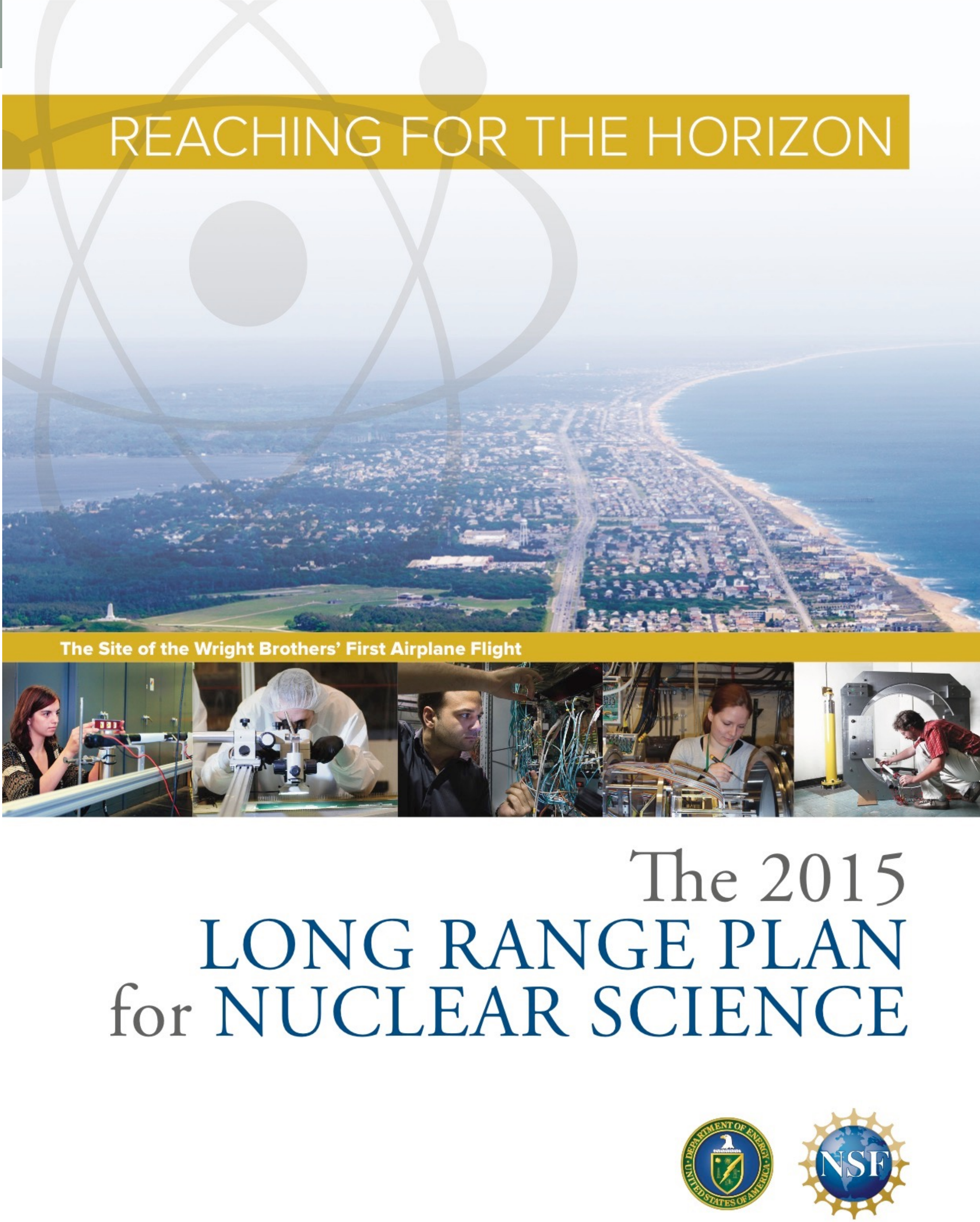


http://science.energy.gov/np/reports

RECOMMENDATION:

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

Initiatives:

Theory

Detector & Accelerator R&D

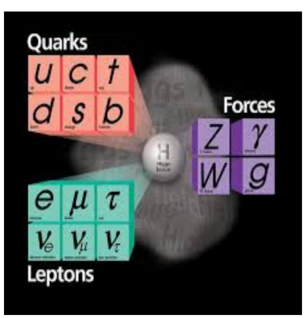
Electron Ion Collider: Science & Status

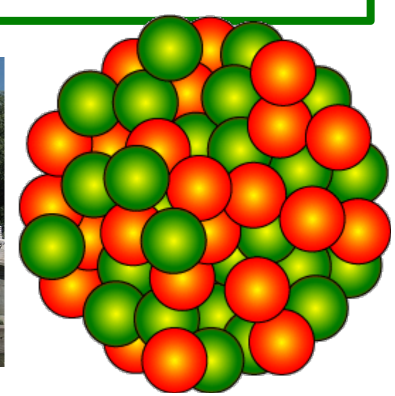
The next QCD frontier

Understanding the Glue that Binds Us All

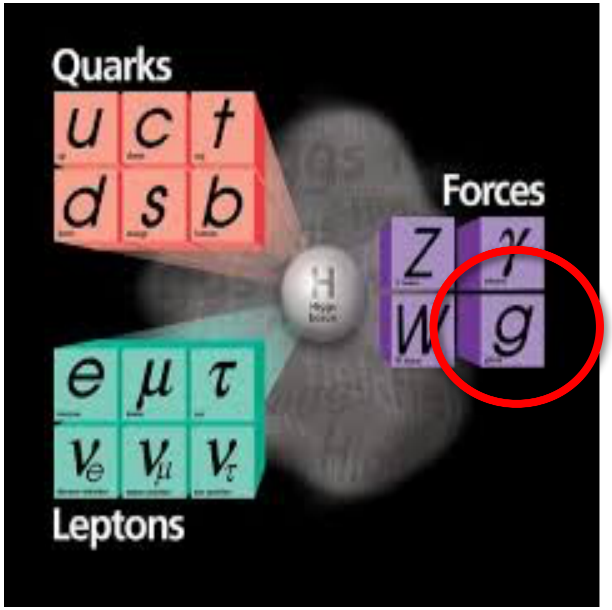
Why the EIC?

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





Gluon in the Standard Model of Physics



Gluon: carrier of strong force (QCD)

Chargeless, massless, but carries color-charge

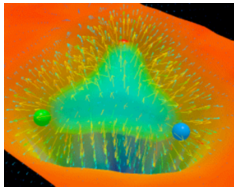
Binds the quarks and gluons inside the hadrons with tremendous force! (Strong force)

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 95% of the mass of the nucleons:

Without gluons, there would be no nucleons,

no atomic nuclei… no visible world!

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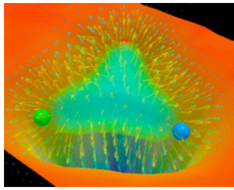

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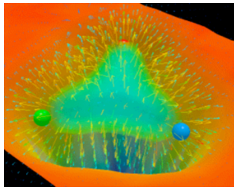

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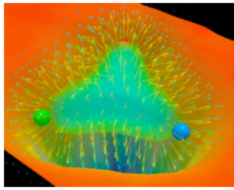

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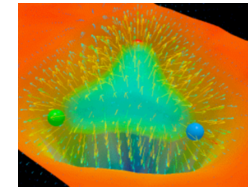

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Experimental insight and guidance crucial for complete understanding of *how* hadron & nuclei emerge from quarks and gluons

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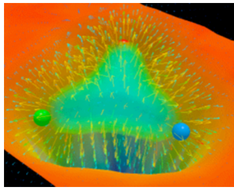

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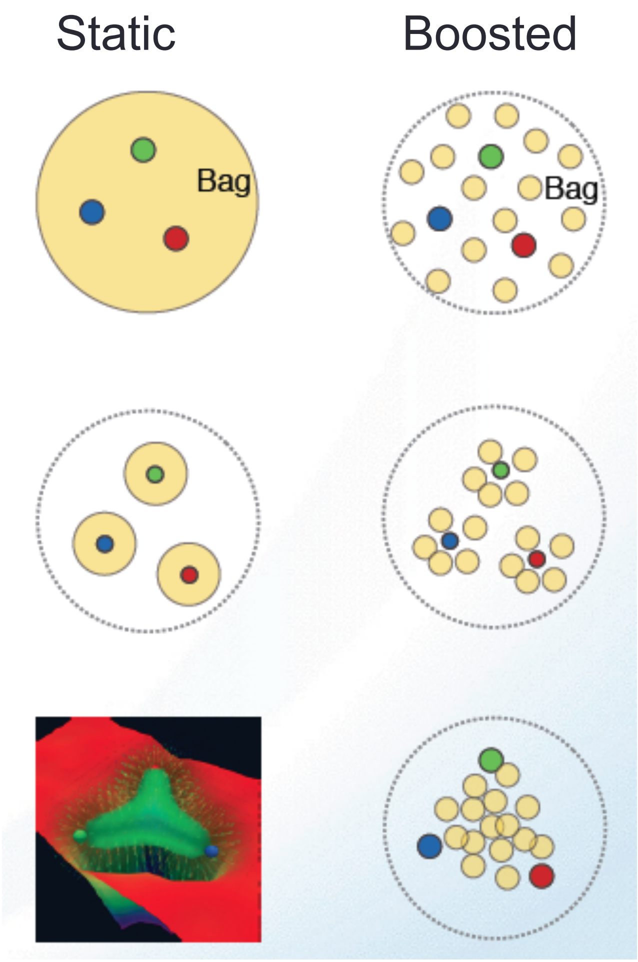
CONFINEMENT!

What does a proton look like?



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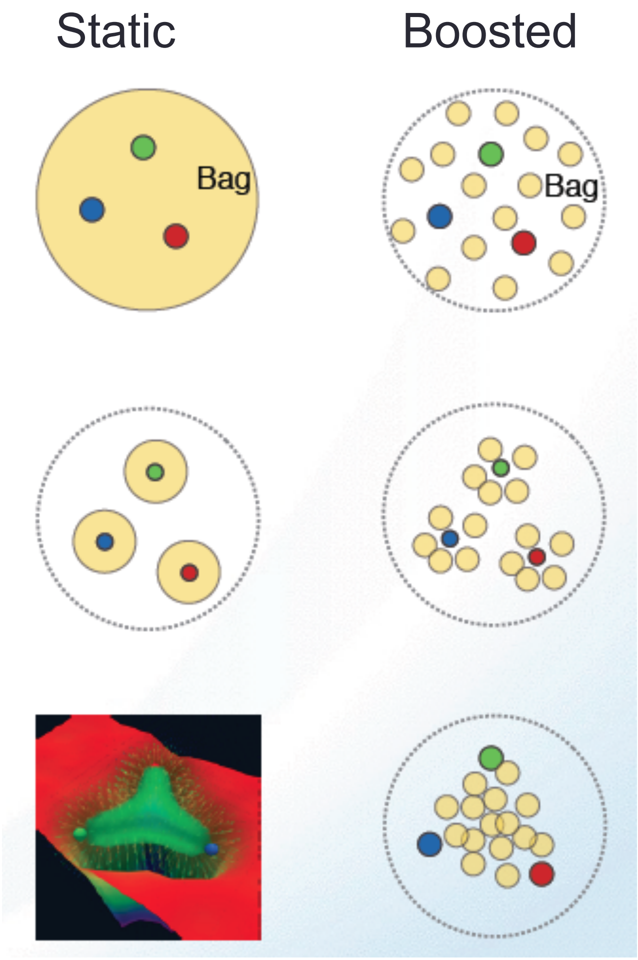

Bag Model: Gluon field distribution is wider than the fast moving quarks.
Gluon radius > Charge Radius

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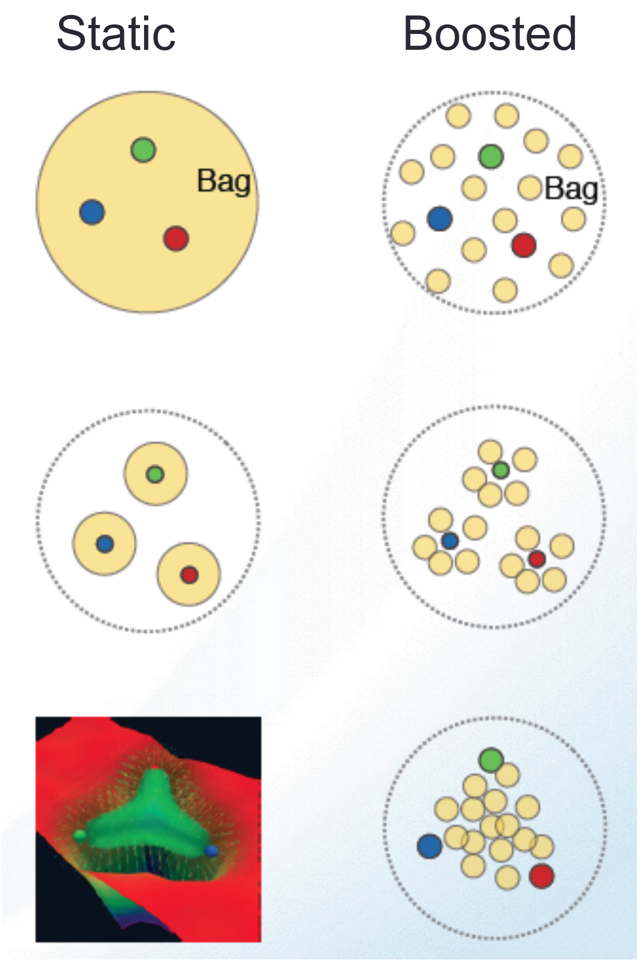

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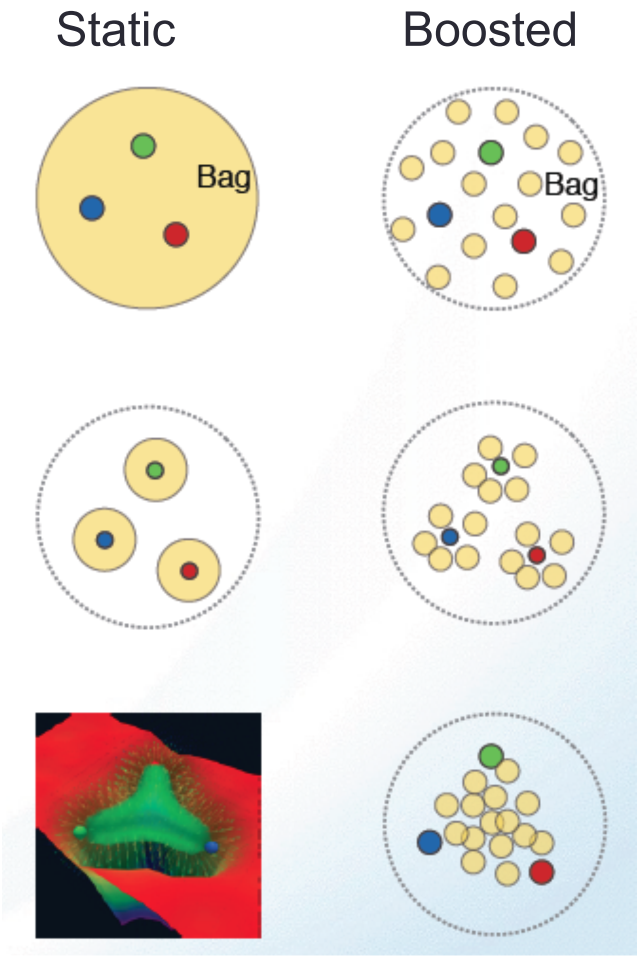

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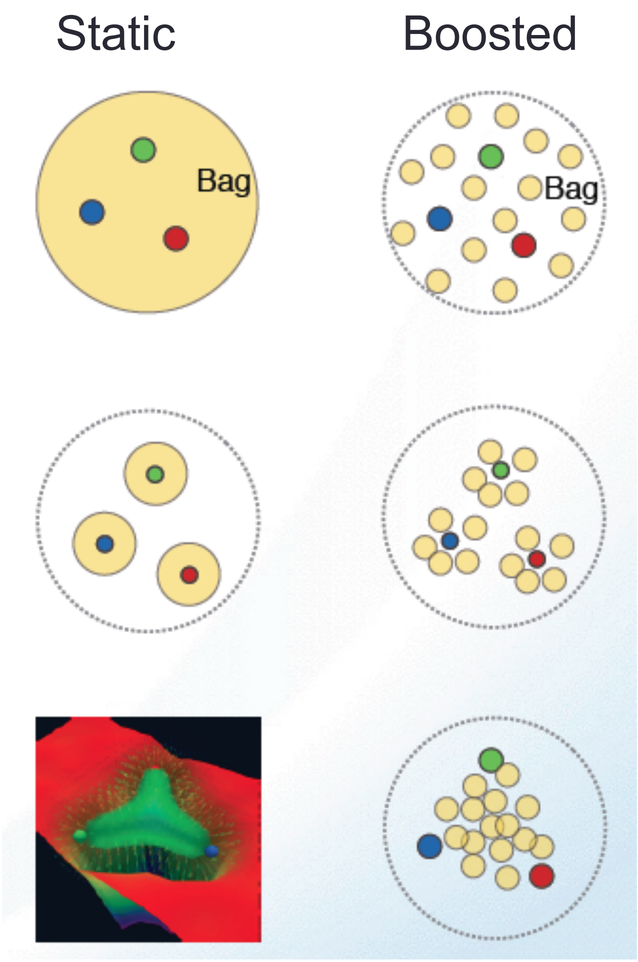
Lattice Gauge theory (with slow moving quarks), gluons more concentrated inside the quarks:
Gluon radius < Charge Radius

What does a proton look like?



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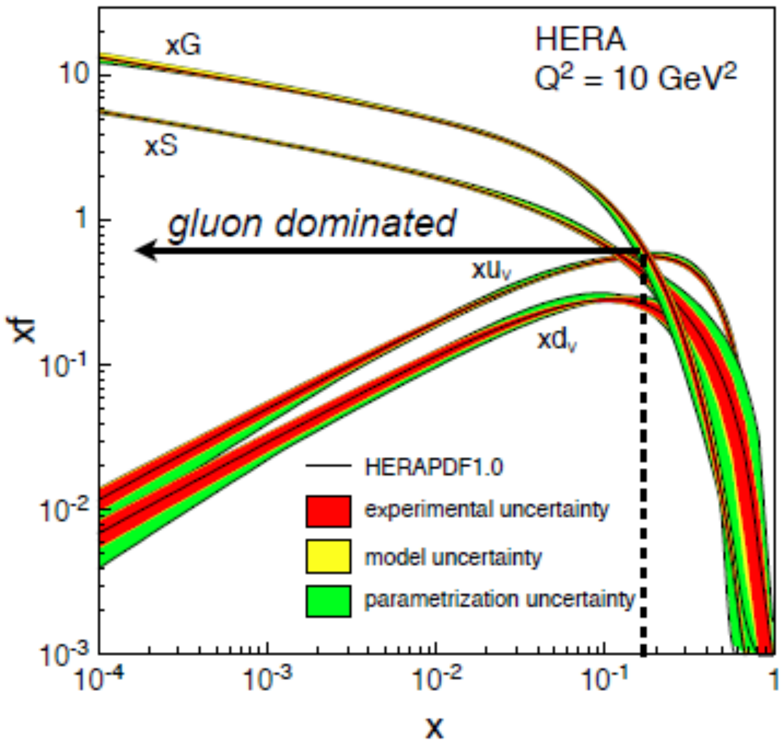
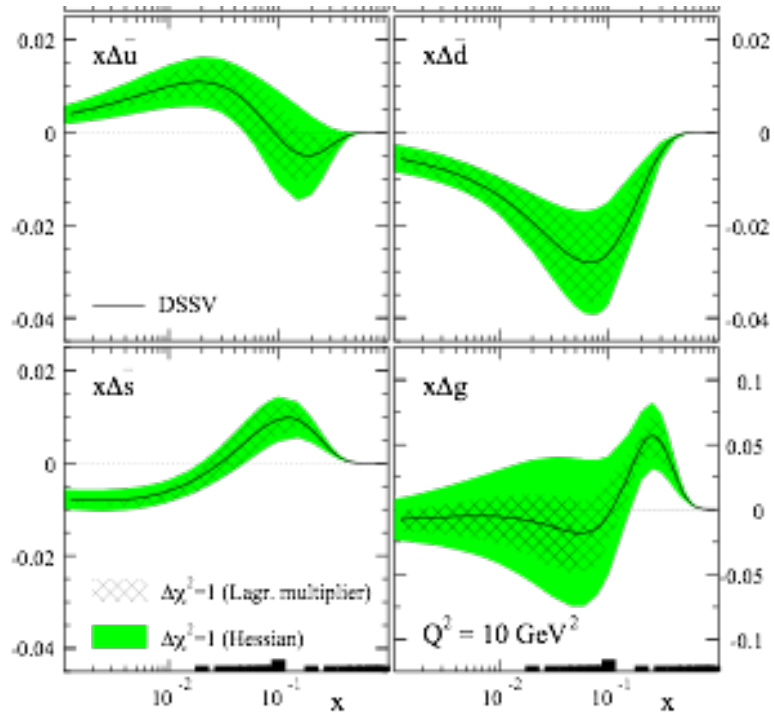
Need transverse images of the quarks *and gluons* in protons

What does a proton look like?
Unpolarized & polarized parton distribution functions





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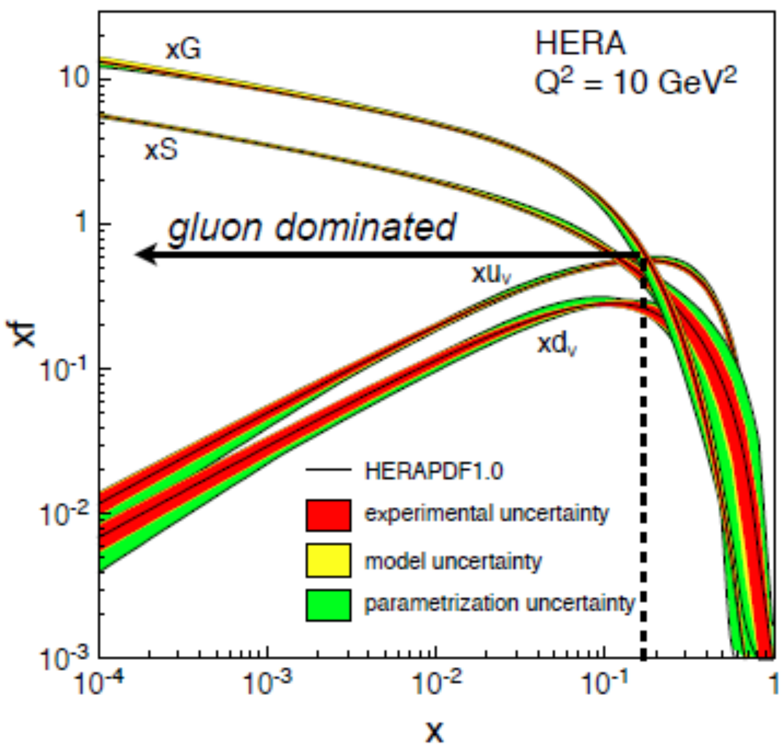
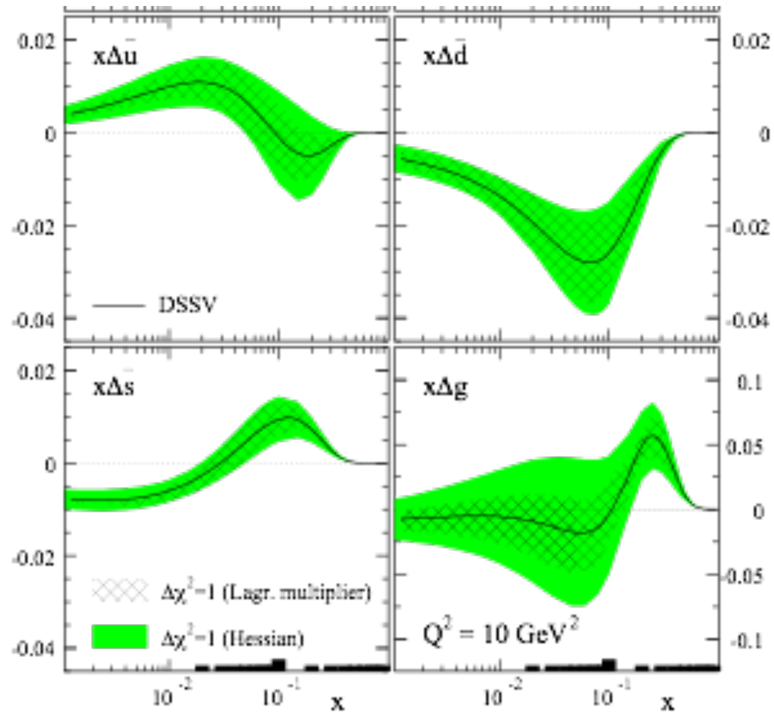




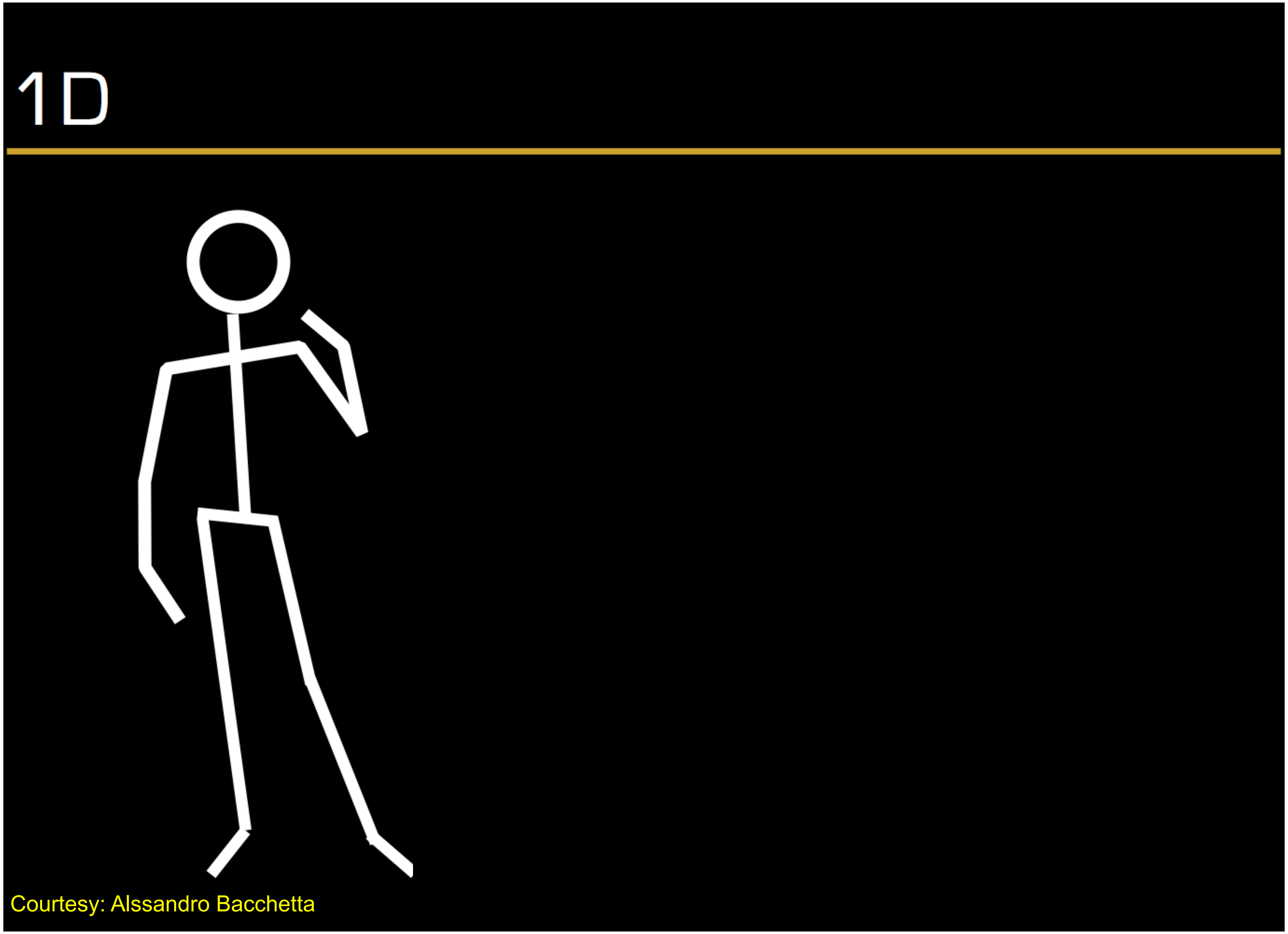
Need to go beyond 1-dimension!

Need 3D Images of nucleons in Momentum & Position space

Could they give us clues on orbital motion of partons?

Understanding the nucleon spin

What do we look like?



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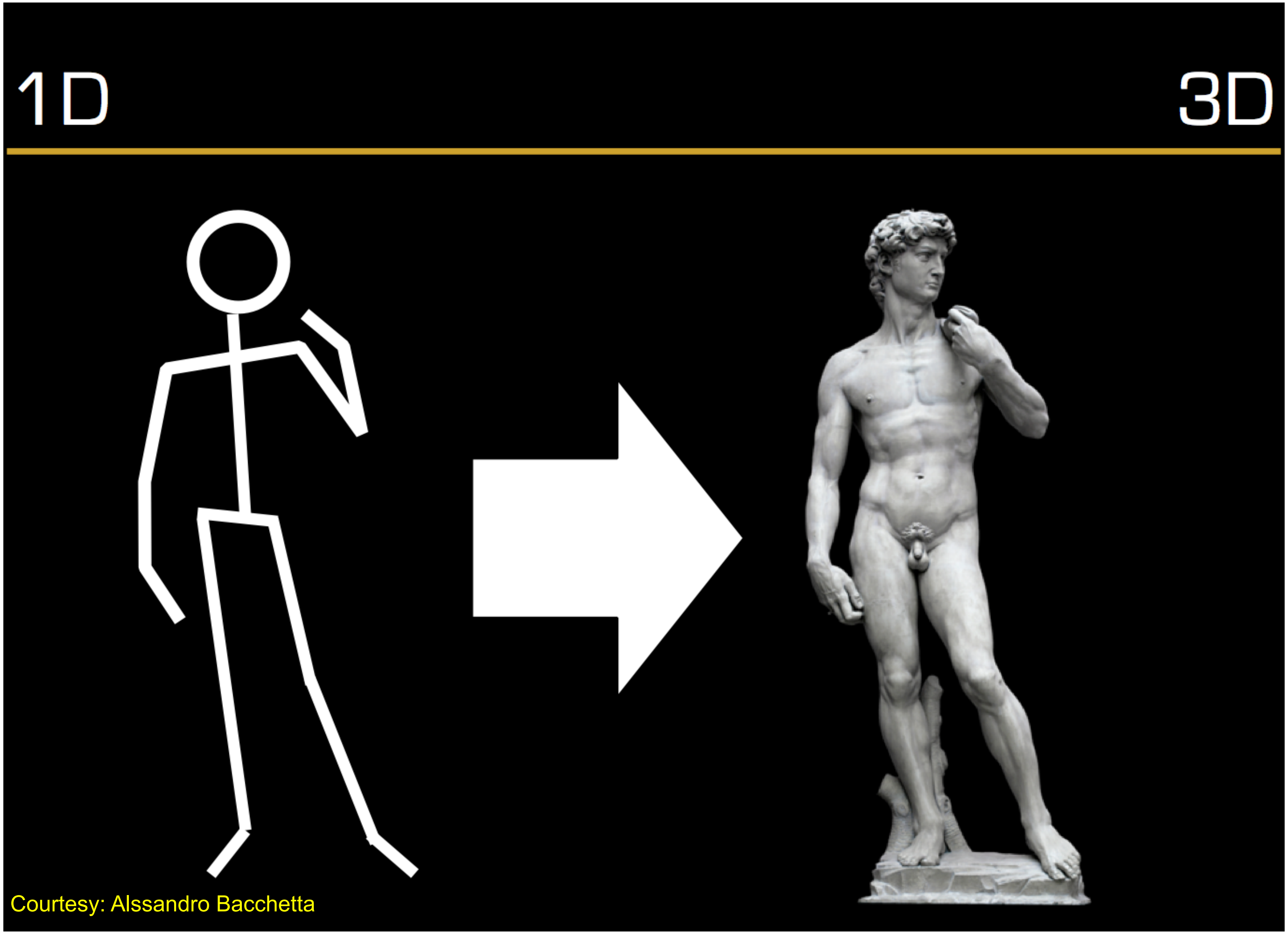

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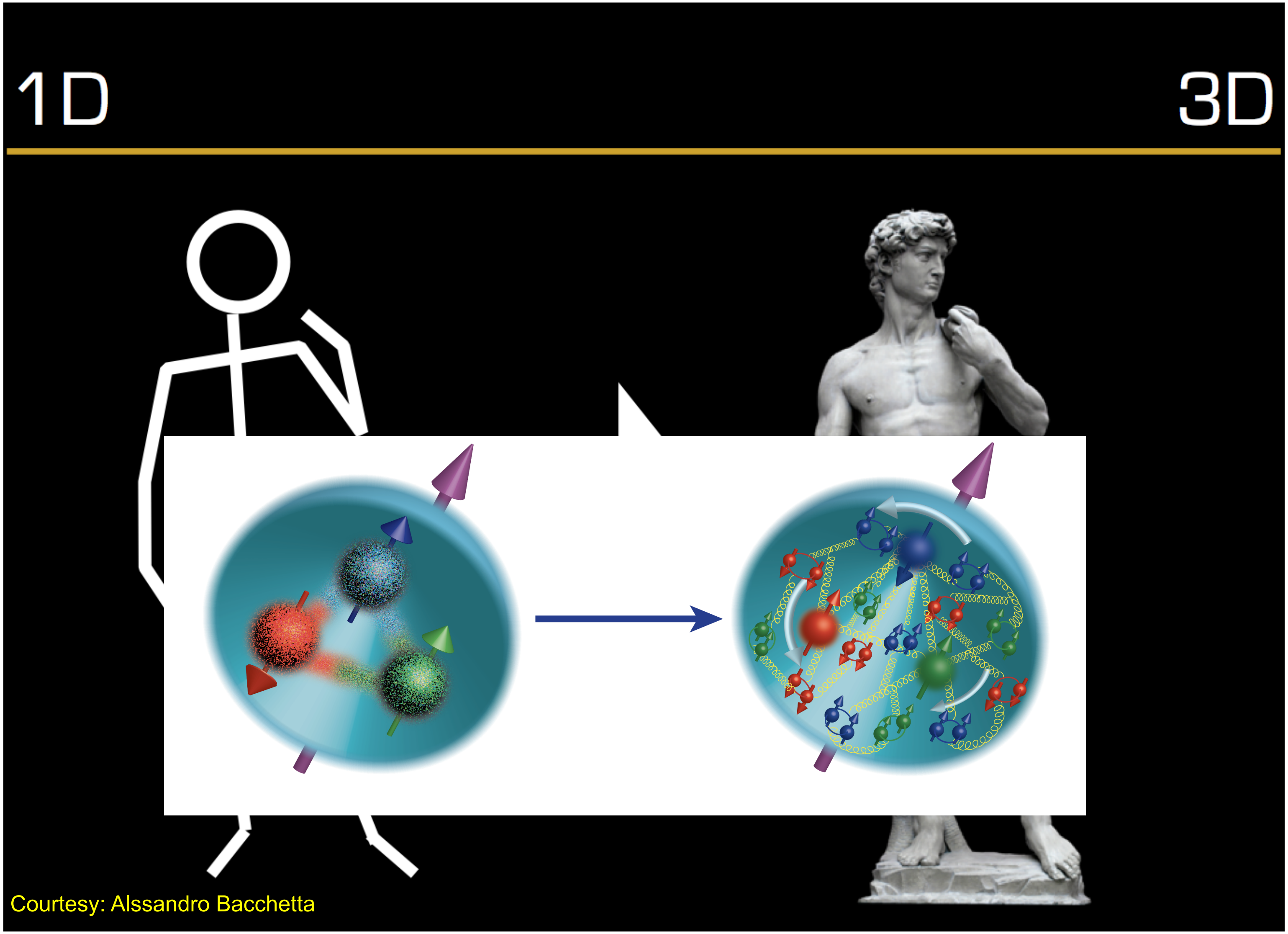
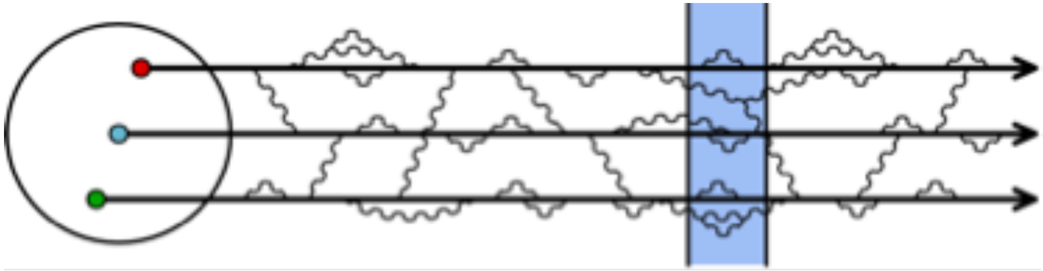


How does a Proton look at low and high energy?

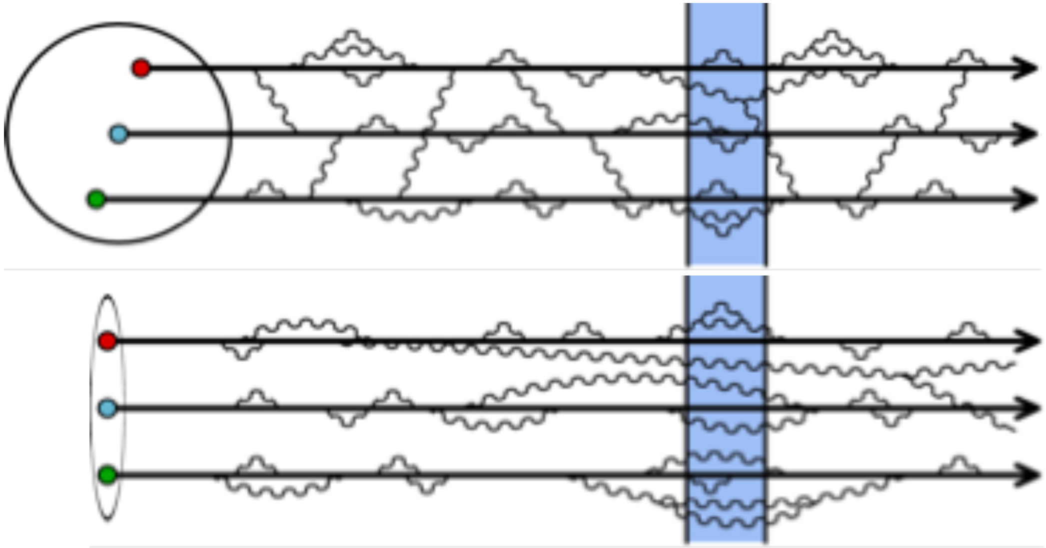
Low energy
High x
Regime of fixed target exp.



How does a Proton look at low and high energy?

Low energy
High x
Regime of fixed target exp.

High energy
Low- x
Regime of a Collider

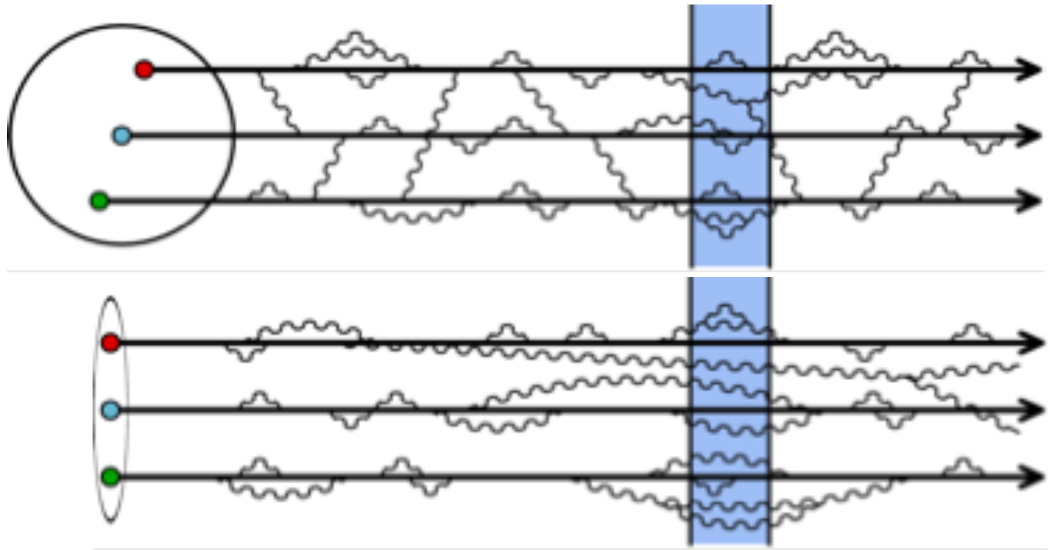


At high energy:

How does a Proton look 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

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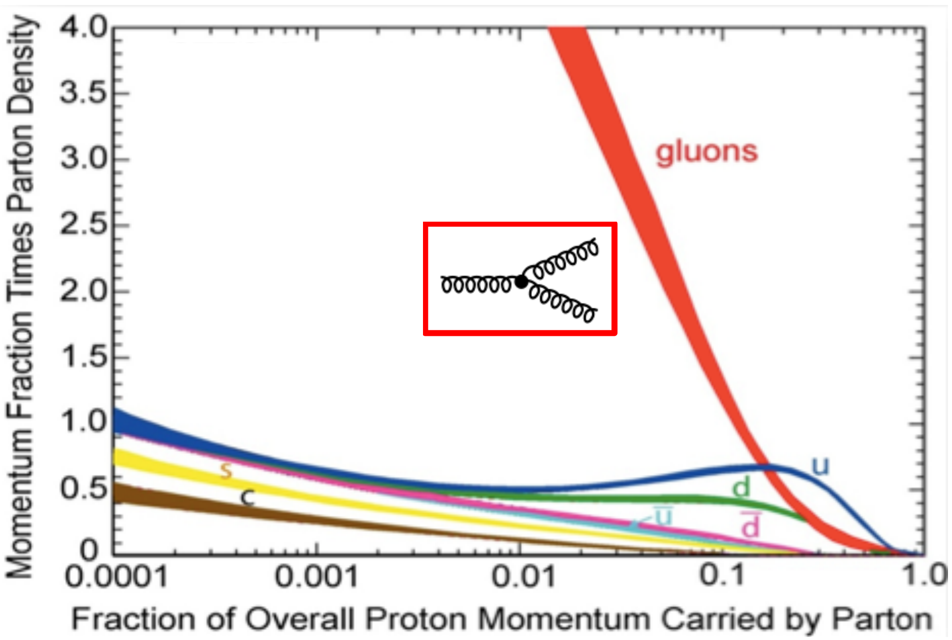

Apparent "indefinite rise" in gluon distribution in proton!

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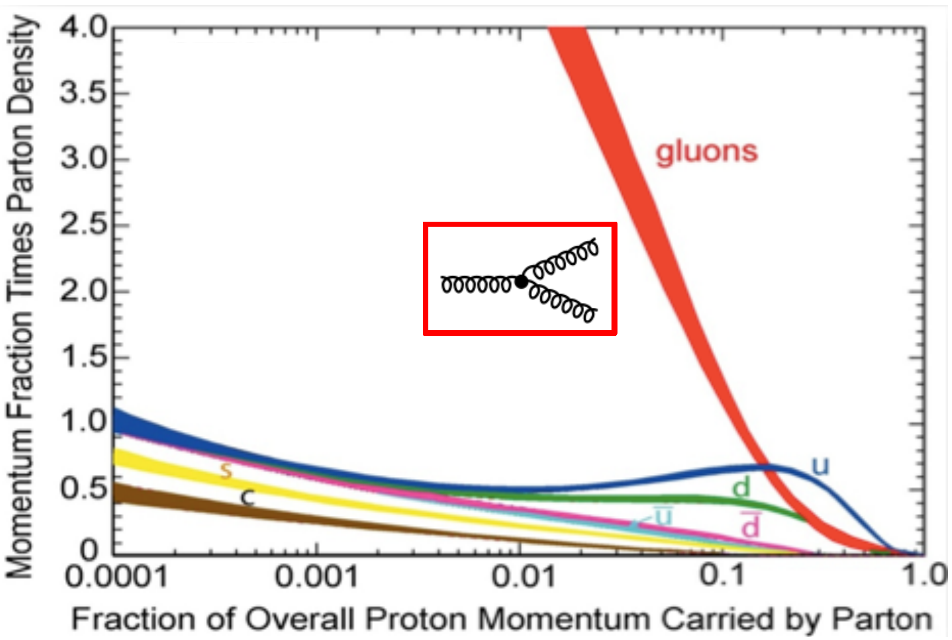

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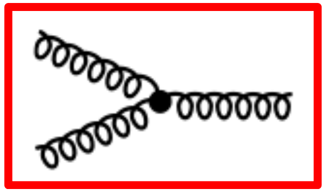
What could **limit this indefinite rise?** → saturation of soft gluon densities via gg→g recombination must be responsible.

recombination

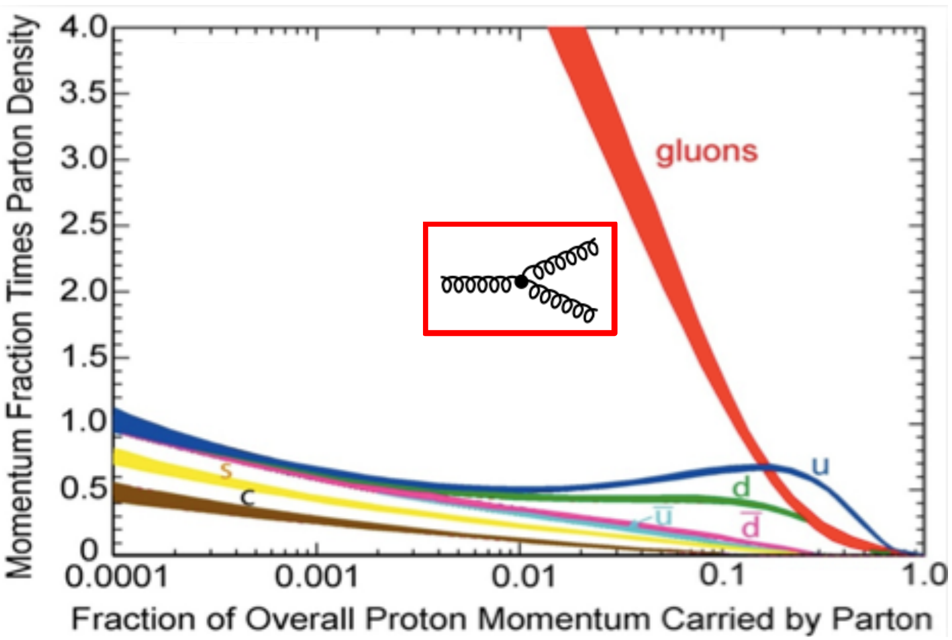


Gluon and the consequences of its interesting properties:

QCD Terra-incognita!

High Potential for Discovery

Gluons carry color charge ➔ Can interact with other gluons!



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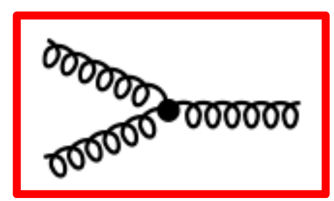


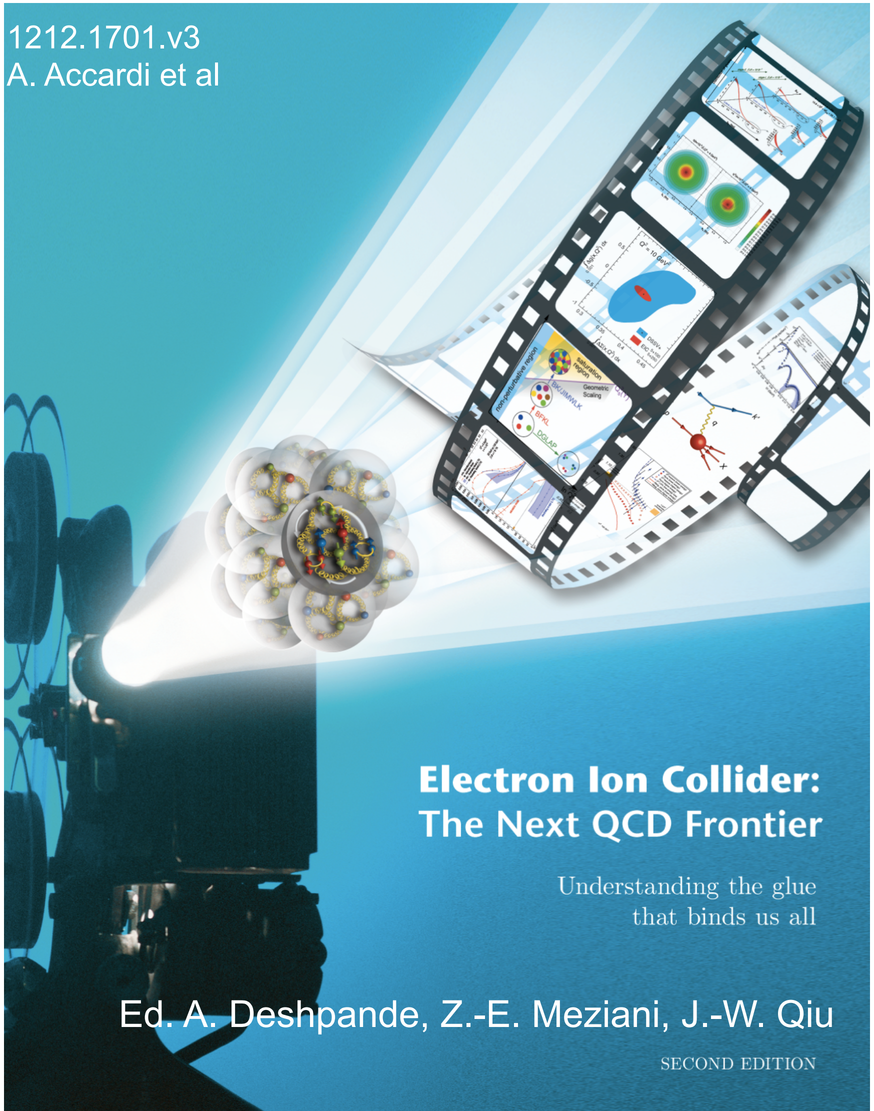
Where? No one has unambiguously seen this before!

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

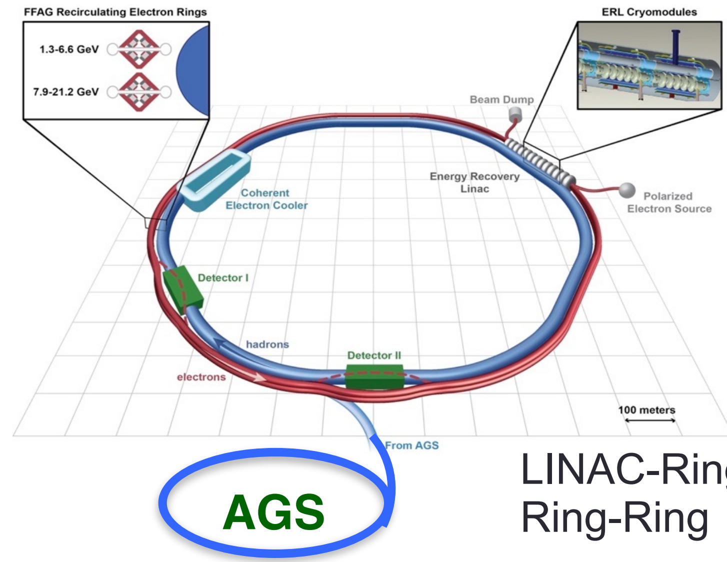
The Electron Ion Collider

Two options of realization!

1212.1701.v3
A. Accardi et al



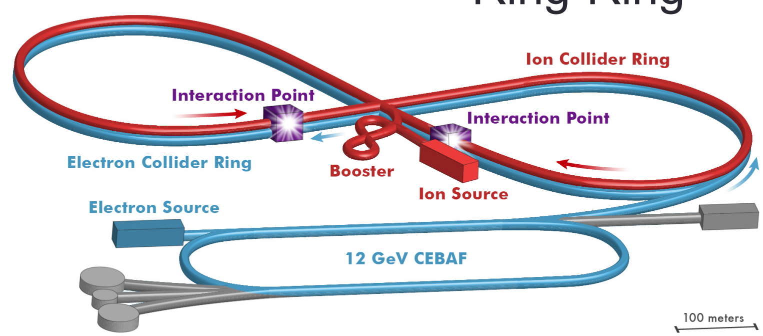
Ed. A. Deshpande, Z.-E. Meziani, J.-W. Qiu



LINAC-Ring
Ring-Ring

Not to scale

Ring-Ring



The Electron Ion Collider

Two options of realization!

For e-N collisions at the EIC:

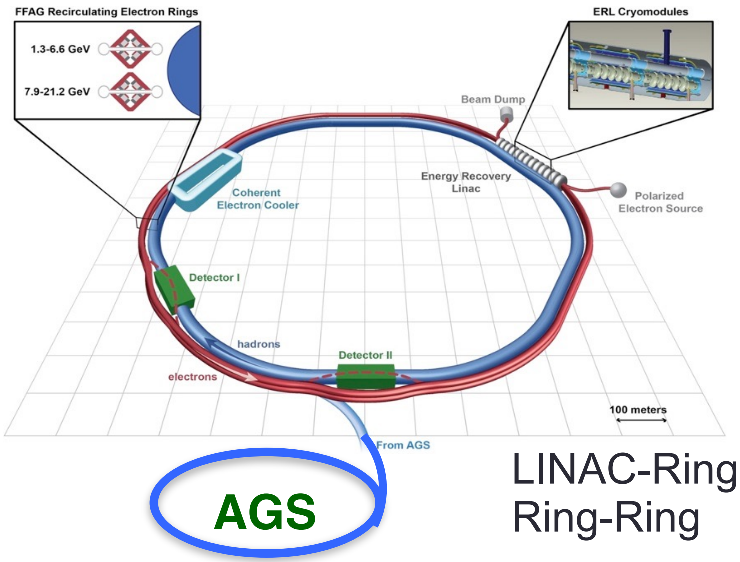
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity L_{ep} ~ 10^{33-34} cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM

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



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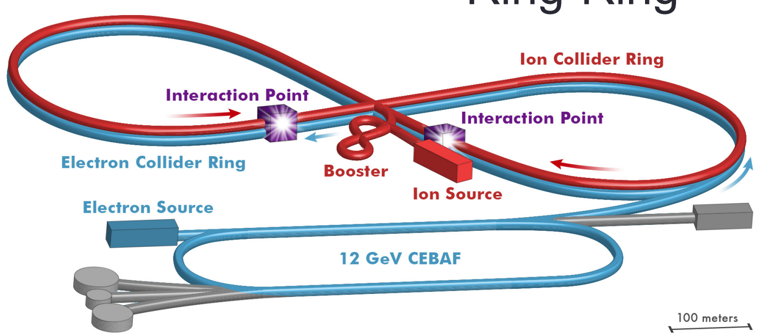
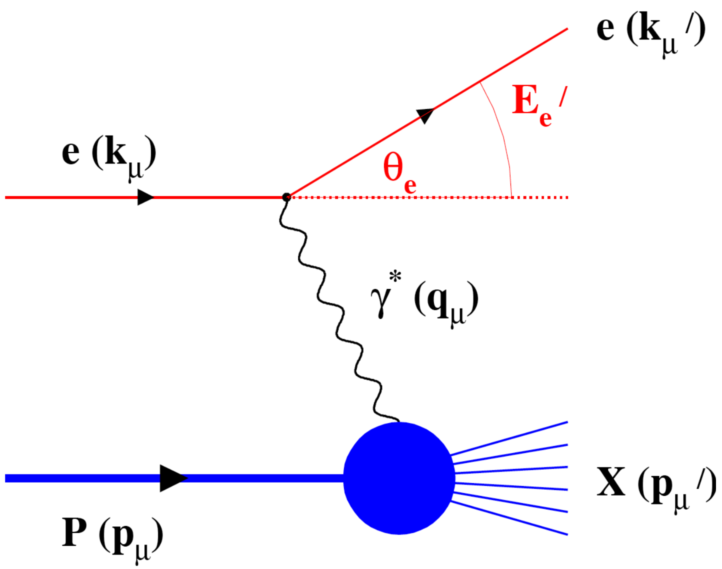


Deep Inelastic Scattering → Precision microscope with superfine control



Q^2 → Measure of resolution

y → Measure of inelasticity

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

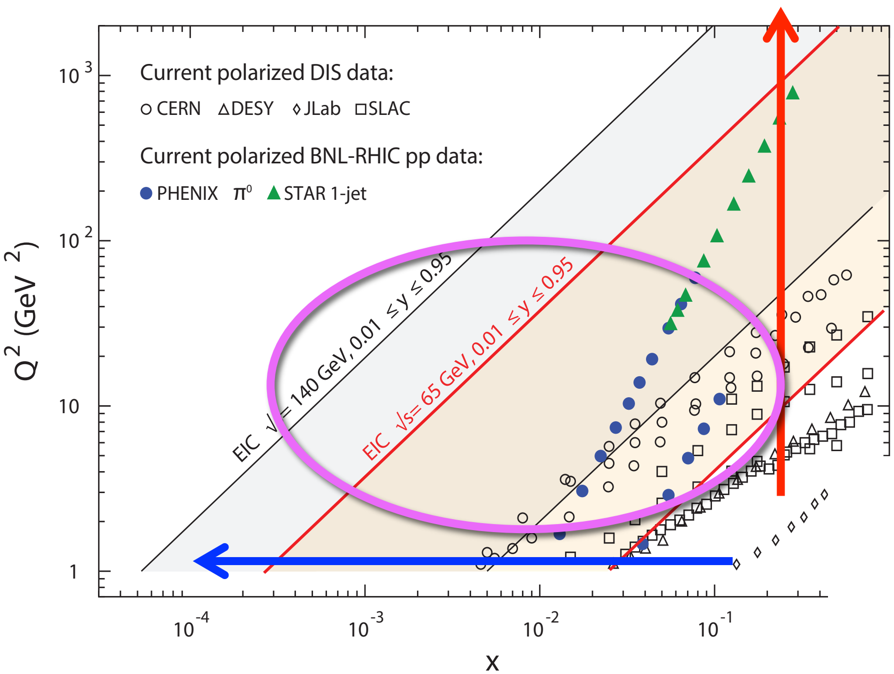
$Q^2 = S\ x\ y$

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)

EIC: Kinematic reach & properties

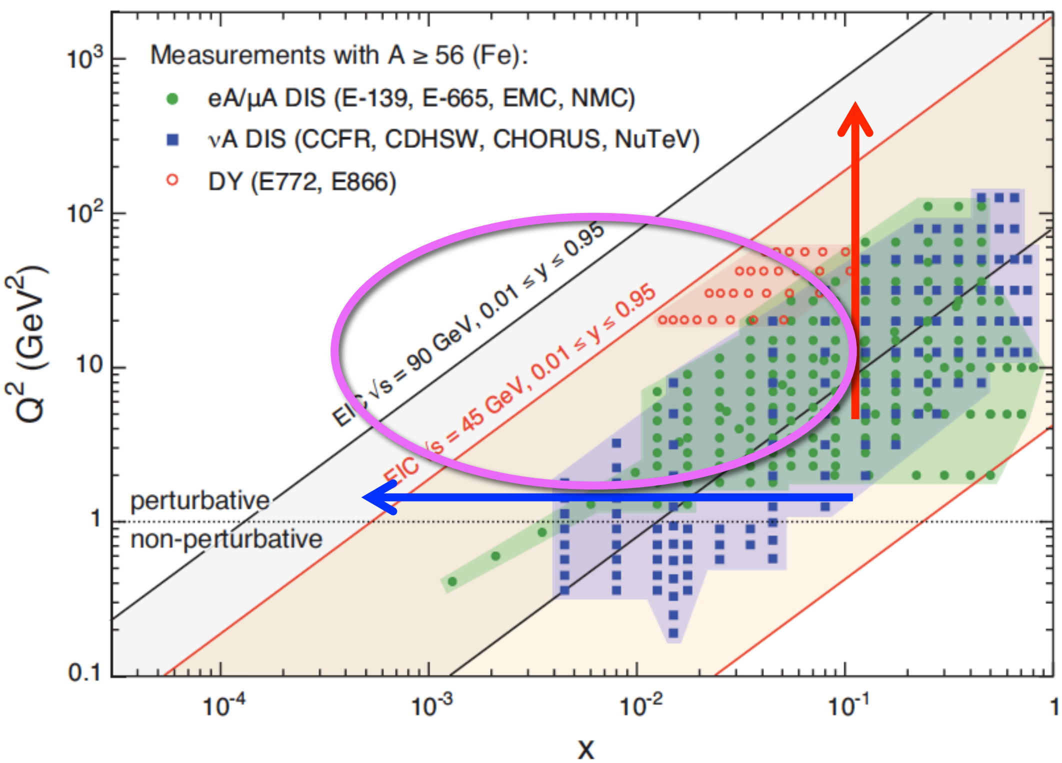


For e-N collisions at the EIC:

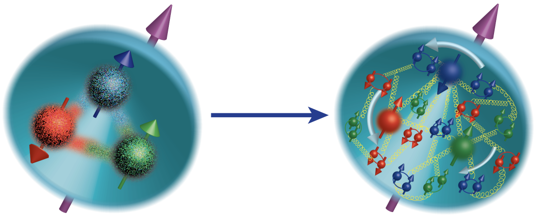
- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

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)

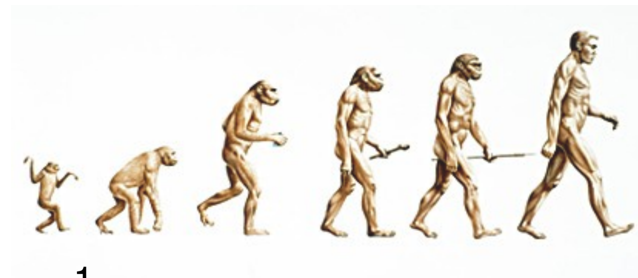


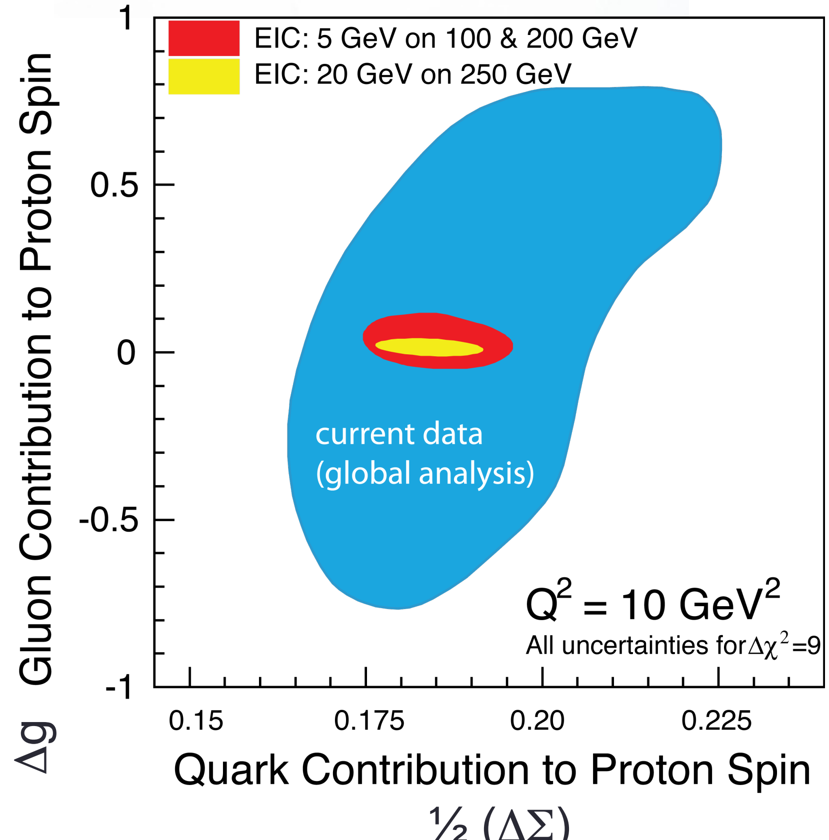
Our Understanding of Nucleon Spin



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

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





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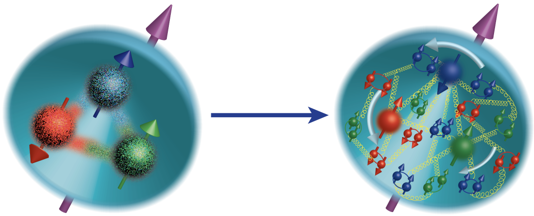

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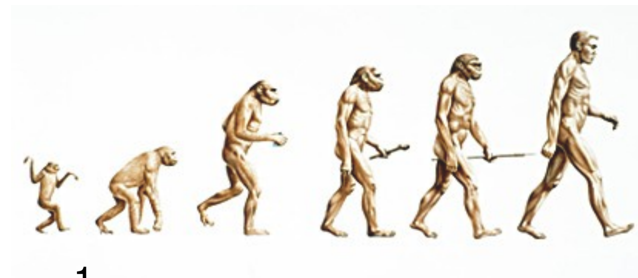

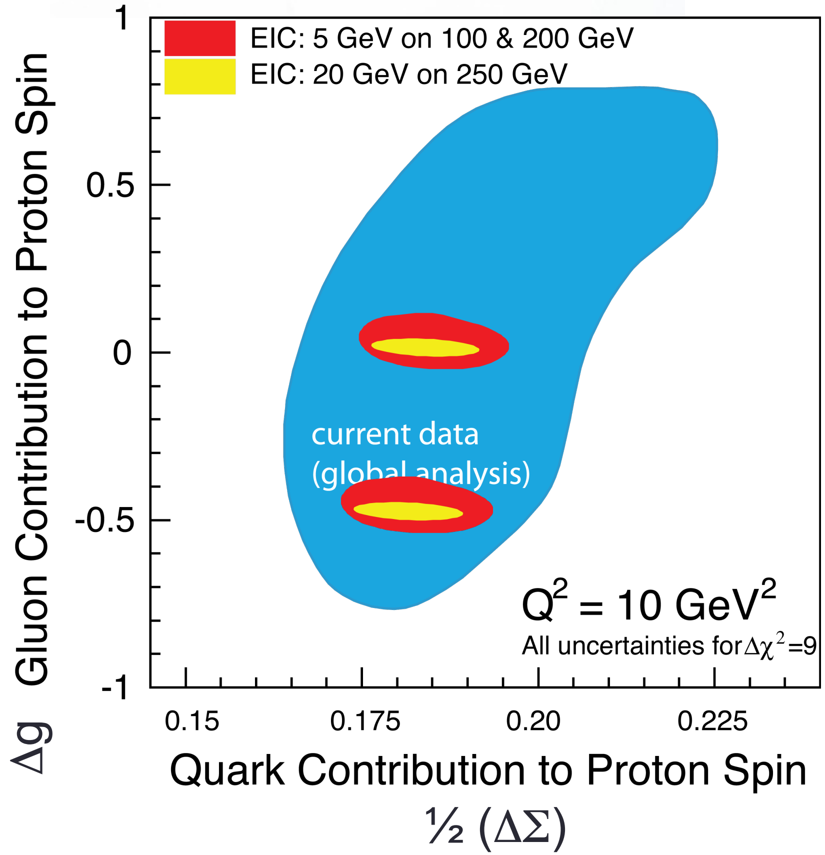

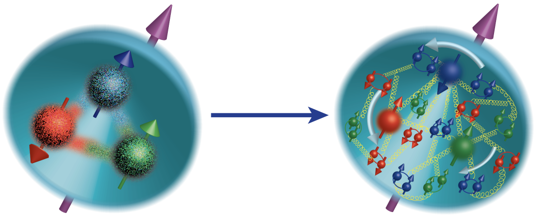

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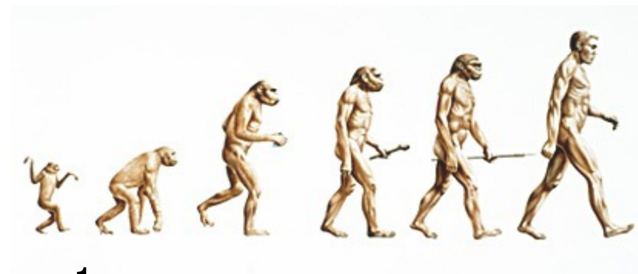

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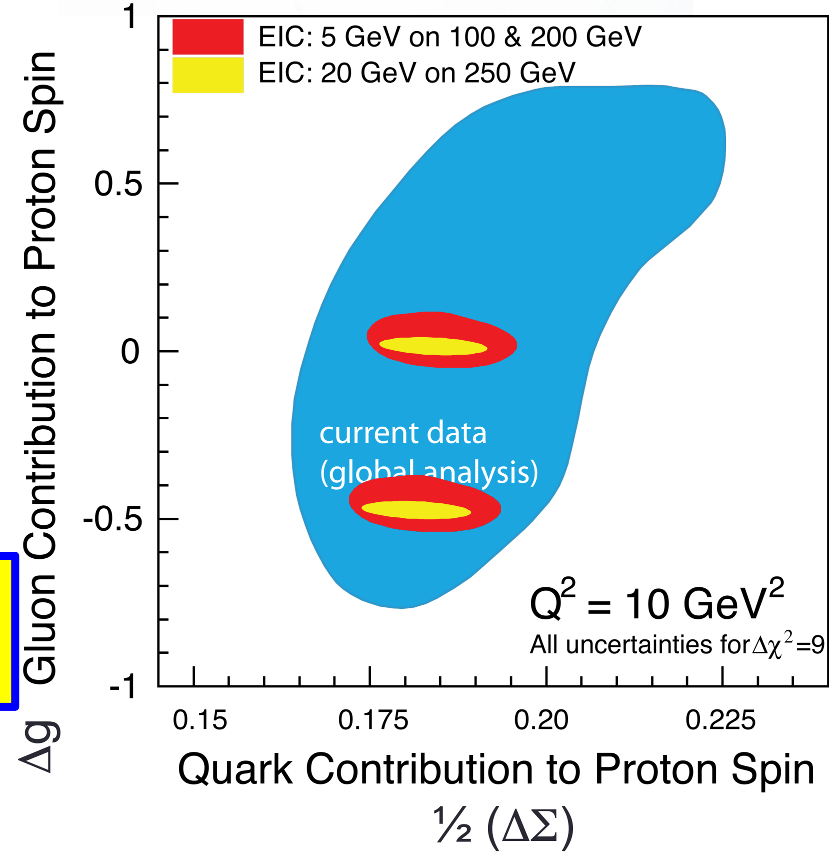


$\Delta\Sigma/2$ = Quark contribution to Proton Spin

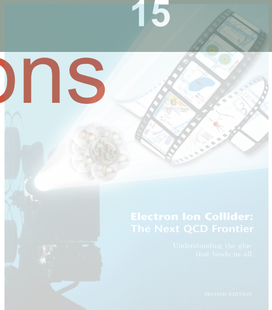
L_Q = Quark Orbital Ang. Mom

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

3-Dimensional Imaging Quarks and Gluons



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

3-Dimensional Imaging Quarks and Gluons

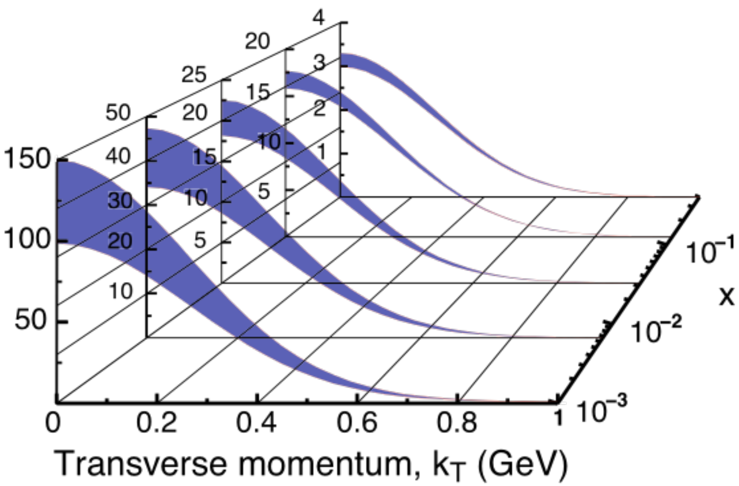
Momentum space

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

$$\int d^2 b_T$$

$$f(x, k_T)$$

Quarks



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

3-Dimensional Imaging Quarks and Gluons

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

Momentum space

$\int d^2 b_T$

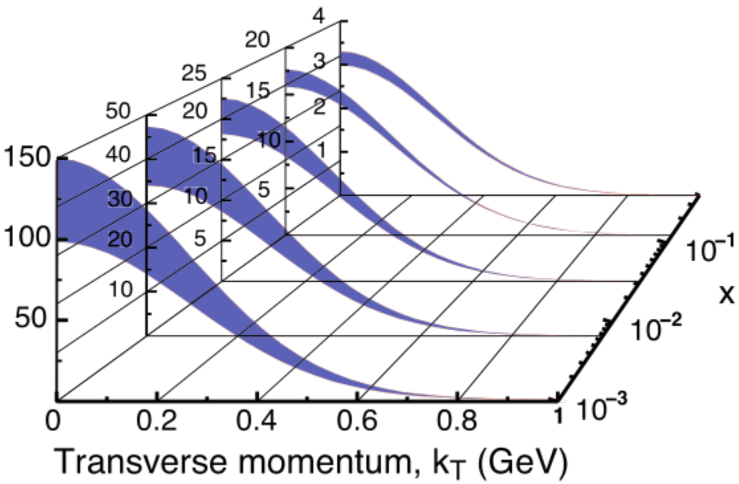
$\int d^2 k_T$

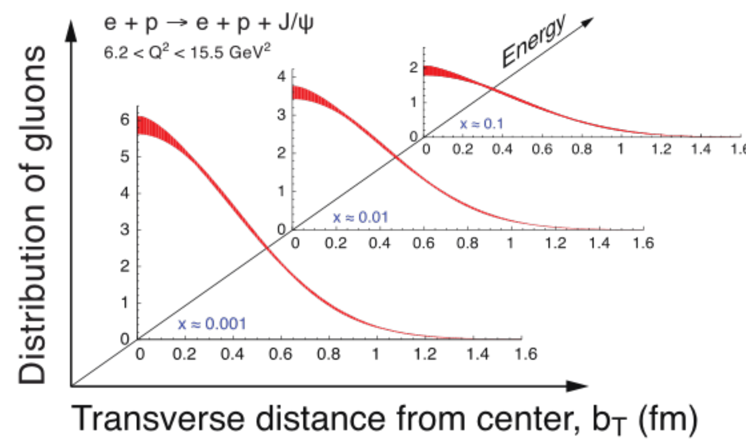
Coordinate space

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

Quarks

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

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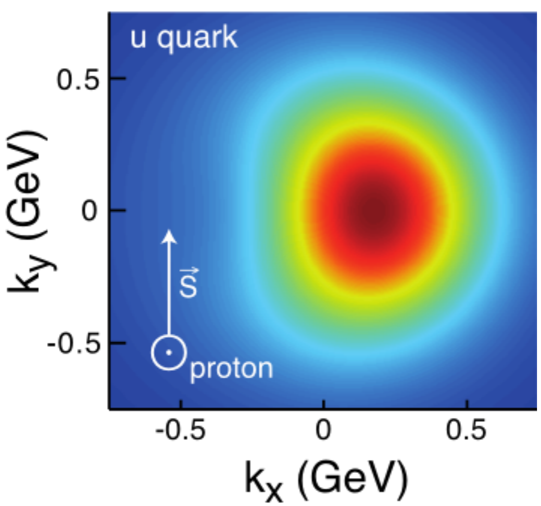

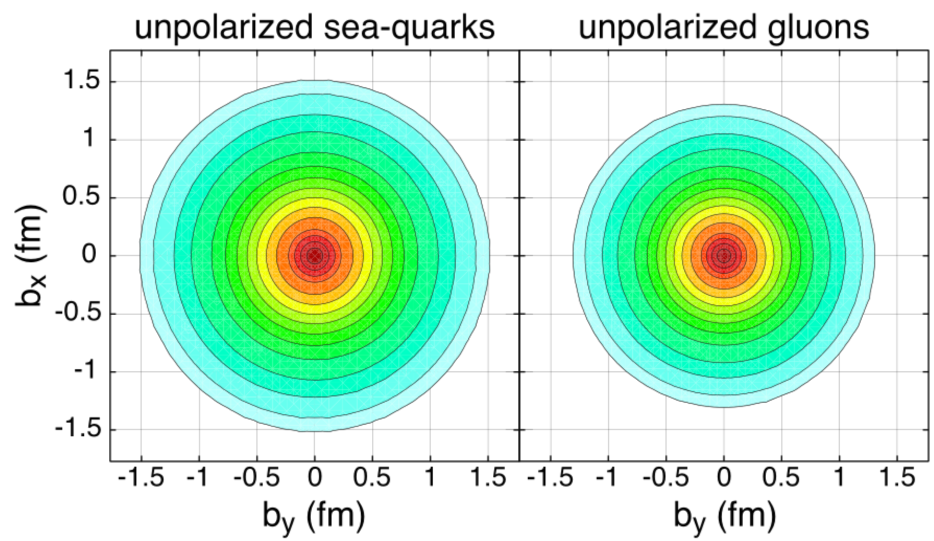

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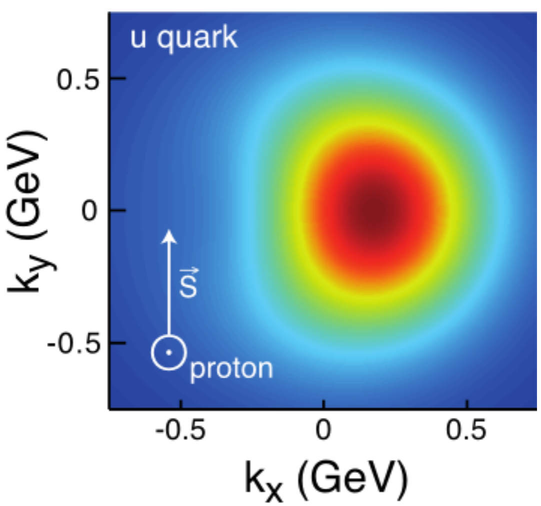
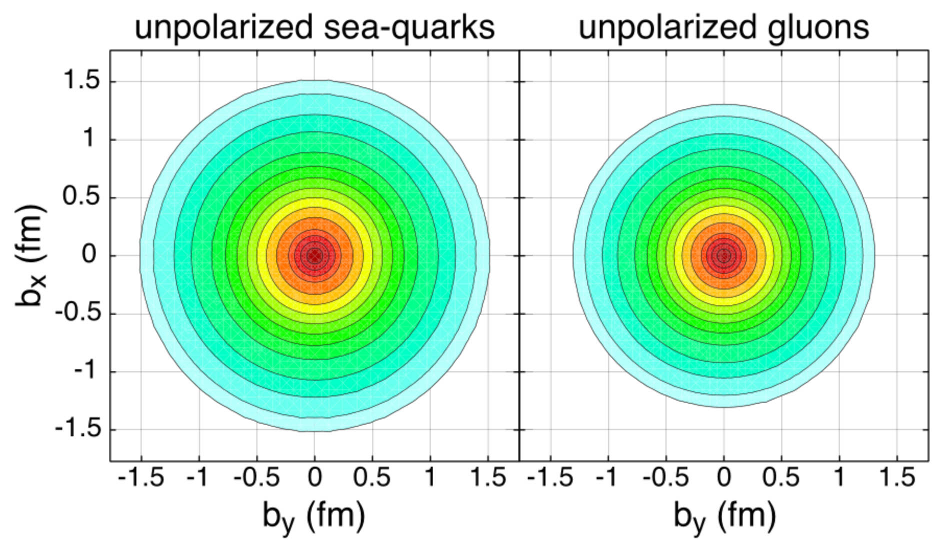
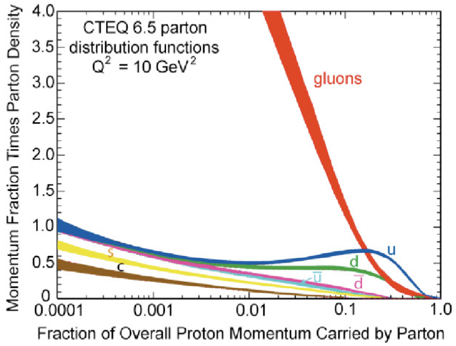


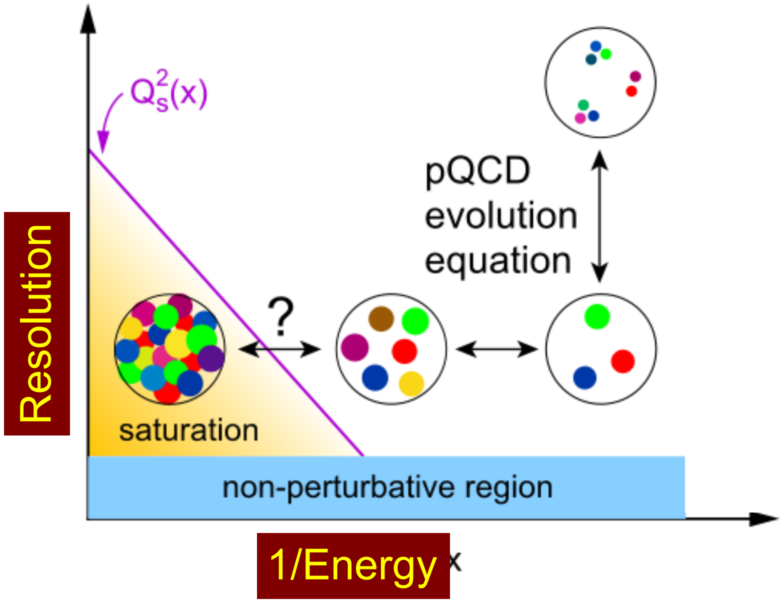


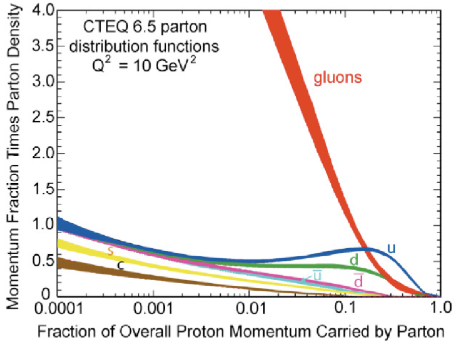
Position r X Momentum p → Orbital Motion of Partons

→ *Directly comparable with Lattice QCD Calculations*

What do we learn from low-x studies?







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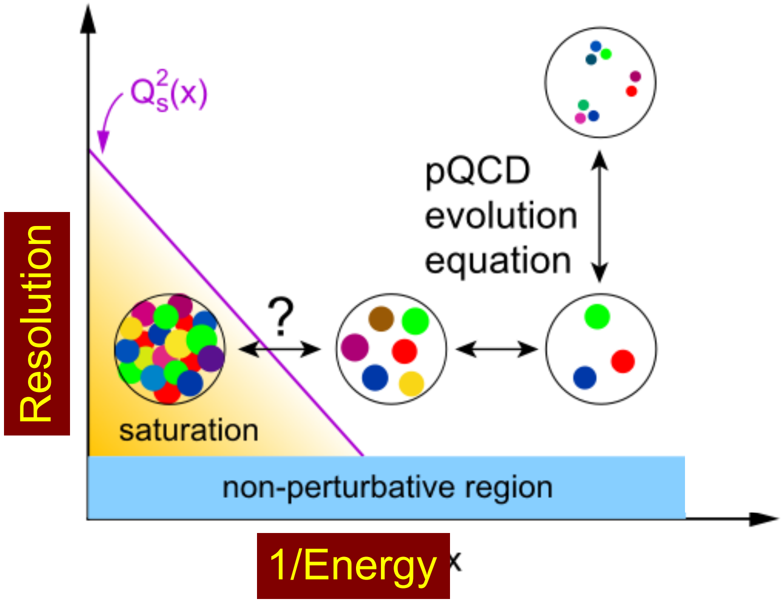

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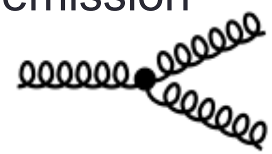
- Saturation Scale $Q_S(x)$ where gluon emission and recombination comparable

gluon emission



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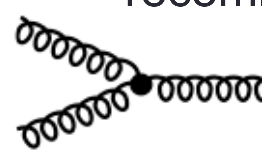
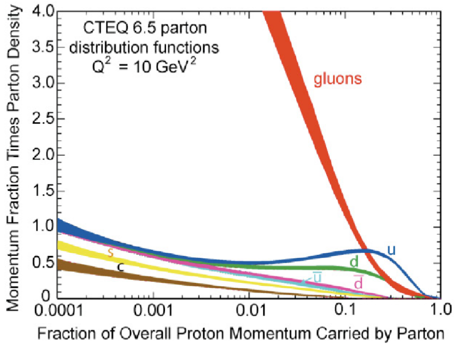


At Q_S



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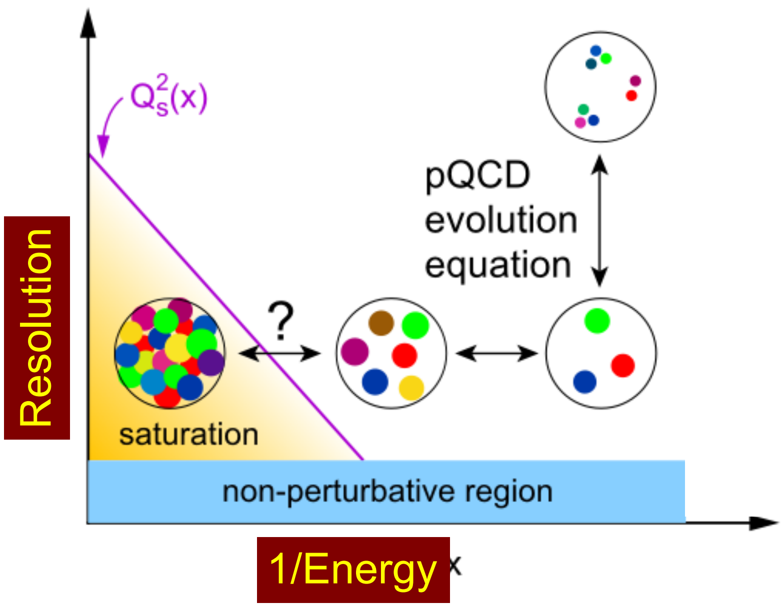

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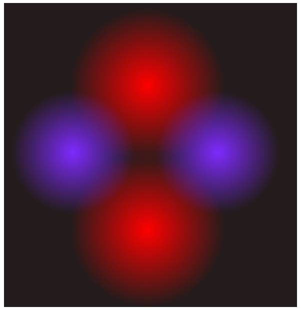
First observation of gluon recombination effects in nuclei:
→leading to a *collective* gluonic system!
First observation of g-g recombination in *different* nuclei
→ **Is this a universal property?**
→ **Is the Color Glass Condensate the correct effective theory?**

Other investigations with nuclei…

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



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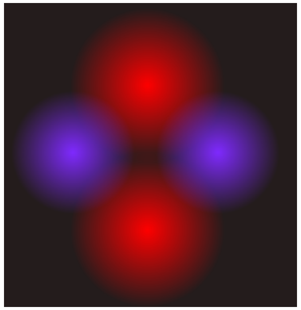

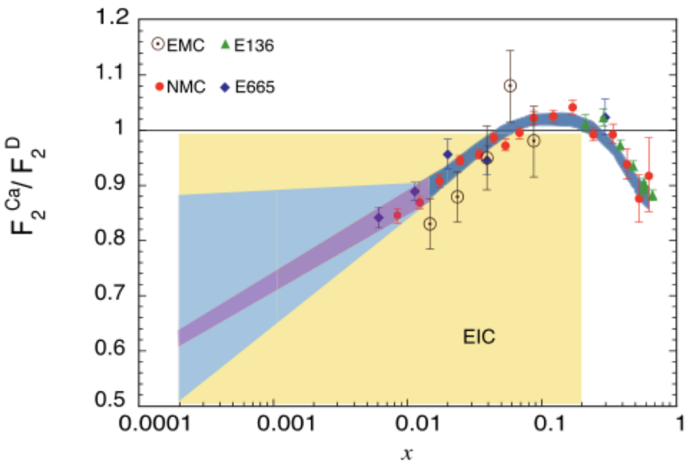

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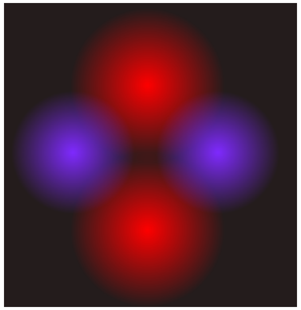

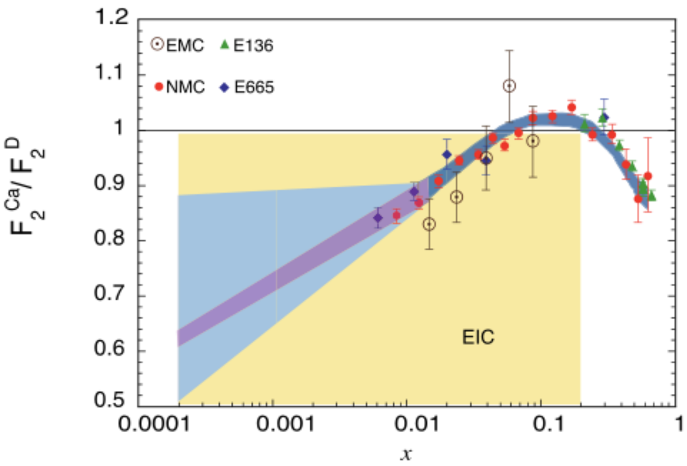

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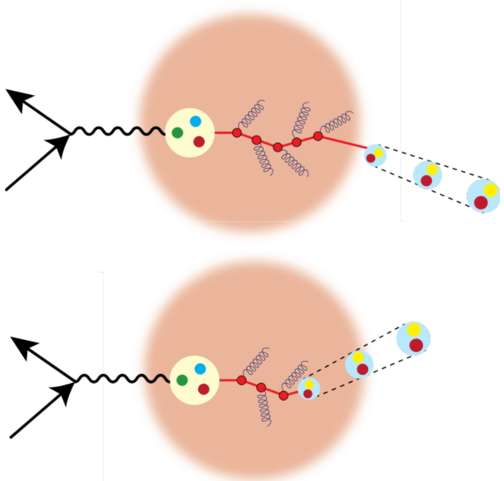
How does nuclear matter respond to fast moving color charge passing through it? (hadronization…. confinment?)



Innovative Accelerator Science

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On going R&D on accelerator concepts and technologies:

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

eRHIC R&D

JLEIC R&D

Most of these are of global interest!

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Office of NP, US DOE is initiating an Accelerator R&D program to address this ~$7M/year starting FY2017.

EICUG Today: 656 Users, 137 Institutes, 27 Countries

355 experimentalists, 111 theorists, 141 accelerator-physicists, 43 unknowns

Community/Collaboration building:

EIC User Group → eicug.org (contact me!)

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Ample opportunities for contributions & participation!

Detector R&D

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

An external committee of 8 experts reviews all proposals

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

→Weekly meetings, workshops and test beam activities already underway

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

→Despite many successes many details to be worked out

Currently the program receives ~$1.3M annually. Intend to request increase by at least factor ~2 if not more in near future.

Recent international requests makes the case for doubling stronger.

Opportunity for non-US Sources to make an impact!

Charge to the National Academy for the review of EIC (2016) (my rendition of the charge to fit on 1 slide)

The committee will assess the scientific justification for a U.S. domestic electron ion collider facility

In particular, the committee will address the following questions:

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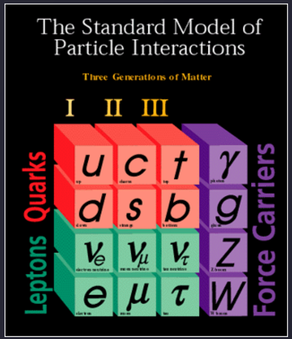
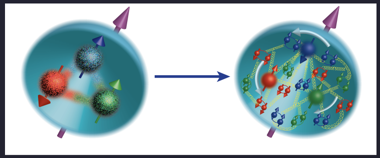
- What are the benefits to US leadership in nuclear physics?
- What are the benefits to other fields of science and to society?

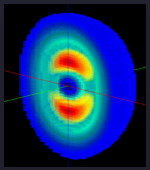
Path forward for the EIC:

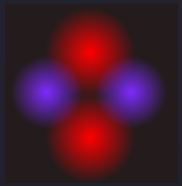
- Science Review by National Academy of Science (& Engineering & Arts) (National Research Council)
- Positive NAS review will trigger the DOE's CD process
  - CD0 (acceptance of the critical need for science by DOE) FY18
  - EIC-Proposal's Technical & Cost review → FY19 (site selection)
  - CD2 requires site selection
  - Major Construction funds ("CD3") by 2022/23"
  - Assuming 1.6% sustained increase over inflation of the next several years (Long Range Plan)

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

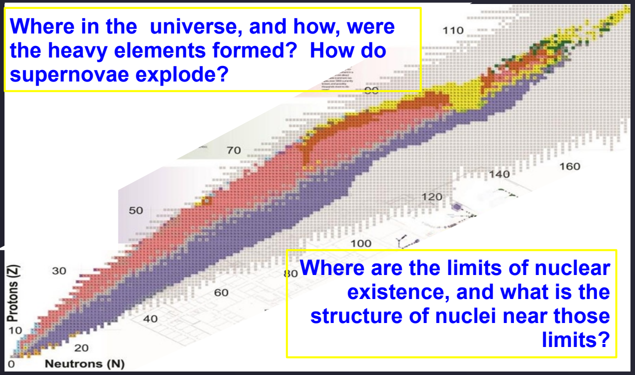






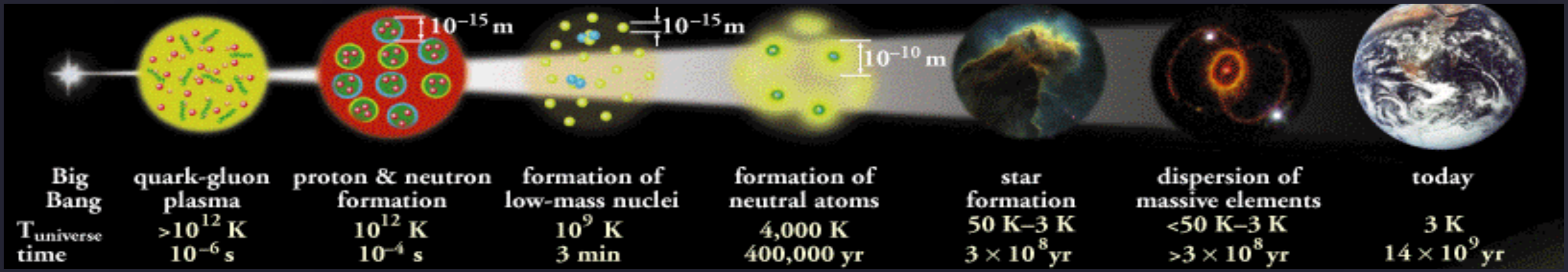


How are the properties of protons and neutrons, and the force between them, built up from quarks, antiquarks and gluons? What is the mechanism by which these fundamental particles materialize as hadrons?



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?



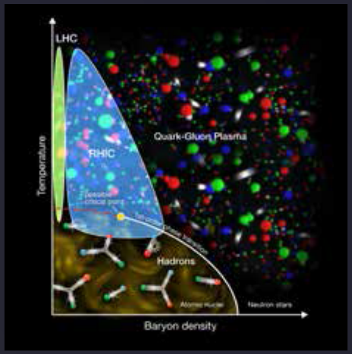
What is the nature of the different phases of nuclear matter through which the universe has evolved?

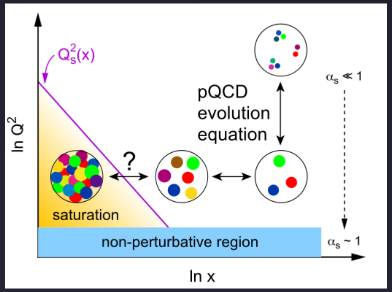
Do nucleons and all nuclei, viewed at near light speed, appear as walls of gluons with universal properties?

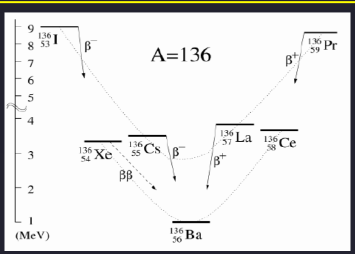
How can the properties of nuclei be used to reveal the fundamental processes that produced an imbalance between matter and antimatter in our universe?

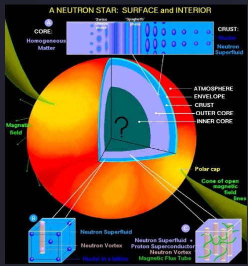
How are the nuclear building blocks manifested in the internal structure of compact stellar objects, like neutron stars?

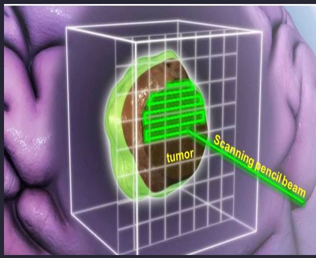
How can technologies developed for basic nuclear physics research be adapted to address society's needs?











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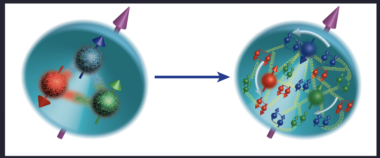

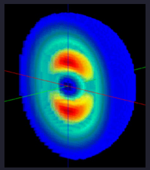

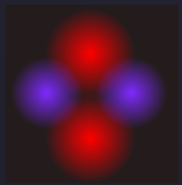

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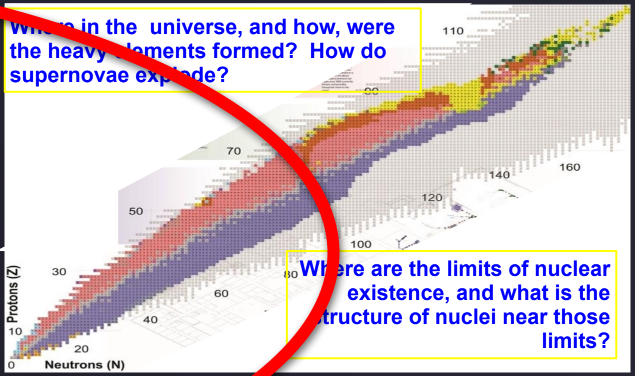

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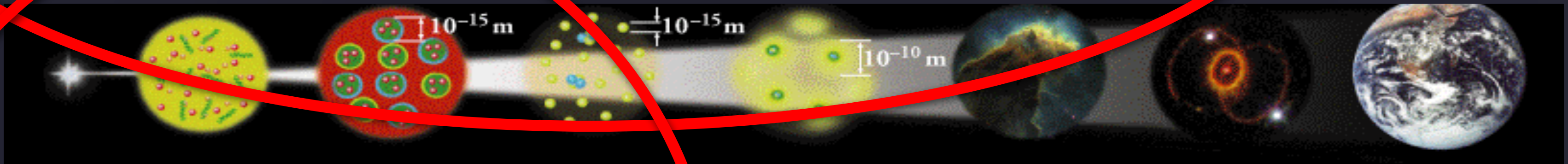

Big Bang	quark-gluon plasma	proton & neutron formation	formation of low-mass nuclei	formation of neutral atoms	star formation	dispersion of massive elements	today
$T_{universe}$	$>10^{12}$ K	10^{12} K	10^{9} K	4,000 K	50 K–3 K	<50 K–3 K	3 K
time	10^{-6} s	10^{-4} s	3 min	400,000 yr	3×10^{8} yr	$>3 \times 10^{8}$ yr	14×10^{9} yr

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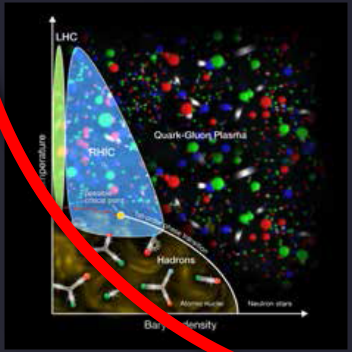

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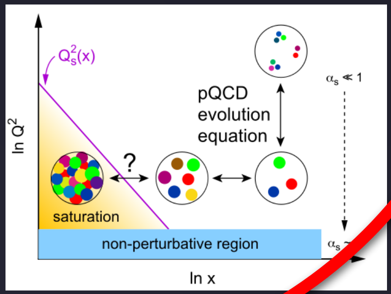

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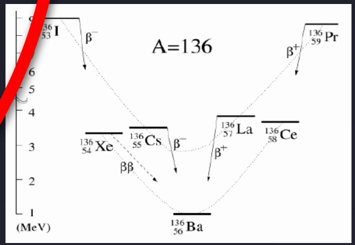

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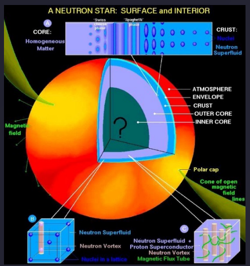

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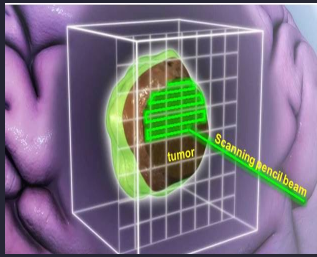

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→ ***The bridge between sea quark/gluons to Nuclei***

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→ ***High potential for discovery***

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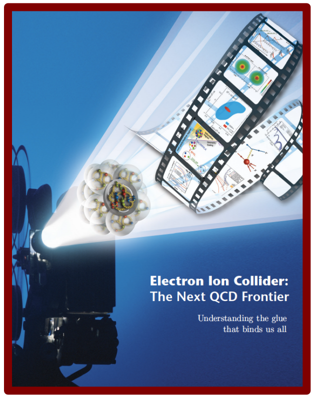
Future QCD studies, particularly for Gluons, demands an Electron Ion Collider

NSAC agrees and we are moving forward!

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.

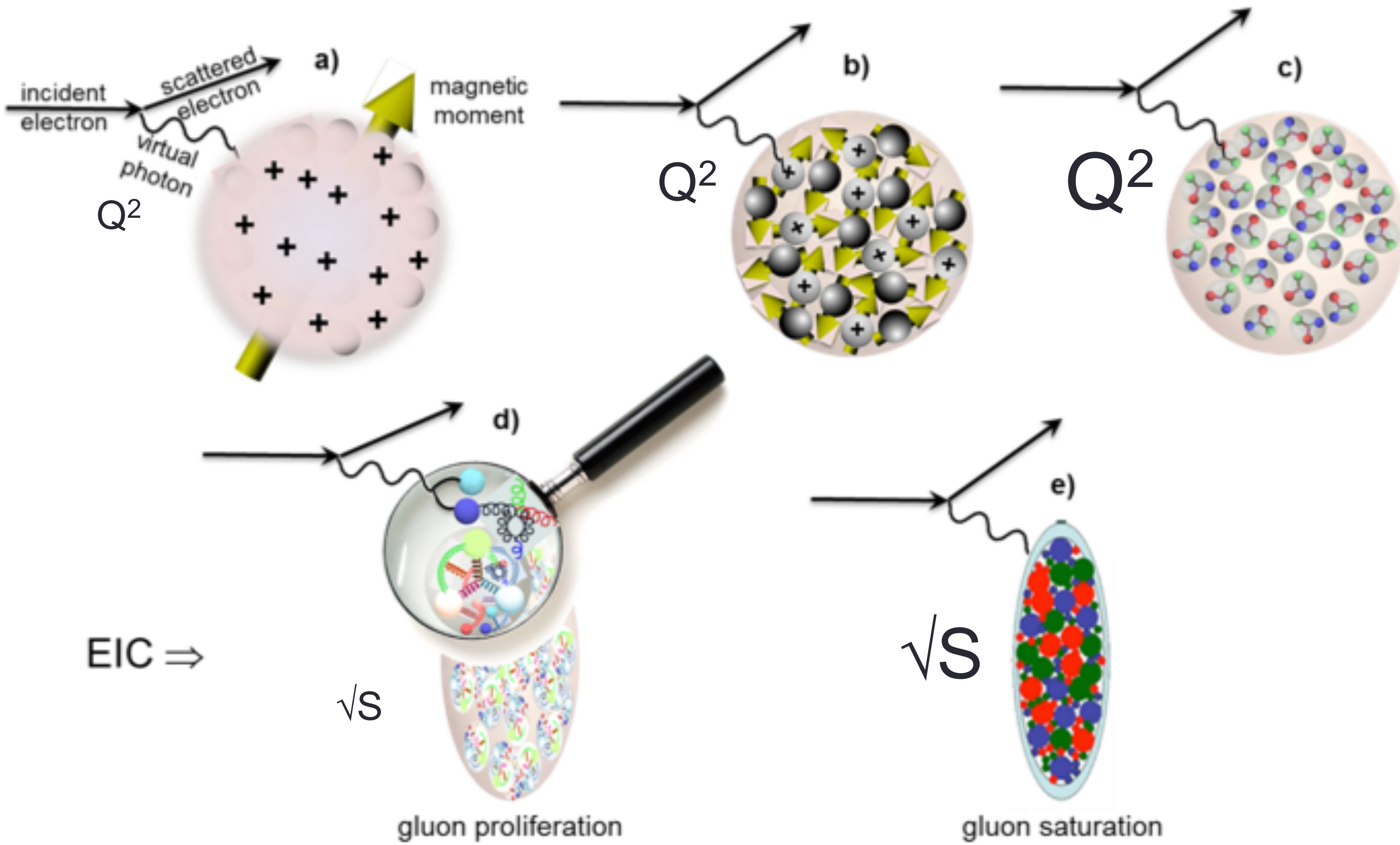


Without the EIC White Paper Writing Group the EIC White Paper would not have existed.
Special thanks to Dr. Jianwei Qiu and Prof. Zein-Eddine Meziani, my Co-Editors for the EIC White Paper
See: arXiv:1212.1701.v3 , A. Accardi et al.

The eRHIC and JLEIC machine design teams

Also gratefully acknowledge recent input from: E. Aschenauer, M. Diefenthaler, R. Ent, R. McKeown, Z. Meziani, B. Mueller, R. Milner, J.-W. Qiu, R. Yoshida

Deep Inelastic Scattering allows the Ultimate Experimental Control



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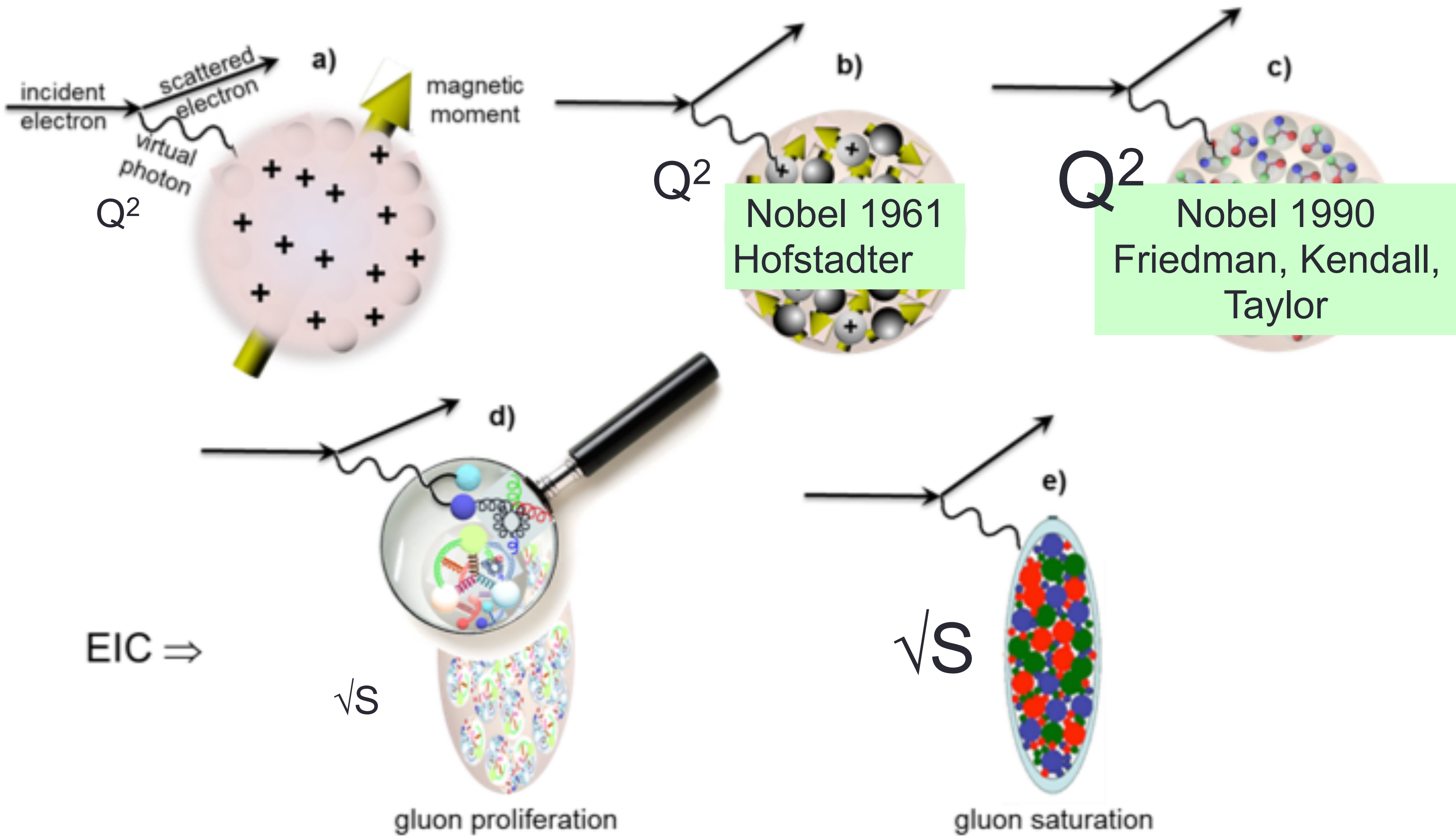
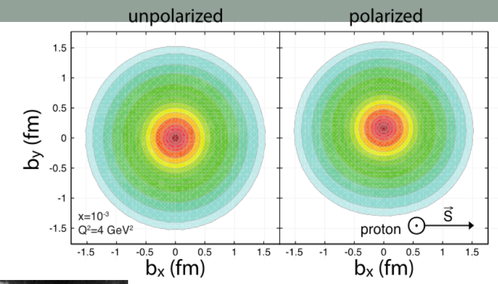


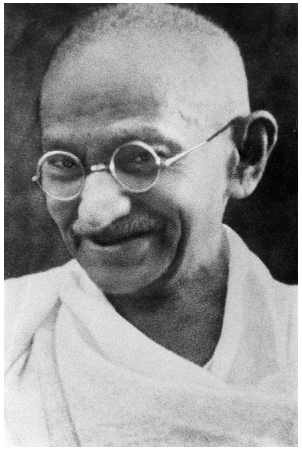


Spatial Imaging of quarks & gluons

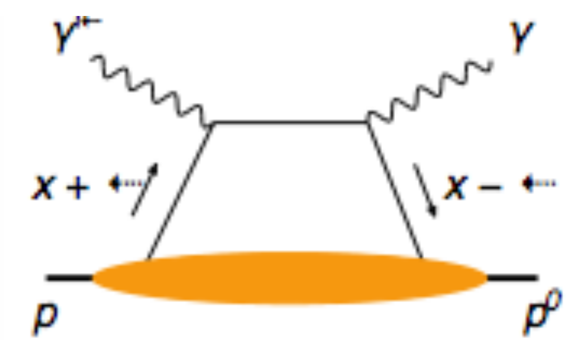
Generalized Parton Distributions

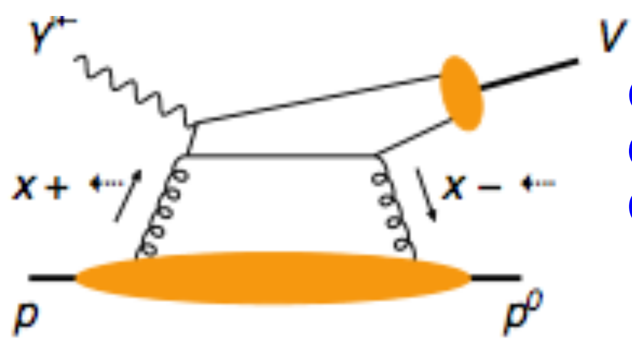
Historically investigations of nucleon structure and dynamics involved breaking the nucleon….

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

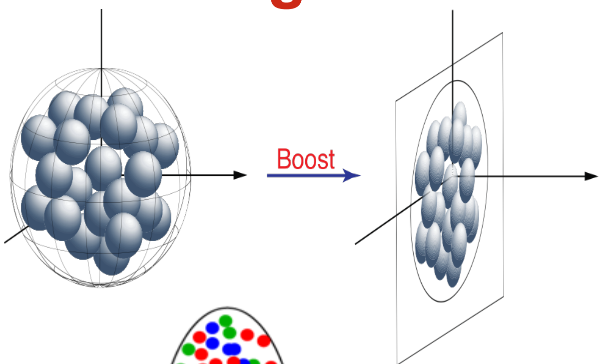
Fourier transform of momentum transferred=(p-p') → Spatial distribution

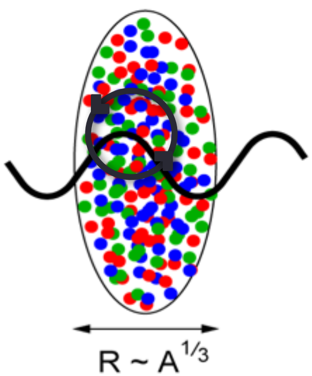
Exclusive measurements → measure "everything"

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 →





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

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

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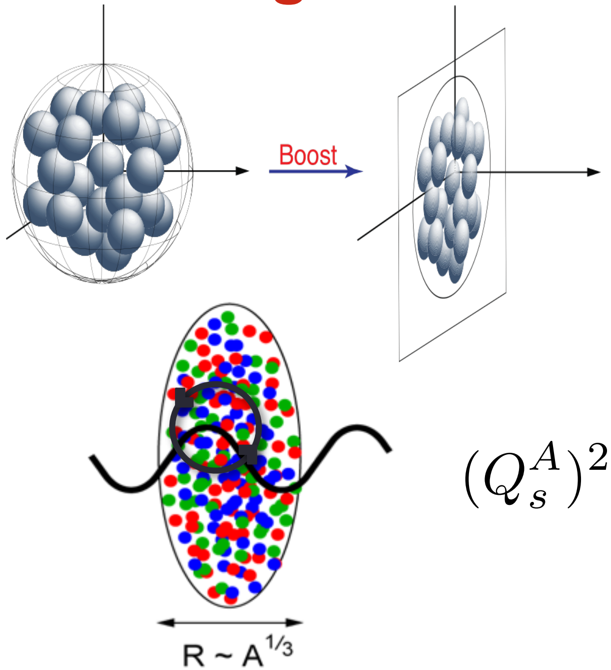

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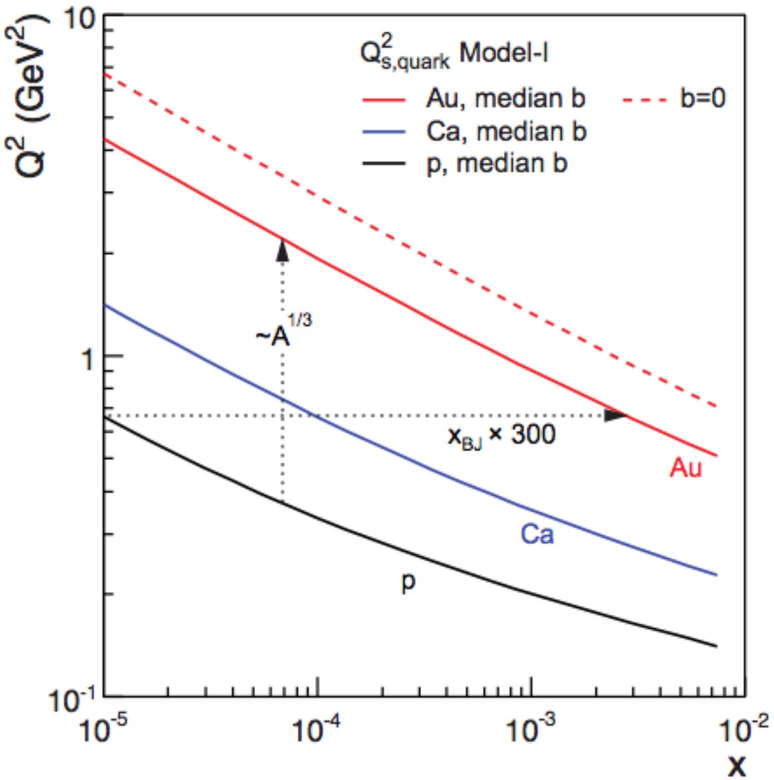

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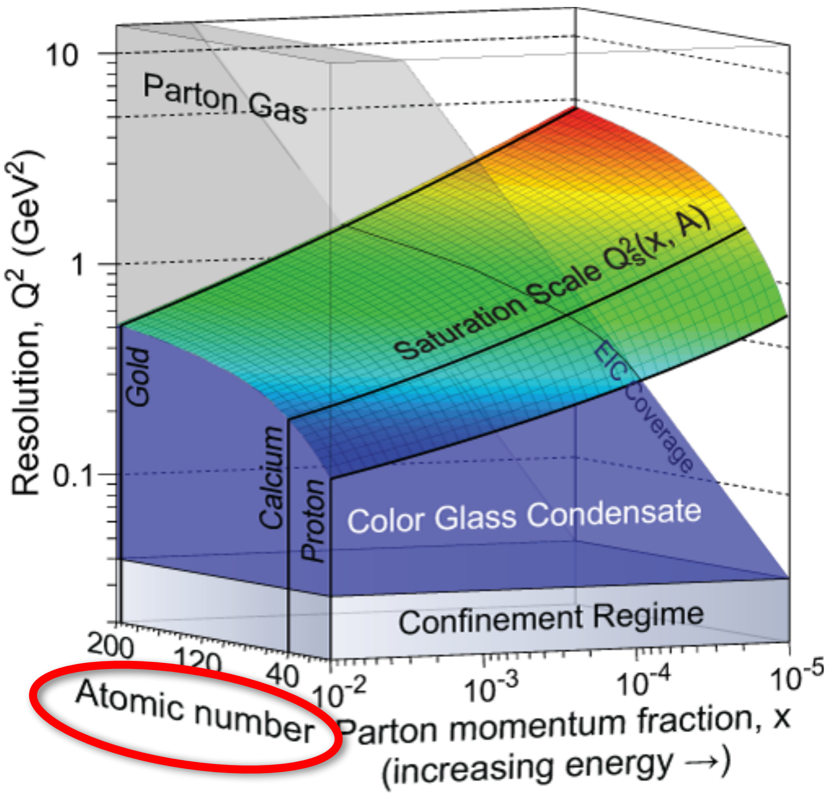

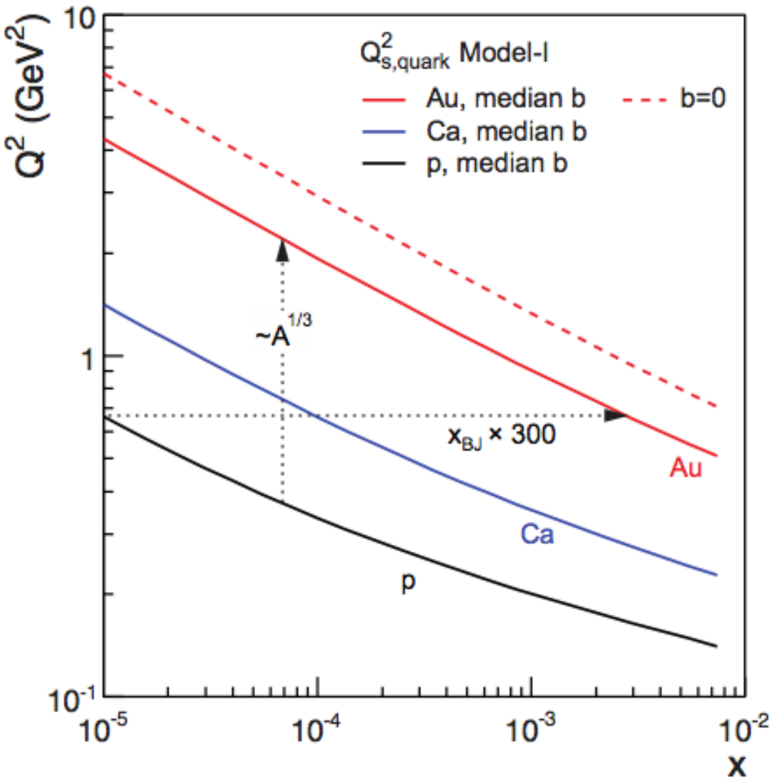

How to explore/study this new phase of matter?

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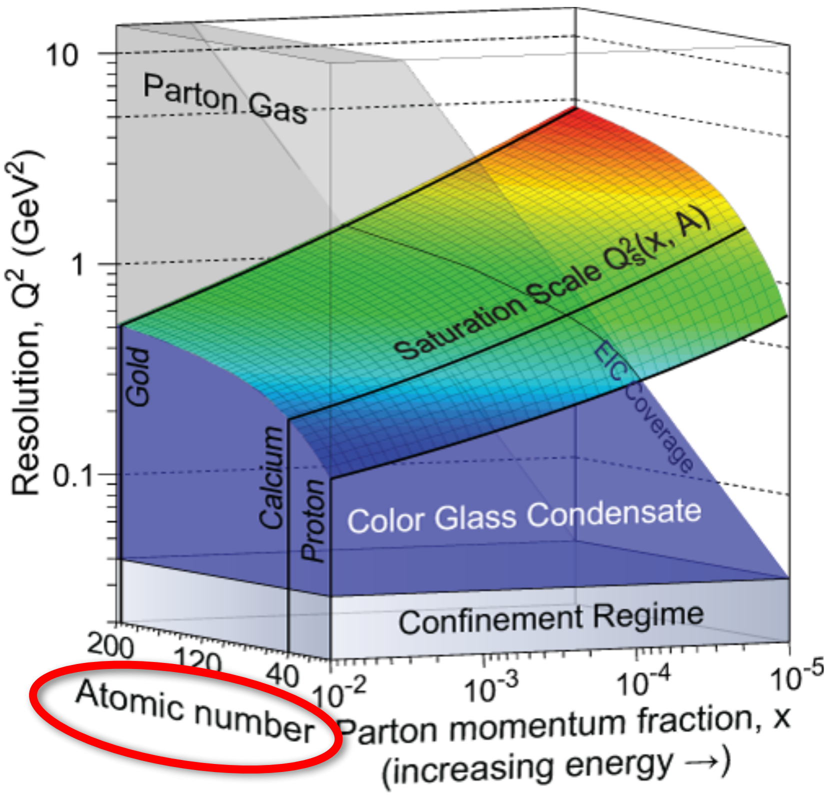
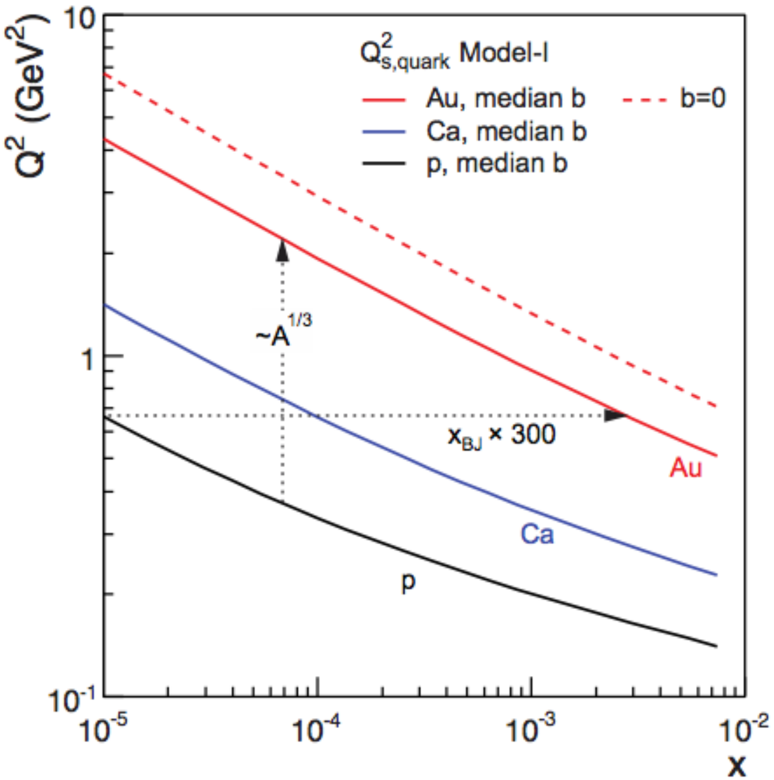
Advantage of nucleus →



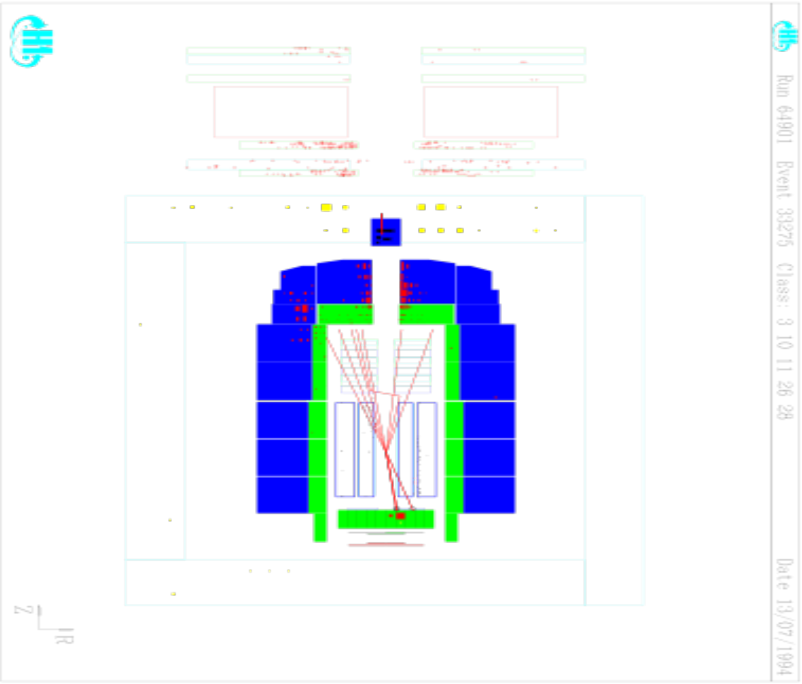


Enhancement of Q_S with A:

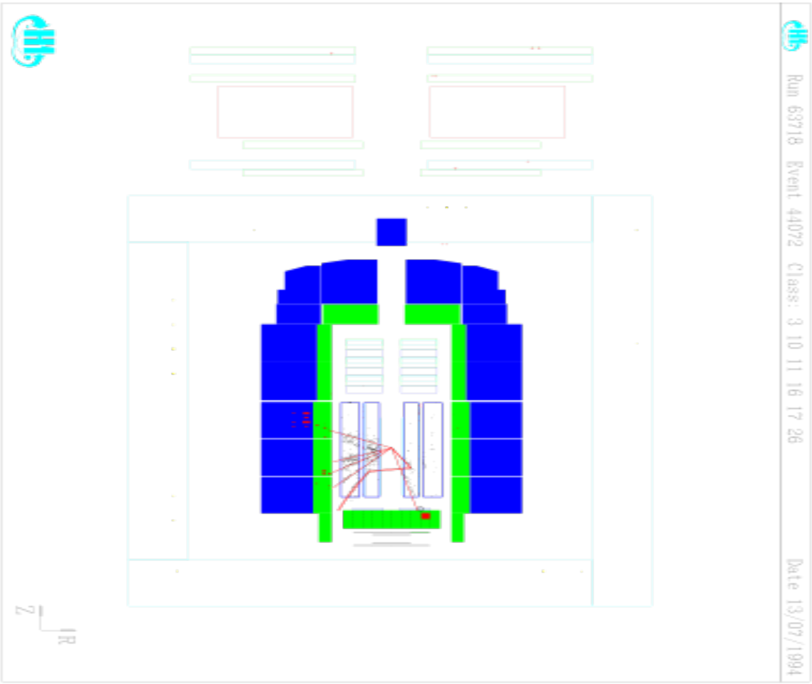
Saturation regime reached at significantly lower energy (read: "cost") in nuclei

HERA Surprise… diffractive events

Deep Inelastic Scattering



Diffractive Scattering



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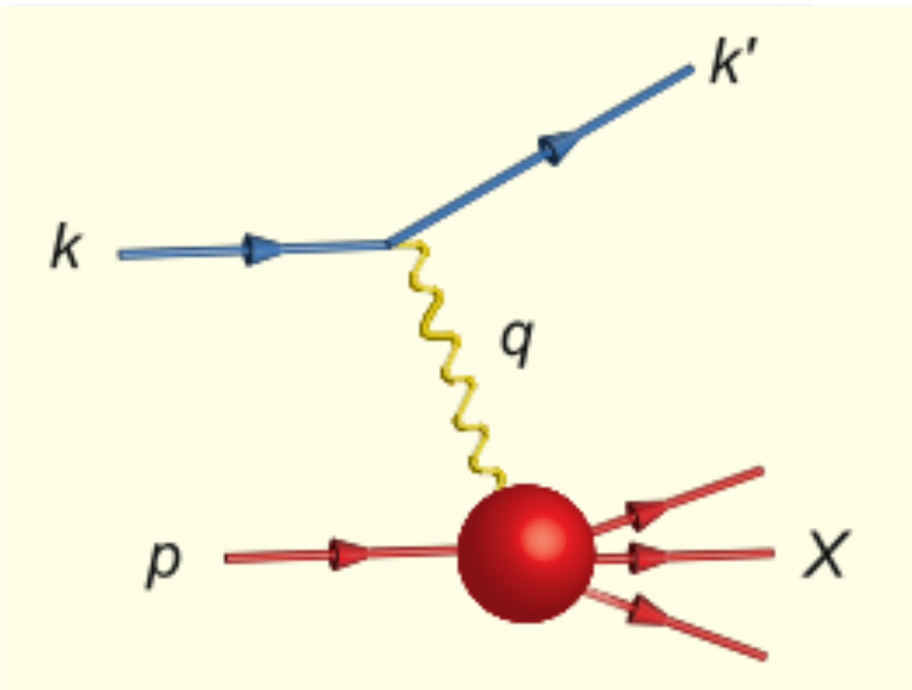
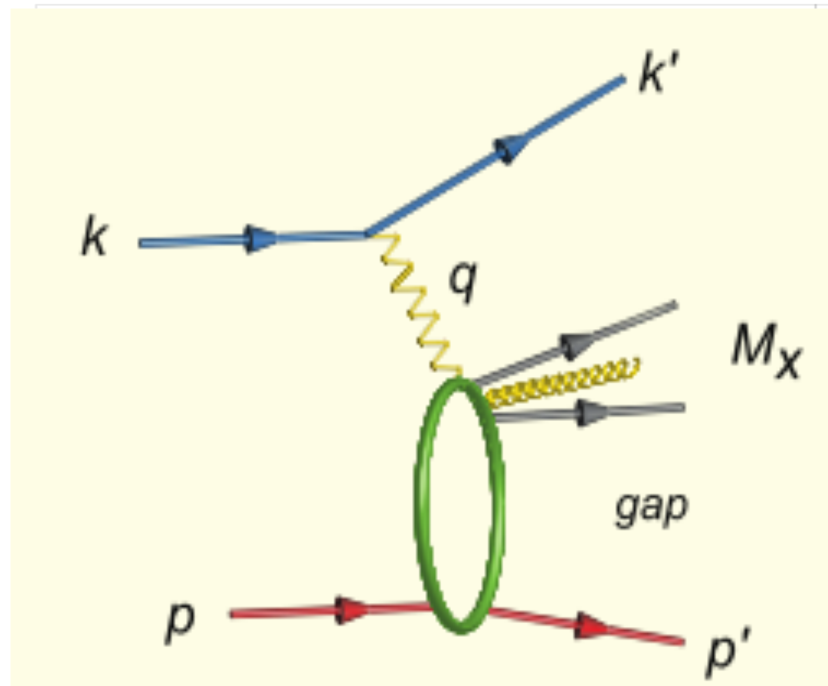


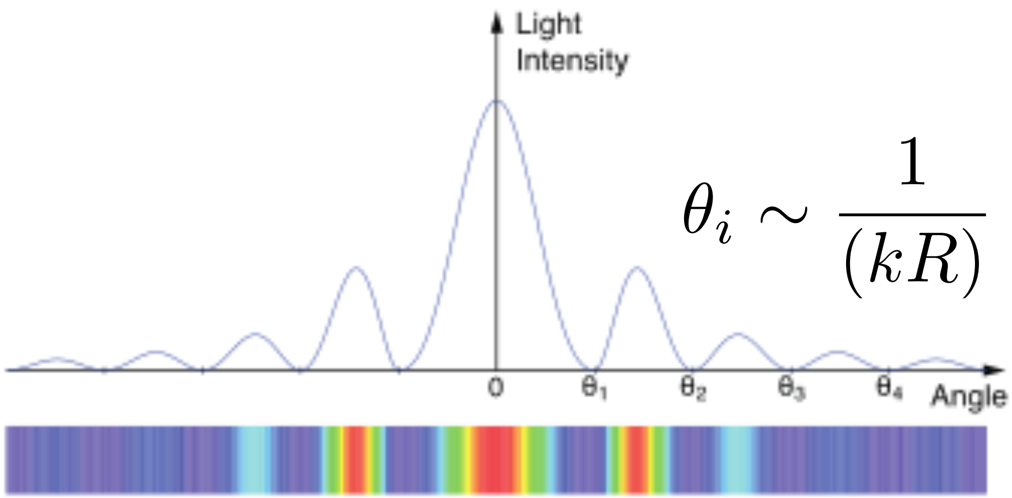
Diffractive Scattering



Diffraction in Optics and high energy scattering

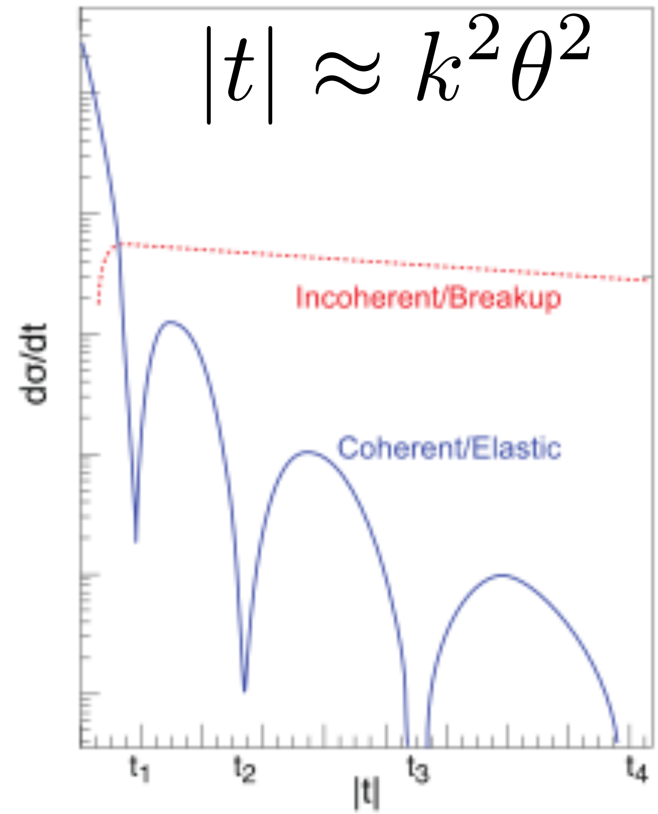
Light with wavelength λ obstructed by an opaque disk of radius R suffers diffraction:

k → wave number

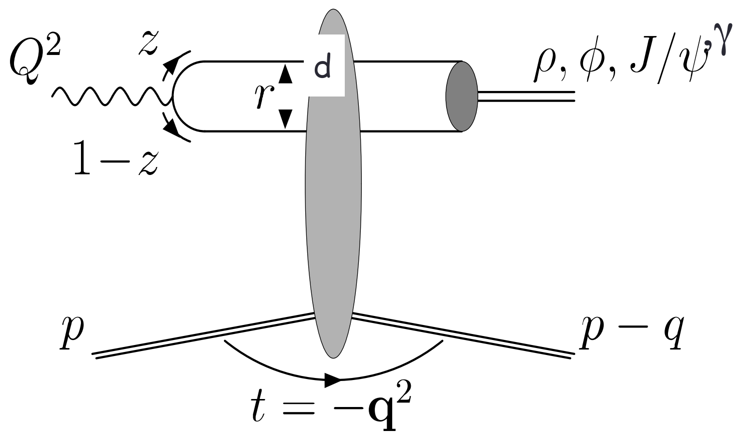


$$\theta_i \sim \frac{1}{(kR)}$$

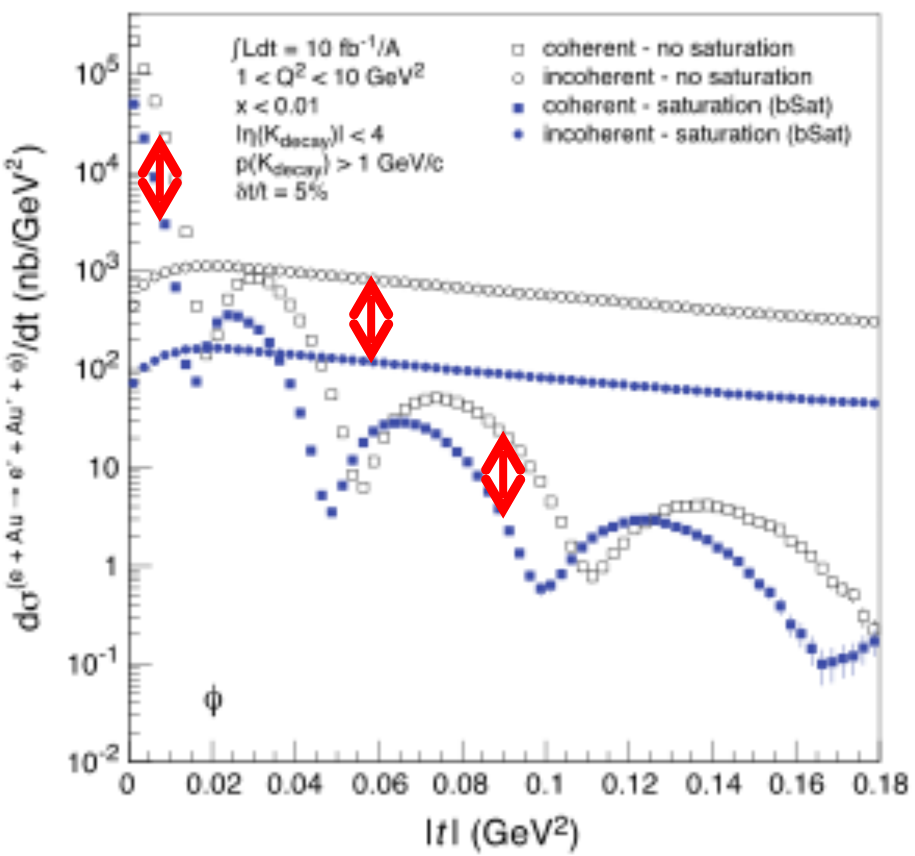
$$|t| \approx k^2\theta^2$$



Transverse imaging of the gluons nuclei



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



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

Experimental challenges being Studied.