The Electron-Ion Collider
An electron attoscope

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KMI, Nagoya
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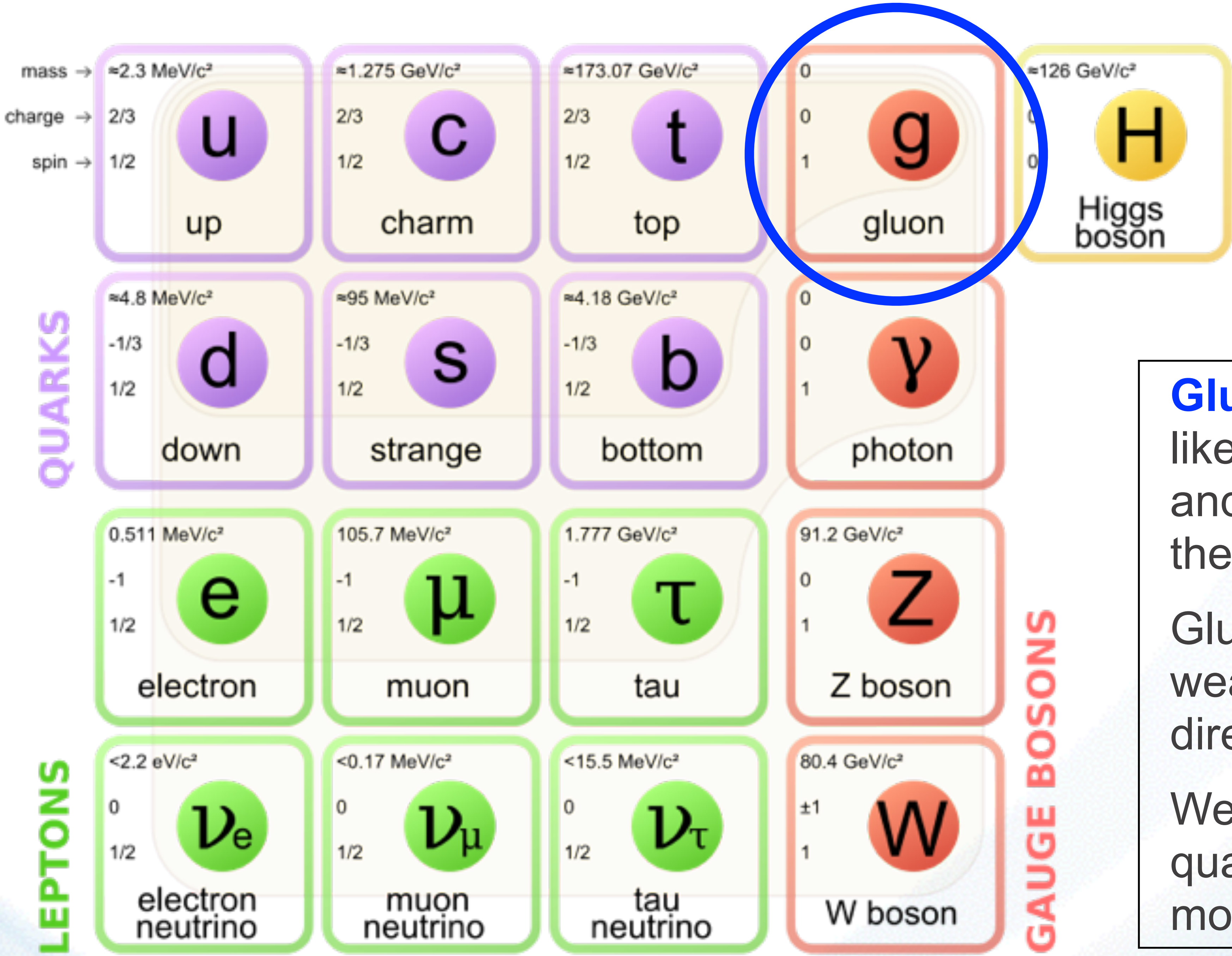
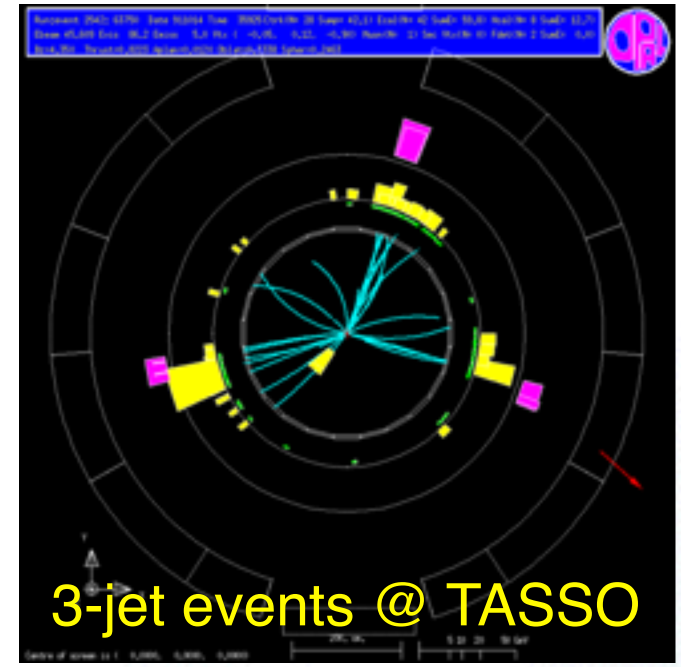
BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

Standard Model particles





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

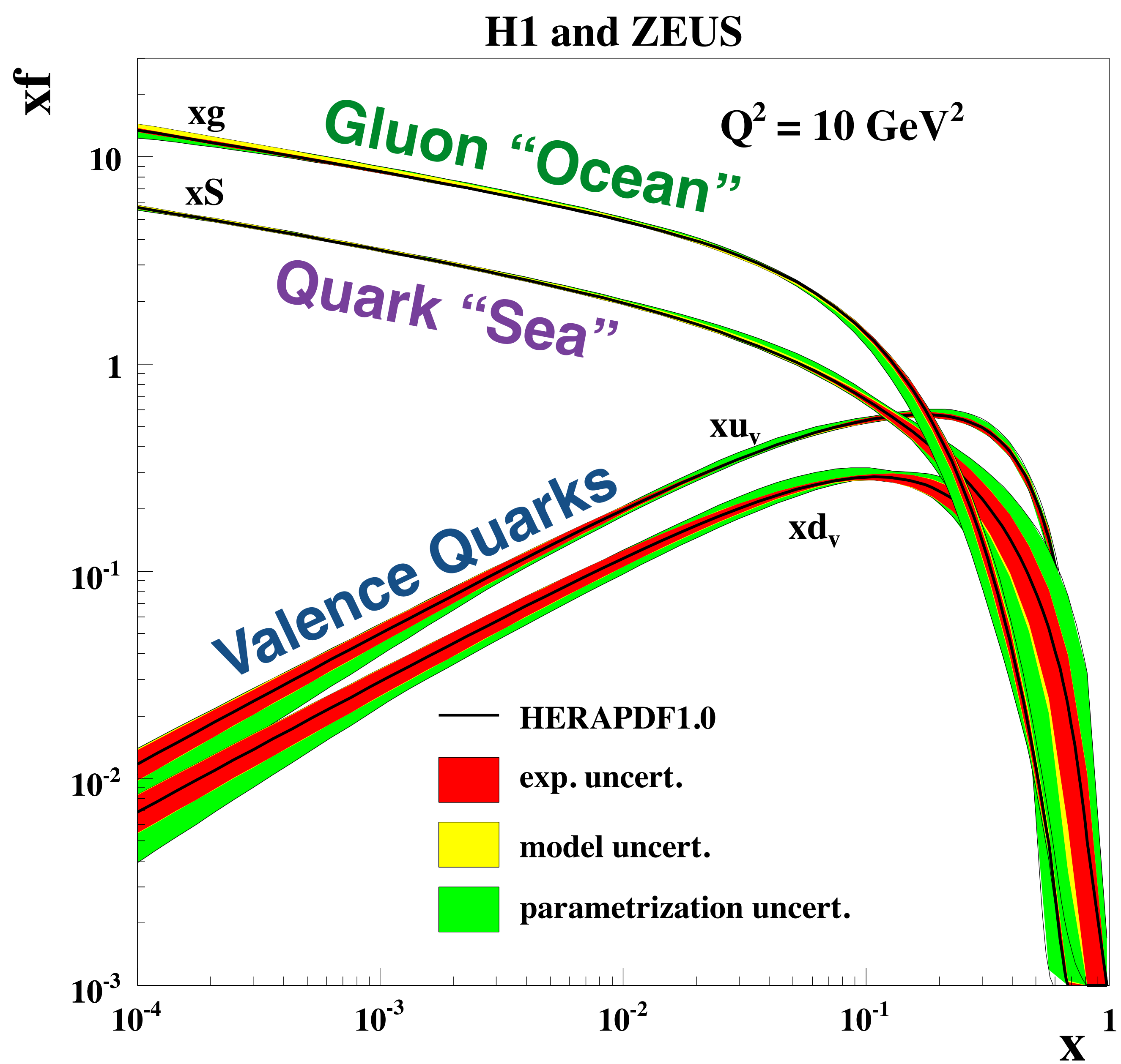
Gluons carry no electric or weak charge - they cannot directly interact with photons.

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

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

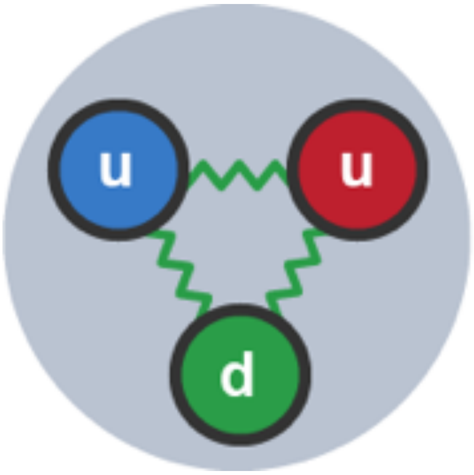


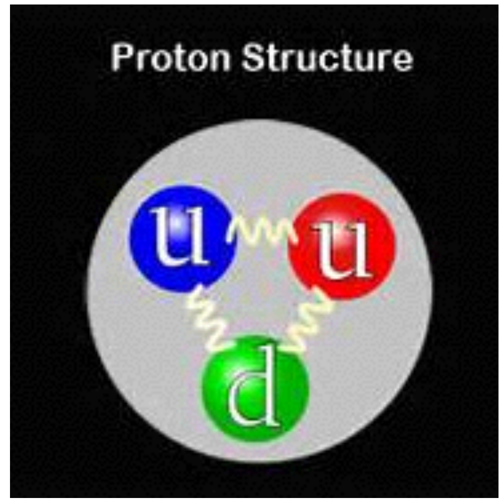
The Quark "Sea" derives from the Gluon "Ocean" by gluon splitting into a quark-antiquark pair: suppressed by factor $N_F\alpha_s/\pi$.

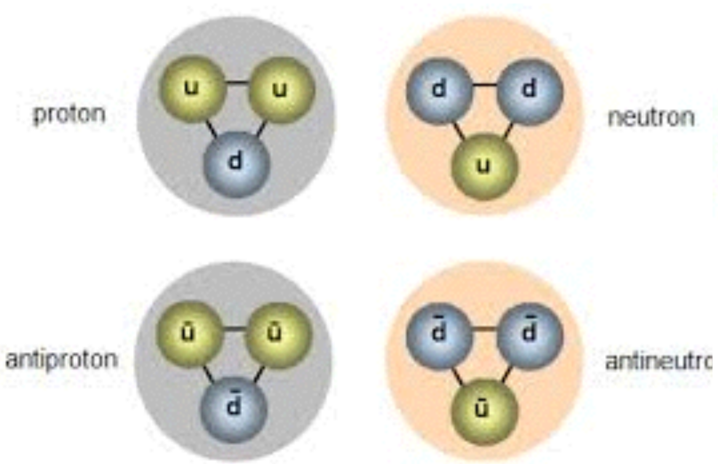
Clean separation of gluons and sea quarks from valence quarks requires experiments probing $x < 0.01$, or nucleon energies of order 100 GeV.

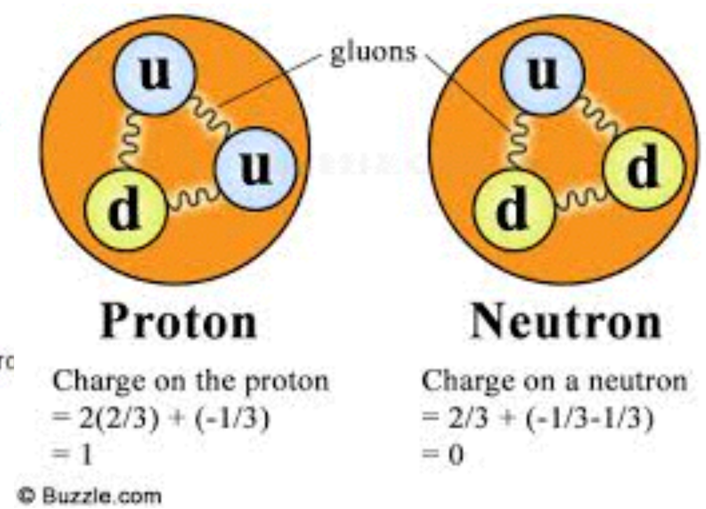
RHIC provides polarized protons up to 255 GeV and nuclei up to 100 GeV/nucleon.

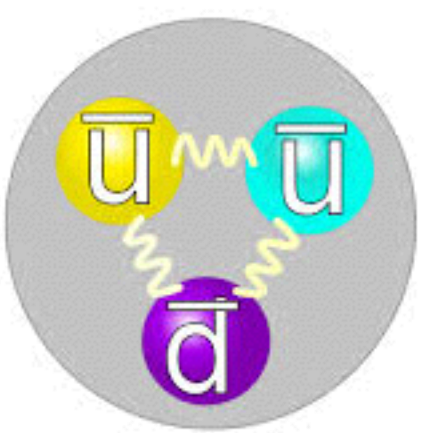
Where are the gluons?

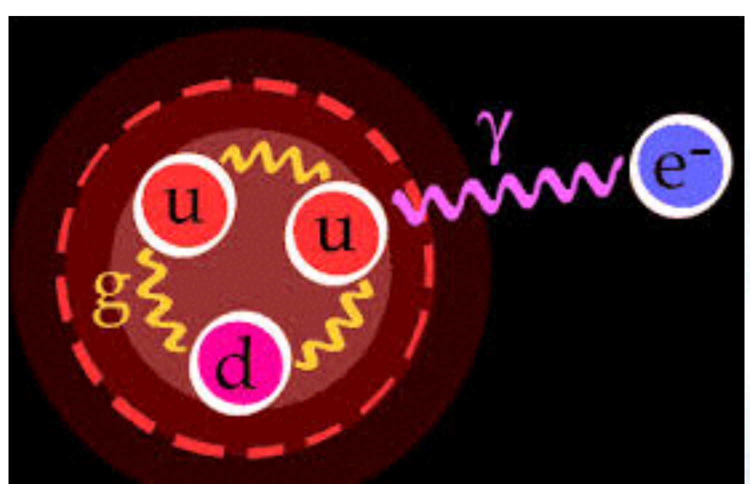












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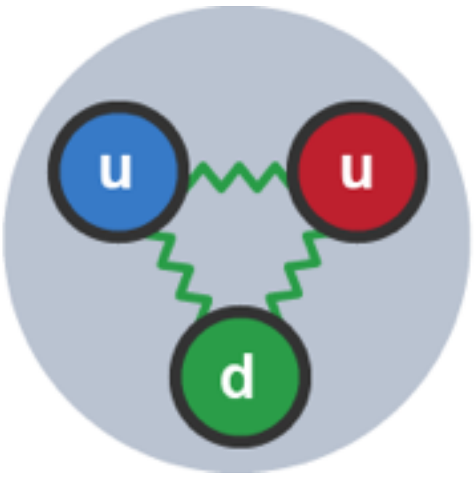
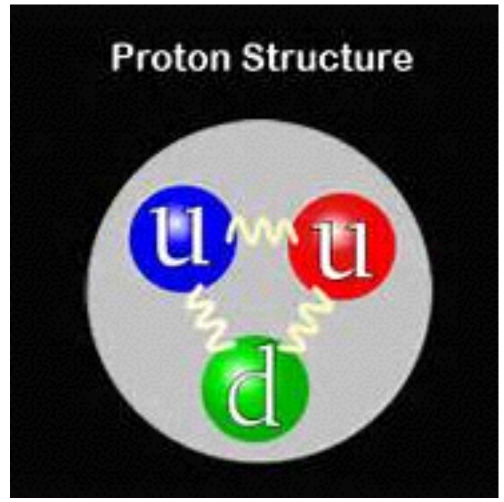
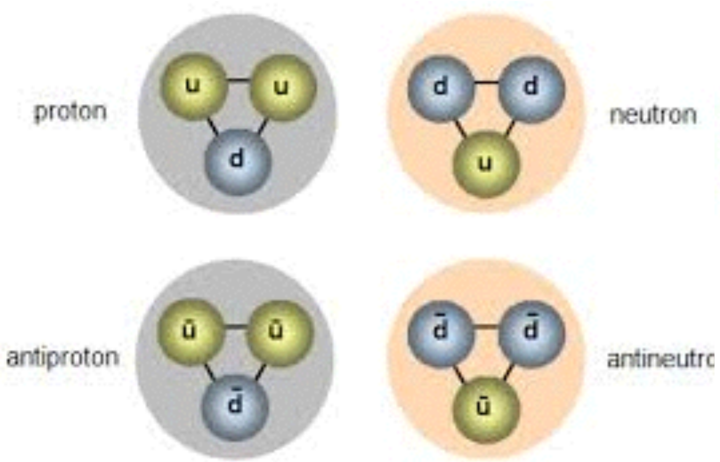
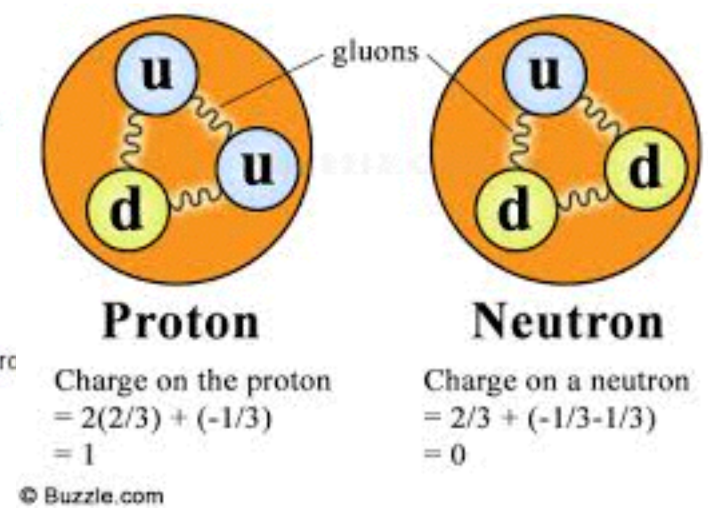
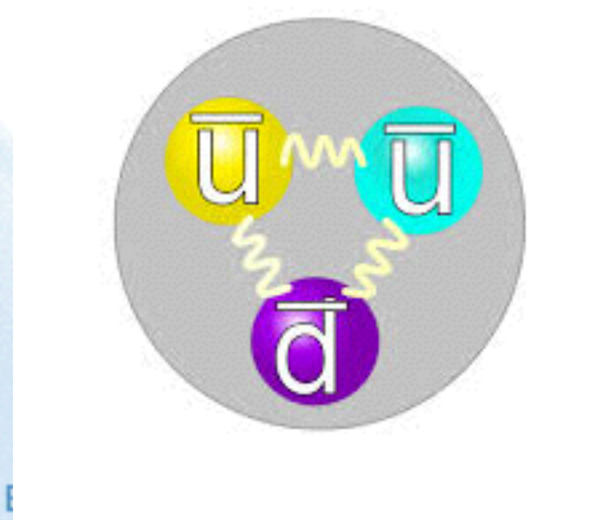
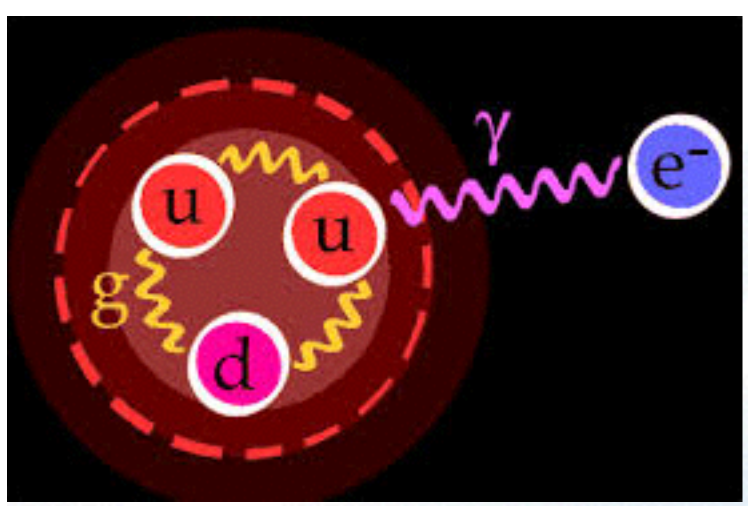


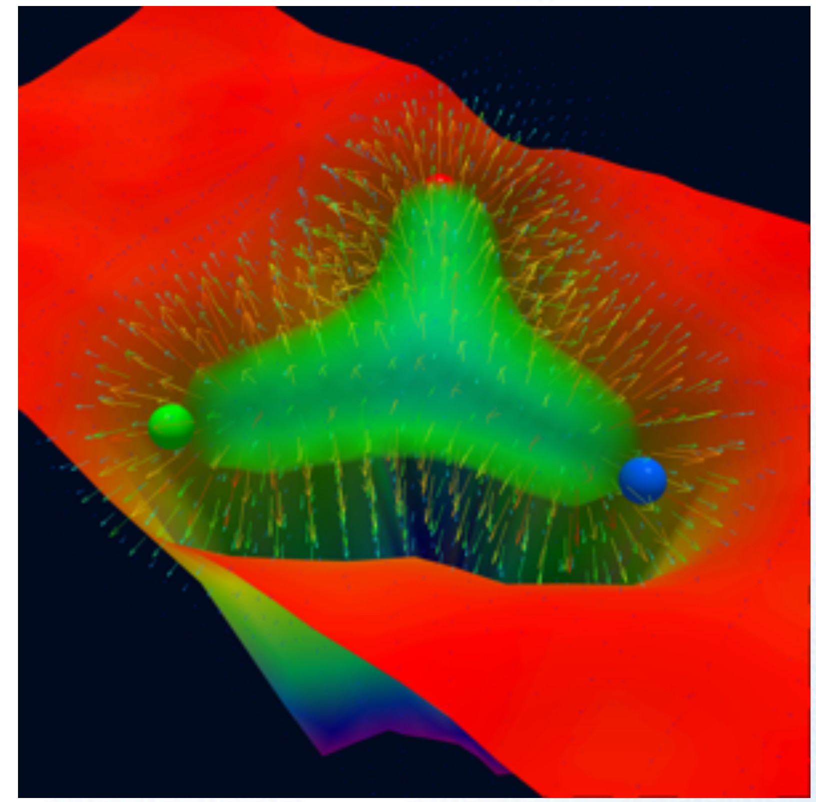










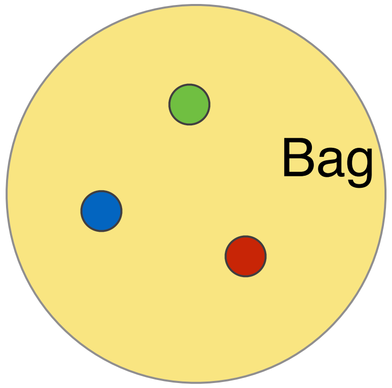


Lattice simulation with artificially frozen quarks

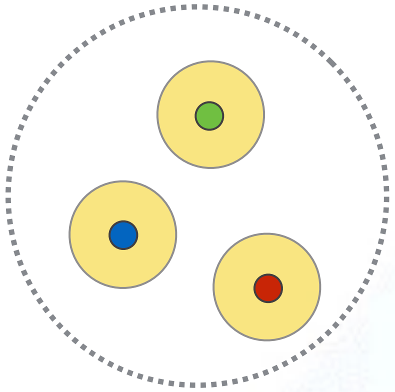
D. Leinweber (Adelaide)

Where are the gluons?

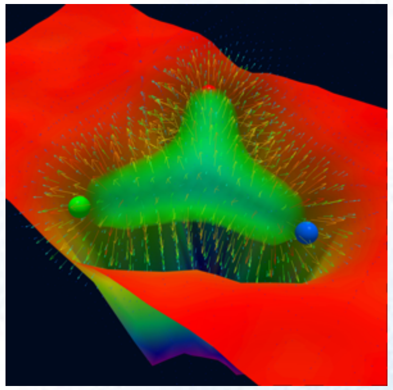
- Bag model:
  - Field energy distribution is wider than the distribution of fast moving light quarks



- 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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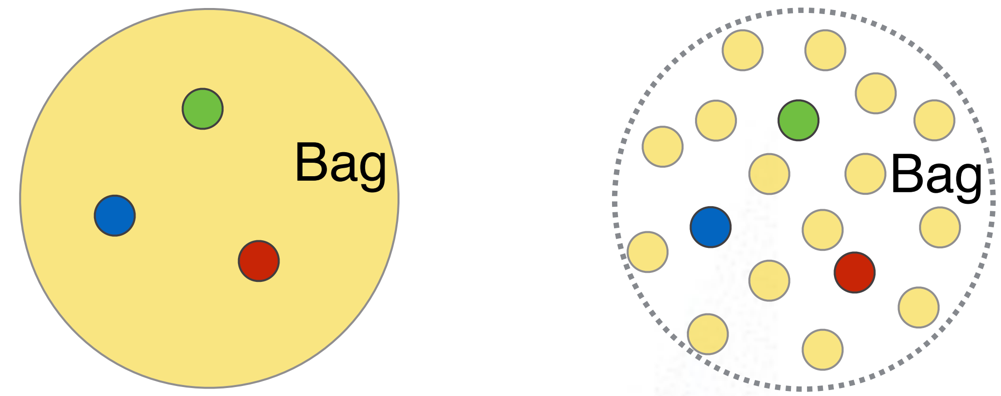

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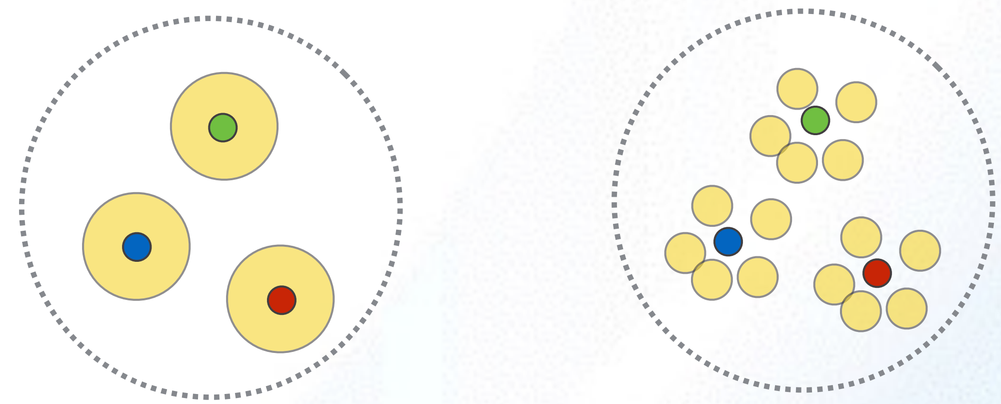

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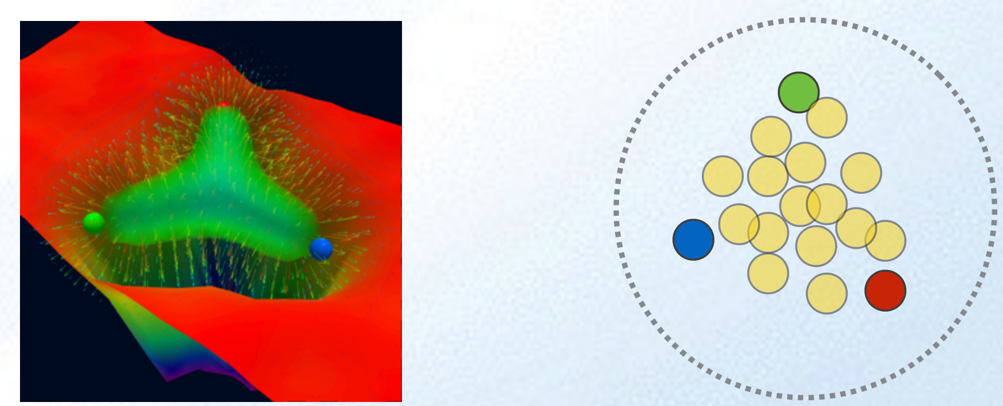
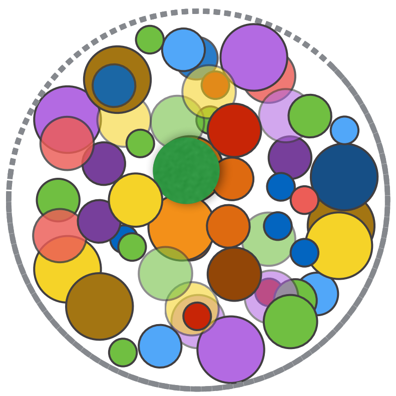


Partons at $Q^2 \sim$ few GeV^2



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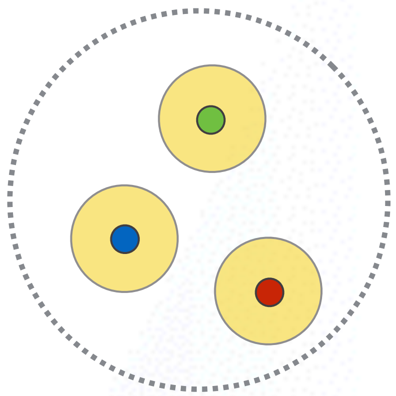


Gluon saturation

Sea partons (gluons and sea quarks)

Confined valence quarks

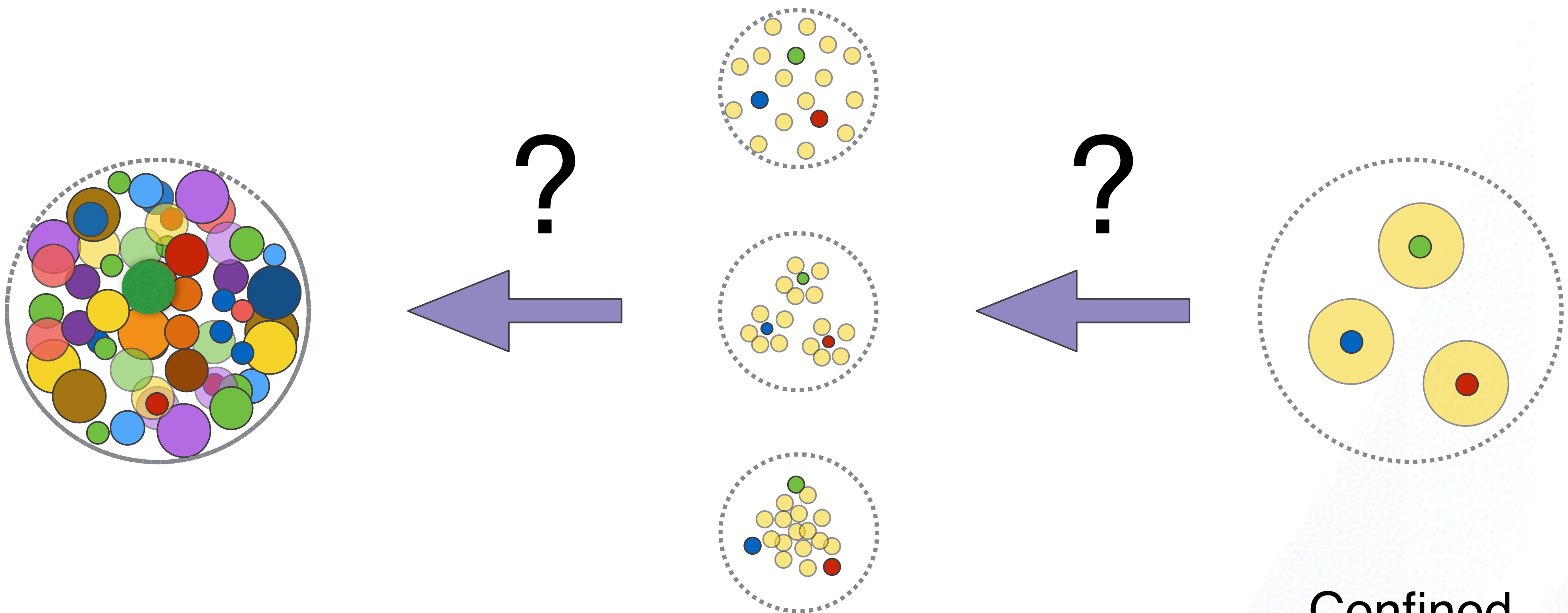
x: 10^{-N} ... 0.001, 0.01, 0.1, 1

Theoretically under control at weak coupling

EIC domain
Weakly or strongly coupled?

JLab 12 GeV program will explore

Partons at Q^2 ~ few GeV^2



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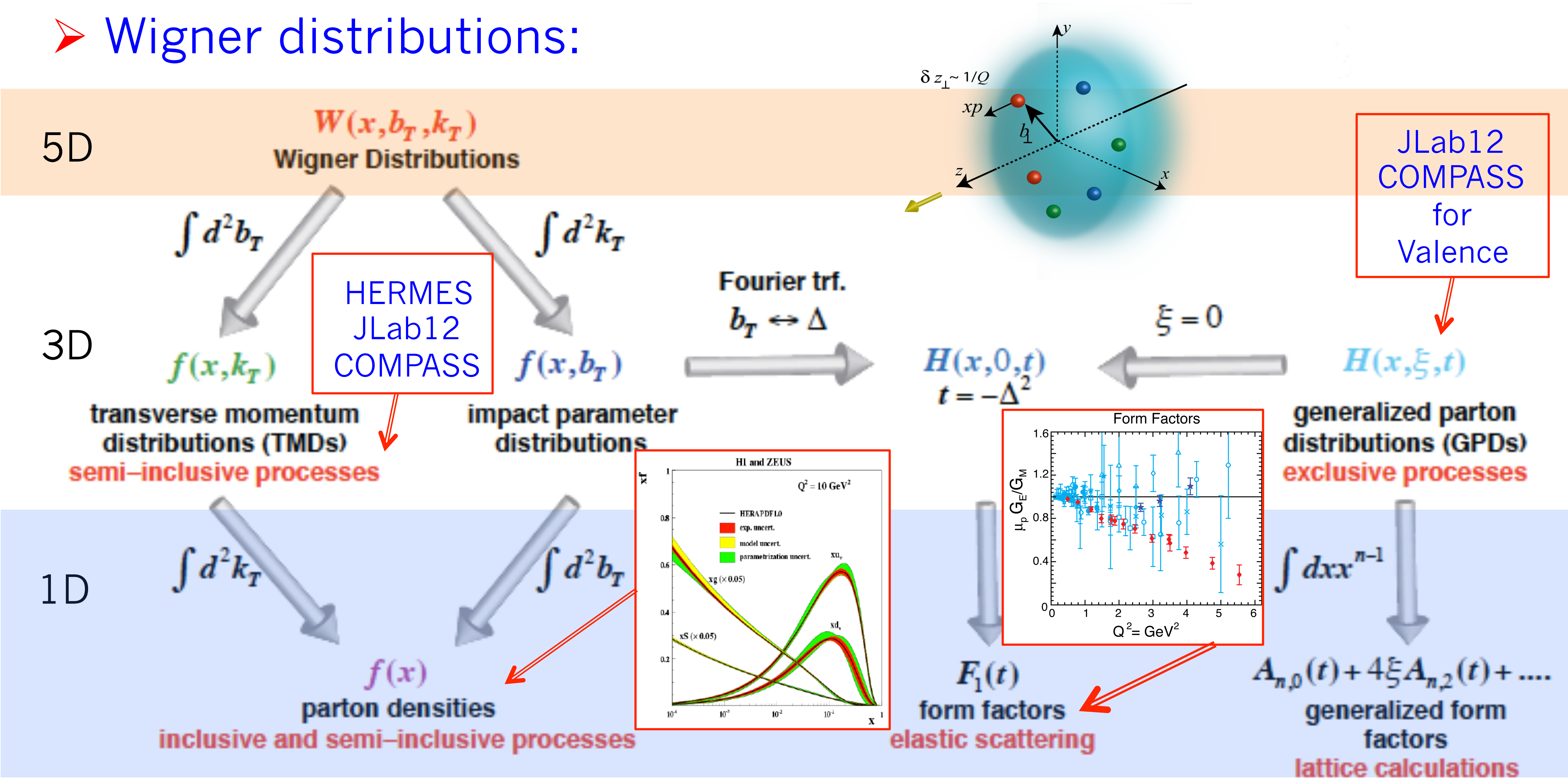
Formalism

➤ 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)**

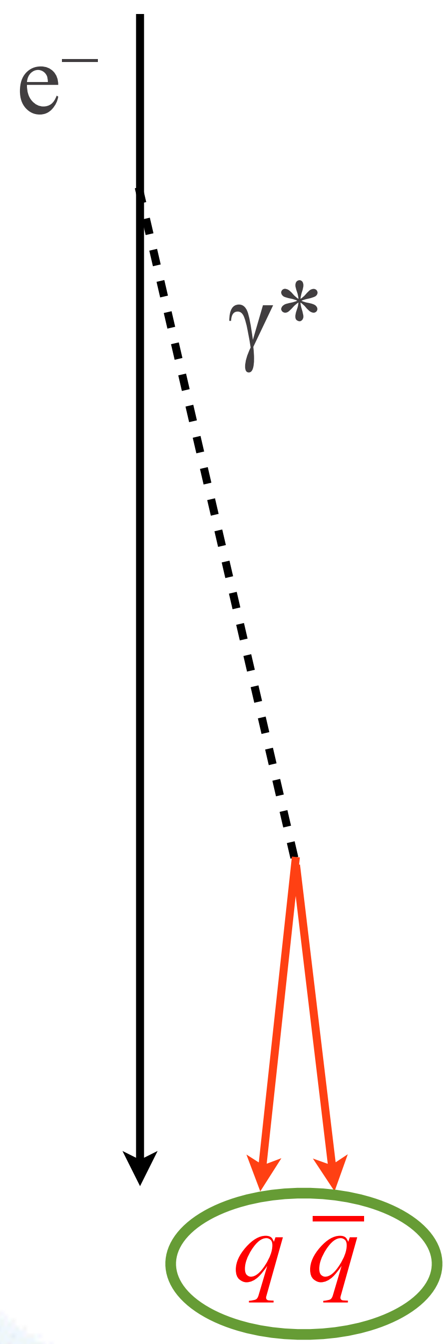
TMDs and GPDs

- The quantum state of the proton is an amplitude distribution with phases among different configurations. Like a hologram versus a photograph. Different “angles of view” i.e. different observables weight the phases differently. There is not a single probabilistic picture of the proton, but many, depending on the observable and the frame of motion.
- The 3-gluon vertex enters not only into the structure of the rest frame state, but also into the boost operator.
- Transverse Momentum Distributions (TMDs) probe the parton transverse dynamics, while Generalized Parton Distributions (GPDs) remain collinear, but measure the transverse distribution of partons.
- TMDs at large k_T probe parton correlations. Large k_T behavior is sensitive to short-range parton-parton correlations (similar to the high p_T response in nuclei, which probes NN correlations).

The Electron-Ion Collider:

An Attoscope for Gluons

EIC: A color dipole attoscope



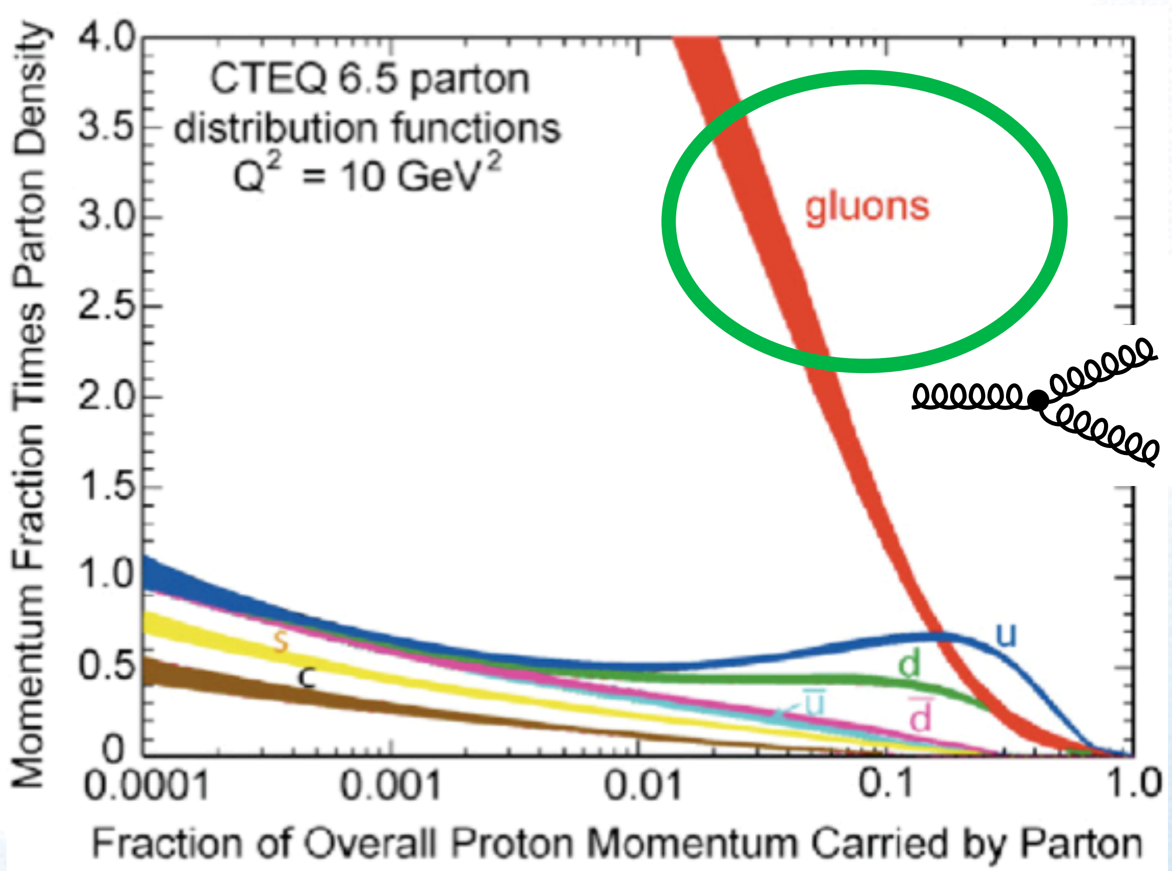
Color dipole "sees" gluons

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!

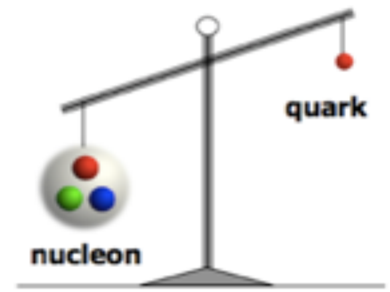


HERA was the 1st generation color dipole microscope.

Limited intensity and no polarization.

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

Proton mass and spin



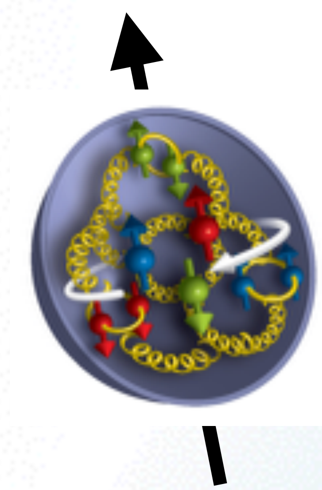
$m_q \sim 10$ MeV

$m_N \sim 1000$ MeV

- **Proton mass puzzle:**

  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

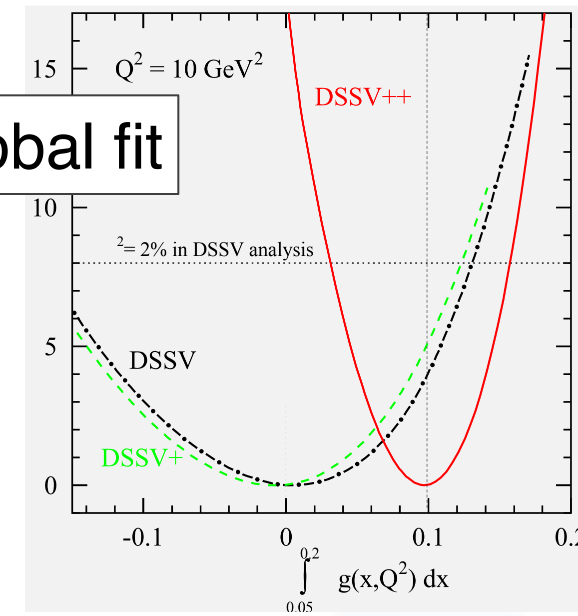
How does the glue bind quarks and itself into a proton and nuclei?

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

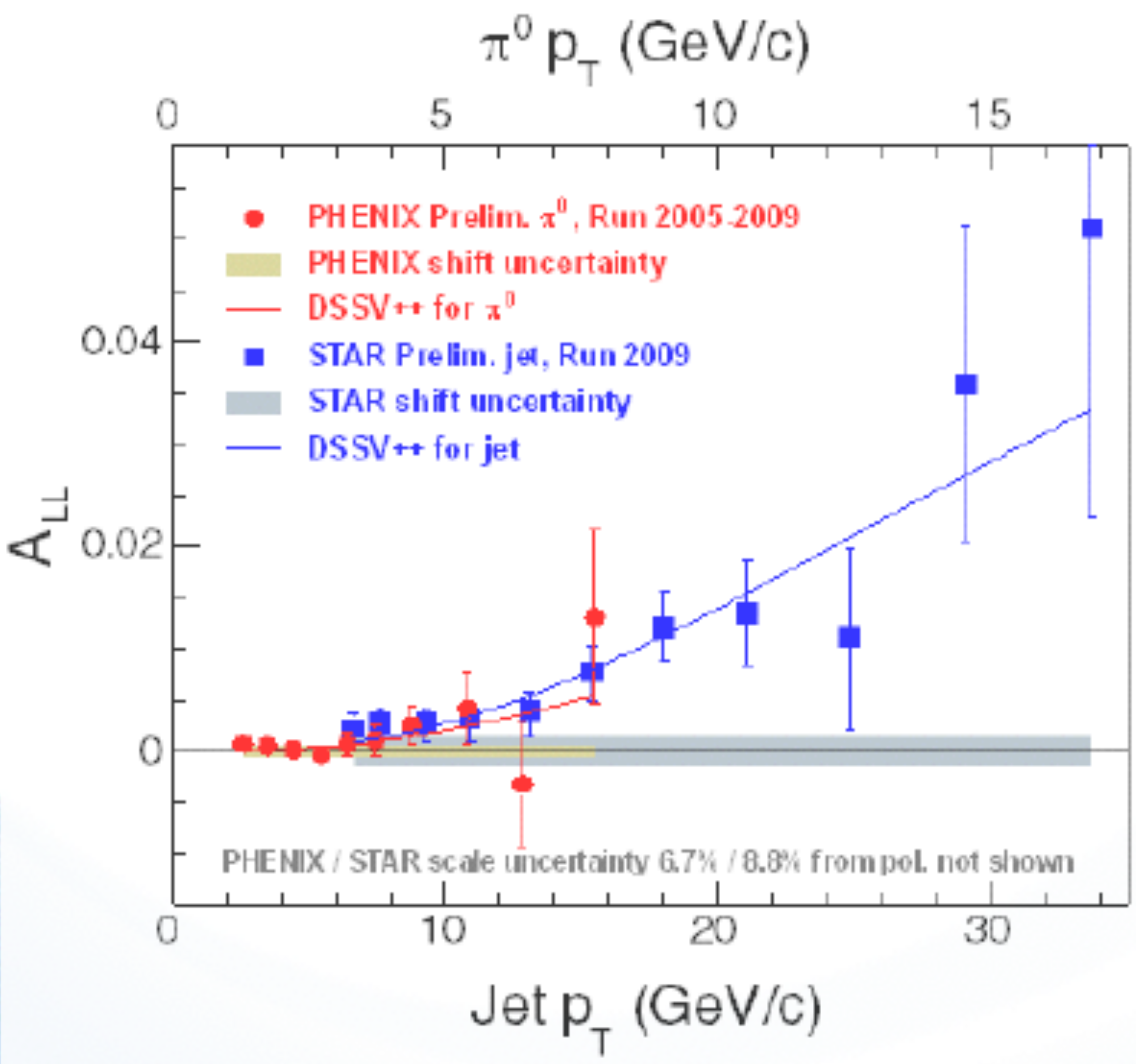
Δg from π^0 and jets

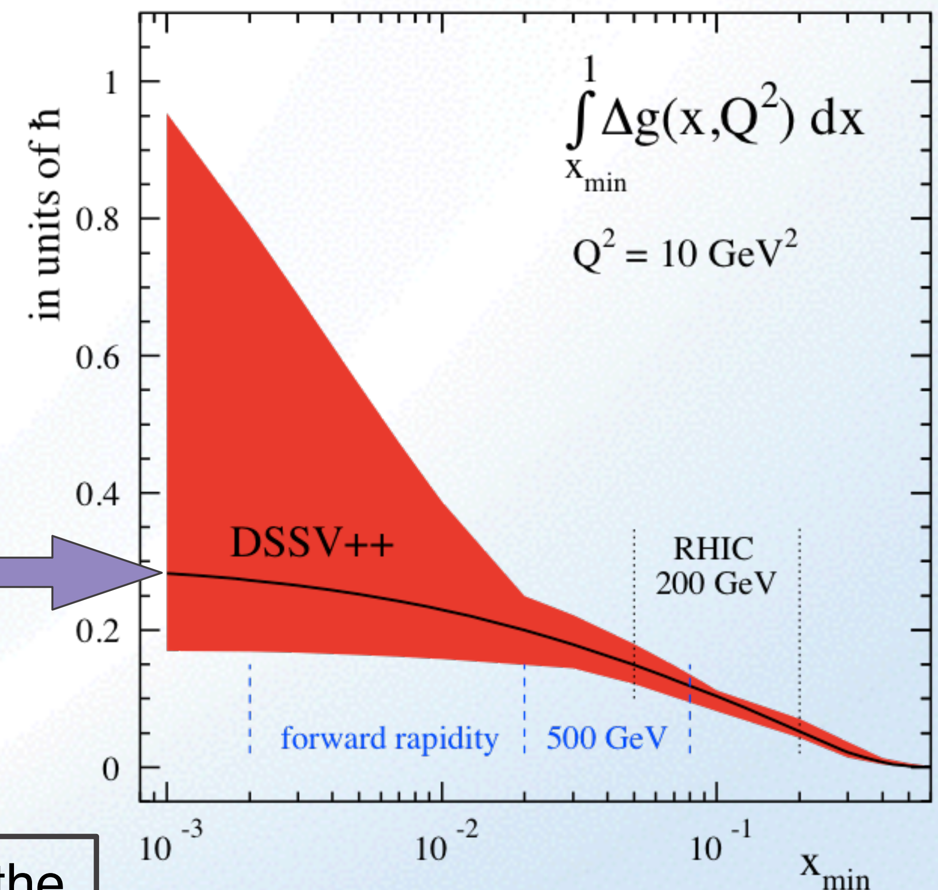
$$S = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L \qquad \Delta G = \int_0^1 \Delta g(x)\,dx$$

QCD global fit



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





~60% of the proton spin?

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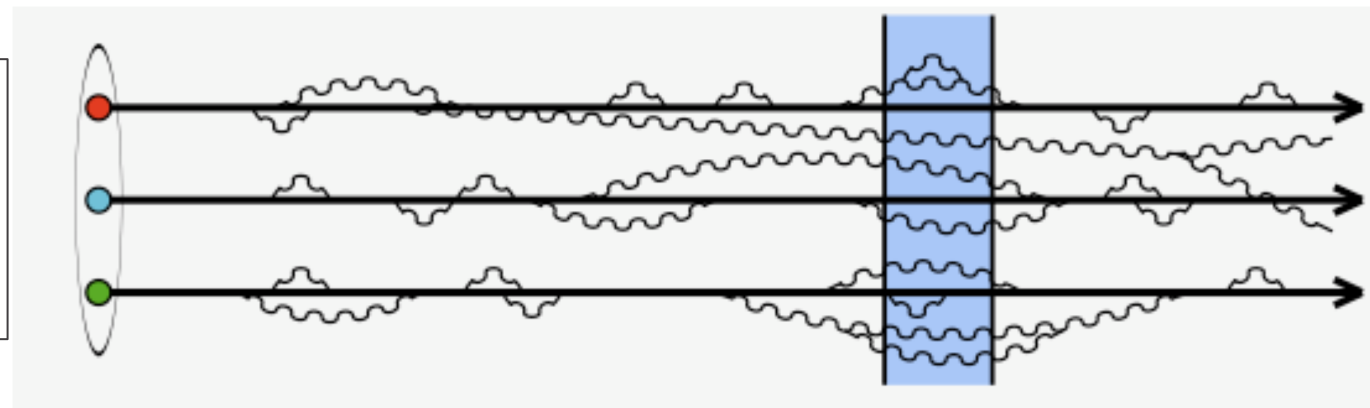
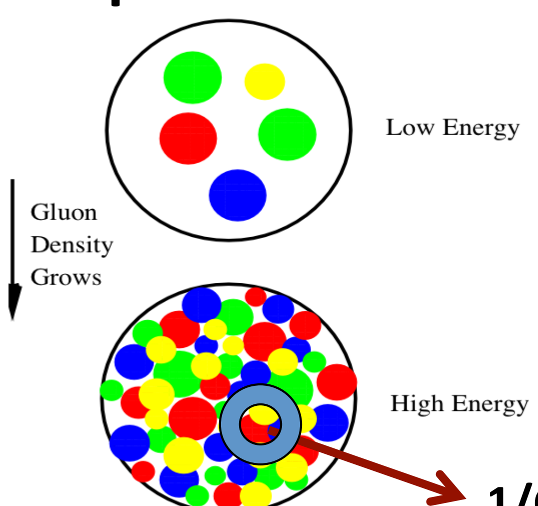
Saturation

Gluon saturation at high energy
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)

$1/Q_S^2$ Saturation scale Q_s

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

From nuclei to QGP - How?

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 recent PHHENIX article, arXiv:1312.6676)? Or is something more akin to the 4-D shadow of a 5-D gravitational shock wave?

Hadronization and Confinement

How do hadrons emerge from a created quark or gluon?

Neutralization of color = hadronization

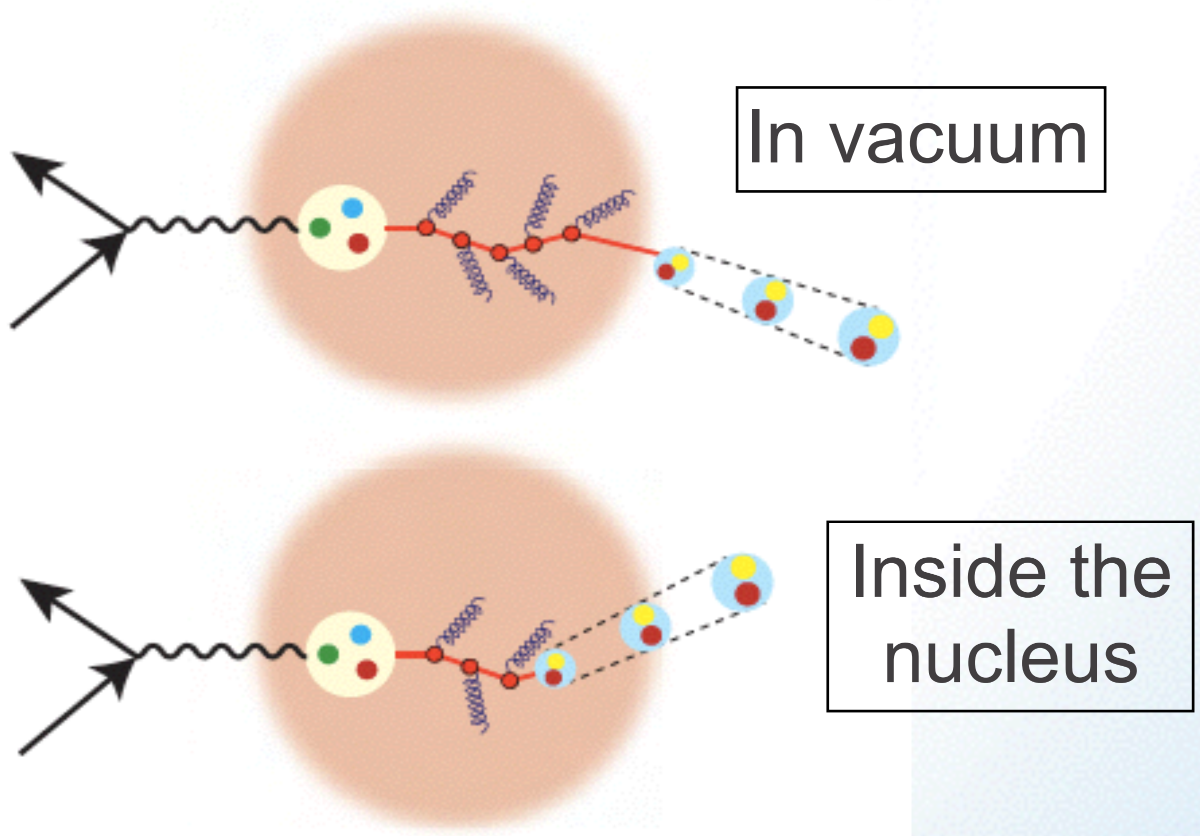
- **Femtometer detector/scope:**

  Nucleus, a laboratory for QCD

- **Quark/gluon properties:**

  Initial-condition for hadronization

  Semi-inclusive DIS

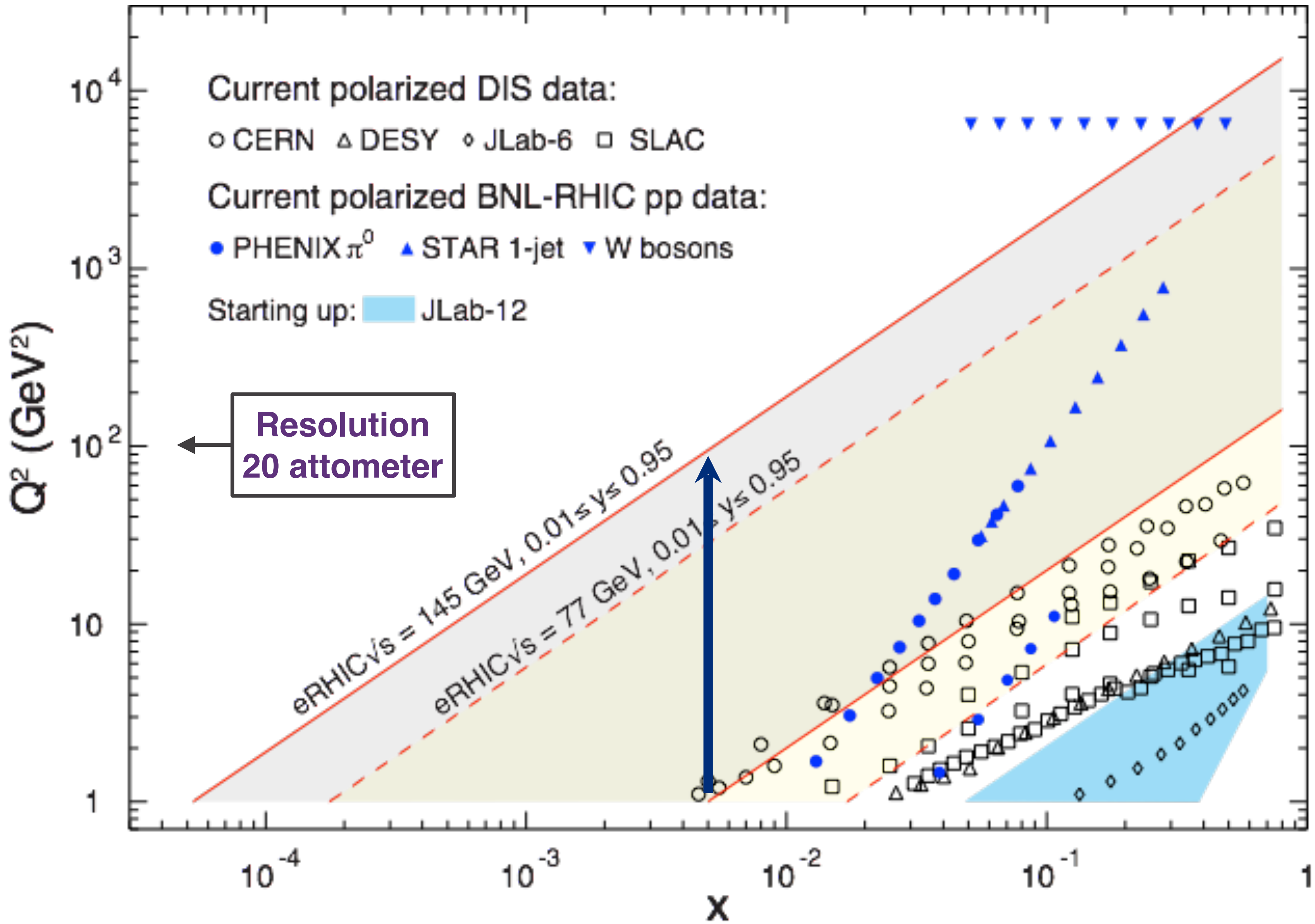


From the EIC White Paper

- **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!

Requirements: √s and Polarization



polarized
ep*, µ*p*, *pp

$Q^2 \approx s \cdot x \cdot y$

- Need to reach low-x where gluons dominate (ΔG, ΔΣ range!)
- Flexible energies (see also structure functions later)
- Need sufficient lever arm in Q^2 at **fixed** x (evolution along Q^2 or x)
- Electrons and protons/light nuclei (p, He^3 or d) highly polarized (70%)

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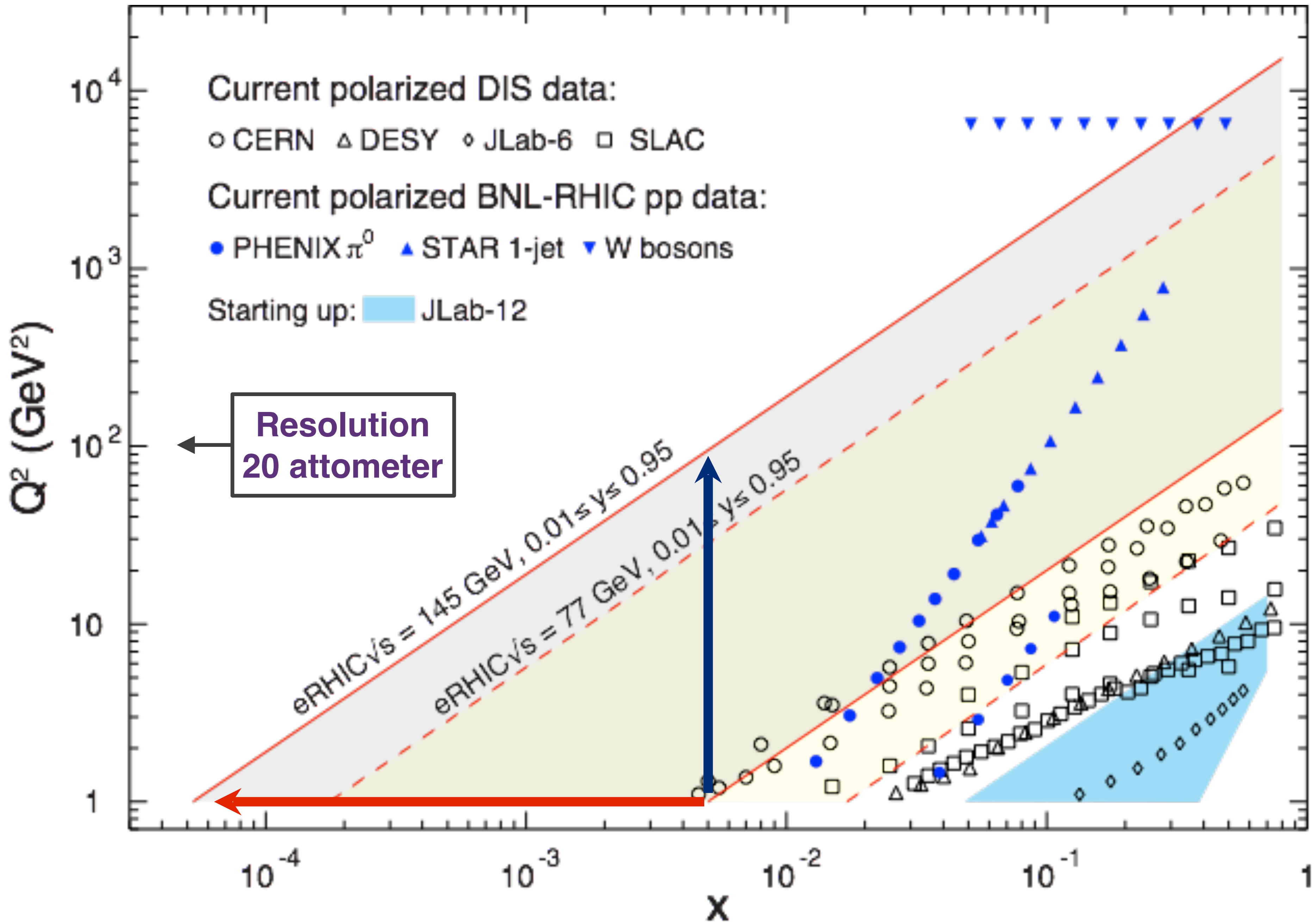

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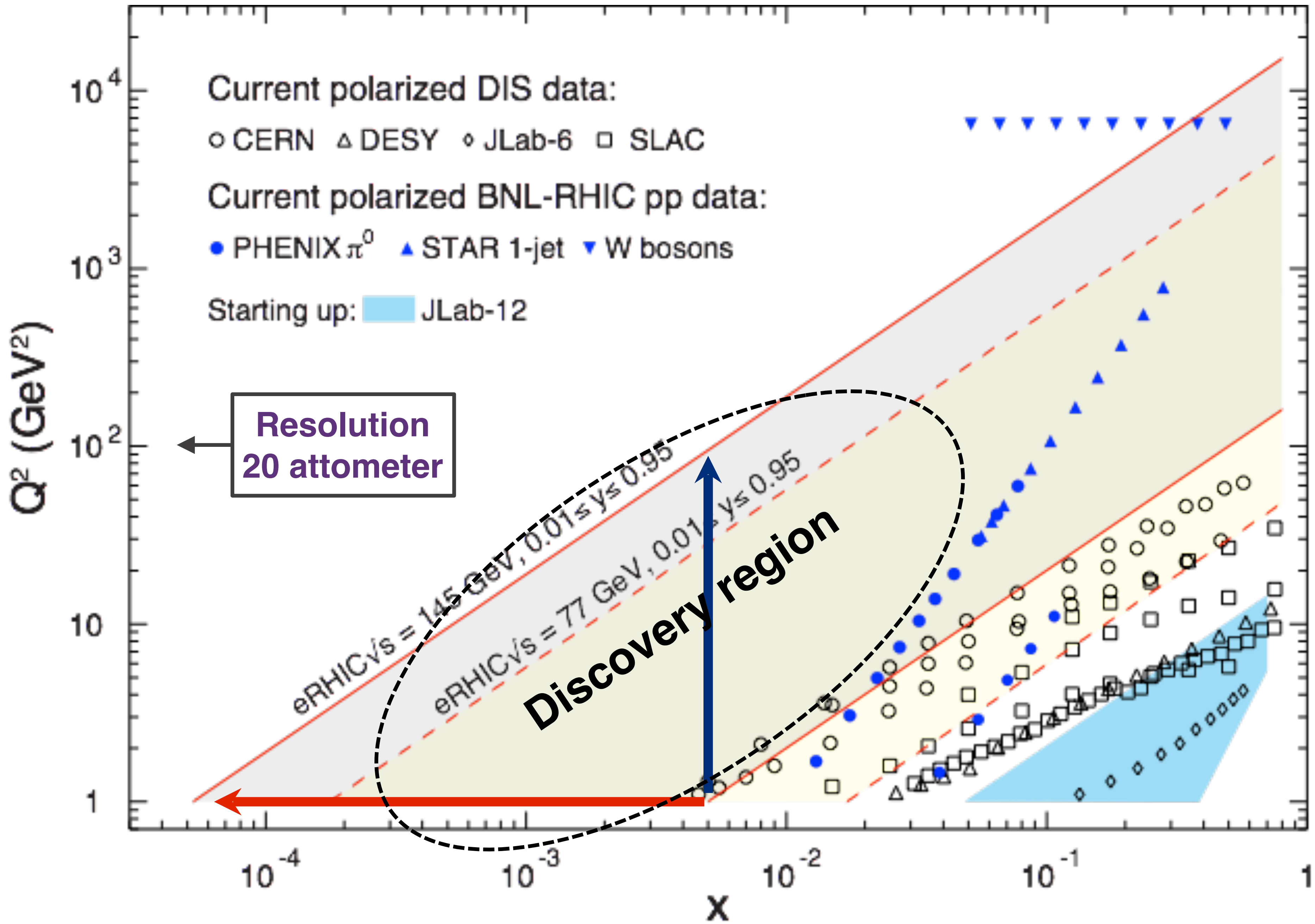

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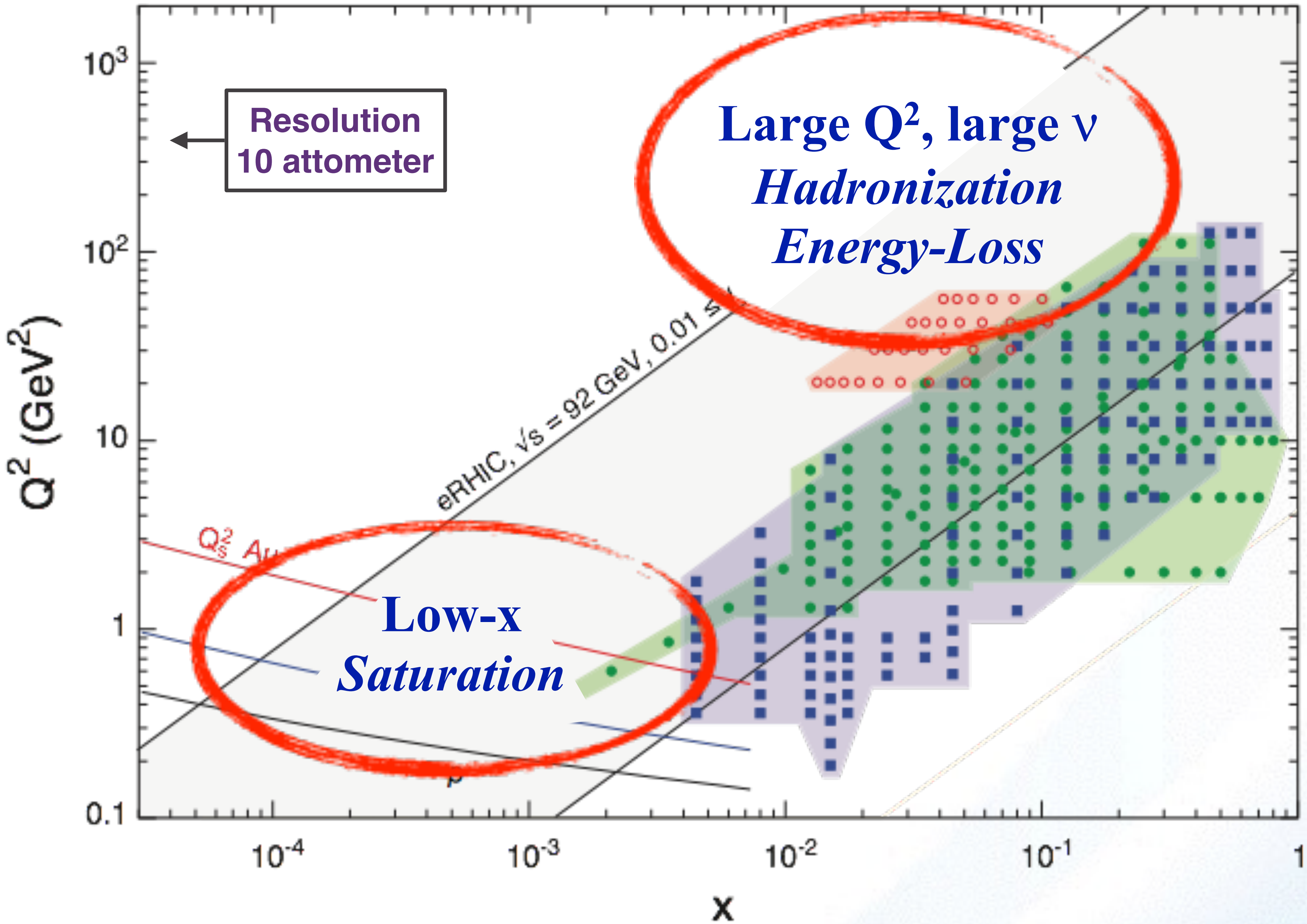
Requirements: √s and Beam Masses



eA, μA, νA
(A ≥ Fe)

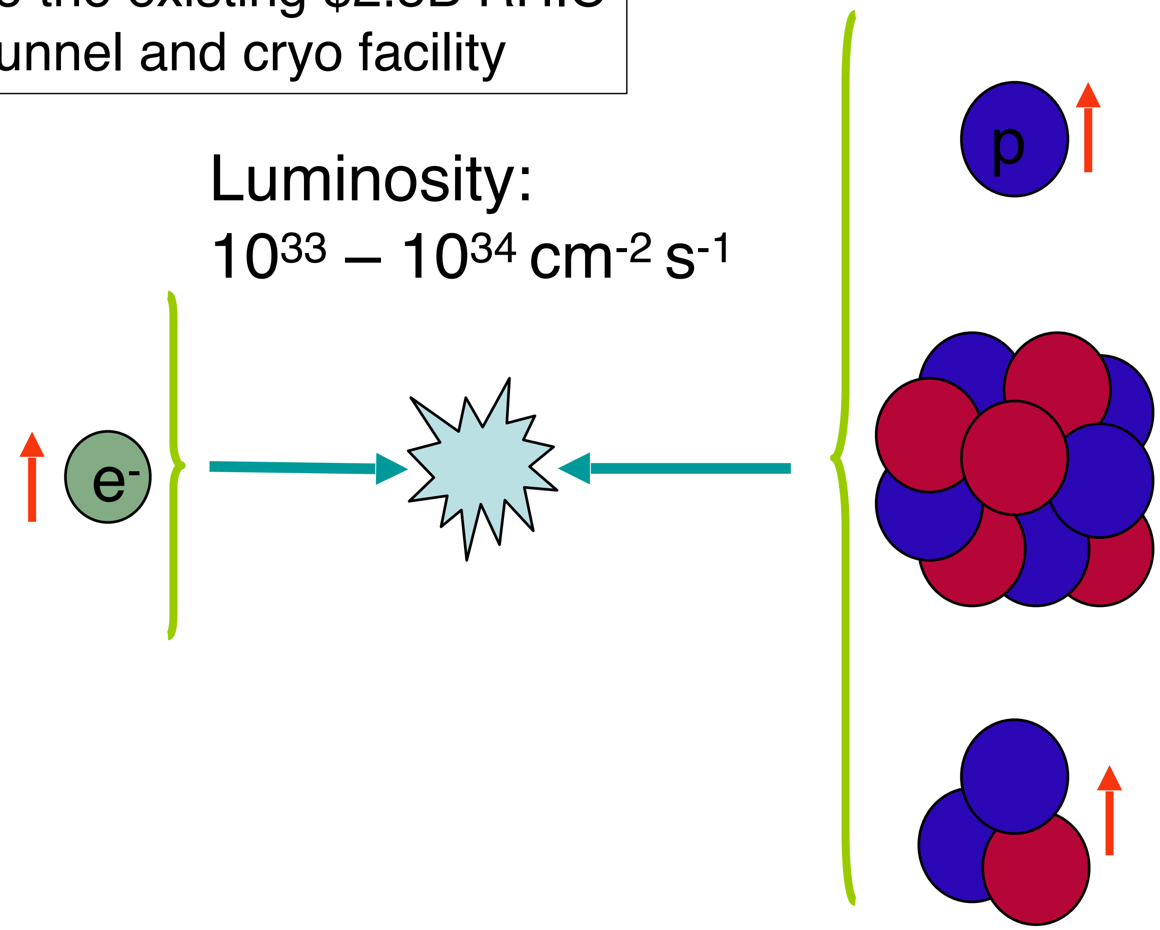
- Saturation physics needs low-x reach and wide range of nuclei (A dependence) up to the heaviest A (Q_s enhancement): d ➟ U
- Needs sufficient lever arm in Q^2 down to at least $x = 10^{-3}$ to verify non-linear evolution equations of CGC

eRHIC:
EIC @ BNL

eRHIC: Electron Ion Collider at BNL

Add an electron accelerator to the existing $2.5B RHIC including existing RHIC tunnel and cryo facility

80% polarized electrons:
6.6 – 21.2 GeV

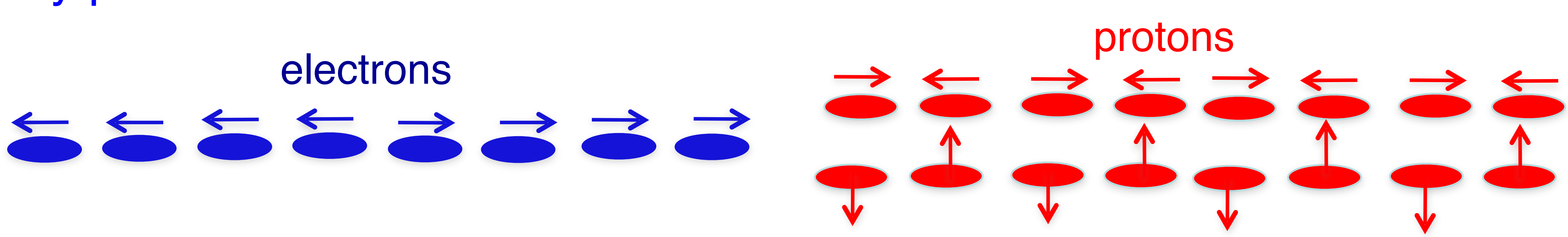


70% polarized protons
25 - 250 (275*) GeV

Light ions (d, Si, Cu)
Heavy ions (Au, U)
10 - 100 (110*) GeV/u

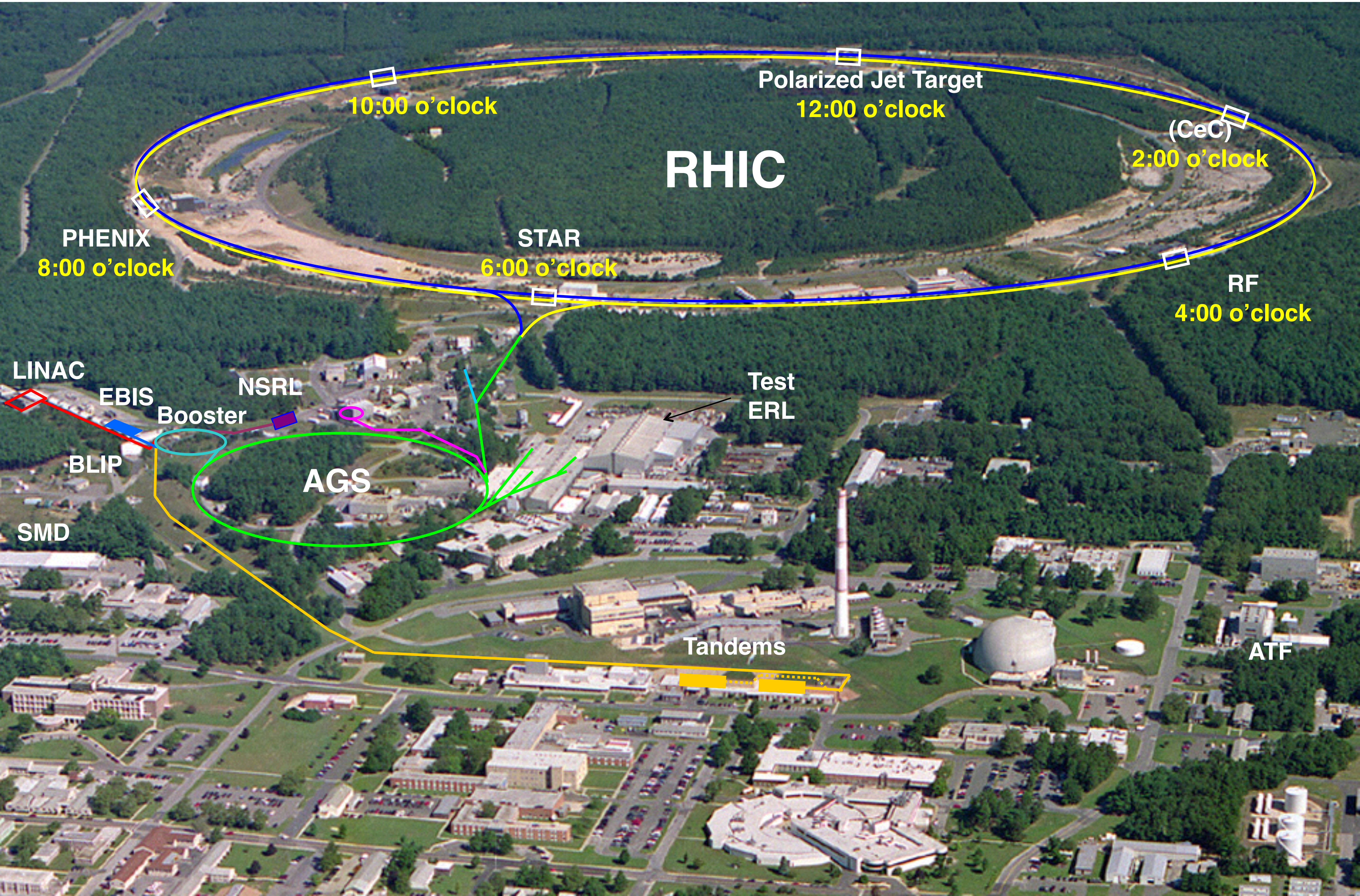
Pol. light ions (He-3)
17 - 167 (184*) GeV/u

- Center-of-mass energy range: 30 – 145 GeV
- Full electron polarization at all energies
  Full proton and He-3 polarization with six Siberian snakes
- Any polarization direction in electron-hadron collisions:

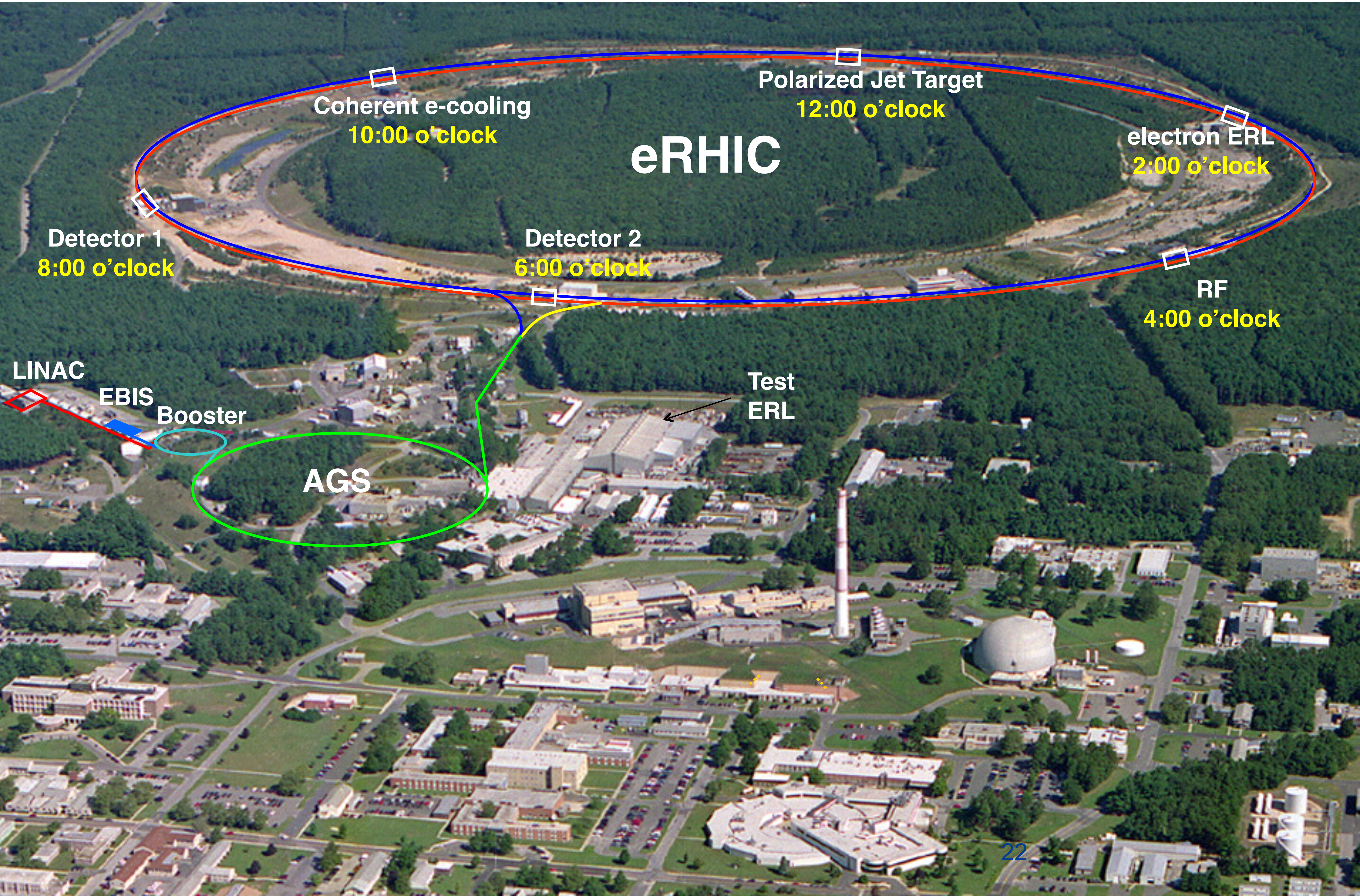


* It is possible to increase RHIC ring energy by 10%

RHIC – Hadron & Nucleus Collider



eRHIC – Polarized Electron-Ion

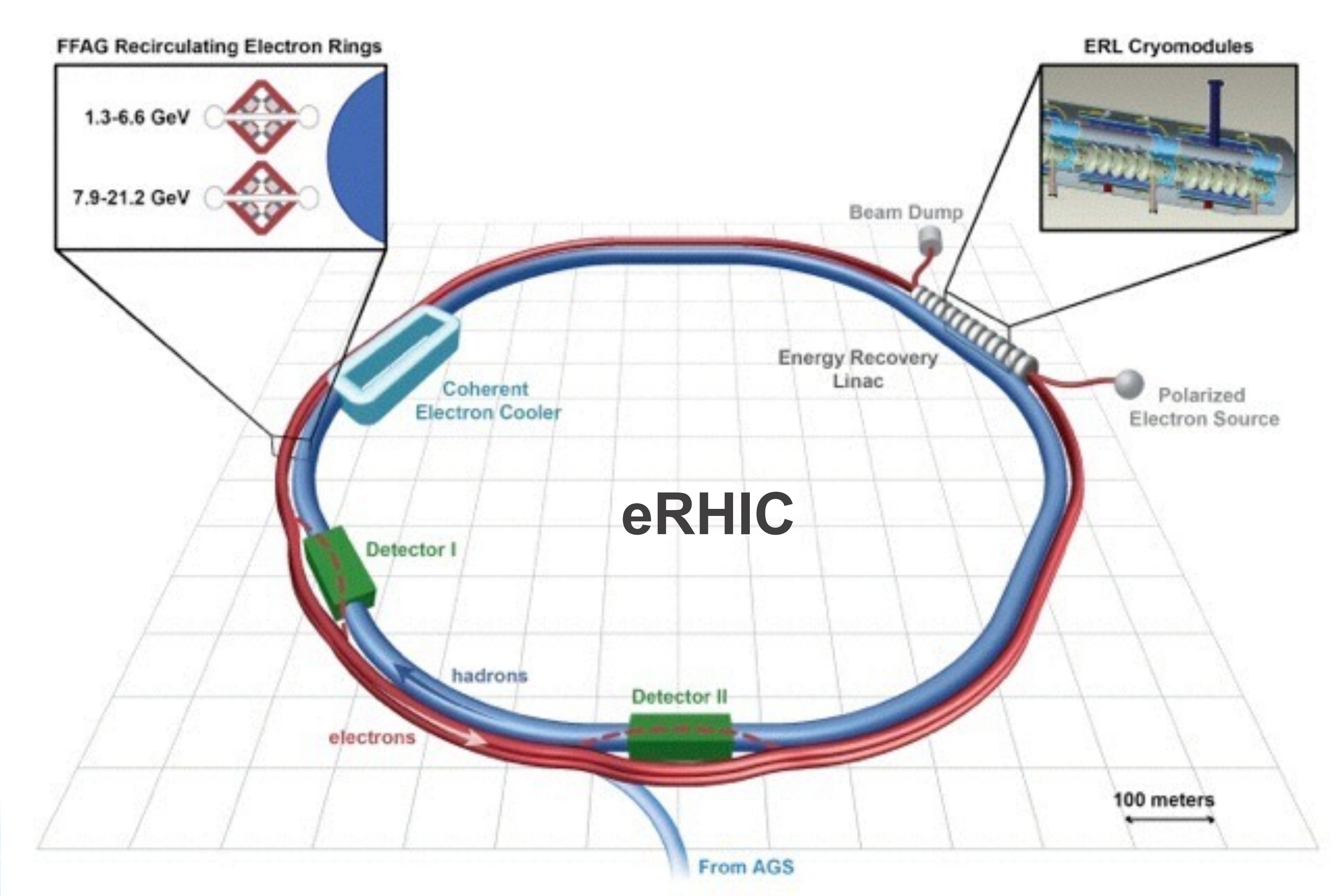


EIC Design

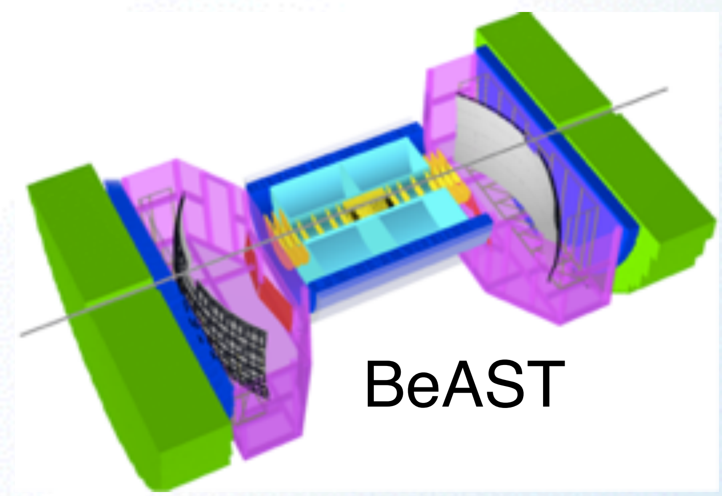
Detector Options

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

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

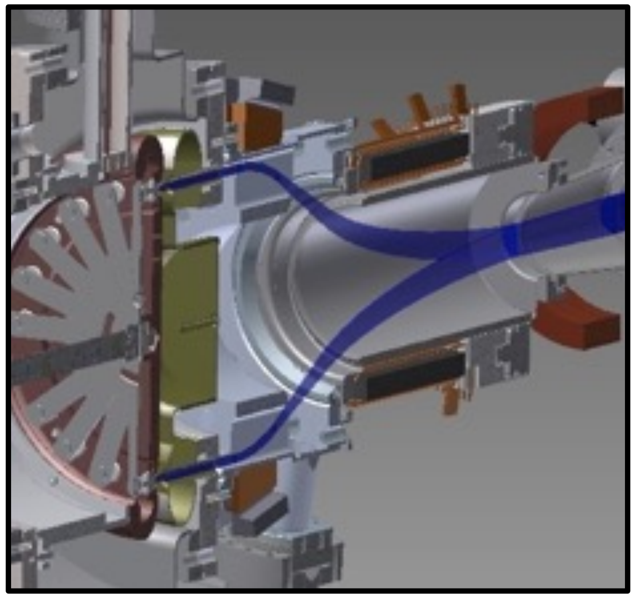


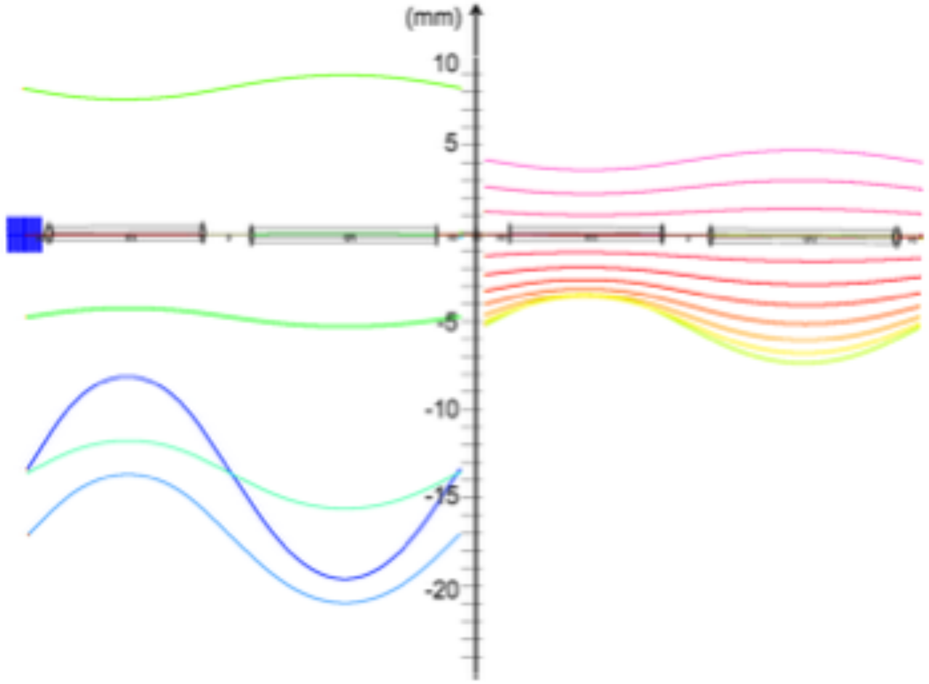
When completed, eRHIC will be the most advanced and energy efficient accelerator in the world



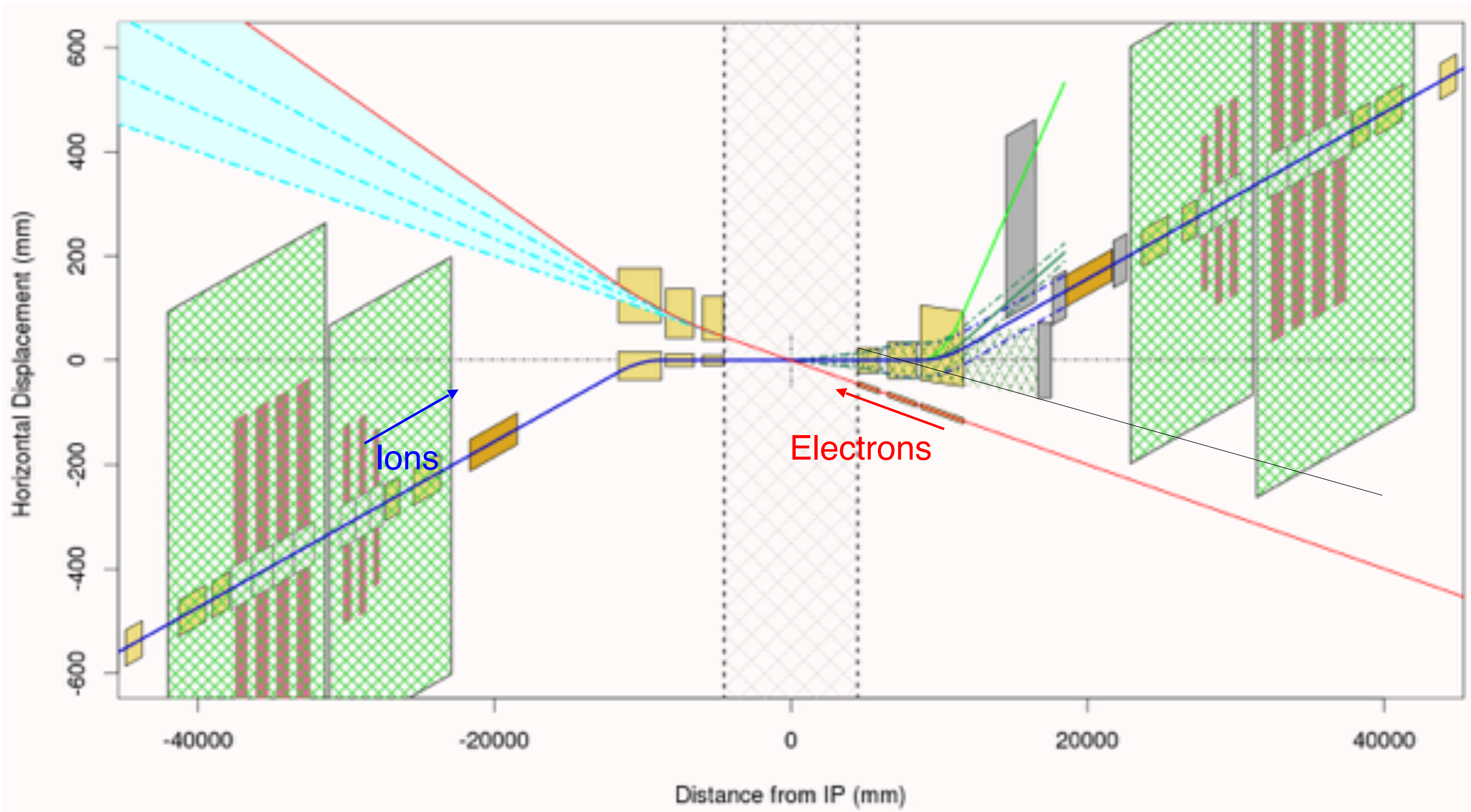
Innovations and challenges of eRHIC

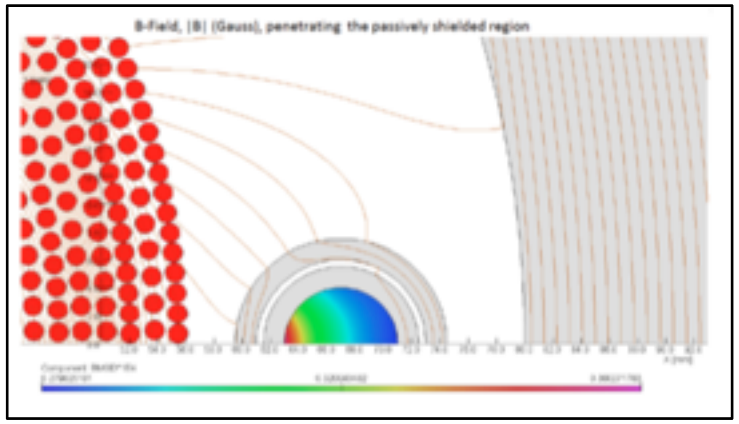
- High intensity (50mA) polarized electron source using multi-cathode gun ("Gatling Gun")
- Energy Recovery Linac with 98% recovery efficiency (energy loss from synchrotron radiation)
- Up to 16 re-circulations of the electron beam through the same 1.32 GeV Linac
- Novel FFAG lattice allows 16 beam re-circulations using only two beam transport rings
- Permanent magnet technology is used for the FFAG beamline magnets eliminating the need for power supplies, power cables and cooling.
- Strong cooling of hadron beams gives high luminosity while minimizing electron beam current and synchrotron radiation loss.



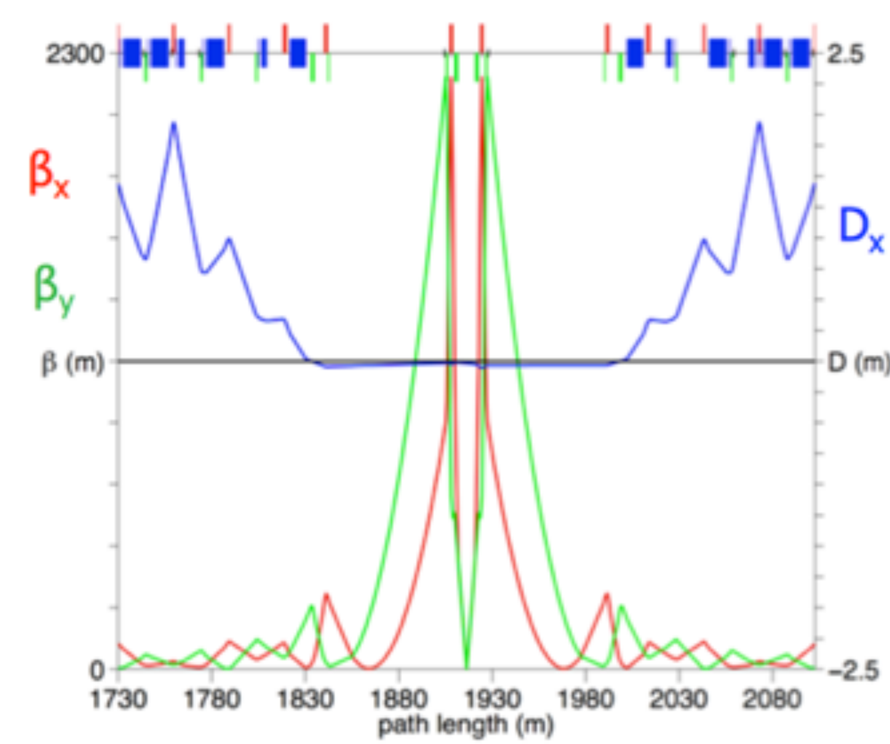


eRHIC high-luminosity IR with $\beta^* = 5$ cm

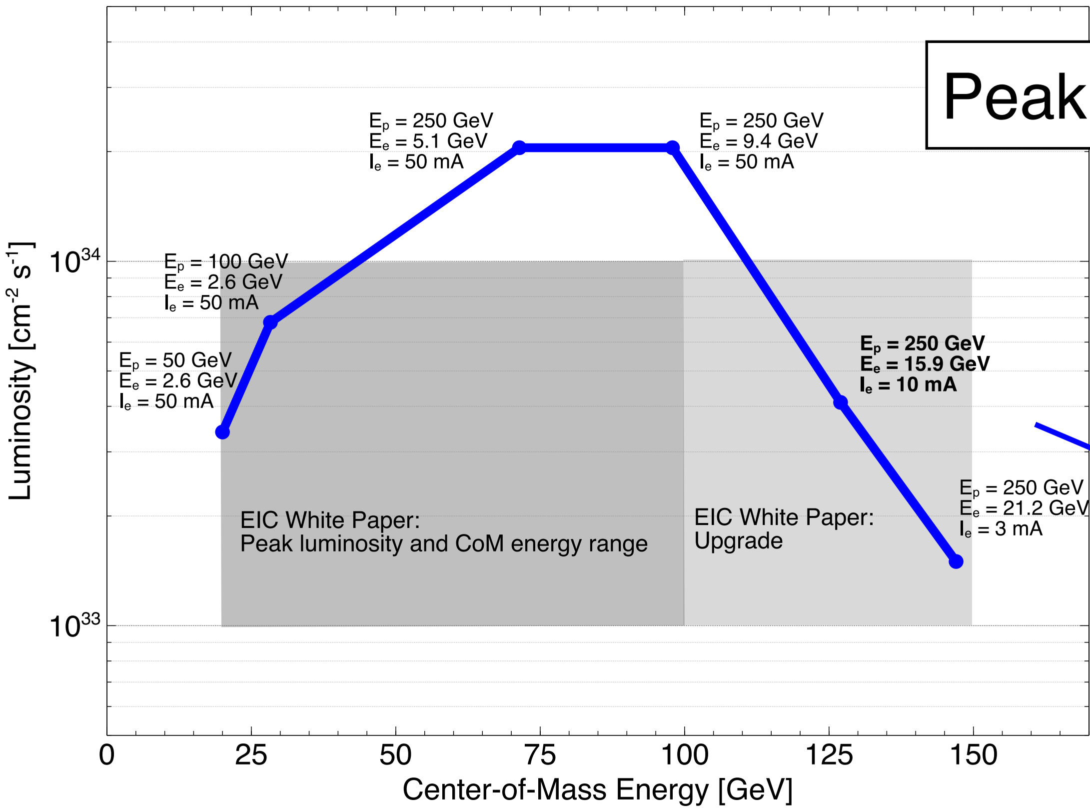




- 10 mrad crossing angle and crab-crossing
- 90 degree lattice and beta-beat in adjacent arcs (ATS) to reach beta* of 5 cm with good dynamic aperture
- Combined function triplet with large aperture for forward collision products and with field-free passage for electron beam
- Only soft bends of electron beam within 60 m upstream of IP

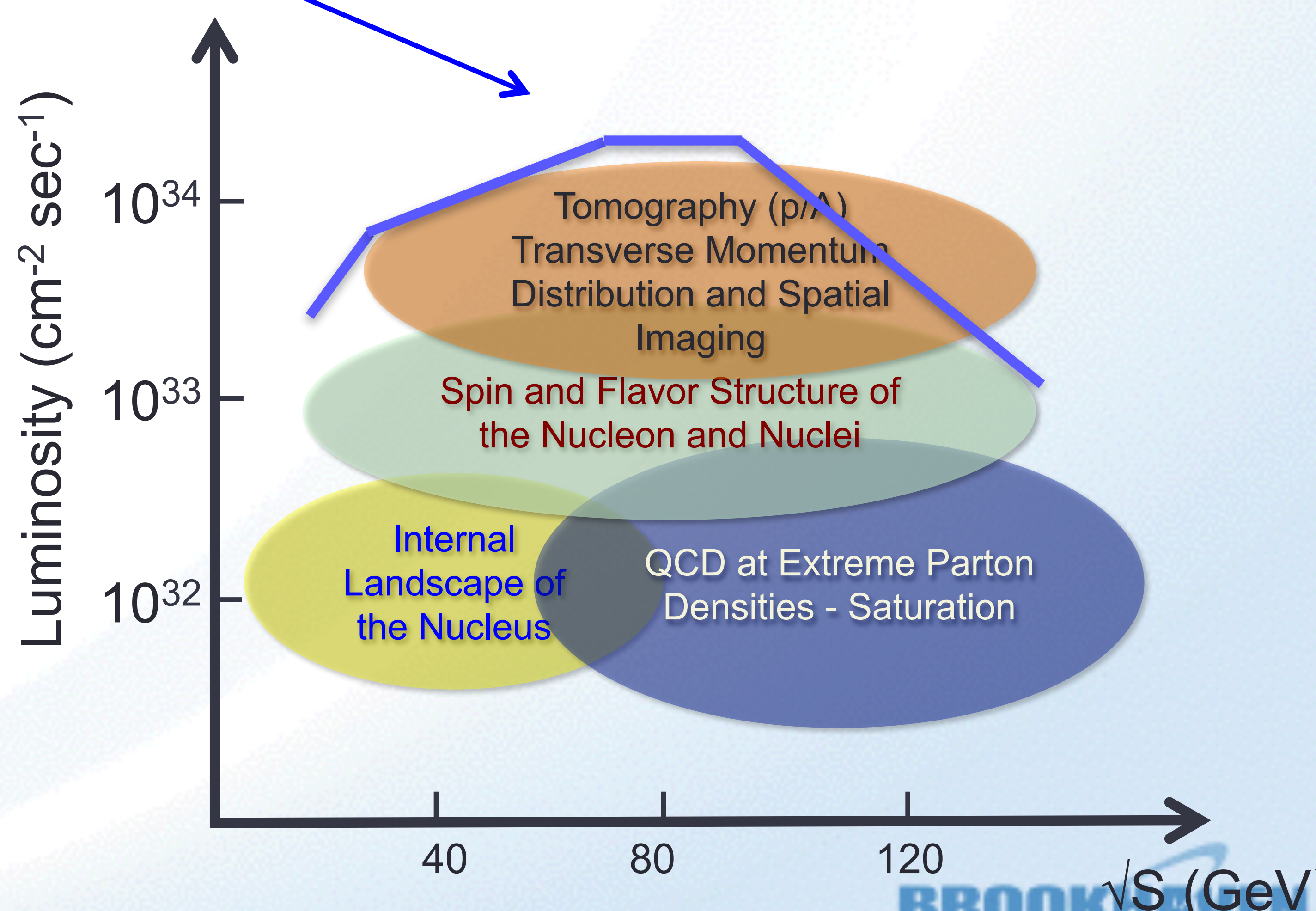


Design goals match physics goals



Peak luminosity vs. CM energy

EIC requirements for physics opportunities

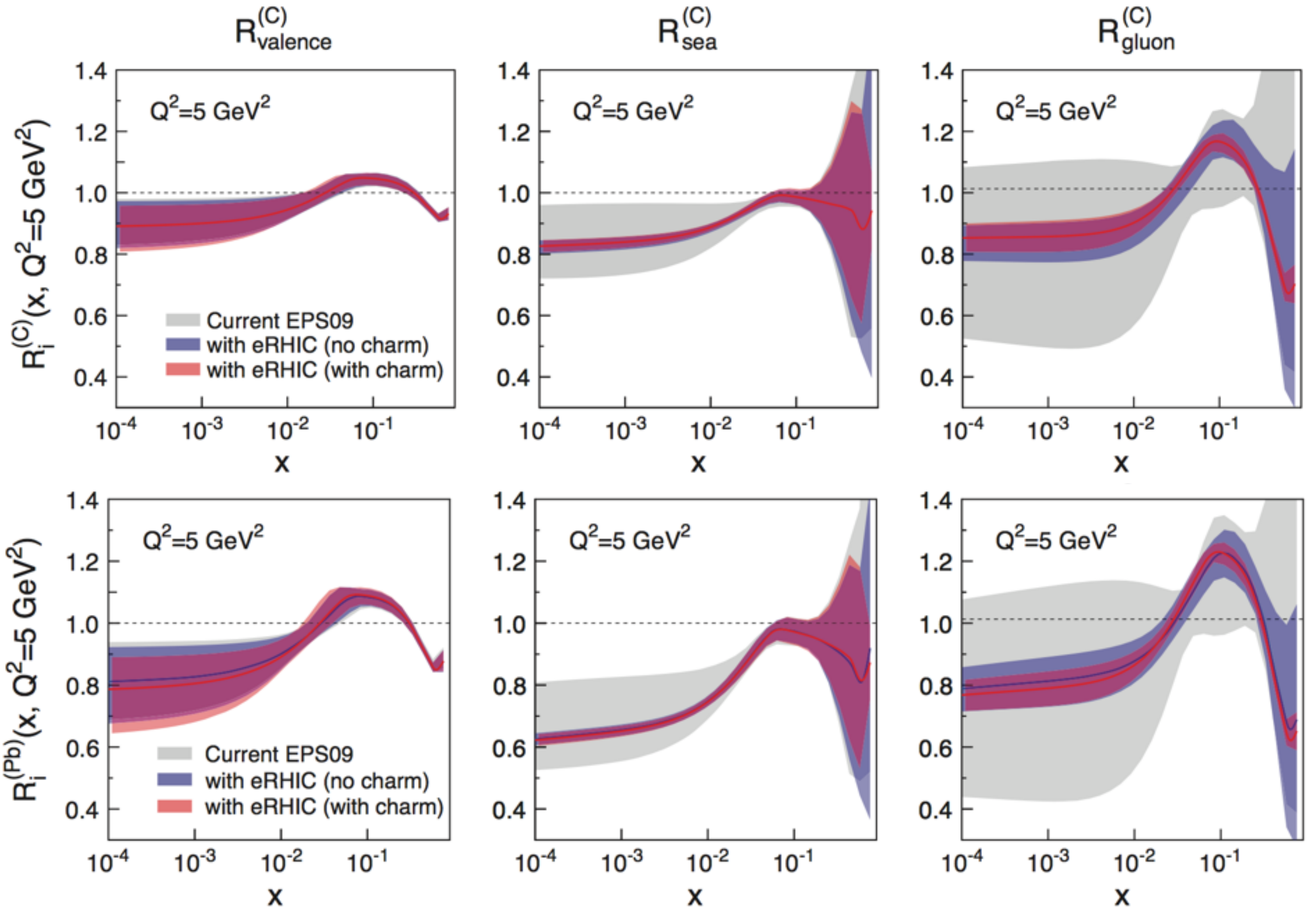


Detector requirements:

- **Good PID (*e*/*h* and π, *K*, *p*)**
- **Wide acceptance to reach edges of kinematic range**
- **Ongoing generic EIC detector R&D program**

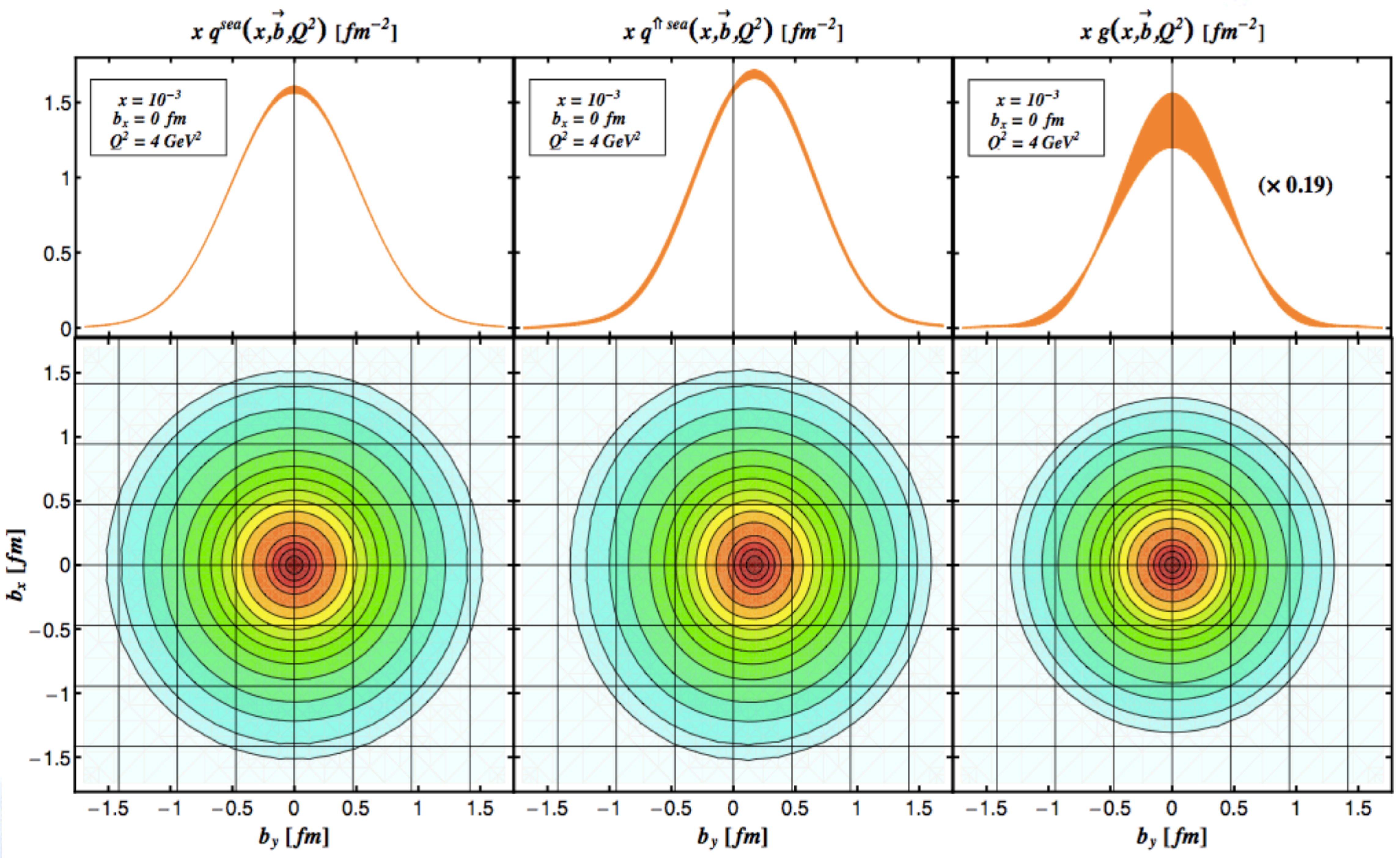
Selected Measurements

PDFs: Impact on nuclear modification



Imaging quarks and gluons

using Generalized Parton Distributions (GPD's):



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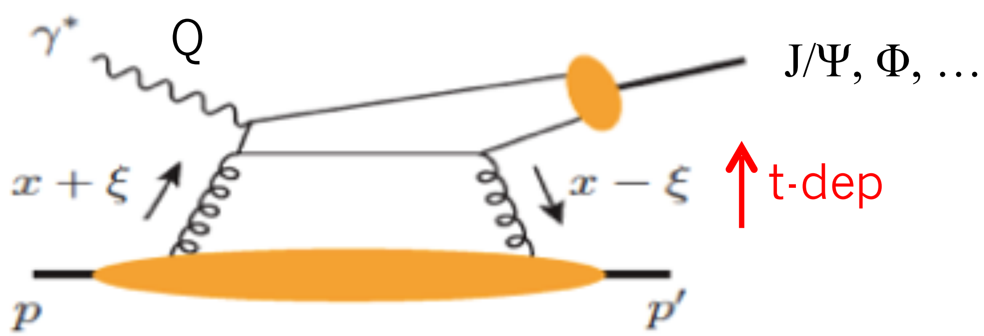
Imaging gluons

- ➢ **Exclusive vector meson production:**



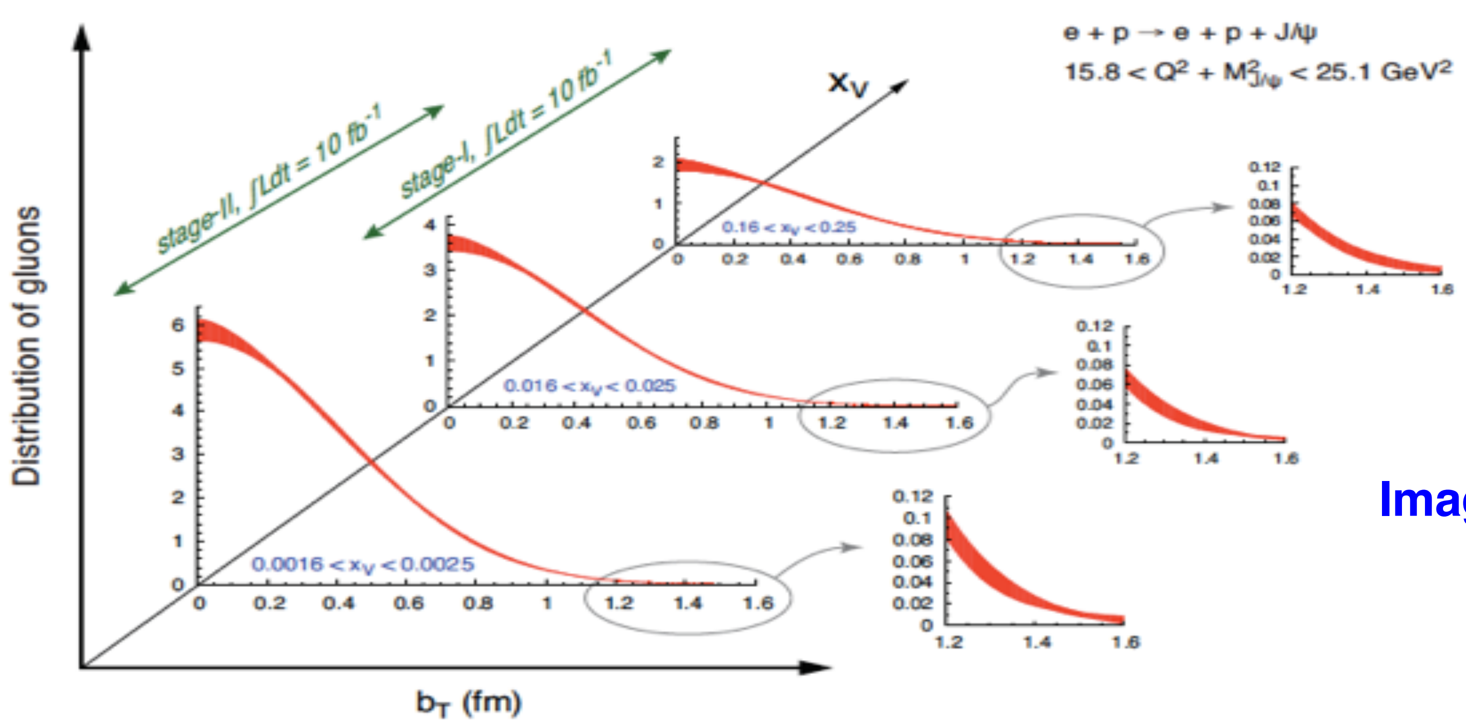
$$\frac{d\sigma}{dx_B dQ^2 dt}$$

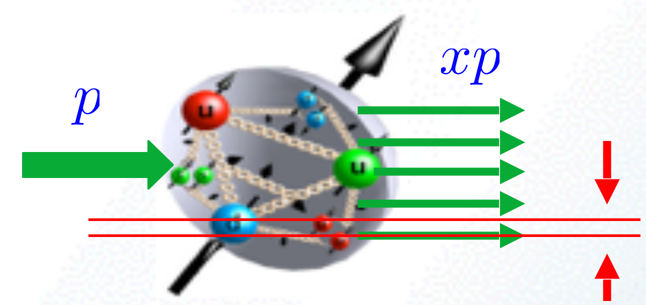
Fourier transform of the t-dependence

➡ Spatial imaging of glue density

Resolution ~ 1/Q or 1/M_Q

- ➢ **Gluon imaging from simulation:**





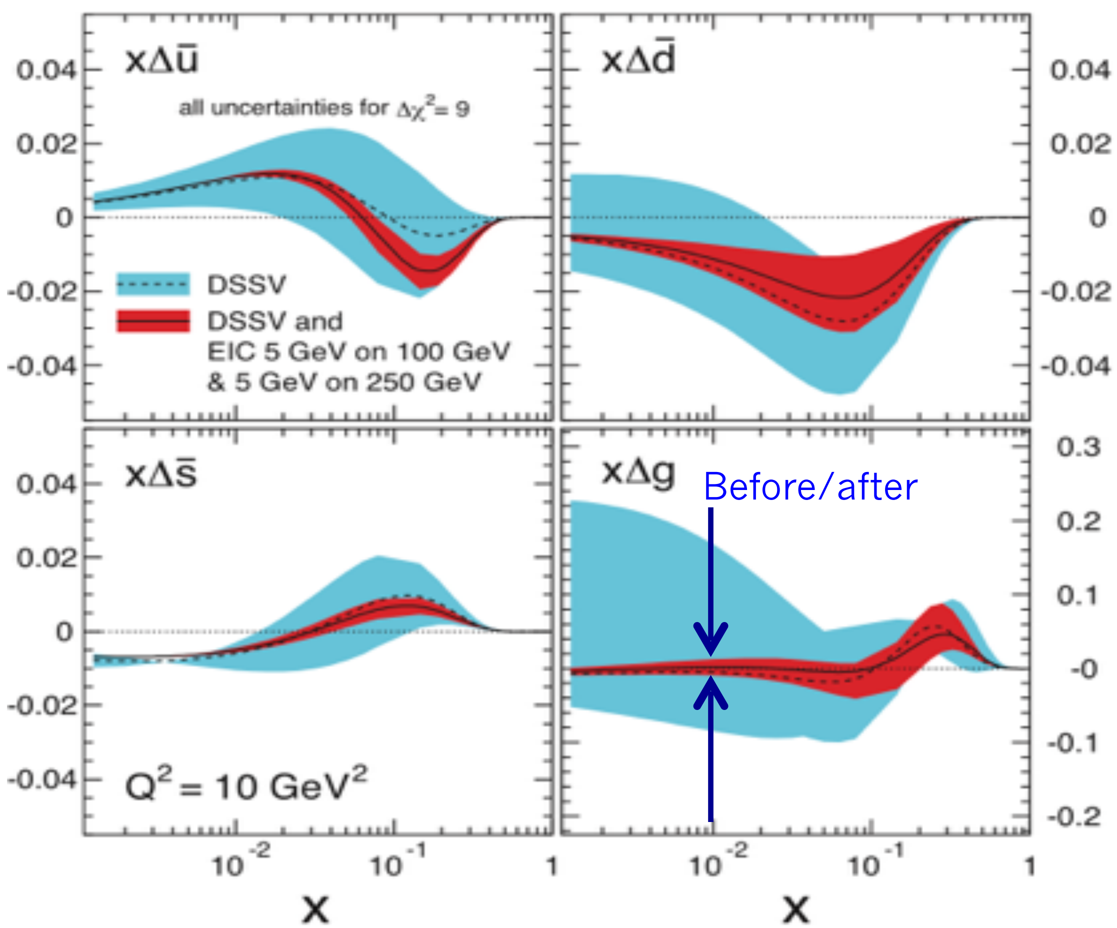
Images of transverse gluon distributions from exclusive J/ψ production

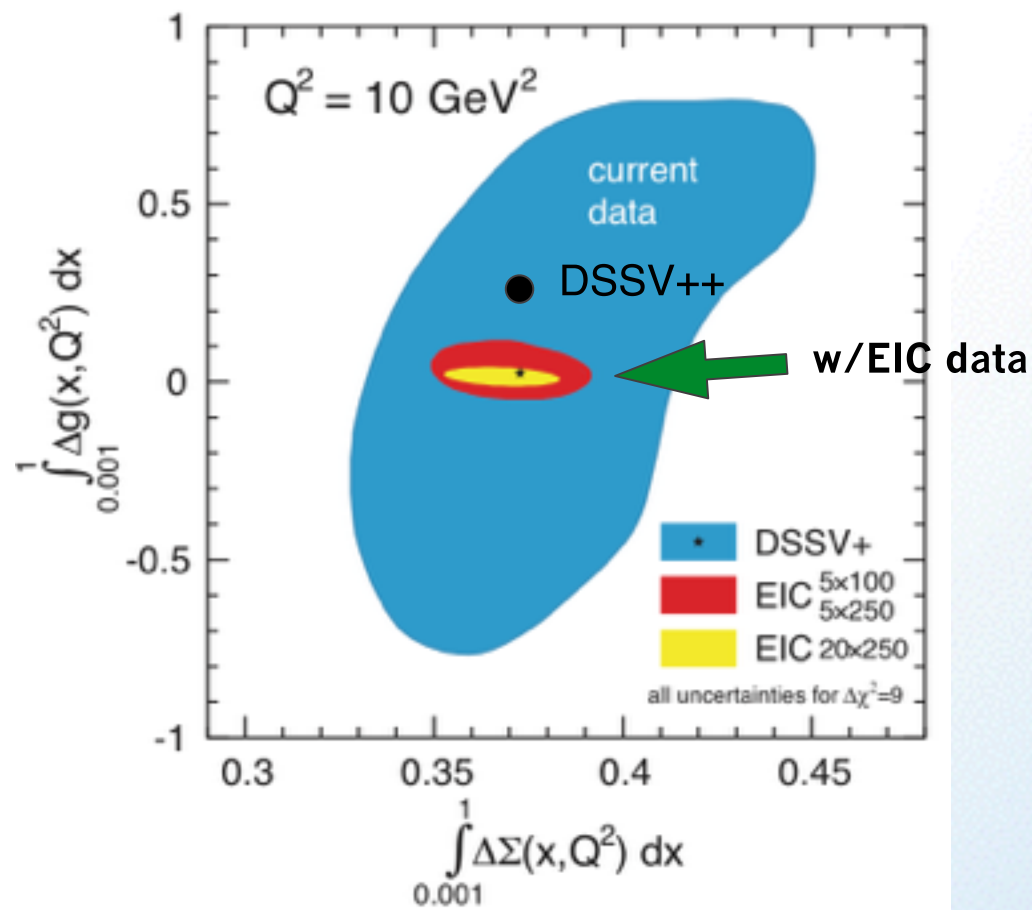
Only possible at the EIC: From the valence quark region deep into the gluon / sea quark region

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!

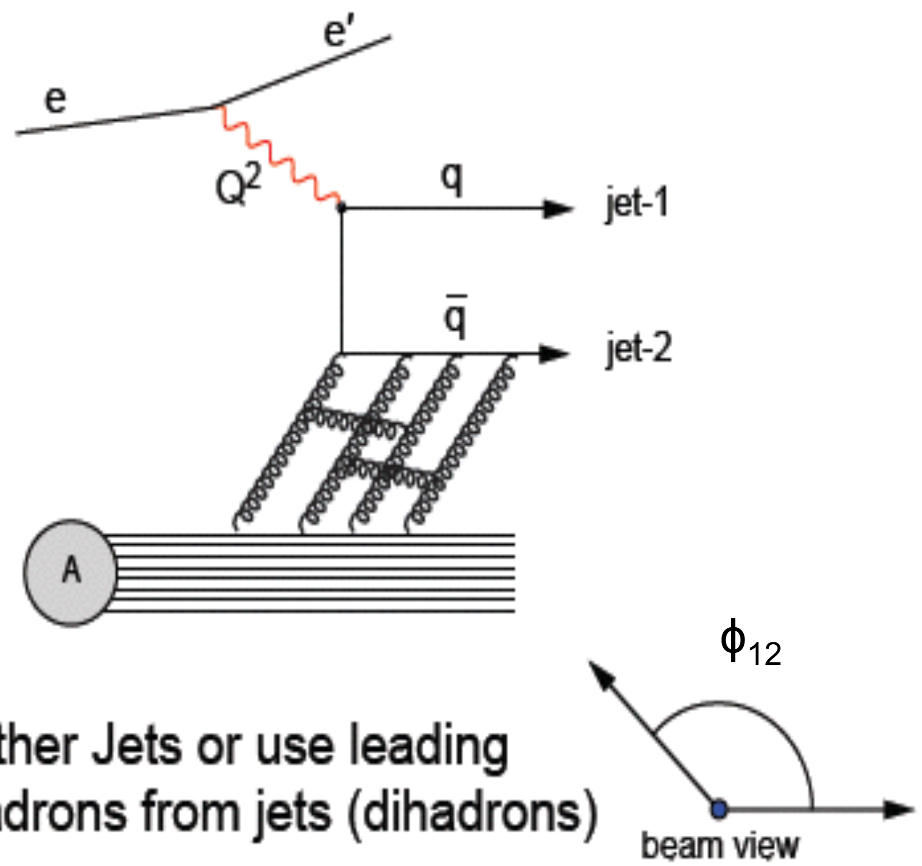
➢ **Solution to the proton spin puzzle:**

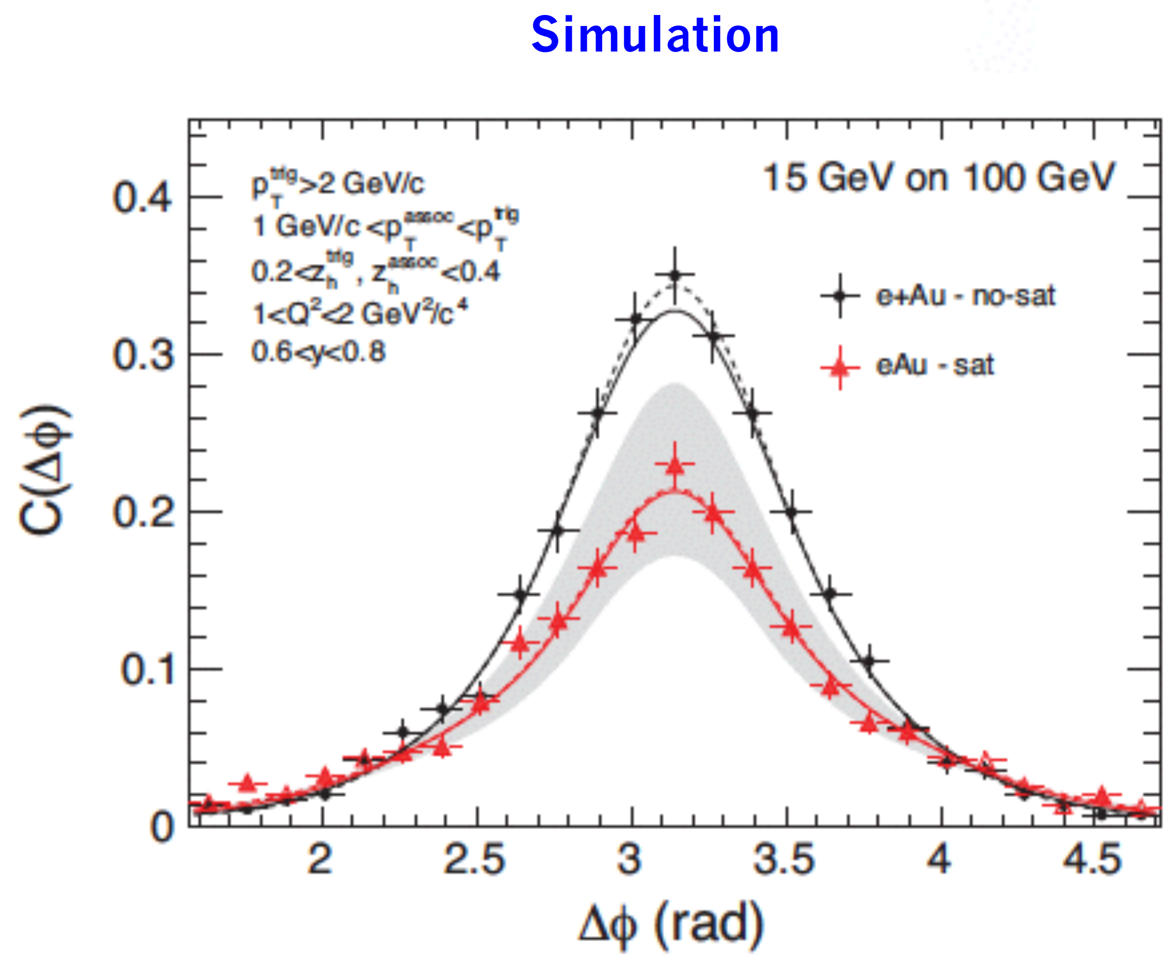
◇ ***Precision measurement of ΔG – extends to smaller x regime***

◇ ***Orbital angular momentum – motion transverse to proton's momentum***

Probing gluon saturation

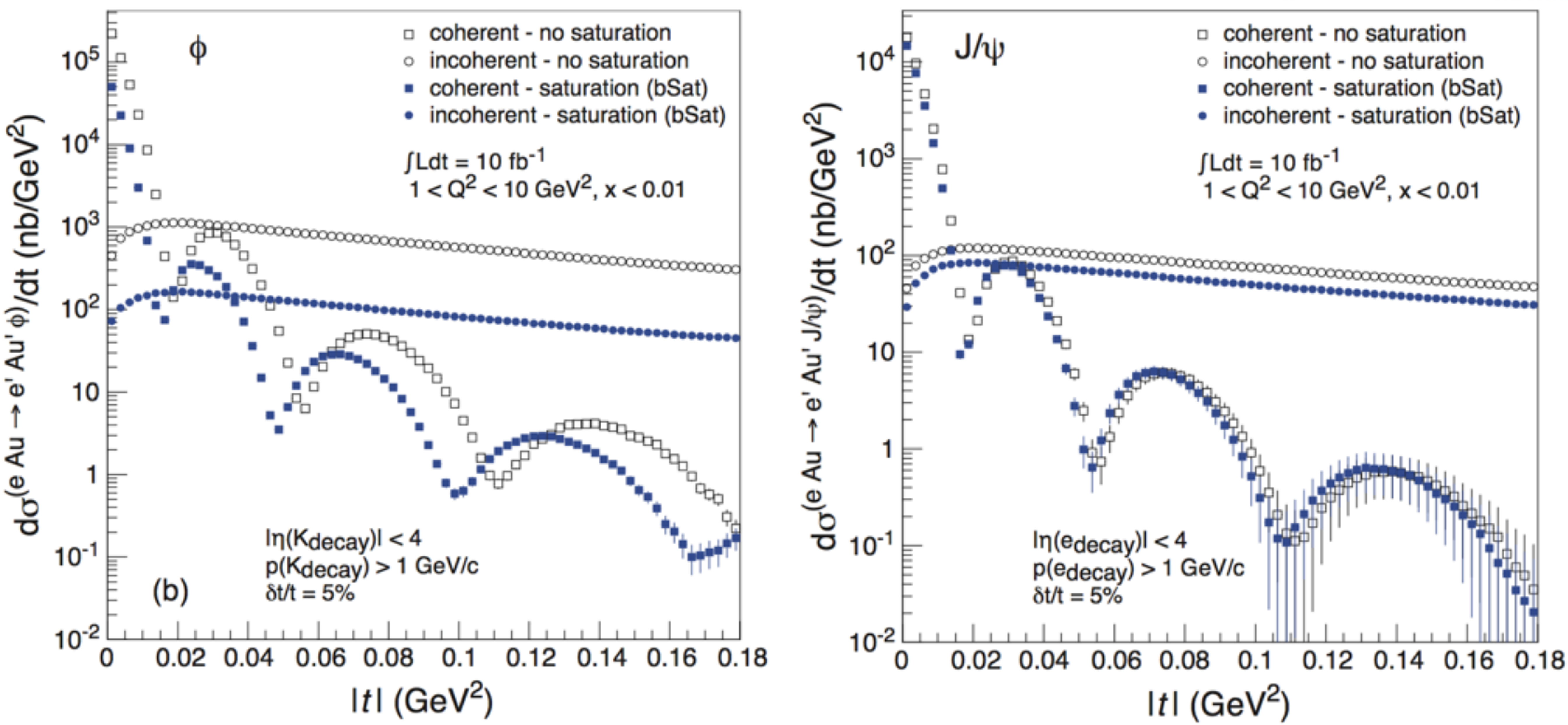
➢ **Strong suppression of di-hadron correlation in eA:**





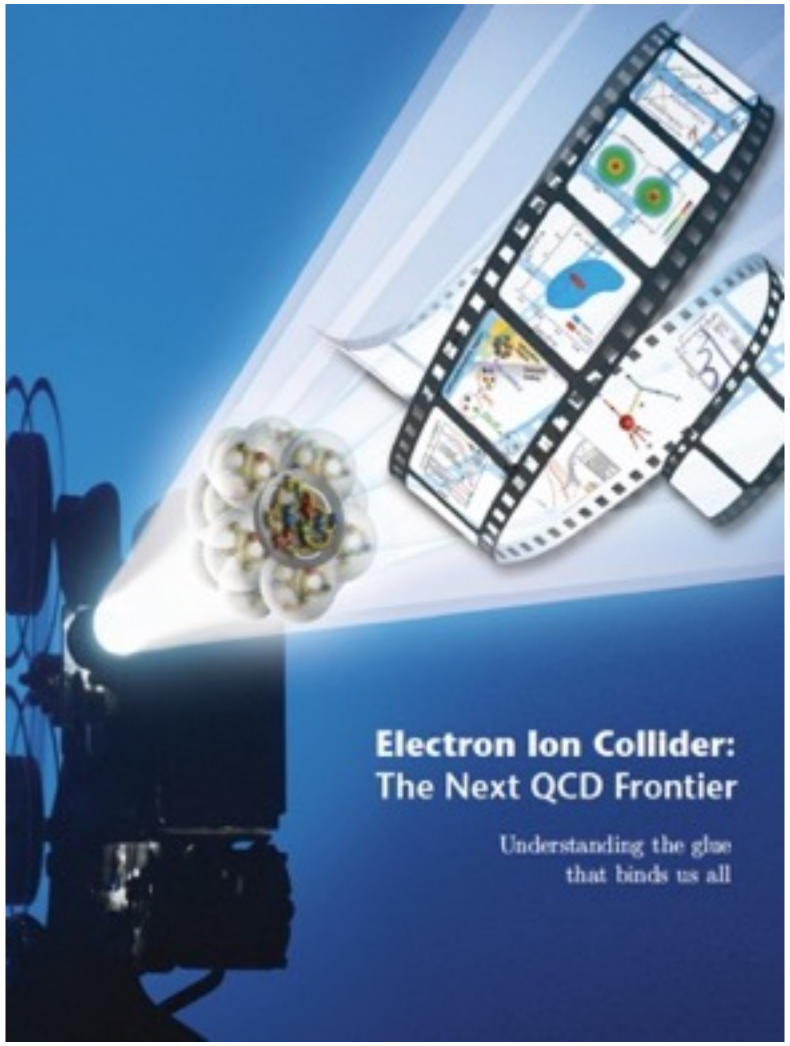
- ◇ This has never been measured in e+A (only in d+Au, where it is ambiguous)
- ◇ Correlation directly probes the saturated gluon distribution in a large nucleus
- ◇ **Suppression of back-to-back hadron correlation**

Exclusive vector meson production



Towards Imaging!

EIC - Why now?



EIC White Paper
(arXiv:1212.1701)
recently updated

Why now?

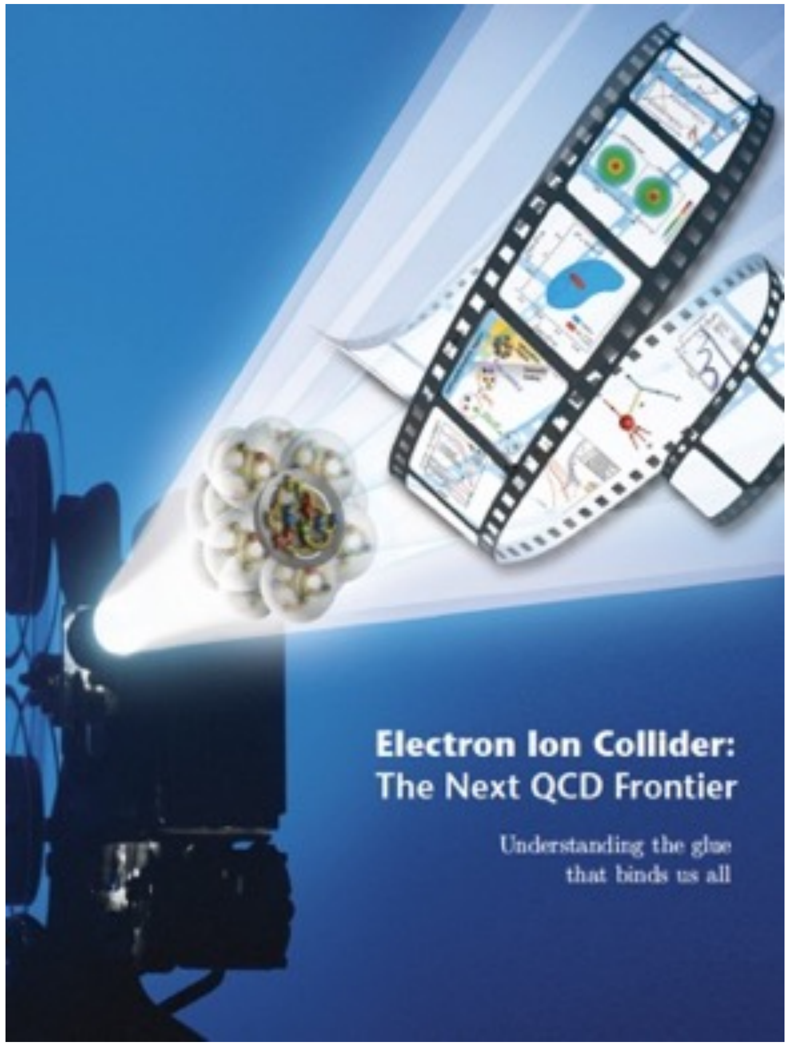
A set of **compelling physics questions** has been formulated.

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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The new U.S. Long Range Plan for Nuclear Science will contain a strong recommendation for an Electron-Ion Collider.