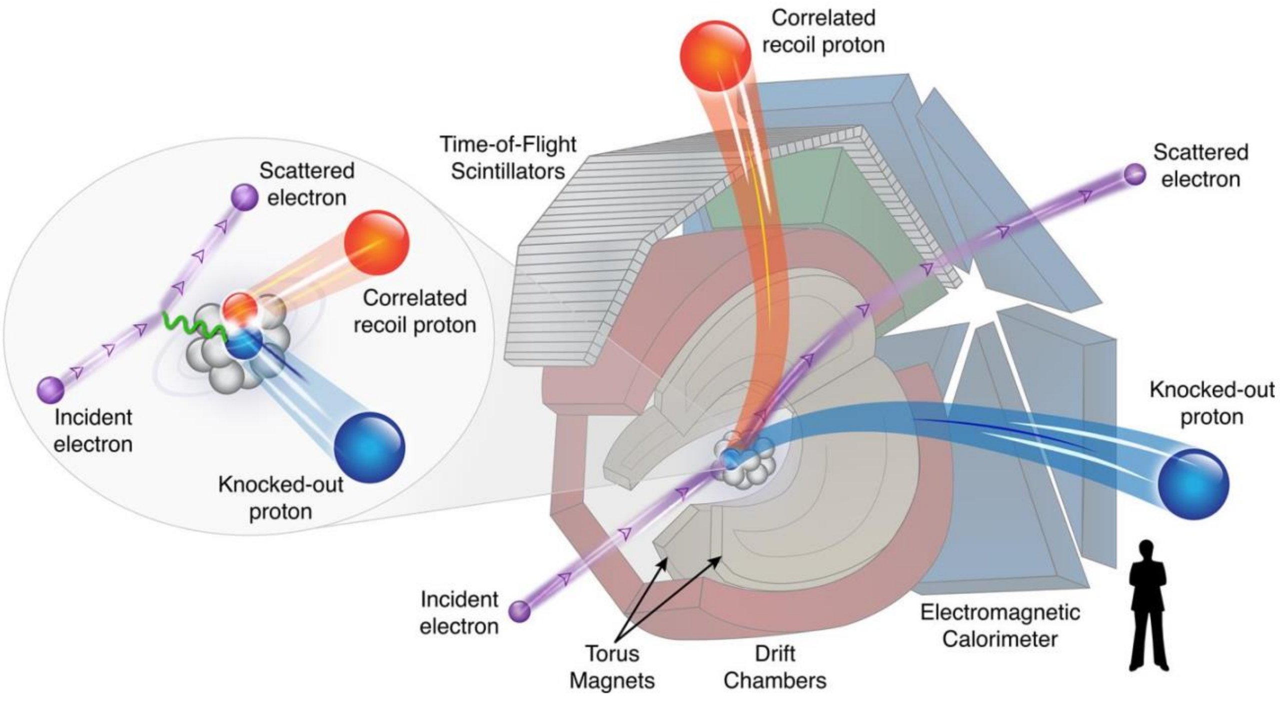


Illustration of the CLAS detector with a reconstructed two-proton knockout event.

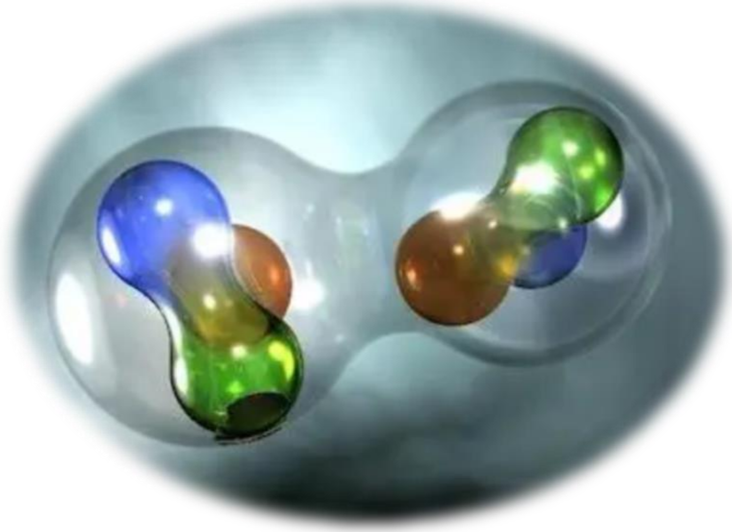


Illustration of a 2N-SRC Pair.

Science 346 (2014)

The Short Range nucleon-nucleon correlations

- The extracted ratio of two-nucleon knockout to single proton knockout events.

- The ratio of proton-neutron to proton-proton two nucleon knockout events.

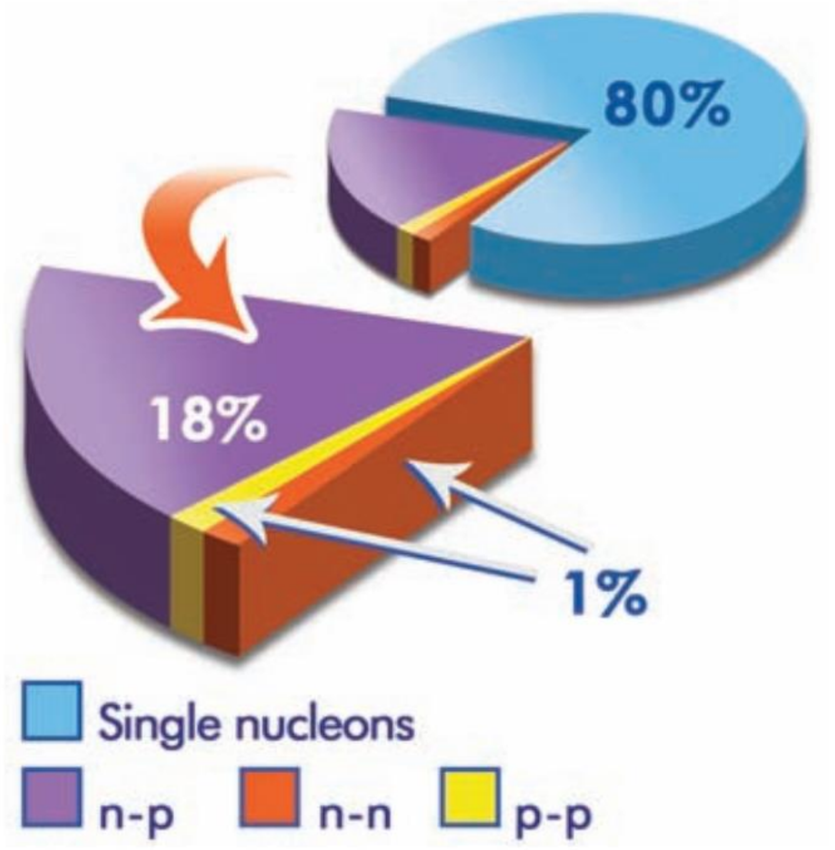


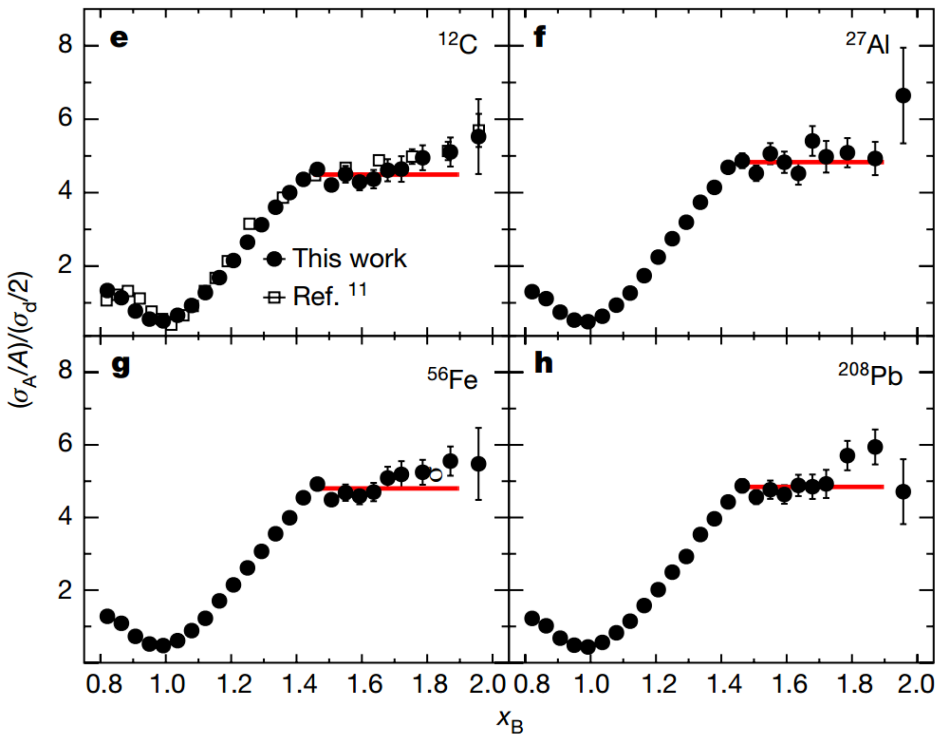
Fig. 3. The average fraction of nucleons in the various initial-state configurations of ^{12}C.

CLAS Collaboration, Science 320 (2008)

The Short Range nucleon-nucleon correlations

- In the region $Q^2 \sim 2 - 4\ \mathrm{GeV}^2$ and $x_p \geq 1.45 - 1.9$, $x_p = \dfrac{Q^2}{2\mathrm{p}.q}$.

- The structure of these configurations is independent of the surrounding nuclear environment, resulting in the same shape of the high momentum tail in all nuclei.



CLAS Collaboration, Nature 566 (2019)

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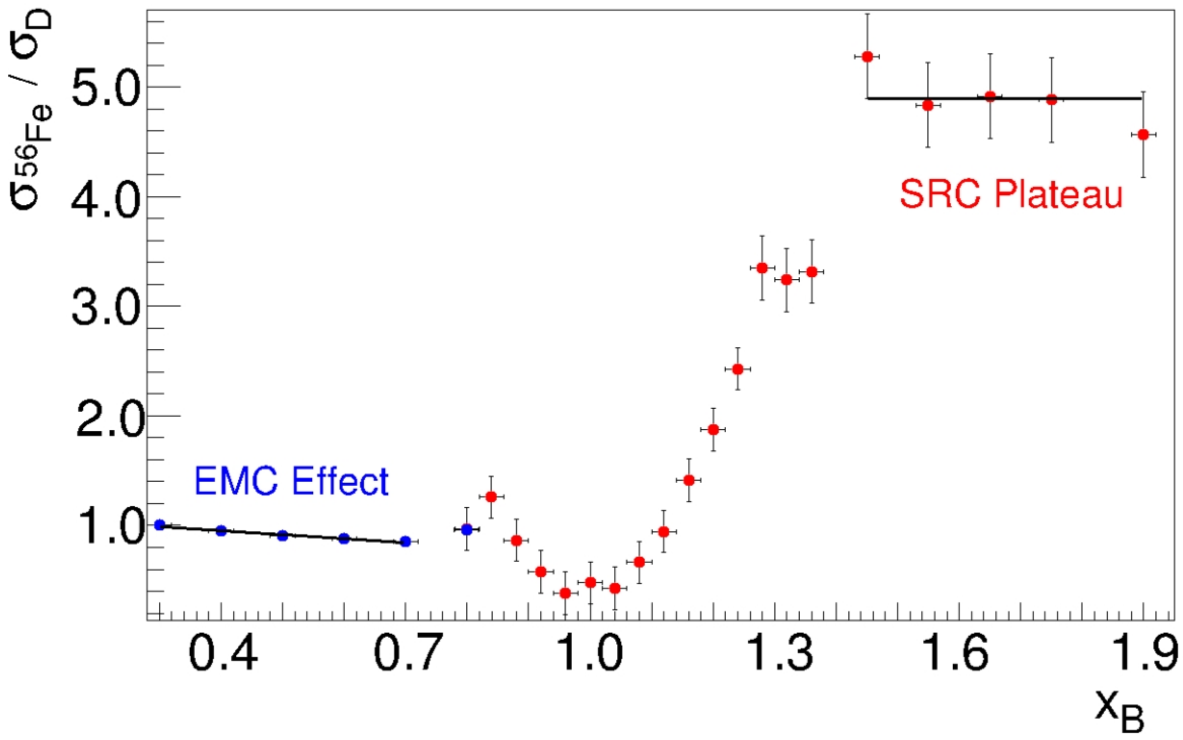
Linear relation between EMC and SRC

- If we combine the EMC and SRC when considering the partonic structure of nucleon.



- The per-nucleon electron inelastic scattering cross section is **smaller** or **larger** than those of deuterium.

EMC effect: slope of the ratio of the per-nucleon deep inelastic electron scattering cross sections of nucleus A relative to deuterium dR_{EMC}/dx $(0.35 \leq x_p \leq 0.7)$.

SRC scale factor: ratio of cross sections in the plateau region $a_2(A/d) = \frac{2}{A}[\sigma_A/\sigma_d]$ $(1.5 \leq x_p \leq 2.0)$.

Linear relation between EMC and SRC

- **Here comes the important observation.**

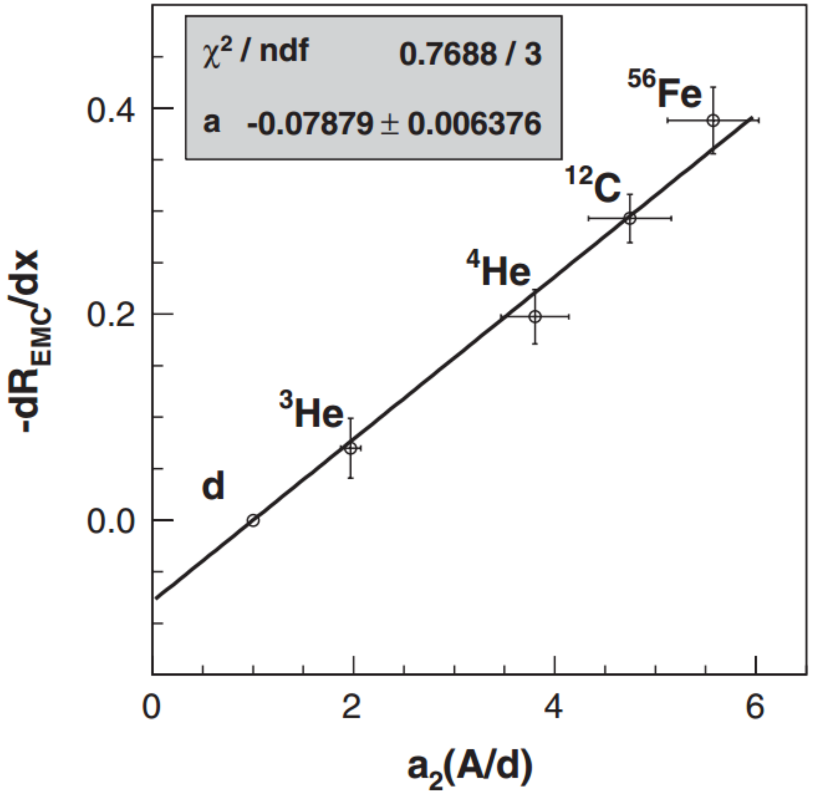
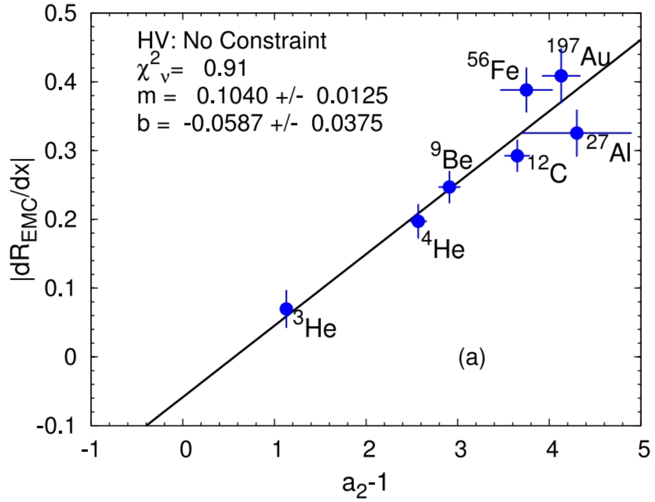
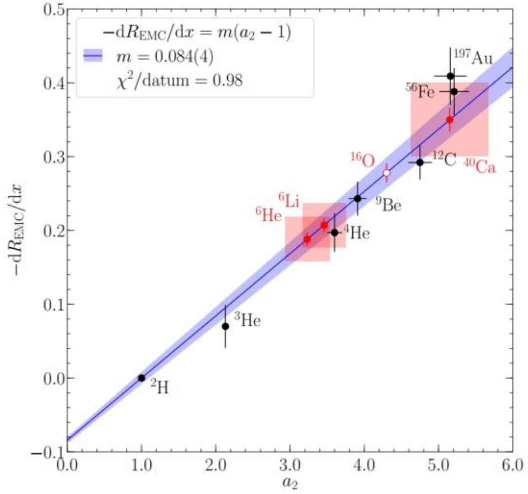


FIG. 1. The EMC slopes versus the SRC scale factors. The uncertainties include both statistical and systematic errors added in quadrature. The fit parameter is the intercept of the line and also the negative of the slope of the line.

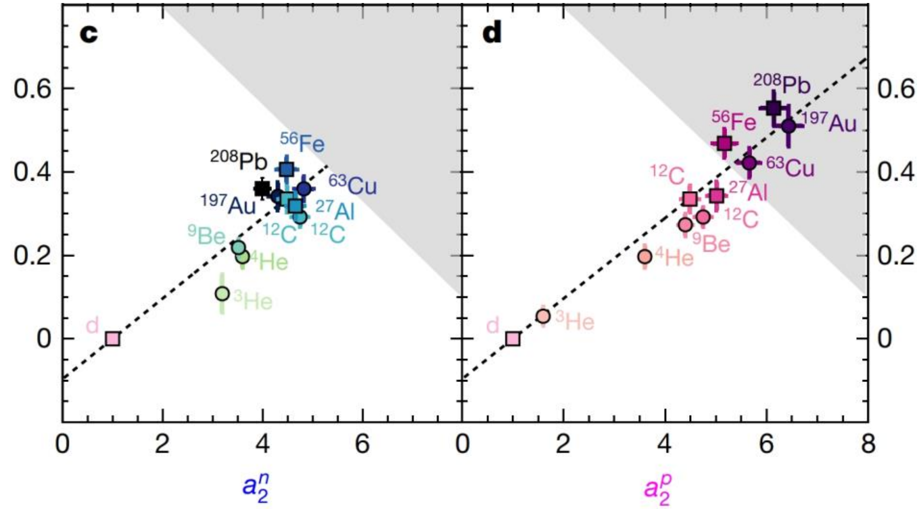
Phys. Rev. Lett. 106 (2011)



Phys. Rev. C 86 (2012)



J. Phys. G 47 (2020)



CLAS Collaboration, Nature 566 (2019)

Linear relation between EMC and SRC

- This phenomenological relationship has led to renewed interest in understanding how strongly correlated nucleons in the nucleus may be affecting the deep-inelastic results.

- **Support:**

  - *Short Range Correlations and the EMC Effect in Effective Field Theory, Phys.Rev.Lett. 119 (2017):*
  "The empirical linear relation … is a natural consequence of scale separation and it can be derived using effective field theory."

- **Suspicion:**

  - *Do short-range correlations cause the nuclear EMC effect in the deuteron? Phys.Rev.Lett. 125 (2021):*
  "… this analysis does not support the hypothesis that there is a causal connection between nucleons residing in SRCs and the EMC effect."

Linear relation between EMC and SRC

- **Progress in Quark Nuclear Physics:**

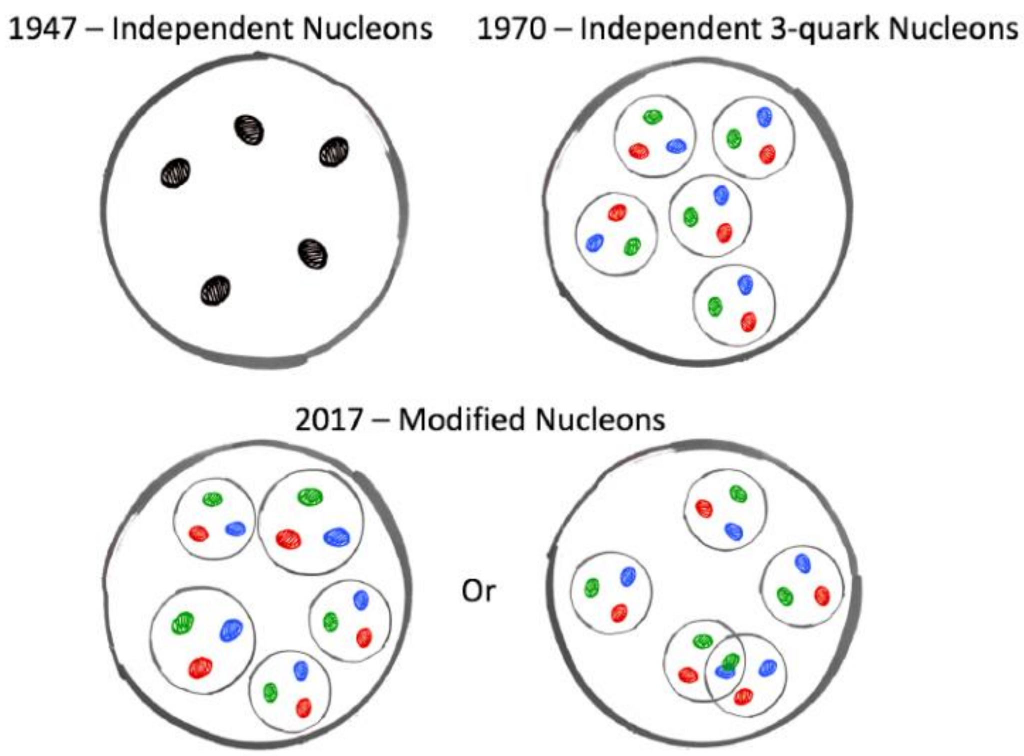


FIG. 29. Evolution of nuclear physics from structureless nucleons in the 1940s to independent three-quark nucleons in the 1970s to the modified nucleons of today, either modified single nucleons (left) or modified two-nucleon configurations (right).

Rev. Mod. Phys. 89 (2017)

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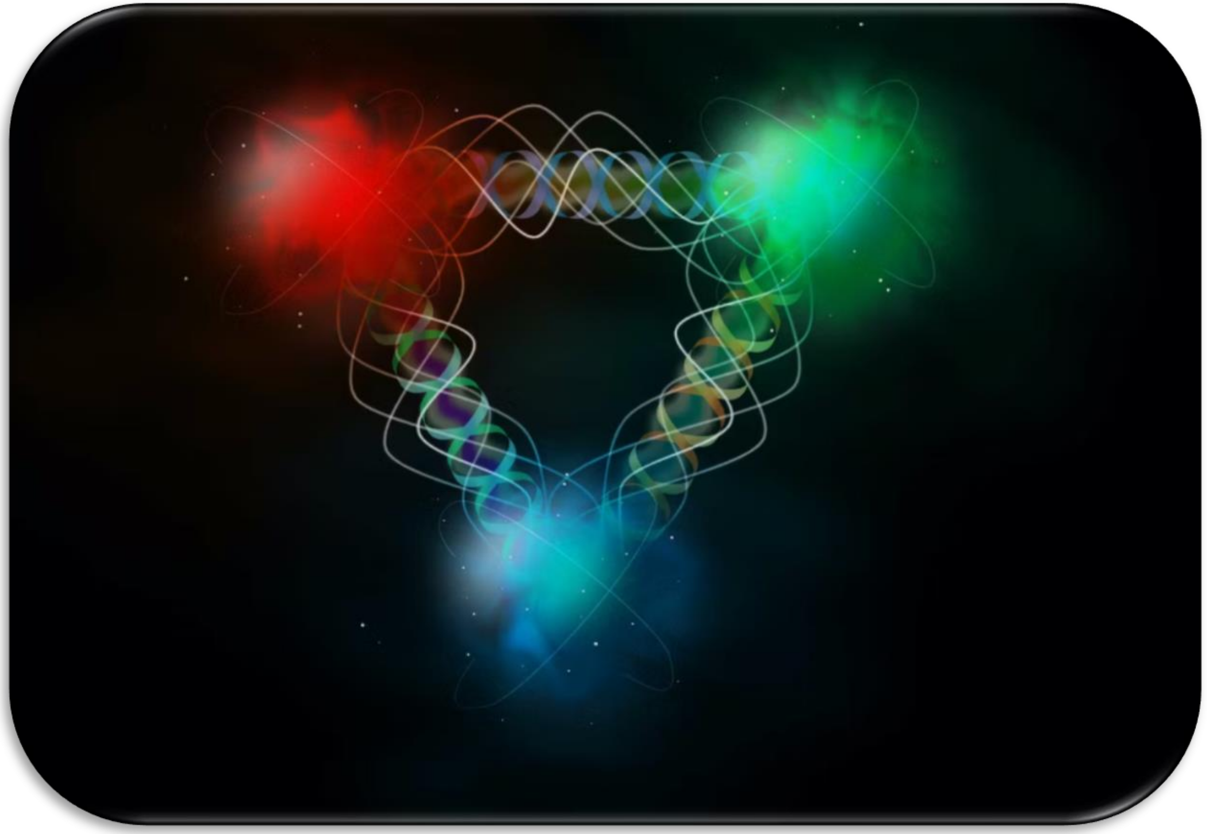
The gluons in nuclei

- The existing studies on the relation between EMC and SRC are mainly limited to the quark sector.



How about the gluons?

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

https://www.inverse.com/innovation/nuclear-emc-effect-explained

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.

- *Phys.Rev.D 96 (2017):* "An EIC will offer possibilities to constrain the gluon density in nuclei via measurements of the charm structure function."

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

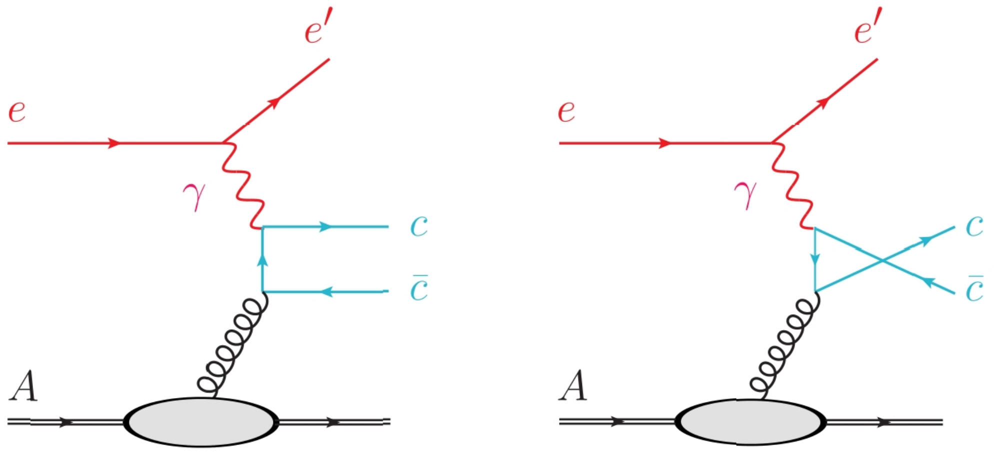


FIG. 1: Photoproduction of the heavy quark pair $c\bar{c}$ through photon-gluon fusion at leading order.

EMC and reduced cross section

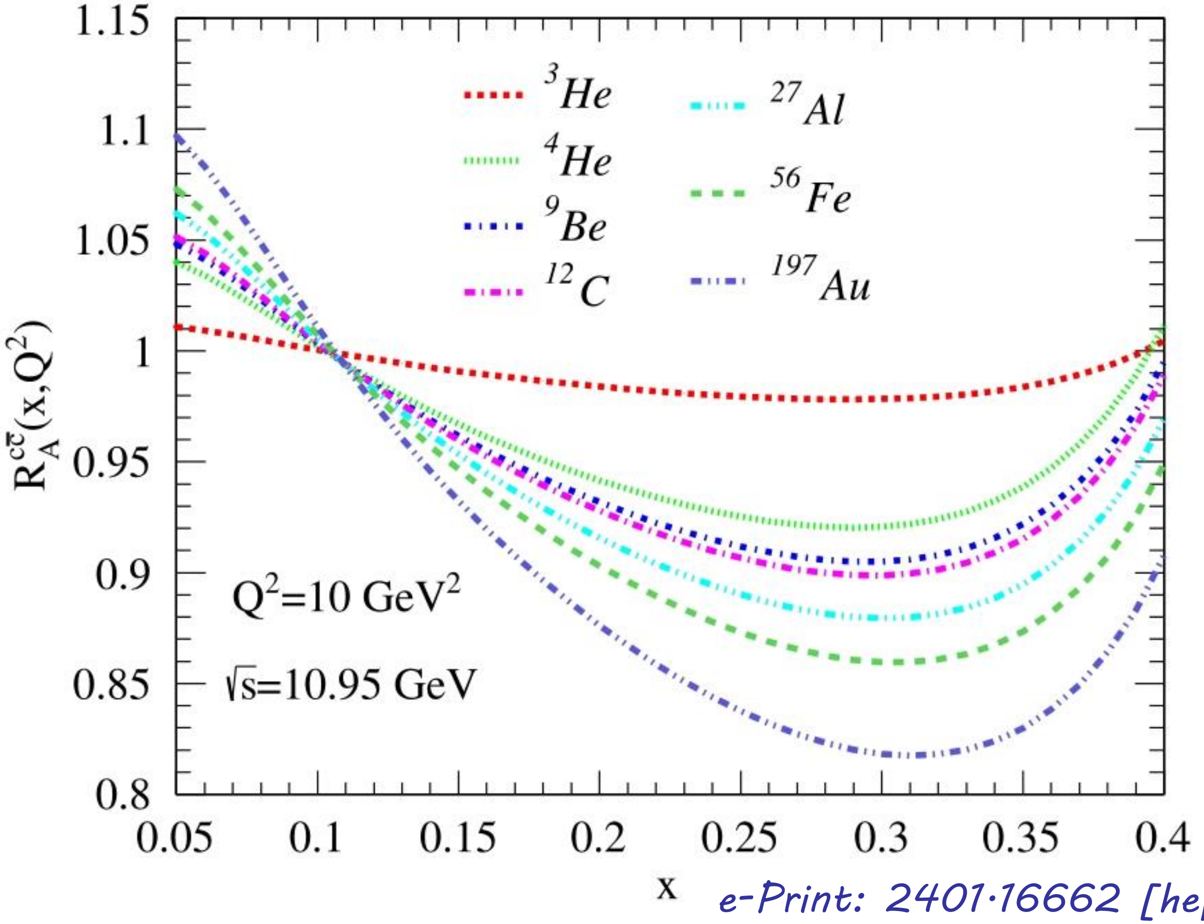
- The gluon nPDF can be parameterized through the gluon PDF in a free proton

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

Eur.Phys.J.C 82 (2022)

- Define the nuclear modification

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



e-Print: 2401.16662 [hep-ph]

EMC and reduced cross section

- Quantify the strength of the gluon EMC effect for nucleus A by the slope of $R_A^{c\bar{c}}$, i.e.,$\left|dR_A^{c\bar{c}}/dx\right|$.

Nucleus	$\|dR_A^{c\bar{c}}/dx\|$	$(\sigma_A^{sub}/A)^{\mathrm{I}}$	$(\sigma_A^{sub}/A)^{\mathrm{II}}$
^{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

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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.

Phys.Lett.B 498 (2001)

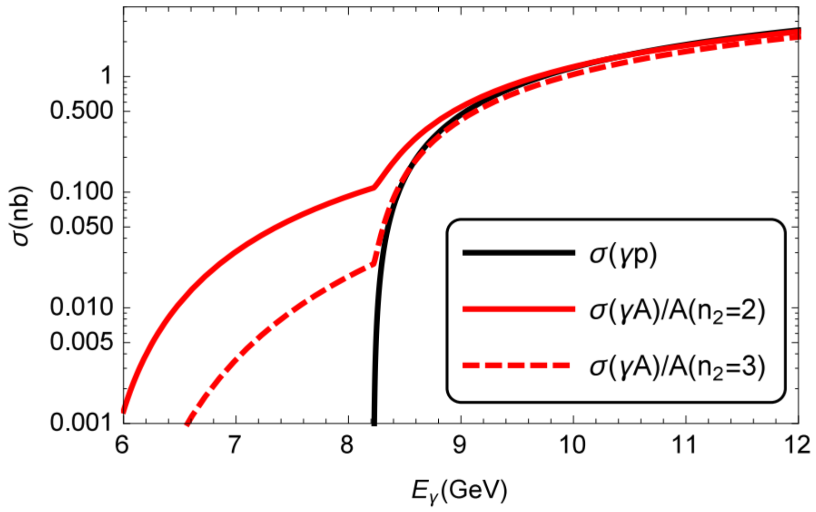

FIG. 2. Threshold and sub-threshold J/ψ production in γp and γA collisions.

Phys.Lett.B 801 (2020)

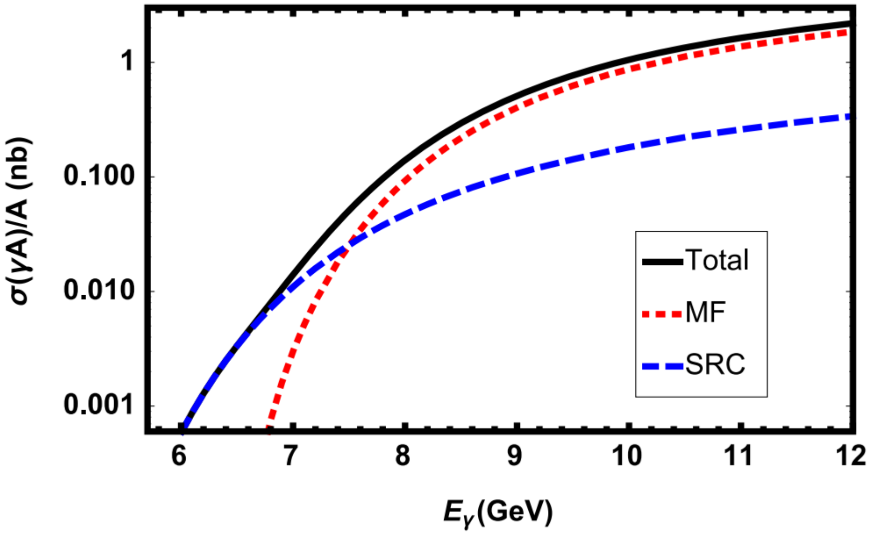

Fig. 3. Sub-threshold J/ψ production in photon-Carbon collisions as a function of incoming photon energy E_γ. We have estimated $P_{MF} = 0.84$ for the mean field normalization in Eq. (12).

Phys.Lett.B 803 (2020)

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Linear gluon EMC-SRC relation

- We will follow the chiral effective field theory analysis in *Phys.Rev.Lett. 119 (2017)* and derive a linear relation between the **magnitude of the gluon EMC effect** and the **sub-threshold J/ψ production cross section.**

- The Mellin moments of gluon nPDF

$$\langle A;p|\mathcal{O}_g^{\mu_0\cdots\mu_n}|A;p\rangle = \langle x_g^n\rangle_A(Q^2)p^{(\mu_0}\cdots p^{\mu_n)}\,.$$

$$\mathcal{O}_g^{\mu_0\cdots\mu_n} = G_a^{\alpha(\mu_0}iD^{\mu_1}\cdots iD^{\mu_{n-1}}G_{a,\alpha}^{\ \ \mu_n)}$$

$$\langle x_g^n\rangle_A(Q^2) = \int_{-A}^{A} x^n g_A(x,Q^2)dx\,.$$

$$\mathcal{O}_g^{\mu_0\cdots\mu_n} \to: \langle x_g^n\rangle_N M^n v^{(\mu_0}\cdots v^{\mu_n)}N^\dagger N\left(1+\delta_n N^\dagger N\right)+\ldots:$$

$$\langle x_g^n\rangle_A = A\langle x_g^n\rangle_N + \langle x_g^n\rangle_N\delta_n(\Lambda,Q^2)\langle A|:(N^\dagger N)^2:|A\rangle\,.$$

Linear gluon EMC-SRC relation

- The gluon nPDF can be divided

$$g_A(x,Q^2)/A \simeq g(x,Q^2) + g_2(A,\Lambda)\,\tilde{f}_g(x,Q^2,\Lambda)\,.$$

- The same relation also holds for the reduced cross section

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

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

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

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

Linear gluon EMC-SRC relation

- The ratio of $g_2(A,\Lambda)$ for different nuclei

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

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

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

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

Linear gluon EMC-SRC relation

- The sub-threshold cross section is calculated $\left(\sigma_d^{sub}/2\right) = 3.2$ pb. *Phys.Lett.B 803 (2020)*

- Estimation of (σ_A^{sub}/A) for different nuclei.

Strategy 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.

Strategy II

- ➢ Making use of the parameterization in EPPS21

$$\frac{g_2(A,\Lambda)}{g_2(A',\Lambda)} = \frac{R_g^A(x,Q^2)-1}{R_g^{A'}(x,Q^2)-1}\,.$$

Eur.Phys.J.C 82 (2022)

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
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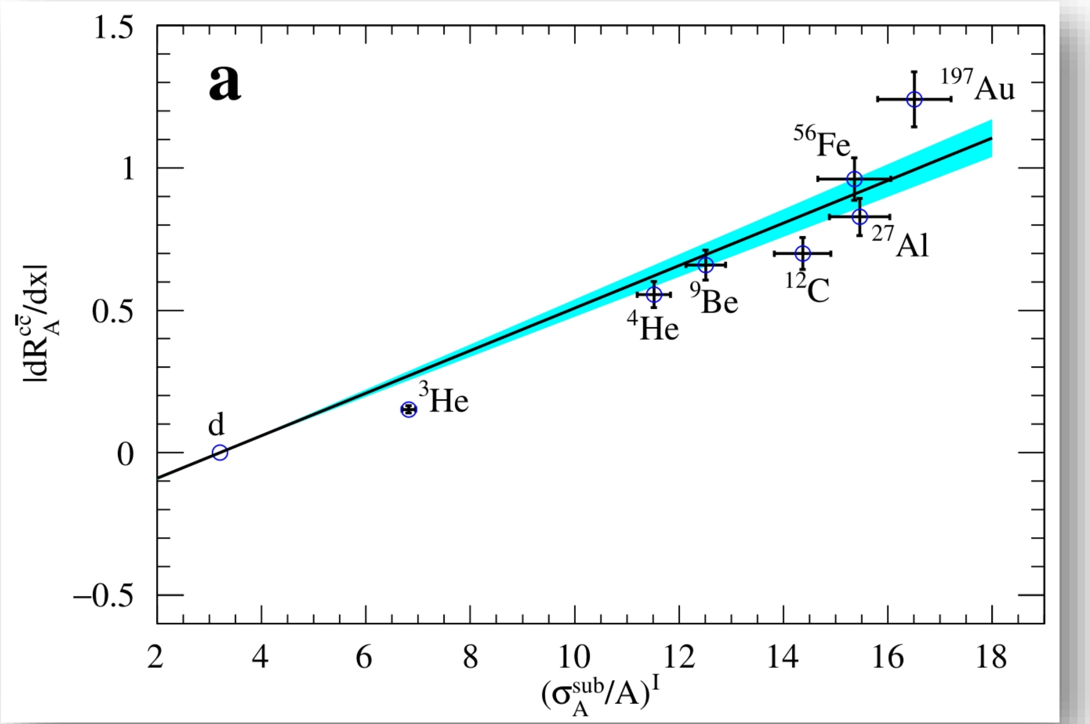

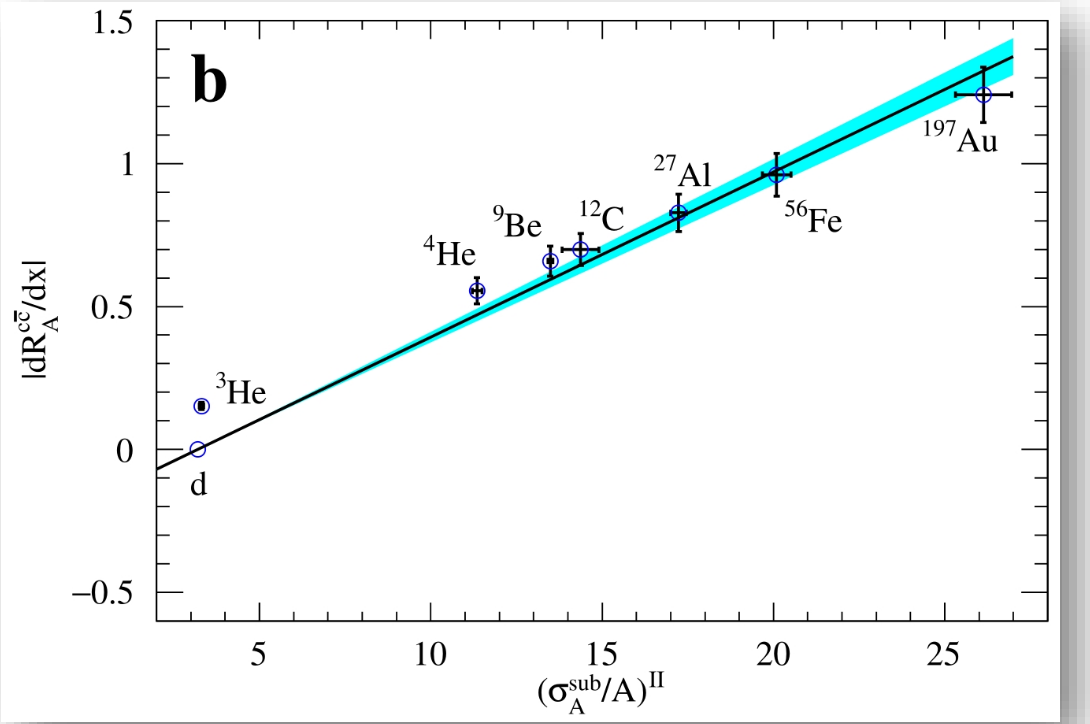

$$|dR_A^{c\bar{c}}/dx| = (0.0747 \pm 0.0045) \times \left[(\sigma_A^{sub}/A)^{\mathrm{I}} - (\sigma_d^{sub}/2)\right] .$$

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

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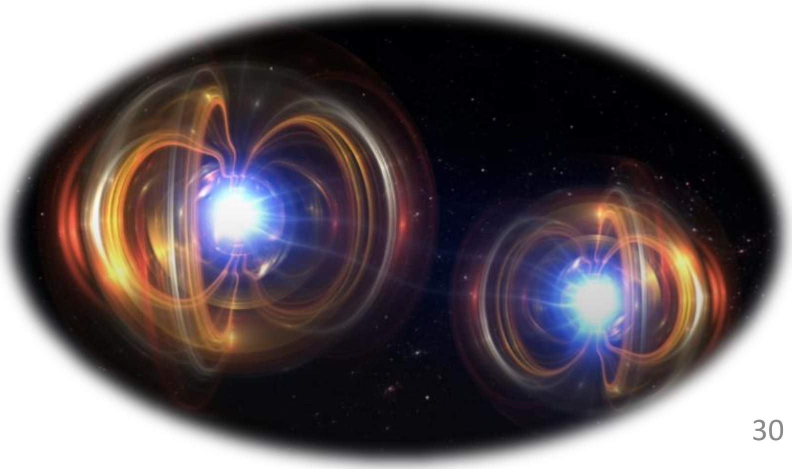
Summary

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

- We derive a linear correlation between the magnitude of the gluon EMC effect and the sub-threshold J/ψ production cross section.

- This presents an independent test of the nuclear modification of gluon distribution function and the universal influence of SRCs on parton distributions in nucleon.

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Happy new year！
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