Why We Need An EIC

The view from 30,000 feet

Berndt Mueller
ALD for NPP

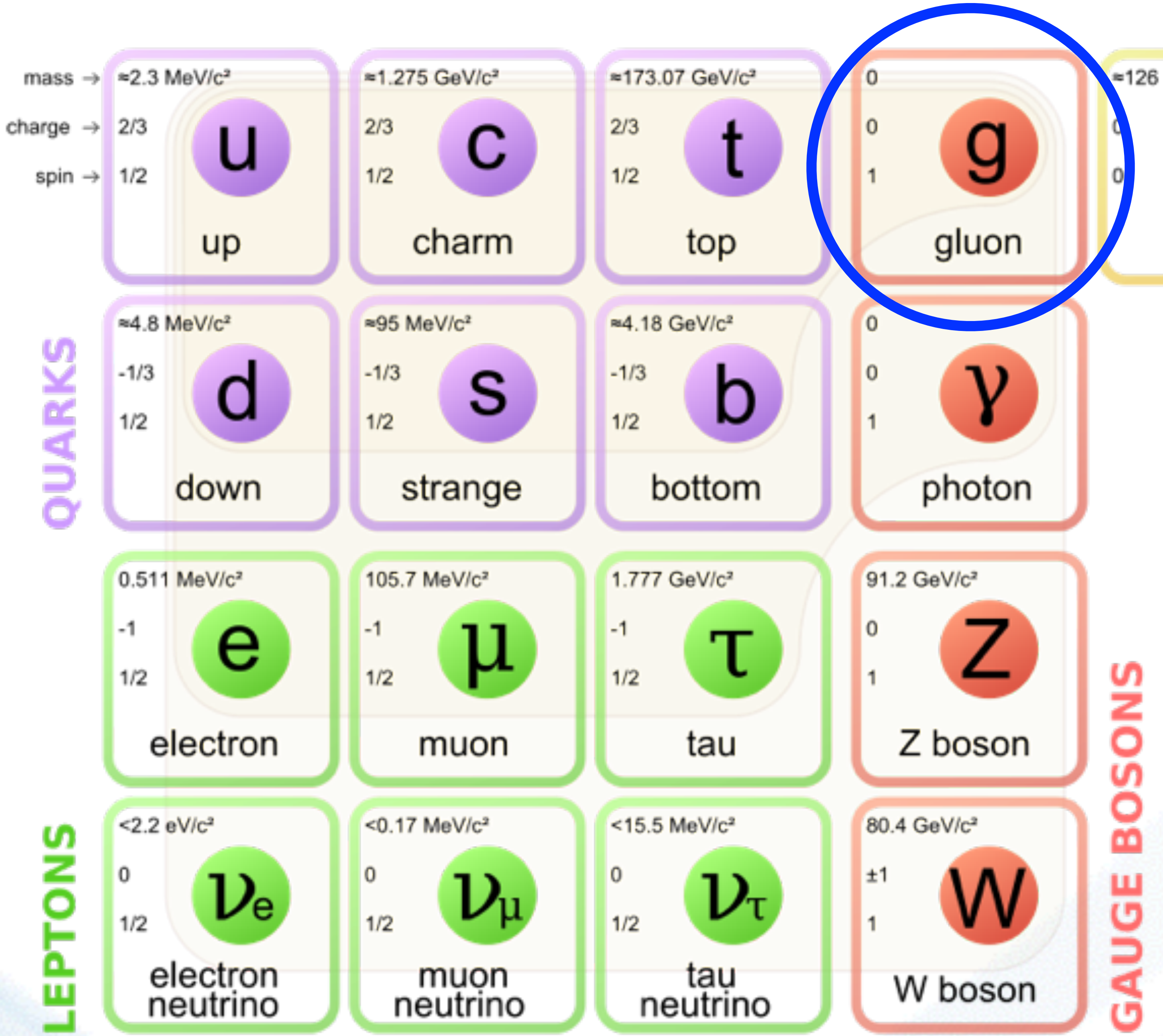
The 2013 NSAC *Subcommittee on Future Facilities* identified the physics program for an Electron-Ion Collider as ***absolutely central*** to the nuclear science program of the next decade.

QCD Town Meeting
14 September 2014

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery
Office of Science
U.S. DEPARTMENT OF ENERGY

The Mysterious Gluon

Standard Model particles

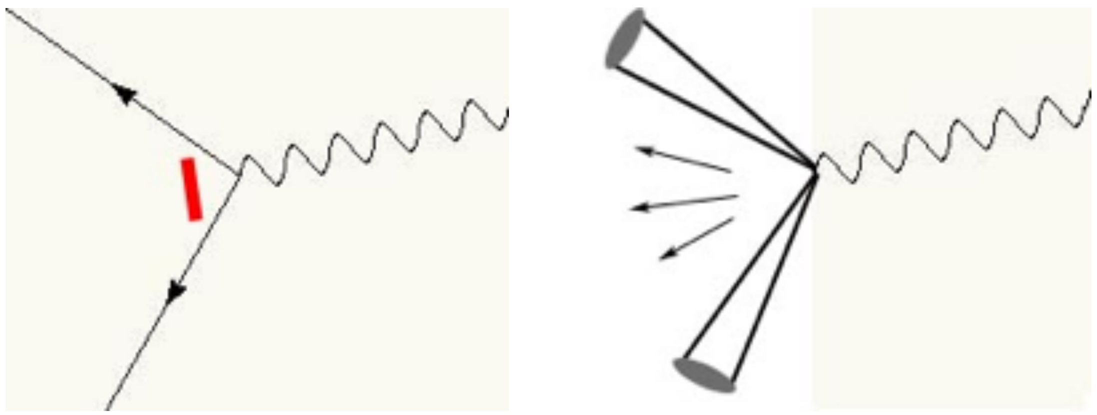


Gluons are **gauge bosons** like **photons** [massless (?) and spin 1], but they carry the SU(3) **color** charge.

Gluons carry no electric or weak charge - they cannot directly interact with photons.

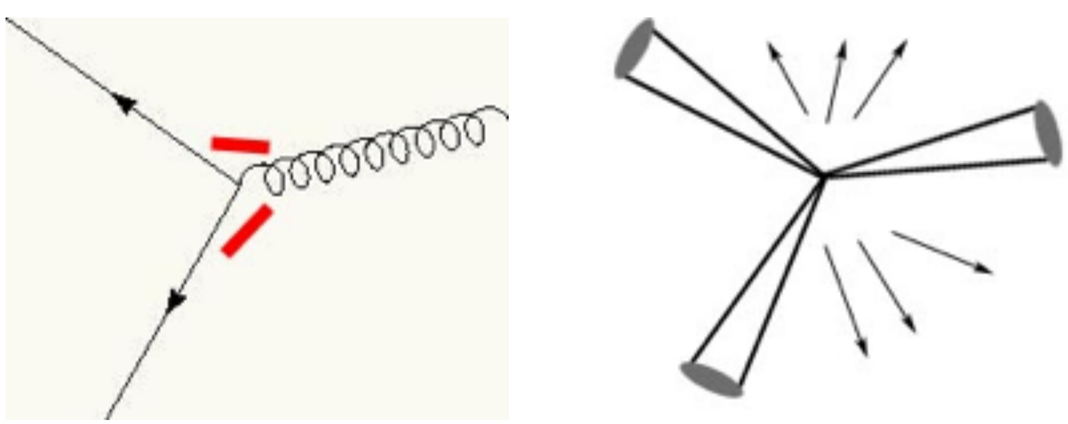
We know their coupling to quarks and self-coupling with moderate precision.

Three-jet events



quark-antiquark-photon “3-jet”

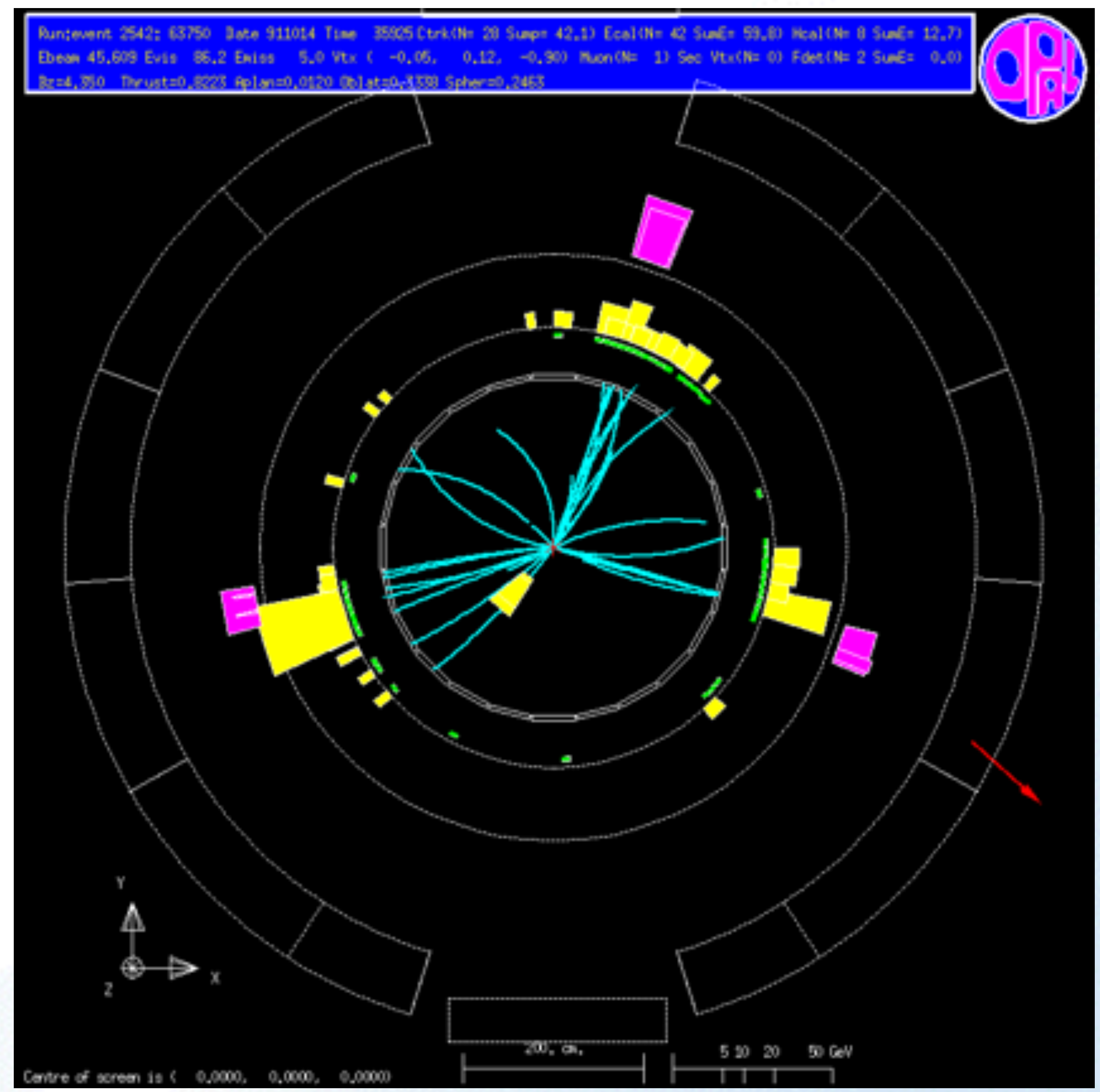
= color flux tube (Lund “string”)



quark-antiquark-gluon 3-jet

Originally discovered by TASSO @ PETRA

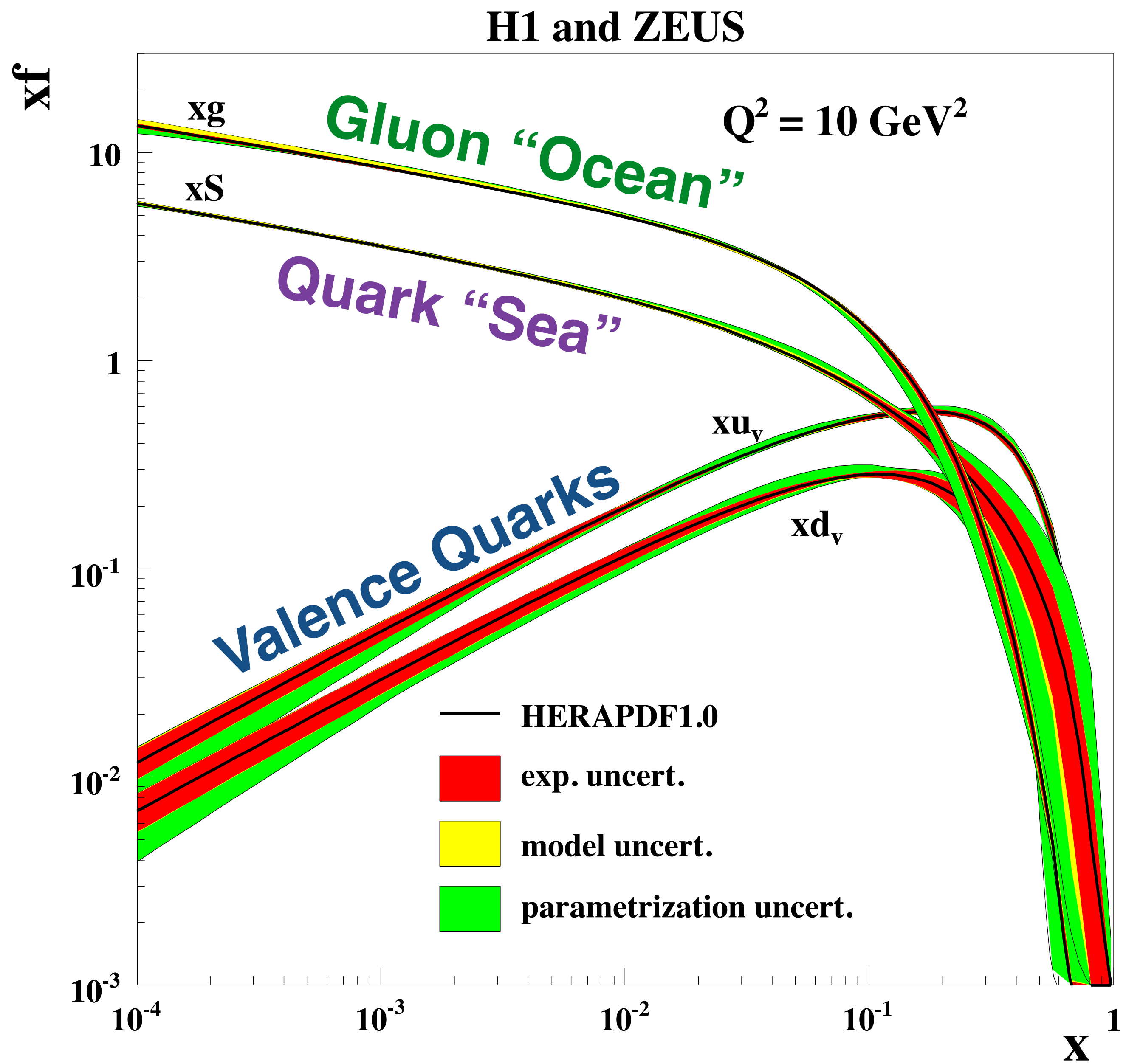
Later explored in great detail at LEP



Gluons are weird particles

- Gluons, like quarks, never occur in isolation.
- So far, gluons have only been observed as short-lived, virtual quanta.
- States solely made of gluons (“glueballs”) should exist, but have never been unambiguously identified.
- Free space without glue fields is unstable against the spontaneous formation of chromo-magnetic fields.
- We are constantly immersed in a gluon condensate, similar to the Higgs condensate: $\langle G^2 \rangle^{1/4} \approx 0.6$ GeV.
- The detailed structure of the gluon condensate and the mechanism by which it creates quark confinement is still unknown - many different models compete.

Gluon Ocean and Quark Sea



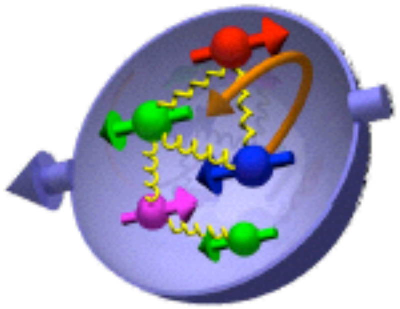
The Quark "Sea" derives from the Gluon "Ocean" by gluon splitting into a quark-antiquark pair: suppressed by factor $N_F\alpha_s/\pi$.

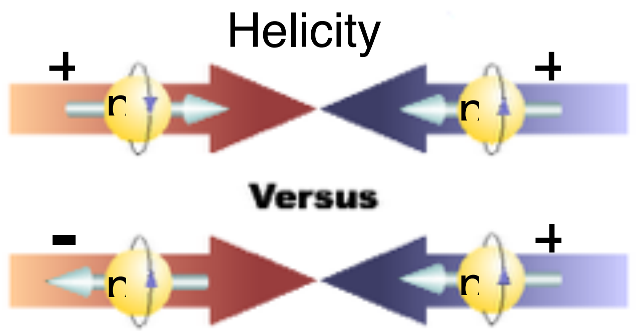
Clean separation of gluons and sea quarks from valence quarks requires experiments probing $x < 0.01$, or nucleon energies of order 100 GeV.

RHIC provides polarized protons up to 255 GeV and nuclei up to 100 GeV/nucleon.

Where is the proton spin?

$$S = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$





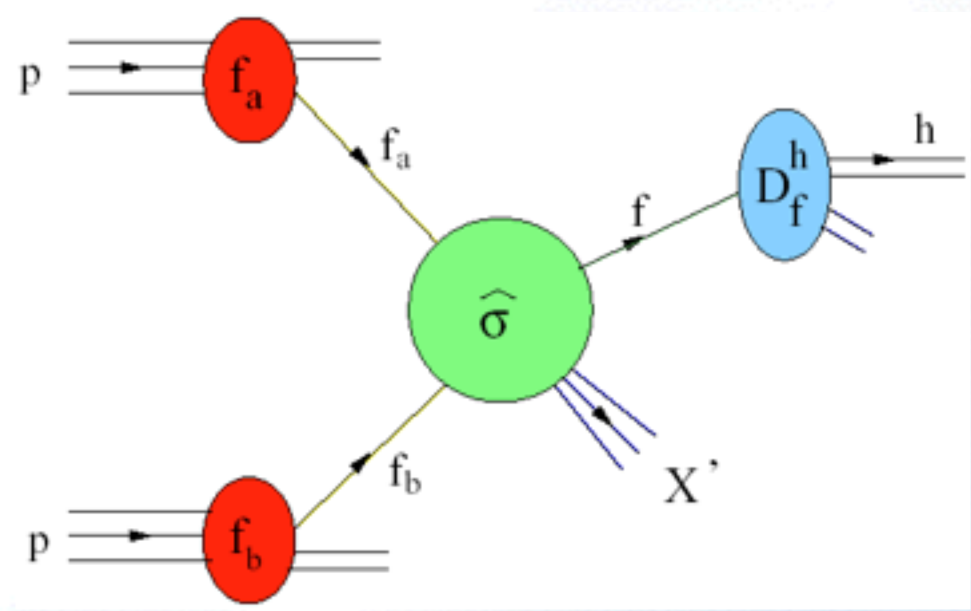
- Polarized DIS tells us that $\Delta\Sigma \approx 0.3$

- Q^2 evolution in polarized DIS gives information on gluon polarization but limited kinematic coverage leaves ΔG poorly constrained

- A primary goal of RHIC Spin program is to map $\Delta g(x)$

$$\Delta G = \int_0^1 \Delta g(x)\,dx$$

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}}$$

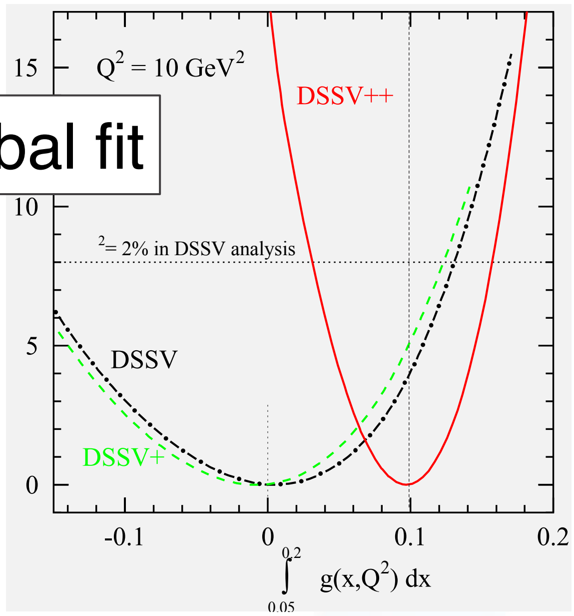


$$A_{LL} \propto [\omega_{gg}]\Delta g \Delta g + [\omega_{gq}\Delta q]\Delta g + [\omega_{qq}\Delta q \Delta q]$$

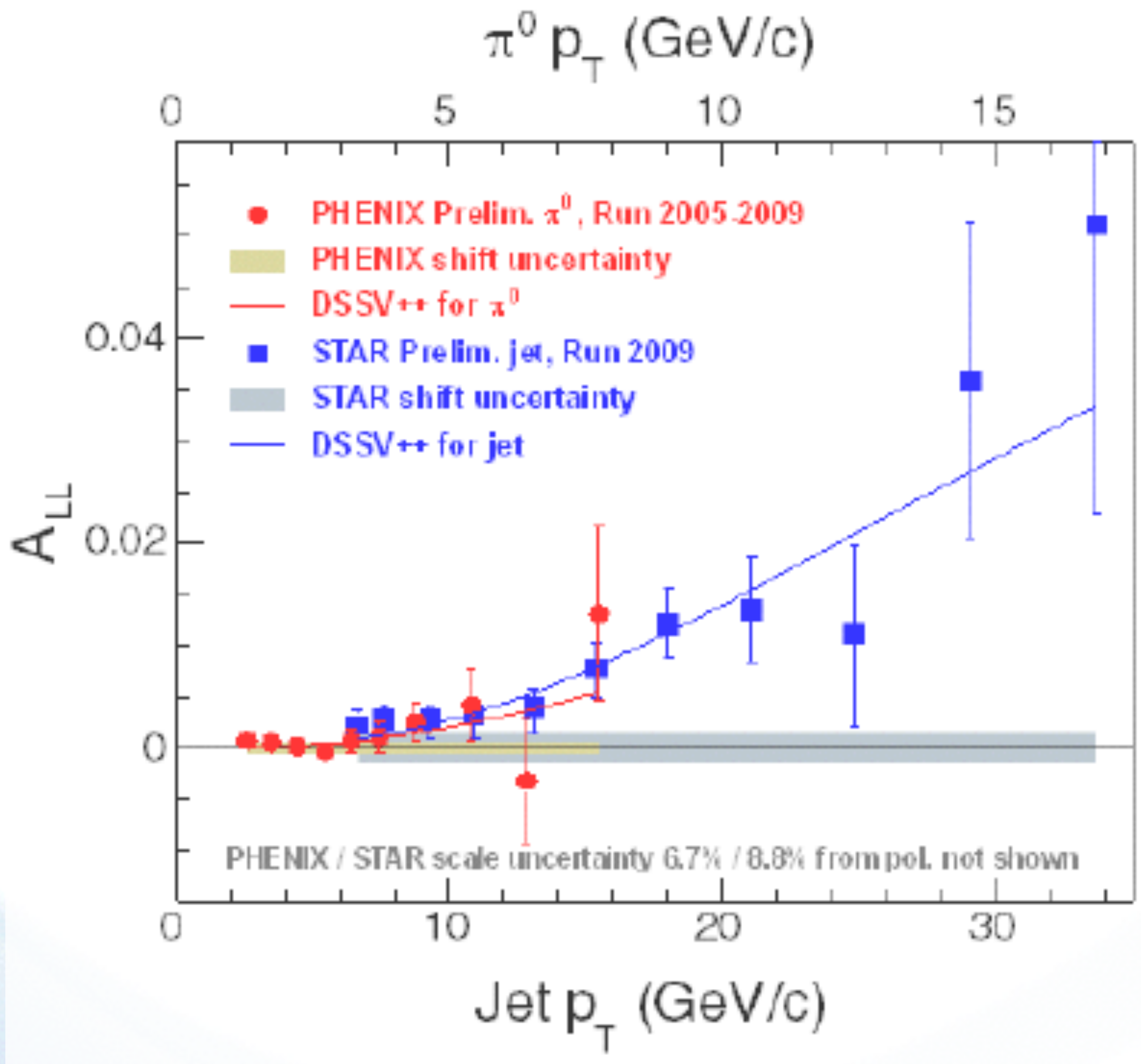
Δg from π^0 and jets

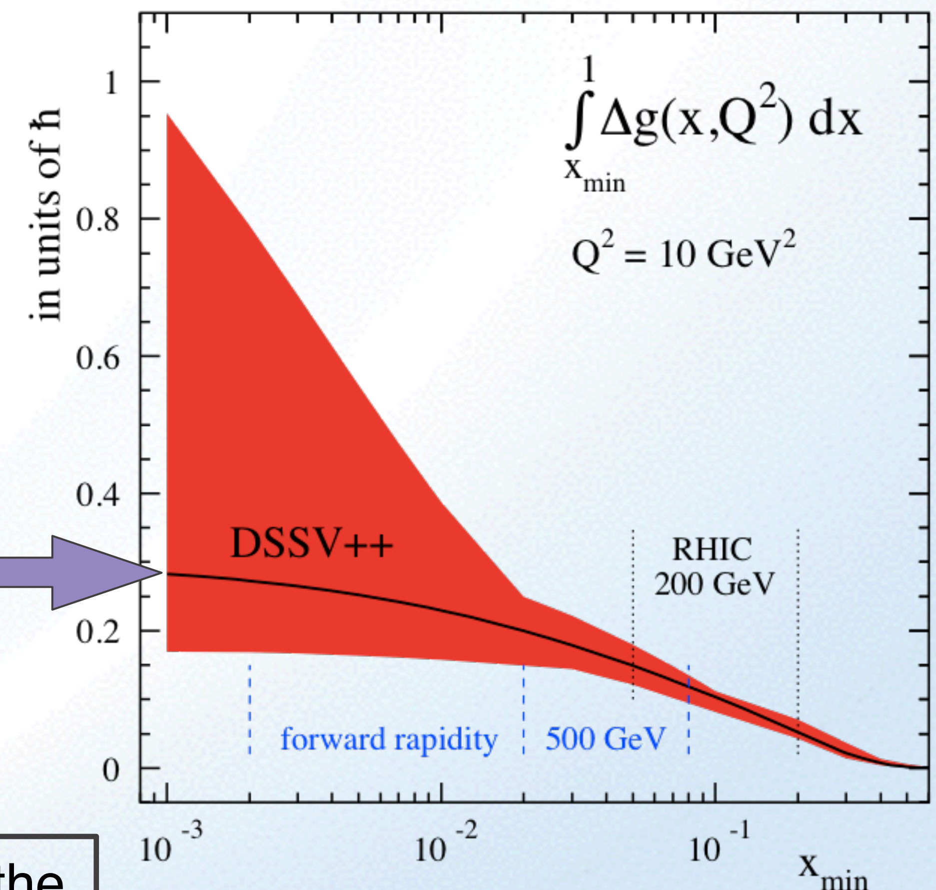
PHENIX: π^0 production
STAR: jet production

QCD global fit



$$\int_{0.05}^{0.2} \Delta g(x)\,dx = 0.1 {}^{+0.06}_{-0.07}$$



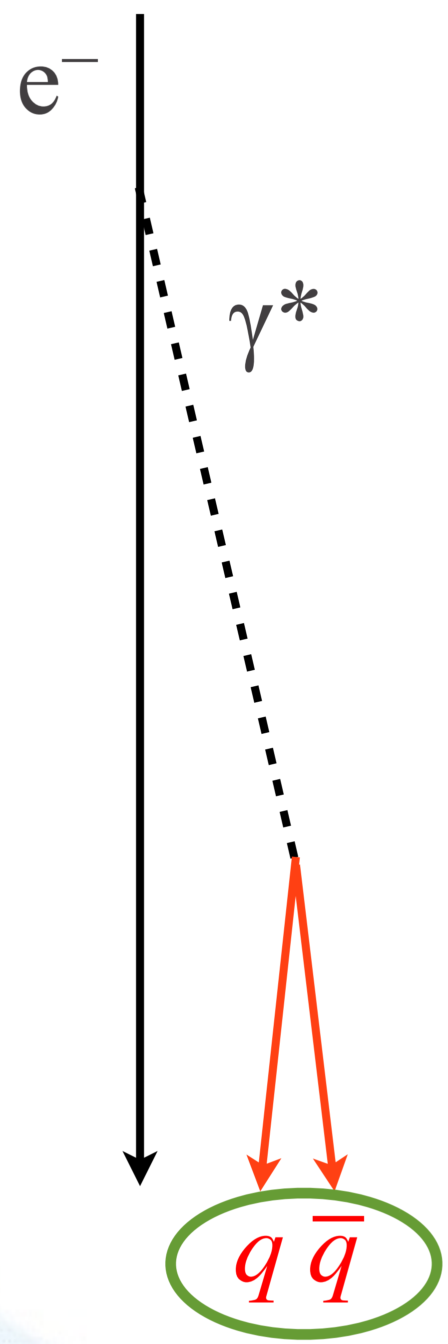


~60% of the proton spin?

The Electron-Ion Collider:

A Microscope for Gluons

EIC: A color dipole microscope



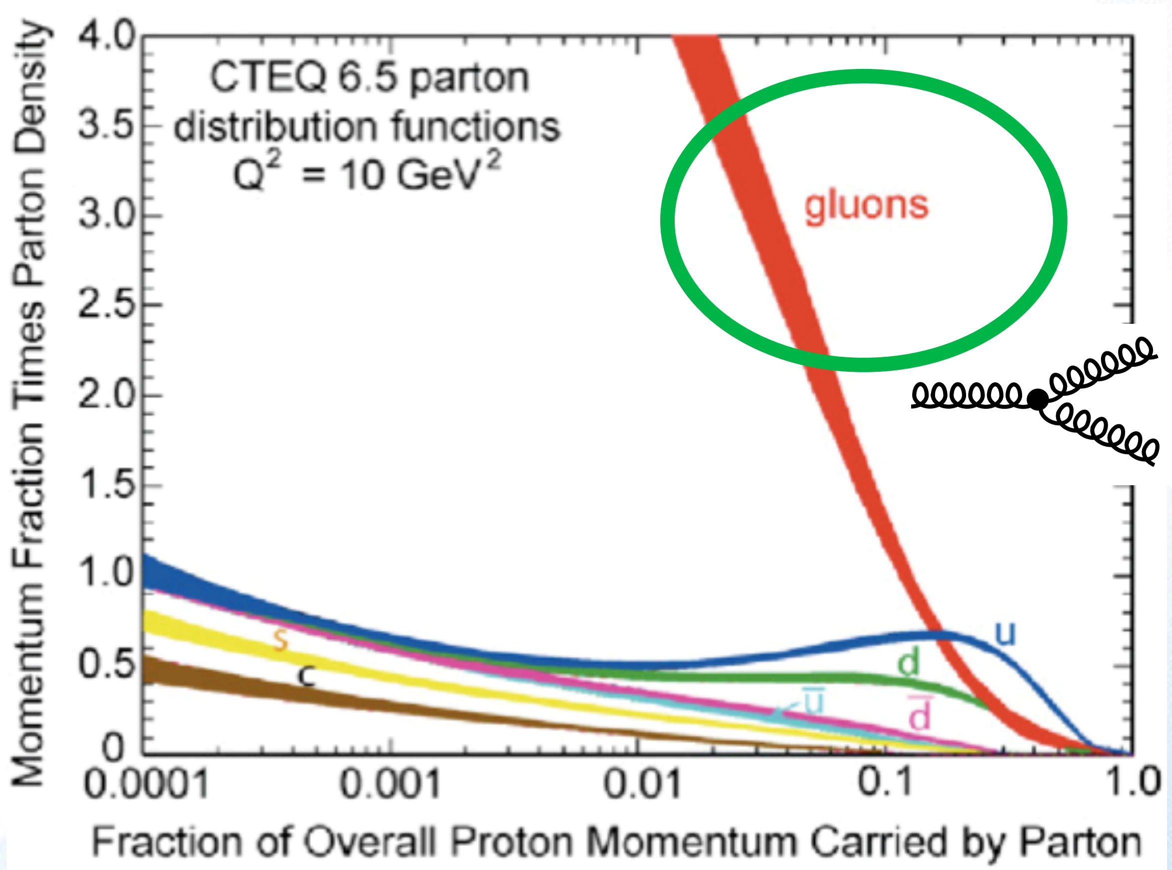
Color dipole "sees" gluons

Free color charges (quarks, gluons) do not exist, but color dipoles do! Virtual photons are a good source.

Two resolution scales:

- momentum k (longitudinal)
- virtuality Q (transverse)

⇒ More powerful than an optical microscope!



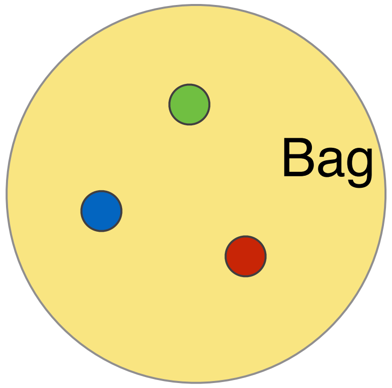
HERA was the 1st generation color dipole microscope.

Limited intensity and no polarization.

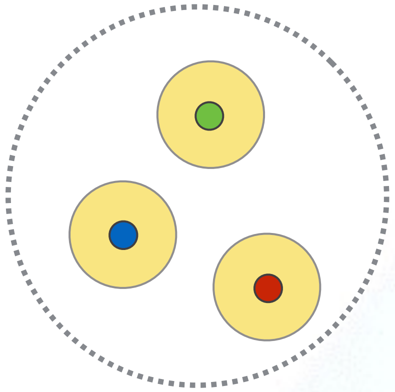
The EIC will be the 2nd generation color dipole microscope!

Where are the gluons?

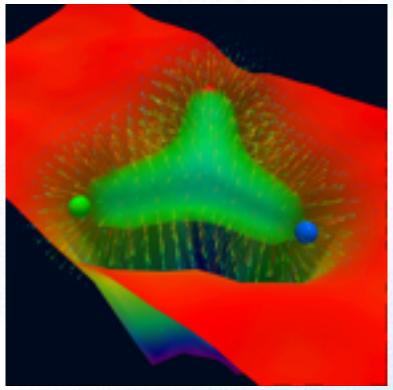
- Bag model:
  - Field energy distribution is wider than the distribution of fast moving light quarks



- Constituent quark model:
  - Gluons and sea quarks “hide” inside massive quarks
  - Sea parton distribution similar to valence quark distribution



- Lattice gauge theory:
  - (with slow moving quarks)
  - gluons are more concentrated than quarks



Where are the gluons?

Boosted Nucleon

- Bag model:
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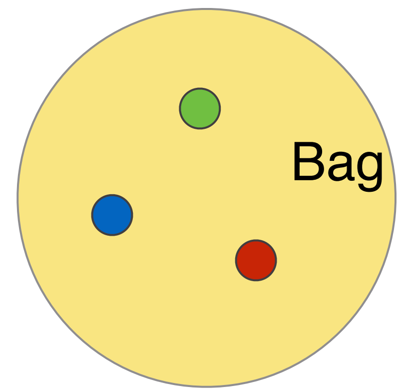

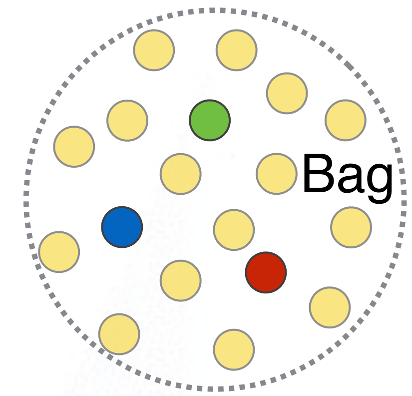

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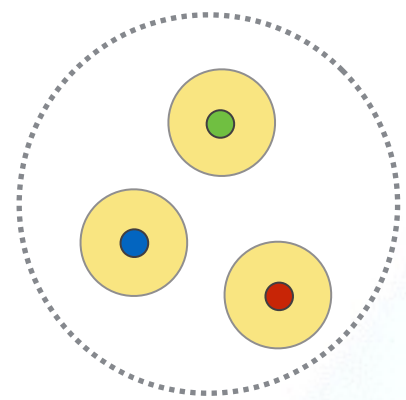

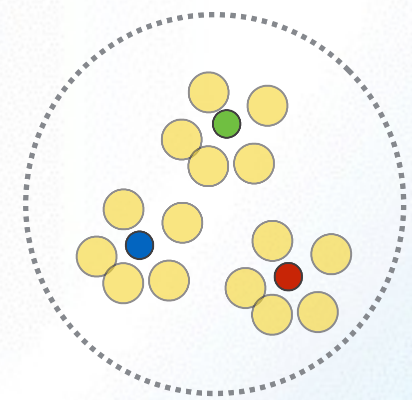

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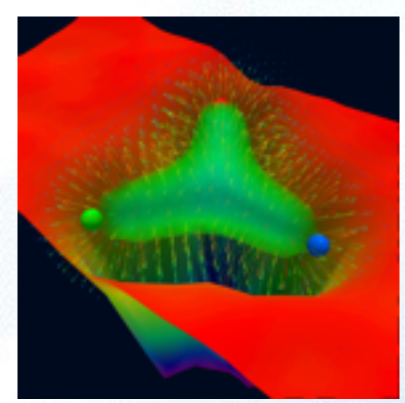
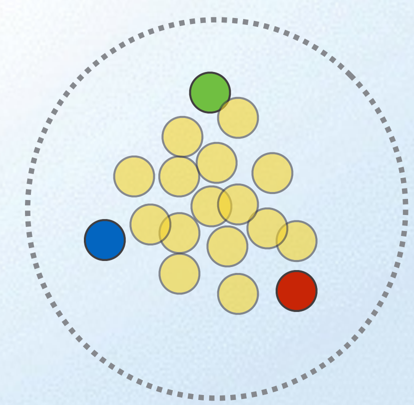
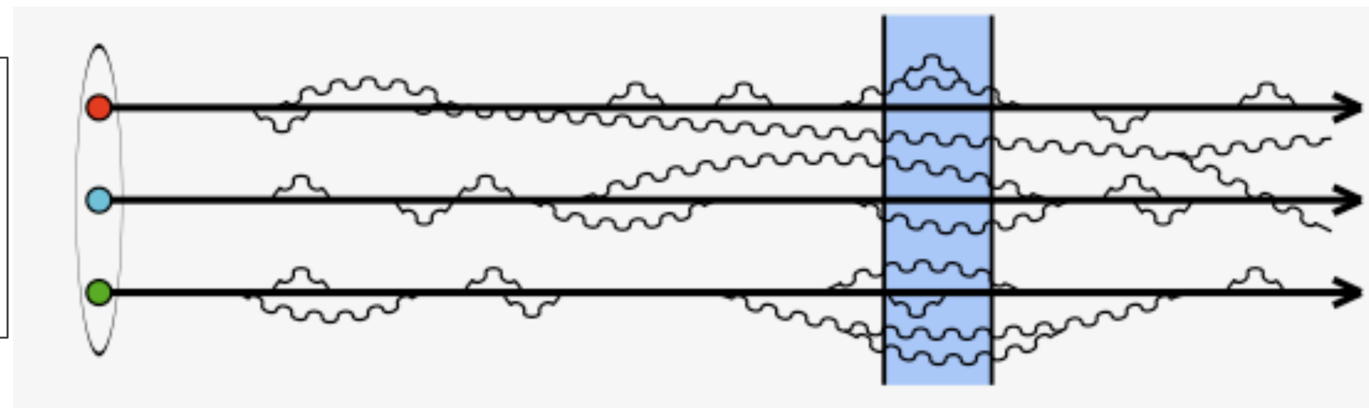




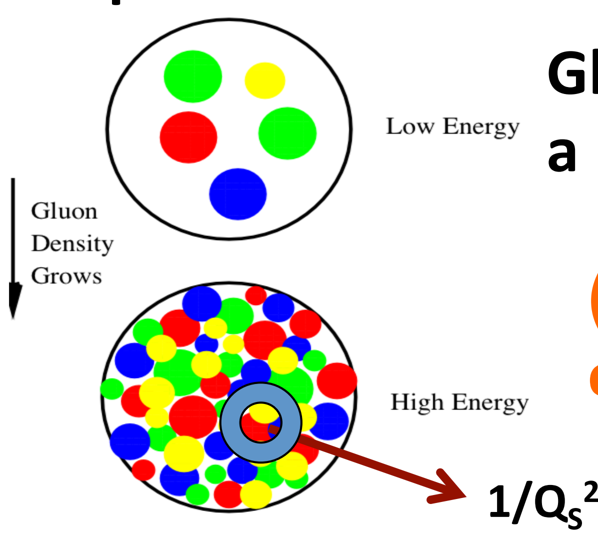
Saturation

Gluon Saturation in large nuclei: classical coherence from quantum fluctuations

With increasing energy more and more gluons are exposed until their wave functions "overlap"



Wee parton fluctuations dilated on strong interaction time scales

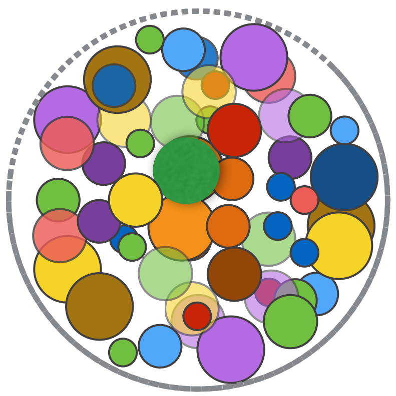


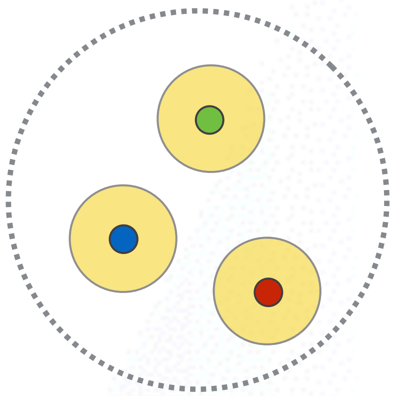
Gluon density saturates at a maximal value of ~ $1/\alpha_S$ ➔ gluon saturation

(Equivalent to perturbative unitarization of cross-section in rest frame of target)

Caveat: Weak coupling picture may not apply in the interesting range
($x > 10^{-3}$, Q^2 ~ few GeV^2)

Partons at Q^2 ~ few GeV^2





Gluon saturation

Sea partons (gluons and sea quarks)

Confined valence quarks

x

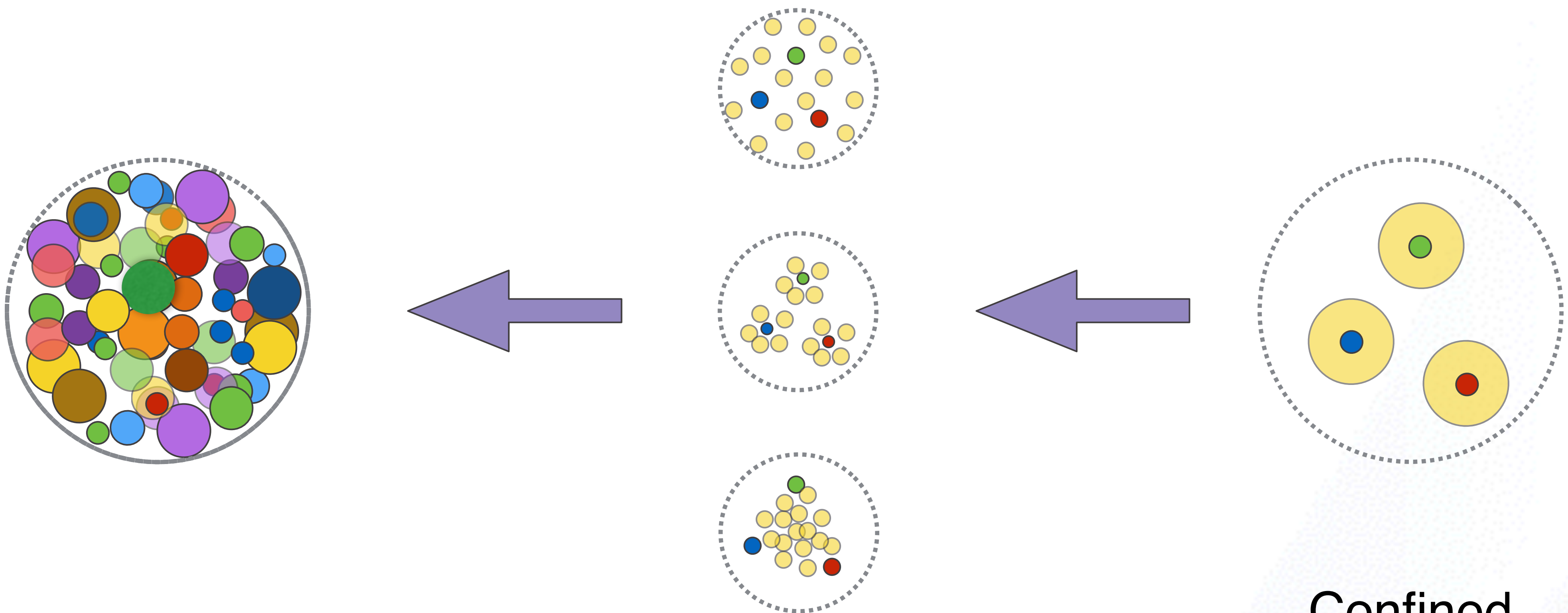
10^{-N} .... 0.001 — 0.01 — 0.1 — 1 →

Theoretically under control at weak coupling

EIC domain
Weakly or strongly coupled?

JLab 12 GeV program will explore

Partons at $Q^2 \sim$ few GeV^2



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x: 10^{-N} ...... 0.001 — 0.01 — 0.1 — 1

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EIC domain
Weakly or strongly coupled?

JLab 12 GeV program will explore

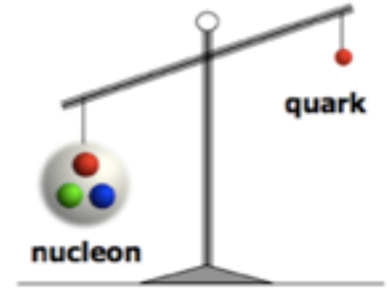
Why should RHICers care?

Is the relevant component of the nuclear wave function that turns into a quark-gluon plasma when nuclei collide a weakly coupled color glass condensate? Or is it generated by the decoherence of strongly coupled gluon fields surrounding colliding valence quarks (see arXiv: 1312.6676)? Or is something more akin to the 4-D shadow of a 5-D gravitational shock wave?

EIC - the ultimate QCD Laboratory

The big questions I

- **Proton mass puzzle:**



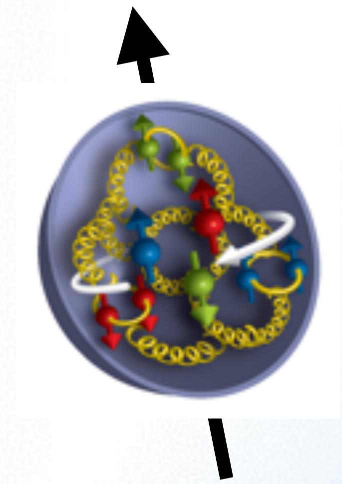
$m_q \sim 10$ MeV

$m_N \sim 1000$ MeV

Quarks carry ~1% of the proton's mass

How does glue dynamics generate the energy for the nucleon mass?

- **Proton spin puzzle:**



Quarks carry only ~30% of the proton's spin

How does quark and gluon dynamics generate the rest of the proton's spin?

- **3D structure of nucleon:**

Color Confinement

Asymptotic freedom

200 MeV (1 fm)

2 GeV (1/10) fm)

Q (GeV)

Probing momentum

How does the glue bind quarks and itself into a proton and nuclei?

Can we scan the nucleon to reveal its 3D structure?

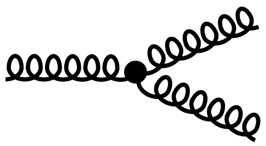
The big questions II

How do gluons saturate in nuclei into a new form of matter?

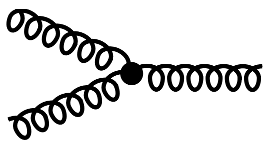
Color Glass Condensate

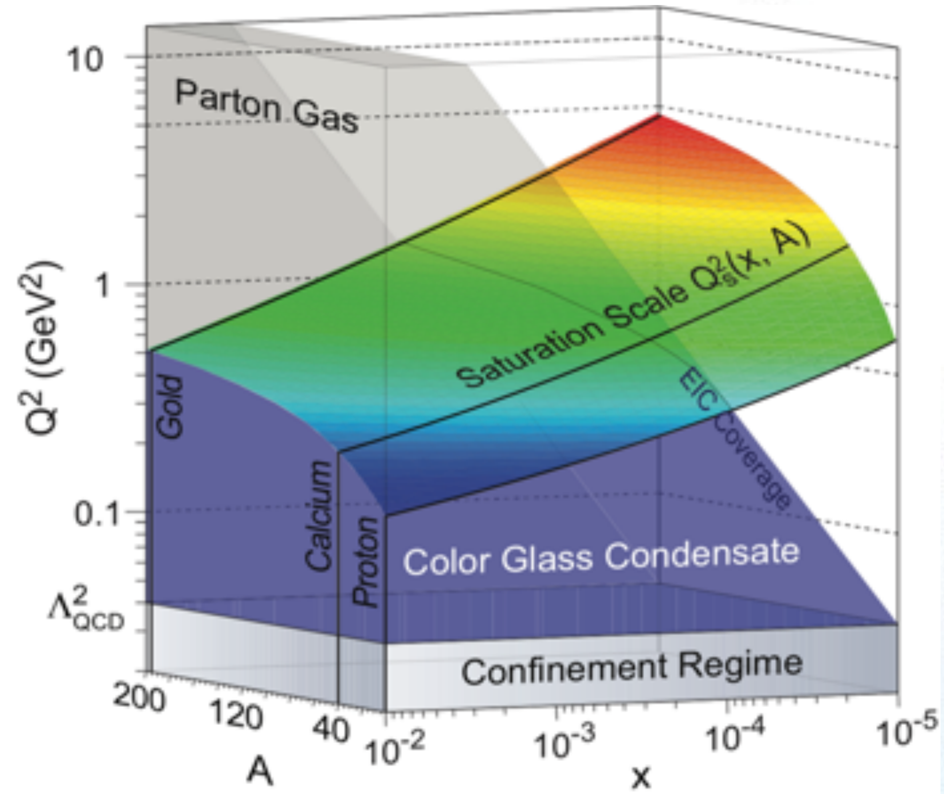
- **Gluons, unlike photons:**

Split:



Fuse:





- ✧ Dynamical scale Q_s from the balance
- ✧ New conceptual framework
- ✧ Universal properties (CGC)

From the EIC White Paper

- **Where does the saturation of gluon densities set in?** Is there a simple boundary that separates this region from that of more dilute quark-gluon matter? If so, how do the distributions of quarks and gluons change as one crosses the boundary? Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?

Needs a heavy ion beam!

The big questions III

How do hadrons emerge from a created quark or gluon?

Neutralization of color = hadronization

- **Femtometer detector/scope:**

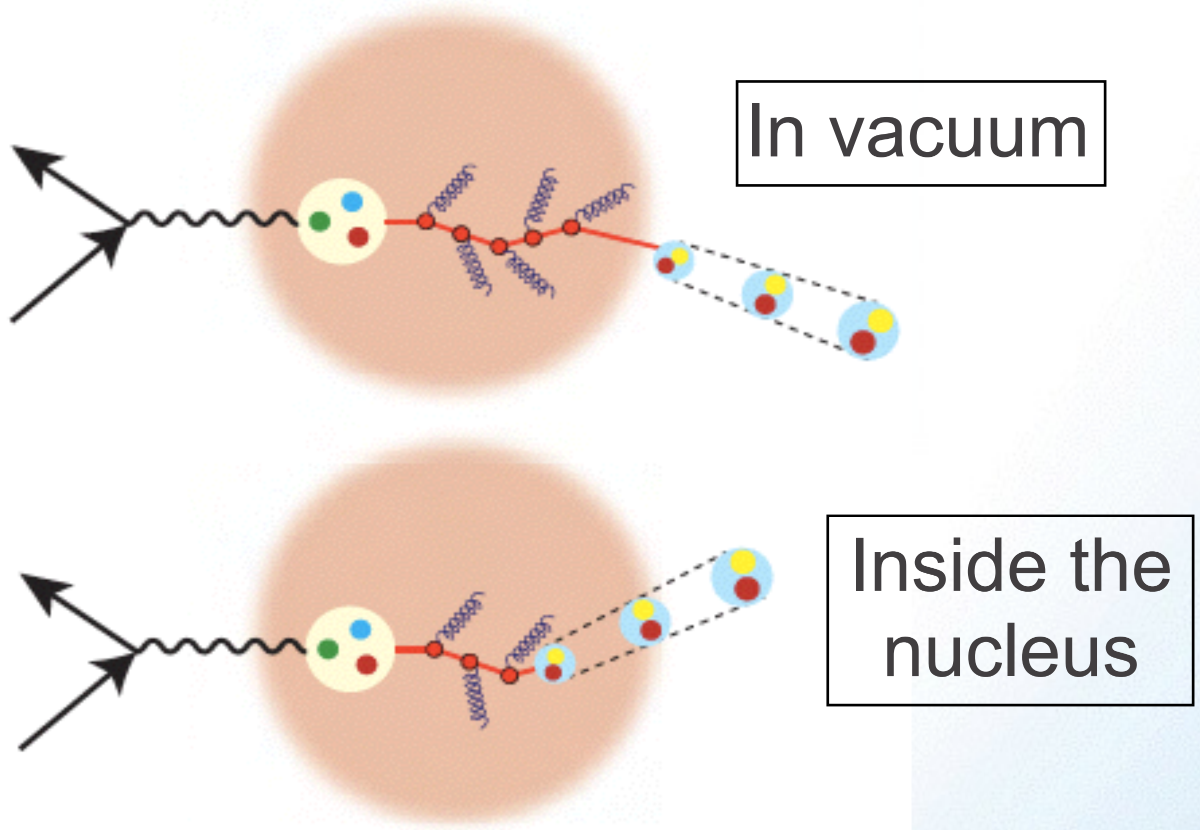
  Nucleus, a laboratory for QCD

- **Quark/gluon properties:**

  Initial-condition for hadronization

  Semi-inclusive DIS

From the EIC White Paper



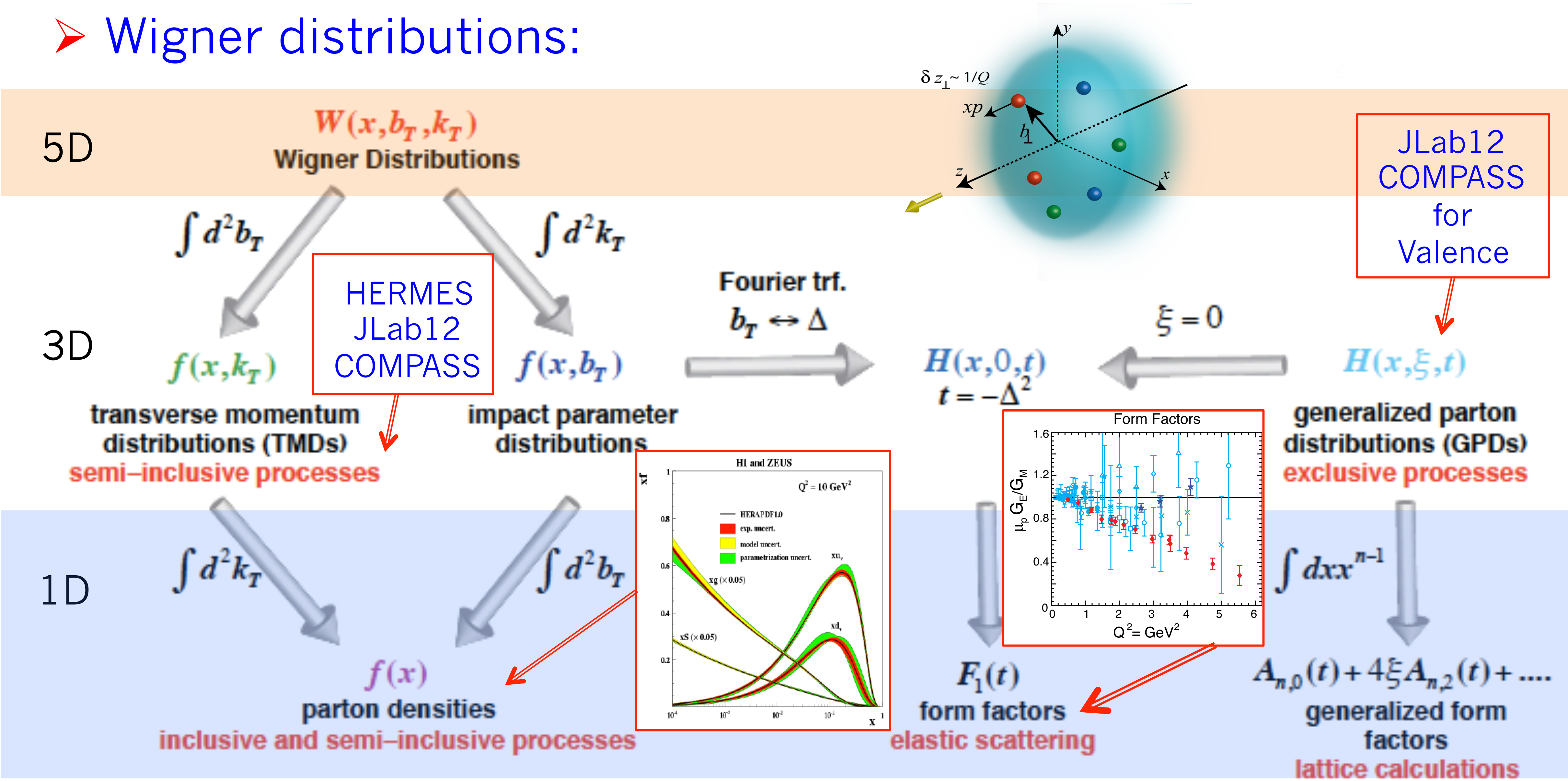
- **How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?** How does the transverse spatial distribution of gluons compare to that in the nucleon? How does nuclear matter respond to a fast moving color charge passing through it? Is this response different for light and heavy quarks?

Needs a probe to precisely control the initial condition!

Selected Measurements

Formalism

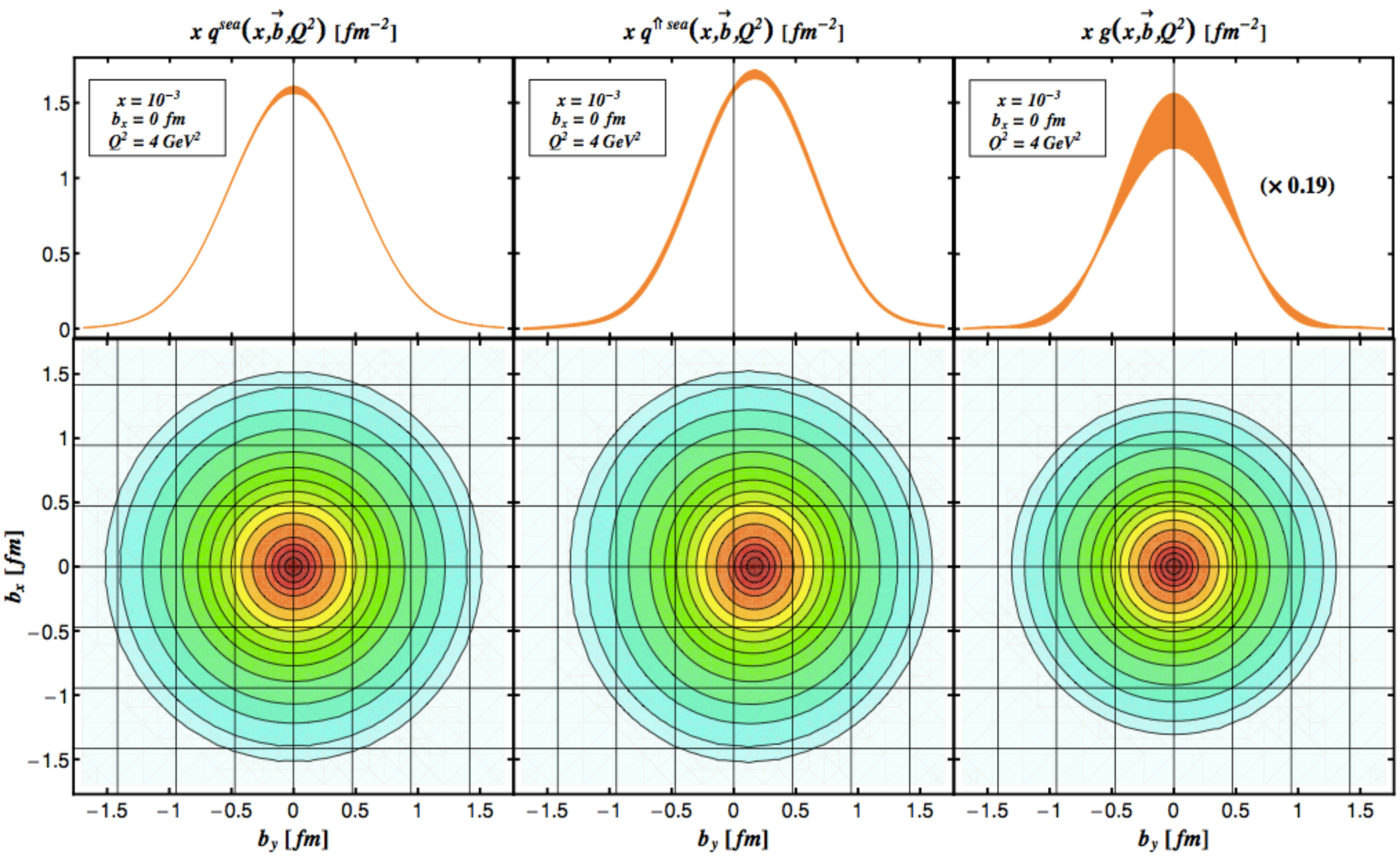
- Wigner distributions:



- EIC – 3D imaging of sea and gluons:
  - **TMDs – confined motion in a nucleon (semi-inclusive DIS)**
  - **GPDs – Spatial imaging of quarks and gluons (exclusive DIS)**

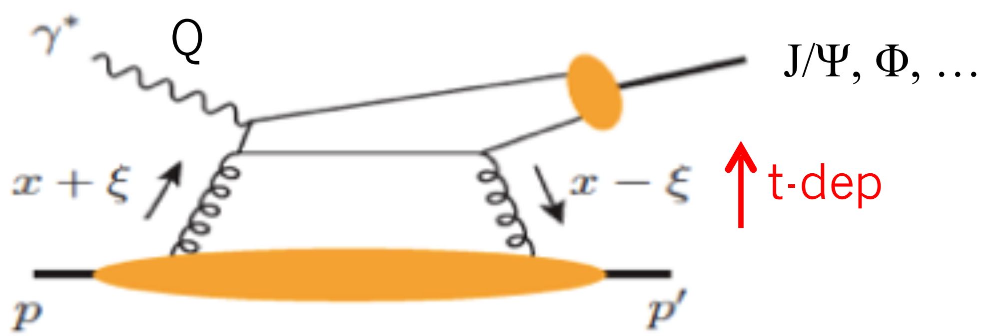
Imaging quarks and gluons

using Generalized Parton Distributions (GPD's):



Imaging gluons

➢ **Exclusive vector meson production:**



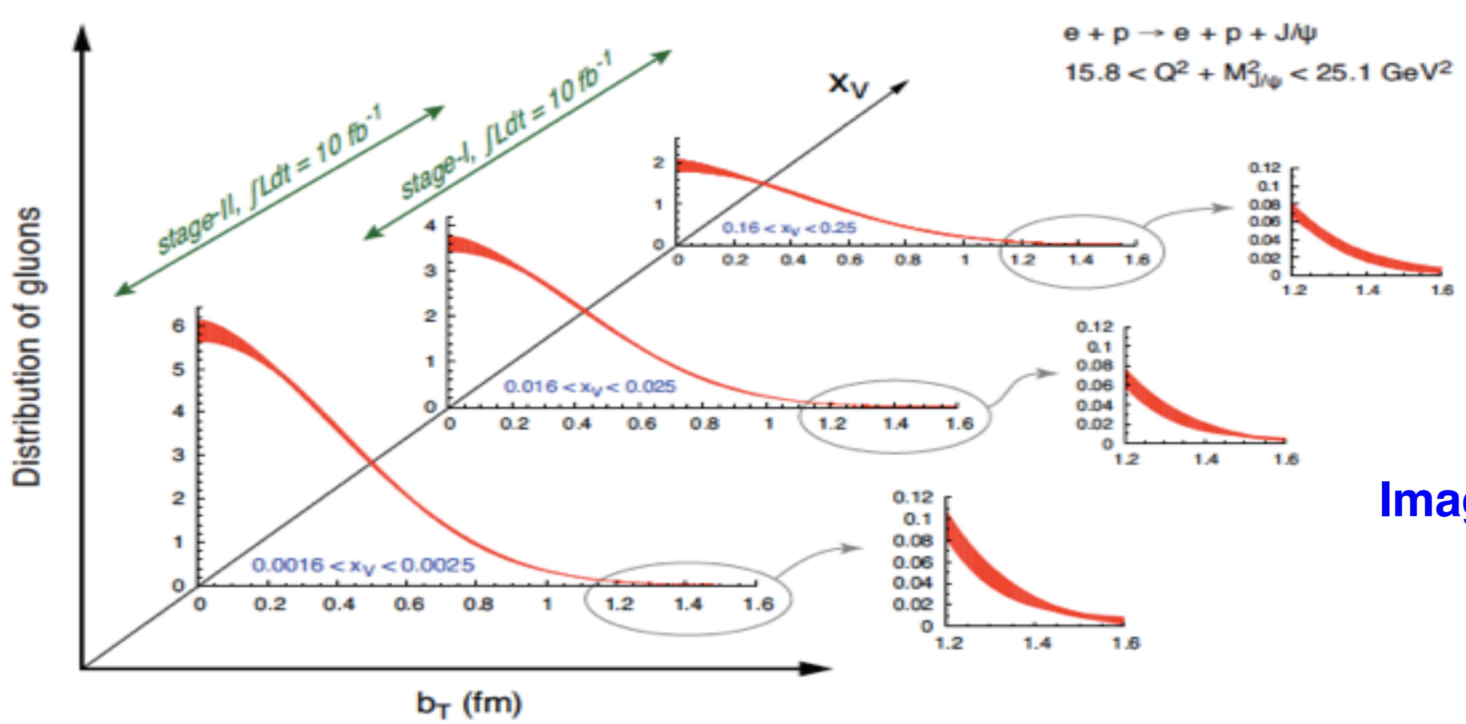
$$\frac{d\sigma}{dx_B dQ^2 dt}$$

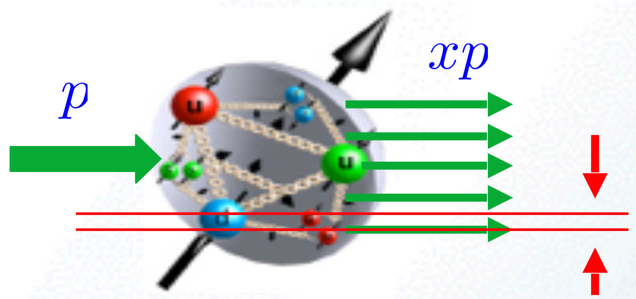
Fourier transform of the t-dependence

➡ Spatial imaging of glue density

Resolution ~ 1/Q or 1/M_Q

➢ **Gluon imaging from simulation:**





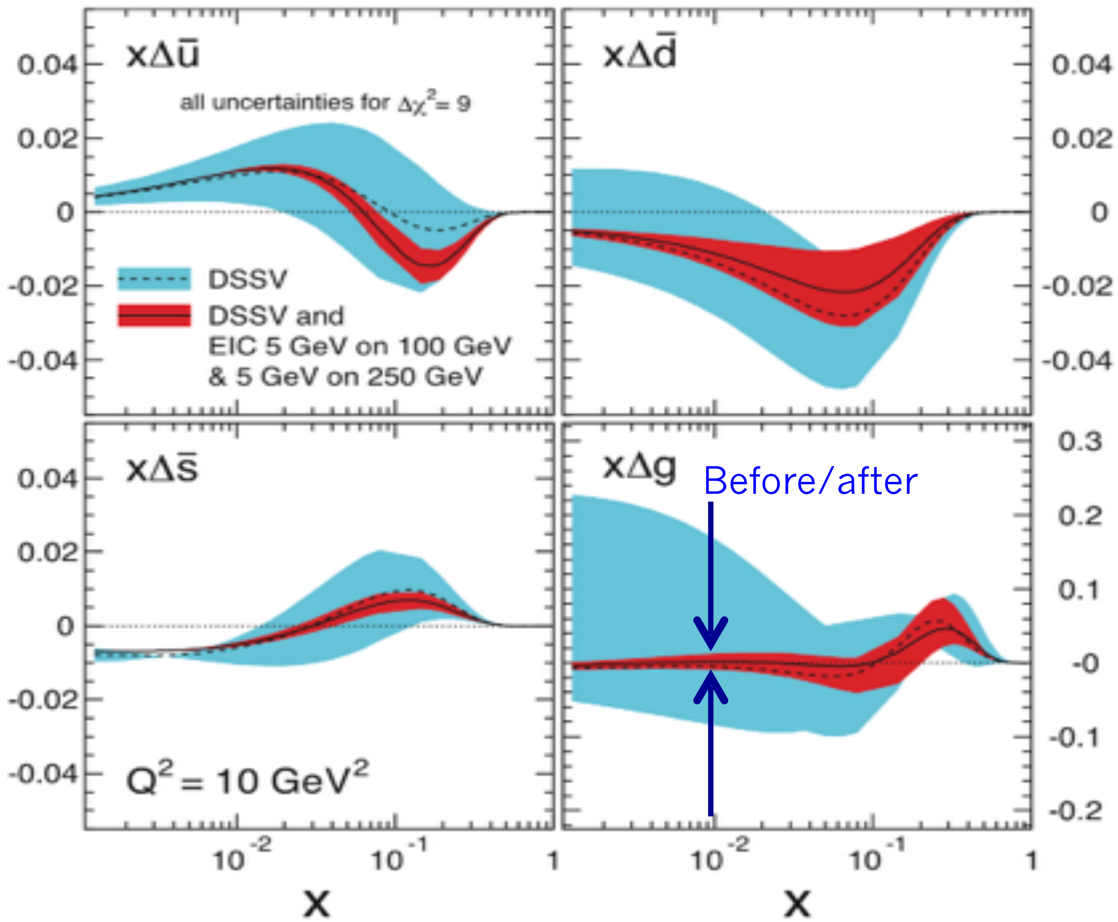
Images of transverse gluon distributions from exclusive J/ψ production

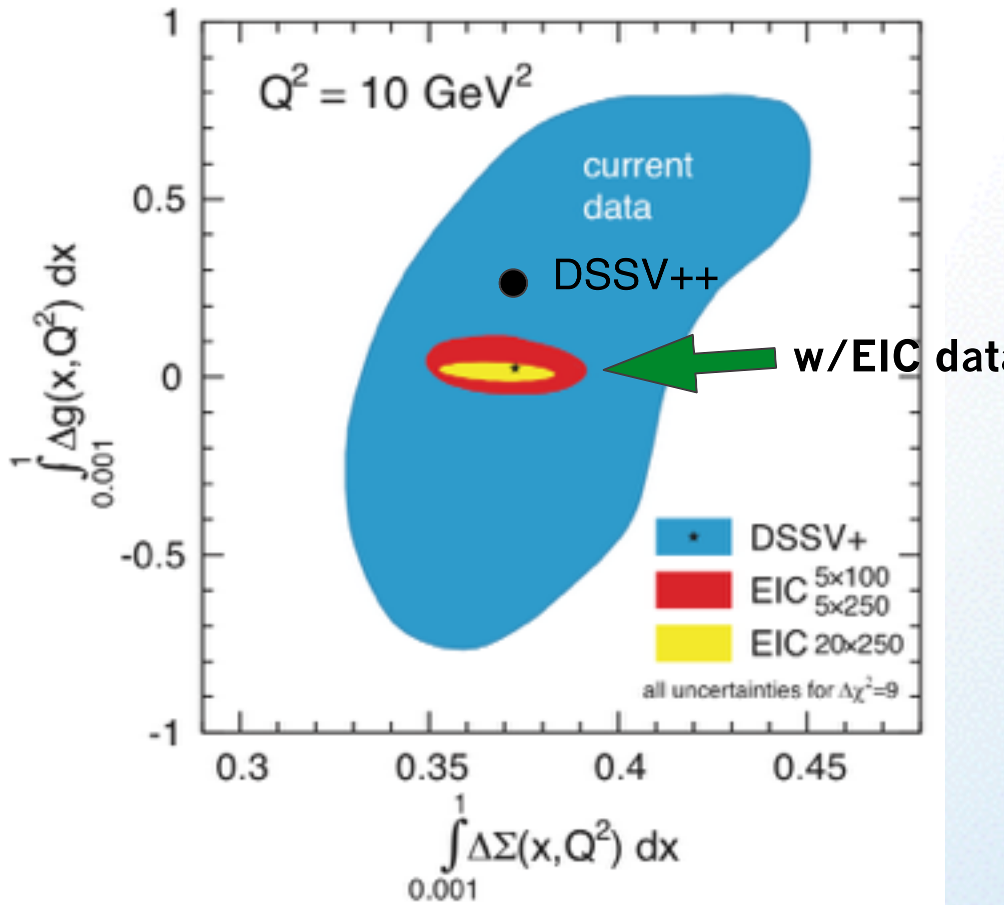
Only possible at the EIC: From the valence quark region deep into the gluon / sea quark region

Solving the spin puzzle

➢ **The EIC – the decisive measurement** (in 1st year of running)**:**

(Utilizing the wide Q^2, x range accessible at the EIC)





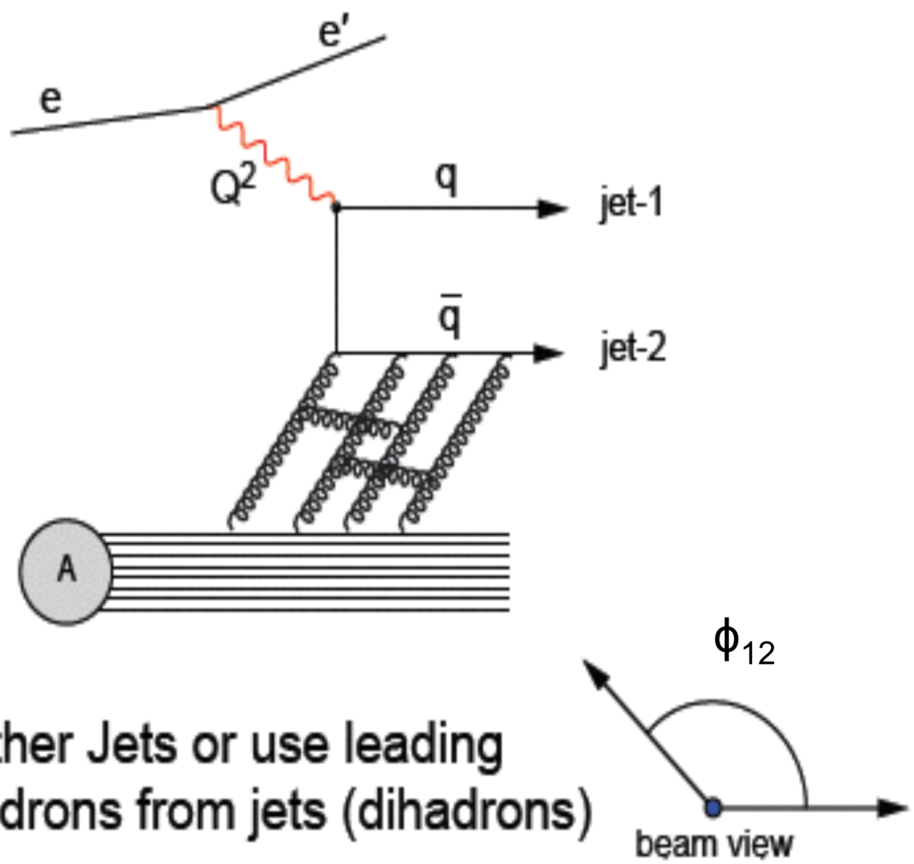
No other machine in the world can perform this measurement!

➢ **Solution to the proton spin puzzle:**

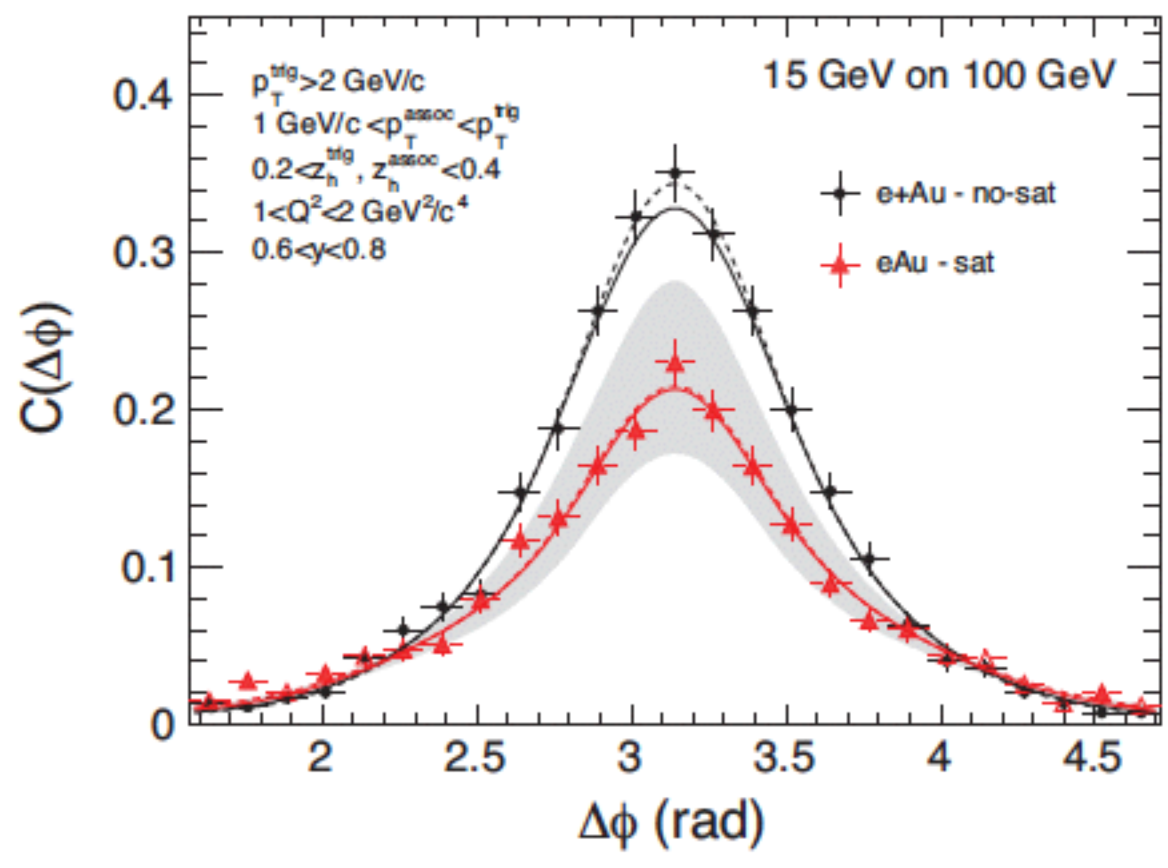
- ◇ ***Precision measurement of ΔG – extends to smaller x regime***
- ◇ ***Orbital angular momentum – motion transverse to proton's momentum***

Probing gluon saturation

➢ **Strong suppression of di-hadron correlation in eA:**



Simulation



- This has never been measured in e+A (only in d+Au, where it is ambiguous)
- Correlation directly probes the saturated gluon distribution in a large nucleus
- **Suppression of back-to-back hadron correlation**

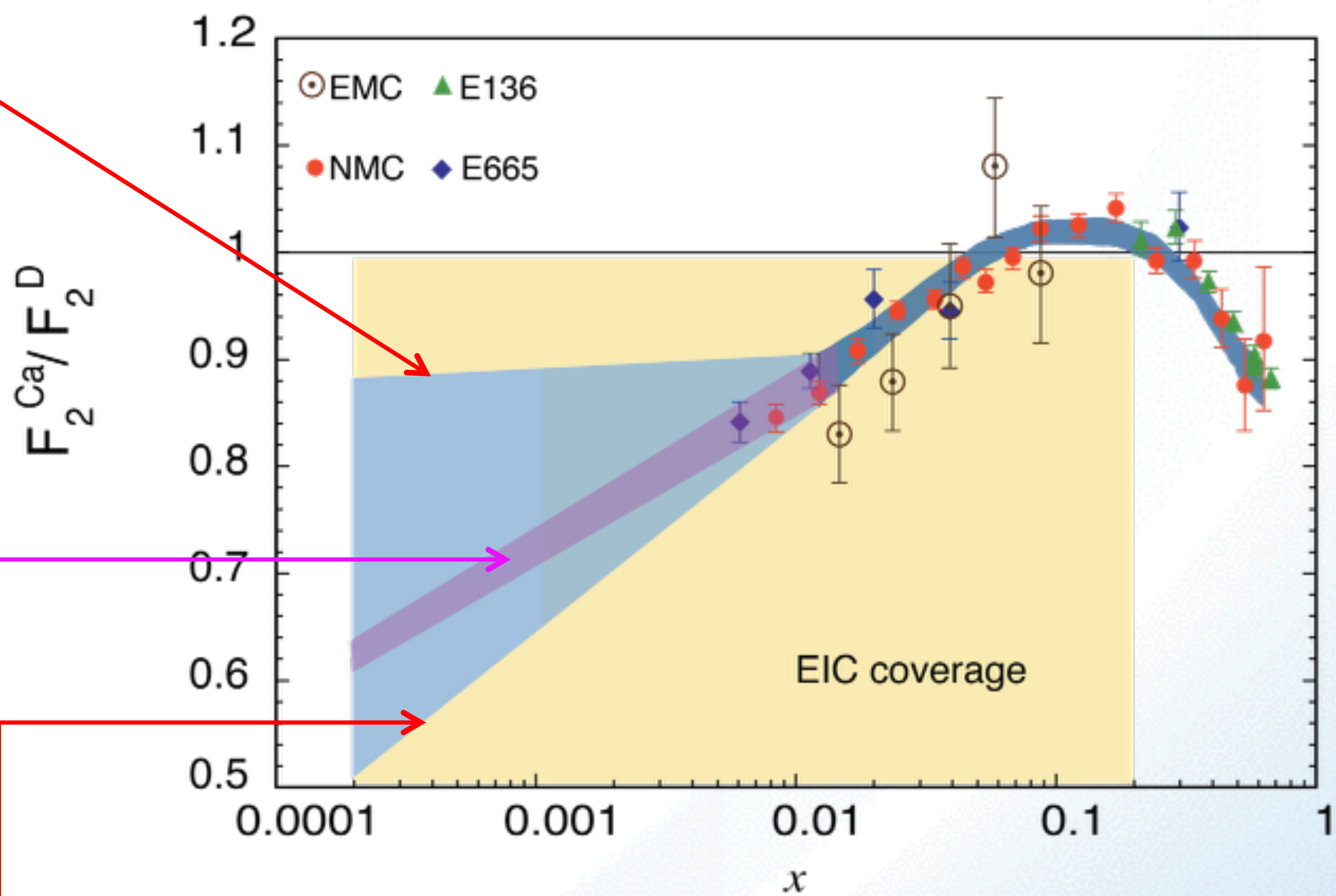
Color range in a nucleus

➢ Ratio (F_2^A/F_2^D) of DIS structure functions:

Longitudinal
color force range
~ size of nucleon

Systematic error

Longitudinal
color force range
~ size of nucleus
(assumed in CGC
saturation models)



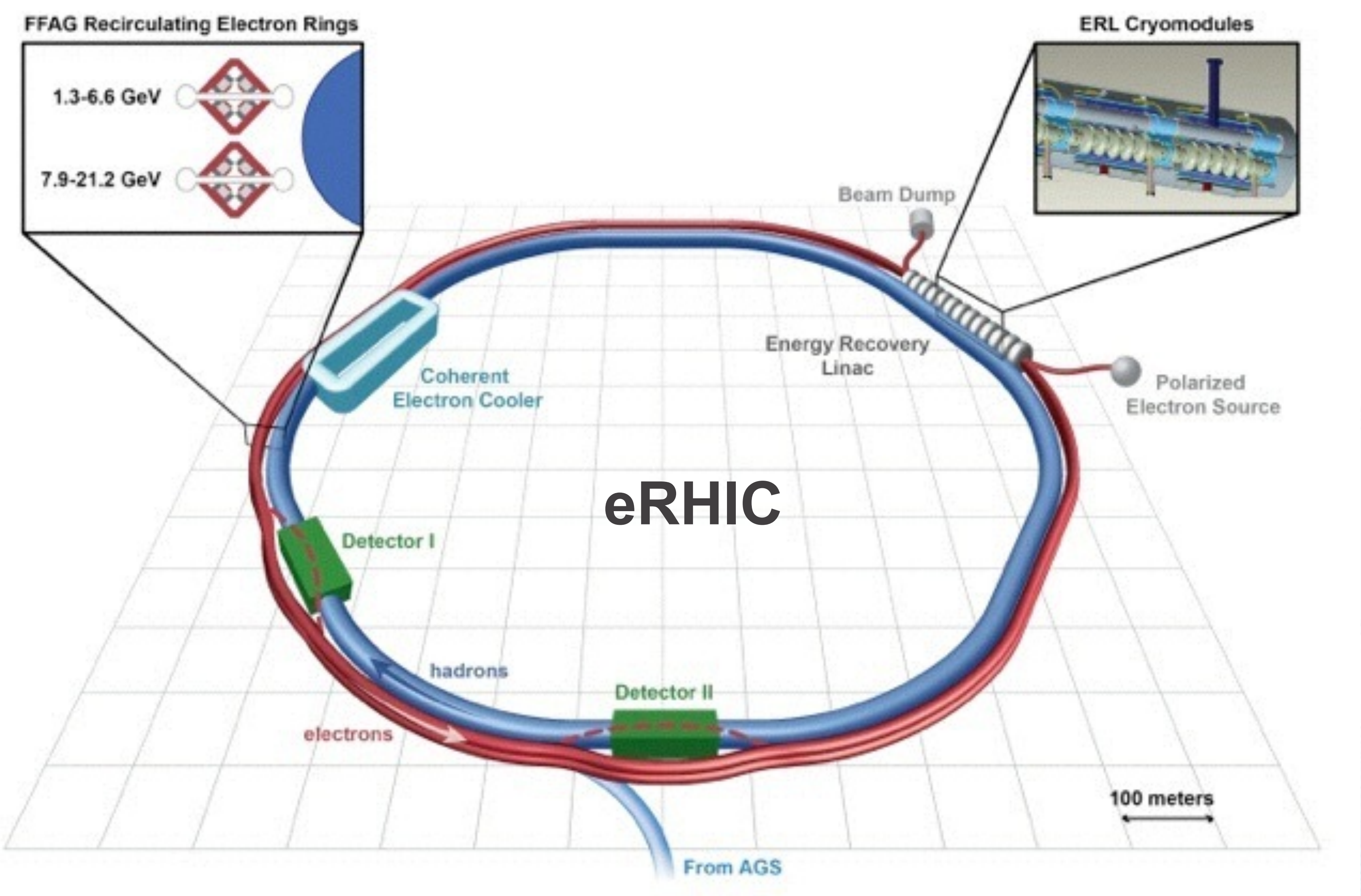
A clean measurement is only possible at the EIC !

eRHIC:
EIC @ BNL

EIC Design

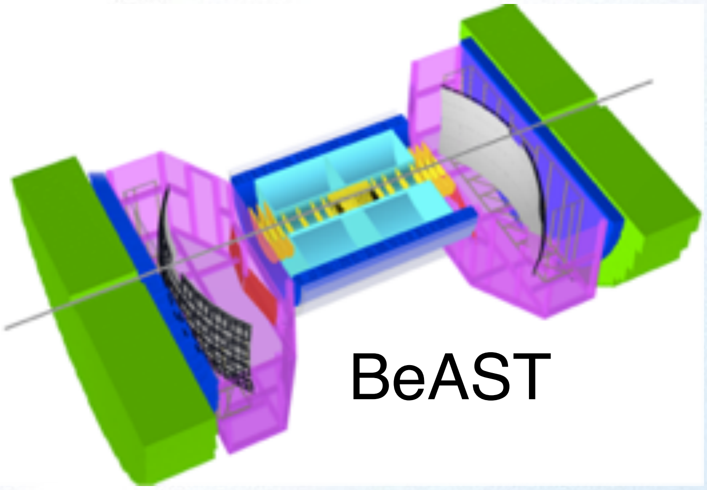
eRHIC ERL + FFAG ring design @ $10^{33}/cm^2s$

15.9 GeV e^- + 255 GeV p or 100 GeV/u Au.



When completed, eRHIC will be the most advanced and energy efficient accelerator in the world

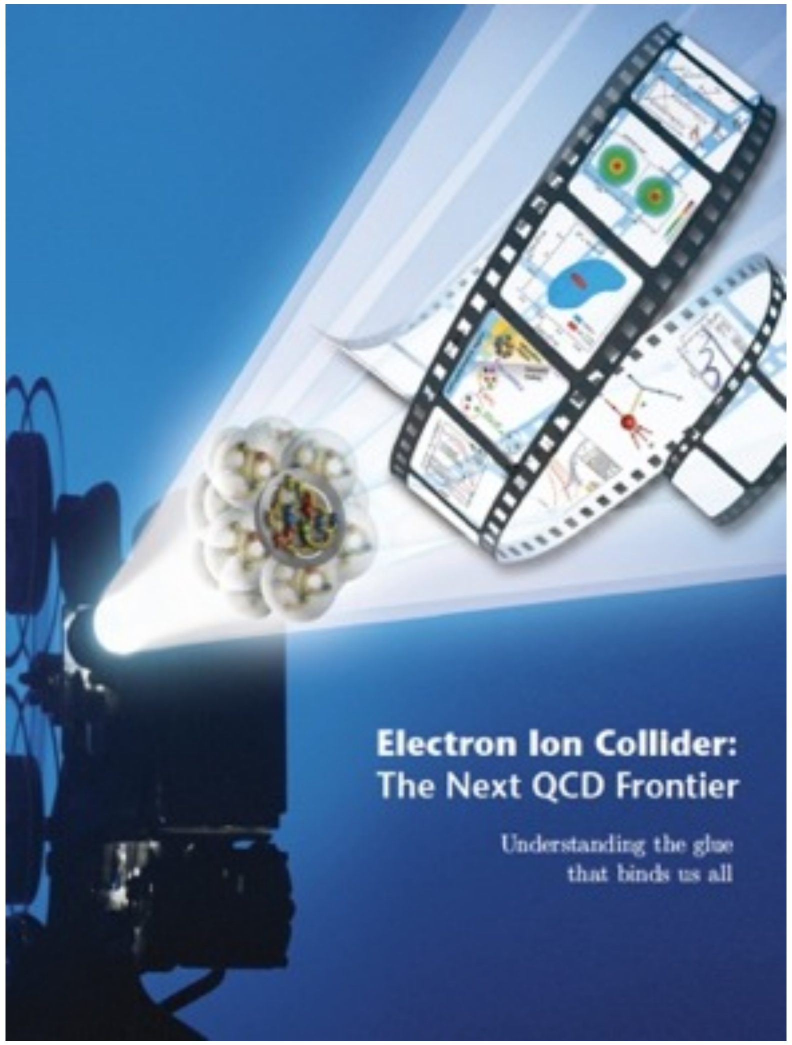
Detector Options



The eRHIC Concept

- eRHIC will be a unique, world leading accelerator facility combining several innovative concepts:
  - World's first linac-ring collider
  - 99.8% efficient energy recovery linac (ERL)
  - FFAG arcs each propagating beams with multiple energies
  - Low cost permanent magnets for the recirculating arcs
  - Coherent e-cooling (CeC) for record high beam brightness
  - "Crab" crossings for high luminosity interaction regions
- eRHIC is a cost effective realization of an EIC.
- eRHIC can cover the whole science program outlined in the EIC white paper from Day 1.
- eRHIC can be upgraded in steps to 10^{35} $cm^{-2}s^{-1}$ luminosity.
- Upgraded RHIC detectors could serve as powerful, cost effective EIC detectors at Day 1.

EIC - Why now?



EIC White Paper
(arXiv:1212.1701)
to be updated soon

Why now?

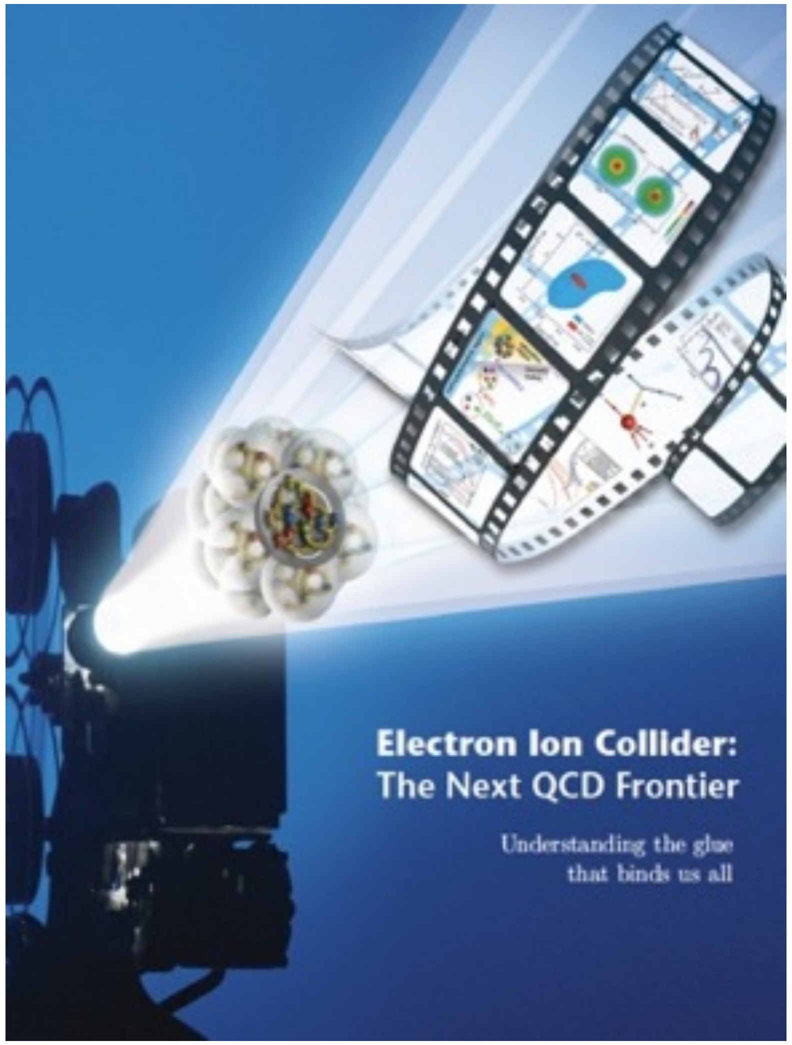
A set of **compelling physics questions** has been formulated.

A set of **measurements** has been identified that can **provide answers** to many of the open questions about the gluon structure of the proton and of nuclei.

A **powerful formalism** has been developed over the past decade that connects measurable observables to rigorously defined properties of the QCD structure of nucleons and nuclei.

Accelerator technology has reached a state where a capable EIC can be constructed at an affordable cost.

EIC - Why now?



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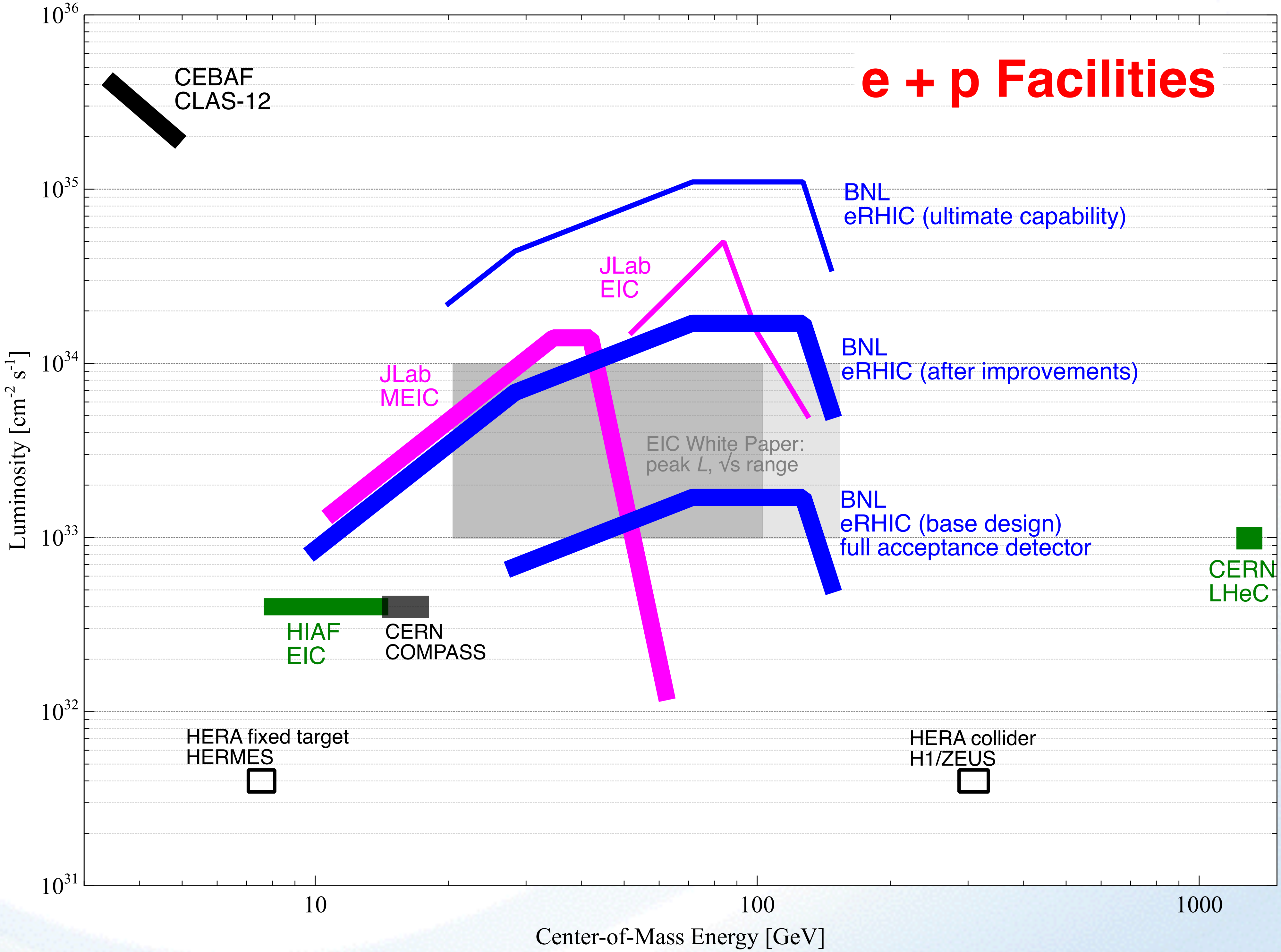
Nuclear Science needs an EIC.
The U.S. should lead the way.

Back-up slides

e+p Luminosity Landscape



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