Gluon Distribution in Nuclear Matter

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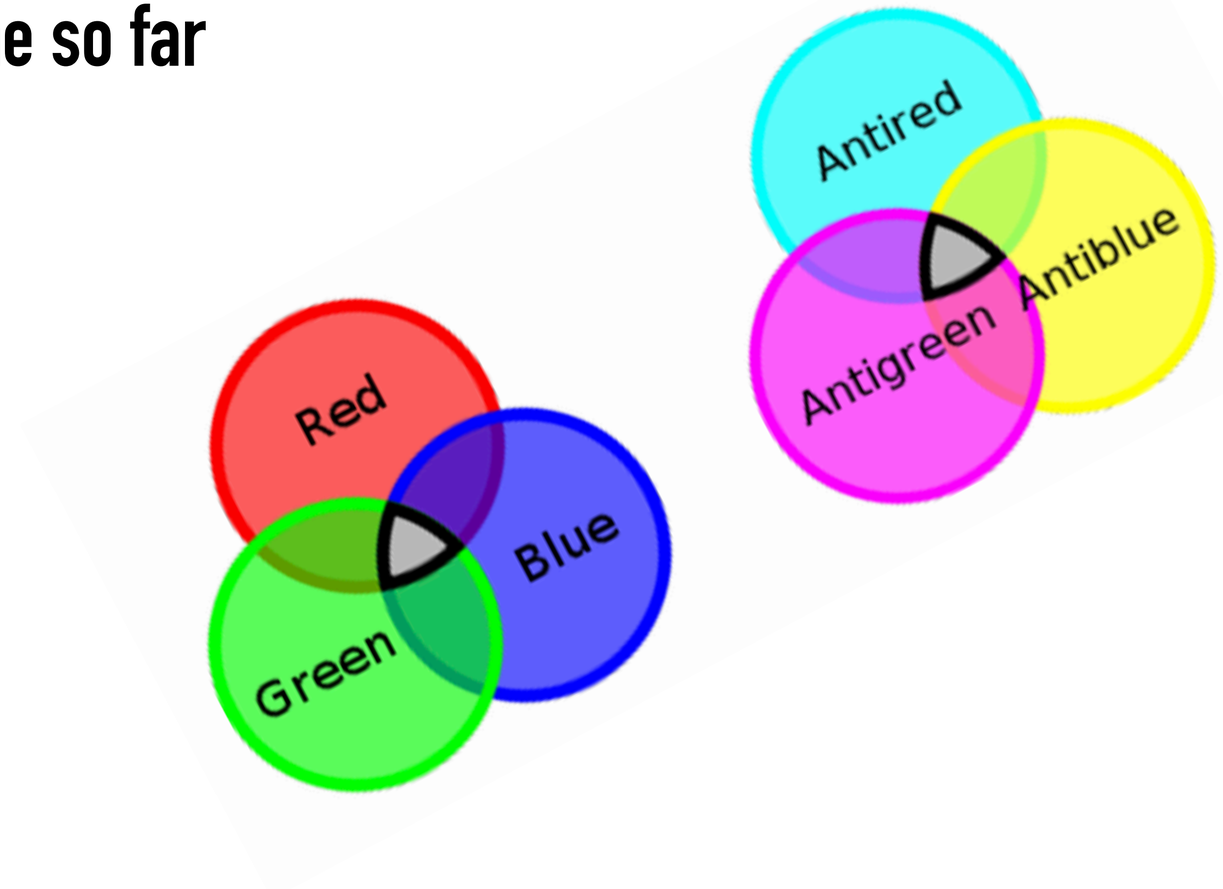
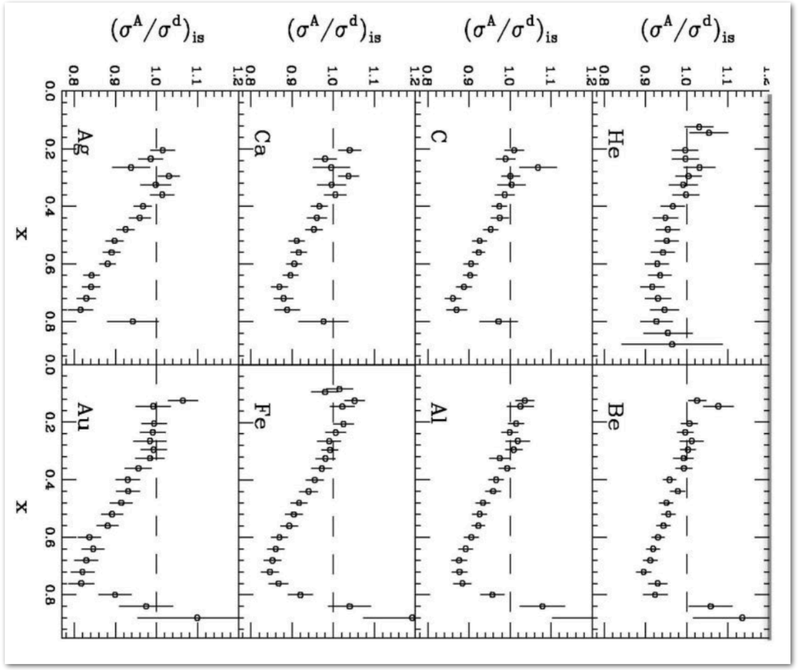


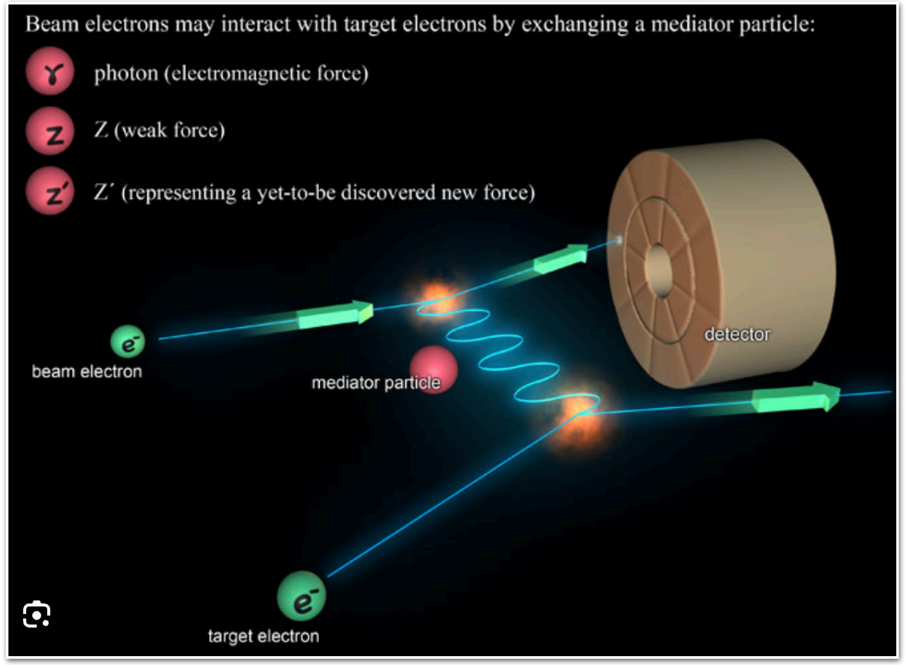
EMC Effect

- Medium modifications—European Muon Collaboration (EMC) effect [J.J. Aubert et. Al, Phys. Lett. B 123 (1983) 275, J.Gomez et al, Phys. ReV. D 49 (1994) 4348]

Ratio of cross-section for different nuclei is not constant



SLAC-PUB 3859 (1985)



- Observing the ratios of the spin-independent structure of heavy nuclei to that of the deuteron $[F_{2A}(x)/F_{2D}(x)]$ modify substantially in the valence region of Bjorken-x—Still challenging task in modern nuclear physics

Studies on EMC Effect

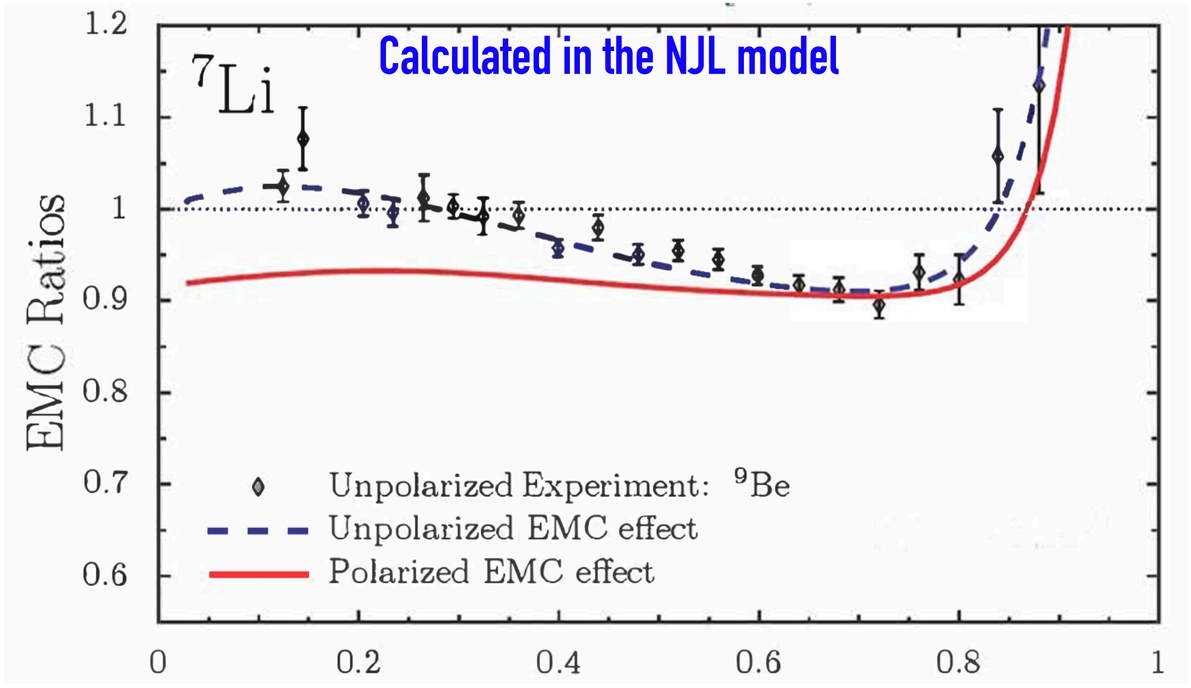
- EMC found that the valence structure of a nucleus was very different from that of a free nucleon
- Several explanations have been suggested:

1. It was expected that the strong Lorentz scalar and vector mean fields exist in a nucleus on the internal structure of the nucleon-like clusters
2. Effect on the modification of the structure of nucleons involved in short-range correlations (SRC)

- As complementary results to those two puzzles, Thomas et al, proposed spin-independent EMC effect and Isovector EMC effect—was planned to measure in JLaB [Anthony Thomas, Int. J. Mod. Phys. E 27 (2019) 12, 1840001 and references therein]

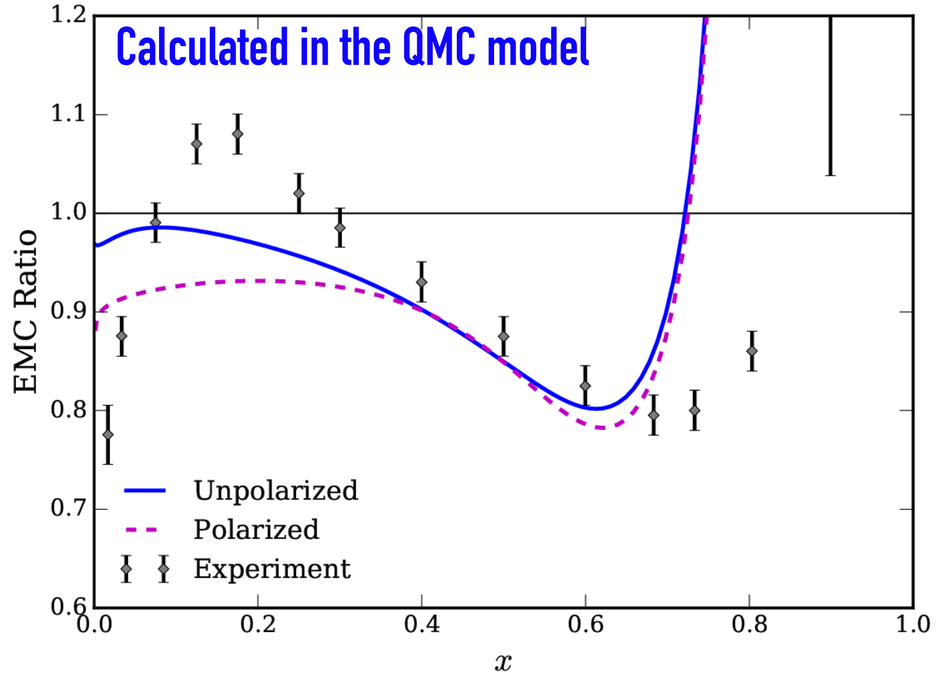
Studies on EMC Effect

Result for the spin-dependent and independent EMC effect for the proton in nuclear medium at $Q^2 =$ 5 GeV^2



Cloet et al, PRL 95, 052302 (2005)

Result for the spin-dependent and independent EMC effect for the proton in nuclear medium at $Q^2 =$ 10 GeV^2



Tronchin et al, PLB 783, 247 (2018)

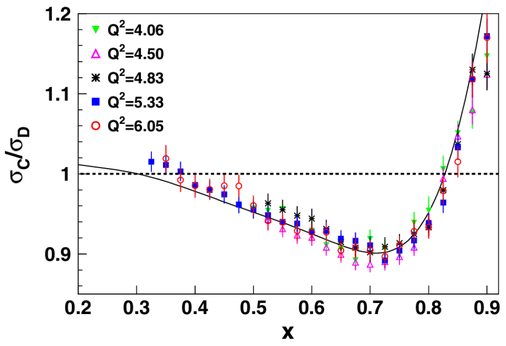
- Initial work was calculated in the MIT bag model, NJL model, and QMC model

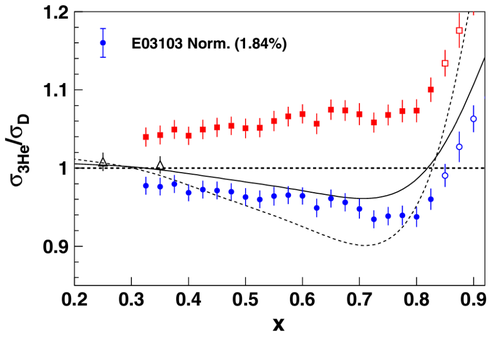
Studies on EMC Effect

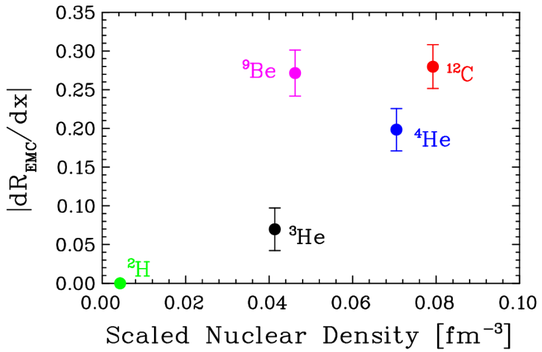
PRL **103,** 202301 (2009) PHYSICAL REVIEW LETTERS week ending 13 NOVEMBER 2009

New Measurements of the European Muon Collaboration Effect in Very Light Nuclei

- Jefferson Lab has measured for a time the EMC effect for ^{3}He at large-x and a significant improvement for ^{4}He—-triggered more works of qPDF and gPDF in NM
- New data on the EMC effect suggested that the nuclear dependence of the quark distributions may depend on the local nuclear environment

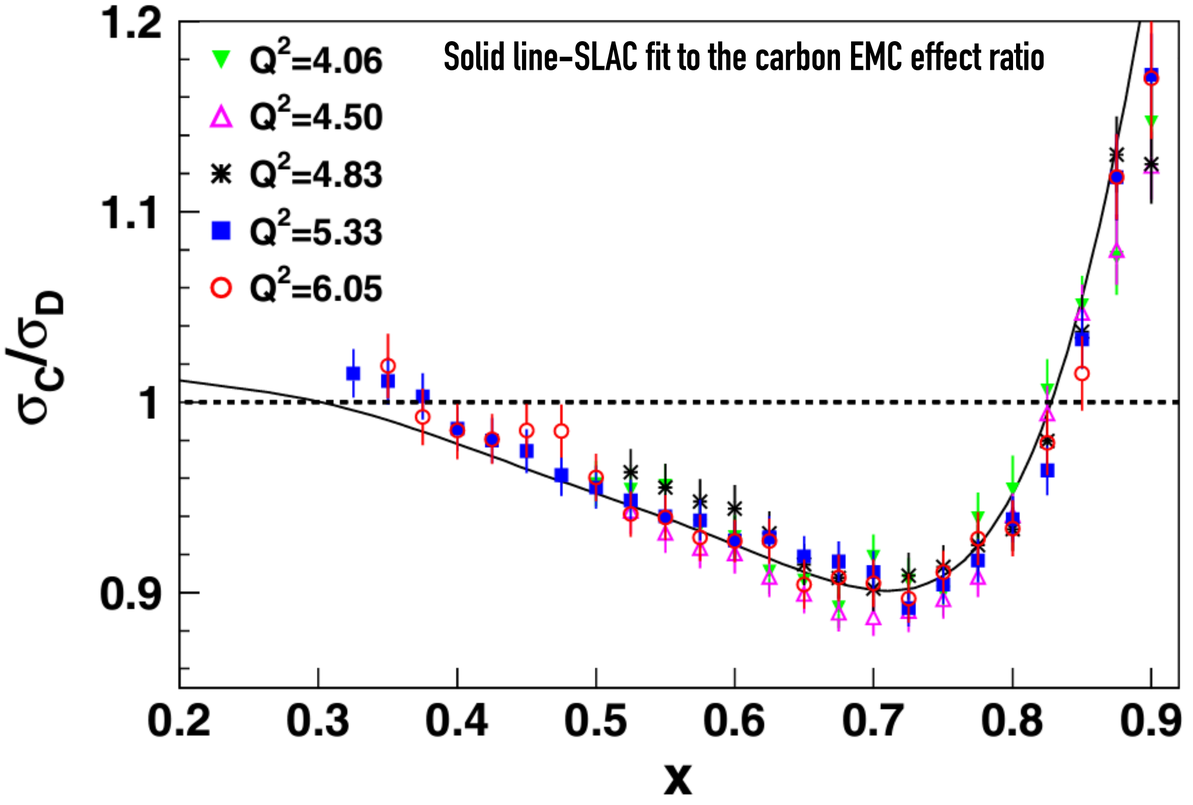






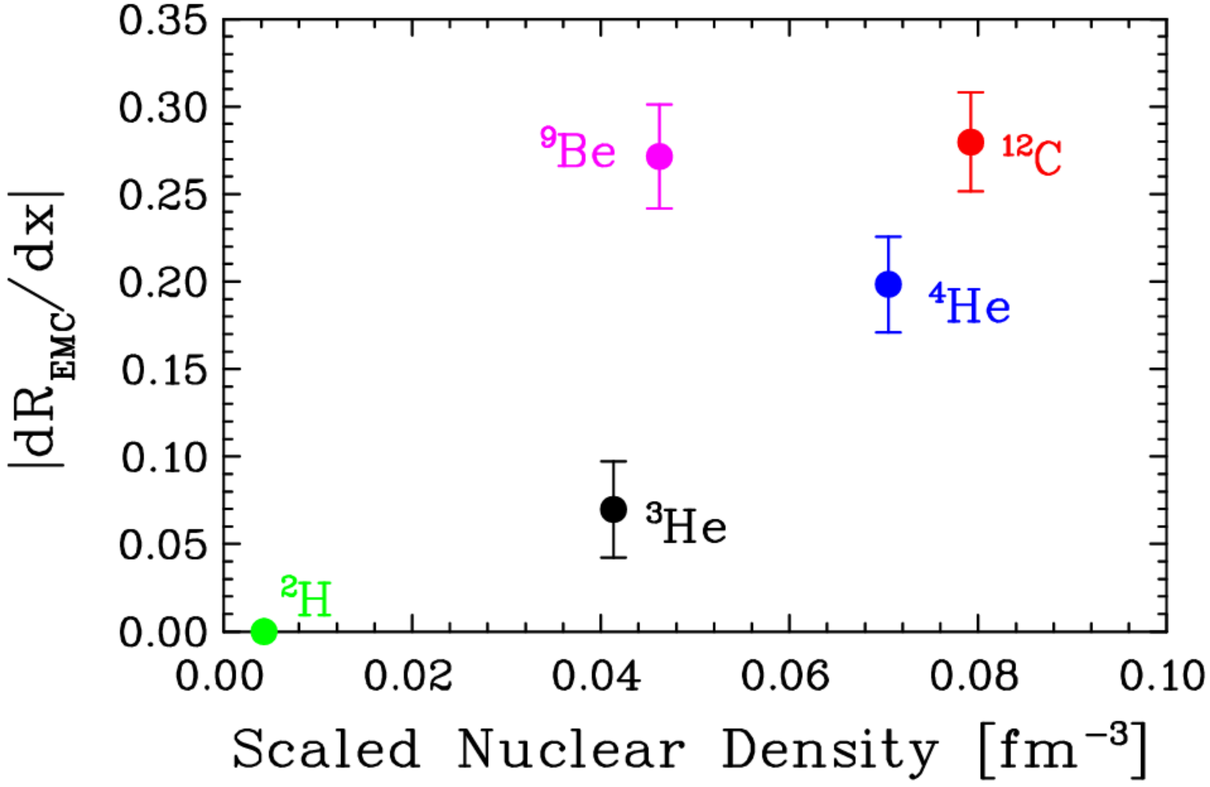
Studies on EMC Effect

Carbon EMC Ratios for different Q^2



Gomez et al, PRD 49, 4348 (1994)

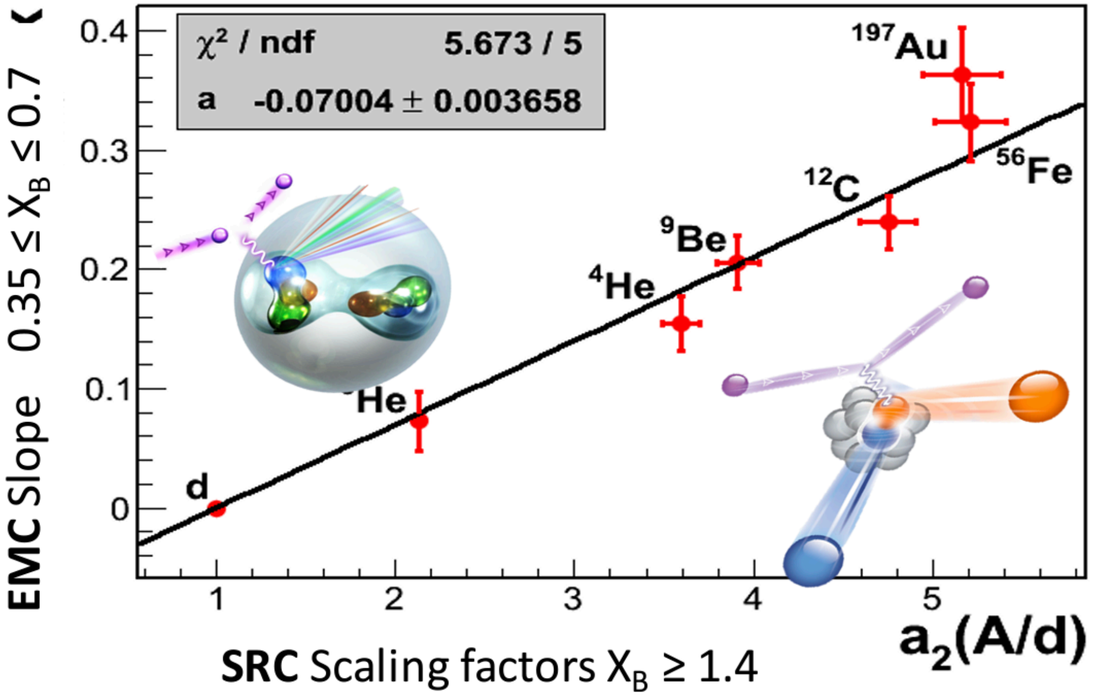
The slope of the isoscalar EMC ratio for $0.35 < x < 0.7$



J. Seely et al, PRL 103, 2022301 (2009)

Studies on EMC Effect

Slope EMC



O. Hen et al, PRC 85, 047301(2012) Weinstein et al, PRL 106, 052301 (2011)

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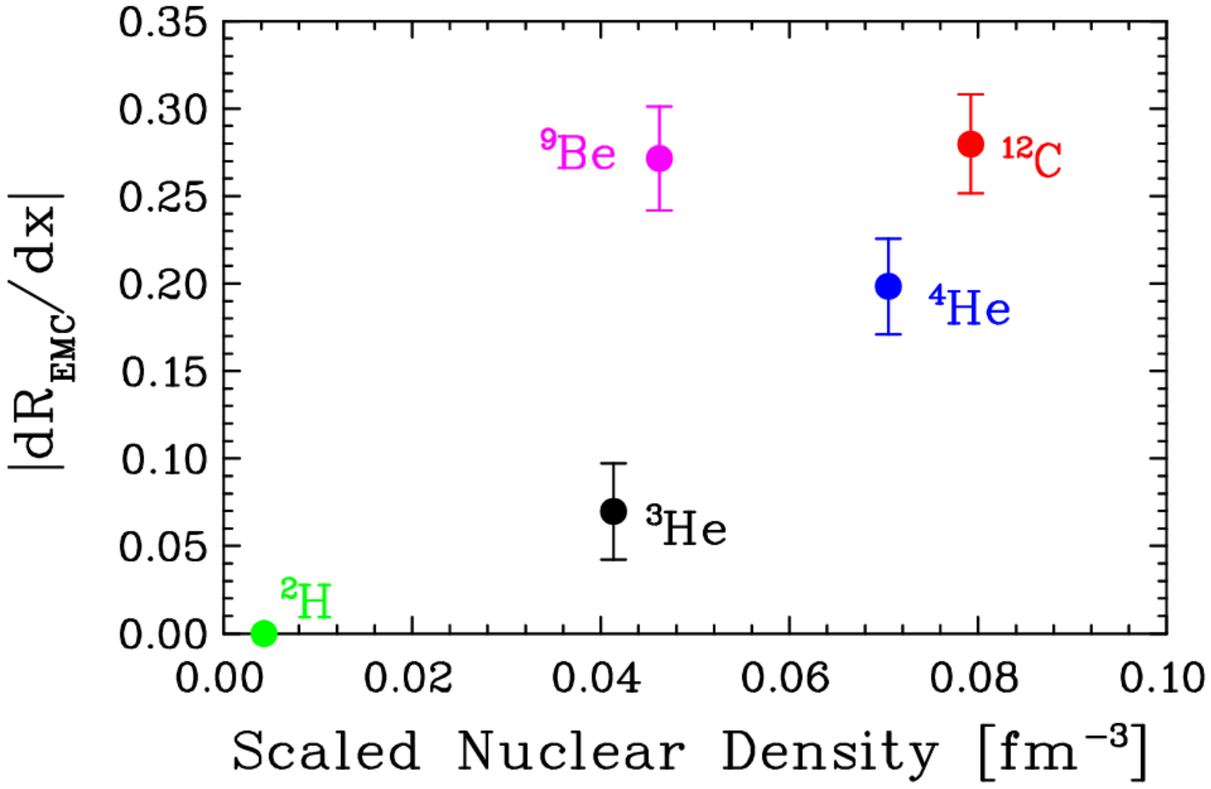
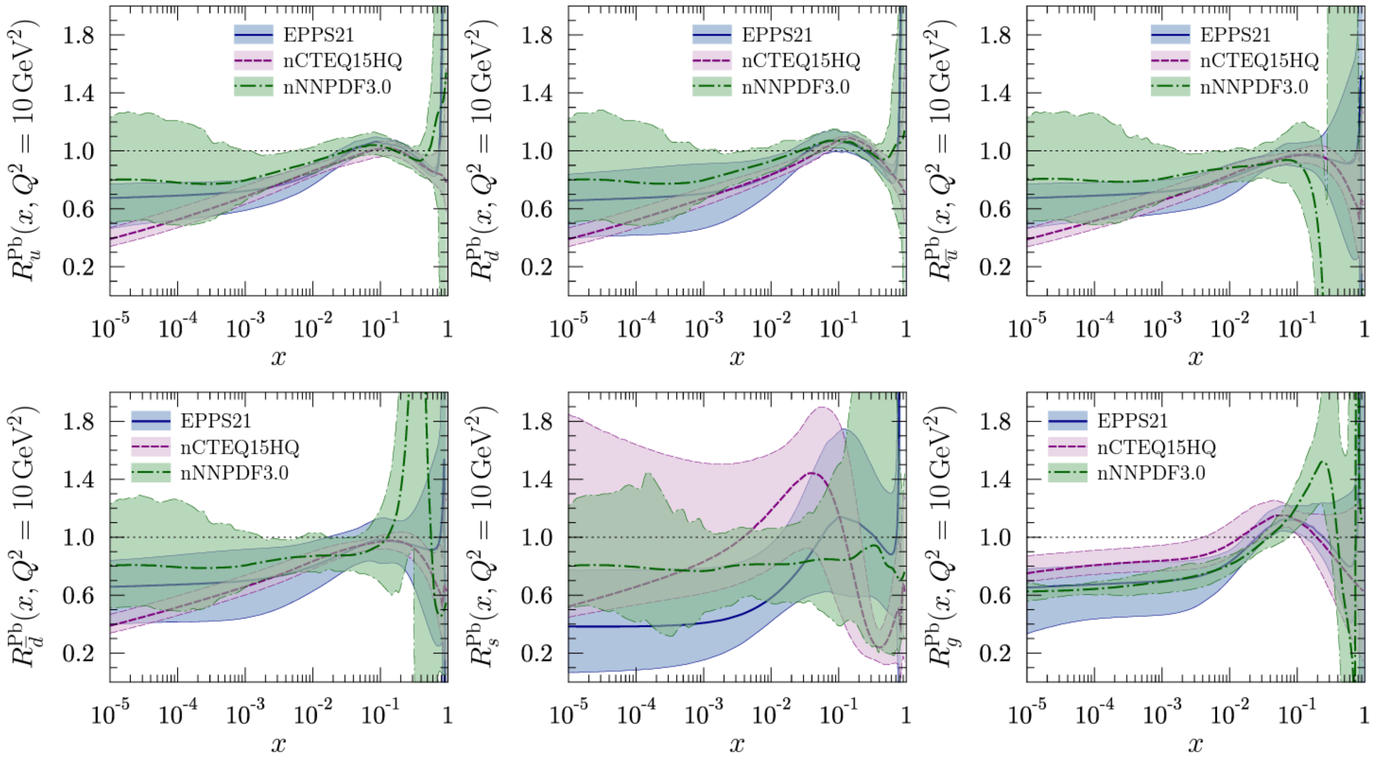


J. Seely et al, PRL 103, 2022301 (2009)

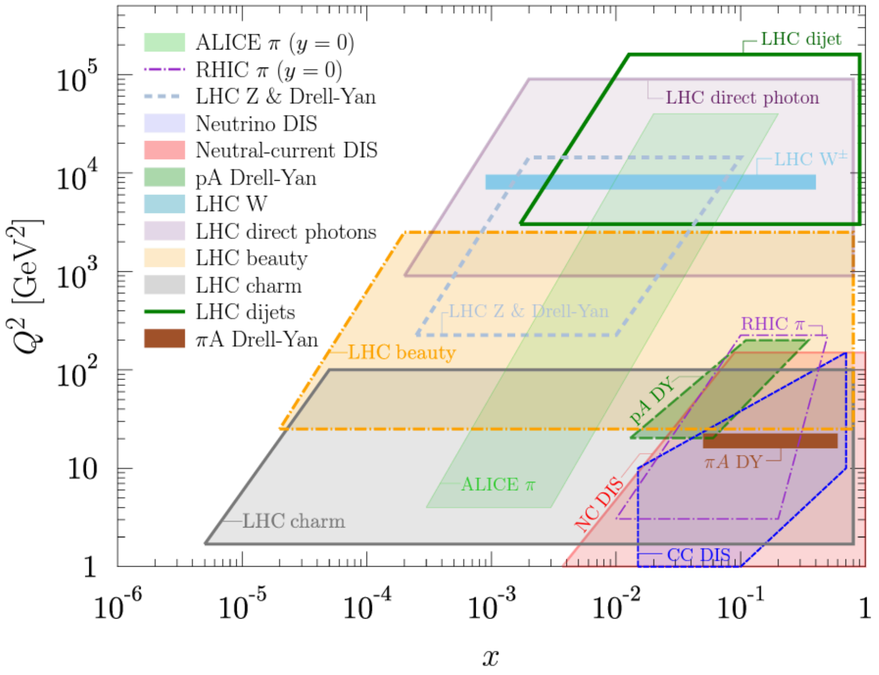
Nuclear PDF from Global Analysis

Nuclear PDF from Global Analysis



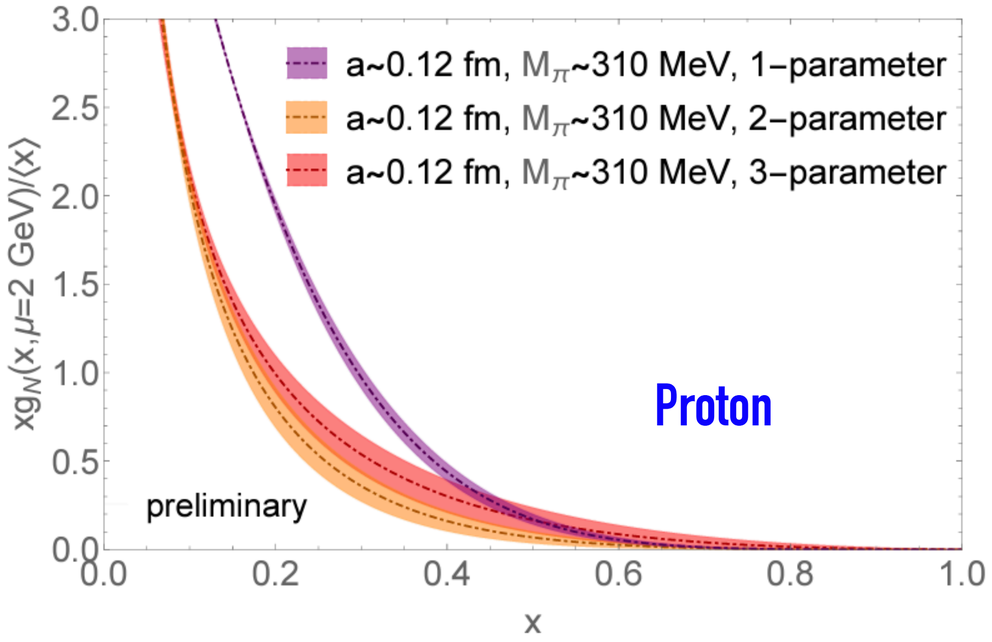
Klasen et al, 2311.00450 (2023)

A plot of Q^2 and x for lepton-A, pion-A, and proton-A

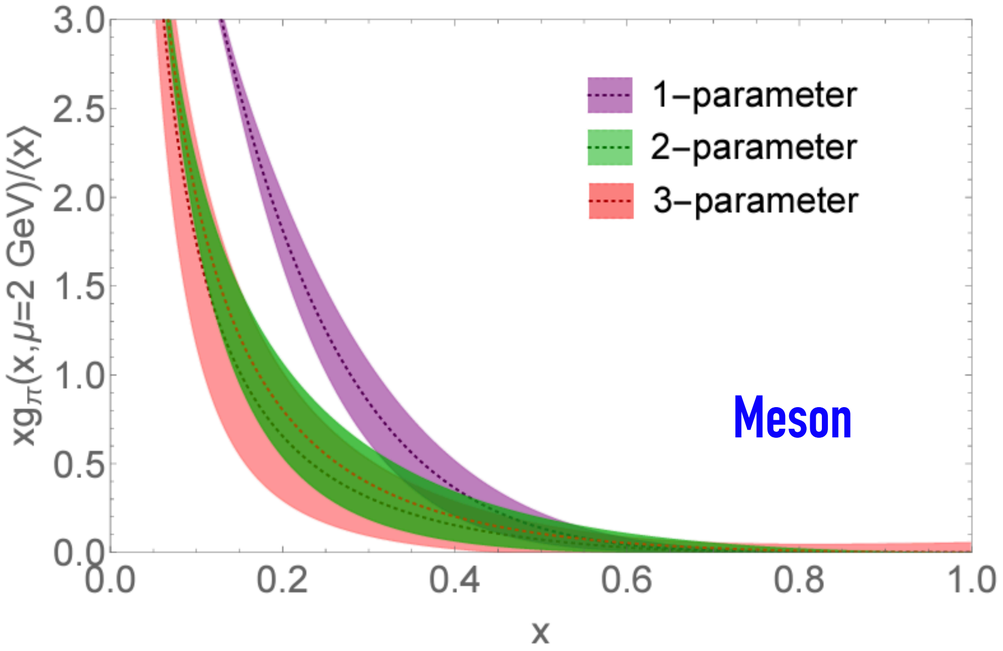


Gluon Distribution From Lattice

- Free space gPDF for proton and mesons—Extract the pion and nucleon x-dependent gluon PDFs at 3 pion masses and the lattice spacings



Zhouyou Fan and Huey-Wn Lin, PoS (Lattice2021) 628

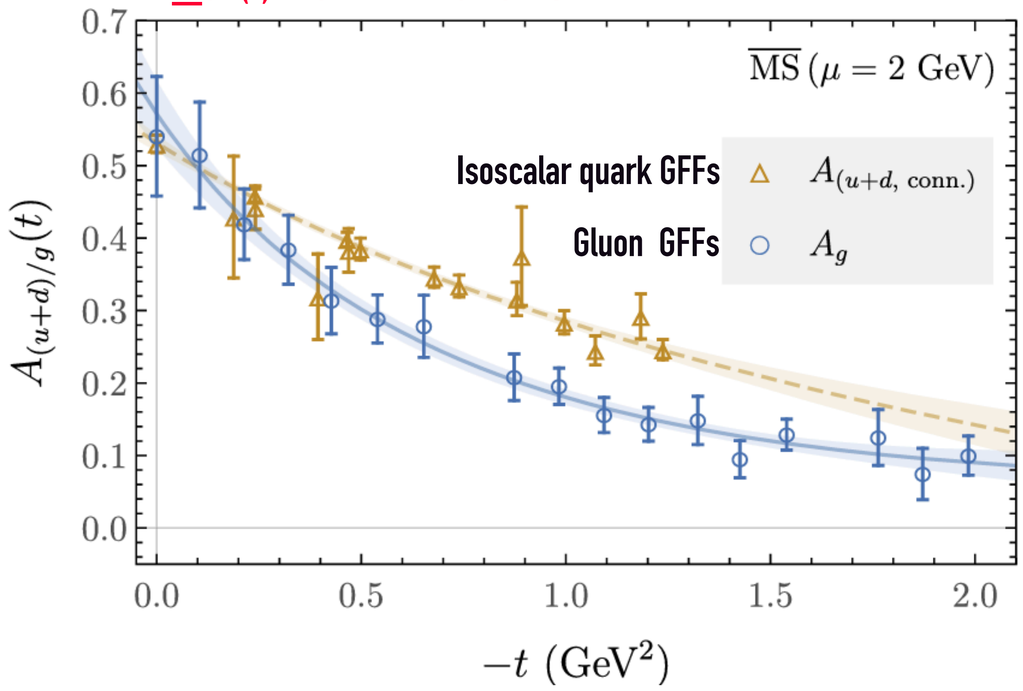


MORE WORKS ON gPDF . . .

Gluon GFFs From Lattice

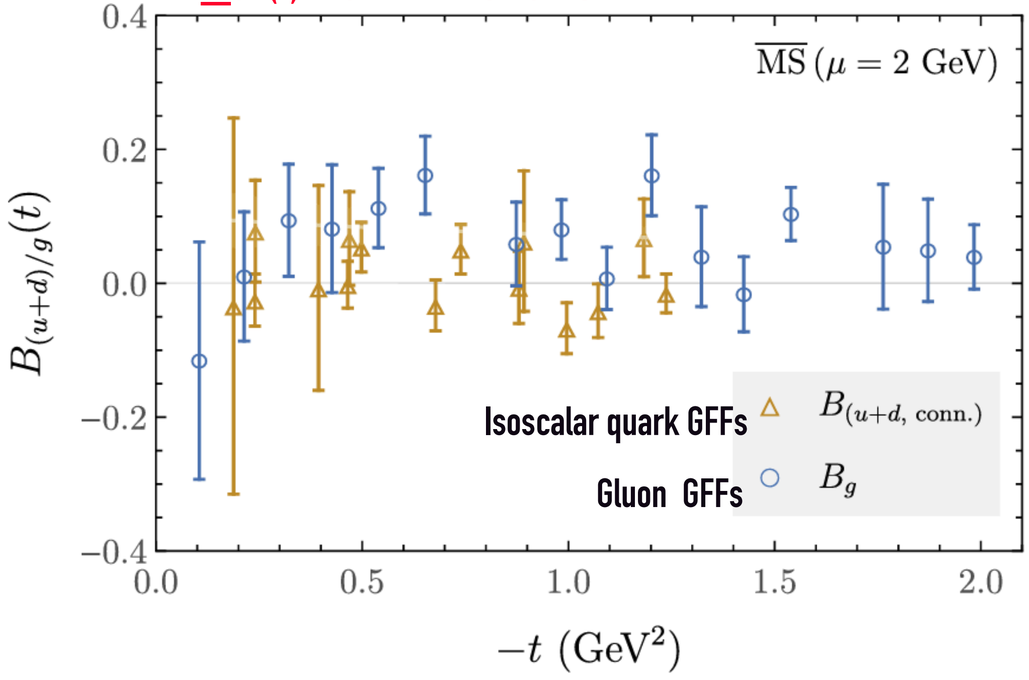
- Free space gluon GFF for nucleon at $m_\pi \sim 450$ MeV

A_a (t) FORM FACTORS



P.E.Shanahan, Deltmold, PRD 99, 014511 (2019)

B_a (t) FORM FACTORS

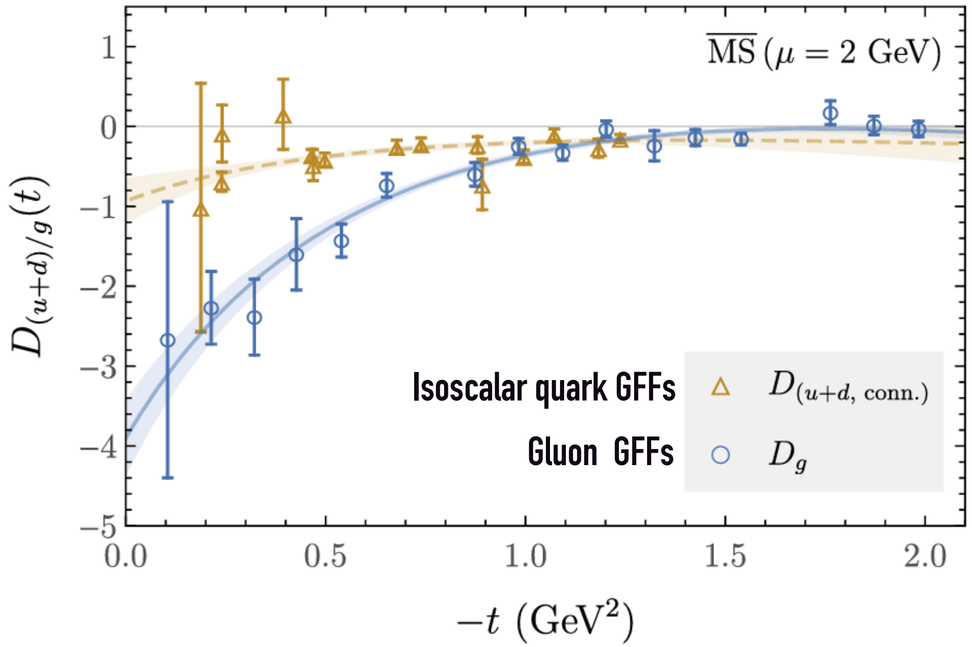


MORE WORKS ON GLUON GFFs . . .

Gluon GFFs From Lattice

- Free space gluon GFF for nucleon at $m_\pi \sim 450$ MeV

D_a (t) FORM FACTORS



P.E.Shanahan, Deltmold, PRD 99, 014511 (2019)

$$\int_{-\infty}^{\infty}\frac{d\lambda}{2\pi}e^{i\lambda x}\langle p',s'|\bar{\psi}_q\left(-\frac{\lambda}{2}n\right)\gamma^\mu\mathcal{U}_{[-\frac{\lambda}{2}n,\frac{\lambda}{2}n]}\psi_q\left(\frac{\lambda}{2}n\right)|p,s\rangle$$
$$= H_q(x,\xi,t)\bar{U}(p',s')\gamma^\mu U(p,s)$$
$$+ E_q(x,\xi,t)\bar{U}(p',s')\frac{i\sigma^{\mu\nu}\Delta_\nu}{2M}U(p,s)+\cdots,$$

Quark GFFs

$$\int_{-1}^{1}\mathrm{d}x\,xH_q(x,\xi,t) = A_q(t)+\xi^2 D_q(t),$$
$$\int_{-1}^{1}\mathrm{d}x\,xE_q(x,\xi,t) = B_q(t)-\xi^2 D_q(t),$$

$$\int_{-\infty}^{\infty}\frac{d\lambda}{2\pi}e^{i\lambda x}\langle p',s'|G_a^{\{\mu\alpha}\left(-\frac{\lambda}{2}n\right)\left[\mathcal{U}^{(A)}_{[-\frac{\lambda}{2}n,\frac{\lambda}{2}n]}\right]_{ab}G_{b\alpha}^{\nu\}}\left(\frac{\lambda}{2}n\right)|p,s\rangle$$
$$=\frac{1}{2}\Bigg(H_g(x,\xi,t)\bar{U}(p',s')P^{\{\mu}\gamma^{\nu\}}U(p,s)$$
$$+E_g(x,\xi,t)\bar{U}(p',s')\frac{P^{\{\mu}i\sigma^{\nu\}\alpha}\Delta_\alpha}{2M}U(p,s)\Bigg)+\cdots,$$

$$\int_0^1\mathrm{d}x\,H_g(x,\xi,t) = A_g(t)+\xi^2 D_g(t),$$
$$\int_0^1\mathrm{d}x\,E_g(x,\xi,t) = B_g(t)-\xi^2 D_g(t).$$

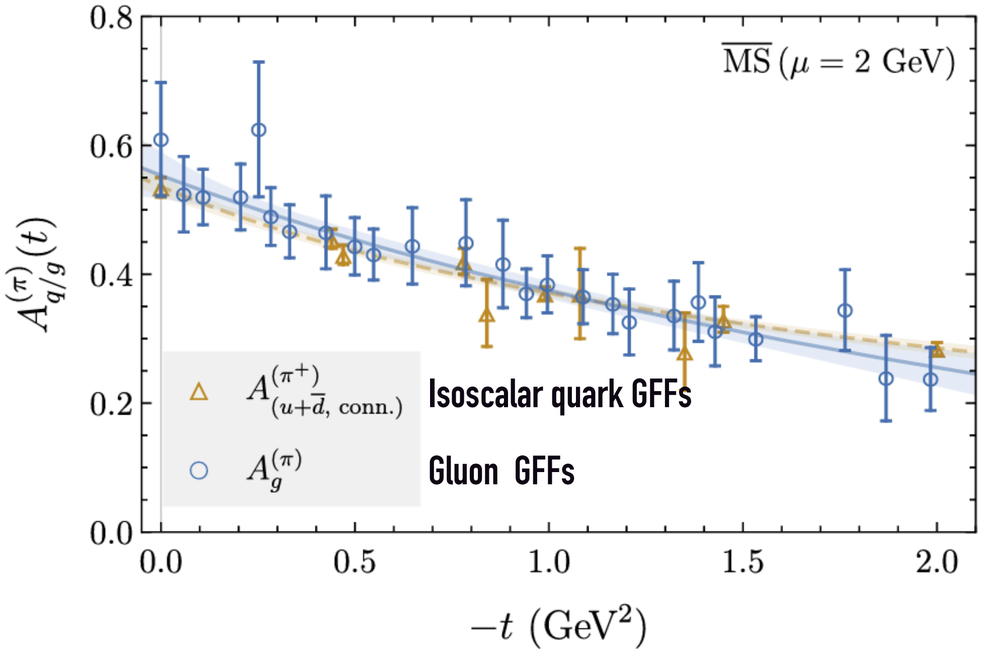
Gluon GFFs

MORE WORKS ON GLUON GFFs . . .

Gluon GFFs From Lattice

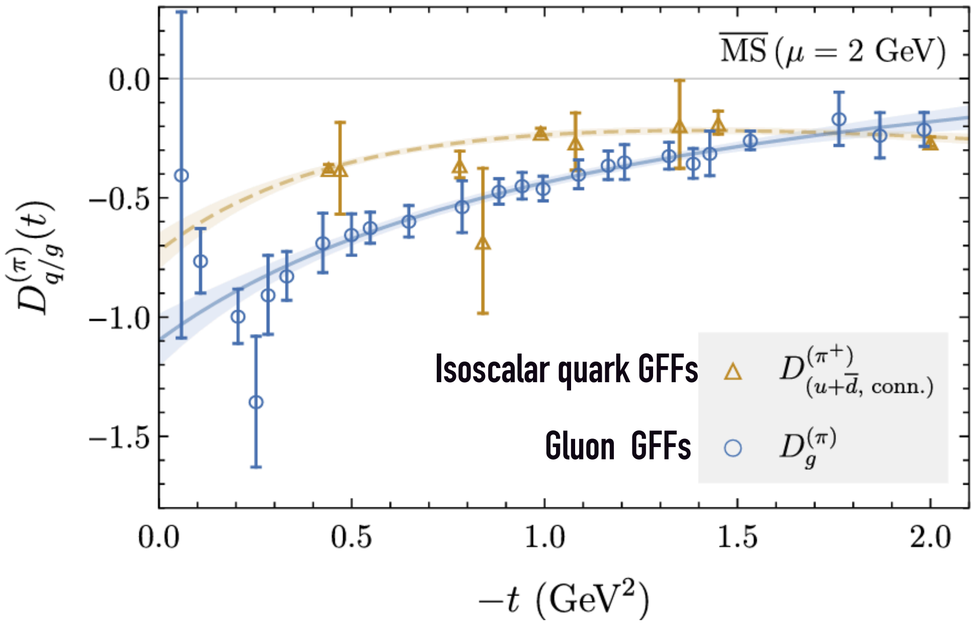
- Free space gluon GFF for pion at $m_\pi \sim 450$ MeV—systematic uncertainties still large—need more precise calculation

A_a (t) FORM FACTORS

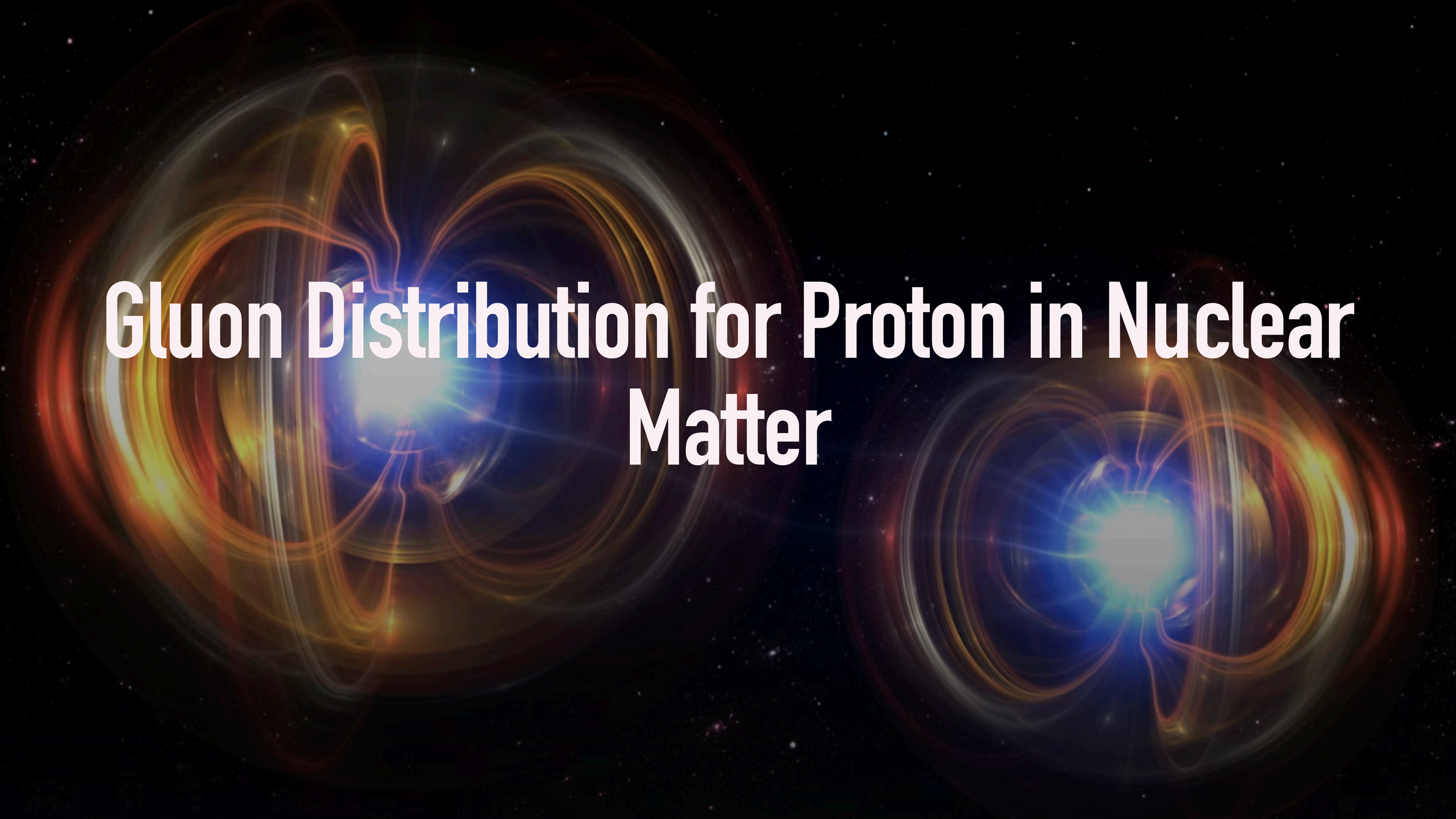


P.E.Shanahan, Deltmold, PRD 99, 014511 (2019)

B_a (t) FORM FACTORS



MORE WORKS ON GLUON GFFs . . .



Gluon Distribution for Proton in Nuclear Matter

Gluon Distribution for Proton in NM

- Spin-independent quark light-cone momentum distribution in a free nucleon

$$q(x) = -\mathrm{i} \int \frac{\mathrm{d}^4 k}{(2\pi)^4} \delta\left(x - \frac{k^+}{p^+}\right) \mathrm{Tr}\left(\gamma^+ M(p,k)\right)$$

- Spin-dependent $\Delta q(x)$ can be obtained by replacing $\gamma^+ \to \gamma^+\gamma_5$
- Analogously, nucleon PDF in NM

1. The dressed quark propagator is modified by including the mean scalar and vector fields

2. The Fermi motion is considered in the standard convolution formalism

- The gluon and sea-quark PDFs are dynamically generated via QCD evolution

Gluon Distribution for Proton in NM

- The unpolarized EMC effects for gluons

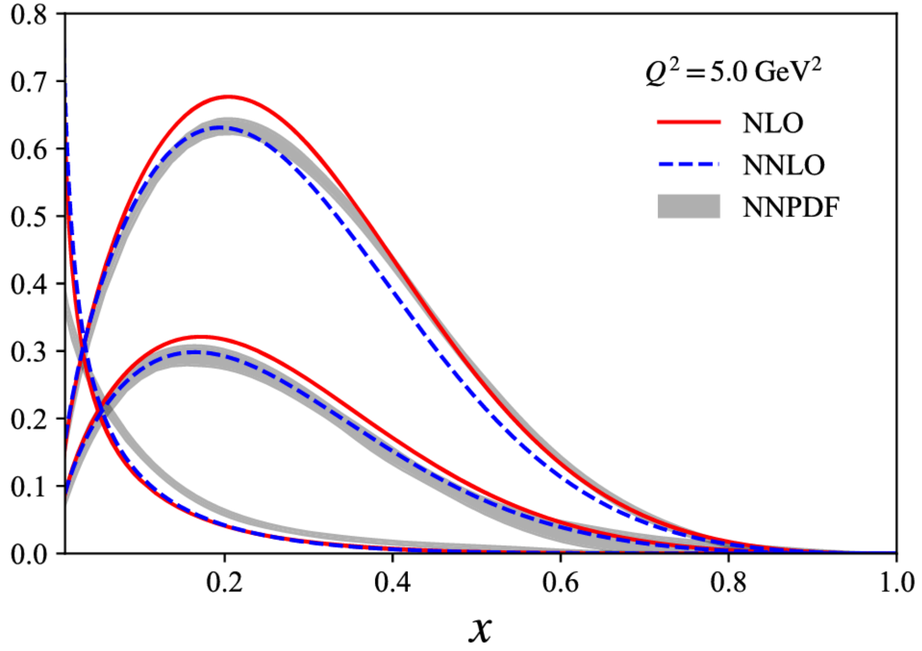
$$R_{\mathrm{G}} = \frac{g_{\mathrm{A}}(x)}{Z/A g_{\mathrm{p}}(x) + N/A g_{\mathrm{n}}(x)} \to \frac{g_{\mathrm{A}}(x)}{g_{\mathrm{p}}(x)}$$

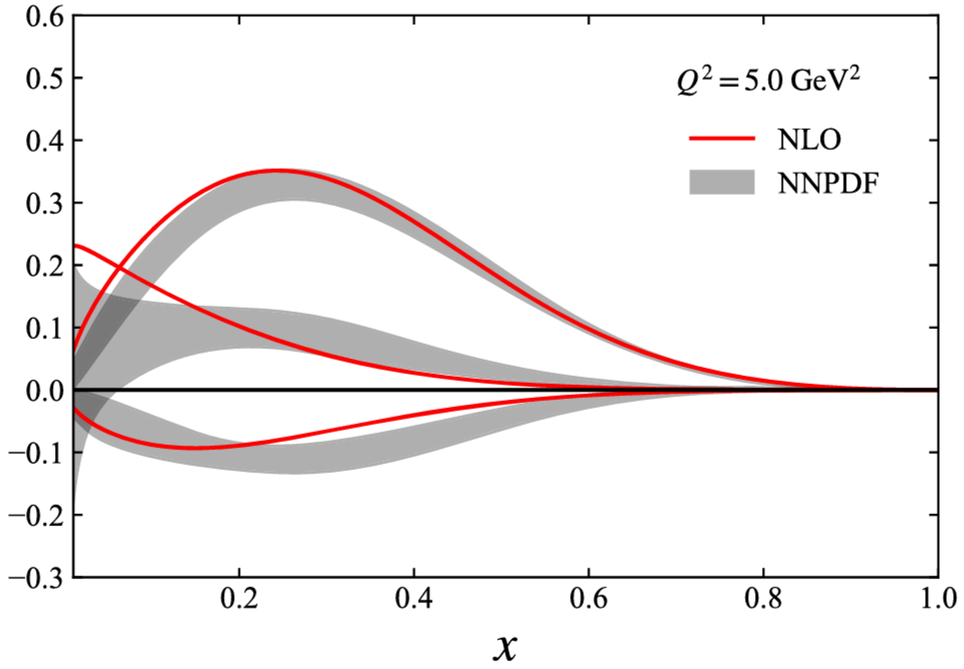
- The polarized EMC effect for gluons

$$\Delta R_{\mathrm{G}} = \frac{\Delta g_{\mathrm{A}}(x)}{P_{\mathrm{p}} \Delta g_{\mathrm{p}}(x) + P_{\mathrm{n}} \Delta g_{\mathrm{n}}(x)} \to \frac{\Delta g_{\mathrm{A}}(x)}{\Delta g_{\mathrm{p}}(x)}$$

Gluon Distribution for Proton in NM

- Gluon structure in NM and nuclei is computed in the NJL model within a mean-field approach of nuclear structure based on the bound nucleon modifications of structure—**Gluon EMC effect**





X-G. Wang, W. Bentz, Cloet, and Anthony Thomas, JPGNPP 49, 03LT01 (2022)

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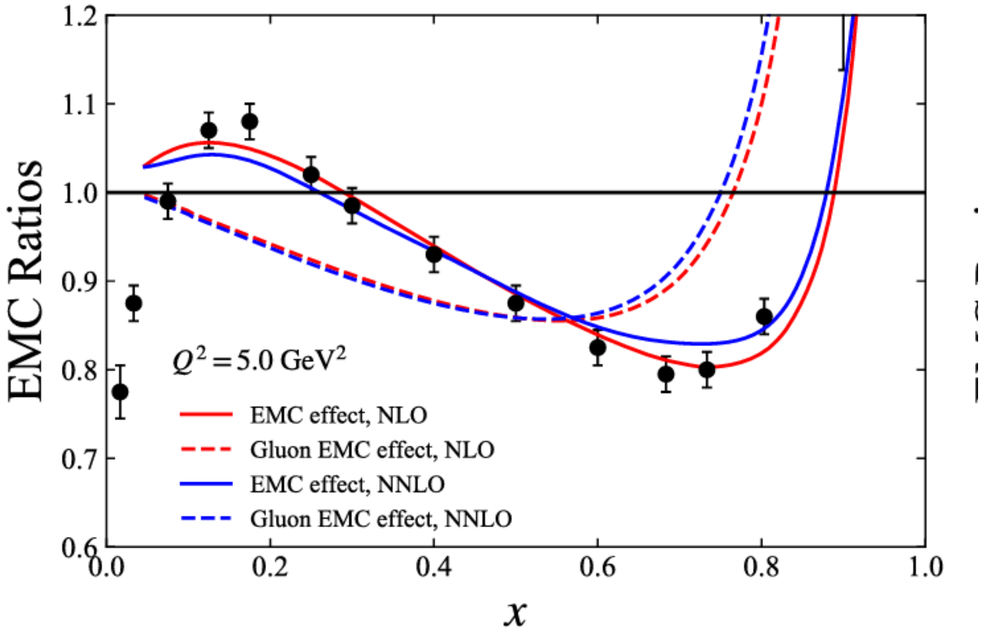
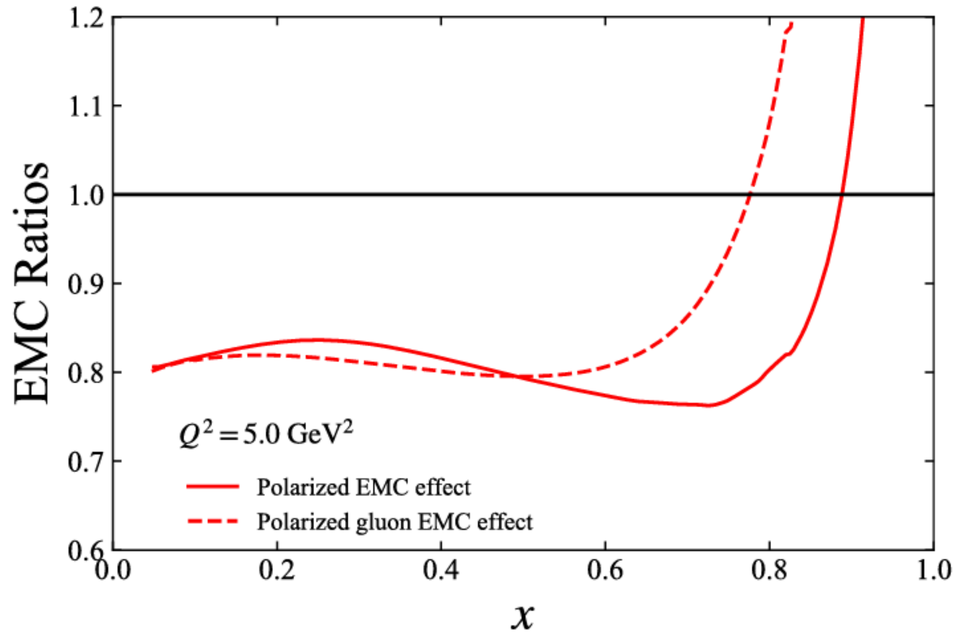
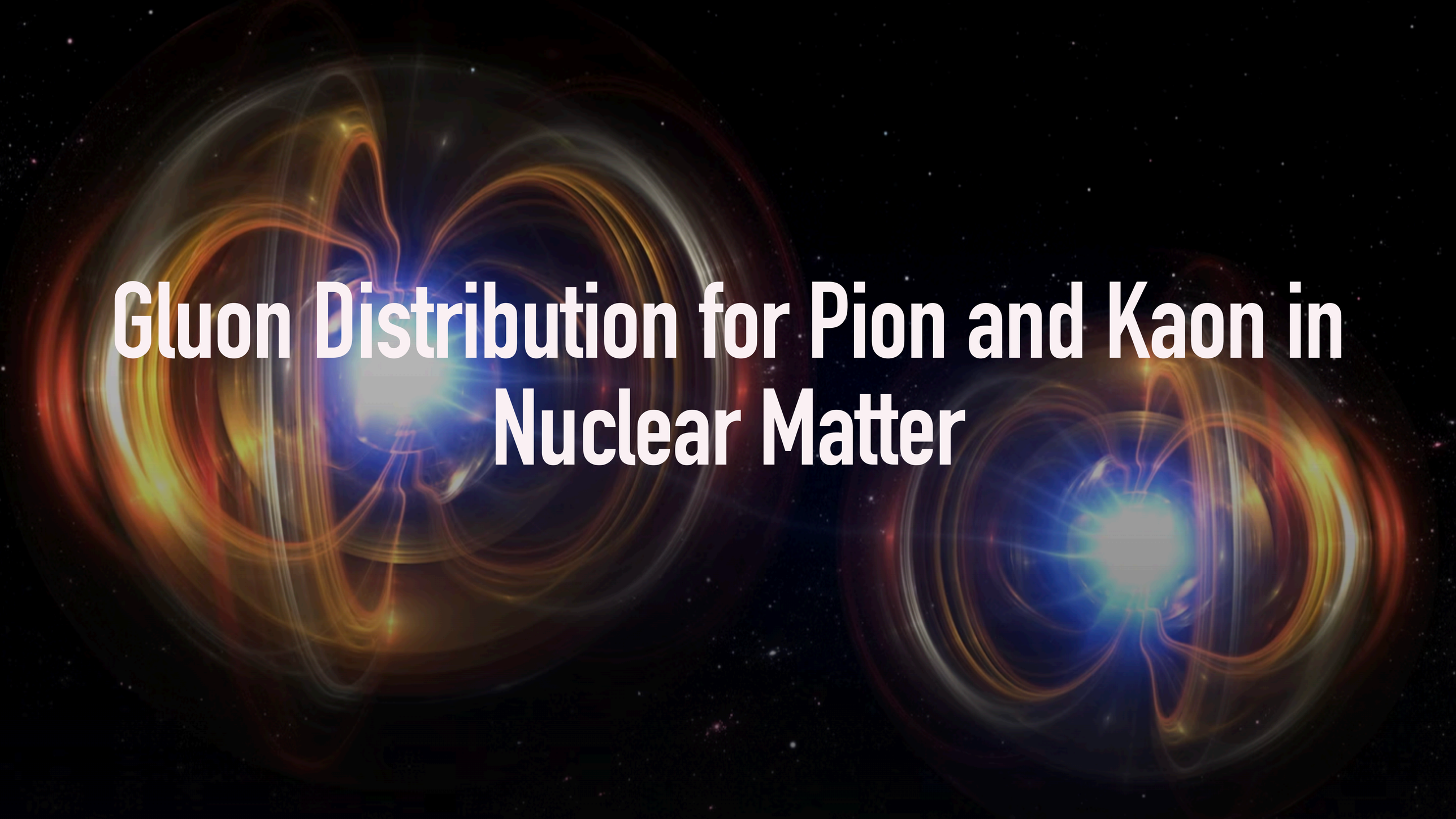




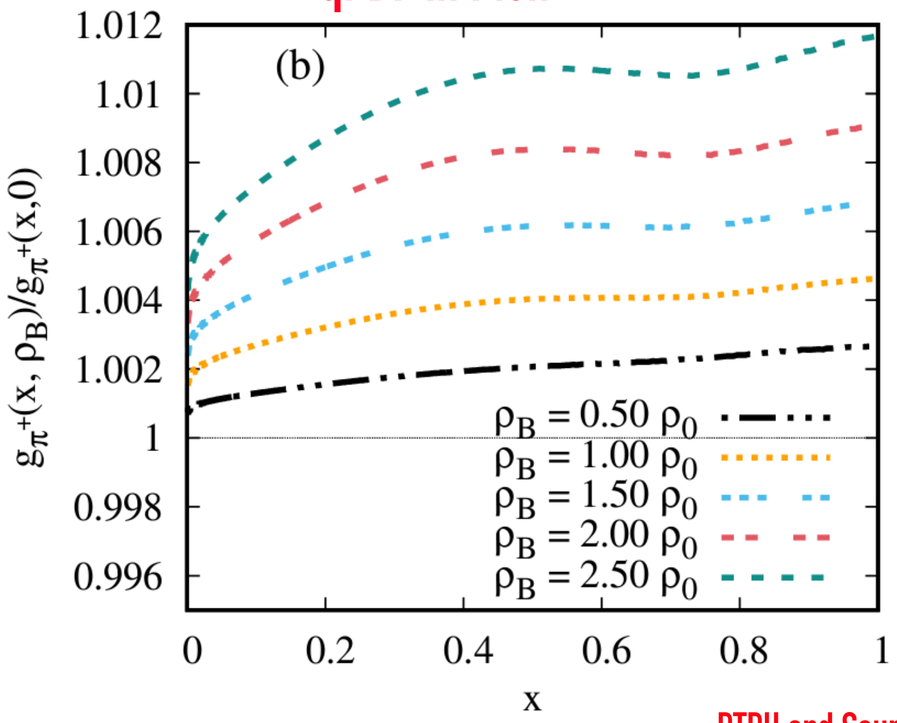
X-G. Wang, W. Bentz, Cloet, and Anthony Thomas, JPGNPP 49, 03LT01 (2022)


Gluon Distribution for Pion and Kaon in
Nuclear Matter

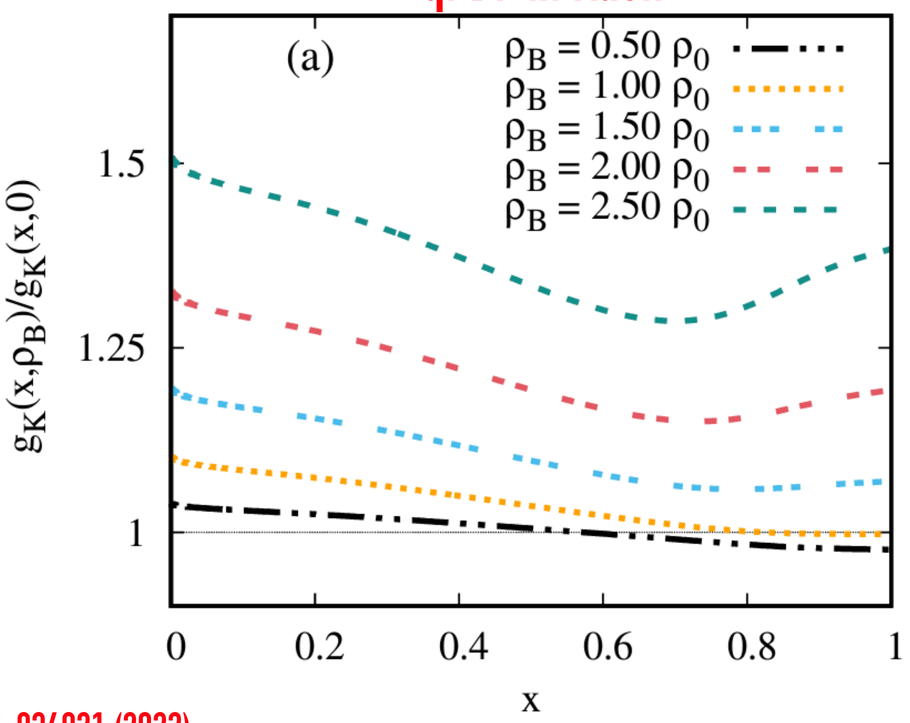
Gluon Distribution for Meson in NM

- Calculating in the NJL model (PDF and Nuclear Medium)—gPDF is extracted using DGLAP QCD evolution at $Q^2 = 16$ GeV^2

qPDF in Pion



qPDF in Kaon

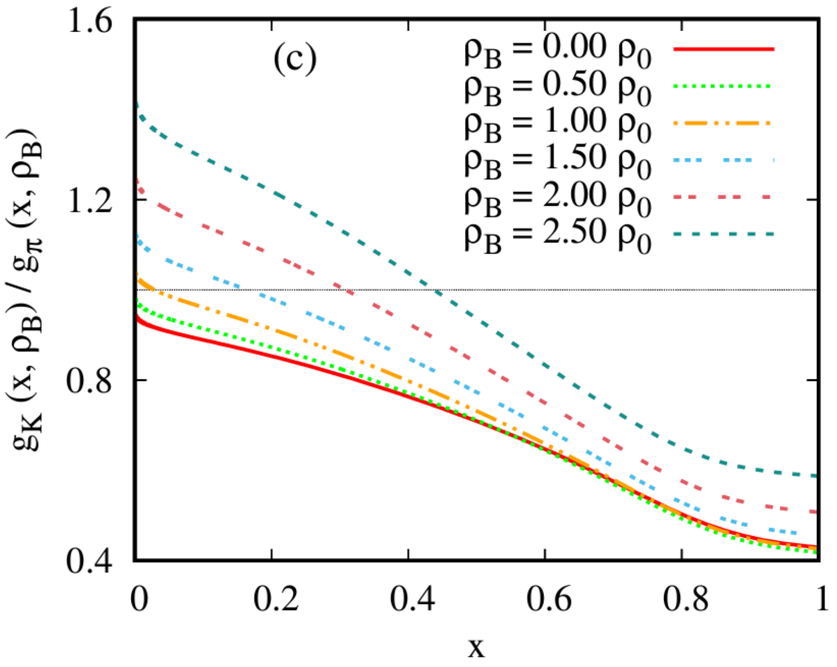


PTPH and Seung-il Nam, PRD 105, 034021 (2022)

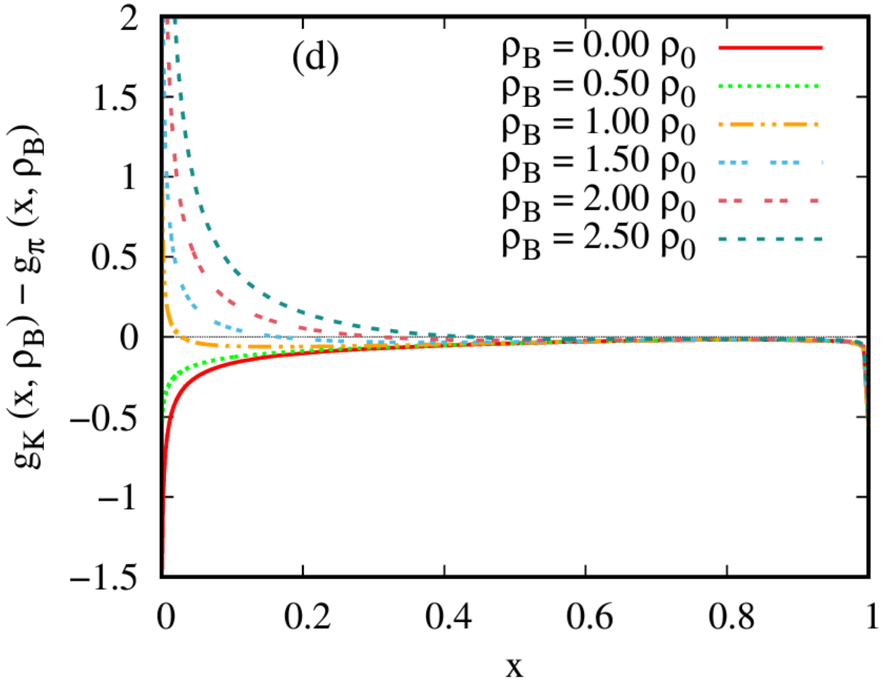
Gluon Distribution for Meson in NM

- Calculating in the NJL model (PDF and Nuclear Medium)—gPDF is extracted using DGLAP QCD evolution at $Q^2 = 16\,\mathrm{GeV}\hat{}2$

gPDF Ratio Kaon to Pion



gPDF Kaon and Pion Differences



- The qPDF for the pion and kaons in nuclear medium and finite nuclei

PTPH, JJ. Cobos-Martinez, Yongseok Oh, and K. Tsushima, PRD 100, 094011 (2019)

PTPH and Seung-il Nam, PRD 105, 034021 (2022)

Summary and Outlook

- The result for the gluon PDF (gPDF) has been investigated in the NJL model and the result looks promising
- The gPDF in proton and meson in the lattice has been provided, it would be interesting to see the gPDF of hadrons in NM in a lattice—**This study may provide useful guidance for lattice before we have a result from experiments**
- Need more studies on gPDF for hadrons in NM or finite nuclei—complicated systems—using other sophisticated theoretical models to obtain a rigorous and precise result
- GPD, TMD for proton in NM and nuclei deserve further study to provide insight into gluon distributions

Thank You Very Much for your Attention!

This talk was supported by NRF-2018R1A5A1025563, NRF-2022R1A2C1003964, and NRF-2022K2A9A1A06091761