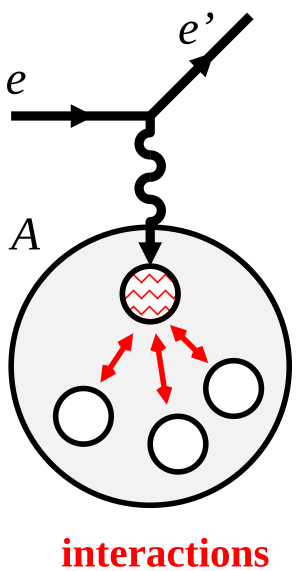
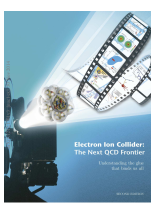
From JLab12 to EIC: QCD in nuclei

C. Weiss (JLab), 2018 JLab User Group Meeting, 19-Jun-2018

Jefferson Lab





- Nucleon interactions

  Hadronic and QCD description

  Non-nucleonic degrees of freedom

- Partonic structure of nuclei

  EMC effect $x > 0.3$ — JLab12, EIC

  Antishadowing $x \sim 0.1$ — EIC

  Shadowing, coherence $x \ll 0.1$ — UPC, EIC

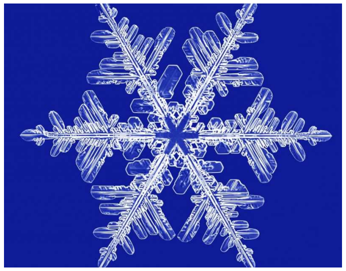
  Nonlinear effects and saturation

- QCD phenomena in final states

  Color transparency, propagation — JLab12, EIC

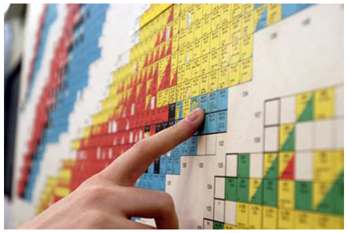
Nucleon interactions: Context

Q: How do nucleon interactions arise from QCD?



- Intellectual gain: Emergent phenomena

  General concept in complex systems



- Predictive power: EFT methods and matching

  Effective DoF and dynamics at scales M_π, $\sqrt{\epsilon_d m}$

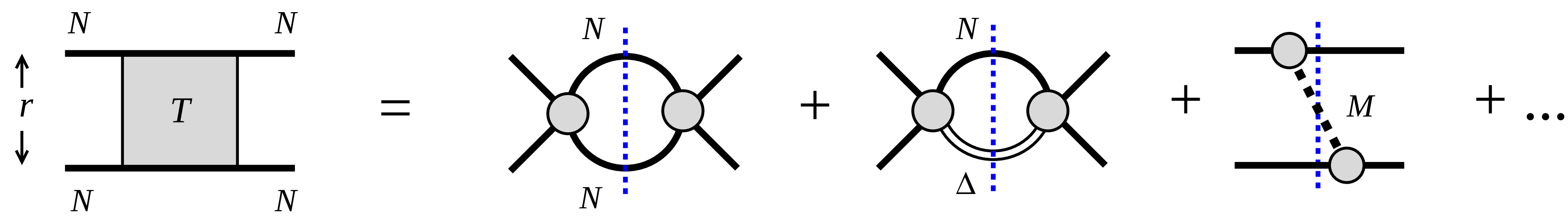
  Import short-distance information through
  effective interactions derived from QCD

- Extreme temperatures and densities

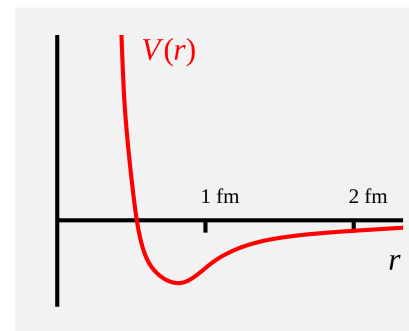
  Astrophysical systems, neutron stars, early universe

  Heavy-ion collisions

Nucleon interactions: Hadronic description



- Interactions involve non-nucleonic degrees of freedom:
  QM + relativity



- Low-energy nuclear structure and reactions ($k \sim k_\mathrm{F}$)
  do not resolve intermediate states: NN potential,
  EFT contact interactions

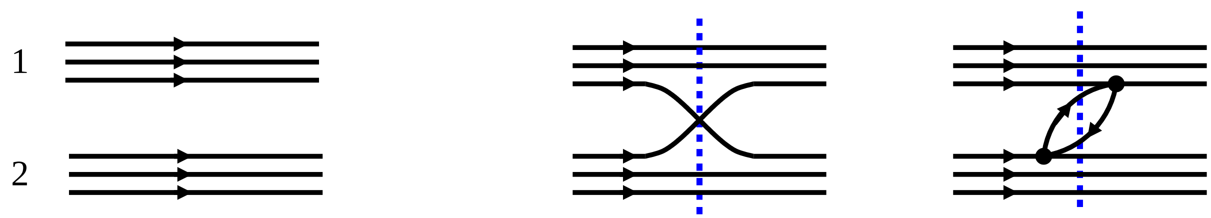
- High-energy processes can resolve intermediate states:
  "Origin" of interactions

JLab 6/12 GeV: Short-range correlations, high-momentum components → Talks Cruz Torres, Schmookler, Schmidt, Hauenstein

Nucleon interactions: QCD description

$$|N\rangle \; = \sum_{\text{configs}} |qqq...\bar{q}q...g...\rangle$$ coherent superposition

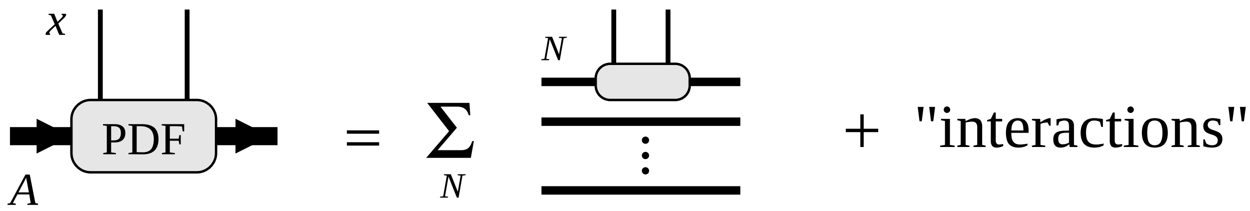
$$|N_1 N_2\rangle_{\text{int}} \; = \; (...)_1(...)_2 \; + \;$$ other configs!



- NN interactions change superposition of quark/gluon configurations compared to free nucleons ($\leftrightarrow$ non-nucleonic DoF) Frankfurt, Strikman 81+

- High-energy short-distance processes on nuclei (DIS, etc.) can give insight into QCD origin of NN interactions

Nucleon interactions: Nuclear parton densities



DIS on nucleus: QCD factorization, nuclear PDF $\langle A | \, \hat{\mathcal{O}}_{\mathrm{QCD}}(\mu^2) \, | A \rangle$

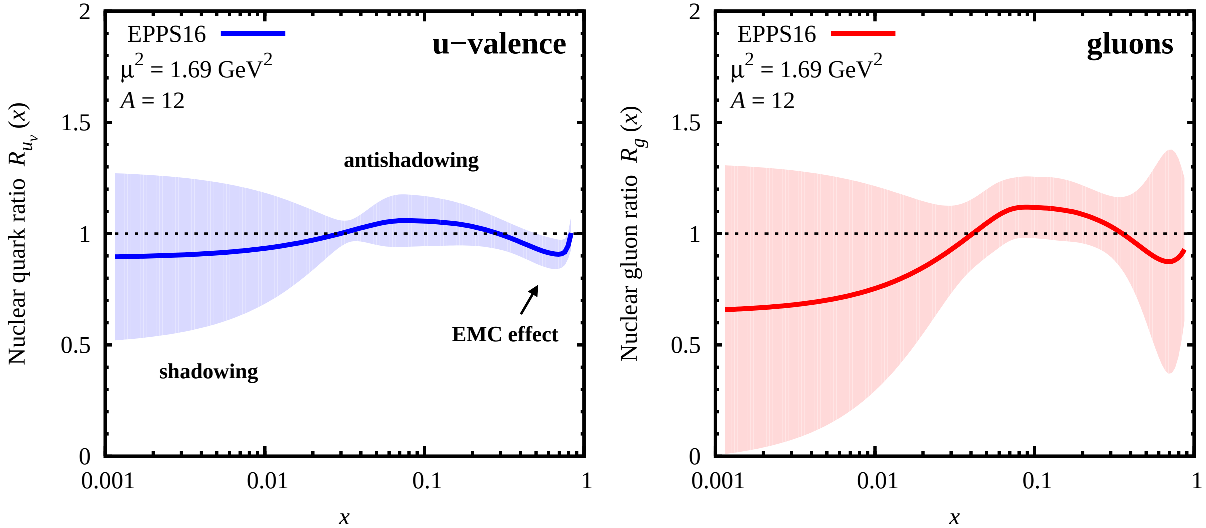
Compare nuclear PDF with sum of nucleons × Fermi motion $\rightarrow$ interactions

Physical questions

- What are the modifications of quarks/gluon densities at different x?
- What are the relevant distances in the nucleon interactions?
- What are the relevant non-nucleonic configurations/states?

Different interactions & configurations are at work at different x!

Nucleon interactions: Physical regimes



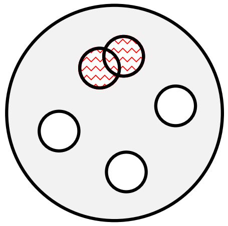
$0.3 < x < 0.8$	EMC effect
$0.05 \lesssim x < 0.2$	antishadowing
$x < 0.01$	shadowing

Global analysis Eskola et al. 16

EMC effect

Suppression of valence quark density in nucleus

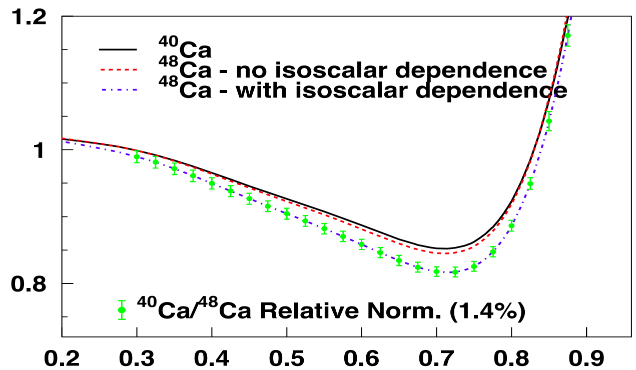
Likely caused by short-range NN interactions $r < 1$ fm

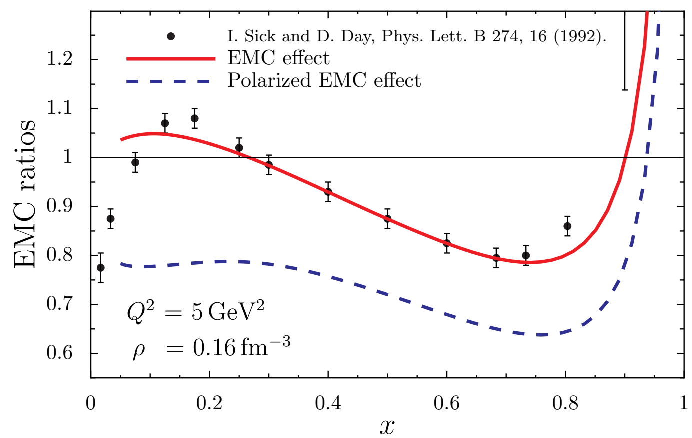


Configurations? Dynamical models and critique
Review: Malace, Gaskell, Higinbotham, Cloet 14

Basic properties unknown: Isospin, spin dependence?
Gluons? Distances?

EMC effect: JLab12





- Leading vs. higher twist

  Q^2 scaling of F_{2A} at large x

  Nuclear dependence of $R = \sigma_L/\sigma_T$

- Isospin dependence

  $^3\mathrm{H} \leftrightarrow {}^3\mathrm{He}$ comparison, $^{40}\mathrm{Ca}/{}^{48}\mathrm{Ca}$ ratio

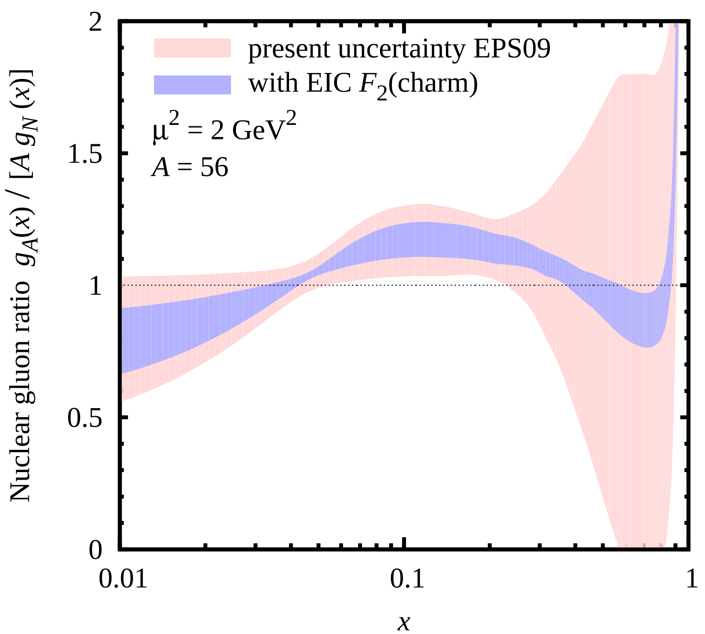
- Polarized valence quarks

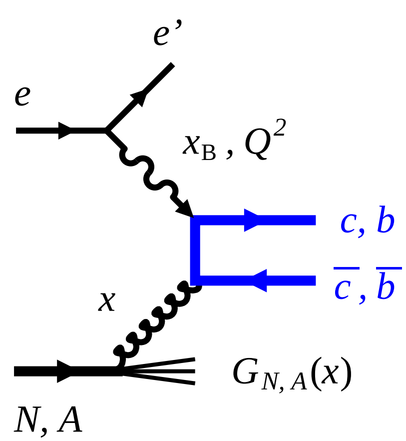
  Model predictions Cloet, Bentz, Thomas 05+

[• Tagging, EMC-SRC connection → later

JLab12: Comprehensive study of EMC effect in valence quarks

EMC effect: EIC





- Gluonic EMC effect?

  Relevant quark/gluon configurations?

- EIC: Q^2-dependence of F_{2A}, F_{LA}

  Wide kinematic coverage

- EIC: Heavy quark production

  Good sensitivity to large-x gluons

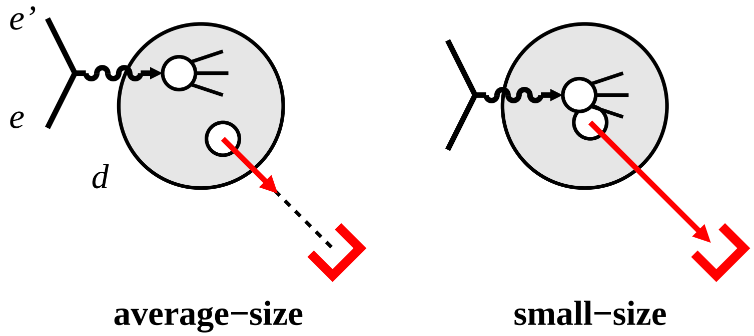
  Medium-energy collider well suited (e/N $\sim$ 10/100 GeV)

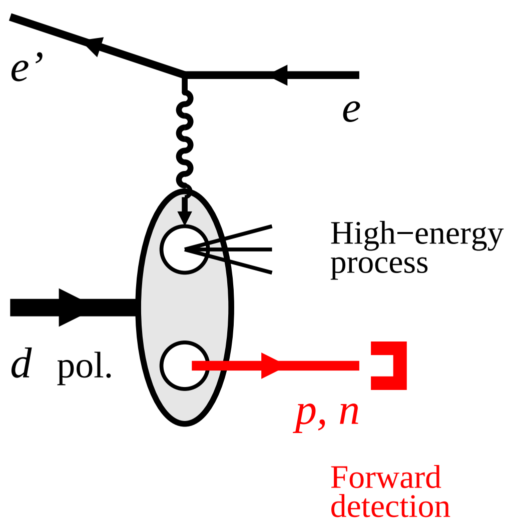
  New methods of charm reconstruction

  Feasibility and impact studied
  JLab LDRD Project 2016/17 CW et al. [webpage]
  [arXiv:1610.08536], [arXiv:1608.08686]

  See also: Aschenauer et al. PRD 96 114005 (2017)

EMC effect: Tagging





- What NN distances cause modification?

  Nuclear breakup detection can control nucleon configuration during DIS process

  Deuteron: Spectator nucleon tagging

- JLab12: Tagged DIS experiments
  CLAS12 BONuS, Hall A → Talk Horn

- EIC: Spectator tagging program

  Forward detection of p, n

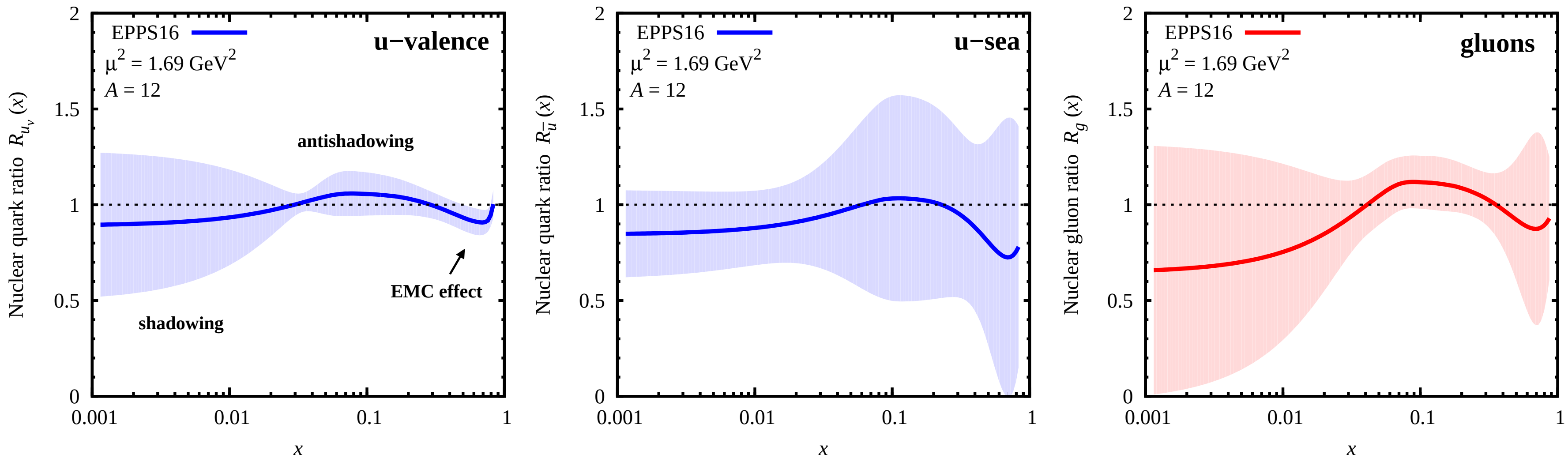
  Good coverage and momentum resolution

  Polarized deuteron tagging possible
  JLab 2014/15 LDRD project CW et al. [webpage]

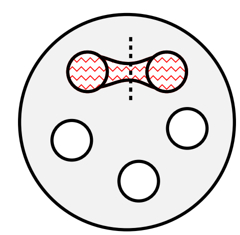
- Theoretical questions

  Initial-state effects vs. final-state interactions in spectator momentum distribution
  Ciofi degli Atti, Kopeliovich, Kaptari 03+; Strikman CW 2018

Antishadowing: Physics



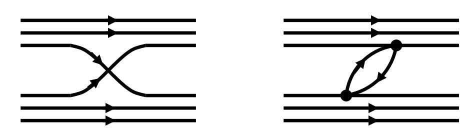
Enhancement of nuclear quark density $q + \bar{q}$ at $x \sim 0.1$



Likely caused by NN interactions at average distances

Quarks vs. antiquarks, flavor separation?

Nucleon interactions through quark or meson exchange?



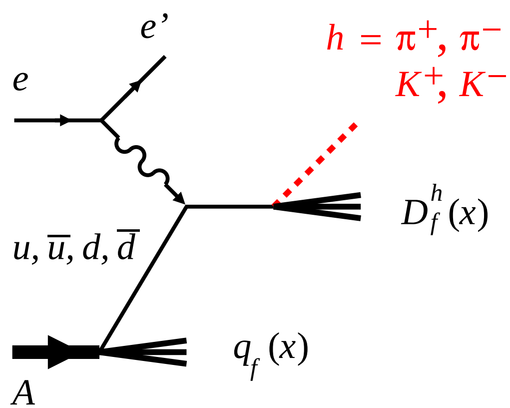
quark exchange

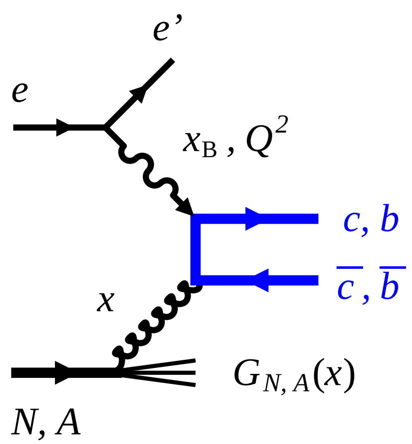
meson exchange

Gluon antishadowing?

Gluon shadowing at $x \ll 0.1$ requires compensating antishadowing for momentum sum rule. Dynamical model: Frankfurt, Guzey, Strikman 17

Antishadowing: EIC





- Charge-flavor separation of nuclear PDFs at $x \sim 0.1$ with semi-inclusive $\pi^{\pm}, K^{\pm}$

  Same techniques as ep SIDIS

  Separate charges/flavors using cross section ratios

  Distinguish initial-state effects from nuclear final-state interactions using A–dependence

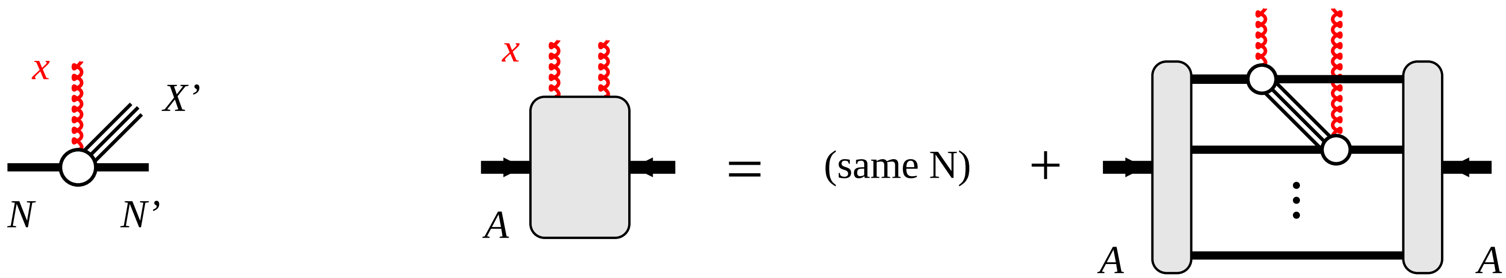
  Simulations in progress
  Zhihong Ye, Hauenstein, Higinbotham, CW

- Nuclear gluons at $x \sim 0.1$ with open charm

  Large antishadowing effect expected

- Enlarged data set for global analysis

Shadowing: Physics



- Nucleon: Removal of gluon with $x \ll 0.1$ can leave nucleon intact
  $N \to g + X' + N'$. "Diffraction." Observed at HERA

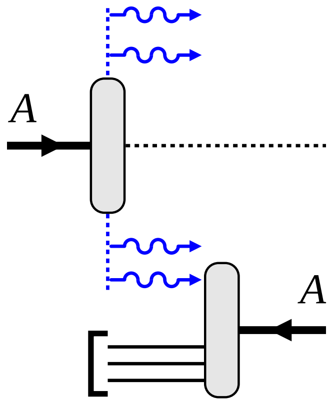
- Nuclear gluon density: Interference of gluon attachments to different nucleons
  Interaction effect. QCD analogue of Gribov's theory of shadowing 70s

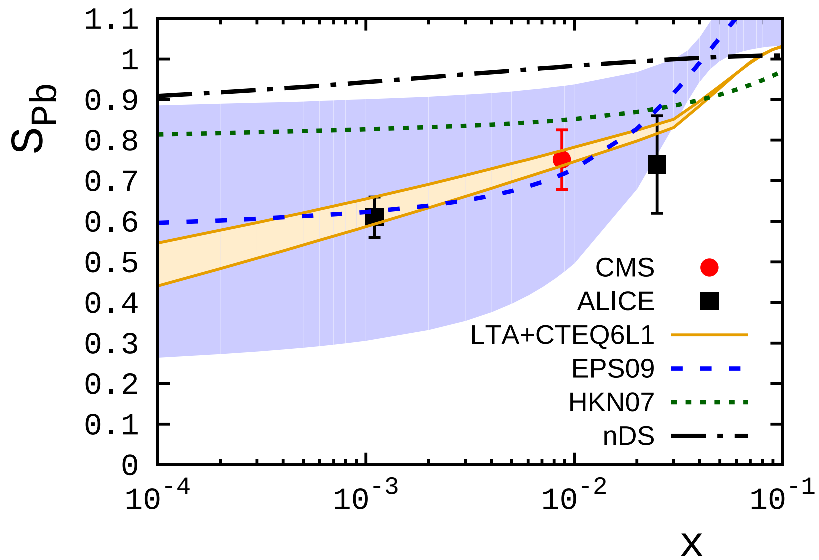
  Suppresses nuclear gluon density at $x \ll 0.1$. "Shadowing."
  Leading-twist effect!

  Calculable in terms of diffractive nucleon PDF and nuclear wave function
  Frankfurt, Guzey, Strikman 12+

  Coherent phenomenon, result of action of multiple nucleons

Shadowing: Ultraperipheral collisions LHC





- UPCs at LHC enable high-energy photoproduction $W \sim$ 500-1500 GeV

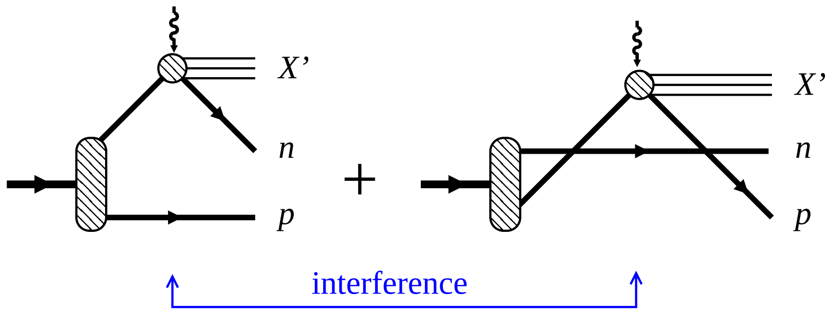
- Coherent J/ψ production data support leading-twist gluon shadowing

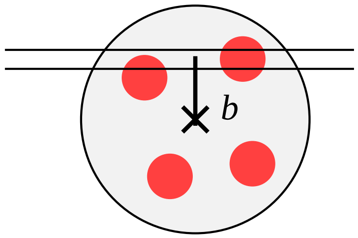
  $\gamma + A \to J/\psi + A^*$, involves theoretical analysis

- Open questions

  Test interference mechanism? Leading vs. higher-twist shadowing?
  Quark vs. gluon shadowing, singlet/nonsinglet?

Shadowing: EIC





- Shadowing in tagged DIS on deuteron

Guzey, Strikman, CW, in progress

  Large shadowing effect in recoil momentum dependence

  Detailed test of interference mechanism in $N = 2$ system

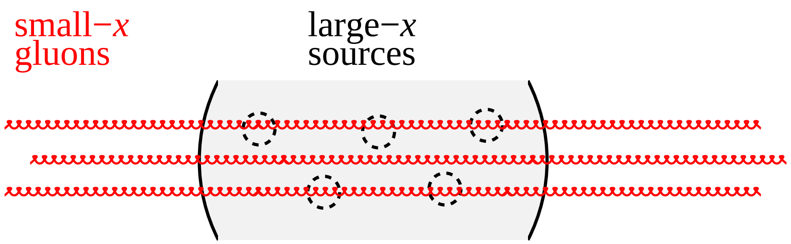
- $N = 3$ shadowing from other light ions: ^{3}He, ^{4}He, ...

- Shadowing in coherent scattering: Impact parameter dependence
  Guzey et al., Kowalski, Caldwell 10

- Gluon shadowing from global PDF analysis

  Leading vs. higher twist

Nonlinear effects and saturation



- New dynamical scale in nuclei at small x

  $Q_s(x) \sim$ gluons / transverse area

  Non-linear evolution equations with recombination
  Balitsky, Kovchegov; JIMWLK

  Classical fields: Color Glass Condensate
  McLerran, Venugopalan

  Extreme form of "nucleon interactions"

- Phenomena

  $p_T \sim Q_s$ in forward hadron/jet production in $pA/\gamma A/\gamma^* A$

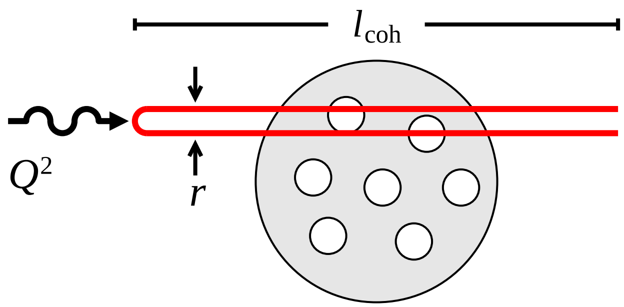
  Correlations and multiple hard processes in pA/AA

  Breakdown of Bjorken scaling in F_{2A}, F_{LA}

- LHC $pA/\gamma A$ forward hadron/jet production will see **whether** it is there: Highest energy/smallest x, final-state signatures

- EIC $eA/\gamma A$ can explain **how** it happens: Shadowing, initial condition of small–x evolution, Q^2-dependence, transverse geometry

QCD phenomena in final states

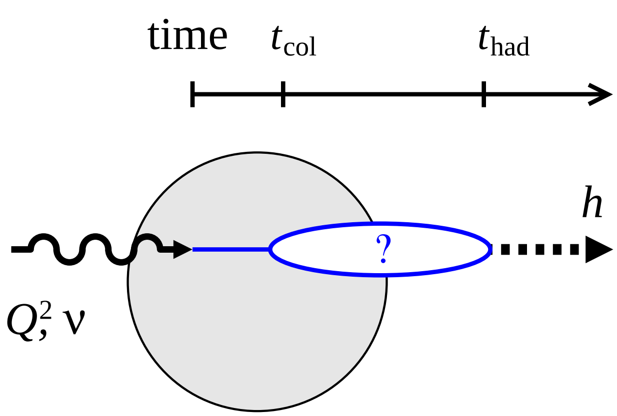


- Color transparency

  Fundamental prediction of QCD $\sigma \propto r^2$ $(r \to 0)$

  EIC: $l_{\mathrm{coh}} \gg R_A$, $Q^2 \sim$ few 10 GeV^2

  Necessary for saturation: Disappearance



- Color propagation in matter → Talk Mineeva

  Mechanisms: Energy loss, attenuation?

  Time scales: Color neutralization, hadron formation

  JLab12: Hadronization inside nucleus

  EIC: $\nu \sim$ 10–100 GeV. Move hadronization in/out

  Q^2 dependence, heavy-quark probes

  Jets and substructure in eA
  New area for EIC. Great interest. Synergies with heavy-ion physics.
  Topical workshops 2018

Summary

- Nucleon interactions in QCD as unifying perspective

  "Next step" after nucleon structure

- JLab12 and EIC complementary

  JLab12: Short-range correlations, EMC effect in valence quarks

  EIC: EMC effect of gluons, antishadowing, shadowing, approach to saturation

- Tagging extends physics reach of nuclear DIS measurements

  Control nuclear configuration during high-energy process

- EIC physics program in context of LHC

  Ultraperipheral collisions explore energy frontier in EM processes

  Nonlinear effects should be seen in $pA/\gamma A$

  Much to do for EIC: Control partonic kinematics, Q^2-dependence,
  initial condition for small-x evolution, . . .