

# From RHIC to the EIC

## Exploring the Quark Sea and the Gluon Ocean

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**BROOKHAVEN**  
NATIONAL LABORATORY

*a passion for discovery*



# The Mysterious Gluon

# Standard Model particles

	mass →	charge →	spin →					
QUARKS	$\approx 2.3 \text{ MeV}/c^2$	$2/3$	$1/2$	u up	$\approx 1.275 \text{ GeV}/c^2$	$2/3$	$1/2$	c charm
					$\approx 173.07 \text{ GeV}/c^2$	$2/3$	$1/2$	t top
					0	0	1	g gluon
								H Higgs boson
LEPTONS	$\approx 4.8 \text{ MeV}/c^2$	$-1/3$	$1/2$	d down	$\approx 95 \text{ MeV}/c^2$	$-1/3$	$1/2$	s strange
					$\approx 4.18 \text{ GeV}/c^2$	$-1/3$	$1/2$	b bottom
					0	0	1	$\gamma$ photon
GAUGE BOSONS	$0.511 \text{ MeV}/c^2$	-1	$1/2$	e electron	$105.7 \text{ MeV}/c^2$	-1	$1/2$	$\mu$ muon
					$1.777 \text{ GeV}/c^2$	-1	$1/2$	$\tau$ tau
					$91.2 \text{ GeV}/c^2$	0	1	Z Z boson
LEPTONS	$< 2.2 \text{ eV}/c^2$	0	$1/2$	$\nu_e$ electron neutrino	$< 0.17 \text{ MeV}/c^2$	0	$1/2$	$\nu_\mu$ muon neutrino
					$< 15.5 \text{ MeV}/c^2$	0	$1/2$	$\nu_\tau$ tau neutrino
					$80.4 \text{ GeV}/c^2$	$\pm 1$	1	W W boson

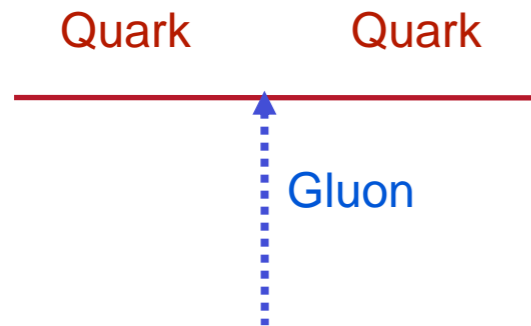
**Gluons** are **gauge bosons** like **photons** (massless and spin 1), but they carry the SU(3) **color** “charge”.

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

# Quantum chromodynamics

= Gauge theory of SU(3) color

Quark emits or absorbs a gluon



Gluon emits or absorbs a gluon

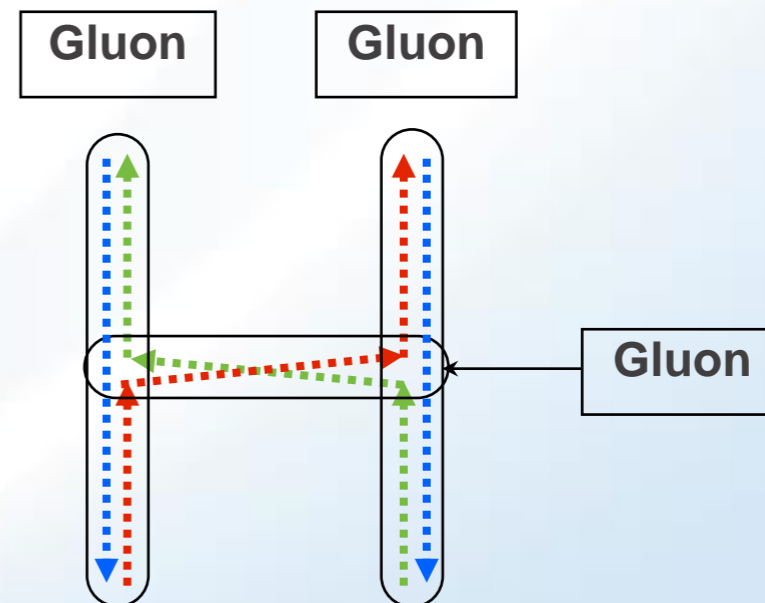
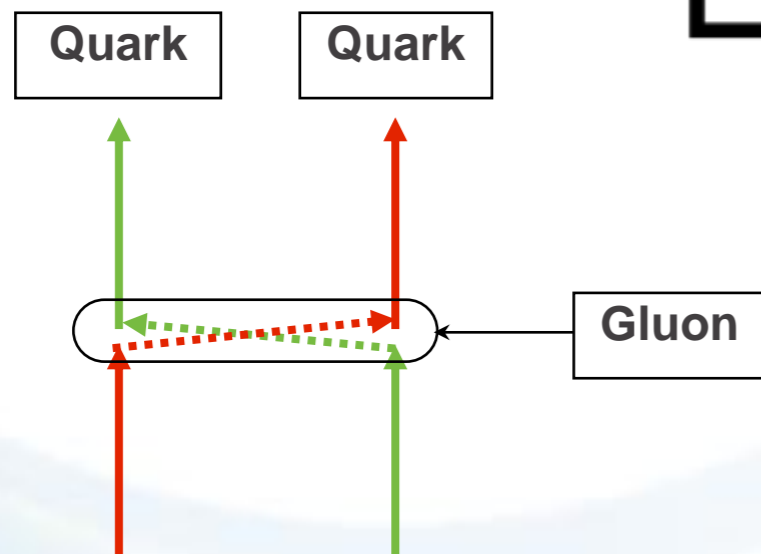


Gluon scatters on another gluon

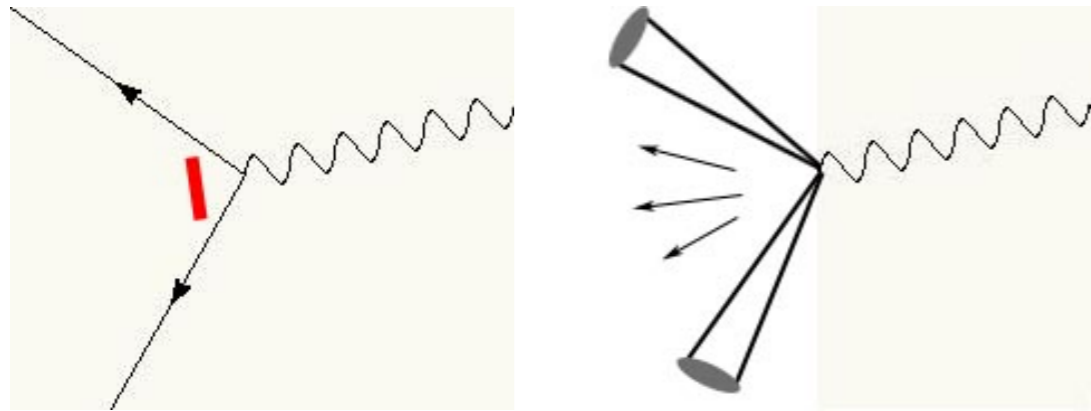


$$L_{\text{QCD}} = -\frac{1}{4} \sum_a (\partial_\mu A_\nu^a - \partial_\nu A_\mu^a + gf_{abc} A_\mu^b A_\nu^c)^2 + \sum_f \bar{q}_f (i\gamma^\mu \partial_\mu + gA_\mu^a T_a - m_f) q_f$$

**Color Flow**

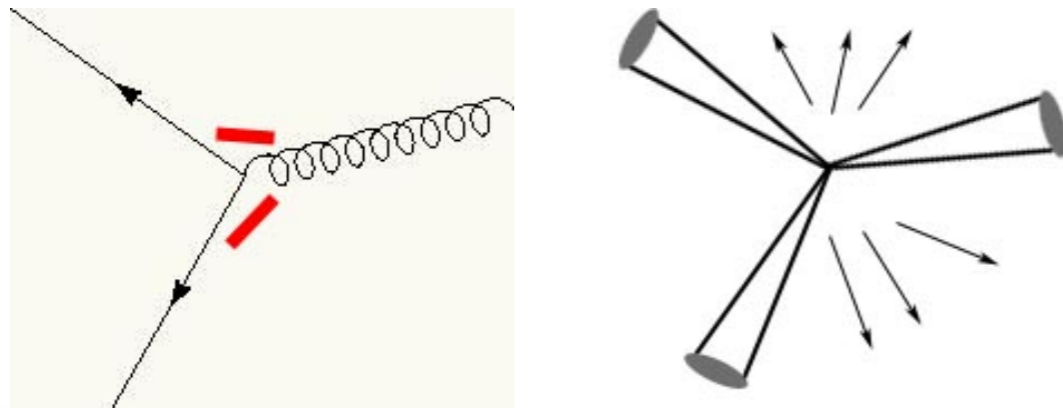


# Three-jet events



quark-antiquark-photon 3-jet

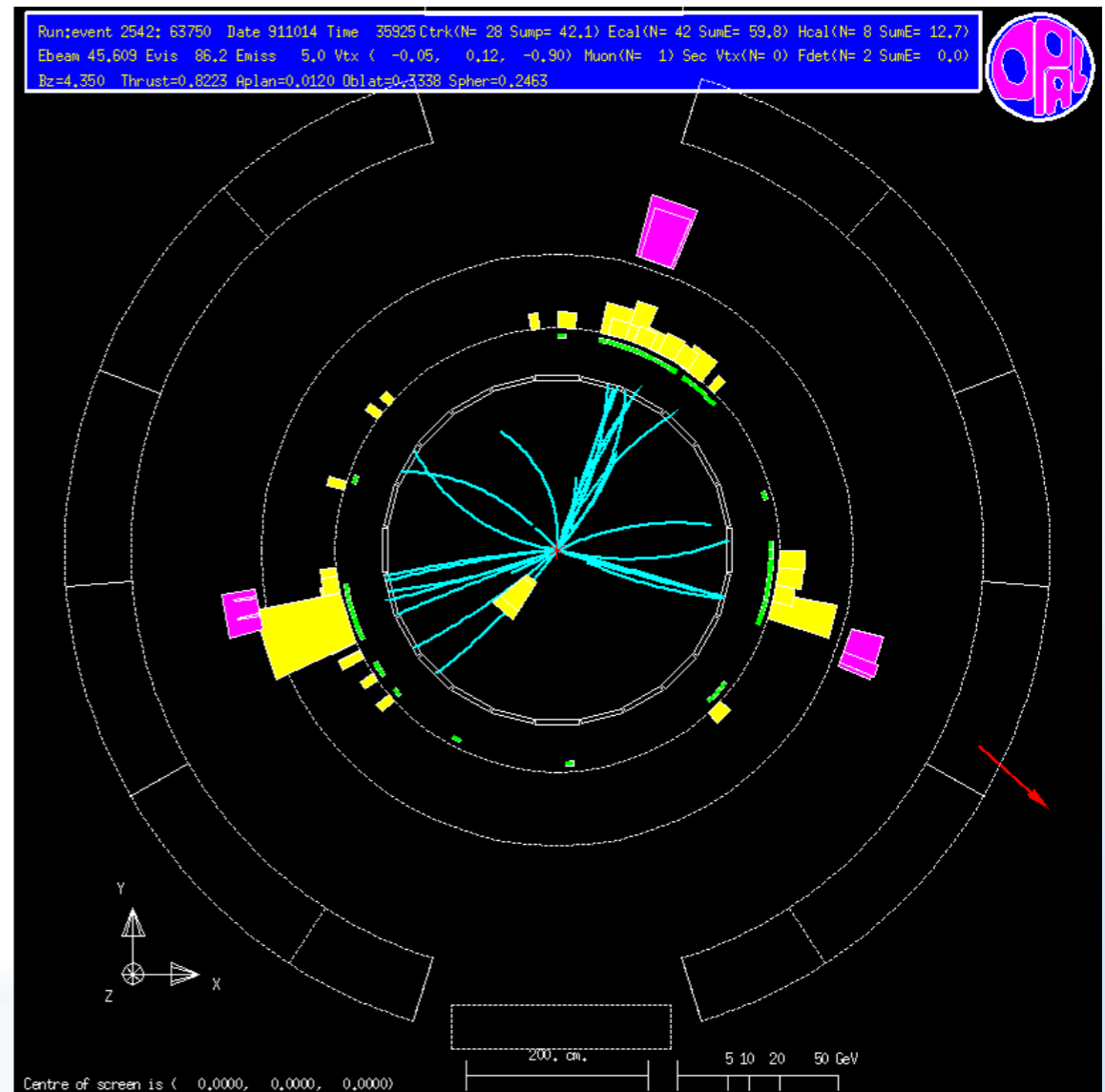
— = color flux tube (Lund “string”)



quark-antiquark-gluon 3-jet

Originally discovered by TASSO @ DORIS

Later explored in great detail at LEP

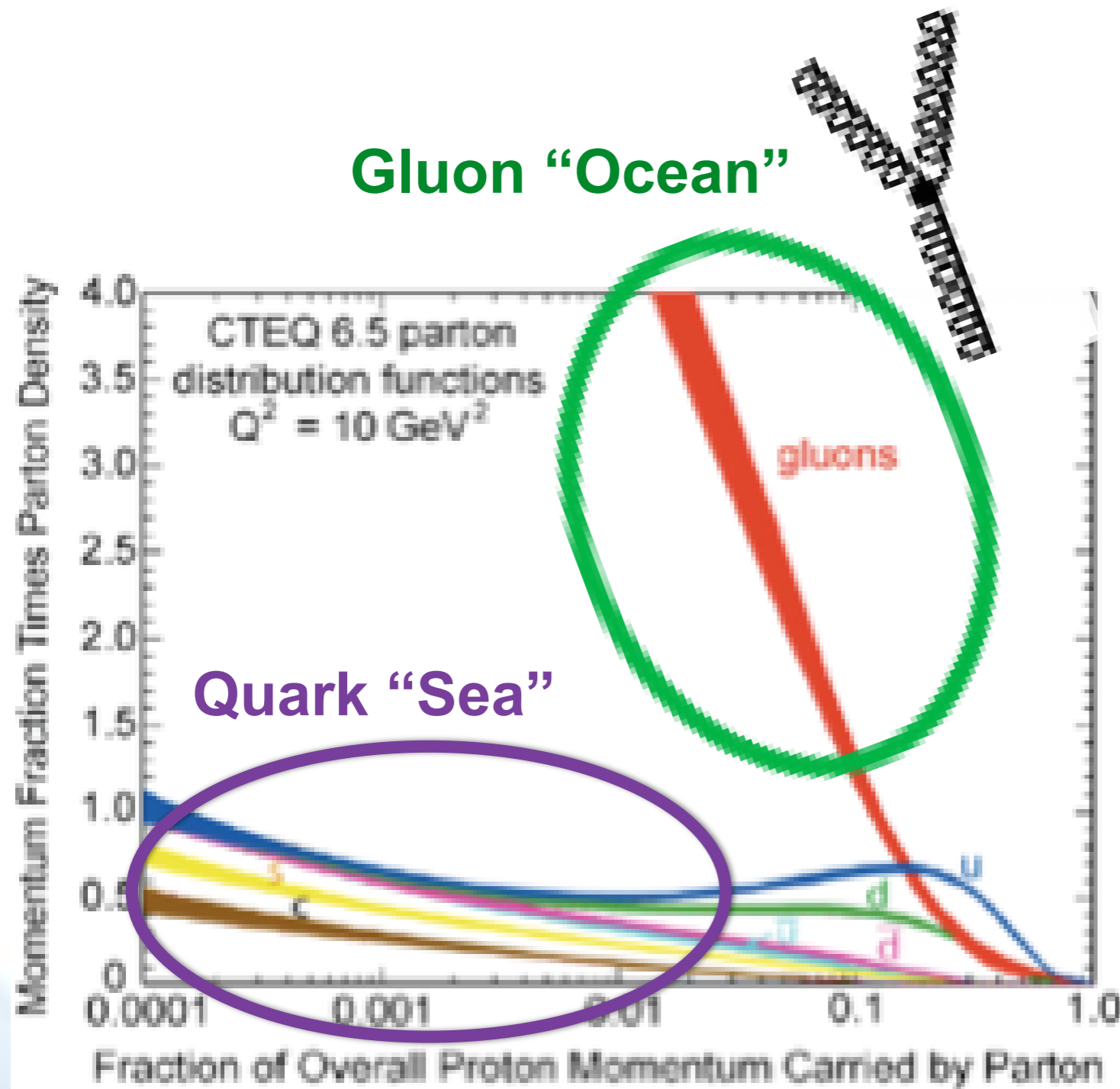


# Gluons are strange objects

- Gluons, like quarks, never occur in isolation.
- Quarks are always accompanied by virtual gluons.
- States solely made of gluons (“glueballs”) should exist, but have not 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, just like the Higgs condensate:  $\langle G^2 \rangle^{1/4} \approx 0.6 \text{ GeV}$ , with  $\langle E^2 \rangle = - \langle B^2 \rangle$ , so that the energy density  $\langle E^2 + B^2 \rangle / 2 = 0$ .
- 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



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

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

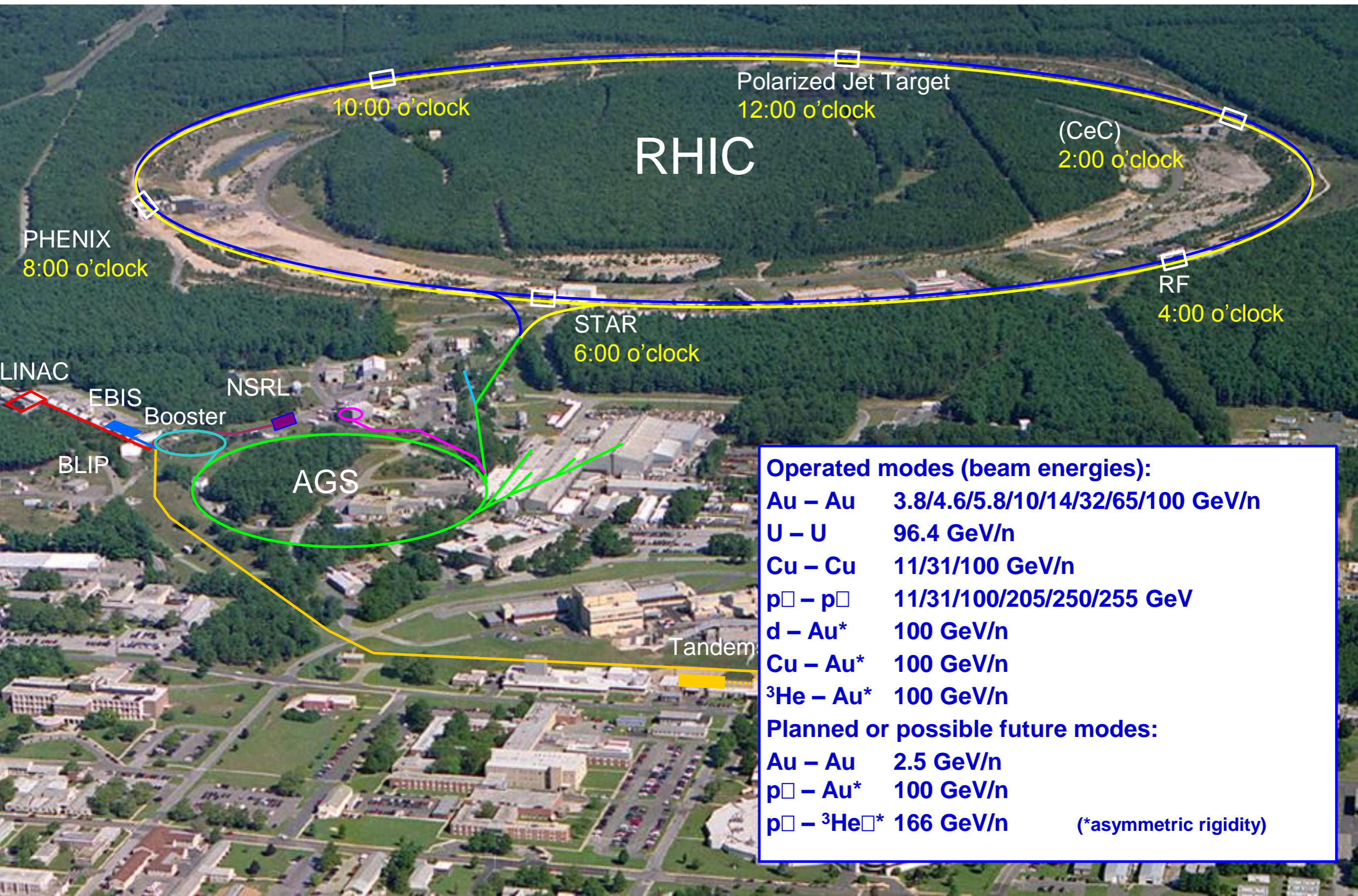
RHIC provides polarized protons of up to 255 GeV and nuclei up to uranium up 100 A GeV.

RHIC:

A universal hadron collider



# RHIC – a High Luminosity (Polarized) Hadron Collider



## Operated modes (beam energies):

Au – Au	3.8/4.6/5.8/10/14/32/65/100 GeV/n
U – U	96.4 GeV/n
Cu – Cu	11/31/100 GeV/n
$p^+$ – $p^+$	11/31/100/205/250/255 GeV
d – Au*	100 GeV/n
Cu – Au*	100 GeV/n
$^3\text{He}$ – Au*	100 GeV/n

## Planned or possible future modes:

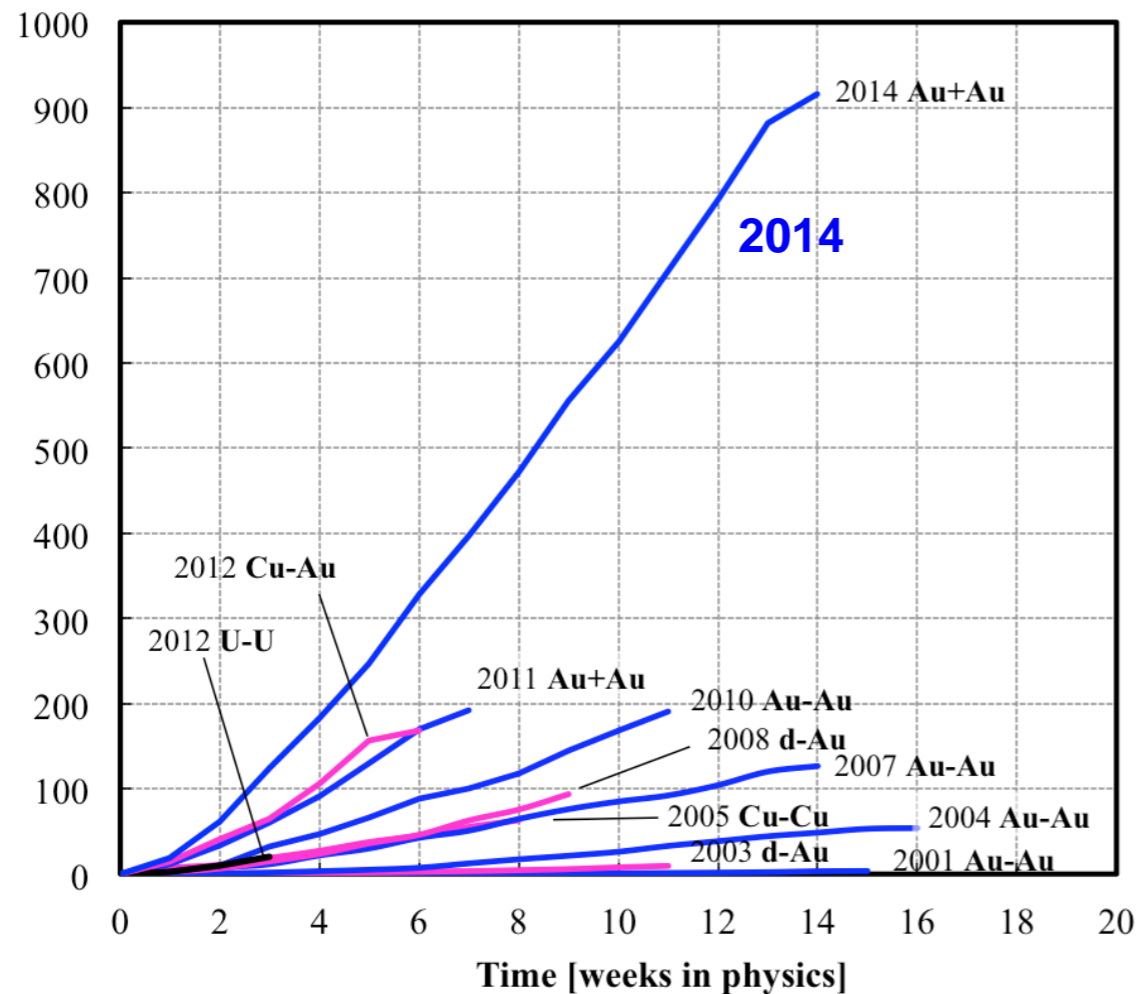
Au – Au	2.5 GeV/n
$p^+$ – Au*	100 GeV/n
$p^+$ – $^3\text{He}^+$ *	166 GeV/n

(\*asymmetric rigidity)

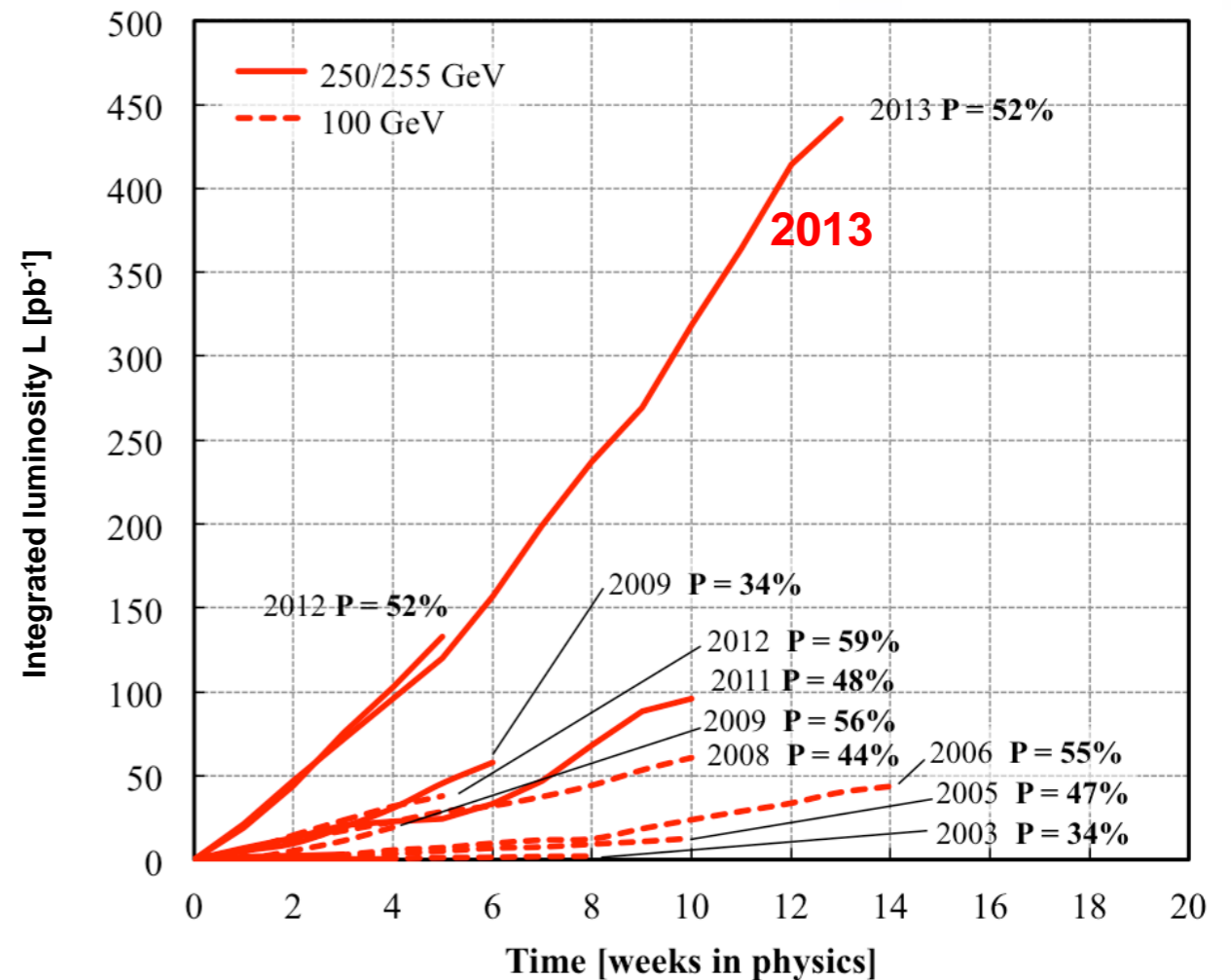


# RHIC-II Performance

## Heavy ion runs



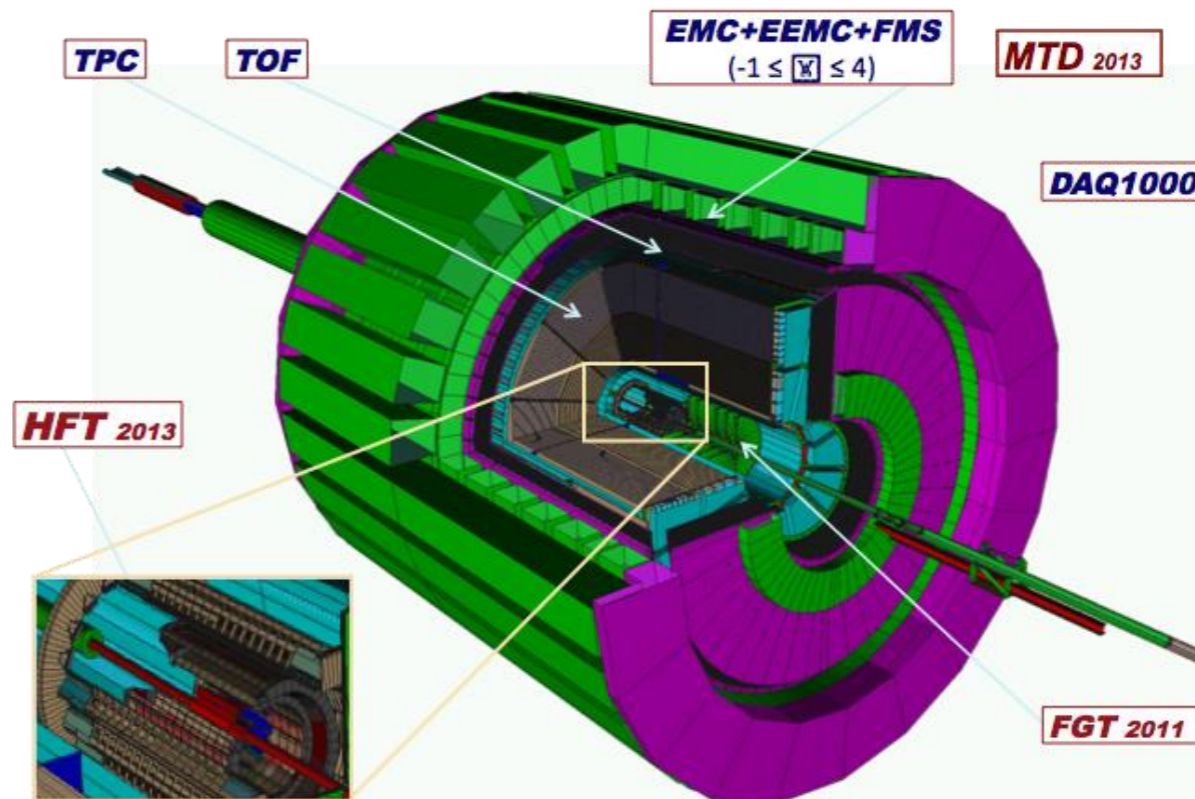
## Polarized proton runs



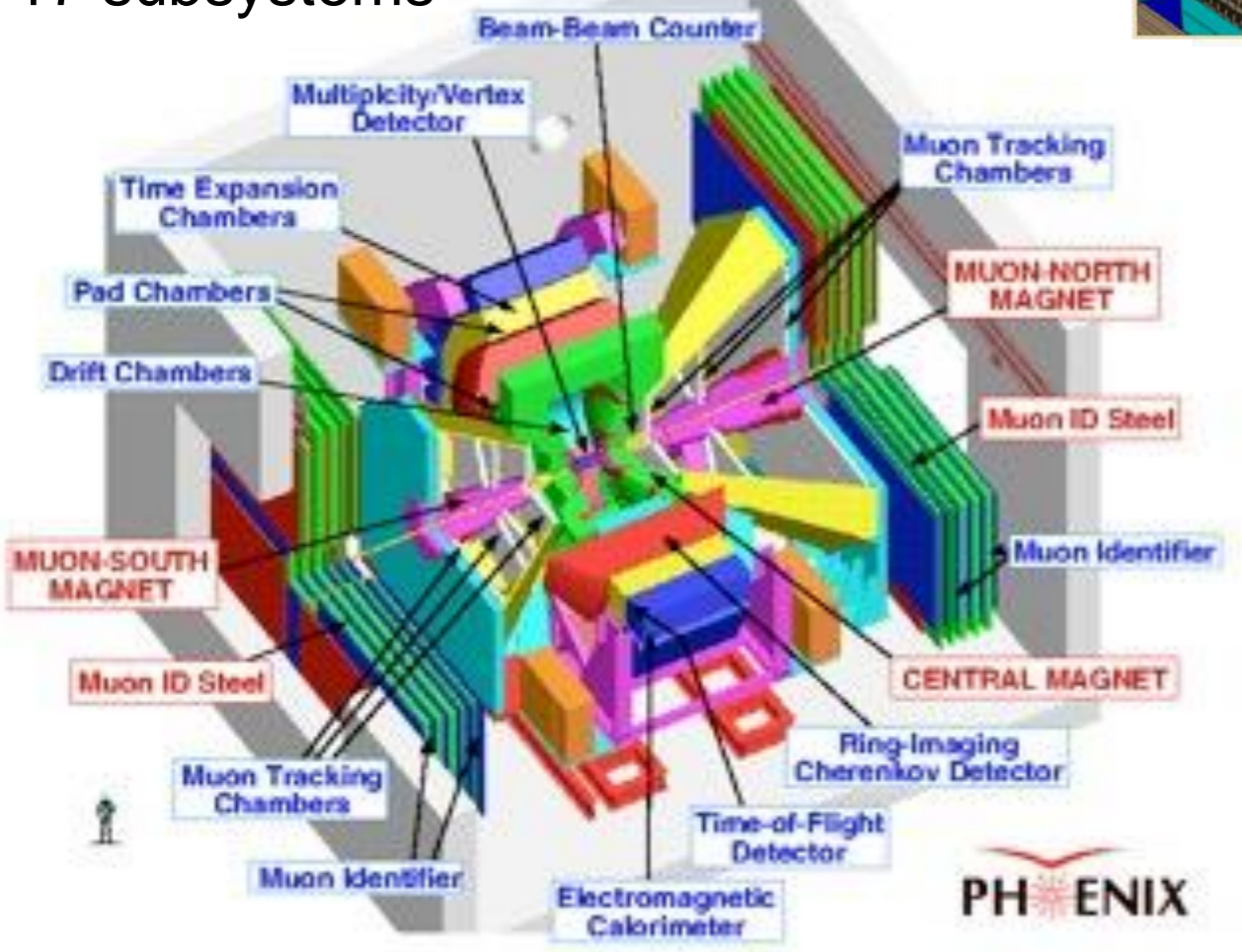
Dramatic increase in performance of RHIC as a result of 3-D stochastic cooling, new high intensity ion source (EBIS), and other improvements (beam-beam compensation, IR compression, etc.).

# RHIC Detectors

STAR Detector



17 subsystems



NEW: Heavy Flavor Tracker





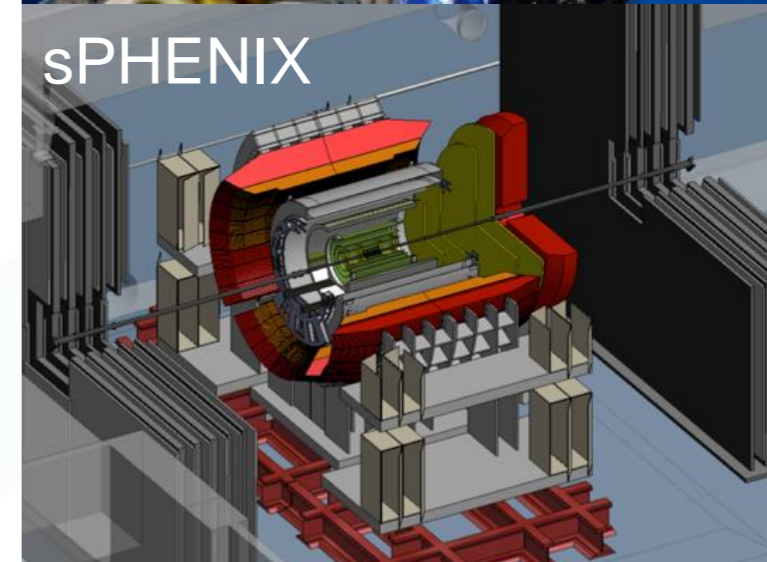
# Completing the RHIC Science Mission

## Status:

- RHIC-II configuration is now complete
  - Vertex detectors in STAR (HFT) and PHENIX
- RHIC Run 14 – Integrated Au+Au luminosity exceeds all previous Au+Au runs combined

## Plan: Complete the RHIC Mission in 3 campaigns:

- **2014/15/16:** Heavy flavor probes of the QGP, transverse polarized proton measurements
  - Install low energy e-cooling in 2017
- **2018/19:** High precision scan of the QCD phase diagram
  - Install sPHENIX upgrade in 2020
- **2021/22:** Precision measurements of jet quenching and quarkonium suppression, forward p+A physics
  - RHIC shutdown and transition to eRHIC



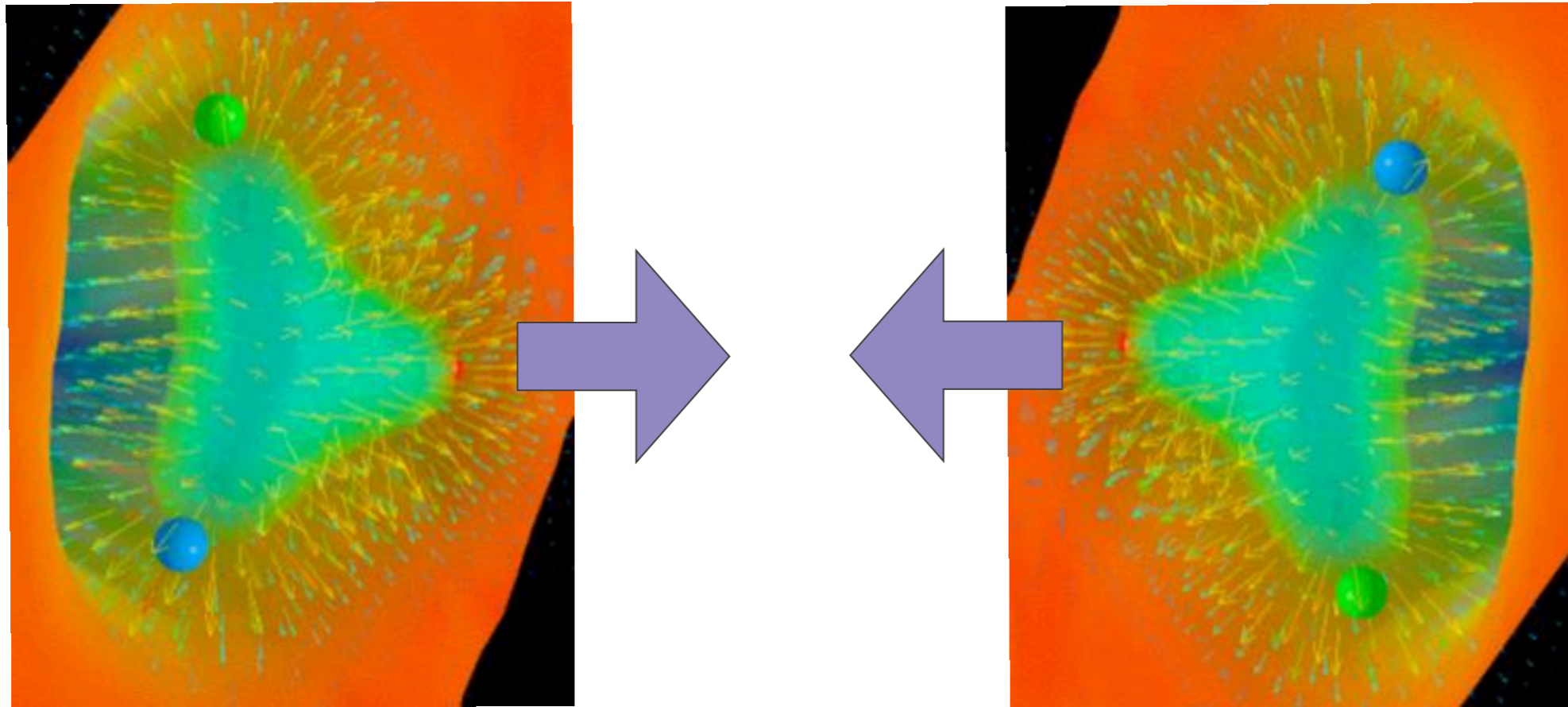
RHIC remains a unique discovery facility

Gluon liberation  
or

What does hot “empty” space  
look like?

# Melting the QCD vacuum

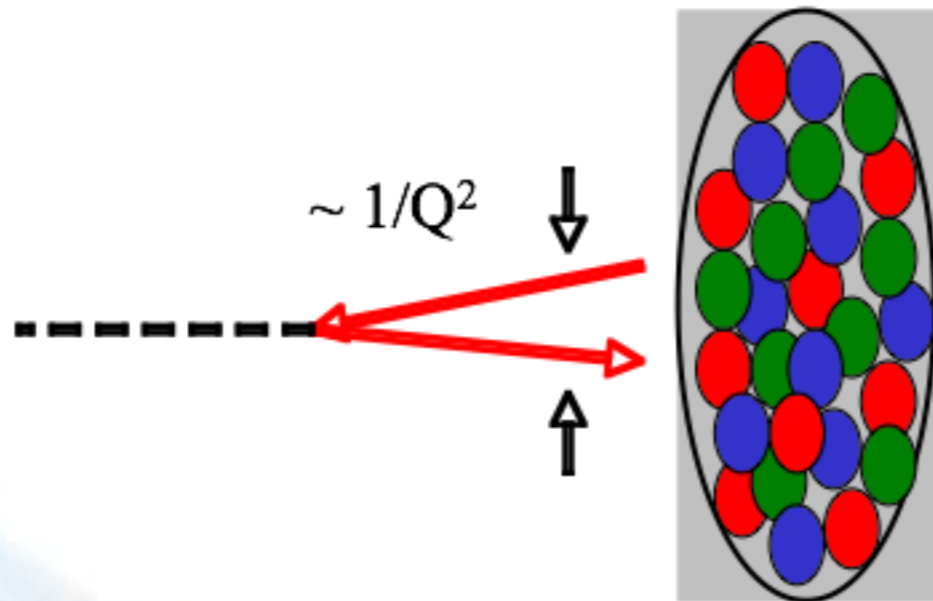
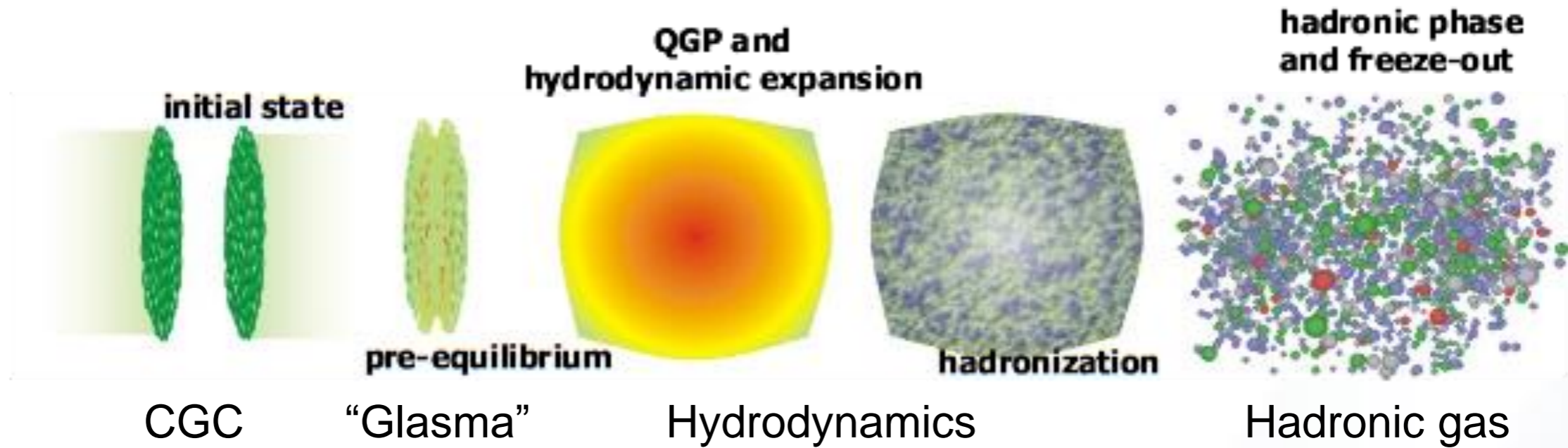
What RHIC does:



RHIC collides many nucleons (as atomic nuclei) and thereby liberates the gluons into a highly excited state (“glasma”) that thermalizes into a quark-gluon plasma.



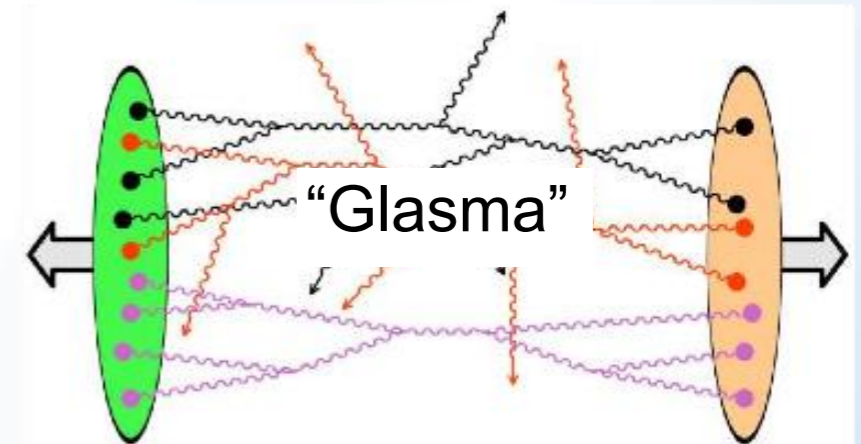
# Consensus Model Anno 2014



Color Glass Condensate

$$\Rightarrow Q_s^2(x, A)$$

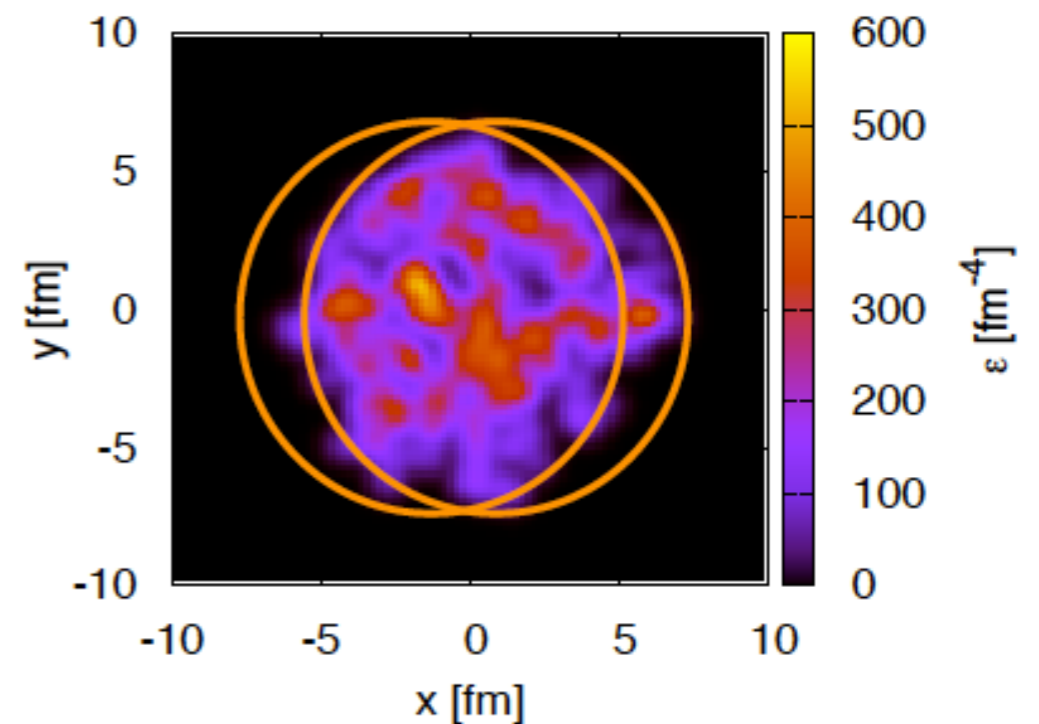
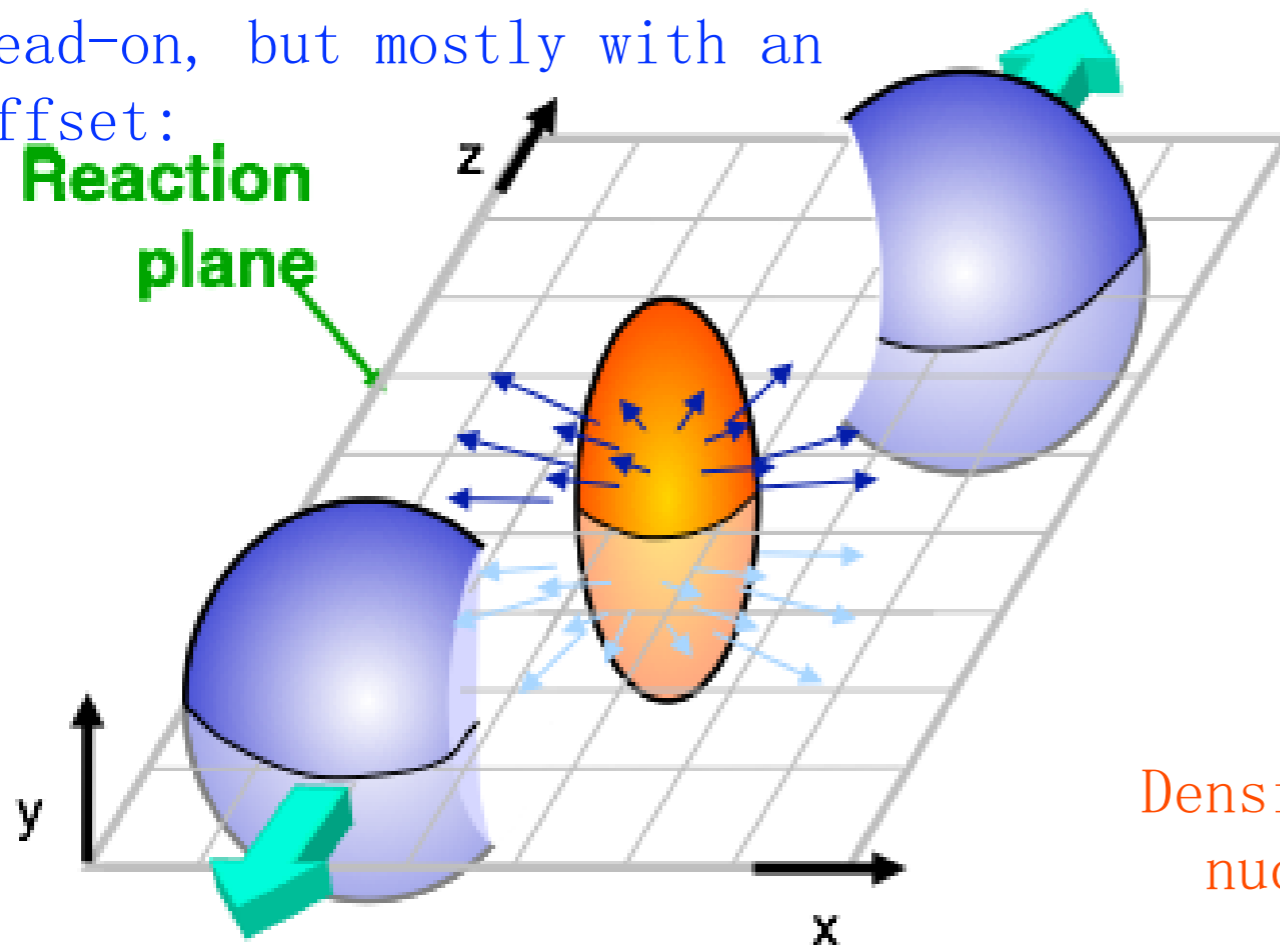
$$\text{gluon density} \times \text{area} \sim \frac{A^{1/3} x^{-0.3}}{Q_s^2} \approx 1$$



# Elliptic flow “measures” | QGP

- two nuclei collide rarely head-on, but mostly with an offset:

Reaction plane



Density fluctuations in the colliding nuclei are sampled event by event

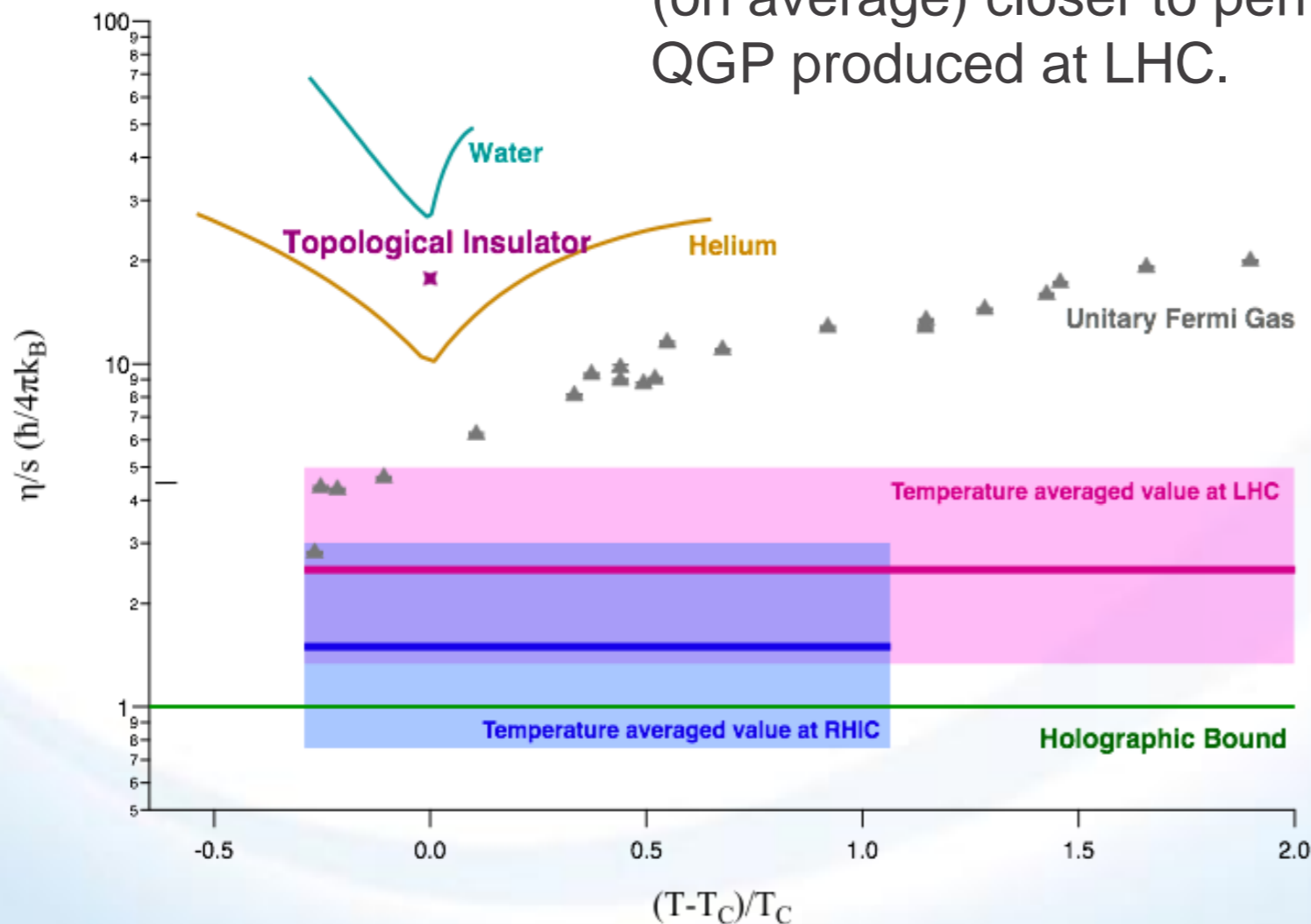
$$2\pi \frac{dN}{d\phi} = N_0 \left( 1 + 2 \sum_n v_n(p_T, \eta) \cos n(\phi - \psi_n(p_T, \eta)) \right)$$

anisotropic flow coefficients

event plane angle

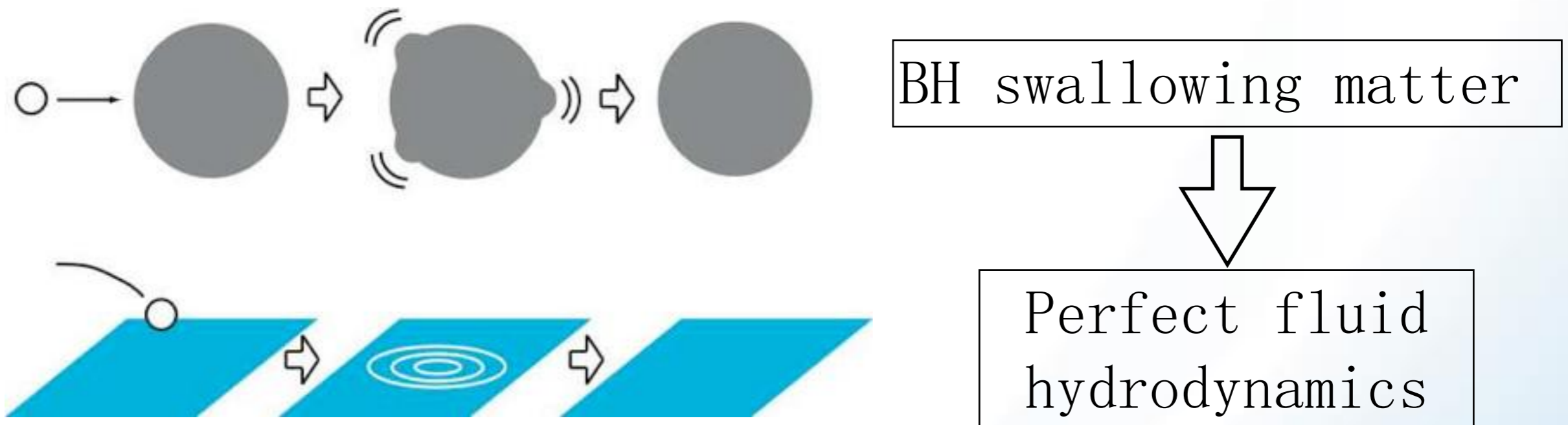
# Hot glue is a “perfect” fluid

- Hot matter produced in collisions at RHIC/LHC is a **liquid** quark-gluon plasma (QGP). The plasma is made up of individually flowing gluons and quarks, not quarks bound into baryons and mesons.
- The QGP is a strongly coupled nearly “**perfect**” liquid ( $\eta/s$  near the quantum limit  $1/4\pi$ ). RHIC’s cooler QGP is (on average) closer to perfection than the 40% hotter QGP produced at LHC.



# The Black Hole connection

Dynamics of hot QCD matter can be mathematically (holography) mapped onto black hole dynamics in 4+1 dimensions (AdS<sub>5</sub> space).



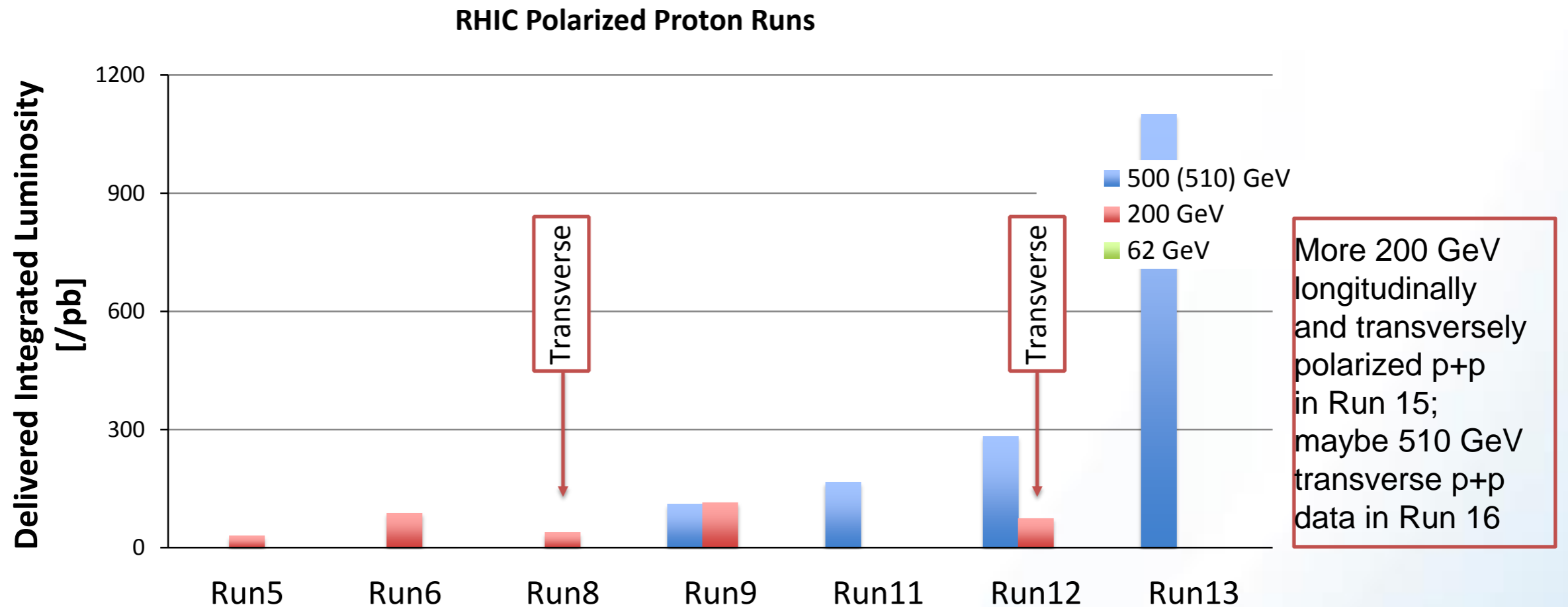
Formation of hot QCD matter at RHIC is analogous to formation of a black hole, tied to information loss. Relies on the notion that 't Hooft coupling  $g^2 N_c \sim 12$  is large enough to apply the classical limit of the dual theory:

$$\eta / s \geq 1 / 4\pi$$

Gluon polarization  
or  
Where is the proton spin?



# RHIC Spin program



## Longitudinal Spin Structure

- **Gluon Spin**
- **Sea Quark Spin**

## Transverse Spin Structure

- Sivers Effect
- Collins Effect
- Higher Twist

Upgrades in process  
Planned for Run 15

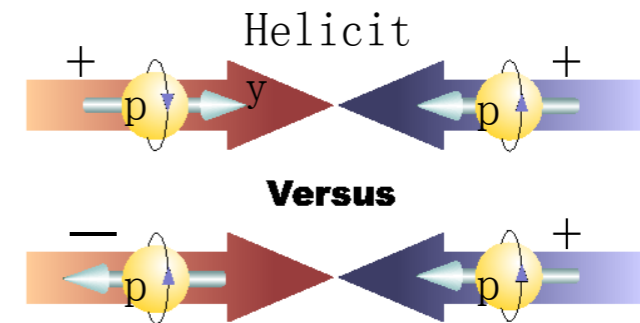
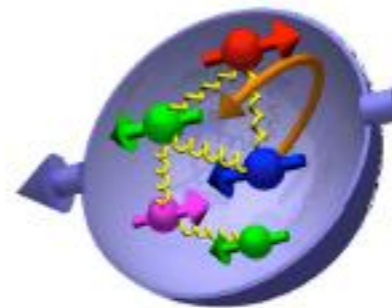


# Where is the proton spin?

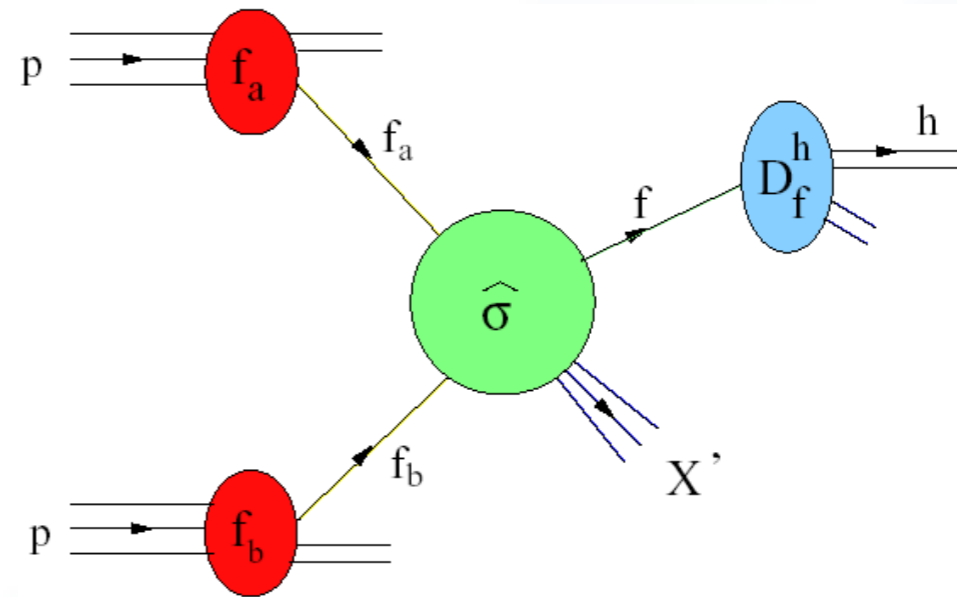
$$S = \frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + L$$

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

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



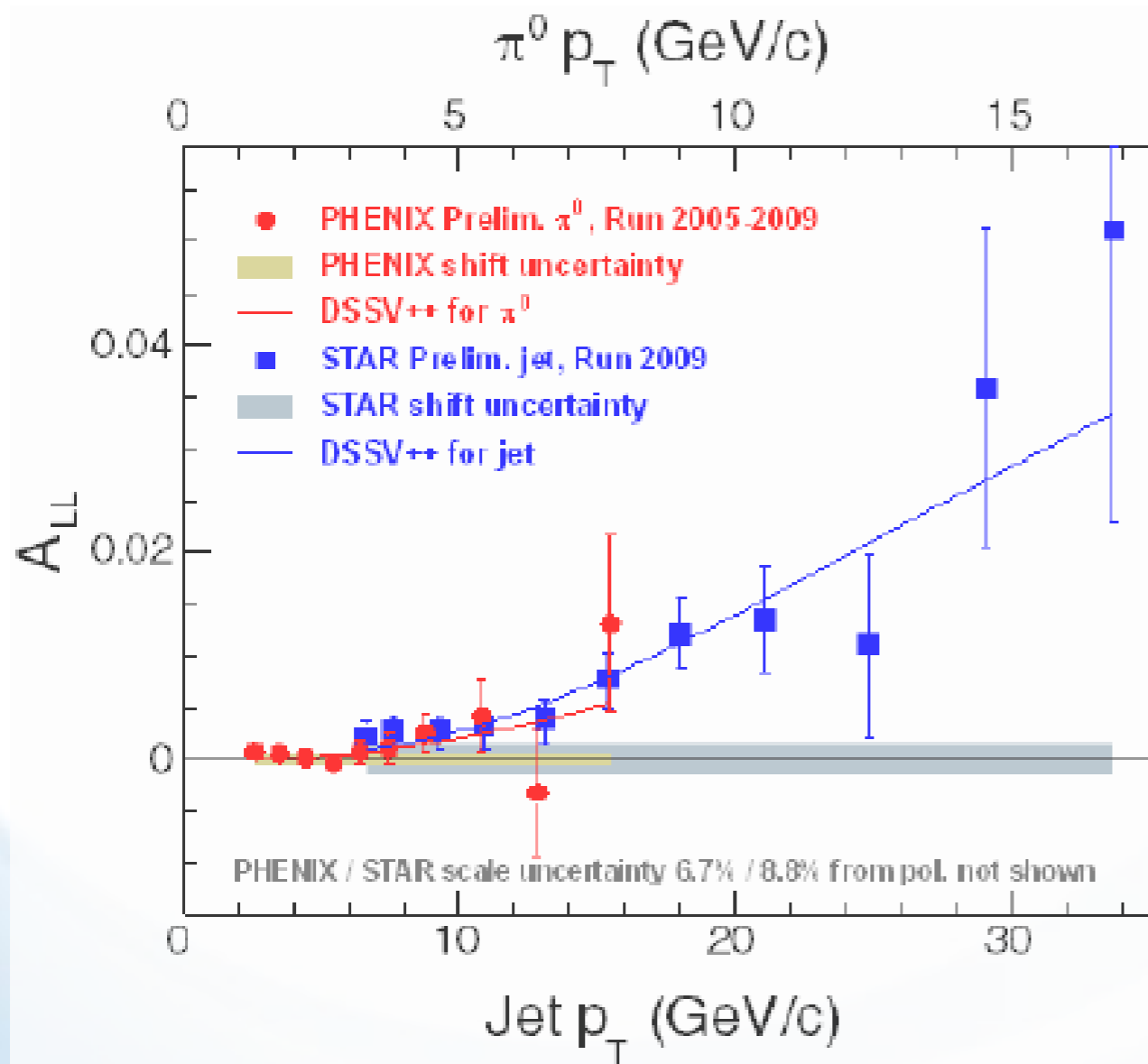
$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}}$$



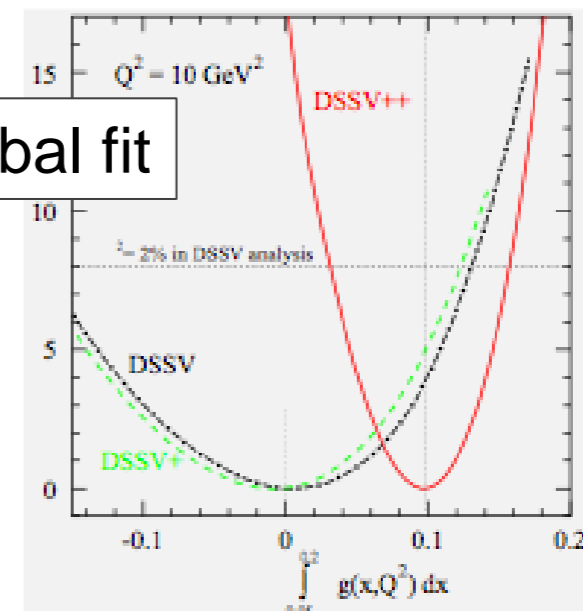
$$A_{LL} \propto [\omega_{gg}] \Delta g \Delta g + [\omega_{gq}] \Delta q \Delta g + [\omega_{qq}] \Delta q \Delta q$$

# $\Delta g$ from $\pi^0$ and jets

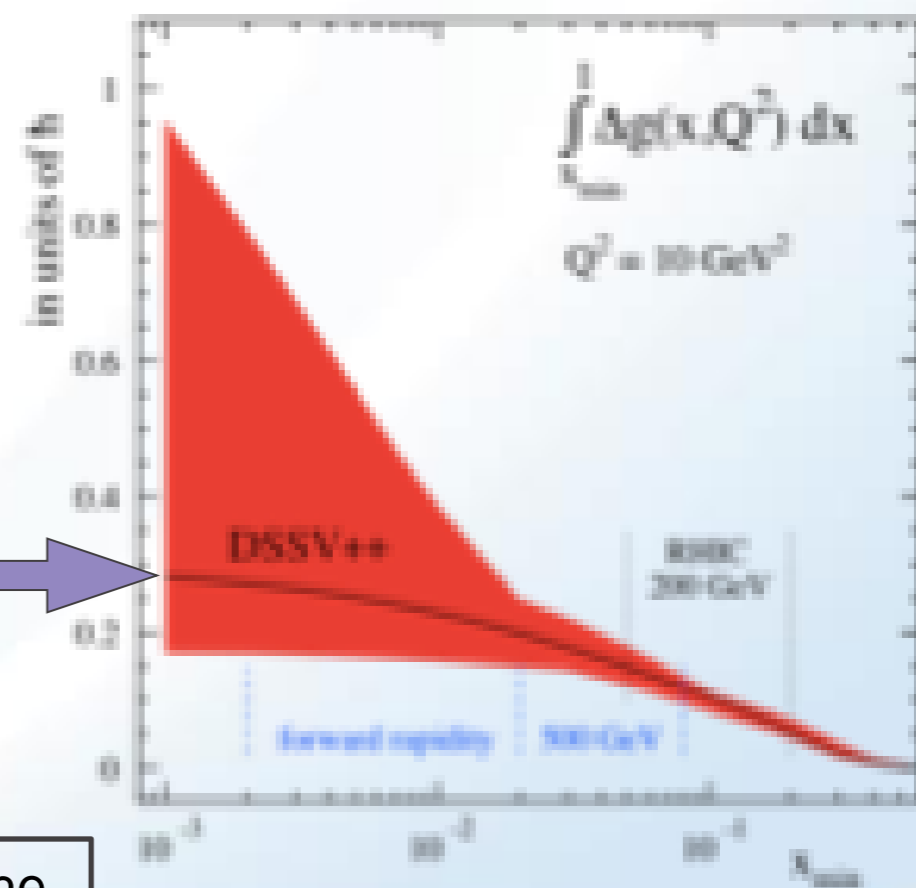
PHENIX:  $\pi^0$  production  
 (less sensitive, dominated by quarks)  
 STAR: jet production  
 (higher gluon contribution)



QCD global fit



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

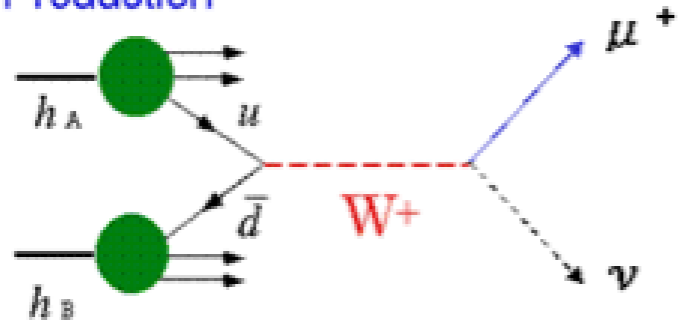


~60% of the proton spin?

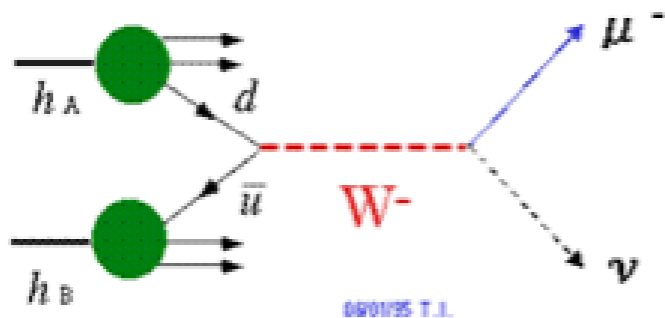
# Sea quark polarization

$$A_L^{W^+} = -\frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

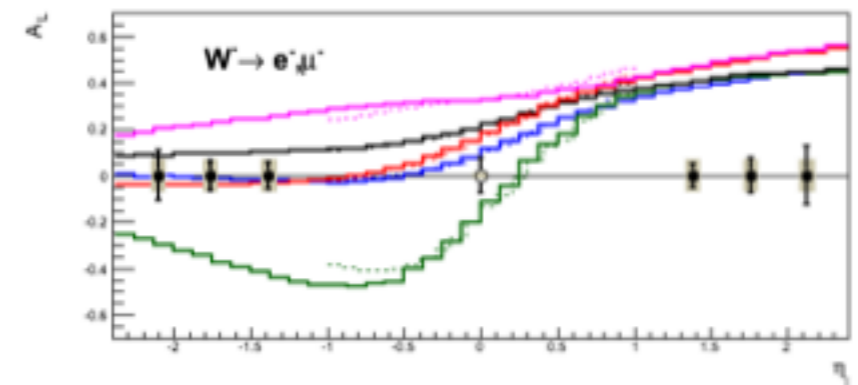
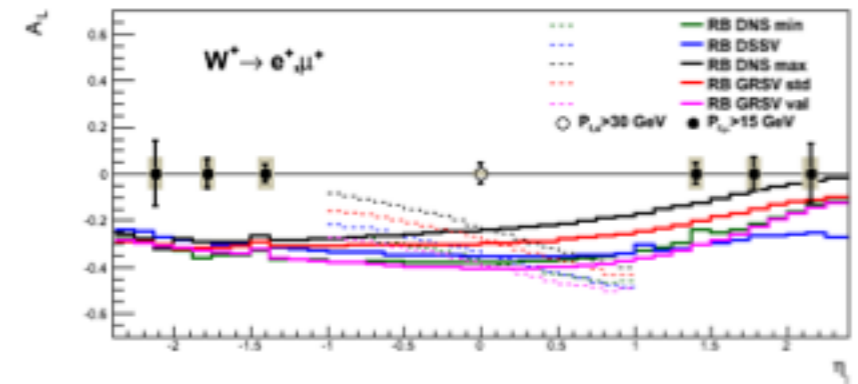
W<sup>+</sup> Production



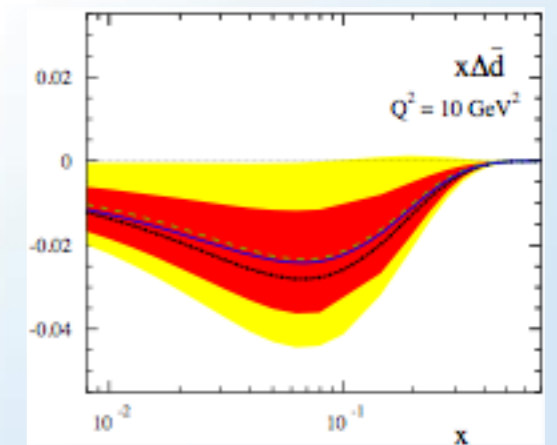
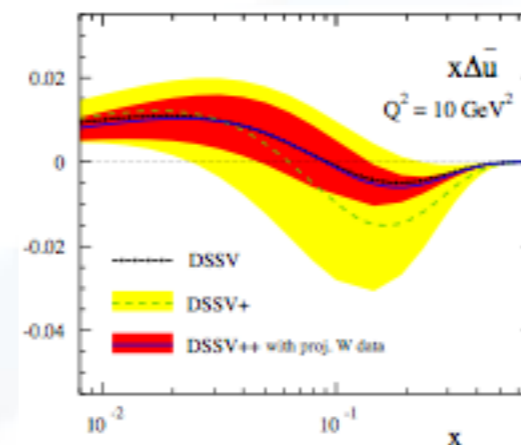
W<sup>-</sup> Production



## Projected results from Run 13



- Self analyzing due to parity violating W-decay
- Clean flavor separation possible in different kinematic regions
- No fragmentation uncertainty



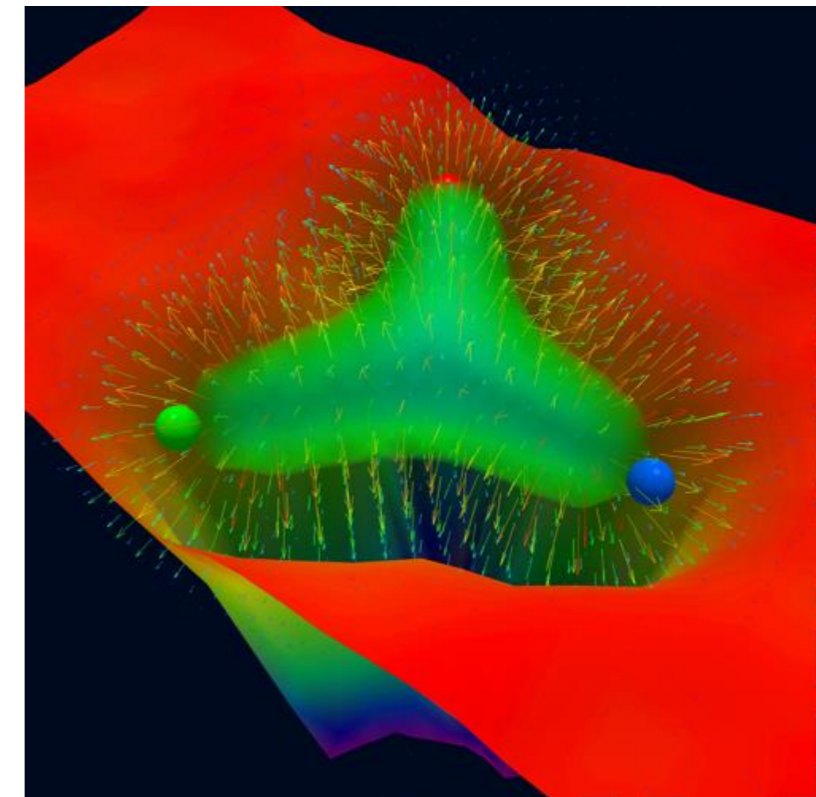
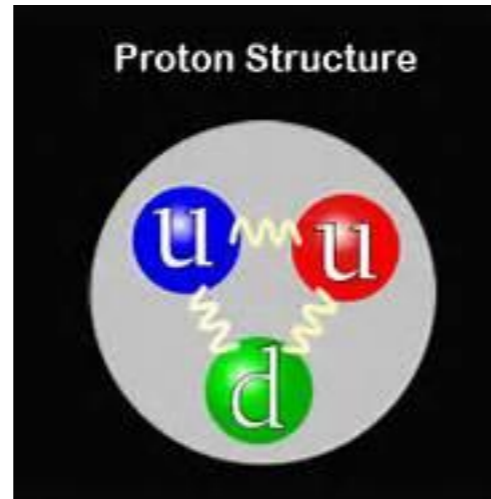
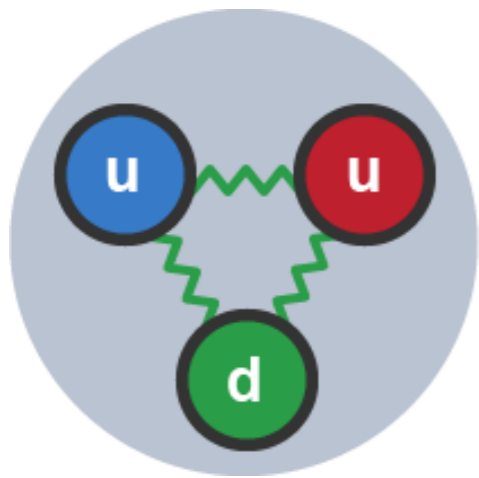
Existing data

Existing data + Run13 Data

# The Electron-Ion Collider:

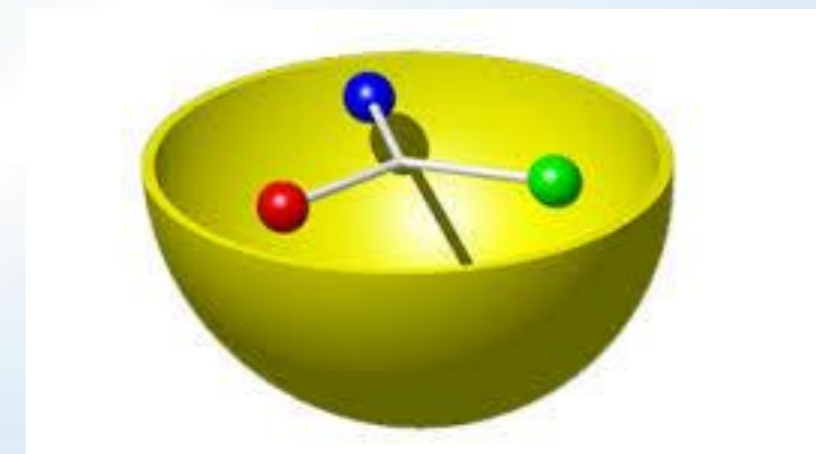
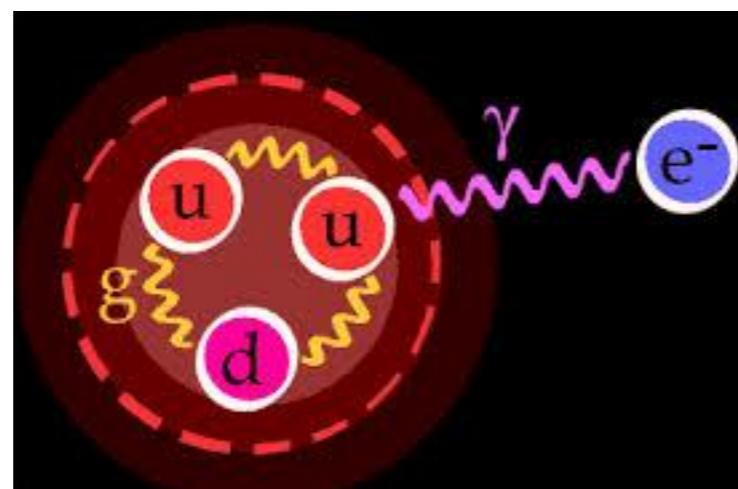
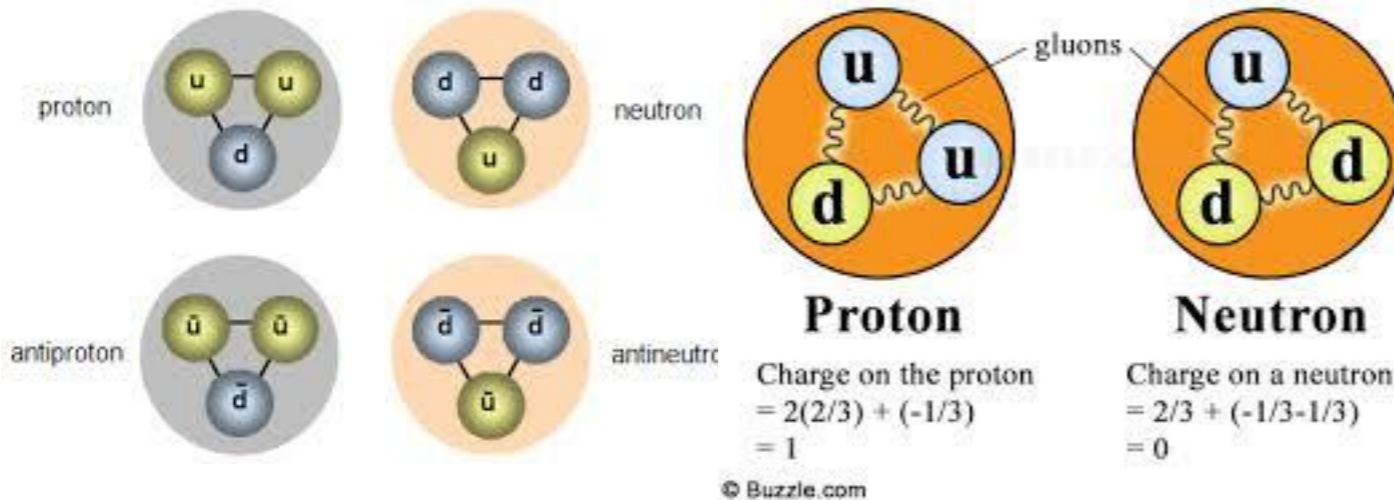
## A Microscope for Gluons

# Where are the gluons?



Lattice simulation with artificially frozen quarks

*D. Leinweber (Adelaide)*





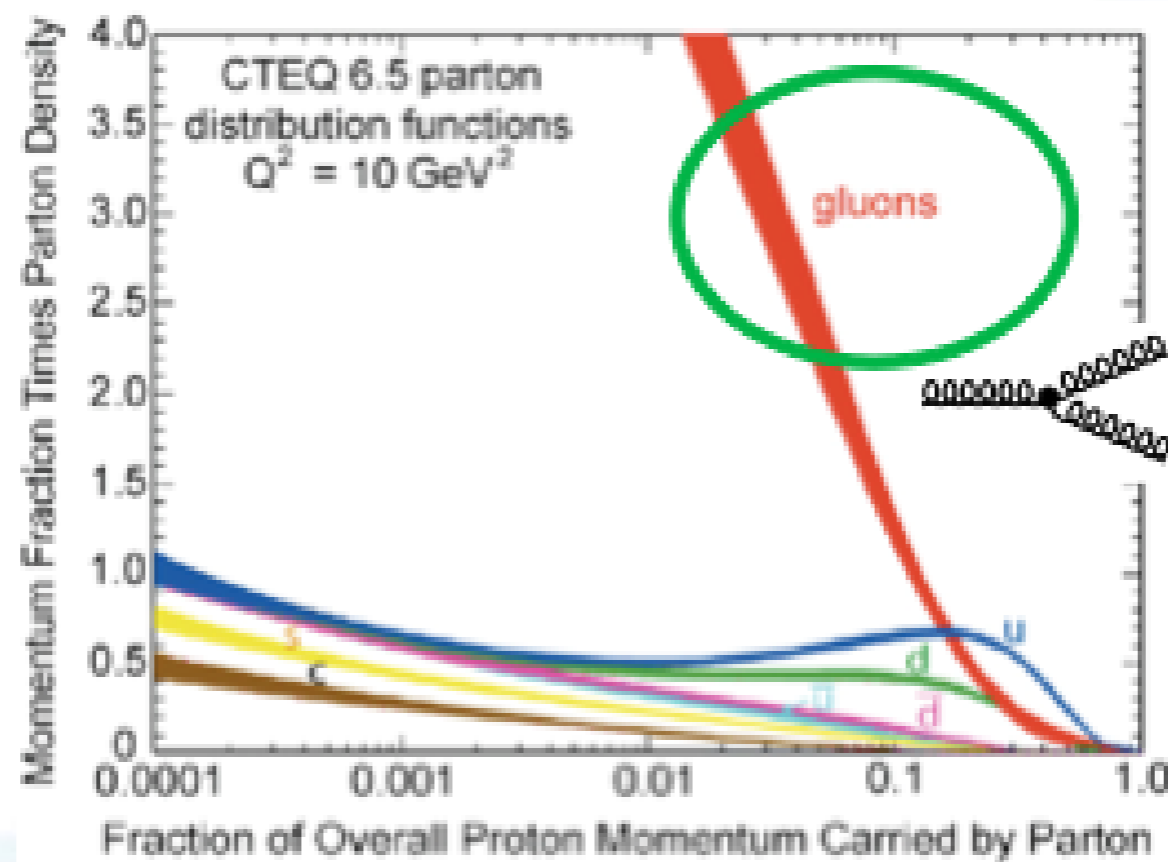
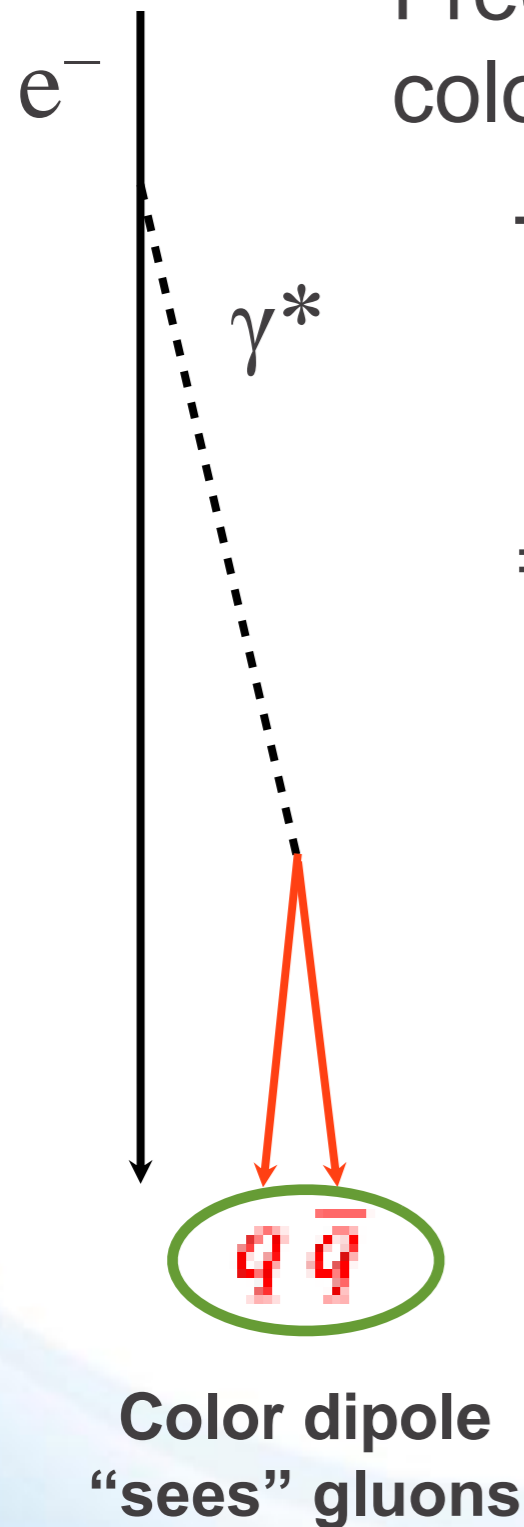
# EIC: A color dipole microscope

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!



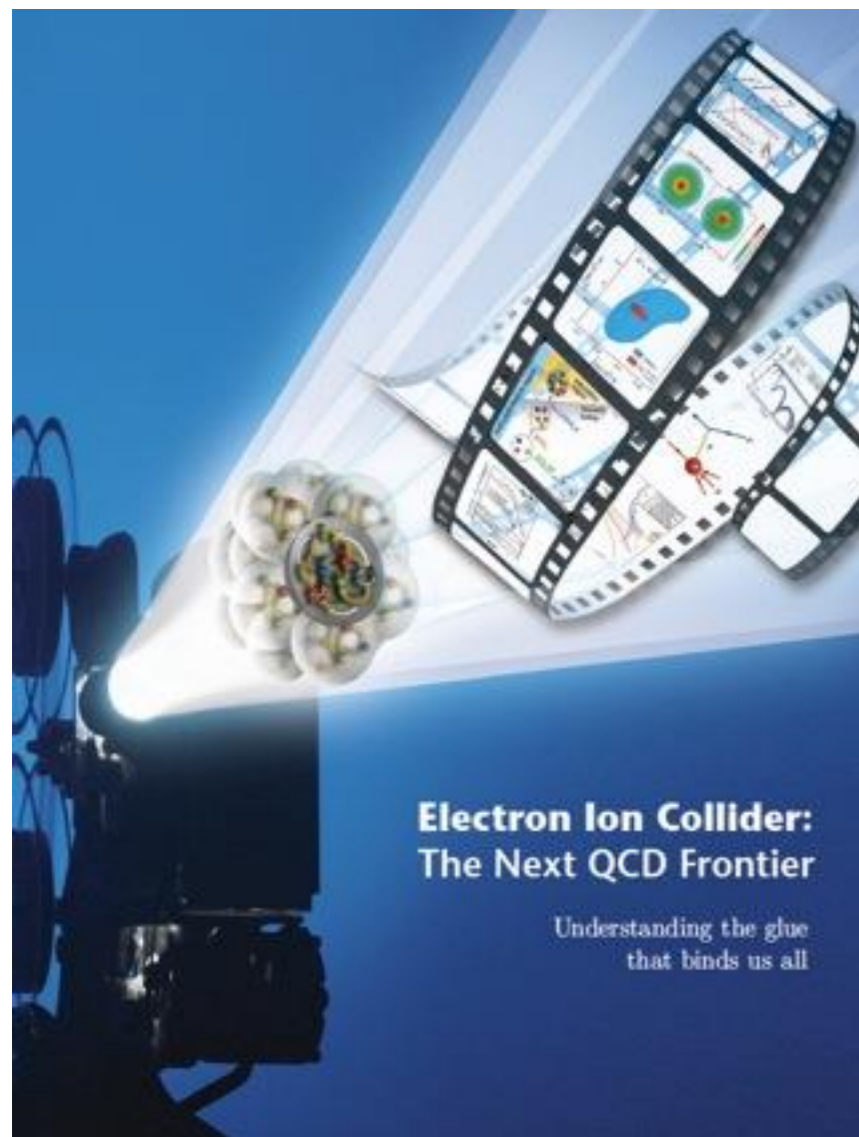
HERA was the 1<sup>st</sup> generation color dipole microscope.

Limited intensity and no polarization.

The EIC will be the 2<sup>nd</sup> generation color dipole microscope!

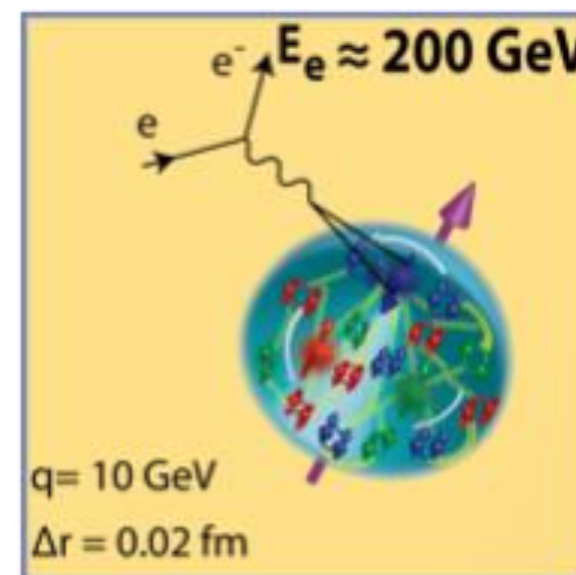


# Electron-Ion Collider (EIC)



The EIC White Paper  
(arXiv:1212.1701)

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.



## Why now?

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.

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

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

# EIC - the ultimate QCD Laboratory

# EIC: A QCD laboratory

## ➤ Proton mass puzzle:

Quarks carry  $\sim 1\%$  of the proton's mass

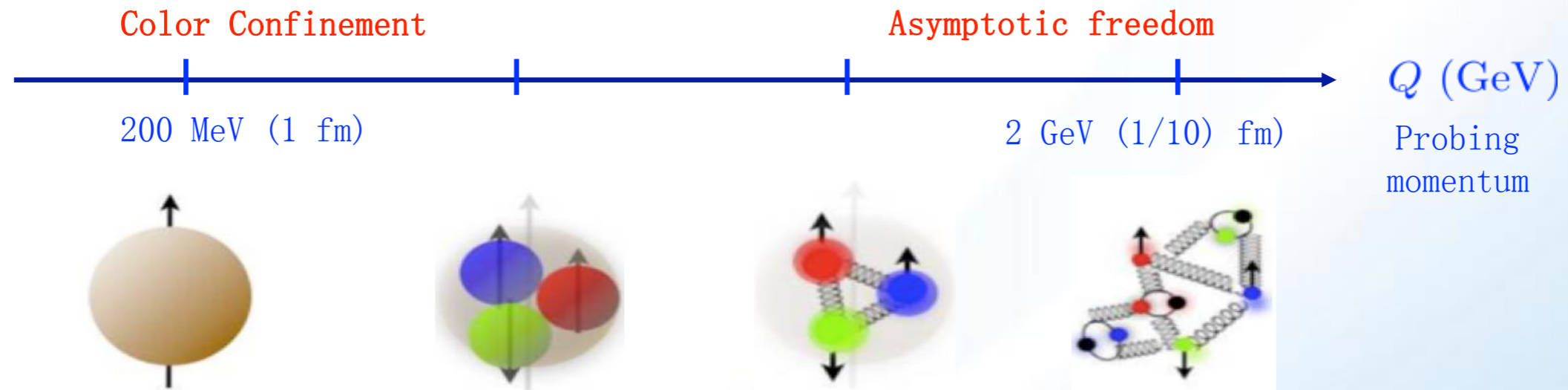
How does glue dynamics generate the energy for the nucleon mass?

## ➤ Proton spin puzzle:

Quarks carry only  $\sim 30\%$  of the proton's spin

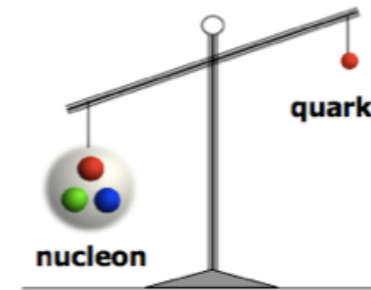
How does quark and gluon dynamics generate the rest of the proton's spin?

## ➤ 3D structure of nucleon:



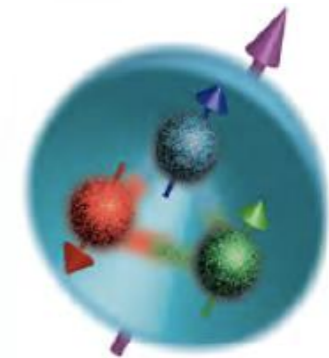
How does the glue bind quarks and itself into a proton and nuclei?

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



$$m_q \sim 10 \text{ MeV}$$

$$m_N \sim 1000 \text{ MeV}$$



# Fundamental question I

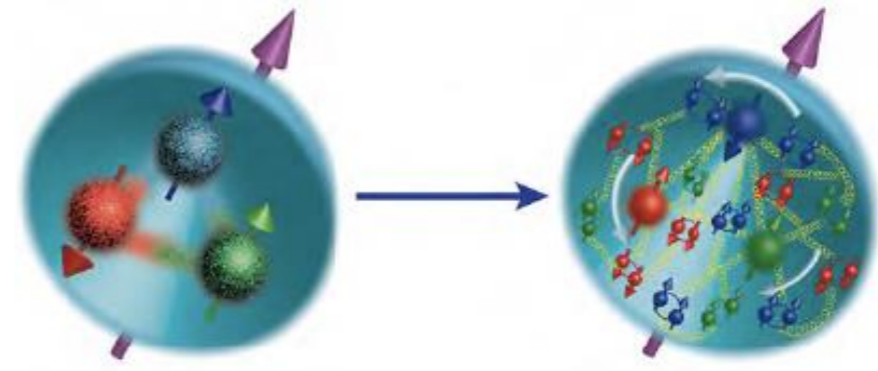
How do quarks and gluons confine themselves into a proton?

“Hints” from known hadron structure

## ➤ Hadron structure:

From the EIC White Paper

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction? What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin?



## ➤ Proton spin:

If we do not understand proton spin from QCD, we do not understand QCD!

It is more than the number  $\frac{1}{2}$ ! It is the interplay between the intrinsic properties and interactions of quarks and gluons

**Needs a polarized proton beam!**



# Fundamental question II

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

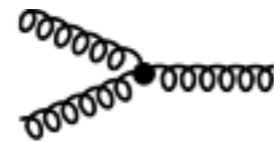
**Color Glass Condensate**

➤ **Gluons, unlike photons:**

Split:



Fuse:

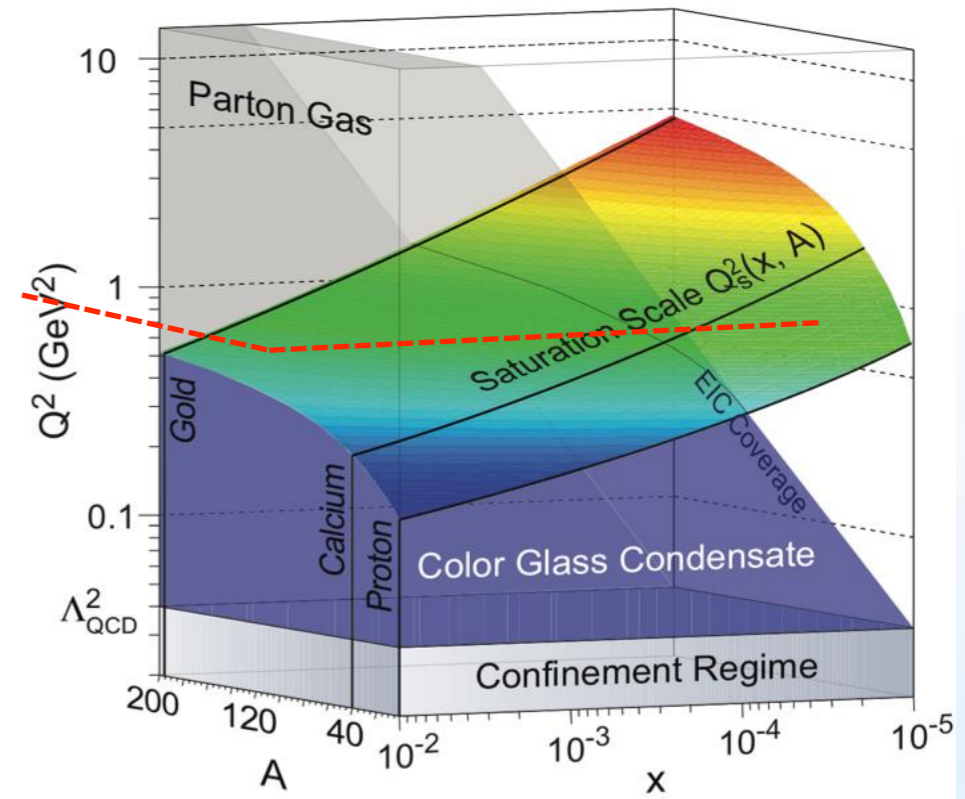


- ✧ Dynamical scale  $Q_s$  from the balance
- ✧ New conceptual framework
- ✧ Universal properties (CGC)

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!**





# Fundamental question III

How do hadrons emerge from a created quark or gluon?

Neutralization of color = hadronization

➤ Femtometer detector/scope:

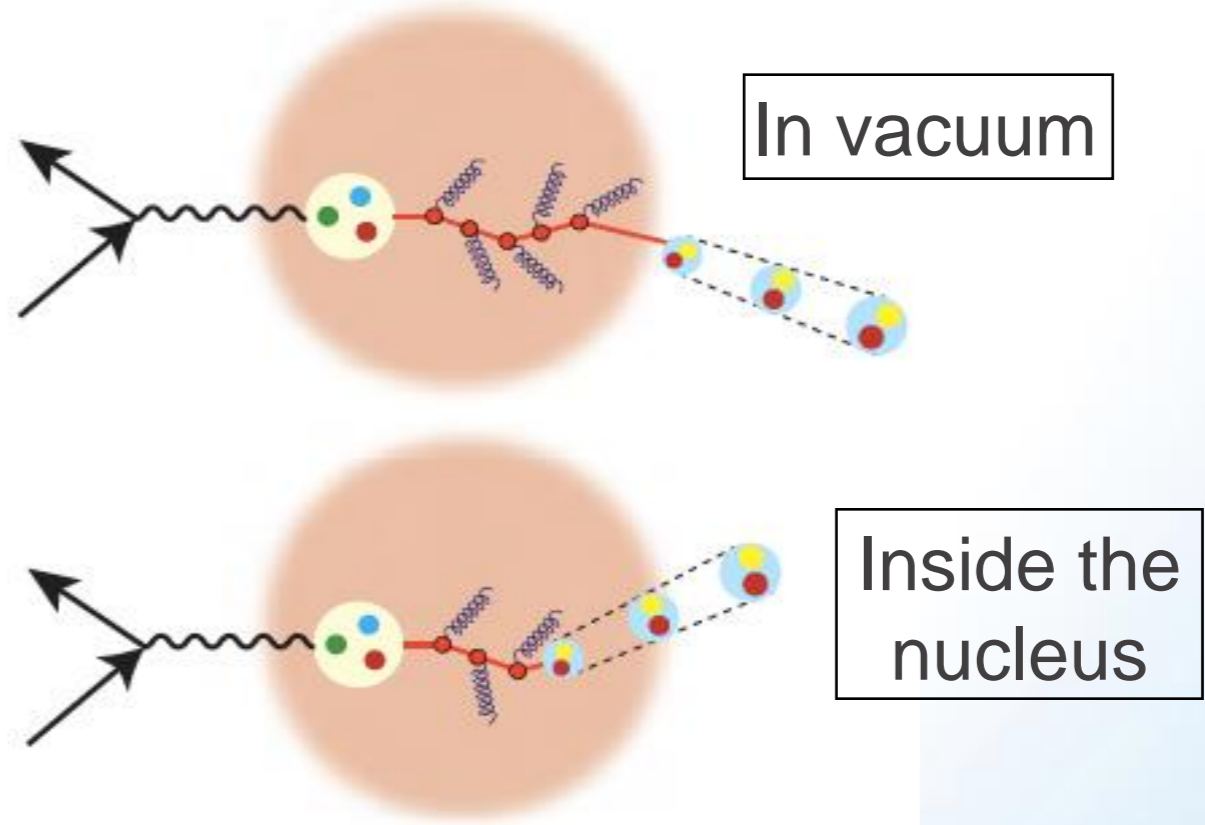
Nucleus, a laboratory for QCD

➤ Quark/gluon properties:

Initial-condition for hadronization

Semi-inclusive DIS

From the EIC White Paper



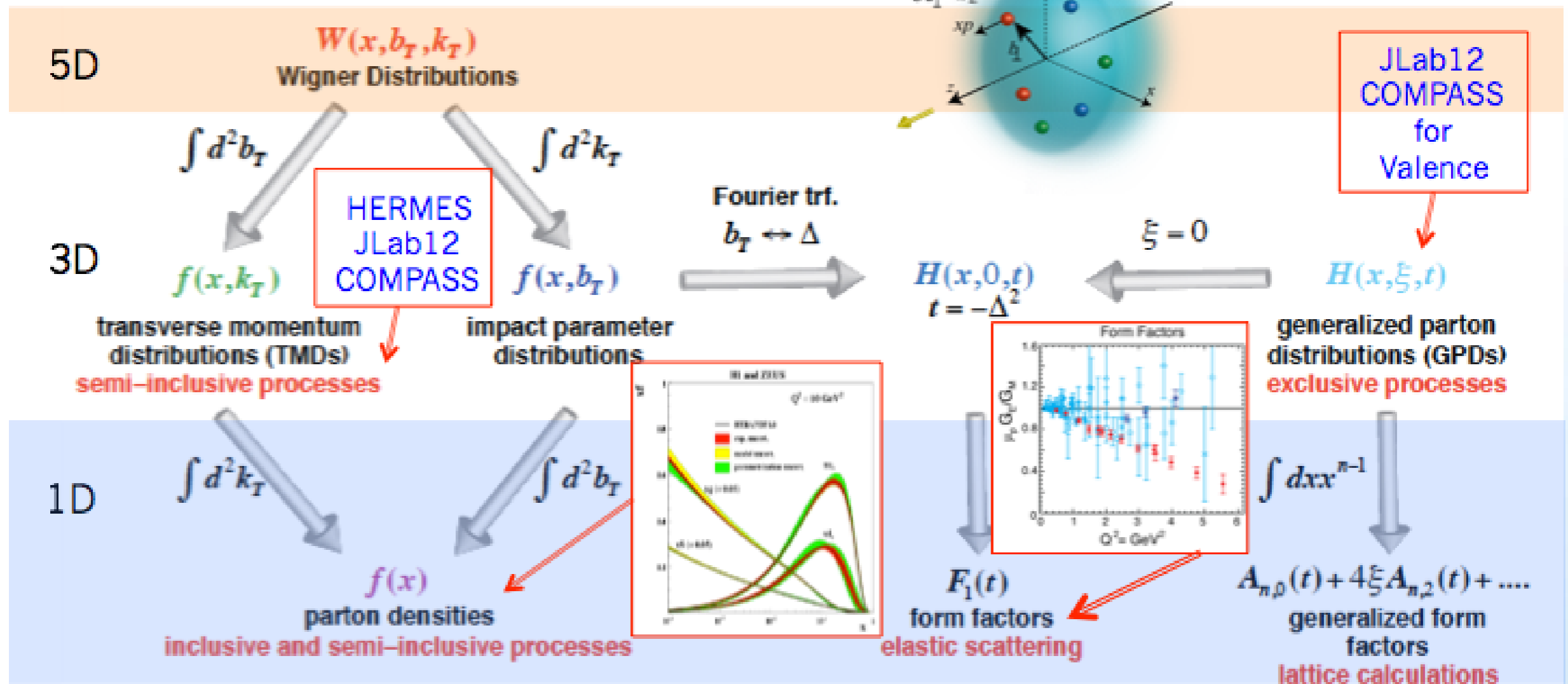
- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei? How does the transverse spatial distribution of gluons compare to that in the nucleon? How does nuclear matter respond to a fast moving color charge passing through it? Is this response different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

Needs a probe to precisely control the initial condition!

# Selected Measurements

# Formalism

## ➤ Wigner distributions:

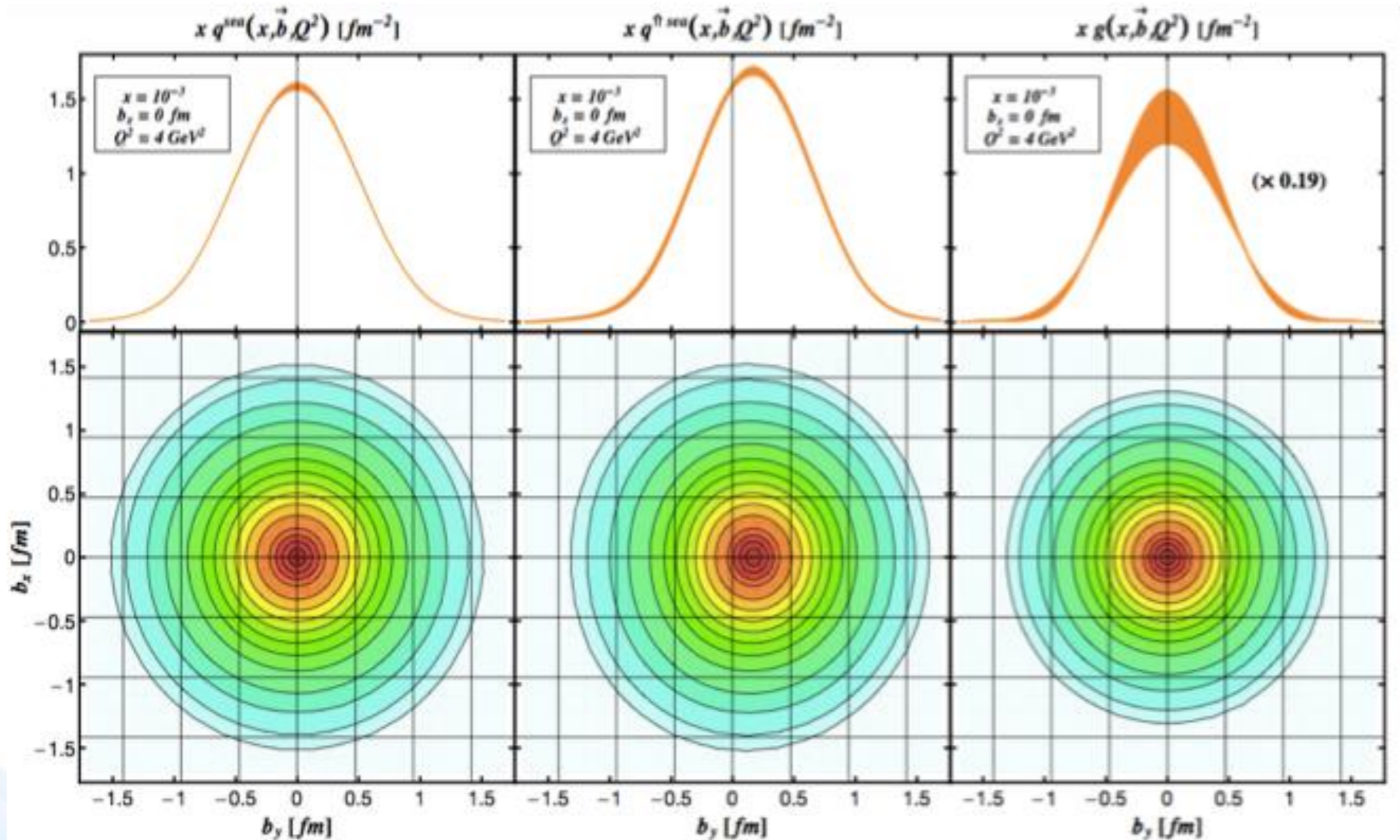


## ➤ EIC – 3D imaging of sea and gluons:

- ◆ TMDs – confined motion in a nucleon (semi-inclusive DIS)
- ◆ GPDs – Spatial imaging of quarks and gluons (exclusive DIS)

# Imaging quarks and gluons

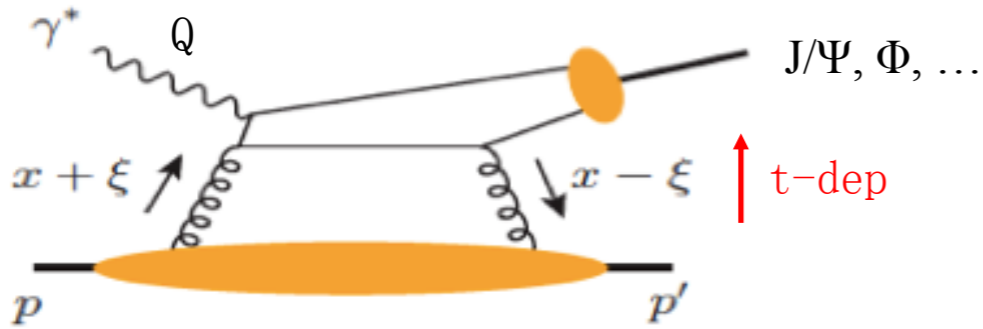
using Generalized Parton Distributions (GPD's):





# Imaging gluons

## Exclusive vector meson production:

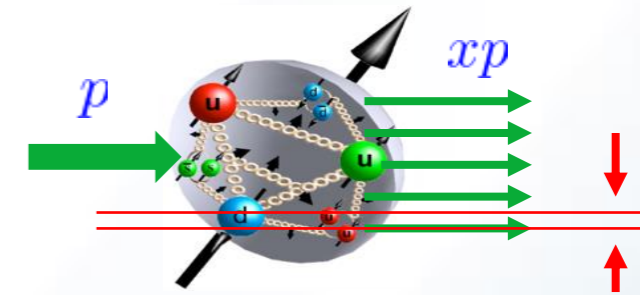
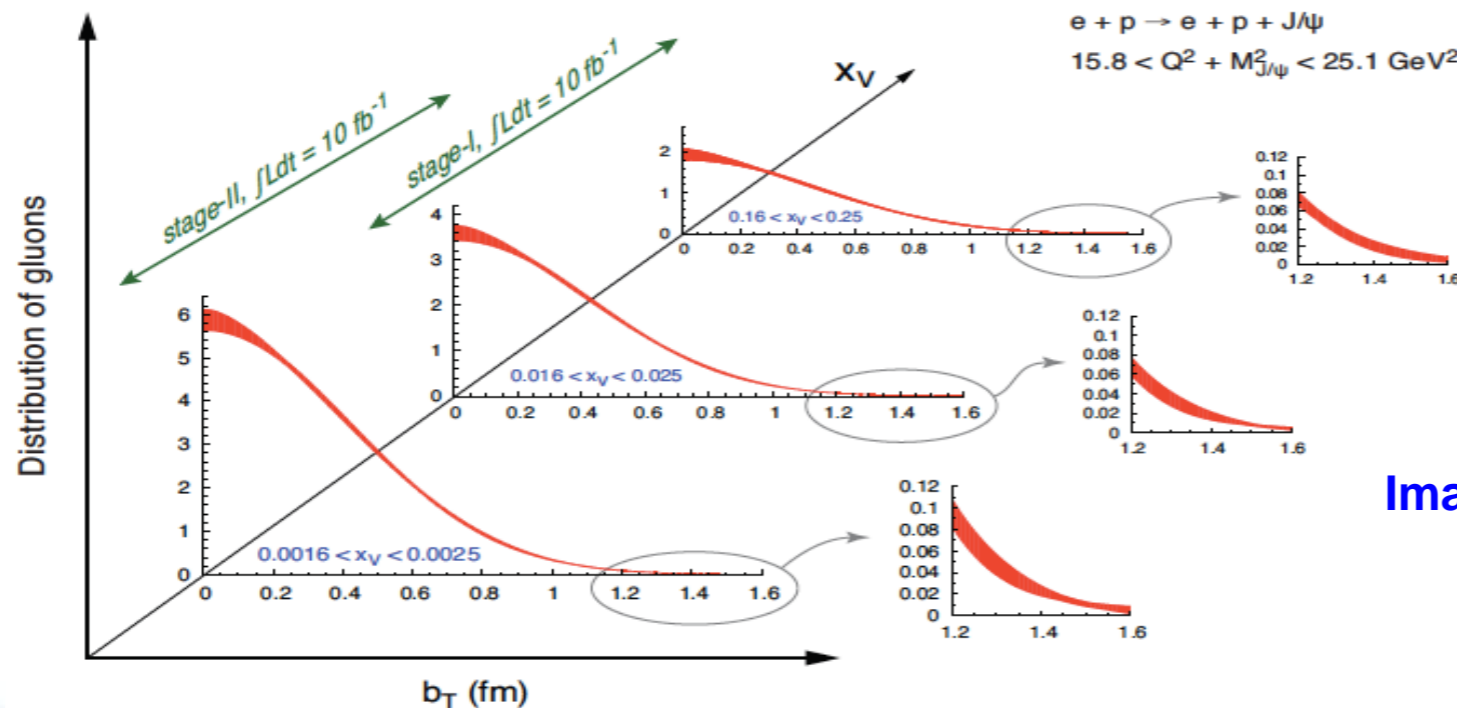


$$\frac{d\sigma}{dx_B dQ^2 dt}$$

Fourier transform of the t-dependence  
 → Spatial imaging of glue density

Resolution  $\sim 1/Q$  or  $1/M_Q$

## Gluon imaging from simulation:



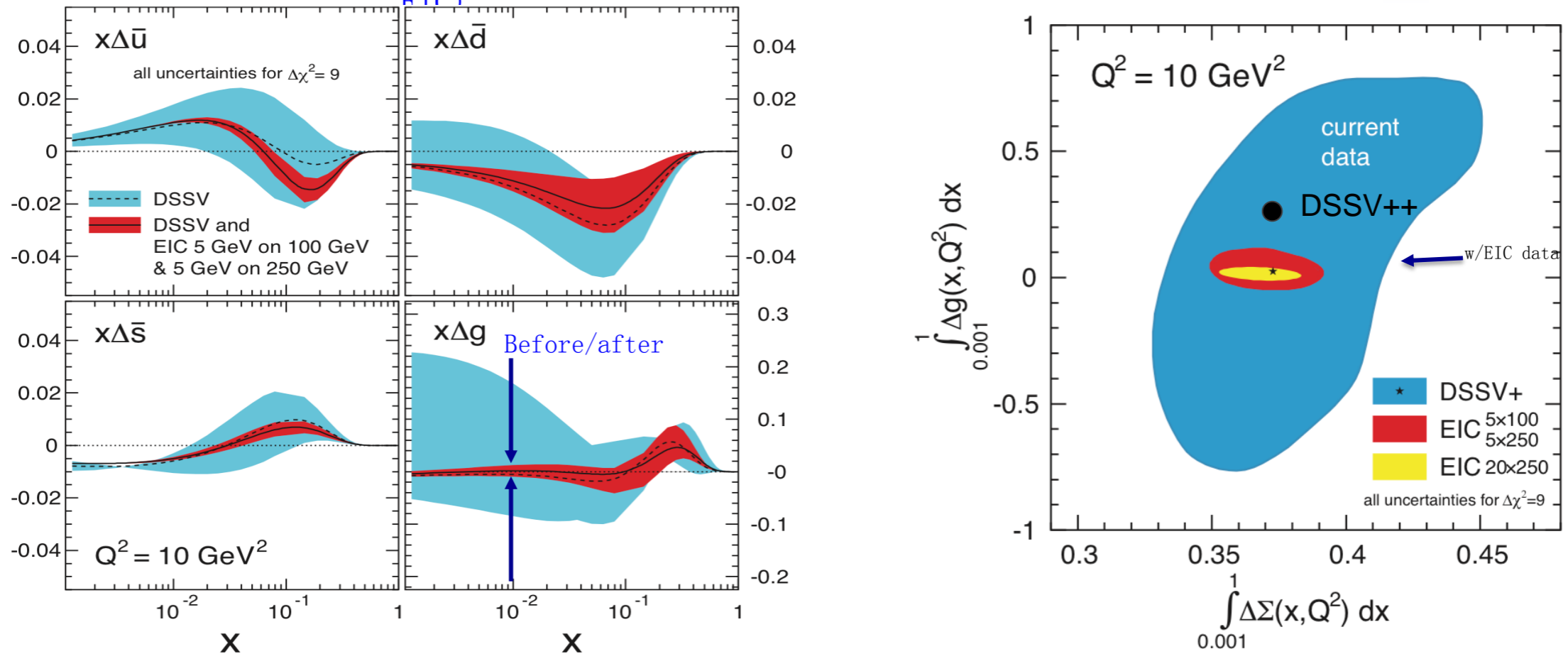
Images of transverse gluon distributions  
 from exclusive J/Psi production

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 1<sup>st</sup> year of running):

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



No other machine in the world can perform this measurement!

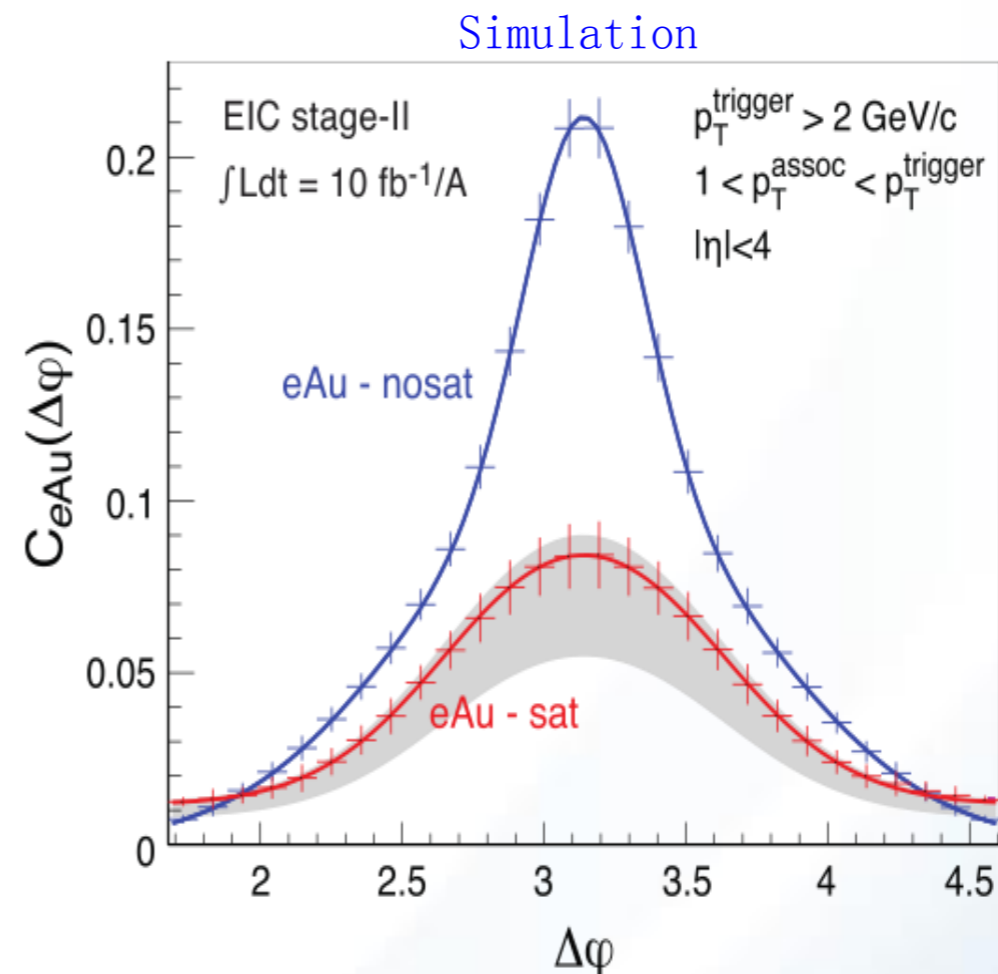
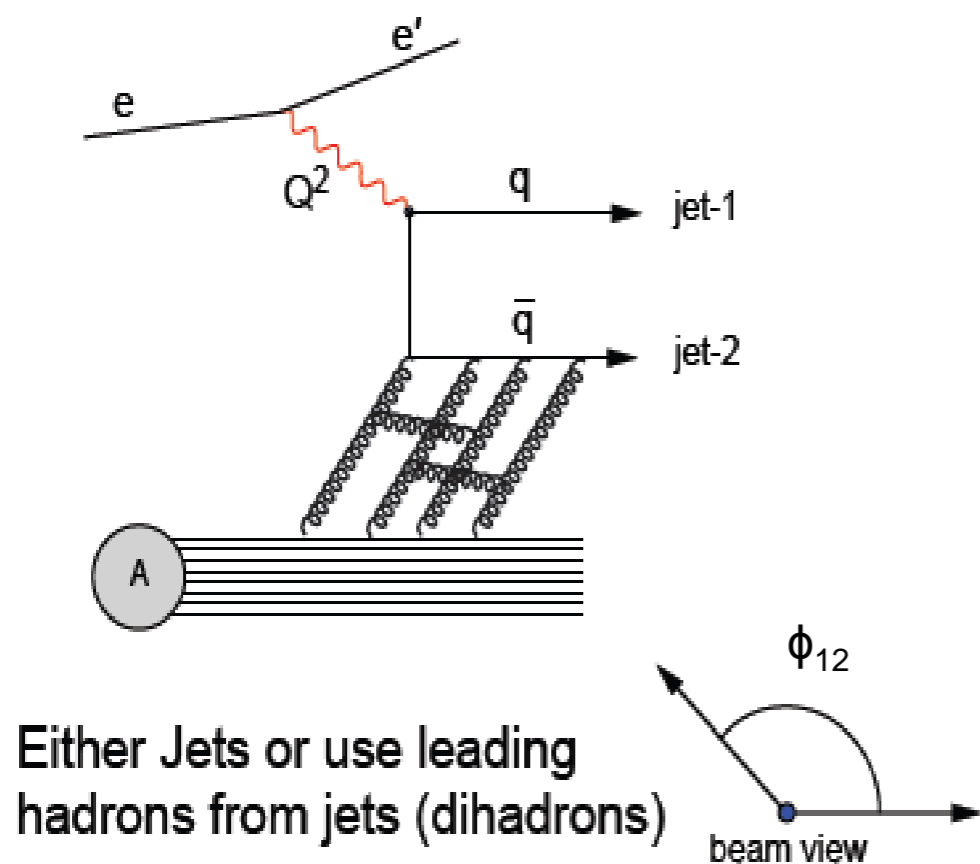
## ○ Solution to the proton spin puzzle:

↗ Precision measurement of  $\Delta G$  – 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 by a factor 2 !**

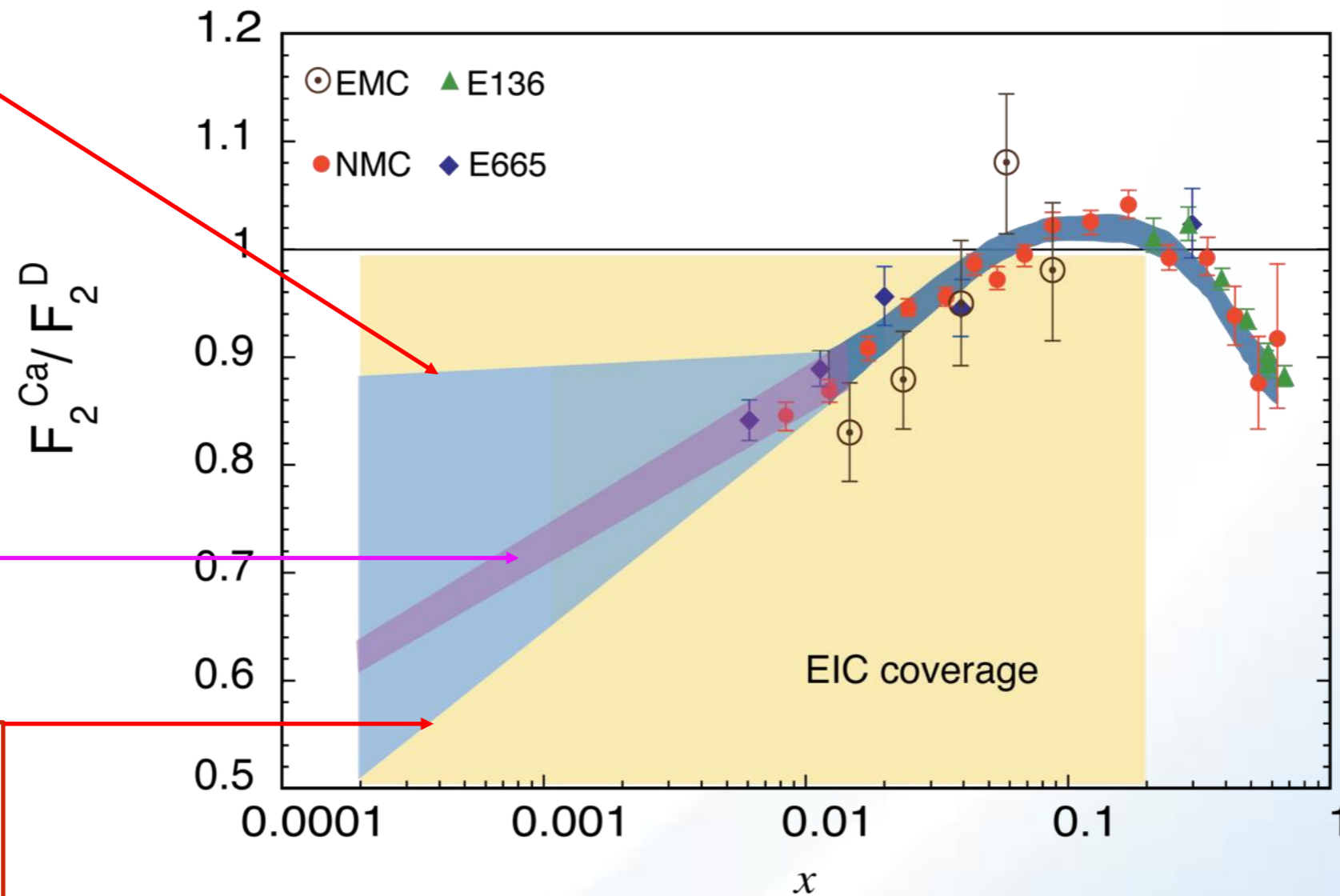
# Color range in a nucleus

○ 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)



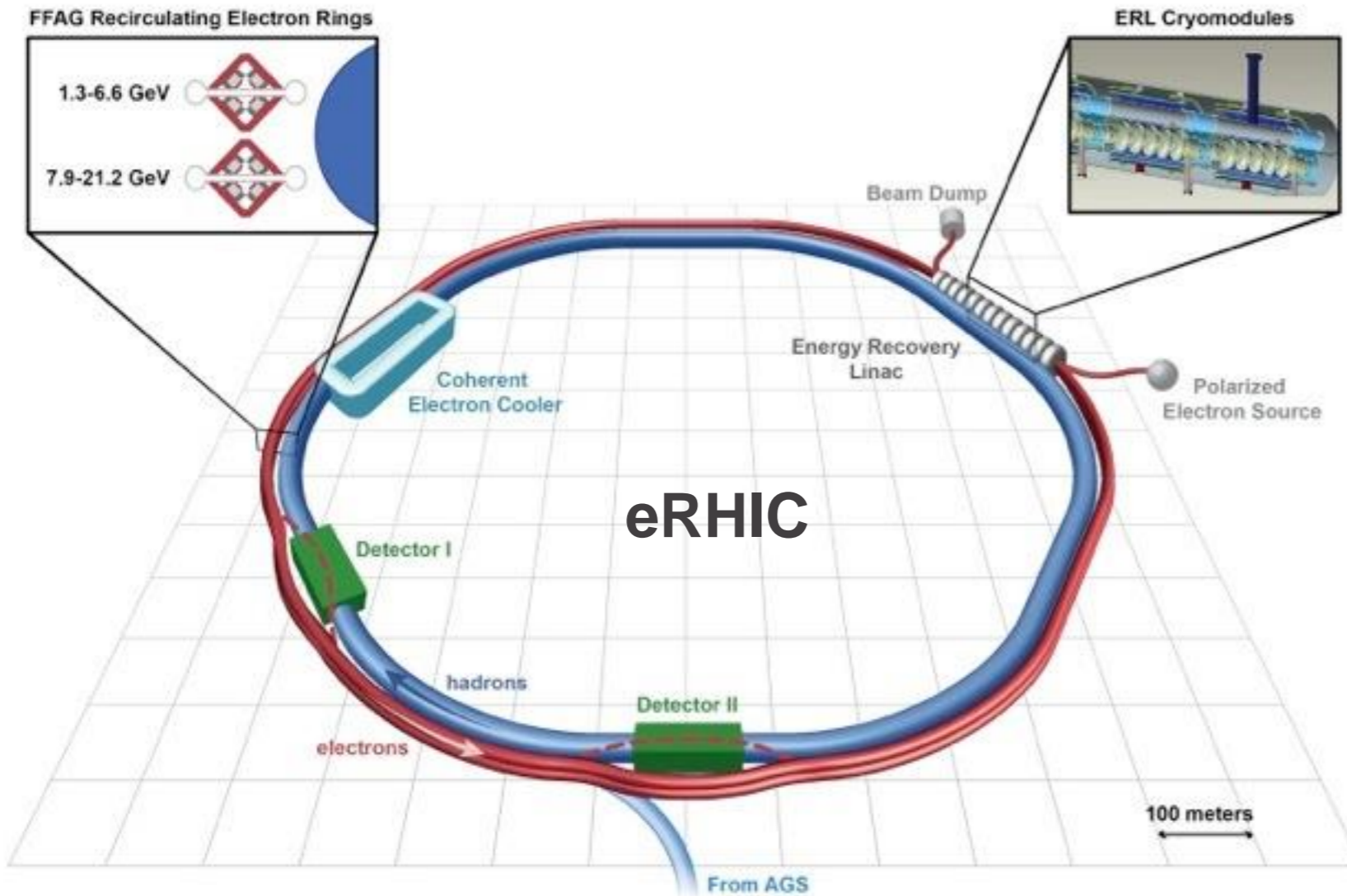
A clean measurement is only possible at the EIC



# eRHIC: EIC @ BNL

# EIC Design

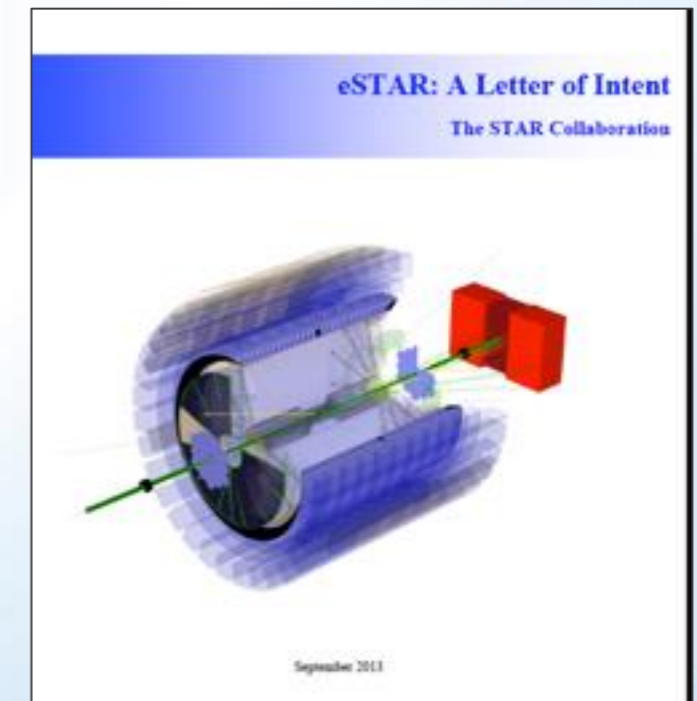
eRHIC ERL + FFAG ring design @  $10^{33}/\text{cm}^2\text{s}$   
15.9 GeV  $e^-$  + 255 GeV p or 100 GeV/u Au.



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



**ePHENIX and eSTAR  
Letters of Intent**



# A revolutionary 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 FFAG arcs
  - Coherent e-cooling (CeC) for record high beam brightness
  - “Crab” crossings for low background interaction regions
- While some of these concepts have been tested at other facilities, their unique combination will create a “green” collider facility of unprecedented energy efficiency at affordable cost.
- Estimated target cost for the accelerator: \$550M. Bottom-up cost estimate is in progress.

# More information

- Much more information about the EIC science case and high profile measurements can be found in the lectures posted on the EIC Advisory Committee meeting website:
- <https://indico.bnl.gov/conferenceDisplay.py?confId=727>
- The site also contains a link to the recently completed eRHIC Design Study
- The EIC Whitepaper can be found on the preprint archive: [arXiv:1212.1701](https://arxiv.org/abs/1212.1701)
- [A EIC Users Meeting was held at Stony Brook University, June 24-27, 2014 \(Organizers: A. Deshpande, Z-E. Meziani & R. Milner\)](#)
- The science case for an EIC will be presented at to the NSAC Long Range Plan Working Group in Spring 2015.