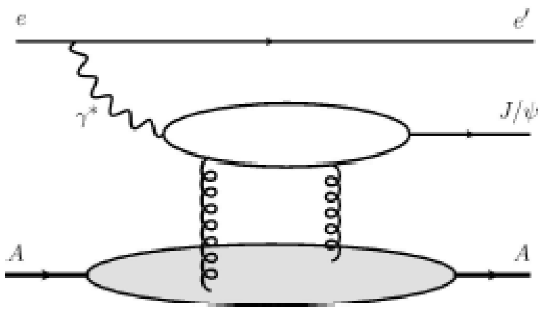
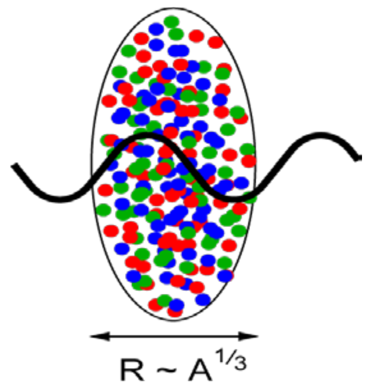
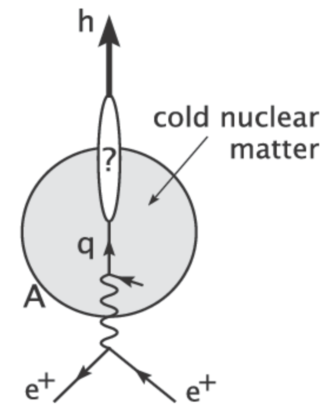
Future Directions: Studying Nuclear Matter at the Electron-Ion Collider







Christine A. Aidala

LANL Heavy Ion Physics
Internal Review
January 10, 2012

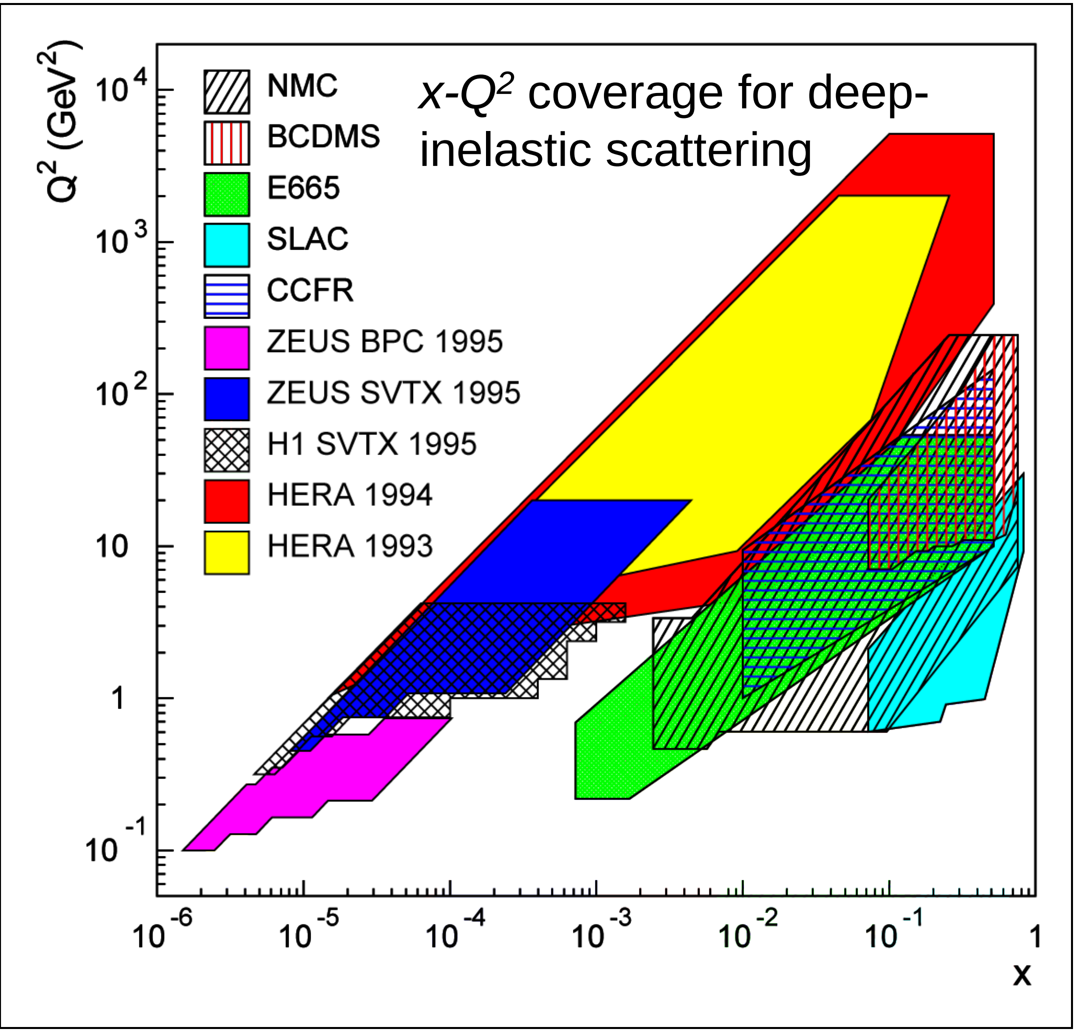
Why an Electron-Ion Collider?

The Electron-Ion Collider (EIC)

- A proposed new facility capable of colliding a beam of (polarized) electrons with a variety of hadronic beams:
  - Polarized protons
  - Polarized light ions (e.g. ^{3}He)
  - (Unpolarized) light and heavy ions

- *Collider* rather than fixed-target facility—reach higher energies
  - Can use perturbative QCD methods
  - Can study new effects such as gluon saturation
- *Electromagnetic* rather than hadronic probes
  - Simpler to interpret
  - *But* will also want to cross-check and test newfound understanding against data from (more complex) hadronic collisions!
- Compare to HERA e+p collider (shut down 2007)
  - Only unpolarized proton beams at HERA, no nuclear beams
  - EIC lower energies than HERA, but expected EIC luminosities 100-1000x greater

Kinematic coverage and a new Electron-Ion Collider



Existing data over wide kinematic range for (unpolarized) lepton-proton collisions.

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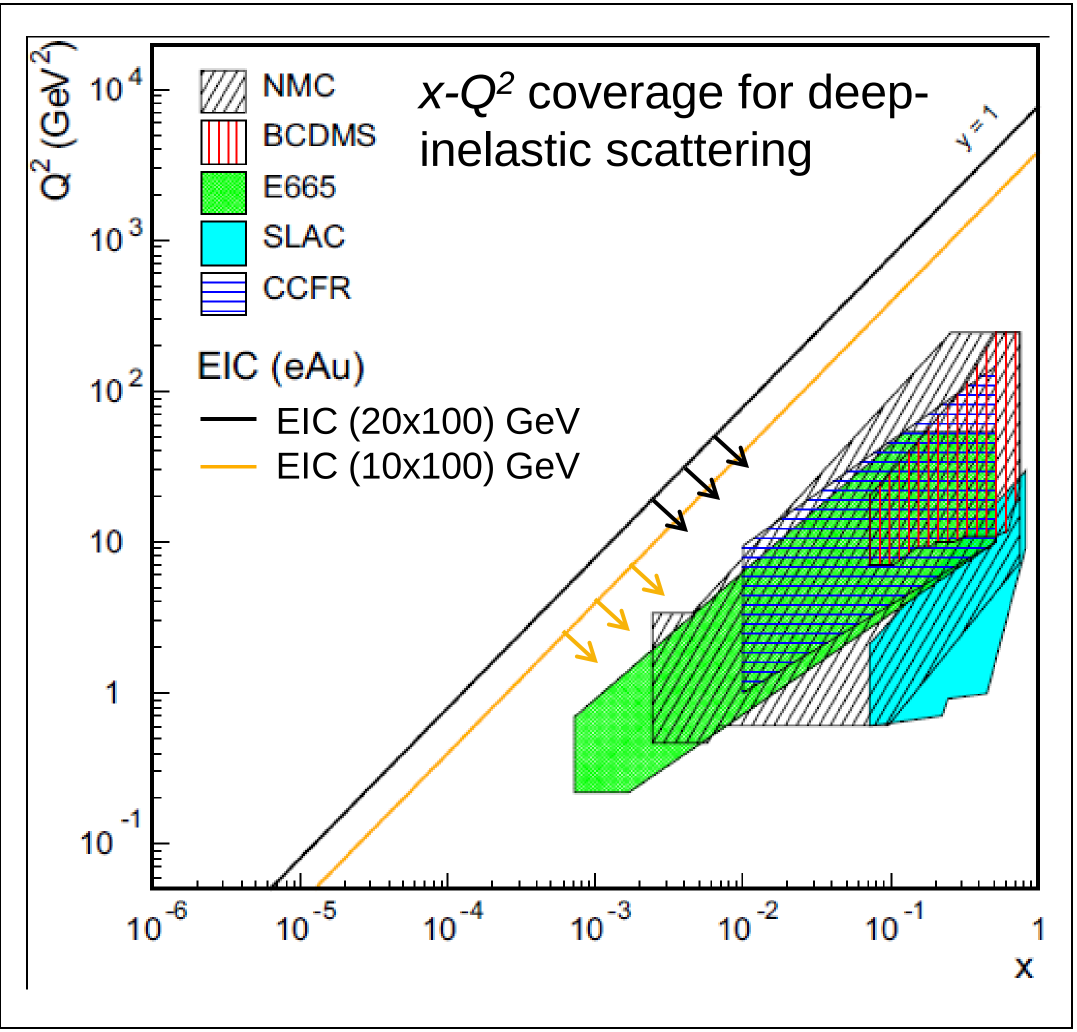


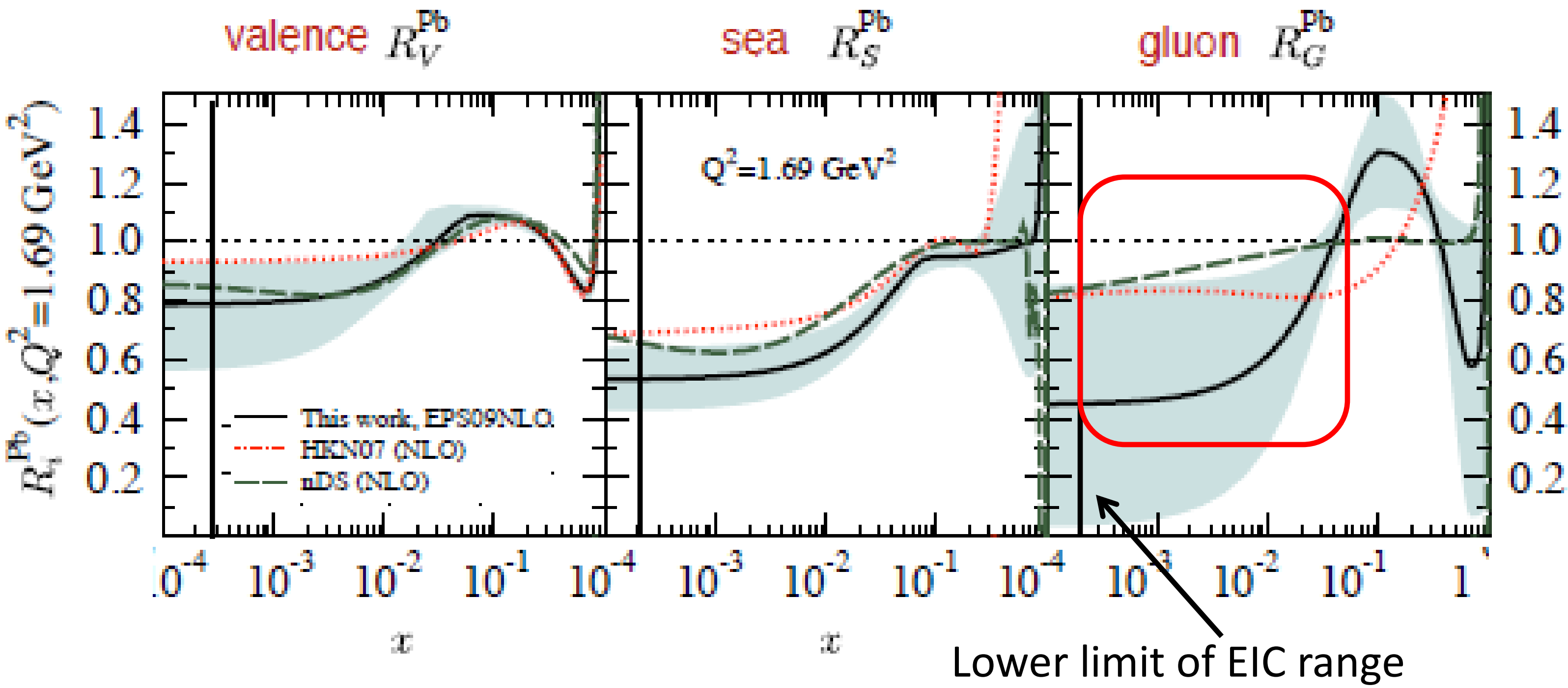
Existing data over wide kinematic range for (unpolarized) lepton-proton collisions.

Lots of unexplored territory for lepton-nucleus collisions!

Ultimate goal: Understand the nucleons and nuclei of the world around us in terms of their quark and gluon degrees of freedom

Nuclear modification of pdfs

JHEP 0904, 065 (2009)

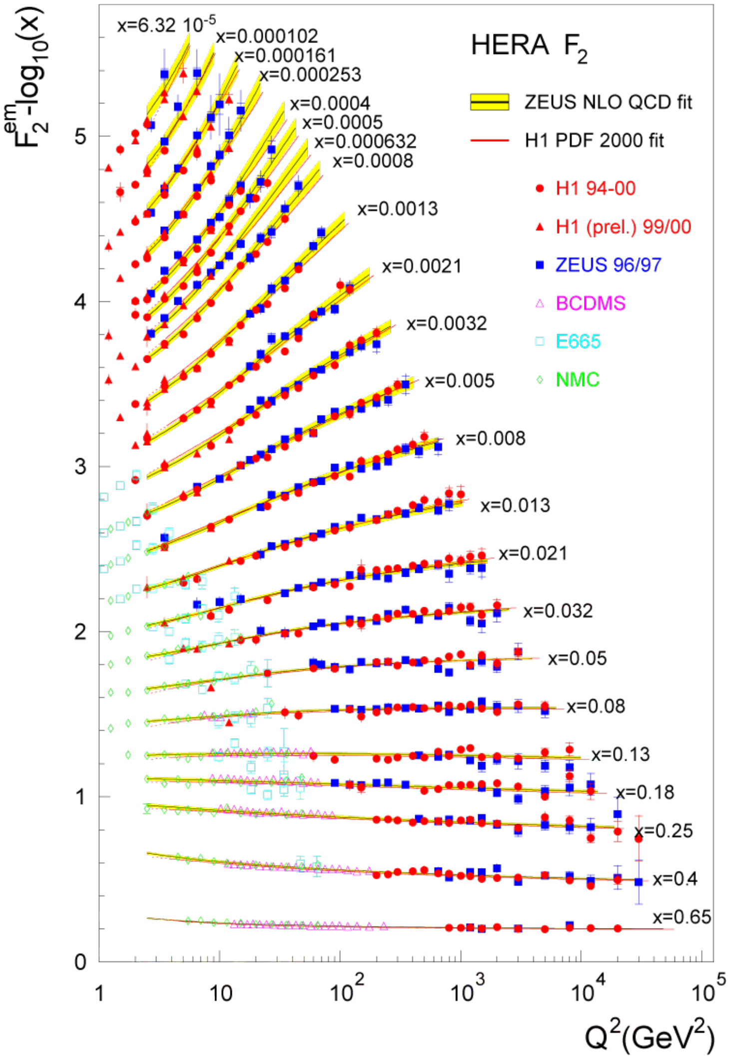


Rich and intriguing differences in partonic structure of nuclei compared to free nucleons, which vary with the linear momentum probed! How are these differences generated??
-Especially large uncertainties on gluon distribution in nuclei

Study in detail at the EIC!

Accessing gluons with an electroweak probe

$$\text{DIS}: \quad \frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$



Access the gluons in DIS via scaling violations:

$dF_2/d\ln Q^2$ and linear DGLAP evolution in Q^2 → $G(x,Q^2)$

OR

Via F_L structure function

→Requires measurements at several values of √s $\quad y = \frac{Q^2}{xs}$

OR

Via dihadron production

Accessing gluons with an electroweak probe

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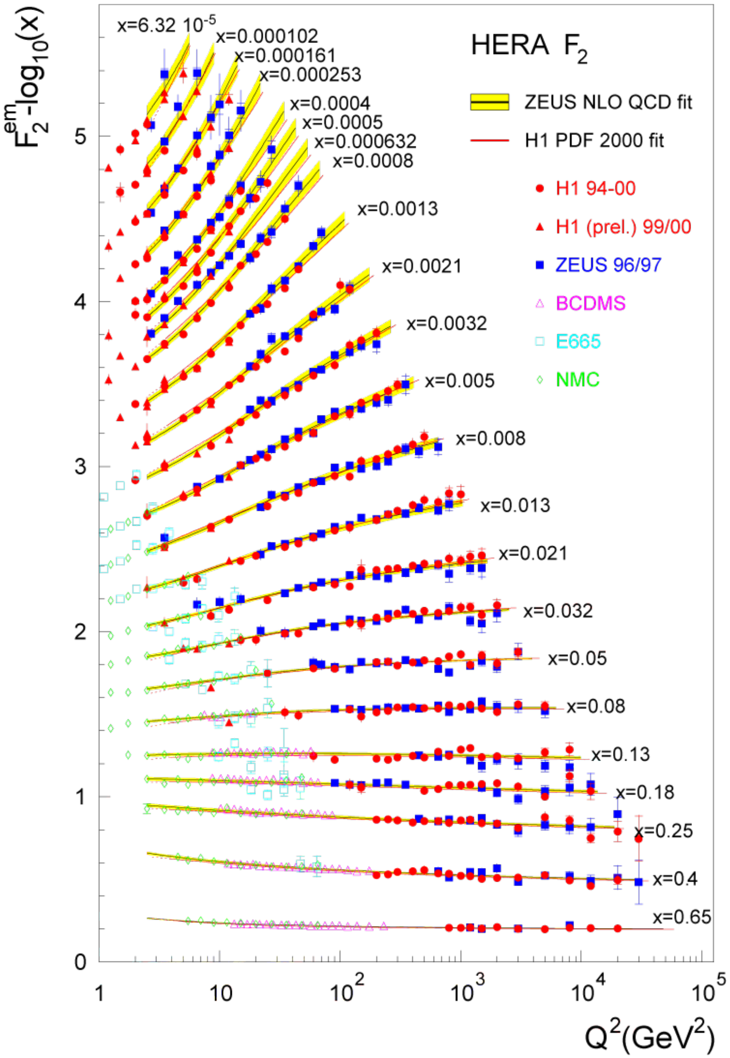

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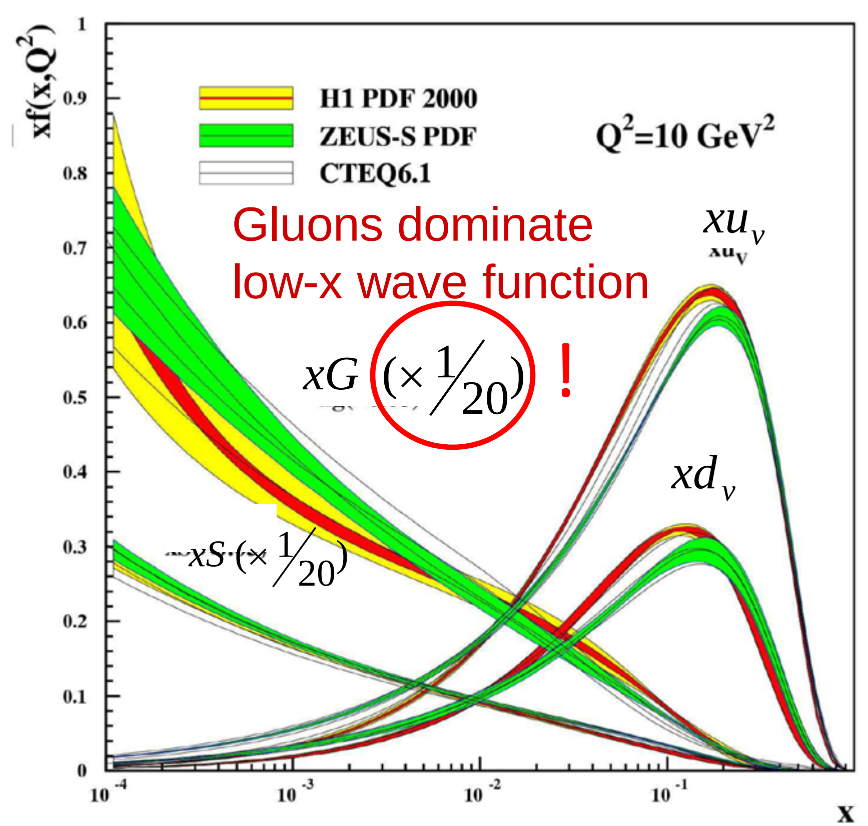

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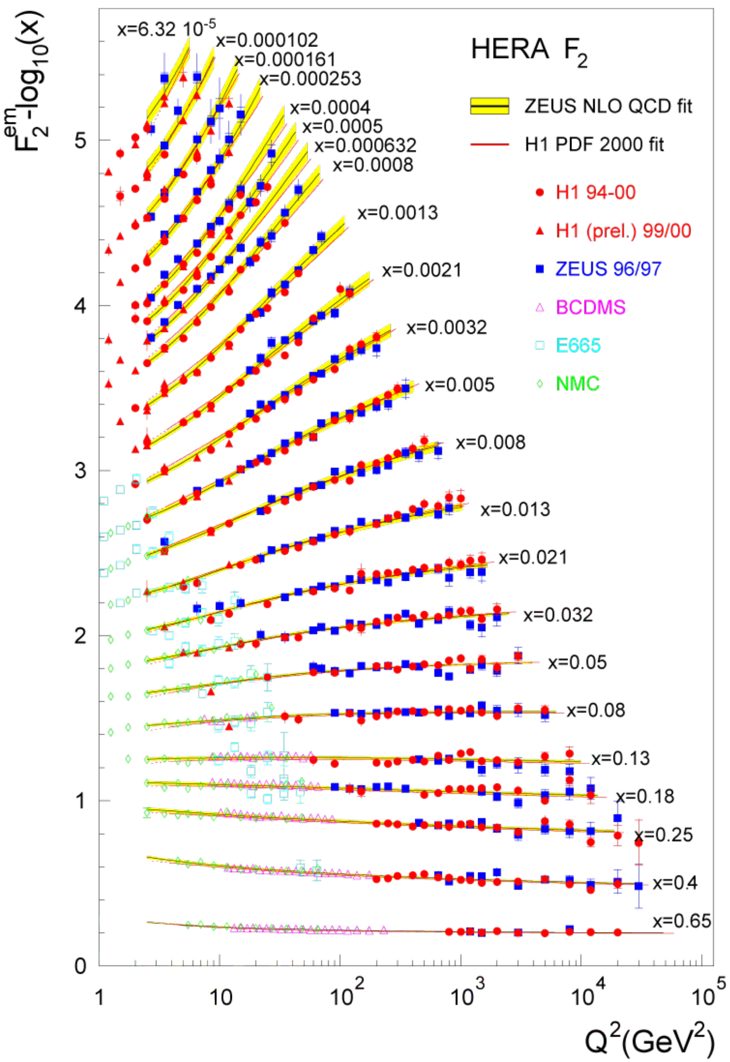

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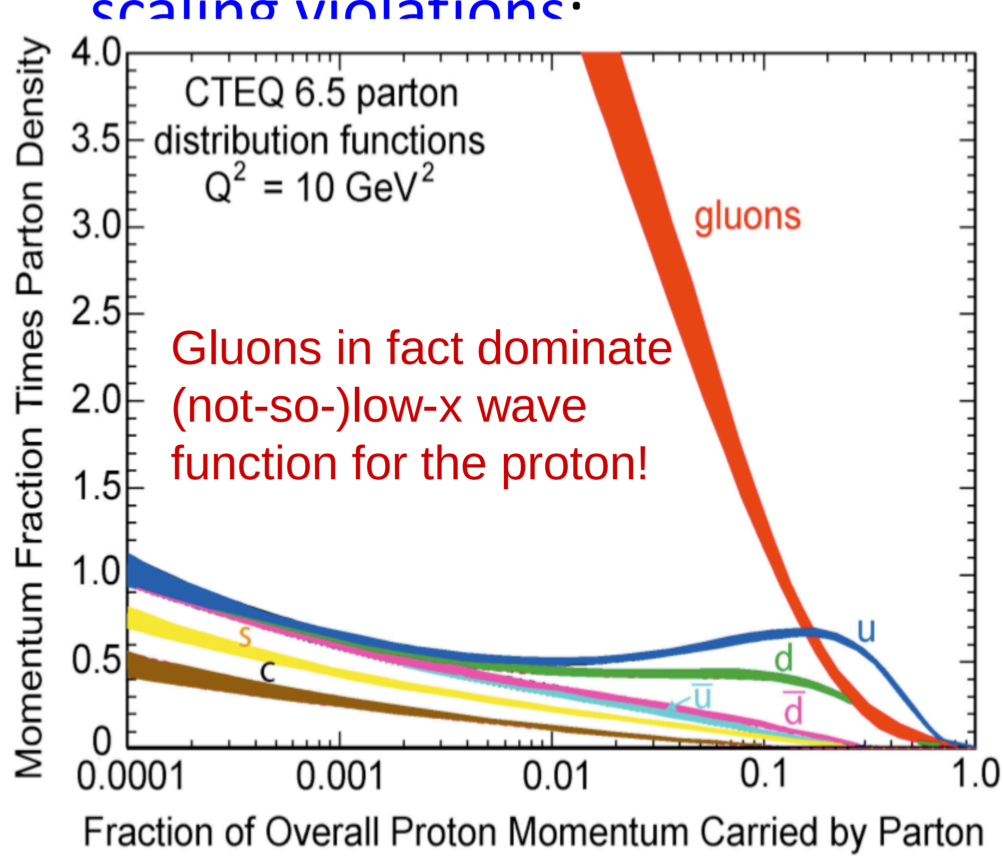
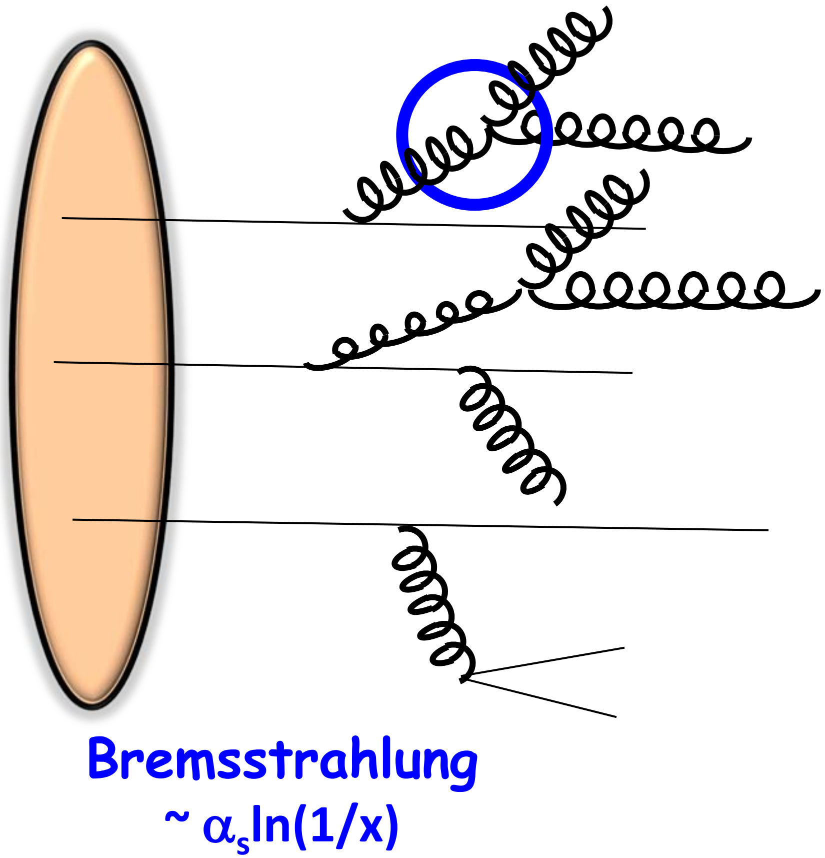
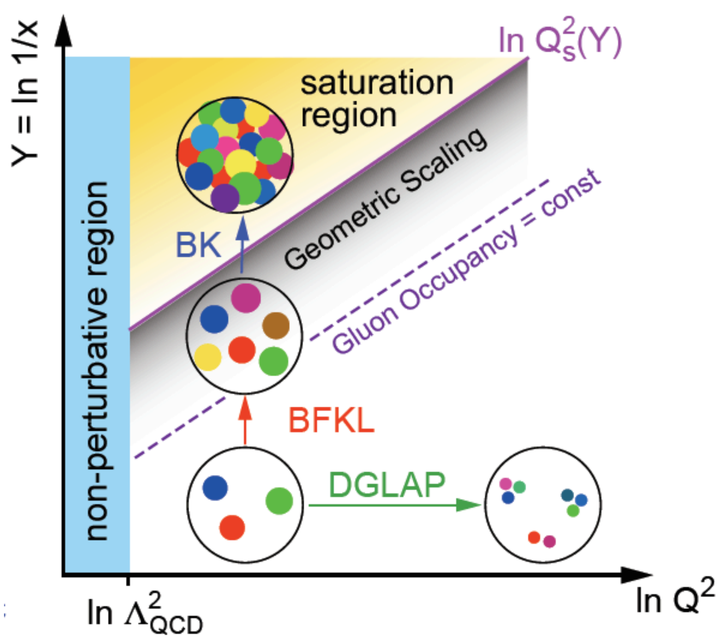


Non-linear QCD and gluon saturation

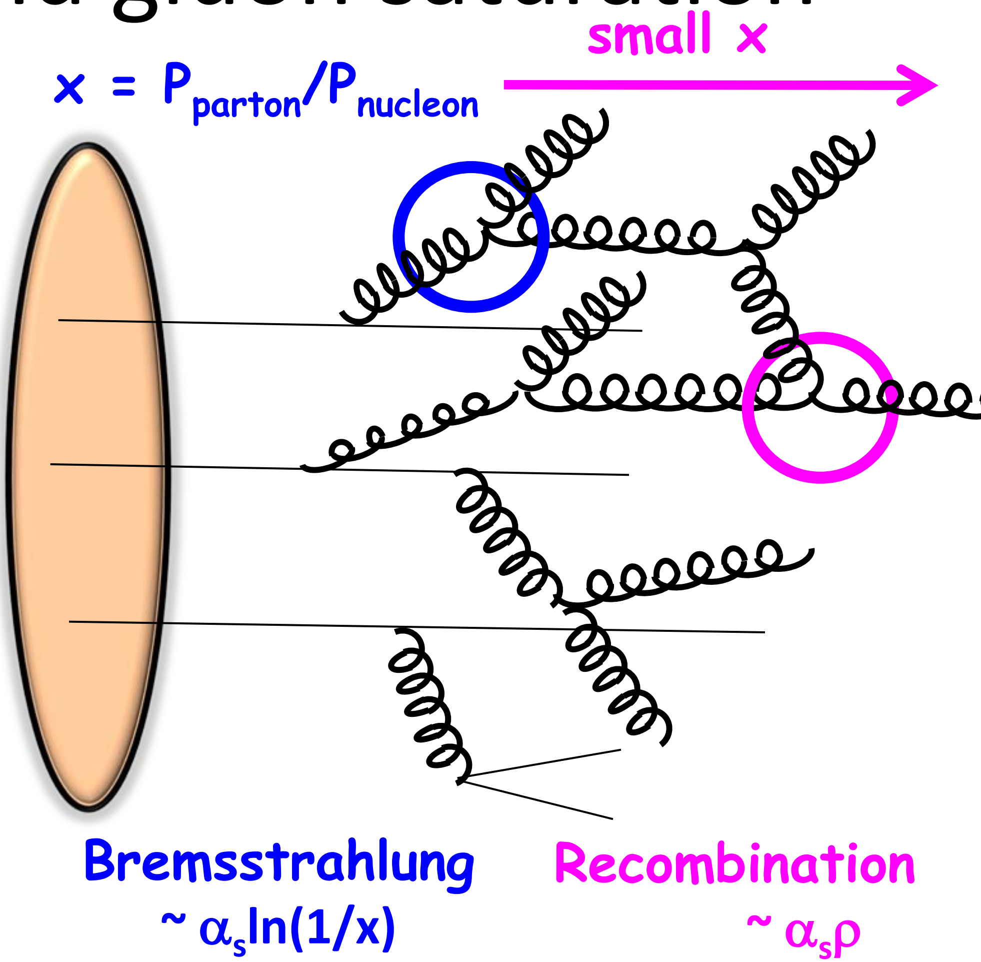
- At small x, linear (DGLAP or BFKL) evolution gives strongly rising g(x) → Violation of Froissart unitarity bound

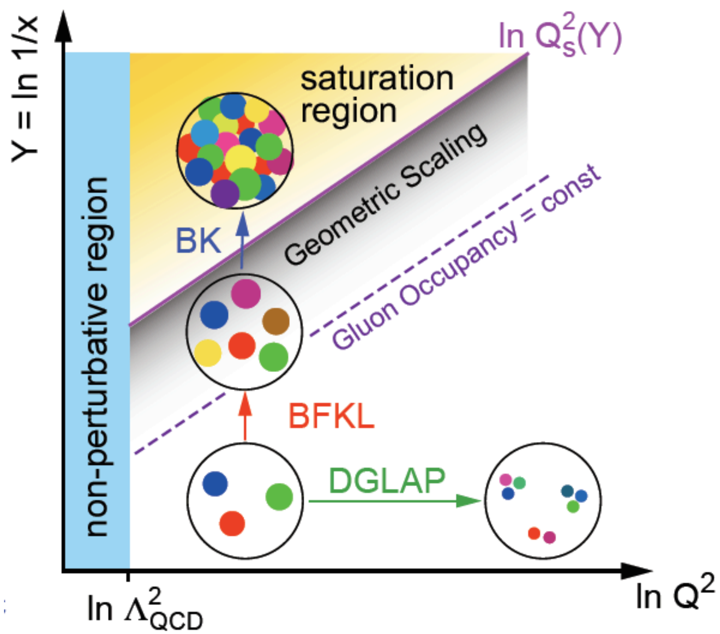




Non-linear QCD and gluon saturation

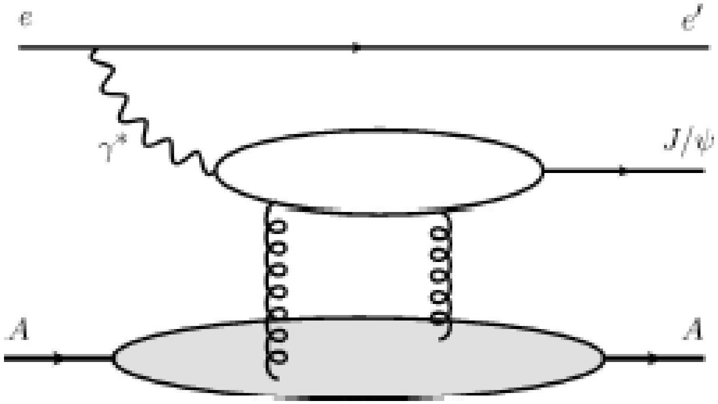
- At small x, linear (DGLAP or BFKL) evolution gives strongly rising g(x) → Violation of Froissart unitarity bound
- Non-linear (BK/JIMWLK) evolution includes recombination effects → gluon saturation

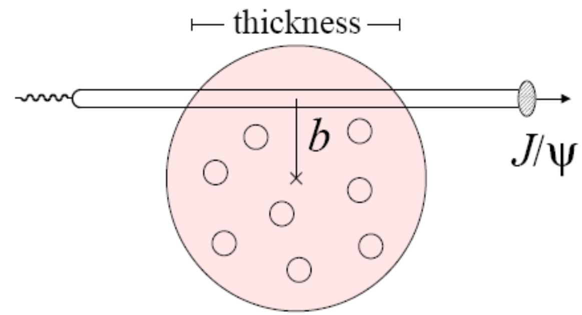




Easier to reach saturation regime in nuclei than nucleons due to $A^{1/3}$ enhancement of saturation scale → e+A collisions clean environment to study non-linear QCD!

Impact-parameter-dependent nuclear gluon density via exclusive J/Ψ production in e+A





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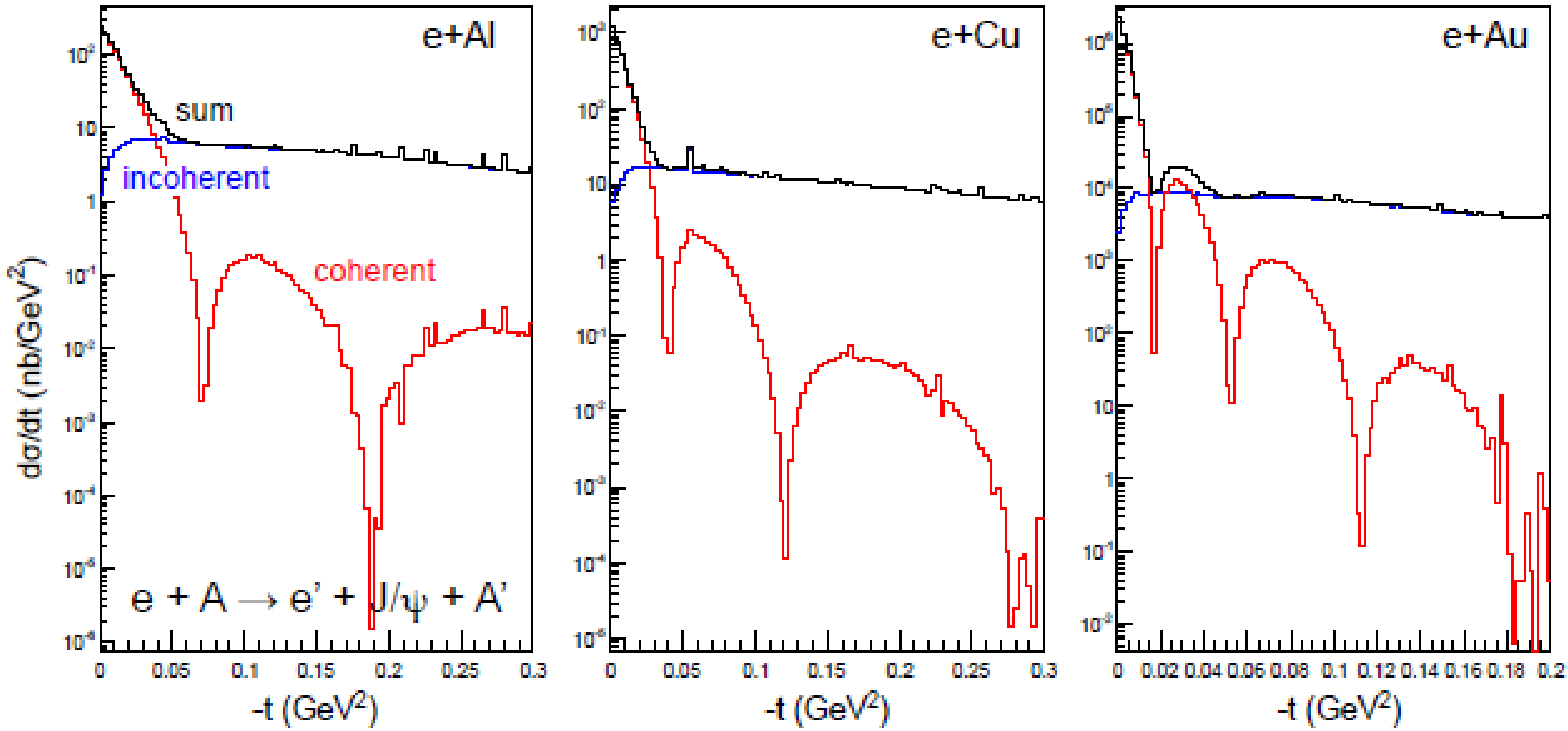
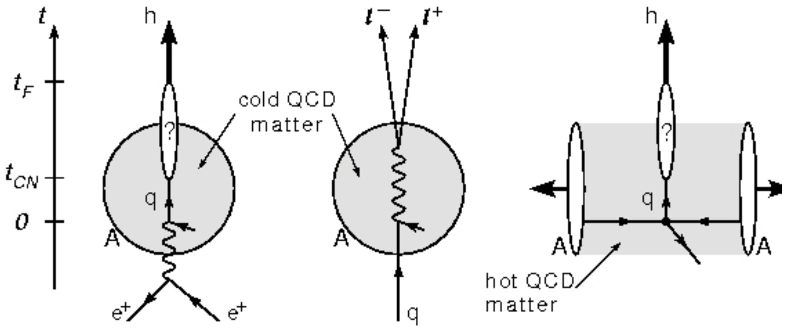
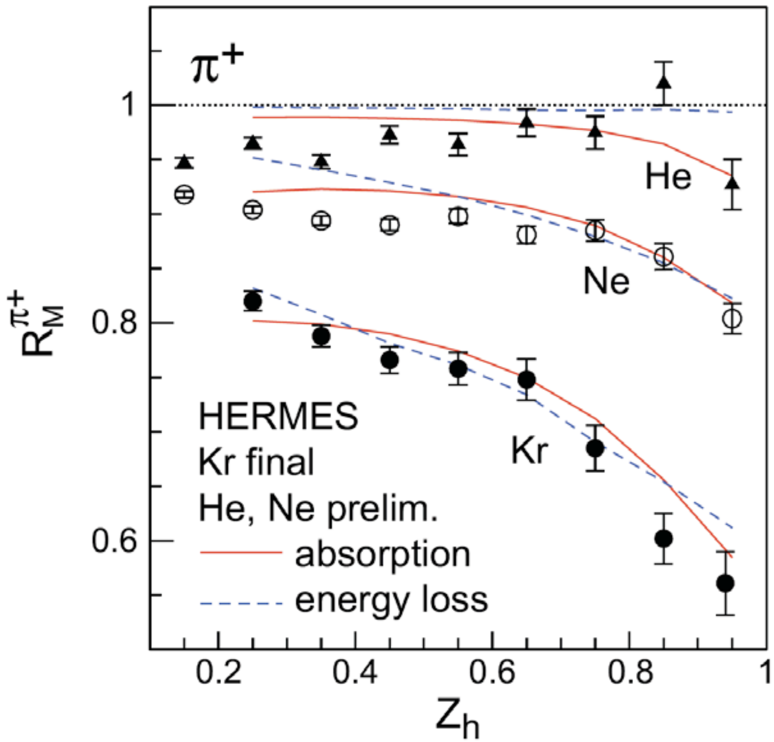


Coherent diffraction pattern extremely sensitive to details of gluon density in nuclei!

- Experimentally suppress incoherent background by vetoing events with nuclear breakup (e.g. seen in Zero-Degree Calorimeters)

Parton propagation in matter and hadronization



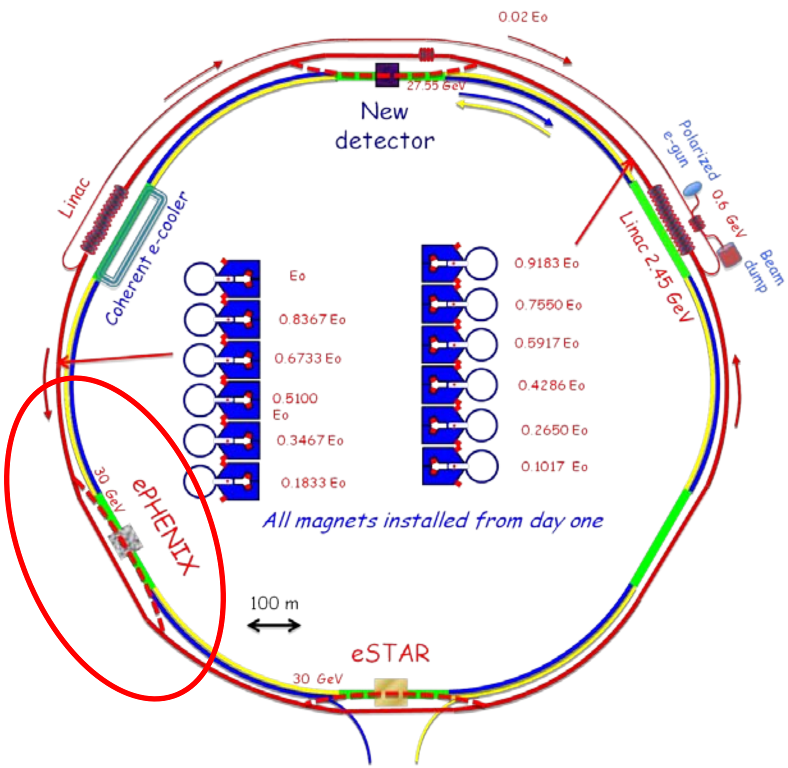


- Interaction of fast color charges with matter?
- Conversion of color charge to hadrons?
- Existing data → hadron production modified on nuclei compared to the nucleon!

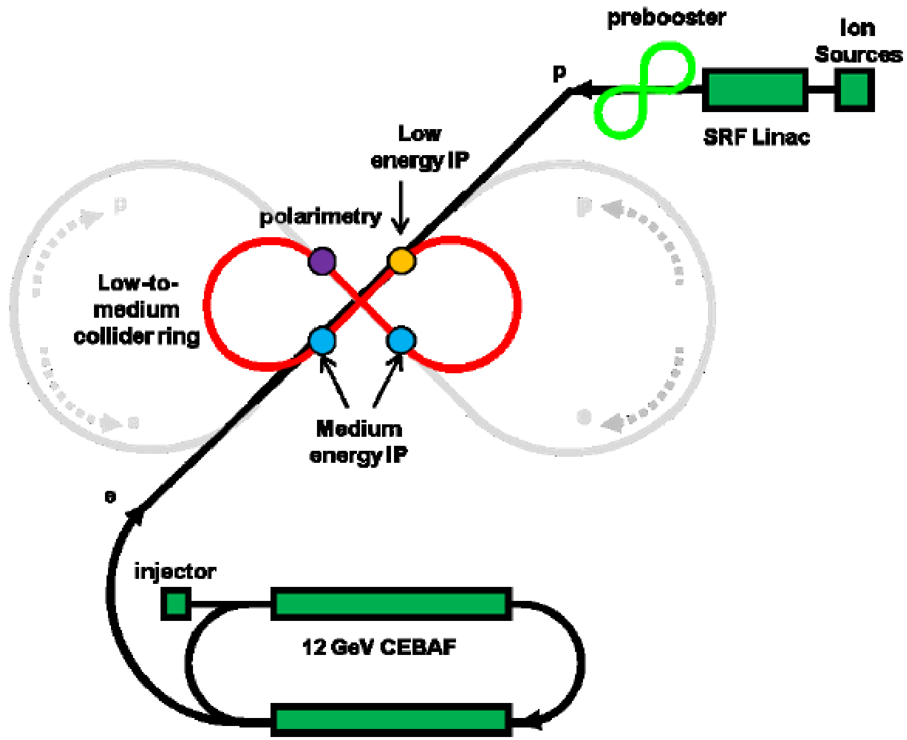
EIC will provide tremendous statistics and much greater kinematic coverage!
-Study quark interaction with CNM
-Study time scales for color neutralization and hadron formation
- *e+A complementary to jets in A+A: cold vs. hot matter*

EIC accelerator concepts

- eRHIC at BNL:
- Add electron ring to RHIC



- ELIC at JLab:
- Add proton/ion beam to CEBAF



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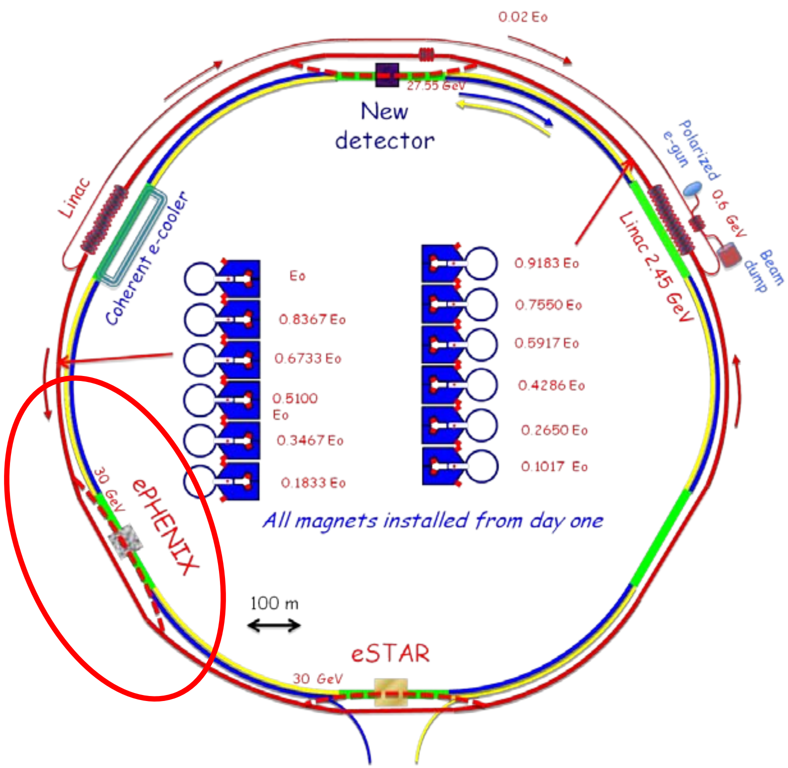
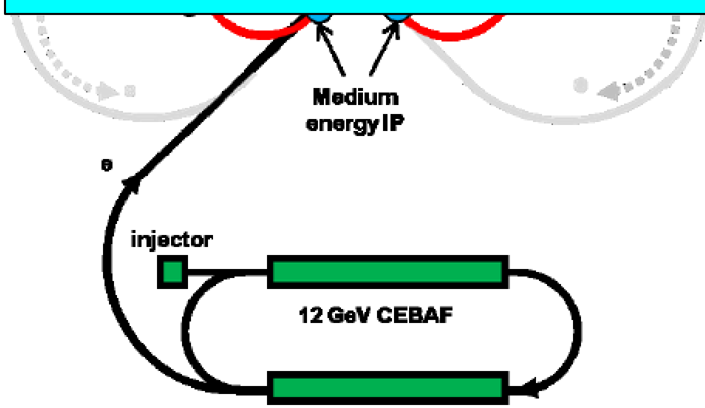
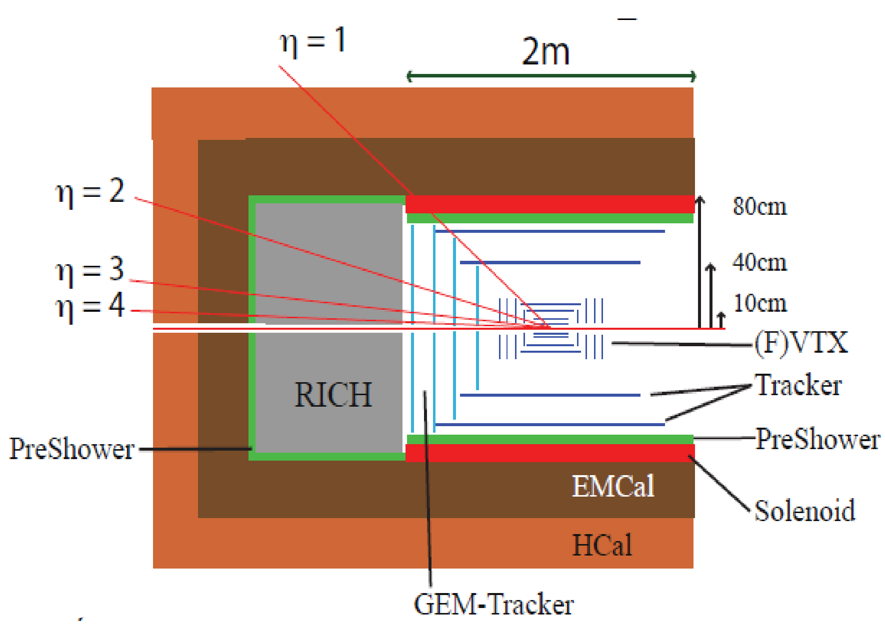


As part of the longer-term planning process underway within PHENIX, considering strategies for A+A/p+A/p+p upgrades program to lead into e+A/e+p program → ePHENIX



From sPHENIX to ePHENIX

- Designing sPHENIX detector such that it could evolve into a suitable detector for e+A/e+p → ePHENIX Task Force created November 2011
  - sPHENIX forward spectrometer should work well for hadron-going-direction at ePHENIX
  - Replace tracking to be lower mass
  - Add electron-going-direction spectrometer
  - Add PID at midrapidity



ePHENIX/EIC: A natural continuation of LANL's RHIC program

- Overarching physics focus of the EIC: Deepen understanding of QCD through study of *nucleon structure and cold nuclear matter*
  - Excellent match with current group interests!
  - Few RHIC institutions have groups in both physics programs—an unusual strength to be exploited
  - LANL currently one of the leading institutions in cold nuclear matter physics within the heavy ion community!

- Facility will unite the nucleon structure and heavy ion physics communities currently brought together at RHIC not by common physics but by a collider with capabilities relevant to both
  - ***LANL well positioned to play a leadership role*** within the EIC if it chooses
  - Leitch, McGaughey established leaders in CNM
  - Aidala, Jiang, Liu extensive experience in nucleon structure

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Time to get involved intellectually is now, as the case for the 2013 LRP is being developed

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LANL's institutional value to the EIC

- Timely buy-in from LANL as an institution also highly valuable in helping to realize the EIC
  - Clear indication of interest at an institutional level a signal to others in the field as well as to funding agencies that the project is garnering support and momentum
  - LANL has significant institutional resources to develop and build major hardware components for a new facility, including LDRD for detector R&D
  - While data-taking at an EIC will be after 2020, relevant nearer-term opportunities exist
    - DOE site-generic EIC detector R&D money available as of FY11
    - Plan to keep sPHENIX forward detectors into ePHENIX era → integrated design process now

Extensive involvement

Broad involvement by LANL PHENIX team in supporting the ongoing long-term planning process within PHENIX

- Participation in December 2011/January 2012 sPHENIX Workfests in Boulder, CO/Knoxville, TN (da Silva, Huang, Jiang, Liu)
- Member of ePHENIX Task Force (Aidala)
- Participation in 2010 INT program in Seattle to develop EIC science case (Aidala, Jiang, Liu)
- Direct involvement in producing PHENIX Decadal Plan document in 2010 (Aidala, Leitch, van Hecke)
- Participation in January 2010 EIC collaboration meeting at Stony Brook (Aidala, Jiang, Leitch, Liu)

Summary

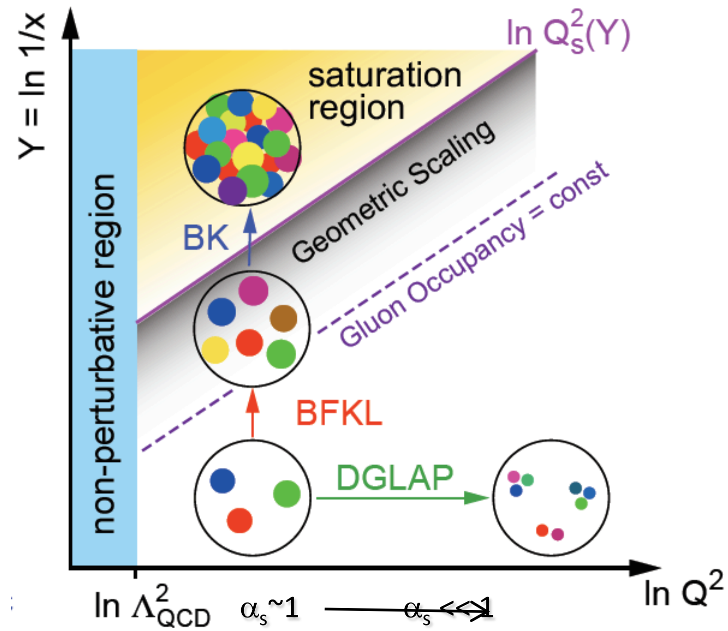
- The EIC promises to usher in a new era of precision measurements that will probe the behavior of quarks and gluons in nucleons as well as nuclei, bringing us to a new phase in understanding the rich complexities of QCD in matter
- The P-25 PHENIX team is well positioned to play a leadership role in ***both*** the e+A and e+p programs at the EIC
- LANL's involvement as an institution would be highly valuable in helping to realize the EIC
- Staged plan offers variety of physics as well as detector opportunities on a range of timescales

Extra

High-density gluon matter: Saturation

- At small x linear evolution gives strongly rising g(x)
- BK/JIMWLK non-linear evolution includes recombination effects → saturation
  - Dynamically generated scale

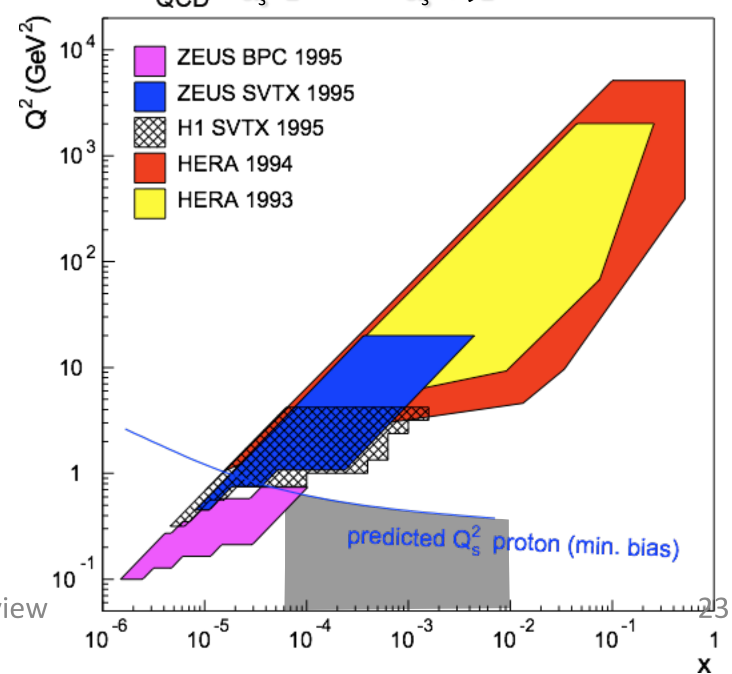
    Saturation Scale: $Q^2_s(x)$
    - Increases with energy or decreasing x
  - Observables scale with $Q^2/Q^2_s(x)$ instead of x and Q^2 separately



HERA (e+p):

Despite high energy range:

- F_2, $G_p(x, Q^2)$ only outside the saturation regime
- Regime where non-linear QCD (saturation phenomena) ($Q < Q_s$) not reached, but close
- Only way in e+p is to increase √s



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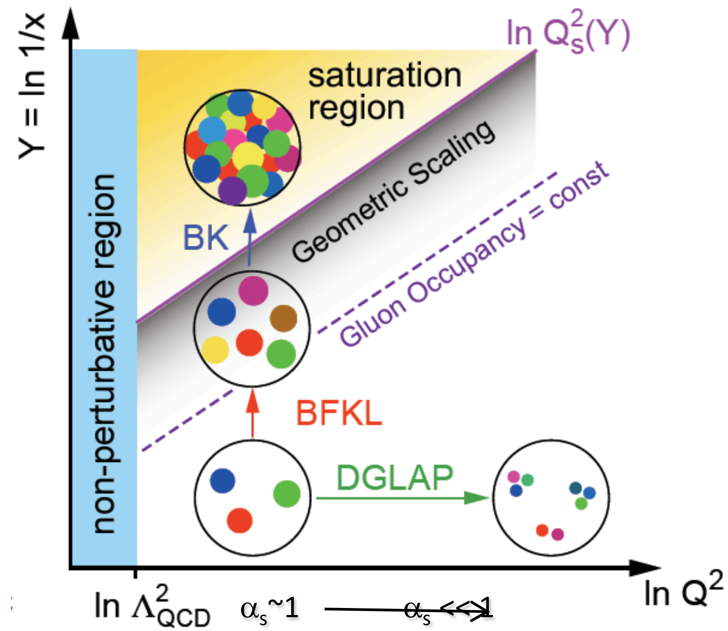
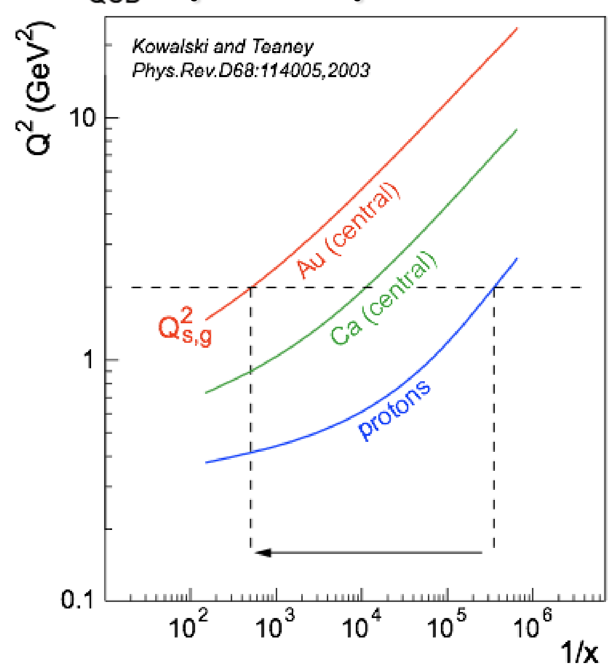


EIC (e+A):

- ❑ Instead of extending x, Q reach

  → increase Q_s
- ❑ Nuclear enhancement of saturation scale:

$$Q_s^2(x, A) \sim Q_0^2 \left(\frac{A}{X}\right)^{1/3}$$

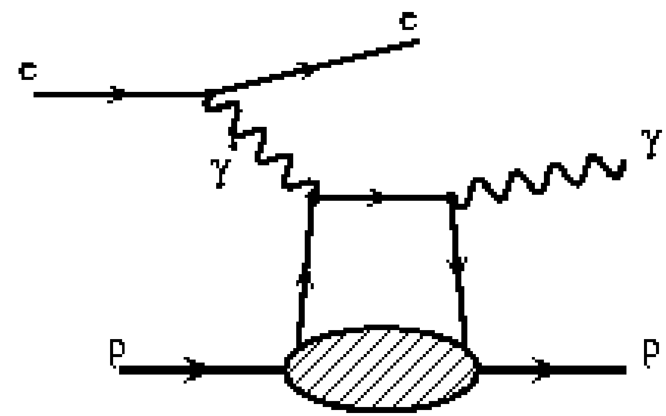


Spatial imaging of the nucleon

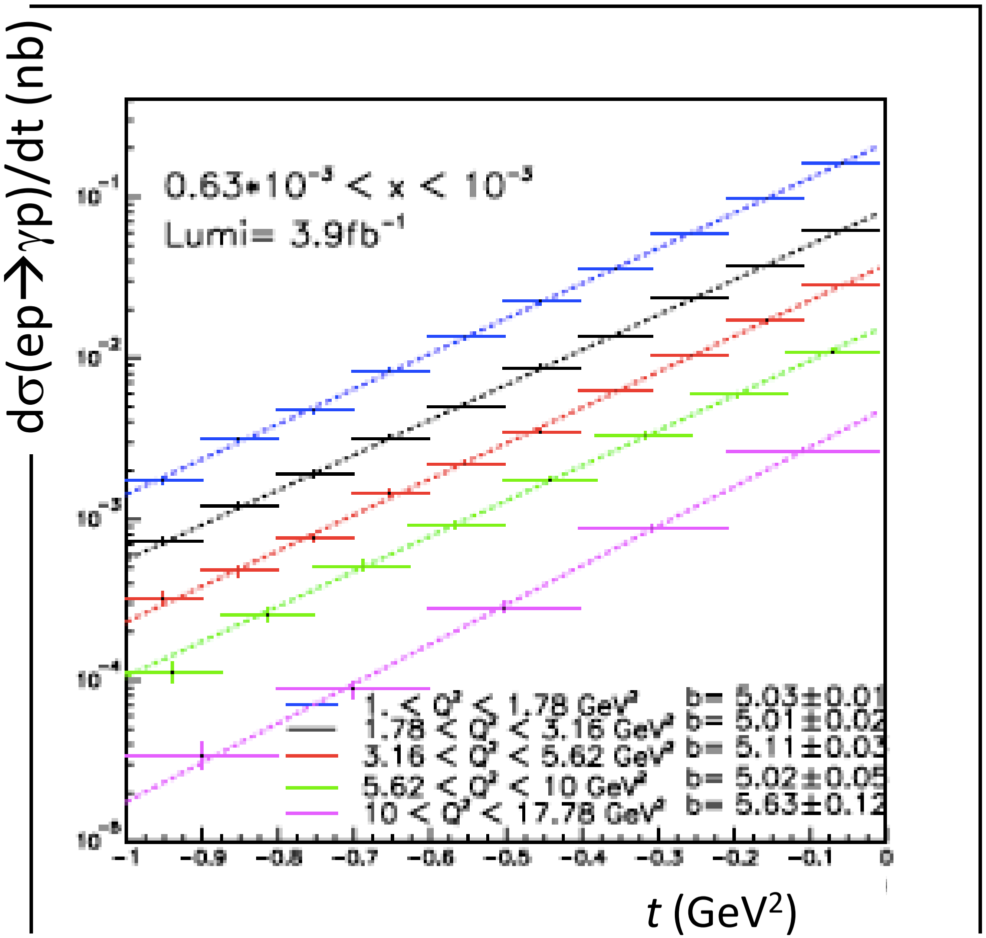
Deeply Virtual
Compton Scattering

Perform spatial imaging via *exclusive* processes
→Detect all final-state particles
→Nucleon doesn't break up

Measure cross sections vs. four-momentum transferred to struck nucleon: Mandelstam *t*



Spatial imaging of the nucleon



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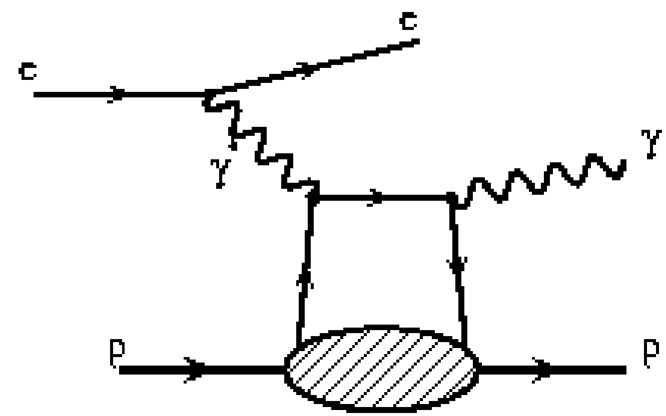

Goal: Cover wide range in *t*.
Fourier transform → impact-parameter-space profiles

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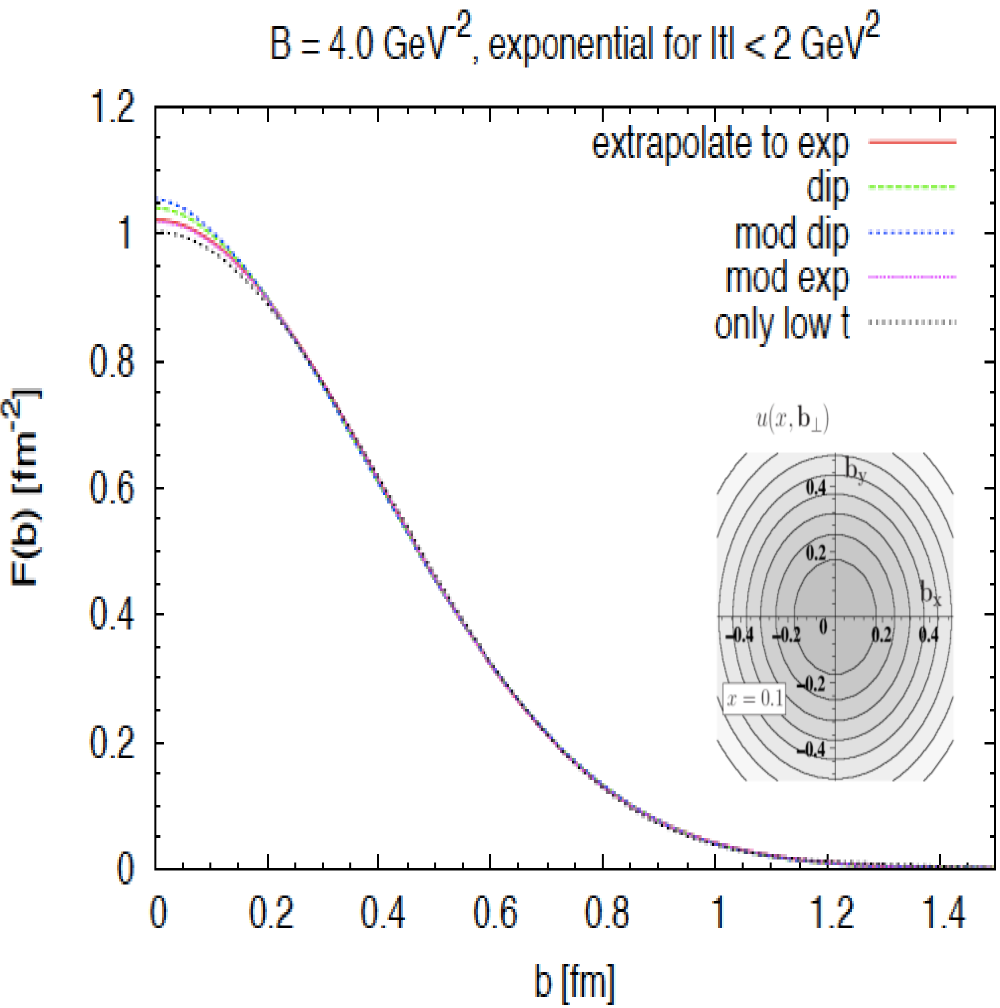

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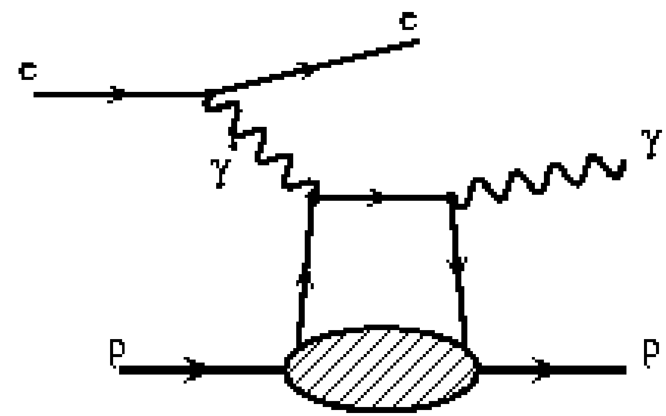
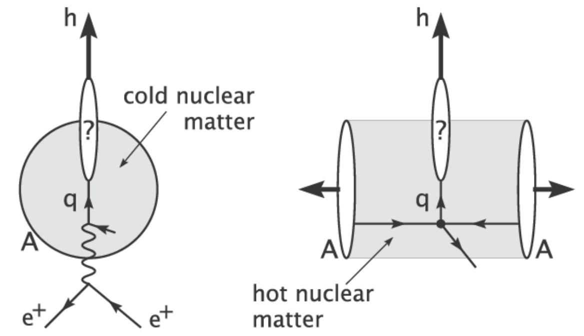


Goal: Cover wide range in *t*. Fourier transform → impact-parameter-space profiles

Obtain *b* profile from slope vs. *t*.

Parton propagation and fragmentation in nuclear DIS

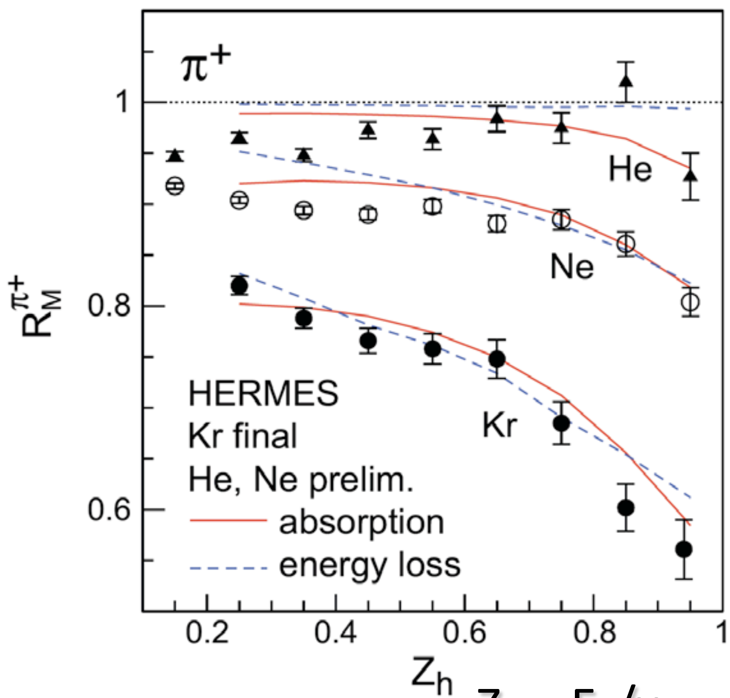


- Nuclear DIS:
  - Clean measurement in ‘cold’ nuclear matter
  - Suppression of high-p_T hadrons analogous to but weaker than at RHIC

Fundamental question:

When do partons get color neutralized?

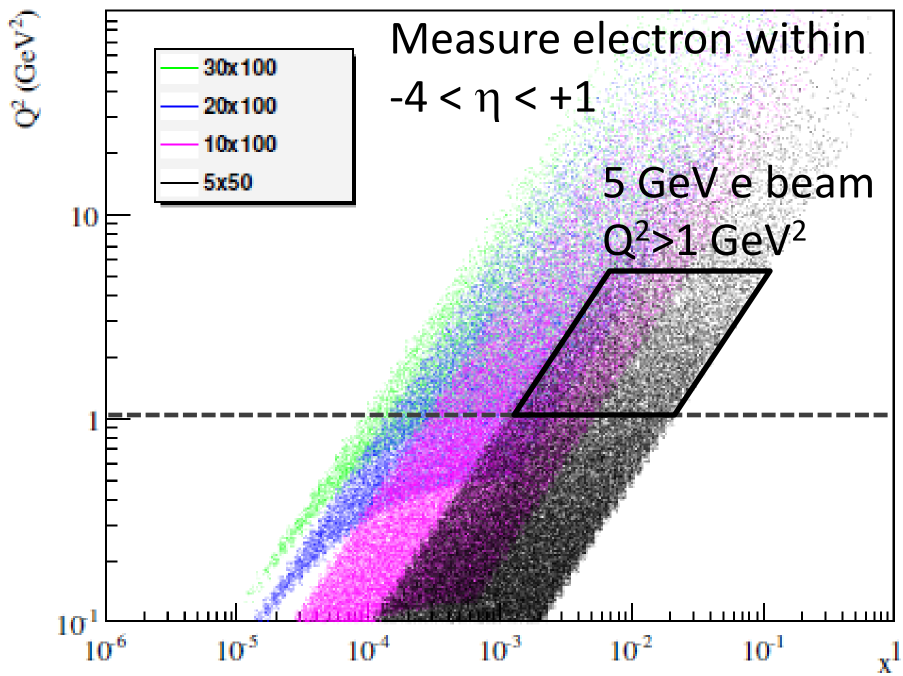
Parton energy loss vs. (pre)hadron absorption

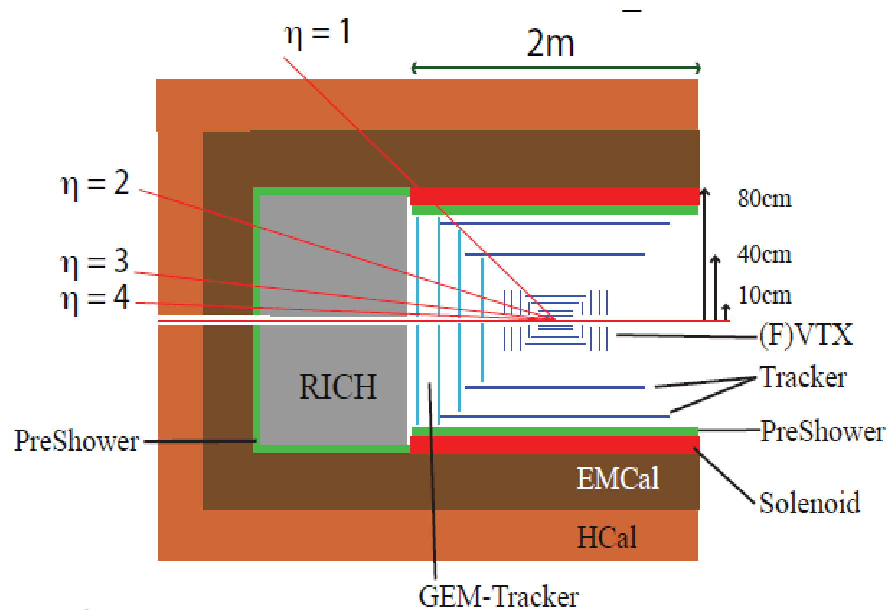


Energy transfer in lab rest frame:
HERMES: 2 < ν < 25 GeV
EIC: 10-1600 GeV!

$z_h = E_h/\nu$

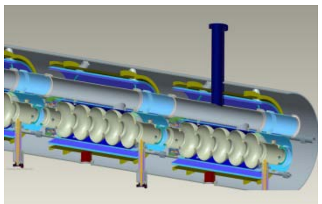
From sPHENIX to ePHENIX: Kinematics with 5 GeV e beam

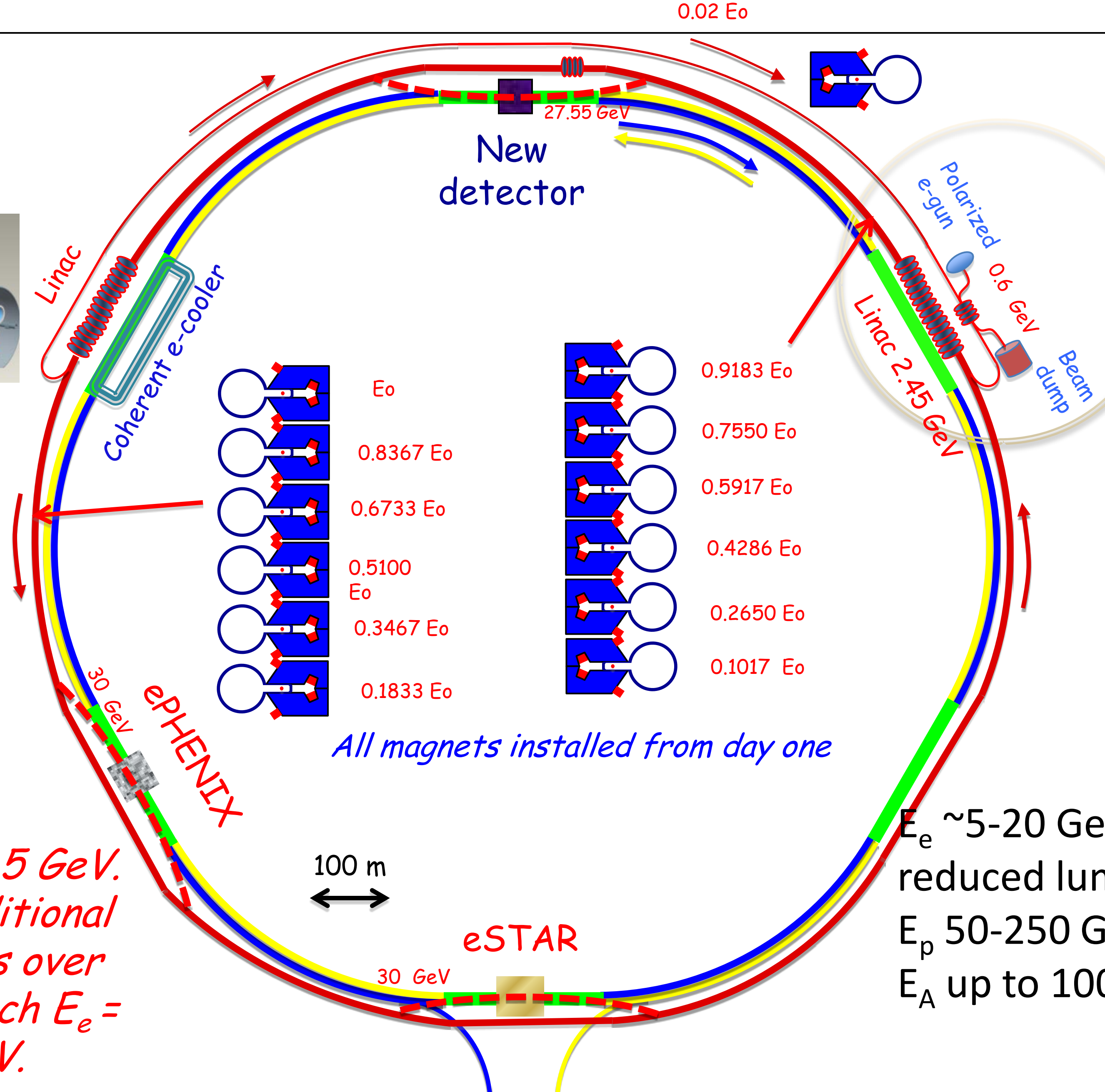


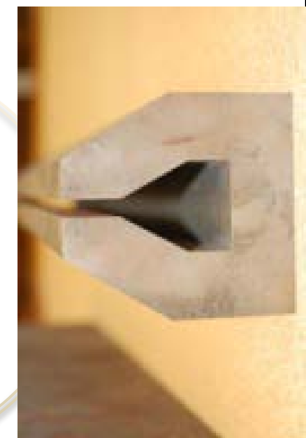


- Would need to plan accordingly—low-mass tracking, energy and angular resolutions, . . .

eRHIC at BNL



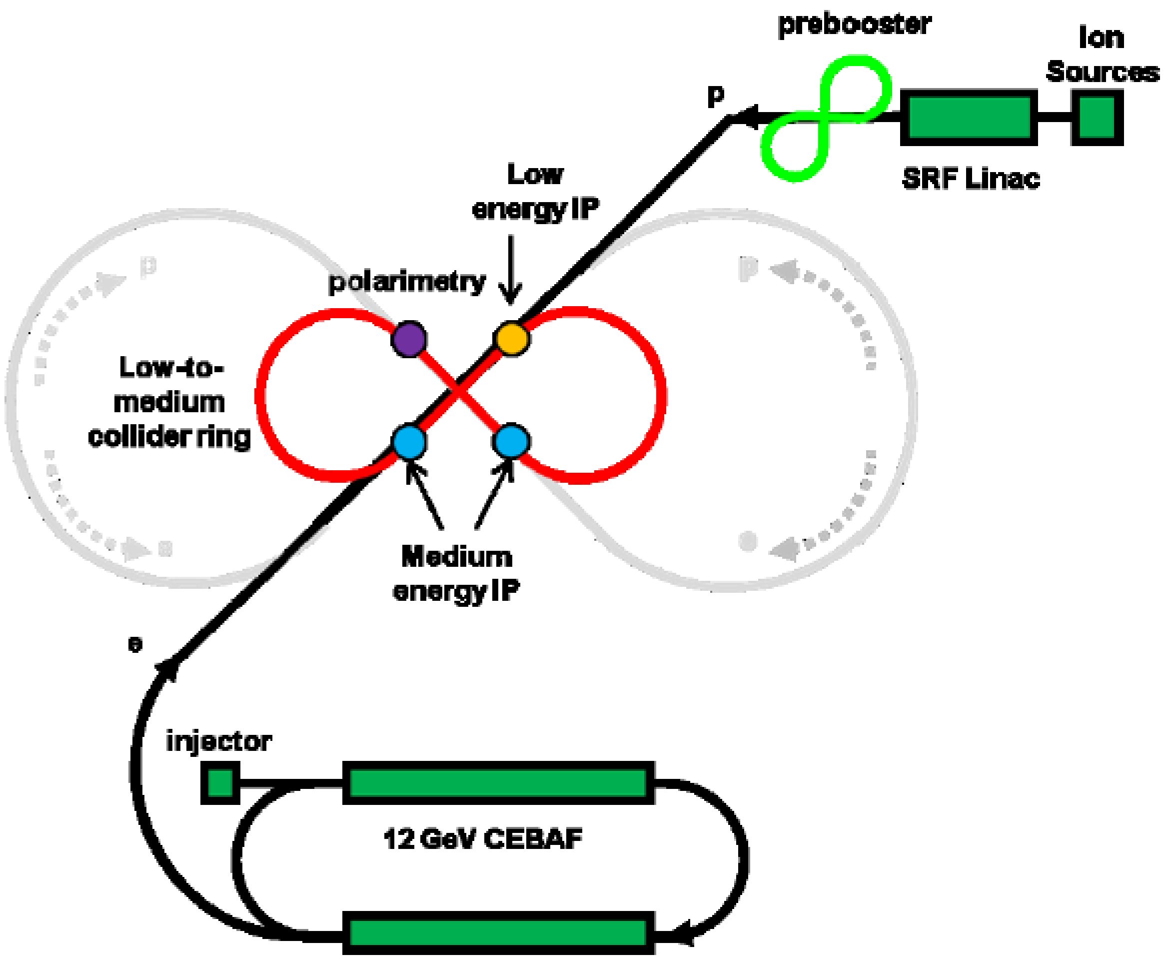




Initial E_e ~ 5 GeV. Install additional RF cavities over time to reach E_e = 30 GeV.

E_e ~5-20 GeV (30 GeV w/ reduced lumi)
E_p 50-250 GeV
E_A up to 100 GeV/n

Medium-Energy EIC at JLab (MEIC)



E_e = 3-11 GeV
E_p ~100 GeV
E_A ~50 GeV/n

Upgradable to high-energy machine:
E_e ~20 GeV
E_p ~ 250 GeV