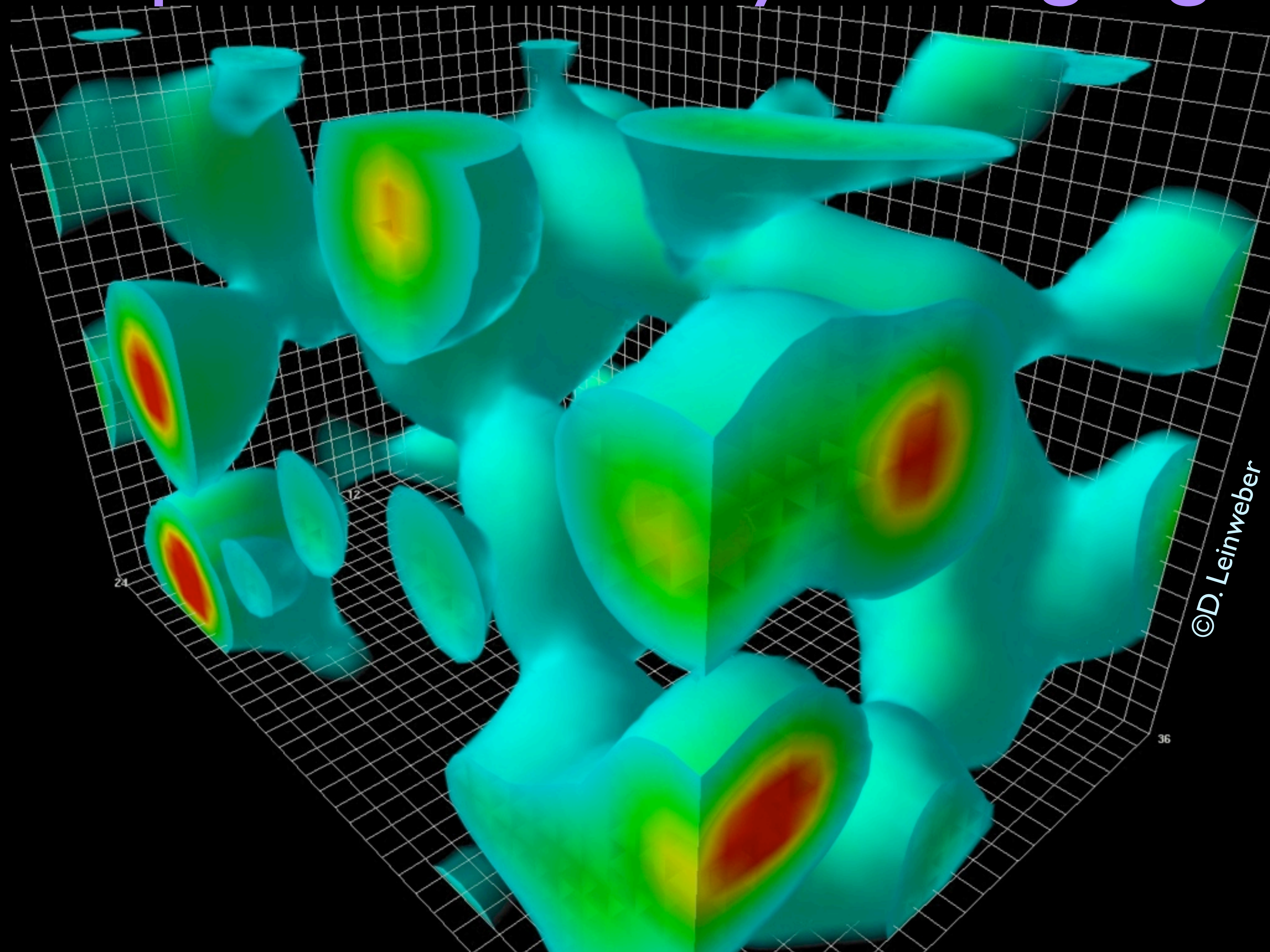
# The Electron-Ion Collider at BNL:
## Capabilities and Physics Highlights

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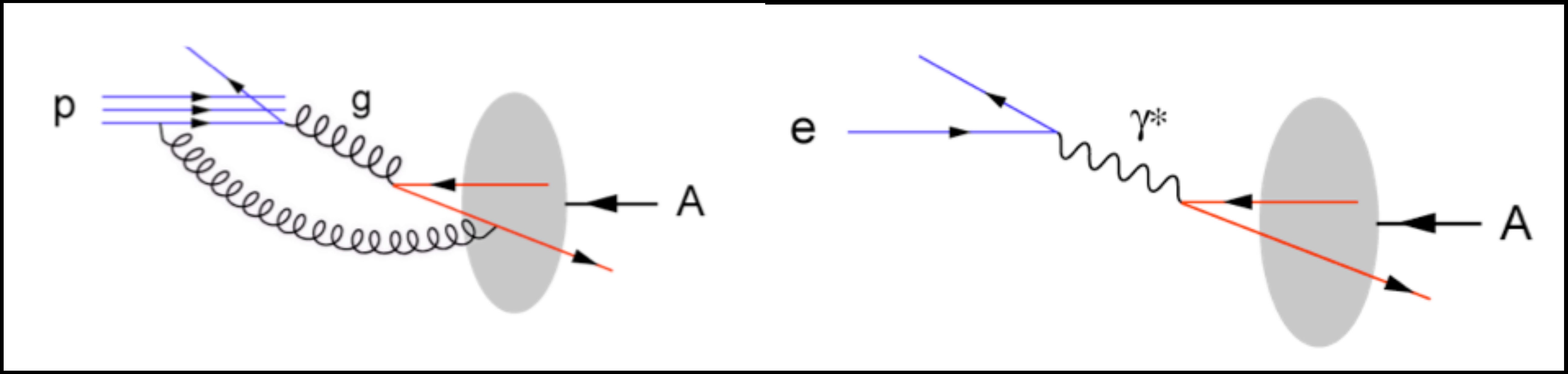
# Outline

- Why do we need
  - electron-ion collider
- What can we do with
  - e + (heavy) A
  - high energy/luminosity polarized e + polarized p
  - new opportunities for spectroscopy
- How can it be realized
  - adding an electron accelerator at RHIC (or adding a hadron accelerator at CEBAF)
  - design and status of eRHIC at BNL

# QCD and Fundamental Structure of Matter

- QCD is THE theory of the strong interaction: Theory of the matter - quarks and gluons
- Hadronic constituent degree of freedom is governed by quarks, but gluons drive the baryonic structure (responsible for > 98% mass) and dominates the QCD vacuum structure
- "Mastering matter" requires the fundamental understanding of gluon dynamics beyond current knowledge: new frontier machine to deeply explore the regime where new degree of freedom emerges

# Accessing gluonic structure



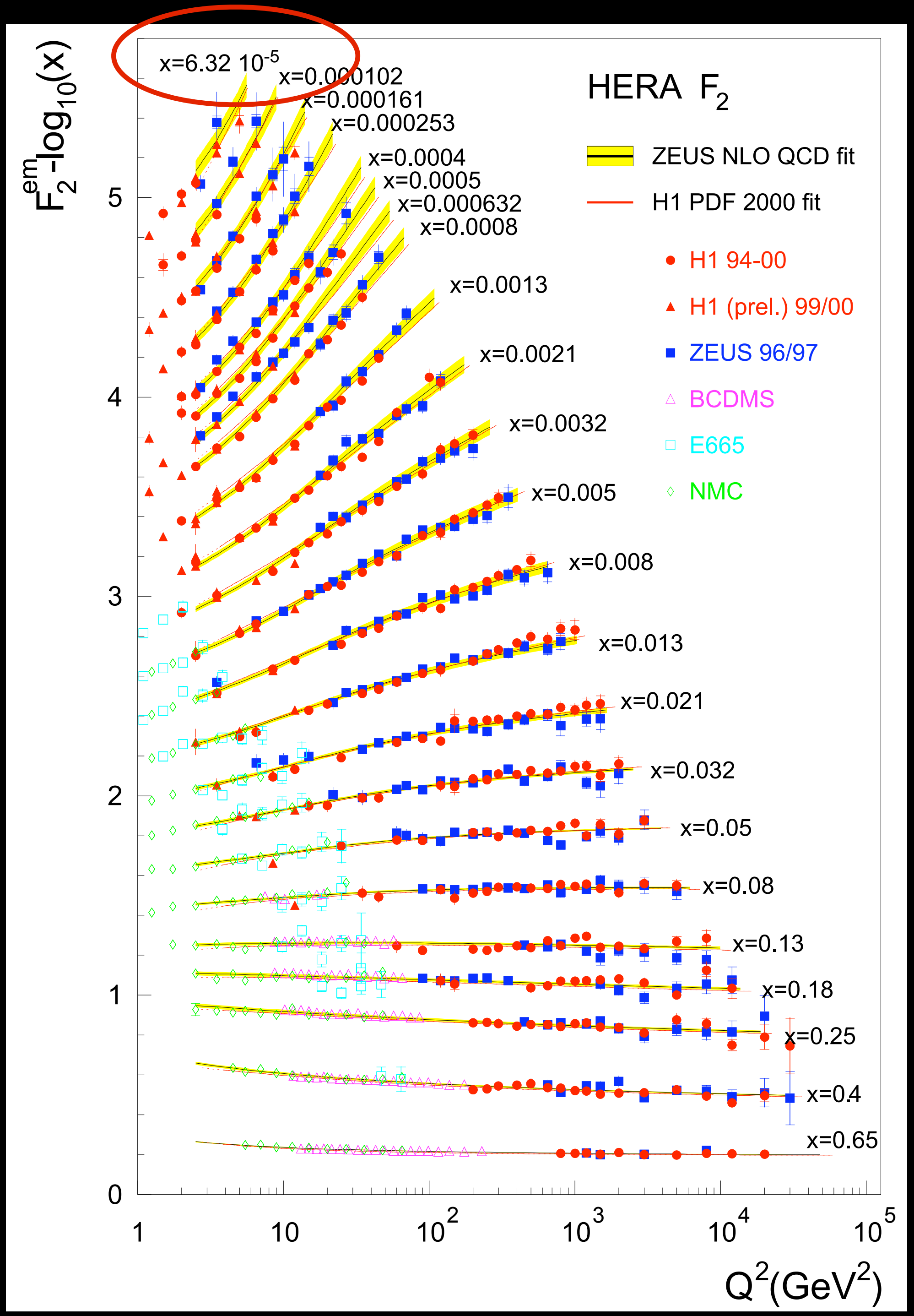

Hadron-Hadron

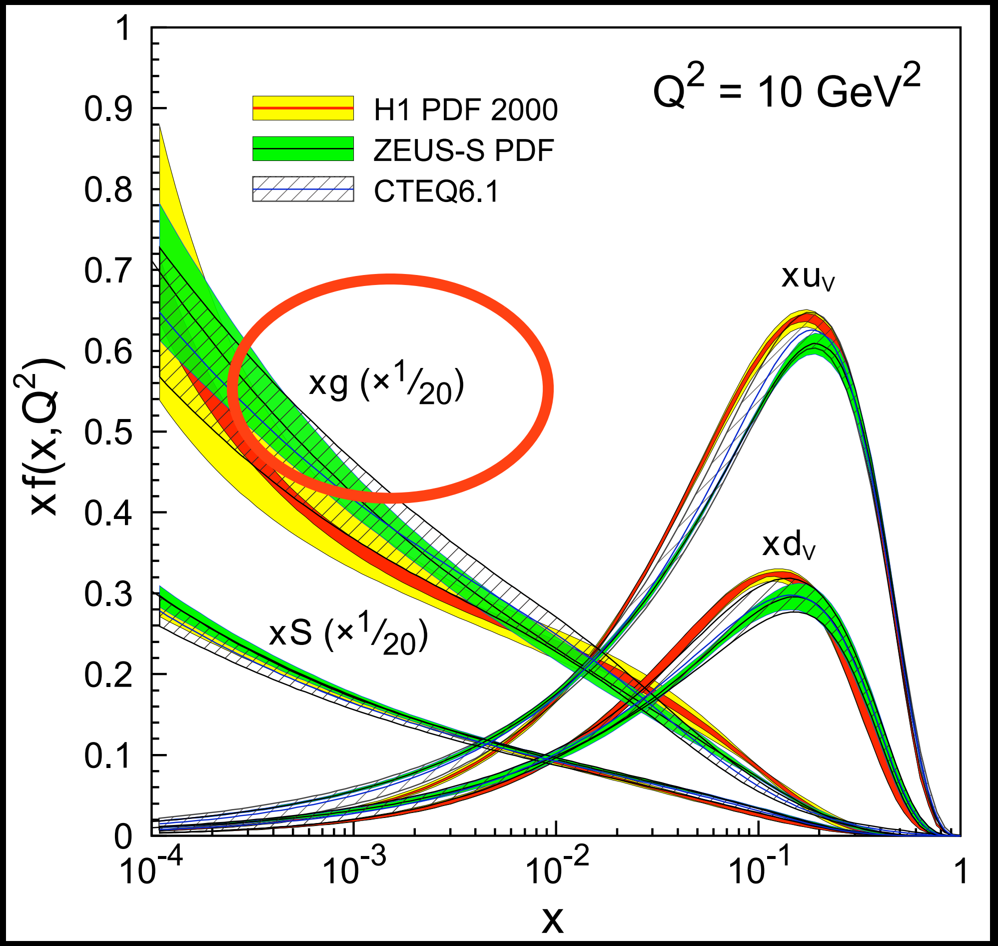
Lepton-Hadron (DIS)

Probe interaction directly via gluons:
Lacks the direct access to partonic kinematics

Indirect access to gluons (electro(-weak) structure function) :
High precision and access to partonic kinematics (x, $Q^2$)

# Glue in Matter: What do we know

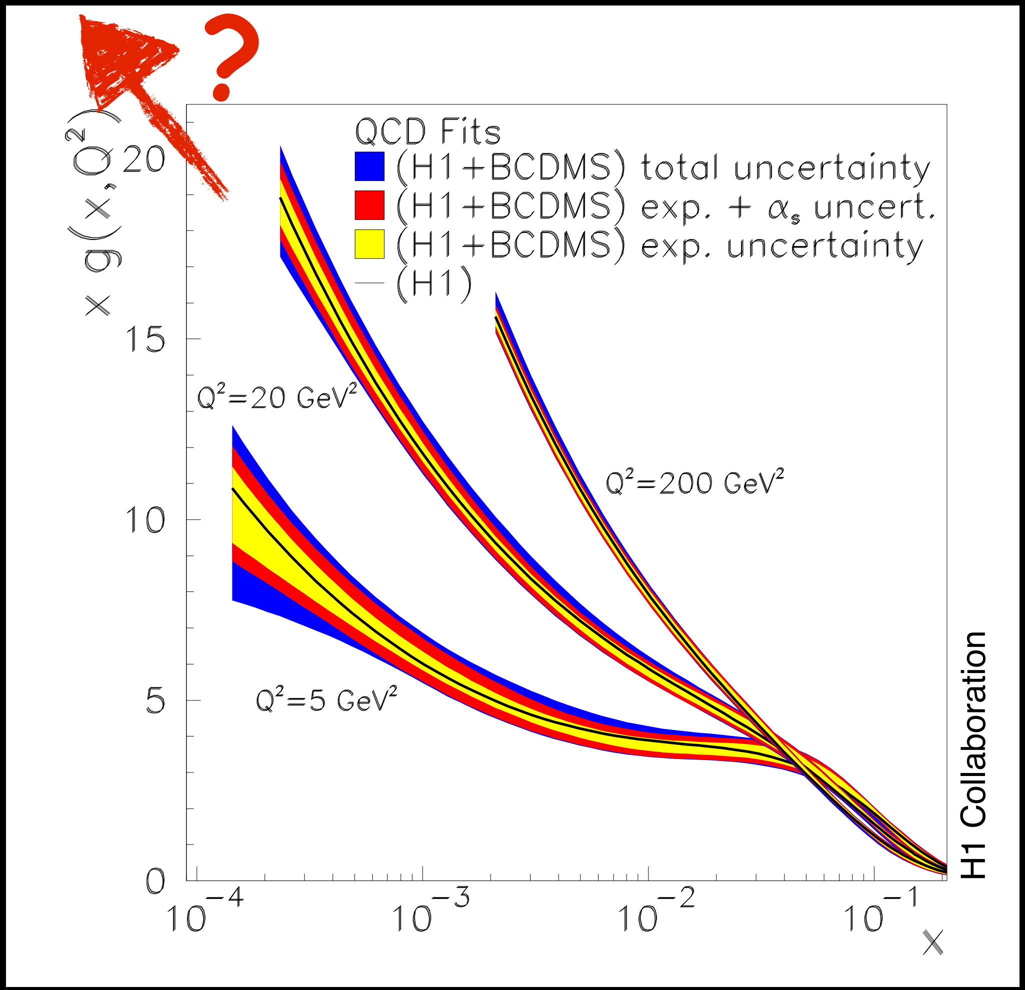


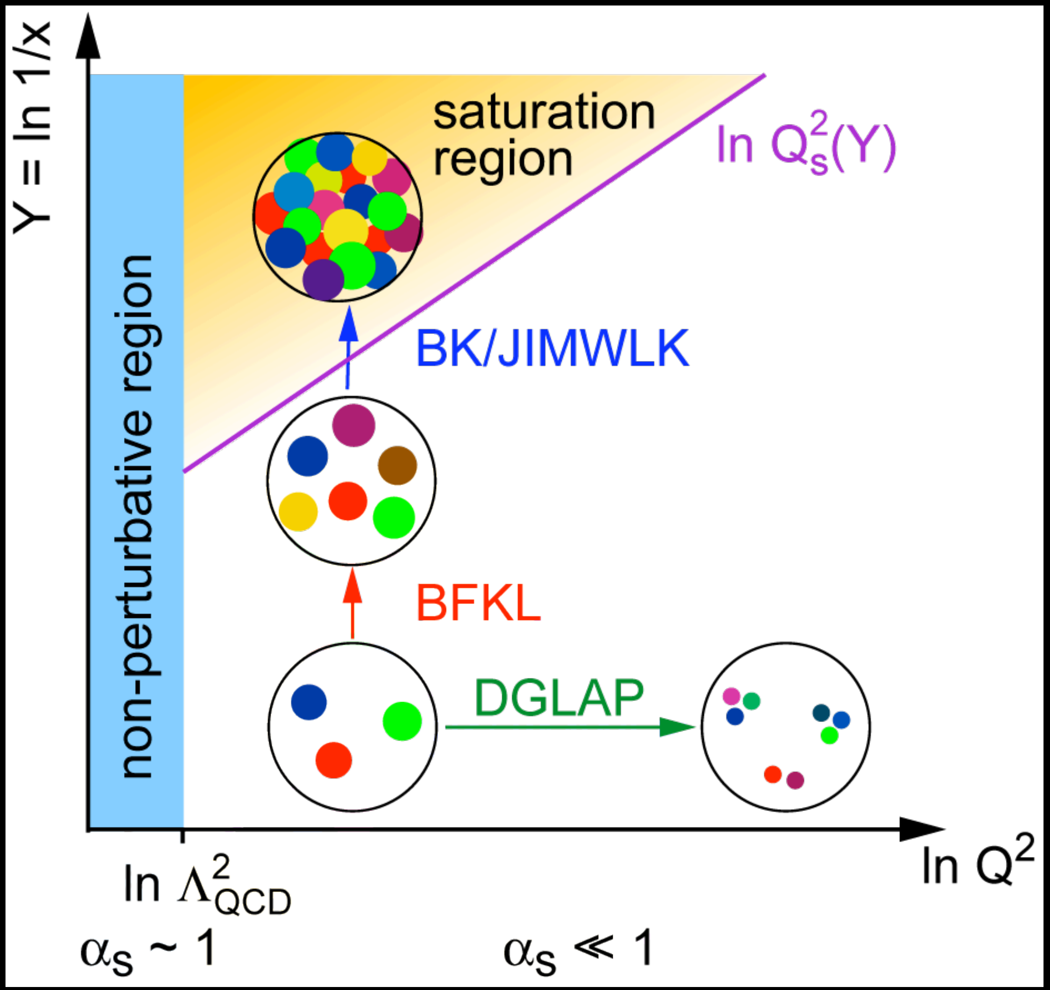




- For smaller values of x, structure function $F_2$ rises strongly with $Q^2$: Simple quark-parton model Bjorken scaling breaks
- NLO QCD and the measurement "broadly similar": limited success
- Gluons dominate at low-x, but the underlying dynamics and the evolution is not well established

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

# How gluons grow

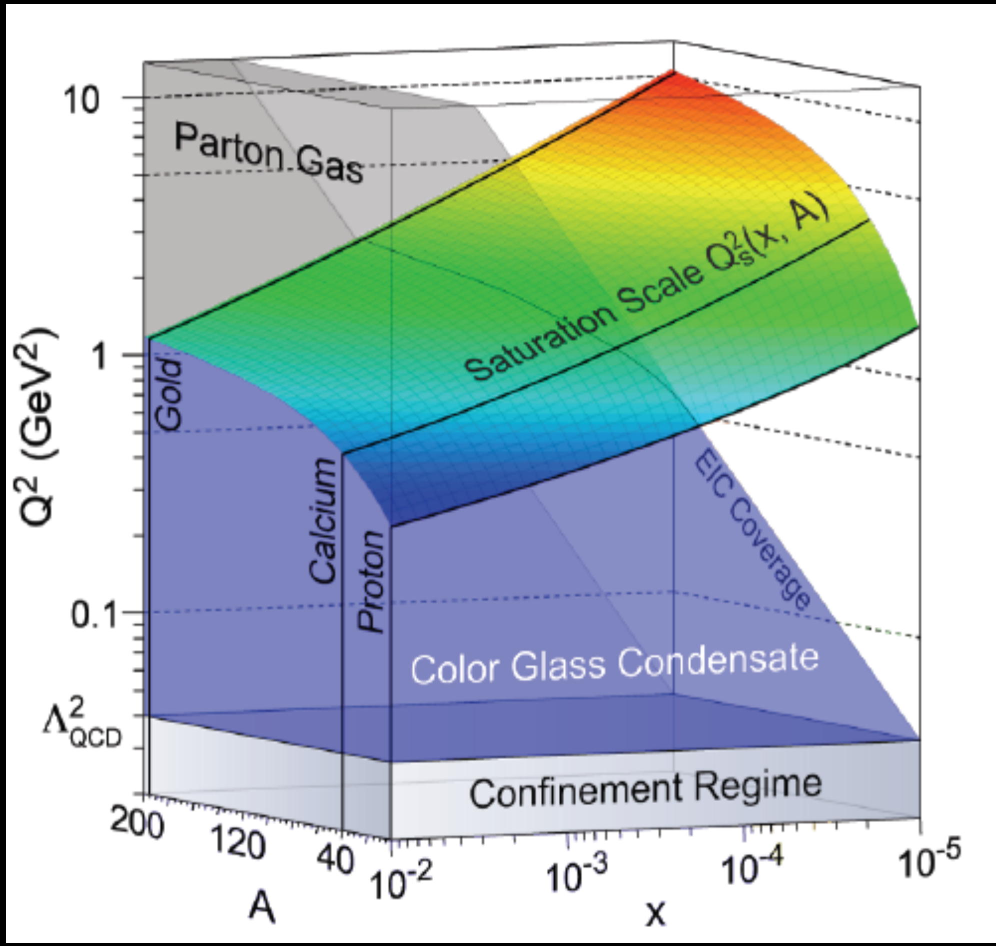



- Linear DGLAP evolution: requires "safety dynamics" to prevent unitarity violation
- Saturation regime arises naturally through non-linear BK/JIMWLK evolution
  - in the Color Glass Condensate (CGC) framework
  - characterized by saturation momentum $Q_S(x,A)$
  - Experimental establishment on the "theoretical evidence" of saturation regime is fundamentally important for understanding of gluonic dynamics - strong interaction

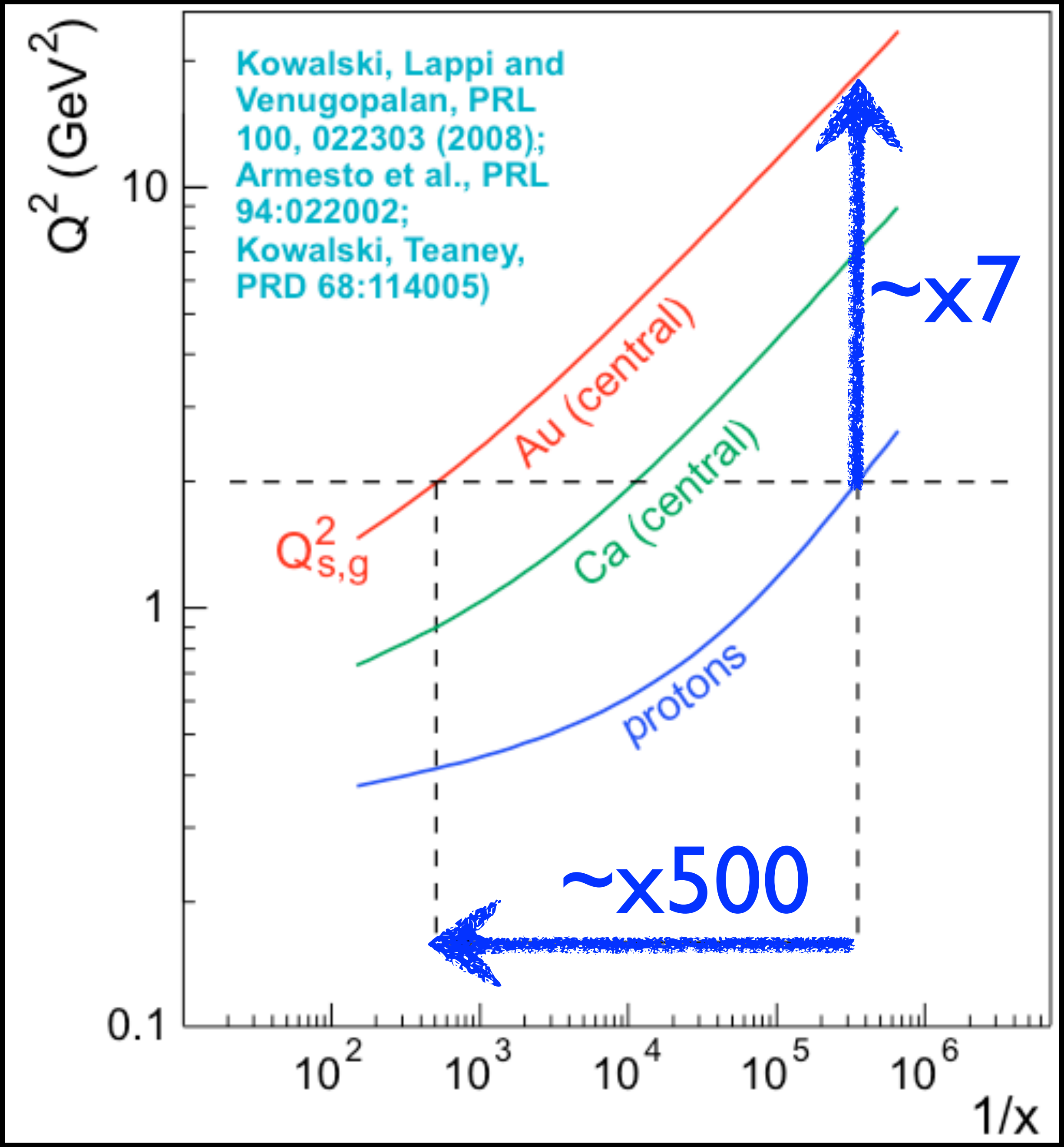
# Estimating saturation scale

- Gluonic saturation/recombination
  - number of gluons per unit of transverse area: $\rho \sim xG(x,Q^2)/\pi R^2$
  - cross-section for gluon recombination: $\sigma \sim \alpha_s/Q^2$
  - saturation occurs when $1 < \rho\sigma \Rightarrow Q^2 < Q_s^2(x)$



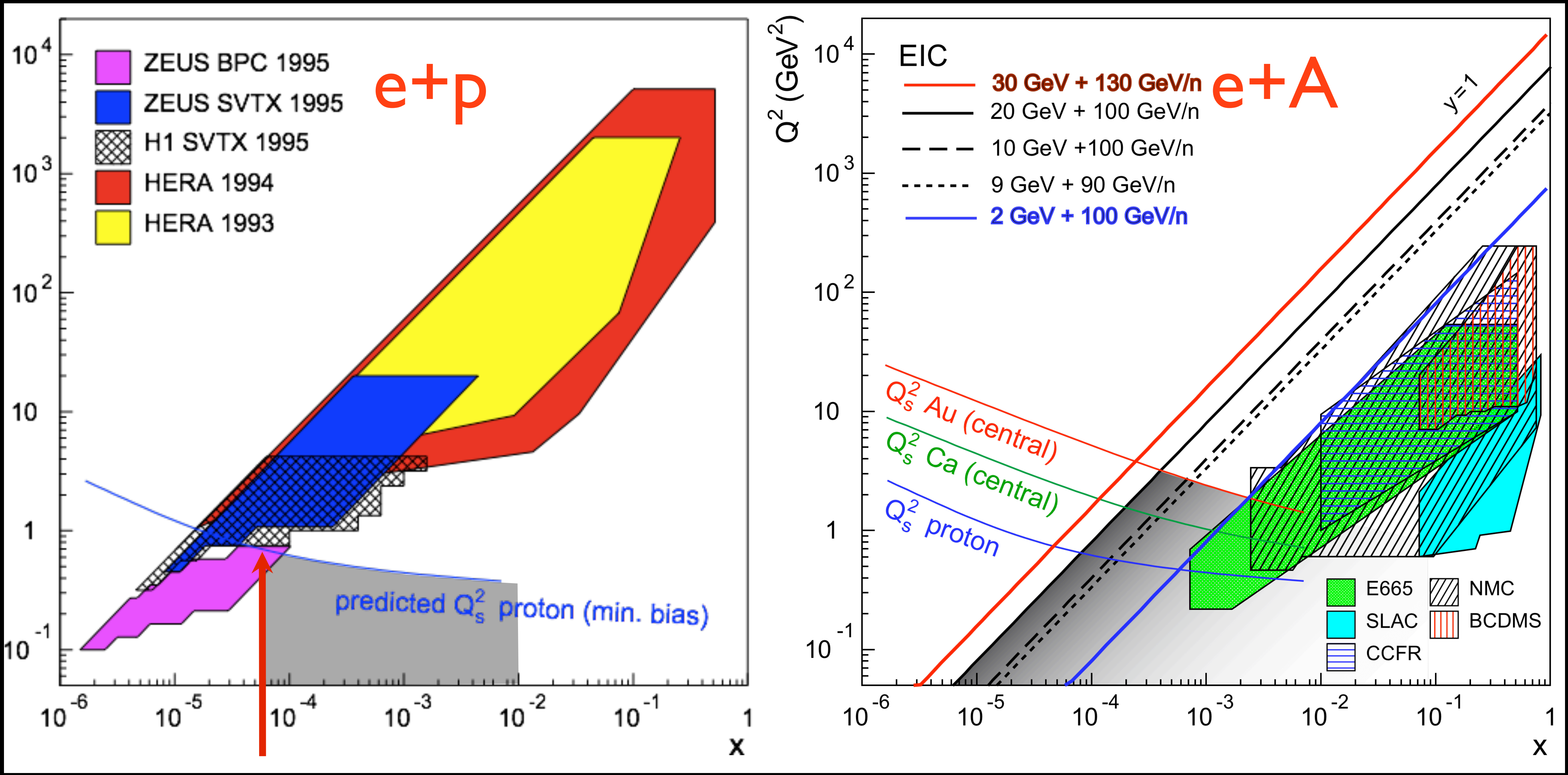

- saturation Qs varies
  - Qs $\propto x^{1/3}$ (phenomenological "geometrical scaling" at HERA)
  - Qs $\propto A^{1/3}$ (Gluons act coherently)
    - **Nuclear enhanced** saturation scale
    - To access saturation: increase energy (~1/x) or **increase $Q_s$ (~$A^{1/3}$)**

# Nuclear enhanced saturation




- With e+p, requiring $Q^2$ lever arm need $\sqrt{s}$ =1-2 TeV (HERA $\sqrt{s}$=320 GeV)
- x~$10^{-3}$ in dAu at RHIC (approaching saturation)
- Saturation scale Qs increases with heavy-ion significantly: Well in reach with e+Au at RHIC

# Probing Saturation regime




- HERA (ep) energy range higher, but $G(x,Q^2)$ in the very limited reach of the saturation regime
- eRHIC (eA) will probe deeply into the saturation region

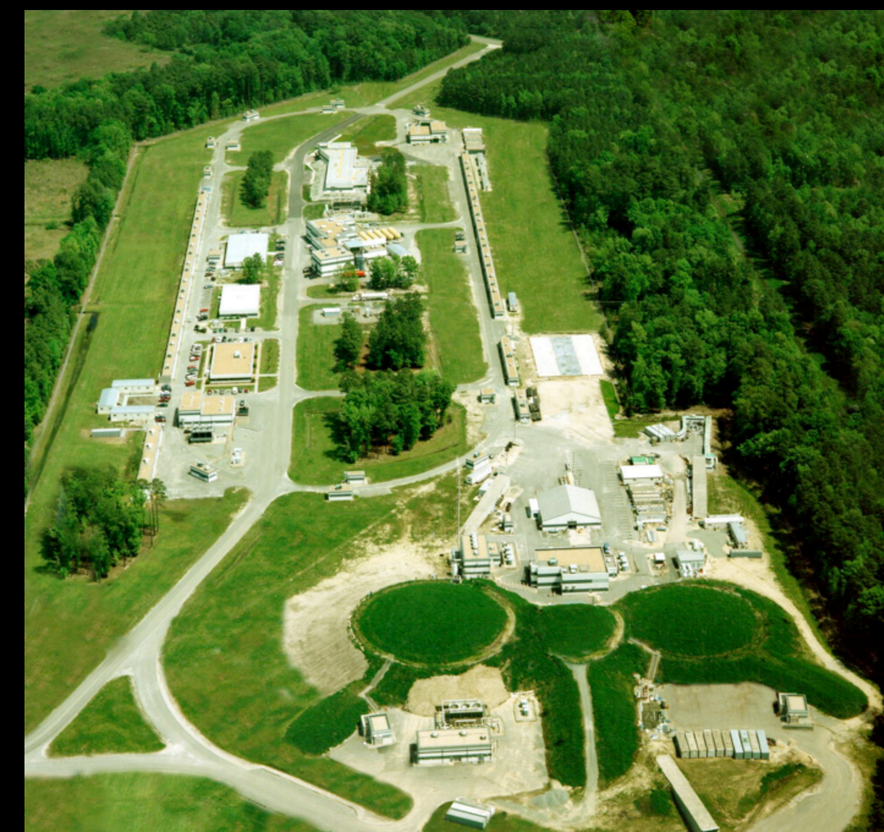
# Two Concepts to Realize an Electron-Ion Collider (EIC)

## eRHIC = RHIC + Electron Ring (ERL)


Stage I: 5+100 GeV/n e+Au
($\sqrt{s}$=45 GeV/n)
Stage II: 30+130 GeV/n e+Au
($\sqrt{s}$=125 GeV/n)

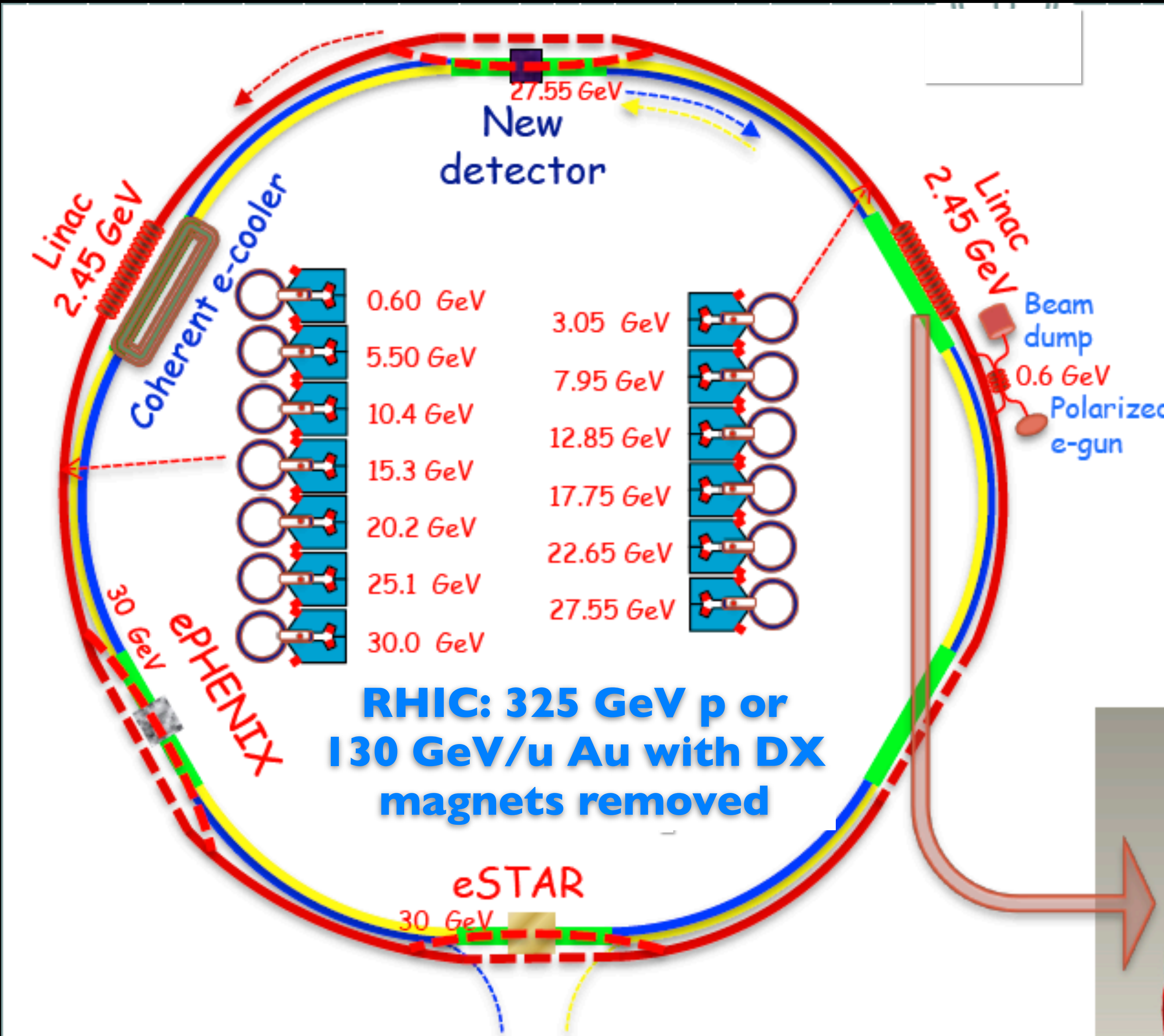
Both designs in 2 stages

## ELIC = CEBAF + Hadron Ring

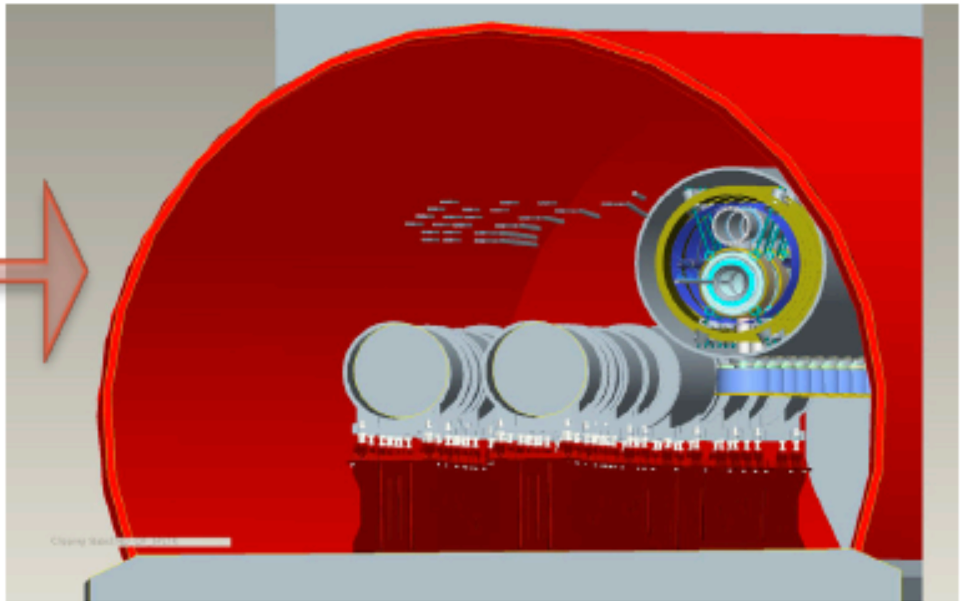


Stage I: 11+40 GeV/n e+Au
($\sqrt{s}$=42 GeV/n)
Stage II: 20+100 GeV/n e+Au
($\sqrt{s}$=89 GeV/n)

# eRHIC Design Under Active Consideration




- **All in-tunnel** approach uses two **energy recovery linacs** and 6 recirculation passes to accelerate the electron beam
- **Staging**: the electron energy will be increased in stages: 5-30 GeV by increasing the linac length



Current design allows for:

- more IP's
- reusing infrastructure + detector components for STAR, PHENIX
- easier upgrade path from 5 GeV eRHIC-I
- minimal environmental impact concerns
- IR design to reach $10^{34}$ luminosity

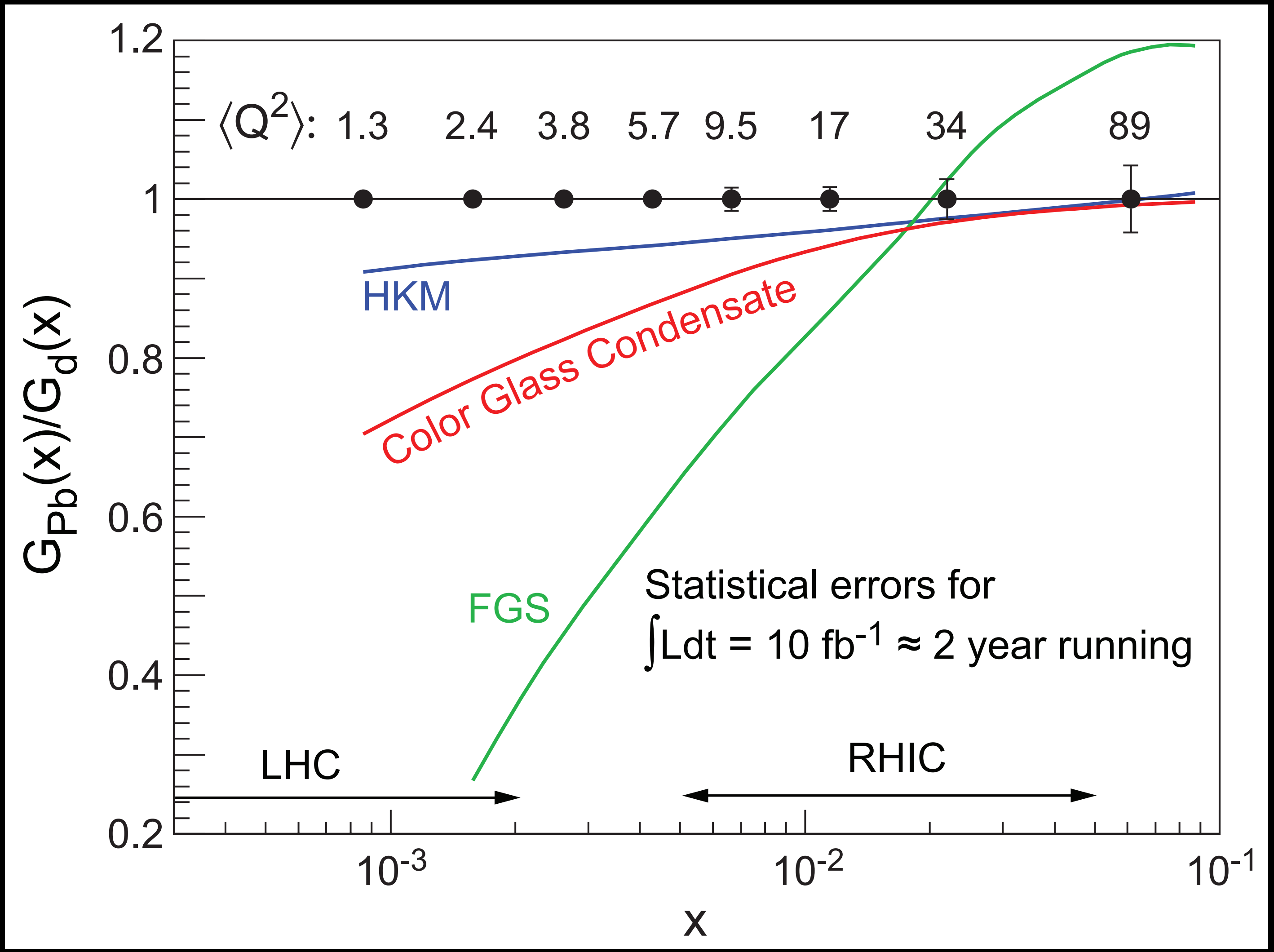
# eRHIC:
# The complete QCD factory

- Versatile $e^{\uparrow}$+A, $e^{\uparrow}$+$p^{\uparrow}$, $p^{\uparrow}$+p,$^{\uparrow}$ A+A (up to U)
- High luminosity: $\mathcal{L}$ (e+p) = $1.5\times10^{34}$ $cm^{-2}s^{-1}$ (HERA $\mathcal{L}$ =$5\times10^{31}$)
- Electron Accelerator
  - Unpolarized and polarized (80%) $e^-$,$e^+$ 5-30 GeV
- RHIC
  - Unpolarized and polarized (70%) protons 50 - 250 (325) GeV
  - Light Ions (d, Si, Cu), Heavy Ions (Au,U) 50-100 (130) GeV/u
  - Polarized light ions ($He^3$)  215 GeV/u

# Key measurements for characterizing glue in matter in high energy electron-Ion collisions

- Precisely mapping momentum and space-time distribution of gluons in nuclei in wide kinematic range including saturation regime through:
  - Inclusive measurements of structure functions ($F_2$,$F_L$): $eA \rightarrow eX$, $eA \rightarrow eX$+gap
  - Semi-inclusive and correlation measurements of final state distributions: $eA \rightarrow e\{\pi, K, \Phi, D, J/\Psi \ldots\}X$
  - Exclusive final states: $eA \rightarrow e\{\rho, \Phi, J/\Psi, \gamma\}A$
- Multiple controls: x, $Q^2$, t, $M_X^2$ for light and heavy nuclei

# Example of the key measurements: Gluon distribution from $F_L$



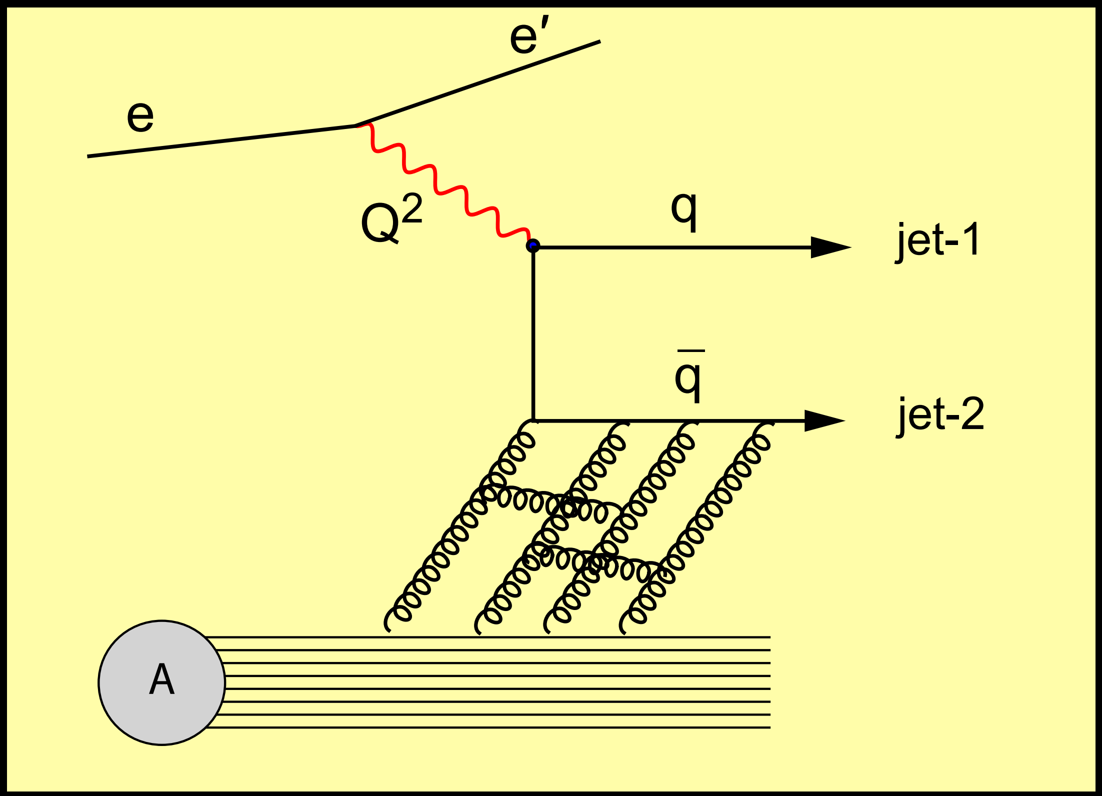

- $F_L \sim \alpha_S G(x,Q^2)$
- Systematic studies of $F_L$ $(A,x,Q^2)$
  - $G(x,Q^2)$ with great precision
  - Distinguish between models
- Utilize wide range of $\sqrt{s}$ of eRHIC

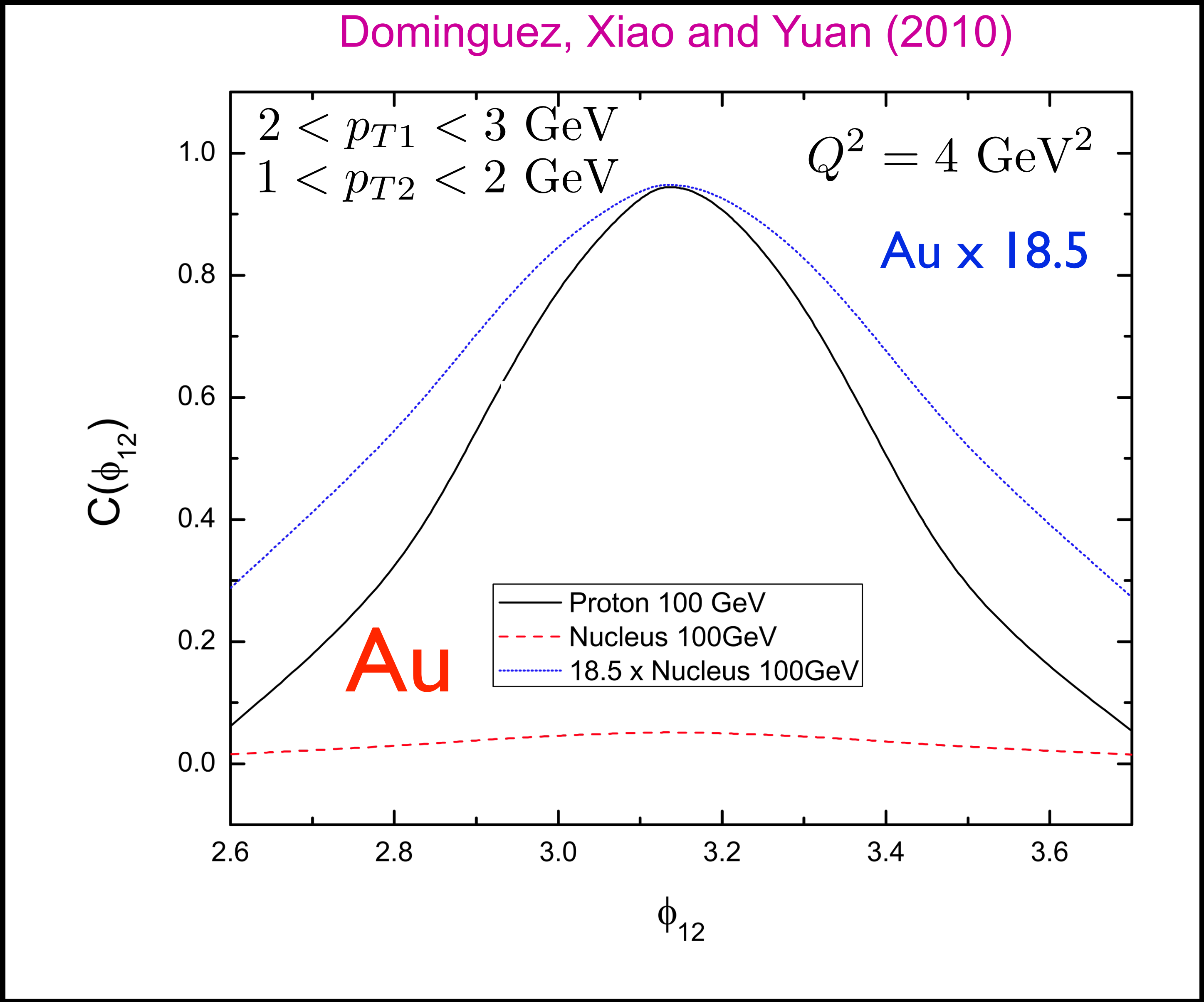
$$\frac{d^2\sigma^{ep\to eX}}{dx dQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2)-\frac{y^2}{2}F_L(x,Q^2)\right]$$

eRHIC: 10 GeV + 100 GeV/n - estimate for 10 fb$^{-1}$

Example of the key measurements:

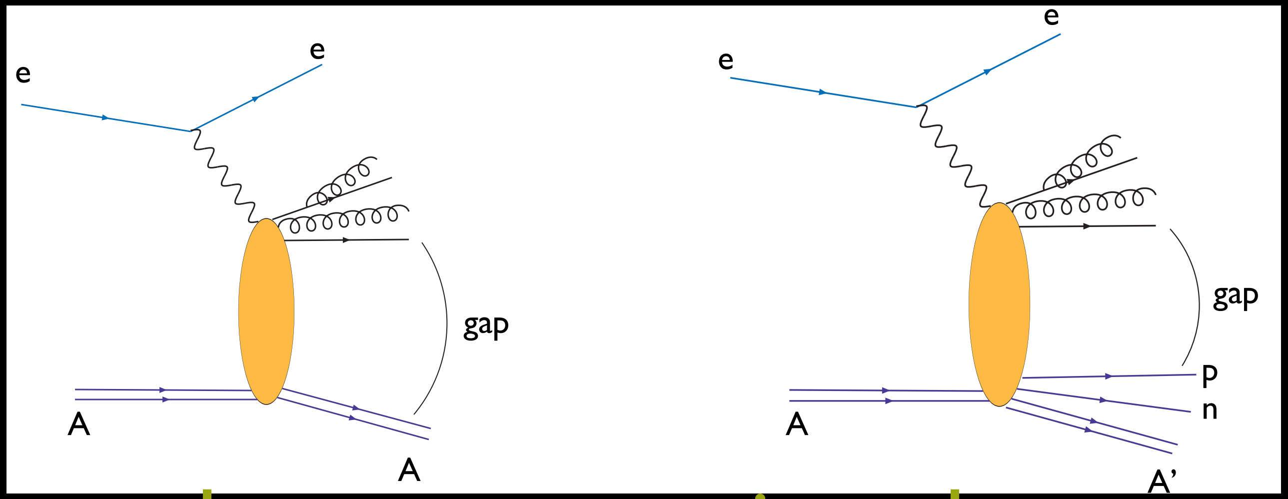
# Imbalance in di-hadron correlations



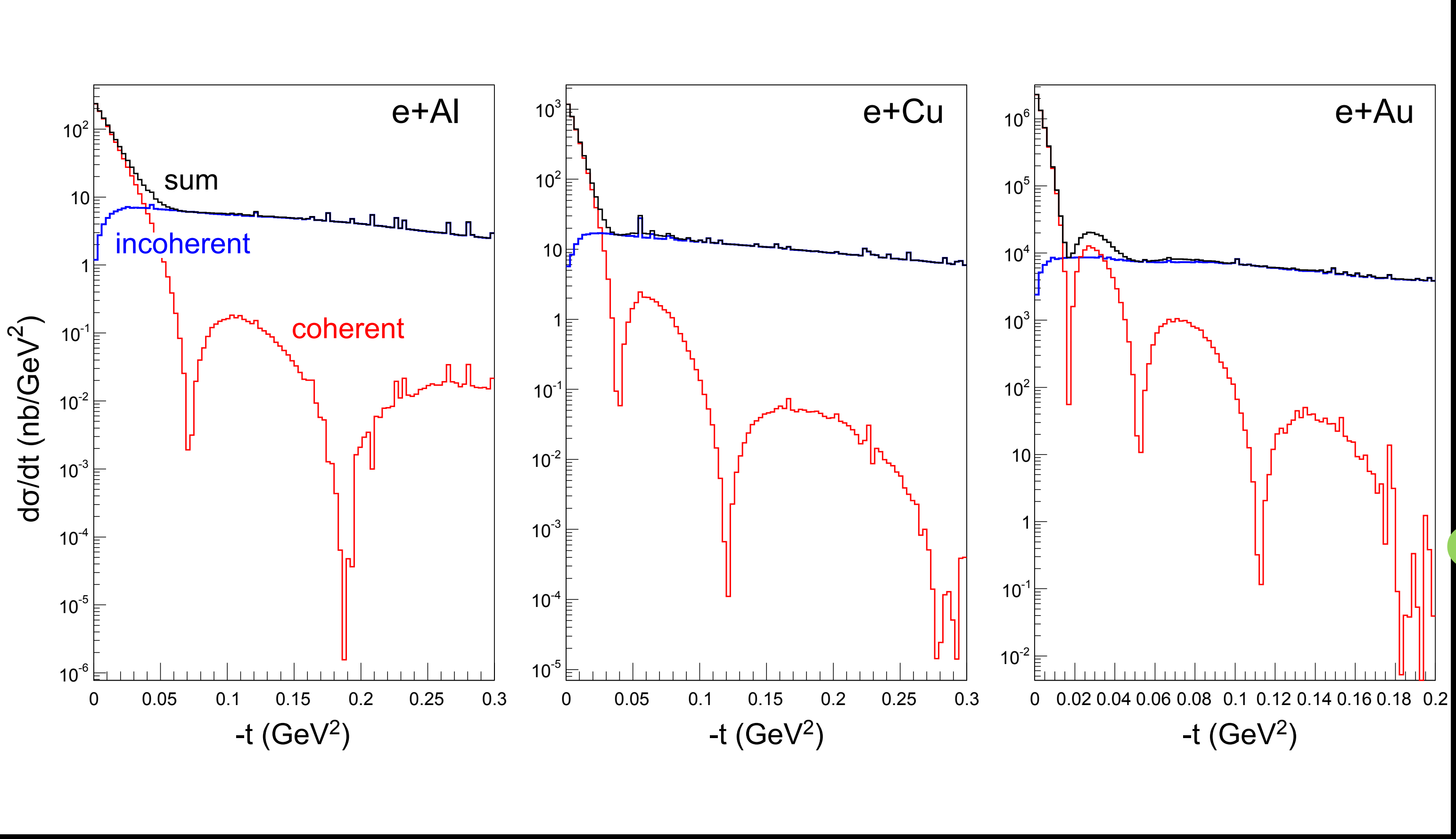




- Suppression of away side peak and increase of width (decorrelation at $\Delta\Phi=\pi$) at large $Q^2$ in eA due to multiple interactions between partons and dense nuclear matter in the CGC frame work

# Example of the key measurements:
# Characterizing saturation regime through exclusive diffractive vector

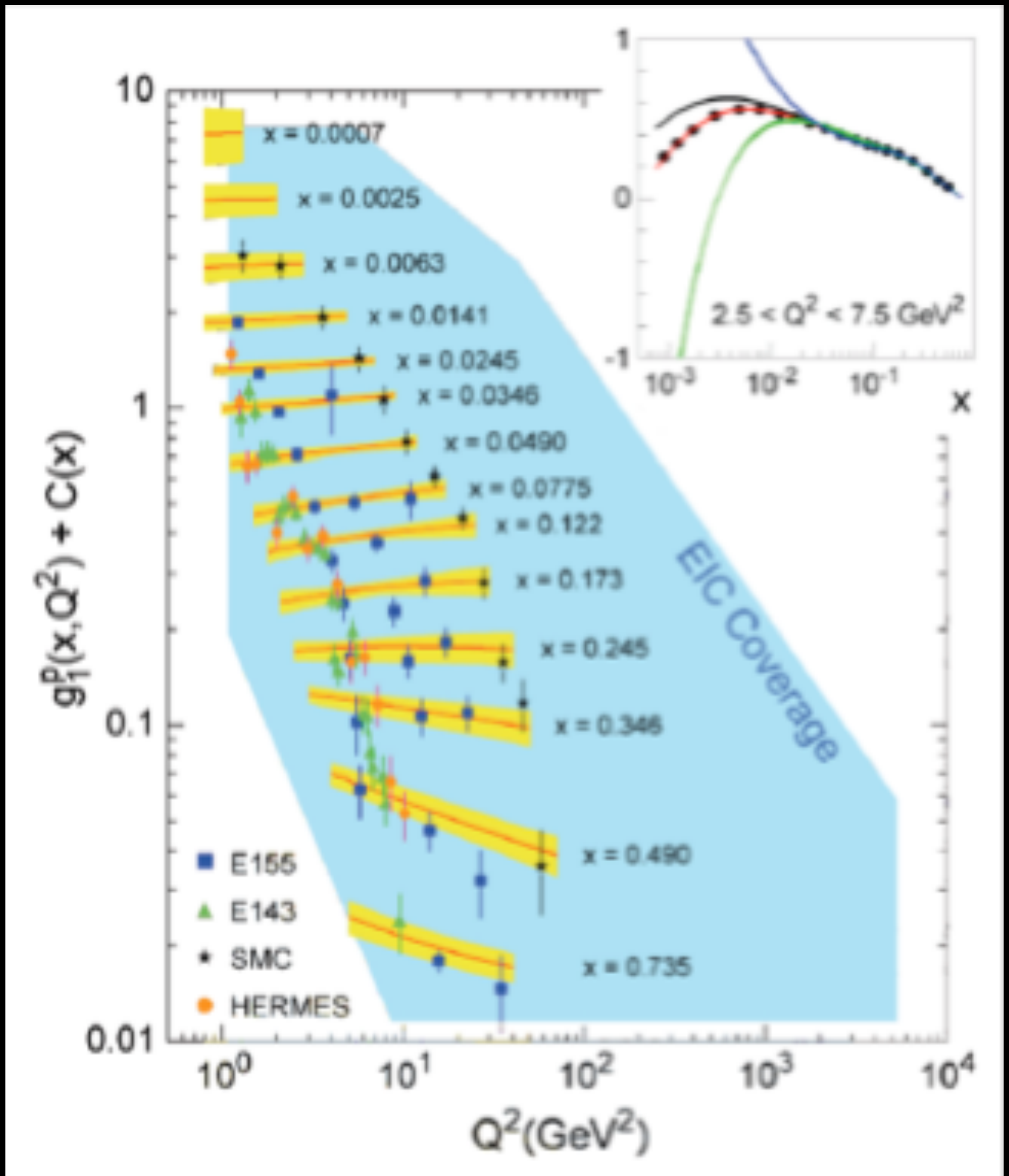



coherent    in-coherent




- eA→e{ρ,Φ,J/Ψ,γ}A
- Novel "strong" probe to investigate gluonic structure of nuclei: color dipole coherent and incoherent diffractive interaction: Sensitive to saturation (√s,b,A)
- Access to spatial distribution of gluons

# polarized e + p at eRHIC:
# Spin and 3d imaging of nucleon

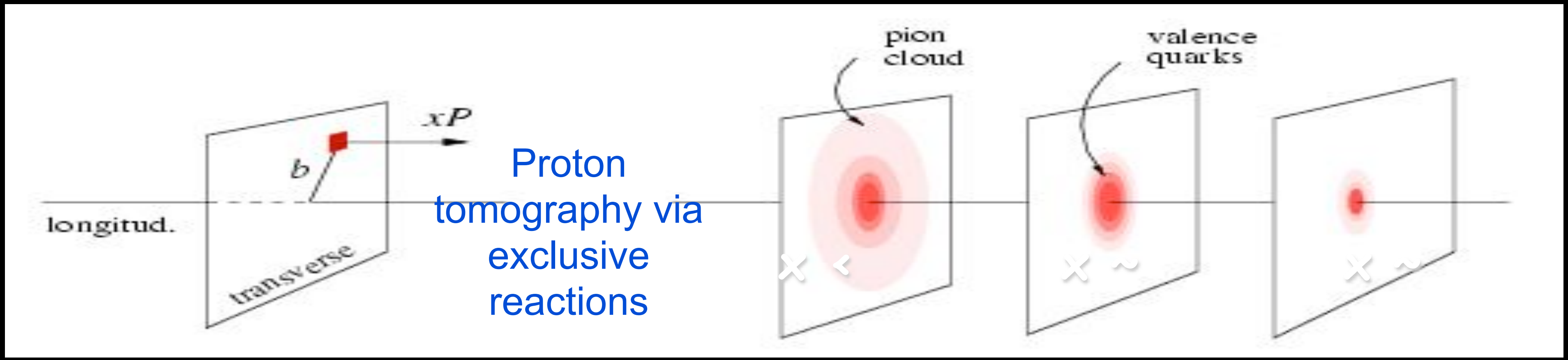



## Important Extension of Nucleon Structure Studies at HERA, RHIC, JLab,…

- DIS, photon-gluon fusion ⇒

Probing gluon spin ΔG at small-x ($x >$ few × $10^{-4}$)

- SIDIS ⇒ Flavor decomposition of sea in broad x range
- DIS at High $Q^2$ ⇒ Electroweak probes of proton spin structure
- Polarized DVCS, exclusive reactions + Lattice QCD ⇒ GPD's ⇒ map low-x transverse position-dependent PDF's



# Summary

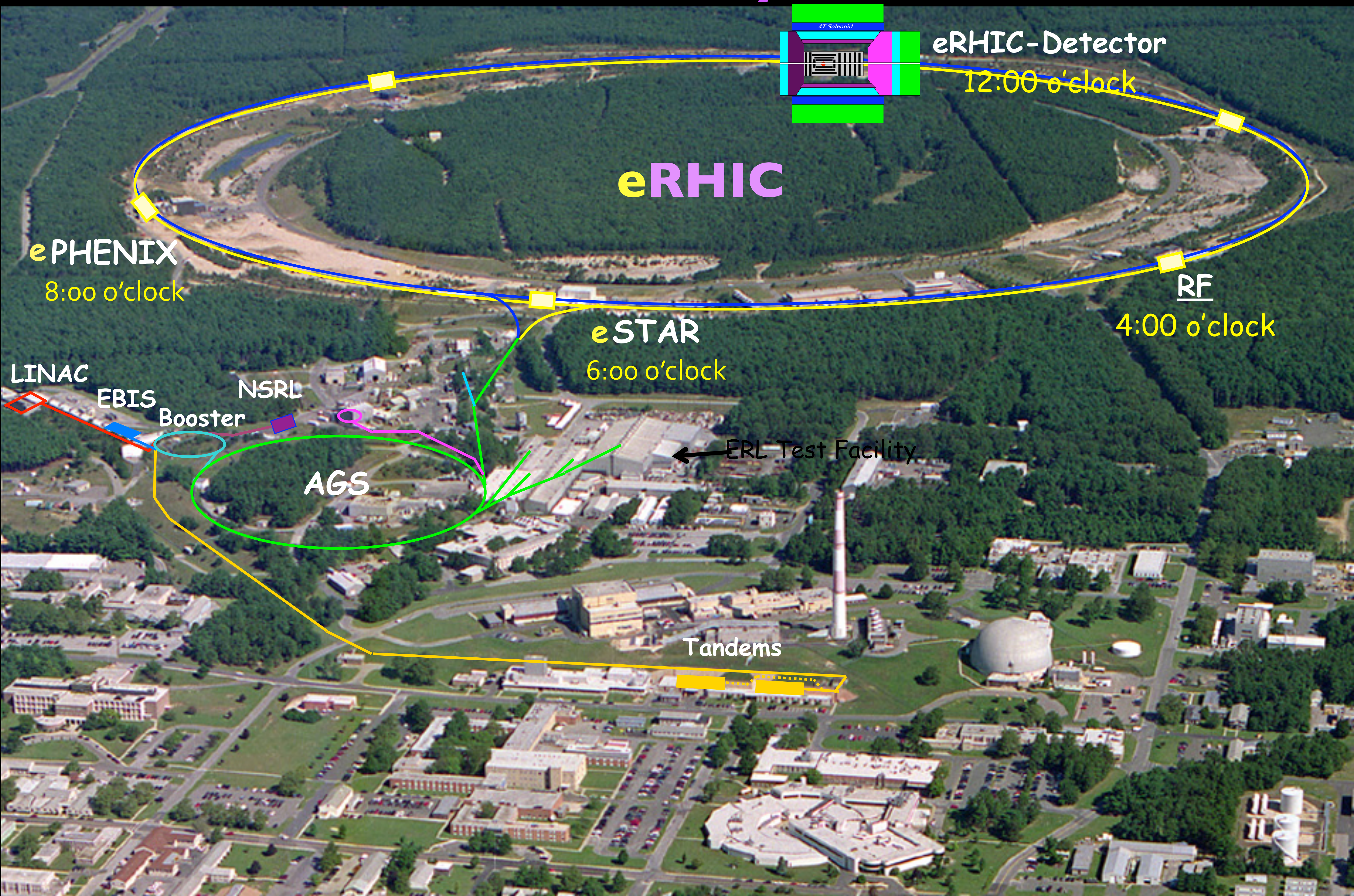
The new proposed versatile and high-luminosity electron-Ion collider (eRHIC) is to study one of the outstanding fundamental questions in QCD:

- Establish and explore new degree of freedom of gluonic property of matter - saturation regime by systematically studying the unprecedentedly accessed kinematic regime.
- Deeply extend the current understanding of nucleon structure: spin and 3d landscape.

# eRHIC: New Opportunities also for Hadron Spectroscopy

- High luminosity (~5 $fb^{-1}$/year)
- Detector and machine designs to accommodate from exclusive photo-production to semi-inclusive DIS over a wide kinematic range with excellent particle reconstruction and PID
- Broad range of reactions and energies with polarization
- Spectroscopy programs being developed: searches for Exotics, heavy quark spectroscopy...
- Join us...

# Thank you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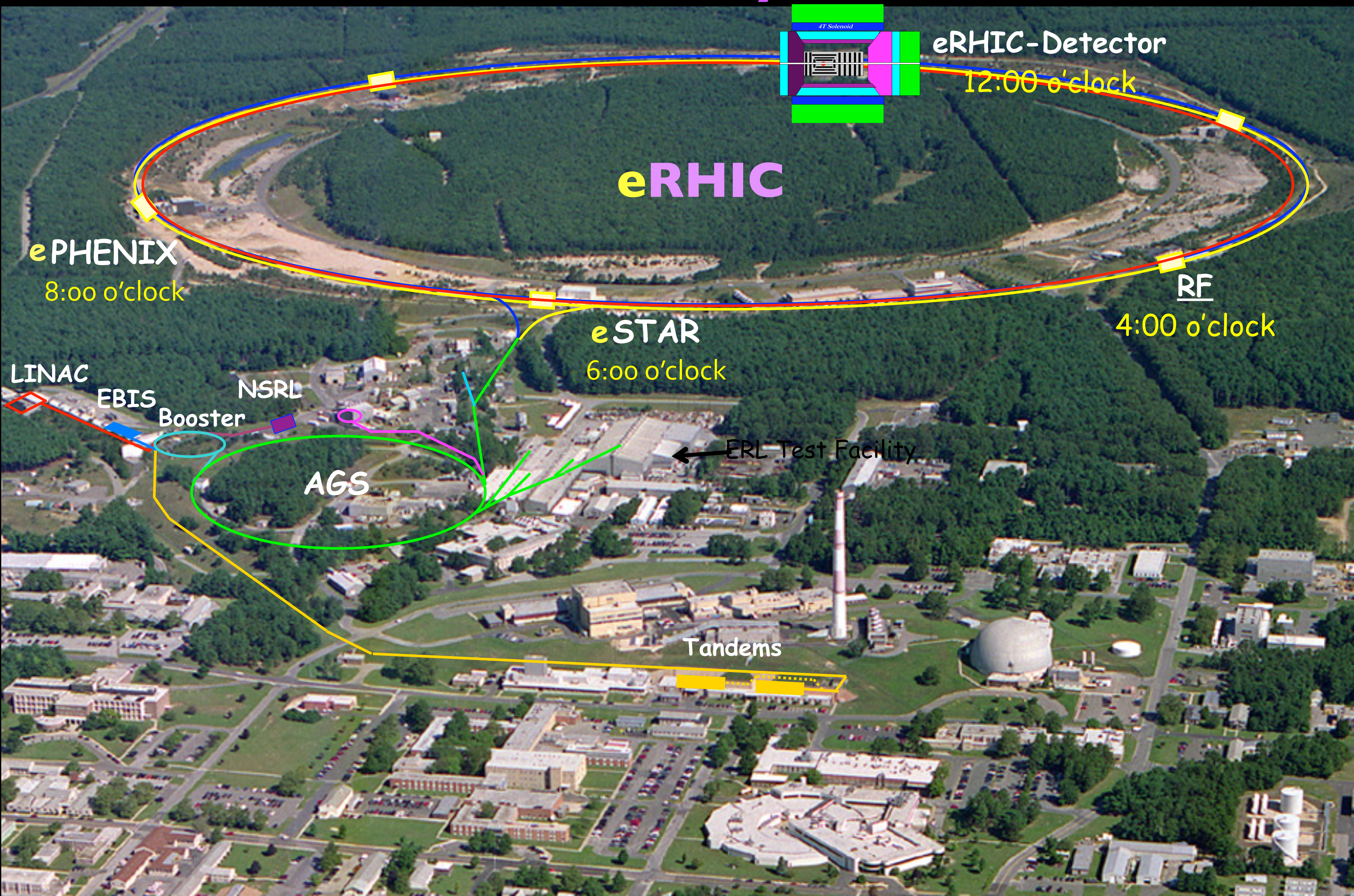
eRHIC-Detector
12:00 o'clock
eRHIC
ePHENIX
8:00 o'clock
RF
4:00 o'clock
eSTAR
6:00 o'clock
LINAC
EBIS
NSRL
Booster
ERL Test Facility
AGS
Tandems

# Thank you



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# Back-up slides

# eA Science Matrix

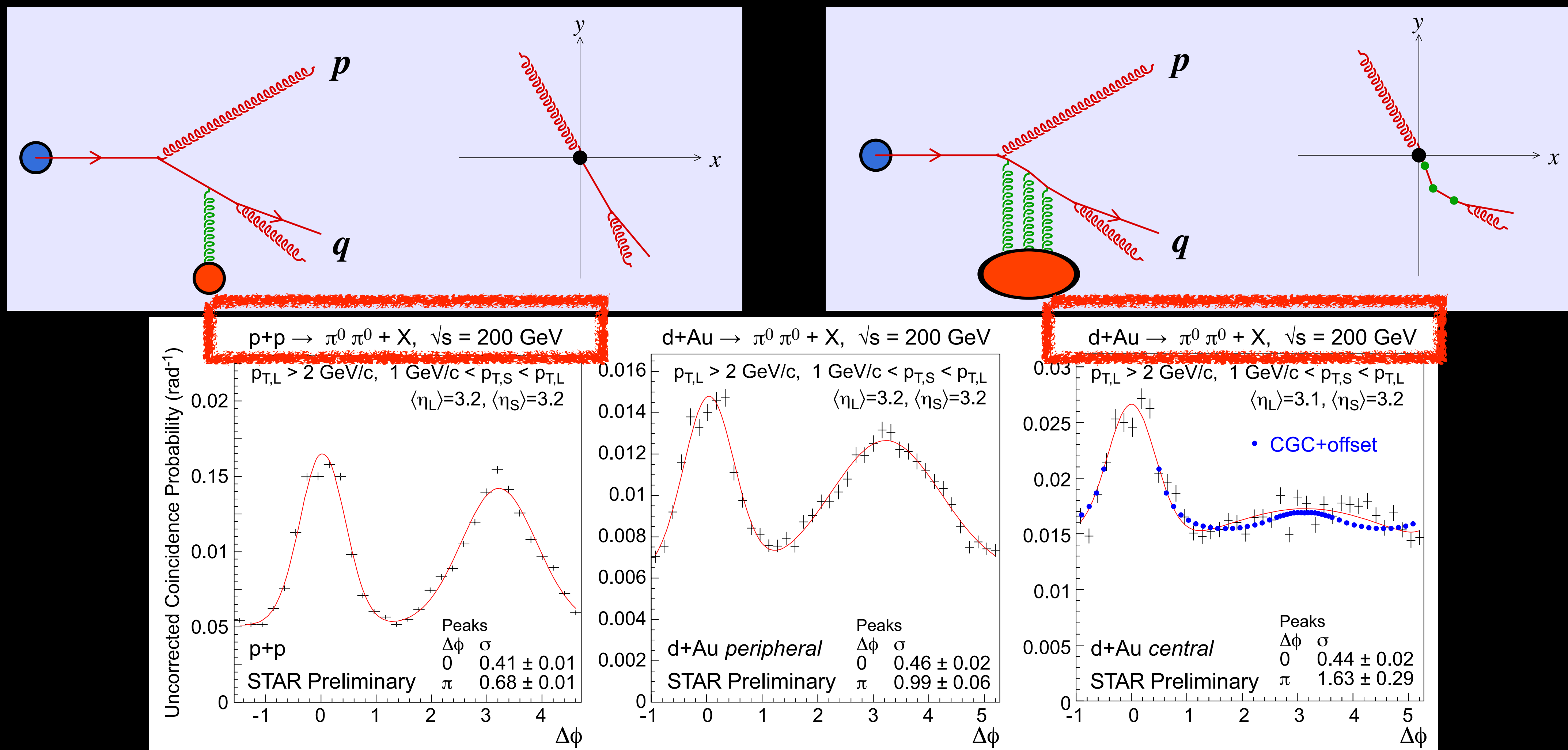
| Primary new science deliverables | What we hope to fundamentally learn | Basic measurements | Typical required precision | Special requirements on accelerator/ detector | What can be done in phase I | Alternatives in absence of an EIC | Gain/Loss compared with other relevant facilities | Comments |
|---|---|---|---|---|---|---|---|---|
| integrated nuclear gluon distribution | The nuclear wave function throughout x-$Q^2$ plane | $F_L$, $F_2$, $F_L^c$, $F_2^c$ | What HERA reached for F2 with combined data | displaced vertex detector for charm | stage 1: large-x & large-$Q^2$<br>need full EIC, for $F_L$ and $F_2^c$ | p+A at LHC (not as precise though) & LHeC | First experiment with good x, $Q^2$ & A range | This is fundamental input for A+A collisions |
| $k_T$ dependence of gluon distribution and correlations | The non-linear QCD evolution - Qs | SIDIS & di-hadron correlations with light and heavy flavours | | Need low-pt particle ID | SIDIS for sure<br>TBD: saturation signal in di-hadron $p_T$ imbalance | 1) p+A at RHIC/LHC, although e+A needed to check universality<br>2) LHeC | Cleaner than p+A: reduced background | |
| b dependence of gluon distribution and correlations | Interplay between small-x evolution and confinement | Diffractive VM production and DVCS, coherent and incoherent parts | 50 MeV resolution on momentum transfer | hermetic detector with 4pi coverage<br>low-t: need to detect nuclear break-up | Moderate x with light and heavy nuclei | LHeC | Never been measured before | Initial conditions for HI collisions –<br>eccentricity fluctuations |

From Fall 2010 INT Workshop

# ep Spin Physics Matrix

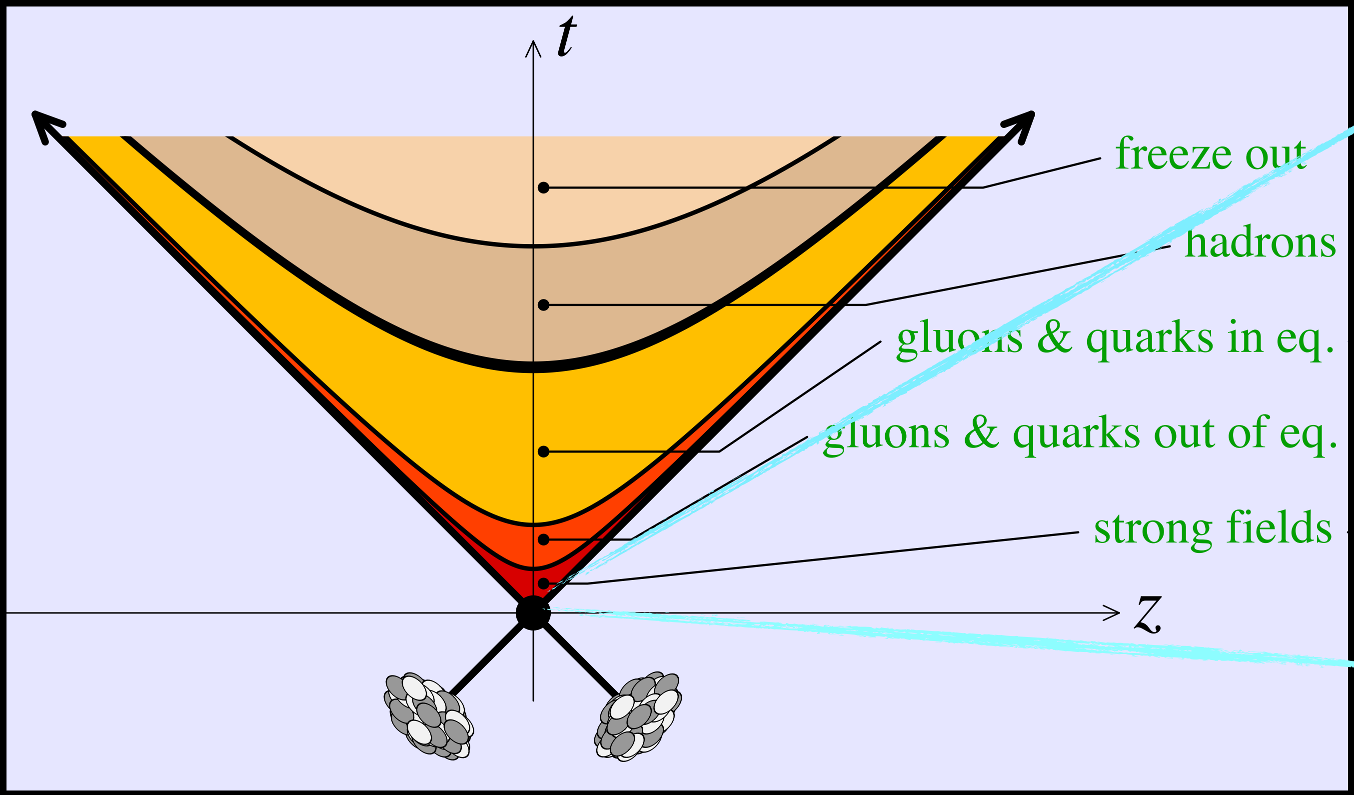
| Science Deliverable | Basic Measurement | Uniqueness and Feasibility | Requirements |
|---|---|---|---|
| spin structure at small x<br>contribution of $\Delta g$, $\Delta\Sigma$ to spin sum rule | inclusive DIS | ✔ | minimal<br>large $x,Q^2$ coverage<br>about $10fb^{-1}$ |
| full flavor separation in large $x,Q^2$ range<br>strangeness, s(x)-s(x) | semi-inclusive DIS | ✔ | very similar to DIS<br>particle ID<br>improved FFs (Belle,LHC) |
| electroweak probes of proton structure<br>flavor separation<br>electroweak parameters | inclusive DIS at high $Q^2$ | ✔<br>some unp. results from HERA | 20x250 to 30x325<br>positron beam<br>polarized $^3$He beam |
| treatment of heavy flavors in pQCD | DIS ($g_1$, $F_2$, and $F_L$) with tagged charm | ✔<br>some results from HERA | large $x,Q^2$ coverage<br>charm tag |
| (un)polarized γ PDFs<br>relevant for γγ physics at an ILC | photoproduction of inclusive hadrons, charm, jets | ✔<br>unp. not completely unknown | tag low $Q^2$ events<br>about 10 $fb^{-1}$ |

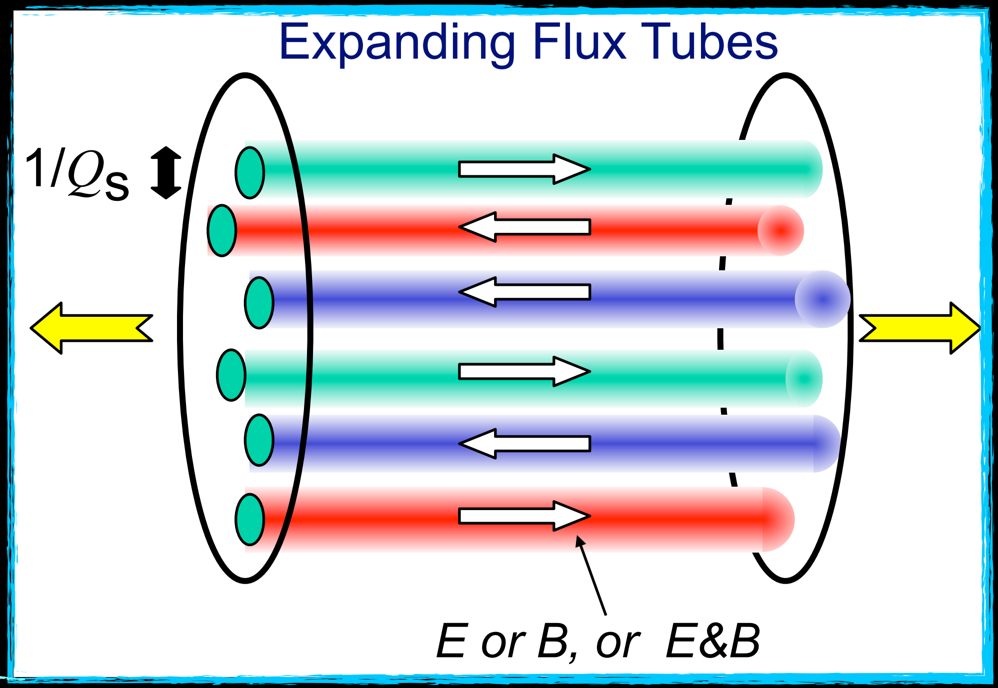
# Saturation at RHIC




- Multiple scattering in the dense nucleus at forward in dAu lead to mono-jet (decorrelation at $\Delta\Phi=\pi$) in CGC frame work ( J. Albacete and C. Marquet, to appear in PRL 2010)
- Estimated $x_A \sim 10^{-3}$

# Implication on understanding initial dynamics at RHIC




- Shattering CGC sheets provides the initial conditions for QGP evolution: "Glasma"
- Considerable success describing
  - Rapid thermalization
  - Long range rapidity correlation (ridge at RHIC and CMS)