WILLIAM & MARY
CHARTERED 1693
Arts & Sciences
Physics

Exploring the fundamental properties of matter with an Electron-Ion Collider

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Theory Center, Jefferson Lab

Acknowledgement: Much of the physics presented here are based on the work of EIC White Paper Writing Committee put together by BNL and JLab managements, …

Eternal Questions

People have long asked

Where did we come from?

The Big Bang theory?

What is the world made of?

Basic building blocks?

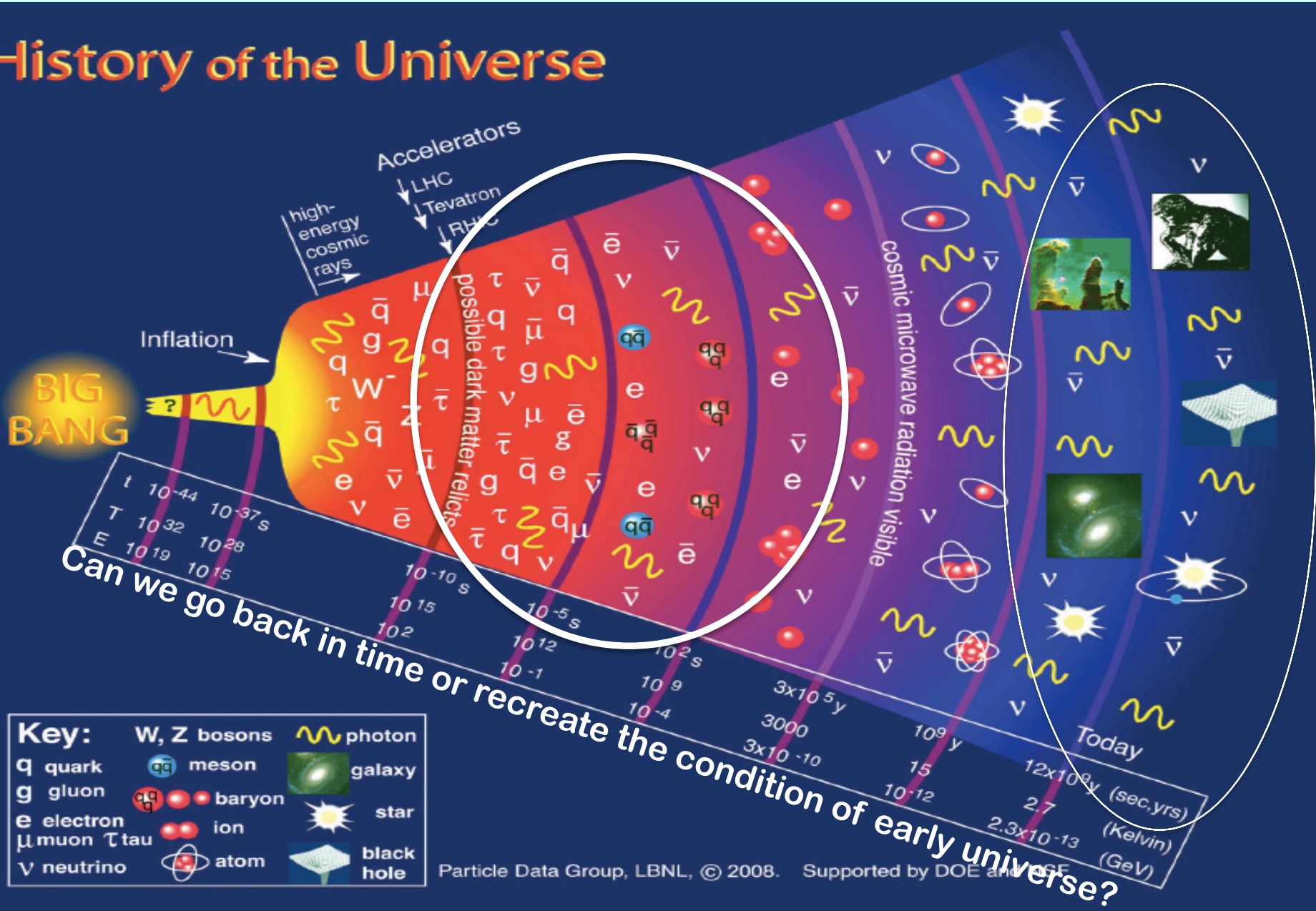
What holds it together?

Fundamental forces?

Where are we going to?

The future?

Where did we come from?



Going back in time?

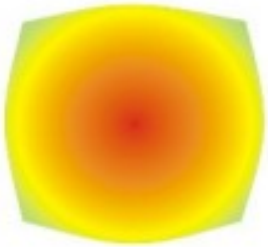
Expansion of the universe

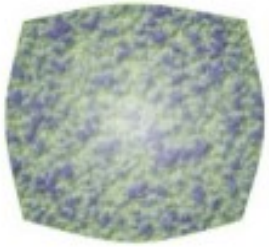
Little Bang in the Laboratory

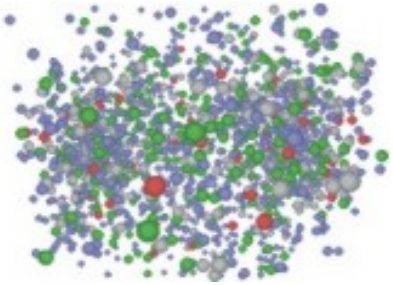
Create a matter (QGP) with similar temperature and energy density

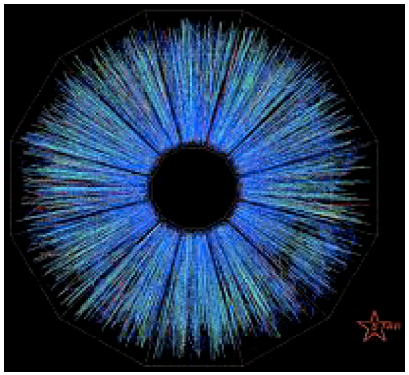
Relativistic heavy-ion collisions – the little bang

❑ A virtual Journey of Visible Matter:







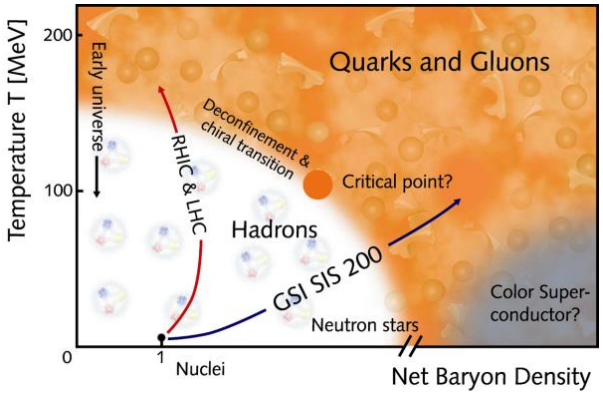


Lorentz contraction | Near collision | Quark-gluon plasma | Hadronization | Freeze-out | Seen in the detector

❑ Discoveries – Properties of QGP:

- ✧ A nearly perfect quantum fluid – NOT a gas!

  at 4 trillion degrees Celsius, Not, at 10^{-5} K like ^{6}Li

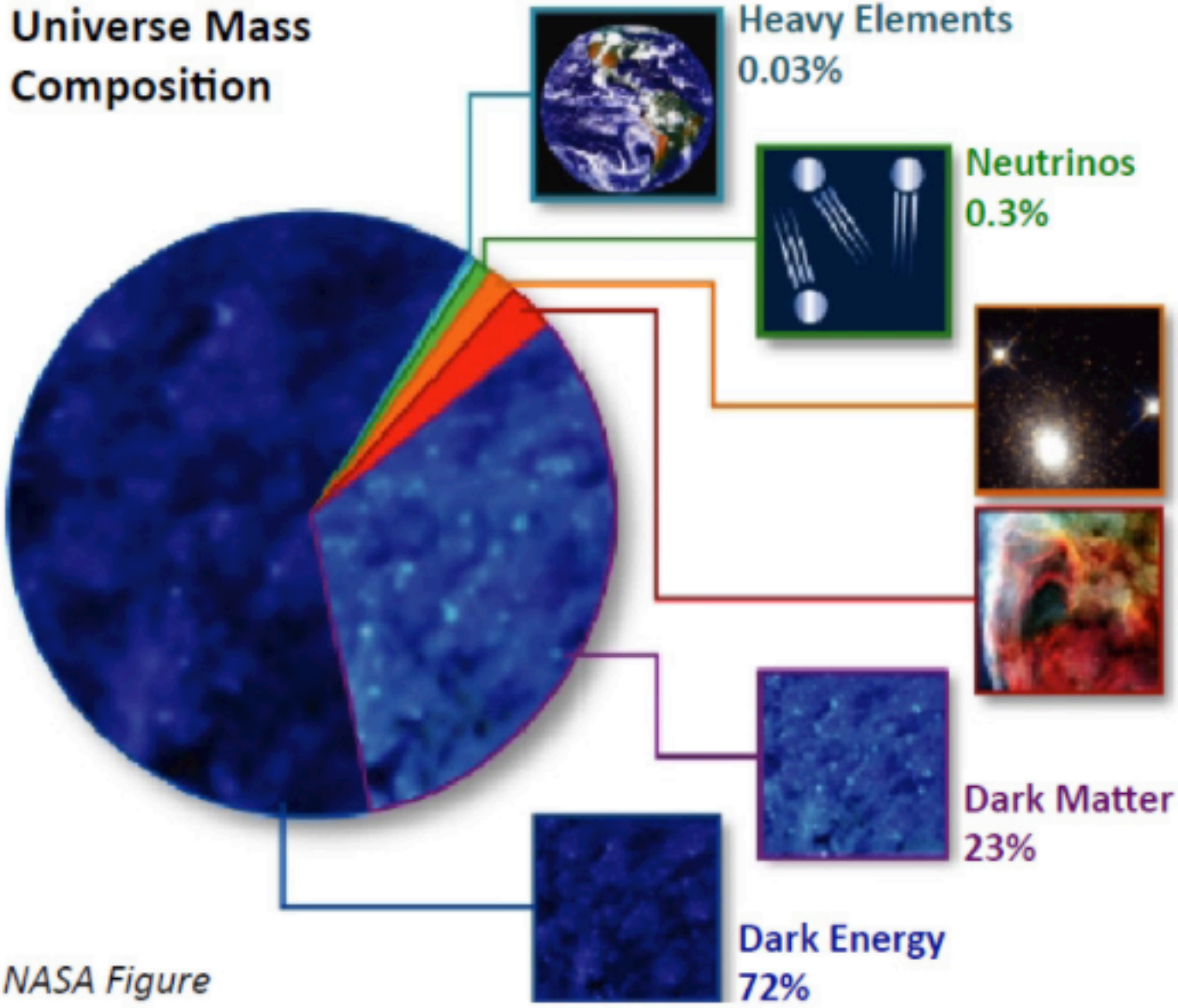


❑ Questions:

- ✧ *How the observed particles were emerged (after collision)?*
- ✧ *Does the initial condition matter (before collision)?*

Properties of visible matter

What the world is made of?



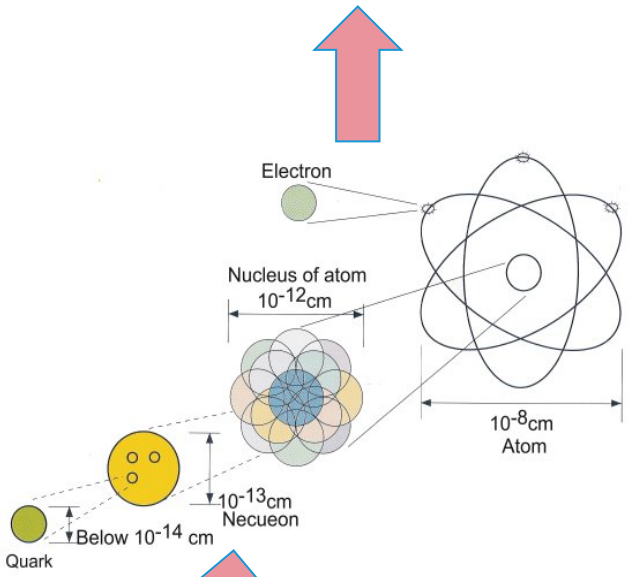
Human is only a tiny part of the universe

But, human is exploring the whole universe!

What hold it together?

❑ Science and technology:

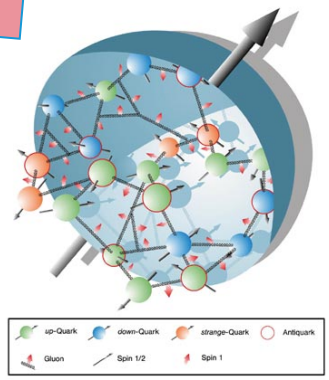
Particle & Nuclear Physics

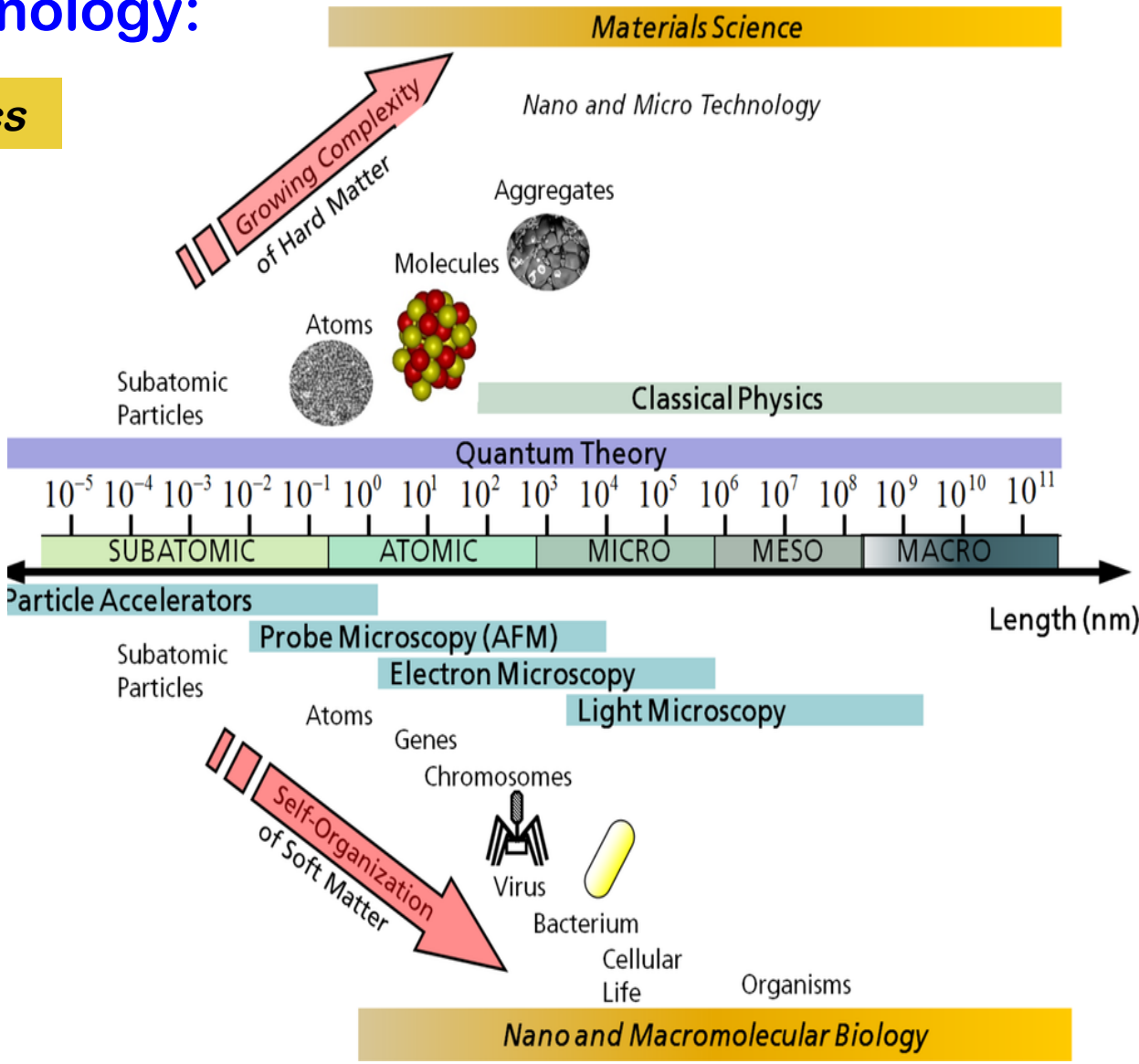


Nucleon:

Proton, or

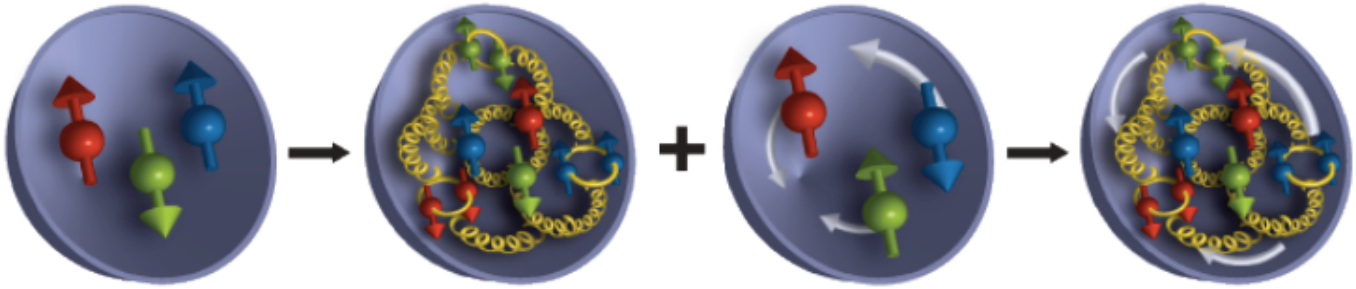
Neutron





Nucleon – building block of all atomic matter

- Our understanding of the nucleon evolves



1970s 1980s/2000s Now

Nucleon is a strongly interacting, relativistic bound state of quarks and gluons

- Quantum Chromodynamics (QCD) bound states:
  - Neither quarks nor gluons appear in isolation!
  - Understanding such systems completely is still beyond the capability of the best minds in the world

- The great intellectual challenge:

Probe nucleon structure without "seeing" quarks and gluons?

Why the EIC?

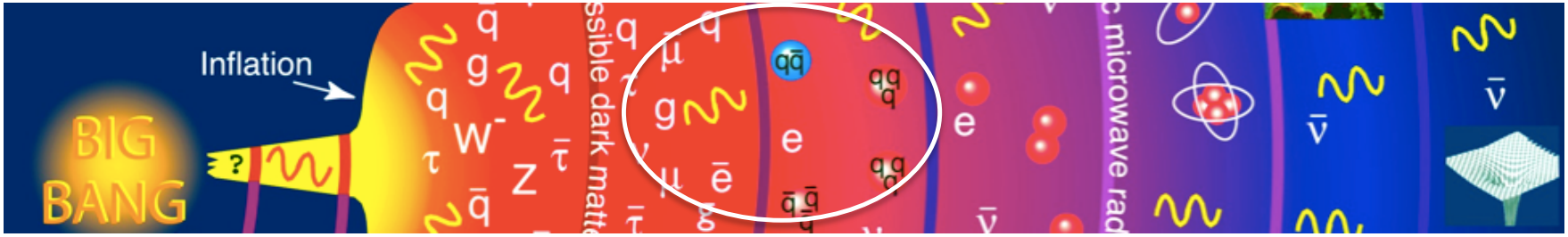
To understand the role of gluons in binding Quarks and Gluons into Nucleons and Nuclei

Outline of the rest of my talk

- 21st Century Nuclear Science
- "Big" questions/puzzles about QCD, …
- The Electron-Ion Collider
- Key deliverables & opportunities, …
- Summary

21st Century Nuclear Science

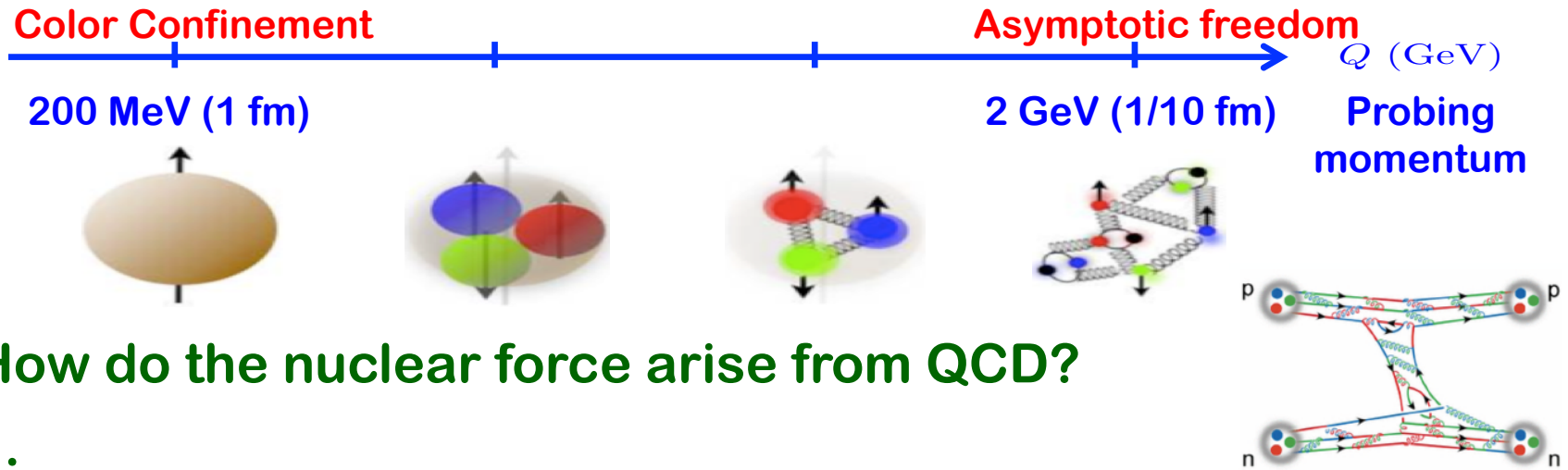
- What is the role of QCD in the evolution of the universe?



- How hadrons are emerged from quarks and gluons?
- How does QCD make up the properties of hadrons?

  Their mass, spin, magnetic moment, …

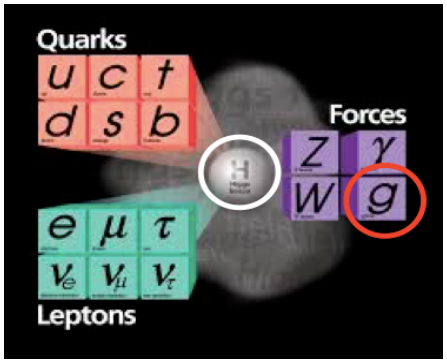
- What is the QCD landscape of nucleon and nuclei?

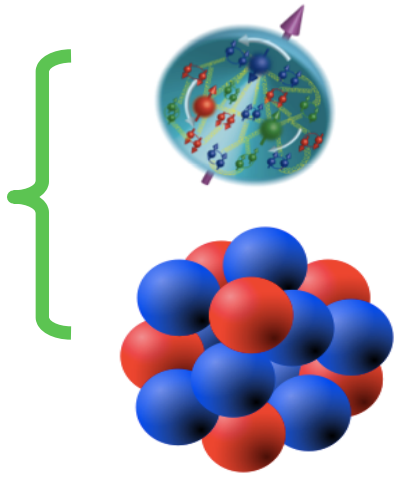


- How do the nuclear force arise from QCD?
- …

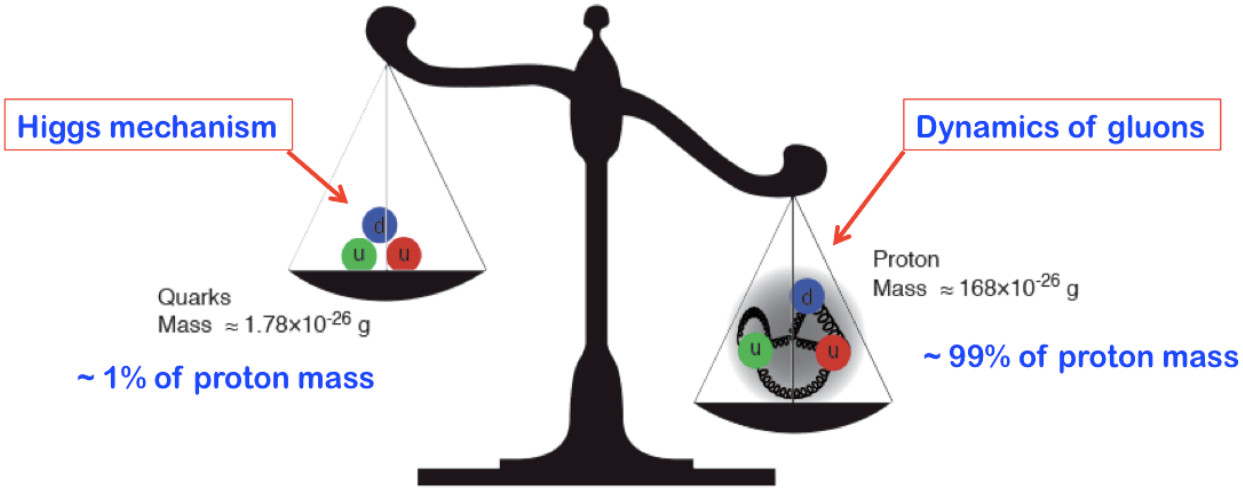
The next QCD frontier

- Understanding the glue that binds us all – the Next QCD Frontier!

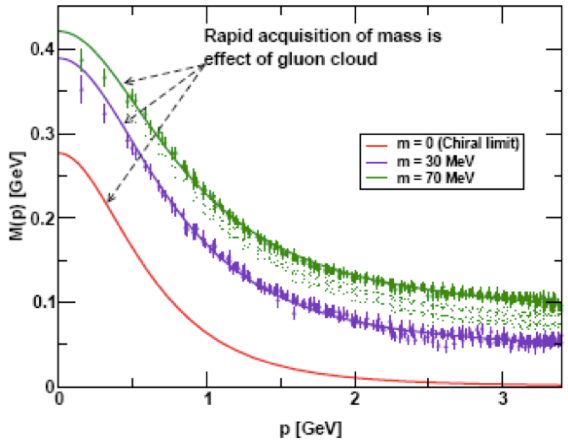




- Gluons are weird particles!
  - ✧ Massless, yet, responsible for nearly all visible mass



"Mass without mass!"



Bhagwat & Tandy/Roberts et al

The next QCD frontier

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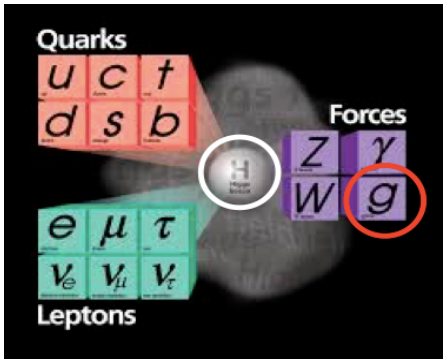

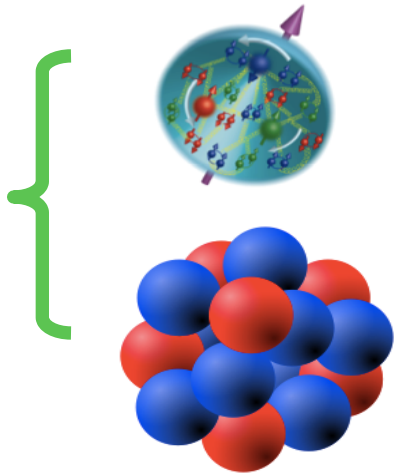

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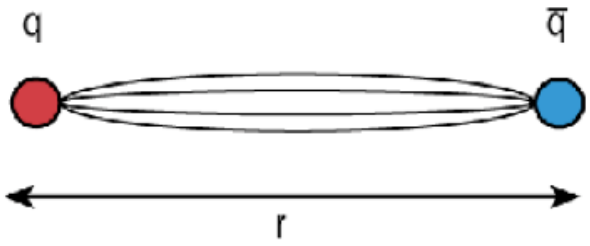
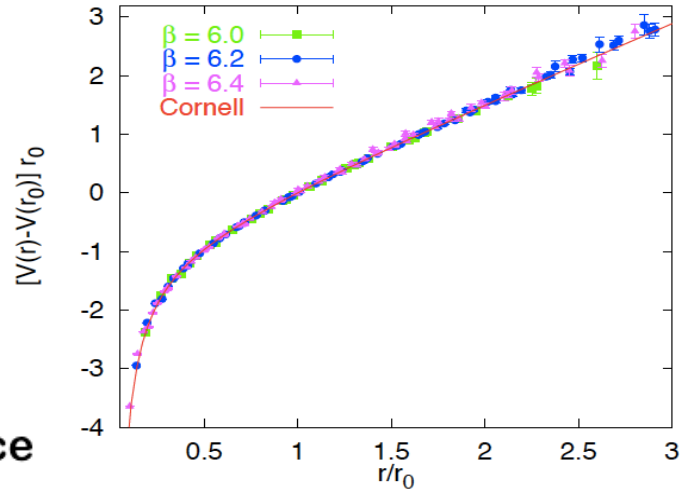
  - ✧ Carry color charge, responsible for color confinement and strong force

Force between a heavy quark pair



Heavy quarks experience a force of ~16 tons at ~1 Fermi (10^{-15} m) distance



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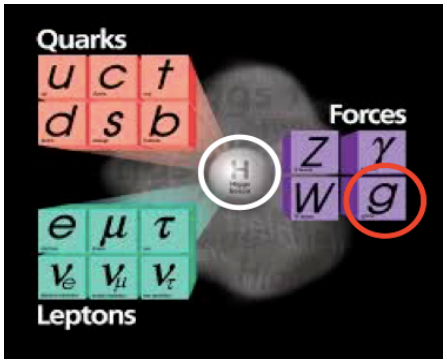

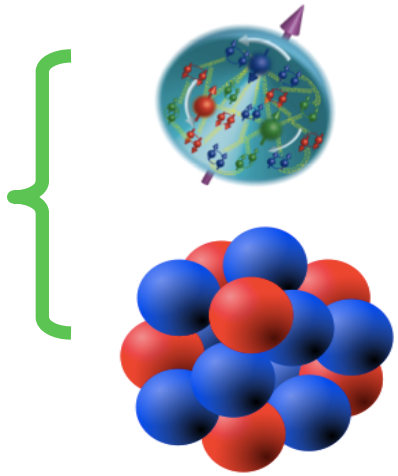

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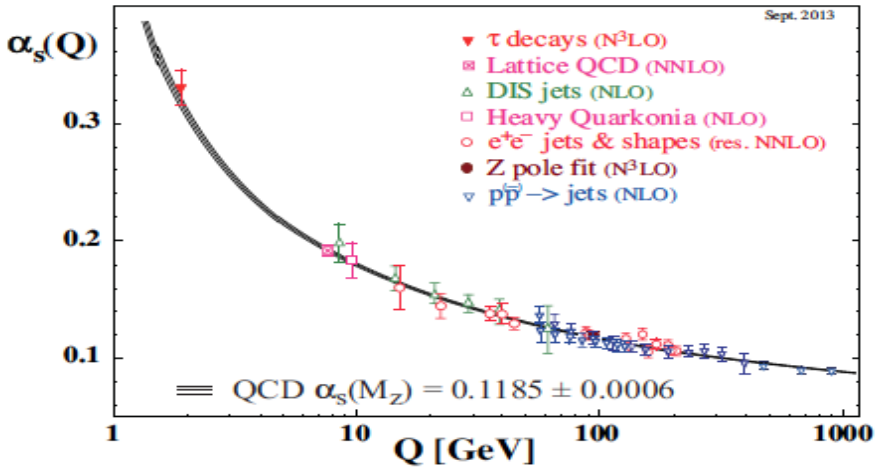
    but, also for asymptotic freedom

Nobel Prize, 2004

→ QCD perturbation theory



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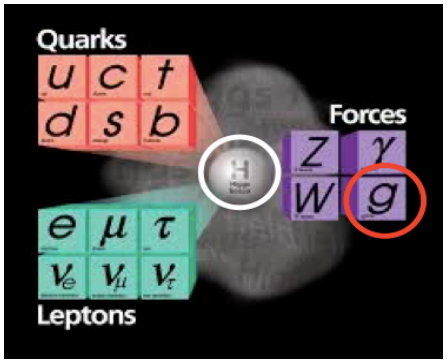

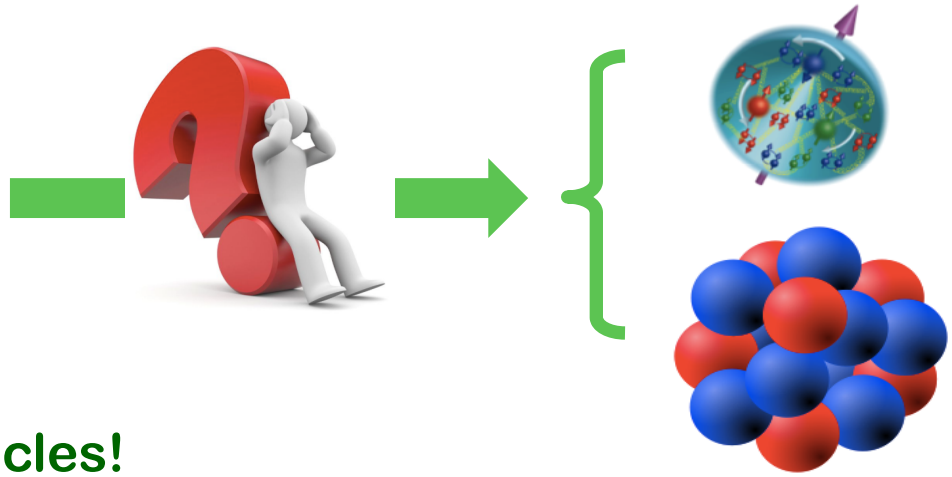

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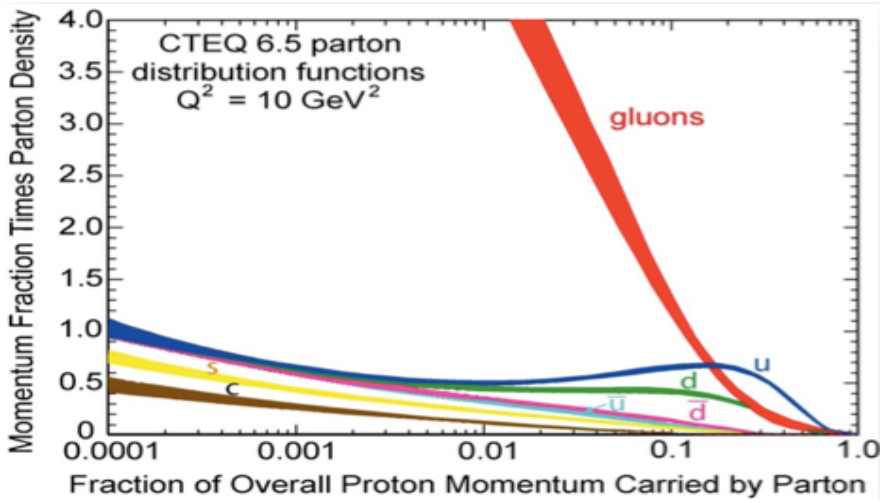
    as well as the abundance of glue



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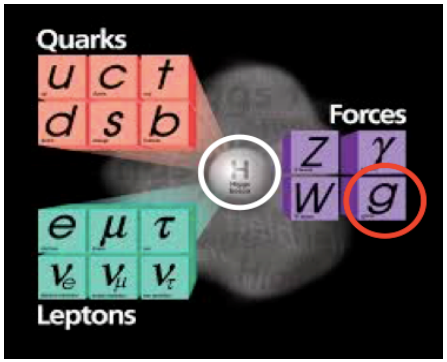

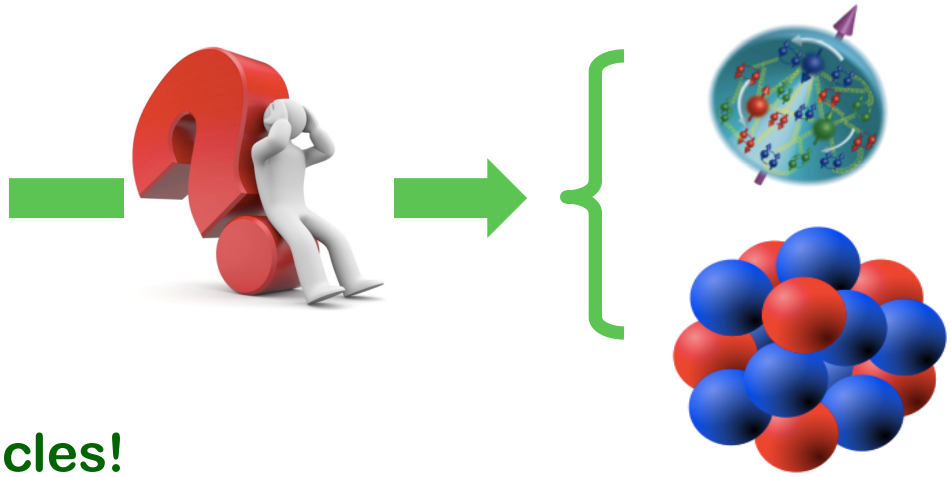

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but, also for asymptotic freedom,

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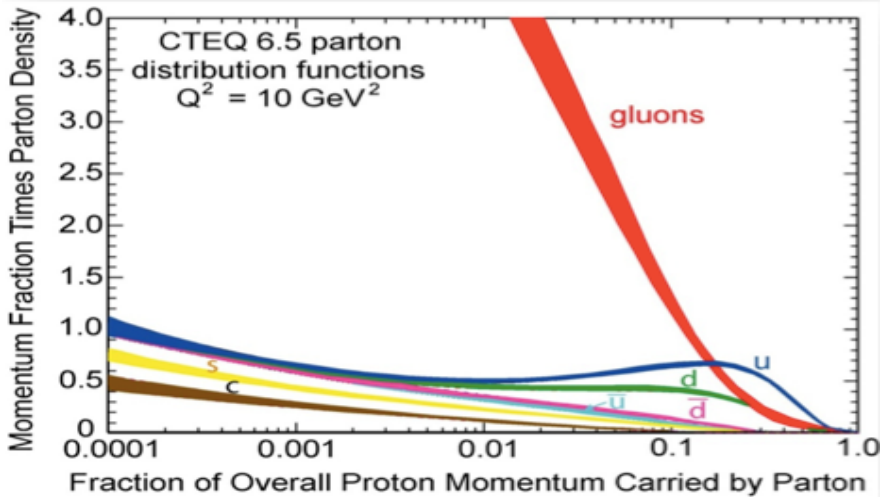
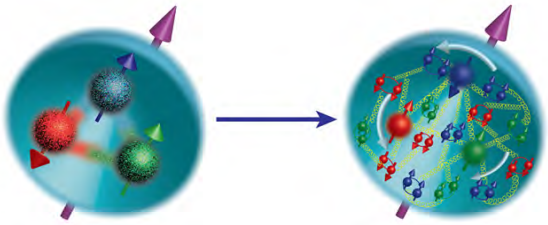
Without gluons, there would be NO nucleons, NO atomic nuclei… NO visible world!



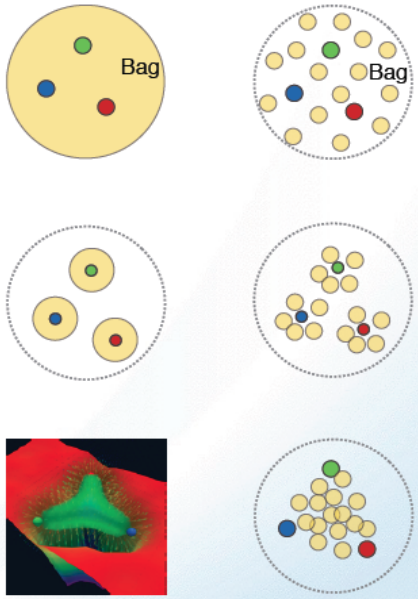
“Big” questions/puzzles about QCD, …

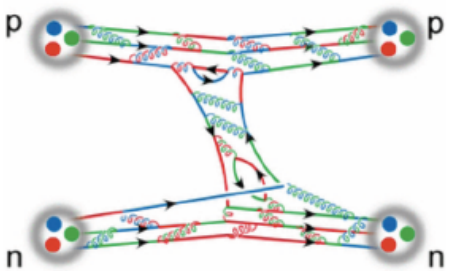
- How quarks and gluons are confined inside the hadrons – 3D structure?
  - Can we develop analytical tools to connect hadron structure and properties at low energy to their parton descriptions at high energy?!

    Hadron mass, spin, confined parton motion, …
    Proton radius: EM charge, quarks, gluons, …
    Nuclear force from QCD, …
  - Can lattice QCD and EFT help?



Static High Energy





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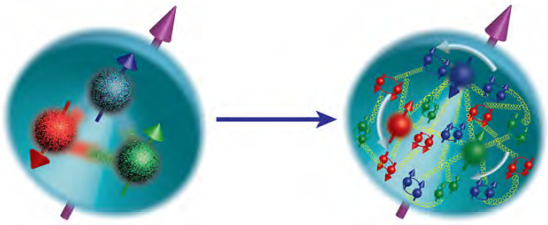

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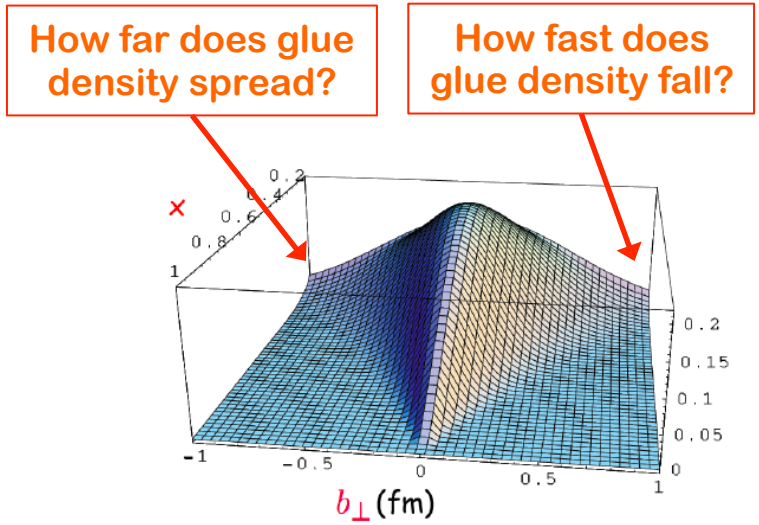
Glue tomography toward small-x



- How does the glue fill out hadron's inner space – 3D glue distribution?
  - Can we develop better probes to go beyond the current accuracy?!

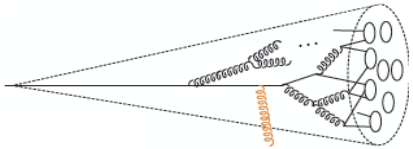
    Glue distribution in proton, and in ions,
    Color confinement radius, …
    Initial condition for HI collision,
    The physics and role of the momentum "x", …

Only possible at EIC

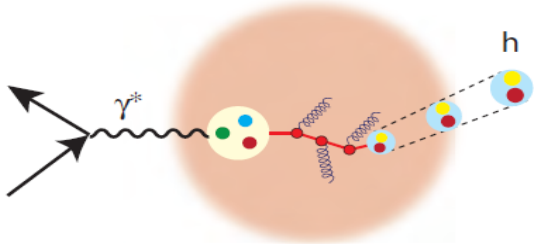
“Big” questions/puzzles about QCD, …

- How hadrons are emerged from the color charge(s)?
  - Can we develop analytical tools to “see” the evolution of the color/jet and to predict the jet structure and the emergence of hadrons?!

    Control of the partonic kinematics?
    Hadronization mechanism?



Jet structure

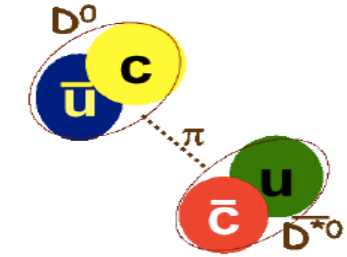


Nucleus as a “vertex detector” at a femtometer scale

- How to understand the family of hadrons?
  - Can we see gluonic excitations in hadron spectrum?
  - Can we understand the newly observed hadronic particles, XYZ, …?
  - XYZ particles at future ep + eA, …

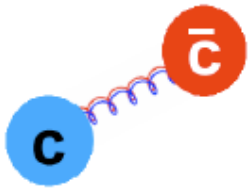
Not covered here!

A new particle explosion?



$D^0 - \bar{D}^{*0}$ “molecule”

diquark-diantiquark

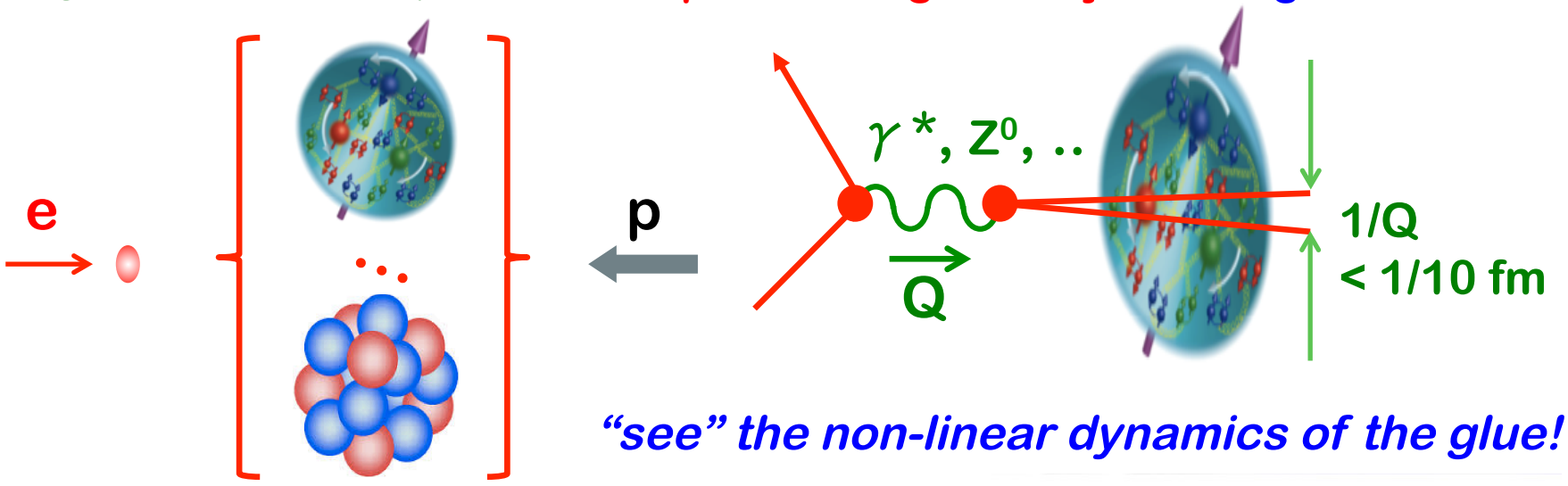


qq̄-gluon“hybrid”

Pentaquarks?

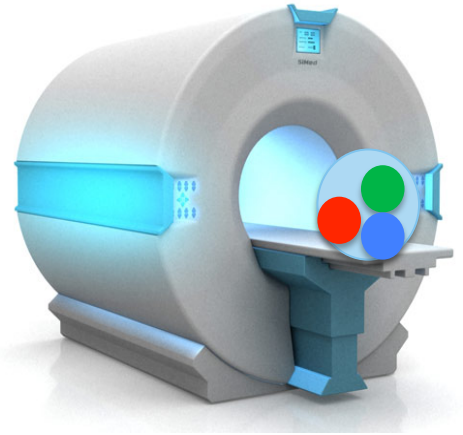
Electron-Ion Collider (EIC)

- A giant "Microscope" – "see" quarks and gluons by breaking the hadron



"see" the non-linear dynamics of the glue!

- A sharpest "CT" – "imagine" quark/gluon without breaking the hadron



  - "cat-scan" the nucleon and nuclei with better than 1/10 fm resolution
  - "see" the proton "radius" of gluon density

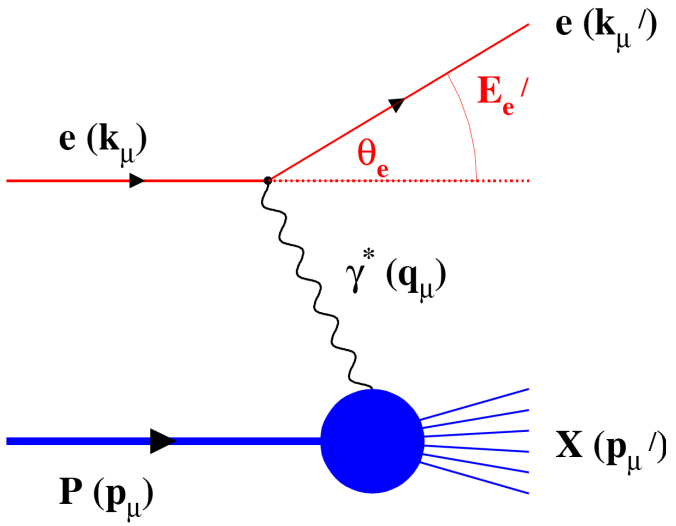
- Why now?

  Exp: advances in luminosity, energy reach, detection capability, …

  Thy: breakthrough in factorization – "see" confined quarks and gluons, …

Many complementary probes at one facility

- **Lepton-hadron facility:**



Q^2 → Measure of resolution

y → Measure of inelasticity

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

$Q^2 = S \times y$

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

Exclusive events: e+p/A → e'+ p'/A'+ h(π,K,p,jet)

Detect every things including scattered proton/nucleus (or its fragments)

EIC: the World Wide Interest

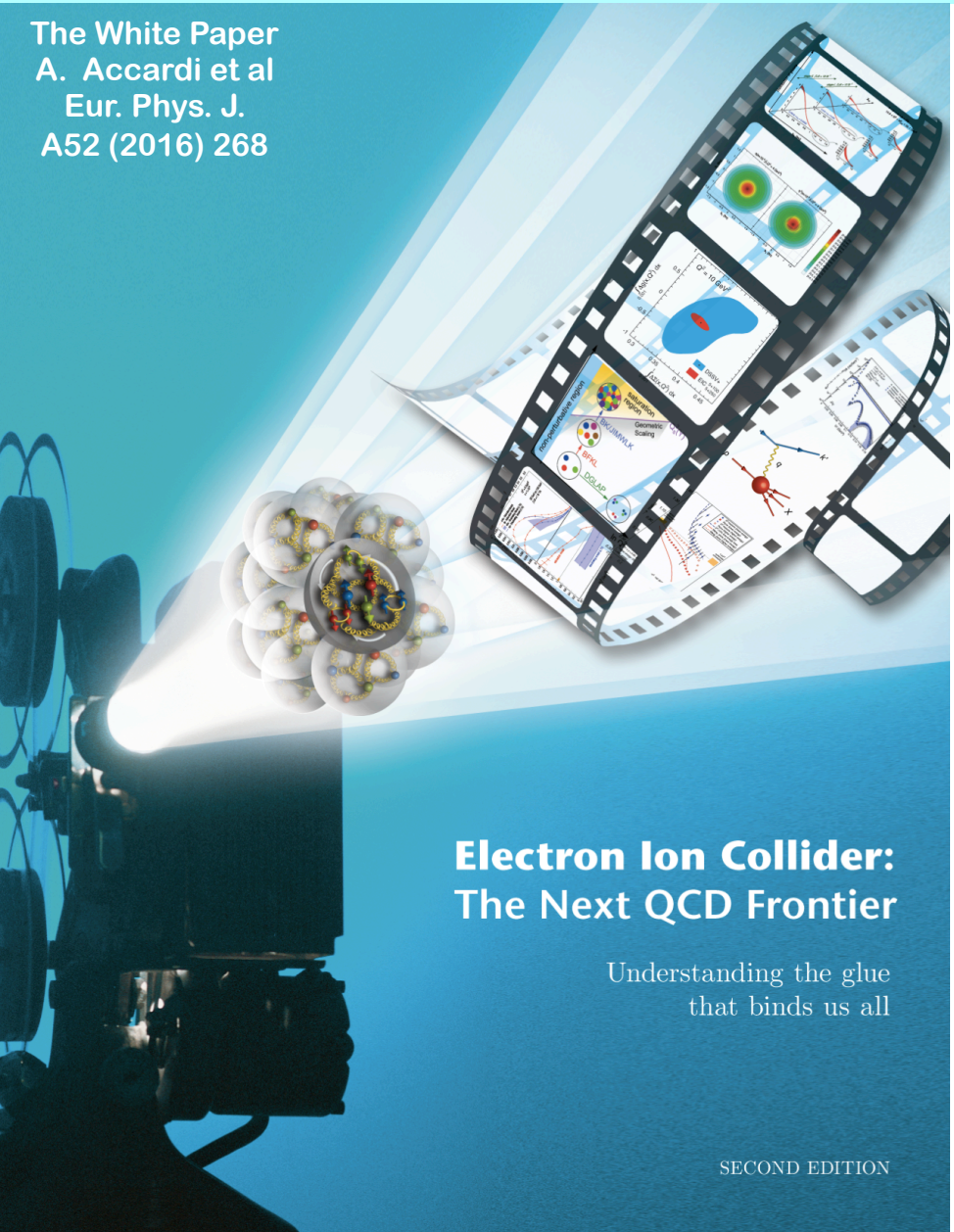
	HERA@DESY	LHeC@CERN	eRHIC@BNL	JLEIC@JLab	HIAF@CAS	ENC@GSI
E_{CM} (GeV)	320	800-1300	45-175	12-140	12 → 65	14
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-5}	5×10^{-5}	$7 \times 10^{-3} \rightarrow 3 \times 10^{-4}$	5×10^{-3}
ion	p	p to Pb	p to U	p to Pb	p to U	p to ~ ^{40}Ca
polarization	-	-	p, ^{3}He	p, d, ^{3}He (^{6}Li)	p, d, ^{3}He	p,d
L [$cm^{-2}\ s^{-1}$]	2×10^{31}	10^{33}	10^{33-34}	10^{33-34}	$10^{32-33} \rightarrow 10^{35}$	10^{32}
IP	2	1	2+	2+	1	1
Year	1992-2007	2022 (?)	2022	Post-12 GeV	2019 → 2030	upgrade to FAIR

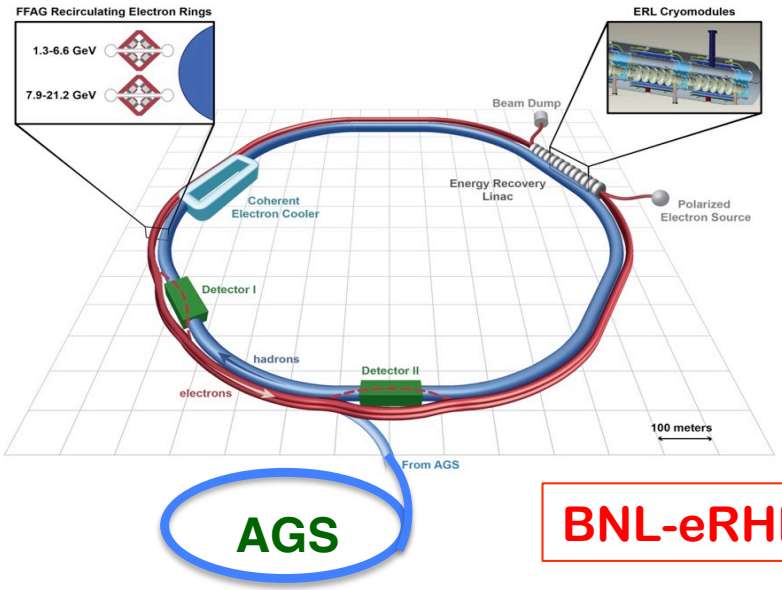
The past

Possible future

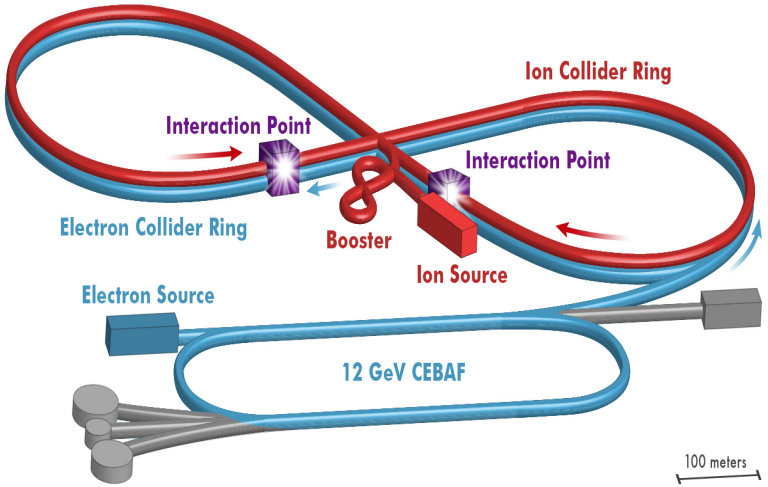
US EIC – two options of realization

The White Paper
A. Accardi et al
Eur. Phys. J.
A52 (2016) 268



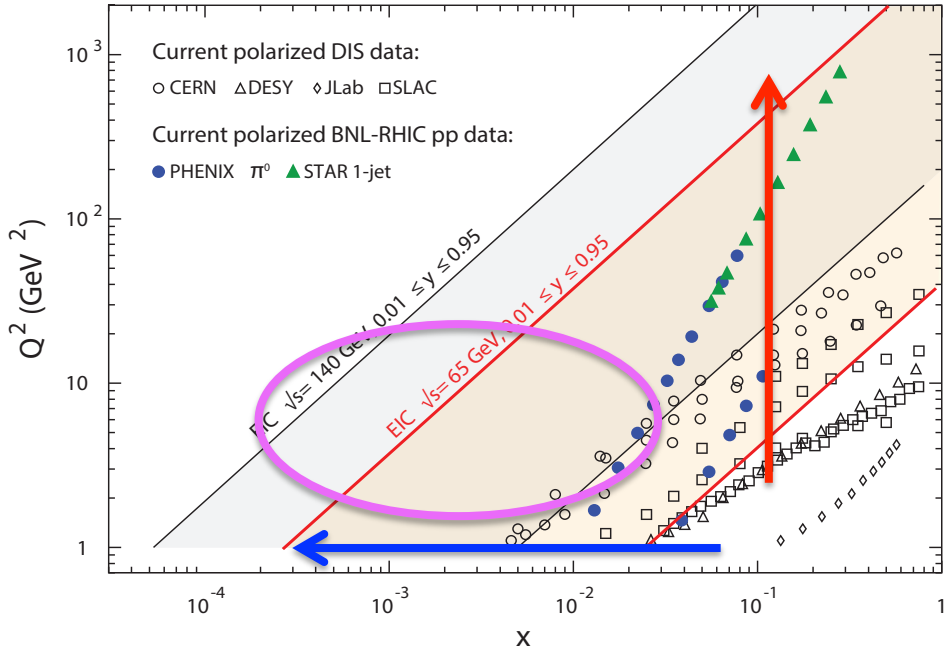


BNL-eRHIC



JLab-JLEIC

US EIC – Kinematic reach & properties

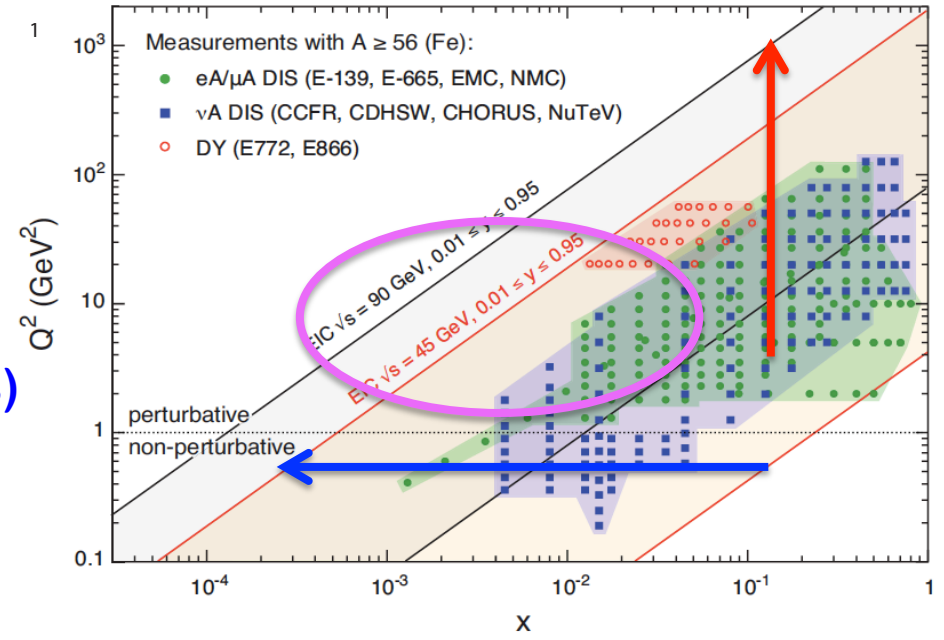


For e-N collisions at the EIC:

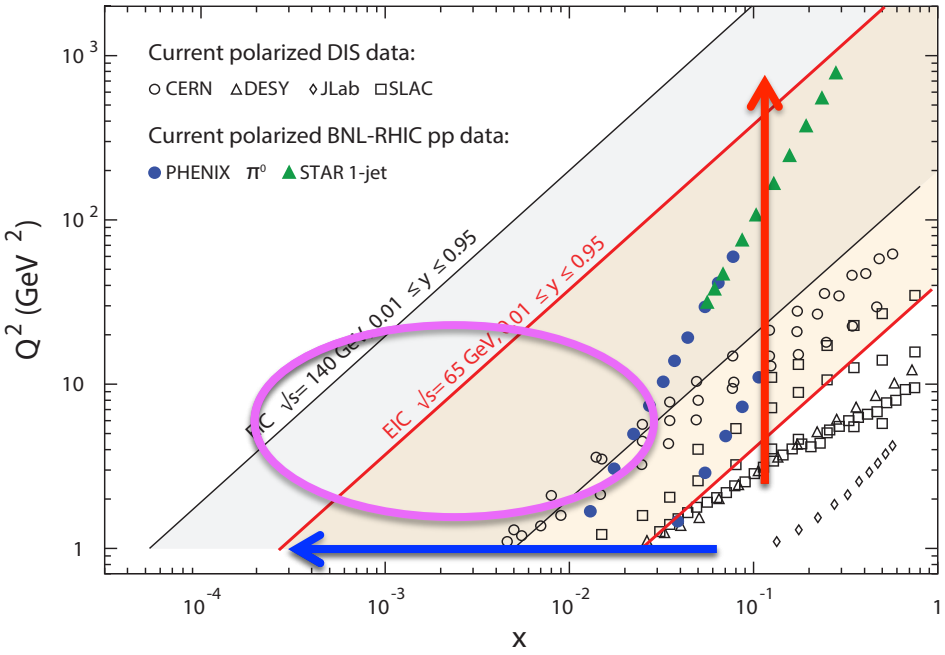
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning from valence to low-x physics
- ✓ 100-1K times of HERA Luminosity

For e-A collisions at the EIC:

- ✓ Wide range in nuclei
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range (evolution)
- ✓ Wide x region (high gluon densities)



US EIC – Kinematic reach & properties



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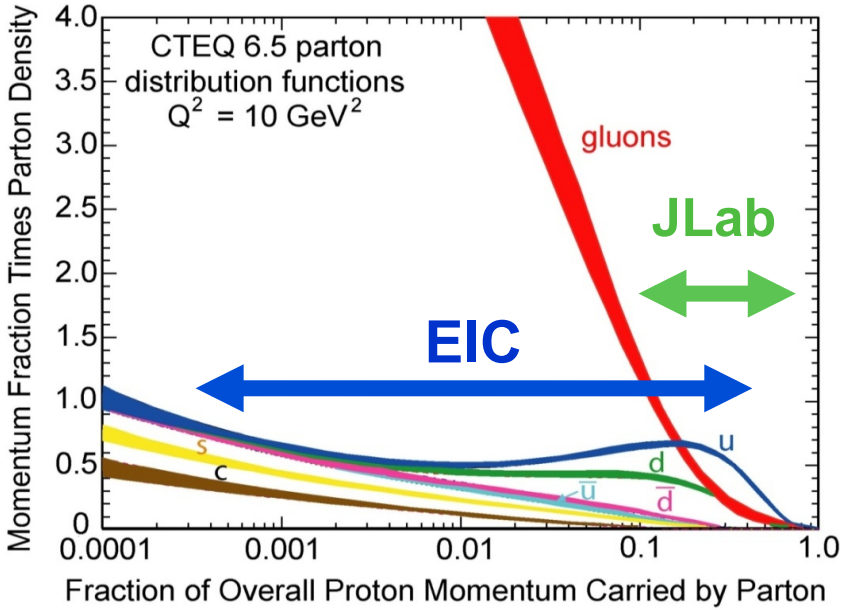
For e-A collisions at the EIC:

- ✓ Wide range in nuclei
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range (evolution)
- ✓ Wide x region (high gluon densities)

EIC explores the "sea" and the "glue", the "valence" with a huge level arm



The key deliverables & opportunities

Why existing facilities, even with upgrades, cannot do the same?

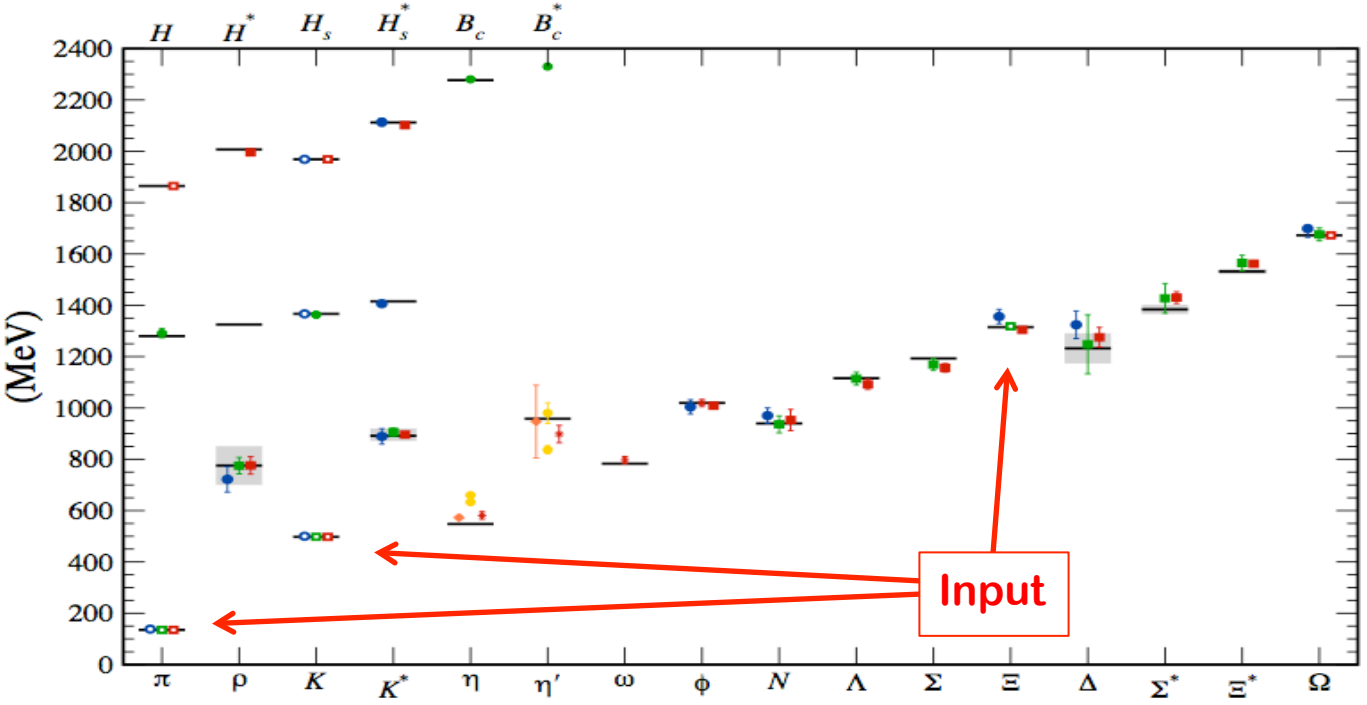
“Big” questions to be answered, …

- How does QCD generate the nucleon mass?

  “… The vast majority of the nucleon’s mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …”

  REACHING FOR THE HORIZON
  The 2015 Long Range Plan for Nuclear Science

- Hadron mass from Lattice QCD calculation:



"Big" questions to be answered, …

- **How does QCD generate the nucleon mass?**

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  REACHING FOR THE HORIZON
  The 2015 Long Range Plan for Nuclear Science

- **Role of quarks and gluons?**

  - QCD energy-momentum tensor:

$$T^{\mu\nu} = \tfrac{1}{2}\,\overline{\psi} i\vec{D}^{(\mu}\gamma^{\nu)}\psi + \tfrac{1}{4}\,g^{\mu\nu}F^2 - F^{\mu\alpha}F^{\nu}{}_{\alpha}$$

  - Trace of the QCD energy-momentum tensor:

$$T^{\alpha}_{\alpha} = \frac{\beta(g)}{2g} F^{\mu\nu,a}F^{a}_{\mu\nu} + \sum_{q=u,d,s} m_q(1+\gamma_m)\overline{\psi}_q\psi_q$$

  QCD trace anomaly $\beta(g) = -(11 - 2n_f/3)\,g^3/(4\pi)^2 + \ldots$

  - Mass, trace anomaly, chiral symmetry break, and …

$$m^2 \propto \langle p|T^{\alpha}{}_{\alpha}|p\rangle \;\Rightarrow\; \frac{\beta(g)}{2g}\langle p|F^2|p\rangle$$

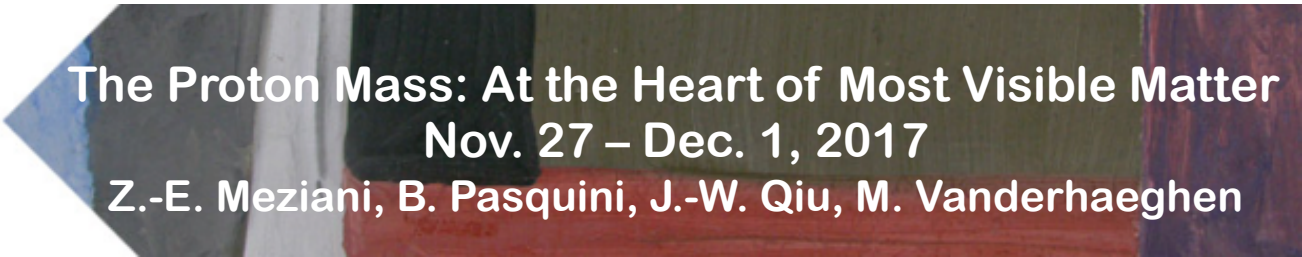
  ⇒ quarkonium production near the threshold, from JLab12 to EIC

“Big” questions to be answered, …

Three-pronged approach to explore the origin of hadron mass:

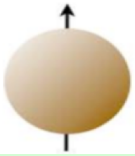
- ✧ lattice QCD
- ✧ mass decomposition – roles of the constituents
- ✧ model calculation – approximated analytical approach

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS



“Big” questions to be answered, …

- How does QCD generate the nucleon’s spin?



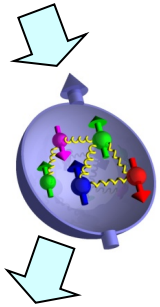
Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g) = \sum \langle P,S|\hat{J}^z_f(\mu)|P,S\rangle$$

Quark helicity
Best known

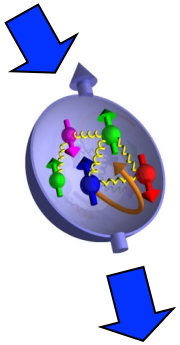
$$\frac{1}{2}\int dx\left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$
$$\sim 30\%$$

Spin “puzzle”



Gluon helicity
Start to know

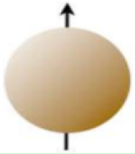
$$\Delta G = \int dx \Delta g(x)$$
$$\sim 20\% (\text{with RHIC data})$$



Orbital Angular Momentum of quarks and gluons
Little known

“Big” questions to be answered, …

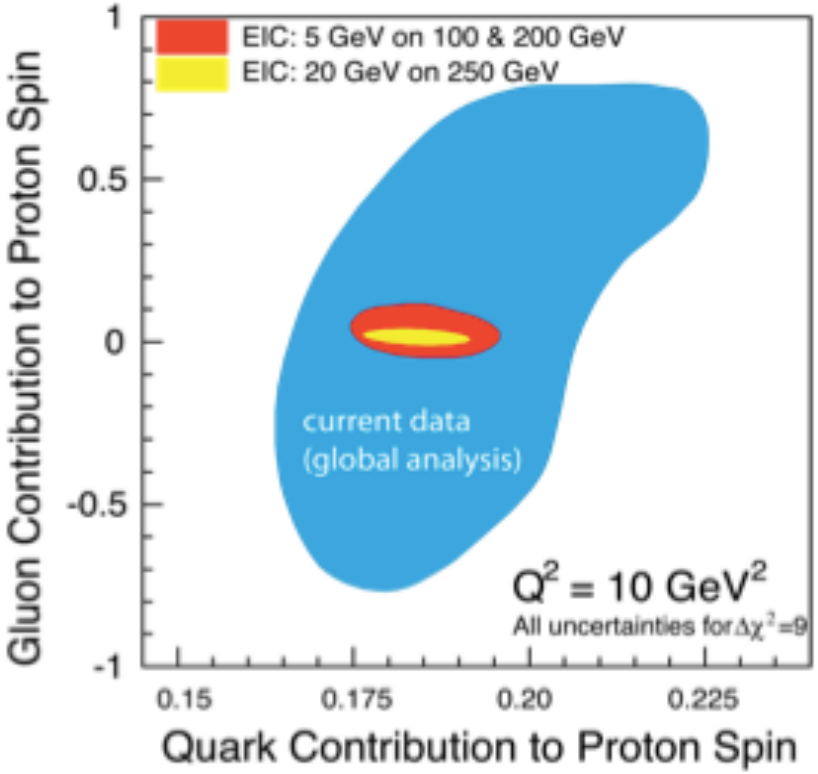
- How does QCD generate the nucleon’s spin?



Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g) = \sum \langle P,S|\hat{J}^z_f(\mu)|P,S\rangle$$

- What can EIC do?



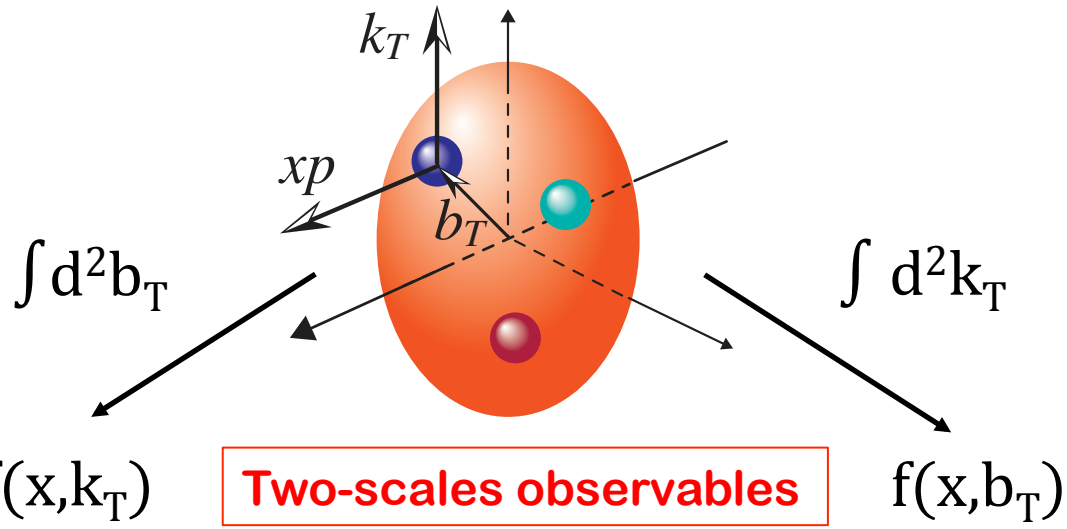
To understand the proton spin, fully, we need to understand the confined motion of quarks and guons in QCD

➡ **TMDs, GTMDs, …**

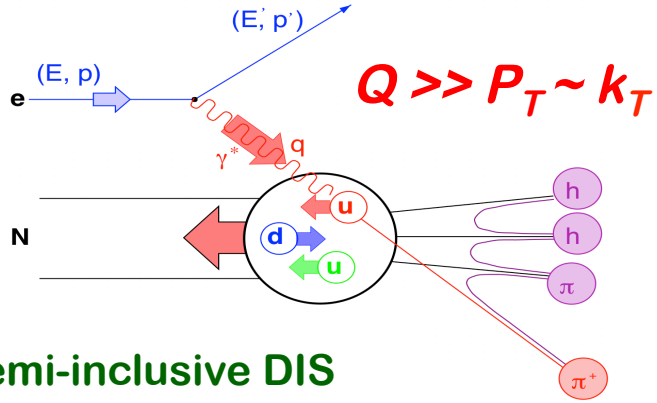
Need “probes” for two-scale observables!

“Big” questions to be answered, …

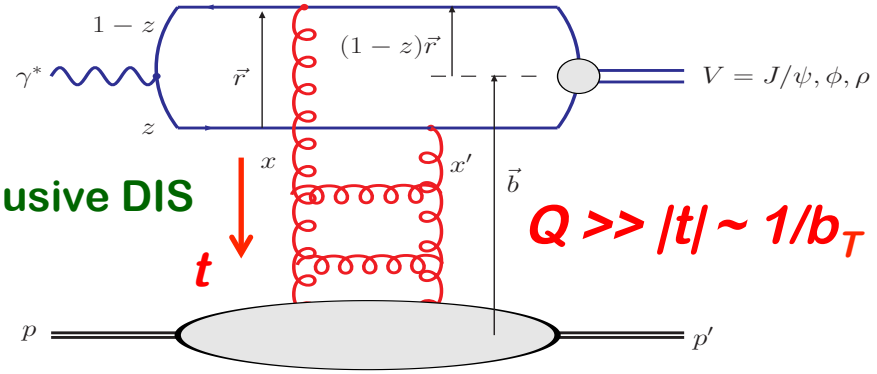
- **3D boosted partonic structure:**



3D momentum space images



2+1D coordinate space images



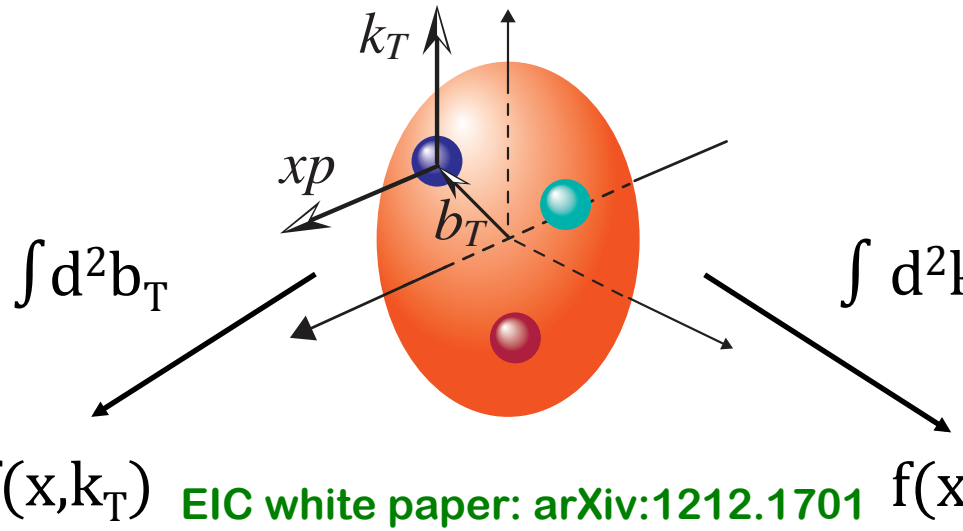
JLab12 – valence quarks, EIC – sea quarks and gluons

“Big” questions to be answered, …

- **3D boosted partonic structure:**

Momentum Space

TMDs



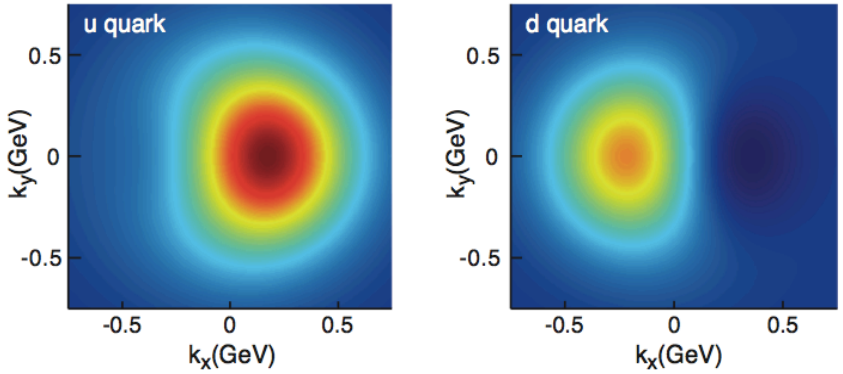
Coordinate Space

GPDs

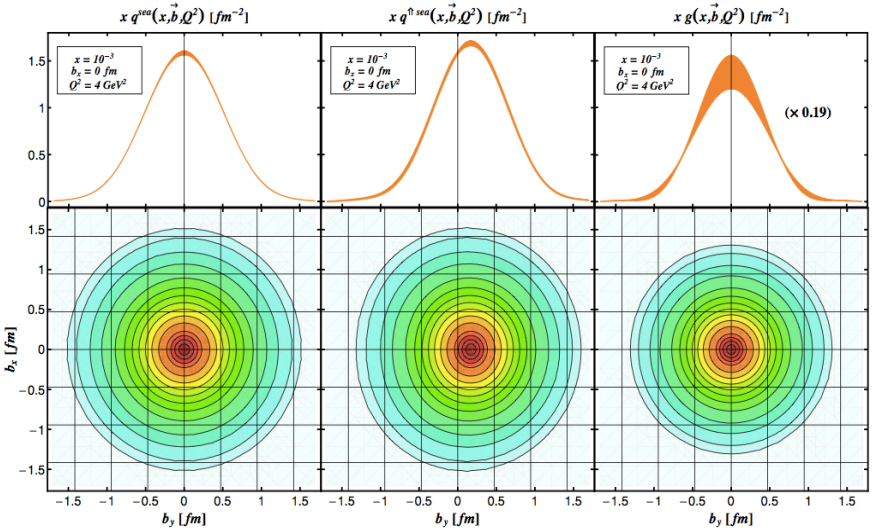
Sivers Function

EIC white paper: arXiv:1212.1701

Imaging



Density distribution of an unpolarized quark in a proton moving in z direction and polarized in y-direction



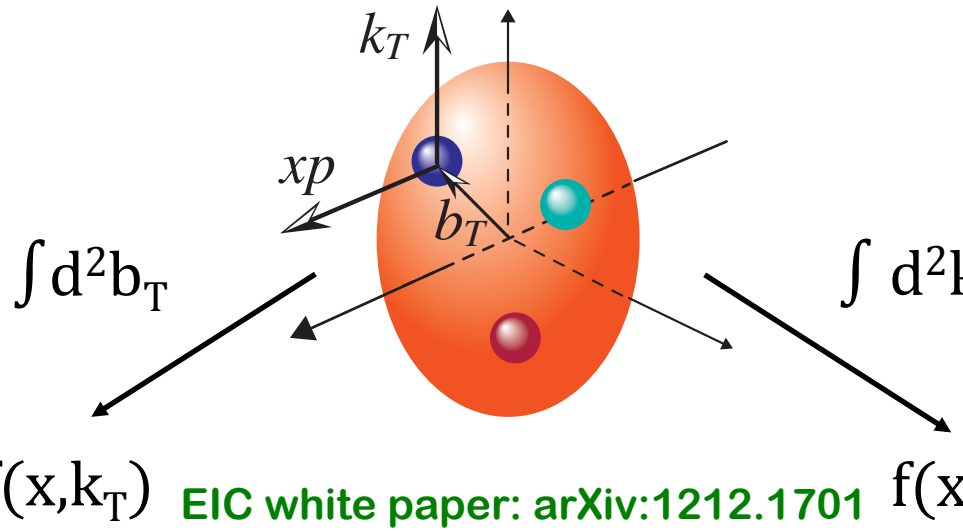
Spatial density distributions – “radius”

“Big” questions to be answered, …

- **3D boosted partonic structure:**

Momentum Space

TMDs



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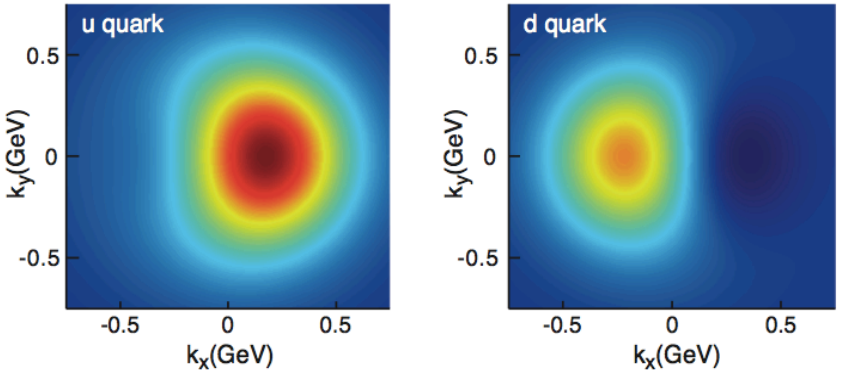
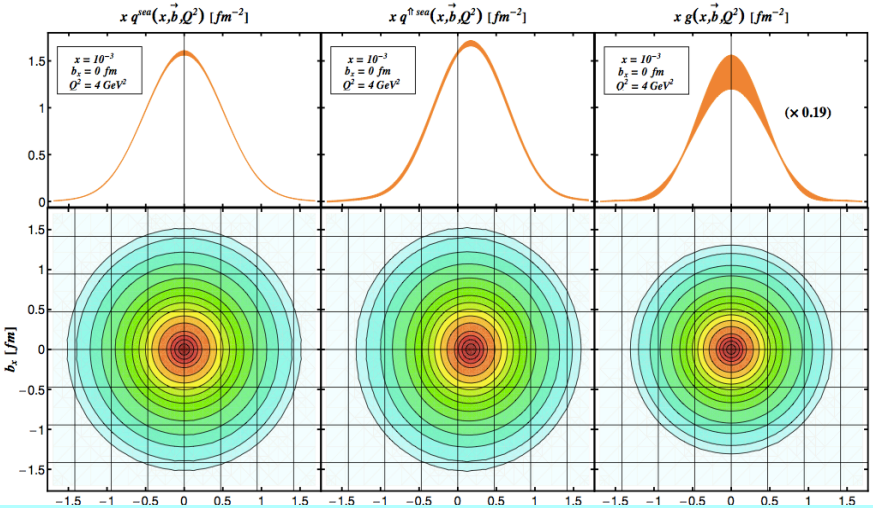




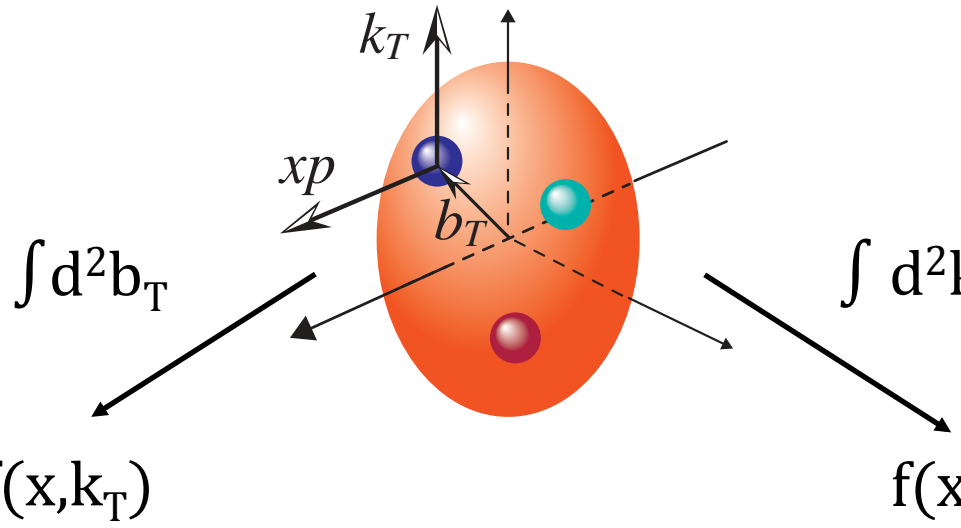
Position *r* x Momentum *p* → Orbital Motion of Partons

“Big” questions to be answered, …

- **3D boosted partonic structure:**

Momentum Space

TMDs



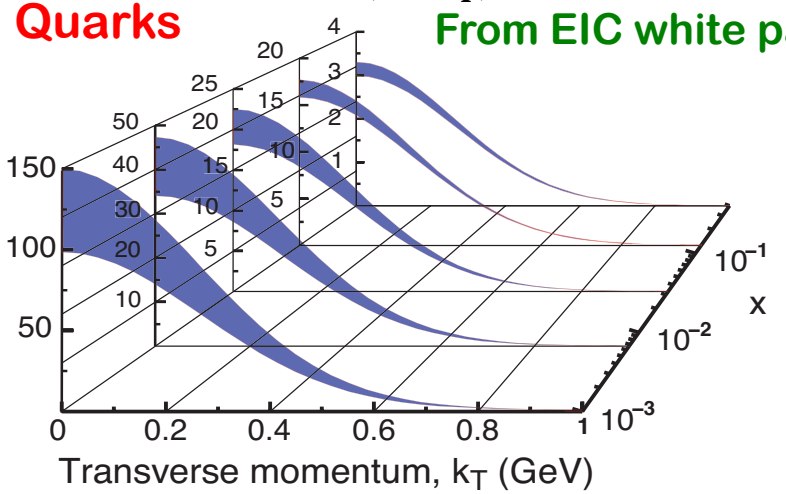
Coordinate Space

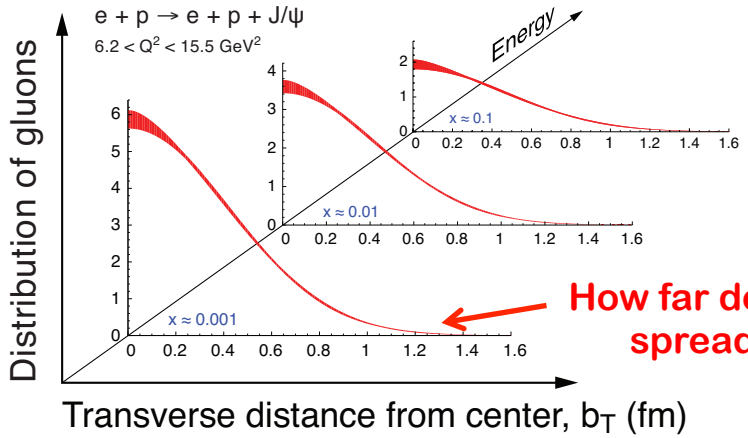
GPDs

Quarks

From EIC white paper: arXiv:1212.1701

Gluons





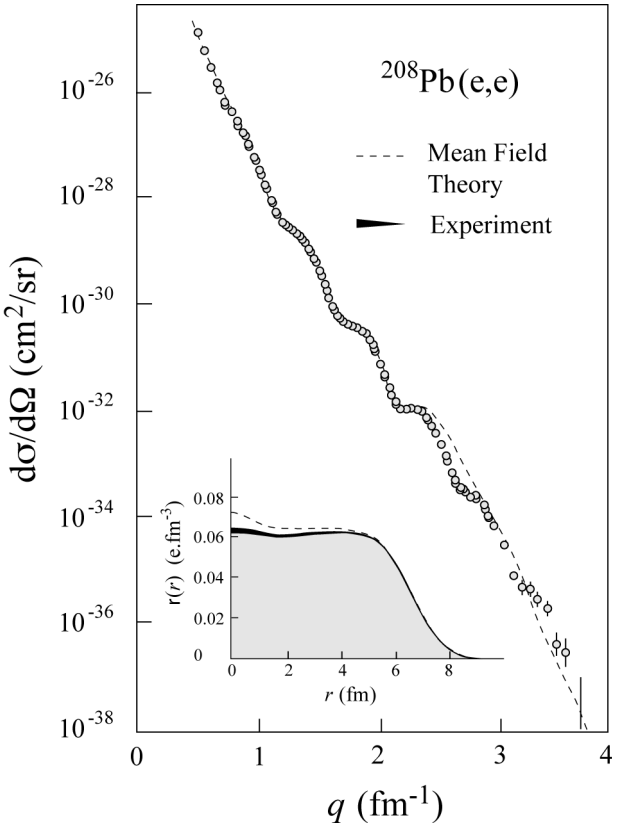
How far does it spread?

Role of momentum fraction -“x”, and nature of pion cloud?

Nuclear landscape, …

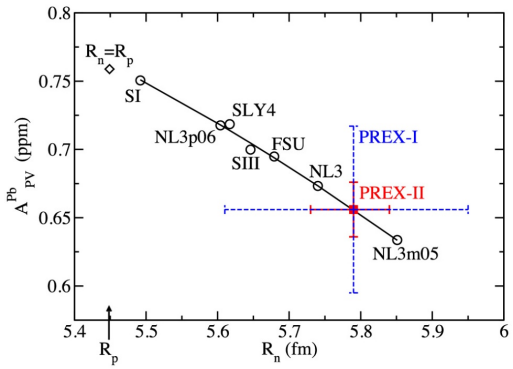
History:
Electromagnetic

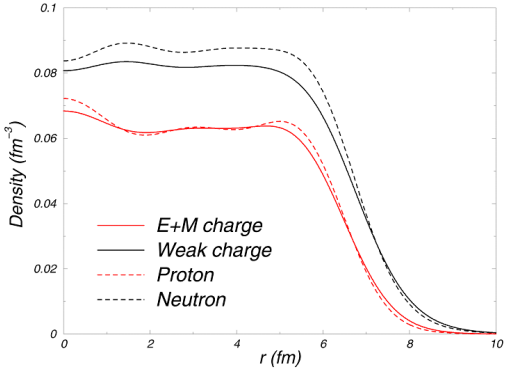
Elastic electron-nucleus scattering → charge distribution of nuclei



Present/Near-future:
Electroweak

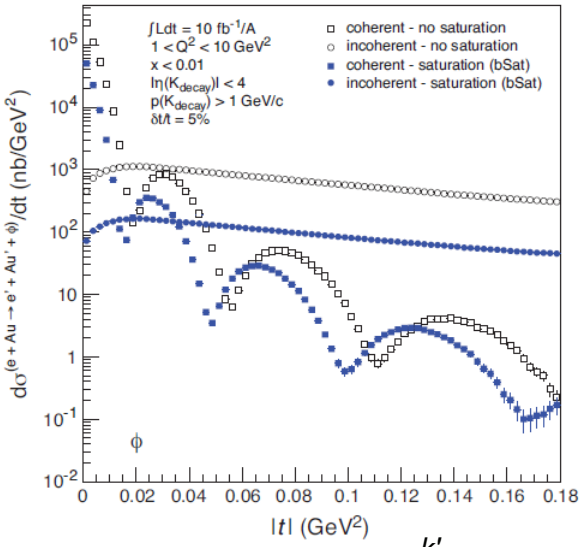
Parity-violating elastic electron-nucleus scattering (or hadronic reactions *e.g.* at FRIB) →

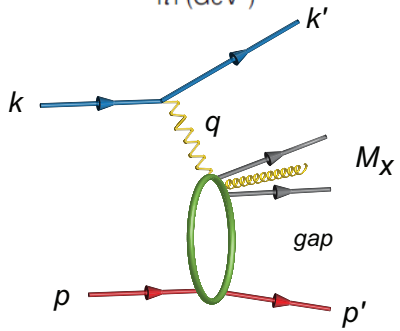




Future: at the EIC:
Color dipole

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





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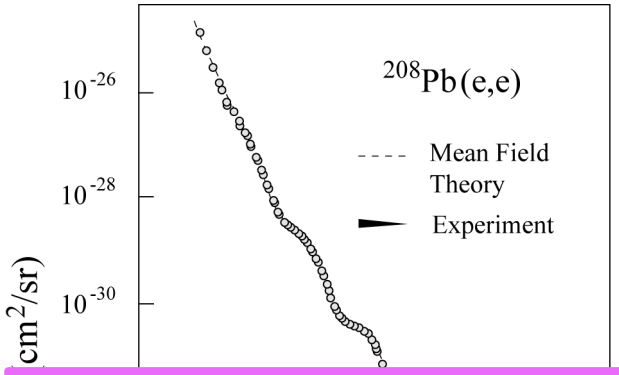

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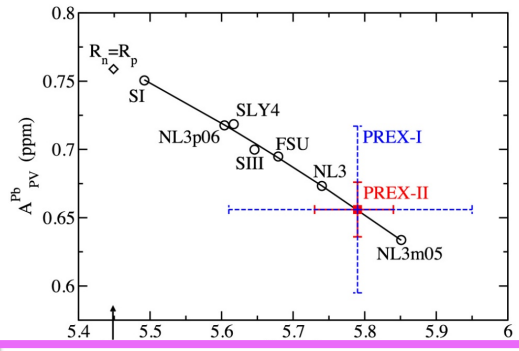

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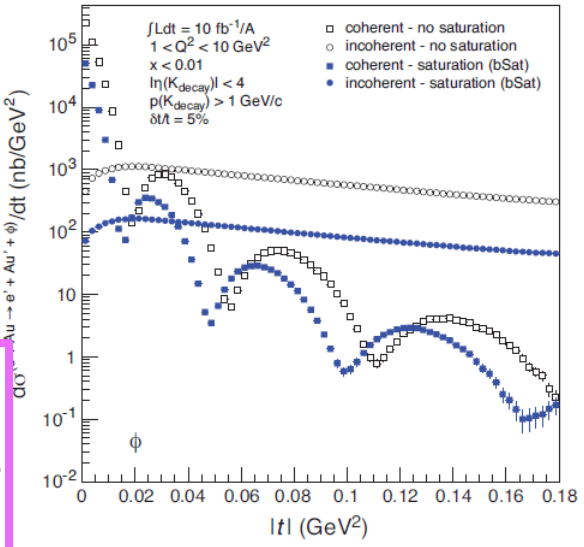
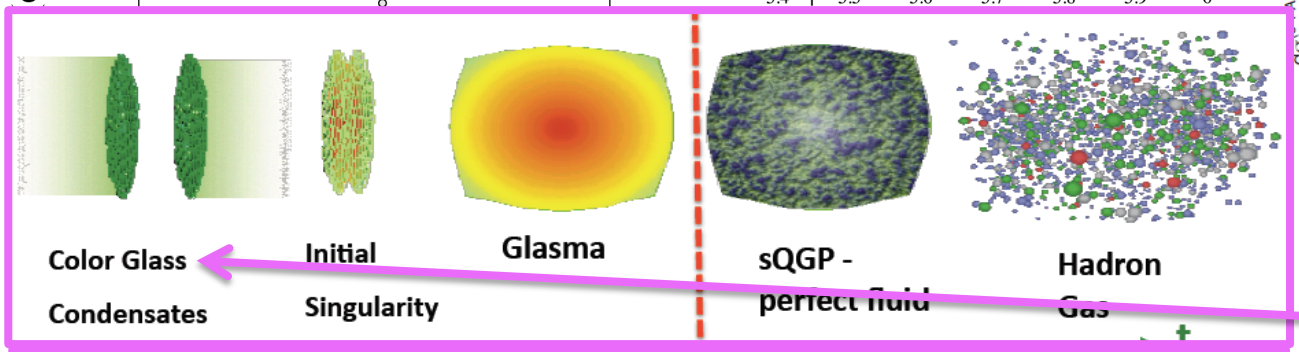


Fourier transform gives unprecedented info on gluon spatial distribution, including impact of gluon saturation

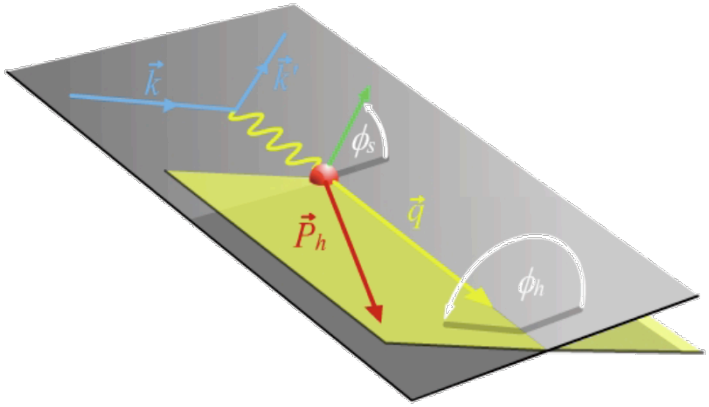


Provide important information for the initial conditions in Nucleus-Nucleus Collisions

Color fluctuation – azimuthal asymmetry at EIC

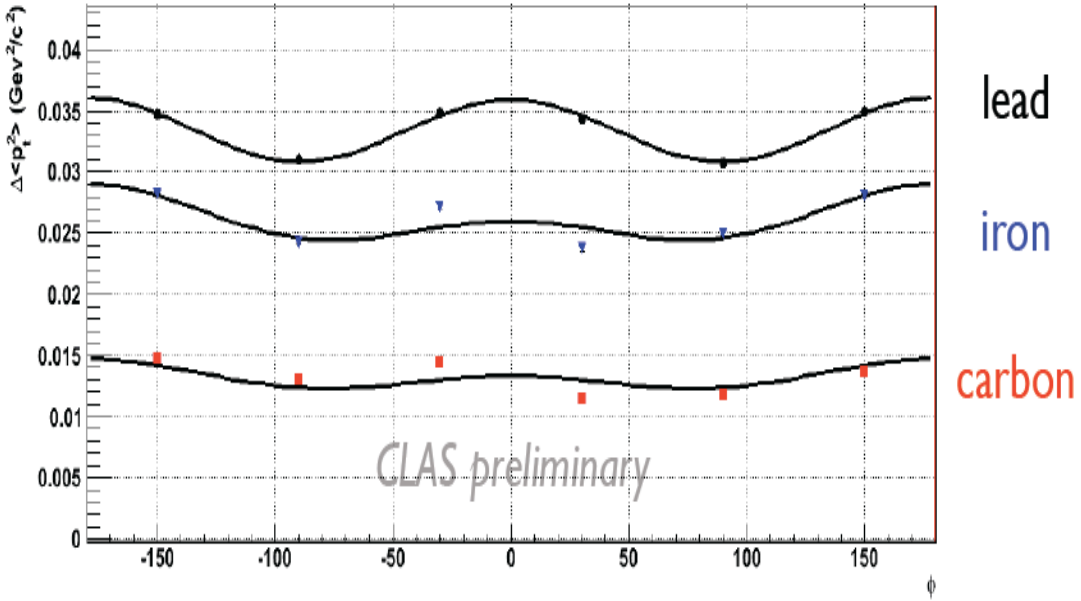
Hicks, KEK-JPAC2013

❑ Preliminary low energy data:



$$\langle p_T^2(\phi_{pq})\rangle_A = \int dp_T^2\, p_T^2 \frac{d\sigma_{eA}}{dx_B dQ^2 dp_T^2 d\phi} \Big/ \frac{d\sigma_{eA}}{dx_B dQ^2}$$

$$\langle \Delta p_T^2(\phi)\rangle_{AN} \equiv \langle p_T^2(\phi)\rangle_A - \langle p_T^2(\phi)\rangle_N$$



Contain terms in cos(ϕ_{pq}) and cos(2ϕ_{pq})
only statistical uncertainties shown

❑ Classical expectation:

Any distribution seen in Carbon should be washed out in heavier nuclei

❑ Surprise:

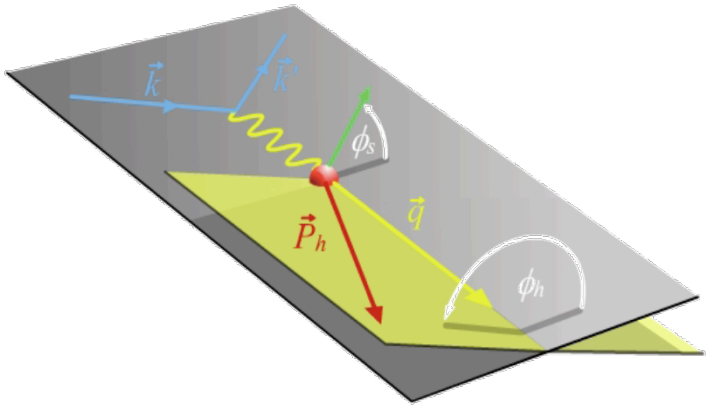
Azimuthal asymmetry in transverse momentum broadening

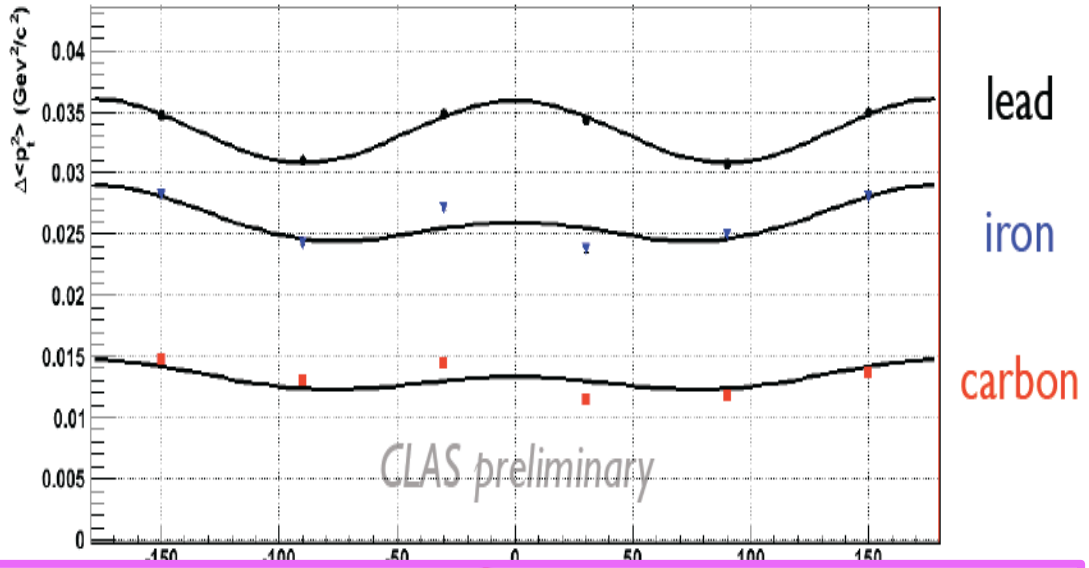
➡ ***Fluctuation and v_n at EIC!***

Color fluctuation – azimuthal asymmetry at EIC

Hicks, KEK-JPAC2013

❑ Preliminary low energy data:





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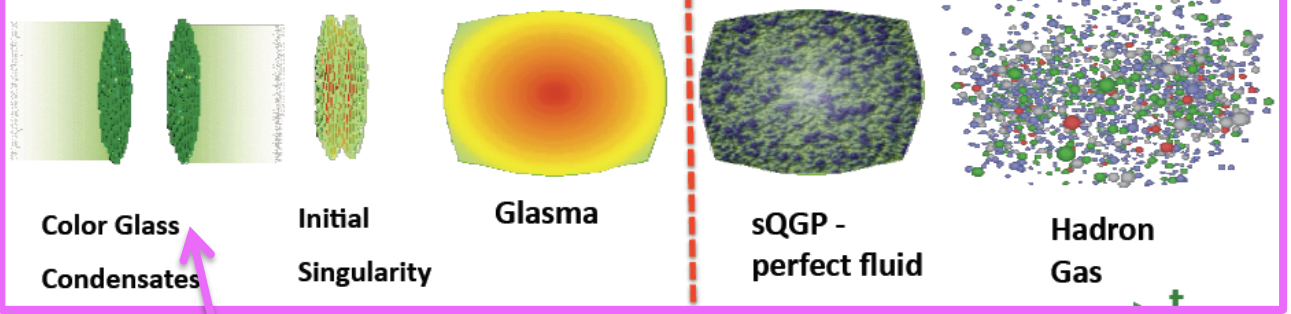
$$\langle \Delta p_T^2(\phi)\rangle_{AN} \equiv \langle p_T^2(\phi)\rangle_A - \langle$$

❑ Classical expecta

Any distribution se

❑ Surprise:

Azimuthal asymmet



Provide important information for the initial conditions in Nucleus-Nucleus Collisions

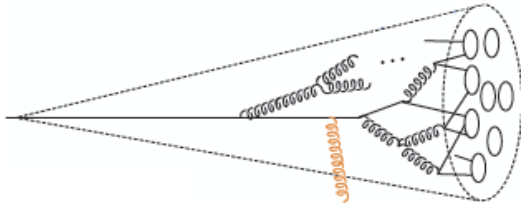
➡ *Fluctuation and v_n at EIC!*

Emergence of hadrons/Jets – A puzzle

- **Emergence of hadrons:**

  How do hadrons emerge from a created quark or gluon?
  How is the color of quark or gluon neutralized?

Jet substructure

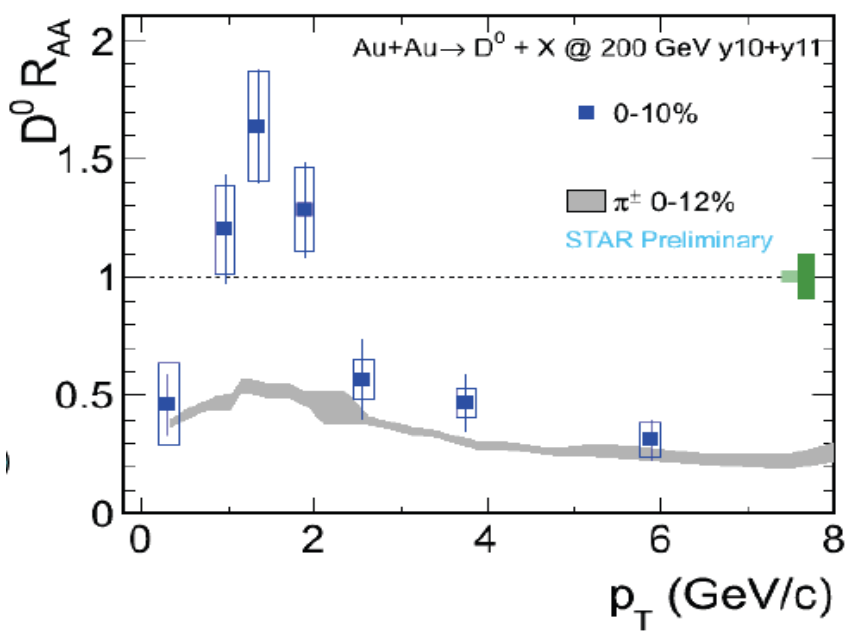


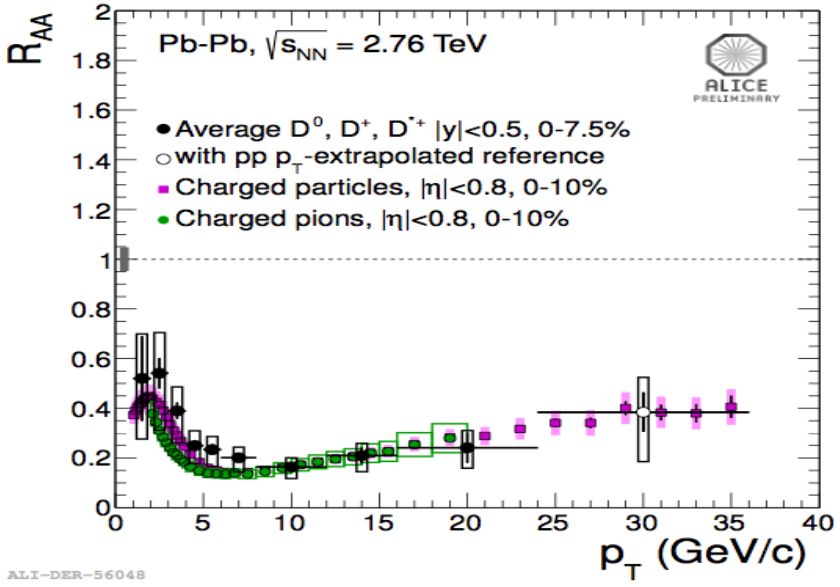
Boosted hadronization

- **Need a femtometer detector or "scope":**

  Nucleus, a laboratory for QCD
  A "vertex" detector: Evolution of hadronization

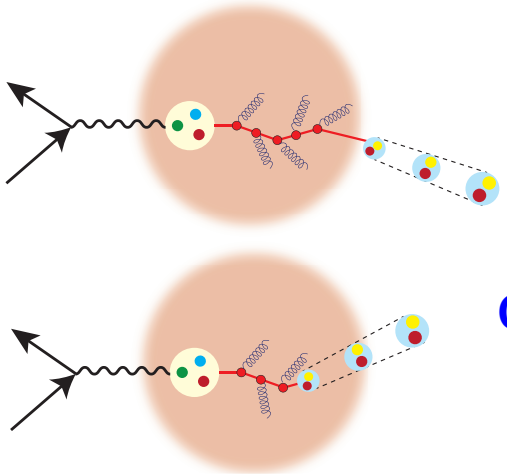
- **Strong suppression of heavy flavors in AA collisions:**





“Big” questions to be answered, …

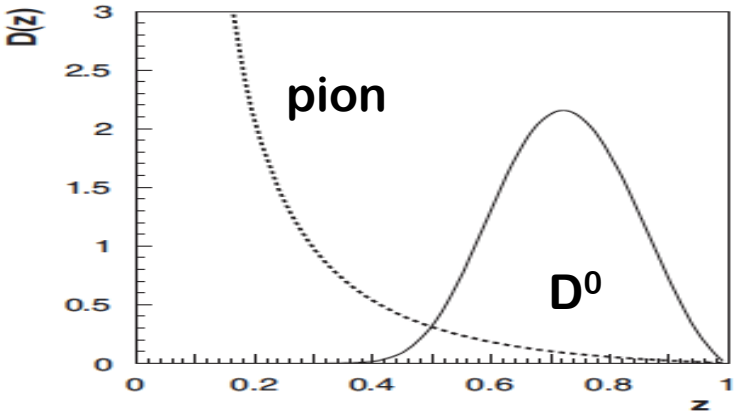
- **Emergence of a hadron?**

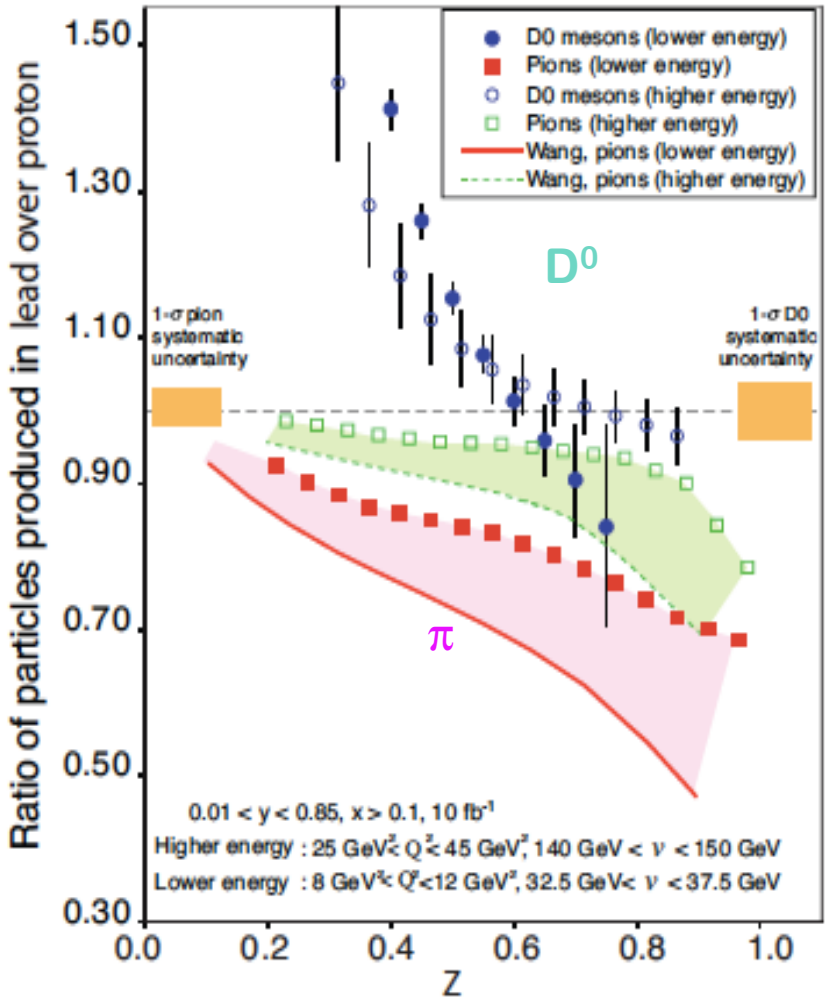


$$\nu = \frac{Q^2}{2mx}$$

Control of ν and medium length!

- **Heavy quark energy loss:**
  - **Mass dependence of fragmentation**

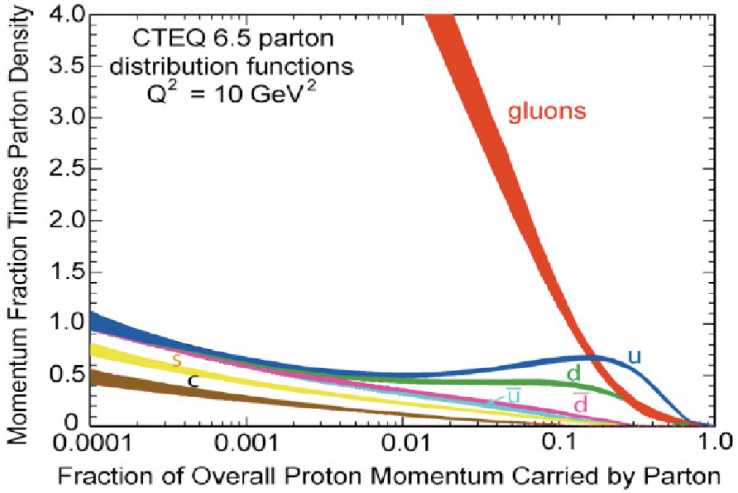




Need the collider energy of EIC and its control on parton kinematics

“Big” questions to be answered, …

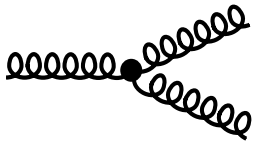
❑ Run away gluon density at small x?



What causes the low-x rise?

gluon radiation

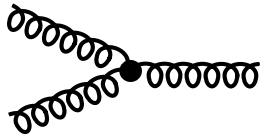
– non-linear gluon interaction



What tames the low-x rise?

gluon recombination

– non-linear gluon interaction



❑ QCD vs. QED:

QCD – gluon in a proton:

$$Q^2 \frac{d}{dQ^2} xG(x,Q^2) \approx \frac{\alpha_s N_c}{\pi} \int_x^1 \frac{dx'}{x'} x' G(x',Q^2)$$

QED – photon in a positronium:

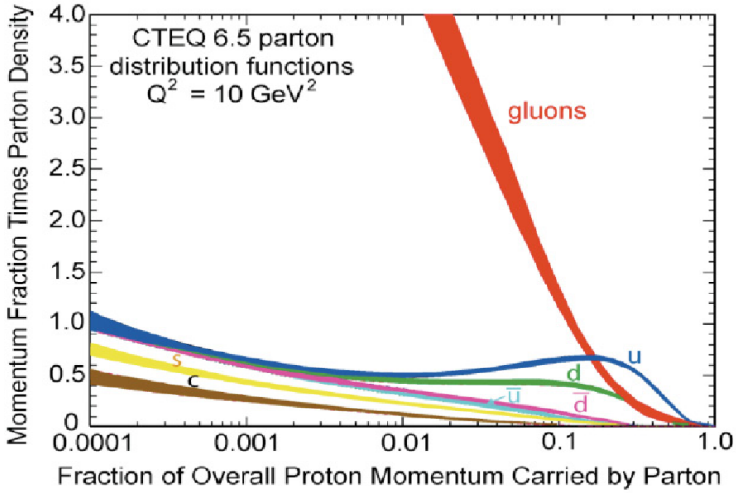
$$Q^2 \frac{d}{dQ^2} x\phi_\gamma(x,Q^2) \approx \frac{\alpha_{em}}{\pi} \left[-\frac{2}{3} x\phi_\gamma(x,Q^2) + \int_x^1 \frac{dx'}{x'} x' [\phi_{e+}(x',Q^2) + \phi_{e-}(x',Q^2)] \right]$$

✧ At very small-x, proton is “black”, positronium is still transparent!

✧ Recombination of large numbers of glue could lead to saturation phenomena

“Big” questions to be answered, …

❑ Run away gluon density at small x?



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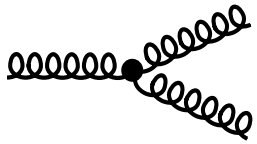

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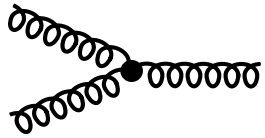
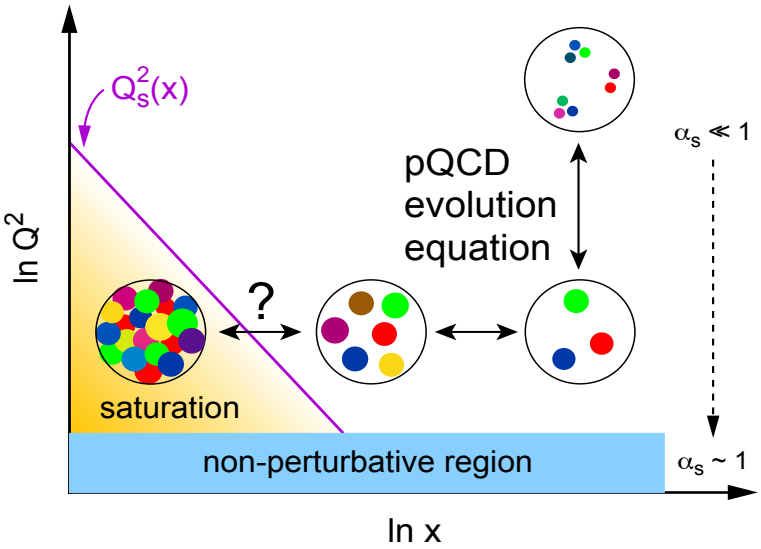
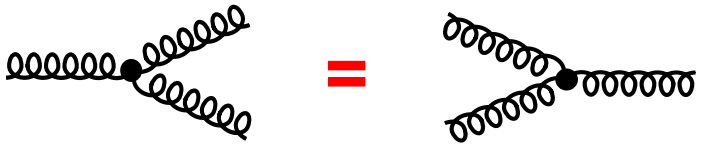


❑ Particle vs. wave feature:



Gluon saturation – Color Glass Condensate

Radiation = Recombination



at Q_s

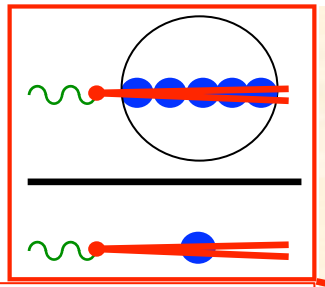
Leading to a collective gluonic system?

with a universal property of QCD?

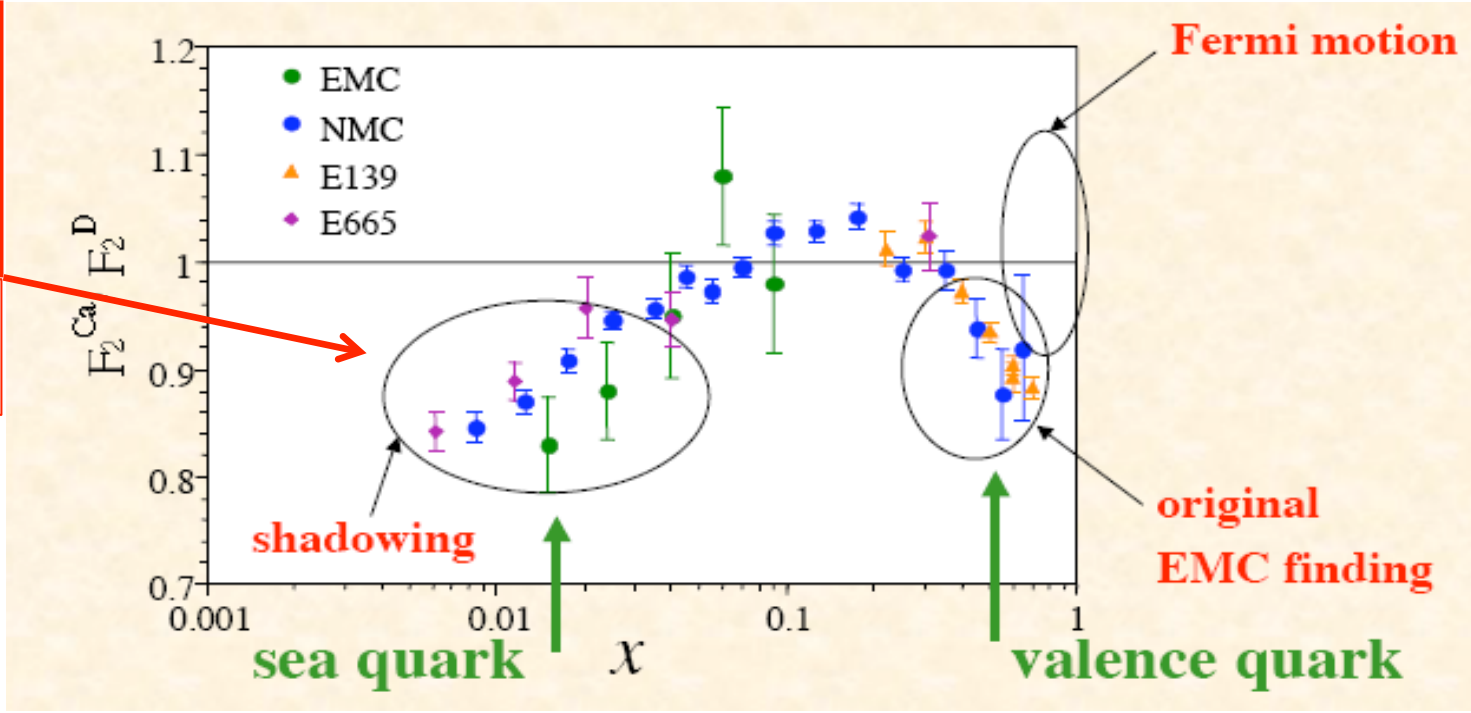
new effective theory QCD – CGC?

An “easiest” measurement at EIC

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



Color localized inside nucleons



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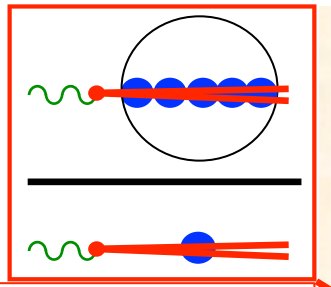

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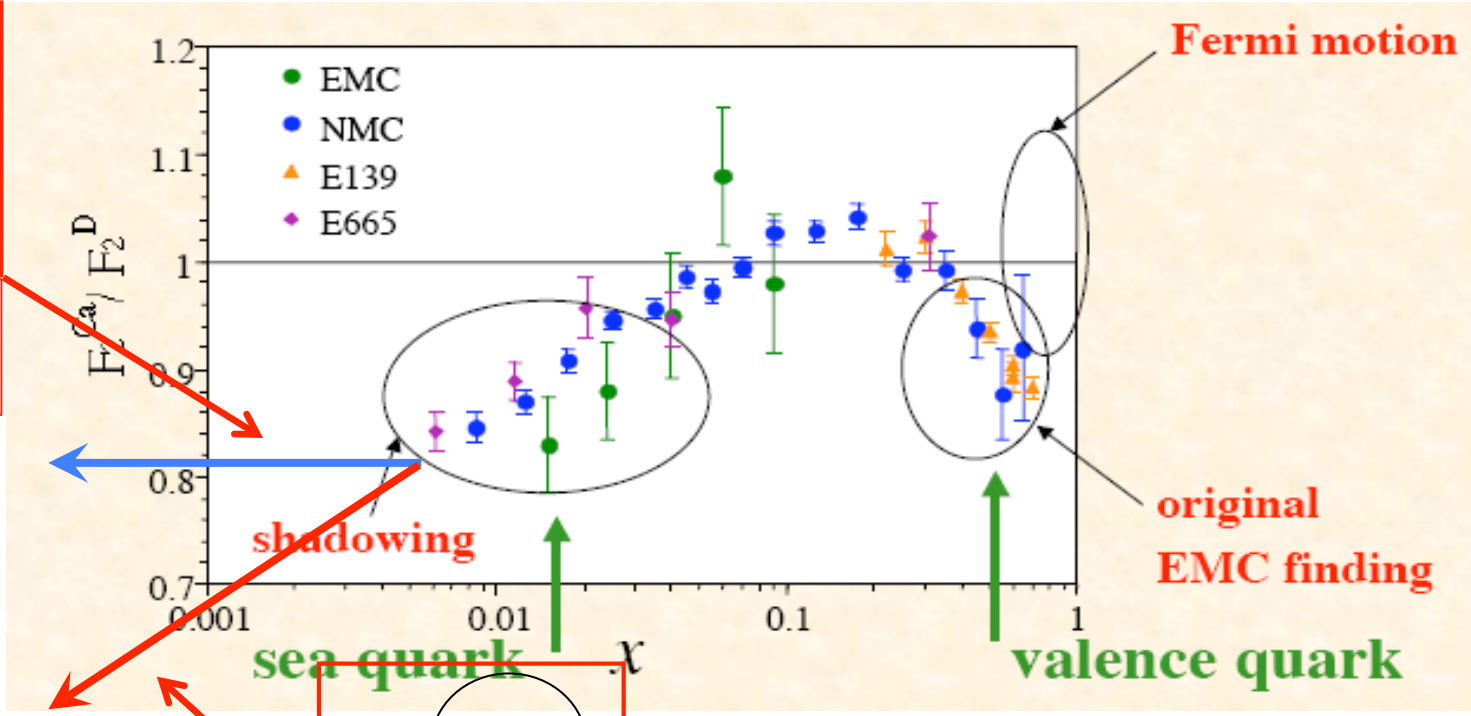
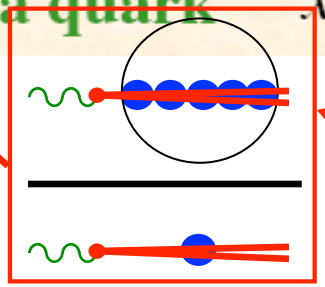




Color leaks outside nucleons

- Questions:

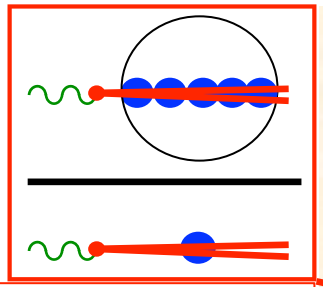
Will the suppression/shadowing continue fall as x decreases?

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

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

An “easiest” measurement at EIC

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

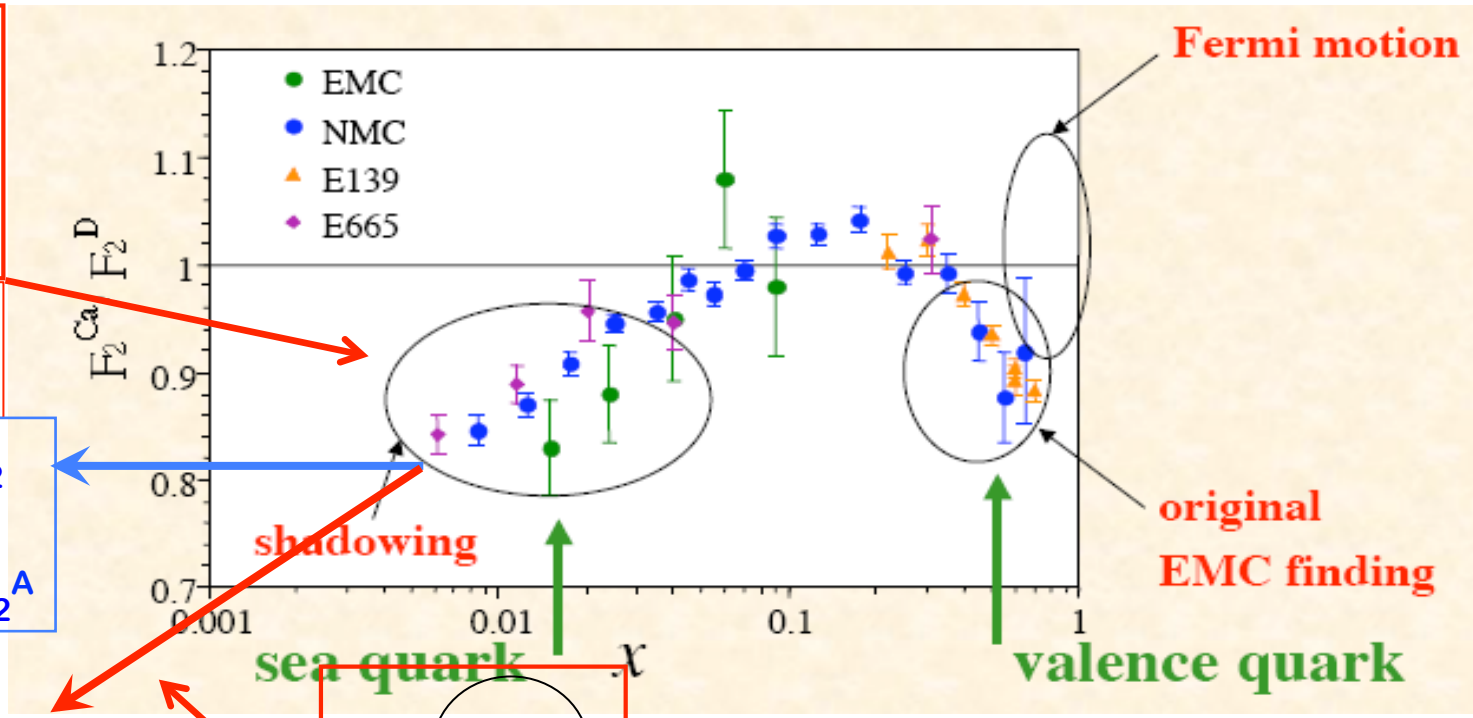


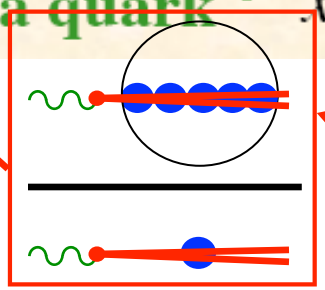
Color localized inside nucleons

Saturation in RF_2

=

No saturation in F_2^A





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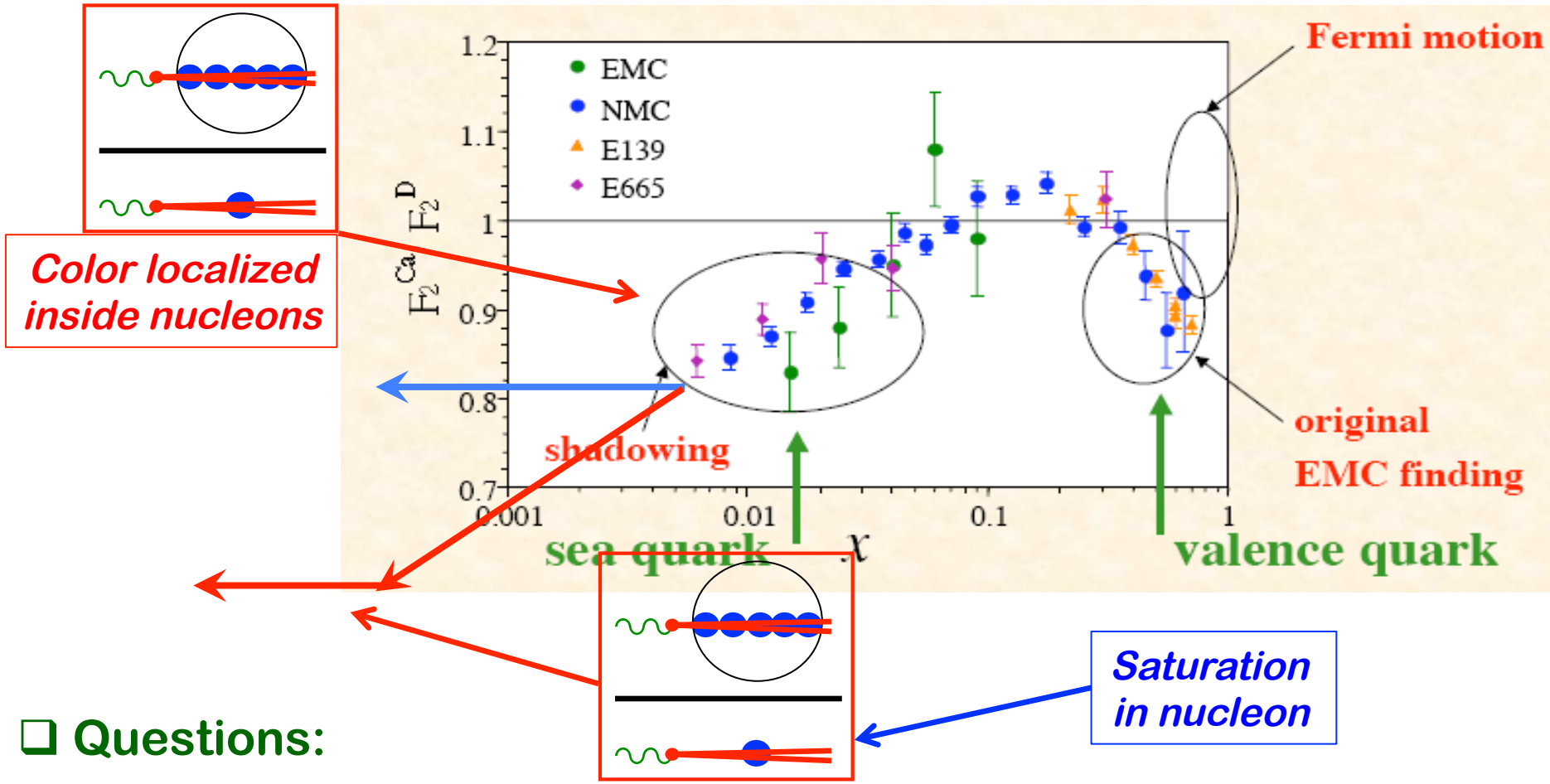

❑ Questions:

Will the suppression/shadowing continue fall as x decreases?

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

Summary

- EIC is a ultimate QCD machine:
  1) to discover and explore the quark/gluon structure and properties of hadrons and nuclei,
  2) to search for hints and clues of color confinement, and
  3) to measure the color fluctuation and color neutralization

- EIC is a tomographic machine for nucleons and nuclei with a resolution better than 1/10 fm

- EIC designs explore the polarization and intensity frontier, as well as the frontier of new accelerator/detector technology

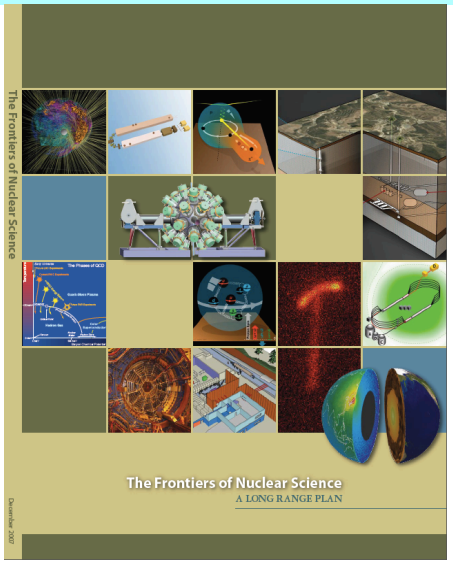
- EIC@US is sitting at a sweet spot for rich QCD dynamics – capable of taking us to the next QCD frontier

Thanks!

U.S. - based Electron-Ion Collider

❑ NSAC 2007 Long-Range Plan:

"An **Electron-Ion Collider (EIC)** with **polarized** beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**."



❑ NSAC Facilities Subcommittee (2013):

"The Subcommittee ranks an EIC as **Absolutely Central** in its ability to contribute to world-leading science in the next decade."

❑ NSAC 2015 Long-Range Plan:

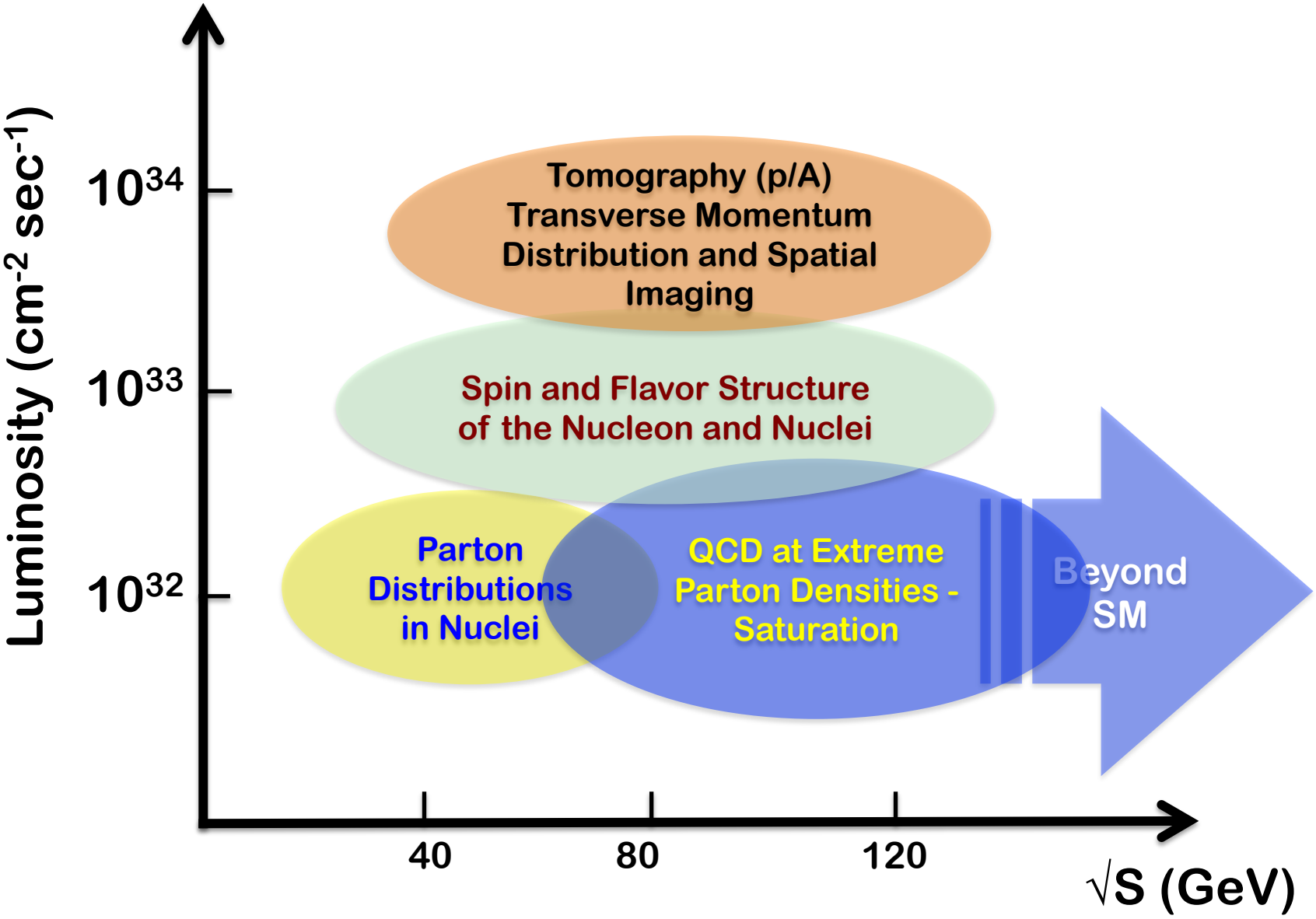
"We recommend **a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB**."

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

❑ EIC User Group Meetings:

Stony Brook University, NY – June 24-27, 2014
UC at Berkeley, CA – January 6-9, 2016
Argonne National Lab, IL – July 7-10, 2016

US EIC – Physics vs. Luminosity & Energies



An immediate consequence

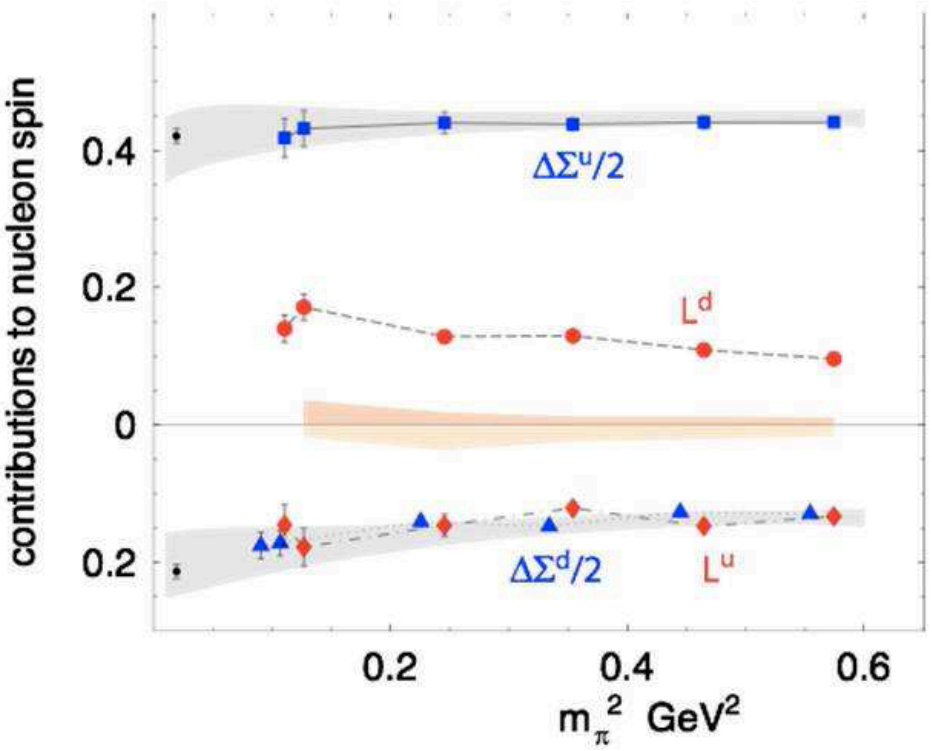
- **Quark GPDs and its orbital contribution to proton's spin:**

$$J_q = \frac{1}{2}\lim_{t\to 0}\int dx\, x\,[H_q(x,\xi,t) + E_q(x,\xi,t)] = \frac{1}{2}\Delta q + L_q$$

The first meaningful constraint on quark orbital contribution to proton spin by combining the sea from the EIC and valence region from JLab 12

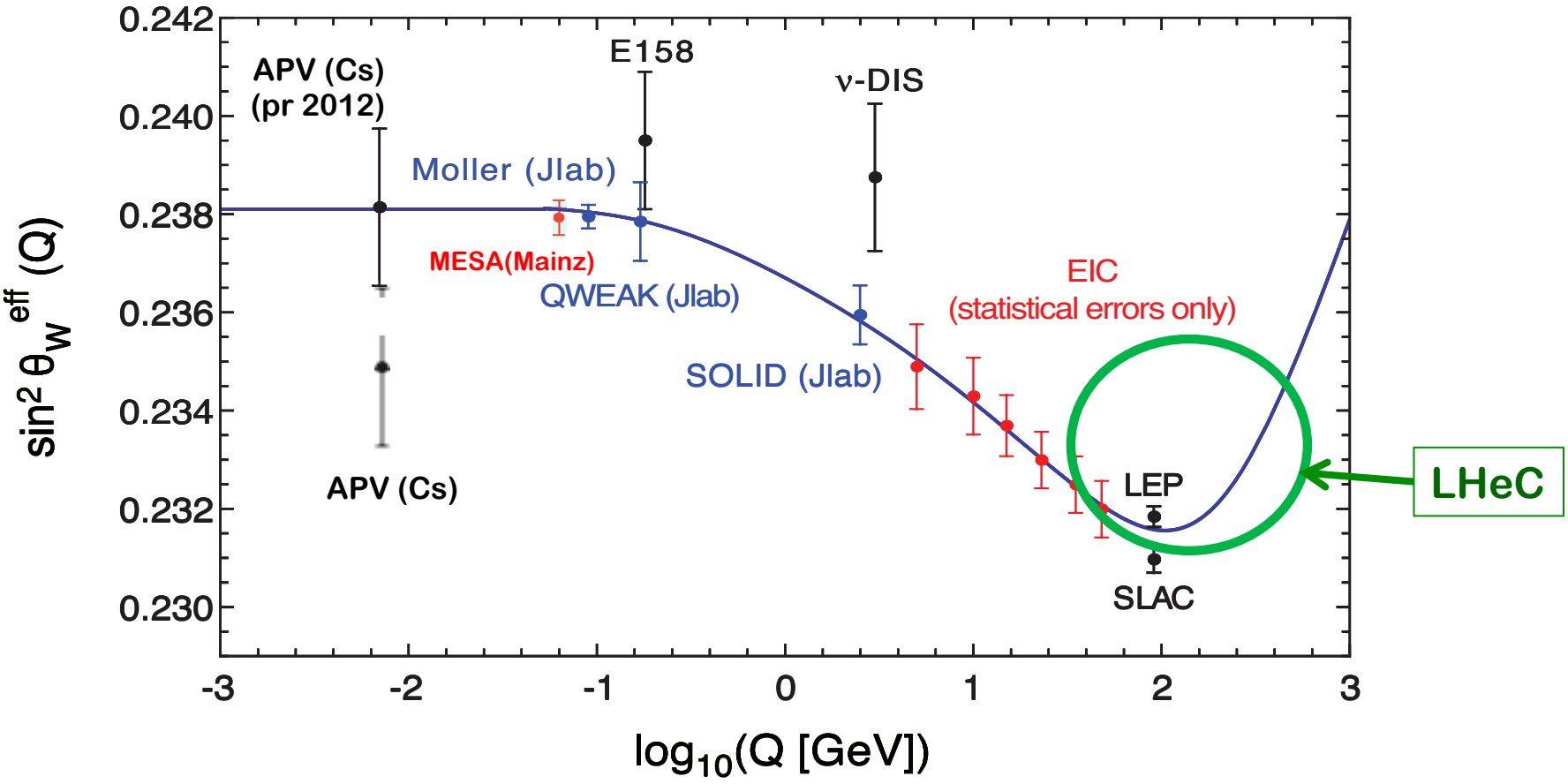
This could be checked by Lattice QCD

$L_u + L_d \sim 0$?



Electroweak physics at EIC

❑ Running of weak interaction – high luminosity:



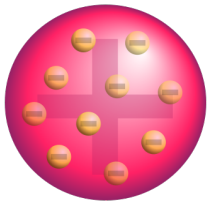
✧ **Fills in the region that has never been measured**

✧ ***have a real impact on testing the running of weak interaction***

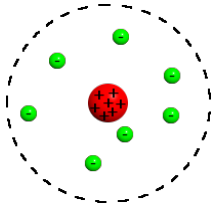
Why 3D nucleon structure?

❑ Rutherford's experiment – atomic structure (100 years ago):

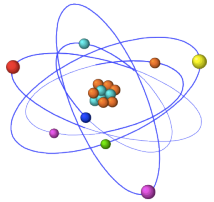
Atom:



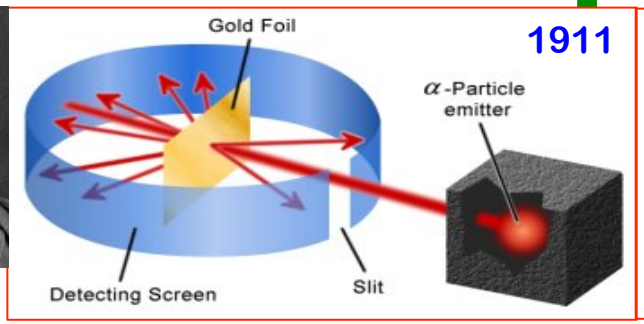
J.J. Thomson's
plum-pudding model



Rutherford's
planetary model



Modern model
Quantum orbitals



Discovery of nucleus
A localized
charge/force center
A vast
"open" space

Discovery of
Quantum Mechanics,
and
the Quantum World!

❑ Completely changed our "view" of the visible world:

- ✧ Mass by "tiny" nuclei – *less than 1 trillionth in volume of an atom*
- ✧ Motion by quantum probability – *the quantum world!*

❑ Provided infinite opportunities to improve things around us:

- ✧ Gas, Liquid, Solid, Nano materials, Quantum computing, …