The Electron-Ion Collider: Tackling Quantum Chromodynamics from the Inside (of Protons and Nuclei) Out

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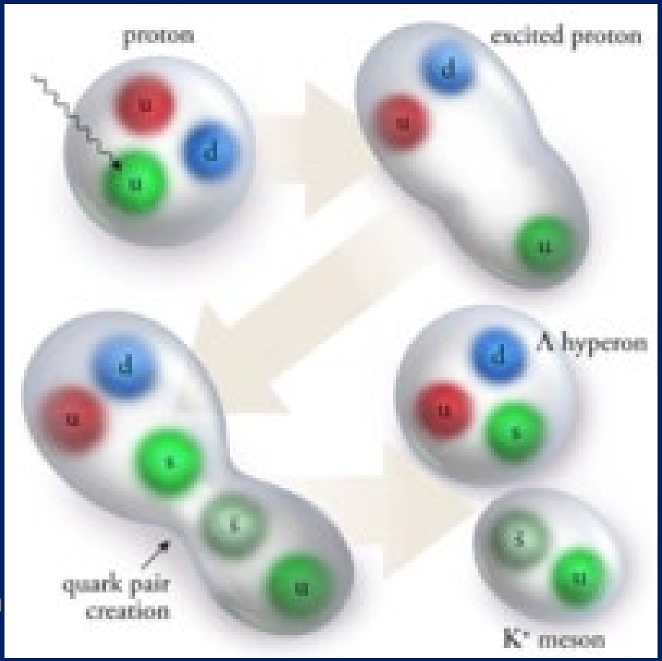
Physics & Astronomy Colloquium
January 15, 2021

Theory of strong nuclear interaction: Quantum Chromodynamics

- Fundamental field theory in hand since the early 1970s—BUT . . .
- Quark and gluon degrees of freedom in the theory cannot be observed or manipulated directly in experiment!

Color *confinement*—quarks and gluons are confined to color-neutral bound states



CLAS Collaboration (including L. El Fassi)
PRL 113, 152004 (2014)
PRL Editor's Choice Oct. 2014

How do we understand the visible matter in our universe in terms of the quark and gluon degrees of freedom of quantum chromodynamics?

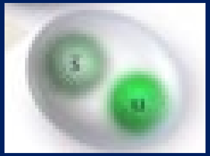
How can studying QCD systems teach us more about fundamental aspects of QCD as a theory?

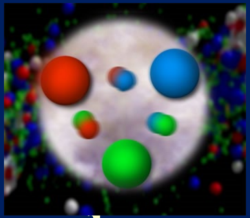
(One way of dividing up) Areas of study in QCD

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

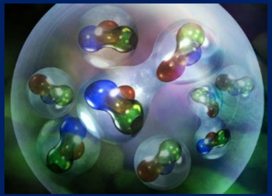
Structure/Properties of QCD matter

- Bound states: Mesons and baryons

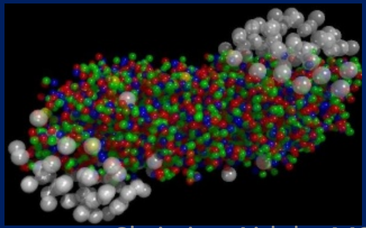


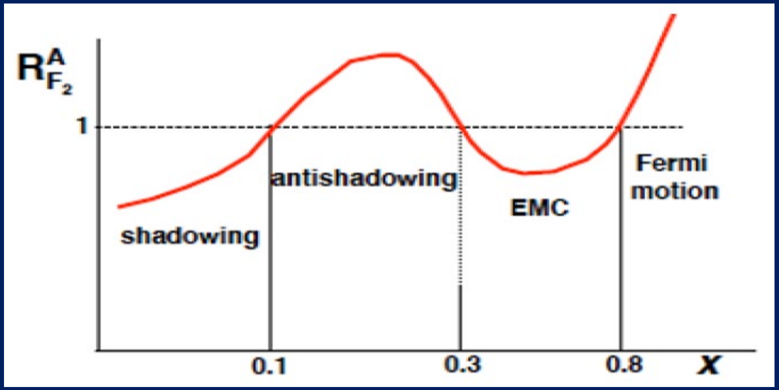


- Bound states of bound states: Nuclei, neutron stars



- Deconfined states: Quark-gluon plasma

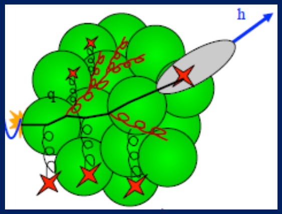




Nuclei aren't just superpositions of free nucleons. Ratio of quark momentum image in nuclei compared to free protons not flat.

Formation of states of QCD matter

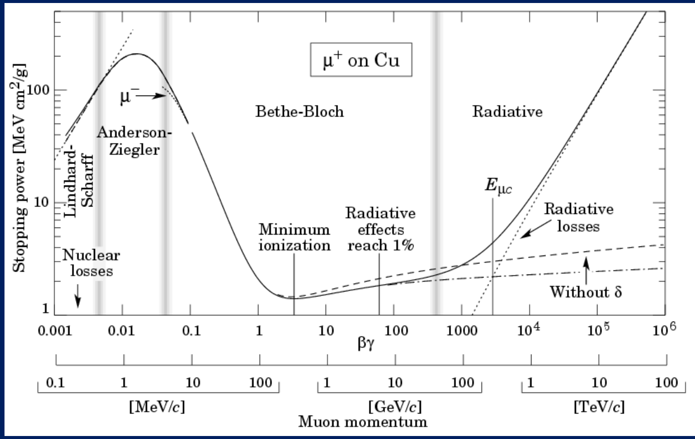
- Bound state formation mechanisms
- Formation of bound states of bound states
- Equilibration of quark-gluon plasma
- Time scales of hadronization/equilibration
- Modification of hadronization in different environments



Knock a quark out of a free proton vs. a nucleus—how is new bound state formation from the scattered quark affected by the presence of the nucleus?

Interactions within QCD

- Quark and gluon energy loss in cold and hot QCD matter
  - What is the analog of the Bethe-Bloch curve for QCD rather than electromagnetism?

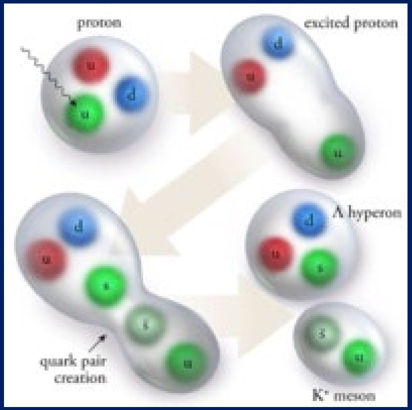


Electromagnetic energy loss of muons passing through copper

- Quantum interference and phase shifts
  - E.g. quantum interference effects in hadronization
    - One quark or gluon → multiple hadrons
    - Multiple quarks or gluons → one hadron

- Color charge flow effects in scattering processes
  - Process-dependent spin-momentum correlations in hadrons
  - Quantum entanglement of quarks across colliding hadrons

Complexity and richness of QCD: Confinement

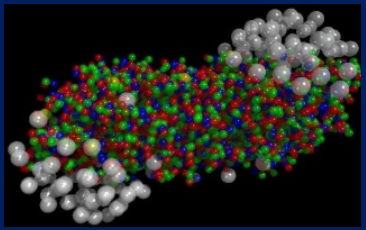


- QCD theory: Quarks and gluons
- QCD experiment: QCD bound states

- Always an interplay between quark vs. bound-state descriptions, reductionist vs. 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
    - Strong coupling α_s decreases with increasing energy scale
  - Provide access to new probes, e.g. heavy quarks (charm and beauty), Z and W bosons

High-energy collisions: Tools to study QCD

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  - Access subnuclear distance scales
  - Form new states of QCD matter

Studying QCD is not energy frontier physics! Simply need sufficient conditions to access the degrees of freedom of interest, which happen to be at very small distance scales!

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  - Allow use of perturbative theoretical tools
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High-energy collisions: Tools to study QCD

Can study QCD via

- Hadron-hadron collisions: proton-proton, proton-nucleus, nucleus-nucleus, antiproton-proton, pion-nucleus, …

- Lepton-hadron collisions: e/μ-proton, e/μ-nucleus, ν-nucleus

- 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, quark 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

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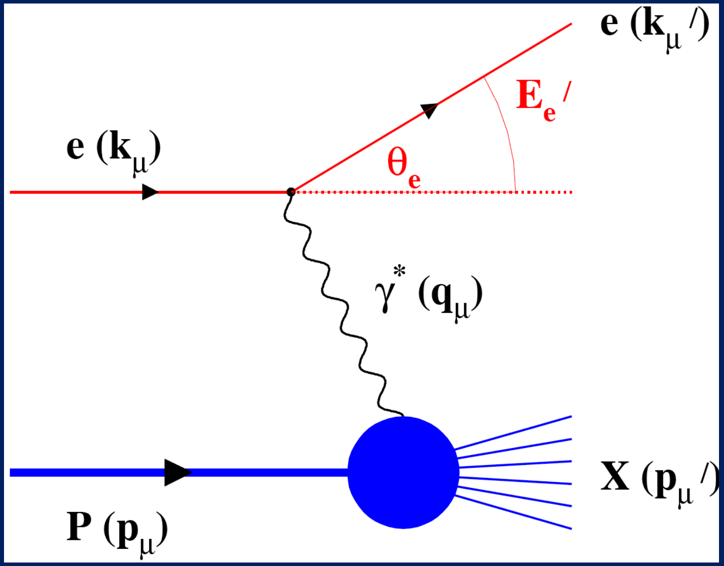
Some aspects we *select* rather than control

- Overlap of colliding nuclei, final-state produced particles and their kinematics, …

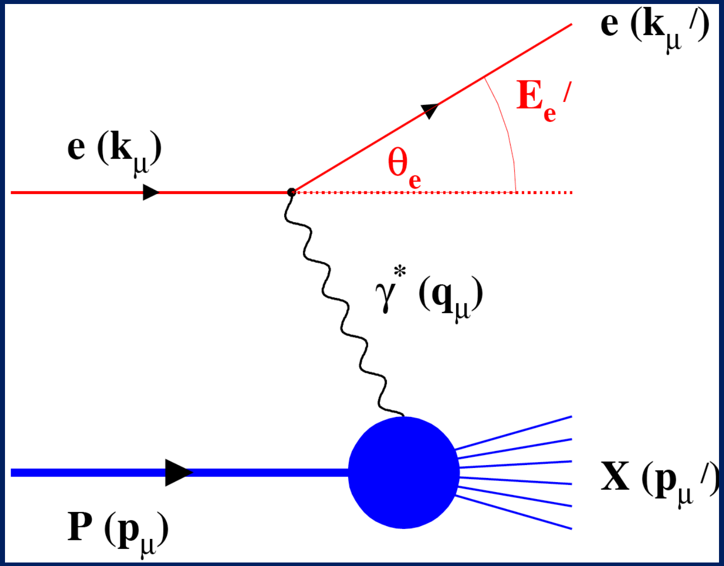
Why an Electron-Ion Collider?

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



Why an Electron-Ion Collider?

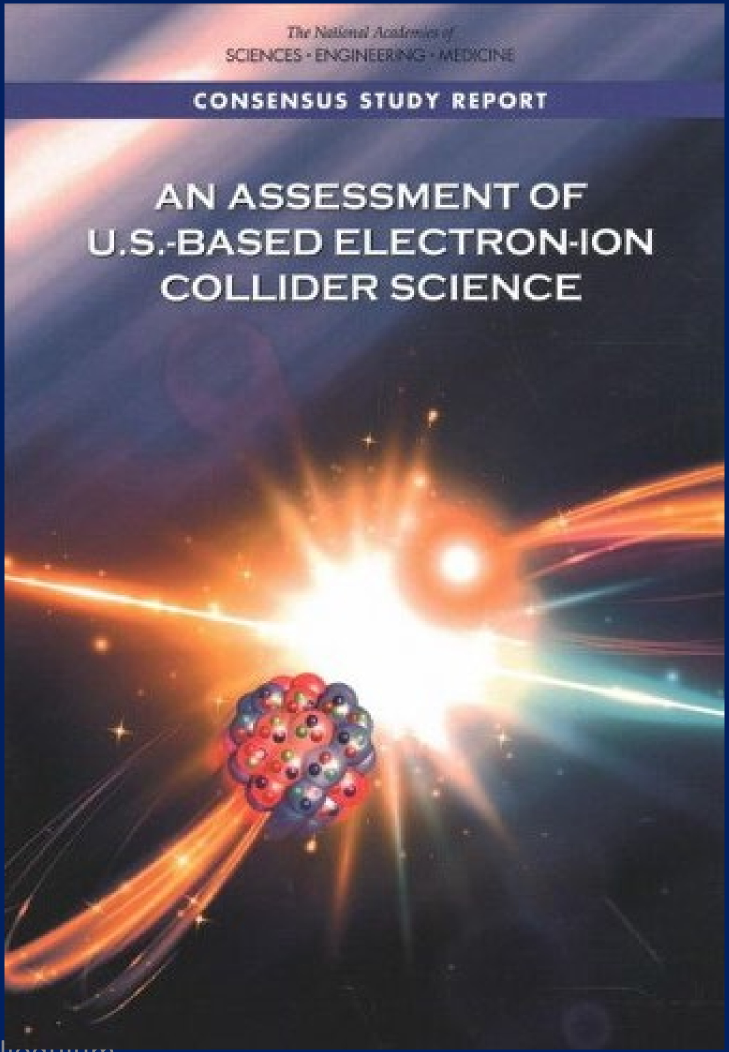
- Electroweak probe
  - "Clean" processes to interpret (QED)
  - Measurement of scattered electron → full kinematic information on quark-level scattering
- Collider mode → Higher energies
  - Quarks and gluons relevant d.o.f.
  - Perturbative QCD applicable
  - Heavier probes accessible (e.g. charm quarks,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



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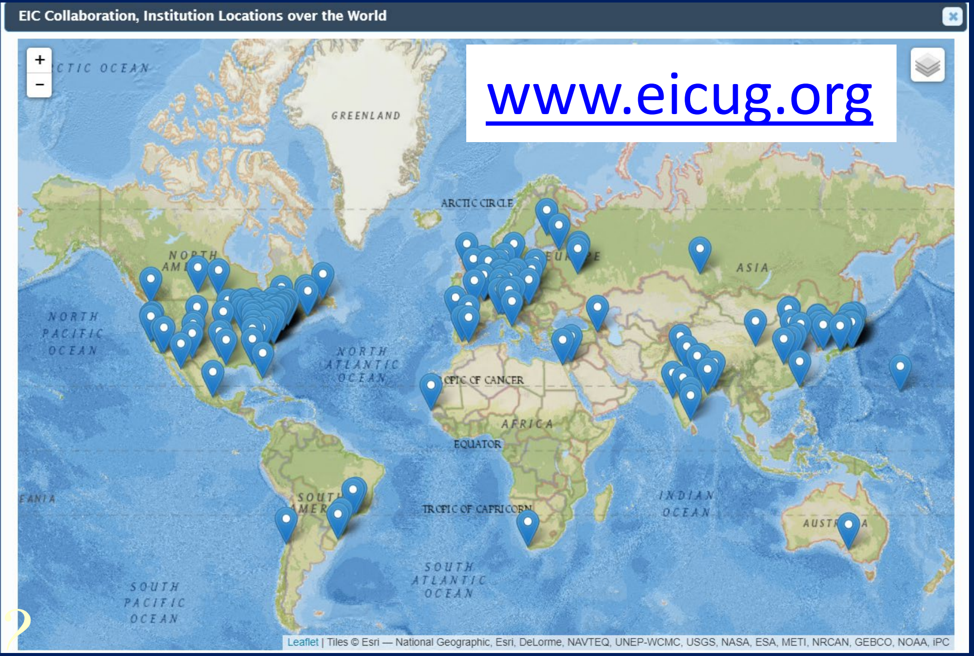


Electron-Ion Collider User Group:
Currently >1200 members from 250 institutions in 34 countries.
(25% theorists, 15% accelerator physicists,
60% experimentalists)

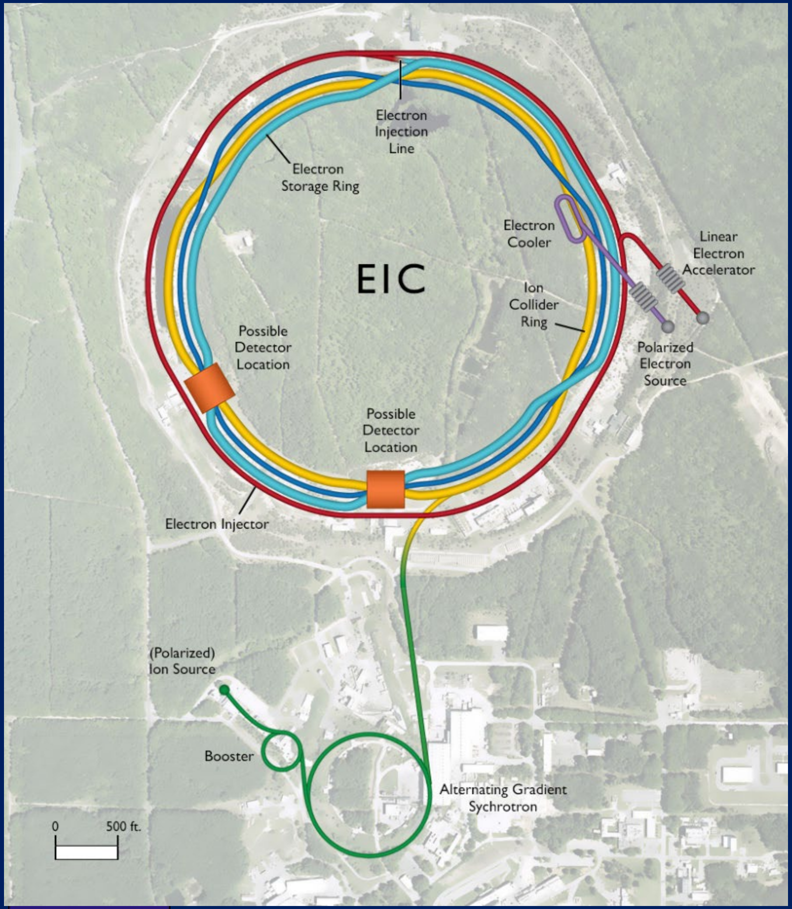
Going beyond previous facility capabilities

- Beams of light → heavy ions
  (i.e. nuclei—the "ions" are fully stripped of all electrons!)
- *Polarized* beams of protons, deuterons, ^{3}He
- Electron beam also polarized

- Previously only fixed-target lepton-nucleus experiments and lepton - polarized hadron experiments
  → EIC will greatly expand kinematic reach of both types of colliding systems

Accelerator configuration

Site selection at Brookhaven National Lab announced January 2020
→ Add electron beam to existing Relativistic Heavy Ion Collider



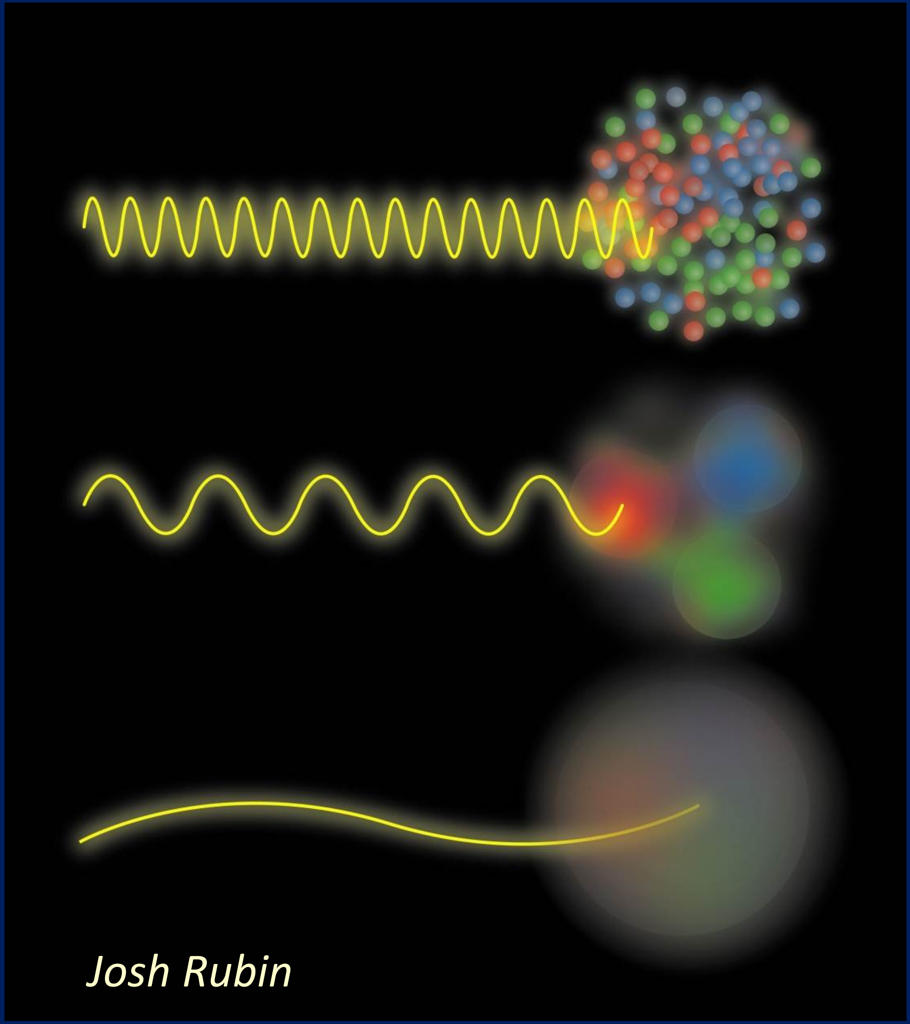
Electron-ion center of mass energy ~20-140 GeV

High luminosity and polarization:

- Luminosities $10^{33\text{-}34}$ cm^{-2} s^{-1}
- Polarized electrons (~70%), E ~ 4-18 GeV
- Polarized protons (~70%), E ~ 24-275 GeV, and heavier ions with E up to 110 GeV

The proton as a "laboratory" for studying QCD

- Proton: simplest stable QCD bound state
- Different energy scales offer information on different aspects of proton internal structure



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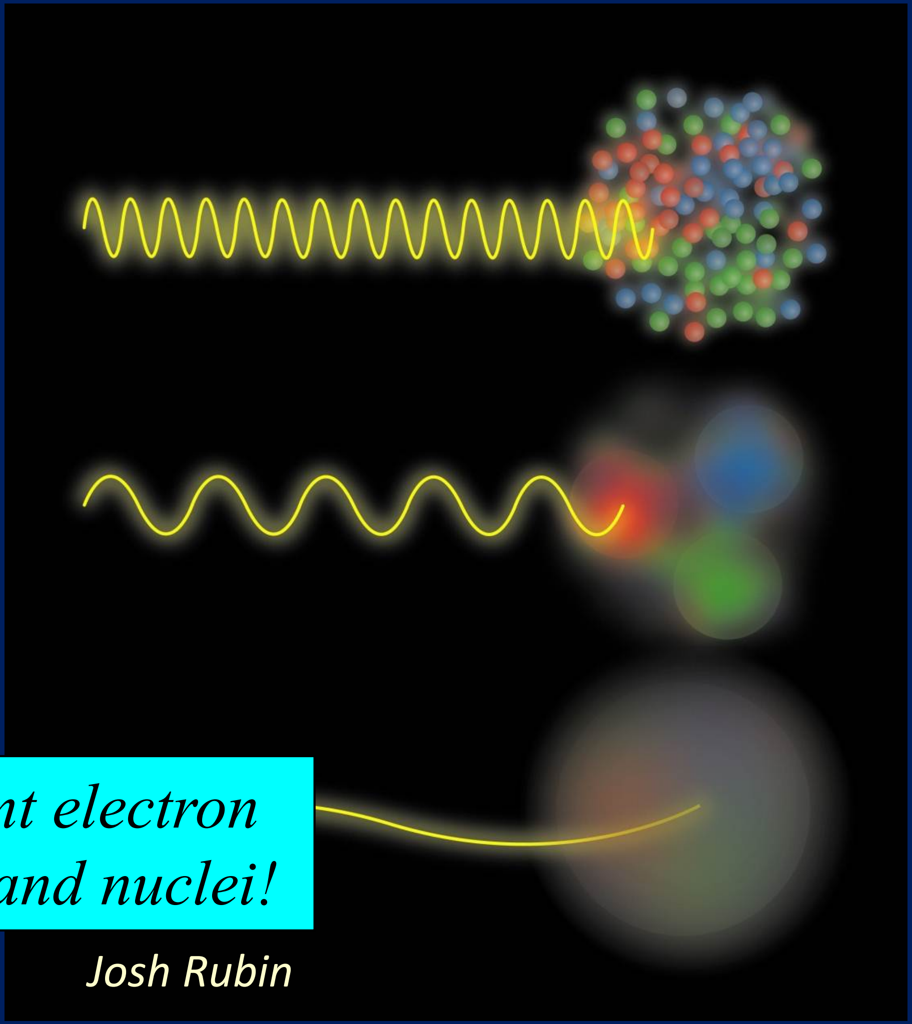

The Electron-Ion Collider: a giant electron microscope for imaging protons and nuclei!

Mapping out the quark-gluon structure of the proton

What does the proton look like in terms of the quarks and gluons inside it?

- *Position*
- *Momentum*
- *Spin*
- *Flavor*
- *Color*

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Vast majority of past five decades focused on *1-dimensional* momentum structure. Since 1990s starting to consider transverse components . . .

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Polarized protons first studied in 1980s. How angular momentum of quarks and gluons add up still not well understood!

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Good measurements of flavor distributions in valence region. Flavor structure for sea quarks still yielding surprises.

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Theoretical and experimental concepts to describe and access position only born in mid-1990s. Pioneering measurements over past ~decade.

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- *Position*
- *Momentum*
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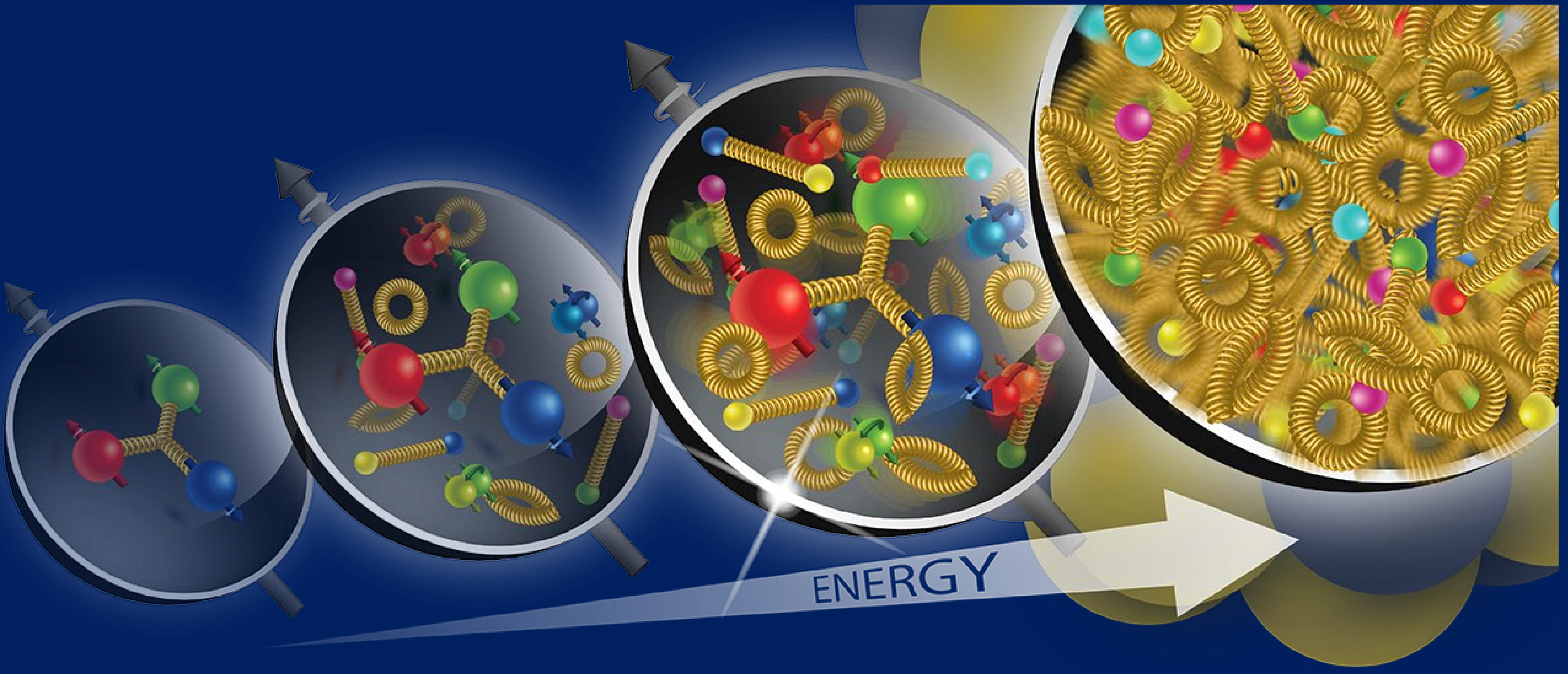
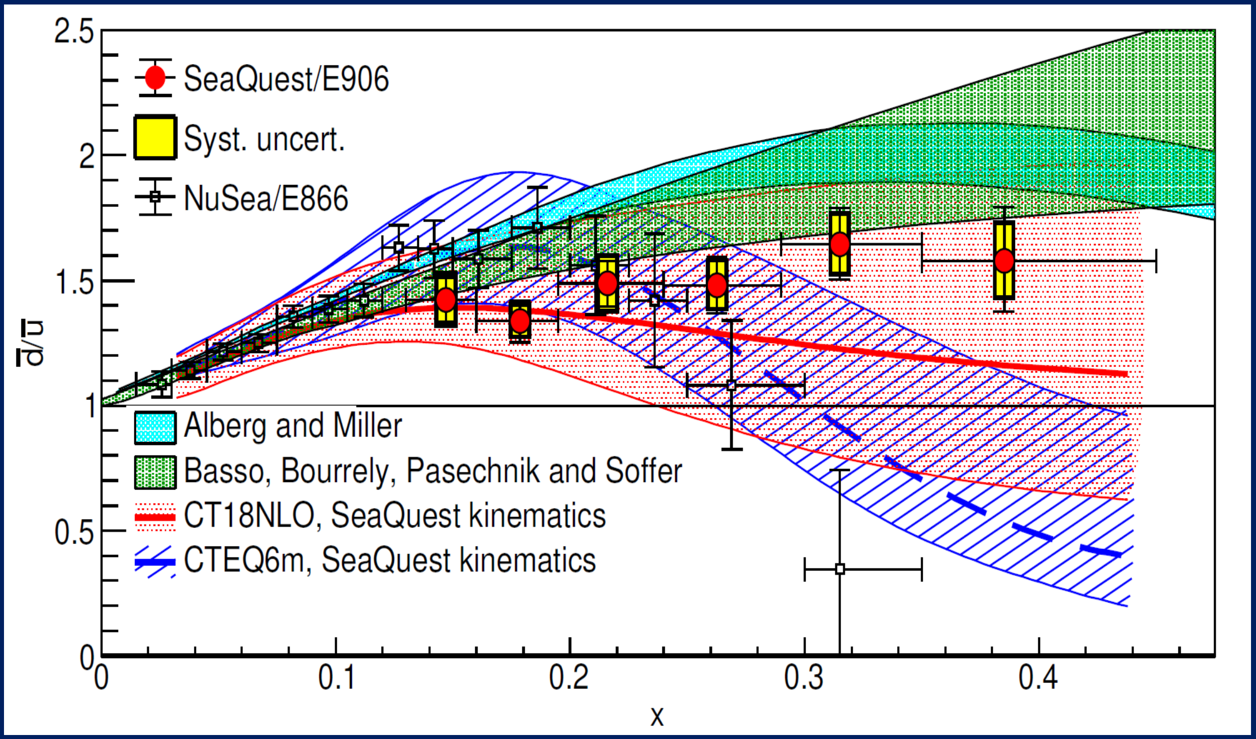
- *Color*

Accounted for theoretically from beginning of QCD, but more detailed, potentially observable effects of color flow have come to forefront in last decade.

Mapping out the quark-gluon structure of the proton



Ongoing surprises in 1-D momentum structure of the proton—even after 50 years!

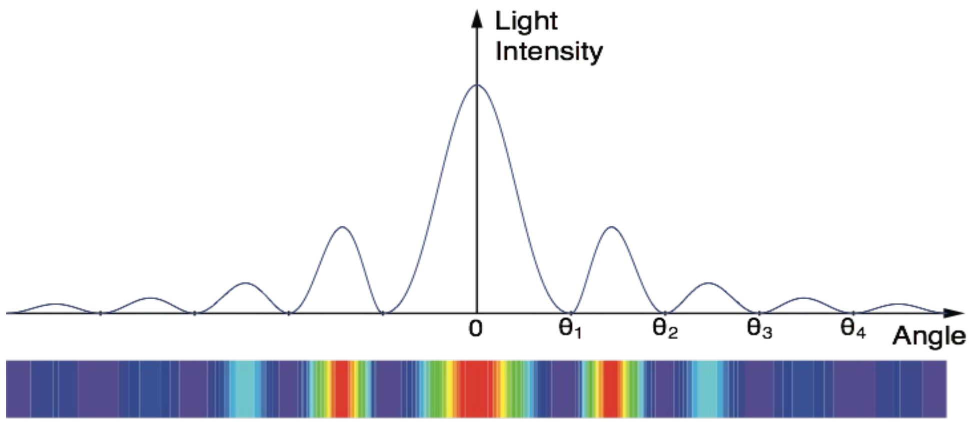


Why are there more down flavor antiquarks in the proton than up antiquarks, and how does the ratio depend on momentum fraction?

Fermilab E906/SeaQuest Collaboration
(including L. El Fassi, MSState postdoc Catherine Ayuso, CAA)
Accepted by *Nature*

Imaging spatial structure of quarks in nuclei: Diffraction

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

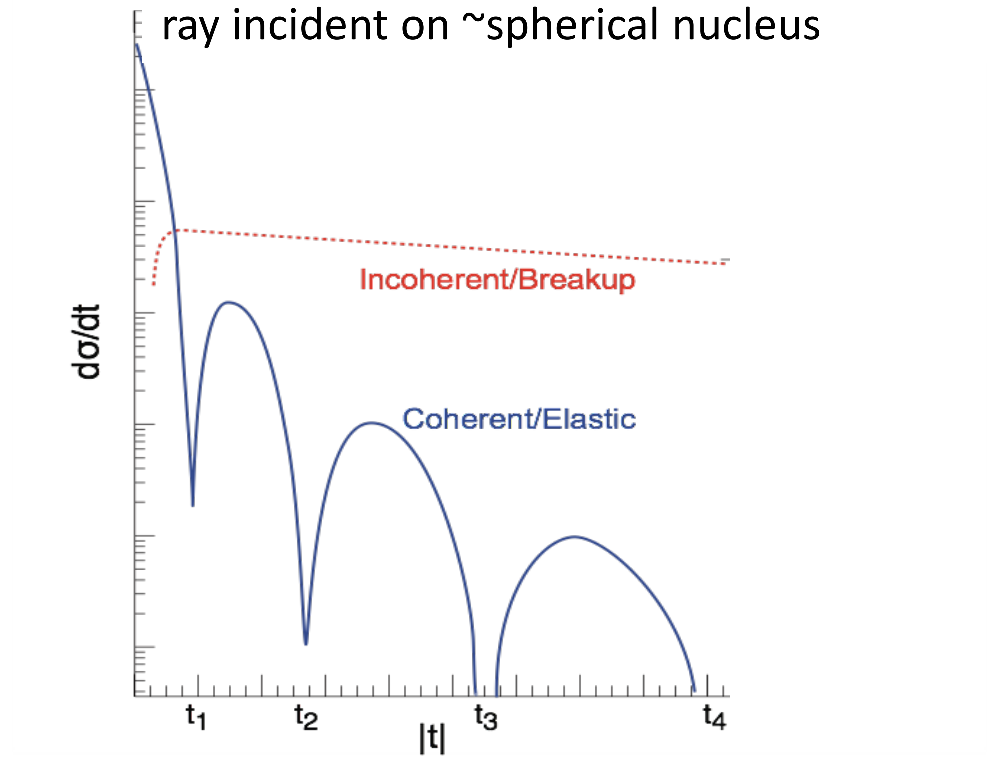


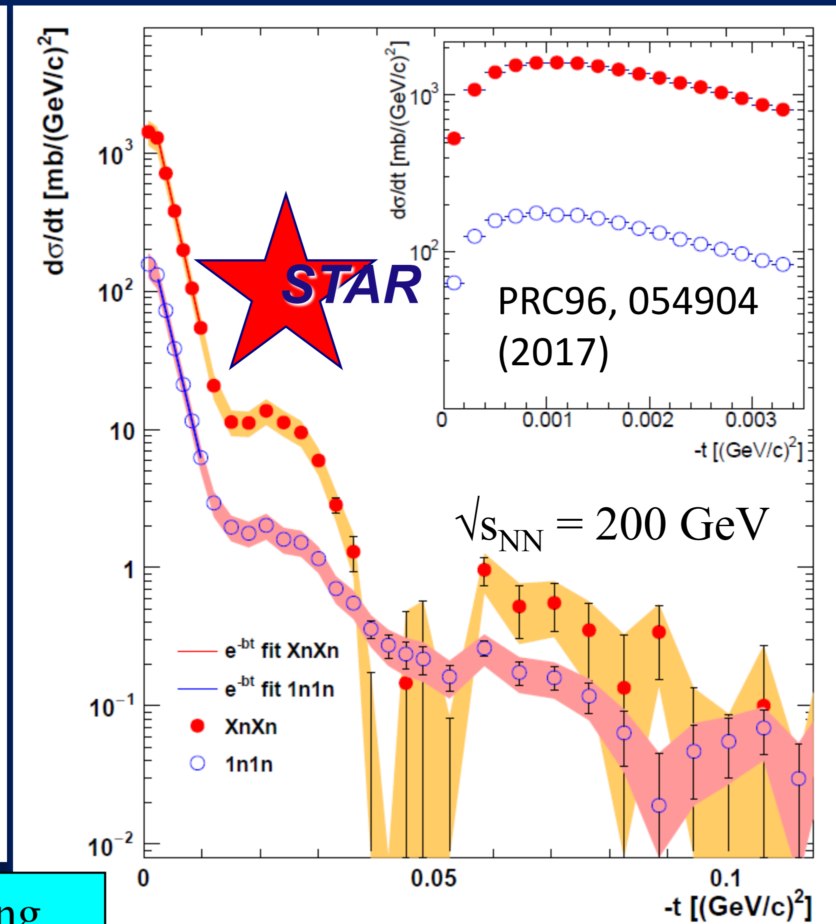
From E. Aschenauer

- 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

Imaging spatial structure of quarks in nuclei: Diffraction

Expected diffraction pattern from gamma ray incident on ~spherical nucleus

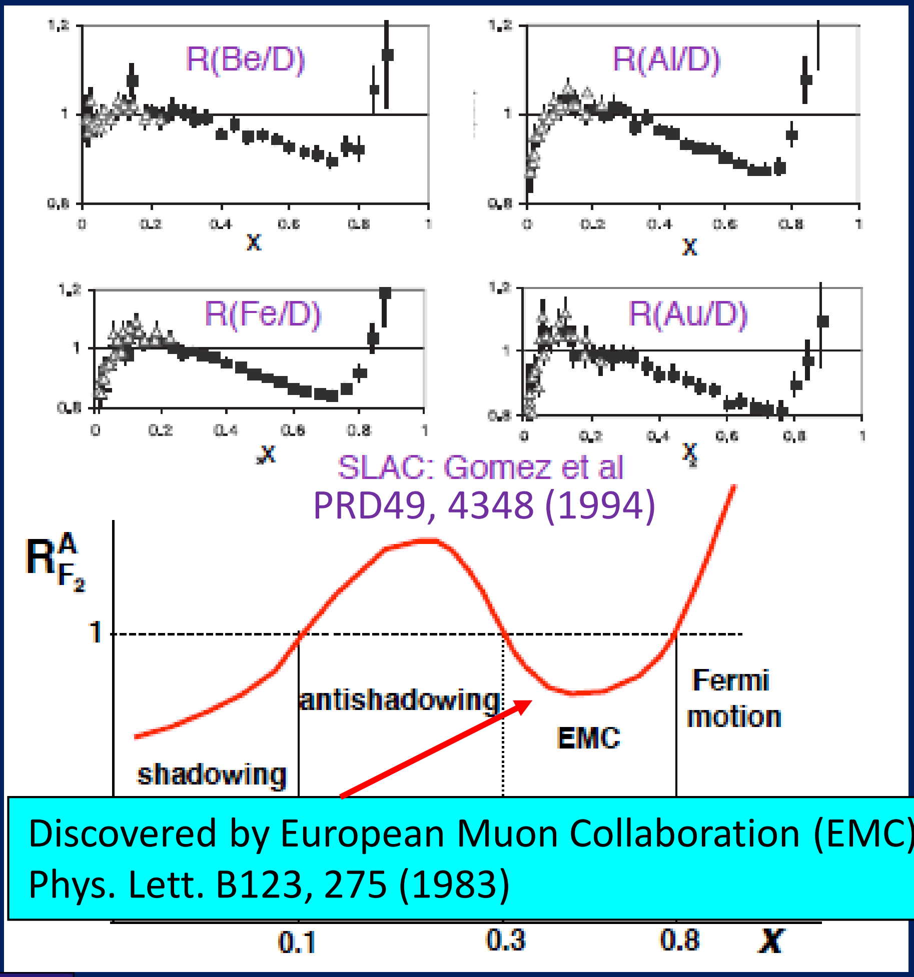




Diffractive ρ meson production in Au+Au ultraperipheral collisions

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

Imaging momentum structure of quarks in nuclei: Not just superimposed protons and neutrons

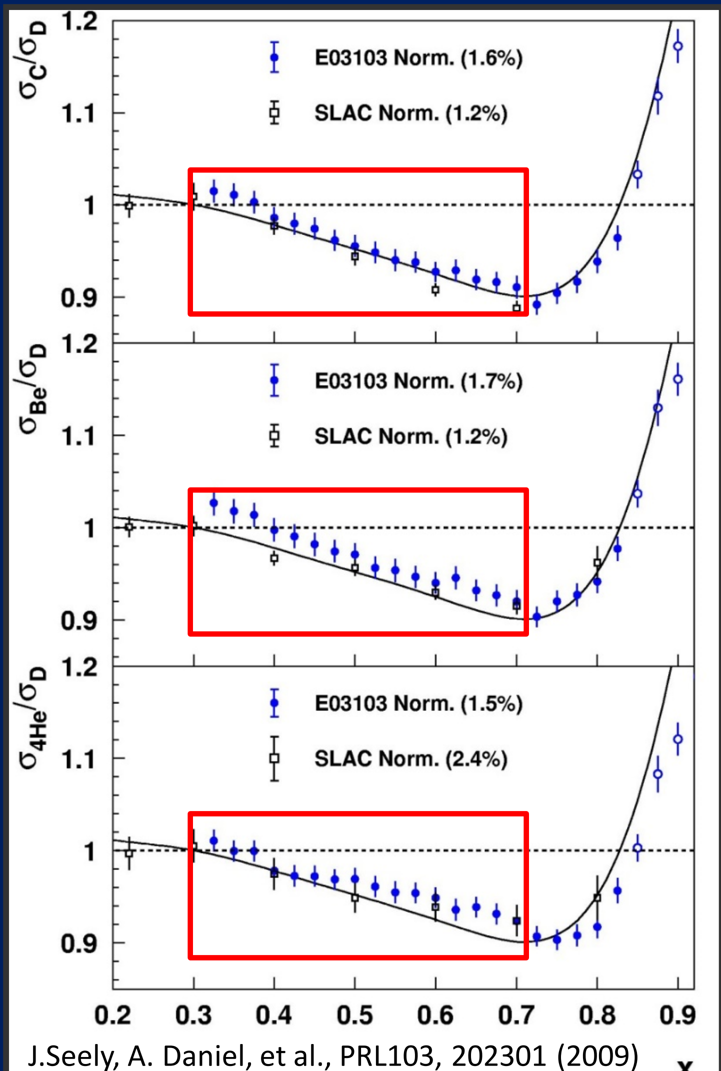


Discovered by European Muon Collaboration (EMC), Phys. Lett. B123, 275 (1983)

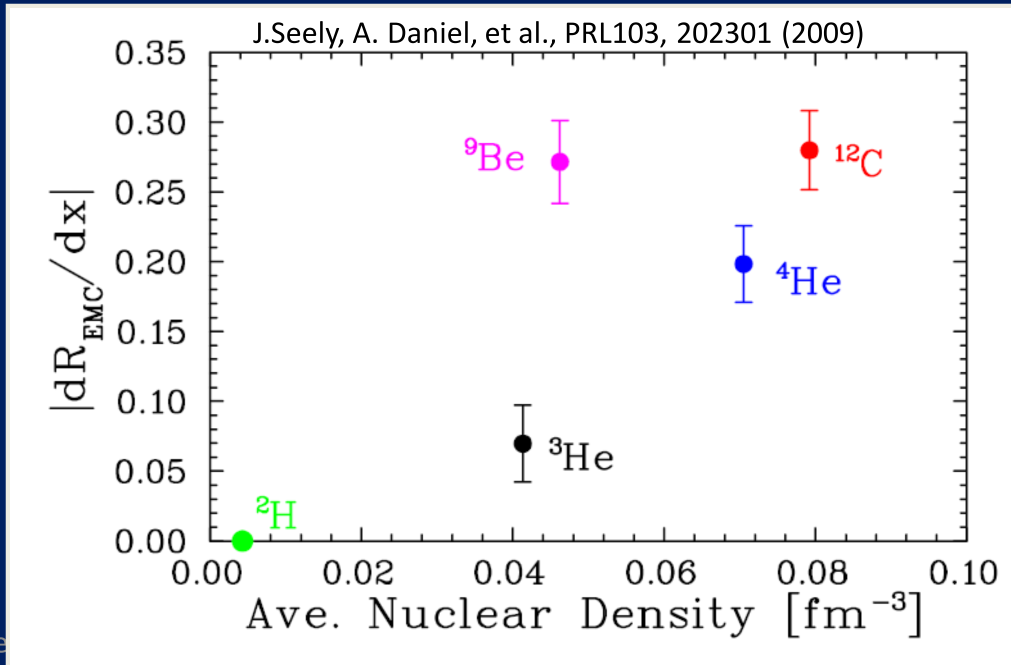
$$R_A \equiv \frac{1}{A}\frac{F_{2A}}{F_{2N}} \neq 1$$

- Ratio of cross section for e-nucleus compared to scaled e-proton collisions, shown vs. quark momentum fraction *x*
- Regions of both enhancement and depletion—still lots to understand in detail!

Imaging momentum structure of quarks in 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…



ristine

Jan 2021

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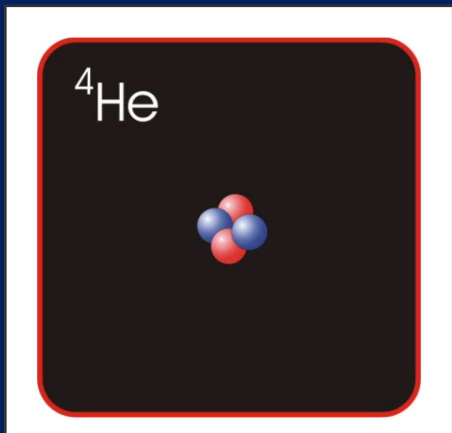
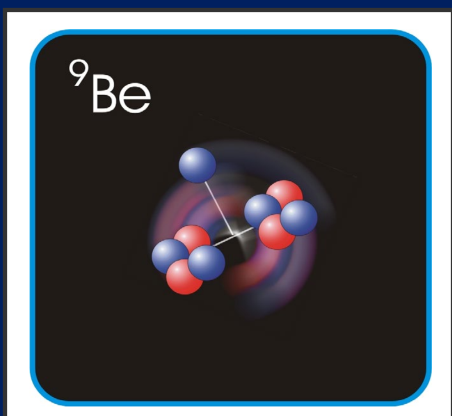
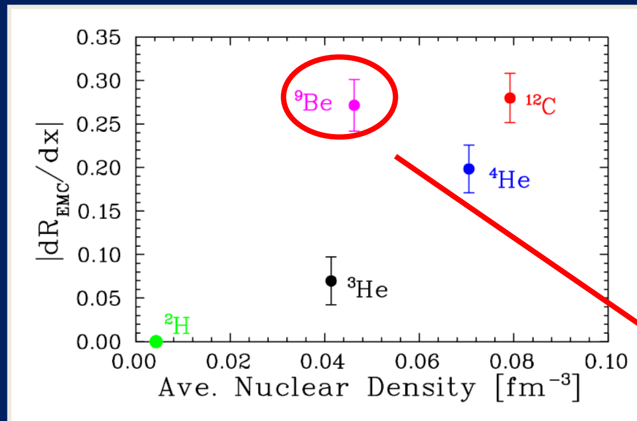
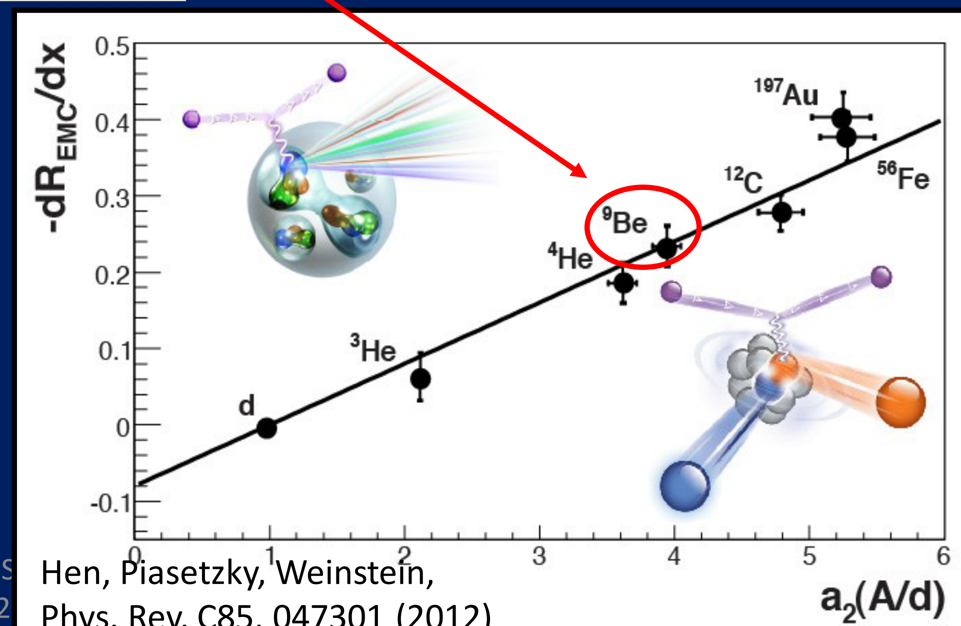






But appears to scale with local density!



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)

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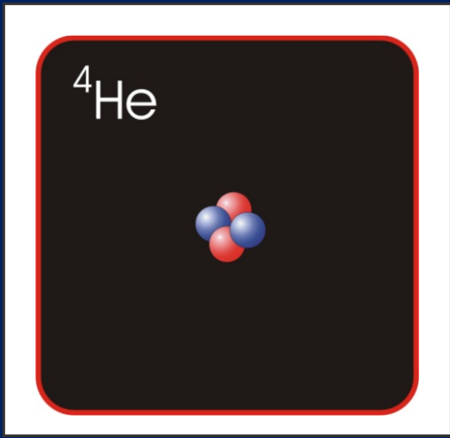

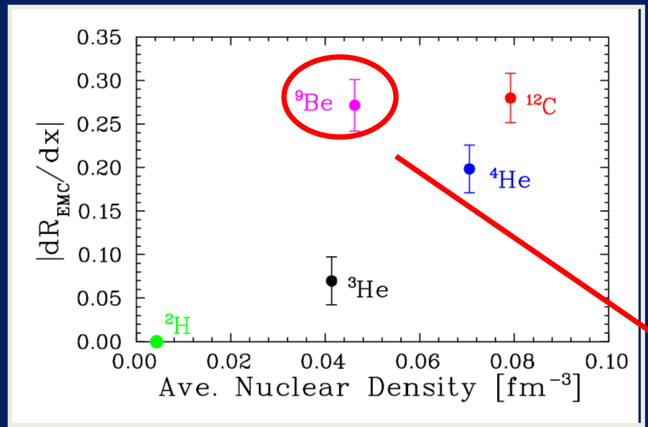

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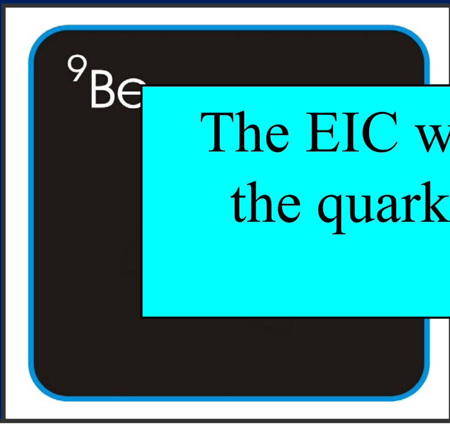
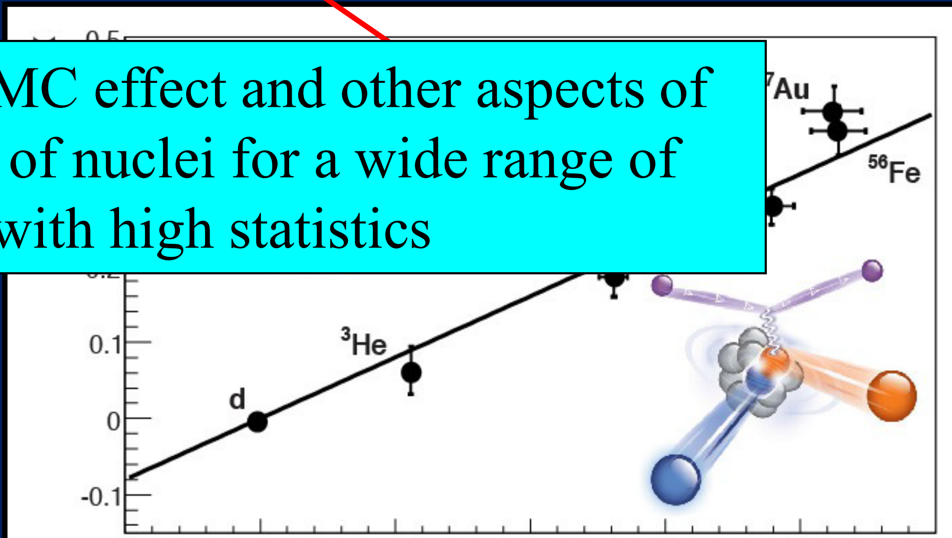


The EIC will investigate the EMC effect and other aspects of the quark and gluon structure of nuclei for a wide range of different A nuclei, with high statistics



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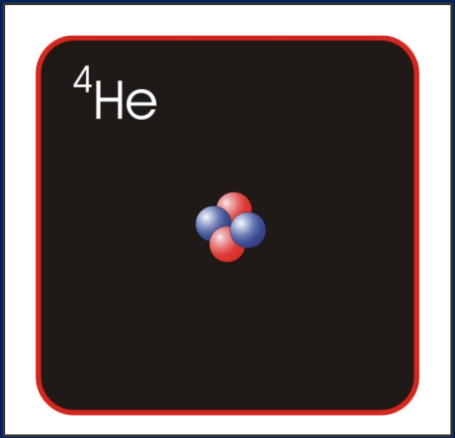

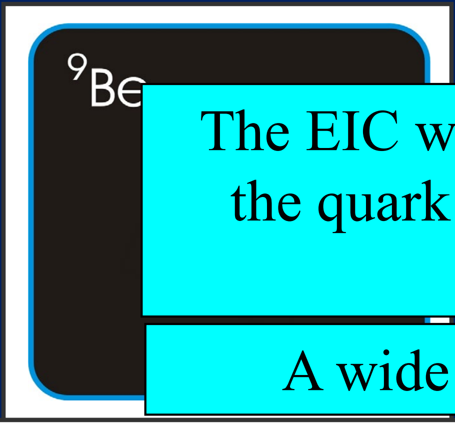

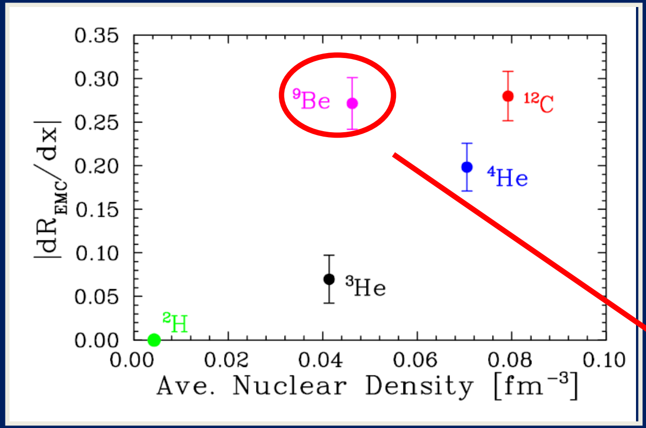

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A wide range of other physics not covered in this talk!

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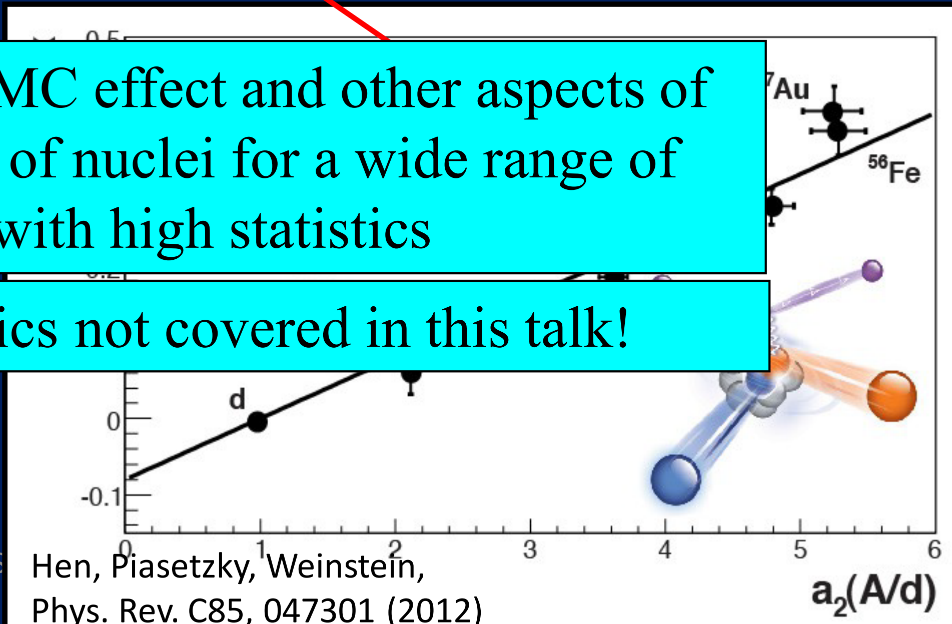

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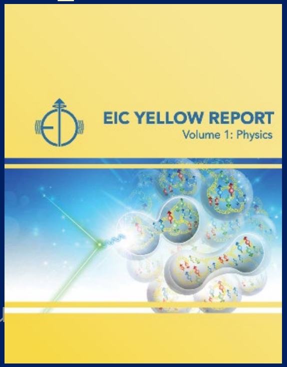
EIC: Status and recent developments

- EIC received U.S. Department of Energy (DOE) "Critical Decision 0" in Dec 2019. $2B-scale project.
- Site selection at BNL announced Jan 2020
- EIC community-wide physics and detector conceptual development over the past year
  - Summaries (>800 pages!) to be published as "Yellow Report" in early 2021
    - MSState postdoc Carlos Gayoso in D. Dutta's group a coauthor
- DOE Critical Decision 1 review later this month
- Call for official detector proposals expected March 2021
- First data anticipated in 2030



Summary (I)

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 (I)

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
- Electron-Ion Collider → next major facility in the ongoing quest to address fundamental questions within QCD
  - How do we describe the structure of 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?

Summary (II)

www.eicug.org

Along with a wealth of expected data from

- electron-proton and -nucleus fixed-target data from **Jefferson Lab**,
- proton-proton and -nucleus data from the **Relativistic Heavy Ion Collider** and **Large Hadron Collider**,
- electron-positron annihilation to hadrons at the **Belle II** experiment,

as well as new opportunities in lower-energy nuclear structure measurements from the **Facility for Rare Isotope Beams**,

the next two decades promise tremendous progress in understanding how the quarks and gluons of QCD lead to the matter of the world around us!

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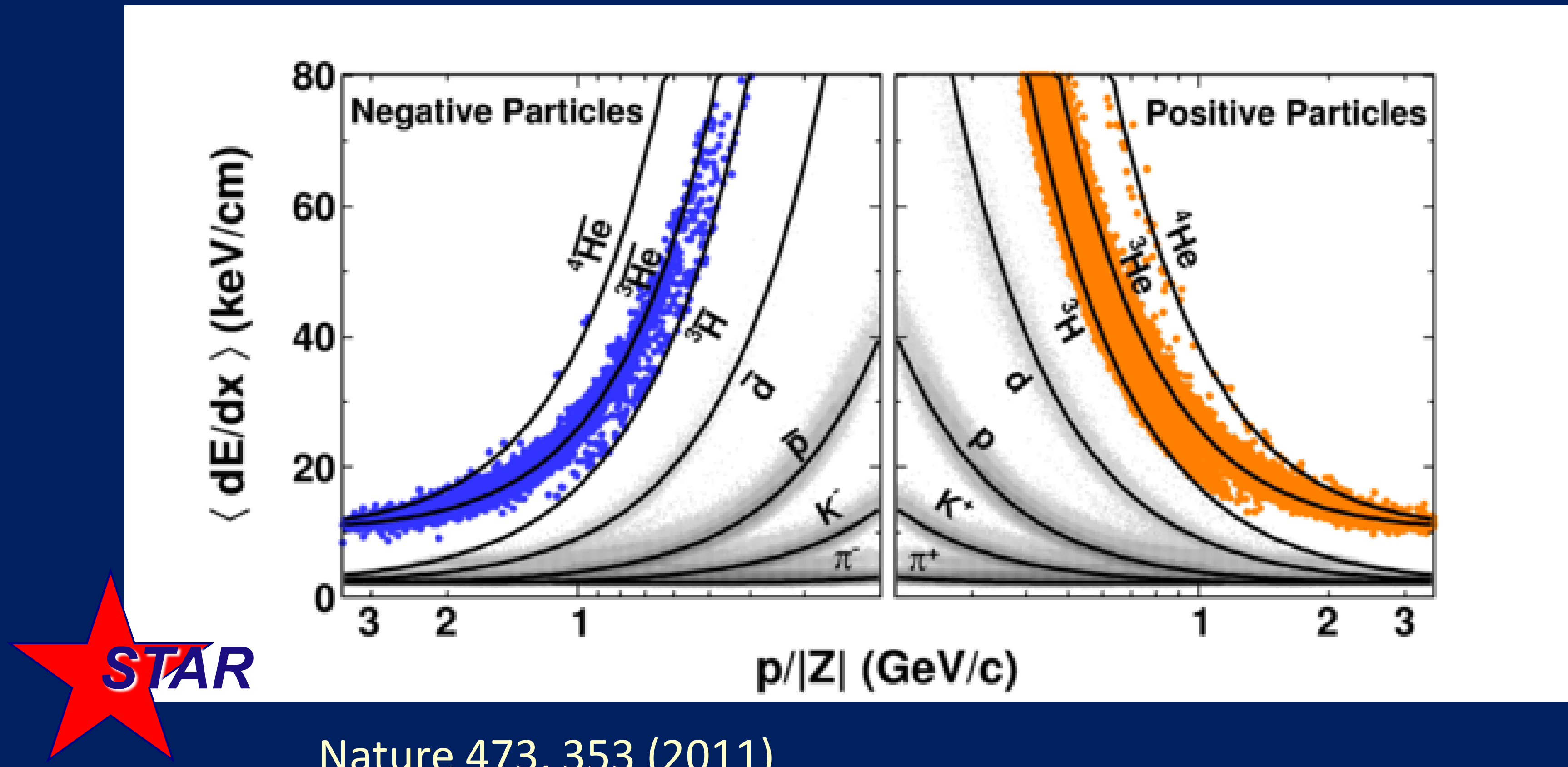
I look forward to seeing how we'll gain even more exquisite control and understanding as we continue to work with our "tabletop" experiments for giants!

Extra

Bound states of hadronic bound states: Creating (anti)nuclei!

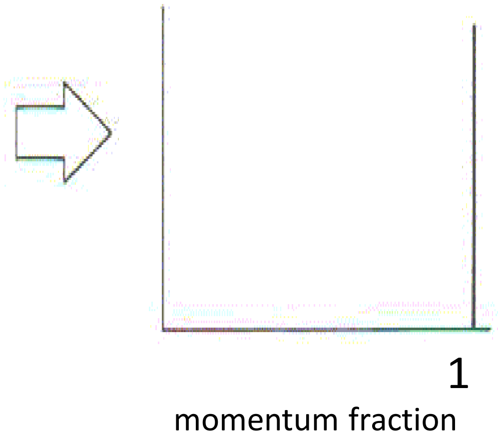


Nature 473, 353 (2011)

Quark distribution functions inside the proton: The language we've developed (so far!)

What momentum fraction would the scattering particle carry if the proton were made of …

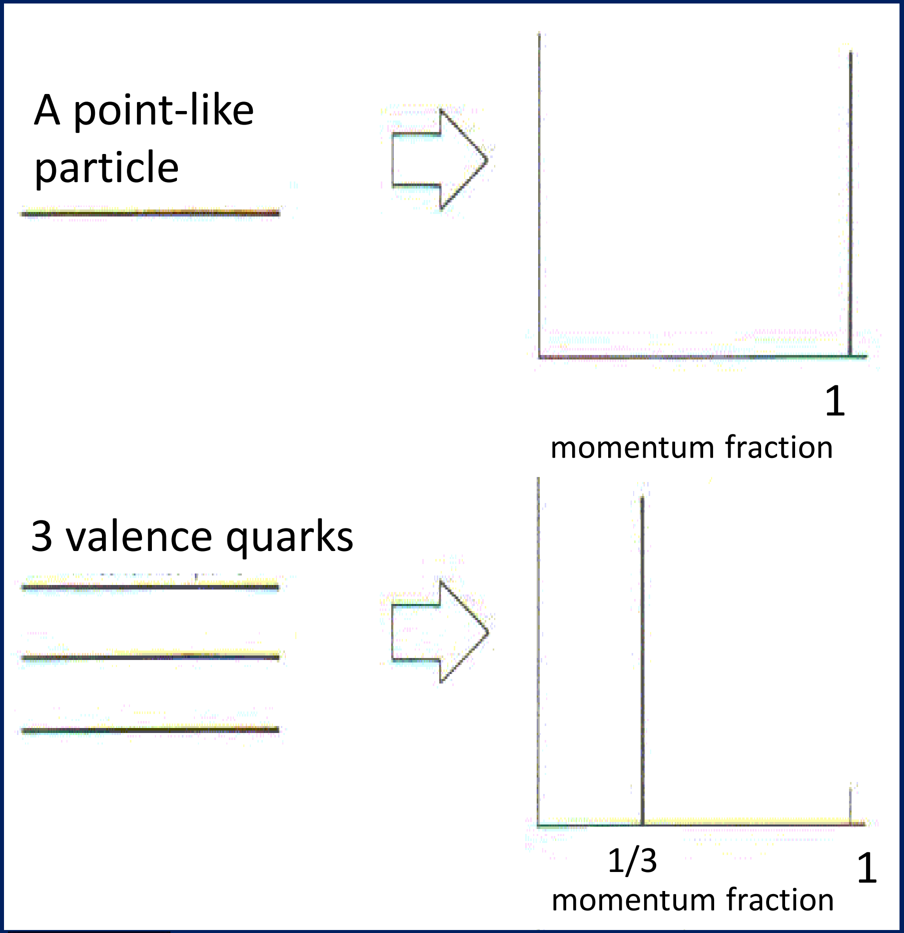
A point-like particle



Halzen and Martin, "Quarks and Leptons", p. 201

Quark distribution functions inside the proton: The language we've developed (so far!)

What momentum fraction would the scattering particle carry if the proton were made of …



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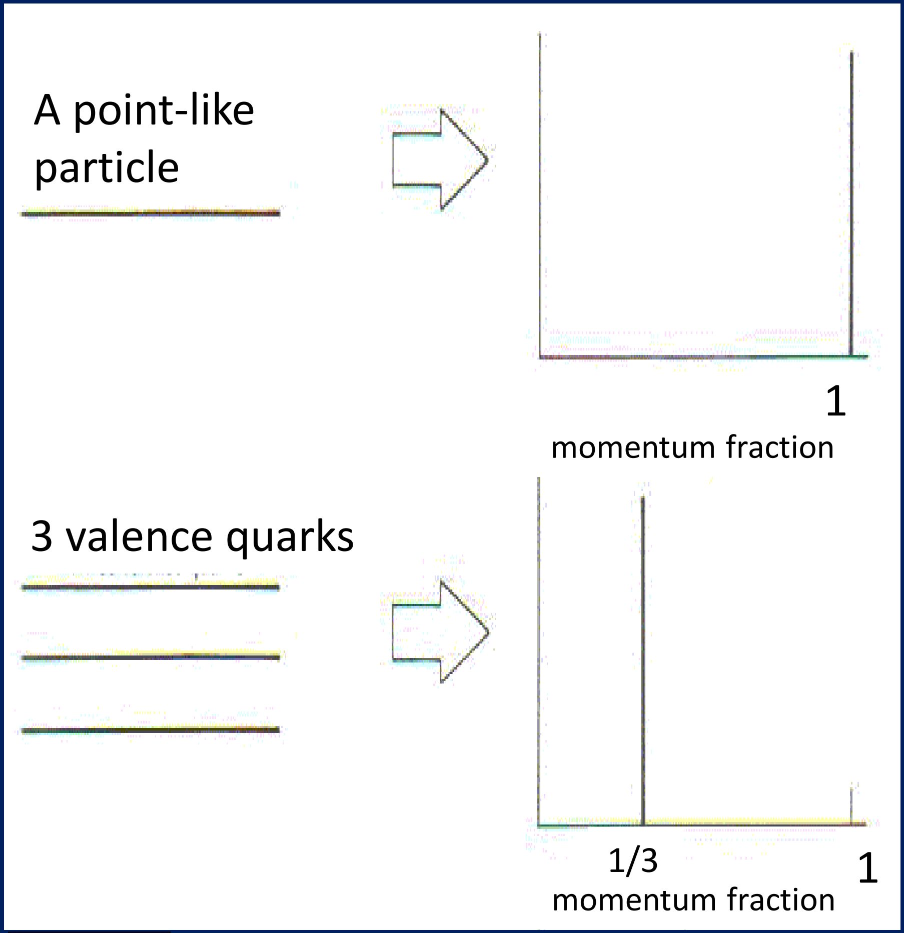

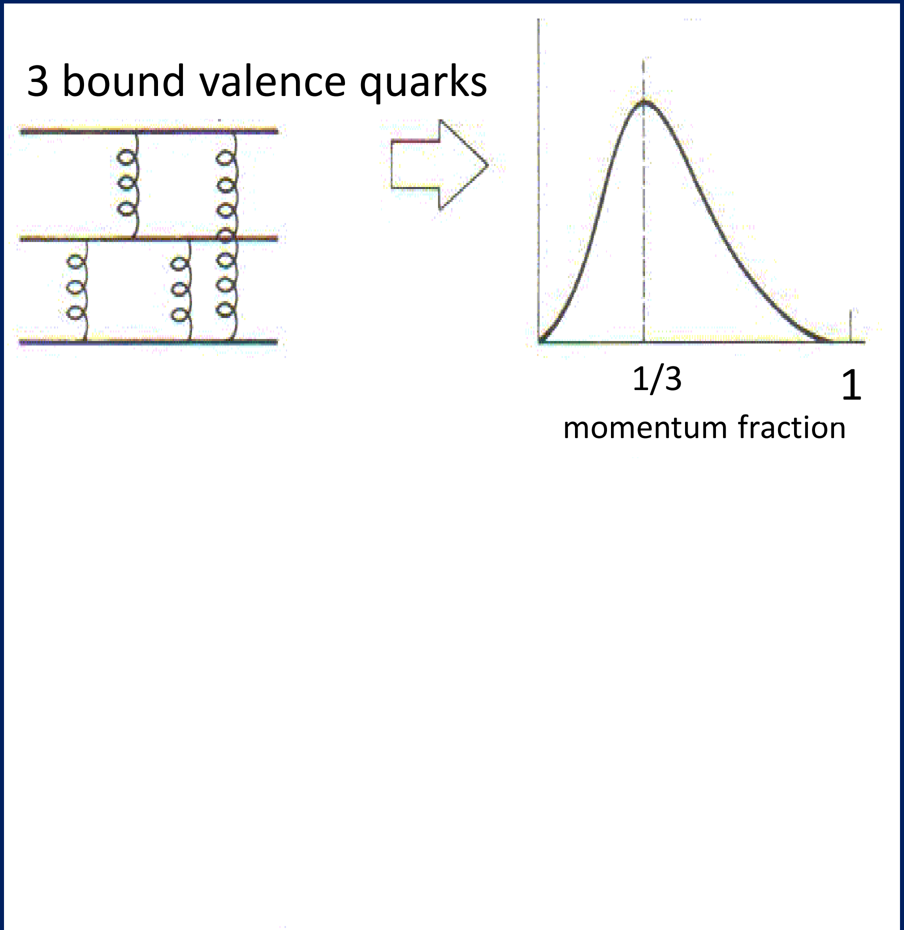

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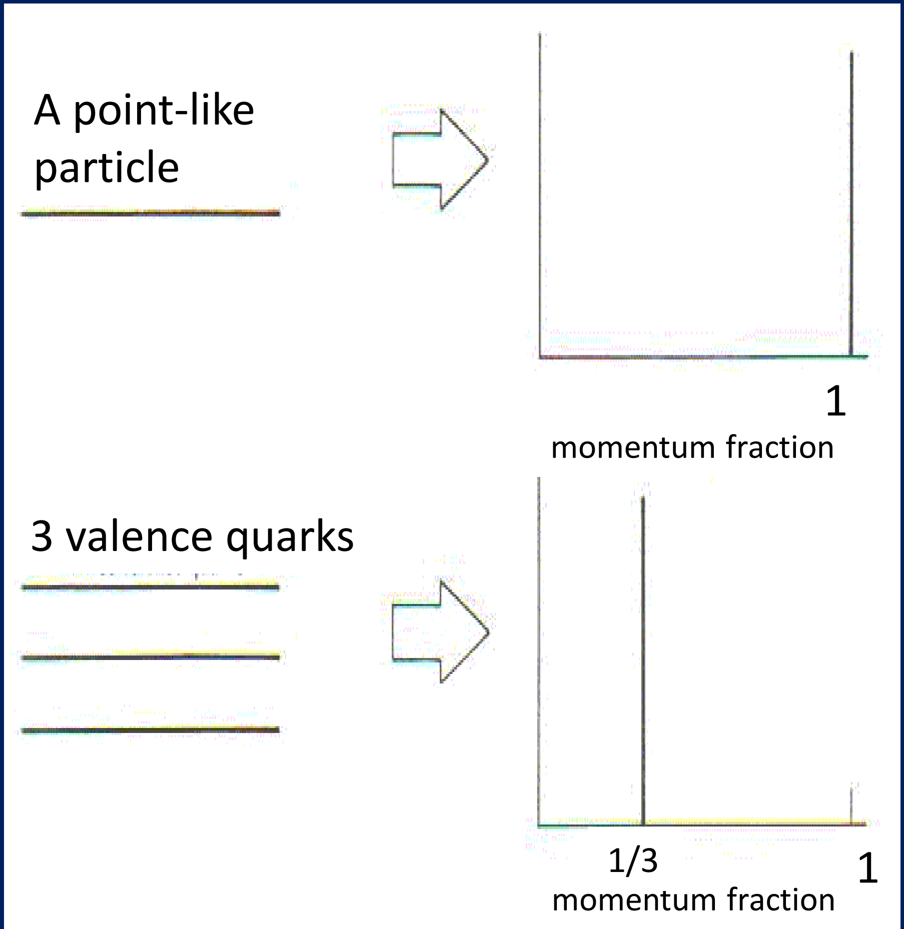
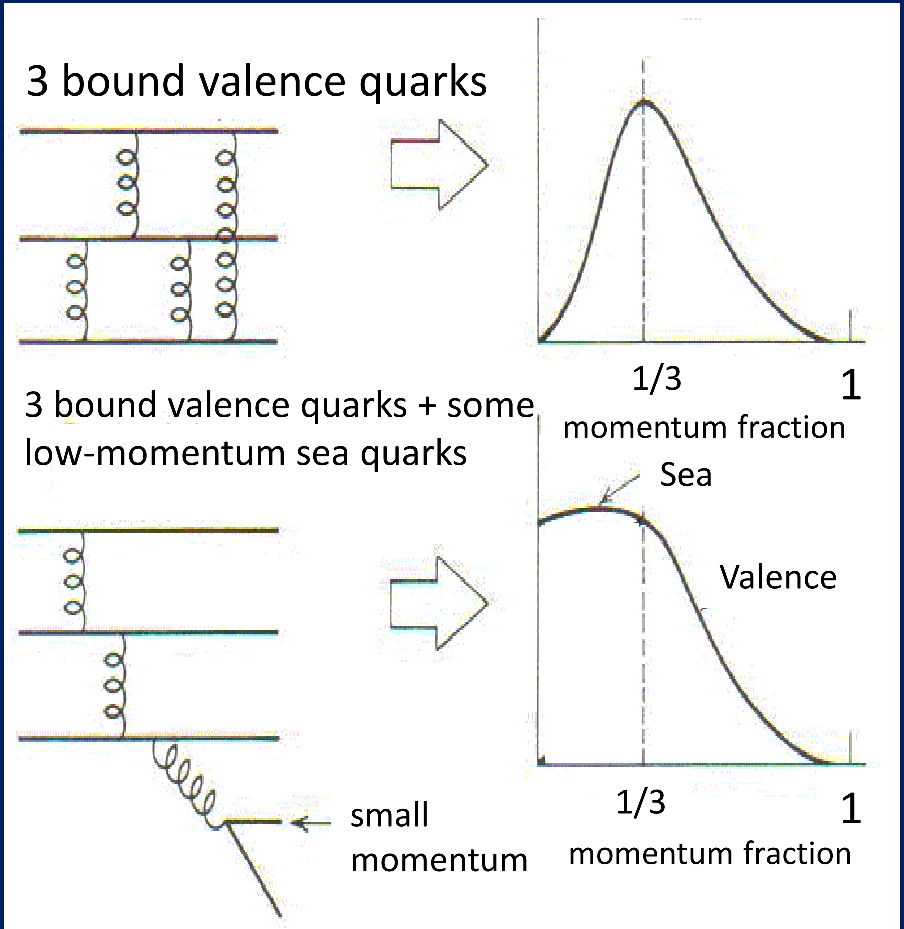
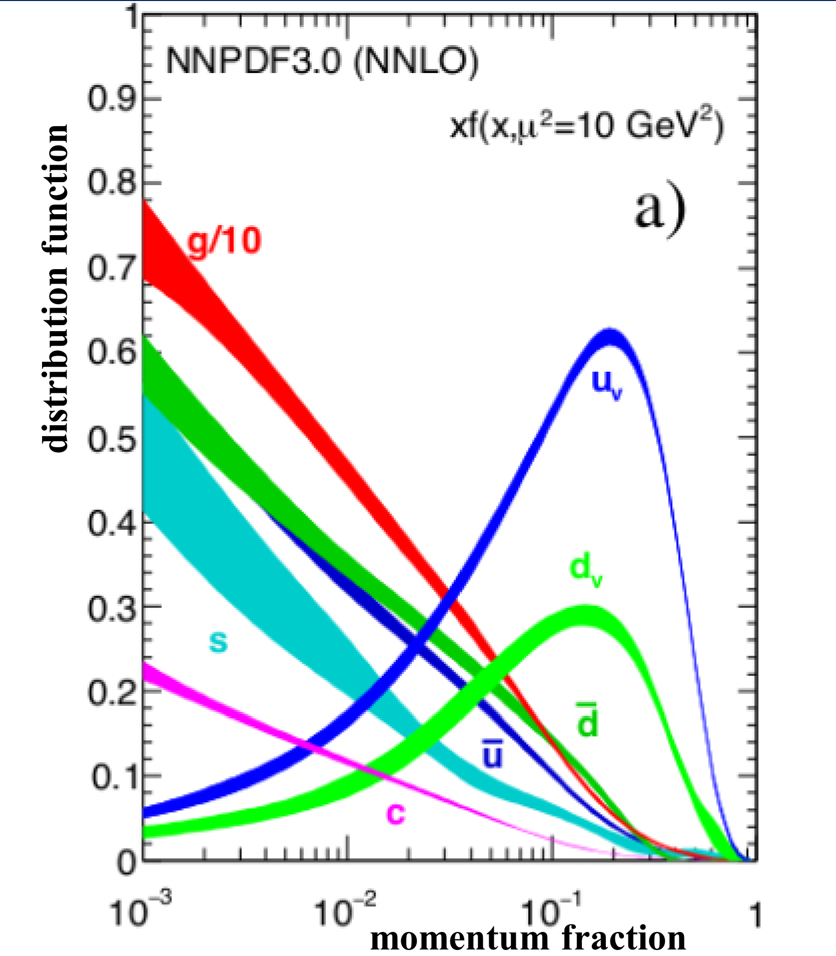




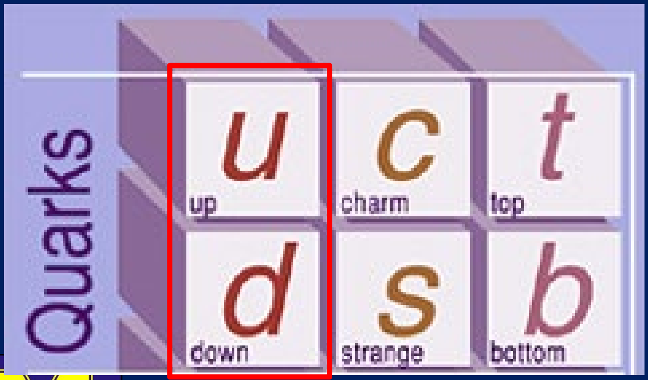
Halzen and Martin, "Quarks and Leptons", p. 201

What have we learned in terms of this picture by now?

- Up and down quark "valence" distributions peaked ~1/3
- Lots of sea quark-antiquark pairs and even more gluons!

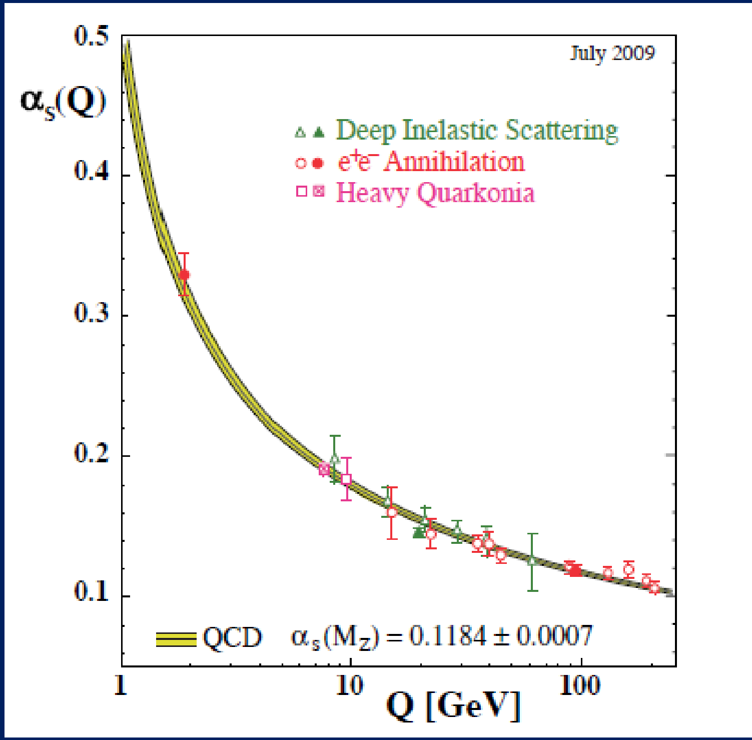


EPJ C76, 647 (2016)



Perturbative QCD

- Take advantage of running of strong coupling constant with energy (*asymptotic freedom*)—weak coupling at high energies (short distances)
- Perturbative expansion as in quantum electrodynamics (but many more diagrams due to gluon self-coupling...)



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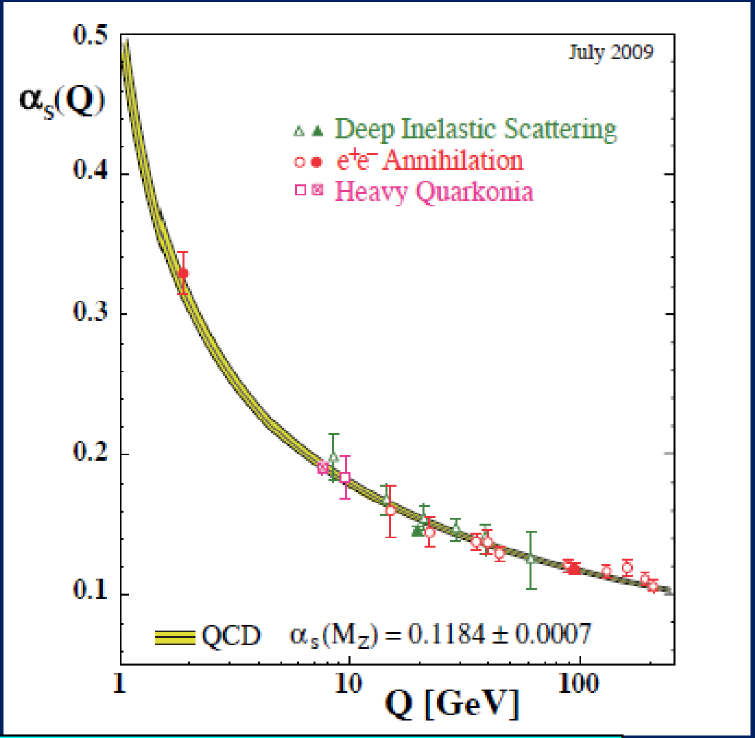


Provides one rigorous way of relating the fundamental field theory to a variety of physical observables

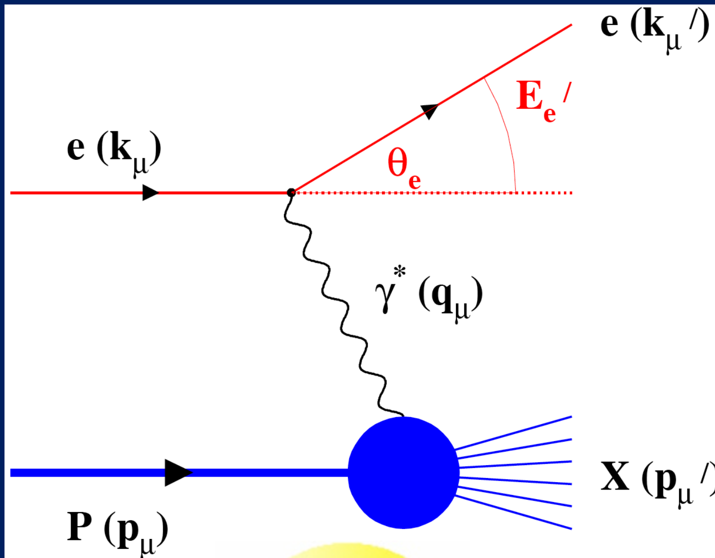
Factorization and universality in perturbative QCD

- Systematically *factorize* short- and long-distance physics
  - Observable physical QCD processes always involve at least one "long-distance" scale of $\sim 10^{-15}$ m describing bound-state structure (confinement)
- Long-distance (i.e. not perturbatively calculable) functions describing structure need to be *universal*
  - Physically meaningful descriptions
  - Portable across calculations for many processes

Constrain functions describing proton structure by measuring scattering cross sections in many colliding systems over wide kinematic range and performing *simultaneous fits to world data*

Accessing quarks and gluons through DIS

Kinematics:



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

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

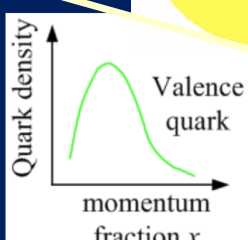
Measure of resolution power

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

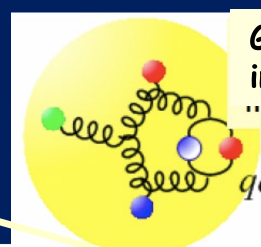
Measure of inelasticity

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

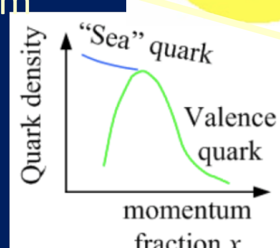
Measure of momentum fraction of struck quark

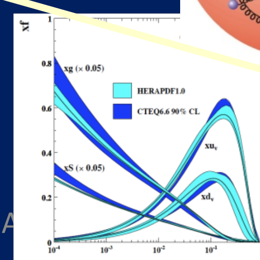


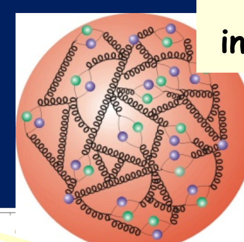
10^{-16}m



Gluon splits into quarks







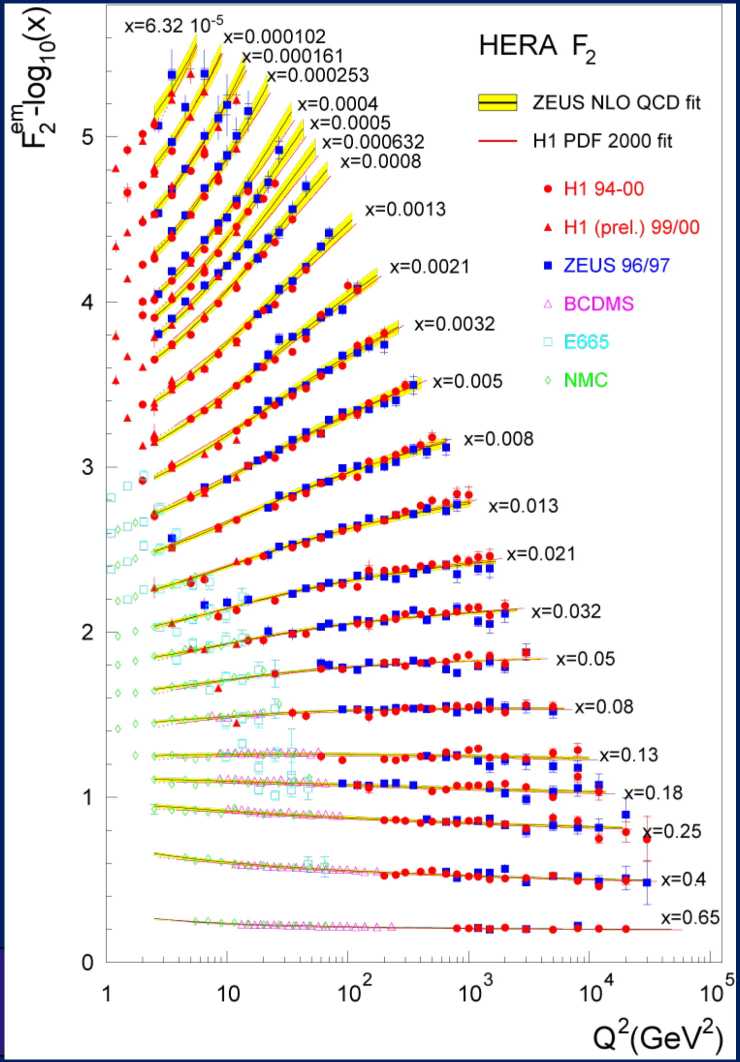
Quark splits into gluon splits into quarks …

10^{-19}m

higher √s increases resolution

Accessing gluons with an electroweak probe

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



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

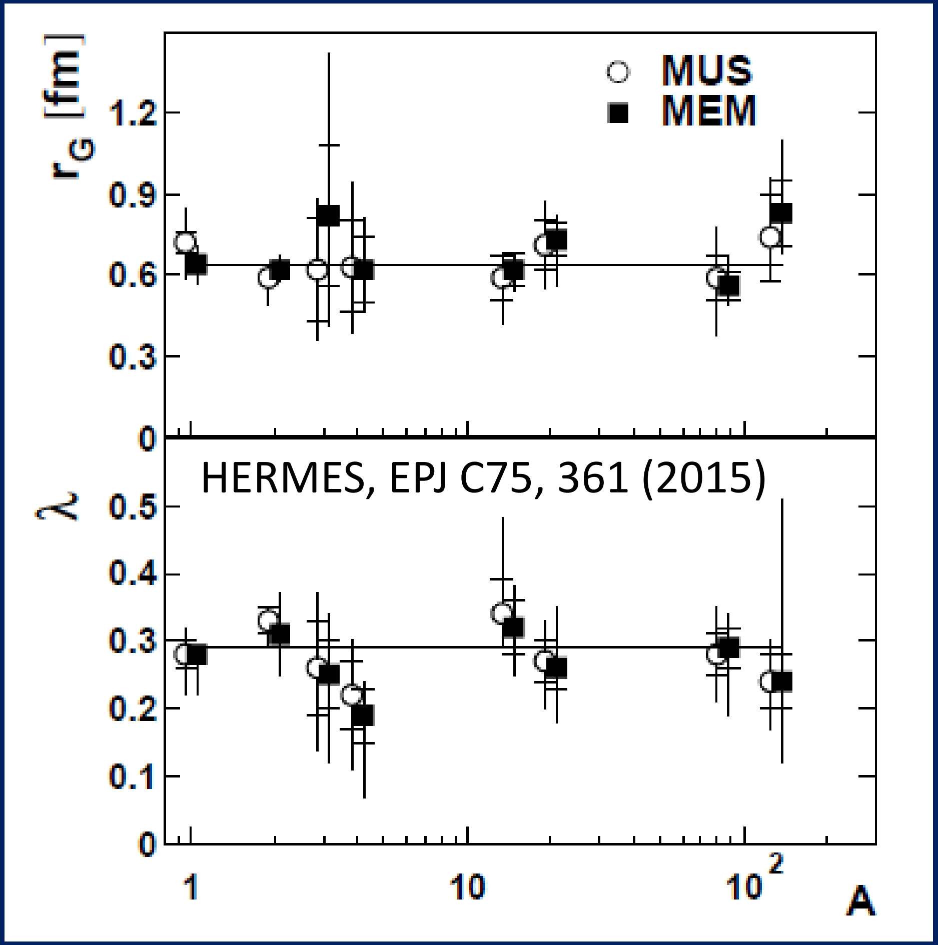
Via dihadron production

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



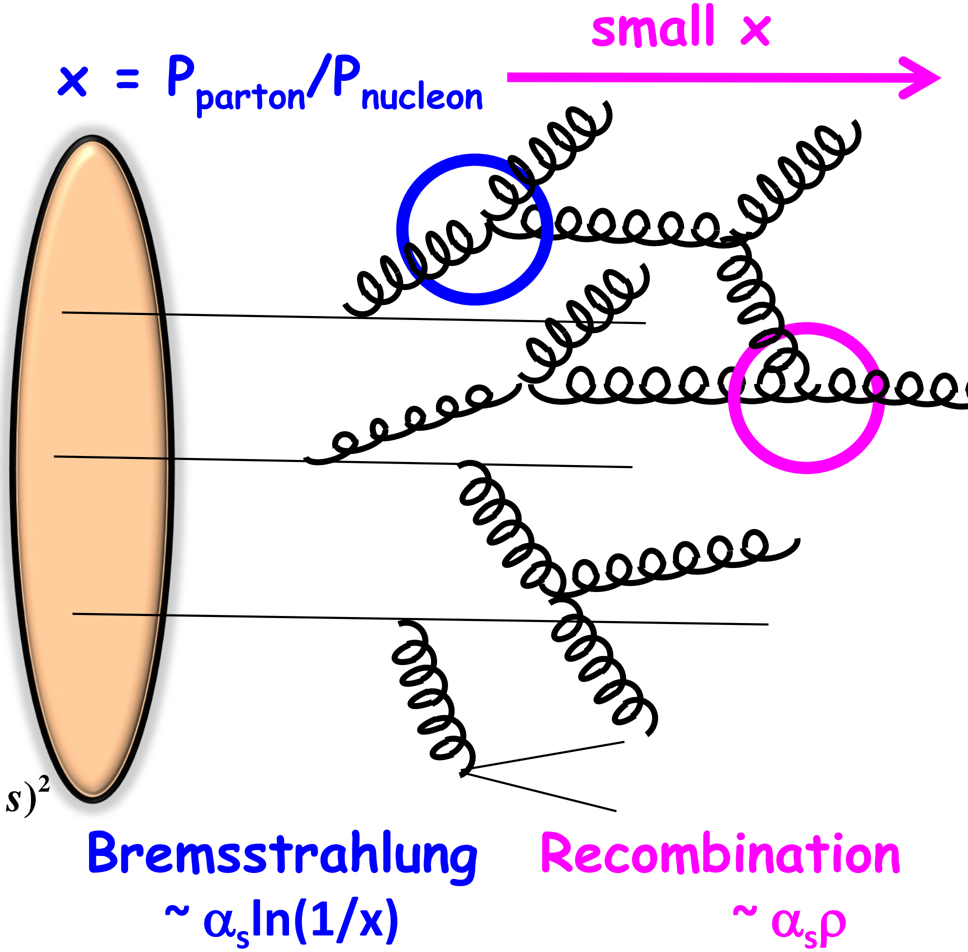
Gluon saturation

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

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

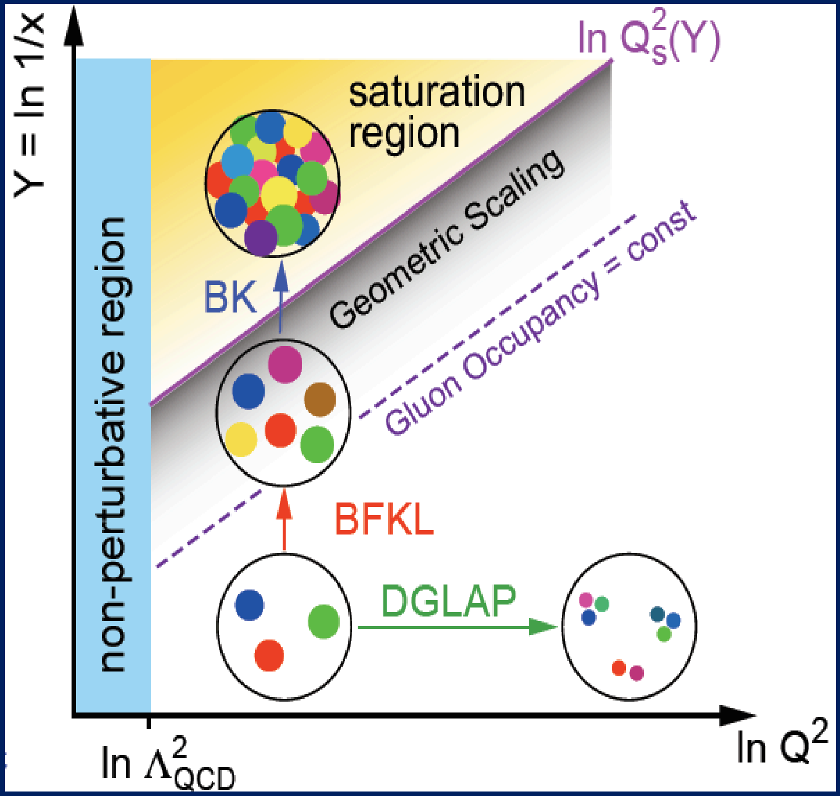
- Dynamically generated scale
  Saturation Scale: $Q^2_s(x)$
  - Increases with energy or decreasing x
- Scale with $Q^2/Q^2_s(x)$ instead of x and Q^2 separately

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

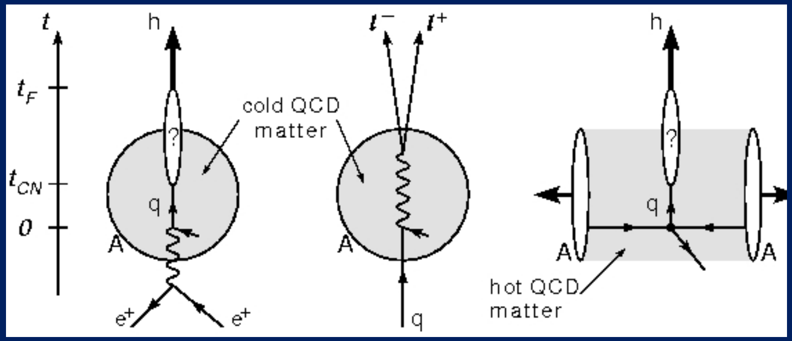


Diffraction to study universal state of gluonic matter: Gluon saturation

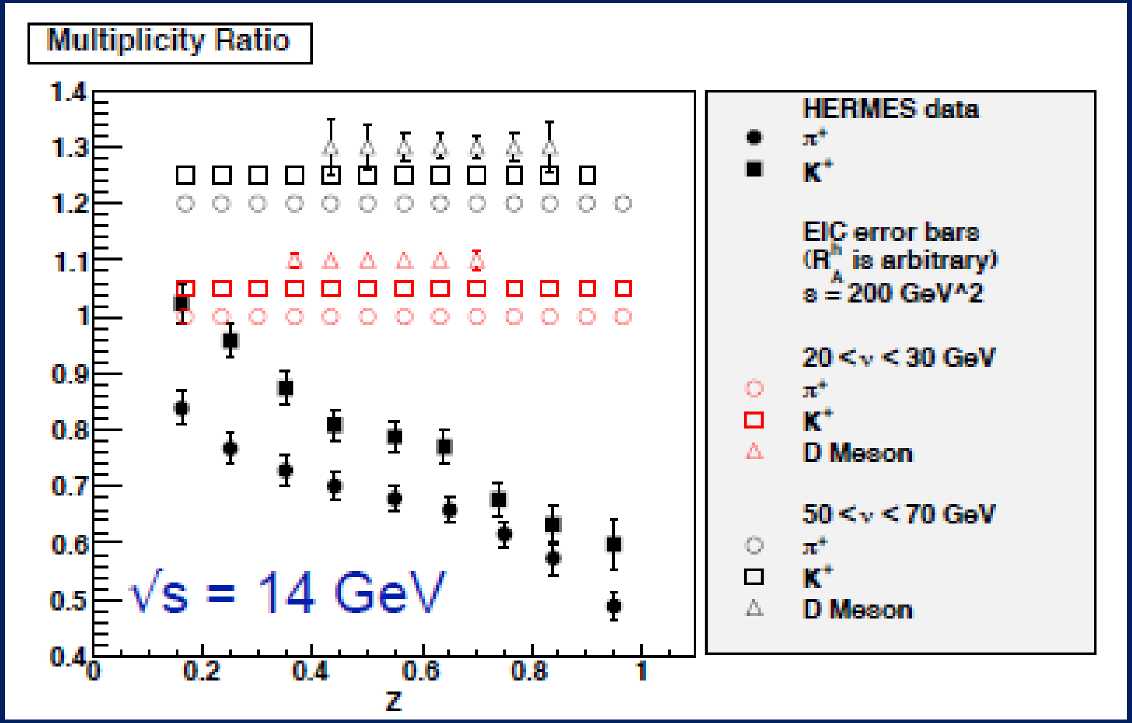
- In addition to probing spatial structure, diffraction is one way to probe gluon saturation within nuclei



Hadronization: Parton propagation in matter



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



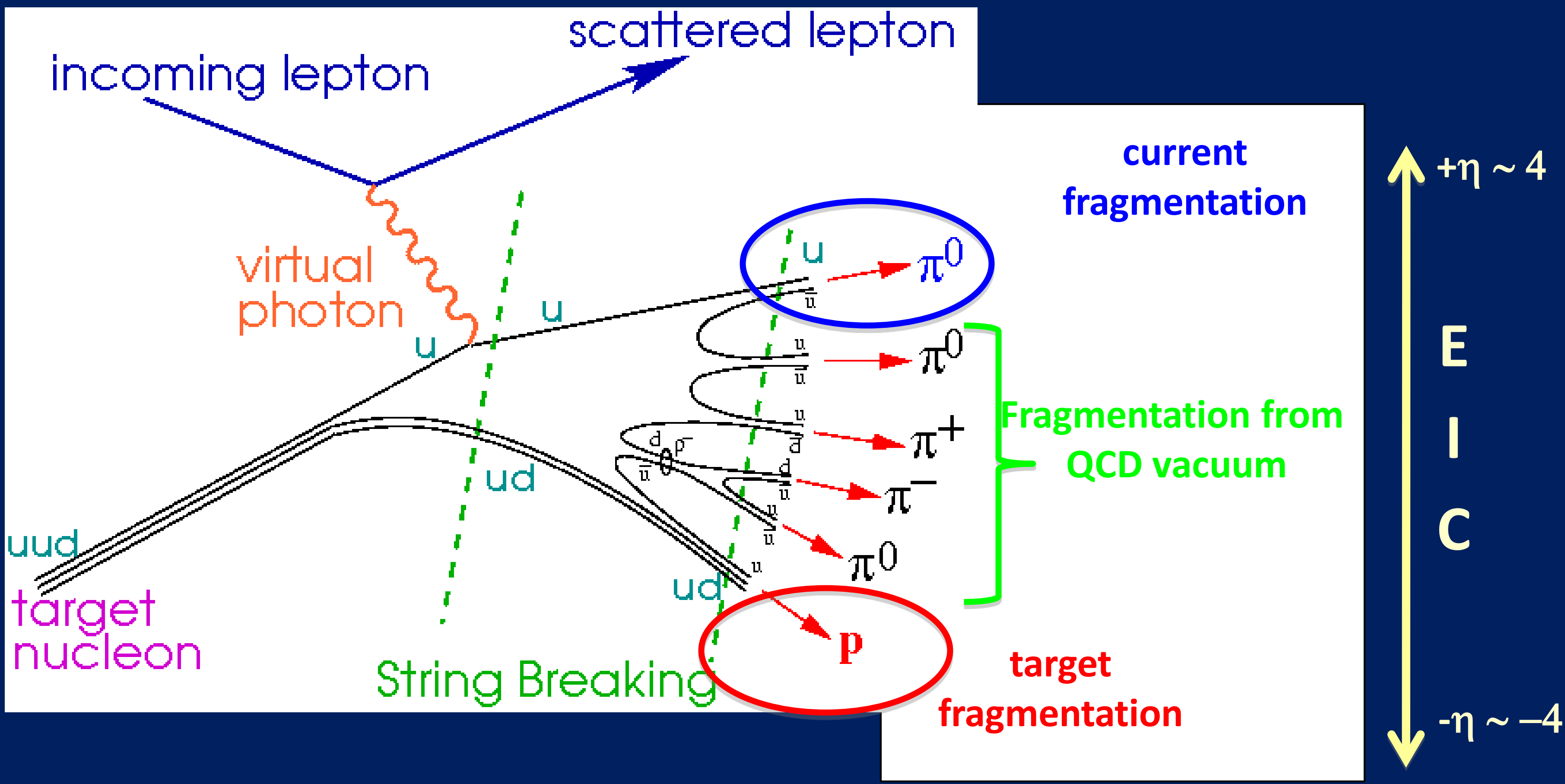
Existing data → hadron production modified on nuclei compared to the nucleon!

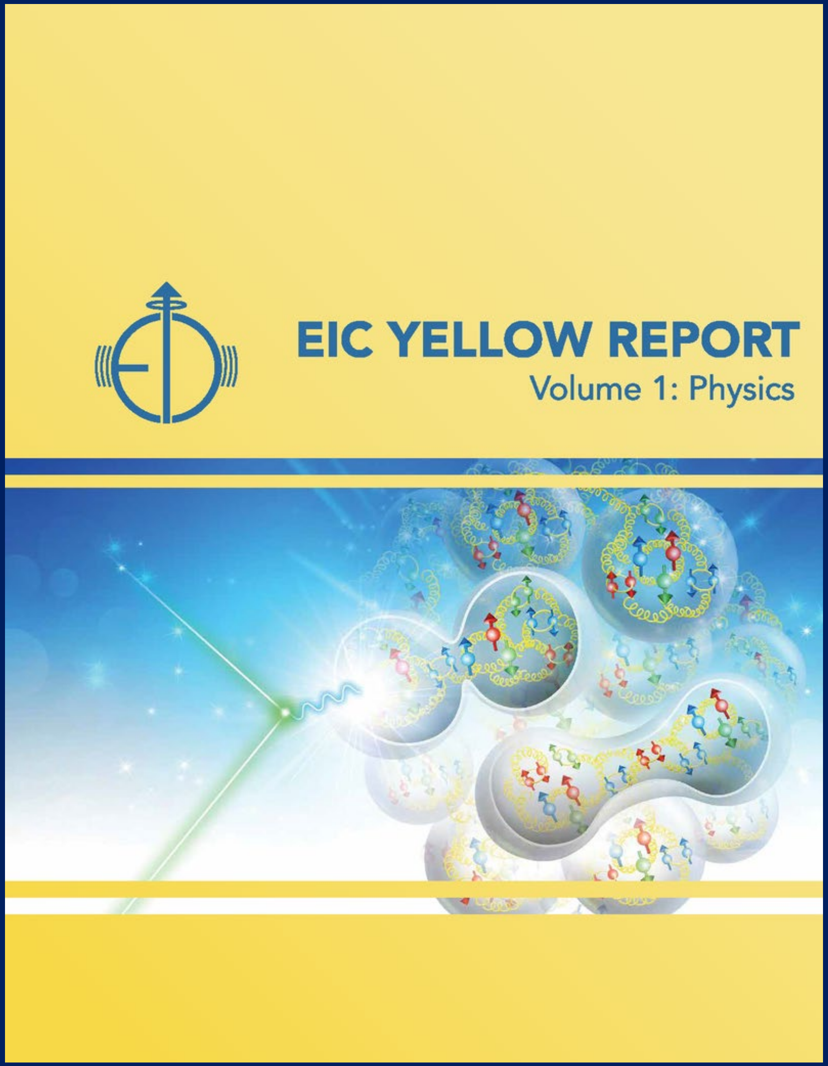
EIC will provide ample statistics and much greater kinematic coverage!

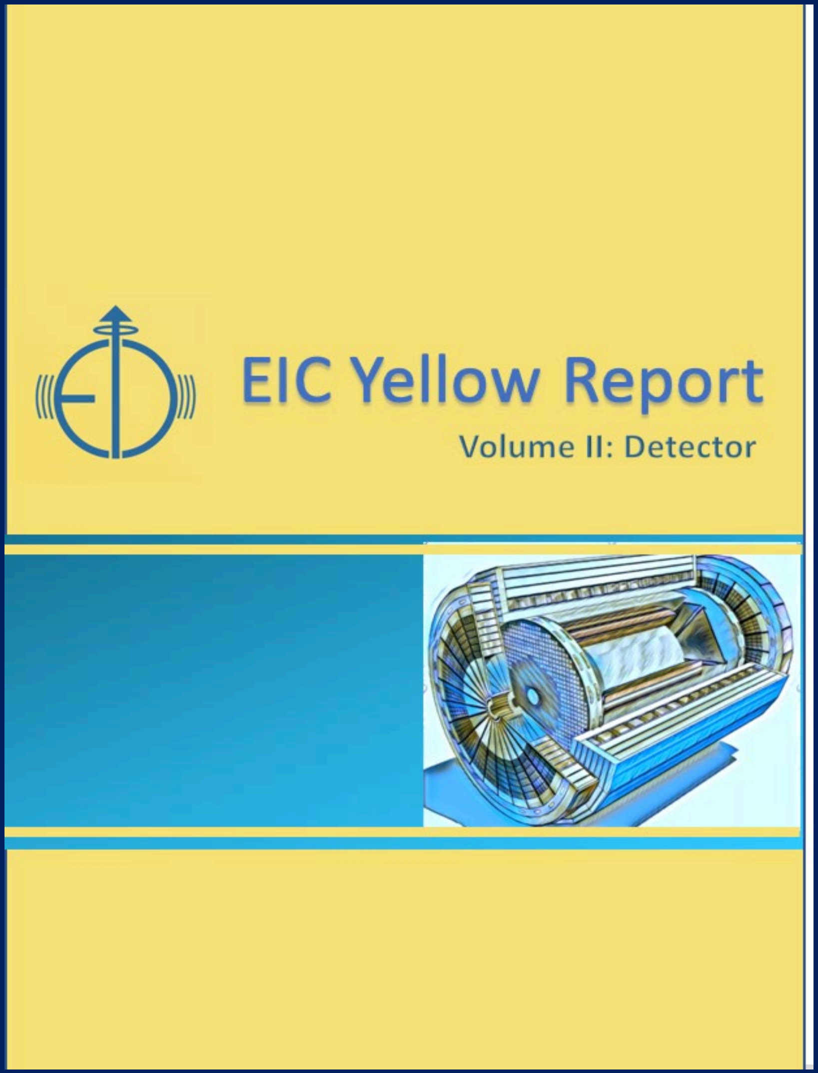
-Study time scales for color neutralization and hadron formation

- e+A complementary to jets in A+A: cold vs. hot matter

Formation of QCD bound states: Hadronization at EIC

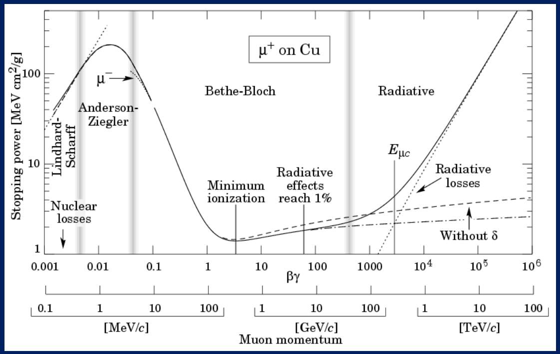



EIC YELLOW REPORT
Volume 1: Physics


EIC Yellow Report
Volume II: Detector

Interactions within QCD

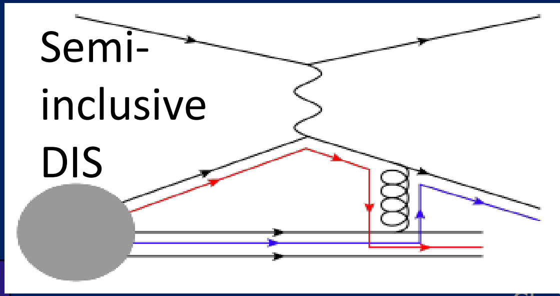
- Quark and gluon energy loss in cold and hot QCD matter
  - I.e. Bethe-Bloch curve for QCD rather than electromagnetism

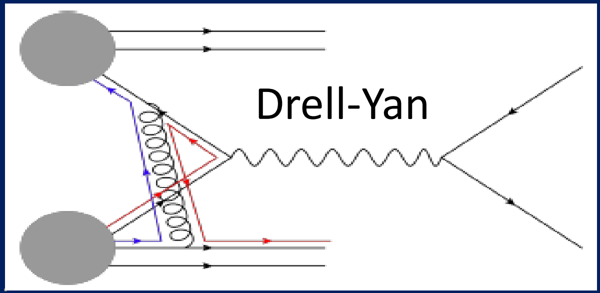


Electromagnetic energy loss of muons passing through copper

- Quantum interference and phase shifts
  - E.g. quantum interference effects in hadronization
    - One quark or gluon → multiple hadrons
    - Multiple quarks or gluons → one hadron

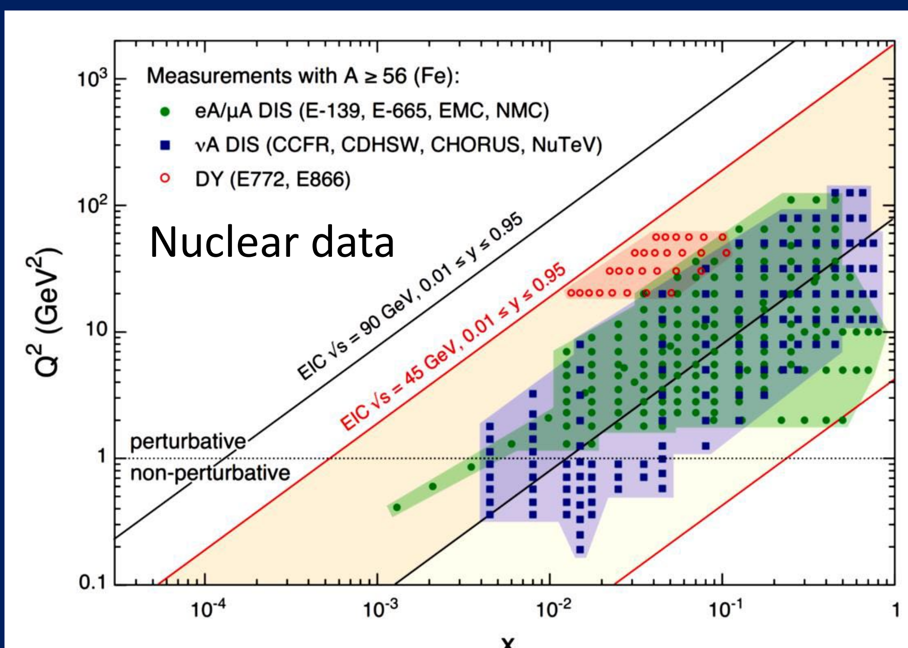
- Color charge flow effects
  - Process-dependent spin-momentum correlations in hadrons
  - Quantum entanglement of quarks across colliding hadrons

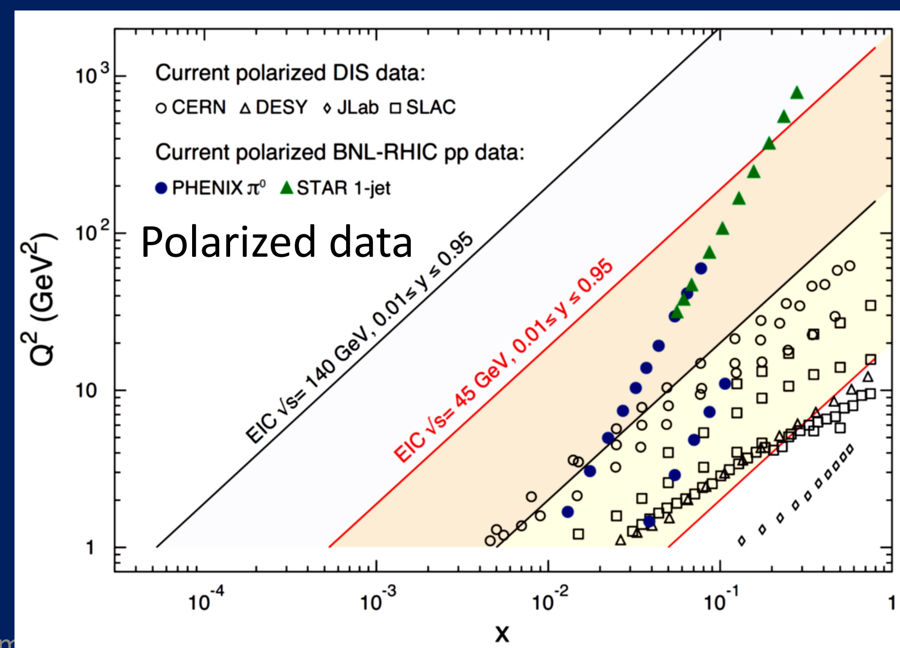




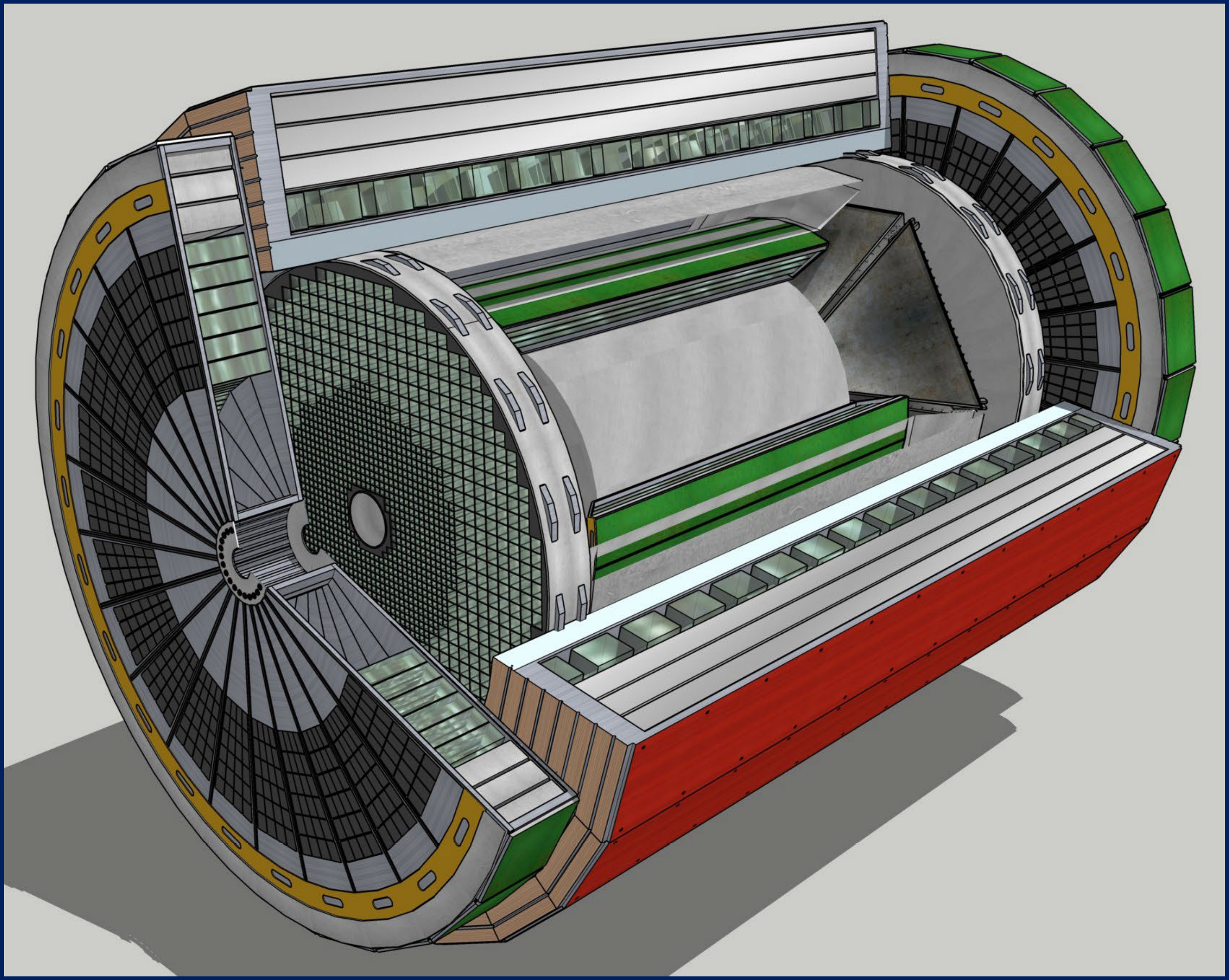
Going beyond previous facility capabilities

- 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





An EIC detector concept



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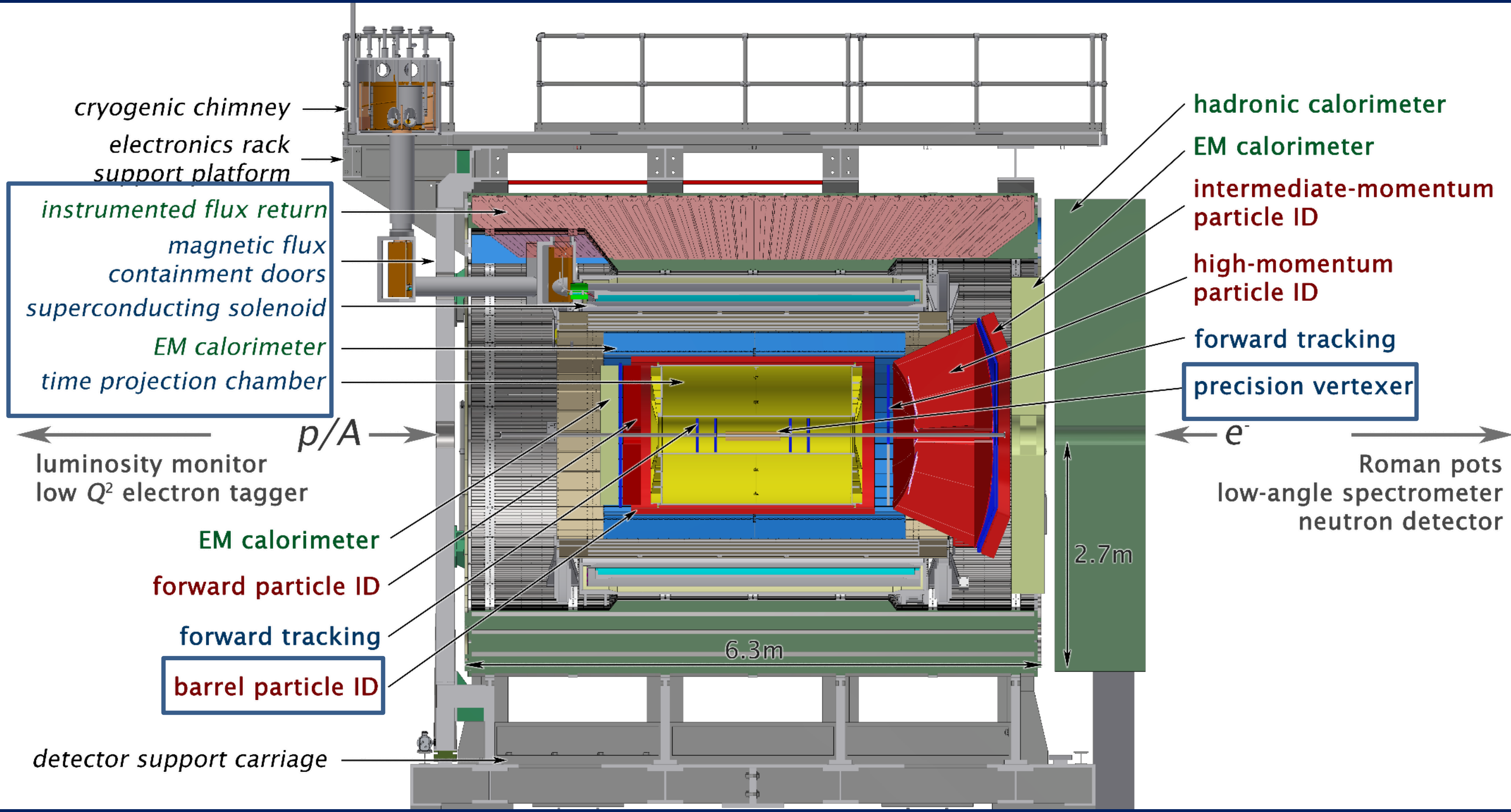

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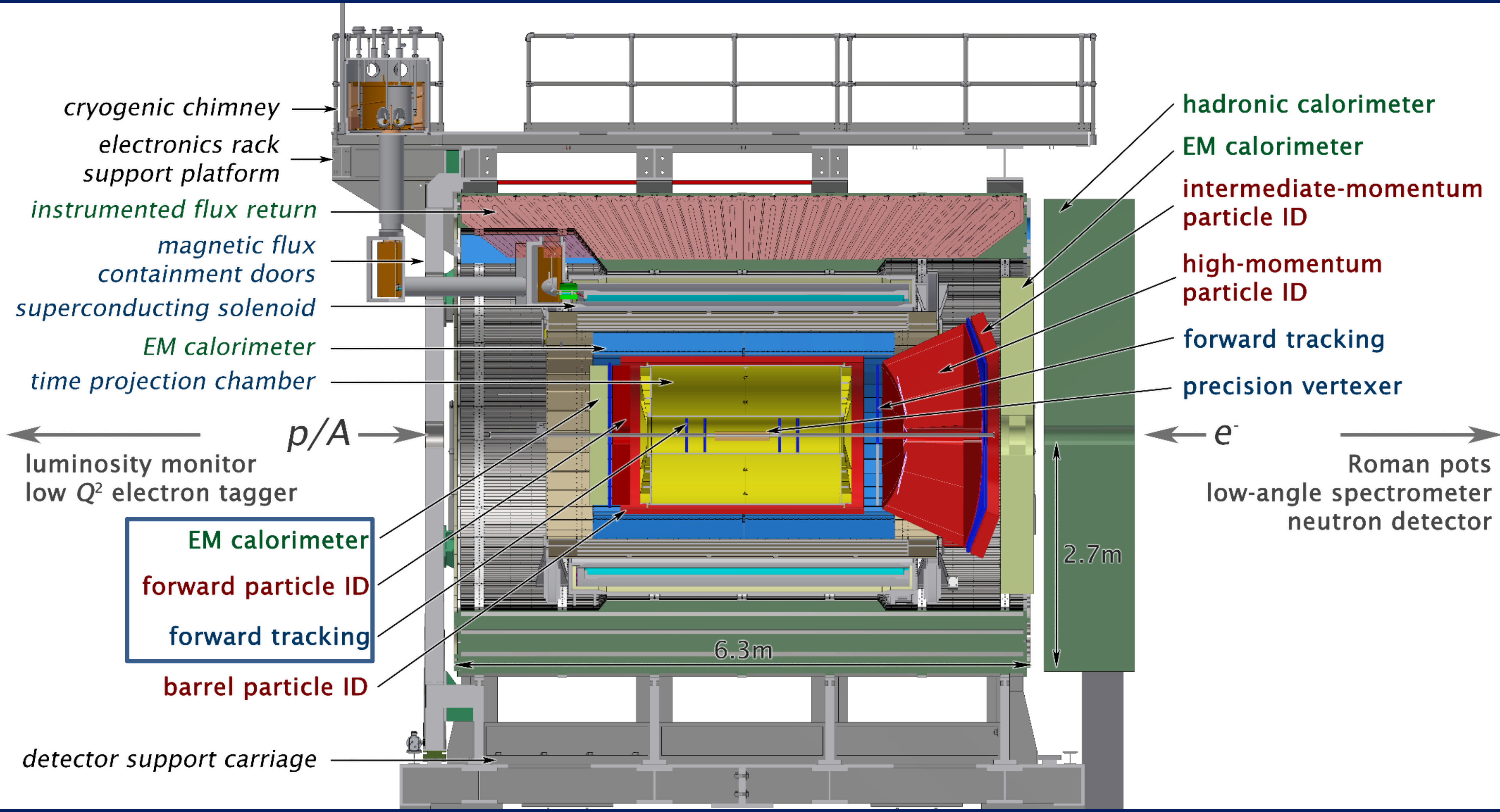

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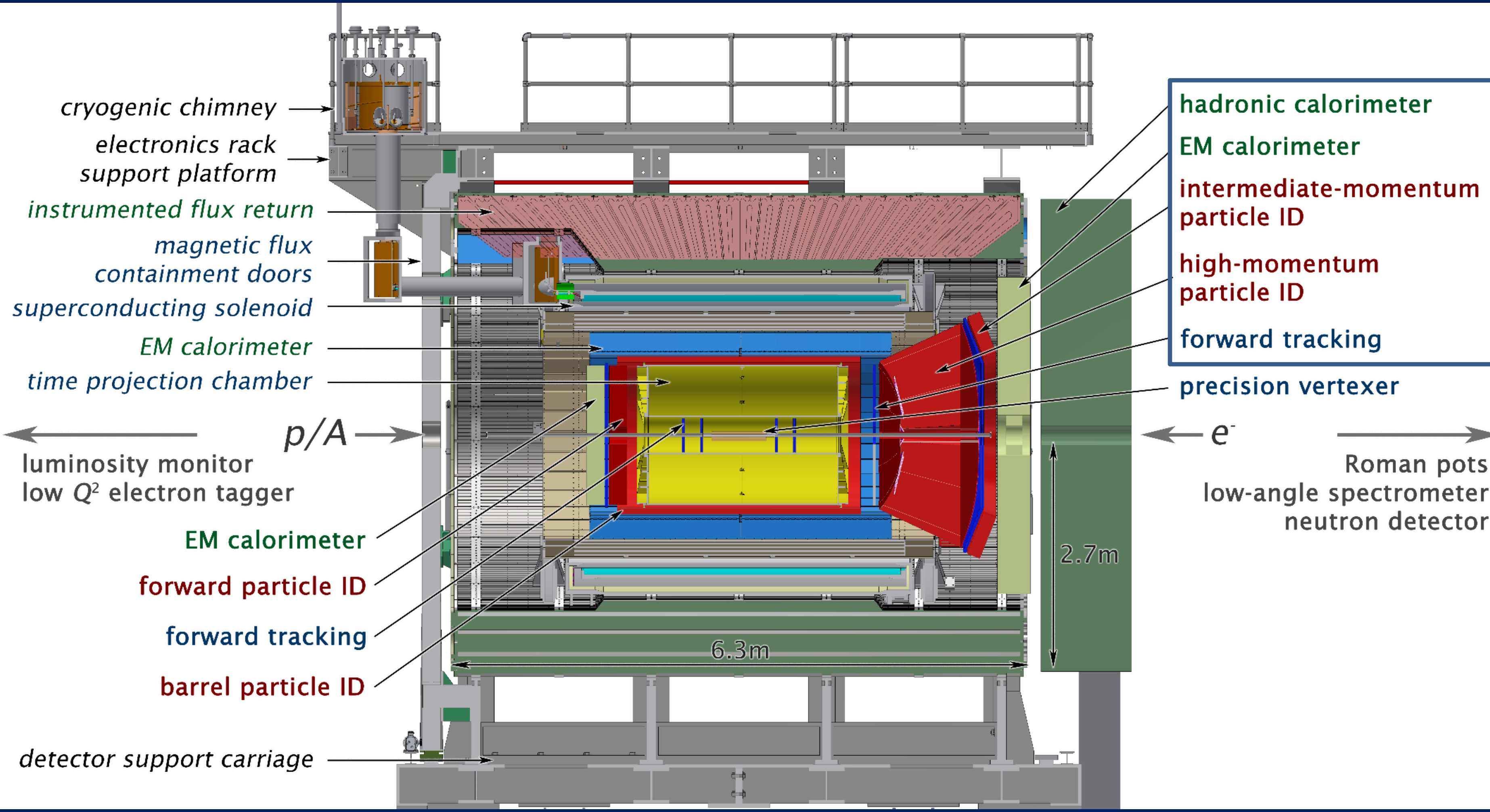

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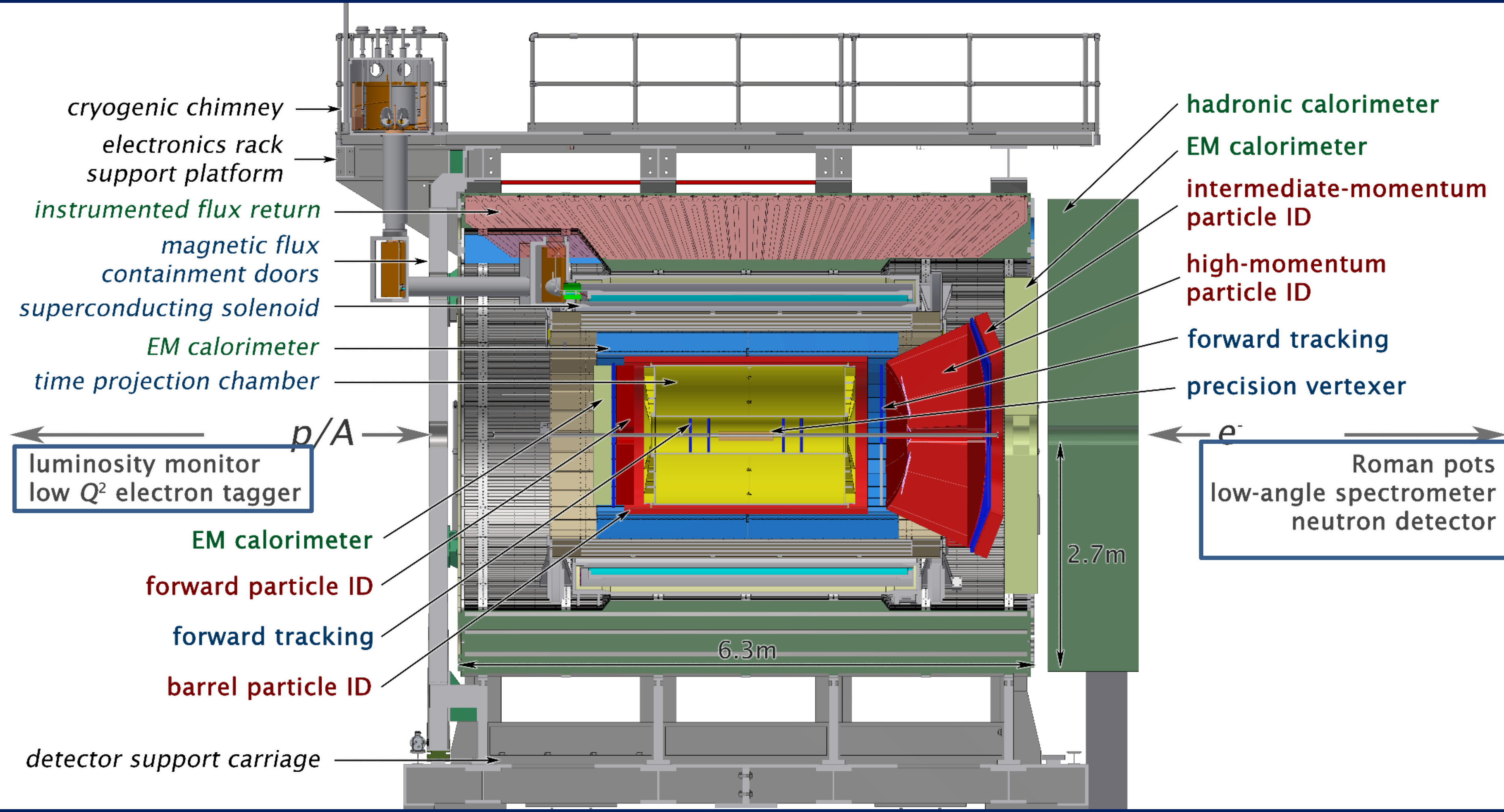

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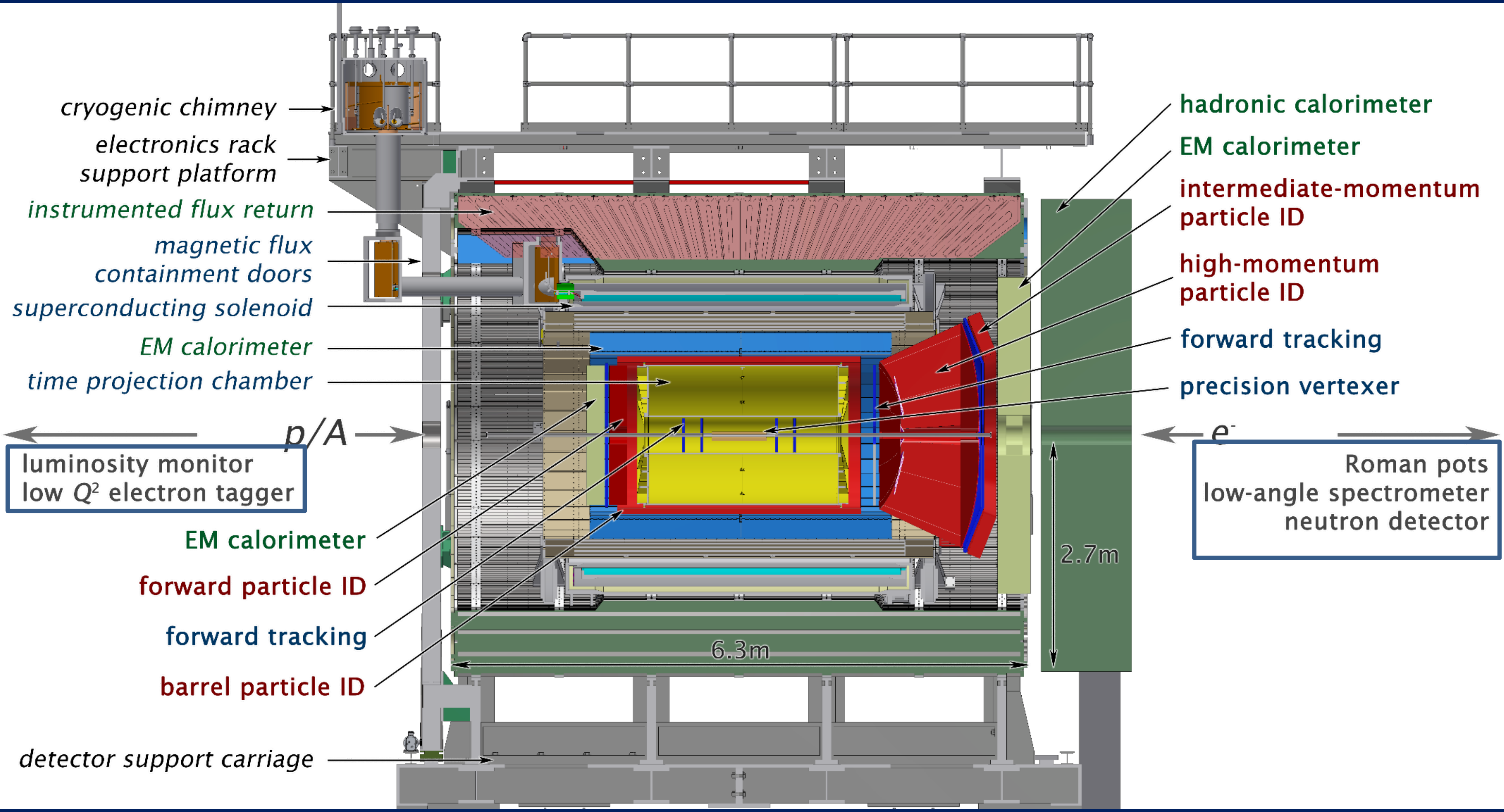
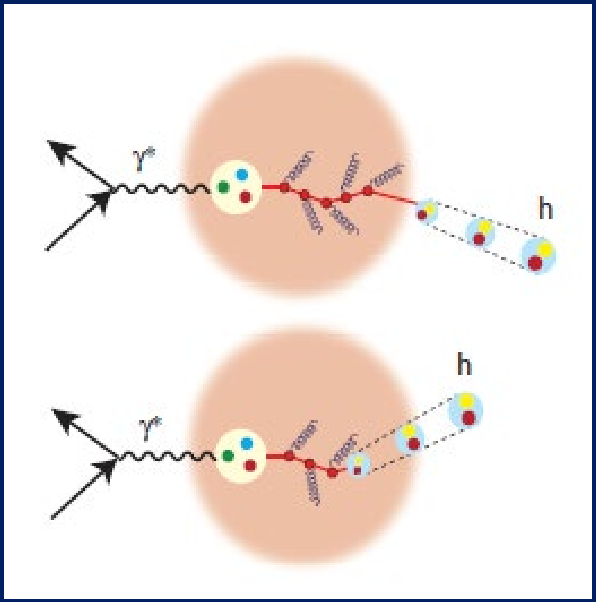
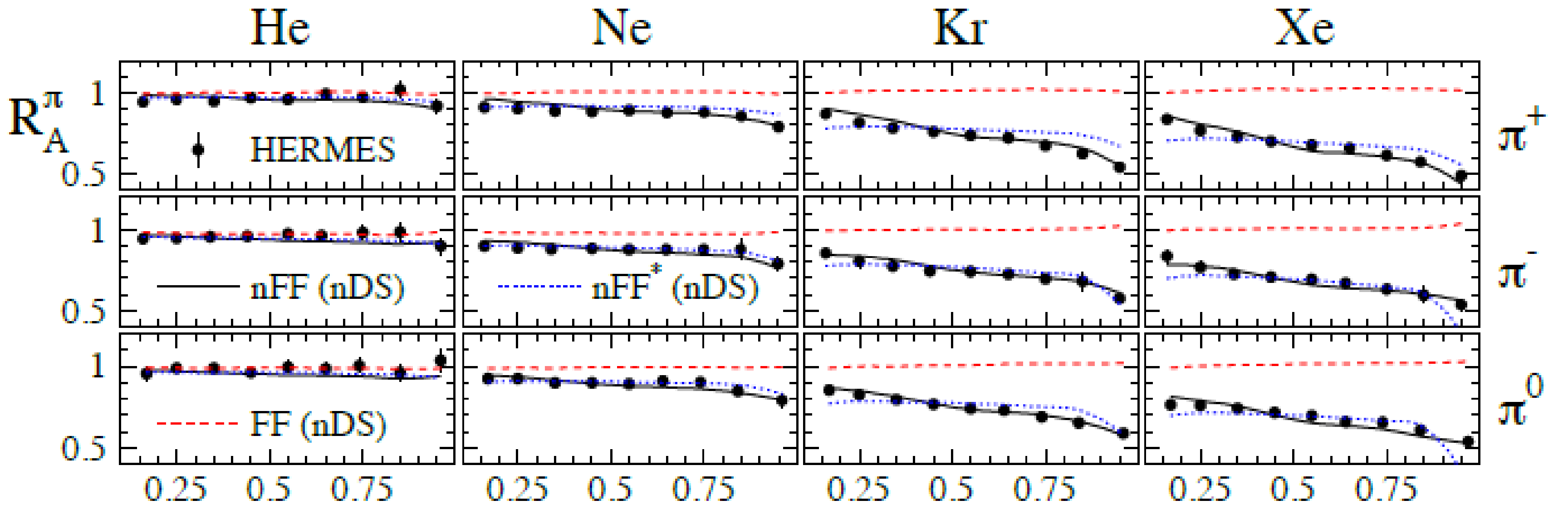


Formation of QCD bound states: Hadronization at EIC

- 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

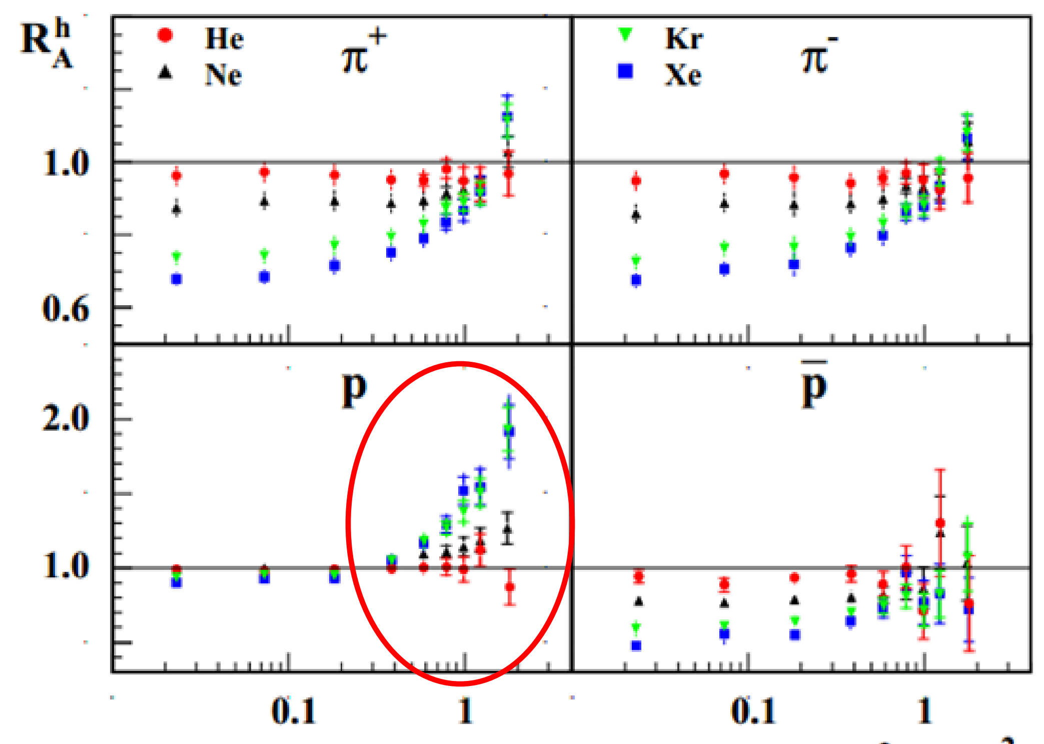


EPJA47, 113 (2011)

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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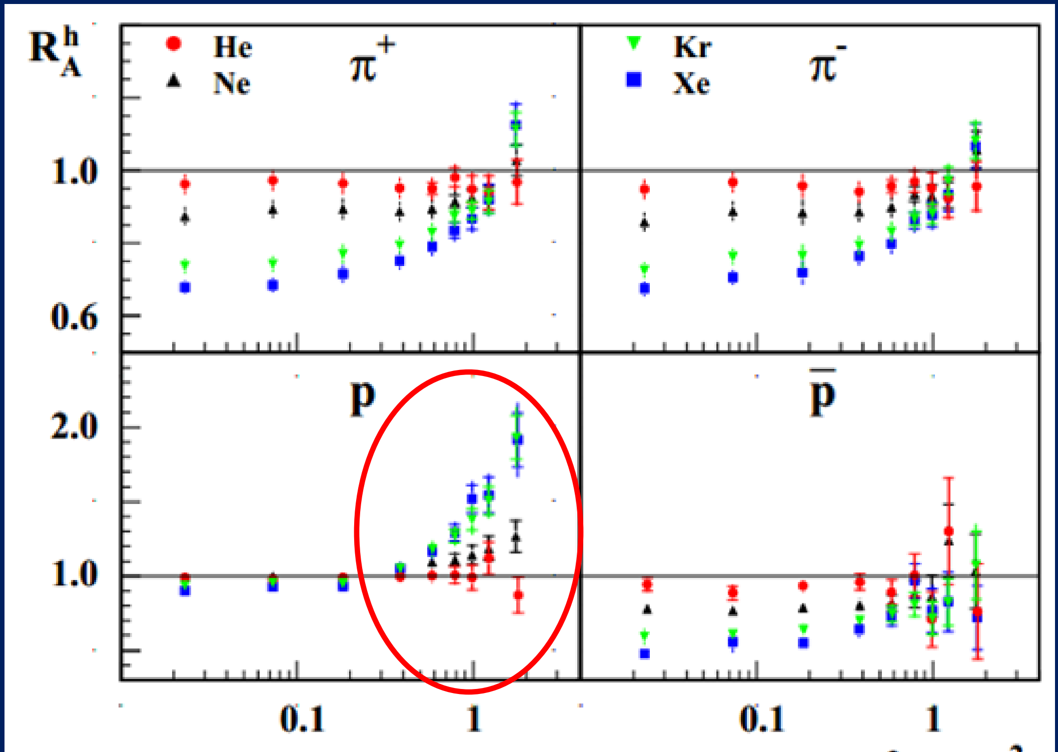
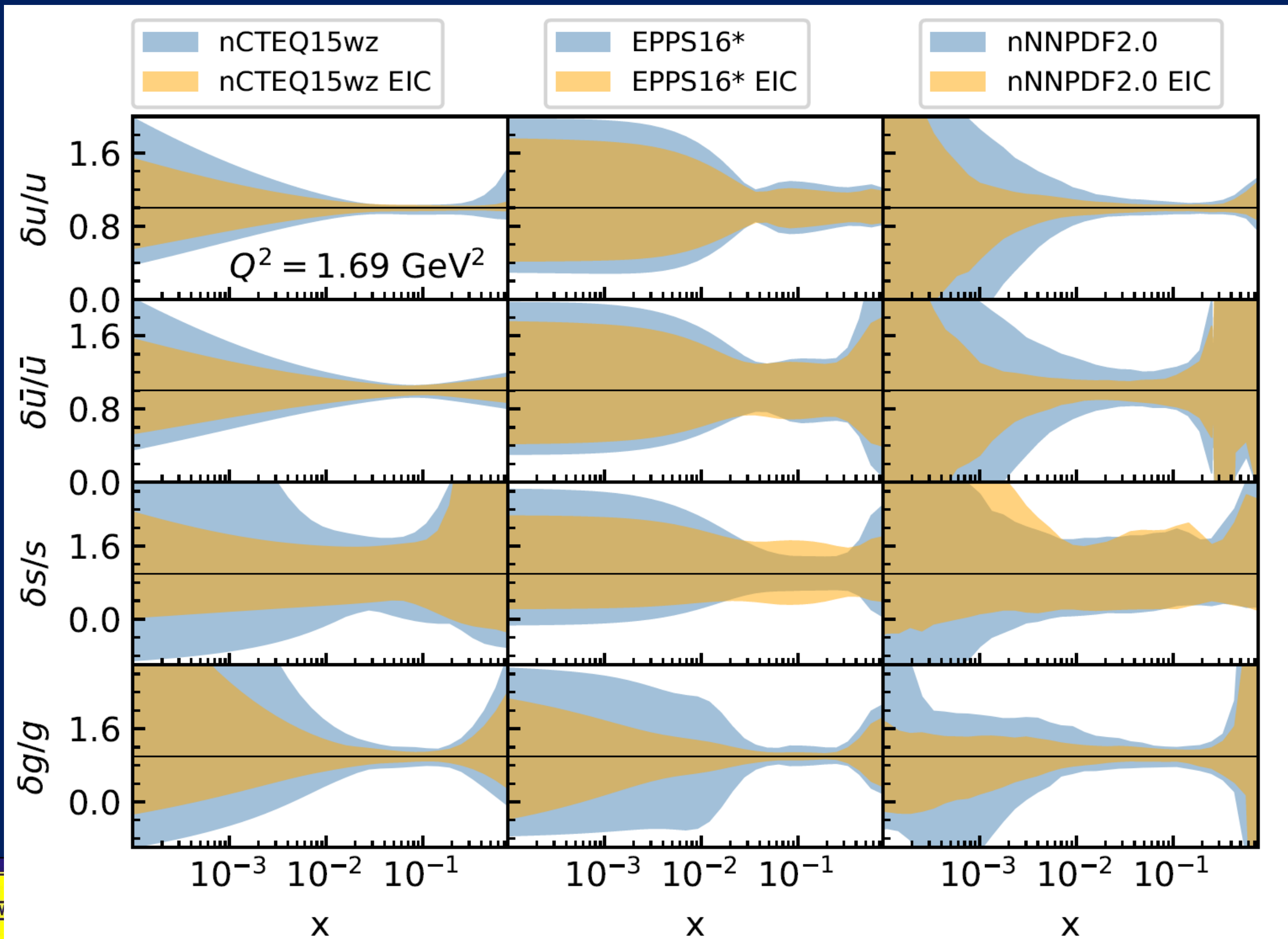


HERMES, NPB780, 1 (2007)

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

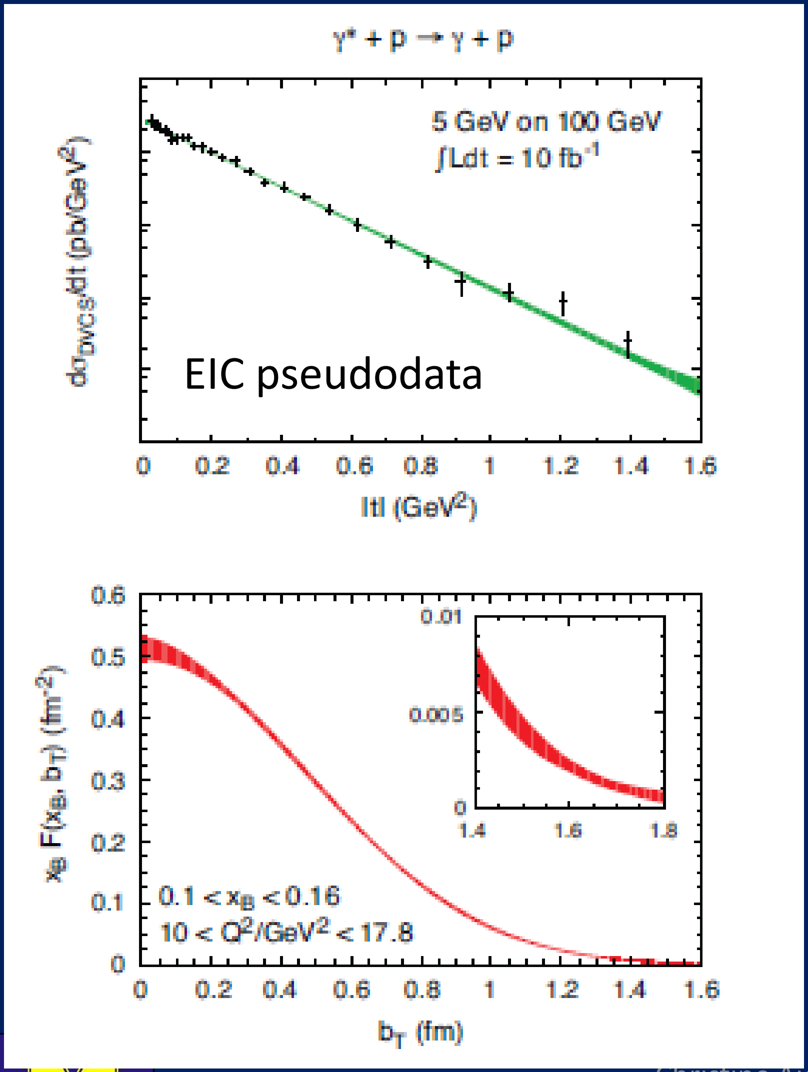
Partonic momentum structure of nuclei: Nuclear parton distribution functions

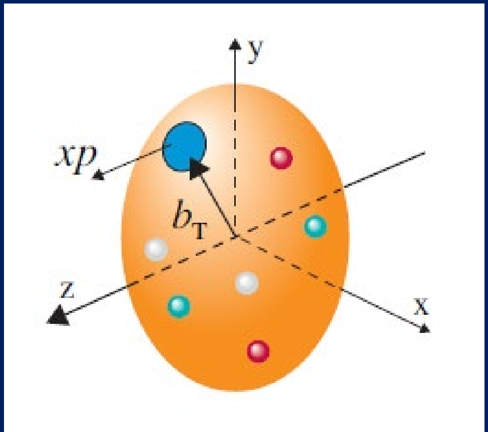
(Traditional collinear, unpolarized) Nuclear PDFs



Expected improvement on uncertainty in nuclear PDFs - from Yellow Report

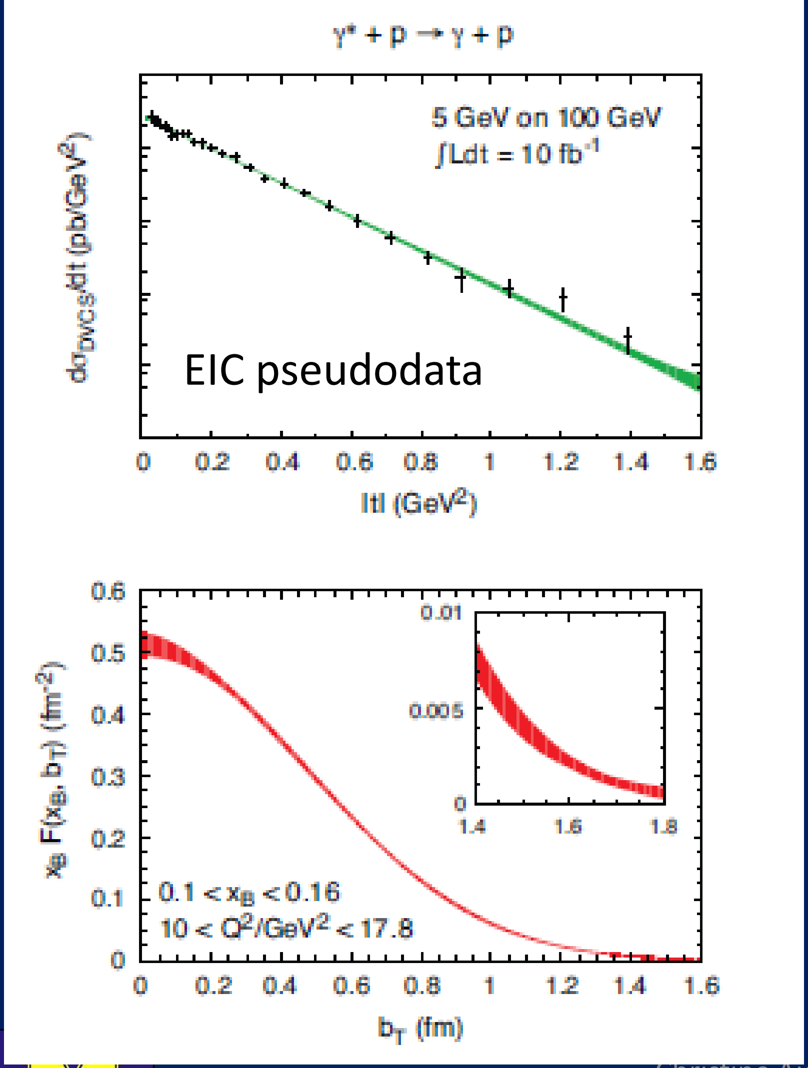
Partonic spatial structure of nuclei: Diffraction

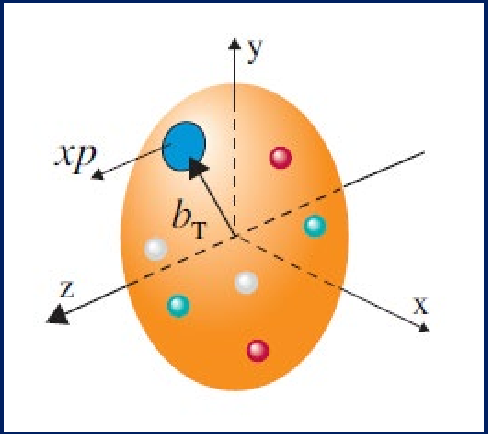




Goal: Cover wide range in *t*.
Fourier transform → impact-parameter-space profiles.
Obtain *b* profile from slope vs. *t*.

Partonic spatial structure of nuclei: Diffraction





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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