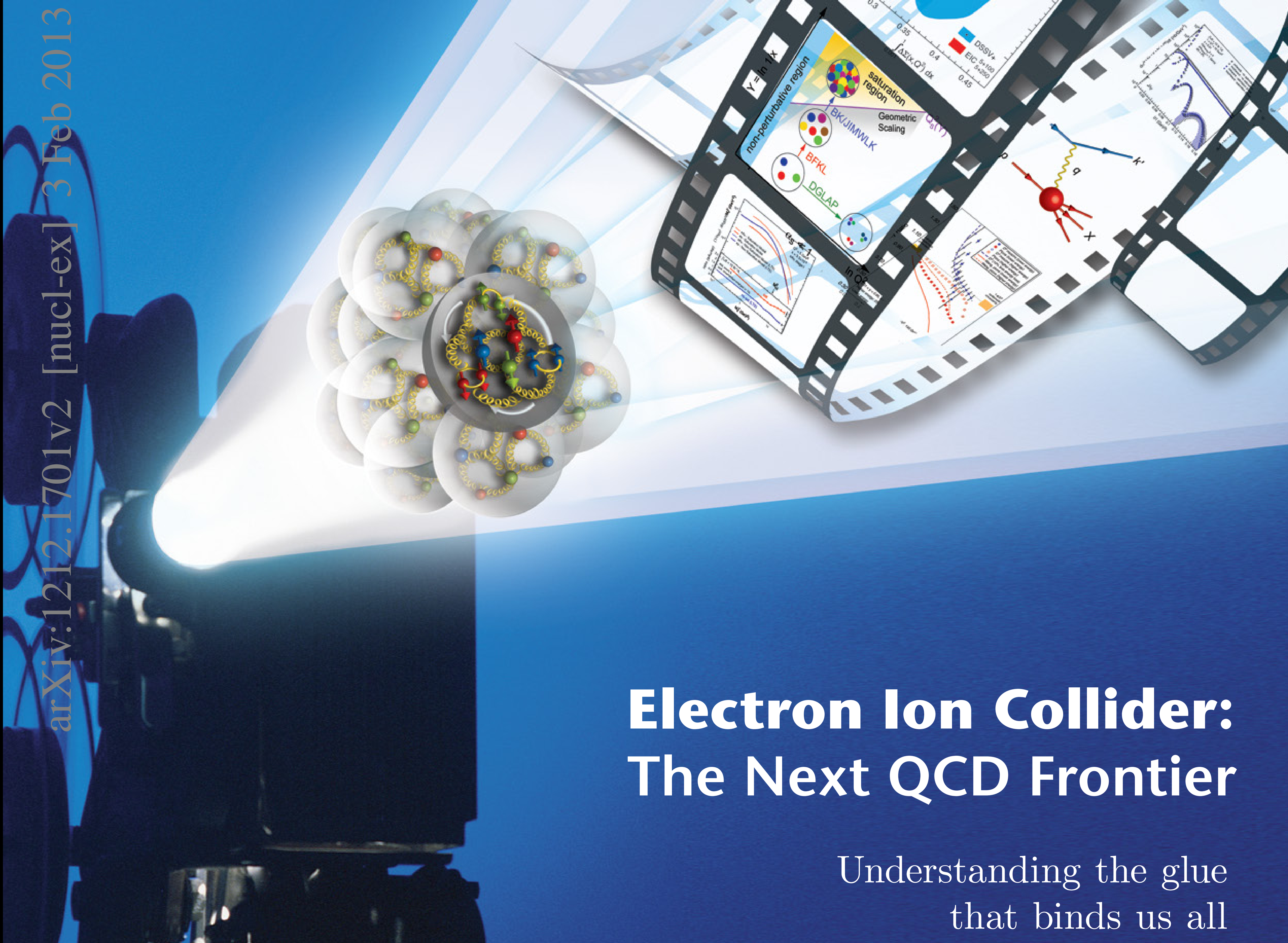
Electron-Ion Collider

J.H. Lee
Brookhaven National Laboratory

Electron Ion Collider: The Next QCD Frontier

Understanding the glue
that binds us all



and that sets the initial stages of high energy nucl. coll.

Most Compelling EIC SCIENCE Questions

How are the gluons and sea-quarks, and their spins, distributed in space and momentum inside the nucleon?

- How are these **quark and gluon distributions correlated** with the over all nucleon properties, such as **spin** direction?
- What is the role of the **motion of sea quarks and gluons** in building the nucleon spin?

Where does the saturation of gluon densities set in?

- Is there a simple **boundary** that separates the region from the 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?

How does the nuclear environment affect the distribution of quarks and gluons and their interaction in nuclei?

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

Electron-Ion Collider

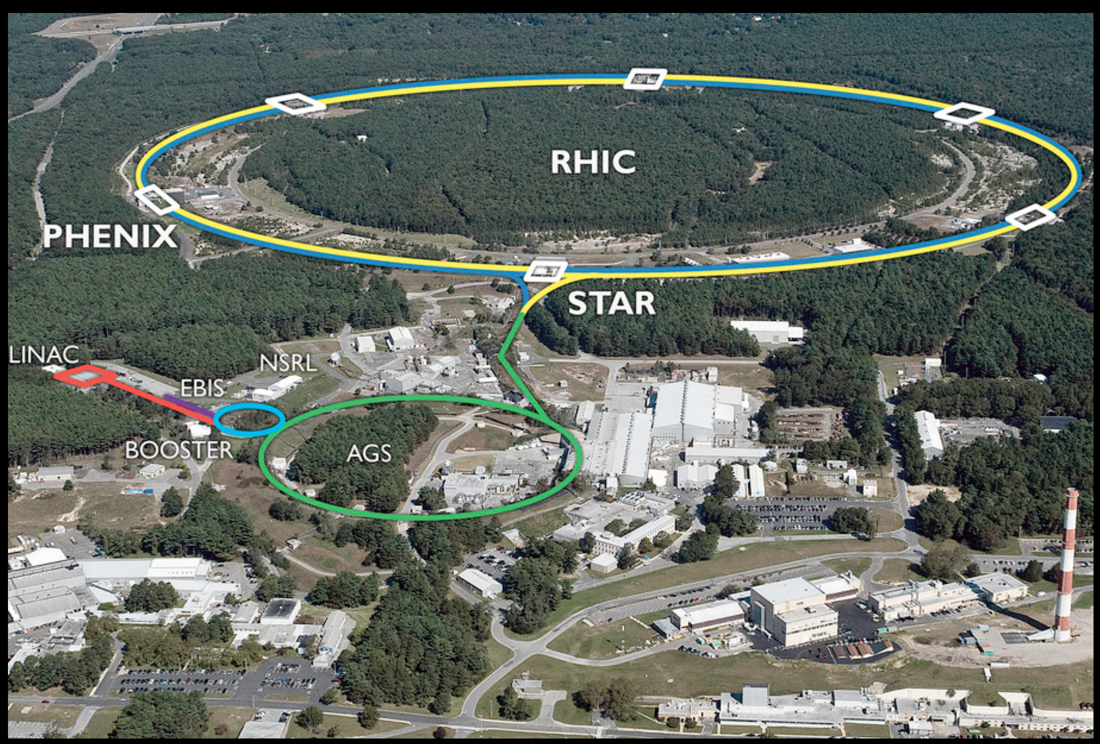
- **An ultimate machine to provide answers to these fundamental QCD questions:**
  - Collider ⇛ kinematic reach into the gluon-dominated regime
  - Electron beam ⇛ precision of the EM interaction as a probe
  - Polarized electron and nucleon beams ⇛ determine the correlations of sea quark and gluon distributions with the nucleon spin
  - Heavy ion beams ⇛ access to the regime of saturated gluon densities, and offer a precise dial in the study of propagation-length for color charges in nuclear matter

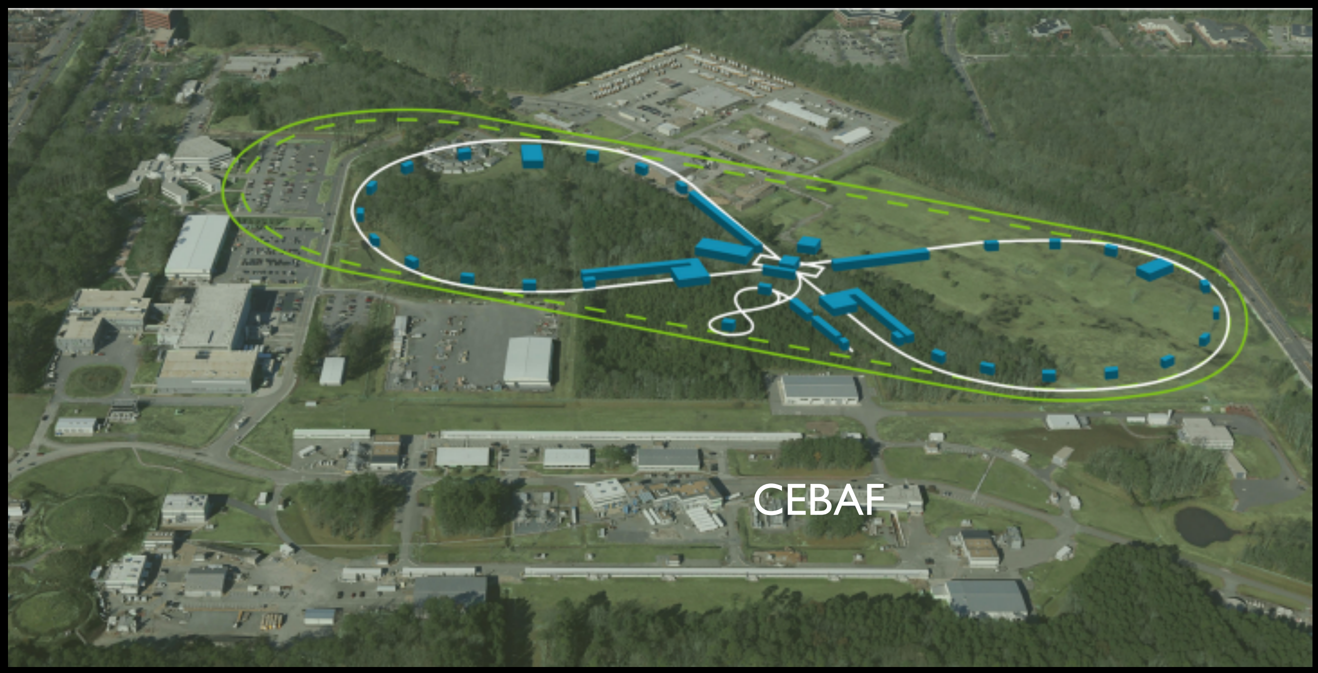
- A machine with high-luminosity polarized electron and proton beams, combined with versatile kinematics and beam species

Two concepts for an EIC in the US

- **eRHIC** at BNL
- RHIC + new electron machine

- **JLEIC** at JLab
- CEBAF + new hadron machine

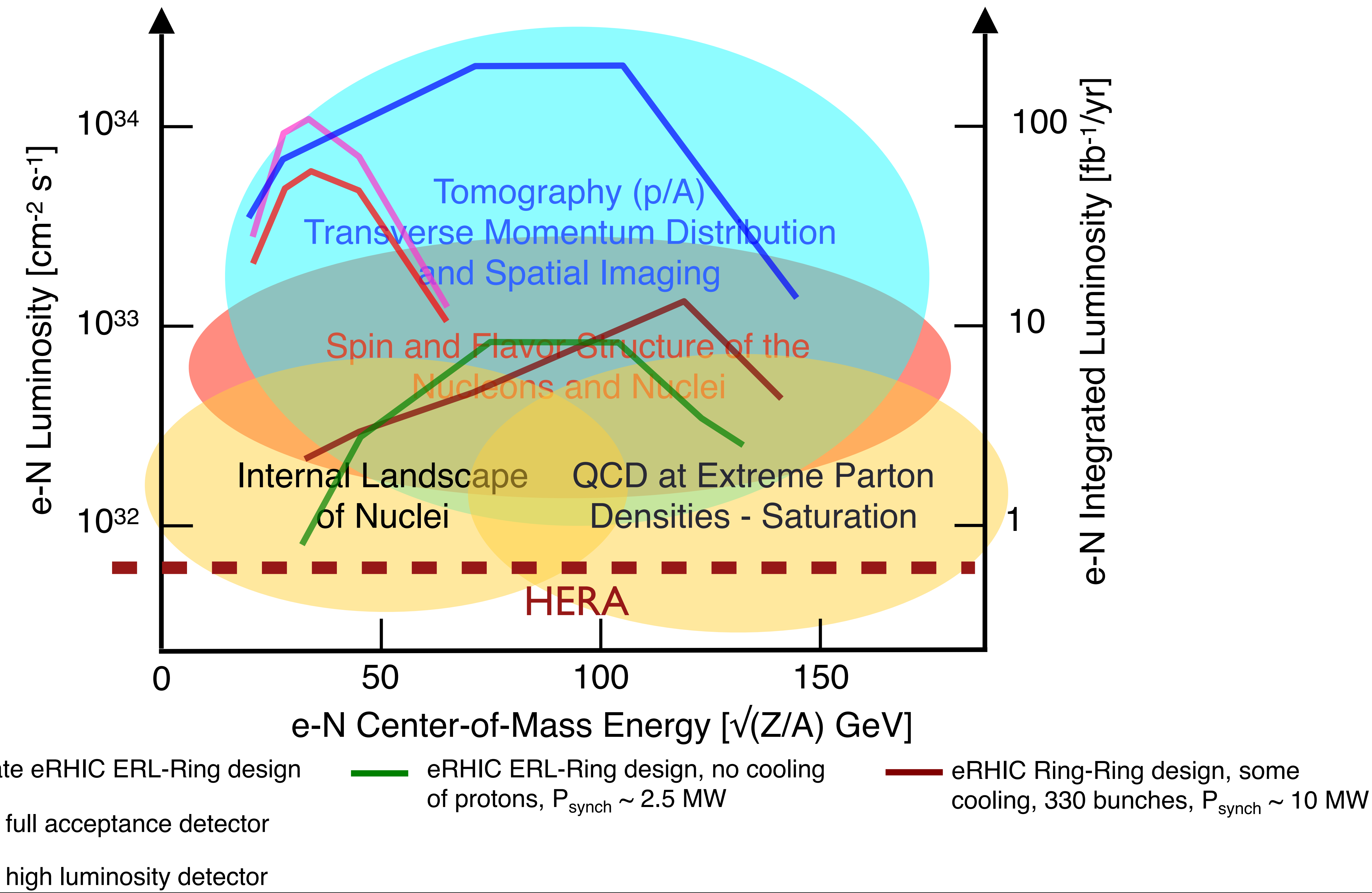




- Maximum utilization of past and current investment
- US Nuclear Science Advisory Committee recommendation (2015): "highest priority for new facility construction"

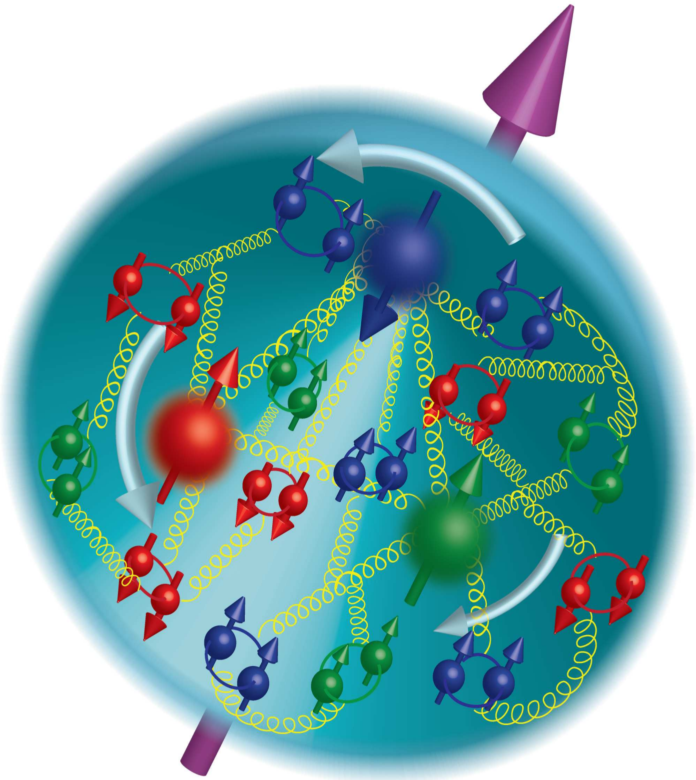
EIC: Luminosity vs energy

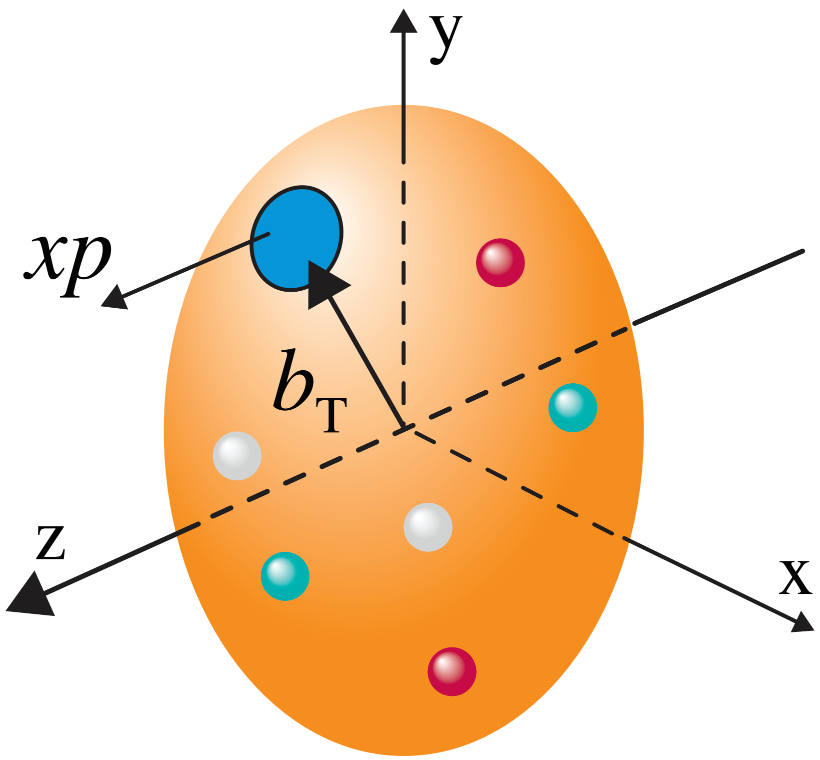
Science case areas indicate the range of peak luminosities with which a statistically significant result can be achieved in about one year (10^7 sec) of running.



Key Measurements :

Spin and three dimensional imaging of nucleon





with inclusive, semi-inclusive, exclusive
DIS and diffraction in ep

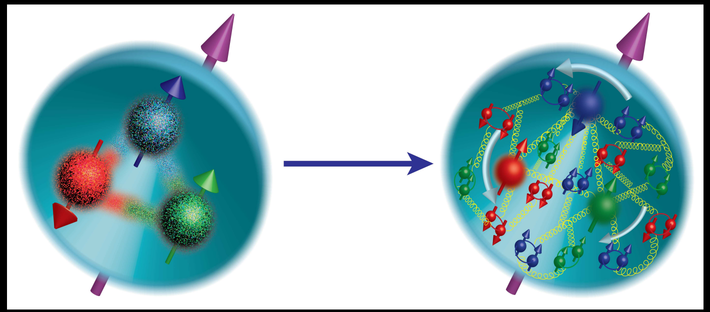
Puzzles: spin of nucleon

- Nucleon Spin: sum of quark, gluon spin and orbital angular momentum

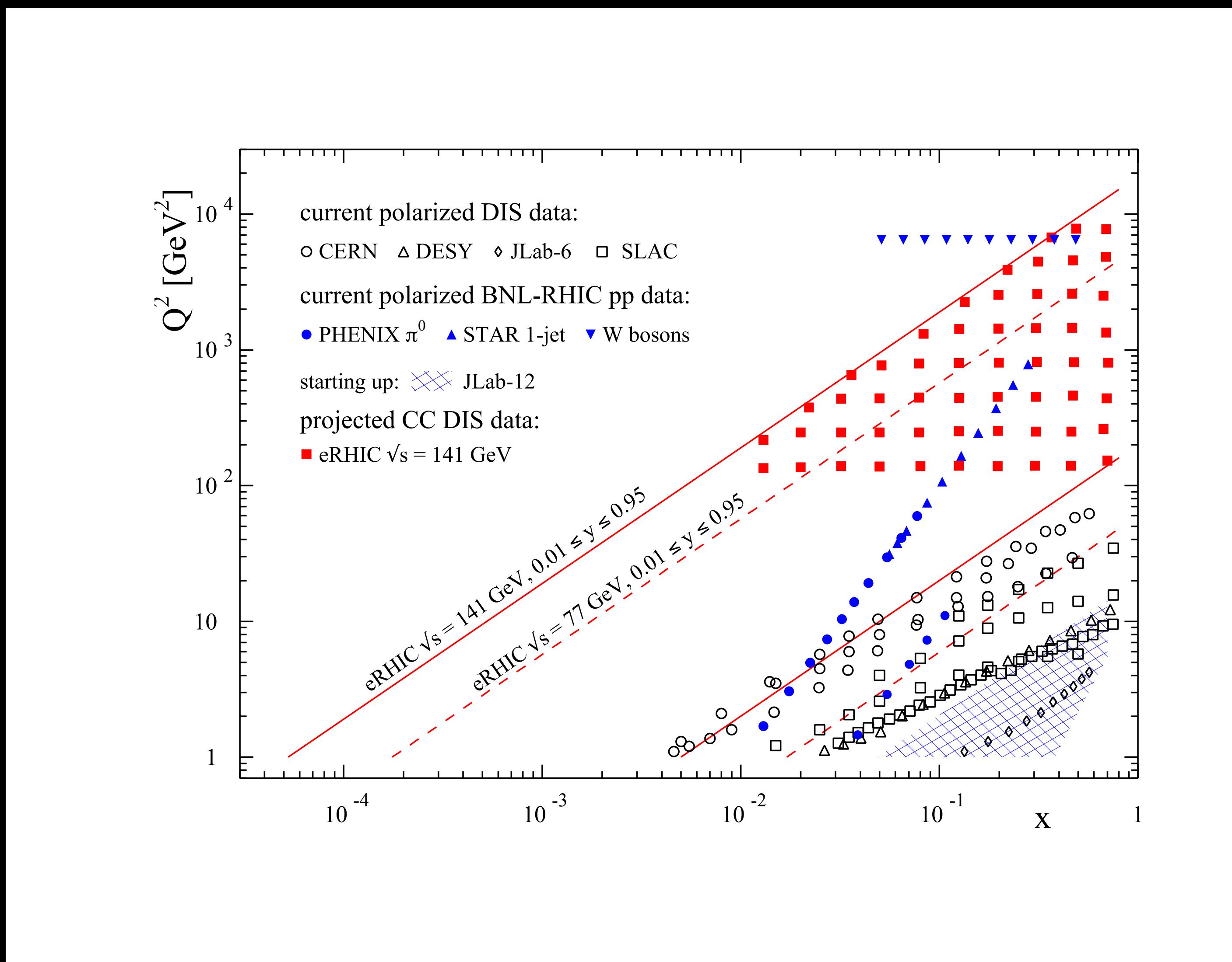
quarks gluons

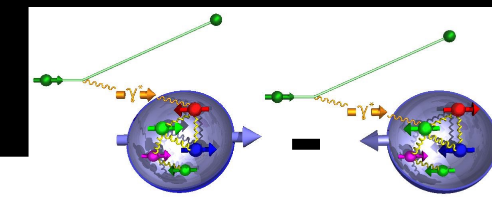
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g \qquad \Delta F = \int_0^1 \Delta f(x)dx$$

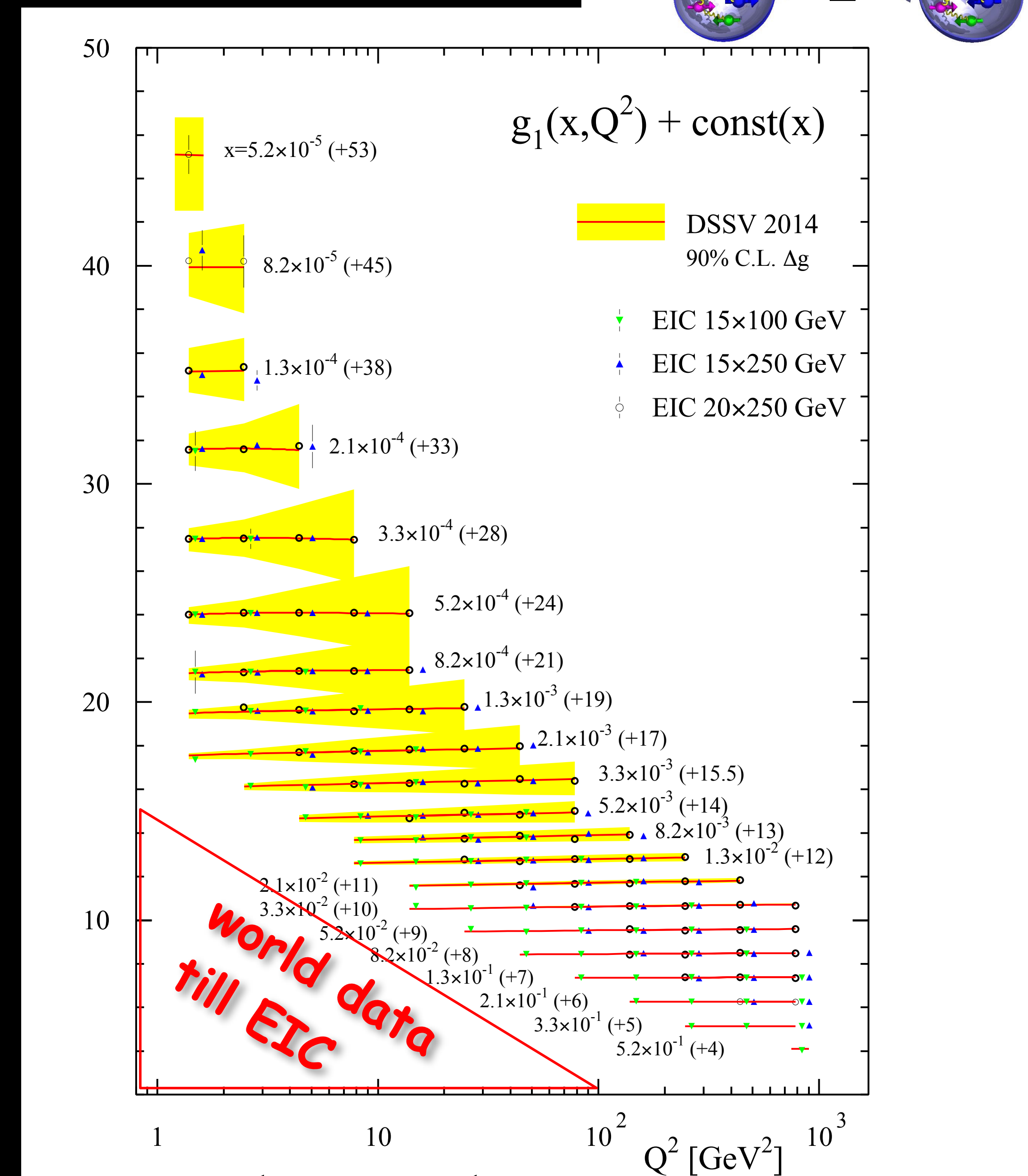
- Quarks ($\Delta\Sigma$) carry ~30% of proton spin (EMC collaboration 1987)
- **Where is the "missing" spin?**
  - gluon contribution in the limited measured range (latest RHIC data) ~20%
- Spin is the interplay between the intrinsic properties and interaction of quarks and gluons



Polarized inclusive DIS







$$\Delta\Sigma(Q^2) = \int_0^1 g_1(x,Q^2)\,dx = \int_0^1 \Delta q_f(x,Q^2)\,dx \rightarrow \text{quark contr.}$$

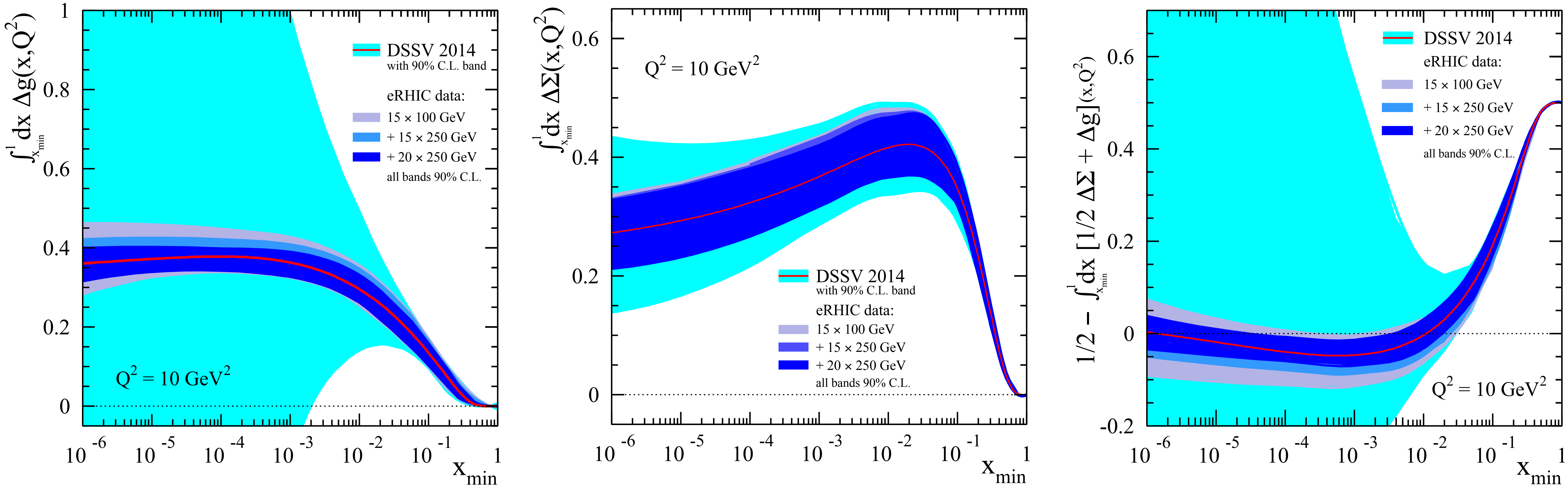
$$\frac{dg_1}{d\log(Q^2)} \sim -\Delta g(x,Q^2) \rightarrow \text{gluon contr.}$$

- Reaching low x ⇒ get into the region where gluons and sea quarks dominate
- Cover wide Q^2 range for each x ⇒ study "scaling violations" ⇒ gluon density
- Access to large Q^2 (at medium-to-large x) ⇒ access to electroweak effects

spin puzzle: will be solved

EIC

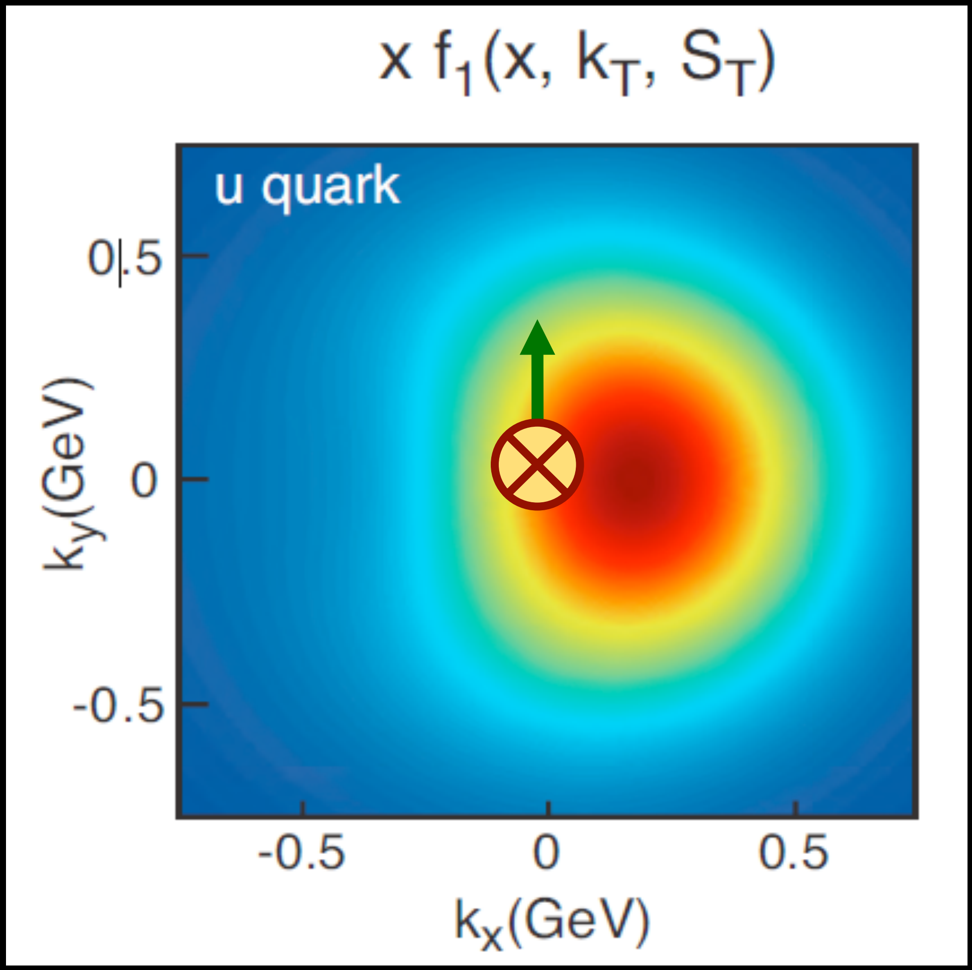
- 15 x 100 GeV (10 fb^{-1} x_{min} = 2.04 10^{-4})
- 15 x 100 + 15 x 250 GeV (10 fb^{-1} x_{min} = 8.15 10^{-5})
- 15 x 100 + 15 x 250 + 20 x 250 GeV (10 fb^{-1} x_{min} = 5.14 10^{-5})



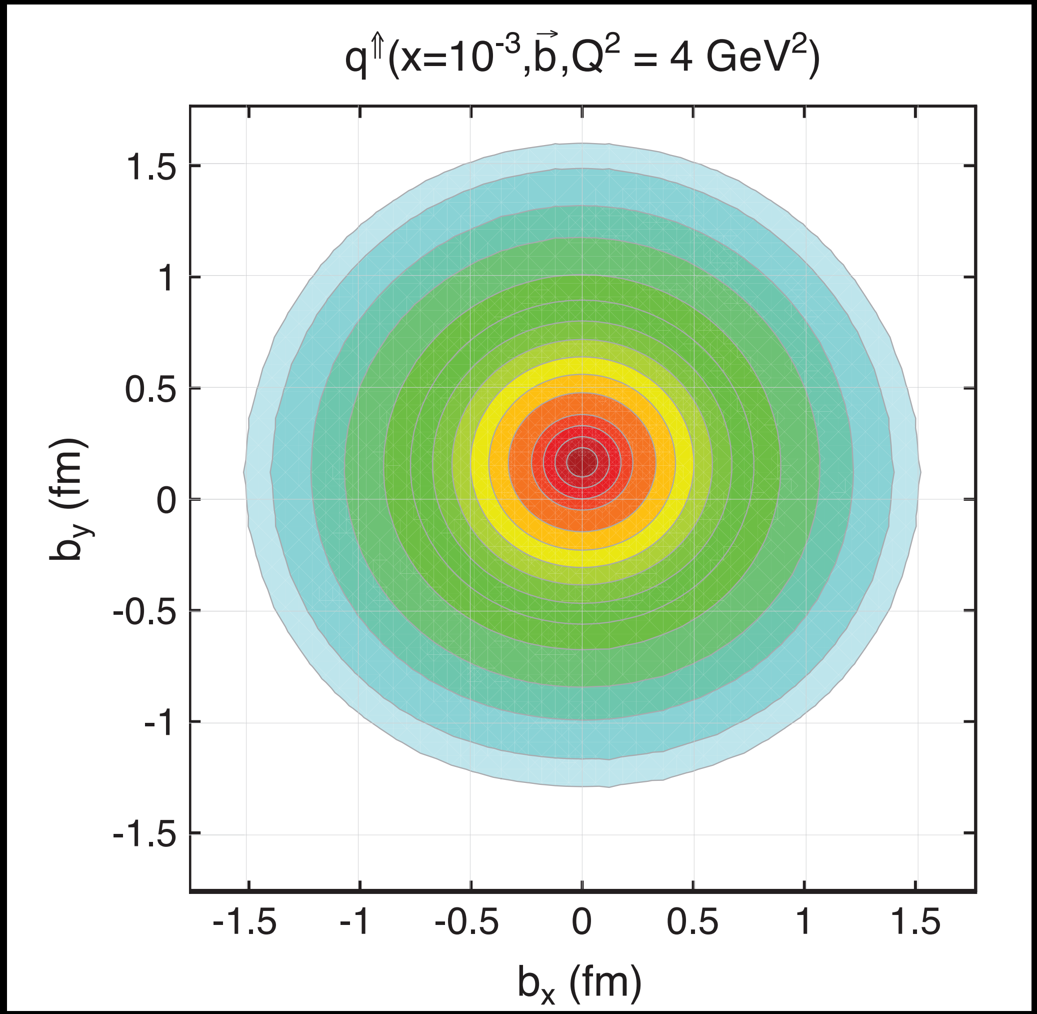
1/2 - Gluon - Quarks = orbital angular momentum

3D imaging of sea and gluons

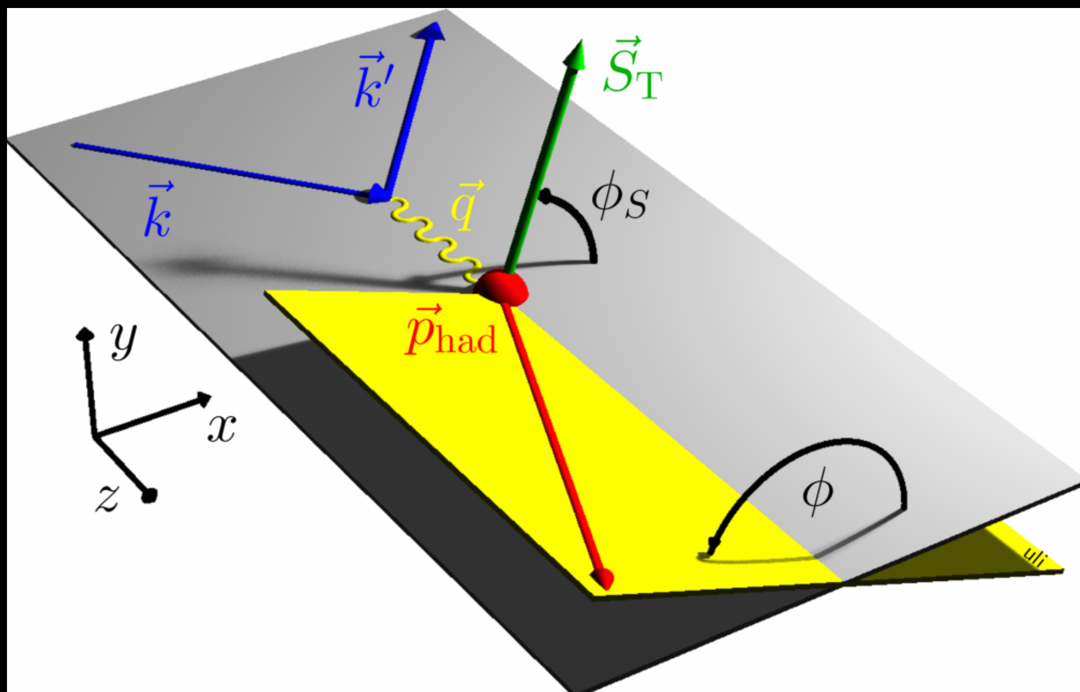
- **Transverse Momentum Dependent** parton distributions (TMDs)
  - confined motion in a nucleon (semi-inclusive DIS)
  - 2+1D picture in momentum space (k_T)

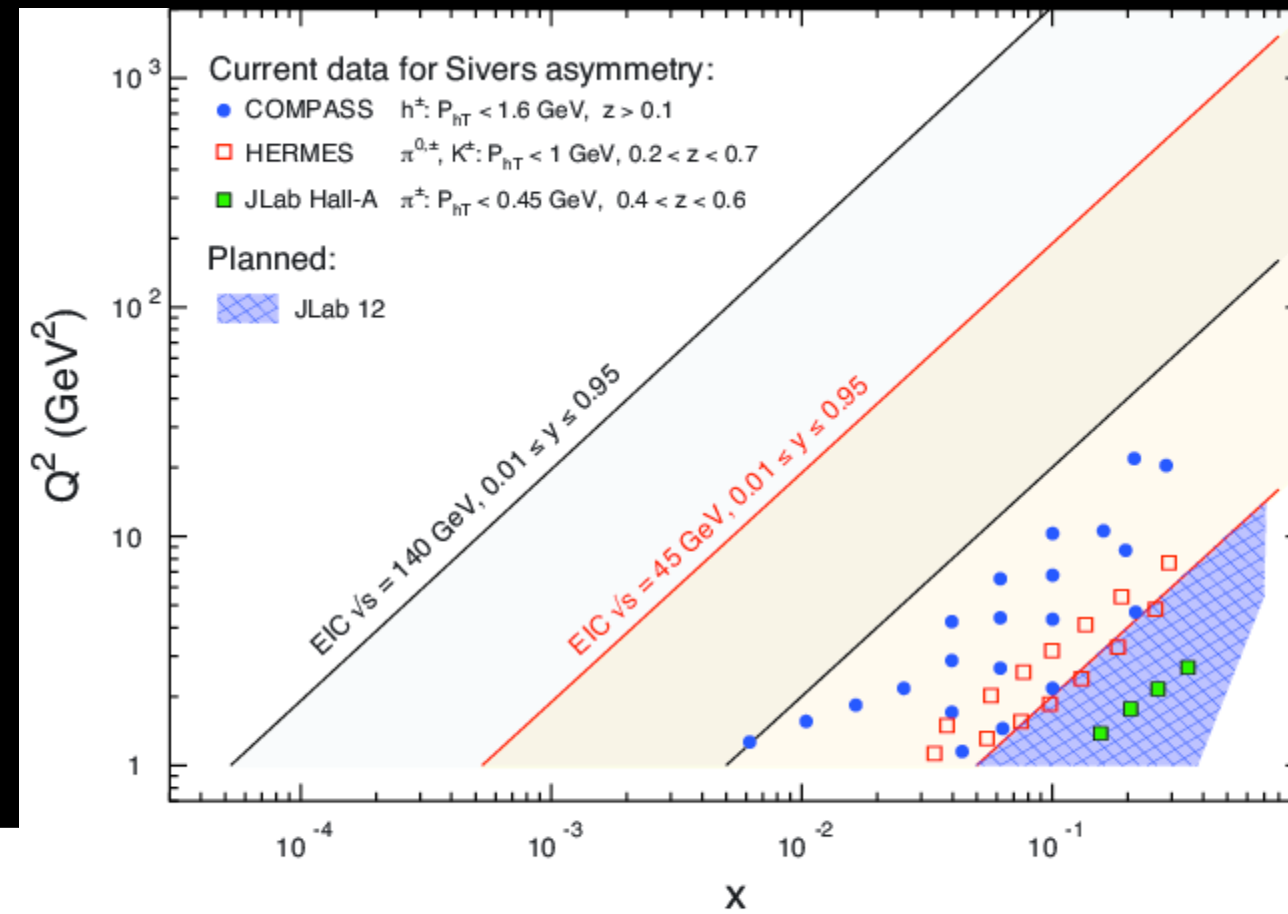


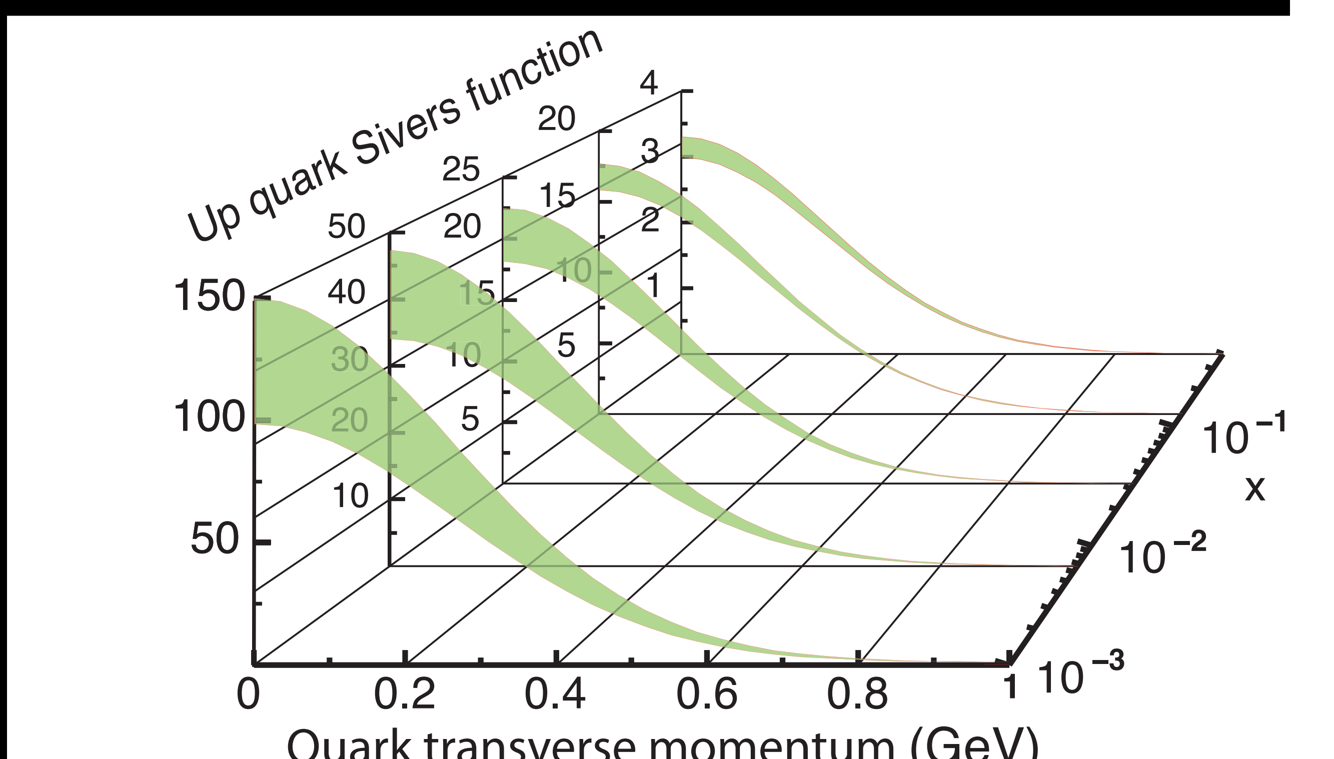
- **Generalized Parton Distributions** (GPDs)
  - Spatial imaging of quarks and gluons (exclusive DIS)
  - 2+1D picture in impact parameter space (b)



TMD measured in semi-inclusive DIS



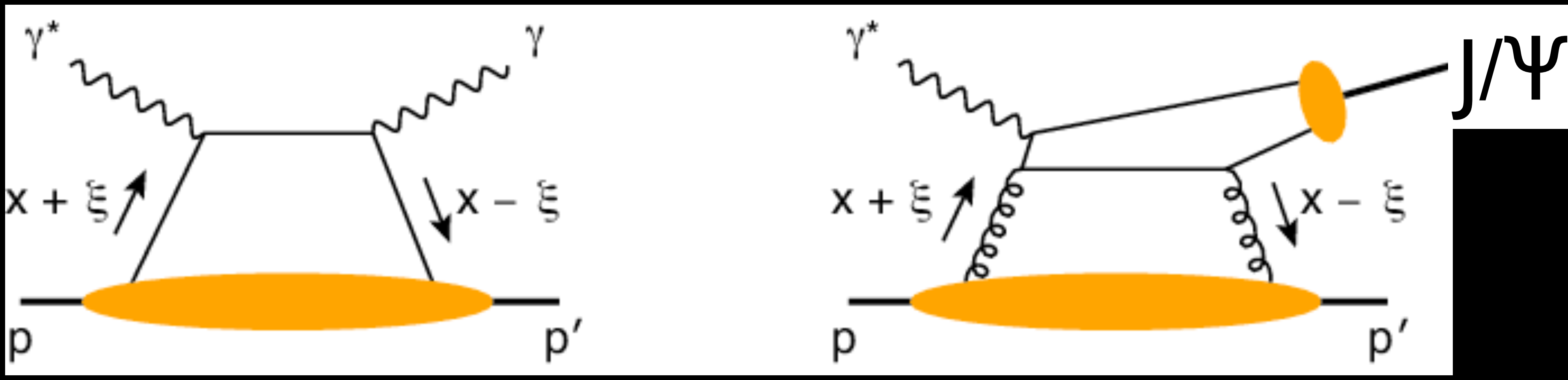


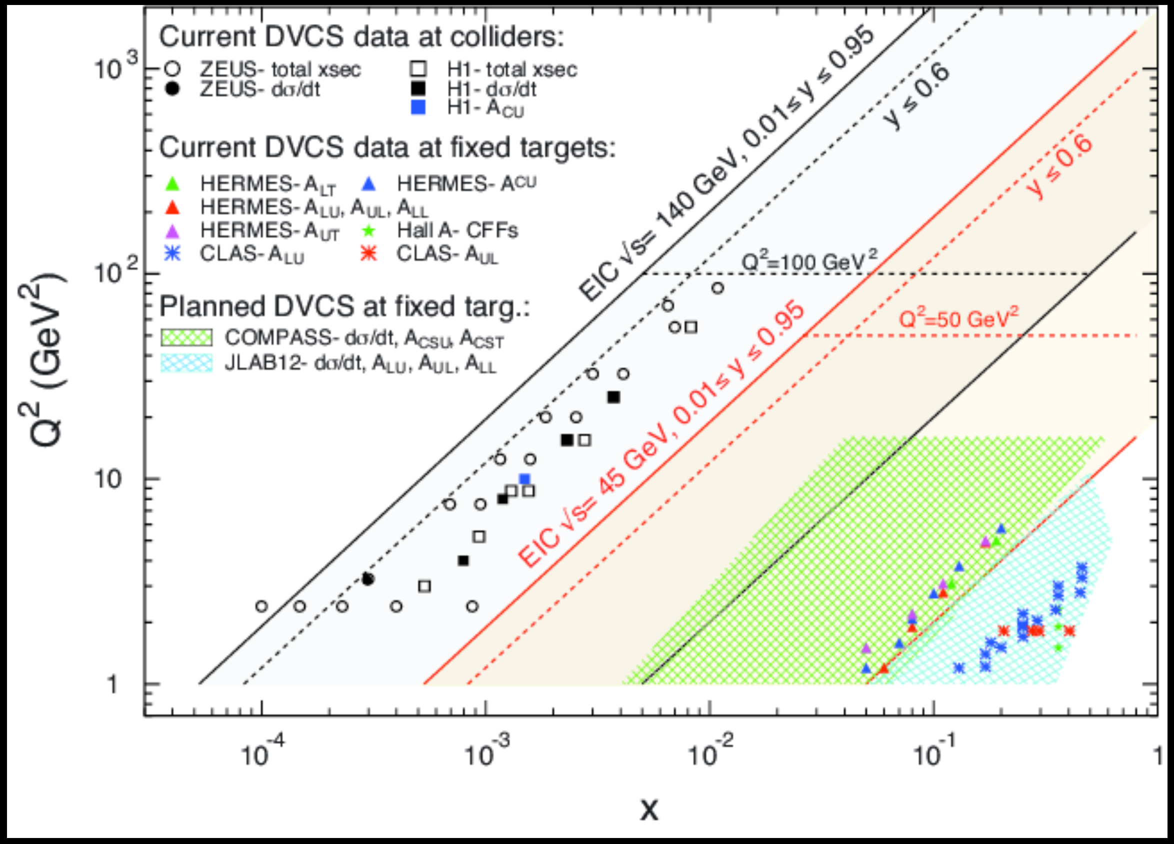


Unpolarized quark inside a transversely polarized proton

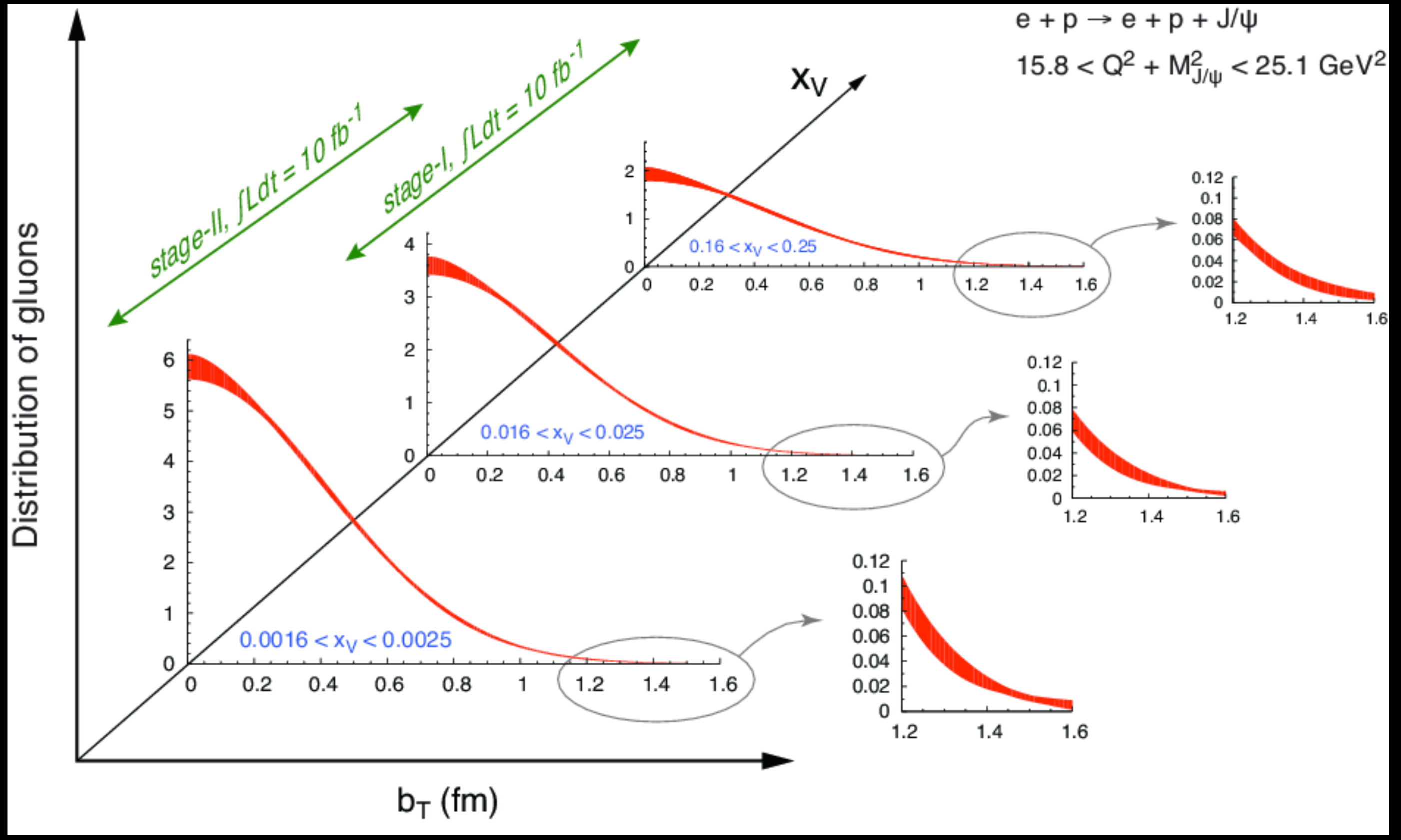
Go beyond the one-dimensional picture in parton TMD distributions

Deeply Virtual Compton Scattering





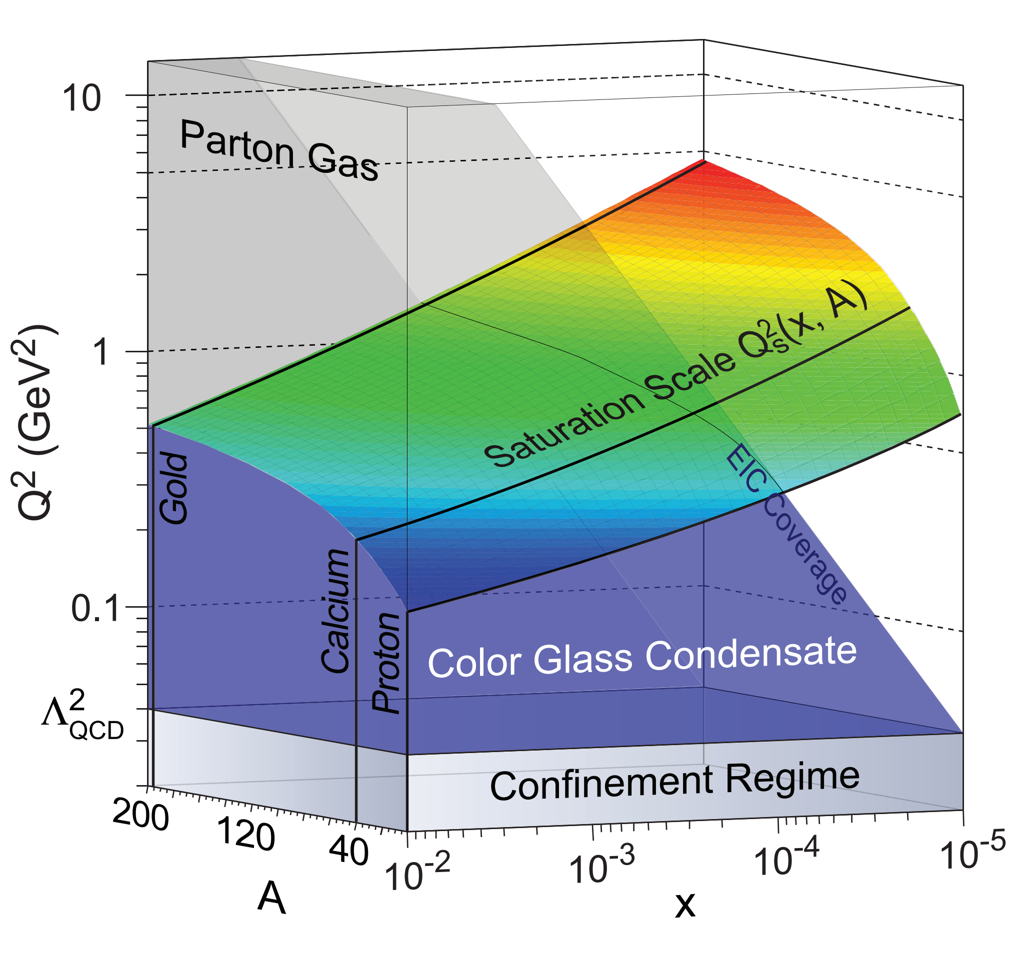
Current data: Limited and mainly unpolarized data at low-*x*

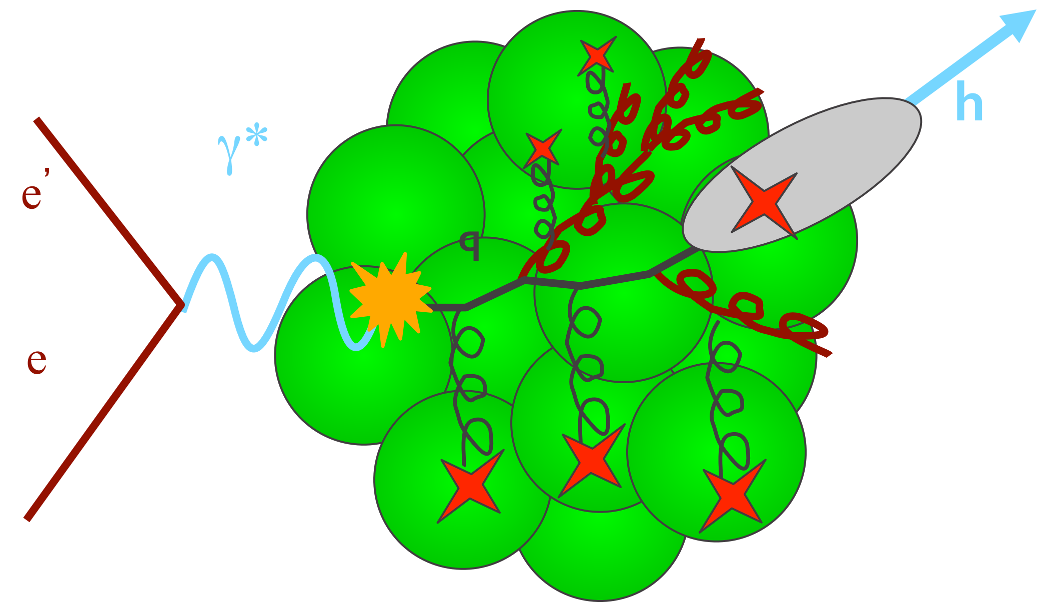


Requires high luminosities at different energies to map out the spatial distribution

Key Measurements in eA:

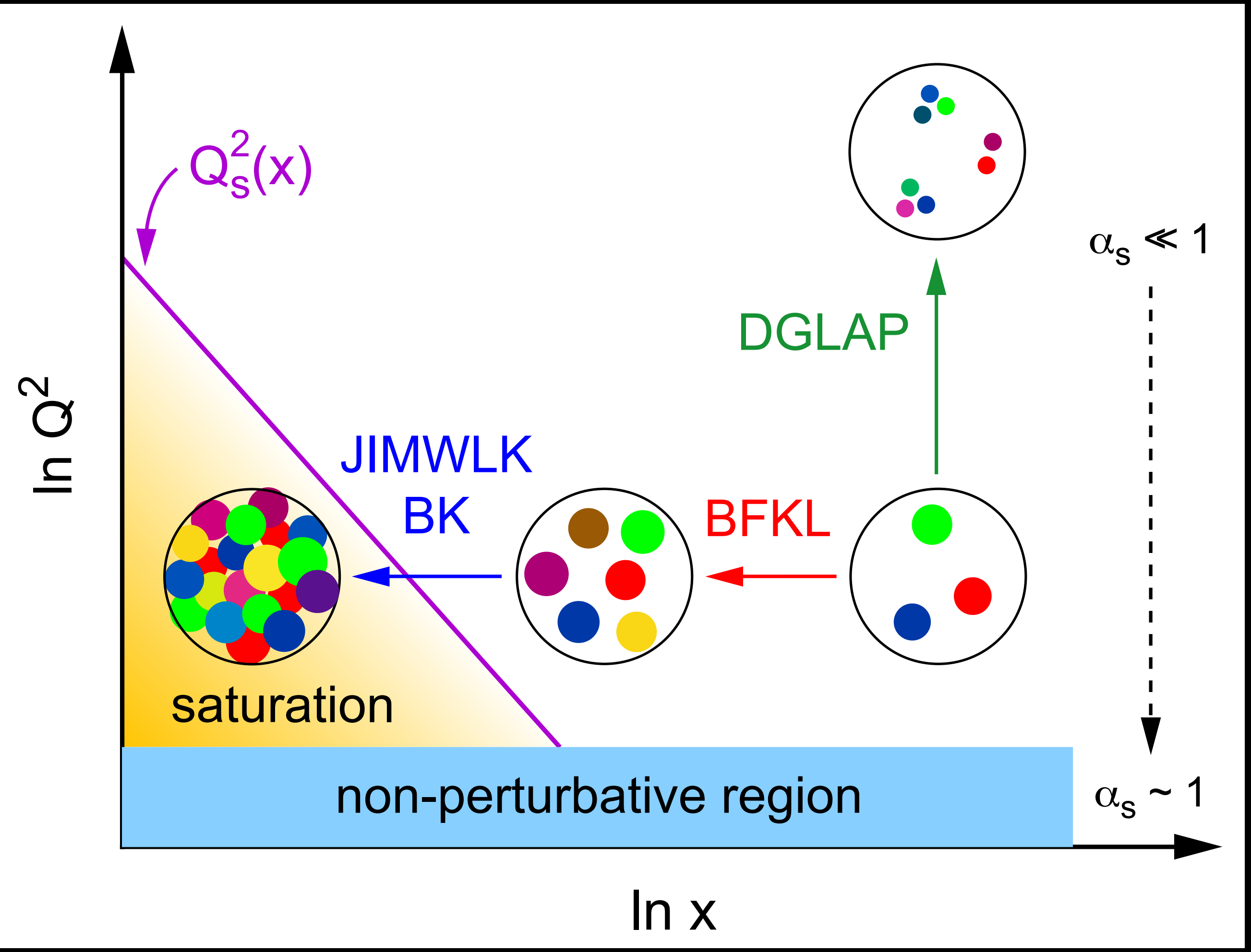
Saturation and spatial-imaging of gluon





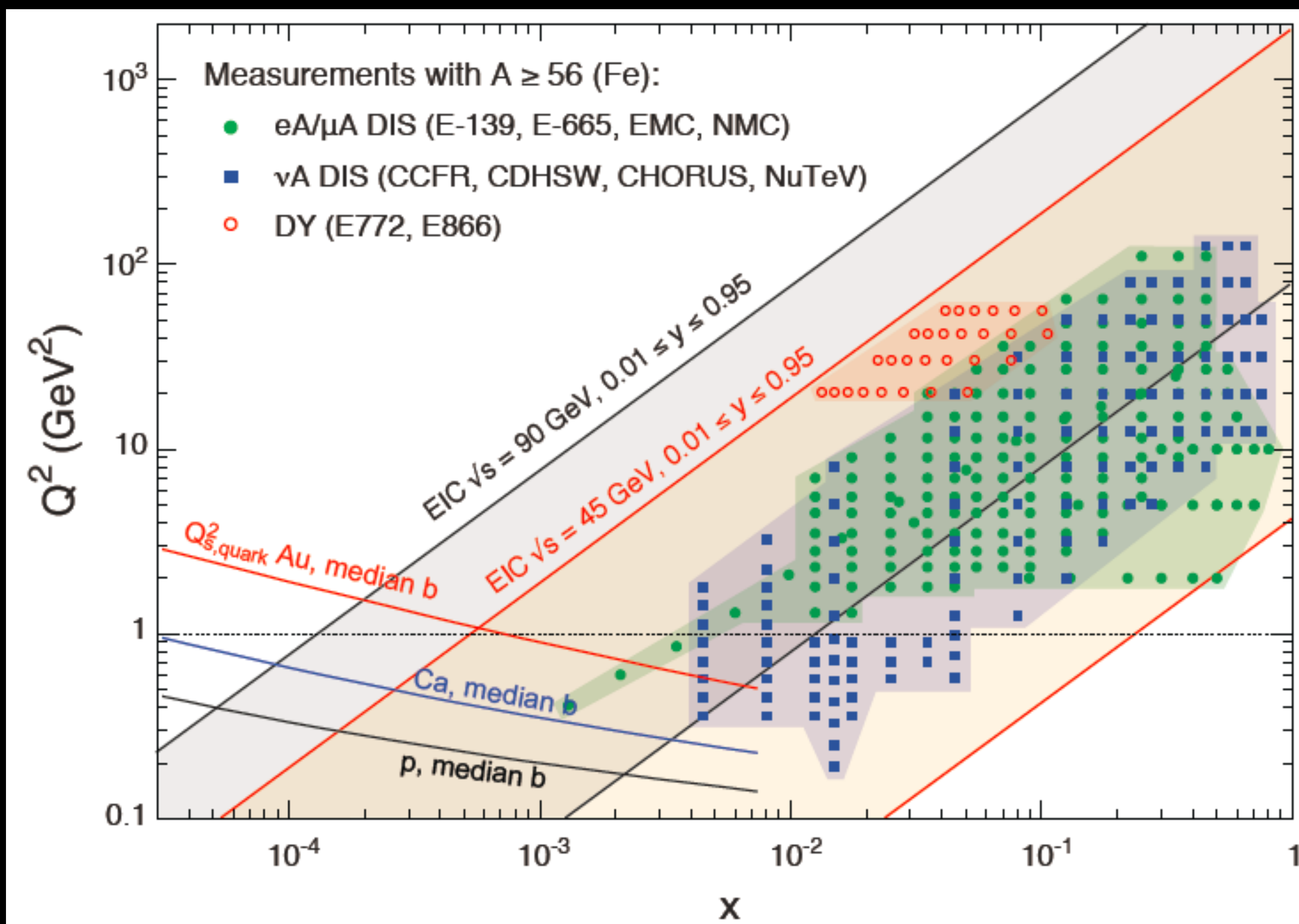
with inclusive, semi-inclusive, exclusive DIS and diffraction in eA

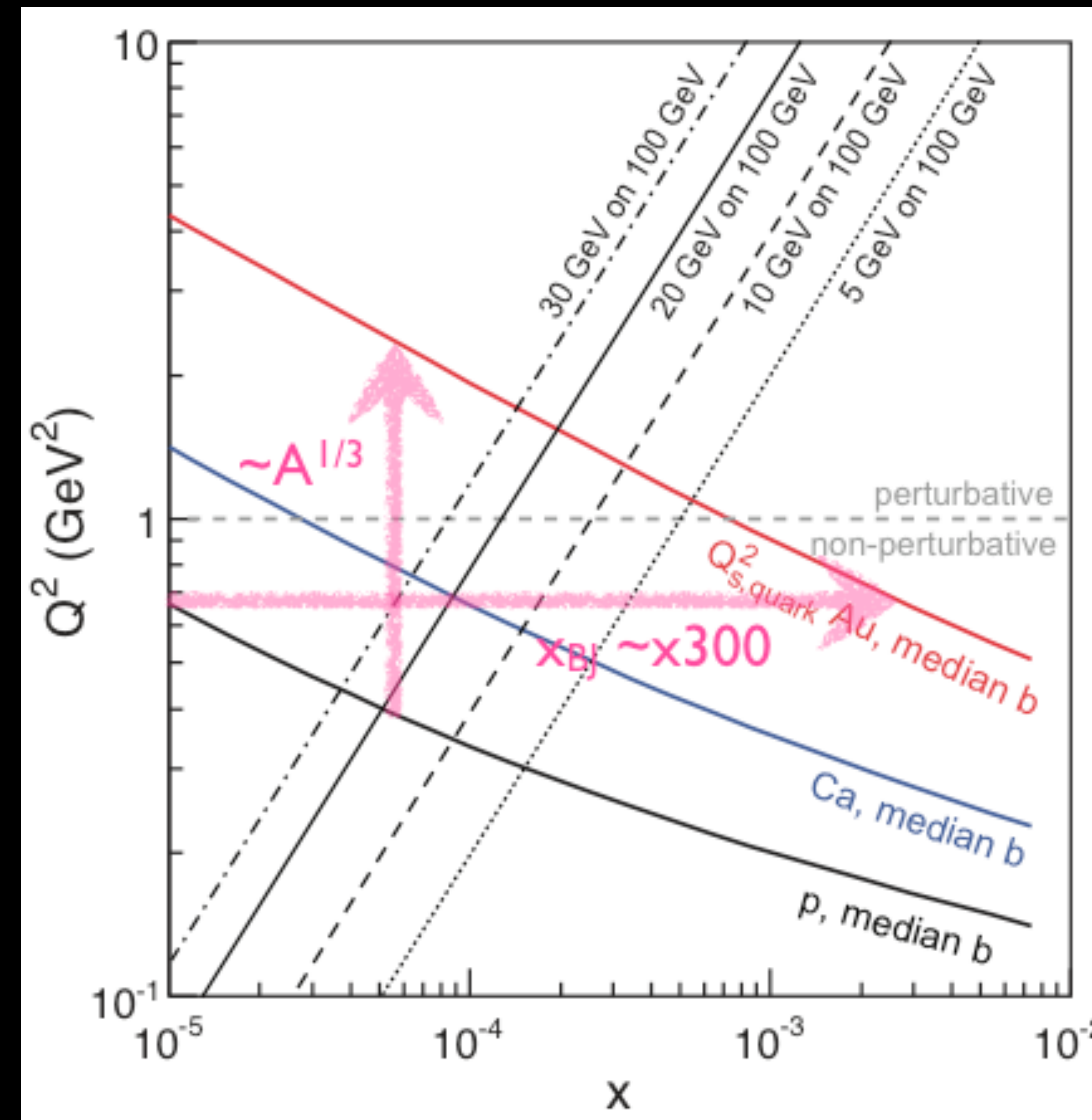
Puzzles: How gluons grow?

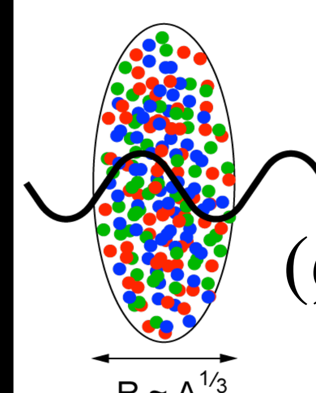


- Linear DGLAP evolution: requires "safety dynamics" to prevent unitarity violation
- Saturation regime arises naturally through non-linear BK/JIMWLK evolution
  - in the Color Glass Condensate (CGC) framework
  - Where does saturation set in?
  - What is the dynamics of saturation process?

Lepton-Nucleus Scattering and nuclear enhanced gluon saturation scale

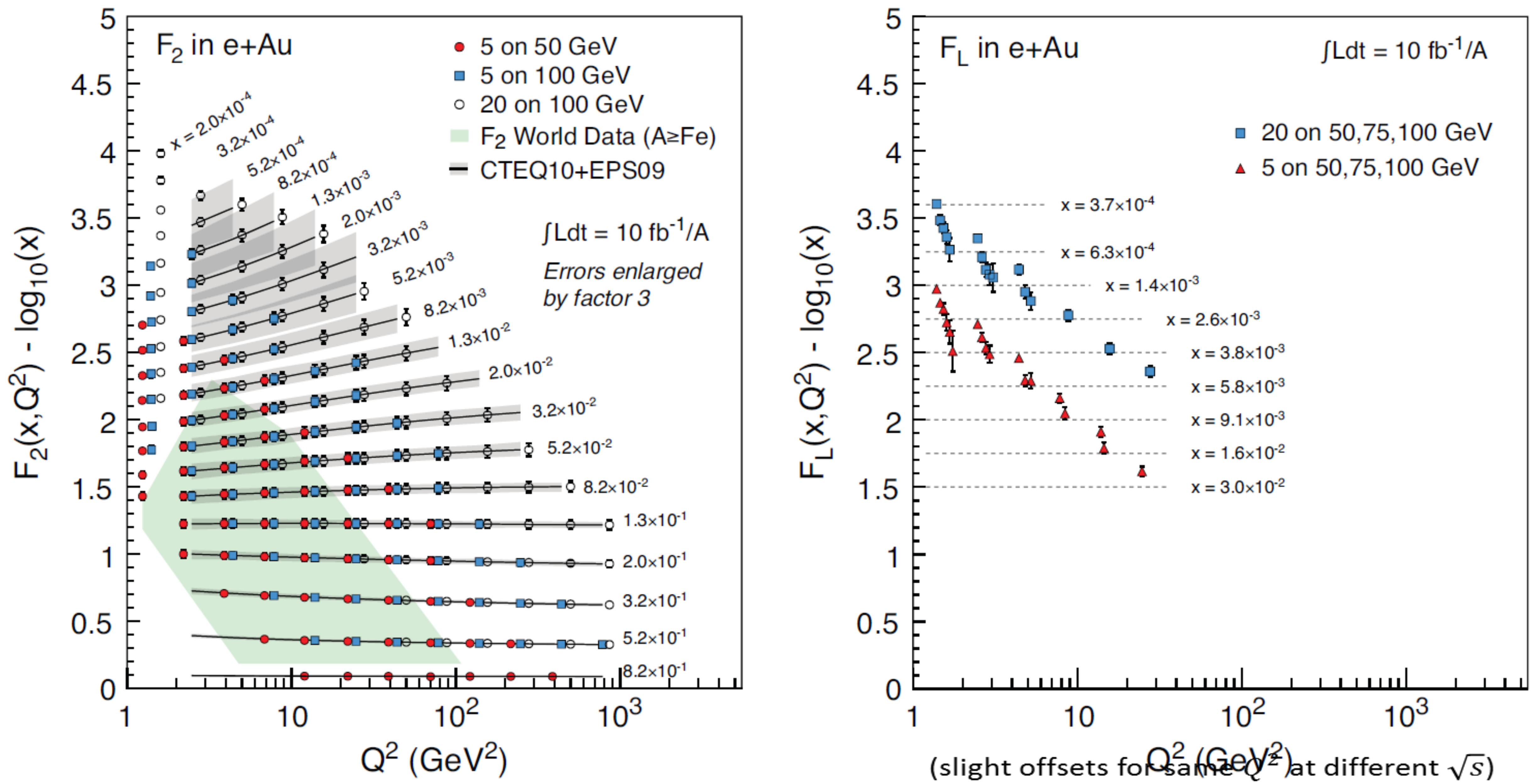






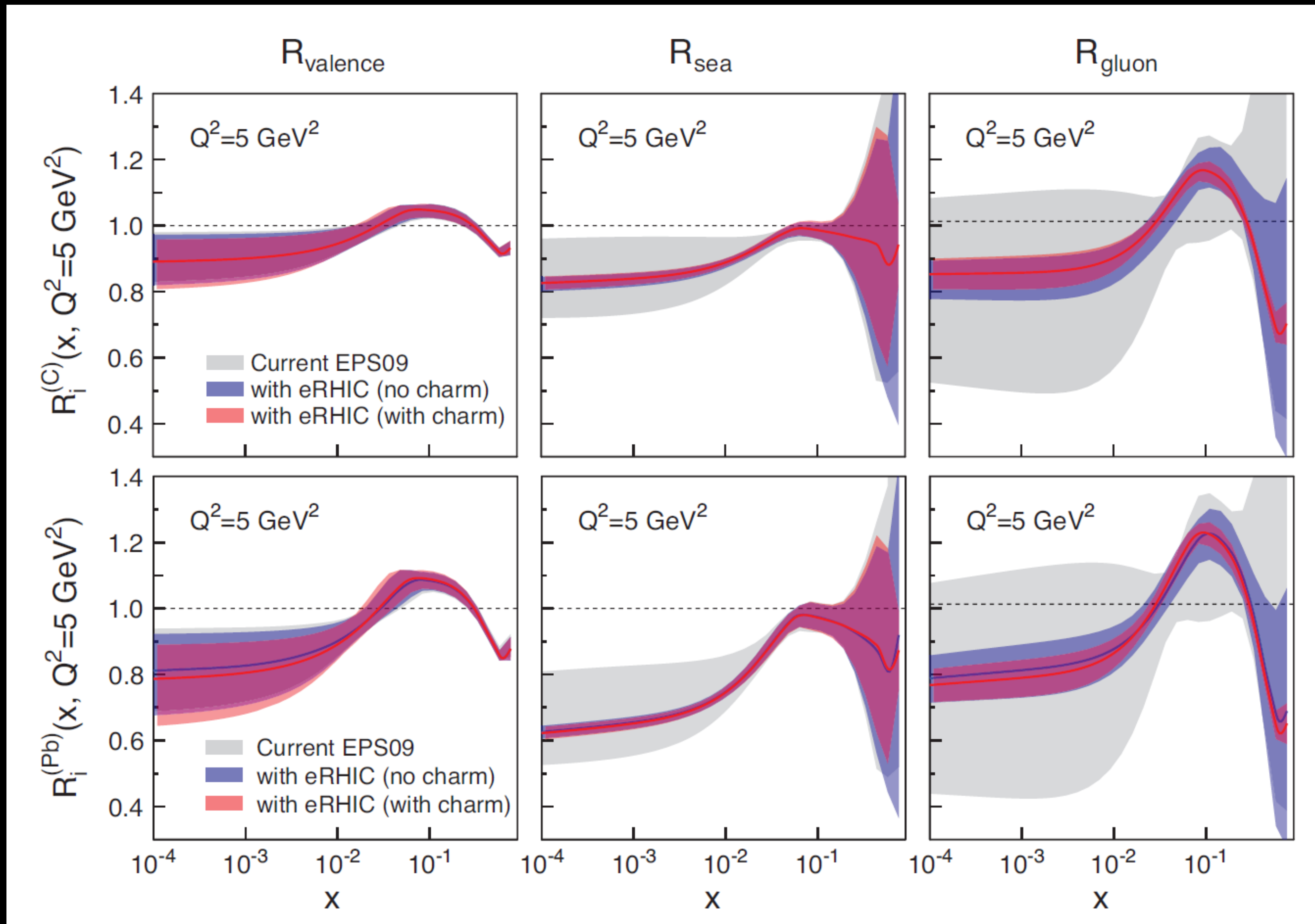
$$(Q_s^A)^2 \approx cQ_0^2\left(\frac{A}{x}\right)^{1/3}$$

nuclear structure function: F_2 and F_L



$$\sigma_r = \left(\frac{d^2\sigma}{dxdQ}\right)\frac{xQ^4}{2\pi[1+(1-y)^2]} = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2}F_L(x,Q^2)$$

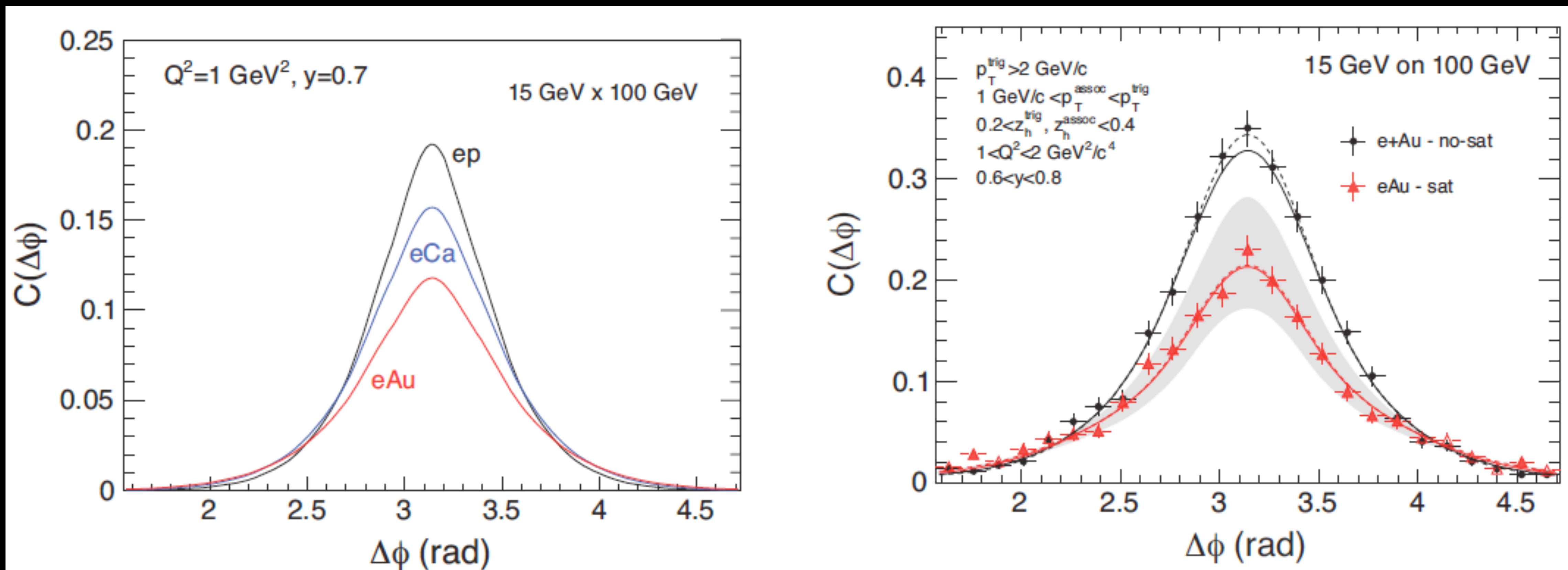
nPDF



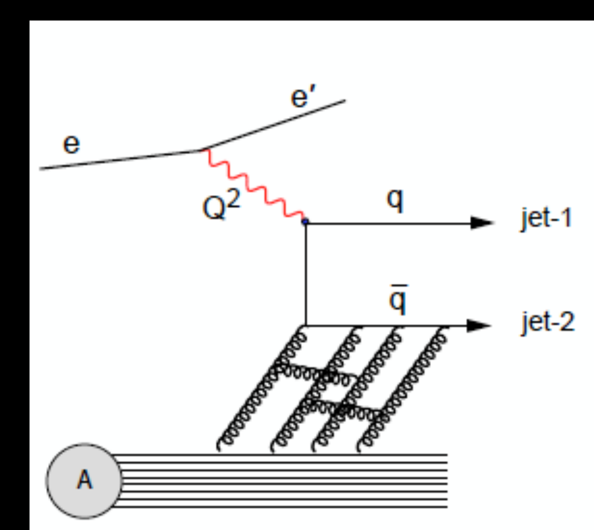
$$R_i = xf_i^A(x,Q^2)/Axf_i^p(x,Q^2)$$

- with A ∫ Ldt = 10 fb^{-1} with experimental smearing

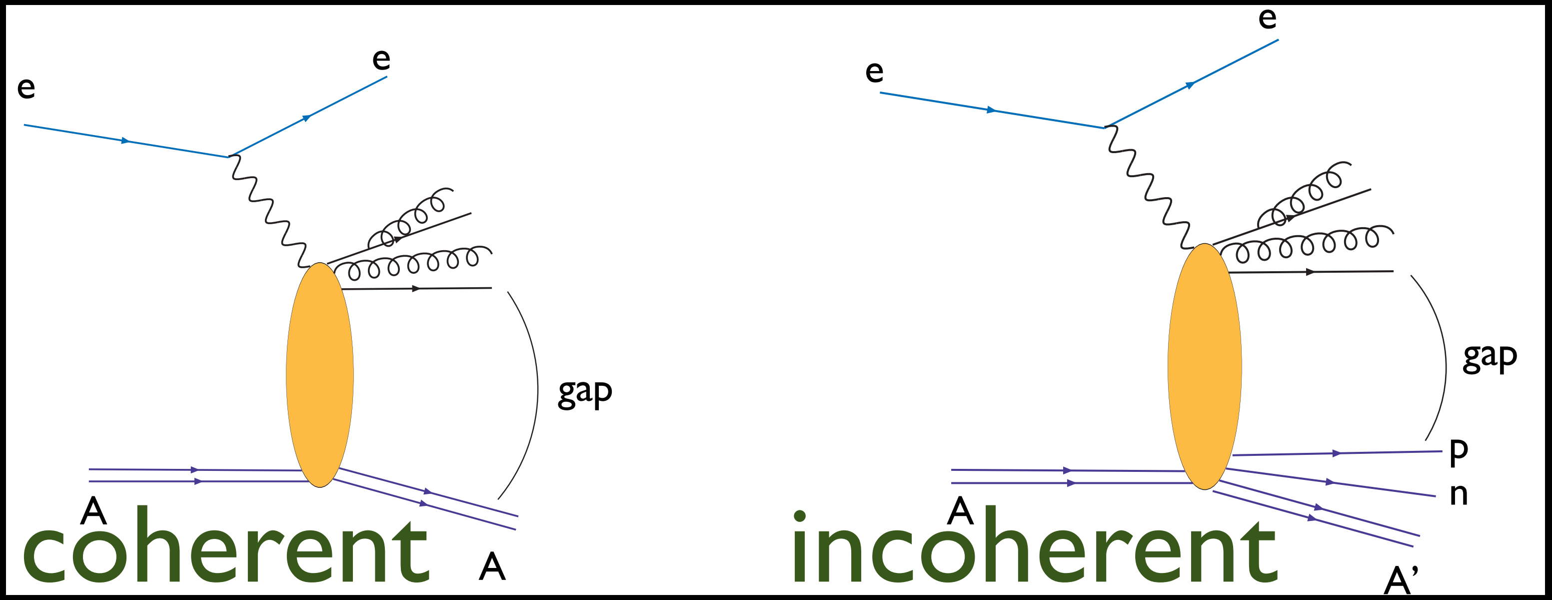
Differential probes of many-body correlations

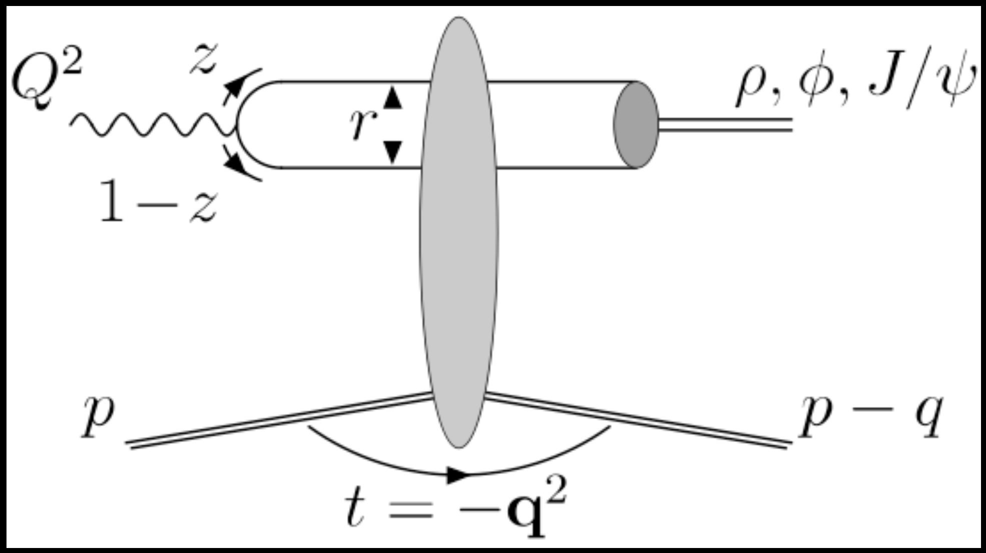


- Di-hadron correlations are very sensitive to the evolution and dynamics of many body correlation
- In the saturation regime (< Qs), large transverse momentum imbalance for the hadron pairs expected, which leads to back-to-back jet/hadron pairs to de-correlation
- EIC expected data from 1 fb^{-1} integrated luminosity at 15(e)x100(p/Au) GeV (< ~1 month running at eRHIC)
- Saturation / no-saturation can be clearly distinguished
- Strong suppression cannot be reproduced by the non-saturation model
- Systematic differential measurement: crossing onset of saturation using $\sqrt{s}$, Q^2, A



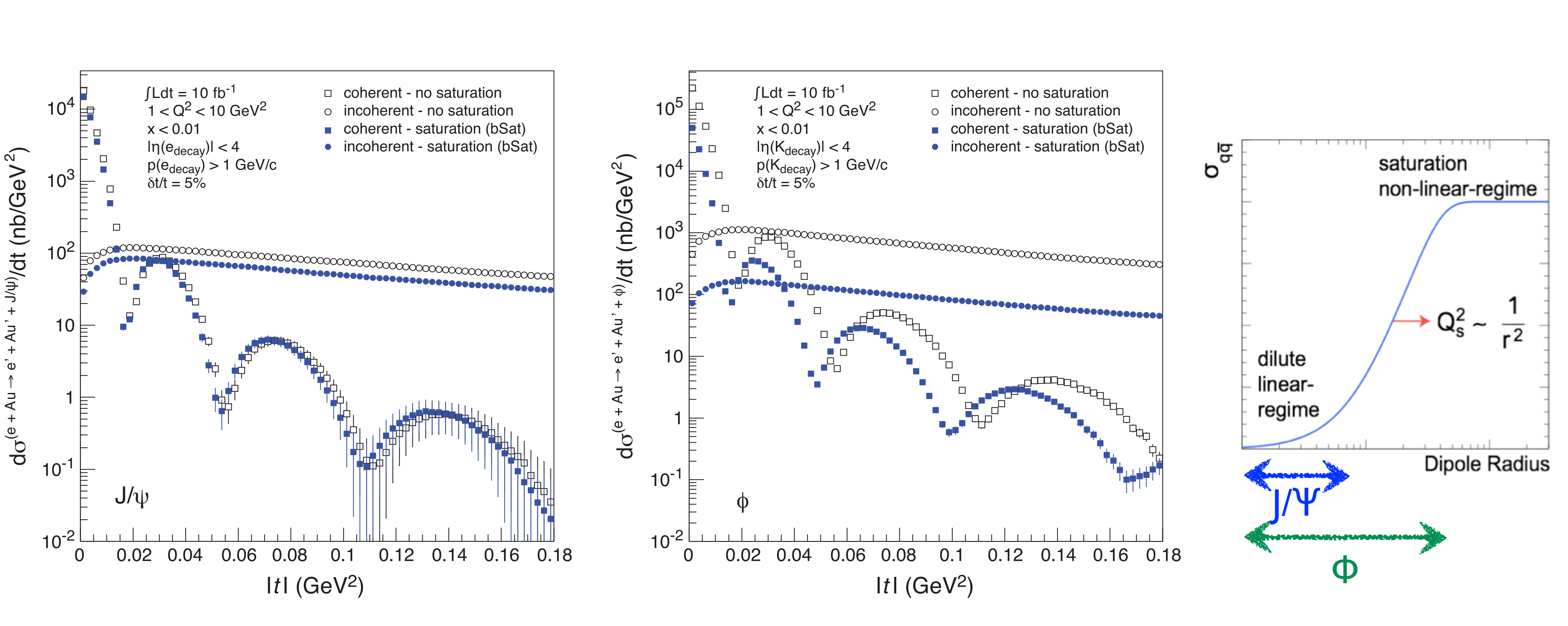
Gluon spatial distribution and correlations in exclusive diffractive Vector Meson production





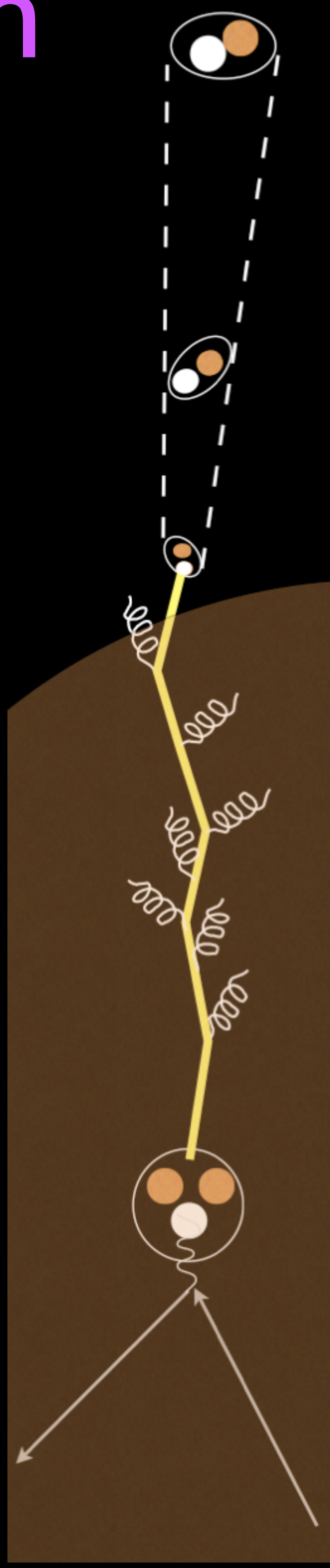
- Novel "strong" probe to investigate gluonic structure of nuclei: color dipole coherent and incoherent diffractive interaction: Sensitive to saturation (s,b,A)
- Large $\sigma_{diff}/\sigma_{total}$ in e+A (~25-40%) compared to e+p (~10-15%)
- Coherent: Access to spatial distribution of gluons
  - Precise transverse imaging of the gluons
  - Modification due to small-x evolution
- Incoherent: Gluon correlations in the transverse plane

Exclusive diffractive vector meson production: J/Ψ and Φ



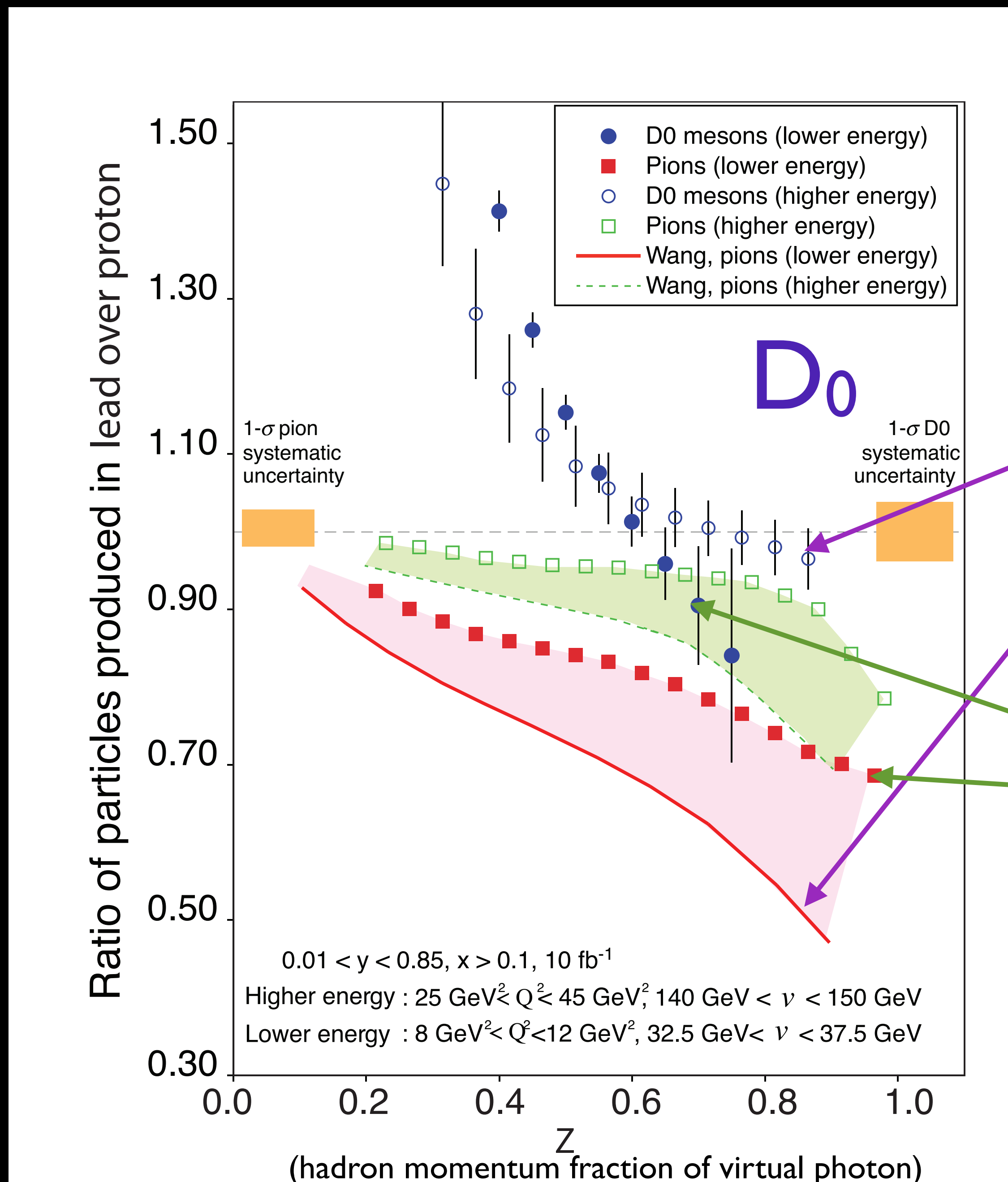
- Probe (VM dipole size) dependent exclusive t-dependent production: yield and pattern sensitive to saturation
- with A∫Ldt = 10 fb^{-1} with experimental smearing

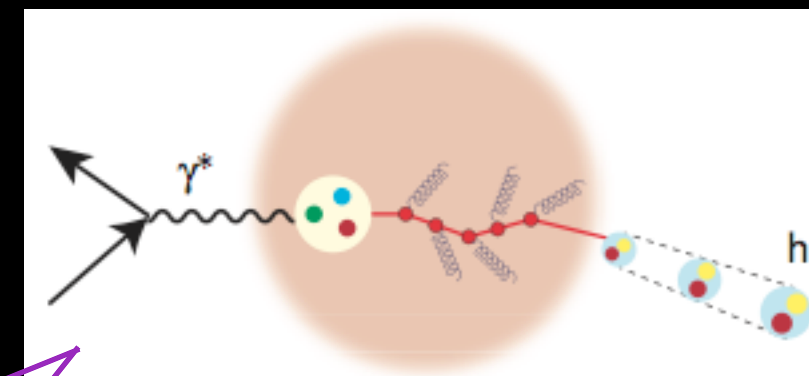
Parton propagation and fragmentation

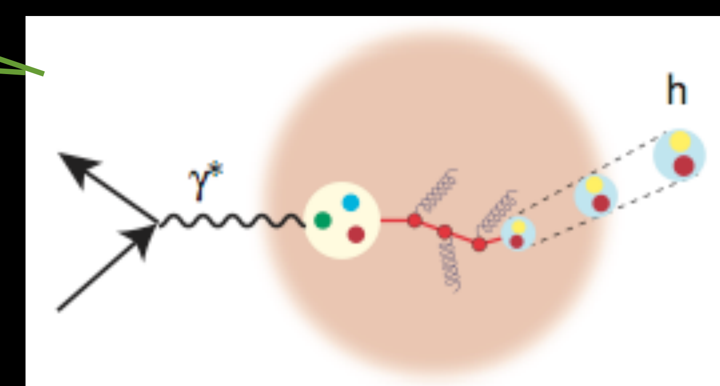


- Nuclei as space-time analyzer
- EIC can measure
  - fragmentation time scale to understand dynamics
  - in medium energy loss to characterize medium
    - gluon bremstrahlung: hadronization outside media
    - prehadron absorption: color neutralization inside the medium
- Observable
  - p_T distribution broadening: direct link to saturation
  - attenuation of hadrons

Hadronization - Energy Loss study in wide kinematic and mass range







- access to heavy-meson: studying mass-dependent hadronization properties - transition mechanism from quarks to hadrons

Summary

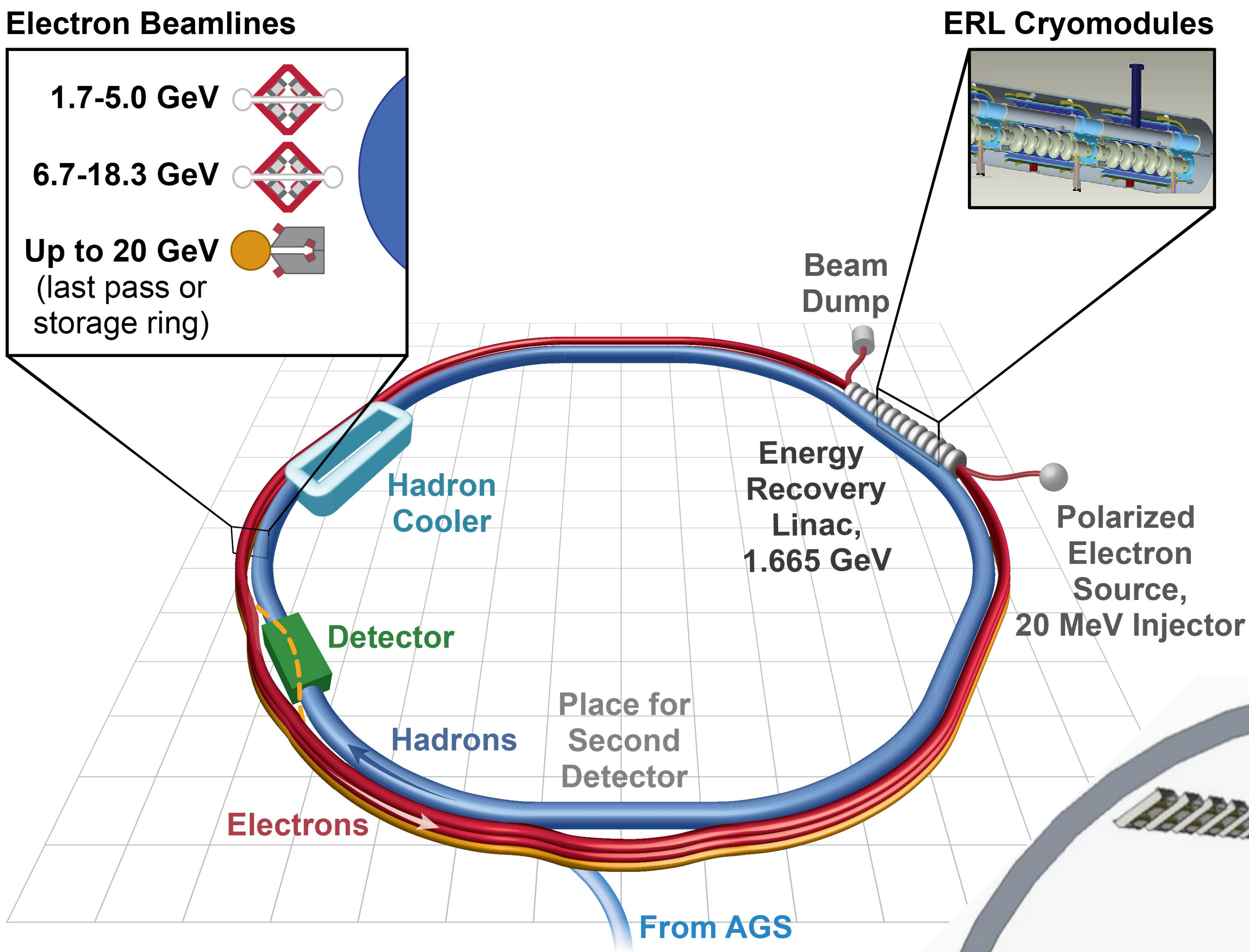
Electron-Ion Collider is to understand the glue that binds us all. It is the brightest sub-femtometer to answer outstanding fundamental questions in QCD through unique and unprecedented measurements:

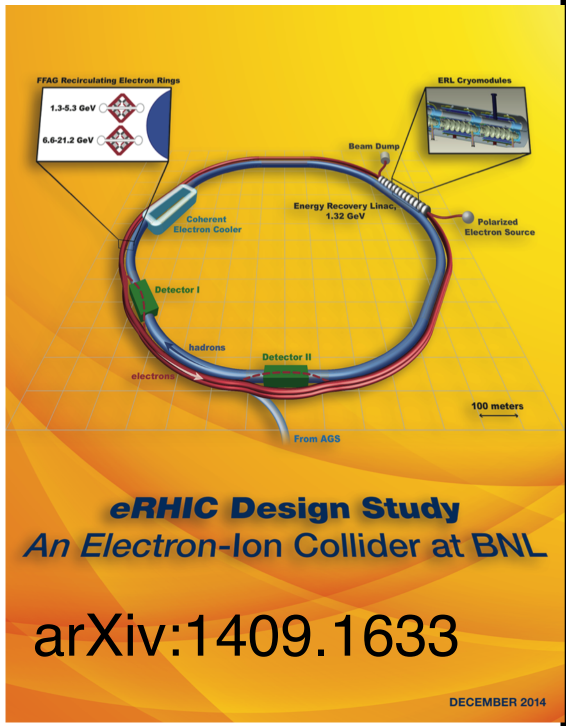
- Deeply extend the current understanding of nucleon structure: spin and 3D landscape.
- Establish and explore new degree of freedom of gluonic property of matter - saturation regime
- Shed light on what governs the transition from quarks to hadrons

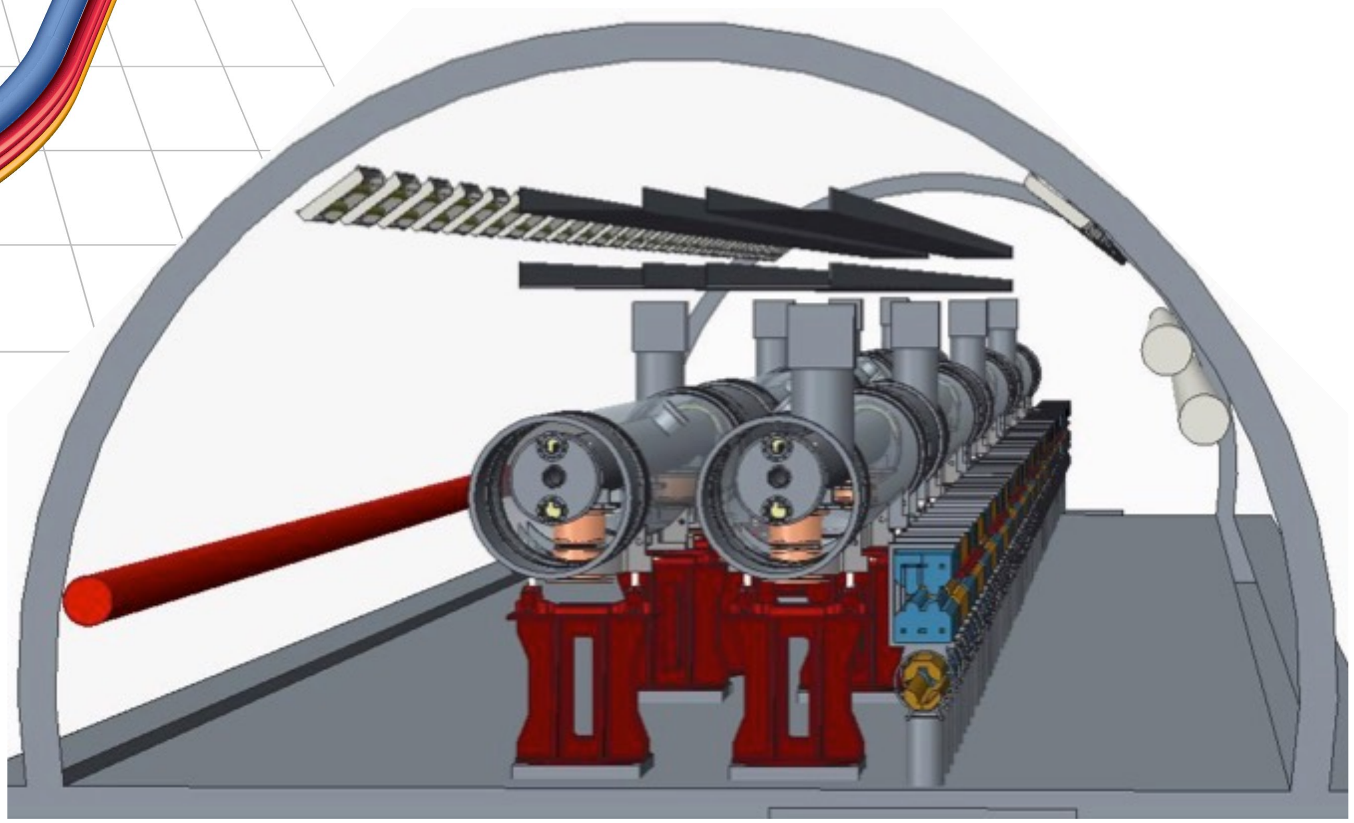
extra

Ultimate eRHIC design

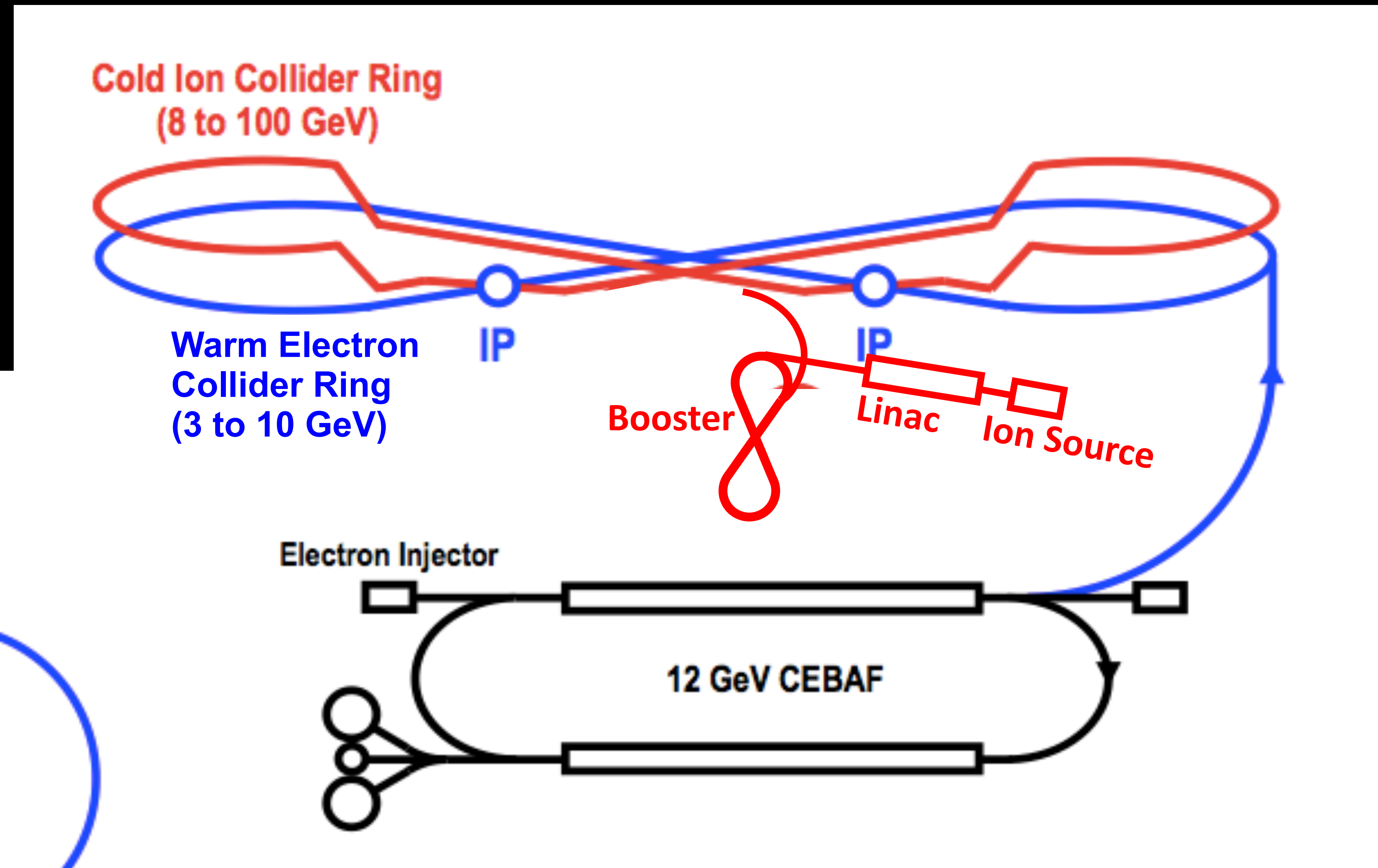
Highly advanced and energy efficient accelerator

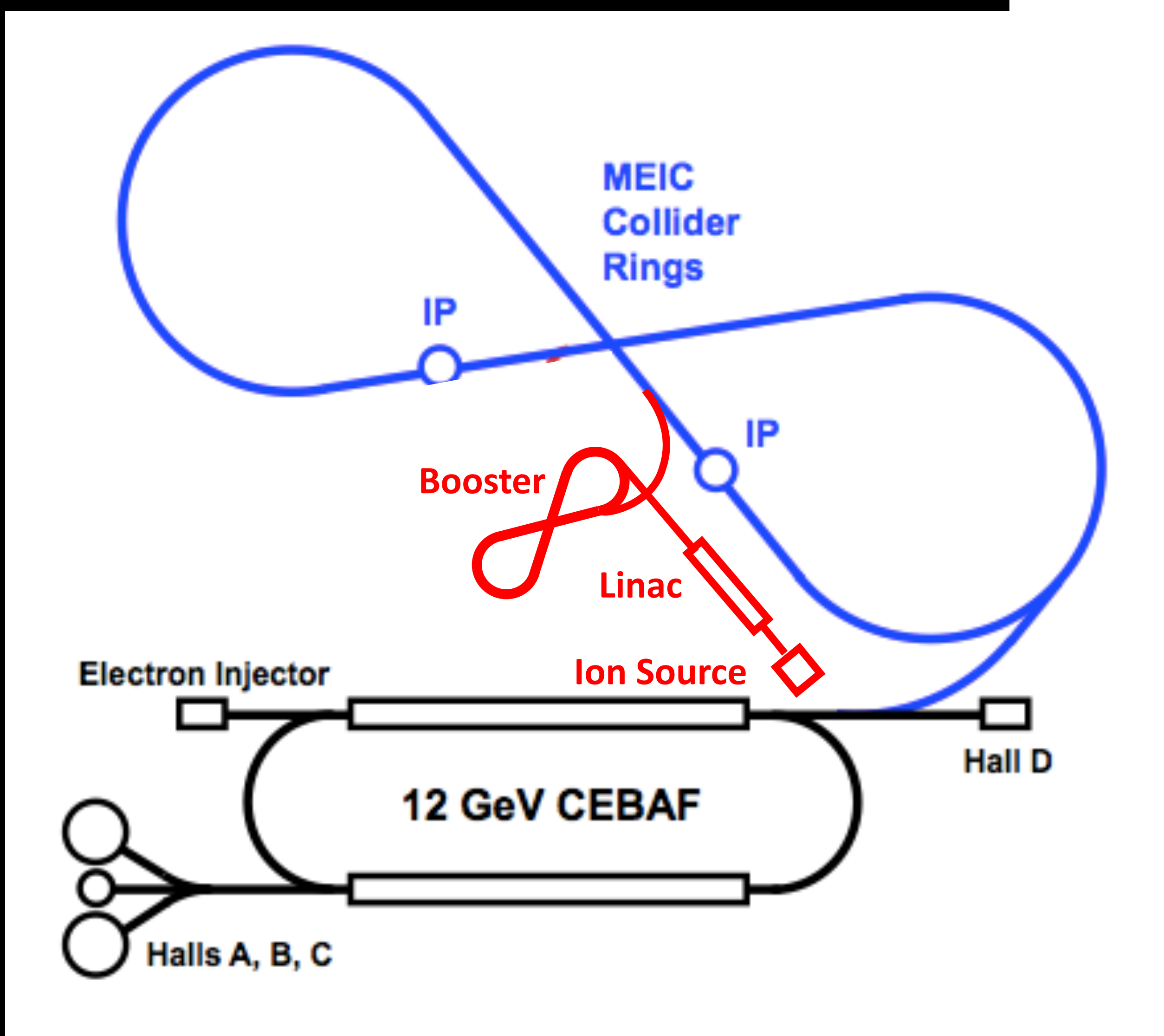






JLEIC Baseline Layout





CEBAF is a full energy injector.