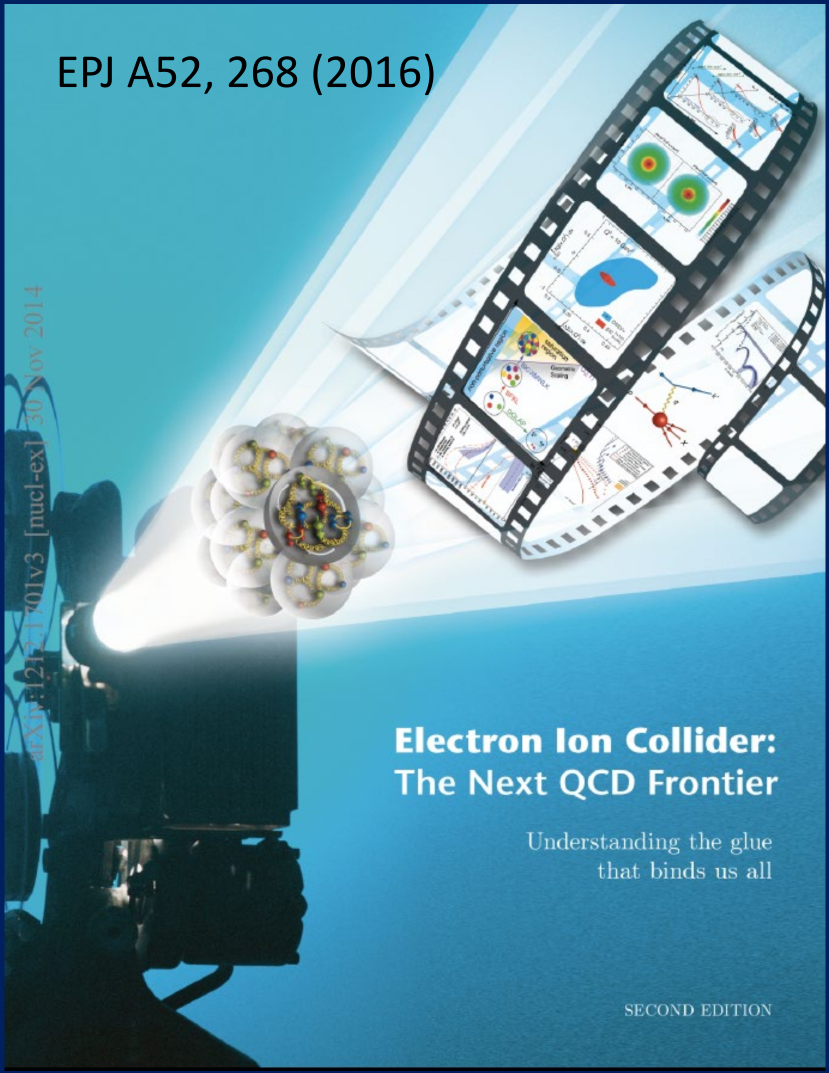
The Electron-Ion Collider: A New Tool for Studying QCD



Christine A. Aidala
University of Michigan

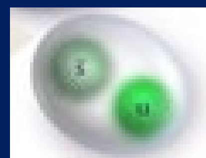
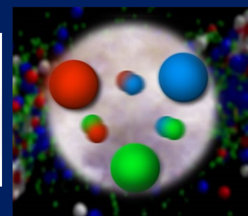
Zimanyi School 2019
Budapest
December 3, 2019

(One way of dividing up) *Areas of study in QCD*

- *Structure/properties* of QCD matter
- *Formation* of states of QCD matter
- *Interactions* within QCD

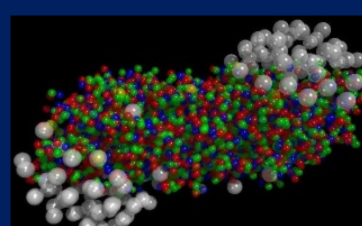
Structure/Properties of QCD matter

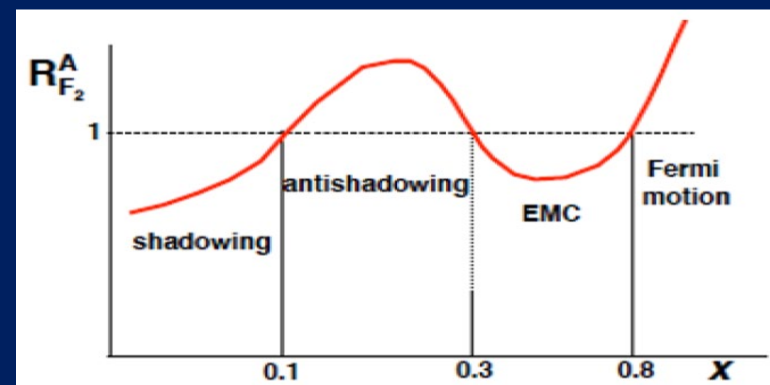
- Bound states: Mesons and baryons

- Bound states of bound states: Nuclei, neutron stars

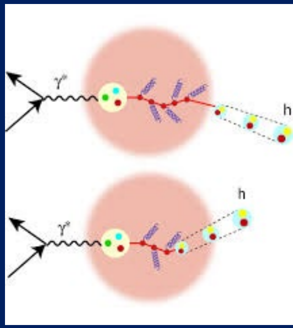

- Deconfined states: Quark-gluon plasma



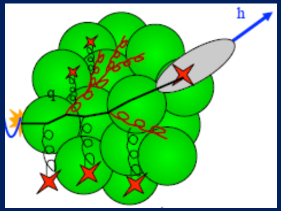


Nuclei aren't just superpositions of free nucleons

Formation of states of QCD matter

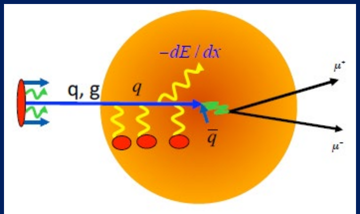


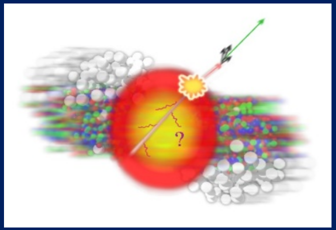
- Hadronization mechanisms
- Formation of bound states of bound states
- Jet structure
- Equilibration of QGP
- Time scales of hadronization/equilibration
- Modification of hadronization in different environments



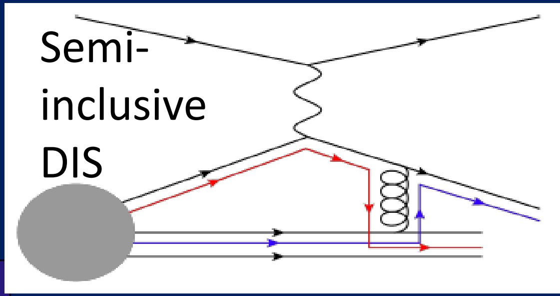
Interactions within QCD

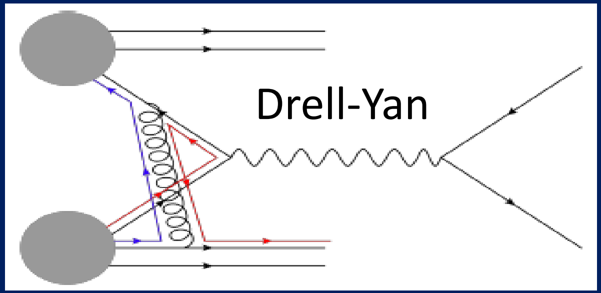
- Parton energy loss in cold and hot QCD matter





- Flow of partons within quark-gluon plasma
- Quantum interference and phase shifts
  - E.g. quantum interference effects in hadronization
    - One parton → multiple hadrons
    - Multiple partons → one hadron
- Color flow effects
  - Process-dependent spin-momentum correlations in hadrons
  - Quantum entanglement of partons across colliding hadrons





Complexity and richness of QCD: Confinement

- QCD theory: Quarks and gluons
- QCD experiment: QCD bound states

- Always an interplay between partonic/hadronic descriptions, reductionist/emergent pictures

High-energy collisions: Tools to study QCD

- Need high (enough) energies to
  - Access subnuclear distance scales
  - Form new states of QCD matter
- High energies can also
  - Allow use of perturbative theoretical tools
  - Provide access to new probes, e.g. heavy flavor, Z/W bosons

High-energy collisions: Tools to study QCD

Can study QCD via

- Hadron-hadron collisions: p+p, p+A, A+A, pbar+p/A, π+A
- Lepton-hadron collisions: e/μ+p, e/μ+A, ν+A
- Lepton-lepton collisions: e^+e^- (hadronization)

High-energy collisions: Control

The more aspects of the collisions we can control/manipulate, the more powerful our tools

- Collision species → state of matter to be studied, geometry, path length, flavor/isospin, electroweak vs. strong interactions
- Energy → distance/time scales, probes accessible, states of matter
- Polarization → spin-spin and spin-momentum correlations in QCD systems or in hadronization, sensitivity to system properties (e.g. gluon saturation)

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Some aspects we *select* rather than control

- Centrality, final-state produced particles and their kinematics

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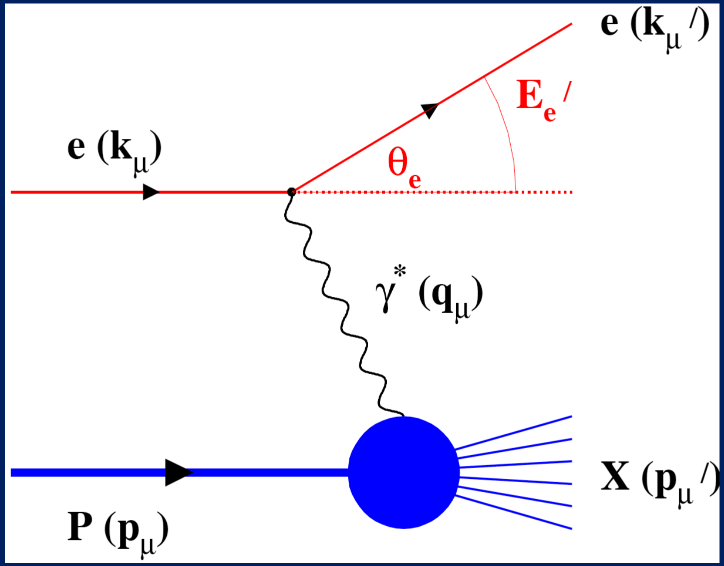
Multidifferential measurements even more powerful

- p_T, rapidity, centrality, angular distribution/correlation, PID, . . .

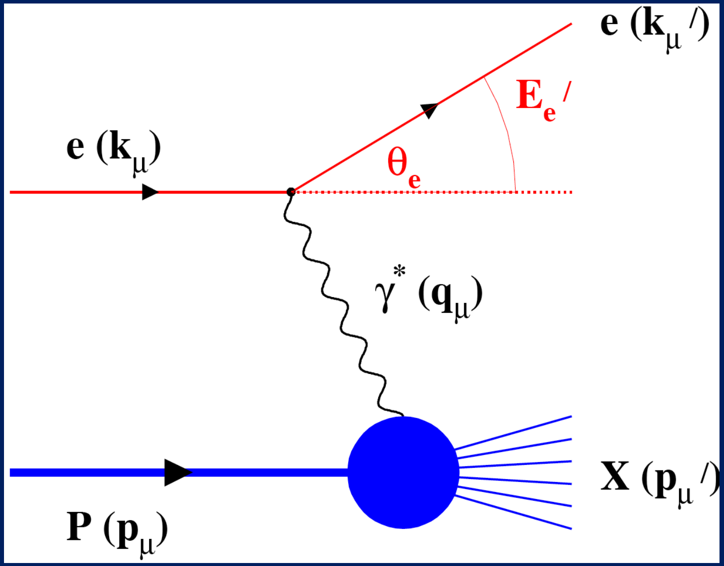
Why an Electron-Ion Collider?

- Electroweak probe
  - "Clean" processes to interpret (QED)
  - Measurement of scattered electron → full kinematic information on partonic scattering



Why an Electron-Ion Collider?

- Electroweak probe
  - "Clean" processes to interpret (QED)
  - Measurement of scattered electron → full kinematic information on partonic scattering
- Collider mode → Higher energies
  - Quarks and gluons relevant d.o.f.
  - Perturbative QCD applicable
  - Heavier probes accessible (e.g. charm, bottom, W boson exchange)



Next-generation QCD facility: The Electron-Ion Collider

Key science questions:

- *How does a nucleon acquire mass?*
- *How does the spin of the nucleon arise from its elementary quark and gluon constituents?*
- *What are the emergent properties of dense systems of gluons?*

See next talk by Yoshitaka Hatta

Next-generation QCD facility: The Electron-Ion Collider

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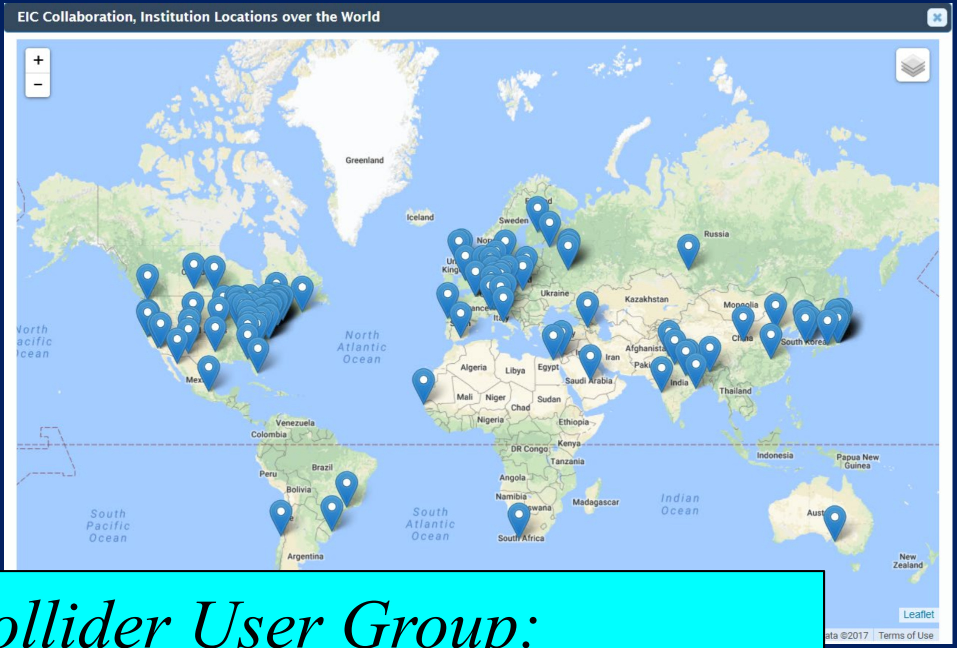
- *W p s*

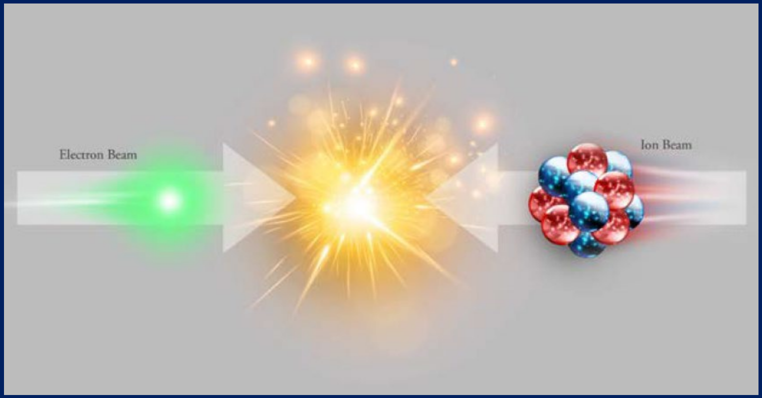


Electron-Ion Collider User Group:
Currently 975 members from 198 institutions in 31 countries. (25% theorists, 15% accelerator physicists, 60% experimentalists)

www.eicug.org

An EIC as envisioned in the 2018 U.S. National Academy of Sciences report

An advanced accelerator that collides beams of electrons with beams of protons and heavier ions.



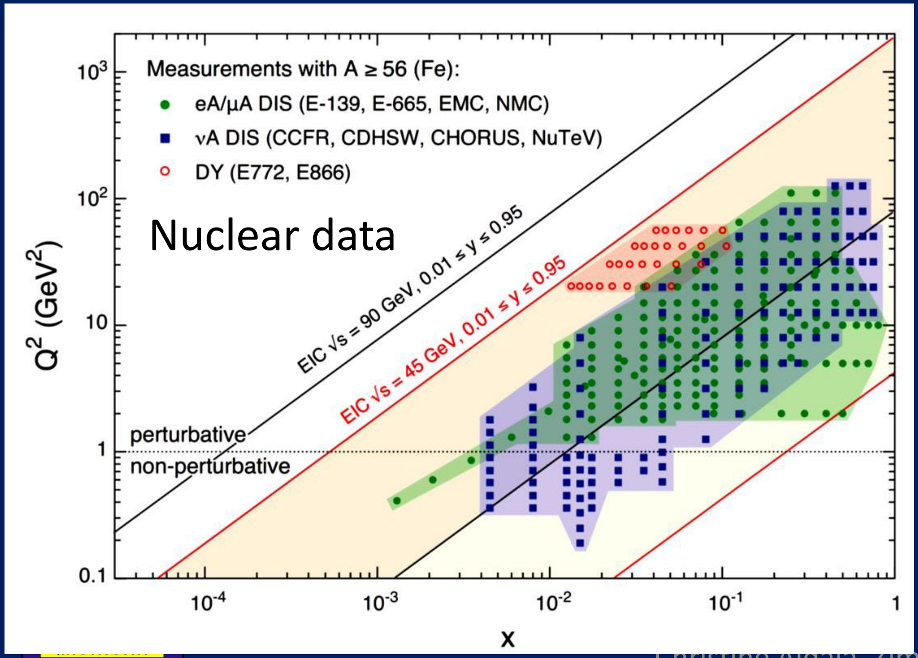
Electron-ion center of mass energy ~20-100 GeV, upgradable to ~140 GeV.

High luminosity and polarization:

- Luminosities $10^{33\text{-}34}$ cm^{-2} s^{-1}
- Highly polarized electrons, E ~ 4 GeV to possibly 20 GeV
- Highly polarized protons, E ~ 30 GeV to ~300 GeV, and heavier ions

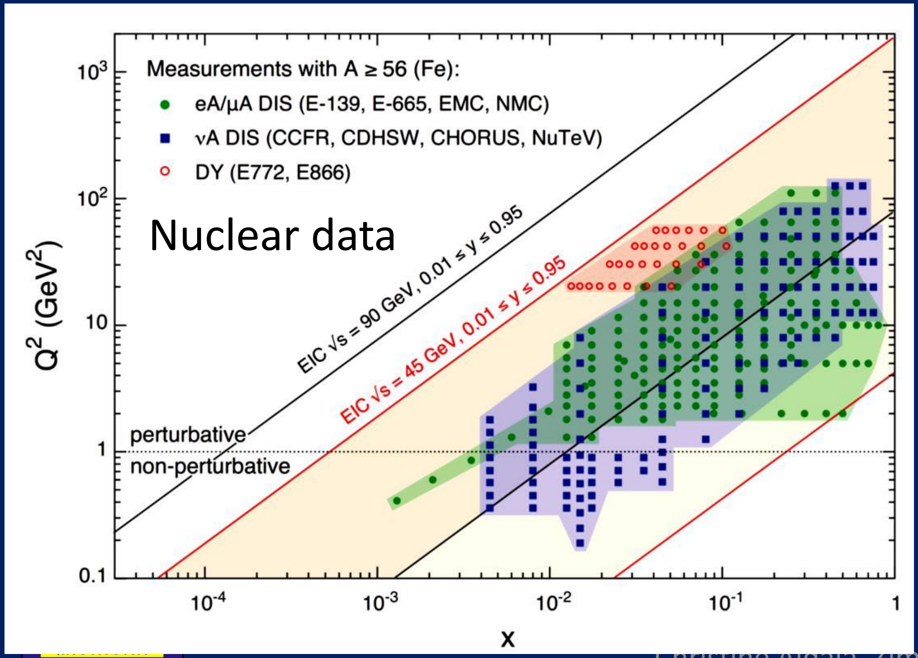
EIC facility concepts

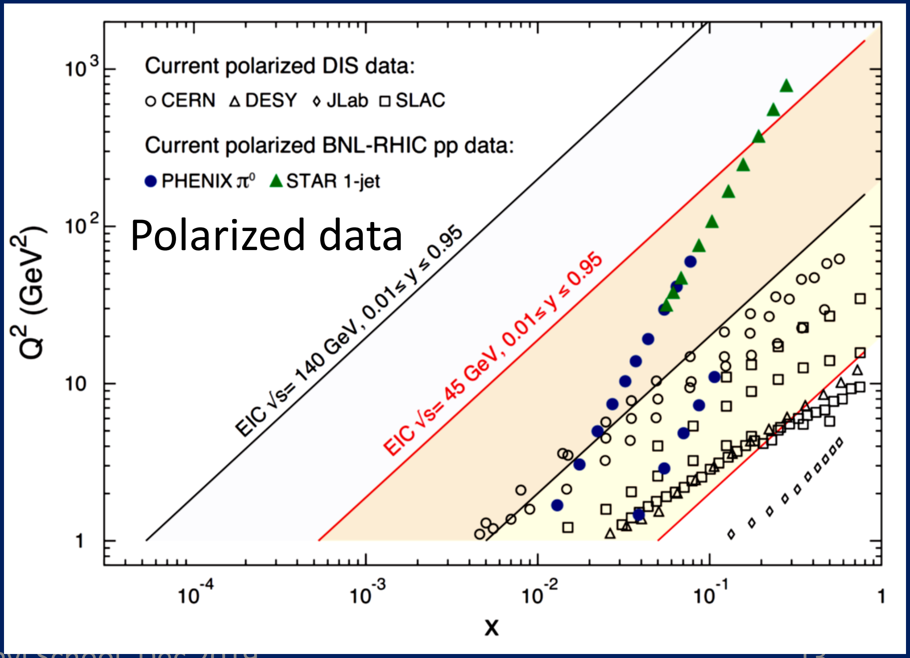
- Beams of light → heavy ions
  - Previously only fixed-target e+A experiments



EIC facility concepts

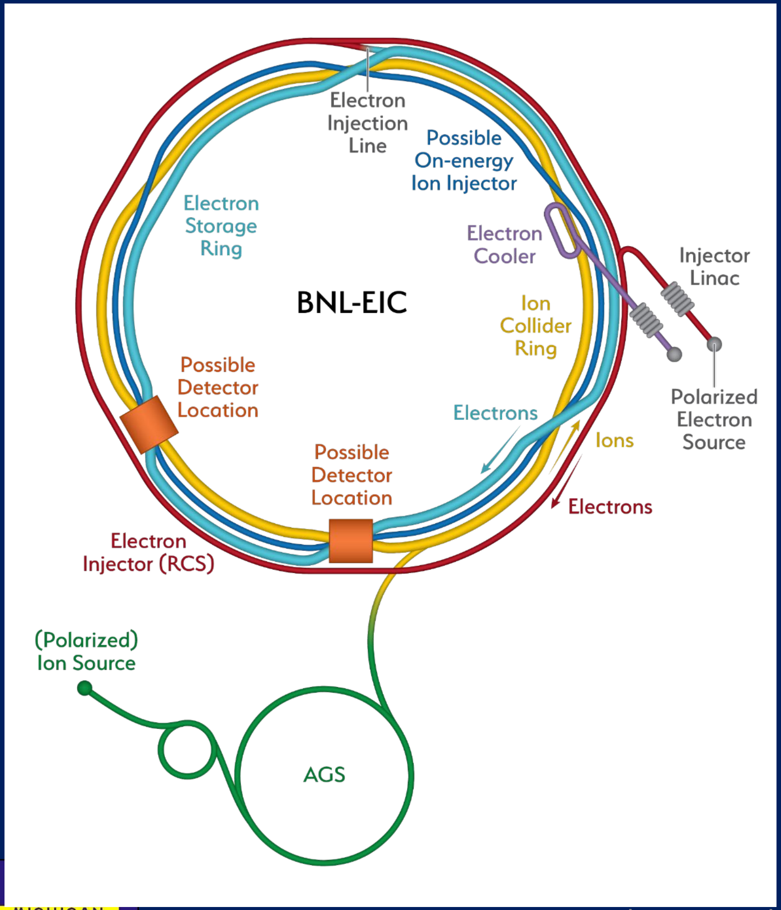
- Beams of light → heavy ions
  - Previously only fixed-target e+A experiments
- *Polarized* beams of p, d/He^3
  - Previously only fixed-target polarized experiments

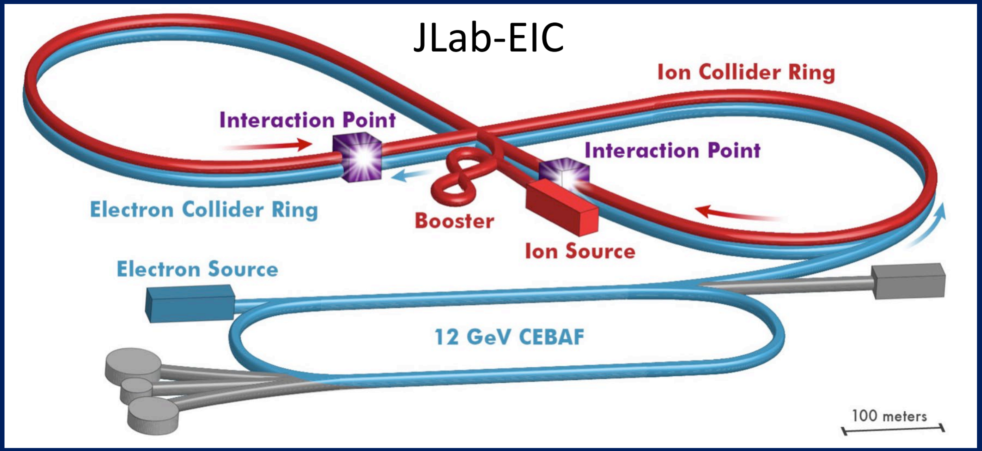




Possible accelerator configurations

Two possible configurations:
Add electron beam to RHIC at Brookhaven National Lab
or add hadron beam to CEBAF at Jefferson Lab





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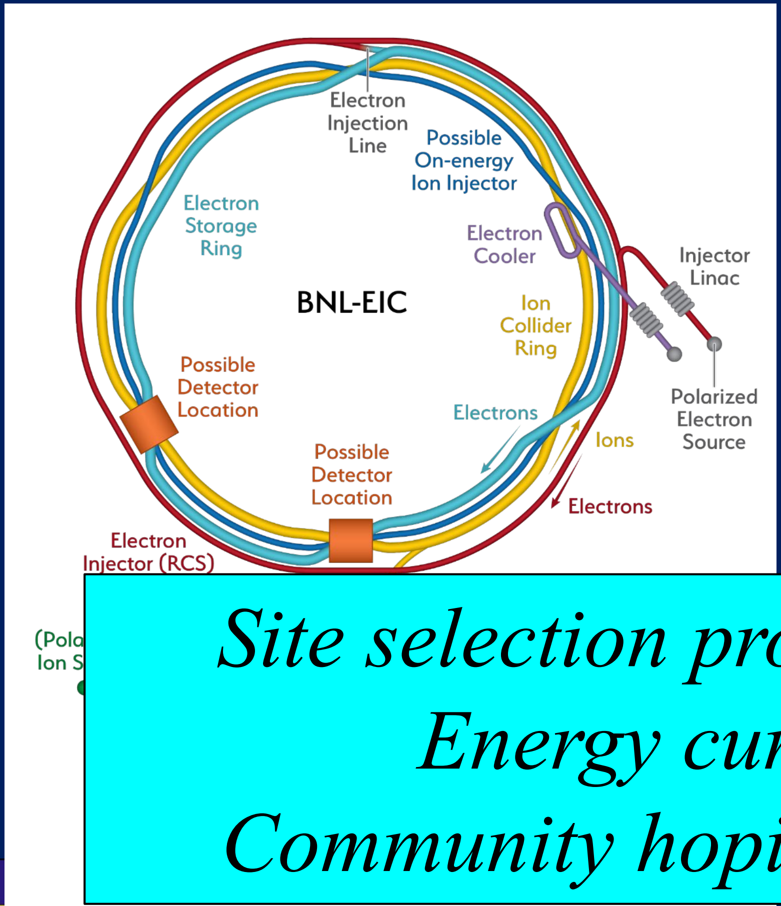
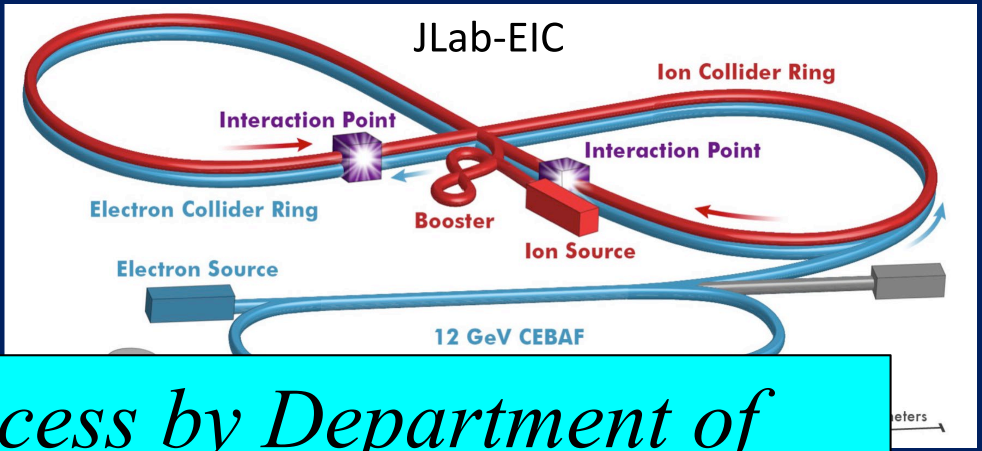
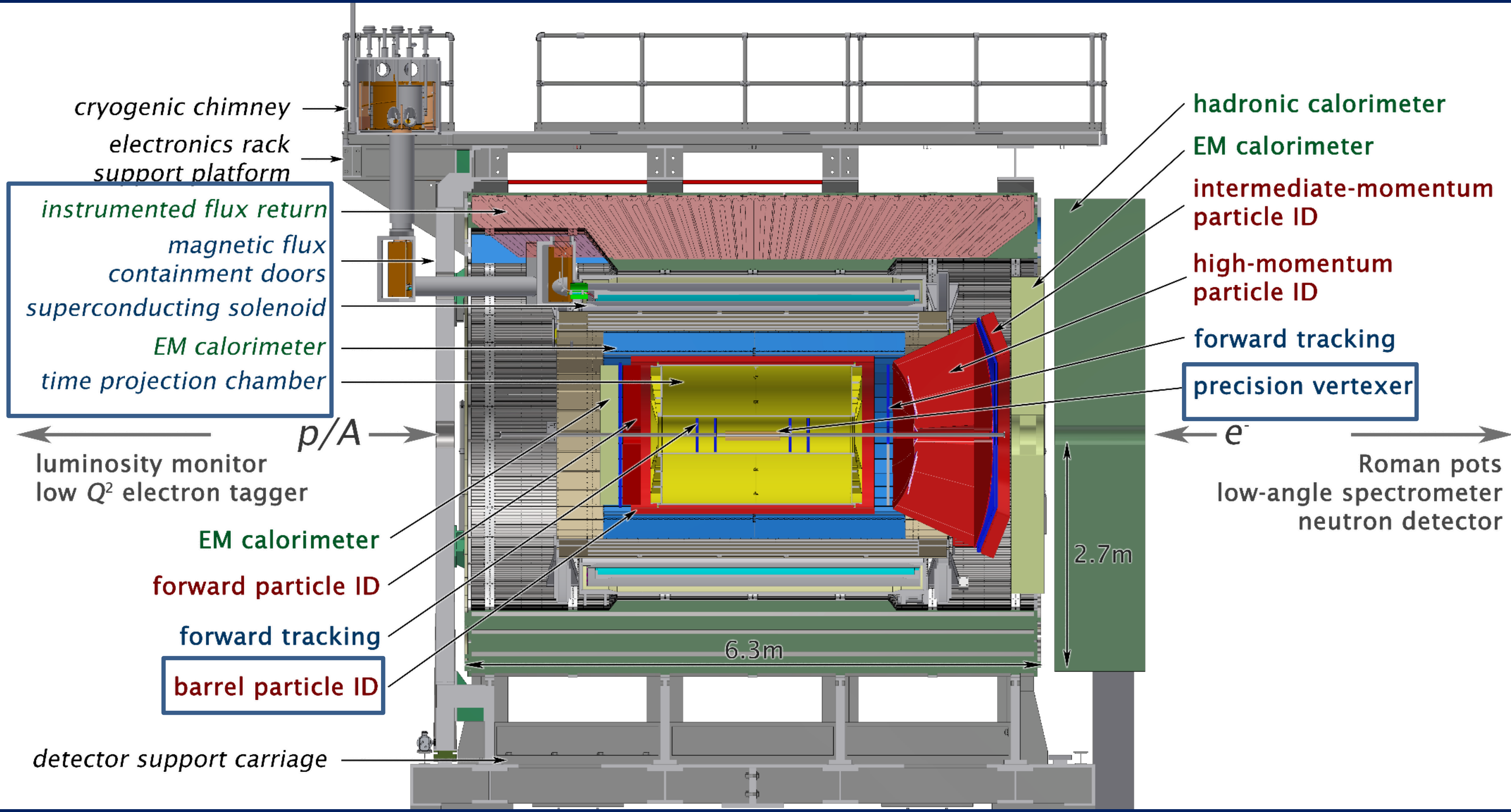




Site selection process by Department of Energy currently underway.
Community hoping for first data ~2030

An EIC detector concept



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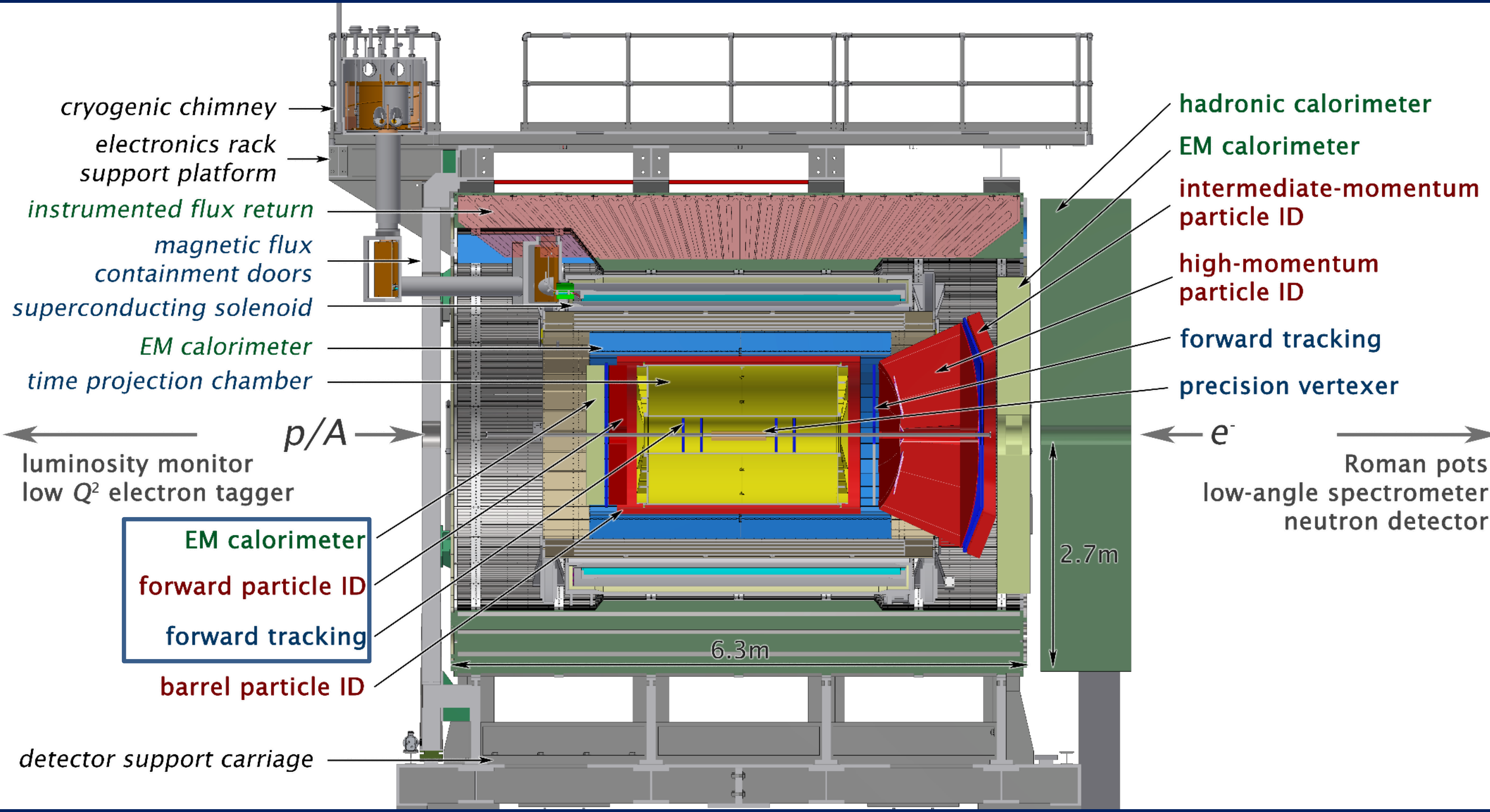

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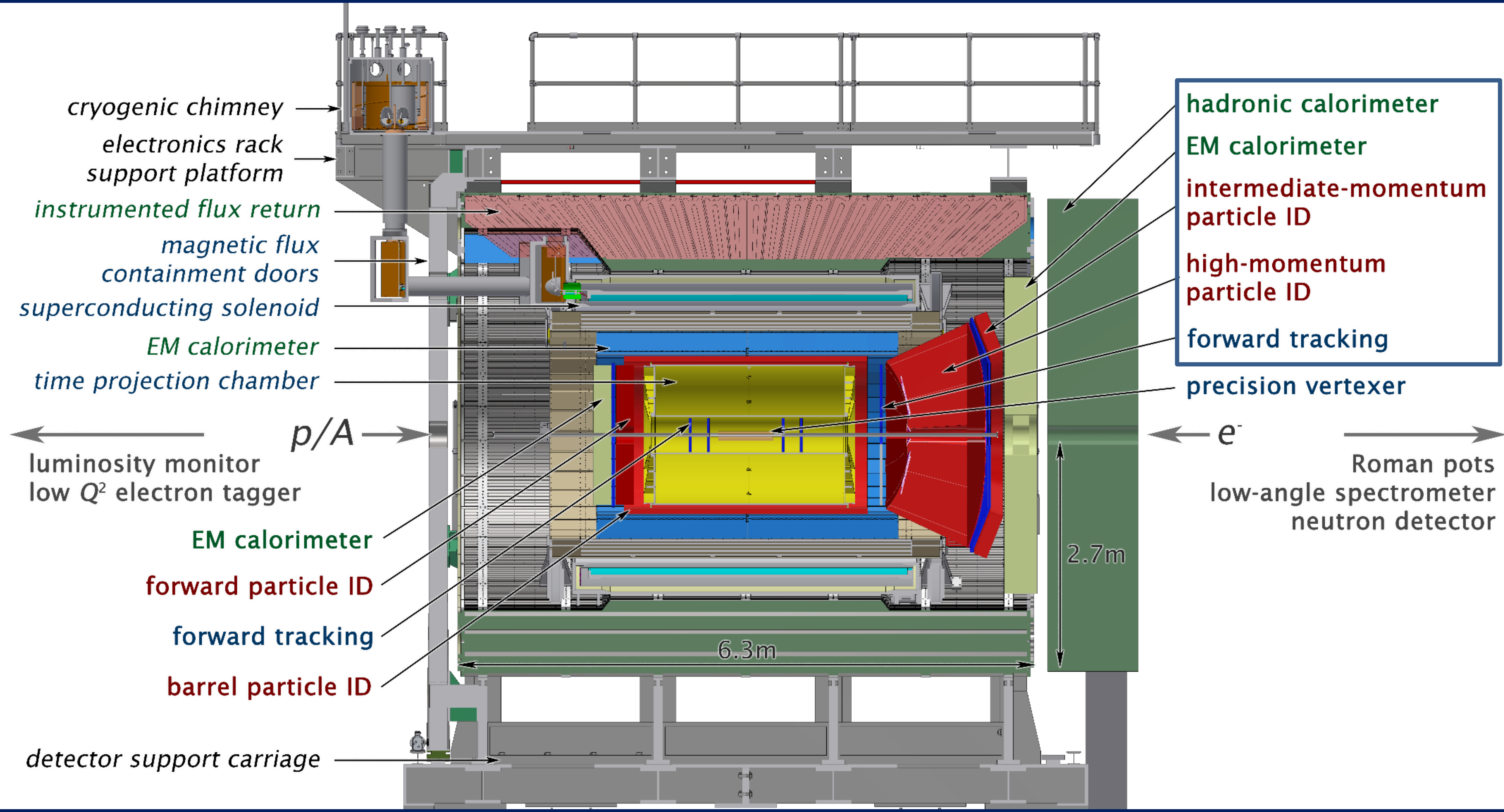

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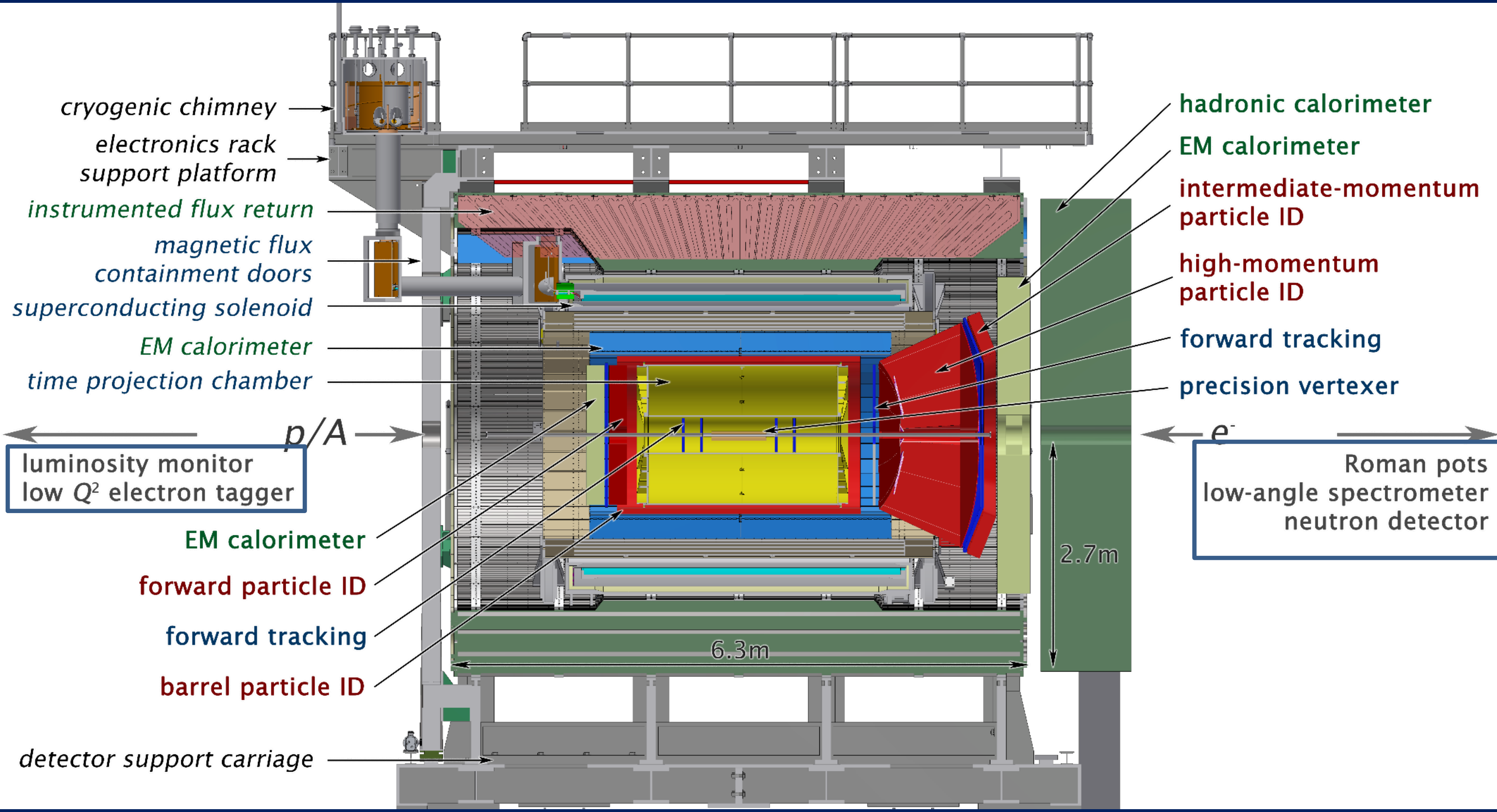

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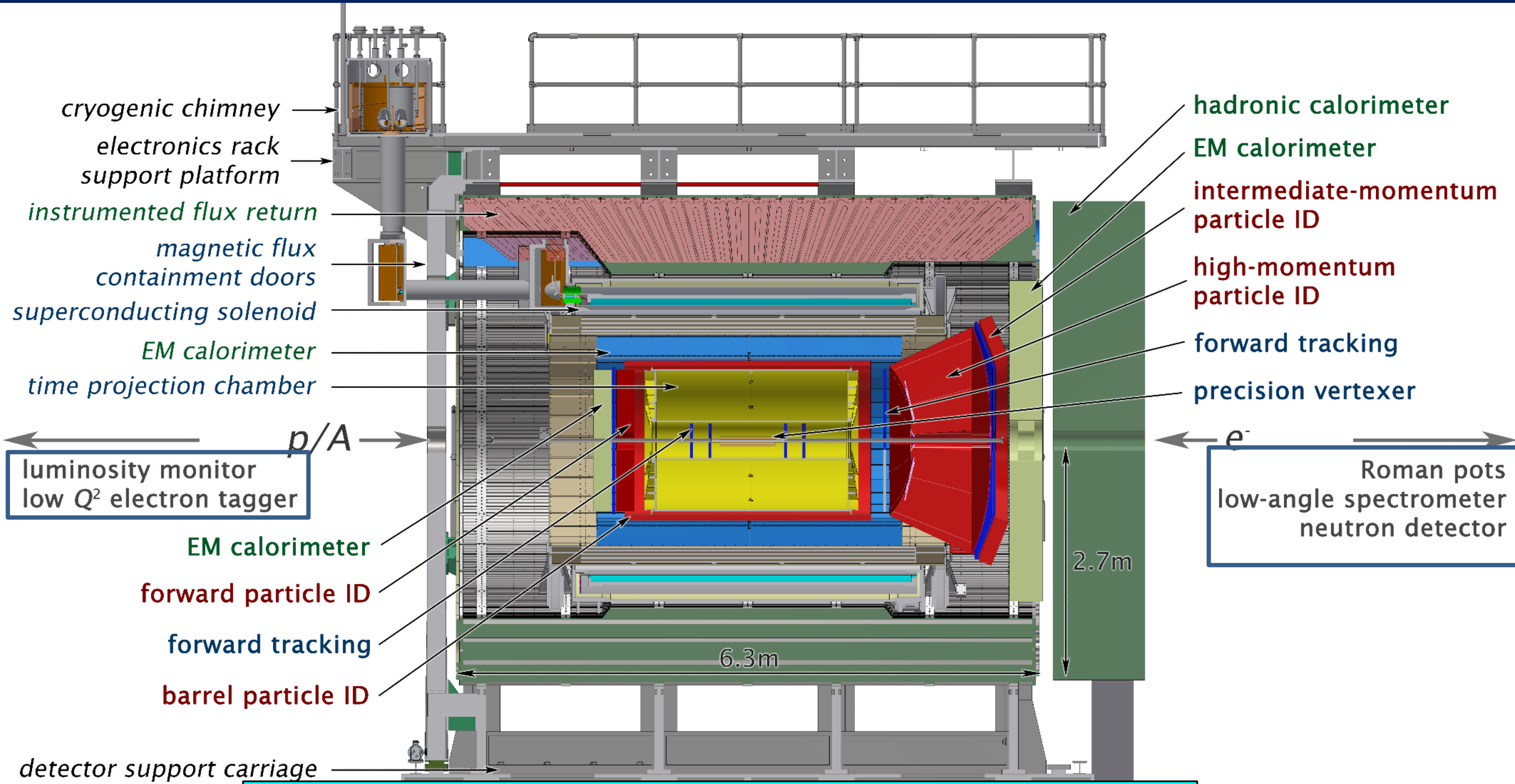
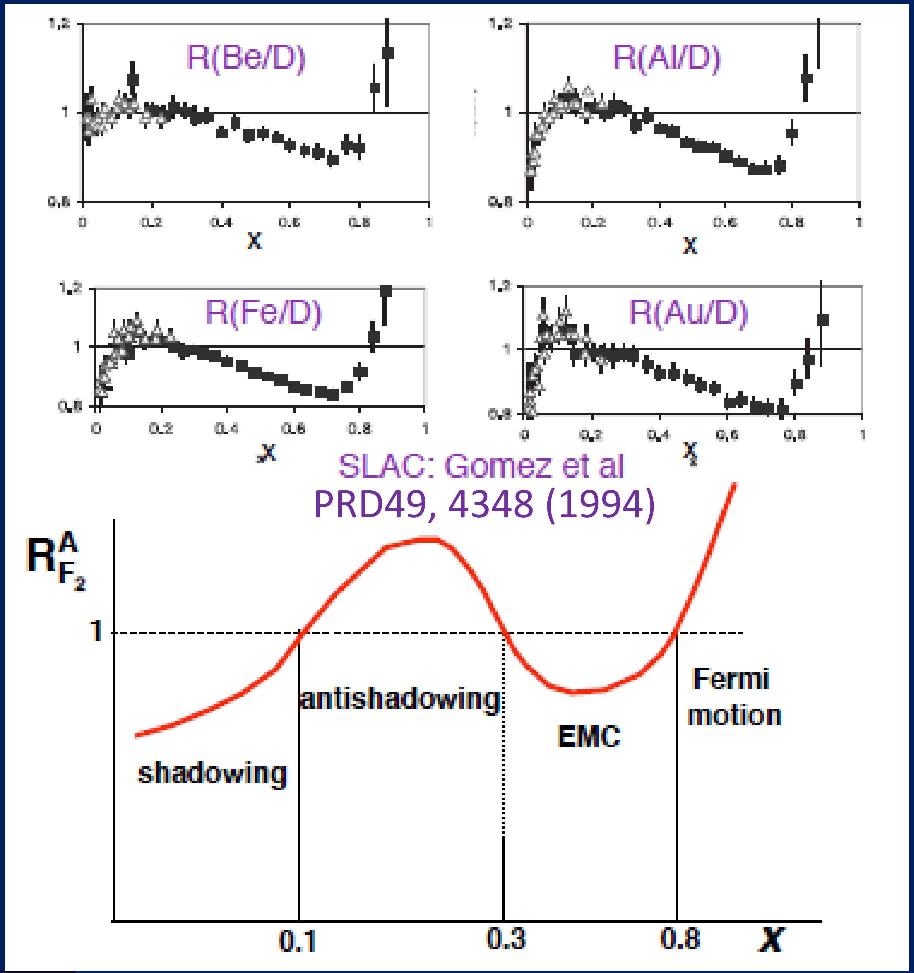


And now for just a bit of the physics . . .

Partonic momentum structure of nuclei: Not just superposed protons and neutrons

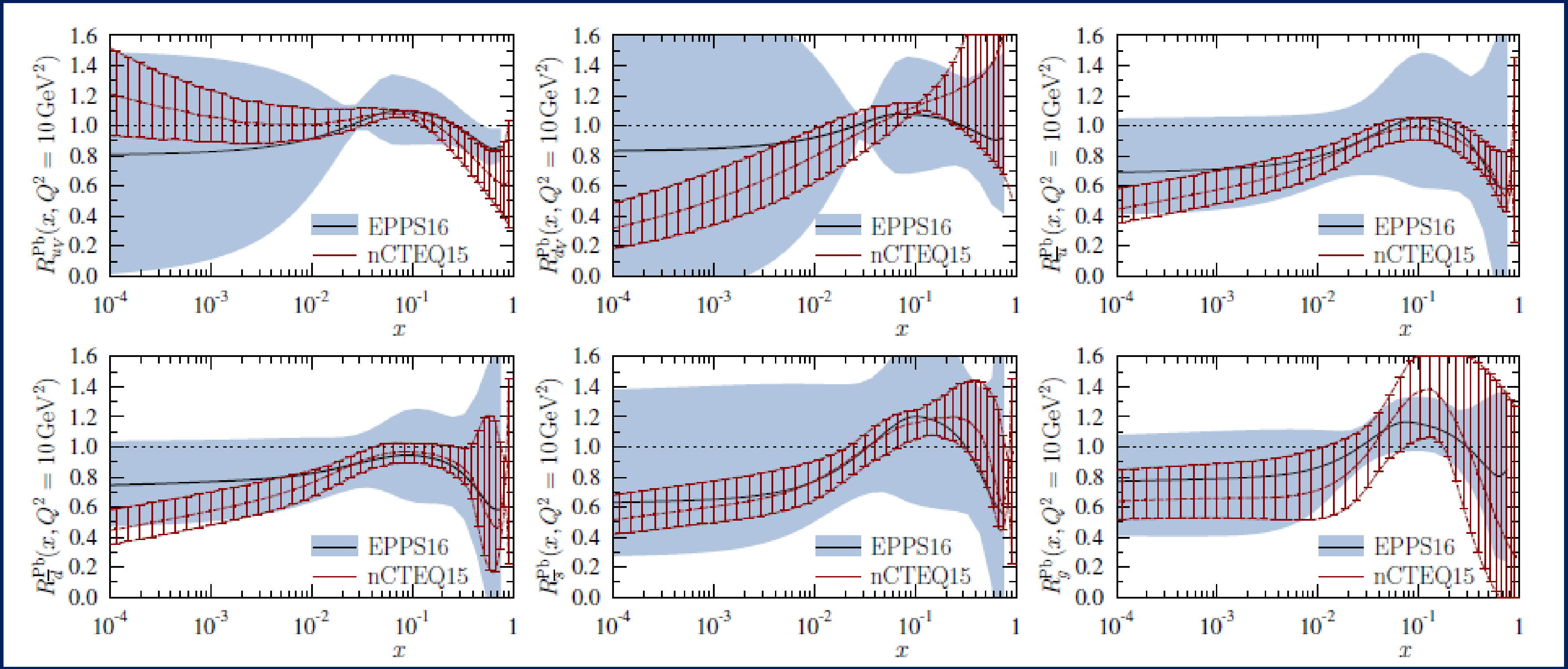


$$R_A \equiv \frac{1}{A}\frac{F_{2A}}{F_{2N}} \neq 1$$

- Ratio of cross section for e+A compared to scaled e+p collisions, shown vs. parton momentum fraction x
- Regions of both enhancement and depletion—only Fermi motion reasonably understood

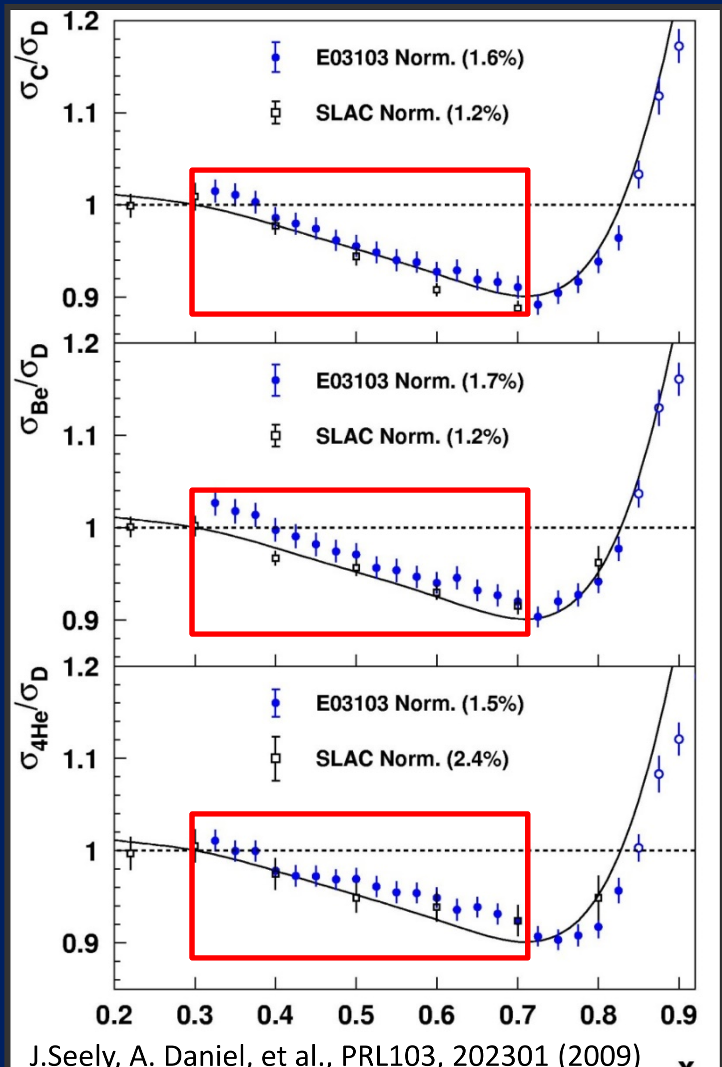
Partonic momentum structure of nuclei: Nuclear parton distribution functions

(Traditional collinear, unpolarized) Nuclear PDFs

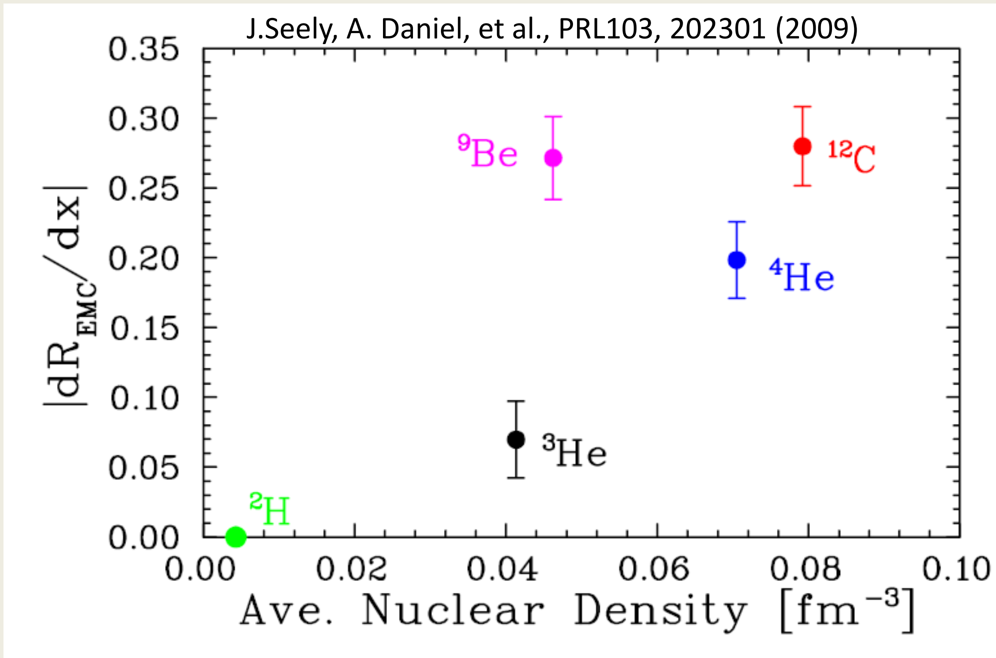


EPPS16 – EPJ C77, 163 (2017)

Partonic momentum structure of nuclei: EMC effect and local density



- Fit slope of ratios for 0.3<x<0.7; compare across nuclei
- EMC slope doesn't scale with A or with avg nuclear density…



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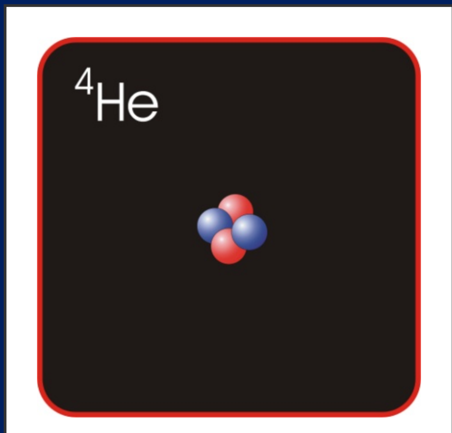
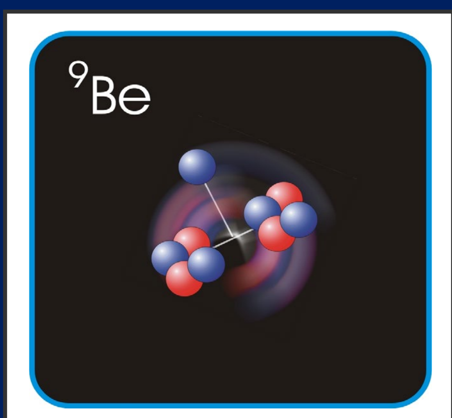
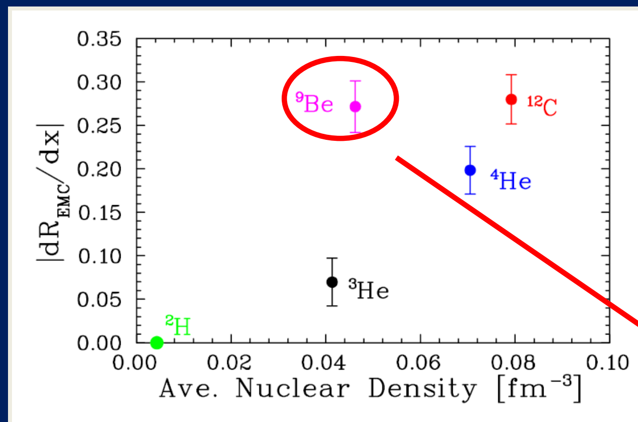
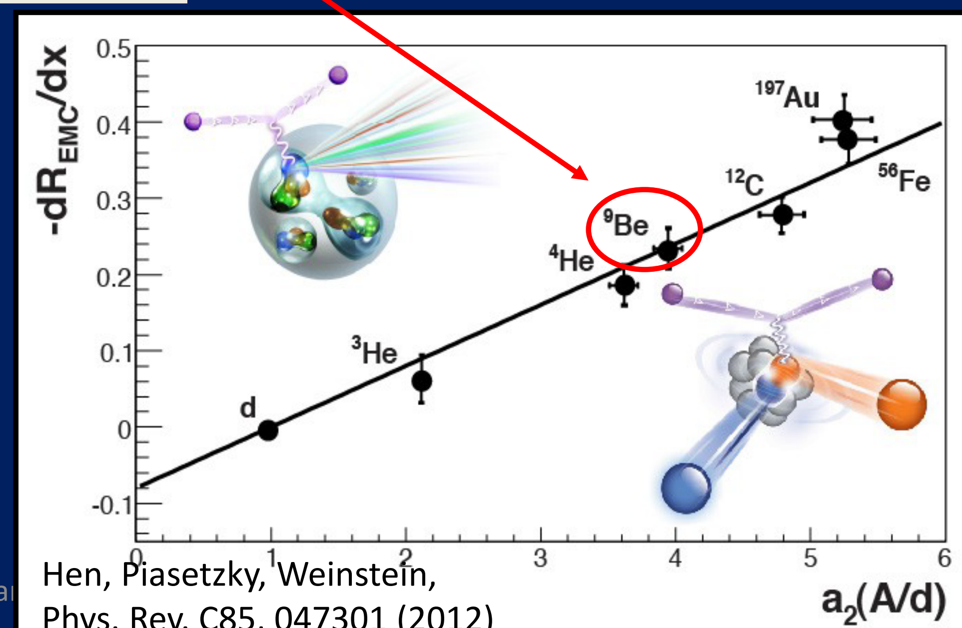






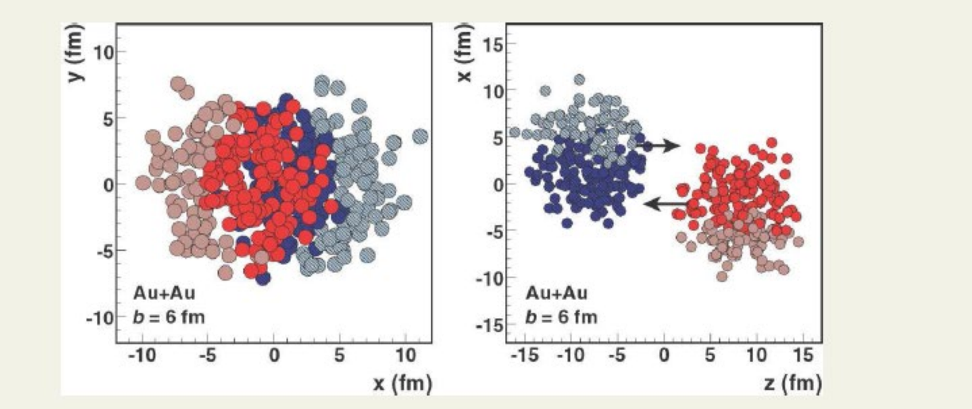
But appears to scale with local density!



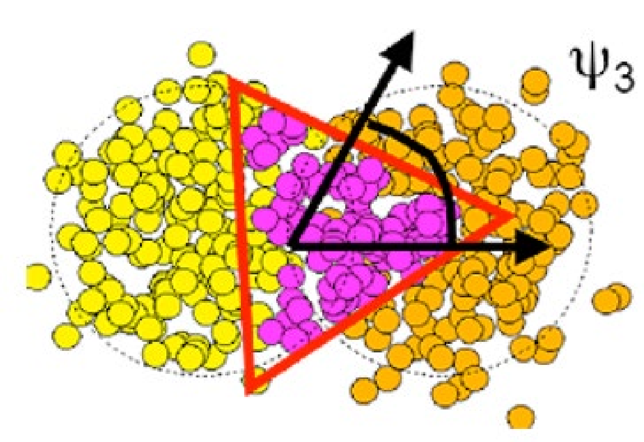
Hen, Piasetzky, Weinstein,
Phys. Rev. C85, 047301 (2012)

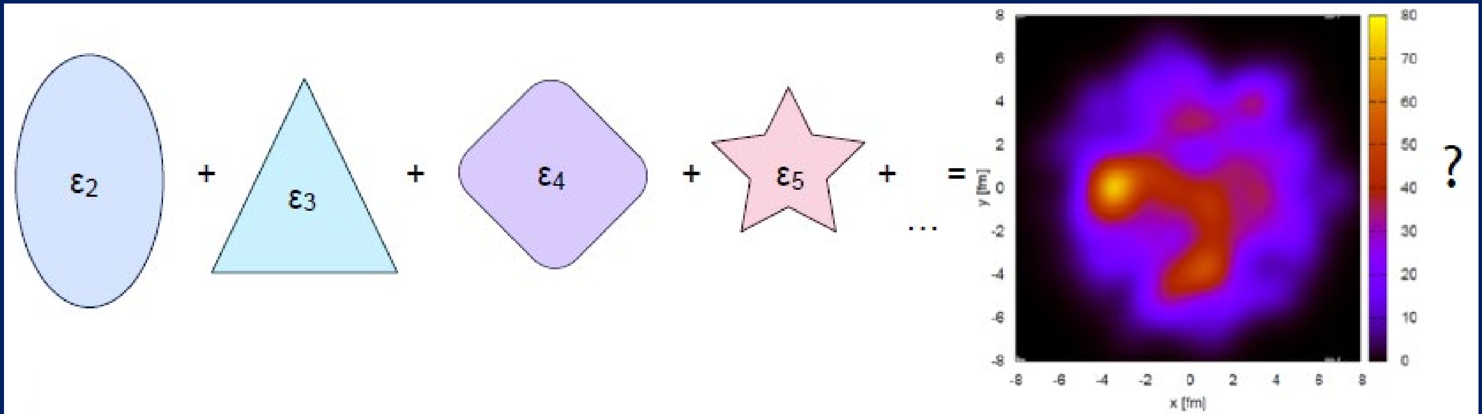
Density determined from *ab initio* few-body calculation
S.C. Pieper and R.B. Wiringa, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)

Local density in nuclei is important!



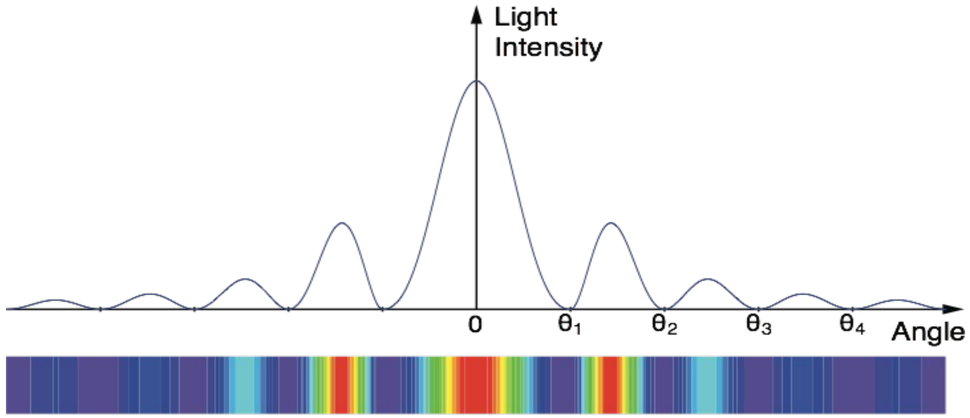
Miller *et al.*, Ann.Rev.Nucl.Part.Sci. 57, 205 (2007)





Partonic spatial structure of nuclei: Diffraction

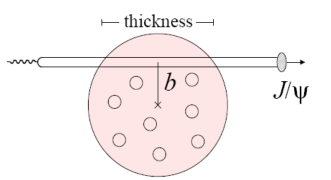
Diffraction pattern from monochromatic plane wave incident on a circular screen of fixed radius



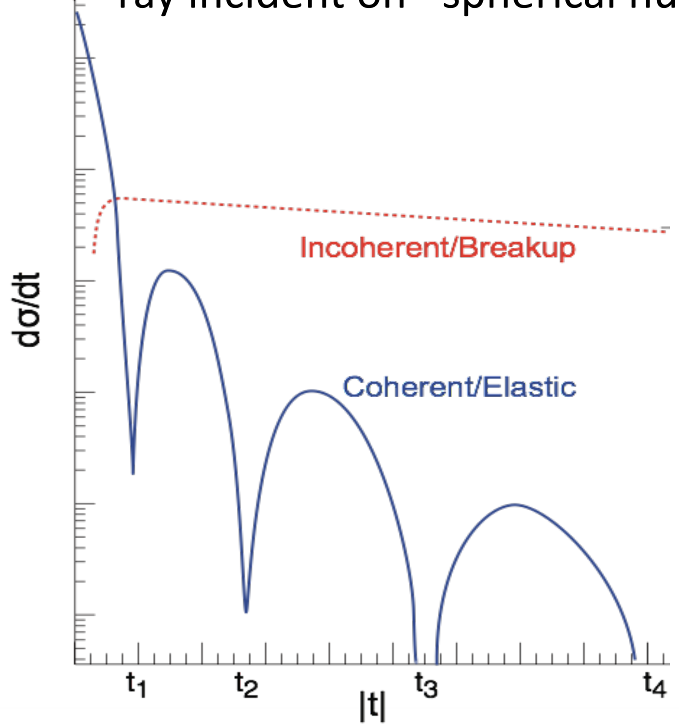
From E. Aschenauer

- X-ray diffraction used to probe spatial structure of atomic crystal lattices
  - Measure in momentum space, Fourier transform to position space
- Nuclear distance scales → Need gamma ray diffraction!
  - Again measure diffractive cross section in momentum space (Mandelstam t), Fourier transform to position space

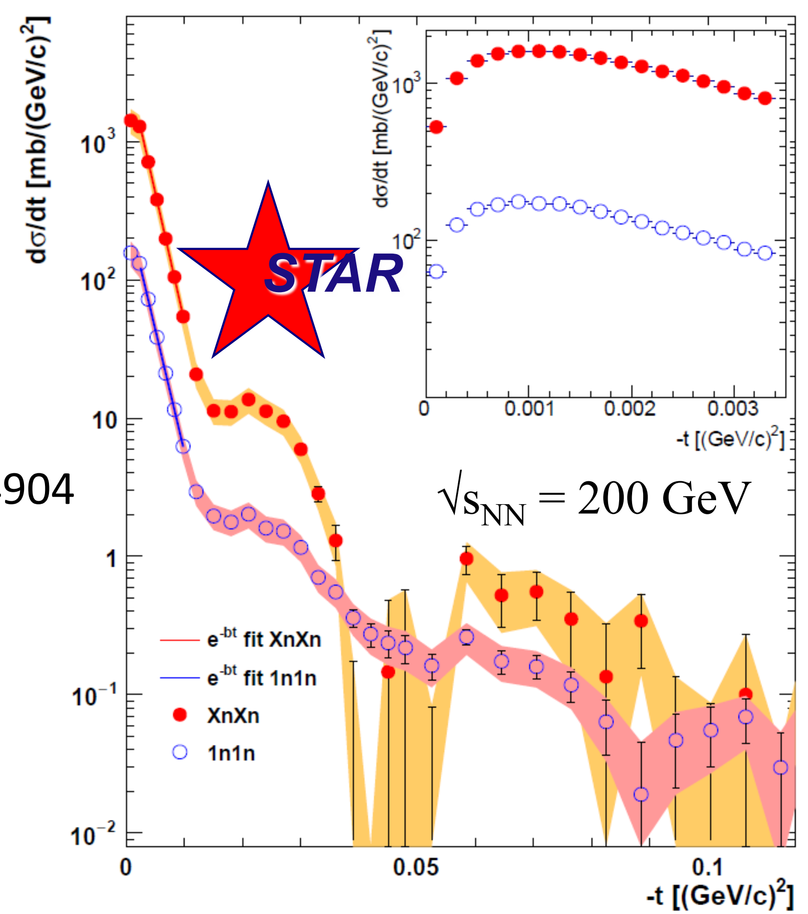
Partonic spatial structure of nuclei: Diffraction



Expected diffraction pattern from gamma ray incident on ~spherical nucleus



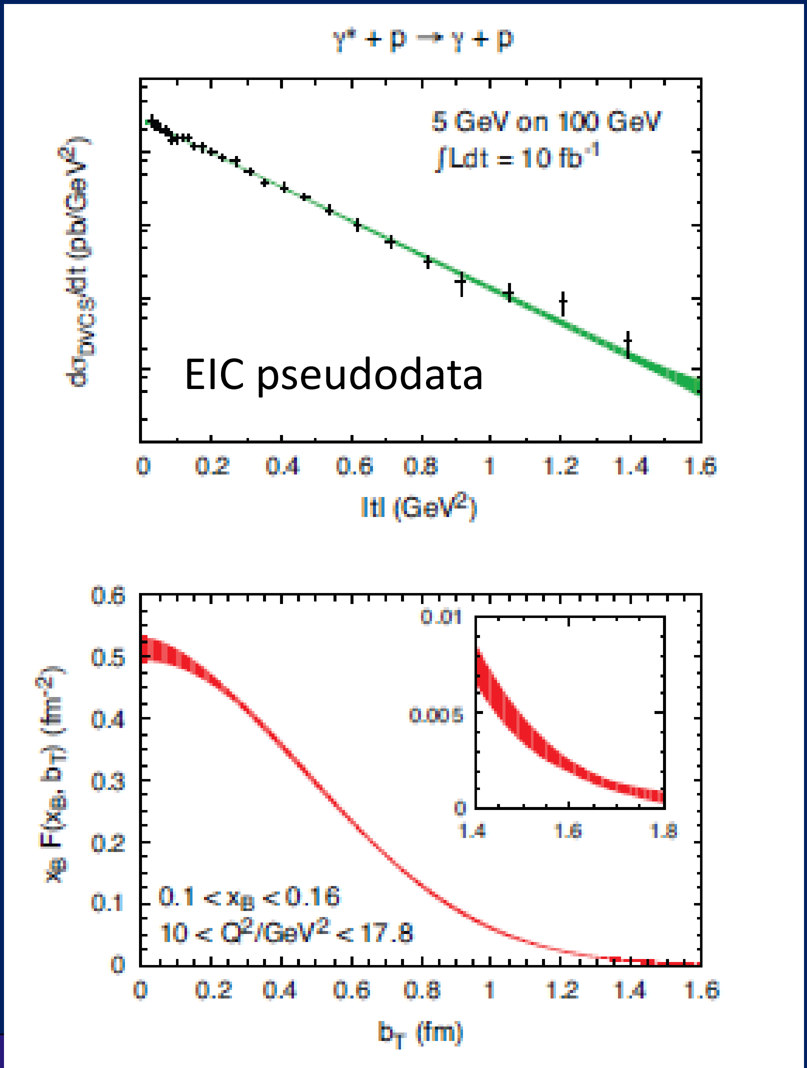
PRC96, 54904 (2017)

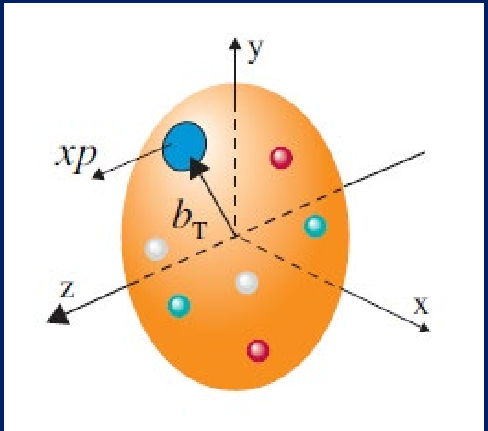


e+A, p+A, or A+A. Probed nucleus in one beam. Gamma emitted by electron or Coulomb-excited proton/nucleus passing nearby in second beam.

Diffractive ρ production in Au+Au ultraperipheral collisions

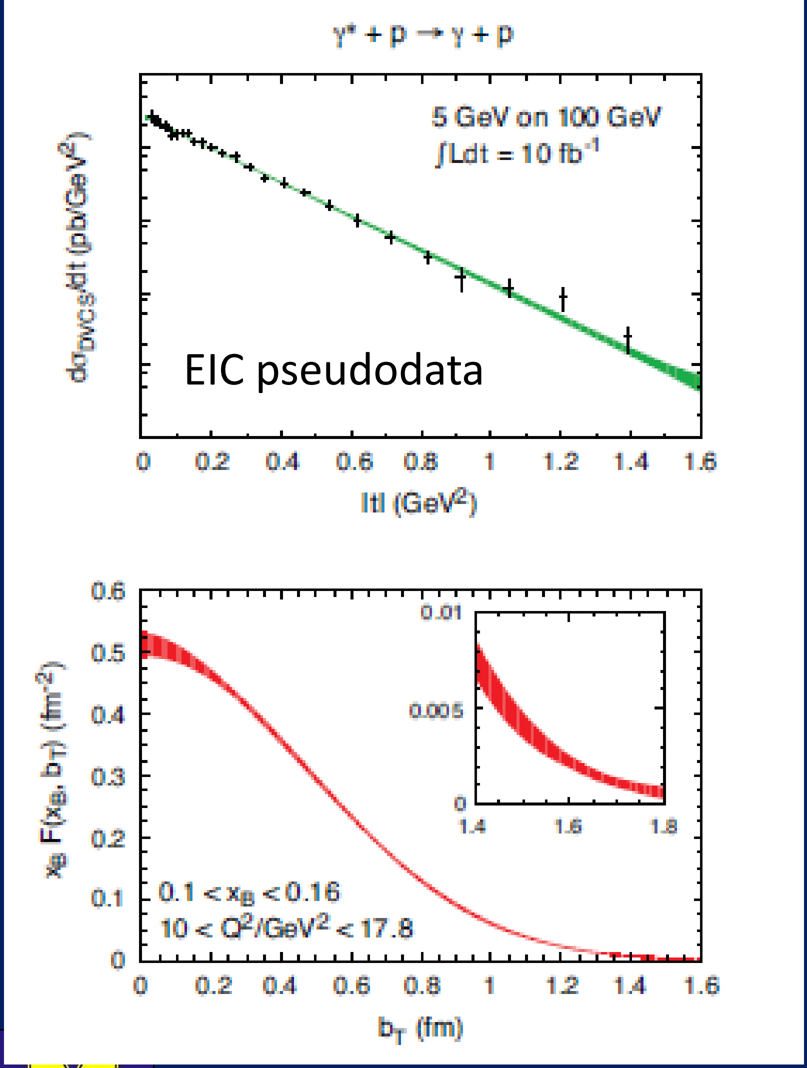
Partonic spatial structure of nuclei: Diffraction

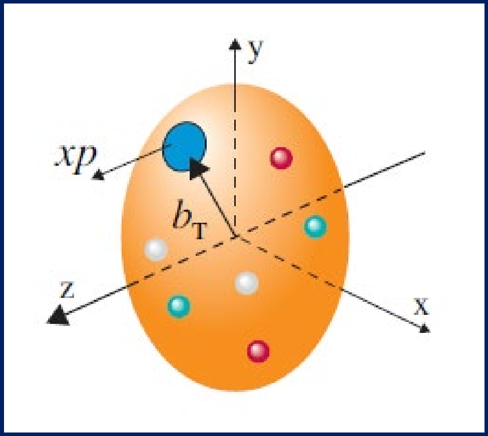




Goal: Cover wide range in *t*.
Fourier transform → impact-parameter-space profiles.
Obtain *b* profile from slope vs. *t*.

Partonic spatial structure of nuclei: Diffraction





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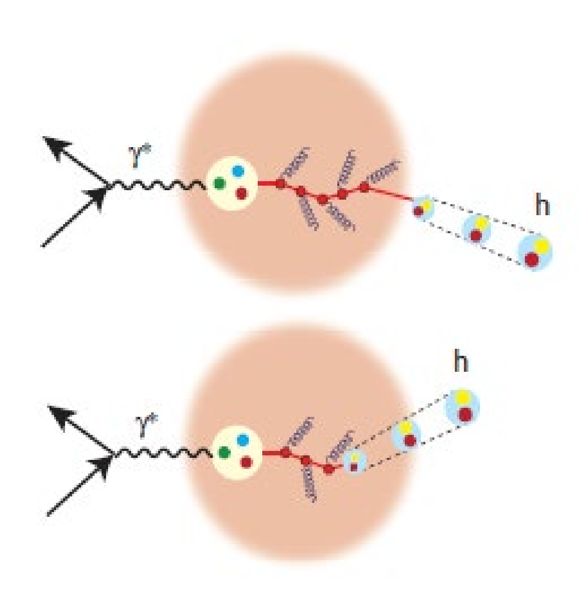
Obtain *b* profile from slope vs. *t*.

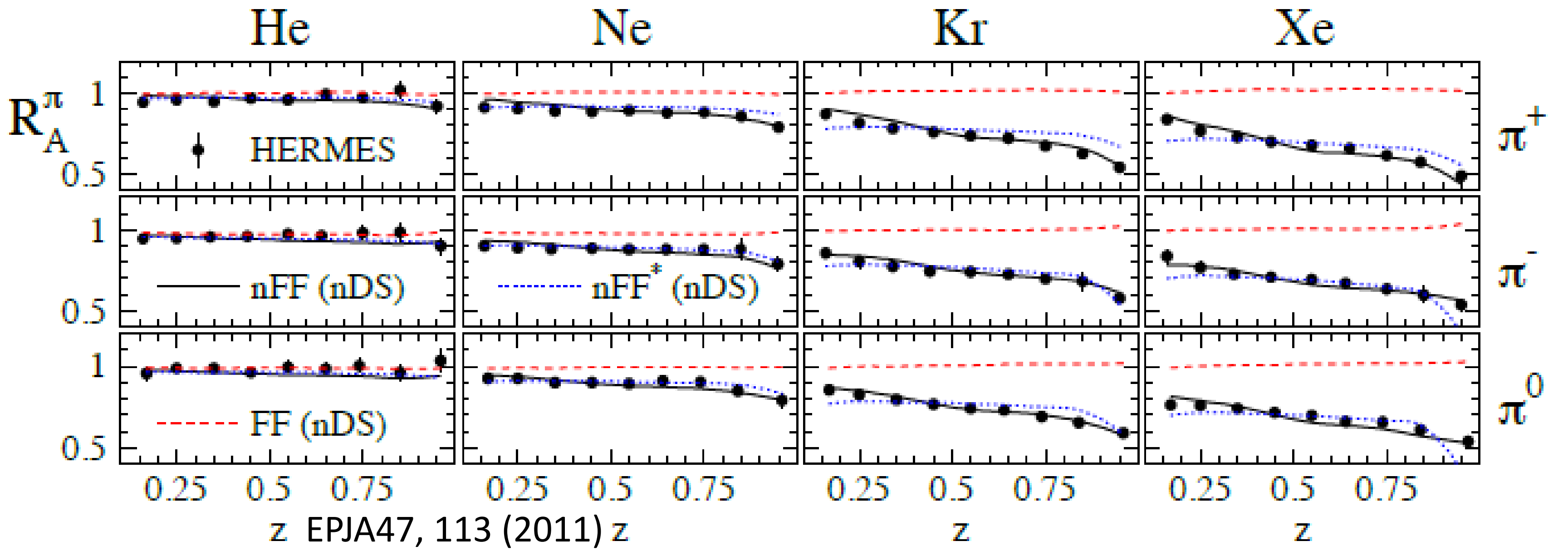
Note: To probe spatial distributions, can also use Bose-Einstein correlations (HBT) in e+A to probe spatial extent of particle production region, as in hadron-hadron collisions

Formation of QCD bound states: Hadronization at EIC

- Use nuclei as femtometer-scale detectors of the hadronization process!
- Wide range of scattered parton energy; small to large nuclei
  - Move hadronization inside/outside nucleus
  - Distinguish energy loss and attenuation



Formation of QCD bound states: Nuclear modification of fragmentation functions

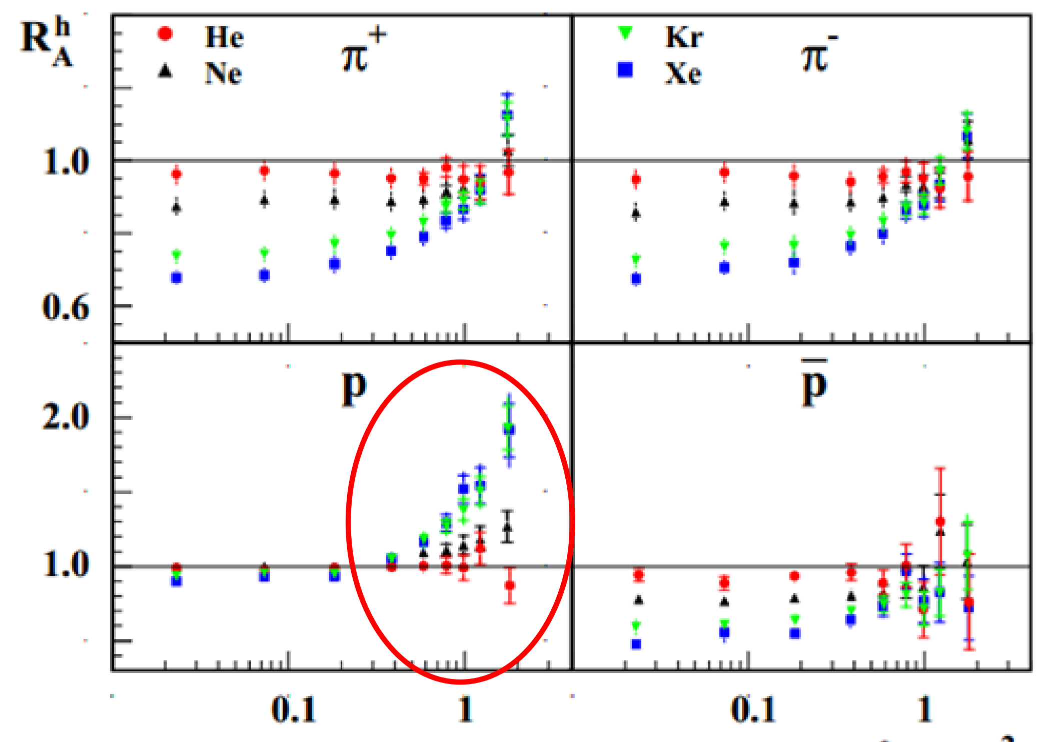


EPJA47, 113 (2011)

As in A+A and p+A, fragmentation functions are modified in e+A with respect to e+p, e.g. suppression of pion production

Formation of QCD bound states: Hadronization in higher-density partonic environments

- Evidence for baryon enhancement also in e+A!
- Baryon enhancement in A+A, p+A, e+A suggests mechanism(s) other than "vacuum fragmentation"
- Binding of nearby partons in phase space?



HERMES, NPB780, 1 (2007)

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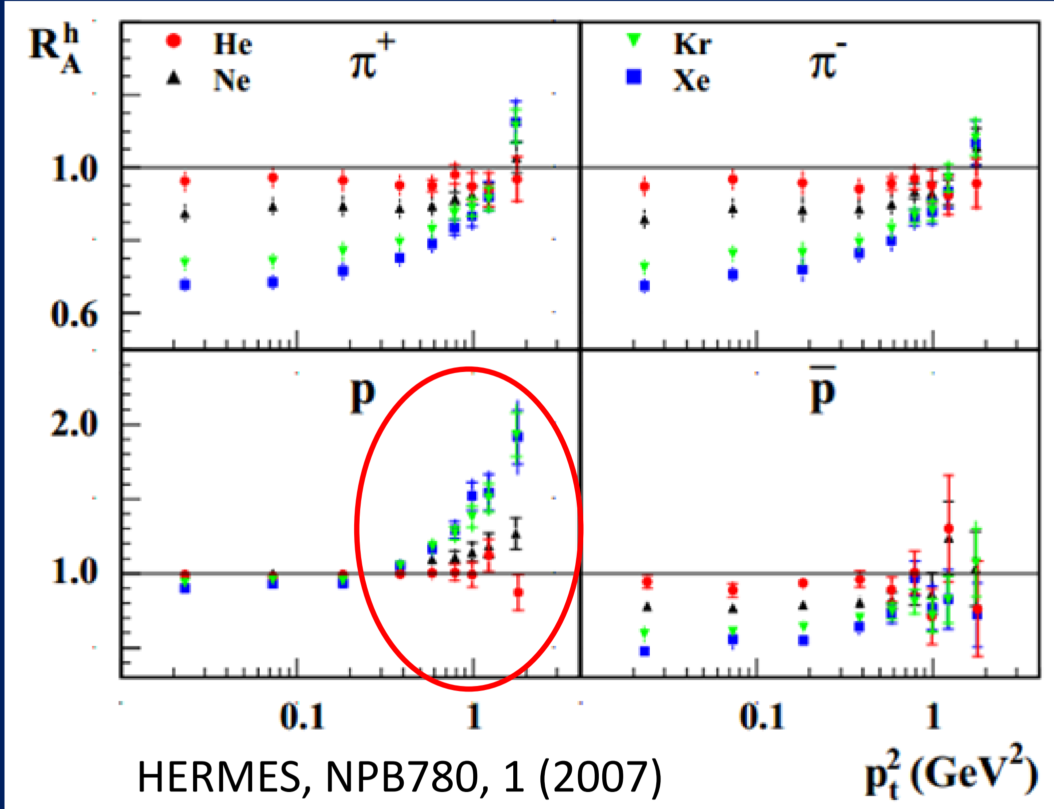

HERMES, NPB780, 1 (2007)

Comprehensive studies of hadronization as well as of propagation of color charges through nuclei possible at EIC

Summary

www.eicug.org

- Complementary facilities, as well as theoretical advances, are allowing us to probe QCD's rich complexities in ever-greater detail, with ever-increasing sophistication
  - Part of new era of QCD as a more mature field

Summary

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- Complementary facilities, as well as theoretical advances, are allowing us to probe QCD's rich complexities in ever-greater detail, with ever-increasing sophistication
  - Part of new era of QCD as a more mature field
- Electron-Ion Collider → next major facility in the ongoing quest to address the fundamental questions of QCD
  - How do we describe different QCD systems in terms of their quark and gluon degrees of freedom?
  - In what ways can colored quarks and gluons form colorless QCD bound states?
  - What are unique properties of QCD interactions?
- *See following talk by Yoshitaka Hatta for more on the physics…*

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Summary

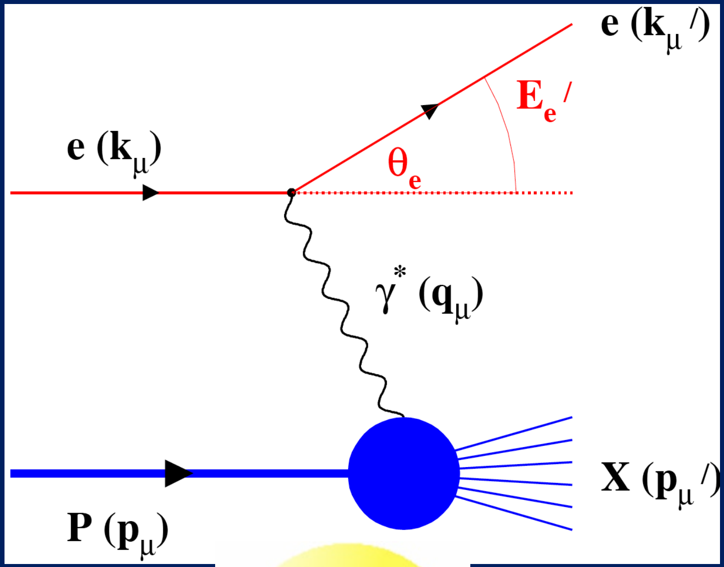
- Complementary facilities, as well as theoretical advances, are allowing us to probe QCD's rich complexities in ever-greater detail, with ever-increasing sophistication
  – Part of new era of QCD as a more mature field
- Electron-Ion Collider → next major facility in the ongoing quest to address the fundamental questions of QCD
  - How do we describe different QCD systems in terms of their quark and gluon degrees of freedom?
  - In what ways can colored quarks and gluons form colorless QCD bound states?
  - What are unique properties of QCD interactions?
- *See following talk by Yoshitaka Hatta for more on the physics…*

Activities toward the realization of the EIC are gaining momentum. Next few years will be critical as experimental collaborations form and detector proposals are developed. New institutions and collaborators always welcome!

Extra

Accessing quarks and gluons through DIS

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 2E_e E'_e (1 - \cos\Theta_{e'})$$

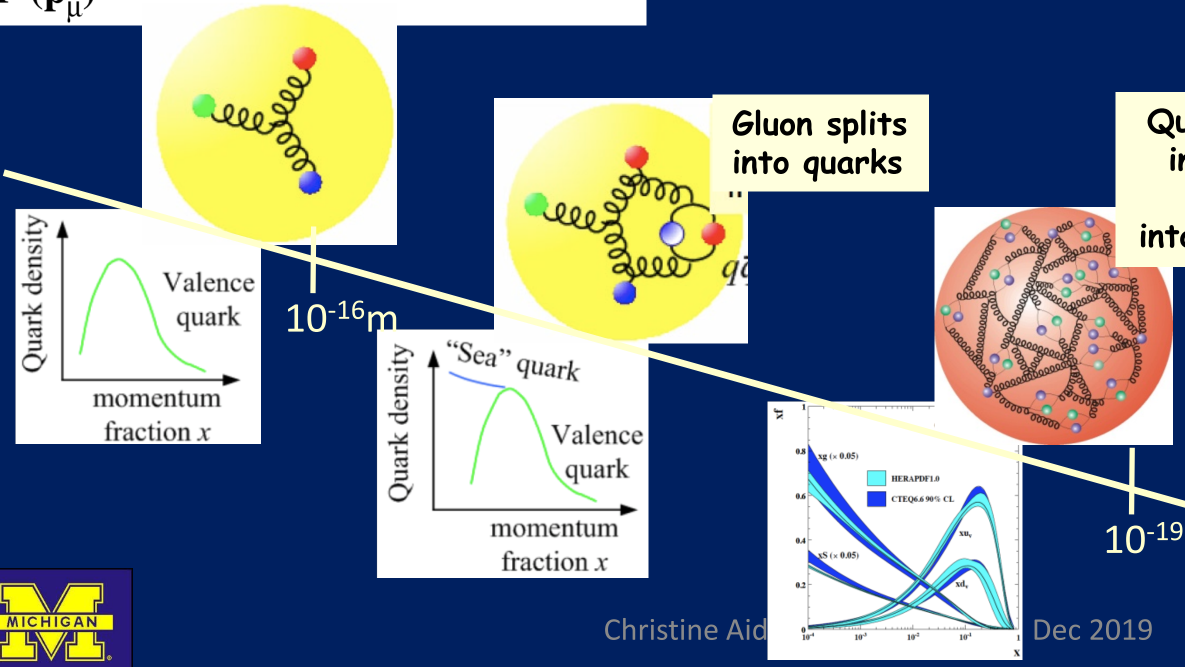
Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

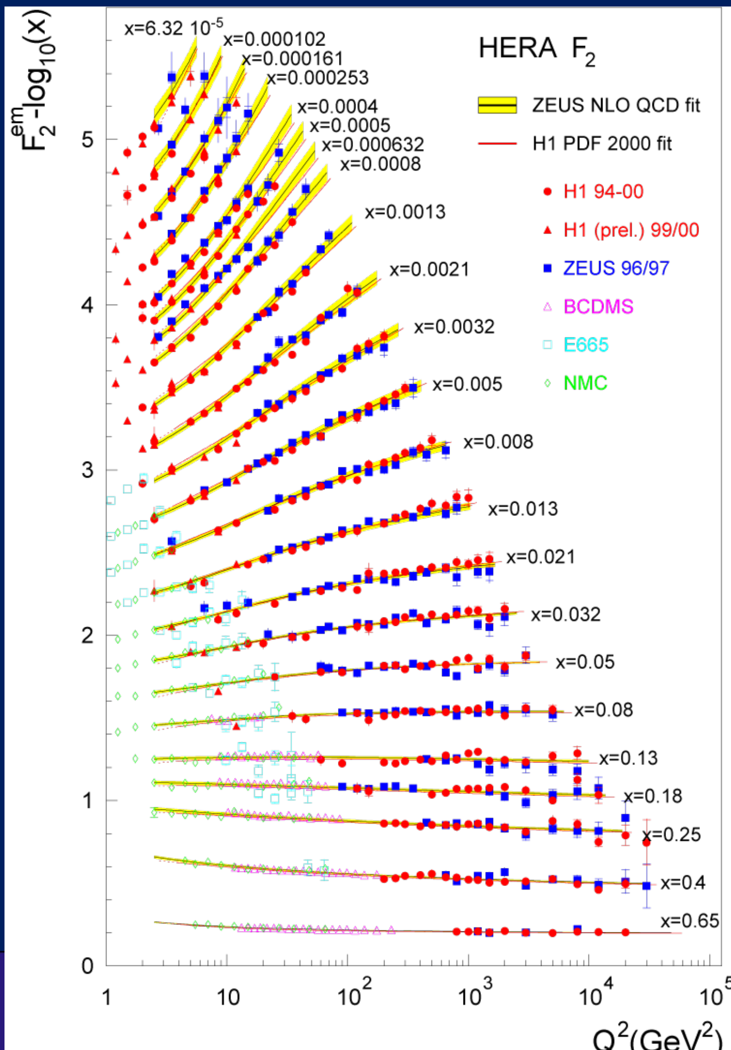
Measure of momentum fraction of struck quark



higher √s increases resolution

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 $Q^2 \rightarrow G(x,Q^2)$

OR

Via F_L structure function

OR

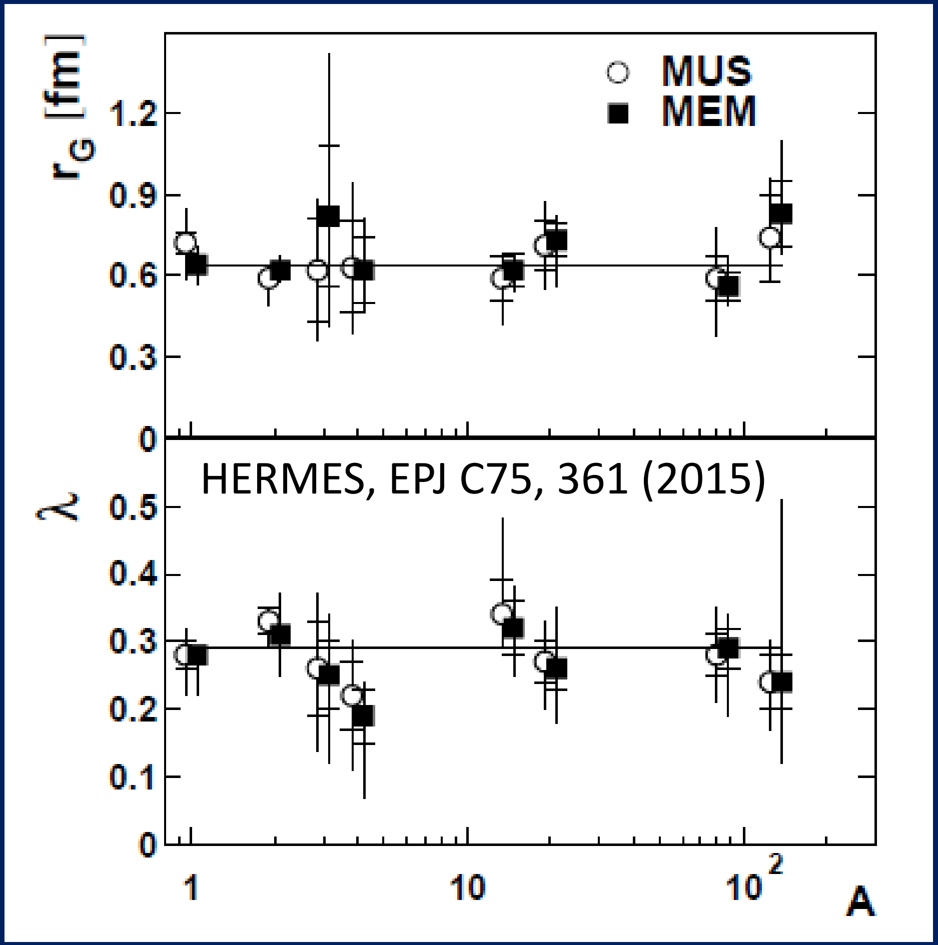
Via dihadron production

OR

Via diffractive scattering

Bose-Einstein correlations for nuclear semi-inclusive DIS

- Sensitive to spatial separation of production of the two particles
- No nuclear dependence found within uncertainties



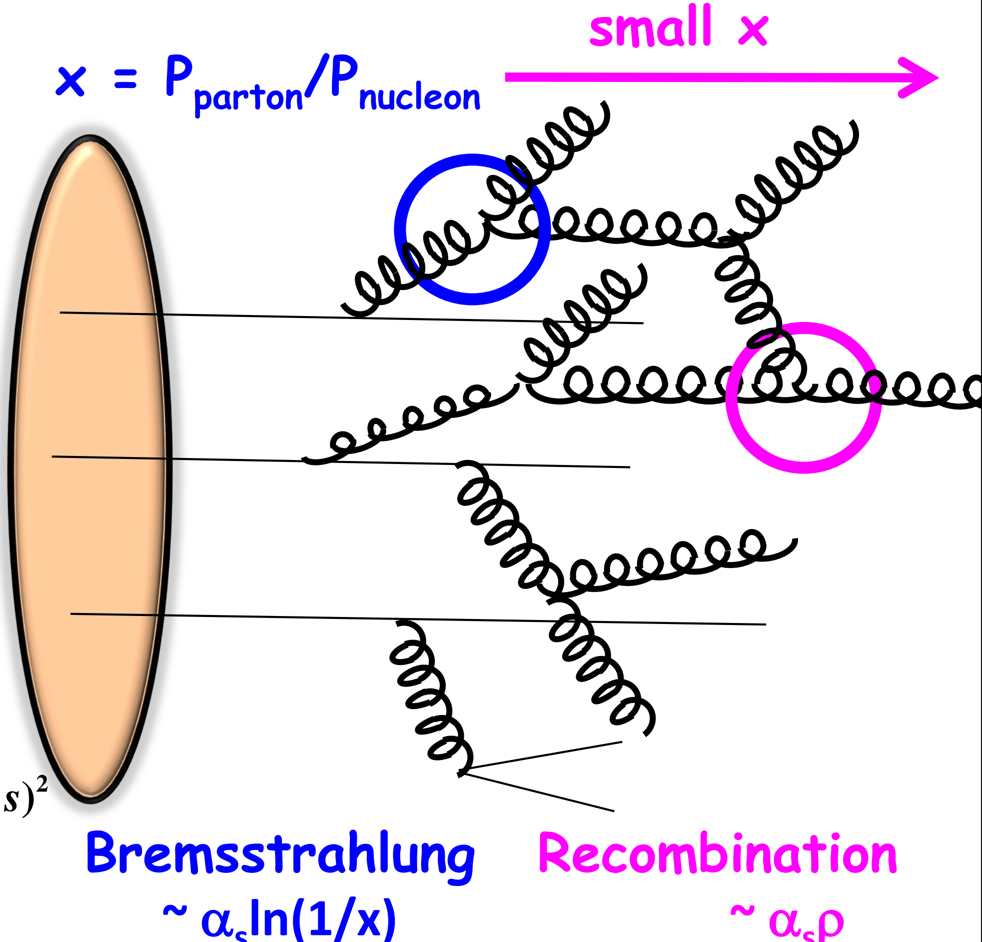
Gluon saturation

At small x linear evolution gives strongly rising g(x) – but must be bounded!

BK/JIMWLK non-linear evolution includes recombination effects → saturation

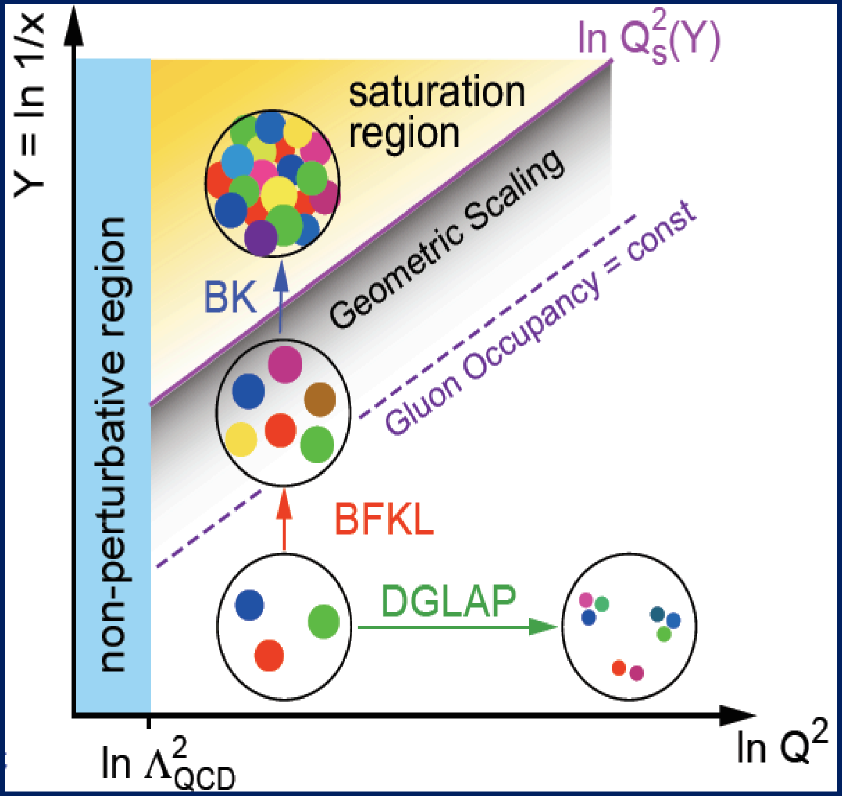
- Dynamically generated scale
  Saturation Scale: $Q^2_s(x)$
  - Increases with energy or decreasing x
- Scale with $Q^2/Q^2_s(x)$ instead of x and Q^2 separately

$$\sigma_{tot} = \frac{\pi}{m_\pi^2}(\ln s)^2$$



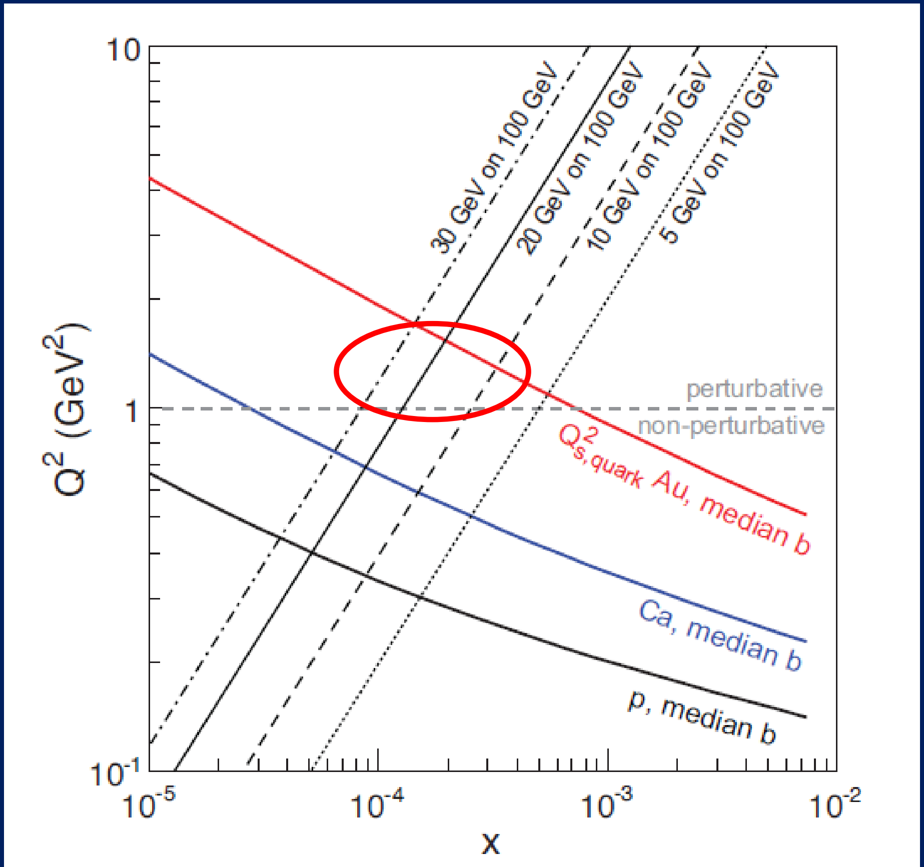
Diffraction to study universal state of gluonic matter: Gluon saturation

- In addition to probing spatial structure, diffraction is one way to probe gluon saturation within nuclei



Diffraction in e+A as a probe of gluon saturation

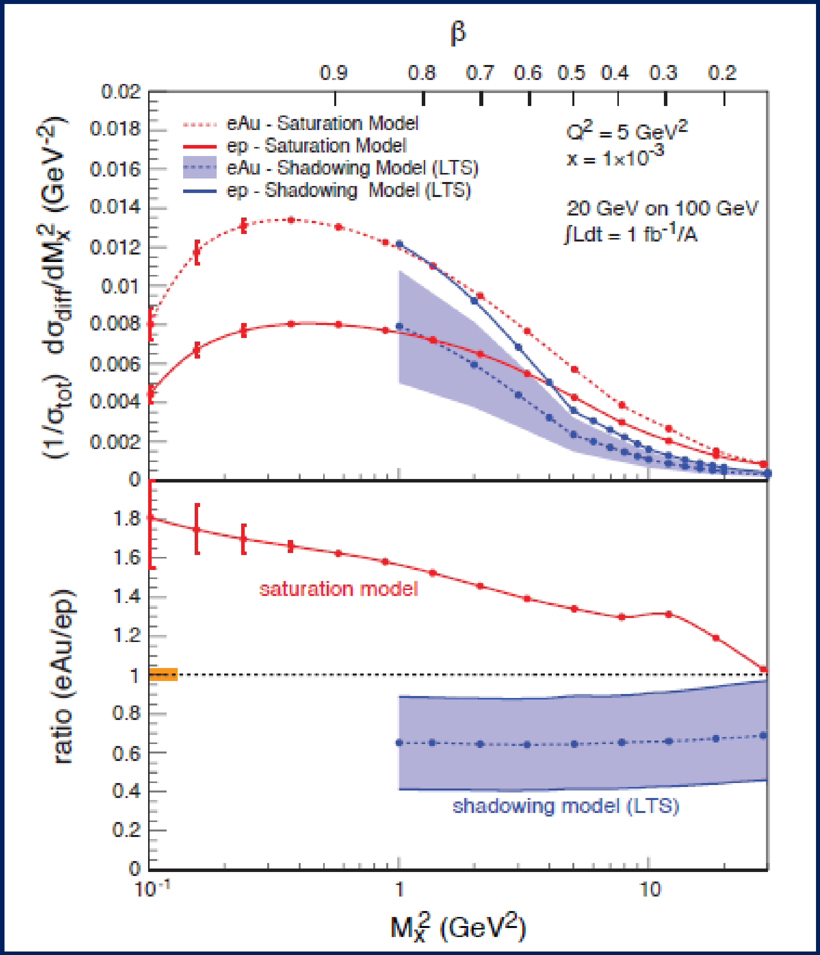
- Fewer potential competing effects in e+p/A than hadron-hadron collisions
- Easier to reach predicted saturation regime with e+A than e+p
- e+Au at higher c.m. energies for EIC will provide window of overlap where both Color-Glass Condensate effective field theory calculations and perturbative QCD calculations can be done and compared



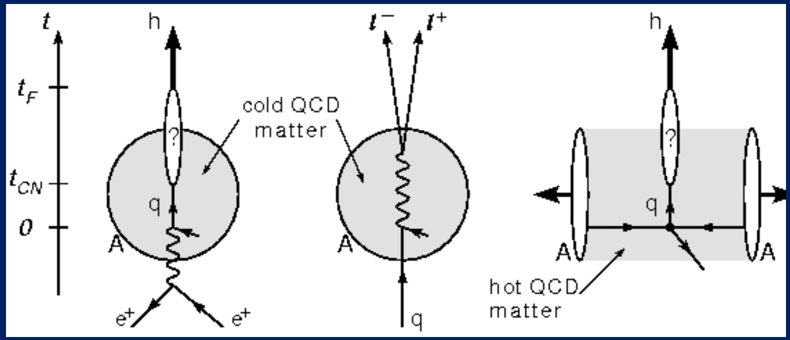
Diffraction in e+A as a probe of gluon saturation

- Top panel: EIC projections for ratio of diffraction cross section to total, along with predictions based on saturation and shadowing models
- Bottom panel: Projections and predictions for *double* ratio: $(\text{diffractive/total})_{e+A}/(\text{diffractive/total})_{e+p}$
  - Very strong handle to distinguish saturation from shadowing!

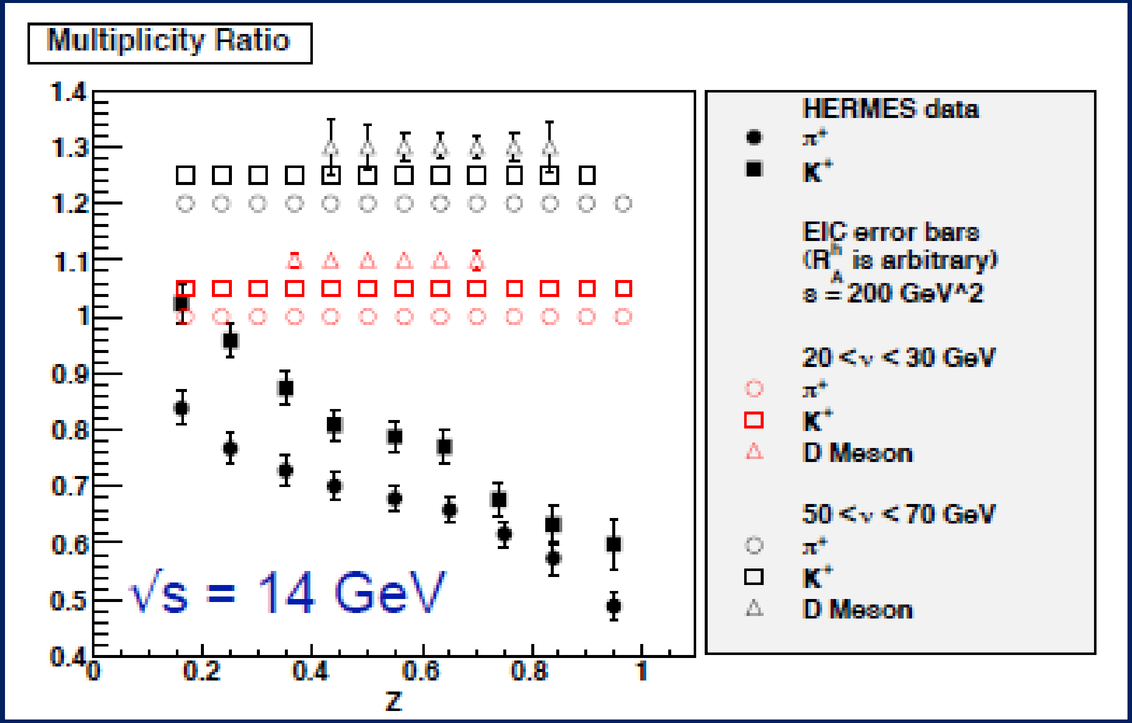
- Note: Saturation can also be probed via 2-particle correlations in e+A, as in p/d+A



Hadronization: Parton propagation in matter



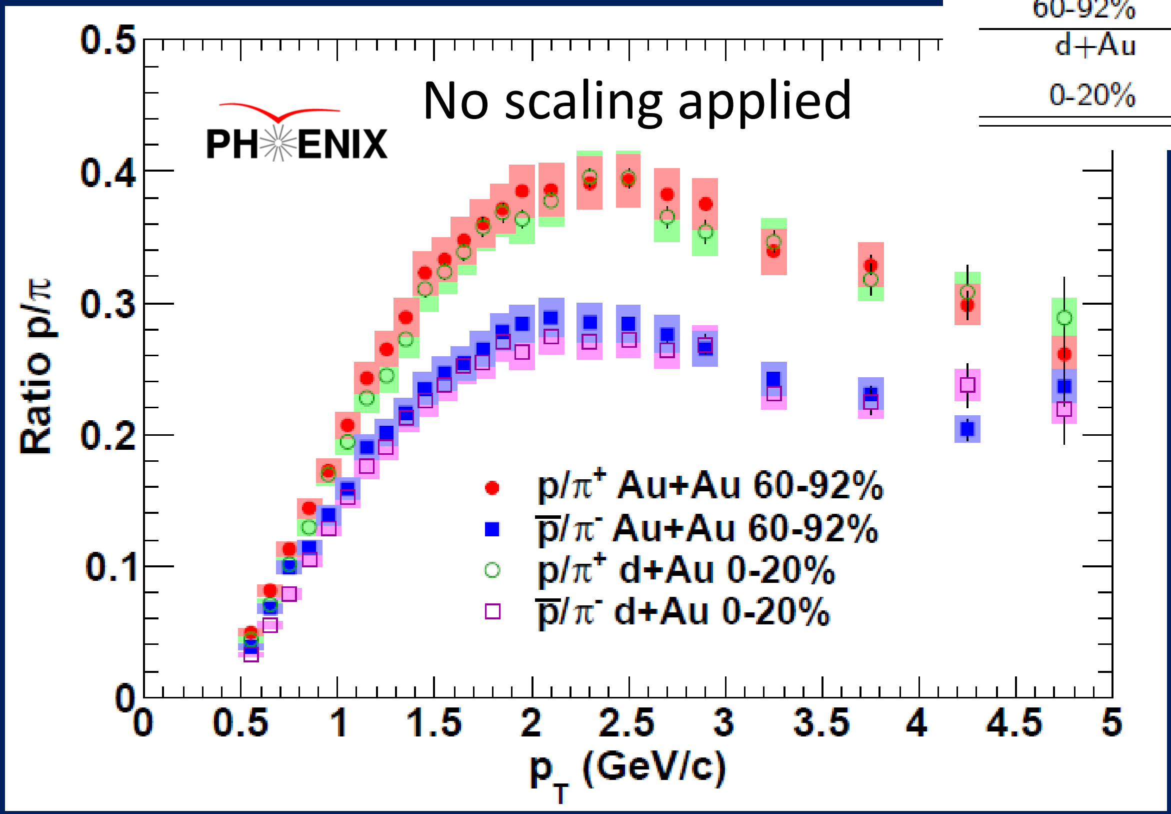
- Interaction of fast color charges with matter?
- Conversion of color charge to hadrons through fragmentation and breakup?



Existing data → hadron production modified on nuclei compared to the nucleon!
EIC will provide ample statistics and much greater kinematic coverage!
-Study time scales for color neutralization and hadron formation
- e+A complementary to jets in A+A: cold vs. hot matter

Formation of QCD bound states: Hadronization in higher-density partonic environments

Centrality	⟨N_{coll}⟩	⟨N_{part}⟩
Au+Au 60-92%	14.8 ± 3.0	14.7 ± 2.9
d+Au 0-20%	15.1 ± 1.0	15.3 ± 0.8



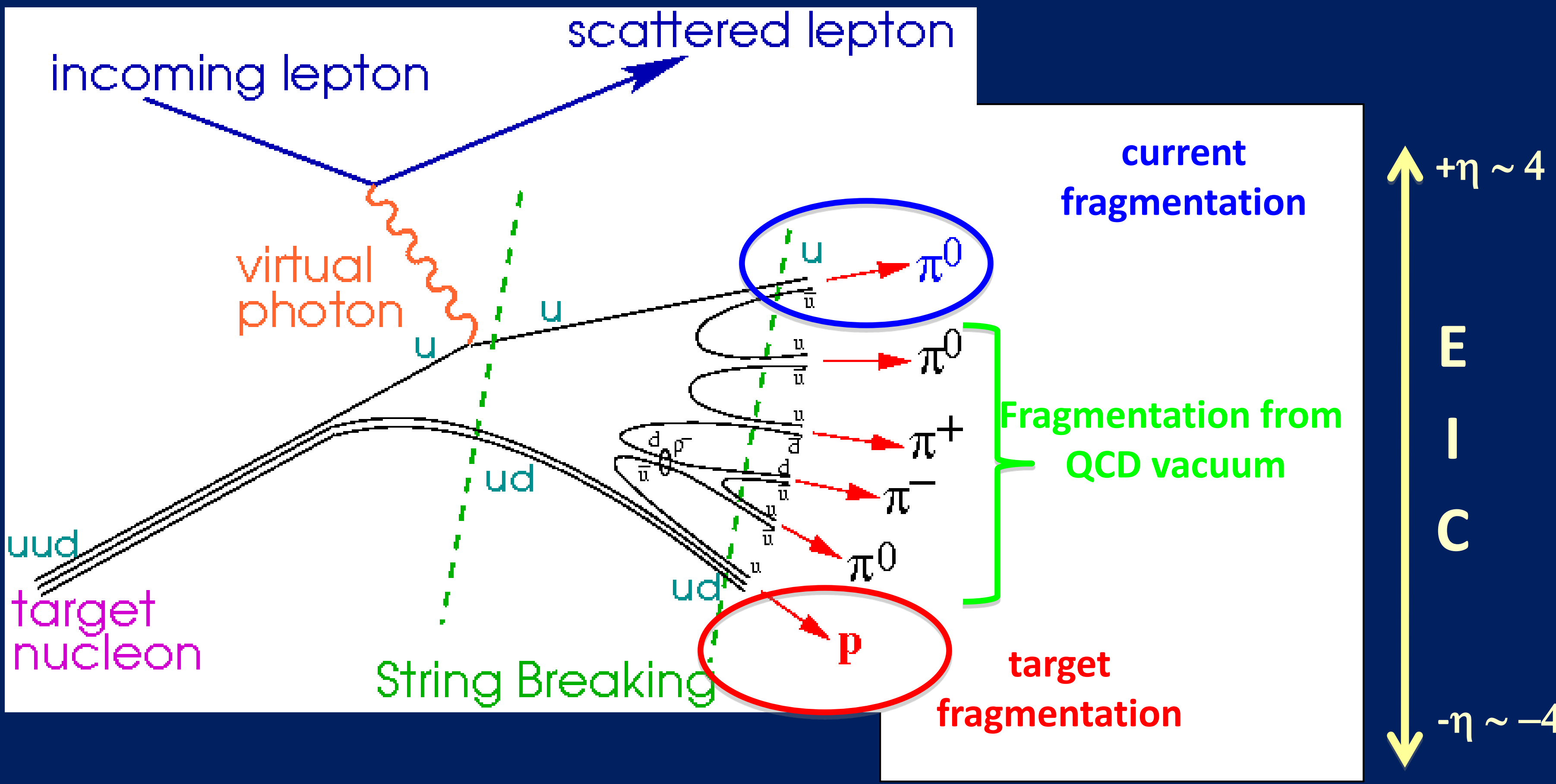
PRC88, 024906 (2013)

Baryon enhancement observed in central A+A but also peripheral A+A and in p/d+A.

p/π ratio for central d+Au and peripheral Au+Au—shape *and* magnitude identical!

Suggests common mechanism(s) for baryon production in the two systems

Formation of QCD bound states: Hadronization at EIC



Formation of QCD bound states: "Target fragmentation" region

- Related to color neutralization of remnant—soft particle production

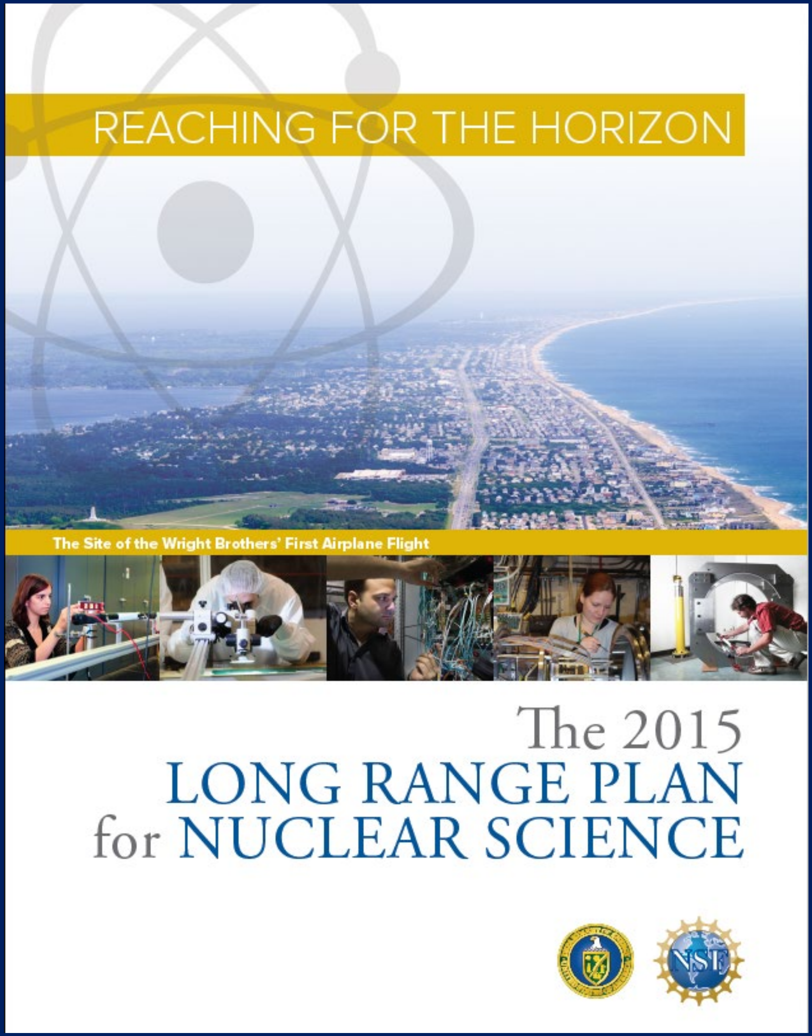
- Electron-Ion Collider will map out target fragmentation region well
  - Collider geometry – easier than in fixed-target to separate "current" from "target" fragmentation

- Connections to
  - "Underlying event" in hadron-hadron collisions
  - Forward hadron production in hadron-hadron collisions
  - Cosmic ray physics

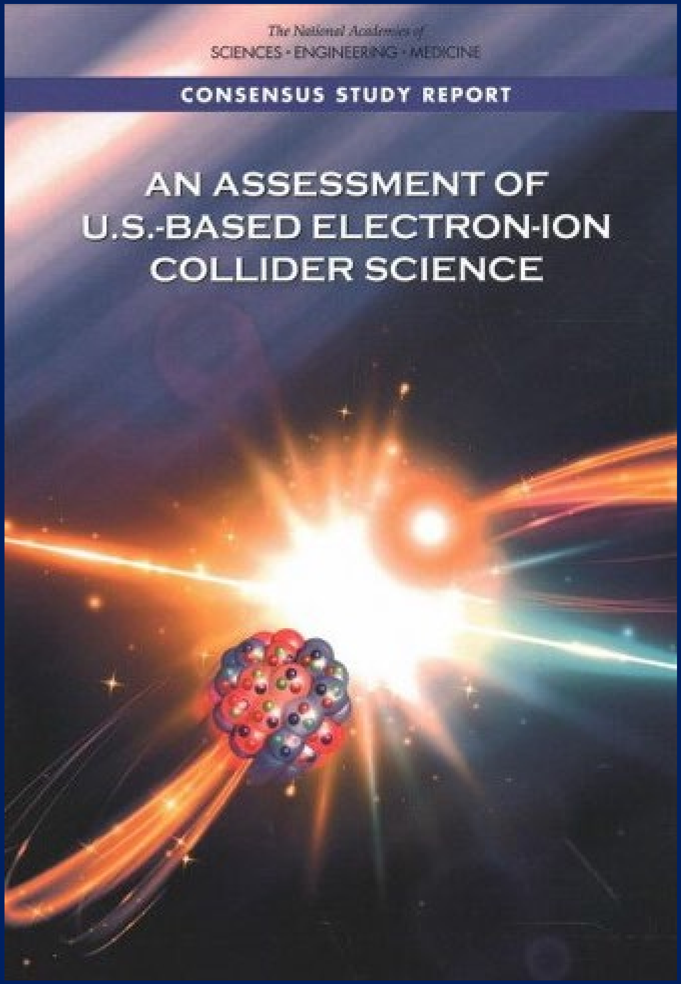
- "Fracture functions" – theoretical tools to describe target fragmentation

2015 U.S. Nuclear Physics Long-Range Plan

- EIC endorsed by U.S. nuclear community as highest priority facility for new construction after completion of Facility for Rare Isotope Beams (FRIB)



2018 U.S. National Academy of Sciences report



2016 – U.S. Dept. of Energy charged National Academy of Sciences with assessing the science case of a U.S.-based Electron-Ion Collider

July 2018 National Academy Consensus Report found that the science that can be addressed by an EIC is “compelling, fundamental, and timely”

EIC: Status and recent developments

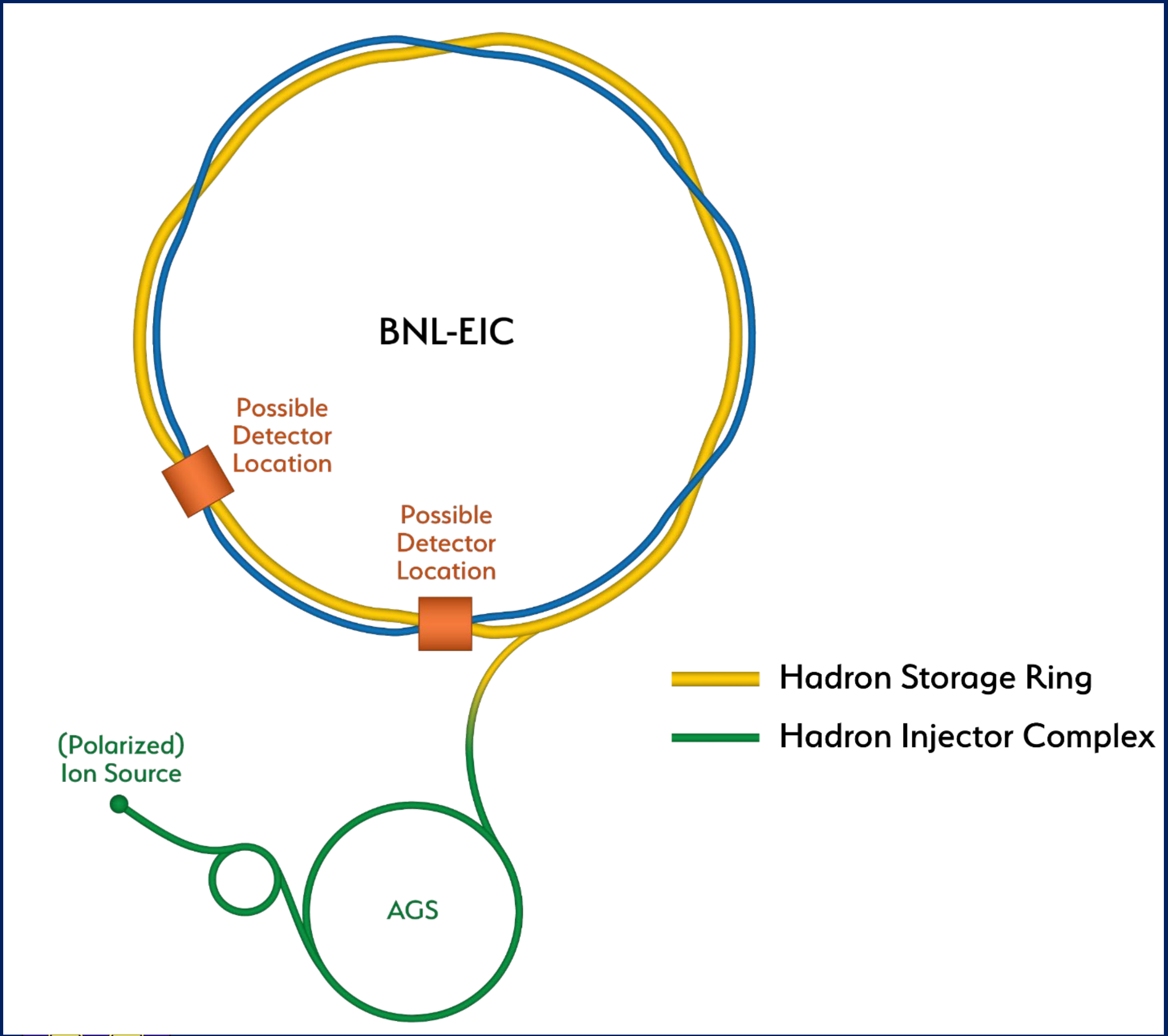
Site selection process underway

- Independent Cost Review to establish cost range
  - Documentation submitted to DOE May 1, 2019, reviewed May-June
  - Final report submitted August 2, 2019
- Site Assessment Panel
  - Convened by DOE Office of Science (chaired by James Siegrist, DOE/HEP)
  - Responses to 6 criteria submitted August 2, 2019
  - Lab presentations, Q&A sessions on October 8, 2019
- Further decision process internal to DOE

EIC: Status and recent developments

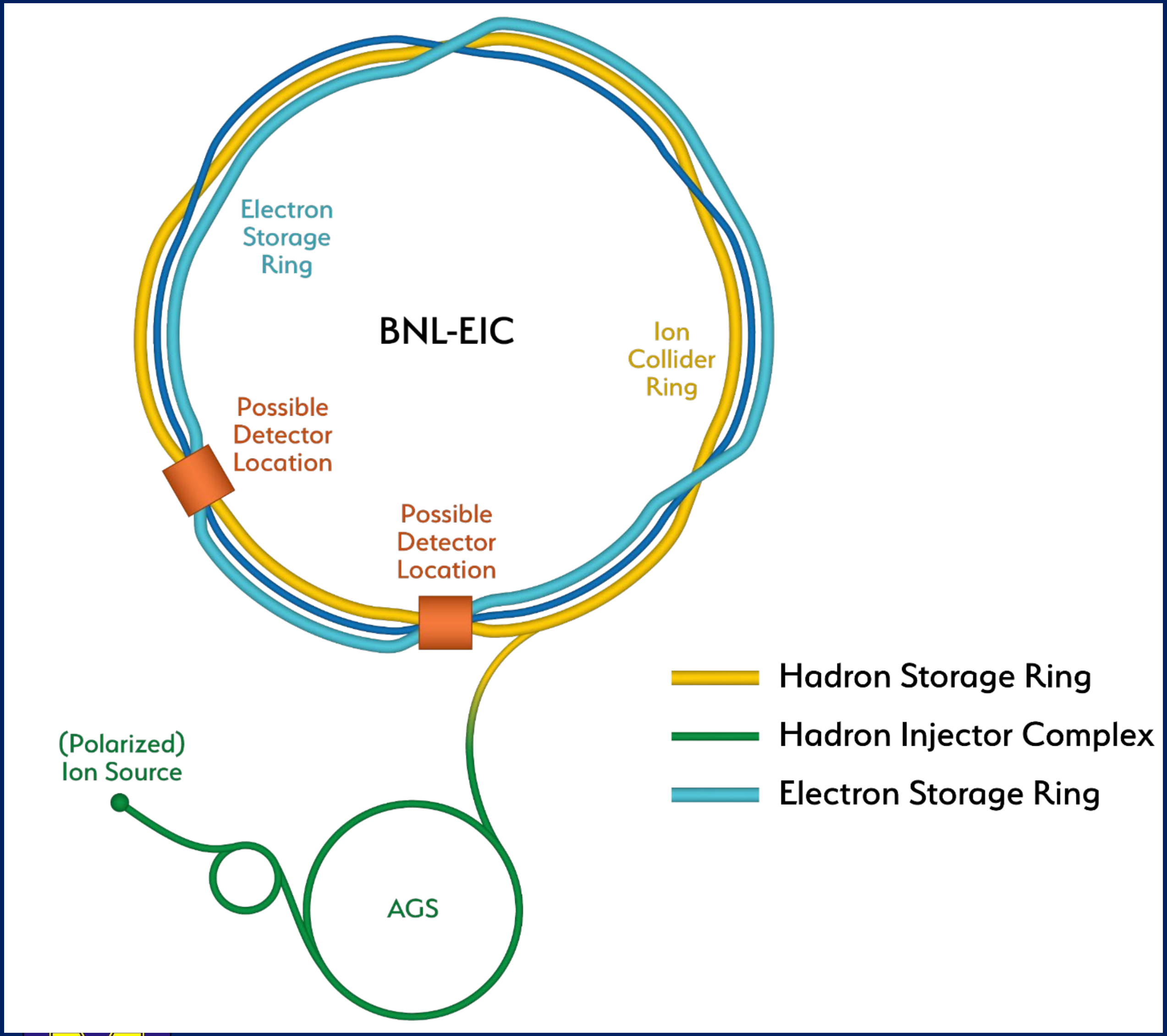
- EIC discussed with funding agencies from various countries at IUPAP Working Group 9 (Nuclear Physics) Meeting, August 2-3, 2019
- Latest annual EIC Users Meeting held in Paris, July 22-26, 2019
- EIC Physics and Detector Conceptual Development
  - 12-18 months study getting started now
  - Two working groups: Physics, Detector concepts
  - 2-day organizational meeting to be held at MIT December 12-13, 2019
  - Summaries to be published as "Yellow Reports" in spring 2021

How RHIC is transformed into an EIC



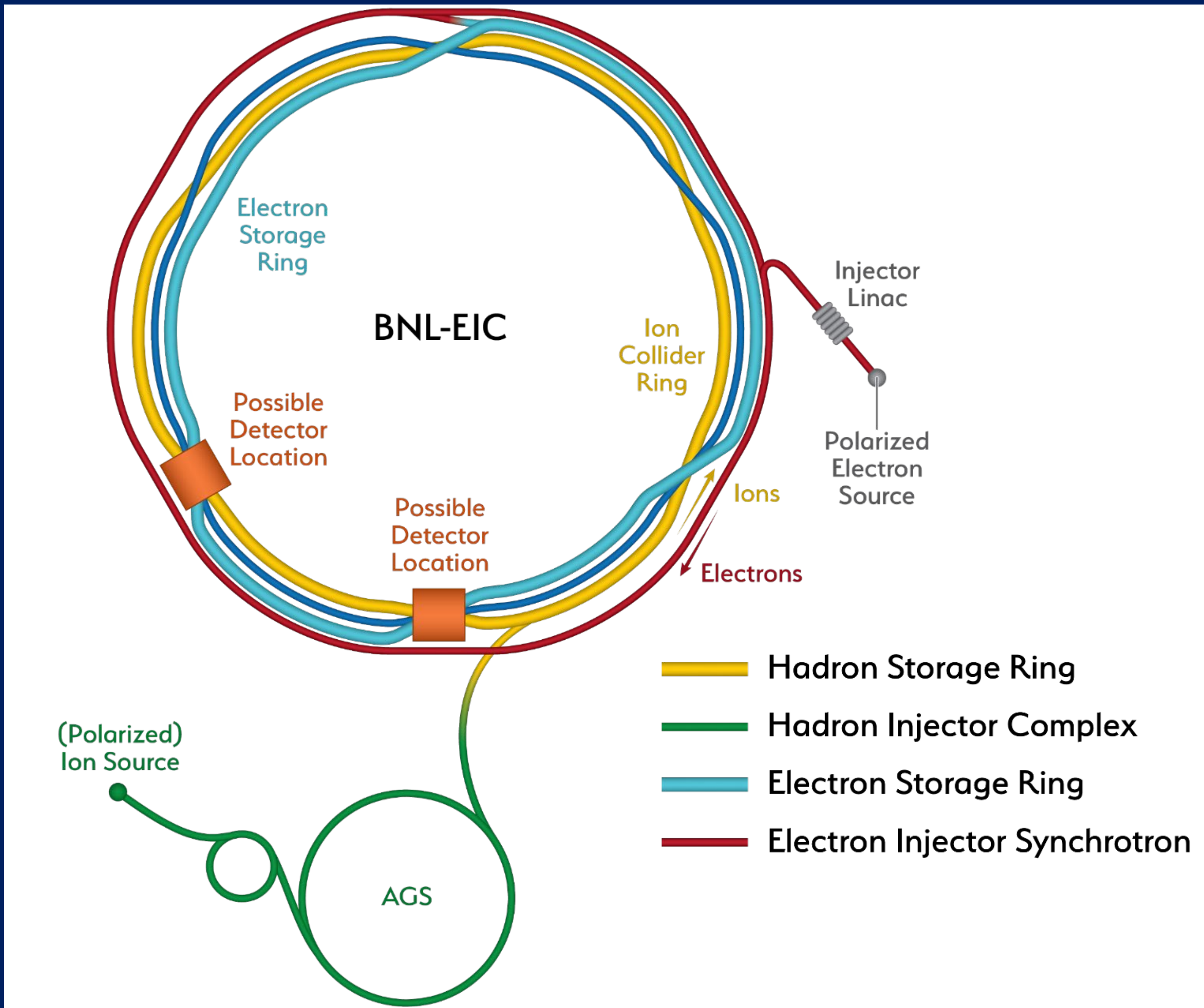
- Existing RHIC with blue and yellow rings

How RHIC is transformed into an EIC



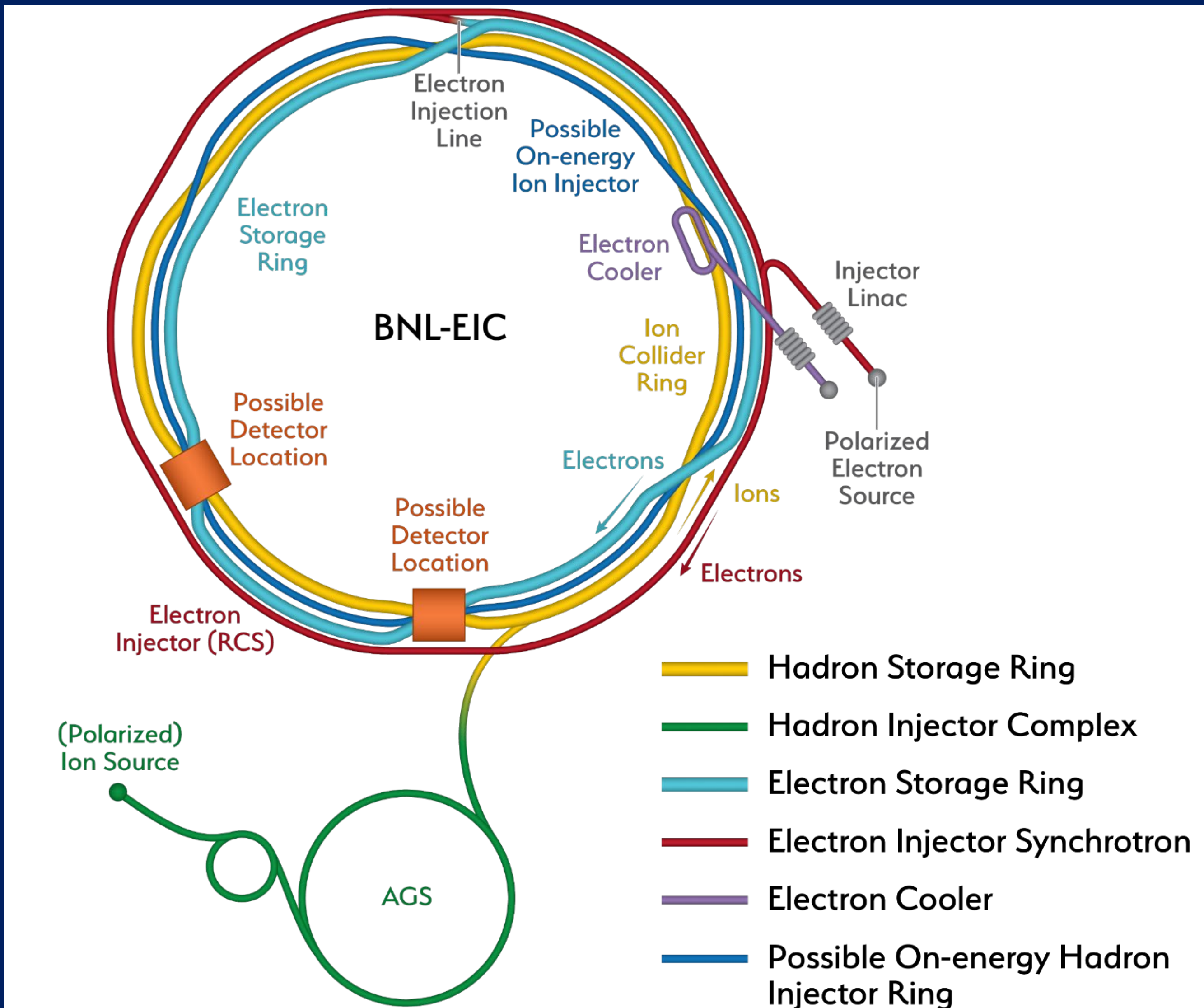
- Add electron storage ring

How RHIC is transformed into an EIC



- Add an electron injector complex with Rapid Cycling Synchrotron

How RHIC is transformed into an EIC



- Strong hadron cooling completes the facility
- Alternate solution also shown using RHIC blue ring