The Nucleus: A laboratory for QCD
Section 7.3 of the Yellow Report

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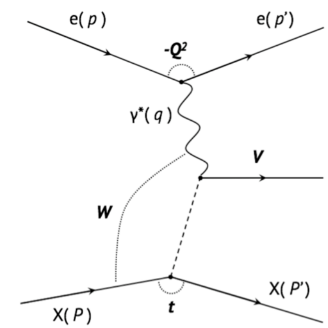
Presented at the Berkeley EIC Yellow Report Meeting, Nov. 2020

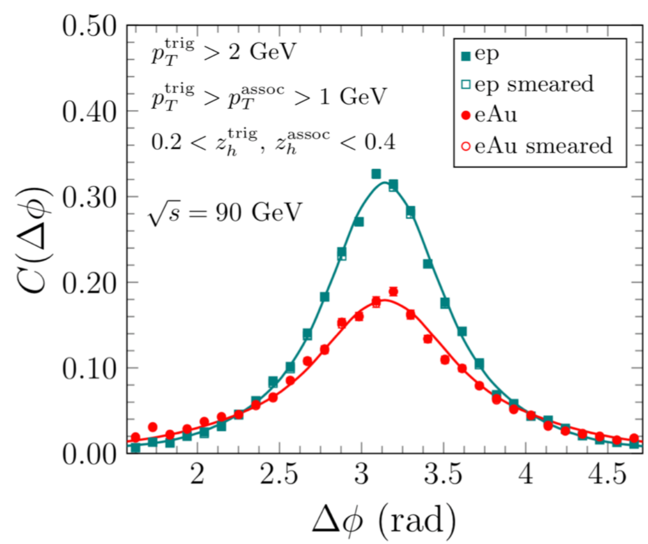


- High parton densities and saturation
- Diffraction
- Nuclear PDFs
- Particle propagation through matter and transport properties
- Collective effects
- Special opportunities with jets and heavy quarks
- Short range correlations, origins of the nuclear force
- Structure of light nuclei
- Coherent and incoherent vector meson production on heavy targets

~39 pages

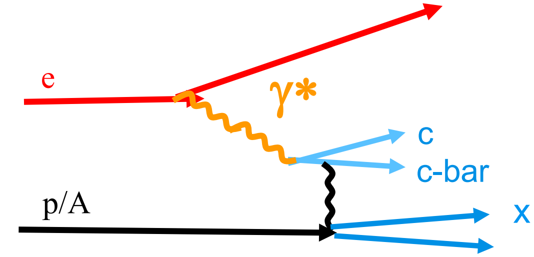
7.3.1 High parton densities and saturation

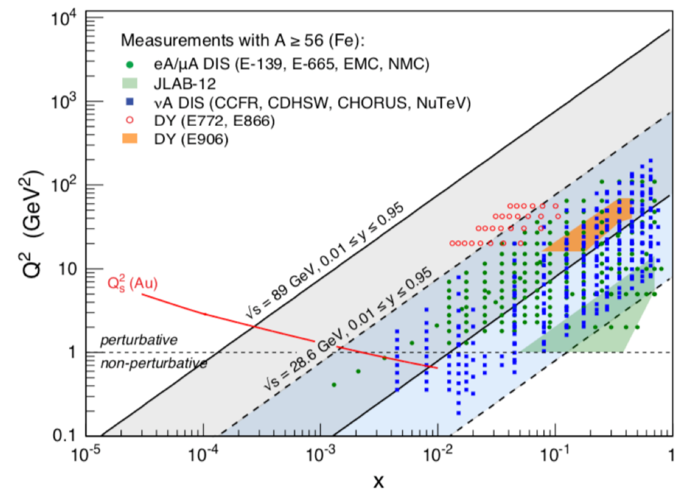
- At high parton densities (see at low Bjorken-x), phenomena like gluon recombination become important
  - Color Glass Condensate
    - Effective field theory for QCD, in the high-density/low-x limit
  - Gluon recombination governed by evolution equations
  - Saturation is important at momenta below the saturation momentum $Q_s(x)$
    - $Q_s^2(x) \sim A^{1/3}/x^{0.2-0.3} \sim 6^*$ larger in heavy nuclei
- Multiple observables
  - Dijet/dihadron angular correlations
  - γ^*p/γ^*A interactions

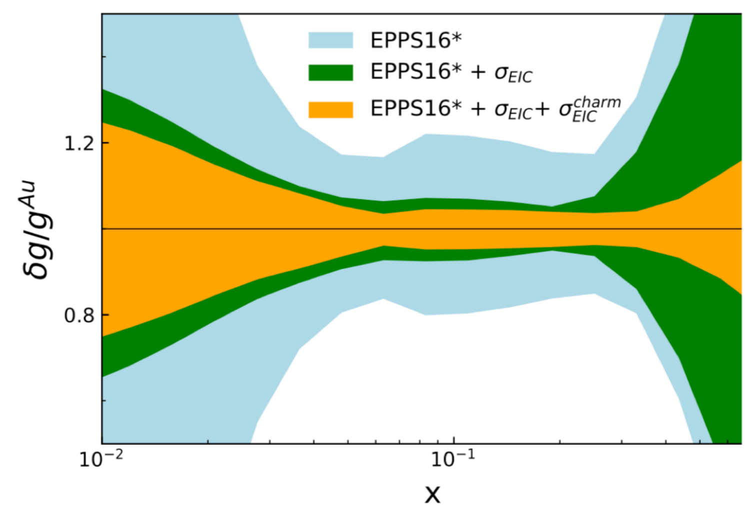


7.3.3 Nuclear PDFs

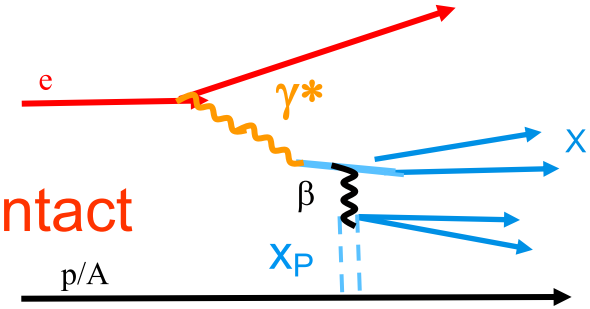
- Nuclear modification factors – ratio of parton distributions in nuclei/distributions in protons
- ep + eA charged-current collisions directly probe quark distributions
  - Wide lever arm gives F_2 and F_L
    - F_L probes gluon distribution
- gluons also probed with heavy quark production
- (Later sections) – gluons probed by vector meson production
- EIC can probe A dependence of nuclear PDFs -> modelling



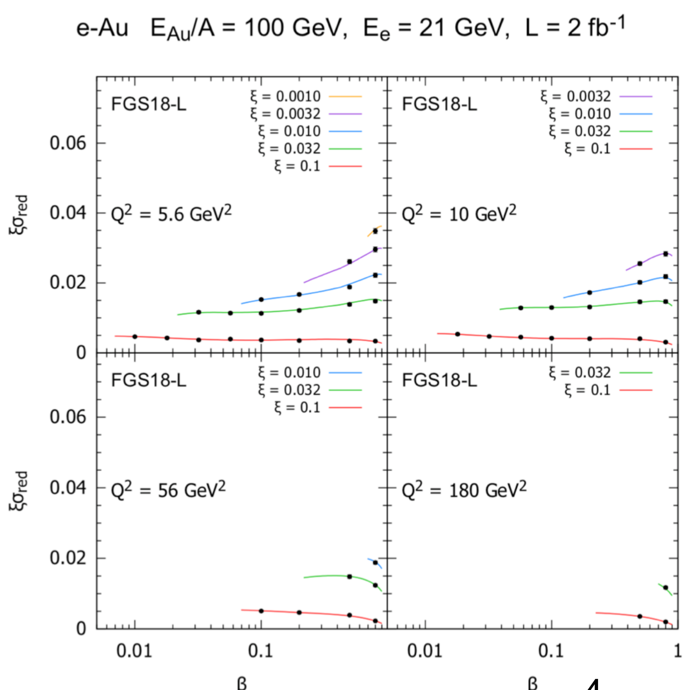




7.3.2 Diffraction

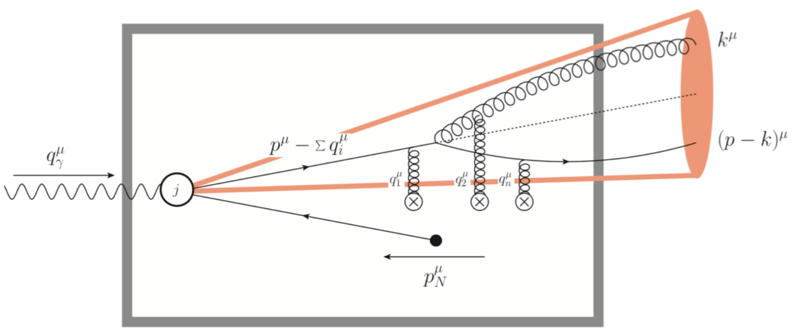


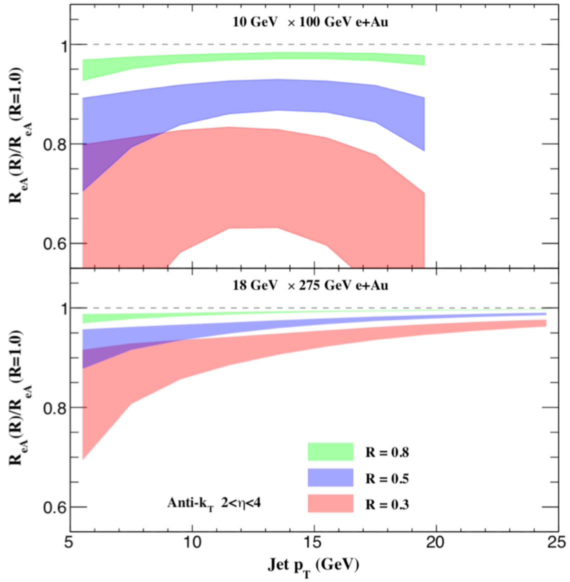
- Diffractive structure functions - like regular structure functions, but the nucleus remains intact
- One variable beyond x
  - x_P – fraction of nucleon momentum carried by Pomeron. Also known as ζ
  - β – fraction of Pomeron momentum carried by the parton that interacts with the γ^*: $\beta = x/x_P$
  - Nuclear modification factor for nuclei
  - Requires measurement of both scattered electron and the final state X. Need M_X
    - Final state like dijet or ???
- Sensitive to gluon distributions
- How universal?
  - Problematic for pp because diffraction requires diffractive reaction + nothing else
  - Universal for ep/eA?



7.3.4 particle propagation through matter and transport properties of nuclei

- How do particles moving through cold nuclear matter altered?
  - Energy loss
  - Scattering
- Jets are a key probe
  - R_{eA} akin to R_{AA} in RHIs
    - Jet p_T cross-section wrt proton reference
  - Structure modifications
    - Broadening
      - Measure R_{eA} as f(cone size)
- Depends on jet velocity in matter
  - Relative velocity depends on rapidity of jet
    - Lower velocity in ion-going direction

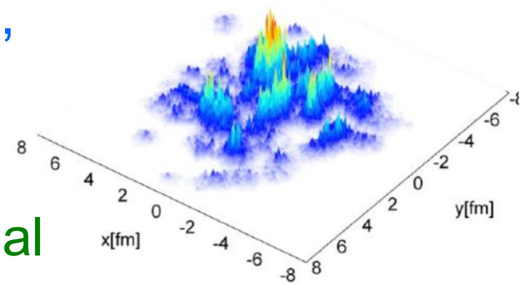




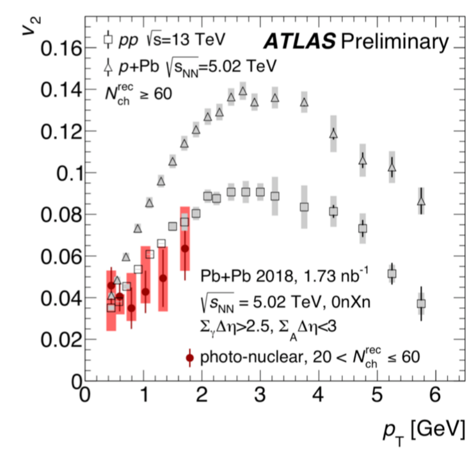
7.3.5 Collective Effects

- Phenomena first observed in heavy ion collisions
- Collective Flow
  - Intrinsic nuclear fluctuations lead to anisotropies, which are reflected in final-state anisotropies
    - Including gluonic hot spots?
    - Measured by Fourier decomposition in azimuthal direction

$$\frac{dN}{d(\phi - \Psi_r)} \propto 1 + \sum_n 2v_n \cos[n(\phi - \Psi_r)]$$



  - In RHI collisions, v_2 dominated by initial anisotropy
  - v_2 seen by ATLAS in γA collisions



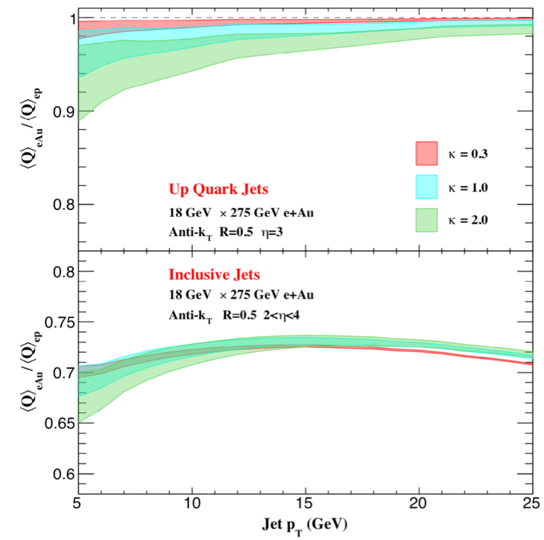
- "The ridge" – near side correlations at large rapidity separations
  - Originally seen in AA collisions. Also seen in high multiplicity pA and pp interactions
    - Multiplicity is an important variable.

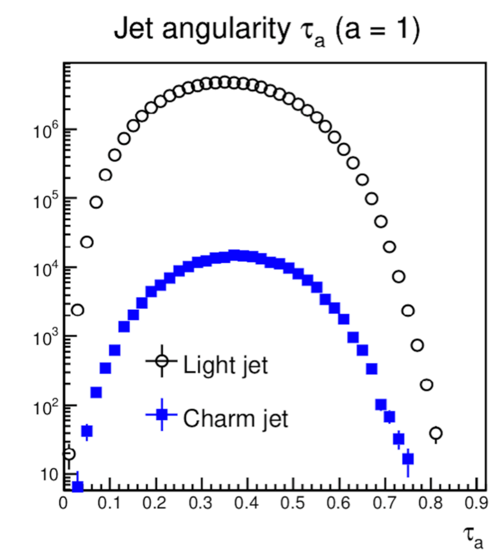
ATLAS: https://cds.cern.ch/record/2679473

7.3.6 – Special opportunities with jets and heavy quarks

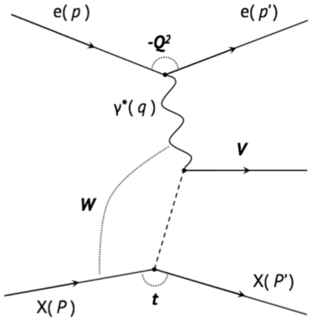
$$Q_{\kappa,\text{jet}} = \frac{1}{\left(p_T^{\text{jet}}\right)^{\kappa}} \sum_{i\in\text{jet}} Q_i \left(p_T^i\right)^{\kappa}, \quad \kappa > 0$$

- Flavor tagged jets and jet charge
  - Jet charge correlated w/ quark/antiquark jets
- Light and heavy flavor tagged jet angularities
  - Map out medium-induced modifications to the jets
  - Potential for flavor-tagging jets
- Energy flow and quantum number correlations in jets





Techniques for gluon imaging



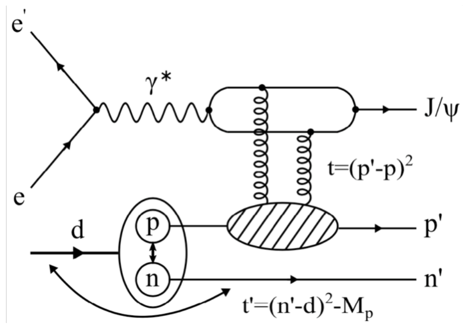
- Many subsections of Section 7.3 use coherent meson production to image gluons in different ways
  - Usually J/ψ, but studying different mesons is useful
  - "Target" must remain intact
  - Bjorken-x related to rapidity: $x=M_V/4\gamma m_p \exp(-y)$
    - Good rapidity coverage important to cover full x range
- They rely on a measurement of $d\sigma/dt$, where t is the squared 4-momentum transfer from the target to the vector meson
- p_T is conjugate to b, so one can Fourier transform $d\sigma/dt$ to get F(b), the distribution of gluons in the target
  - 2-dimensional transform
  - Caveats apply
  - Similar to approach used to find GPDs on proton targets

$$F(b) \propto \frac{1}{2\pi} \int_0^\infty dp_T p_T J_0(bp_T) \sqrt{\frac{d\sigma}{dt}}$$

* = flip sign after each minimum

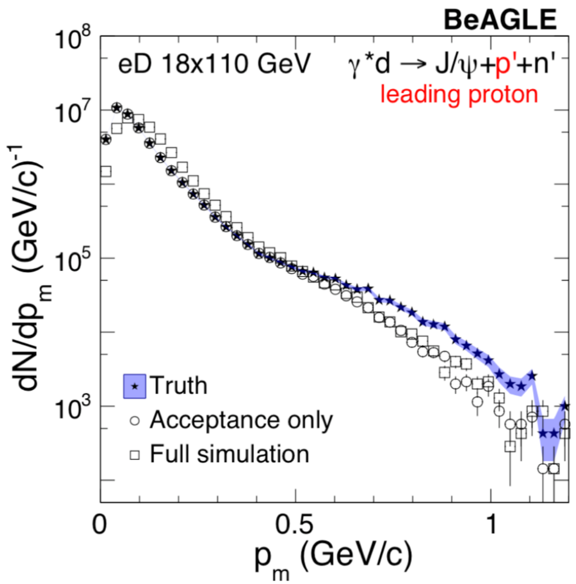
7.3.7 Short range correlations and origins of the nuclear force

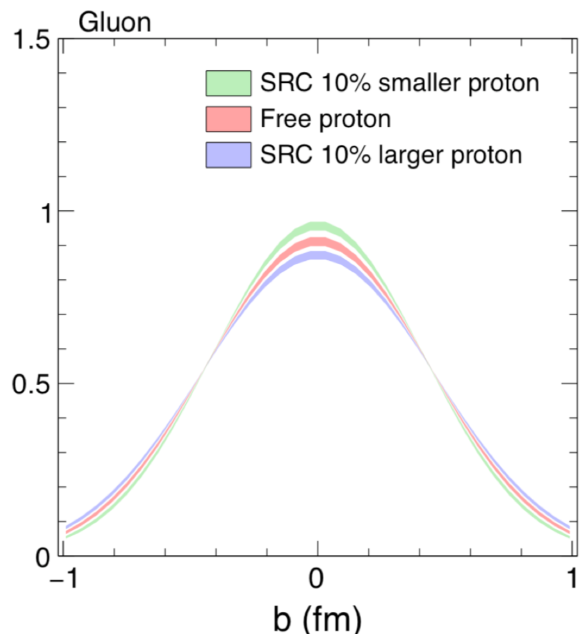
- Short-range nucleon-nucleon correlations (SRCs) may be responsible for the EMC effect
  - What role do gluons play in SRCs?
- Small nuclear separation -> high relative momentum
  - Nuclear momentum leads to partons with x>1
- The EIC will probe valence quarks at higher Q^2 than is possible at Jlab
- Gluons are probed using incoherent vector meson photoproduction
- Use ZDC/proton spectrometer to tag spectator nucleons
- ed is particularly attractive



Nucleon imaging in ed collisions

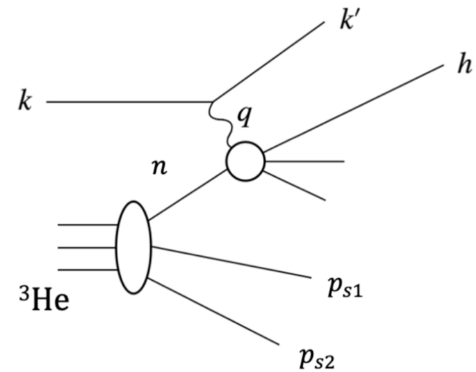
- By selecting spectator momenta with different p_T values, we can select different nucleon-nucleon separations
  - How do gluon spatial distributions in the proton depend on this separation?
- The gluon radius of the proton can be inferred from $d\sigma/dt$ of the vector meson
- The gluon transverse spatial distribution F(b) is given by the 2-dimensional Fourier transform of $d\sigma/dt$



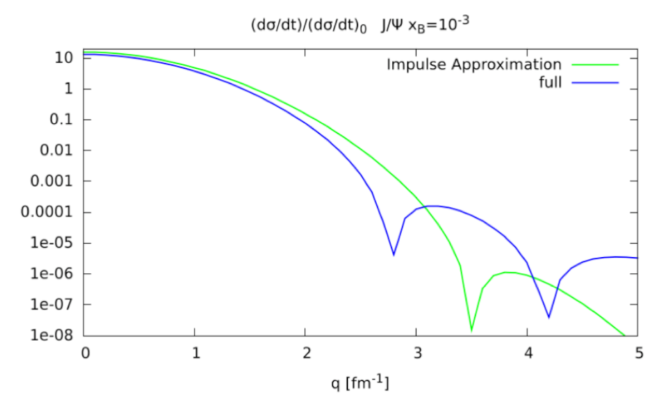


7.3.8 Structure of light nuclei

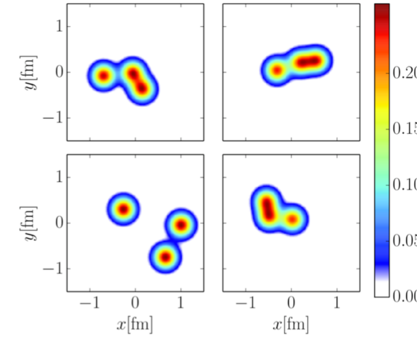
- Deuterium….~nitrogen, including polarized light ions
- Double-spectator tagging for A=3 nuclei
  - ^{3}He with d or pn tagging probes polarized protons
  - ^{3}H with nn tagging allows comparisons between bound and free protons



- Shadowing and antishadowing in light nuclei
- Studies with DIS and SIDIS
- Coherent vector meson production
  - Imaging & direct comparison with theory
  - Separating coherent & incoherent production is an issue
  - Desire to detect scattered intact nucleus to the highest possible t



7.3.9 Coherent and incoherent vector meson production on heavy targets

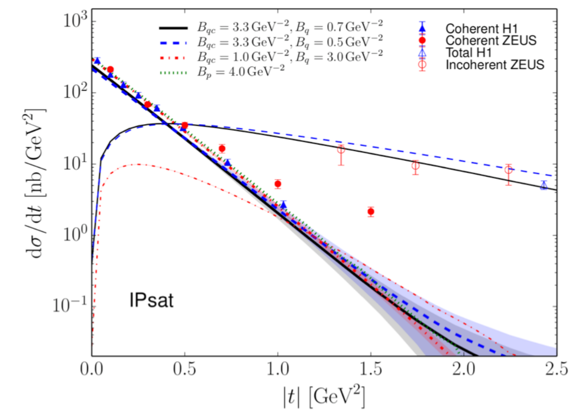


(a) $B_{qc} = 3.3\ \mathrm{GeV}^{-2}, B_q = 0.7\ \mathrm{GeV}^{-2}$

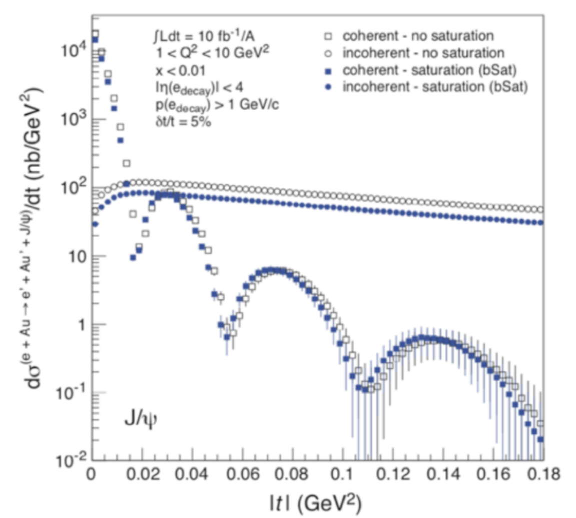
- Coherent photoproduction images entire nucleus, as mentioned previously
- Incoherent photoproduction is sensitive to event-by-event fluctuations in nuclear configuration

$$\frac{d\sigma_{\text{inc}}}{dt} = \frac{1}{16\pi}\left(\left\langle \left|\mathcal{A}(K,\Omega)\right|^2 \right\rangle - \left| \left\langle \mathcal{A}(K,\Omega) \right\rangle \right|^2 \right)$$

  - Nucleon positions
  - Gluonic hot spots



- Challenge is separating coherent and incoherent production
  - Need 500:1 rejection at small and large |t|
    - Unclear if this is possible
      - 100 keV to MeV photons in nuclear frame
      - Au has a long-lived 77 keV state which is not visible in the detector



H.Mantyssari and B. Schenke, PRD **94**, 034042 (2016)

The YR - thoughts for editing

- I have presented an overview of the topics that are described in S7.3 of the Yellow Report.
  - Written by diverse authors from different working groups.
  - There are likely other interesting and relevant topics that are not covered.
- There are still a few placeholders.
- The flow would improve if subsections 7.3.3 and 7.3.2 traded places.
- There is some overlap with other sections.
- There is room for editing to make the material more uniform in level, approach, and, in some cases, number of references.

Conclusions

- Much interesting EIC physics involves nuclear targets
  - High parton densities at low Bjorken-x and saturation
  - Nuclear pdfs and diffractive pdfs
  - Particle propagation through cold nuclear matter
  - Collective effects in cold nuclear matter
  - Short range nuclear correlations
  - Structure of light and heavy nuclei
- Many of these topics involve gluon imaging via vector meson production
  - Requires wide rapidity coverage to cover full range of Bjorken-x
  - For heavy nuclei, requires very good separation between coherent and incoherent production

Backup

Original outline

7.3 The Nucleus: A Laboratory for QCD

7.3.1 High parton densities and saturation (Tuomas Lappi, Bowen Xiao)

- Introduction to gluon saturation
- Inclusive cross sections at small x (inclusive cross section dipole picture, BK evolution, shadowing)
- low-x gluon access via di-jets/di-hadrons/photon-jet correlations (Bowen Xiao, Liang)
- photon+ dijets in the CGC – (R. Venugopalanet al)
- Improved TMD factorization at small x – ITMD (Harmann, Kutak et al)

7.3.2 Diffraction (Tuomas Lappi, Anna Stasto)

7.3.3 Nuclear PDFs (Renee Fatemi, Salvatore Fazio, Nobuo Sato, Barak Schmookler, Ernst Sichtermann)

- nuclear PDFs from Dijet distributions (Klasen, et al.)
- constraints on u and d
- constraints on s
- constraints on heavy quarks
- Discussion of A dependence at EIC

7.3.4 Particle propagation through matter and transport properties of nuclei (Raphäel Dupré, Ivan Vitev)

- Studies of particle production in eA collisions – light and heavy flavor (X. Li et al)
- Energy loss and in-medium evolution (Sievert et al)
- Light hadron production and lessons from HERMES (X. Wang et al)
- Inclusive jet production at the EIC

7.3.5 Collective effects (shadowing, anti-shadowing, ridge, other emergent phenomena) (Tuomas Lappi)

- Multiparticle correlations: ridge, flow-like correlations
- Shadowing, anti-shadowing (if needed, but probably already covered in 7.3.1 , 7.3.7.)
- Other emergent phenomena (?)

7.3.6 Special opportunities with jets and heavy quarks (Ivan Vitev)

- Jet substructure and simulation of charm quark angularities (P. Wong et al)
- Jet charge at the EIC (H. Li et al)
- Models of coherent vs incoherent interactions of jets, LHC connection so far (Y. Mehtar-Tani et al.)

7.3.7 Short-range correlations, origin of nuclear force (Or Hen, Douglas Higinbotham)

- SRCs from QE 2N knockout (Florian Hauenstein, Jackson Pybus)
- SRCs from/with tagged DIS (Jackson Pybus, Mark Baker)
- SRCs from diffractive breakup (Kong Tu, Alex Jentsch, Florian Hauenstein, Jackson Pybus)
- Diffractive breakup on 3He and 3H to further study NN interaction (Or Hen)

7.3.8 Structure of light nuclei (Wim Cosyn, Raphäel Dupré, Or Hen)

- tagging with d/3He/3H [Doug Higinbotham, Or Hen, Wim Cosyn, Christian Weiss, Dien Nguyen, Ivica Friscic, Mark Baker, Jackson Pybus]
- EMC type measurements / medium modifications
- cross check p / n structure (free p / d /3He; n from d/3He/3H)
- understanding FSI
- polarization

7.3.9 Coherent and incoherent photoproduction on heavy targets (Spencer Klein)

- Overview - exclusive photoproduction, the Good-Walker approach and the relationship between incoherent and coherent photoproduction
- Coherent photoproduction and going from dsigma/dt to F(B), the GPD-analog for nuclei
- Incoherent photoproduction, and the sensitivity to gluonic hotspots
- Separating coherent and incoherent photoproduction
- The problems with Good-Walker at low |t|, need for further work, and conclusions