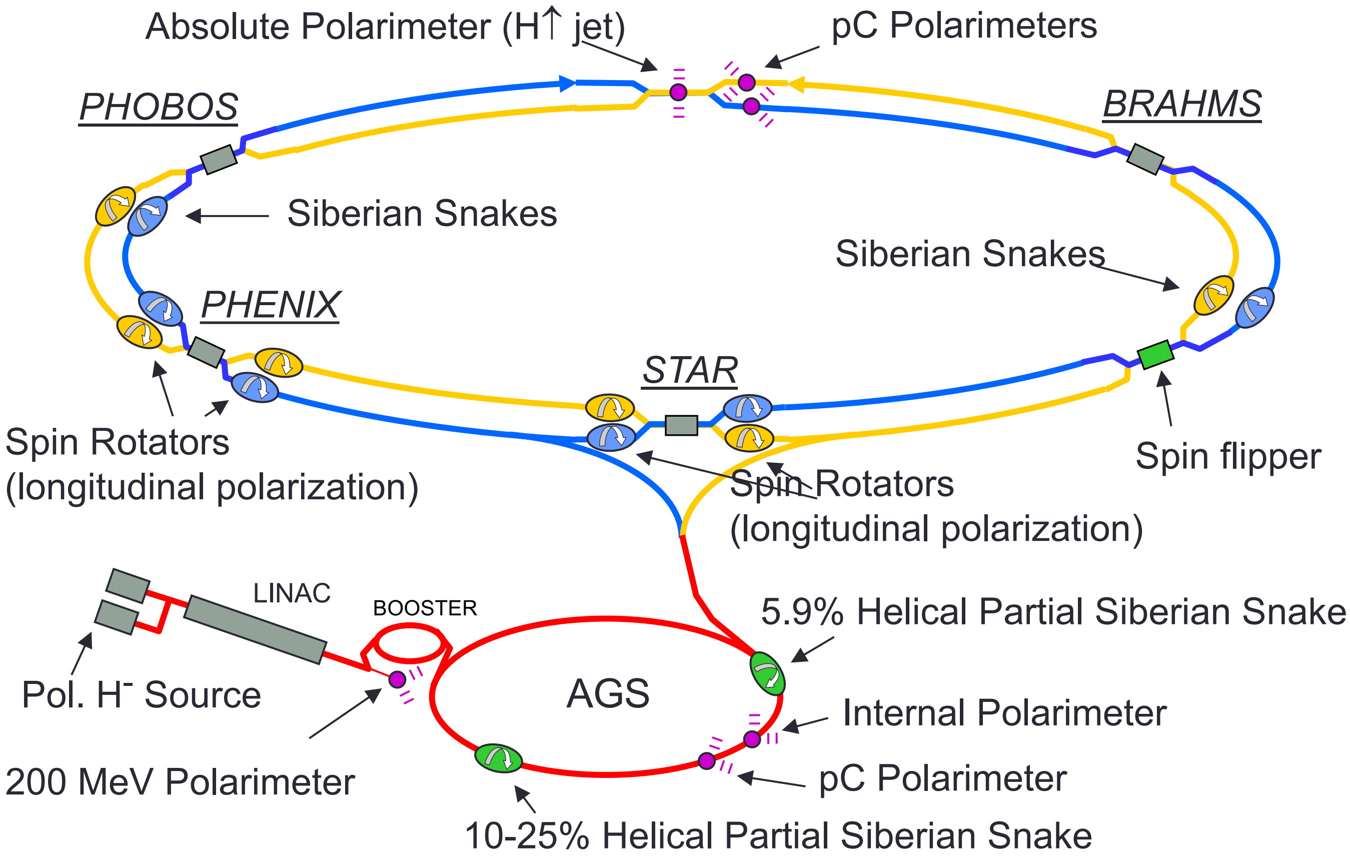
Electron Ion Collider Lecture 2

RHIC Spin (very brief)
EIC and its capabilities

August 6, 2018
Western China High Energy Physics School, Lanzhou

RHIC as a Polarized Proton Collider



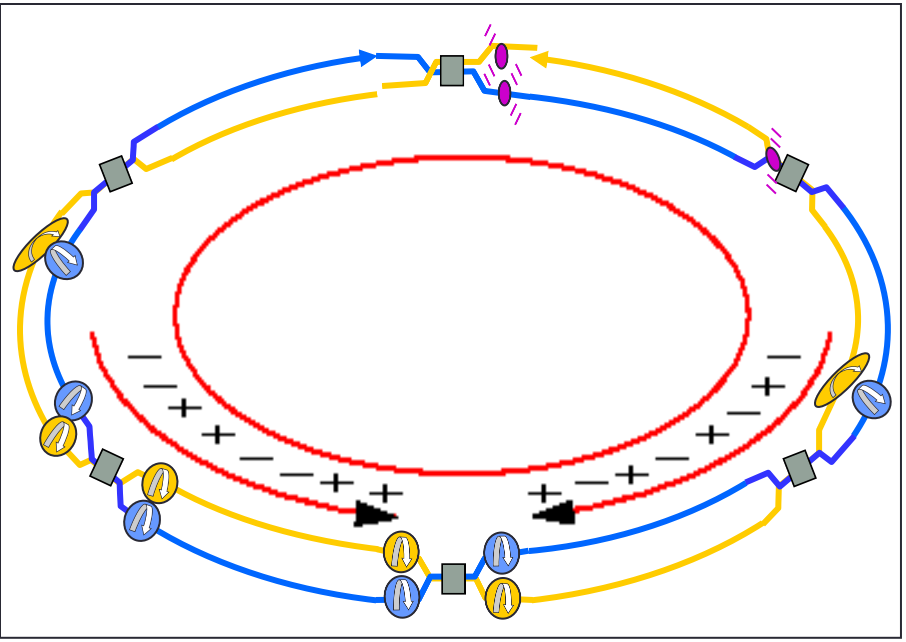
Without Siberian snakes: $\nu_{sp} = G\gamma = 1.79$ E/m → ~1000 depolarizing resonances

With Siberian snakes (local 180° spin rotators): $\nu_{sp} = ½$ → no first order resonances

Two partial Siberian snakes (11° and 27° spin rotators) in AGS

Measuring A_{LL}

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}} = \frac{1}{|P_1 P_2|} \frac{N_{++} - RN_{+-}}{N_{++} - RN_{+-}}; \qquad R = \frac{L_{++}}{L_{+-}}$$



(N) Yield
(R) Relative Luminosity
(P) Polarization

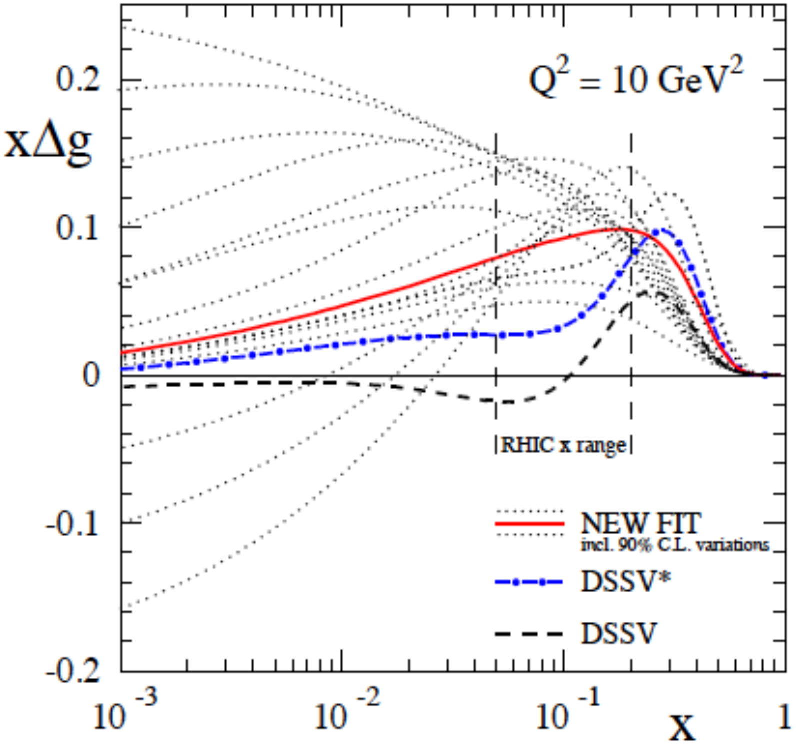
Exquisite control over false asymmetries due to ultra fast rotations of the target and probe spin.

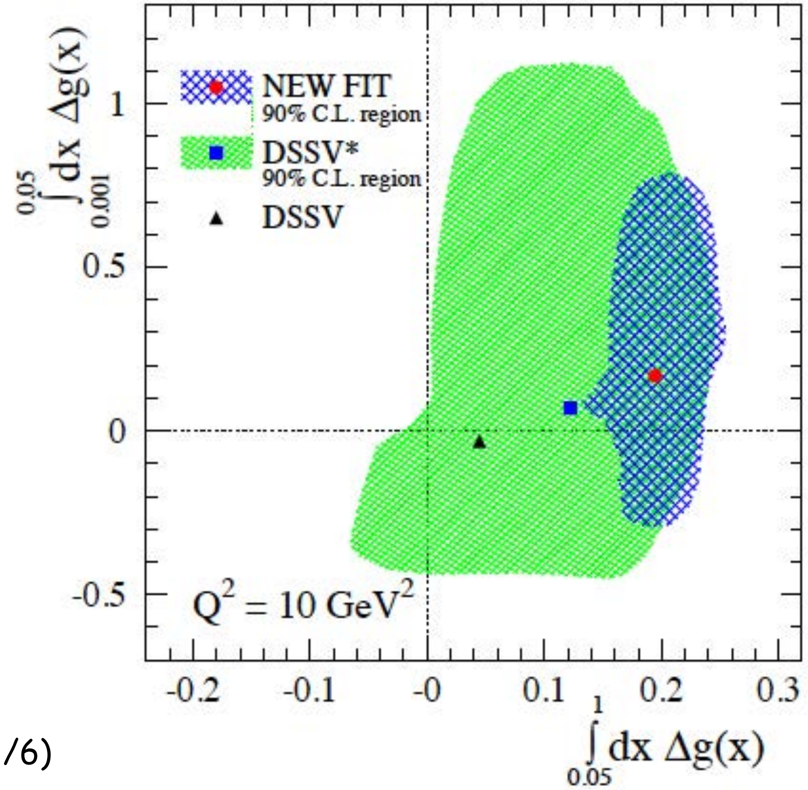
✓ Bunch spin configuration alternates every 106 ns
✓ Data for all bunch spin configurations are collected at the same time
⇒ Possibility for false asymmetries are greatly reduced

Recent global analysis: DSSV

D. deFlorian et al., arXiv:1404.4293

Wide spread at low x (x<0.05) of alternative fits consistent within 90% of C.L.

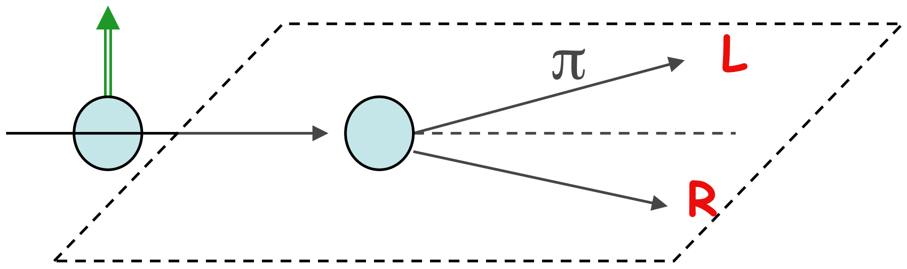




/6)

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma_Q + \boxed{\Delta G} + L_Q + L_G$$

Transverse spin introduction



$$A_N = \frac{N_L - N_R}{N_L + N_R}$$

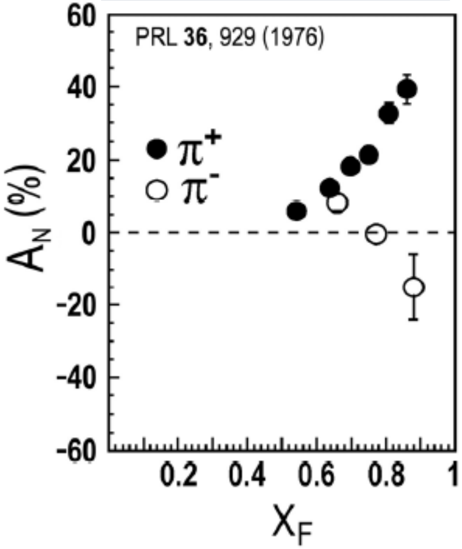
$$A_N \sim \frac{m_q}{p_T} \cdot \alpha_S \sim 0.001$$

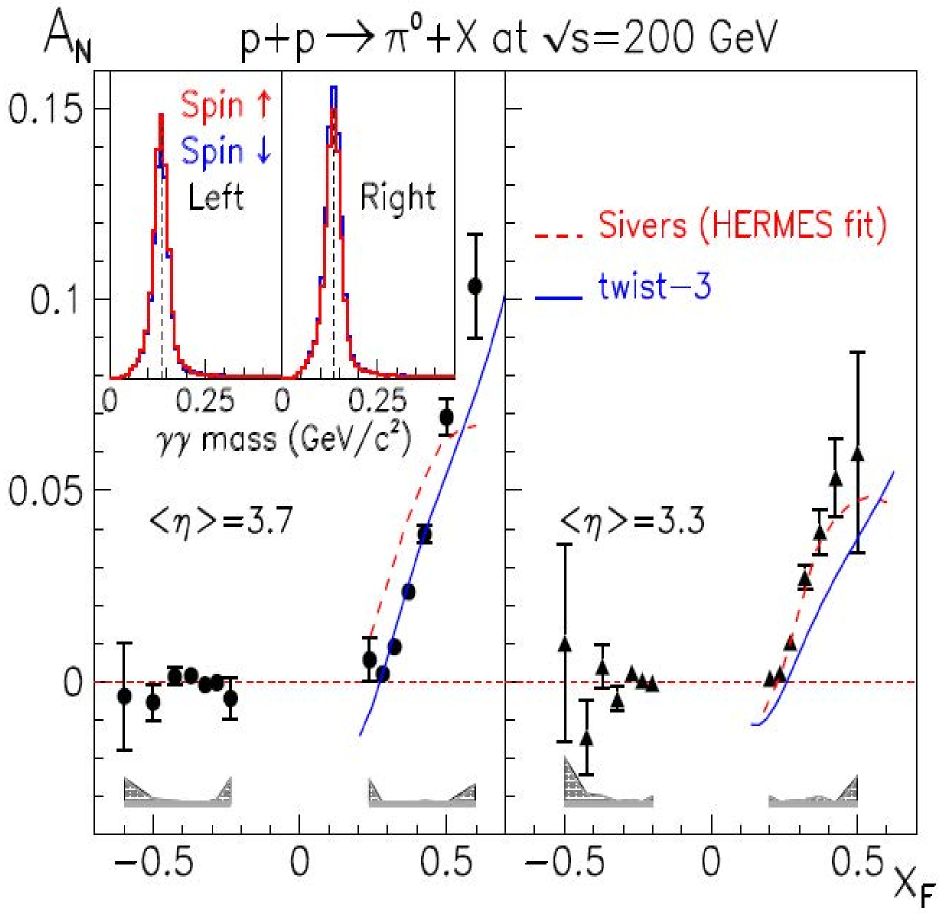
Kane, Pumplin and Repko
PRL 41 1689 (1978)

- Since people starved to measure effects at high p_T to interpret them in pQCD frameworks, this was “neglected” as it was expected to be small….. However….
- Pion production in single transverse spin collisions showed us something different….

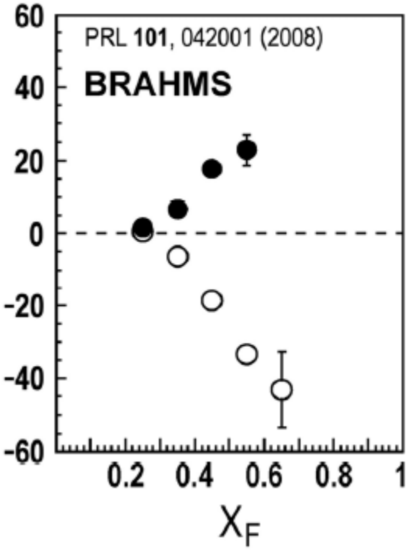
Pion asymmetries: at most CM energies!

ZGS/ANL
√s=4.9 GeV



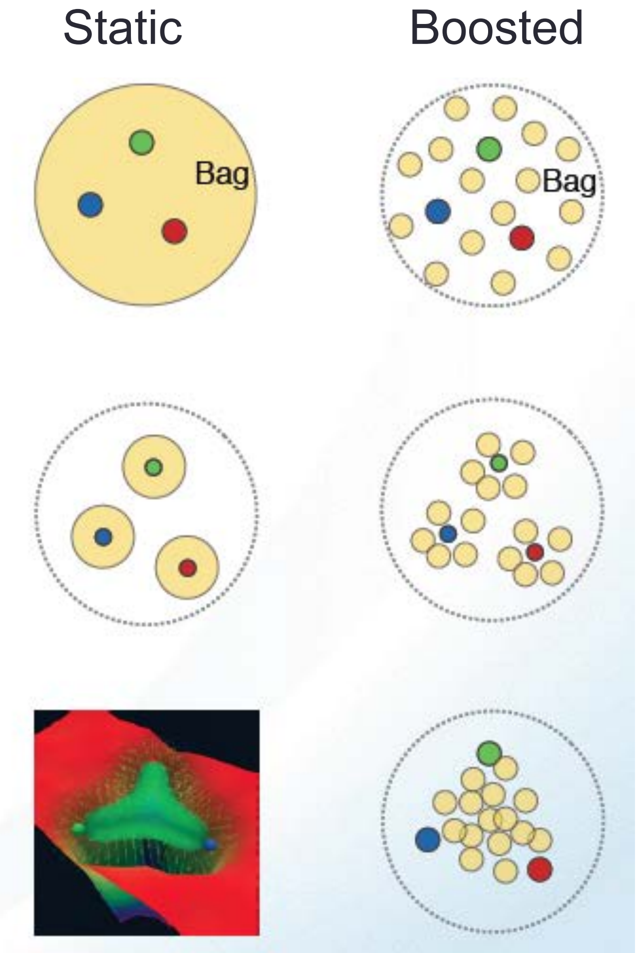


RHIC
√s=62.4 GeV



Suspect soft QCD effects at low scales, but they seem to remain relevant to perturbative regimes as well

What does a proton look like?



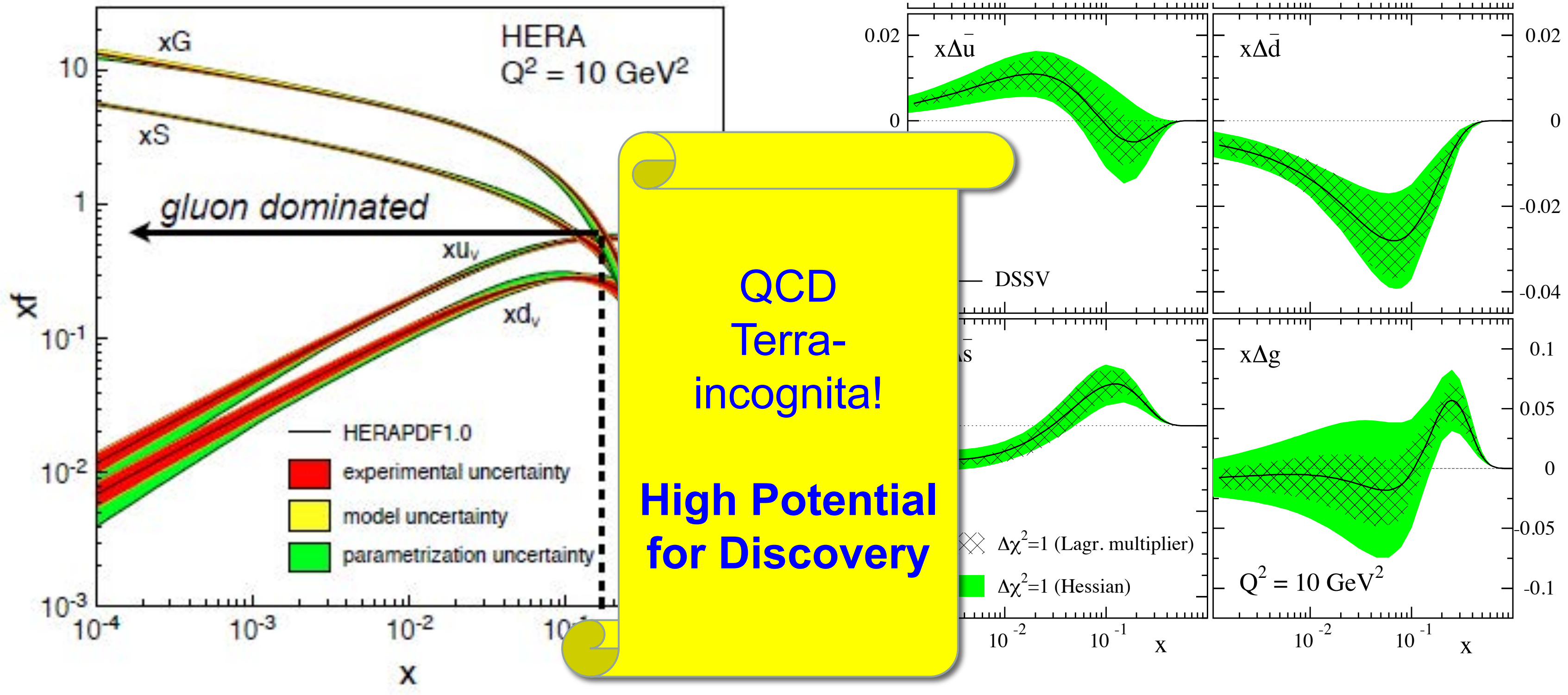
Bag Model: Gluon field distribution is wider than the fast moving quarks.
Gluon radius > Charge (quark) Radius

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

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

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

What do ***gluons*** in protons look like?
Unpolarized & polarized parton distribution functions



QCD Terra-incognita!

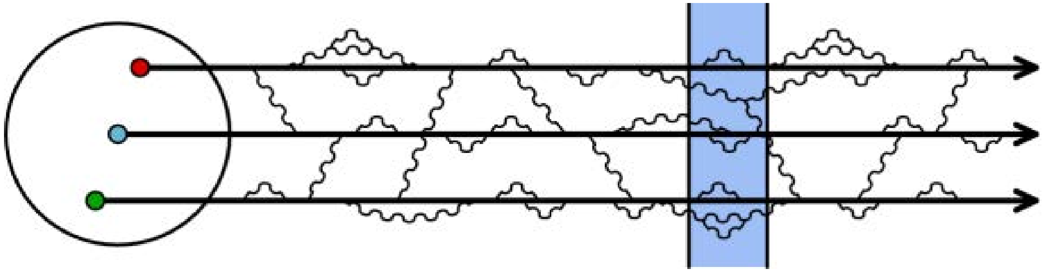
High Potential for Discovery

Need to go beyond 1-dimension!

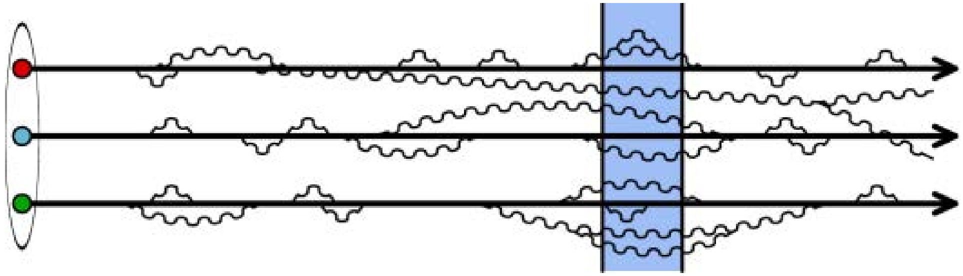
Need (2+1)D image of gluons in a nucleon in position & momentum space

How does a Proton look at low and very 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:

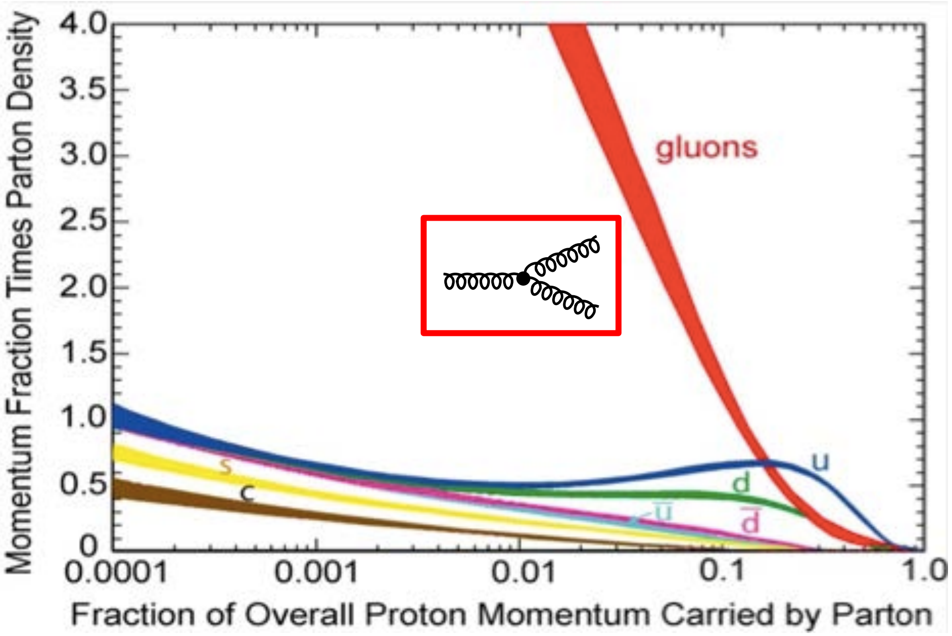
Gluons carry color charge ➔ Can interact with other gluons!

"…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:

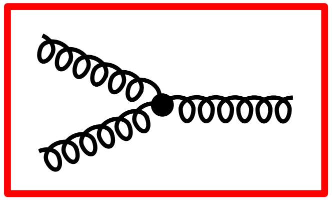
Gluons carry color charge ➔ Can interact with other gluons!



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"

Non-linear Structure of QCD: Fundamental Consequences

- Quark (Color) confinement:
  - Consequence of nonlinear gluon self-interactions
  - Unique property of the strong interaction

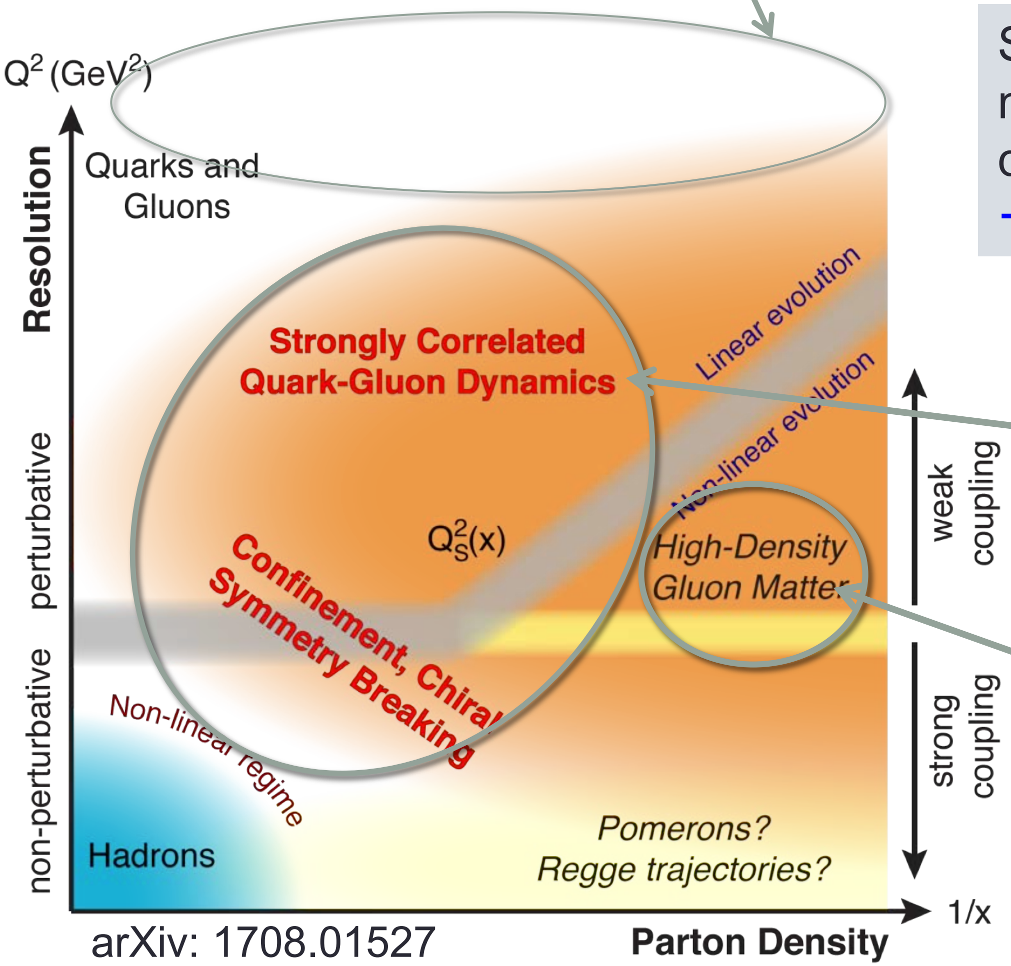
- Strong Quark-Gluon Interactions:
  - Confined motion of quarks and gluons – Transverse Momentum Dependent Parton Distributions (TMDs)
  - Confined spatial correlations of quark and gluon distributions – Generalized Parton Distributions (GPDs)

- Ultra-dense color (gluon) fields:
  - Is there a universal many-body structure due to ultra-dense color fields at the core of **all** hadrons and nuclei?

All expected to be under the "femtoscope" called the EIC

QCD Landscape to be explored by EIC

QCD at high resolution (Q^2) —weakly correlated quarks and gluons are well-described



arXiv: 1708.01527

Strong QCD dynamics creates many-body correlations between quarks and gluons
→ hadron structure emerges

EIC will systematically explore correlations in this region.

An exciting opportunity: Observation by EIC of a new regime in QCD of weakly coupled high density matter

Emergent Dynamics in QCD

Without gluons,* *there would be no nucleons,

no atomic nuclei… no visible world!

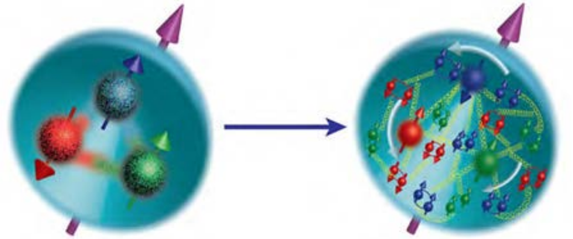
- Massless gluons & almost massless quarks, *through their interactions,* generate most of the mass of the nucleons
- Gluons carry ~50% of the proton's momentum, a significant fraction of the **nucleon's spin**, and are essential for the dynamics of confined partons
- Properties of hadrons are emergent phenomena resulting not only from the equation of motion but are also inextricably tied to the properties of the QCD vacuum. Striking examples besides confinement are spontaneous symmetry breaking and anomalies
- The nucleon-nucleon forces emerge from quark-gluon interactions: how this happens remains a mystery

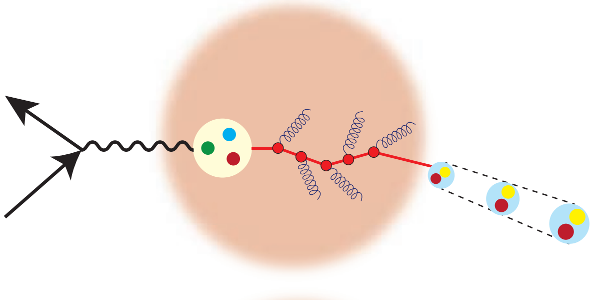
Experimental insight and guidance crucial for complete understanding of *how* hadrons & nuclei emerge from quarks and gluons

A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

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

How do the nucleon properties emerge from them and their interactions?

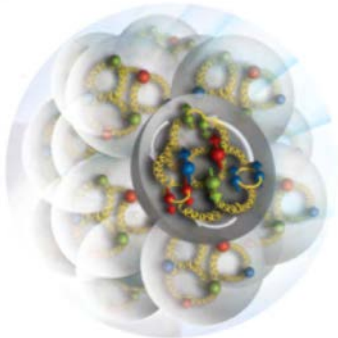




How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

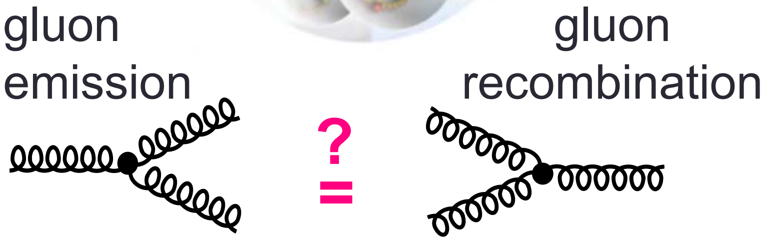
How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?



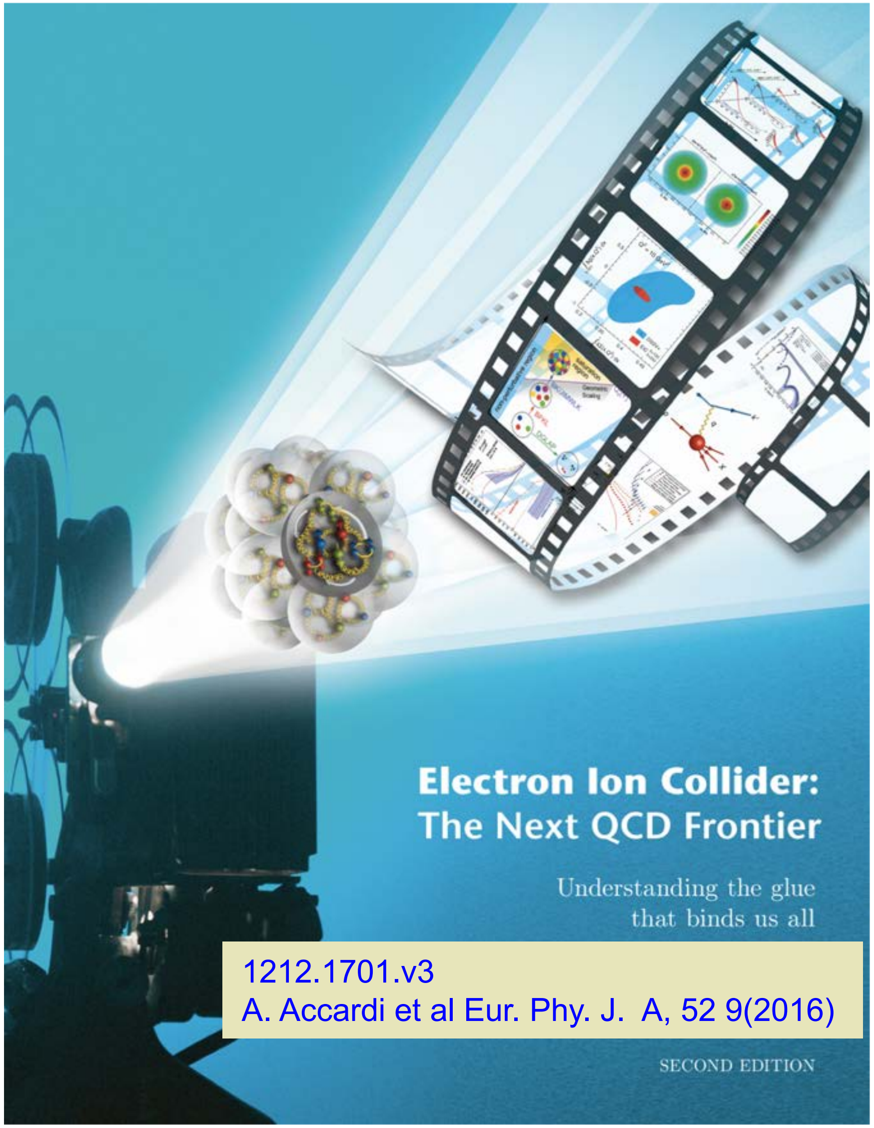
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?



The Electron Ion Collider

Two options of realization!

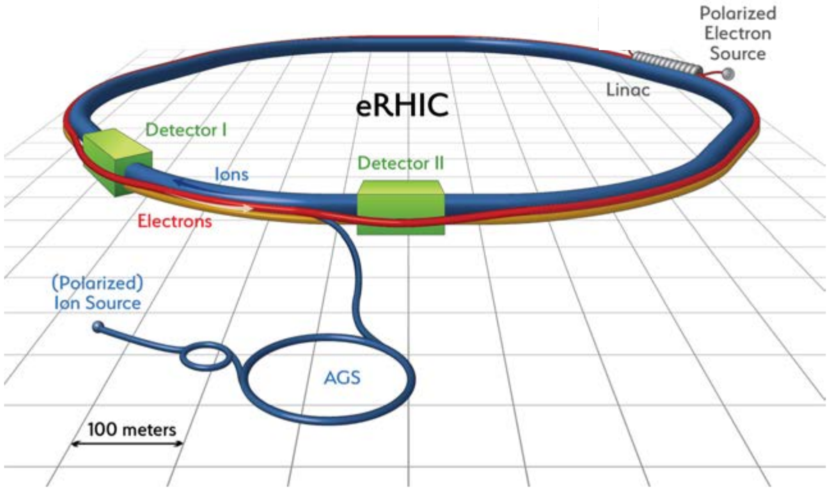


Electron Ion Collider:
The Next QCD Frontier

Understanding the glue
that binds us all

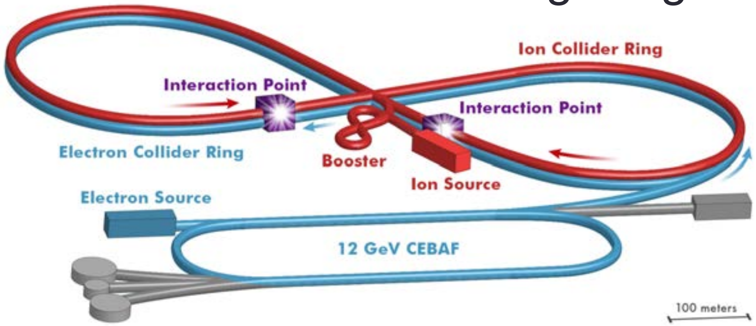
SECOND EDITION

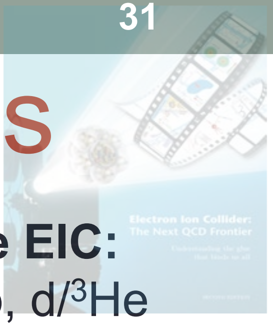
1212.1701.v3
A. Accardi et al Eur. Phy. J. A, 52 9(2016)



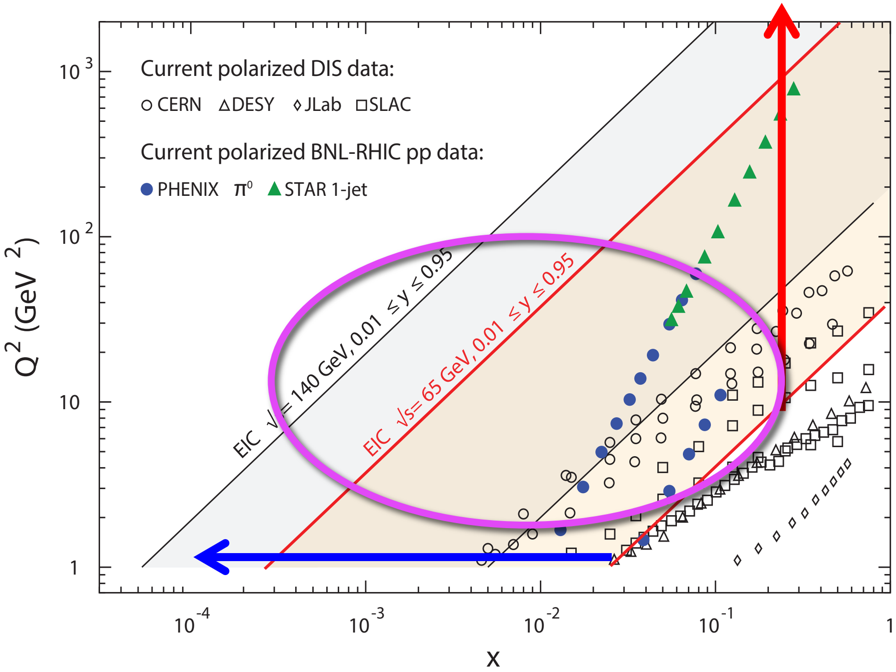
Not to scale

Ring-Ring





EIC: Kinematic reach & properties

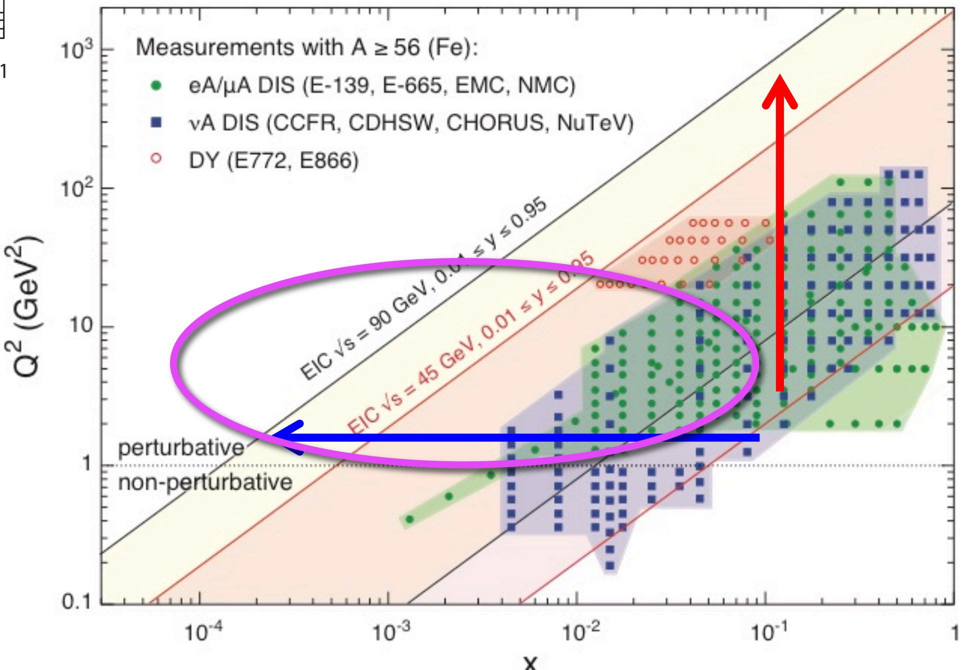


For e-N collisions at the EIC:

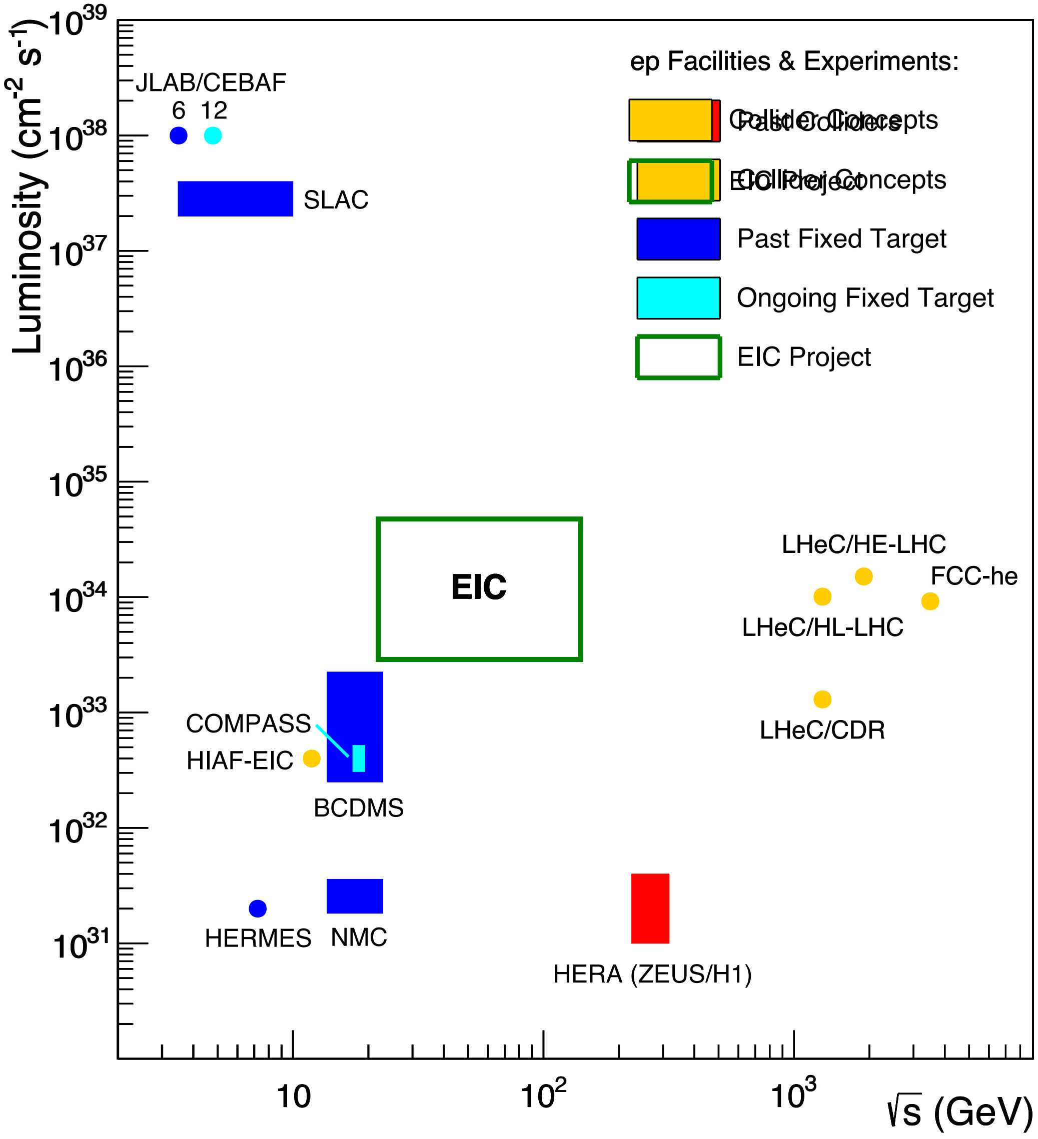
- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

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)



Uniqueness of EIC among all DIS Facilities



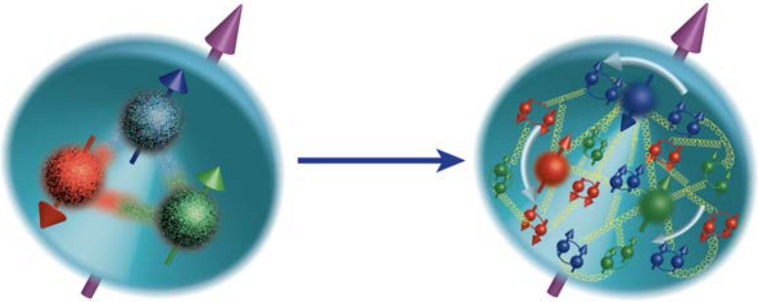
All DIS facilities in the world.

However,
if we ask for:

- high luminosity & wide reach in √s
- polarized lepton & hadron beams
- nuclear beams

EIC stands out as unique facility …

Nucleon Spin: An emergent phenomena



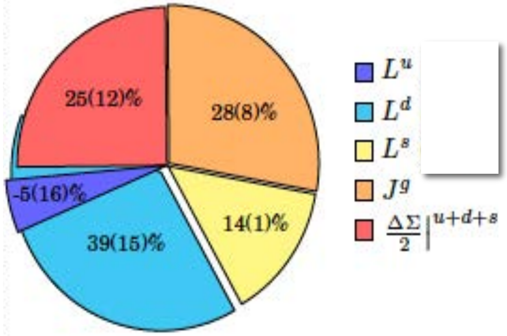
“Helicity sum rule”

$$\frac{1}{2}\hbar = \frac{1}{2}\underbrace{\Delta\Sigma}_{\text{quark contribution}} + \underbrace{\Delta G}_{\text{gluon contribution}} + \sum_q \underbrace{L_q^z + L_g^z}_{\text{orbital angular momentum}}$$

(25 +/- 3%) + (25+/-25%) + ????

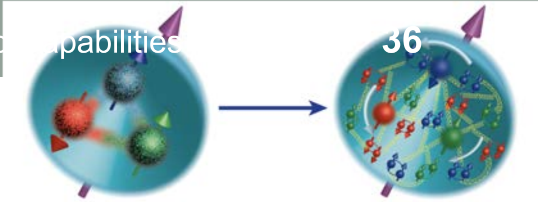
RECENT: Spin on the Lattice:

- **Gluon’s spin contribution on Lattice: $S_G = 0.5(0.1)$**
  Yi-Bo Yang et al. PRL **118**, 102001 (2017)
- **J_q calculated on Lattice QCD:**
  χQCD Collaboration, PRD91, 014505, 2015



Proton as a laboratory for QCD

3D structure of hadrons in momentum and position space….

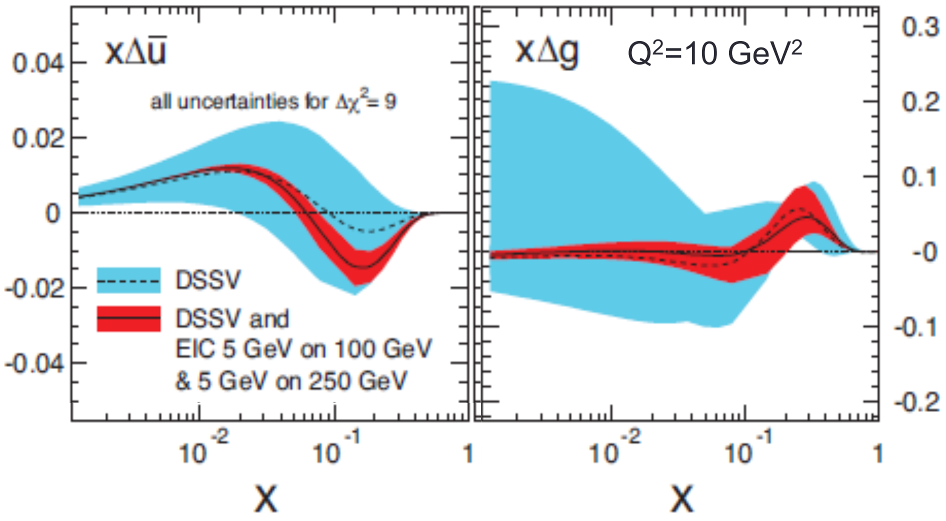


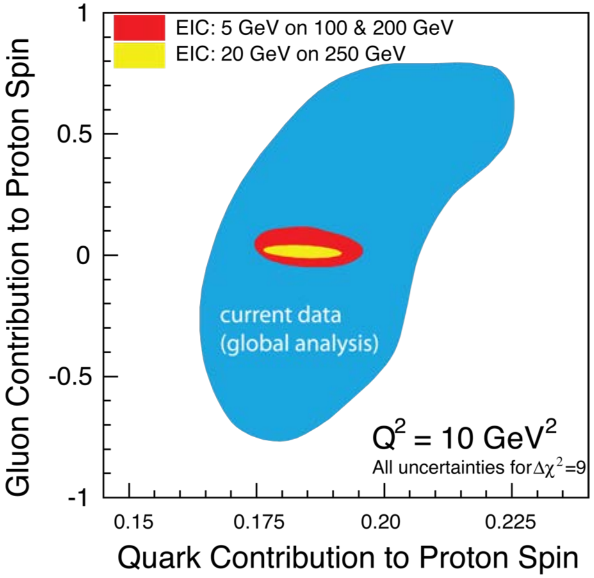
Understanding Nucleon Spin

"Helicity sum rule"

$$\frac{1}{2}\hbar = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{quark contribution}} + \underbrace{\Delta G}_{\text{gluon contribution}} + \underbrace{\sum_q L_q^z + L_g^z}_{\text{orbital angular momentum}}$$

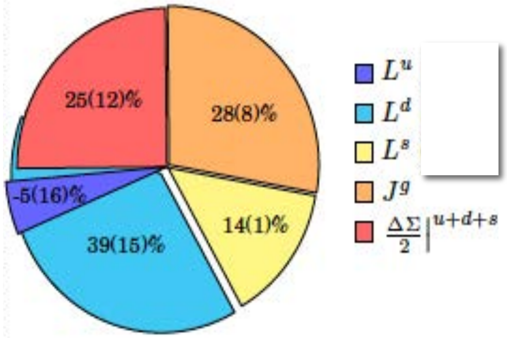
EIC projected measurements:
precise determination of polarized PDFs of quark sea and gluons ➔ precision ΔG and ΔΣ
→ A clear idea of the magnitude of $\sum L_q + L_g$



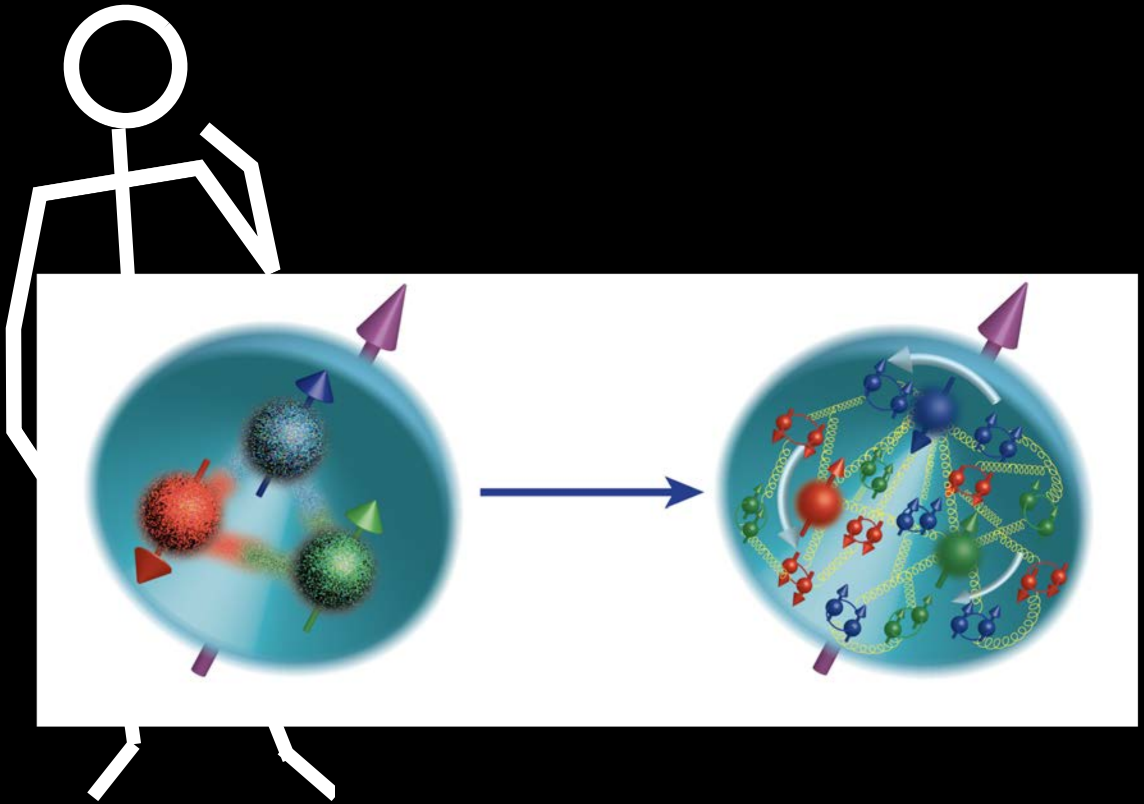


Spin and Lattice: Recent Activities

- ❑ **Gluon's spin contribution on Lattice: S_G = 0.5(0.1)**
  Yi-Bo Yang et al. PRL **118**, 102001 (2017)
- ❑ **J_q calculated on Lattice QCD:**
  χQCD Collaboration, PRD91, 014505, 2015



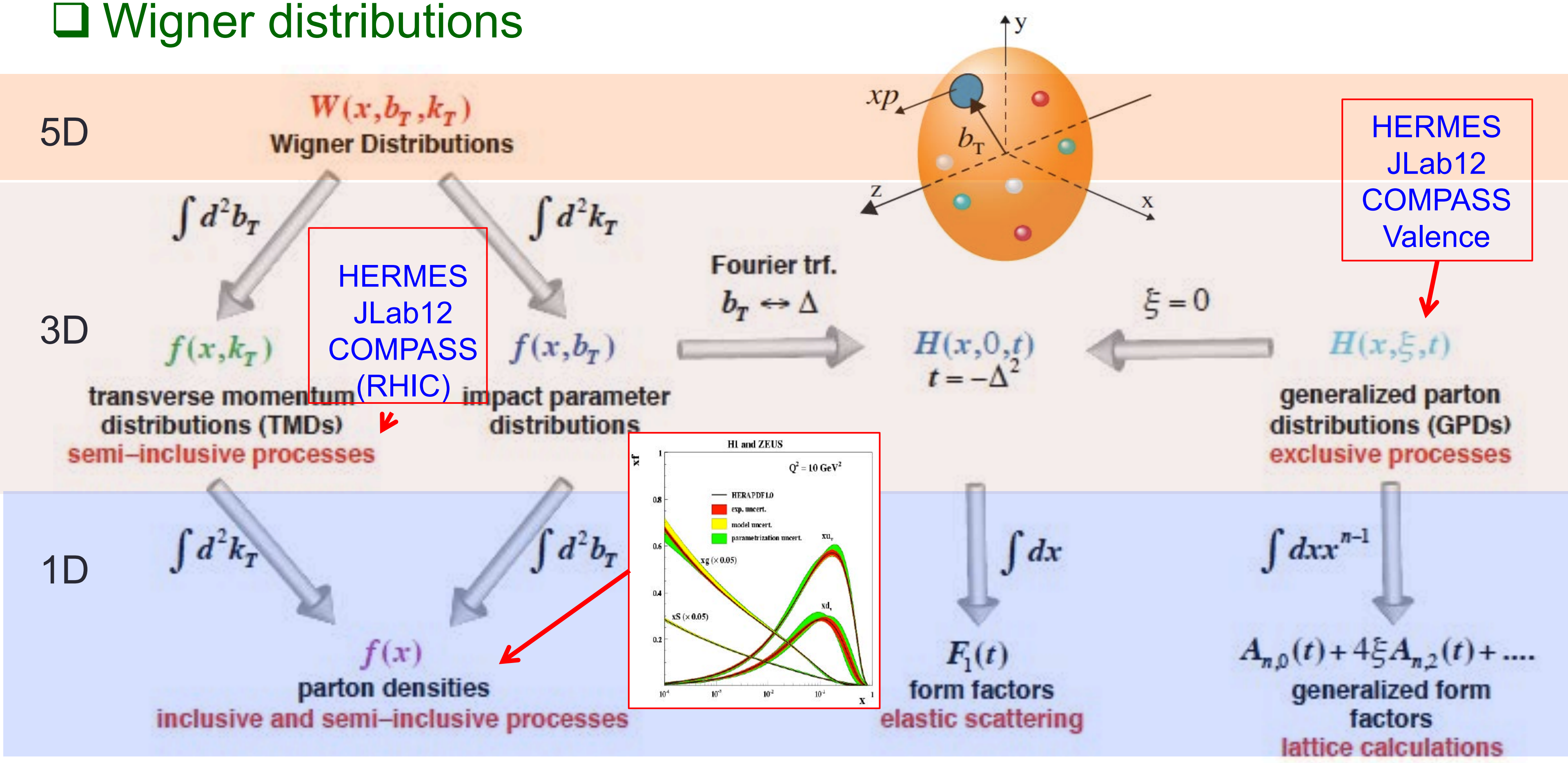
1D



Courtesy: Alssandro Bacchetta

Unified view of the Nucleon Structure

- ❑ Wigner distributions



$W(x, b_T, k_T)$
Wigner Distributions

$\int d^2 b_T$ $\quad$ $\int d^2 k_T$

HERMES
JLab12
COMPASS
(RHIC)

$f(x, k_T)$
transverse momentum distributions (TMDs)
semi–inclusive processes

$f(x, b_T)$
impact parameter distributions

Fourier trf.
$b_T \leftrightarrow \Delta$

$H(x, 0, t)$
$t = -\Delta^2$

$\xi = 0$

HERMES
JLab12
COMPASS
Valence

$H(x, \xi, t)$
generalized parton distributions (GPDs)
exclusive processes

$\int d^2 k_T$ $\quad$ $\int d^2 b_T$ $\quad$ $\int dx$ $\quad$ $\int dx x^{n-1}$

$f(x)$
parton densities
inclusive and semi–inclusive processes

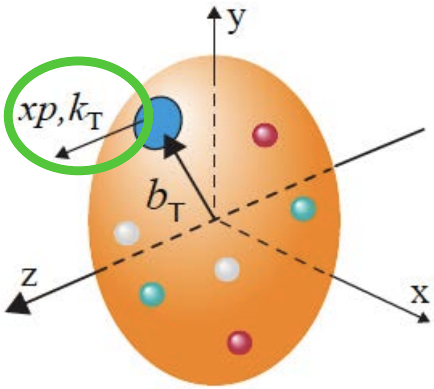
$F_1(t)$
form factors
elastic scattering

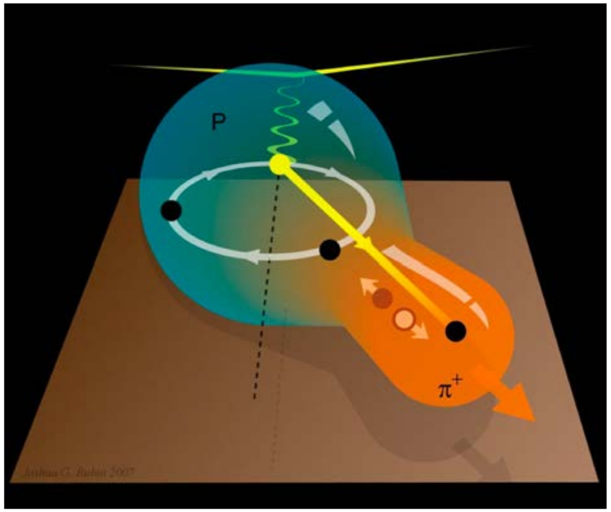
$A_{n,0}(t) + 4\xi A_{n,2}(t) + \ldots.$
generalized form factors
lattice calculations

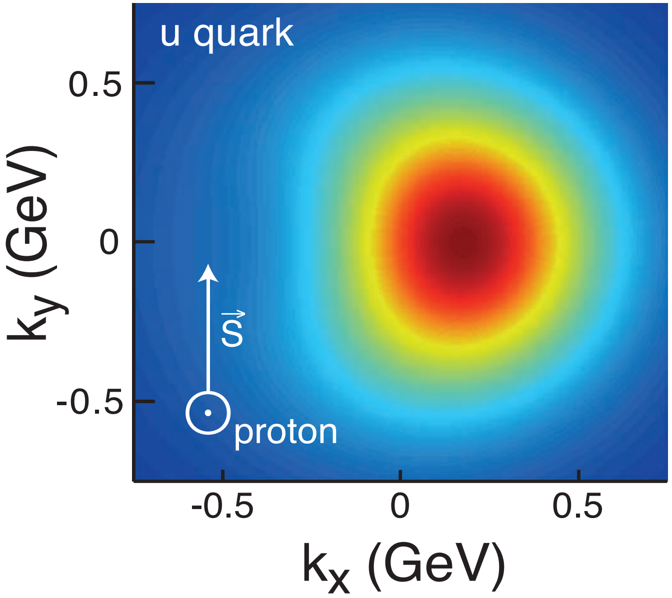
- ❑ (2+1)D imaging Quarks (Jlab/COMPASS) , **Gluons (EIC)**
  - ✧ TMDs – confined motion in a nucleon (semi-inclusive DIS)
  - ✧ GPDs – Spatial imaging of quarks and gluons (exclusive DIS & diffraction)

Measurement of Transverse Momentum Distribution

Semi-Inclusive Deep Inelastic Scattering

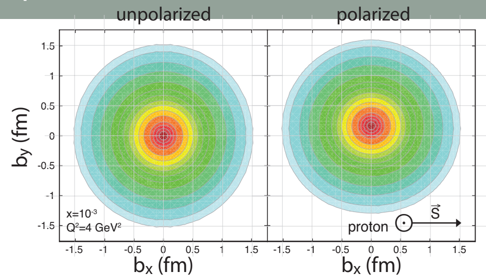






❑ Naturally, two scales:

- ✧ high Q – localized probe
  To “see” quarks and gluons
- ✧ Low p_T – sensitive to confining scale
  To “see” their confined motion
- ✧ *Theory – QCD TMD factorization*

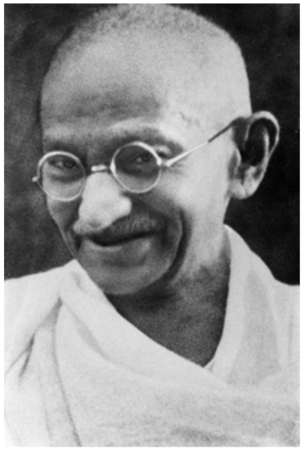


Spatial Imaging of quarks & gluons

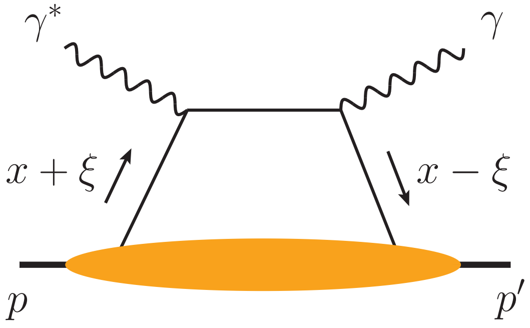
Generalized Parton Distributions

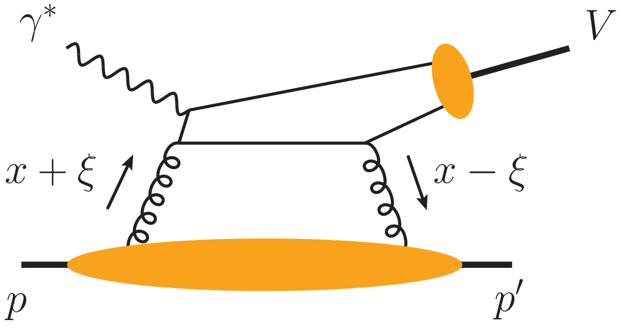
Historically, investigations of nucleon structure and dynamics involved breaking the nucleon…. (exploration of internal structure!)

To get to the **orbital motion** of quarks and gluons we need **non-violent collisions**



Quarks Motion





Gluons: Only @ Collider

Deeply Virtual Compton Scattering

Measure all three final states

e + **p** → e'+ **p'**+ γ

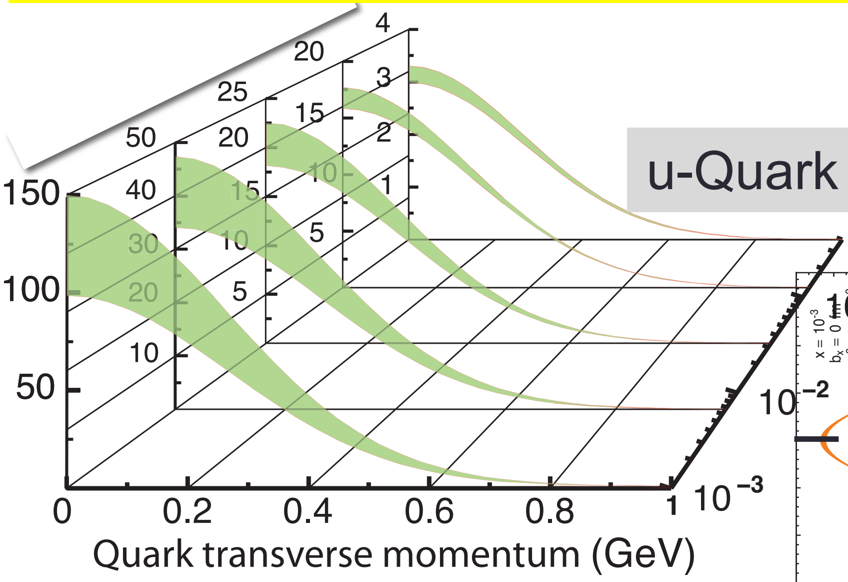
Fourier transform of momentum transferred=(p-p') → Spatial distribution

Exclusive measurements → measure "everything"

2+1 D partonic image of the proton with the EIC

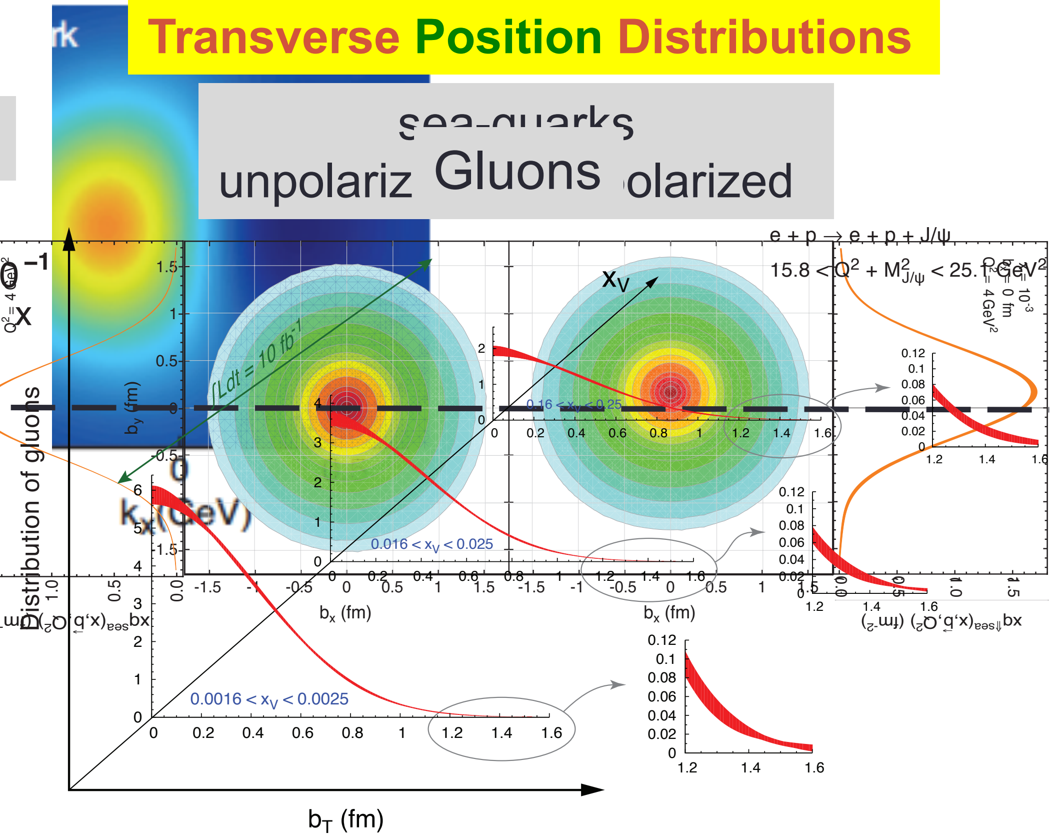
Spin-dependent 3D momentum space images from semi-inclusive scattering

Transverse Momentum Distributions



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

Transverse Position Distributions



Study of internal structure of a watermelon:

A-A (RHIC)

1) Violent collision of melons

2) Cutting the watermelon with a knife

Violent DIS e-A (EIC)

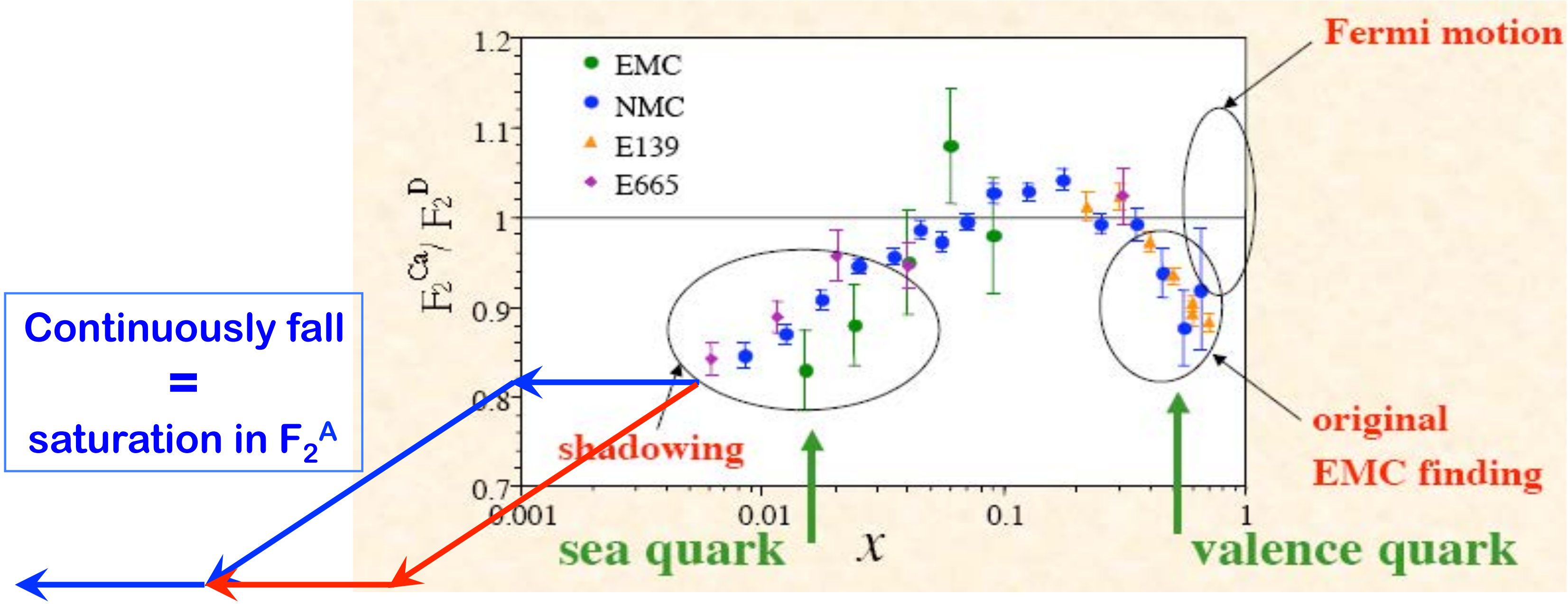
3) MRI of a watermelon

Non-Violent e-A (EIC)

Use of Nuclei as a Laboratory for QCD :

An easy measurement (early program)

- ❑ **Ratio of F_2: EMC effect, Shadowing and Saturation:**



Continuously fall
=
saturation in F_2^A

Saturation in $F_2(D)$

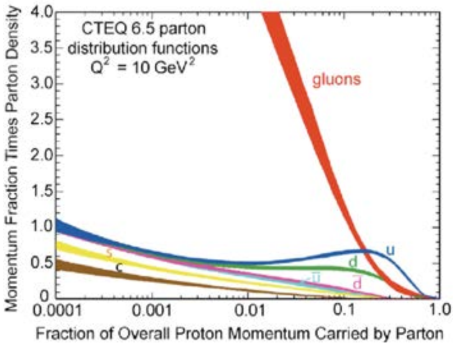
- ❑ **Questions:**

  Will the suppression/shadowing continue fall as x decreases?

  Could nucleus behaves as a large proton at small-x?

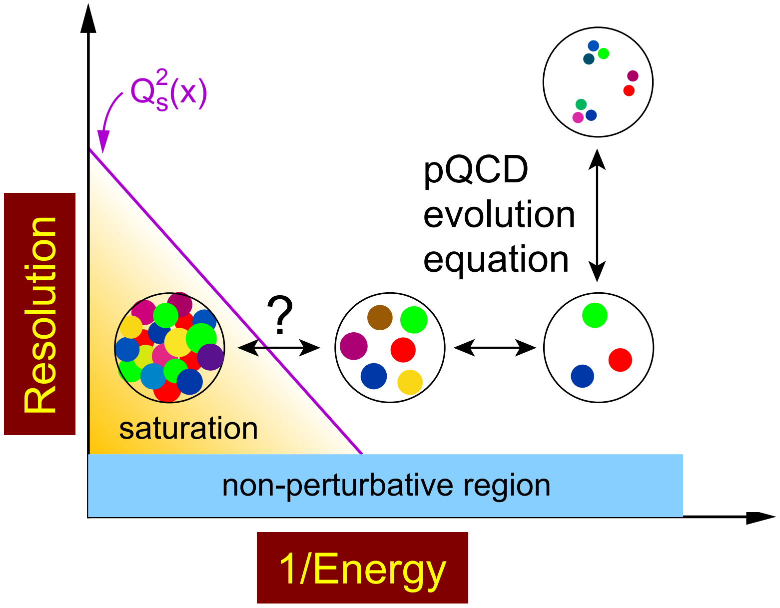
  Range of color correlation – could impact the center of neutron stars!

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

gluon recombination

At Q_S

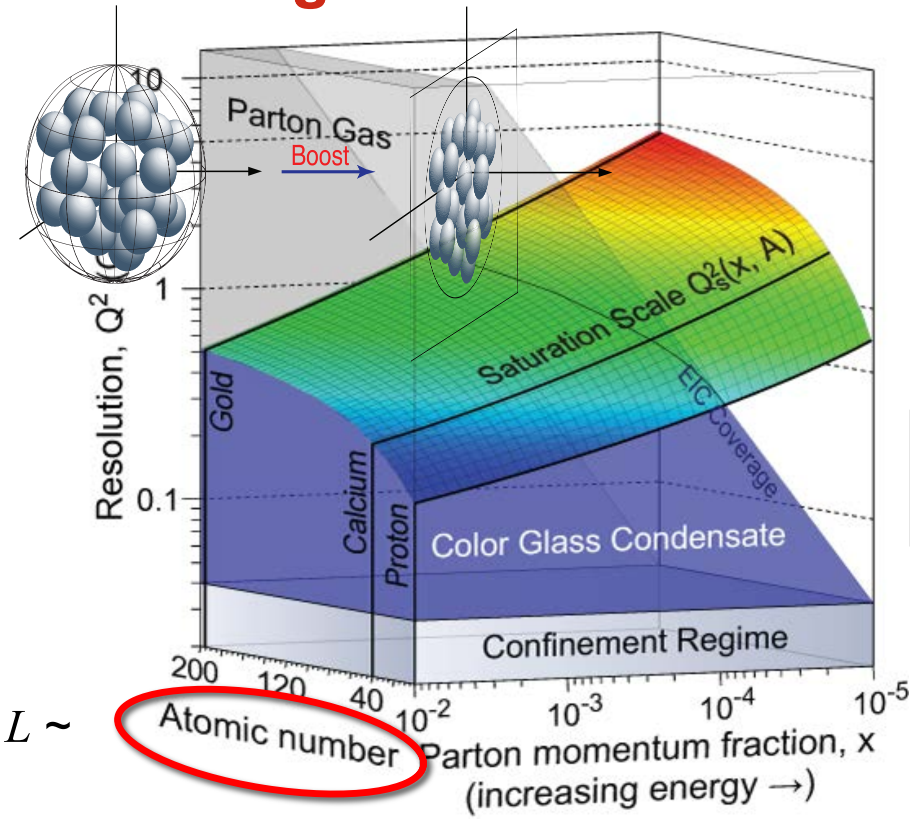
First observation of gluon recombination effects in nuclei:
➔leading to a *collective* gluonic system!
First observation of g-g recombination in *different* nuclei
→ Is this a universal property?
→ Is the Color Glass Condensate the correct effective theory?

How to explore/study this new phase of matter?

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

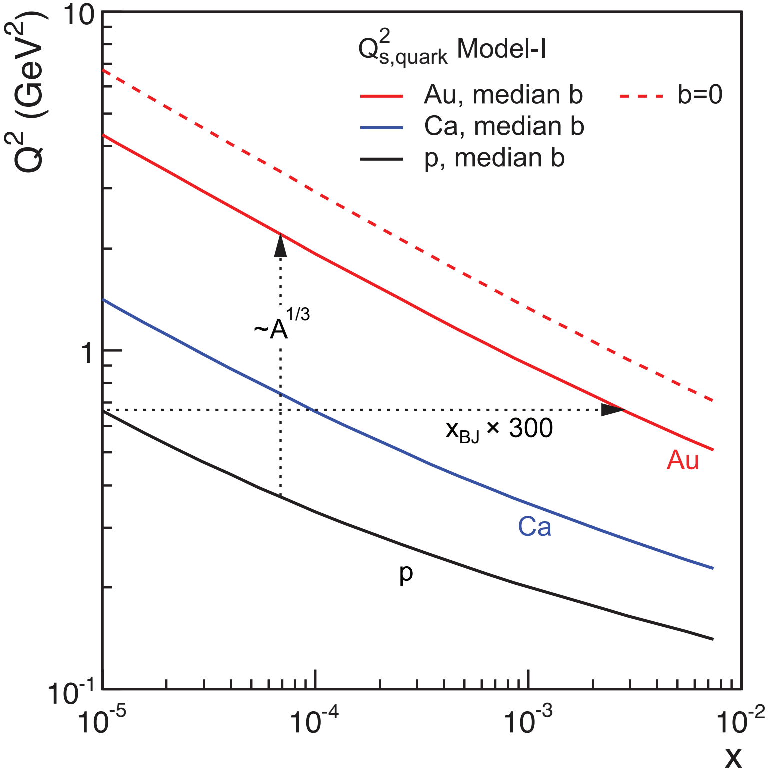
Teaney, Kowalski
Kovchegov et al.

Advantage of nucleus →



$1/3$

$L \sim$

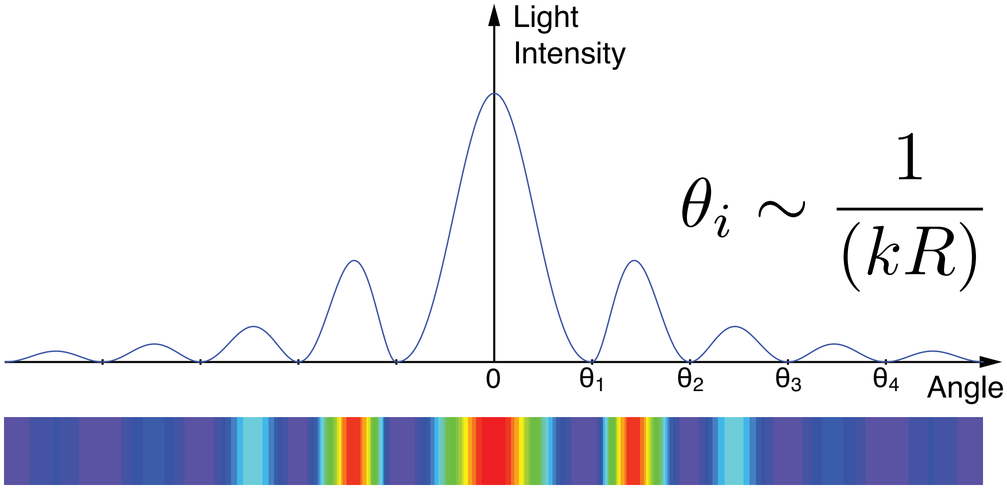


Enhancement of Q_S with A:
Saturation regime reached at significantly lower energy (read: "cost") in nuclei

Diffraction in Optics and high energy scattering

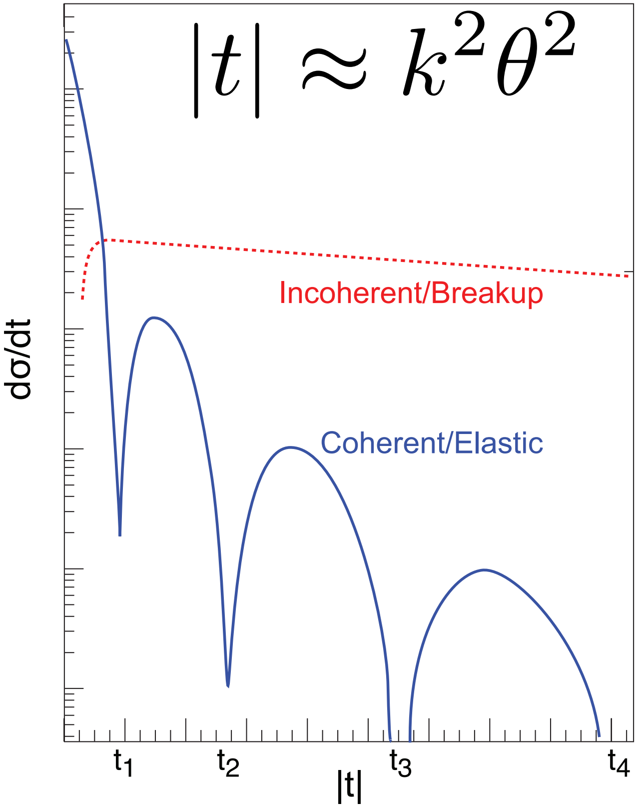
Light with wavelength λ obstructed by an opaque disk of radius R suffers diffraction:

k → wave number



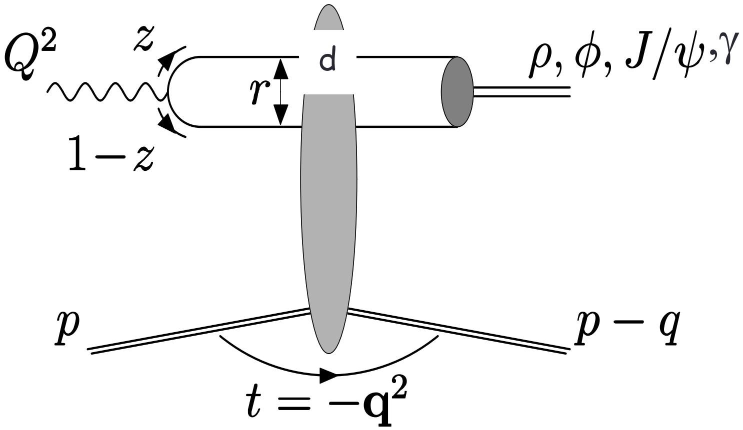
$$\theta_i \sim \frac{1}{(kR)}$$

Calculation of e-A diffraction



$$|t| \approx k^2\theta^2$$

Transverse imaging of the gluons nuclei

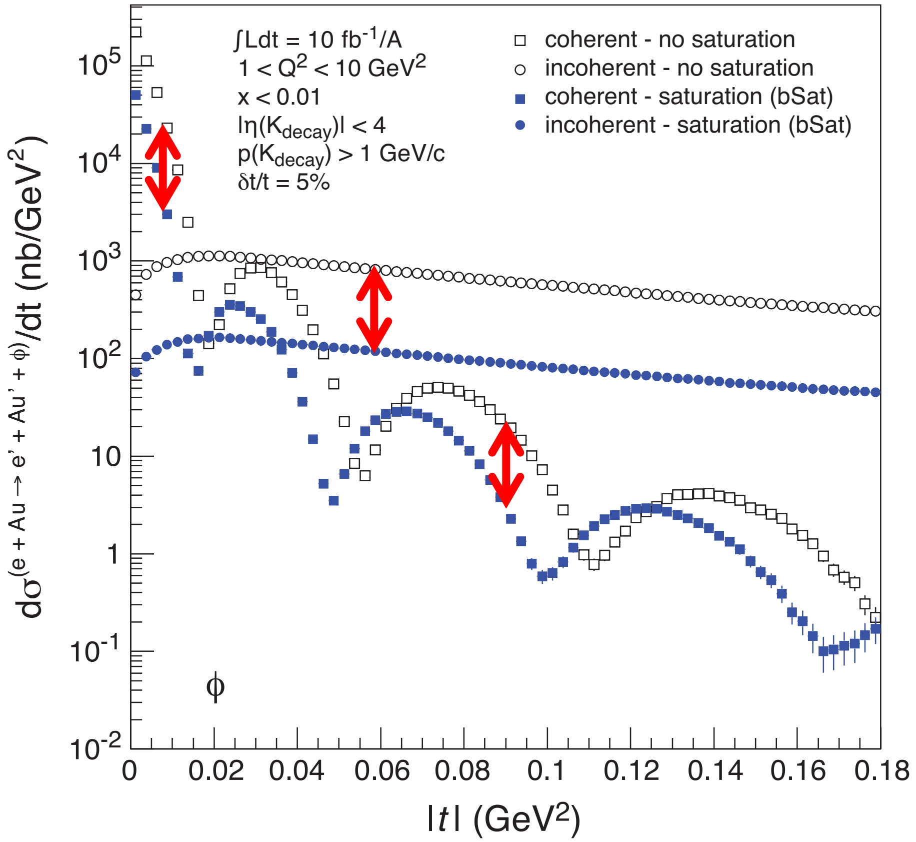


➔Does low x dynamics (Saturation) modify the transverse gluon distribution?

Experimental challenges being Studied.

Diffractive vector meson production in **e-Au**

Diff. MC: “Sartre”

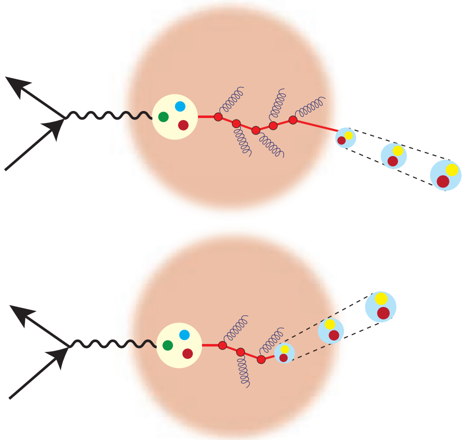


Simulation study by Toll & Ullrich

Emergence of Hadrons from Partons

Nucleus as a Femtometer sized filter

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

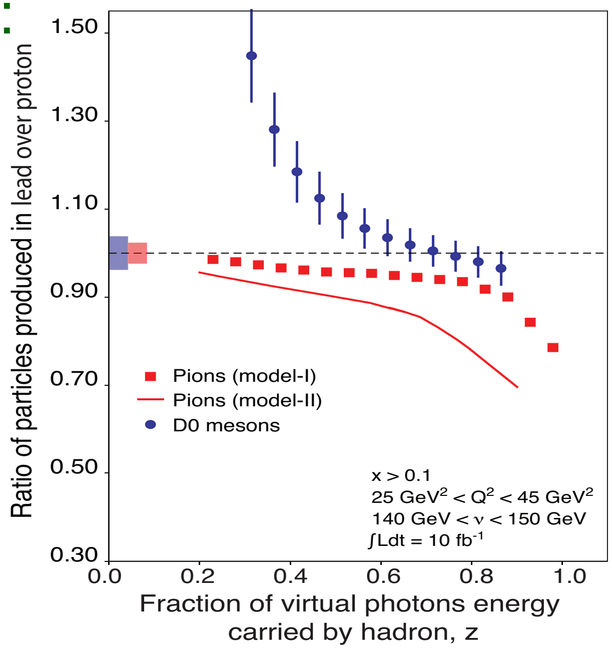


$$\nu = \frac{Q^2}{2mx}$$

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

(colored) Quark passing through cold QCD matter emerges as color-neutral hadron ➔ Clues to color-confinement?

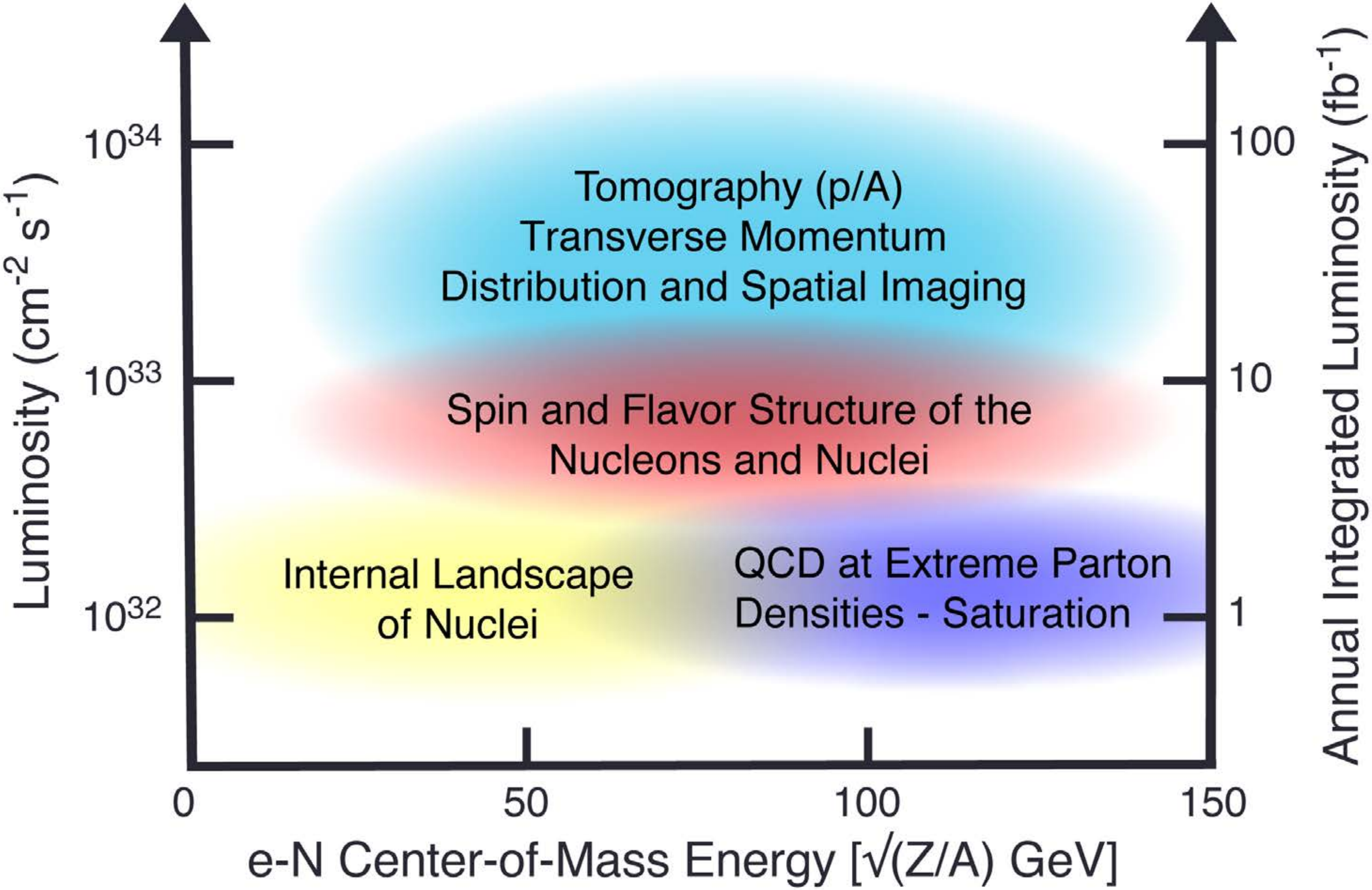
Energy loss by light vs. heavy quarks:



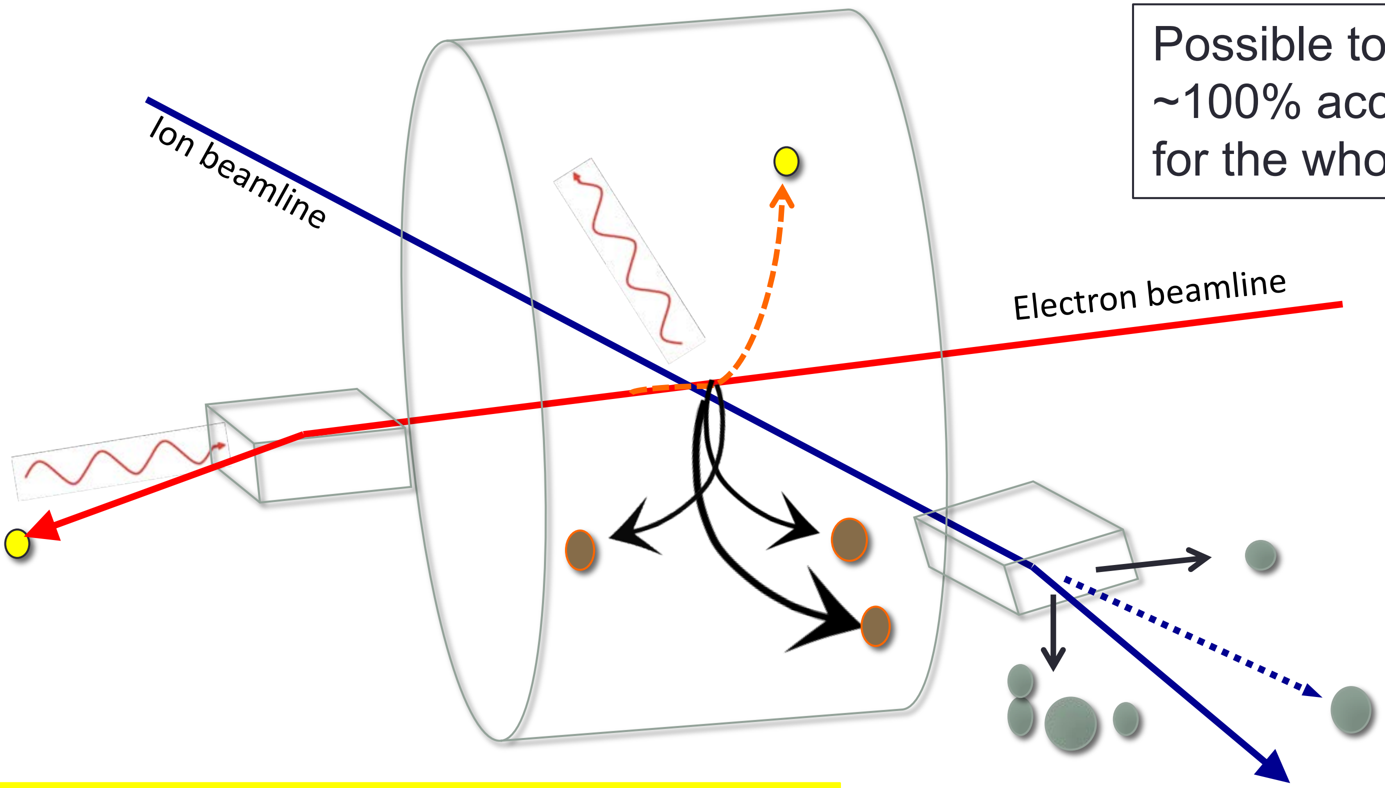
Identify π vs. D^0 **(charm)** mesons in e-A collisions: Understand energy loss of light vs. heavy quarks traversing the cold nuclear matter:
Connect to energy loss in Hot QCD

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

Summary: EIC Physics: CM vs. Luminosity vs. Integrated luminosity



Detector integration with the Interaction Region accelerator components:



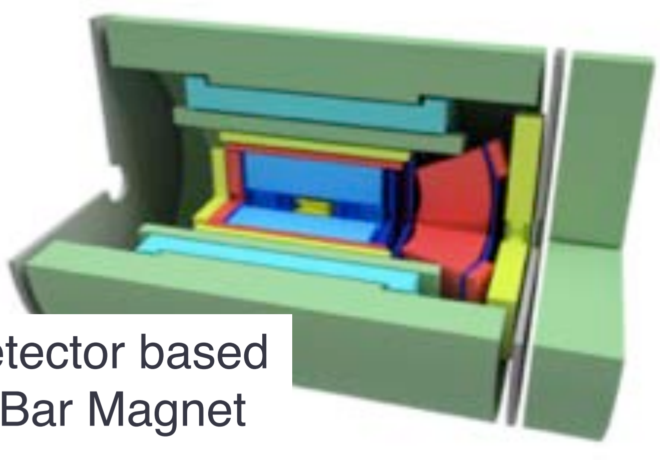
Possible to get ~100% acceptance for the whole event

Total acceptance detector (and IR)

Crossing angles:
eRHIC: 10-22 mrad
JLEIC : 40-50 mrad

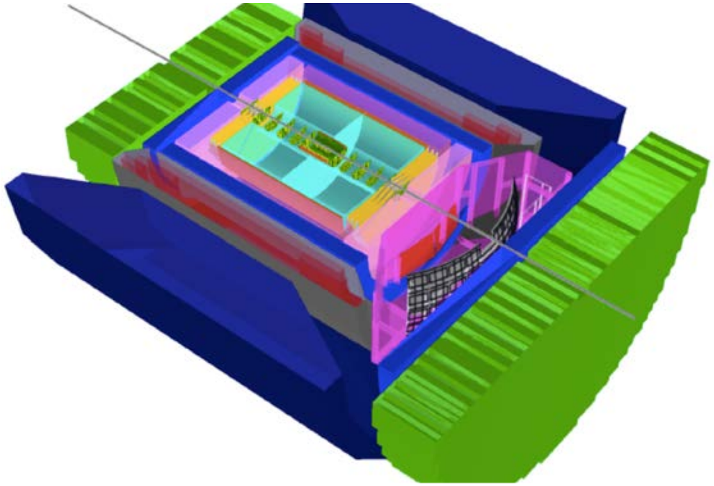
Figure Courtesey: Rik Yoshida

EIC Detector R&D



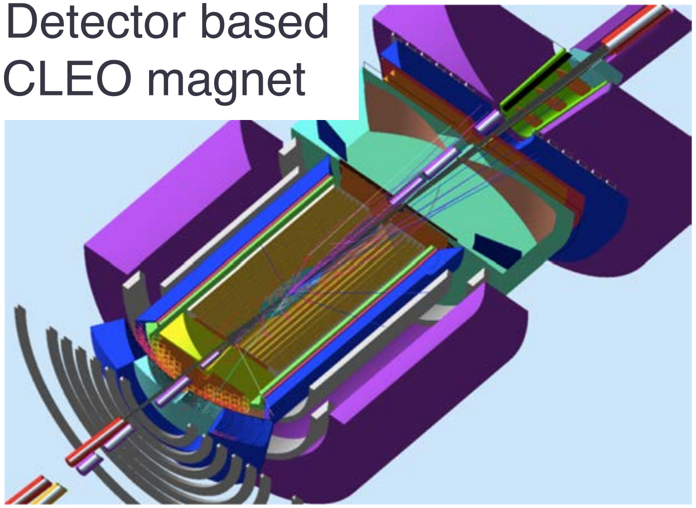
EIC Detector based
on BaBar Magnet

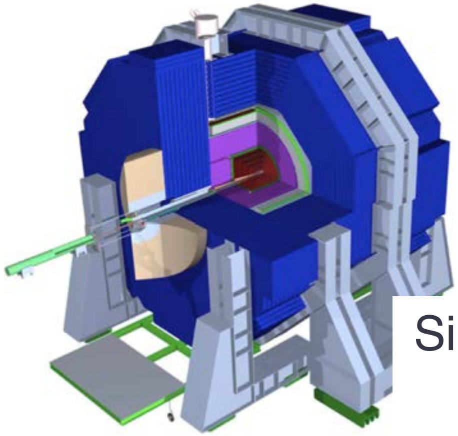
Brookhaven's electron-A Solenoidal Tracker



Ongoing $1M Generic EIC Detector R&D Program managed by BNL

EIC Detector based
on CLEO magnet





SiEIC Detector
(ANL)

REALIZATION….

Detector R&D program + EIC User Group formation ➔ Seeds for future experimental collaboration

Current Detector Design Ideas

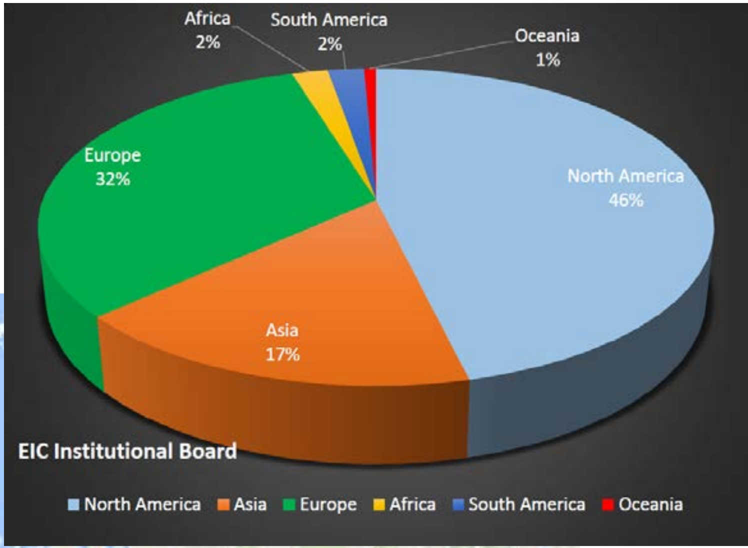
The National Academy of Science (NAS- NRC) Review

The EIC Users Group: EICUG.ORG

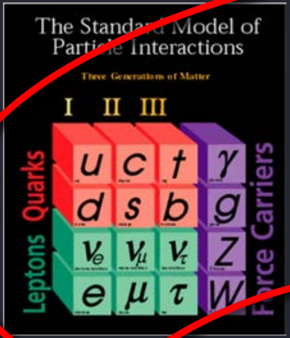
(no students included as of yet)

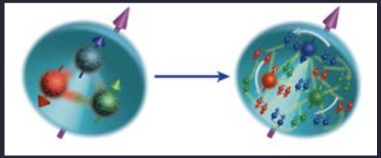
804 collaborators, 30 countries, 170 institutions… (Aug 2018)

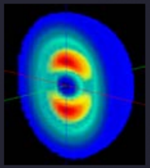
Map of institution's locations

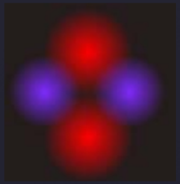


21st Century Nuclear Science: Probing nuclear matter in all Its forms & exploring their potential for applications

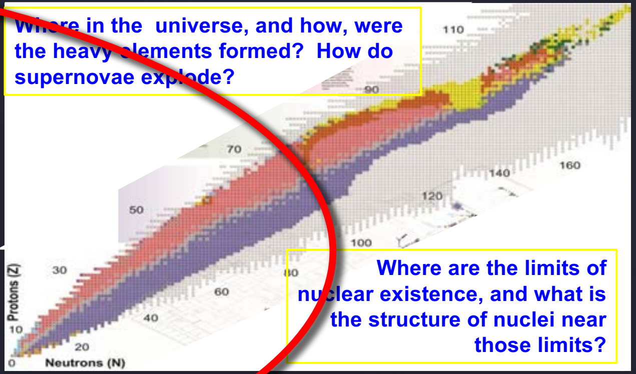






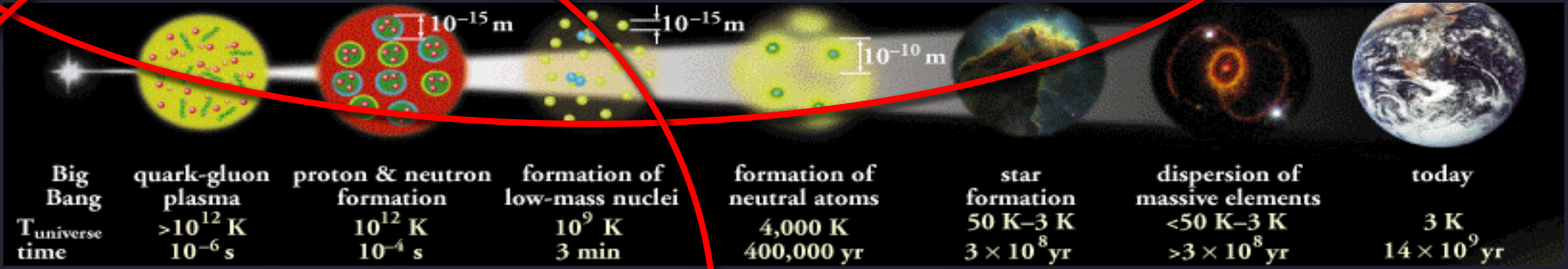


How are the properties of protons and neutrons, and the force between them, built up from quarks, antiquarks and gluons? What is the mechanism by which these fundamental particles materialize as hadrons?

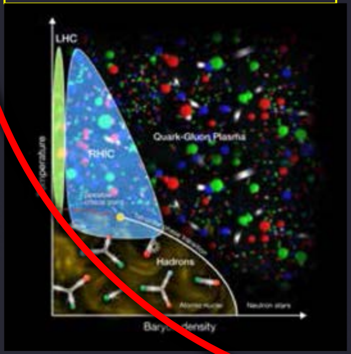


Where in the universe, and how, were the heavy elements formed? How do supernovae explode?

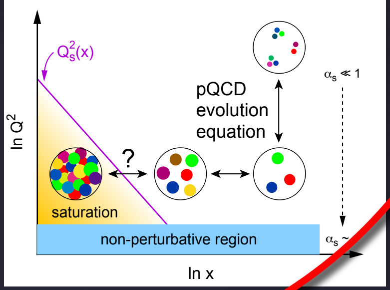
Where are the limits of nuclear existence, and what is the structure of nuclei near those limits?



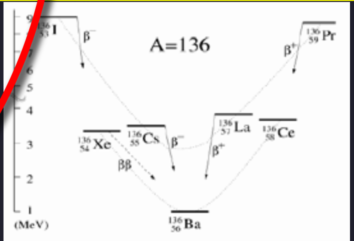
What is the nature of the different phases of nuclear matter through which the universe has evolved?



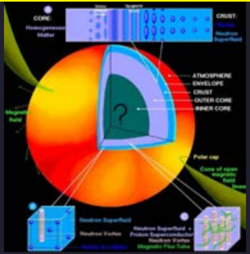
Do nucleons and all nuclei, viewed at near light speed, appear as walls of gluons with universal properties?



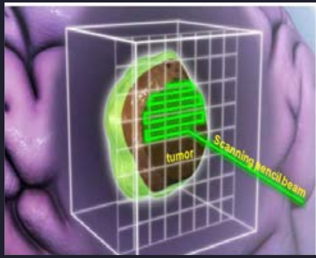
How can the properties of nuclei be used to reveal the fundamental processes that produced an imbalance between matter and antimatter in our universe?



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



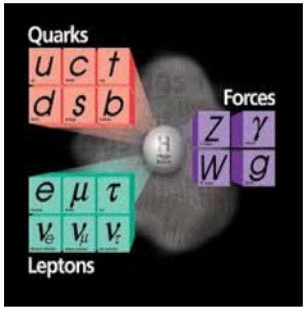
How can technologies developed for basic nuclear physics research be adapted to address society's needs?

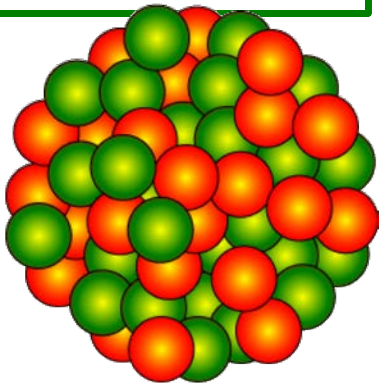


Electron Ion Collider: The next QCD frontier

Understanding the Glue that Binds Us All

Why the EIC? ➔ “**Gluon Imaging**”
To understand the role of gluons in binding quarks & gluons into Nucleons and Nuclei



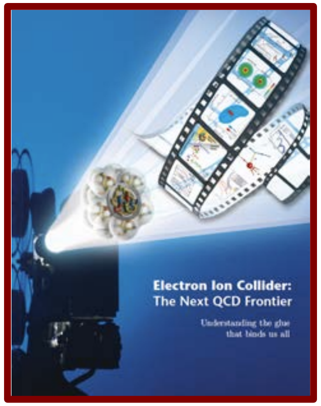


THANK YOU

Thanks to many of my EIC Collaborators and Enthusiasts who led many of the studies presented in this talk
See: arXiv:1108.1713, D. Boer et al.

Gluons and the quark sea at high energies: distributions, polarization, tomography

Without the EIC White Paper Writing Group the EIC White Paper would not have existed.
Special thanks to Dr. Jianwei Qiu and Prof. Zein-Eddine Meziani, my Co-Editors for the EIC White Paper
See: arXiv:1212.1701.v3 , A. Accardi et al.
Eur. Phy. J. A 52, 9 (2016)



Electron Ion Collider:
The Next QCD Frontier

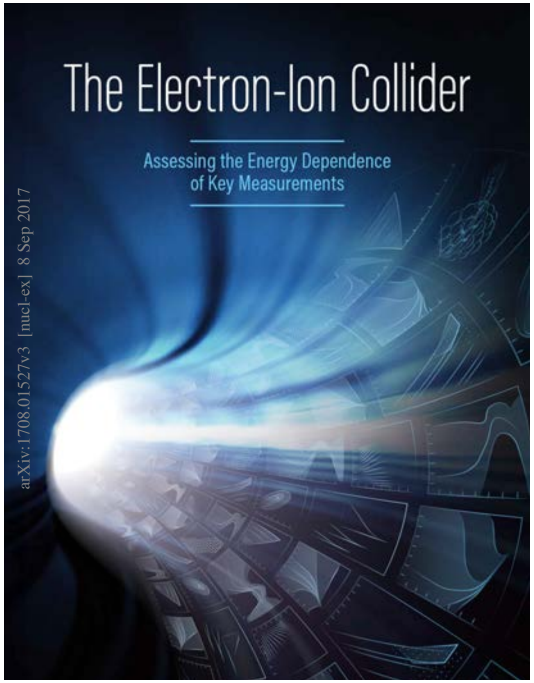
Understanding the glue
that binds us all

The eRHIC and JLEIC machine design teams

Also gratefully acknowledge recent input from: M. Diefenthaler, R. Ent, R. Milner, R. Yoshida

Advantages of (high) energy:

- Precision measurement of proton spin
- Spatial imaging of quarks and gluons
- Charged current interactions as probe of nucleon structure
- Nuclear Structure function
- Gluon saturation studies in nuclei
  - Di-hadron suppression
  - Diffraction
- Physics with Jets:
  - Hadronization, parton shower evolution in strong color fields, dijets, diffractive dijets, photon structure, gluon helicity….



The Electron-Ion Collider

Assessing the Energy Dependence of Key Measurements

arXiv:1708.01527v3 [nucl-ex] 8 Sep 2017

arXiv:1708.01527
E. Aschenauer et al.