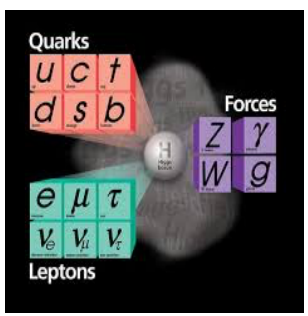
COOL'15
Workshop on Beam Cooling and Related Topics
Sept. 28 - Oct. 2, 2015
Jefferson Lab
Newport News, Virginia USA

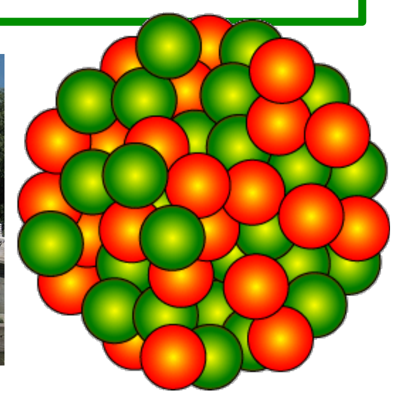
Electron Ion Collider: The next QCD frontier

Understanding the Glue that Binds Us All

Why the EIC?

To understand the role of gluons in binding quarks & gluons into Nucleons and Nuclei

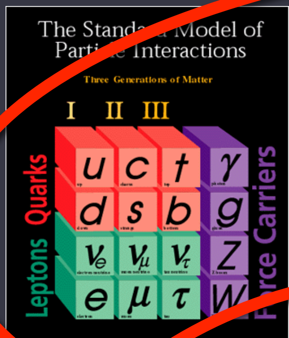


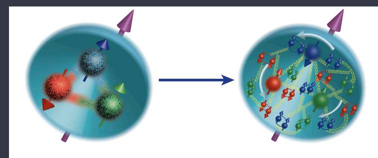


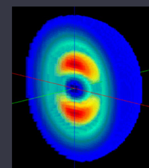
Stony Brook University

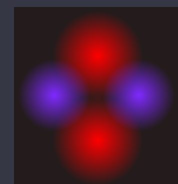
Abhay Deshpande

21st Century Nuclear Science: Probing nuclear matter in all Its forms & exploring their potential for applications

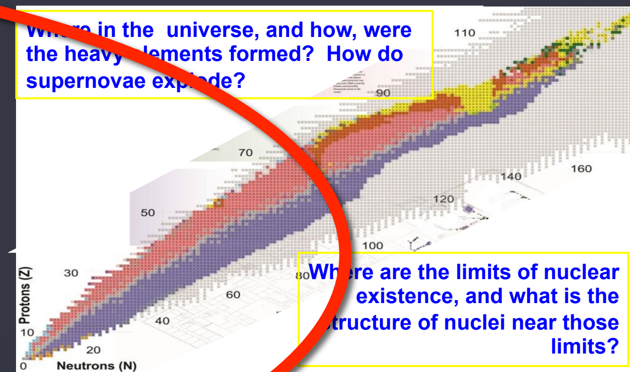






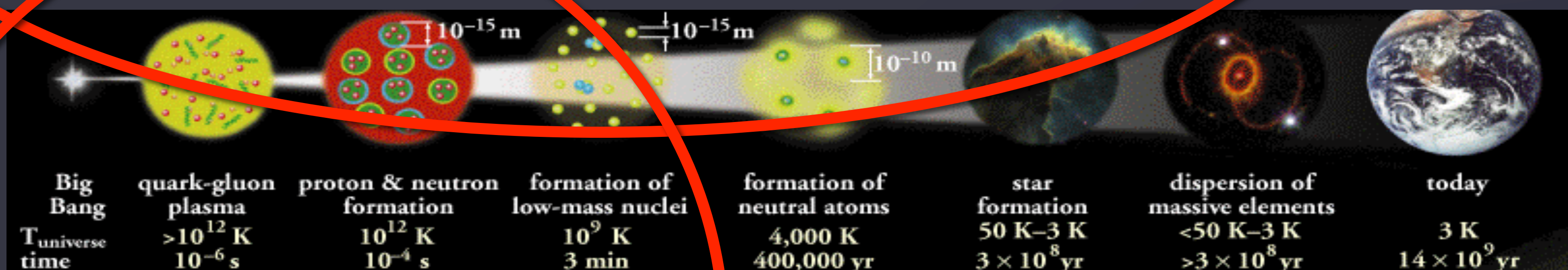


How are the properties of protons and neutrons, and the force between them, built up from quarks, antiquarks and gluons? What is the mechanism by which these fundamental particles materialize as hadrons?

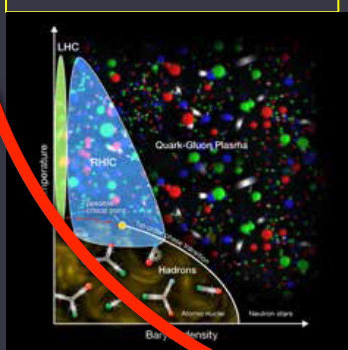


Where in the universe, and how, were the heavy elements formed? How do supernovae explode?

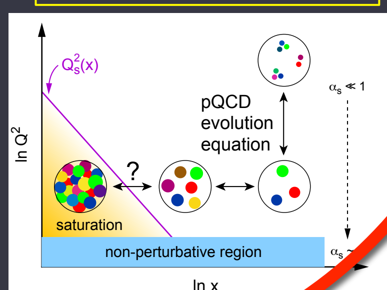
Where are the limits of nuclear existence, and what is the structure of nuclei near those limits?



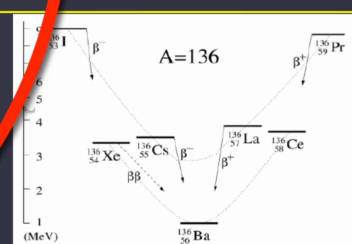
What is the nature of the different phases of nuclear matter through which the universe has evolved?



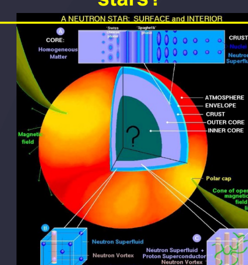
Do nucleons and all nuclei, viewed at near light speed, appear as walls of gluons with universal properties?



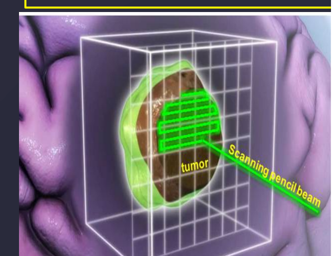
How can the properties of nuclei be used to reveal the fundamental processes that produced an imbalance between matter and antimatter in our universe?



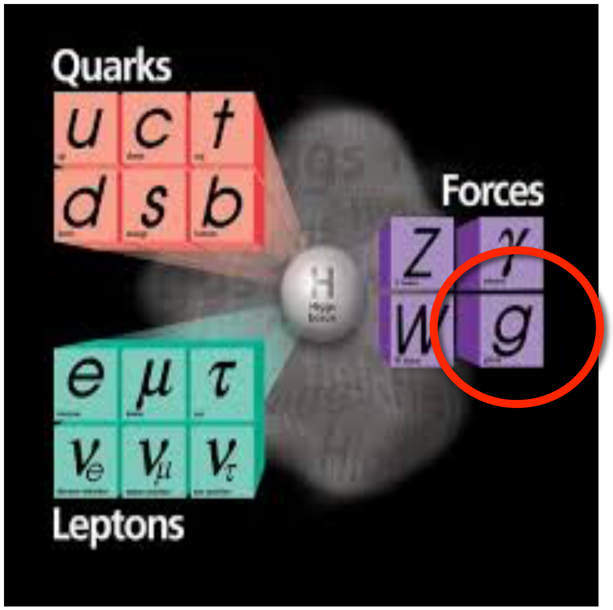
How are the nuclear building blocks manifested in the internal structure of compact stellar objects, like neutron stars?



How can technologies developed for basic nuclear physics research be adapted to address society's needs?



Gluon in the Standard Model of Physics



Gluon: carrier of strong force (QCD)

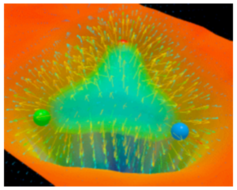
Charge--less, Massless, but carries color-charge

Binds the quarks and gluons inside the hadrons with tremendous force! (Strong force)

At the heart of many un/(ill)-understood phenomena:

Color Confinement, composition of nucleon spin, quark-gluon plasma at RHIC & LHC…

Role of gluons in hadron & nuclear structure



Dynamical generation of hadron masses & nuclear binding

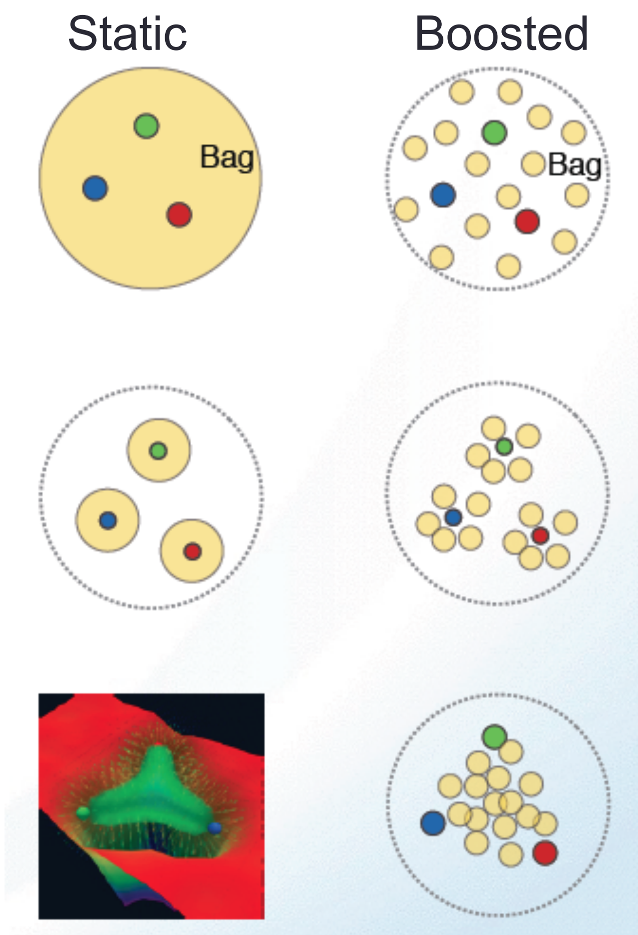
- Massless gluons & almost massless quarks, *through their interactions,* generate more than 98% of the mass of the nucleons:

Without gluons, there would be no nucleons,
no atomic nuclei… no visible world!

- Gluons carry ~50% the proton's momentum, **?%** of the nucleon's spin, and are responsible for the transverse momentum of quarks
- The quark-gluon origin of the nucleon-nucleon forces in nuclei not quite known
- Lattice QCD can't presently address dynamical properties on the light cone

Experimental insight and guidance crucial for complete understanding of *how* hadron & nuclei emerge from quarks and gluons

What does a proton look like?



Bag Model: Gluon field distribution is wider than the fast moving quarks.
Gluon radius > Charge Radius

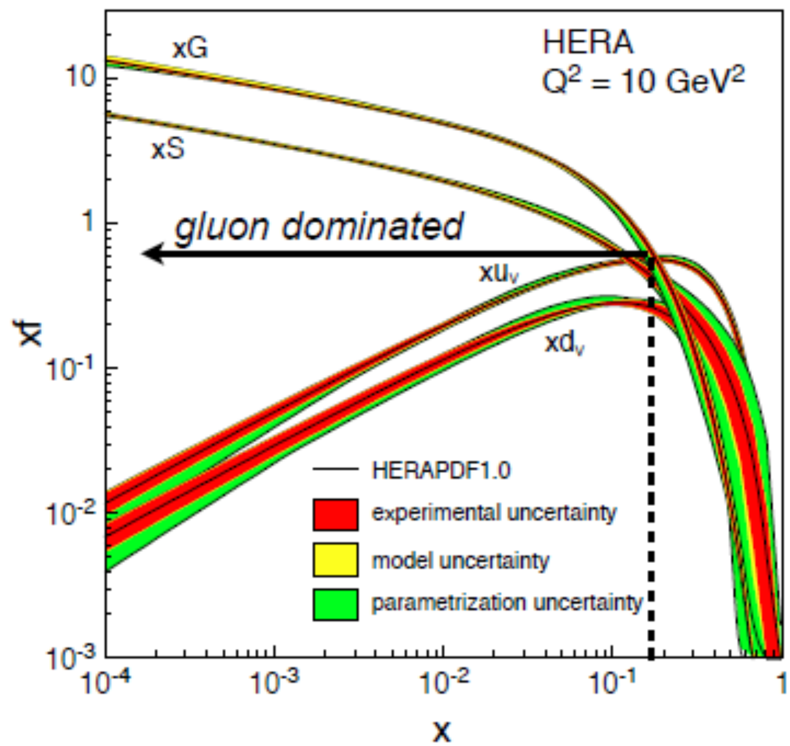
Constituent Quark Model: Gluons and sea quarks hide inside massive quarks.
Gluon radius ~ Charge Radius

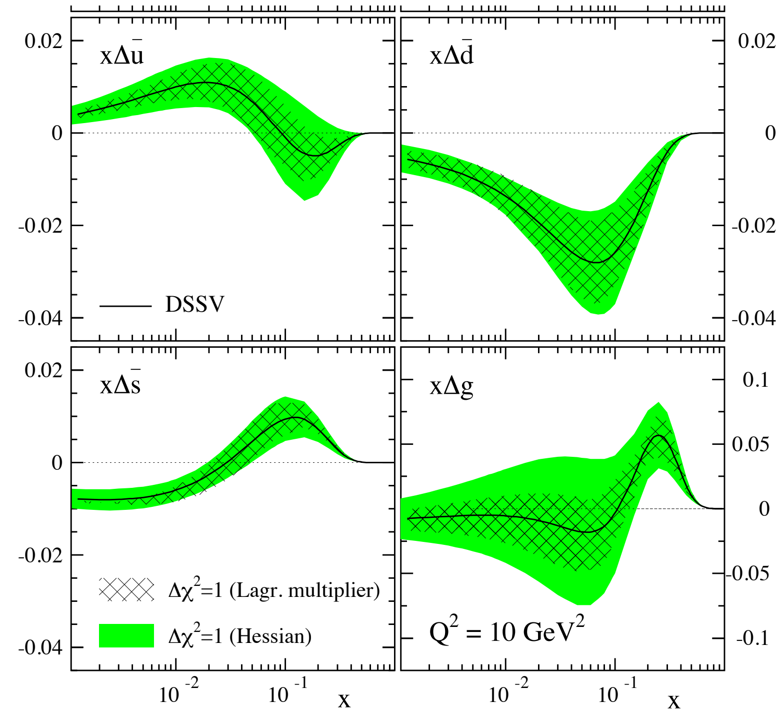
Lattice Gauge theory (with slow moving quarks), gluons more concentrated inside the quarks:
Gluon radius < Charge Radius

Need transverse images of the quarks *and gluons* in protons

What does a proton look like? Unpolarized & polarized

We only *have a* *1-dimensional picture!*





Need to go beyond 1-dimension!

Need 3D Images of nucleons in Momentum & Position space

Could they give us clues on orbital motion of partons?

→ Finally help solve the spin puzzle?

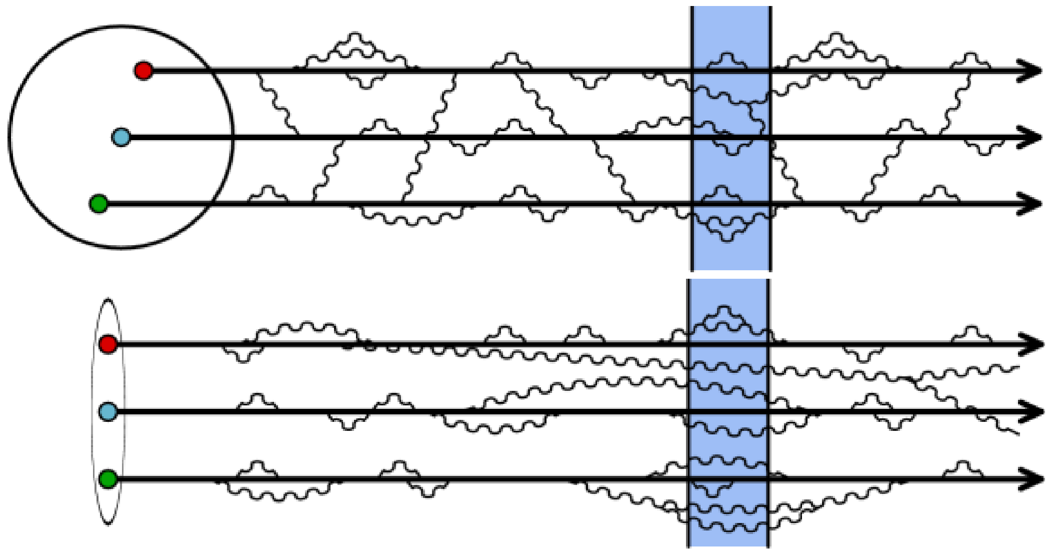
How does a proton look at low and high energy

Understanding the role of gluon in QCD…. (unpolarized!)

Proton at low and high energy:

Low energy
High x
Regime of fixed target exp.

High energy
Low- x
Regime of a Collider



At high energy:

- Wee partons fluctuations are time dilated in strong interaction time scales
- Long lived gluons radiate further smaller x gluons ➔ which intern radiate more……. Leading to a **runaway growth?**

Gluon and the consequences of its interesting properties:

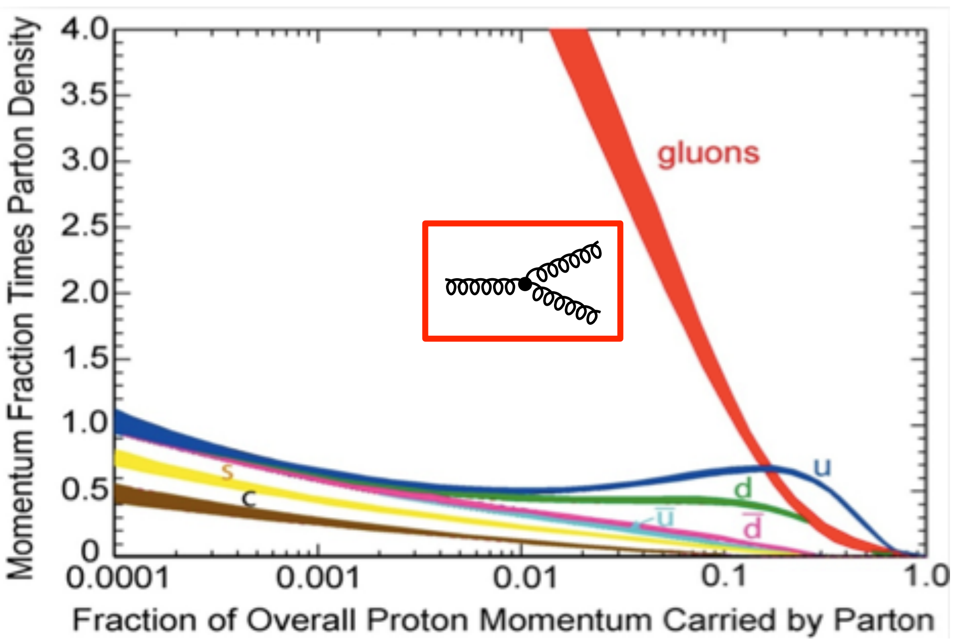
Gluons carry color charge ➔ Can interact with other gluons!

"…The result is a self catalyzing enhancement that leads to a runaway growth. A small color charge in isolation builds up a big color thundercloud…."

F. Wilczek, in "Origin of Mass"
Nobel Prize, 2004

Gluon and the consequences of its interesting properties:

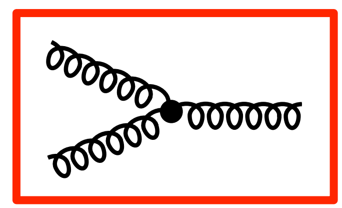
Gluons carry color charge ➔ Can interact with other gluons!



Apparent "indefinite rise" in gluon distribution in proton!

What could **limit this indefinite rise?** → saturation of soft gluon densities via gg→g recombination must be responsible.

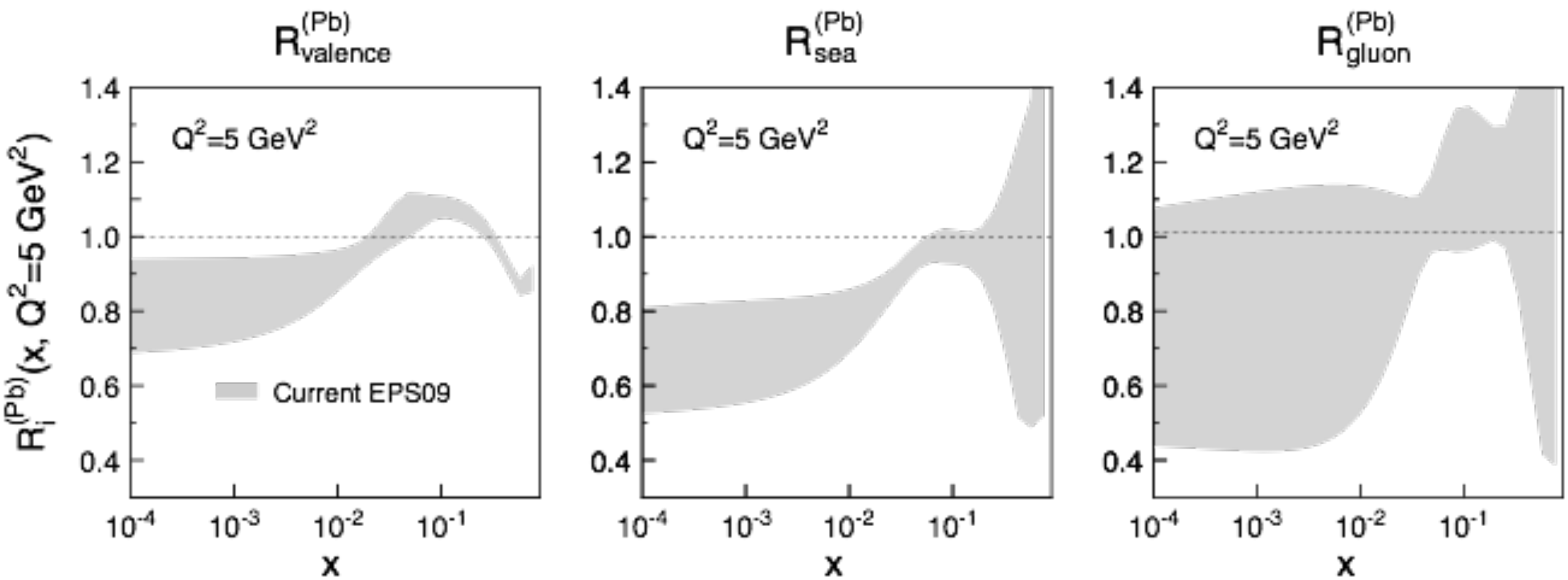
recombination



Where? No one has unambiguously seen this before!

If true, effective theory of this →"Color Glass Condensate"

What does a nucleus look like?



Large uncertainties & only 1-D information!

Need to reduce uncertainties & ***go beyond the 1-dimensions***

Need (2+1)D partonic images of nuclei.

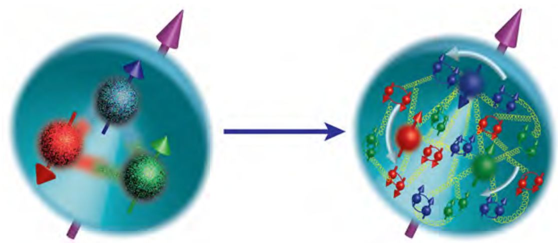
Fully understand: emergence of hadrons in Cold QCD matter &

initial state ←→ properties of QGP formed in AA collisions

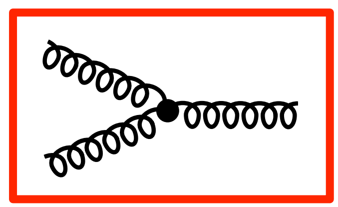
Puzzles and challenges in understanding these QCD many body emergent dynamics

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

Role of Orbital angular momentum?



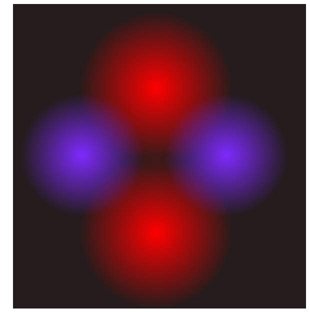
What happens to the gluon density in nuclei at high energy? Does it saturate, in to a gluonic form of matter of universal properties?

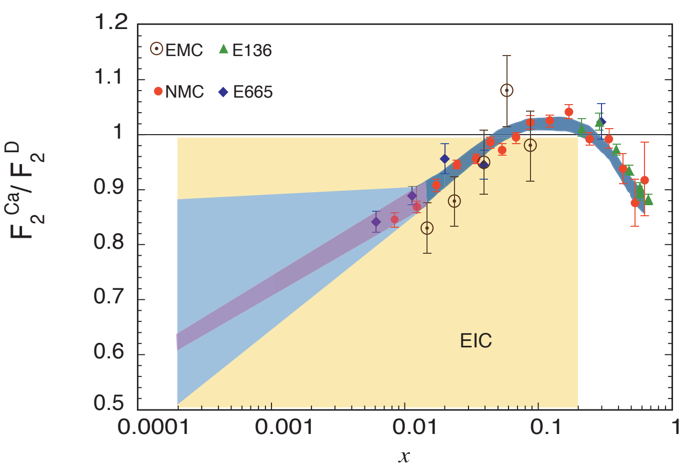


?

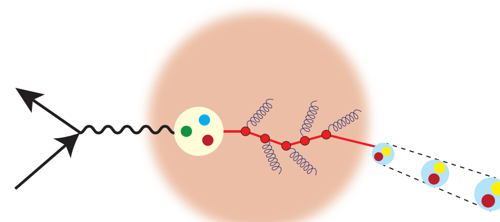
Puzzles and challenges….

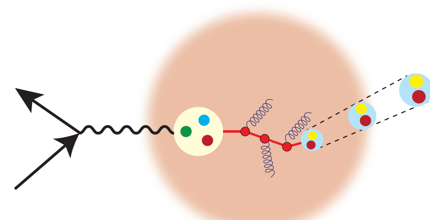
How do gluons and sea quarks contribute to the nucleon-nucleon force?





How does the nuclear environment affect the distributions of quarks and gluons and their interactions inside nuclei?

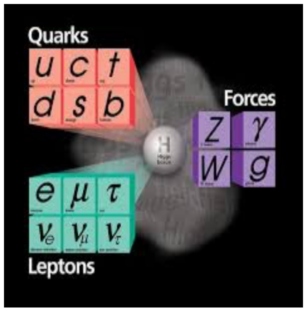


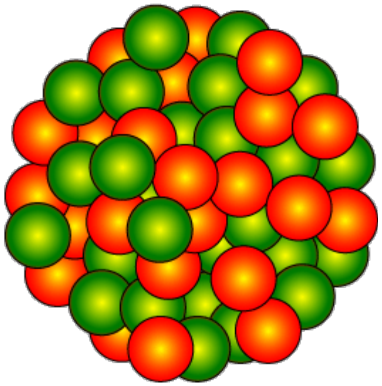


How does nuclear matter respond to fast moving color charge passing through it?

Why we need an EIC?

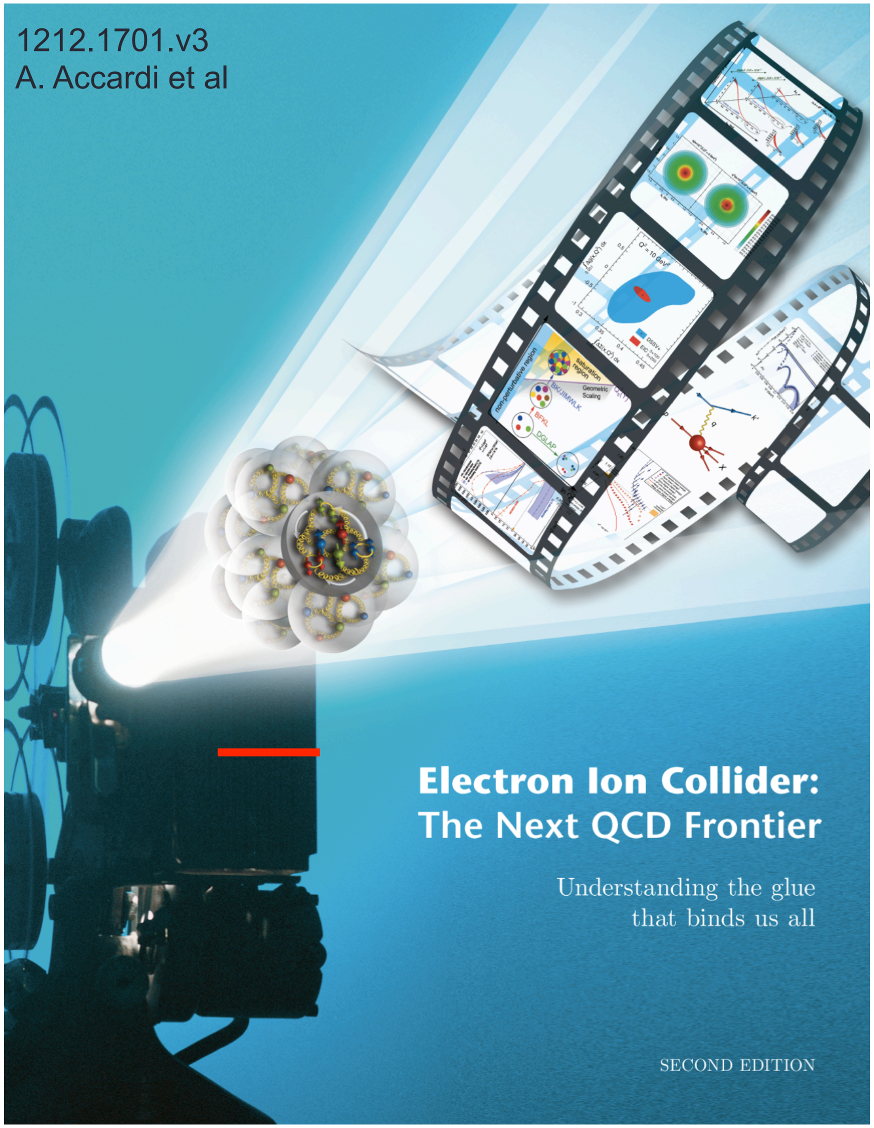
A new facility, EIC, with a versatile range of kinematics, beam polarizations, high luminosity and beam species, is required to ***precisely image*** *the sea quarks and gluons in nucleons and nuclei,* to explore the new QCD frontier of strong color fields in nuclei, and to resolve outstanding issues in understanding nucleons and nuclei in terms of fundamental building blocks of QCD

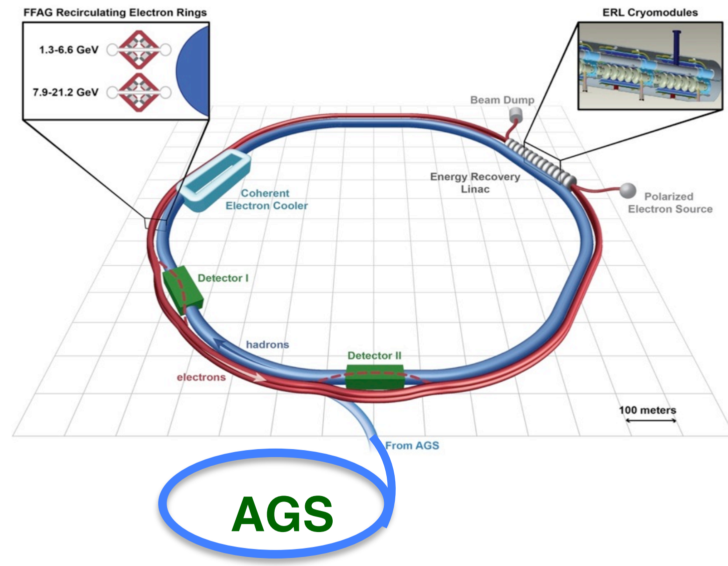


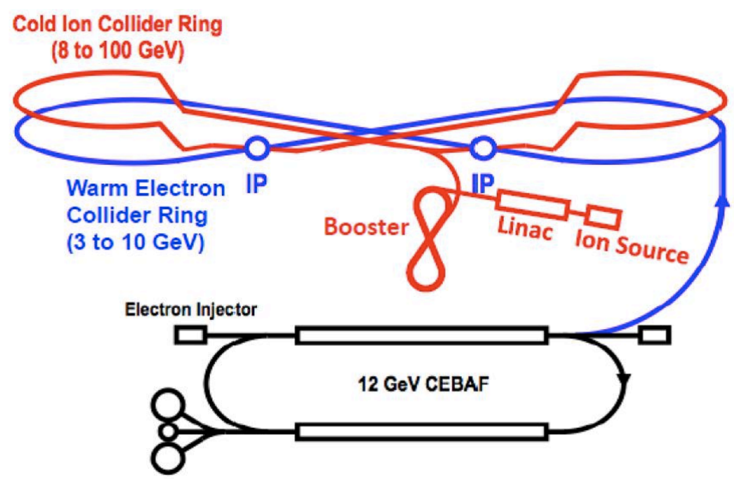


The Electron Ion Collider

Two proposals for realization of the Science Case







The Electron Ion Collider

Two proposals for realization of the Science Case

For e-N collisions at the EIC:

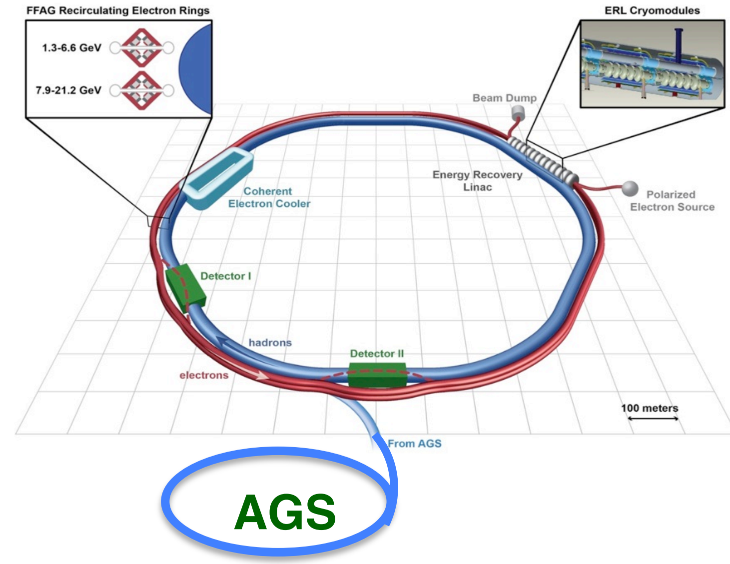
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity L_{ep} ~ 10^{33-34} $cm^{-2}sec^{-1}$
  100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM

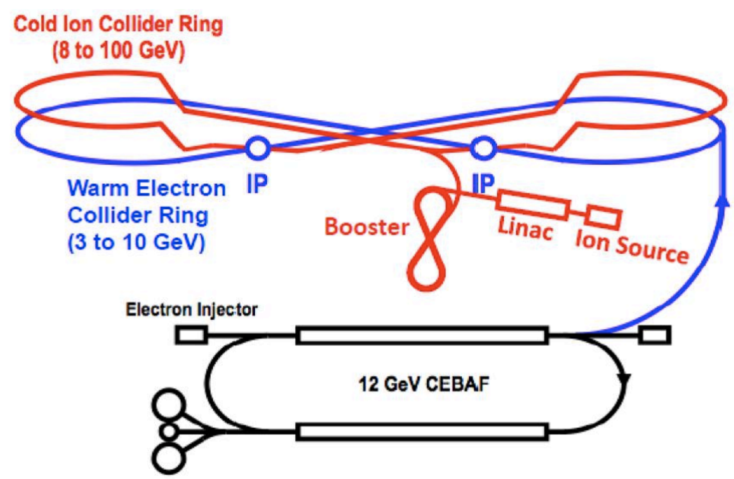
For e-A collisions at the EIC:

- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

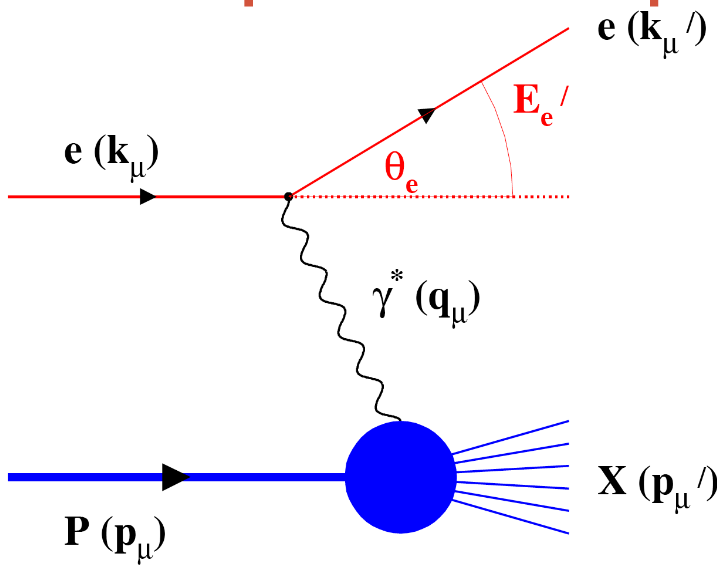
World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

Both designs use DOE's significant investments in infrastructure





Deep Inelastic Scattering → Precision microscope with superfine control



Q^2 →Measure of resolution

y → Measure of inelasticity

x → Measure of momentum fraction
Of the struck quark in a proton

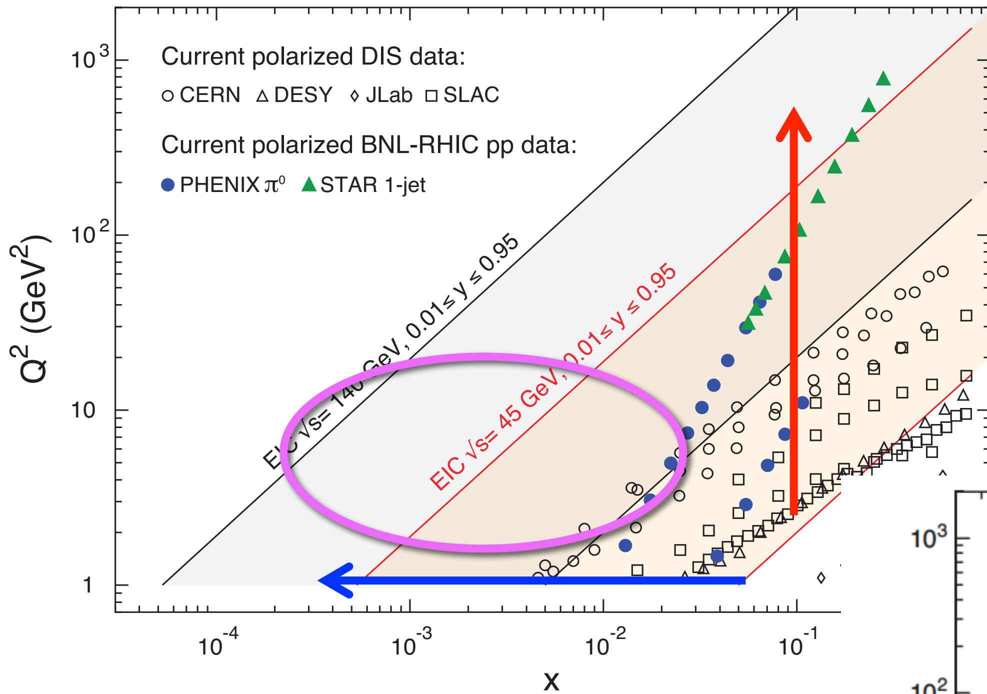
$Q^2 = S\ x\ y$

Inclusive events: e+p/A → e'+X
Detect only the scattered lepton in the detector

Semi-Inclusive events: e+p/A → e'+h(π,K,p,jet)+X
Detect the scattered lepton in coincidence with identified hadrons/jets in the detector

Exclusive events: e+p/A → e'+ p'/A'+ h(π,K,p,jet)
Detect every things including scattered proton/nucleus (or its fragments)

US EIC: Kinematic reach & properties

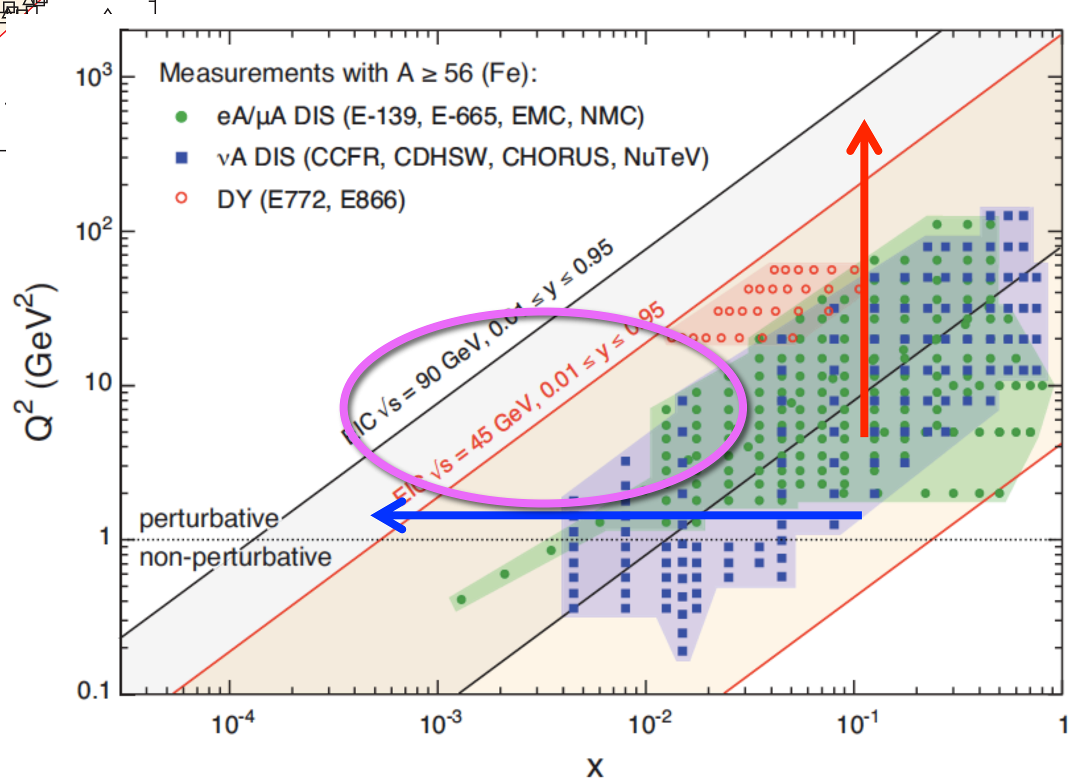


For e-N collisions at the EIC:

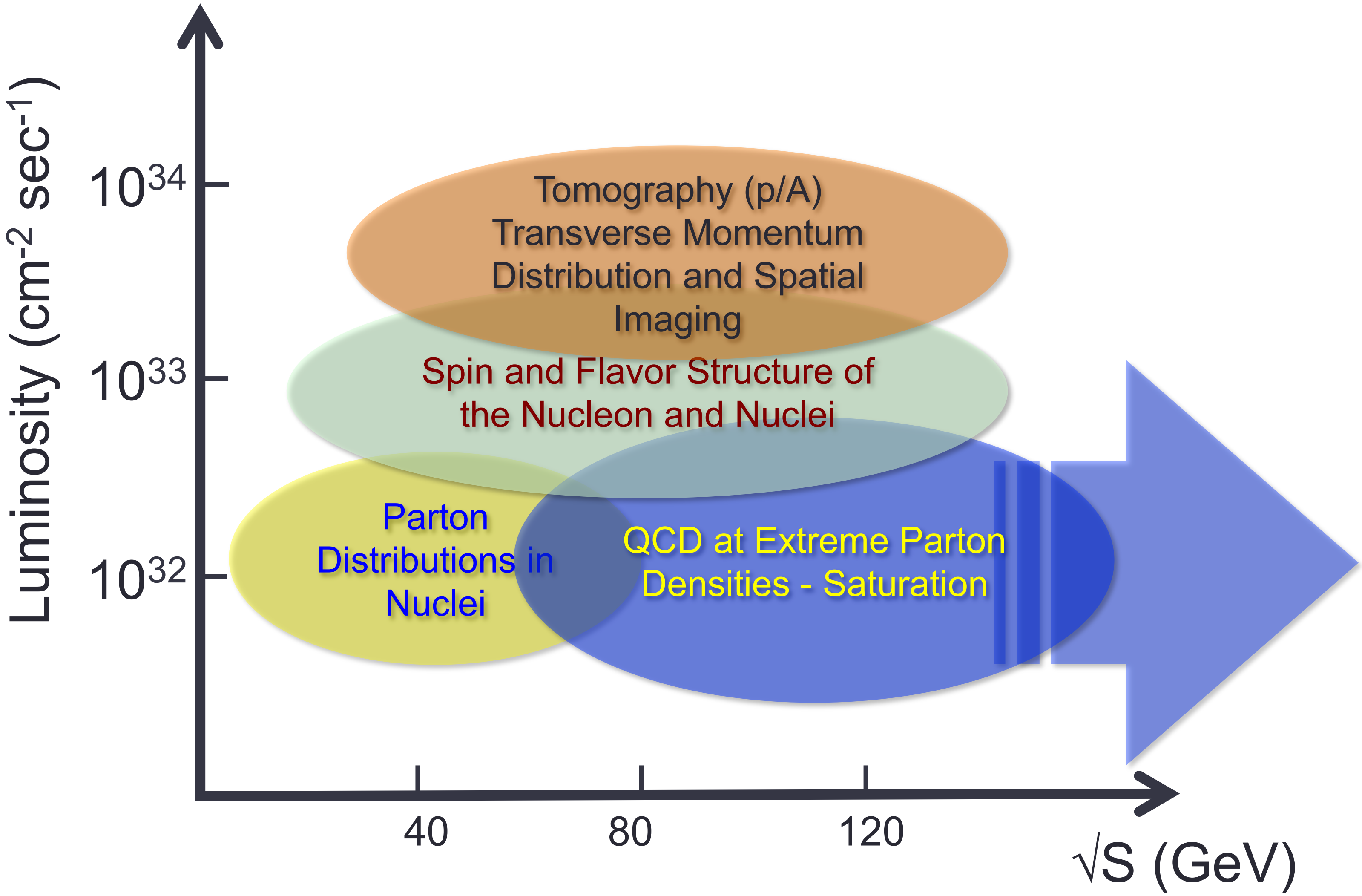
- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

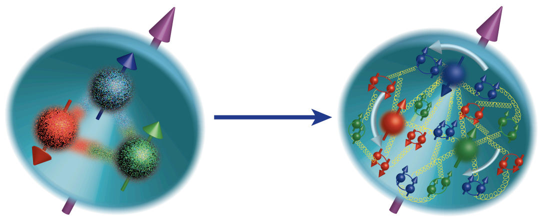
For e-A collisions at the EIC:

- ✓ **Wide range in nuclei**
- ✓ Lum. per nucleon same as e-p
- ✓ Variable center of mass energy
- ✓ Wide x range (evolution)
- ✓ Wide x region (reach high gluon densities)

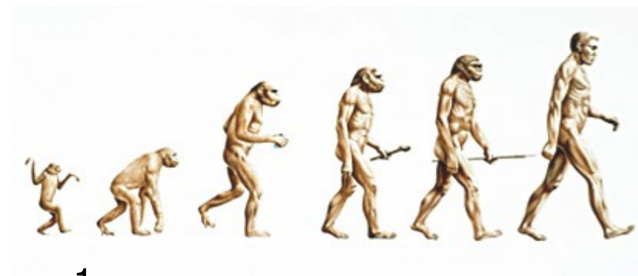


Physics vs. Luminosity & Energy





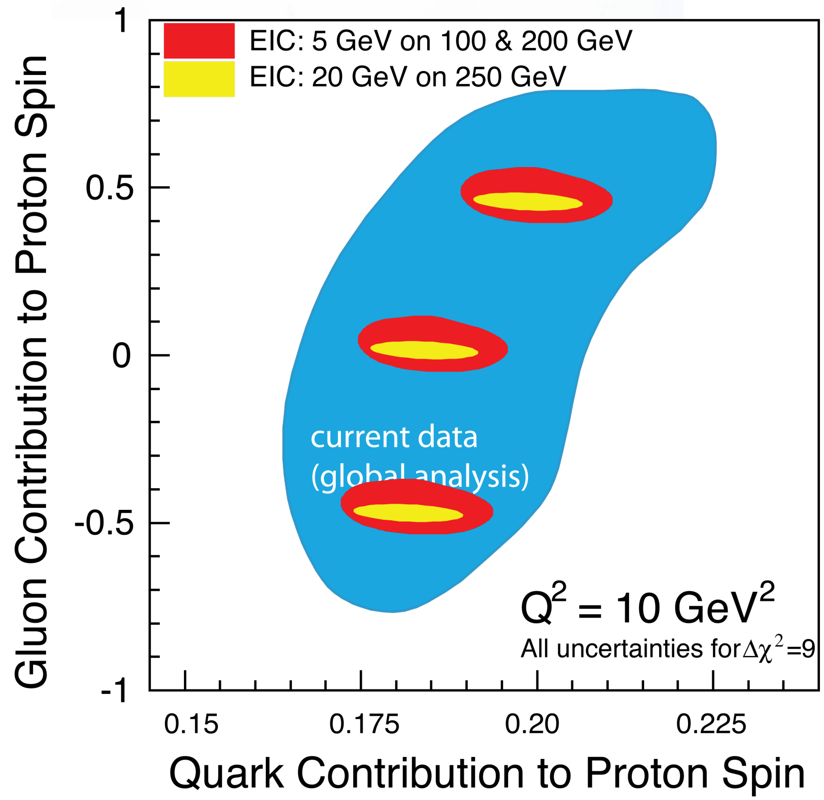
Our Understanding of Nucleon Spin



$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

$\Delta\Sigma/2$ = Quark contribution to Proton Spin
L_Q = Quark Orbital Ang. Mom
Δg = Gluon contribution to Proton Spin
L_G = Gluon Orbital Ang. Mom

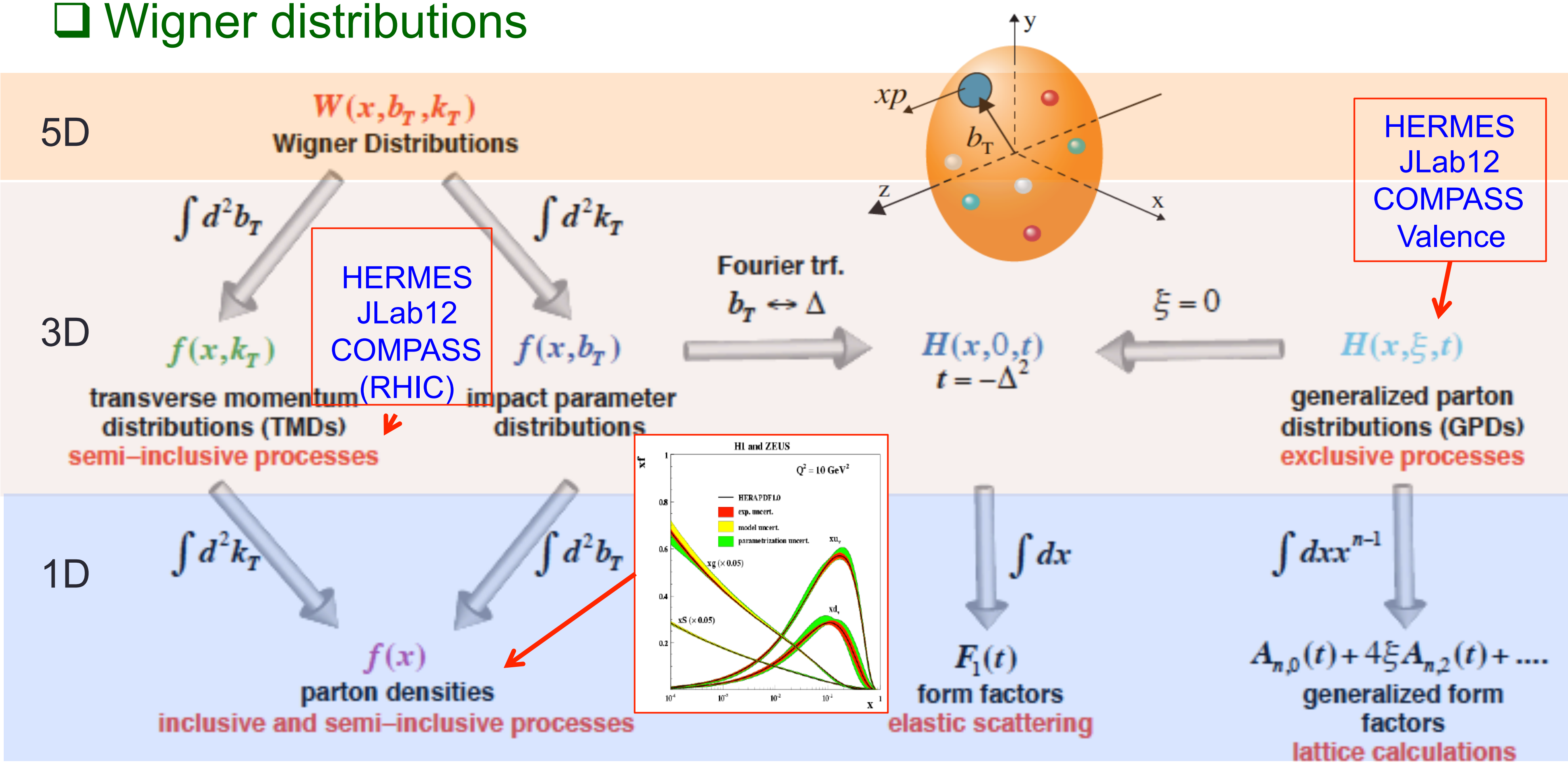
Precision in $\Delta\Sigma$ and Δg → A clear idea Of the magnitude of L_Q+L_G



Unified view of the Nucleon Structure

See Talks by Bachetta, Hatta, Gonzalez, Martin, Kumericki

❑ Wigner distributions



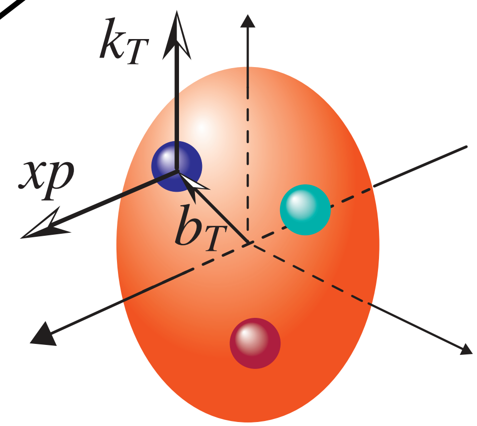
❑ (2+1)D imaging Quarks (Jlab/COMPASS) , **Gluons (EIC)**

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

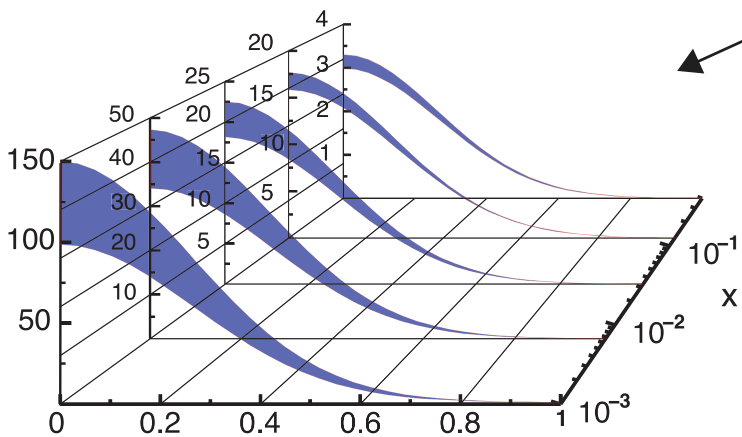
3-Dimensional Imaging Quarks and Gluons

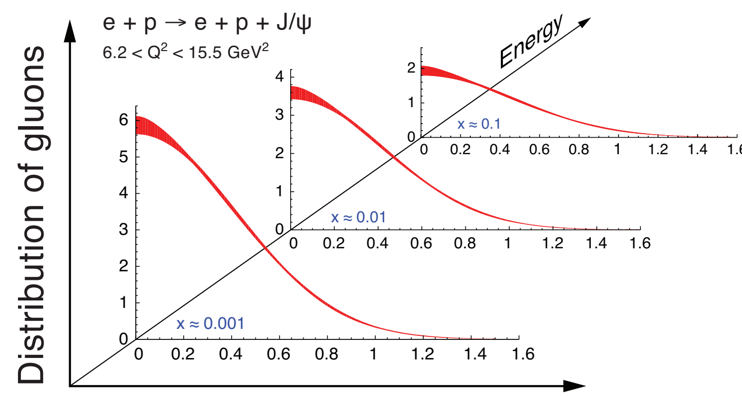
$W(x,b_T,k_T)$

Momentum space $\int d^2b_T$ $\int d^2k_T$ *Coordinate space*



Quarks $f(x,k_T)$ $f(x,b_T)$ Gluons

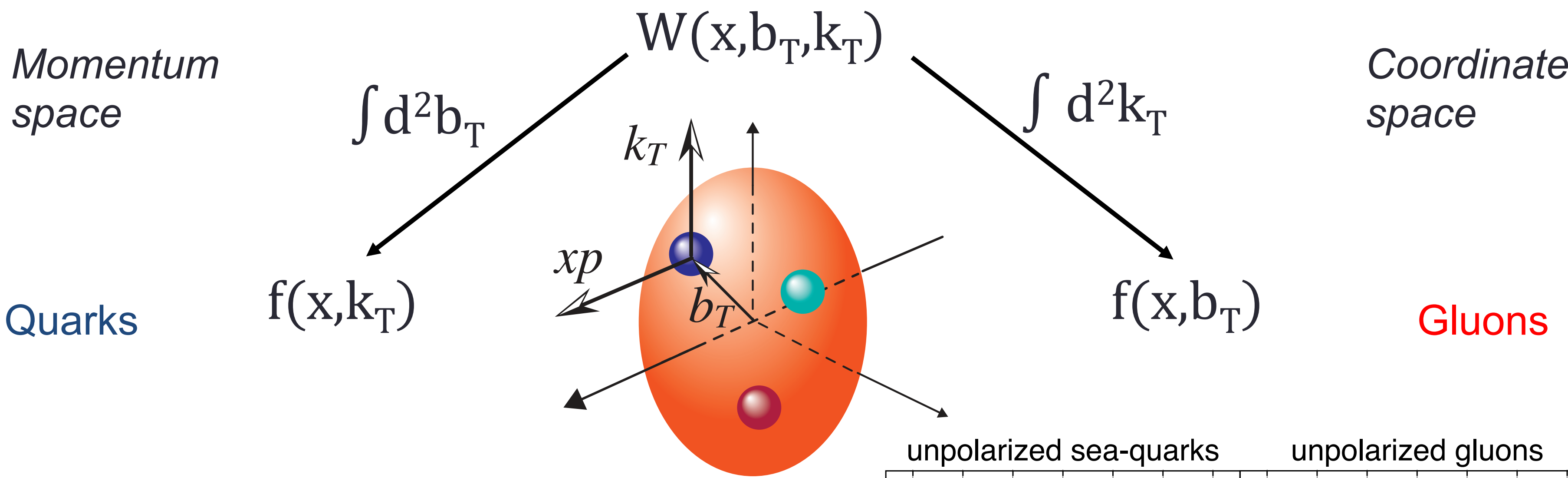


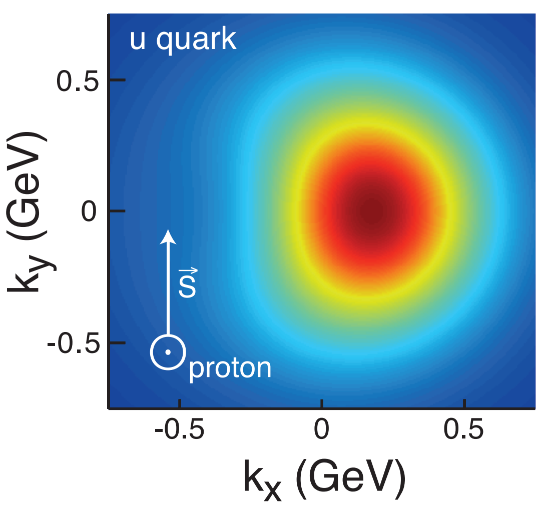


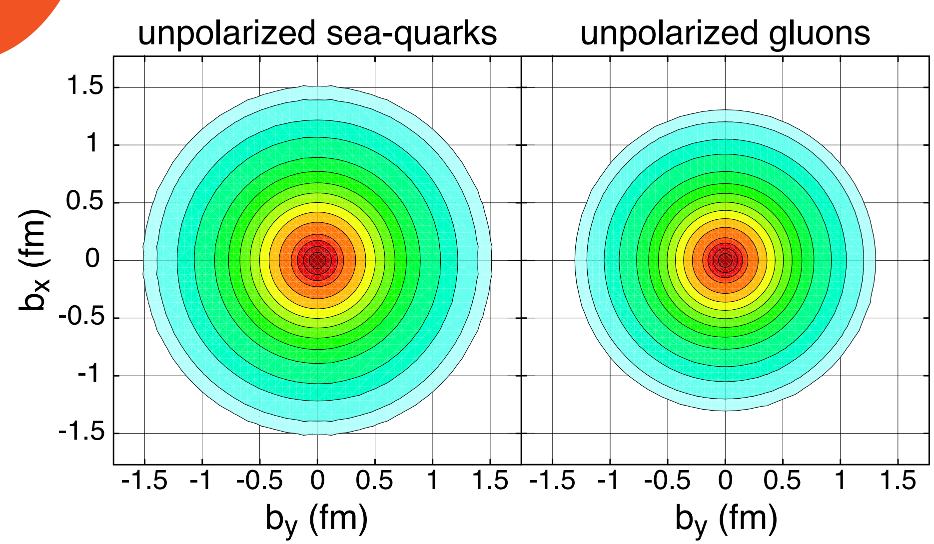
Spin-dependent 3D momentum space images from semi-inclusive scattering

Spin-dependent 2D (transverse spatial) + 1D (longitudinal momentum) coordinate space images from exclusive scattering

3-Dimensional Imaging Quarks and Gluons







Position r X Momentum p → Orbital Motion of Partons

Prospect of direct comparison with lattice QCD

➢ **Quark GPDs and its orbital contribution to the proton spin:**

$$J_q = \frac{1}{2}\lim_{t\to 0}\int dx\, x \quad \textit{(General. Parton Dist.s H,E)} \quad = \frac{1}{2}\Delta q + L_q$$

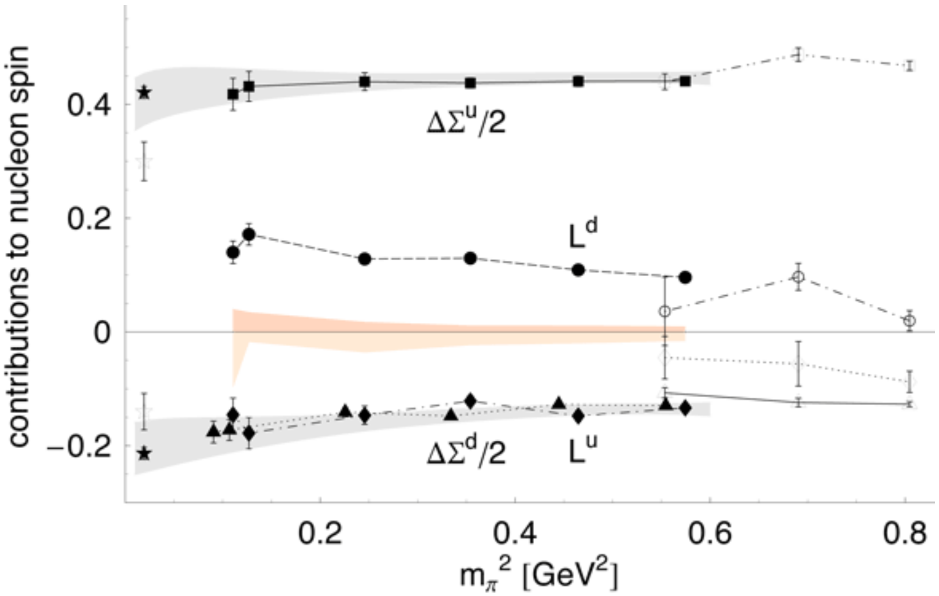
The first meaningful constraint on quark orbital contribution to proton spin by combining the sea from the EIC and valence region from JLab12/COMPASS

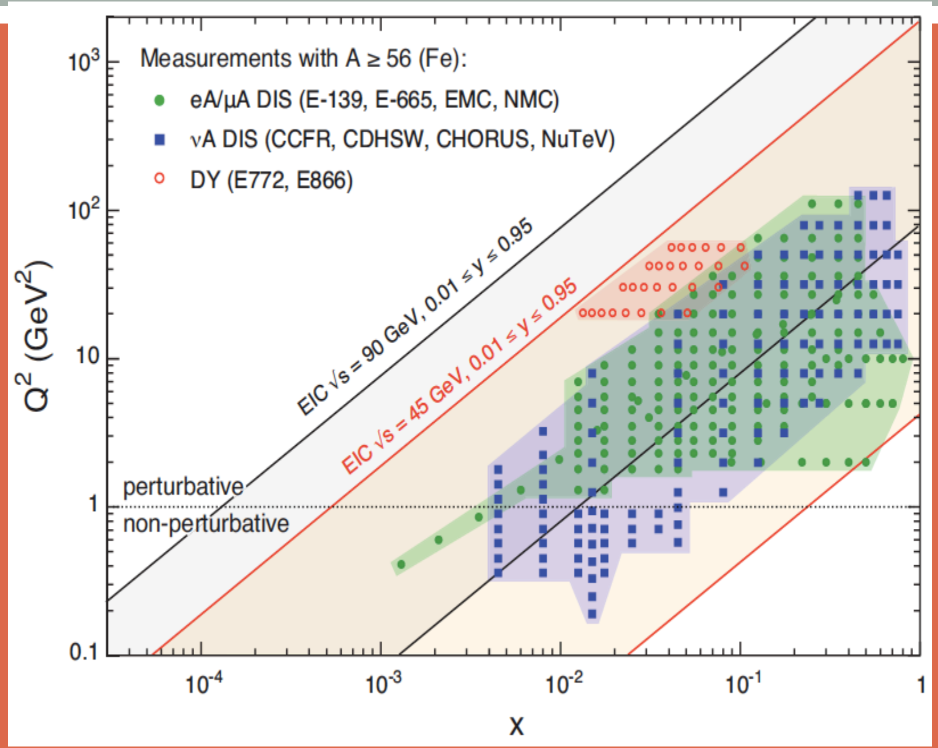
$J_{q,}$ calculated on Lattice QCD:

Future:

New developments on LQCD calculating parton distributions including gluon distributions:

X. Ji et al. PRL 111 (2013) 112002
Y. Hatta, PRD89 (2014) 8, 085030
& Y.-Q. Ma, J.-W. Qiu 1404.6860





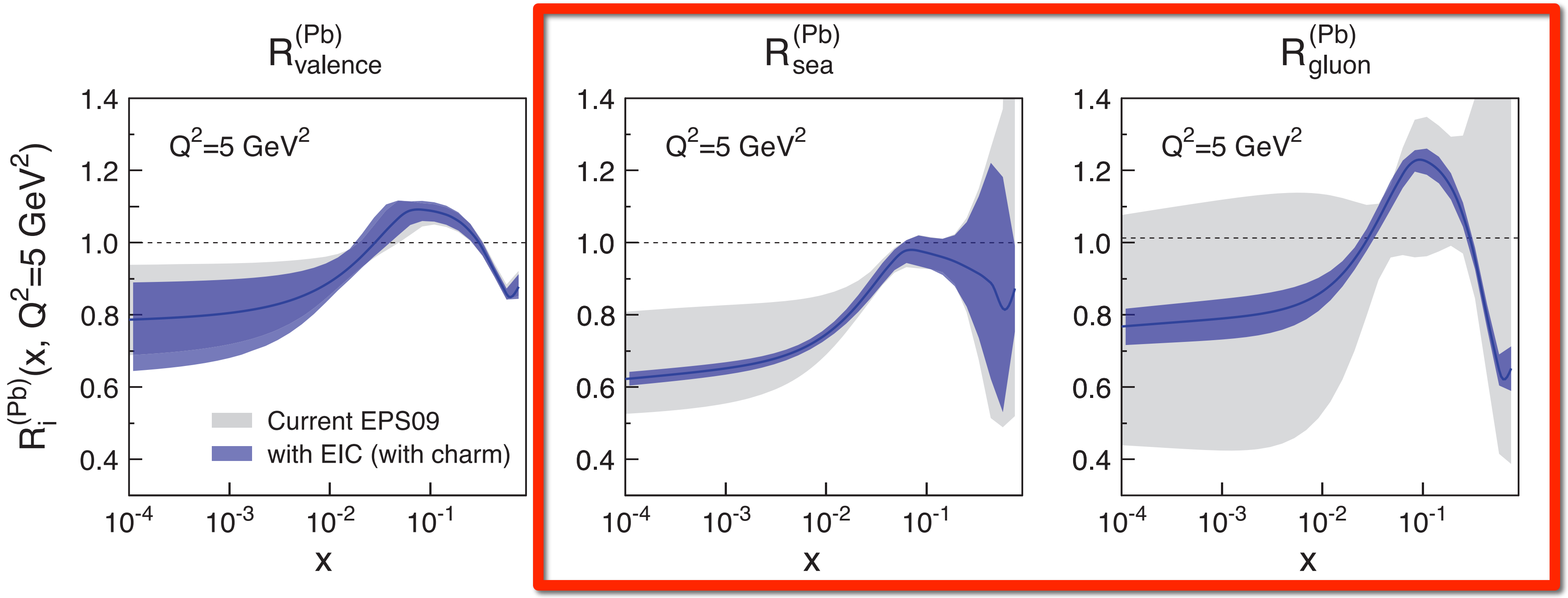
Nucleus: A laboratory for QCD

What do we know about the gluons in nuclei? Very little!

Does gluon density saturate? Does it produce a unique and universal state of matter?

Parton propagation and interaction in nuclei (vs. protons)

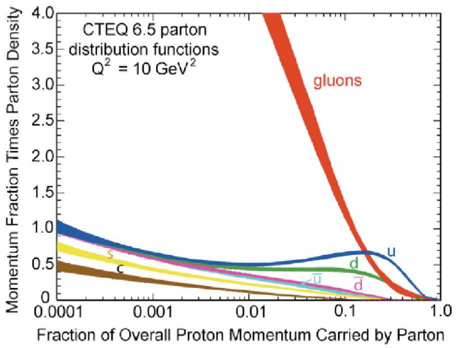
EIC: impact on the knowledge of nPDFs



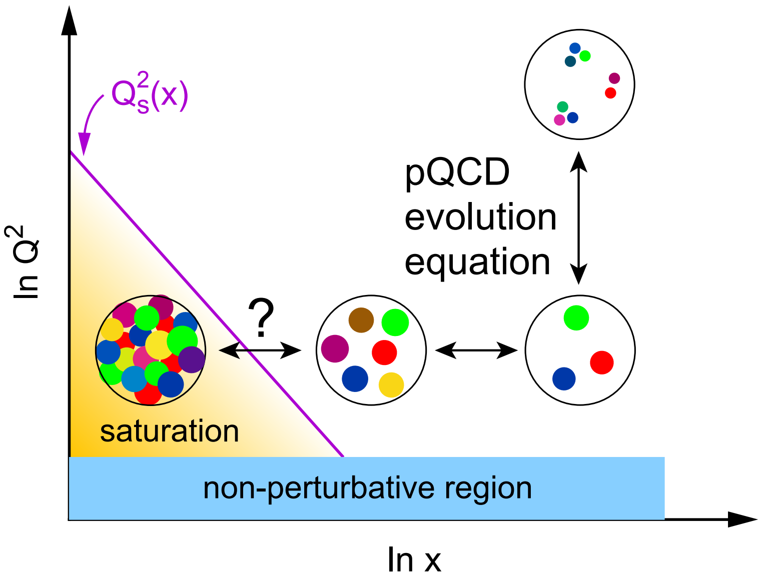
Ratio of Parton Distribution Functions of Pb over Proton:

- Without EIC, large uncertainties in **nuclear sea quarks and gluons**
- With EIC significantly reduces uncertainties

- Impossible for current and future pA data at RHIC & LHC data to achieve



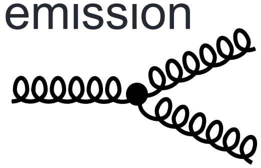
What do we learn from low-x studies?



What tames the low-x rise?

- New evolution eqn.s @ low x & moderate Q^2
- Saturation Scale $Q_S(x)$ where gluon emission and recombination comparable

gluon emission



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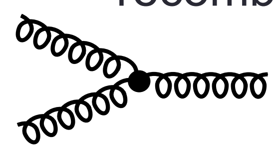


gluon recombination

At Q_S

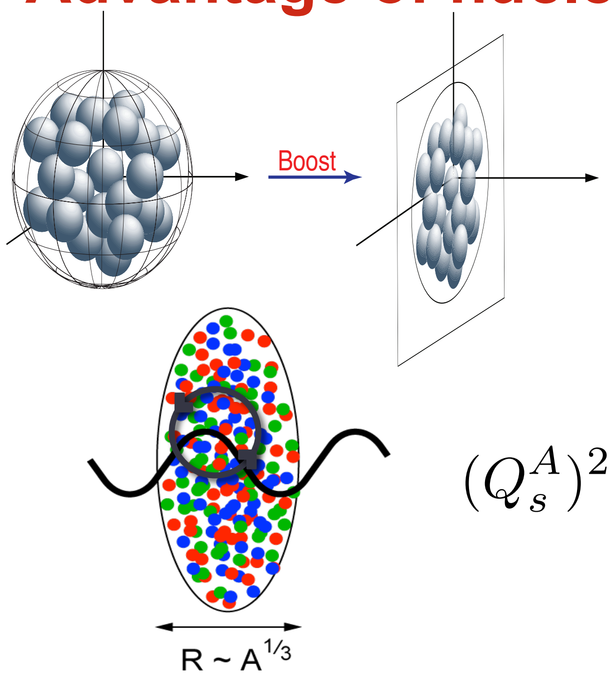
First observation of gluon recombination effects in nuclei:
➔leading to a *collective* gluonic system!

First observation of g-g recombination in *different* nuclei
→ Is this a universal property?
→ Is the Color Glass Condensate the correct effective theory?

How to explore/study this new phase of matter?

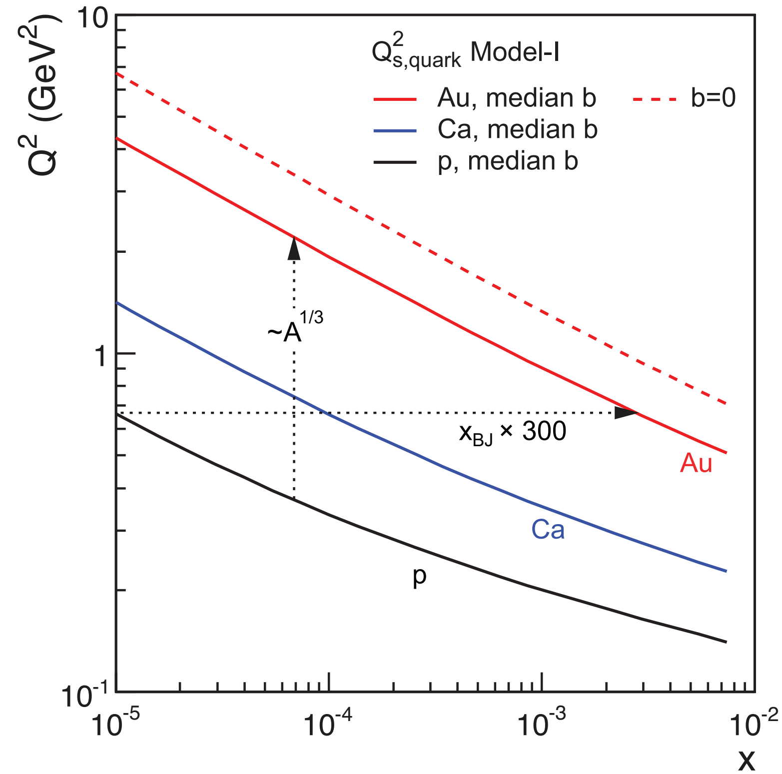
(multi-TeV) e-p collider (LHeC) OR **a (multi-10s GeV) e-A collider**

Advantage of nucleus →



$$(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x}\right]^{1/3}$$

L ~ $(2m_N x)^{-1}$ > 2 R_A ~ $A^{1/3}$



Enhancement of Q_S with A:
Saturation regime reached at significantly lower energy (read: "cost") in nuclei

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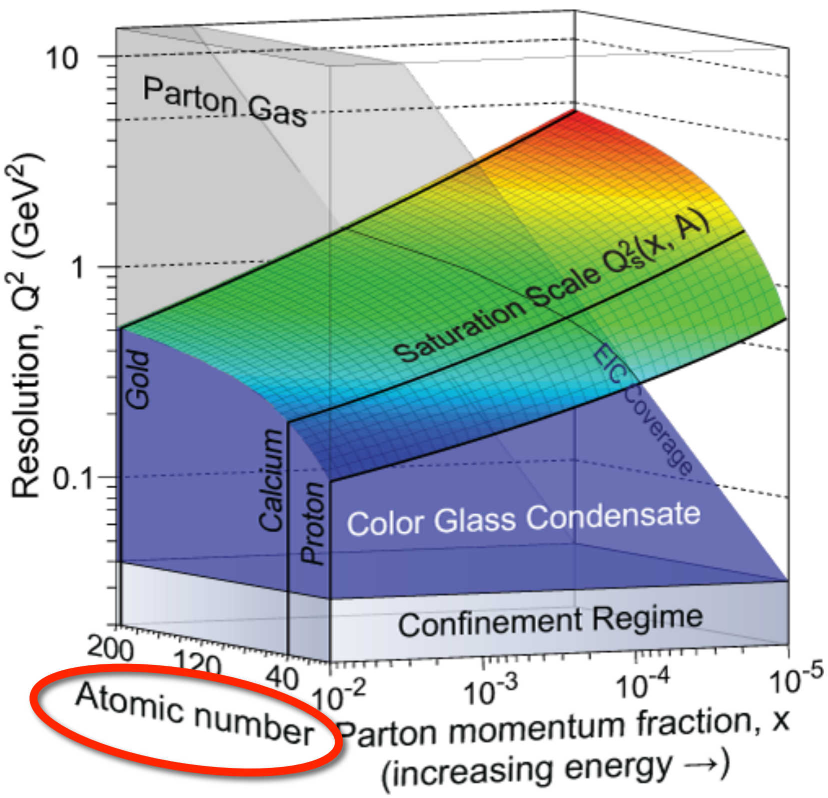
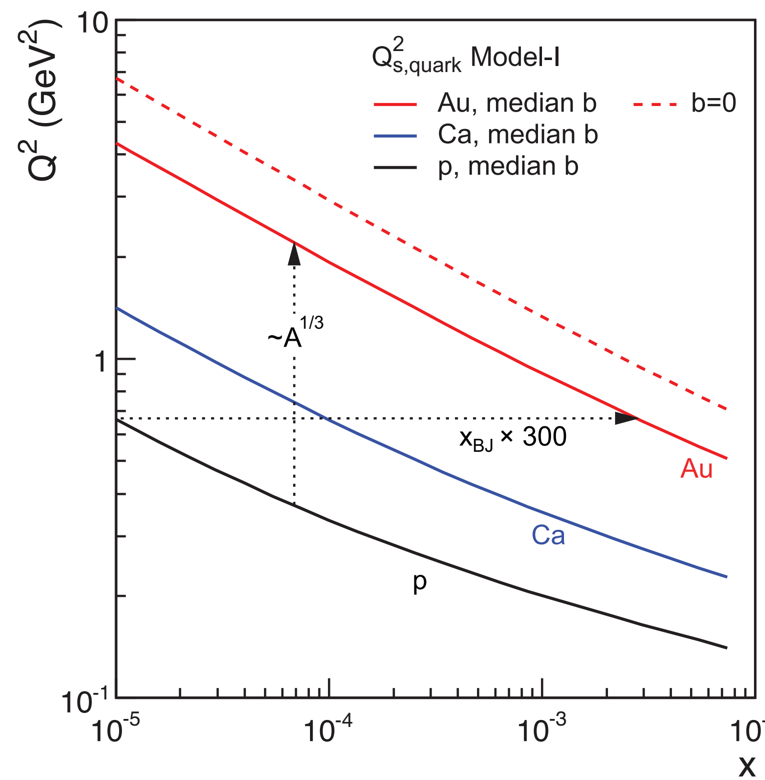


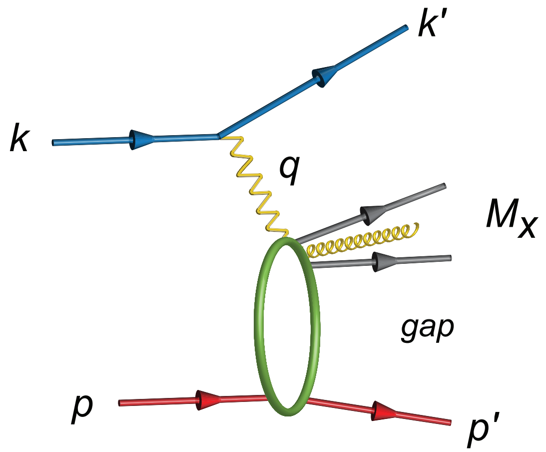


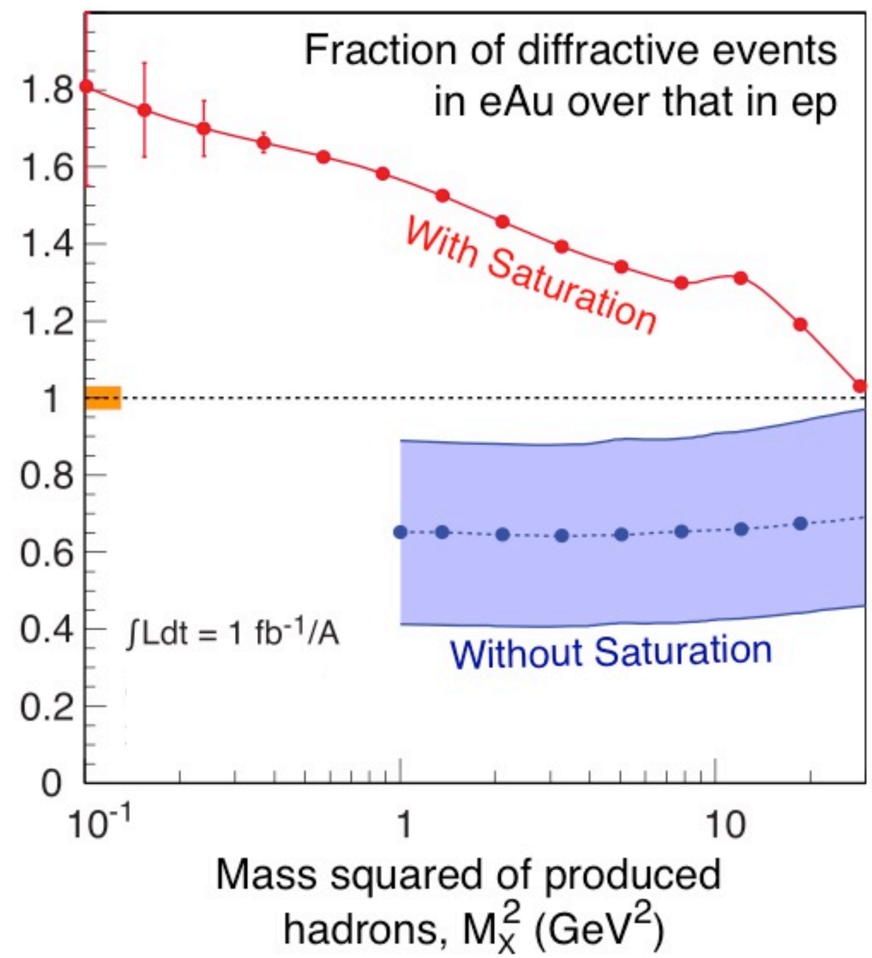
Enhancement of Q_S with A:
Saturation regime reached at significantly lower energy (read: "cost") in nuclei

Saturation/CGC: What to measure?

Many ways to get to gluon distribution in nuclei, but diffraction most sensitive:

$$\sigma_{\text{diff}} \propto [g(x, Q^2)]^2$$





At HERA

ep: 10-15% diffractive

At EIC eA, if Saturation/CGC

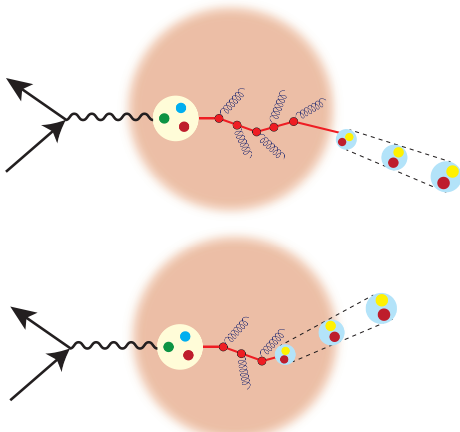
eA: 25-30% diffractive

Emergence of Hadrons from Partons

Nucleus as a Femtometer sized filter

Unprecedented ν, the virtual photon energy range @ EIC : *precision & control*

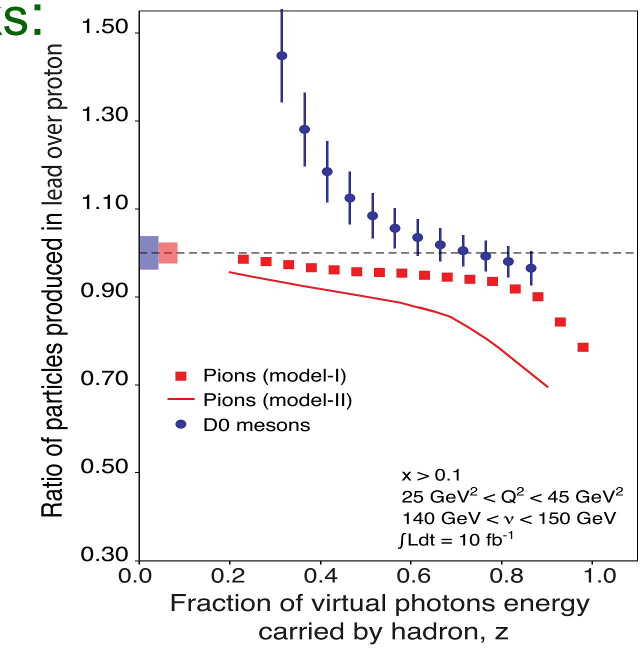
$$\nu = \frac{Q^2}{2mx}$$



Control of ν by selecting kinematics;
Also under control the nuclear size.

Colored quark emerges as color neutral hadron ➔ What is nature telling us about confinement?

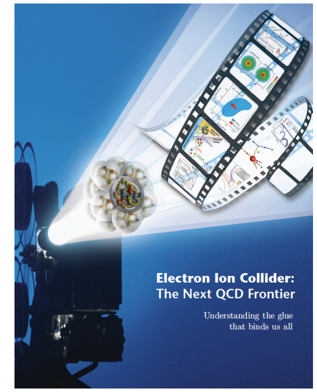
Energy loss by light vs. heavy quarks:



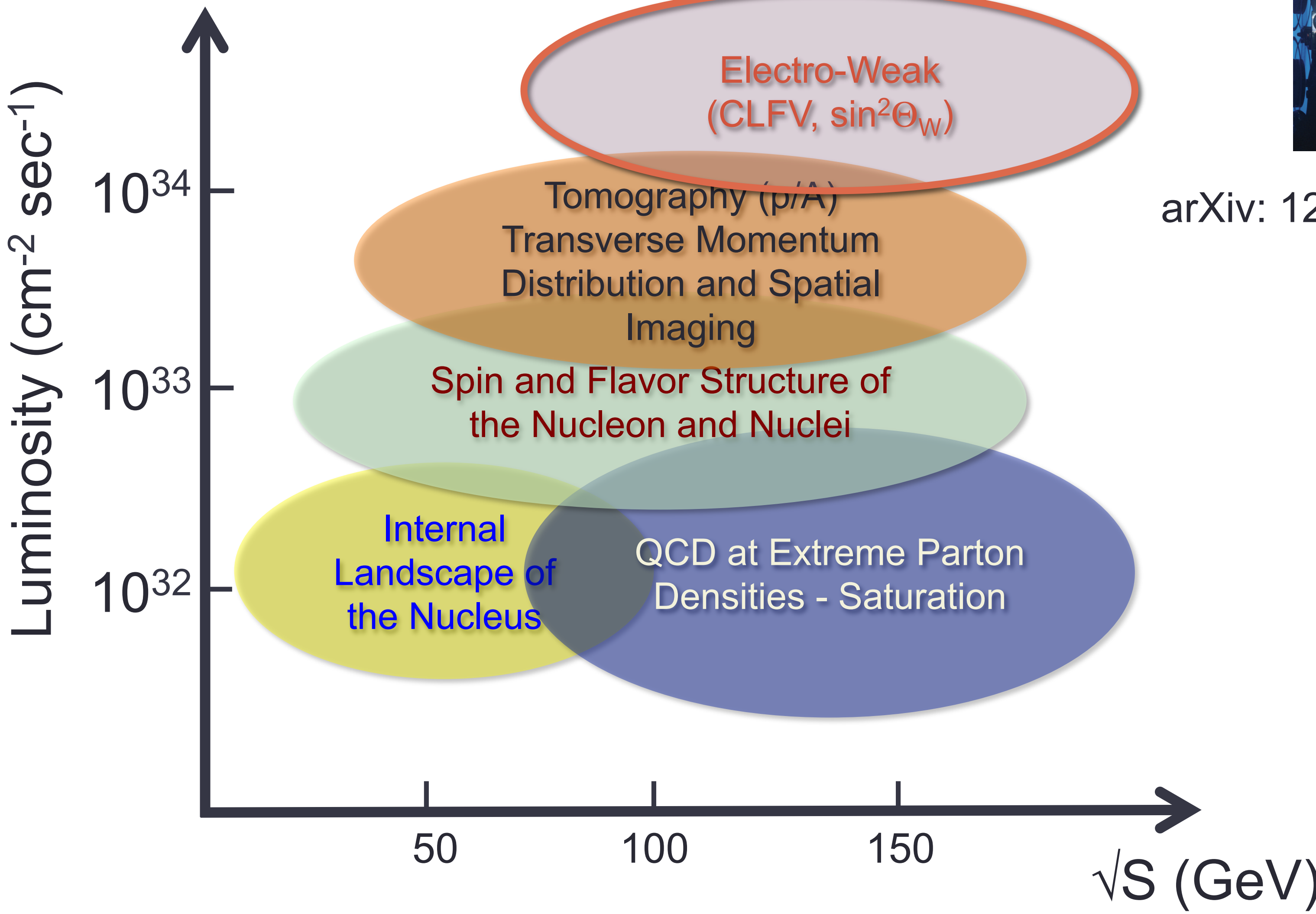
Identify π vs. D^0 **(charm)** mesons in e-A collisions: Understand energy loss of light vs. heavy quarks traversing the cold nuclear matter:
Connect to energy loss in Hot QCD

Need the collider energy of EIC and its control on parton kinematics

Physics vs. Luminosity & Energy

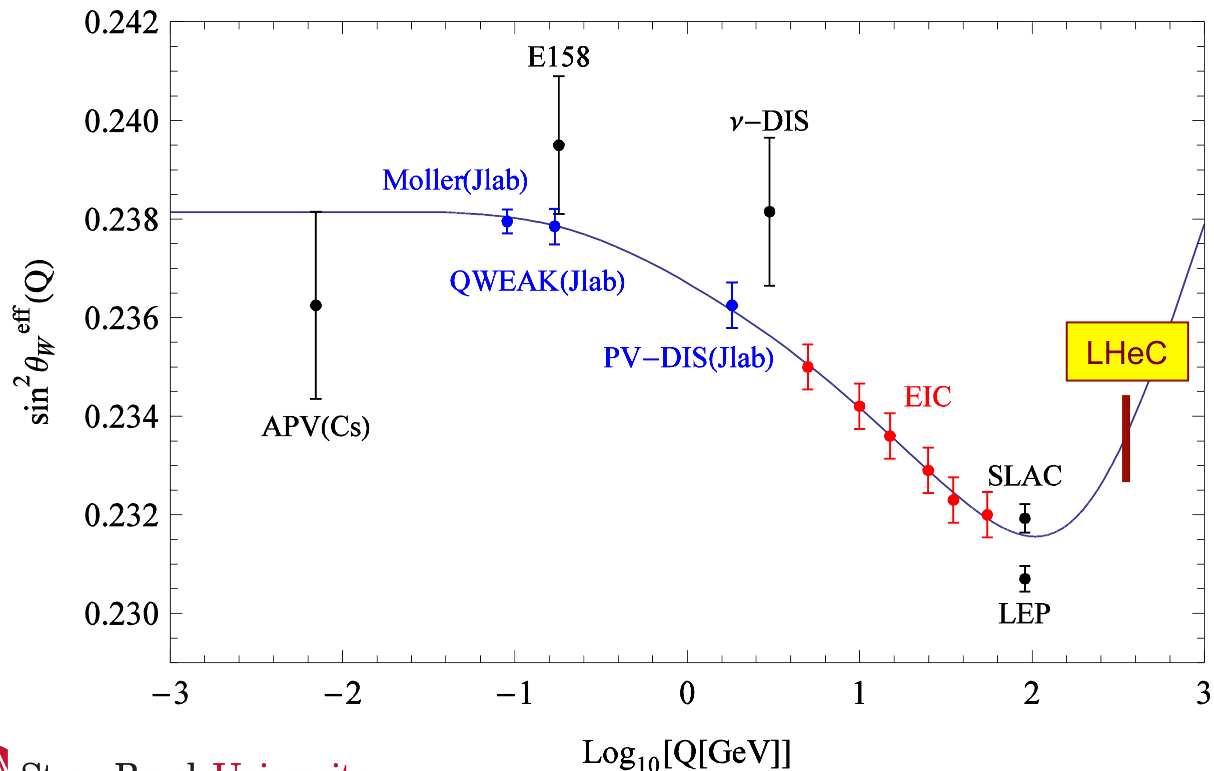


arXiv: 1212.1701.v3



$Sin^2\Theta_W$ with the EIC: Physics Beyond SM

- Precision parity violating asymmetry measurements e/D or e/p
- Deviation from the "curve" may be hints of BSM scenarios including: Lepto-Quarks, RPV SUSY extensions, E_6/Z' based extensions of the SM



Black: measurements

Blue: near future measurements

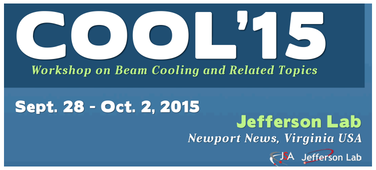
Red: US EIC projections

Maroon: LHeC Projection

Innovative Accelerator Science

On going R&D on accelerator concepts and technologies:

- High current Energy Recovery Linac (ERL)
- High current polarized electron gun
- Coherent electron cooling
- High gradient crab cavities
- Fixed Field Acceleration Gradient beam transport
- Super-ferric magnets
- Figure-8 shaped e/h rings to aid polarization of beams



Most of these are of global interest!

Realizing these for the US EIC requires *cutting edge accelerator science*

Community: Will **YOU** get involved?

EIC User Group: being formed (contact me!)

The EIC Users Meeting at Stony Brook, June 2014:

~180 participants from all over the world (Europeans and Asian QCD group representatives participated actively) :

→ http://skipper.physics.sunysb.edu/~eicug/meetings/SBU.html

Next EIC UG Meeting at University of Berkeley, January 6-9, 2016

Web pages to appear soon for registration and your input

An active Generic Detector R&D Program for EIC underway, (supported by DOE, administered by BNL):

~140 physicists, 31 institutes (5 Labs, 22 Universities, 9 Non-US Institutions) 15+ detector consortia exploring novel technologies for tracking, particle ID, calorimetry

→ *Weekly meetings, workshops and test beam activities already underway*

→ *https://wiki.bnl.gov/conferences/index.php/EIC_R%25D*

→ *MUCH TO BE DONE… despite many successes….*

Ample opportunities for your intellectual leadership and contributions!

Summary:

The EIC will profoundly impact our understanding of the **structure of nucleons and nuclei in terms of sea quarks & gluons** (SM of Physics).

→ ***The bridge between sea quark/gluons to Nuclei***

The EIC will enable **IMAGES** of **yet unexplored regions of phase spaces in QCD** with its high luminosity/energy, nuclei & beam polarization

→ ***High potential for discovery***

Outstanding questions raised by the science at HERMES, COMPASS, RHIC, LHC and Jefferson Lab, have **naturally led us to the Science and design parameters of the EIC: World wide interest and opportunity** in collaborating on the EIC

Accelerator scientists at RHIC, Jlab in collaboration with *many of you, will* provide the **intellectual and technical leadership for to realize the EIC** -- a frontier accelerator facility.

Future QCD studies, particularly for Gluons, demands an Electron Ion Collider.
It is time to realize it!

Thanks to many of my EIC Collaborators and Enthusiasts who helped in preparing these slides for the NSAC Long Range Planning Resolution Meeting.

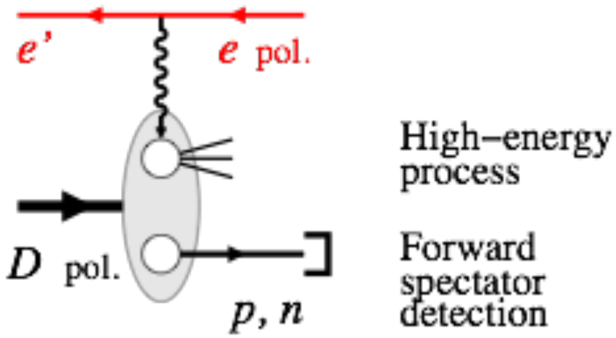
Thanks also to the EIC White Paper Writing Group without whom the EIC White Paper would not have existed.

Special thanks to Dr. Jian-Wei Qiu and Prof. Zein-Eddine Meziani, my Co-Editors for the EIC White Paper

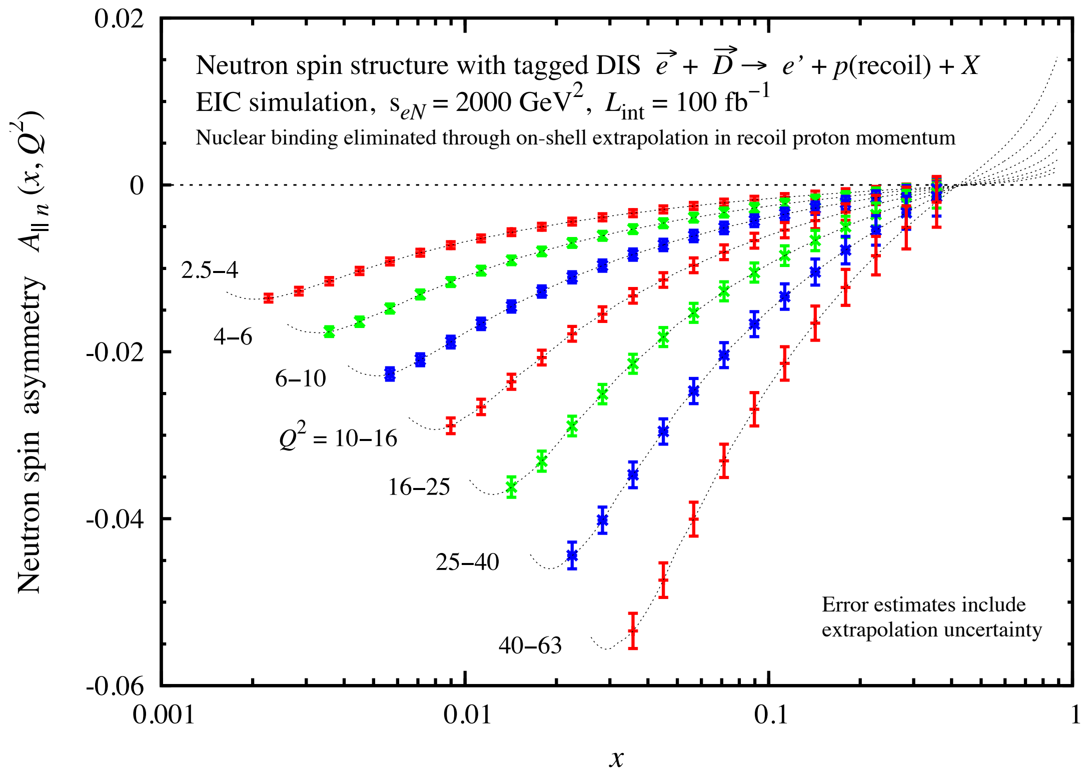
EIC: Why now?

- A set of *compelling physics questions about the gluon's role in nucleons and nuclei* has been formulated
- *Measurements that provide answers* to those compelling questions about have been identified
- *Powerful formalisms* that connect the measurements to rigorously defined properties of QCD structure & dynamics of the nucleons and nuclei have been developed
- Based on the Accelerator R&D since the 2007 LRP, **technical designs of an EIC** using existing facility infrastructure now exist

Nucleon spin the structure & study of nuclear binding



Tag the recoil proton:
Study the neutron's q-g spin structure function.
Also for other few body nuclei



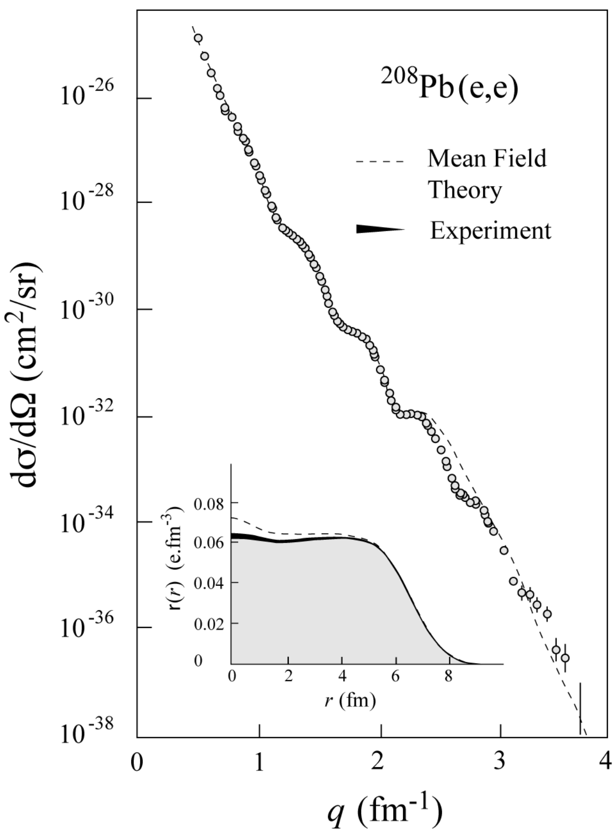
- Another area of interest: Measurement of the kinematics of the spectator nucleon indicator of the strength and (hence) the nature of its *binding* with the in-play nucleon(s):

  → quark-gluon origin of the nuclear binding

Exposing different layers of the nuclear landscape with electron scattering

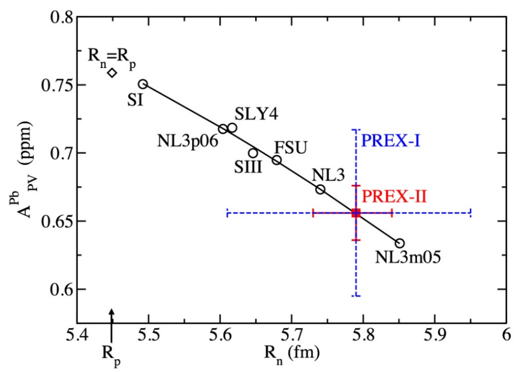
History: Electromagnetic

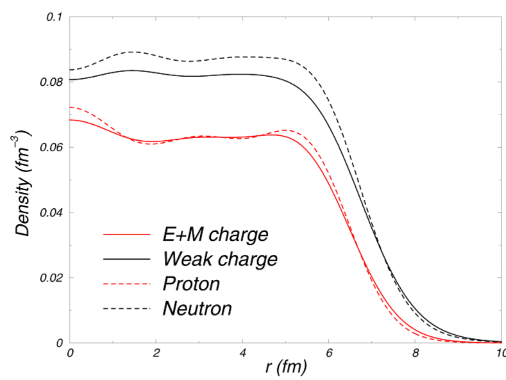
Elastic electron-nucleus scattering → charge distribution of nuclei



Present/Near-future: Electroweak

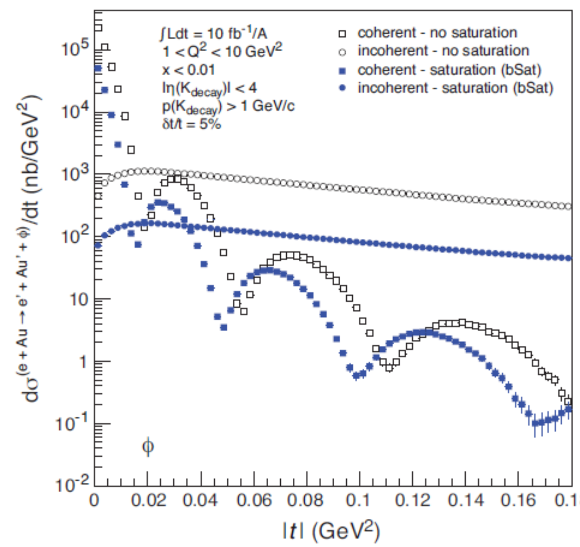
Parity-violating elastic electron-nucleus scattering (or hadronic reactions *e.g.* at FRIB) → neutron skin





Future: at the EIC: Color dipole

ϕ Production in coherent electron-nucleus scattering → gluon spatial distribution in nuclei



Fourier transform gives unprecedented info on gluon spatial distribution, including impact of gluon saturation

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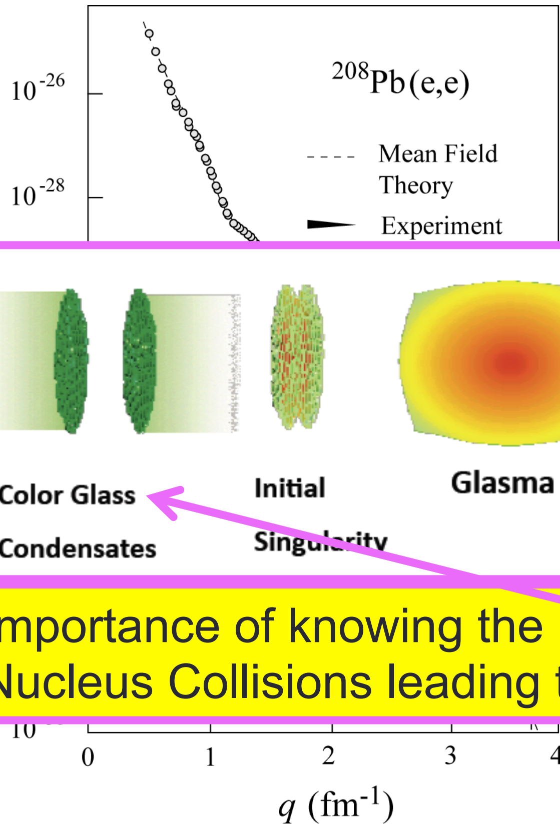

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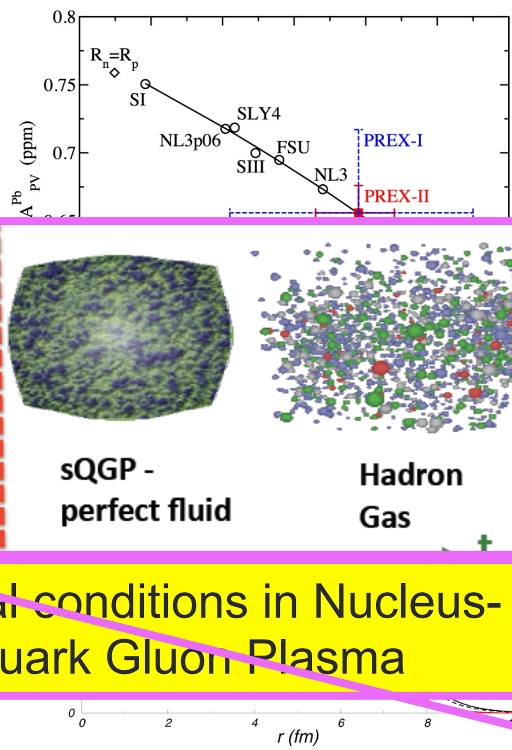

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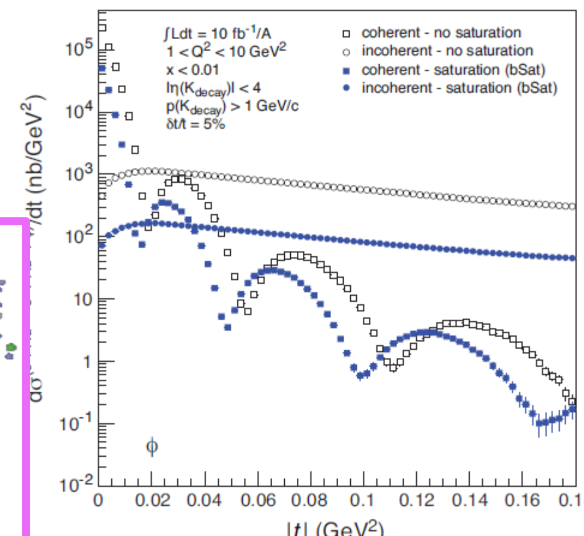
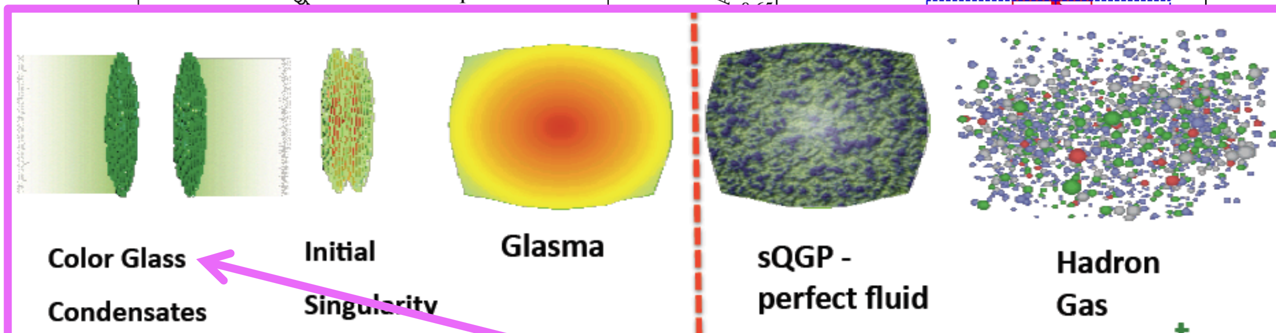
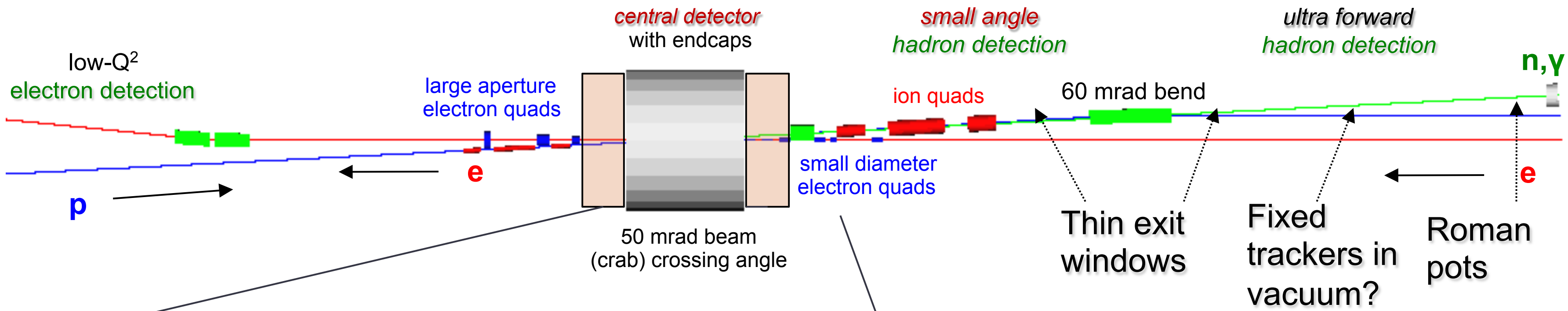


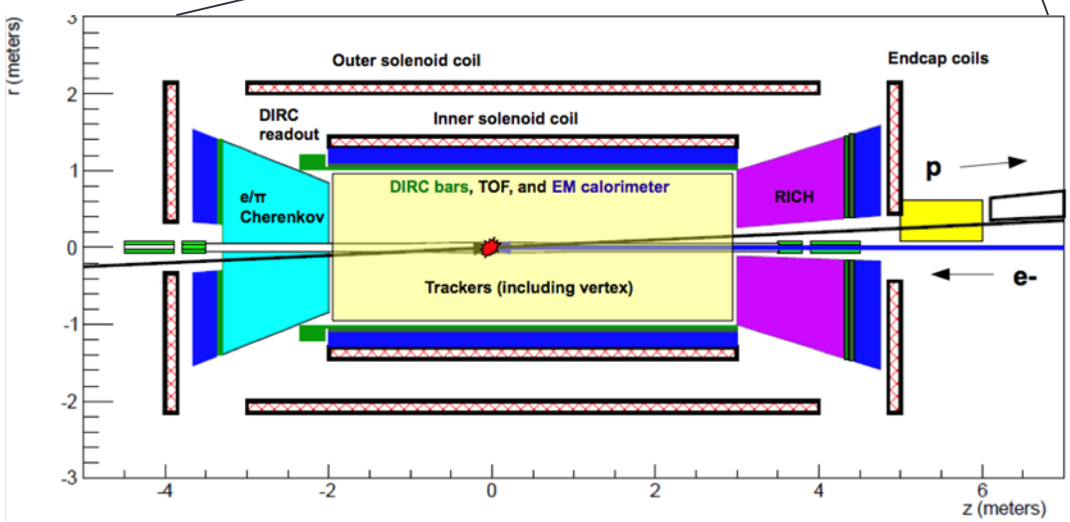


Importance of knowing the initial conditions in Nucleus-Nucleus Collisions leading to Quark Gluon Plasma

Fourier transform gives unprecedented info on gluon spatial distribution, including impact of gluon saturation

EIC at JLab: Integrated IR & Detector

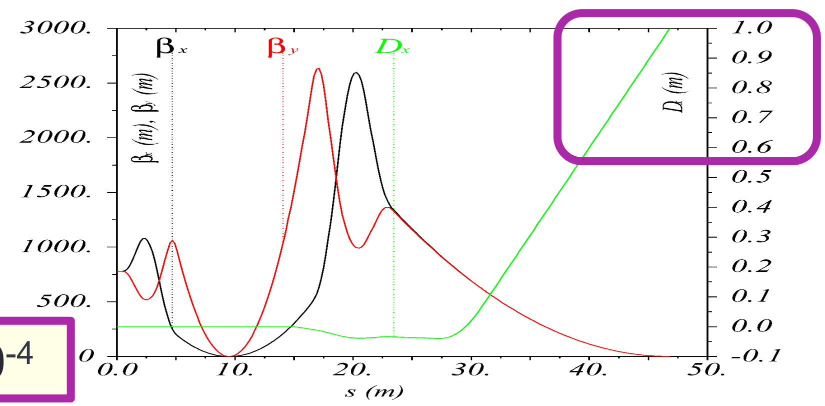




Cartoon of central detector based on dual solenoid a la ILC4 detector, but using the previous iteration interaction region design.

Hadron/Ion detection in 3 stages

- ❑ Endcap with 50 mrad crossing angle
- ❑ Small dipole covering angles to a few degrees
- ❑ Ultra-forward up to one degree, for particles passing accelerator quads



Beamline functions as spectrometer: dp/p < 3×10^{-4}

EIC Detectors & IR

Field-free electron pass thru hadron triplet magnets ⇒ minimize Sync Rad