The University of Kansas

KU | Department of Physics and Astronomy
College of Liberal Arts & Sciences

Understanding the Universe Starts Here

Nuclear Femtography
A new frontier of
Science and Technology

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Theory Center, Jefferson Lab

Physics Colloquium – March 25, 2019

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, …

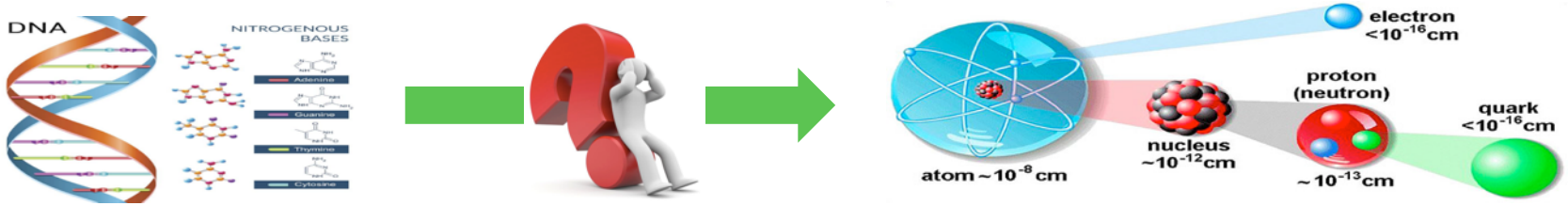
Eternal Questions we have been asking …

- **Where did we come from?**

Global Time: ⟶

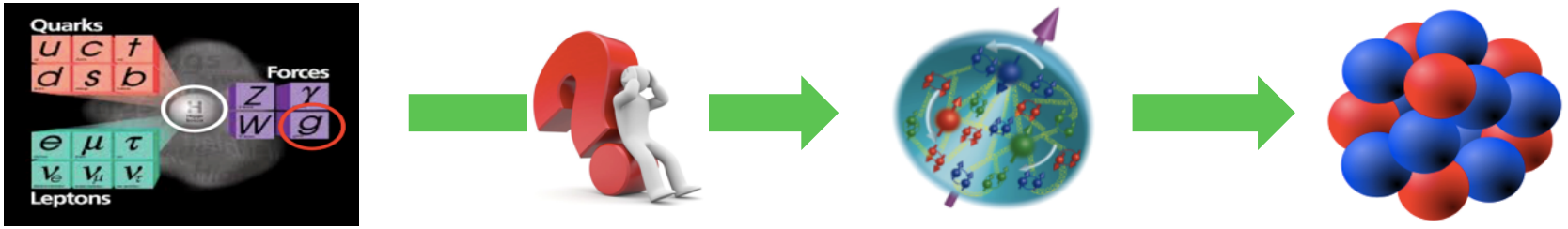
How did hadrons are emerged from the energy, the quarks and gluons?

- **What are we made of?**



What is the internal structure and dynamics of hadrons?

- **What holds us together?**

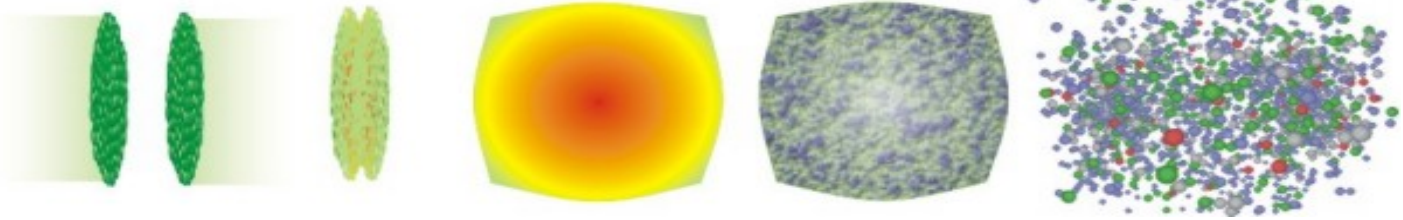


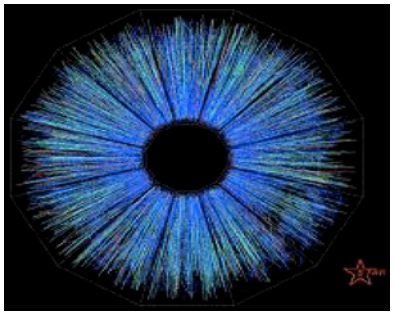
How does the glue bind us all?

Nuclear Femtography: search for answers to these questions at Fermi scale!

Going back in time?

- **Relativistic heavy-ion collisions - RHIC:**





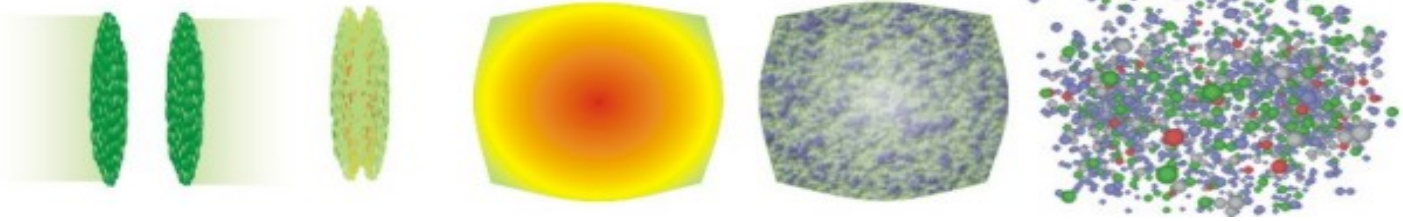
Lorentz contraction | Near collision | Quark-gluon plasma | Hadronization | Freeze-out | Seen in the detector

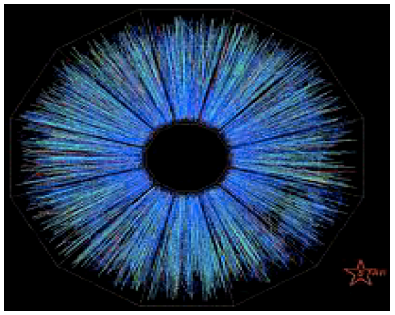
Visible! — "Seeing" the unseen — Visible!

A virtual journey of the visible matter!

Going back in time?

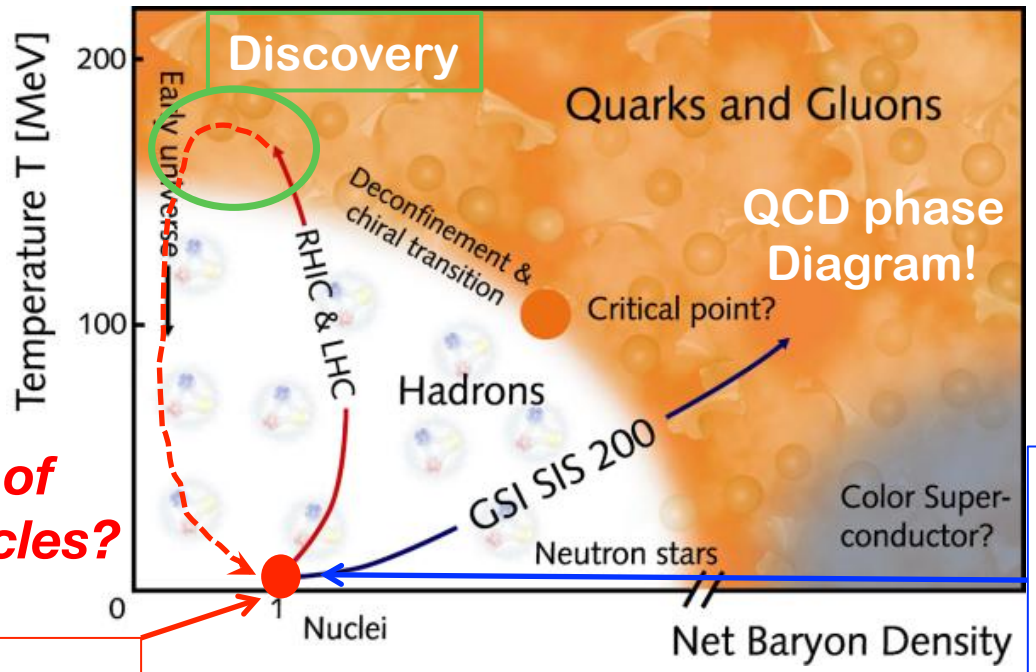
❑ **Relativistic heavy-ion collisions - RHIC:**





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

Visible! **Visible!**



Emergence of hadronic particles?

Where we are now

Partonic structure of hadrons?
initial conditions of RHIC

Outline of the rest of my talk

- From atomic structure to hadron structure:

  From nano-science to femto-science – a quantum jump!
  Nano: electromagnetism, quantum physics, …
  Femto: quantum fluctuation, asymptotic freedom, confinement, …

- Great intellectual challenges for Nuclear Femtography

  Probing quarks and gluons & exploring their interactions
  without being able to "see" them – color confinement!

- What is an Electron-Ion Collider (EIC)?

  JLab12 – a prerequisite of EIC
  US EIC – two options of realization

- What an EIC can do and why other machine cannot do?

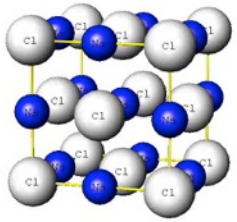
  Major Nuclear Science issues to be studied at an EIC
  EIC is an international effort

- Summary and outlook

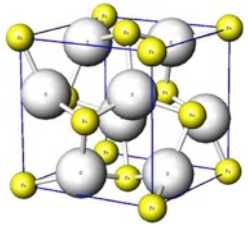
Atomic structure

- **Structure – "a still picture"**

Crystal Structure:

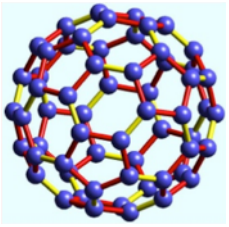


NaCl,
B1 type structure



FeS2,
C2, pyrite type structure

Nano-material:



Fullerene, C60

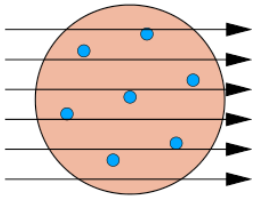
Motion of nuclei is much slower than the speed of light!

- **Atomic structure: dating back to Rutherford's experiment :**

$\alpha + Au \rightarrow \alpha + X$

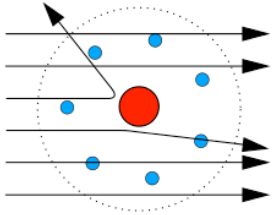
Over 100 years ago

Atom:



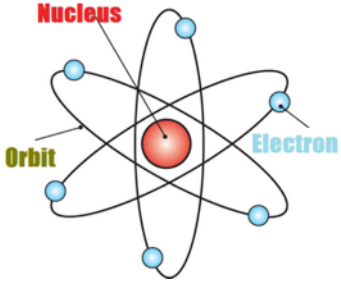
J.J. Thomson's
plum-pudding model

Experiment



Rutherford's
Experiment - Data

Theory



Quantum orbitals

Discovery: ✧ Tiny nucleus – *less than 1 trillionth in volume of an atom*
✧ Quantum probability – *the Quantum World!*

Infinite opportunities to create & improve … !

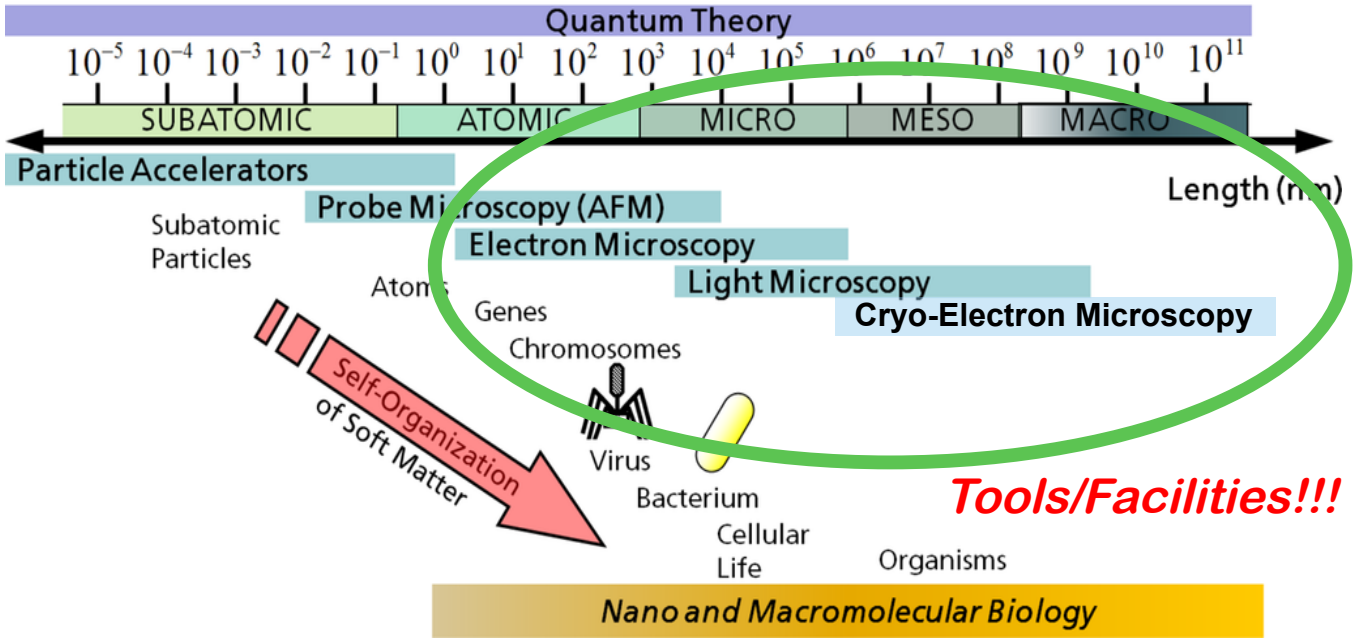
Nano-Science and Technology

❑ The idea:

"There's plenty of room at the bottom"

Feynman, APS meeting at Caltech, December 29, 1959

❑ Need technology/facilities to advance:



Tools/Facilities!!!

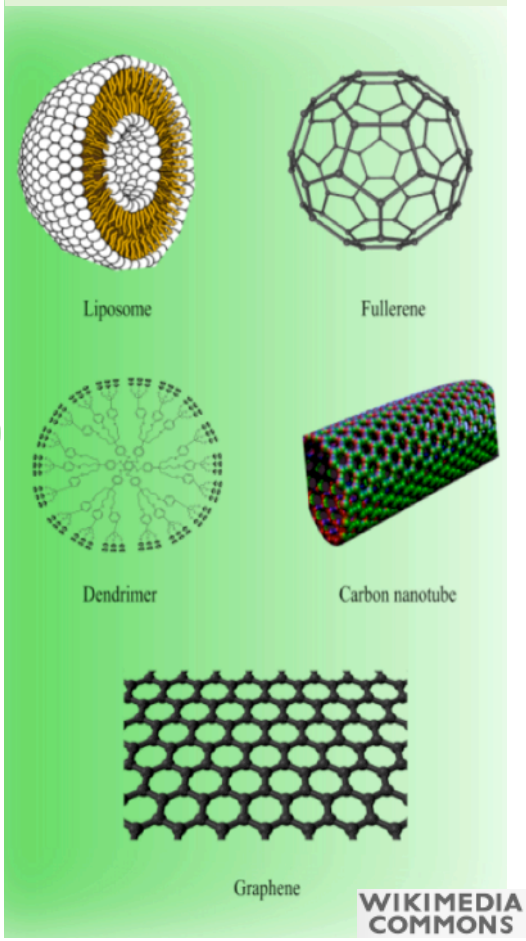
❑ The Support:

National Nanotechnology Initiative

Nano-science (1-100 nm)

NSF proposed to White House in 1999, signed into law in 2003

Nanomaterials



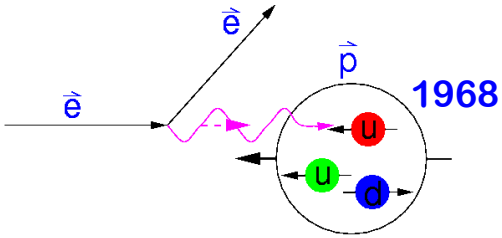
Ensure the role of quantum physics

Hadron structure

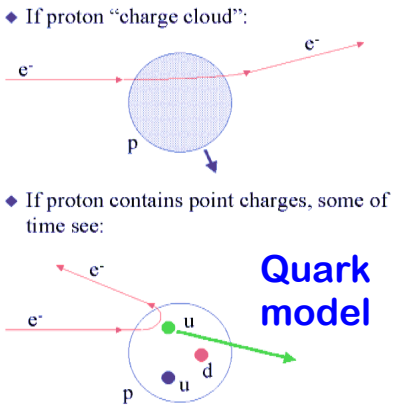
- A modern "Rutherford" experiment (about 50 years ago):

Nucleon: *The building unit of all atomic nuclei*

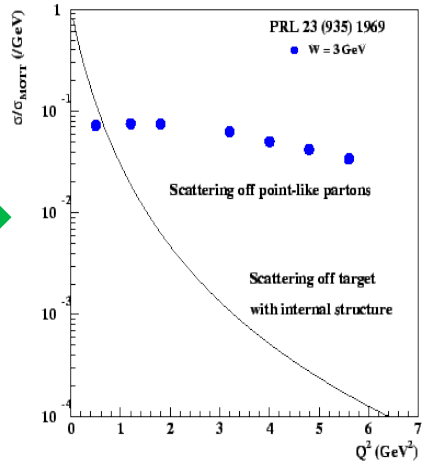
$e + p \rightarrow e + X$



Prediction



Discovery

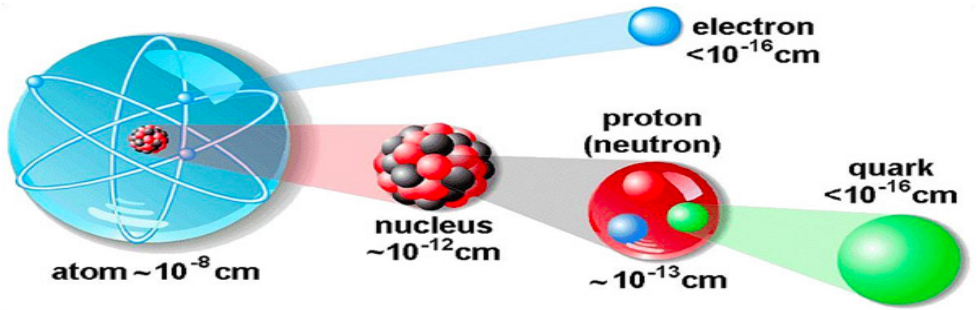


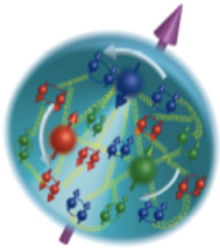
Discovery: ✧ Partons/Quarks – *moving relativistically*

✧ Quantum fluctuation – *parton number is not fixed!*

- NO "still picture" for hadron's partonic structure!

Atomic world:





Birth of Quantum Chromodynamics (QCD) – gluons & color force!

Quantum Chromo-dynamics (QCD)

= A quantum field theory of quarks and gluons =

- **Fields:**

$\psi_i^f(x)$ **Quark fields: spin-½ Dirac fermion (like electron)**

Color triplet: $i = 1, 2, 3 = N_c$

Flavor: $f = u, d, s, c, b, t$

$A_{\mu,a}(x)$ **Gluon fields: spin-1 vector field (like photon)**

Color octet: $a = 1, 2, ..., 8 = N_c^2 - 1$

- **QCD Lagrangian density:**

$$\mathcal{L}_{QCD}(\psi, A) = \sum_f \overline{\psi}_i^f \left[(i\partial_\mu \delta_{ij} - g A_{\mu,a}(t_a)_{ij})\gamma^\mu - m_f \delta_{ij}\right] \psi_j^f$$
$$-\frac{1}{4}\left[\partial_\mu A_{\nu,a} - \partial_\nu A_{\mu,a} - g C_{abc} A_{\mu,b} A_{\nu,c}\right]^2$$
$$+ \text{gauge fixing} + \text{ghost terms}$$

- **QED – force to hold atoms together:**

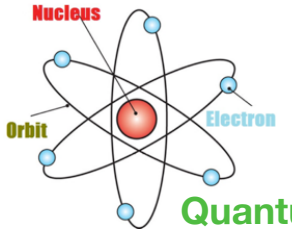
$$\mathcal{L}_{QED}(\phi, A) = \sum_f \overline{\psi}^f \left[(i\partial_\mu - eA_\mu)\gamma^\mu - m_f\right] \psi^f - \frac{1}{4}\left[\partial_\mu A_\nu - \partial_\nu A_\mu\right]^2$$

QCD is much richer in dynamics than QED

Gluons interact with themselves, NO quarks and gluons "seen" in isolation!

Unprecedented intellectual challenge!

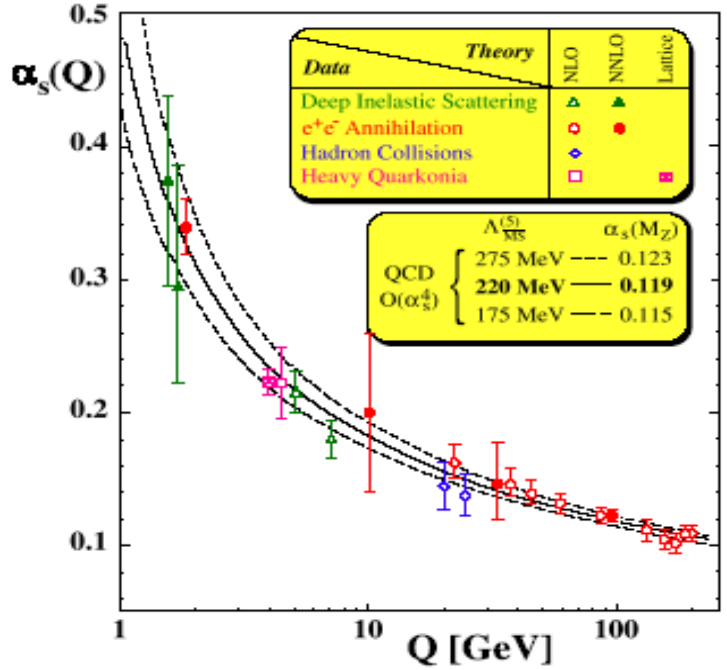
- The *challenge*:
  - *How to probe the quark-gluon dynamics, quantify the hadron structure, study the emergence of hadrons, …, if we cannot see quarks and gluons?*
  - *Gluons are bark, but, carry color!*



Quantum orbits

→ *NO separation between color charges! Color is fully entangled!*

- The *"helper"* – QCD Asymptotic Freedom:



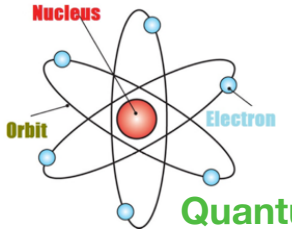
- *Interaction strength:* **Nobel Prize, 2004**

$$\alpha_s(\mu_2) = \frac{\alpha_s(\mu_1)}{1 - \frac{\beta_1}{4\pi}\alpha_s(\mu_1)\ln\left(\frac{\mu_2^2}{\mu_1^2}\right)} \equiv \frac{4\pi}{-\beta_1 \ln\left(\frac{\mu_2^2}{\Lambda^2_{\rm QCD}}\right)}$$

→ *Controllable perturbative QCD calculations at HIGH ENERGY!*

Unprecedented intellectual challenge!

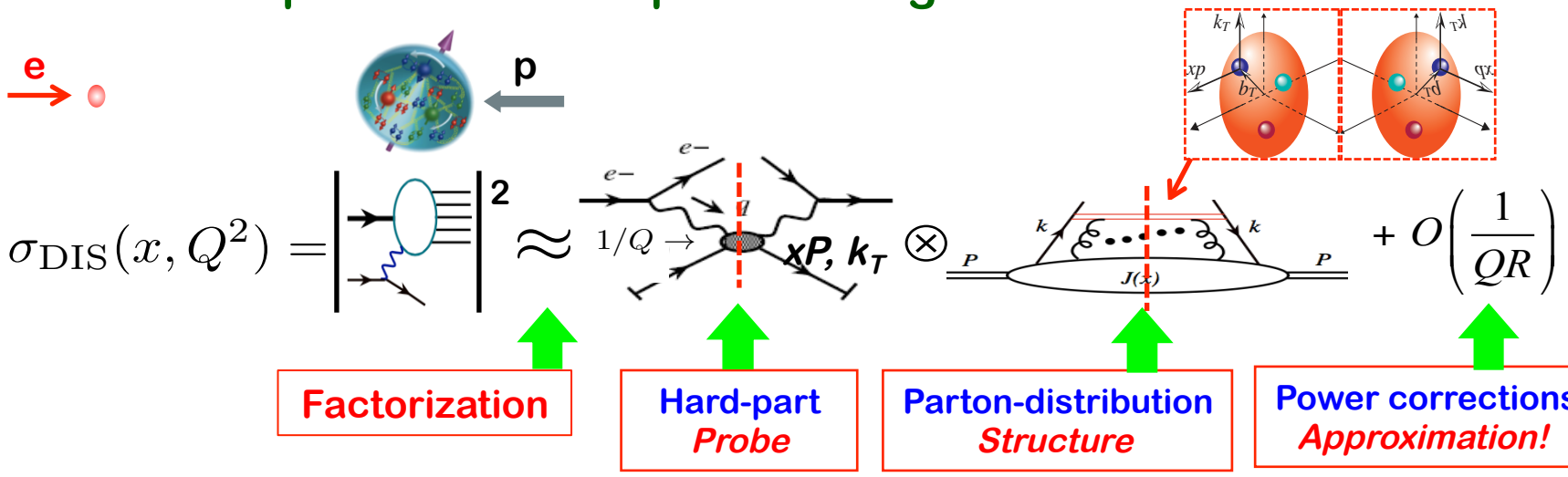
- The *challenge*:
  - *How to probe the quark-gluon dynamics, quantify the hadron structure, study the emergence of hadrons, …, if we cannot see quarks and gluons?*
  - *Gluons are bark, but, carry color!*



Quantum orbits

→ *NO separation between color charges! Color is fully entangled!*

- The *need* – a probe to "see" quarks and gluons:

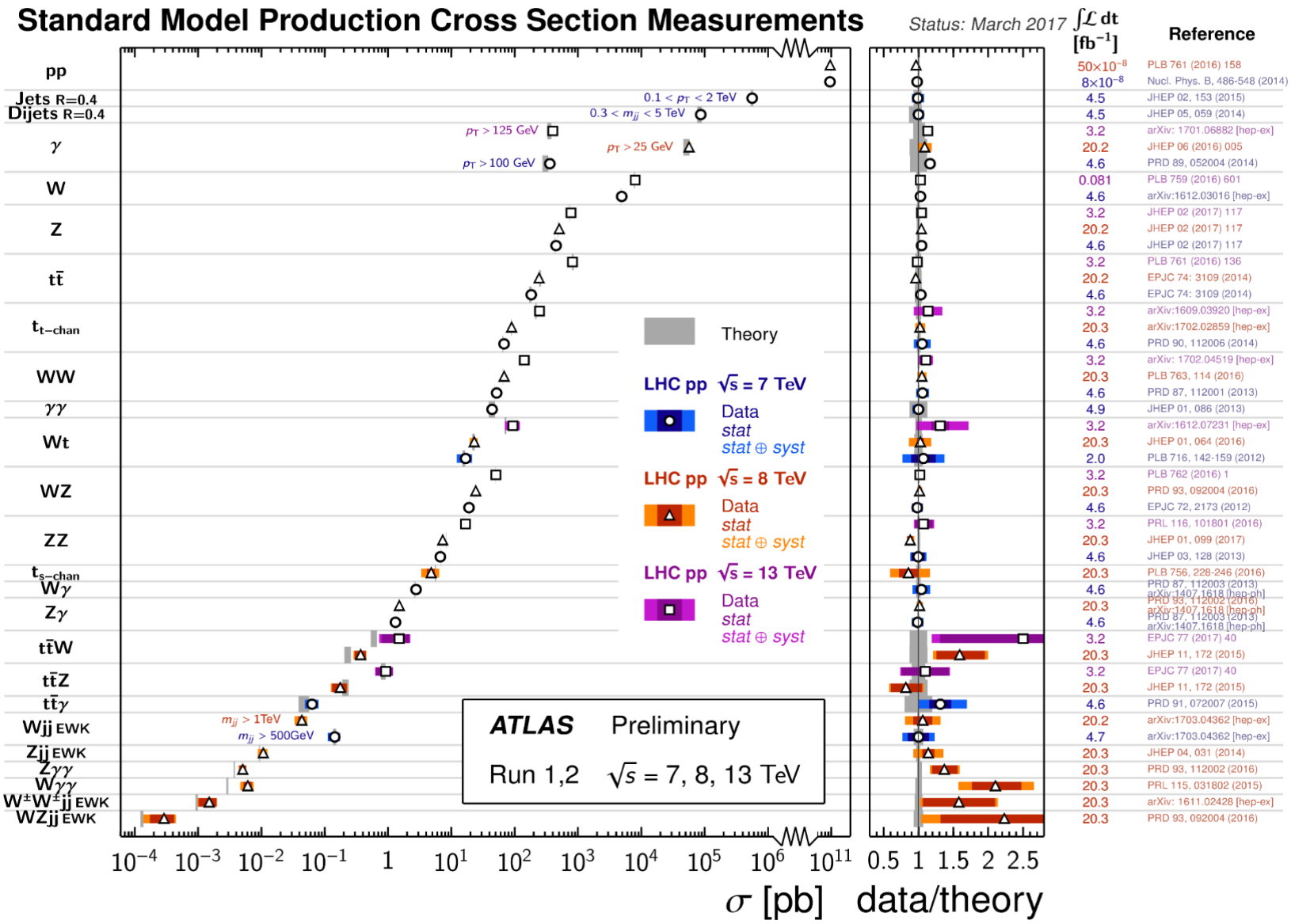


→ *NO "still picture" for hadron structure!*

$f_{q/p}(x, k_T; \mu^2)$

Measurement ⟷ Factorization ⟷ Quantum probabilities!

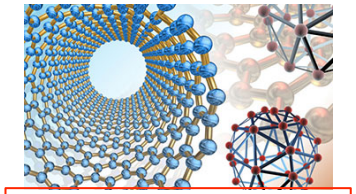
Unprecedented success of QCD and SM!



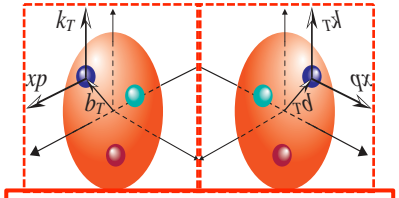
SM: Electroweak processes + QCD perturbation theory works!

From nano-science to femto-science

❑ The idea:



Nano-science
(1-100 nm)

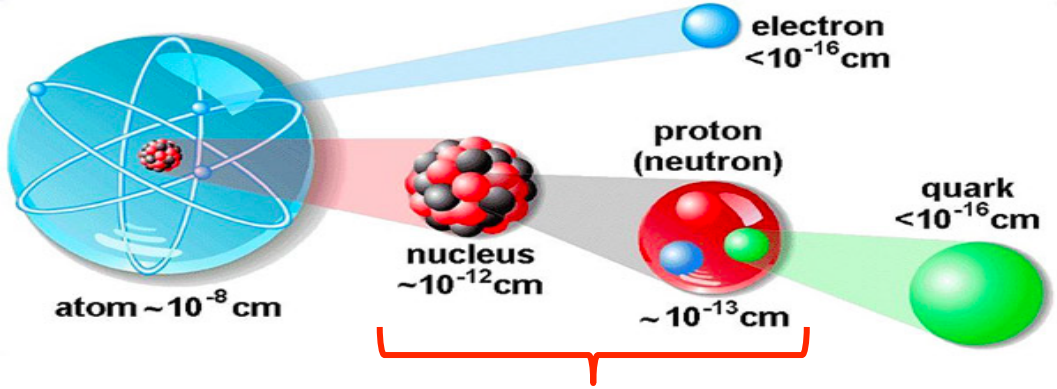


Femto-science
(0.1-10 fm)

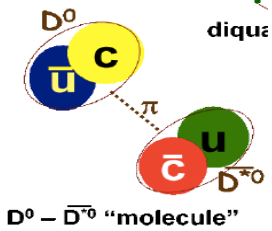
Quantum Probability

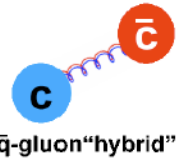
$$\langle P,S|\mathcal{O}(\psi,A^{\mu},...)|P,S\rangle$$

$$f_{q/p}(x,k_T;\mu^2)$$



XYZ-particles





Tetra- quarks?
Penta-quarks?
Molecules?

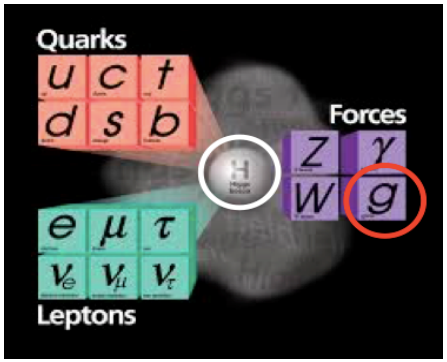
❑ QCD landscape of nucleon and nuclei?

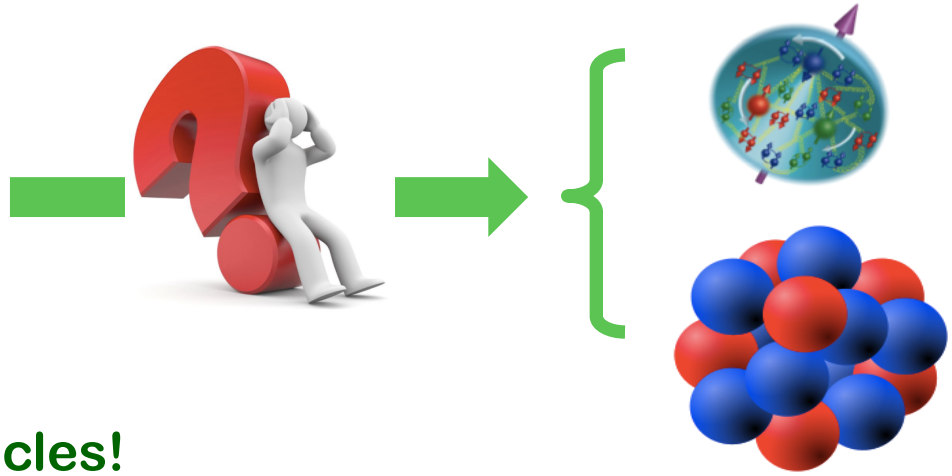
Color Confinement — **Asymptotic freedom** — Q (GeV)

20 MeV (10 fm) — **200 MeV (1 fm)** — **2 GeV (1/10 fm)** — ***Probing scale***

What hold us together?

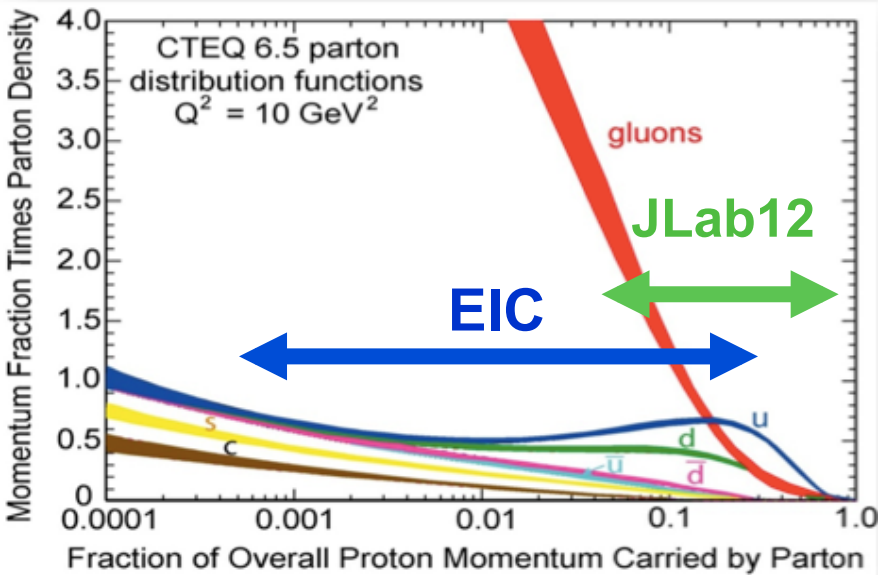
- Understanding the glue that binds us all – Next frontier of SM!





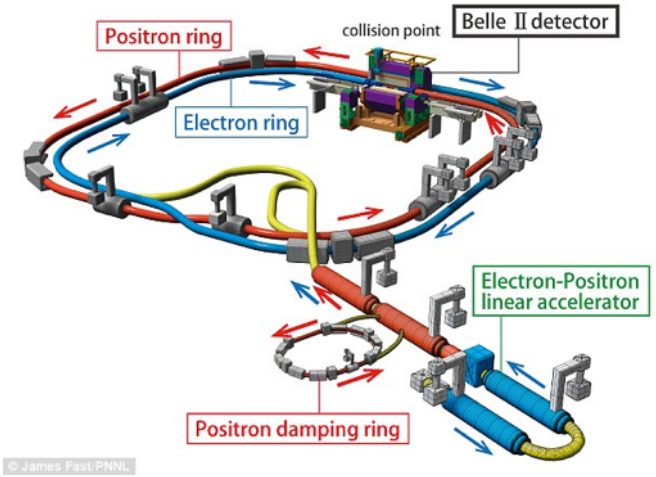
- Gluons are weird particles!
  - ✧ Massless, yet, responsible for nearly all visible mass
  - ✧ Carry color charge, unlike photon, responsible for color confinement but, also for asymptotic freedom, as well as the abundance of glue!

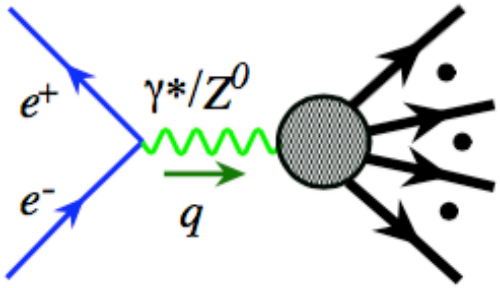
Without gluons, there would be NO nucleons, NO atomic nuclei… NO visible world!



Hard probes from high energy collisions

❑ Lepton-lepton collisions:

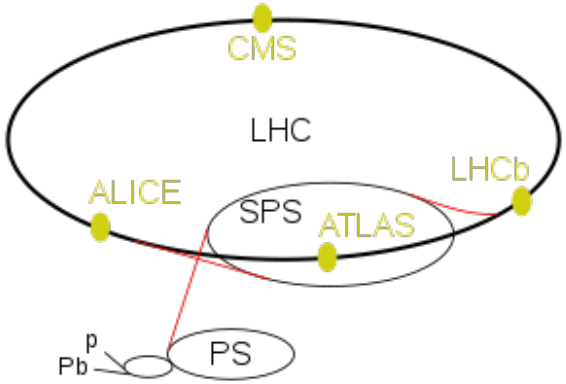


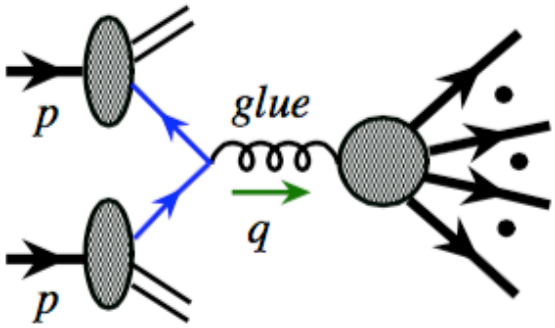


Hadrons

- ✧ No hadron in the initial-state
- ✧ Hadrons are emerged from energy
- ✧ Not ideal for studying hadron structure

❑ Hadron-hadron collisions:





Hadrons

- ✧ Hadron structure – motion of quarks, …
- ✧ Emergence of hadrons, …
- ✧ Initial hadrons broken – collision effect, …

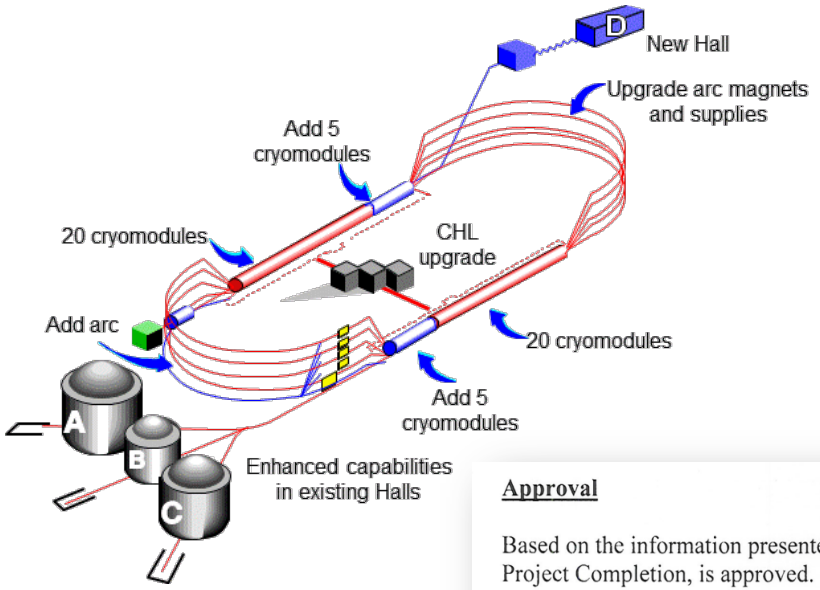
❑ Lepton-hadron collisions:

Hard collision without breaking the initial-state hadron – spatial imaging, …

Jefferson Lab @ 12 GeV

- **Lepton-hadron facility:**

12 GeV CEBAF Upgrade Project is just complete, on-time and on-budget!



Approval

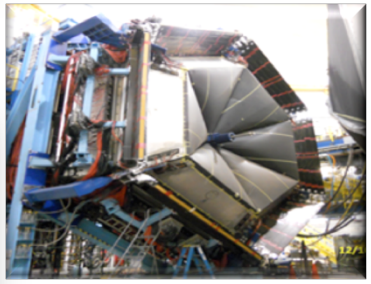
Based on the information presented above and at this review, Critical Decision 4, Approve Project Completion, is approved.

J Binkley — 9/27/17

Dr. J. Stephen Binkley
Deputy Director for Science Programs
Office of Science

Date

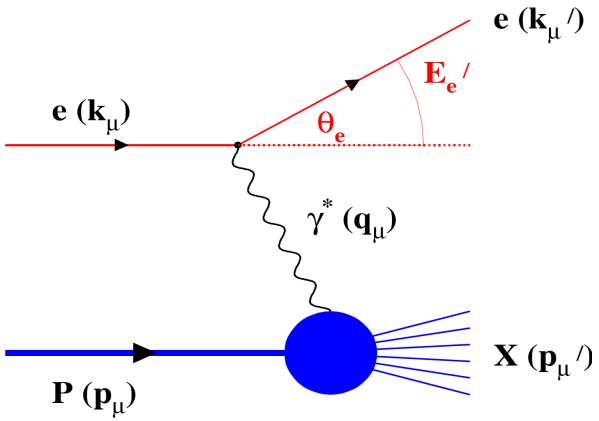
12 GeV CEBAF Upgrade CD-4B (CD-4) ESAAB Approval — Page 8



Project Completion Approved September 27, 2017

Many complementary probes at one facility

- The new generation of "Rutherford" experiment:



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

(Modern Rutherford experiment!)

Semi-Inclusive events: e+p/A → e'+h(π,K,p,jet)+X

Detect the scattered lepton in coincidence with identified hadrons/jets

(Initial hadron is broken – confined motion! – cleaner than h-h collisions)

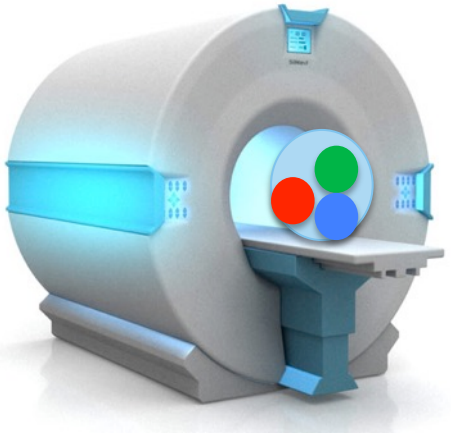
Exclusive events: e+p/A → e'+ p'/A'+ h(π,K,p,jet)

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

(Initial hadron is NOT broken – tomography! – almost impossible for h-h collisions)

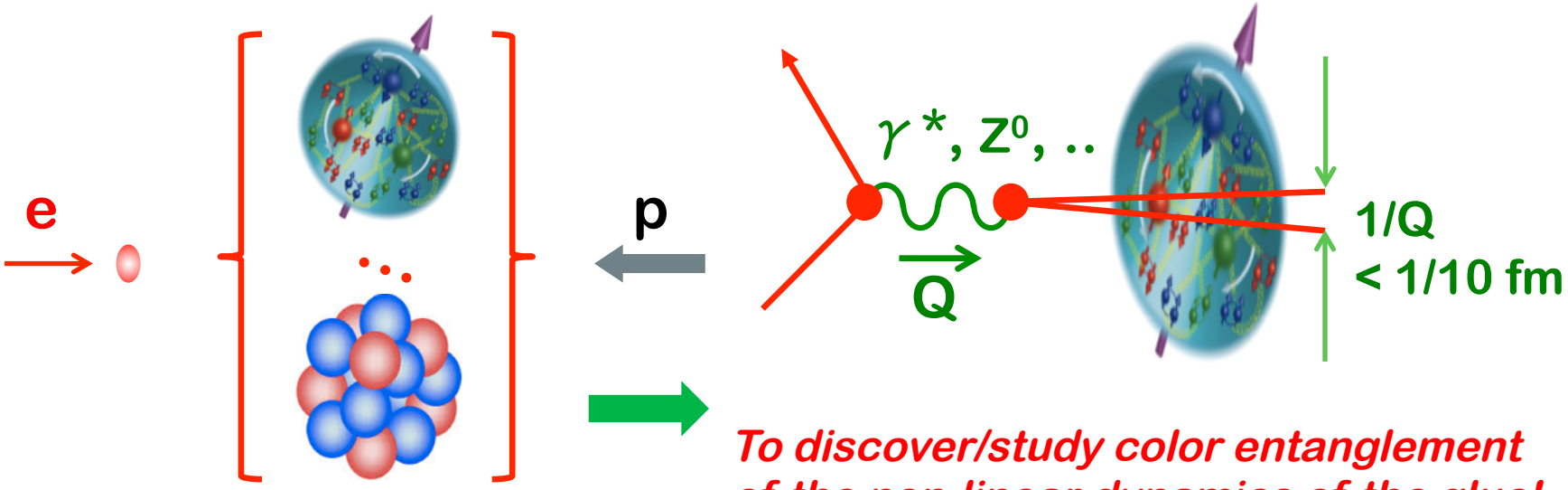
The Electron-Ion Collider (EIC) – the Future!

- A sharpest "CT" – "imagine" quark/gluon structure without breaking the hadron
  - "cat-scan" the nucleon and nuclei with a better than 1/10 fm resolution
  - "see" proton "radius" of quark/gluon density comparing with the radius of EM charge density



→ *To discover color confining radius, hints on confining mechanism!*

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



→ *To discover/study color entanglement of the non-linear dynamics of the glue!*

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

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):**

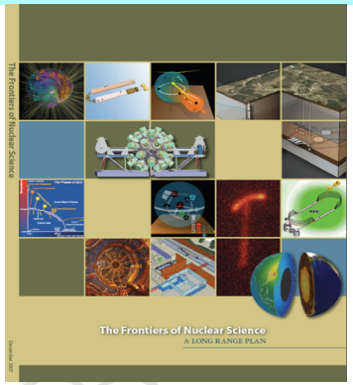
  "The Subcommittee ranks an EIC as Absolutely Central in its ability to contribute to world-leading science in the next decade."

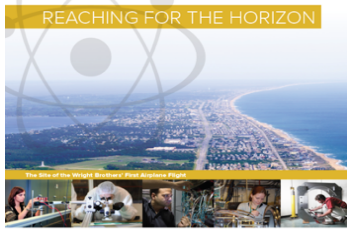
- **NSAC 2015 Long-Range Plan:**

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

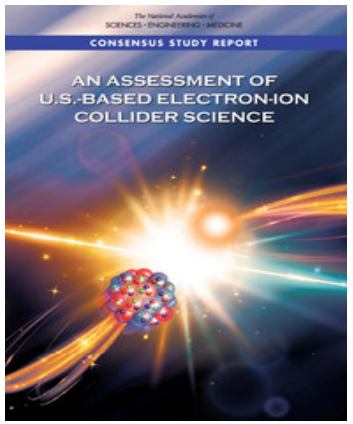
- **Review of National Academy of Science (2018):**

  "… answer science questions that are compelling, fundamental, and timely, and help maintain U.S. scientific leadership in nuclear physics."





The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE



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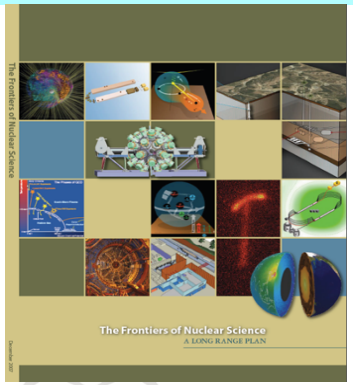

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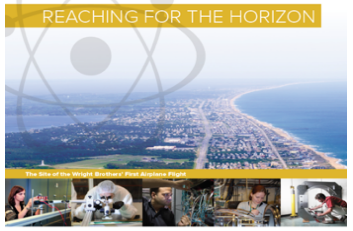

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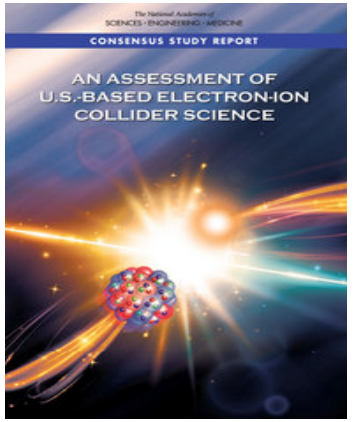


- **Review of National Academy of Science (2018):**

  … three profound questions:

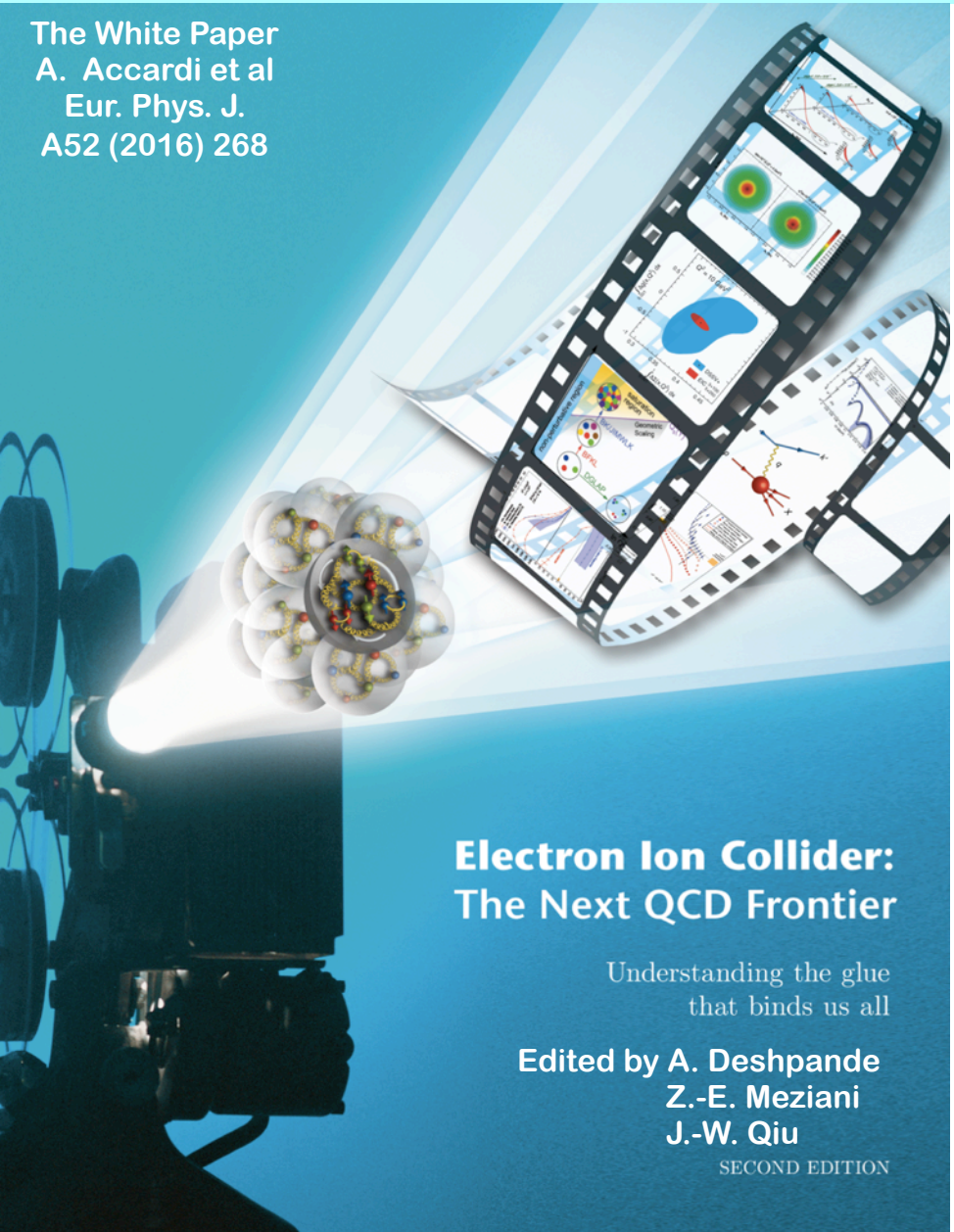
  How does the mass of the nucleon arise?

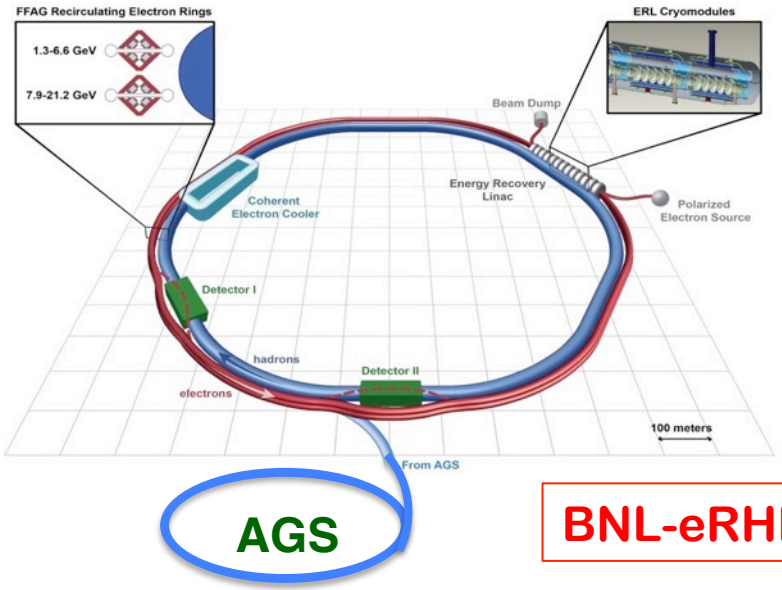
  How does the spin of the nucleon arise?

  What are the emergent properties of dense systems of gluons?

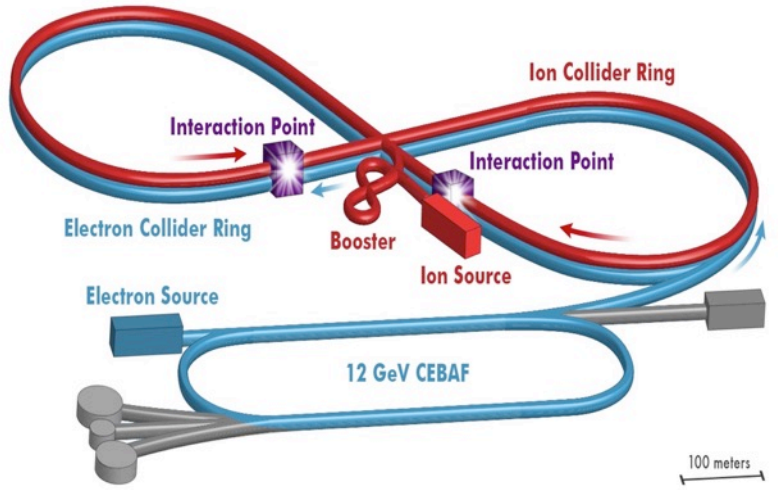
US EIC – Two Options of Realization

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



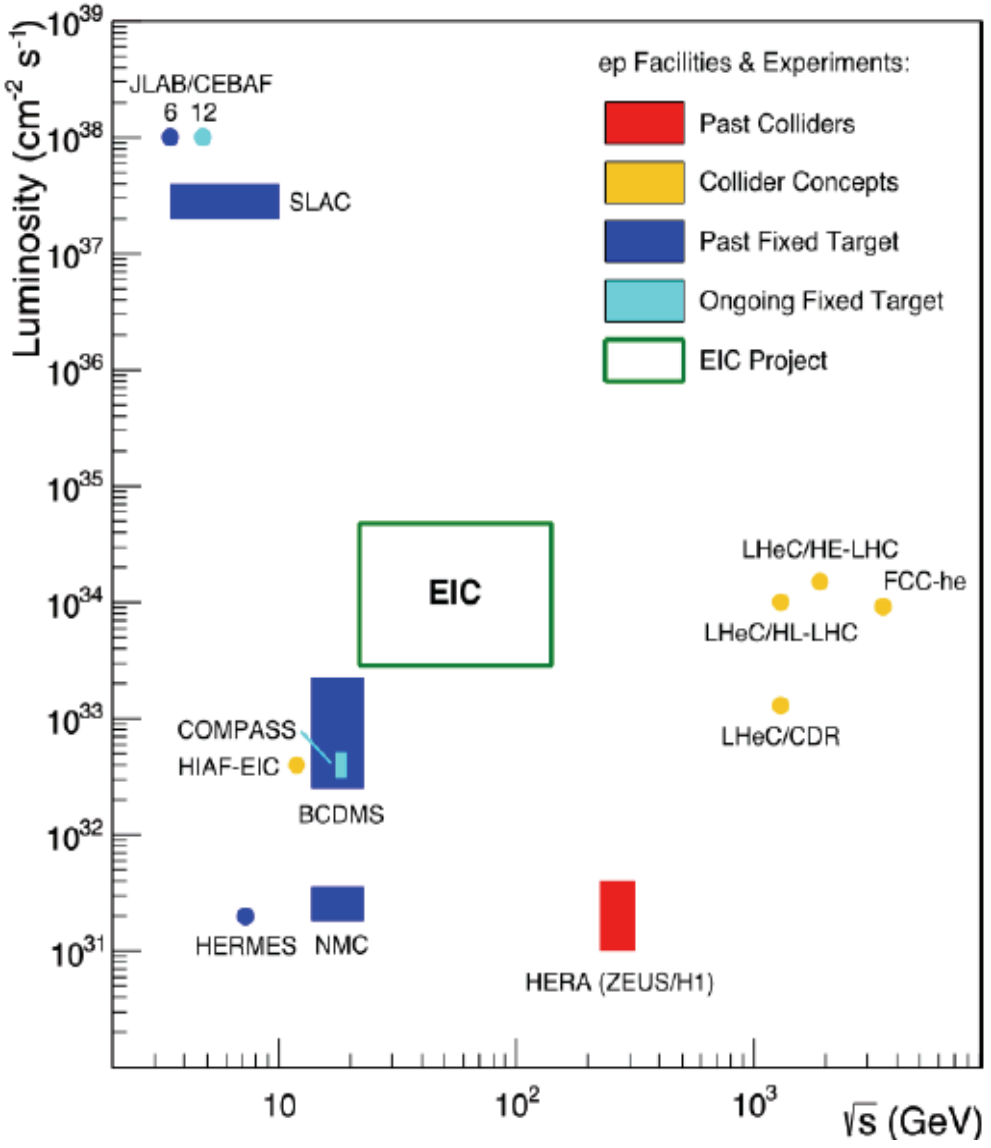


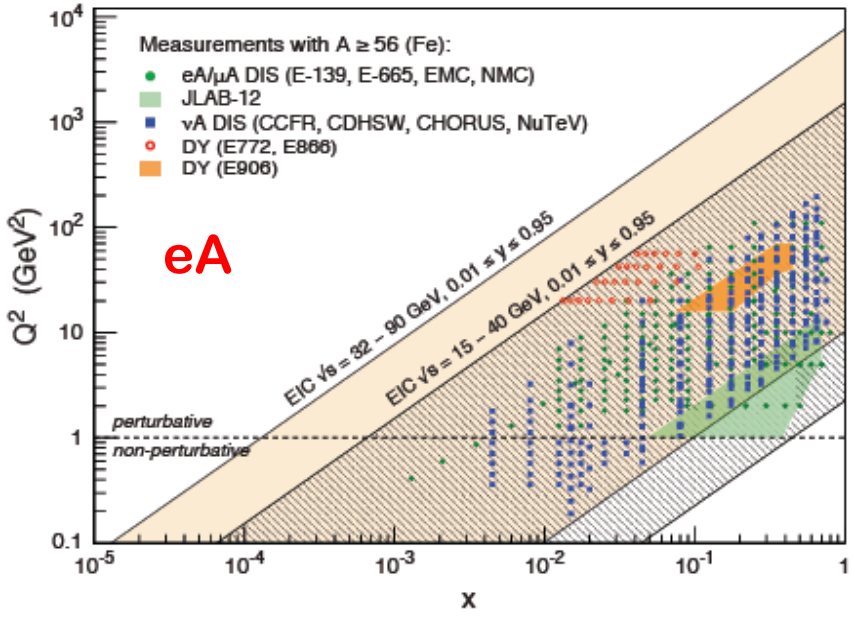
BNL-eRHIC

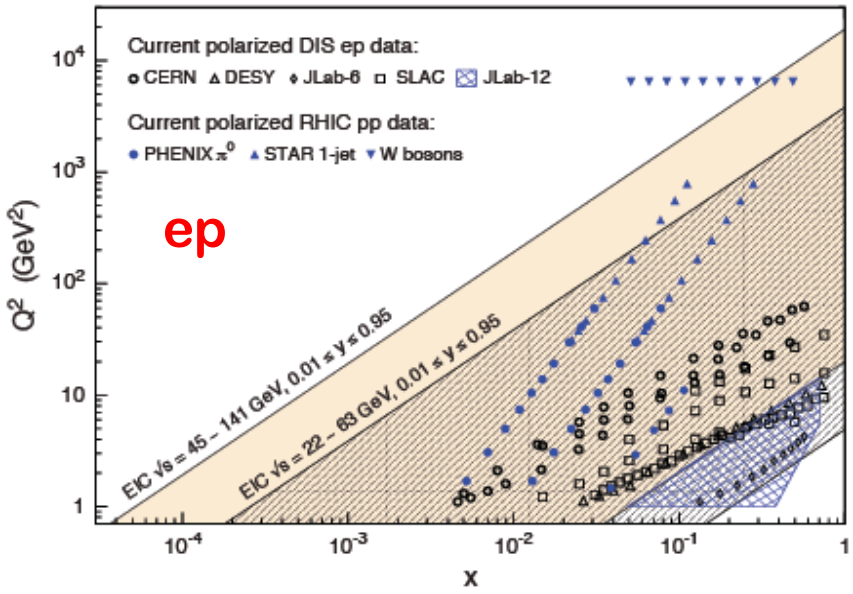


JLab-JLEIC

US EIC – Luminosity & kinematics coverage



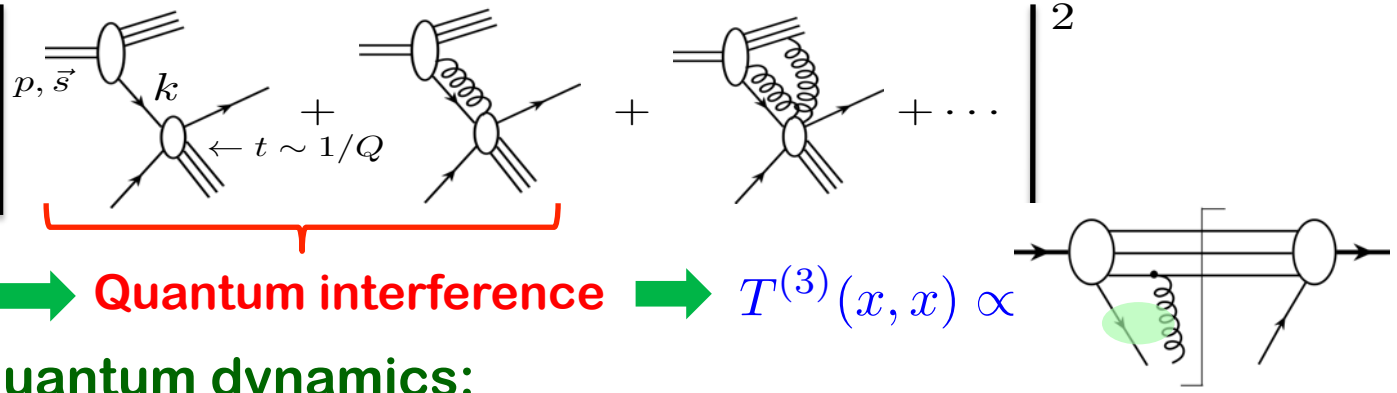




US-EIC – can do what HERA could not do

- **Quantum imaging:**
  - ✧ **HERA discovered: 15% of e-p events is diffractive – Proton not broken!**
  - ✧ **US-EIC: 100-1000 times luminosity – *Critical for 3D tomography!***
- **Quantum interference & entanglement:**
  - ✧ **US-EIC: Highly polarized beams – *Origin of hadron property: Spin, …***
    Direct access to chromo-quantum interference!

$$\sigma(Q,\vec{s}) \propto \left| \right.$$



$$\left. \right|^2$$

$\sigma(s) - \sigma(-s)$ ➡ **Quantum interference** ➡ $T^{(3)}(x,x) \propto$

- **Nonlinear quantum dynamics:**
  - ✧ **US-EIC: Light-to-heavy nuclear beams – *Origin of nuclear force, …***
    Catch the transition from chromo-quantum fluctuation
    to chromo-condensate of gluons, …
    Emergence of hadrons (femtometer size detector!),
    – "a new controllable knob" – Atomic weight of nuclei

US EIC – Deliverables & Opportunities

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

- ✧ Emergence of hadrons
- ✧ Hadron properties:

  mass, spin, …
- ✧ Hadron's 3D partonic structure:

  confined motion, spatial distribution,

  color correlation, fluctuation,

  saturation, …
- ✧ Quantum correlation between

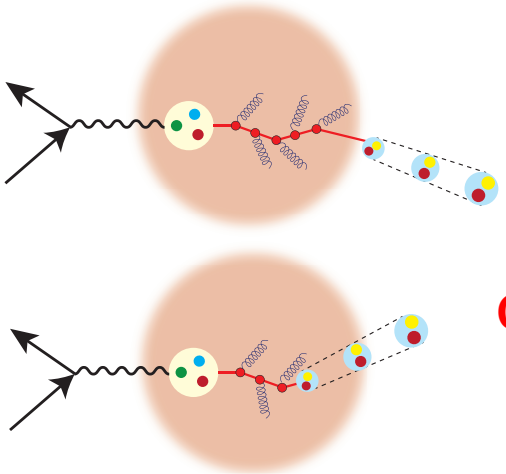
  hadron properties and parton dynamics, …

…

Due to the time, only a few examples to be presented in this talk!

Emergence of Hadrons from quarks & gluons

- **Femtometer sized detector:**

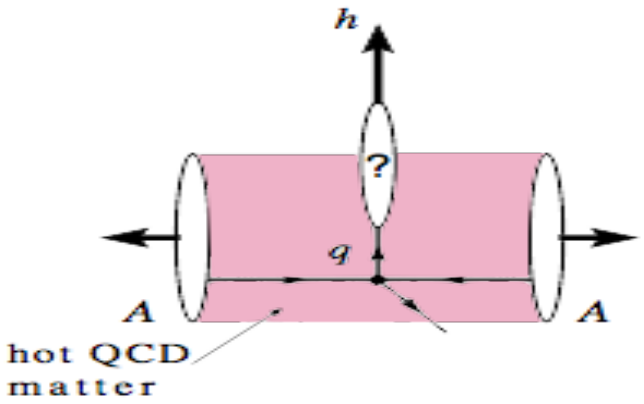


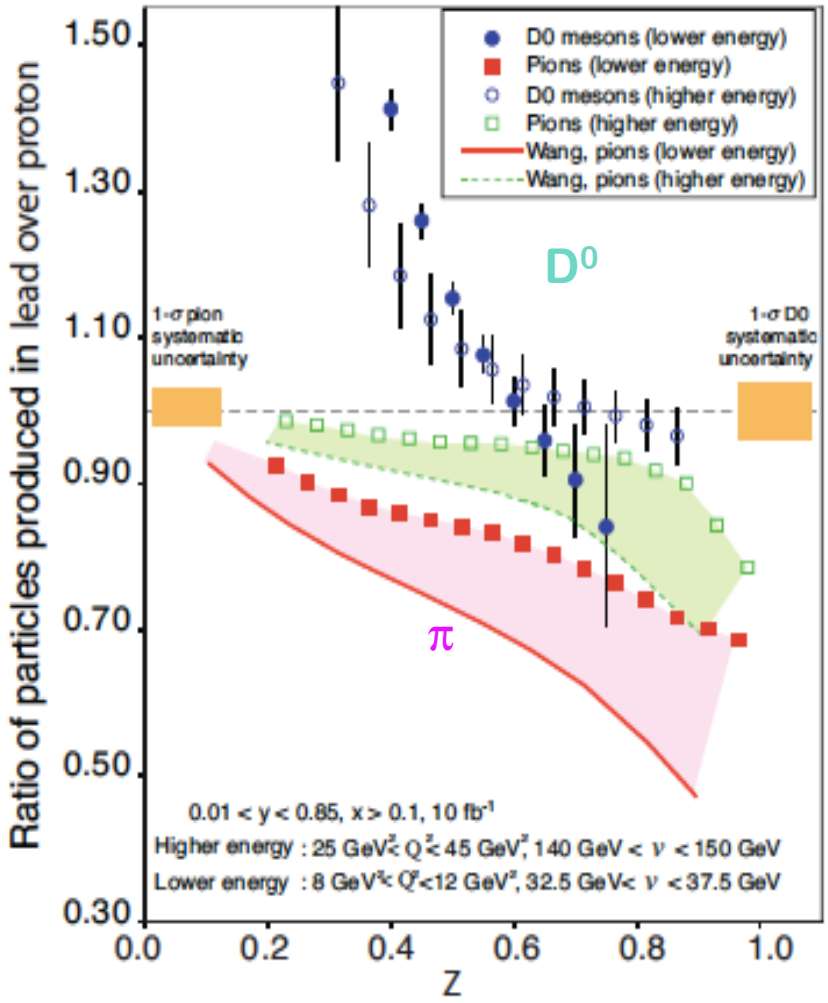
$$\nu = \frac{Q^2}{2mx}$$

Control of ν and medium length!

Mass dependence of hadronization

- **Apply to heavy-ion collisions:**





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

Emergent Hadron Properties from QCD

❑ Mass – intrinsic to a particle:

= Energy of the particle when it is at the rest

✧ QCD energy-momentum tensor in terms of quarks and gluons

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

✧ Proton mass:

$$m = \left. \frac{\langle p | \int d^3x\, T^{00} \, | p \rangle}{\langle p | p \rangle} \right|_{\text{Rest frame}} \sim \text{GeV}$$

❑ Spin – intrinsic to a particle:

= Angular momentum of the particle when it is at the rest

✧ QCD angular momentum density in terms of energy-momentum tensor

$$M^{\alpha\mu\nu} = T^{\alpha\nu} x^{\mu} - T^{\alpha\mu} x^{\nu} \qquad J^i = \frac{1}{2} \epsilon^{ijk} \int d^3x M^{0jk}$$

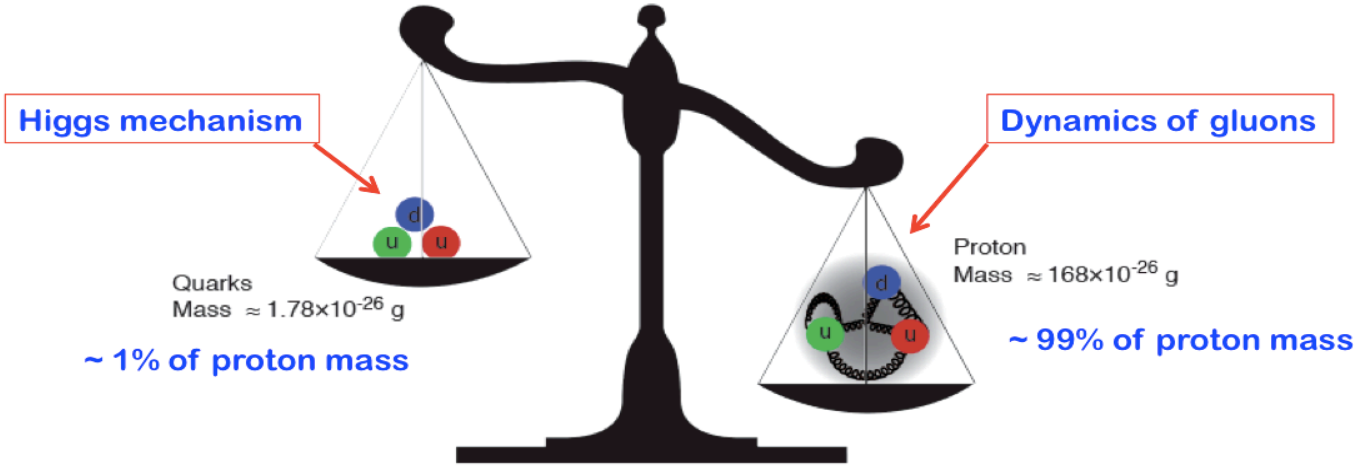
✧ Proton spin:

$$S(\mu) = \sum \langle P, S | \hat{J}^z_f(\mu) | P, S \rangle = \frac{1}{2}$$

If we do not understand proton mass & spin, we do not know QCD!

The Proton Mass

- Nucleon mass – dominates the mass of visible world:



Higgs mechanism is not enough!!! *"Mass without mass!"*

- How does QCD generate the nucleon mass?

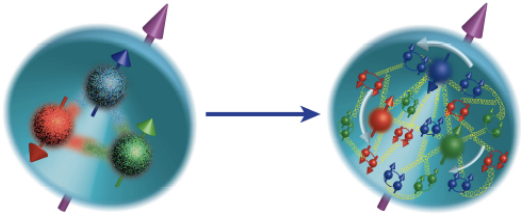
"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

REACHING FOR THE HORIZON

The 2015 Long Range Plan for Nuclear Science

How to quantify and verify this, theoretically and experimentally?

The Proton Mass: from Models to QCD



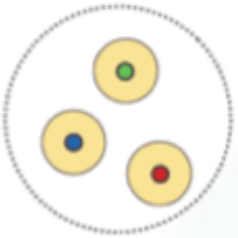
- **Dynamical scale:**
  - ✧ **Asymptotic freedom ⟷ confinement:**

  ➡ **A dynamical scale, $\Lambda_{\rm QCD}$, consistent with $\frac{1}{R} \sim 200$ MeV**

- **Bag model:**

  - ✧ **Kinetic energy of three quarks:** $K_q \sim 3/R$
  - ✧ **Bag energy (bag constant B):** $T_b = \frac{4}{3}\pi R^3 B$
  - ✧ **Minimize $K_q + T_b$:** $M_p \sim \frac{4}{R} \sim \frac{4}{0.88 fm} \sim 912$MeV

- **Constituent quark model:**

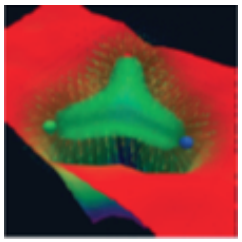


  - ✧ **Spontaneous chiral symmetry breaking:**

    Massless quarks gain ~300 MeV mass when traveling in vacuum

    ➡ $M_p \sim 3\, m_q^{\rm eff} \sim 900$ MeV C. Roberts'talk

- **Lattice QCD:**



  - ✧ **With "heavy" (or slow moving) quarks**

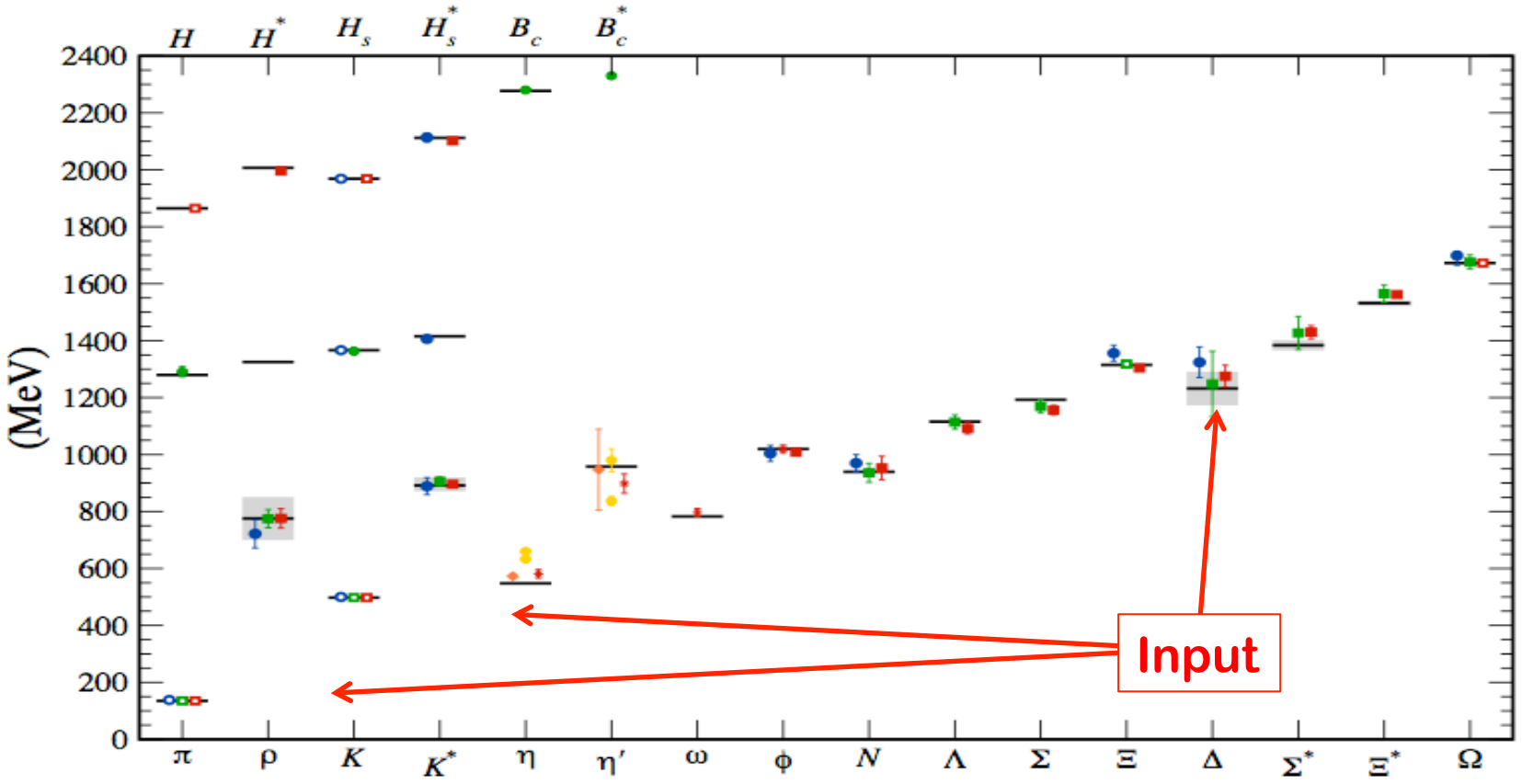
    Energy concentrated in the gluon junction!

    ➡ **Gluon radius < Charge Radius** **EIC!**

    Mass scale: Lattice space – "a"

The Proton Mass: Lattice QCD

- Hadron mass from Lattice QCD calculation:



How does QCD generate this? The role of quarks vs. that of gluons?

The Proton Mass?

- **Role of quarks and gluons?**
  - **Trace of the QCD energy-momentum tensor:** $\beta(g) = -(11 - 2n_f/3)\, g^3/(4\pi)^2 + \ldots$

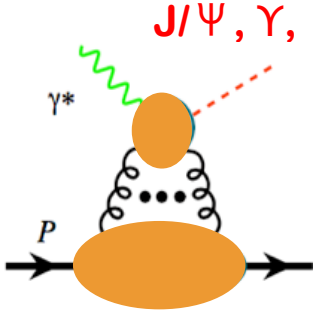
$$T^{\alpha}_{\alpha} = \underbrace{\frac{\beta(g)}{2g} F^{\mu\nu,a} F^{a}_{\mu\nu}}_{\text{QCD trace anomaly}} + \sum_{q=u,d,s} \underbrace{m_q (1+\gamma_m) \overline{\psi}_q \psi_q}_{\text{Chiral symmetry breaking}}$$

  - **Hadron mass:**

    Gluon quantum effect + Chiral symmetry breaking!

  - **From JLab12 to EIC:**

    ➡ *Heavy quarkonium production near the threshold.*



- **Decomposition or sum rules – could be frame dependent!**

$$M_p = \left. \frac{\langle P| \int d^3x\, T^{00} |P\rangle}{\langle P|P\rangle} \right|_{\text{at rest}} = E_q + E_g + \chi_{m_q} + T_g$$

Relativistic motion; χ Symmetry Breaking; Quantum fluctuation

Quark Energy; Gluon Energy; Quark Mass; Trace Anomaly

This is useful if only if individual terms can be measured independently

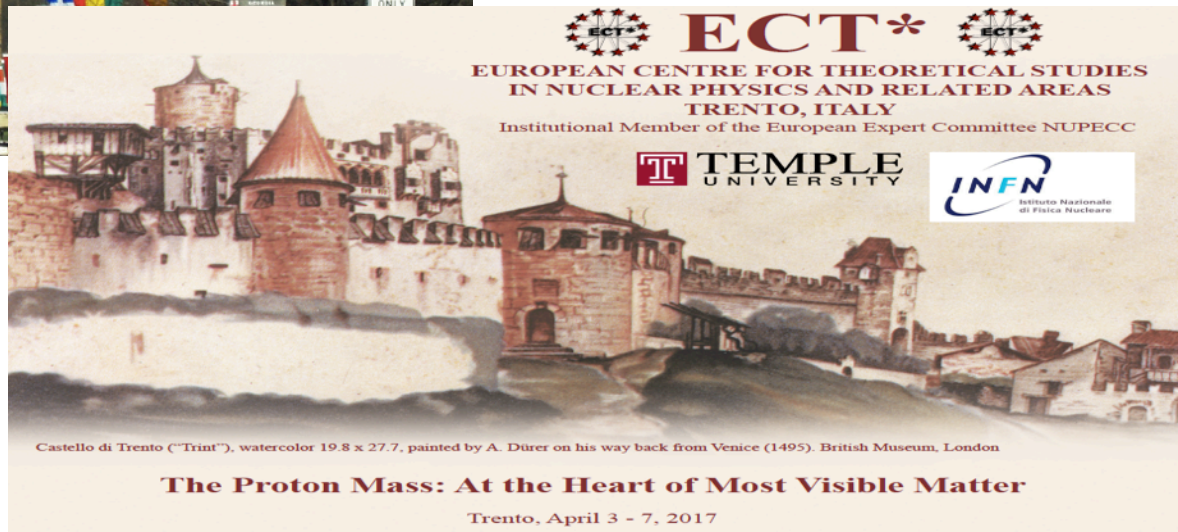
The Proton Mass?

- Three-pronged approach to explore the origin of hadron mass
  - Lattice QCD
  - Mass decomposition – roles of the constituents
  - Model calculation – approximated analytical approach

https://phys.cst.temple.edu/meziani/proton-mass-workshop-2016/

http://www.ectstar.eu/node/2218

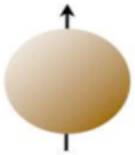
A true international effort!



The Proton Spin

- **The sum rule:** $S(\mu) = \sum_f \langle P,S|\hat{J}^z_f(\mu)|P,S\rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu)$
  - Infinite possibilities of decompositions – connection to observables?
  - Intrinsic properties + dynamical motion and interactions
- **An incomplete story:**

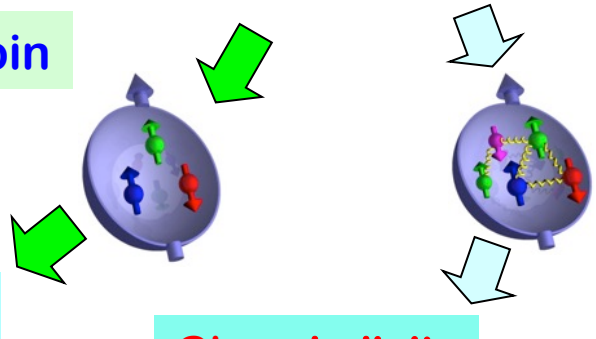
See H. Gao's Plenary Talk



Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

Jaffe-Manohar, 90
Ji, 96, …



Quark helicity
Best known

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

Gluon helicity
Start to know

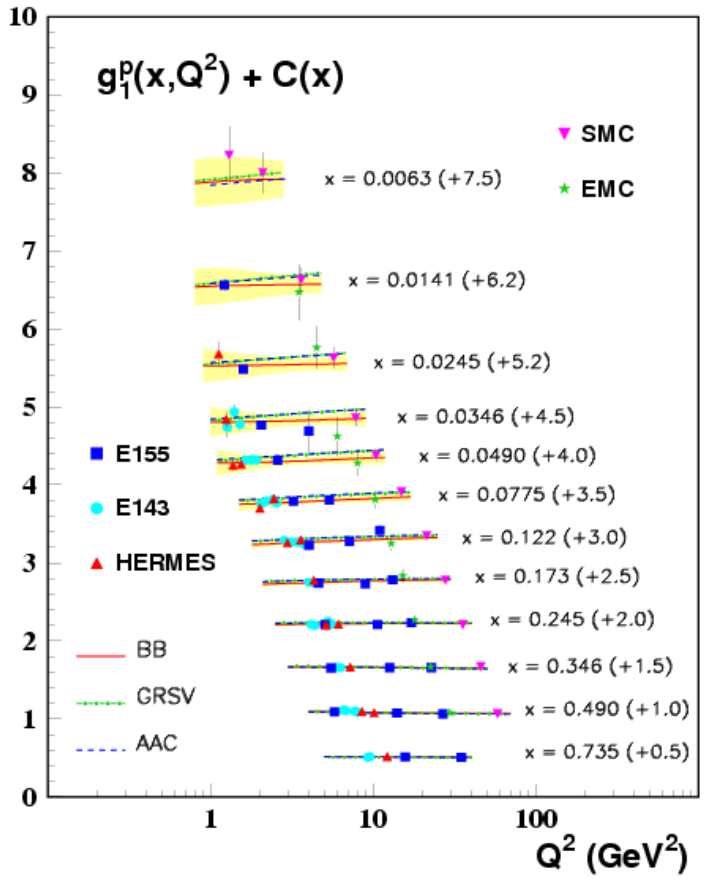
$$\Delta G = \int dx \Delta g(x) \sim 40\% \text{(with RHIC data)}$$

Orbital Angular Momentum of quarks and gluons
Little known

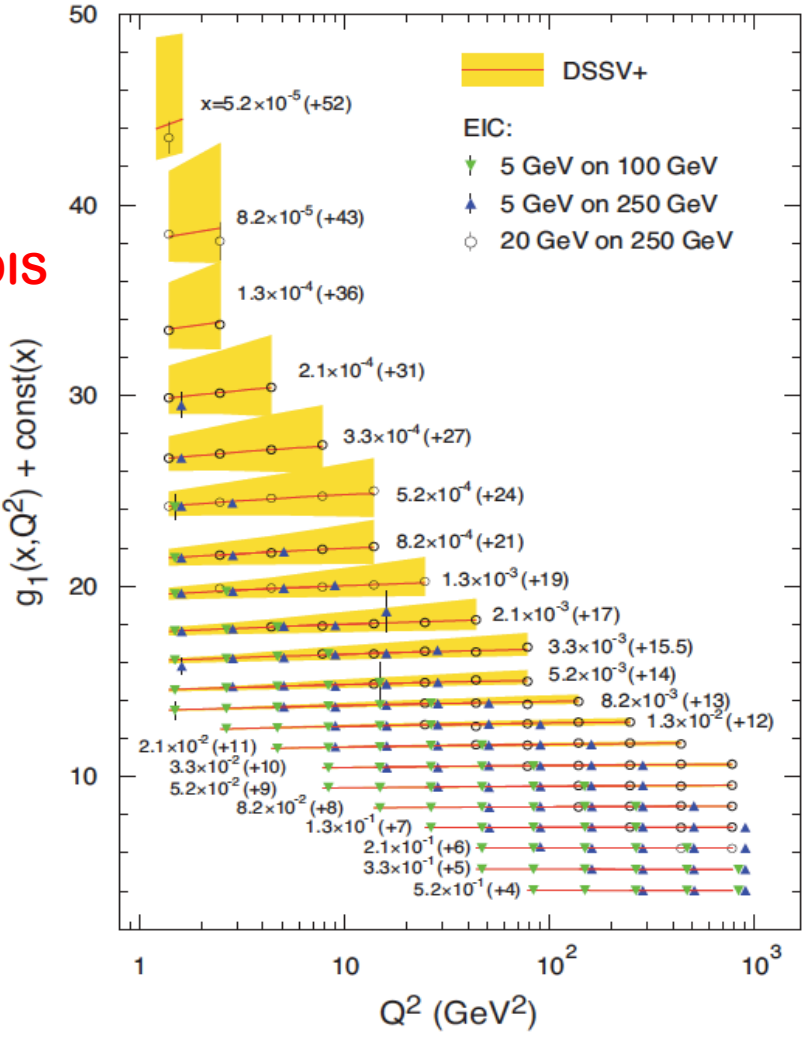
Net effect of partons' transverse motion?

The Proton Spin

❑ The power & precision of EIC:



Polarized DIS at EIC

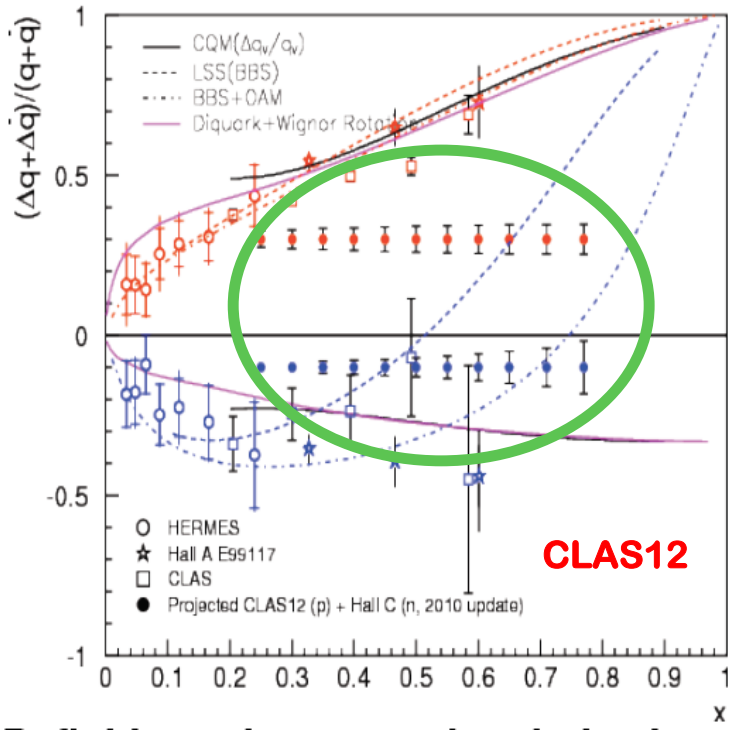


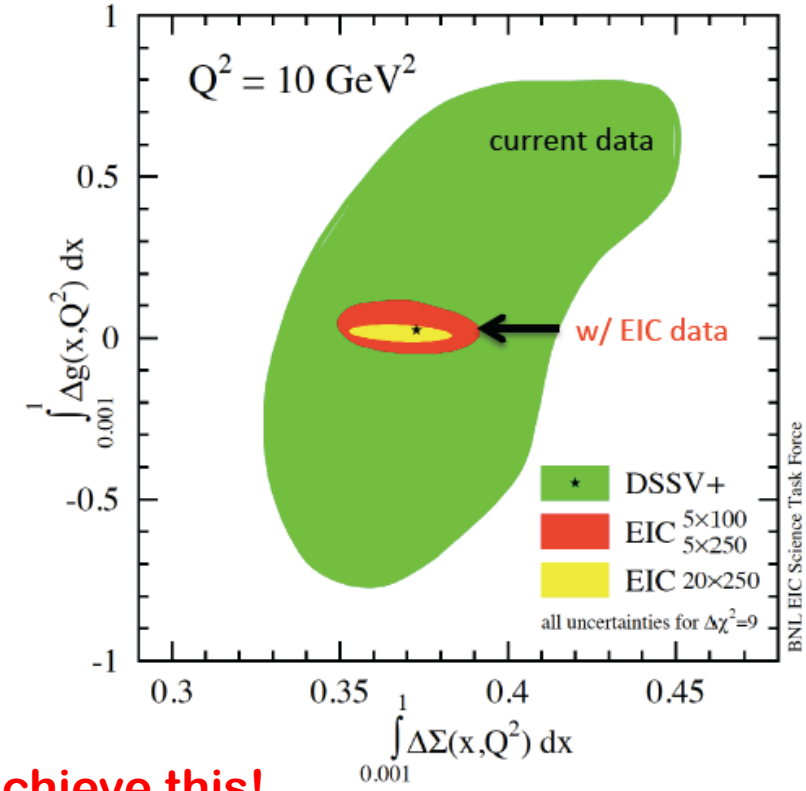
❑ Reach out the glue:

$$\frac{dg_1(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi} P_{qg} \otimes \Delta g(x,Q^2) + \cdots$$

The Proton Spin

❑ Complementary between JLab12 and EIC:





No other machine in the world can achieve this!

❑ Ultimate solution to the proton spin puzzle:

- ✧ ***Precision measurement of Δ g(x) – extend to smaller x regime***
- ✧ ***Orbital angular momentum contribution – measurement of TMDs & GPDs!***

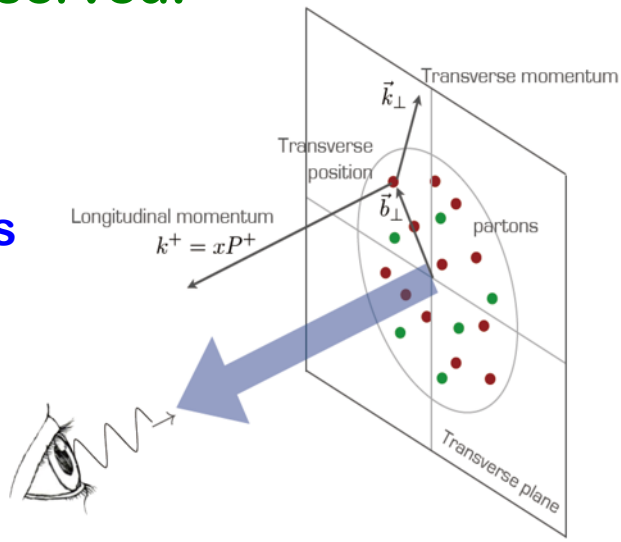
Hadron's 3D partonic structure

❑ **Cross sections with two-momentum scales observed:**

$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$

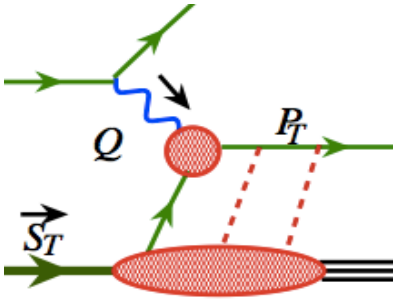
✧ **Hard scale:** Q_1 **localizes the probe particle nature of quarks/gluons**

✧ **"Soft" scale:** Q_2 **could be more sensitive to the structure, e.g., confined motion**



❑ **Two-scale observables at the EIC:**

✧ **Semi-inclusive DIS:**

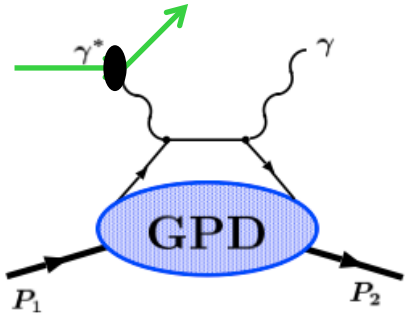


+ …

SIDIS: $Q \gg P_T$

Parton's confined motion encoded into TMDs

✧ **Exclusive DIS:**



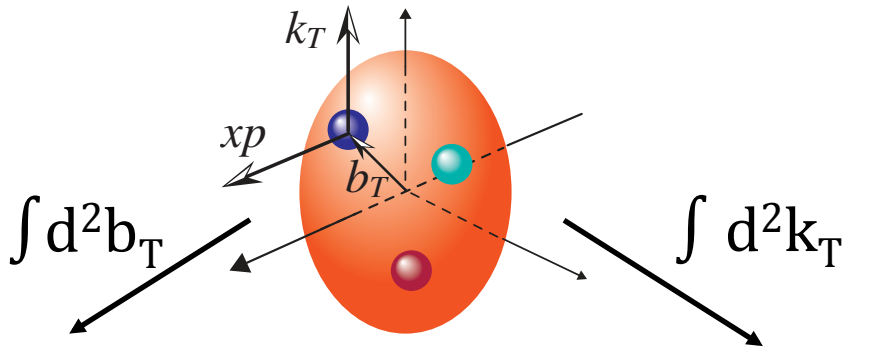
+ …

DVCS: $Q^2 \gg |t|$

Parton's spatial imaging from Fourier transform of GPDs' t-dependence

Theory is solid – unified description

- **Wigner distributions in 5D (or GTMDs):**



- **TMDs & SIDIS as an example:**
  - **Low P_{hT} (P_{hT} << Q) – TMD factorization:**

$$\sigma_{\rm SIDIS}(Q, P_{h\perp}, x_B, z_h) = \hat{H}(Q) \otimes \Phi_f(x, k_\perp) \otimes \mathcal{D}_{f\to h}(z, p_\perp) \otimes \mathcal{S}(k_{s\perp}) + \mathcal{O}\left[\frac{P_{h\perp}}{Q}\right]$$

  - **High P_{hT} (P_{hT} ~ Q) – Collinear factorization:**

$$\sigma_{\rm SIDIS}(Q, P_{h\perp}, x_B, z_h) = \hat{H}(Q, P_{h\perp}, \alpha_s) \otimes \phi_f \otimes D_{f\to h} + \mathcal{O}\left(\frac{1}{P_{h\perp}}, \frac{1}{Q}\right)$$

  - **P_{hT} Integrated - Collinear factorization:**

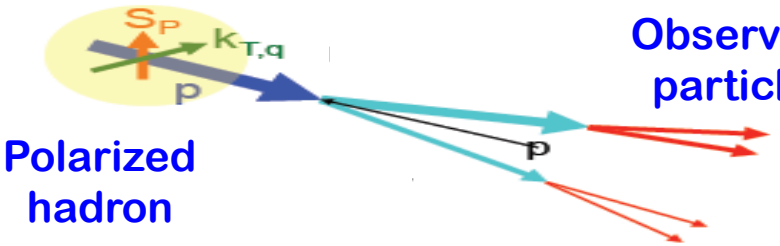
$$\sigma_{\rm SIDIS}(Q, x_B, z_h) = \tilde{H}(Q, \alpha_s) \otimes \phi_f \otimes D_{f\to h} + \mathcal{O}\left(\frac{1}{Q}\right)$$

  - **Very high P_{hT} >> Q – Collinear factorization:**

$$\sigma_{\rm SIDIS}(Q, P_{h\perp}, x_B, z_h) = \sum_{abc} \hat{H}_{ab\to c} \otimes \phi_{\gamma\to a} \otimes \phi_b \otimes D_{c\to h} + \mathcal{O}\left(\frac{1}{Q}, \frac{Q}{P_{h\perp}}\right)$$

Confined motion of quarks & gluons

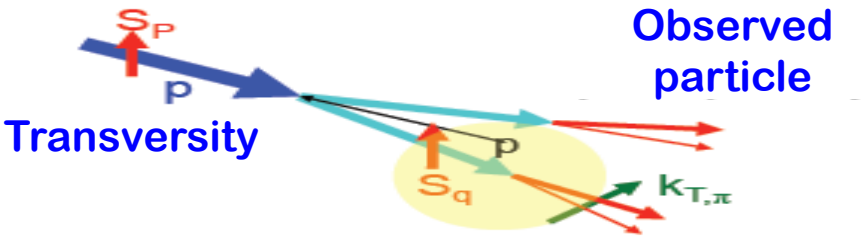
- **Quantum correlation between hadron spin and parton motion:**



Sivers effect – Sivers function

Hadron spin influences parton's transverse motion

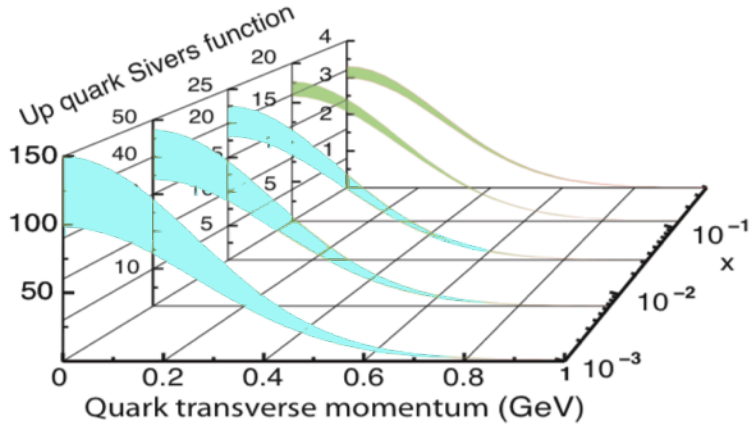
- **Quantum correlation between parton's spin and its hadronization:**

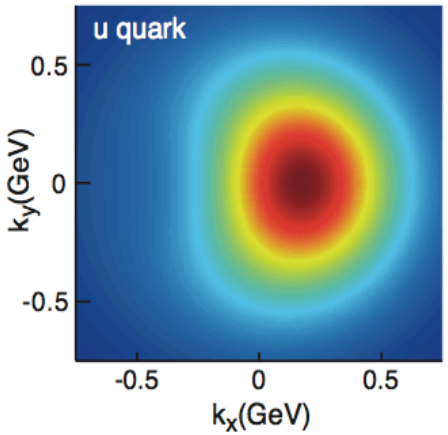


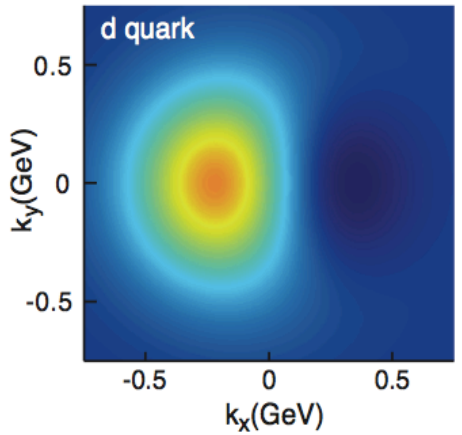
Collins effect – Collins function

Parton's transverse polarization influences its hadronization

- **TMDs and their separation at EIC:**



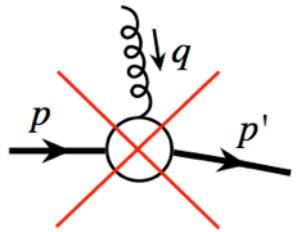




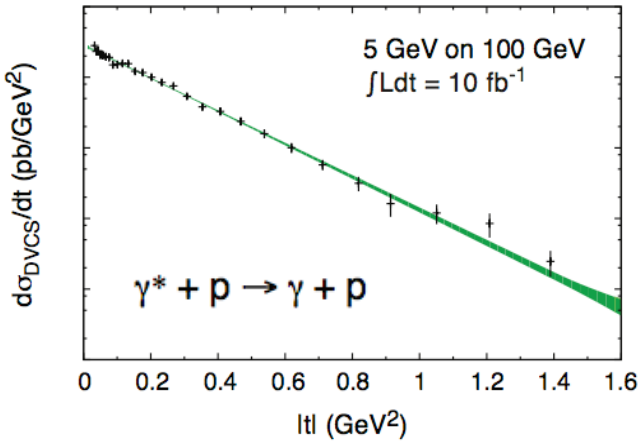
Spatial imaging of quarks & gluons

- **No color elastic nucleon form factor!**

  ➡ *Spatial distribution of quark/gluon densities – GPDs*

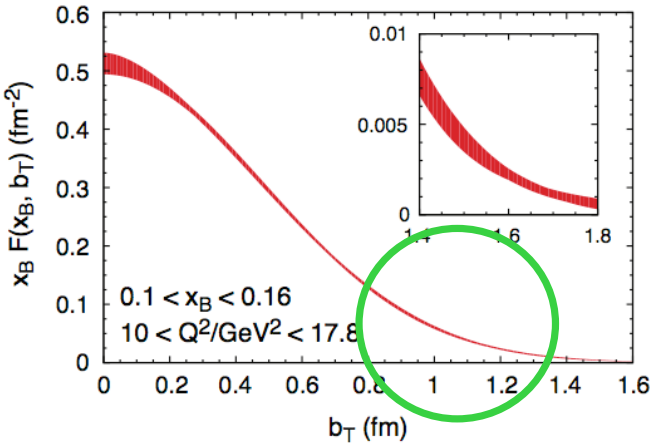


- **DVCS at EIC:**

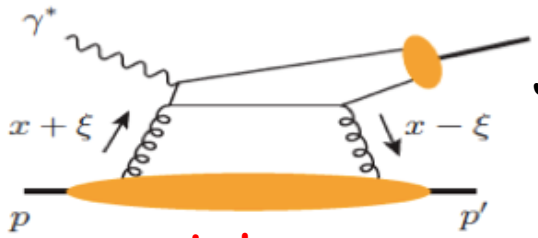


Factorization ➡ **GPDs** ➡ **F.T.**

Proton radius of quarks (x)!



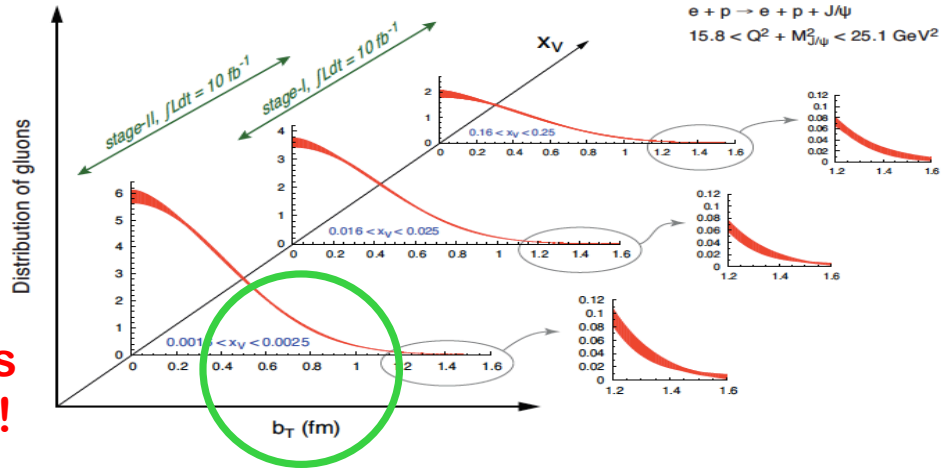
- **"Seeing" the glue at EIC:**



t-dep

J/Ψ, Φ, …

➡

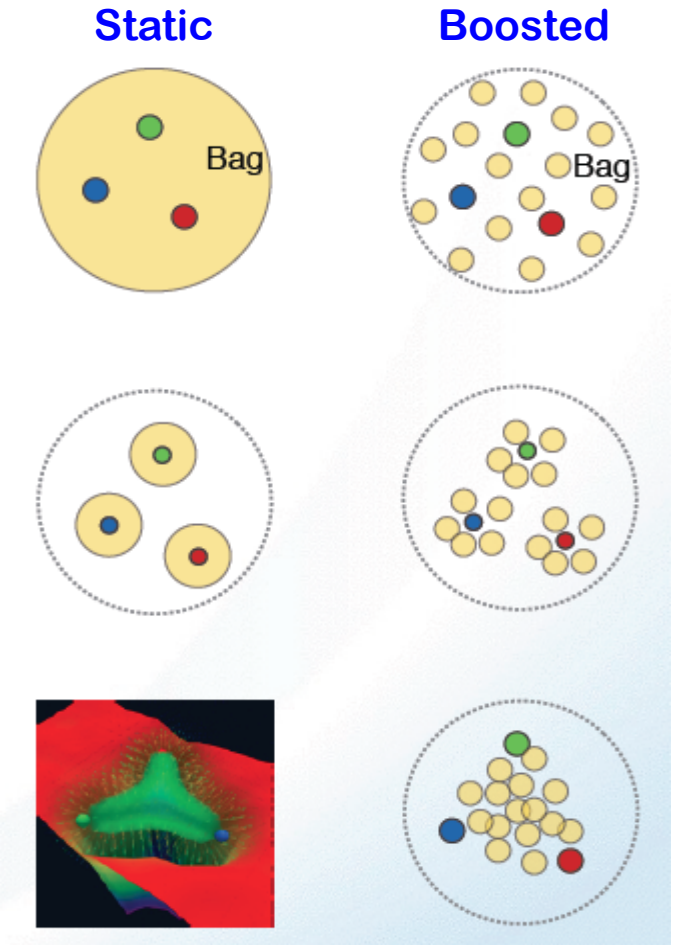


Proton radius of gluons (x)!

Only possible at EIC!

Why 3D nucleon structure?

❑ Spatial distributions of quarks and gluons:



Bag Model:

Gluon field distribution is wider than the fast moving quarks.

Gluon radius > Charge Radius

Constituent Quark Model:

Gluons and sea quarks hide inside massive quarks.

Gluon radius ~ Charge Radius

Lattice Gauge theory (with slow moving quarks):

Gluons more concentrated inside the quarks

Gluon radius < Charge Radius

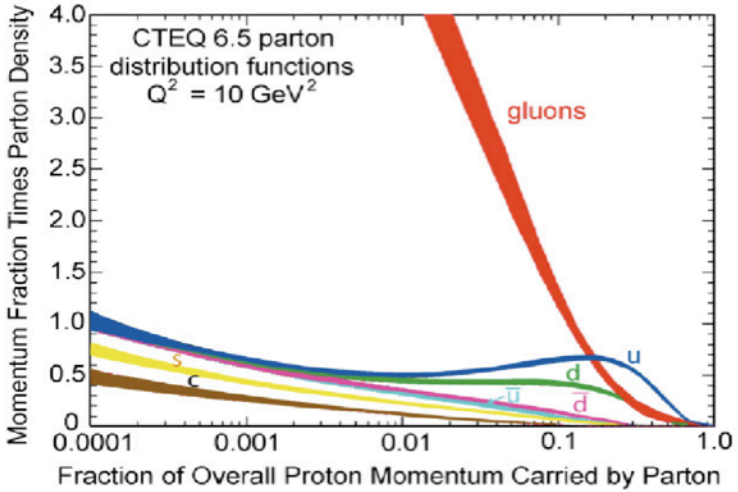
3D confined motion (TMDs) + spatial distribution (GPDs)

Hints on the color confining mechanism

Relation between charge radius, quark radius (x), and gluon radius (x)?

Another HERA discovery

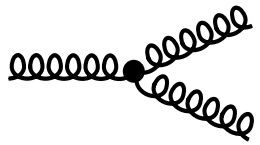
❑ Run away gluon density at small-x?



What causes the low-x rise?

gluon radiation

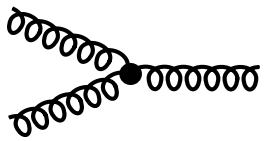
– non-linear gluon interaction



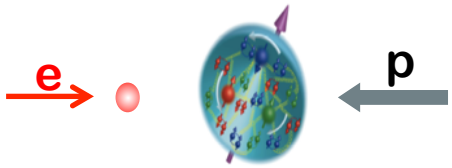
What could tame the low-x rise?

gluon recombination

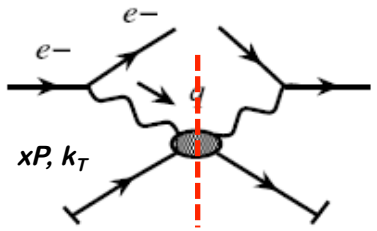
– non-linear gluon interaction

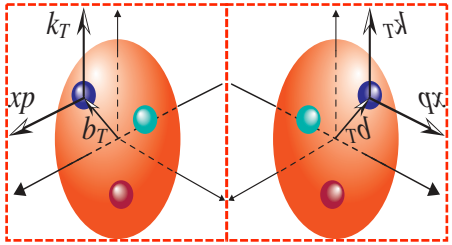


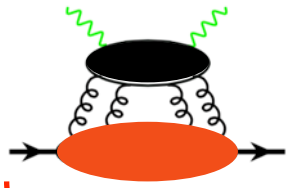
❑ Color entanglement enhanced at small-x:



$$\sigma_{\rm tot}^{\rm DIS} : \quad \otimes \quad + \quad + \ldots$$







$$= \sum_f \hat{C}_f \otimes \Phi_f + \mathcal{O}\left(Q_s^2/Q^2\right) + \mathcal{O}\left(Q_s^4/Q^4\right) + \ldots$$

$\mathcal{O}(1/QR)$

$Q_s^2 \propto$ parton density

Color entangled or correlated between two active partons

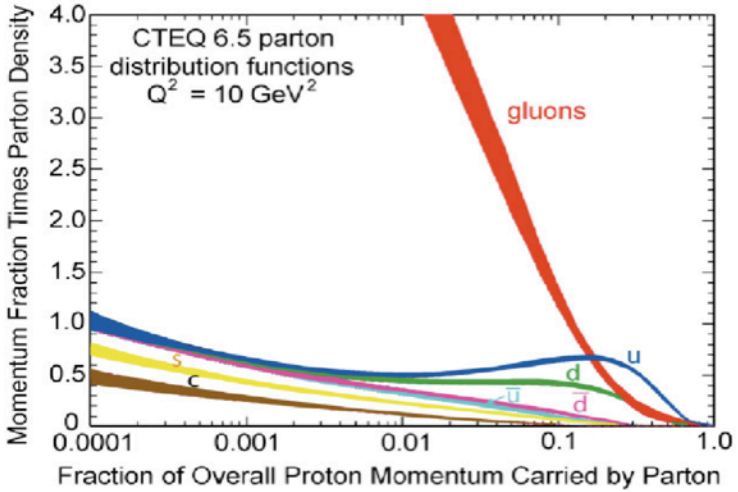
❑ Saturation:

Counting single parton is meaningless if every term is equally important!

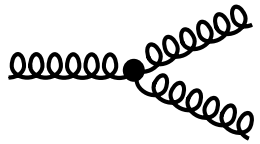
➡ ***Color Glass Condensate (CGC)***

Another HERA discovery

- Run away gluon density at small-x?



What causes the low-x rise?
gluon radiation
– non-linear gluon interaction



What could tame the low-x rise?
gluon recombination
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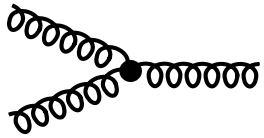
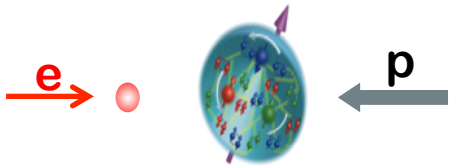
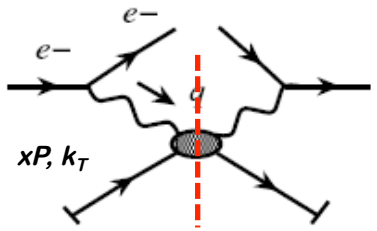
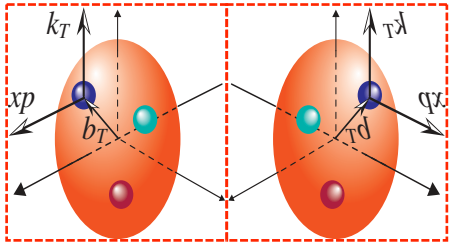


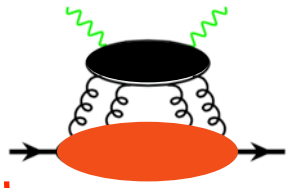
- Color entanglement enhanced at small-x:



$$\sigma_{\rm tot}^{\rm DIS} : \quad \otimes \quad + \quad + \ldots$$







$$= \sum_f \hat{C}_f \otimes \Phi_f + \mathcal{O}\left(Q_s^2/Q^2\right) + \mathcal{O}\left(Q_s^4/Q^4\right) + \ldots$$

$\mathcal{O}(1/QR)$

$Q_s^2 \propto$ parton density

Color entangled or correlated between two active partons

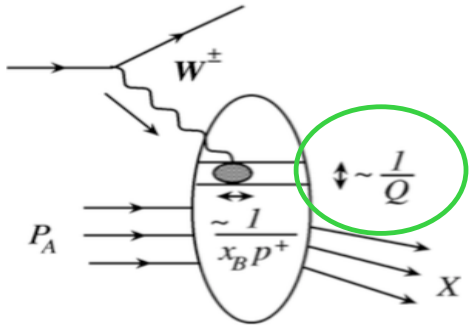
- Saturation:

is a part of QCD!
Where to find it?

Expectation: x=10^{-5} in a proton at Q^2=5 GeV^2

Can a large nucleus help!

❑ The hard probe at small-x is NOT localized:



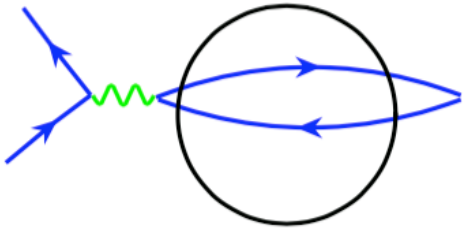
c.m. frame

Longitudinal probing size

> Lorentz contracted nucleon, if

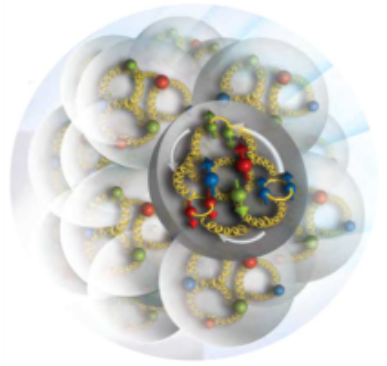
$$\frac{1}{xp} > 2R_A \frac{m}{p} \quad \text{or} \quad x \lesssim 0.01$$

Hadron rest frame



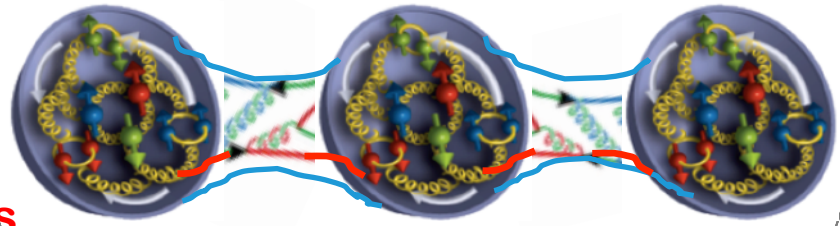
➡ *Hard probe can "see" gluons from all nucleons at the same impact parameter, coherently!*

❑ Help explore the nature of nuclear force!



If we only see quarks and gluons, …

➡



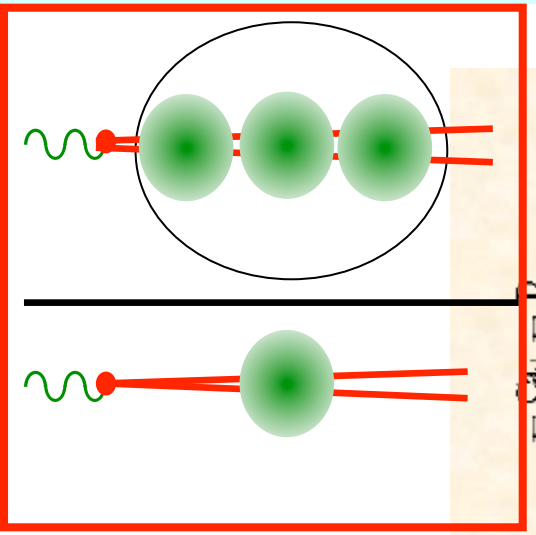
What does a nucleus look like? Does the color of "A" know the color of "B"?

✧ NO ➡ Observed nuclear effect is a coherent collision effect

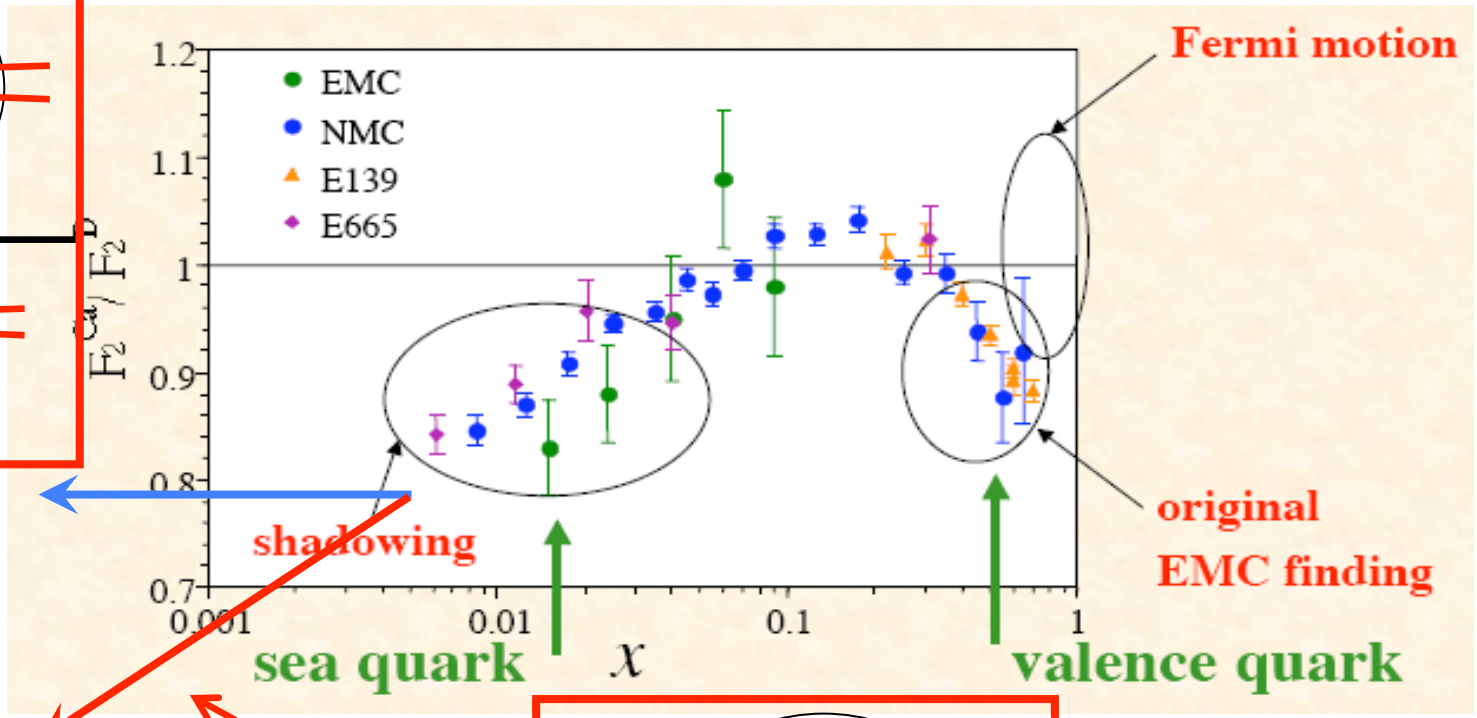
✧ YES ➡ Nucleus could act like a bigger proton at small-x, and could reaching the saturation sooner!

EIC can tell!

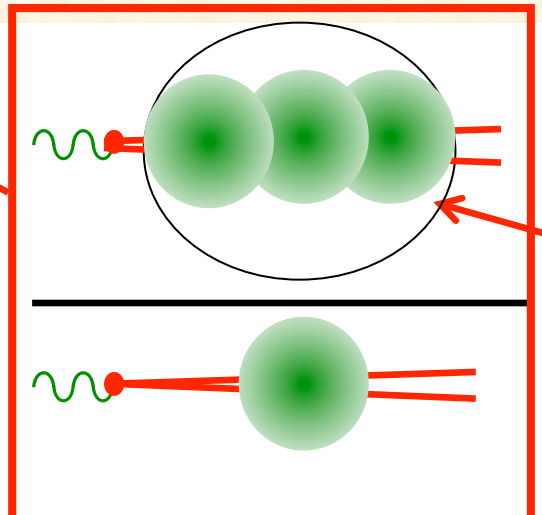
Role of color for nuclear force?



Color localized Inside nucleons



Nucleus as a bigger proton



Color leaks outside nucleons Soft gluon radius is larger

❑ A simple question:

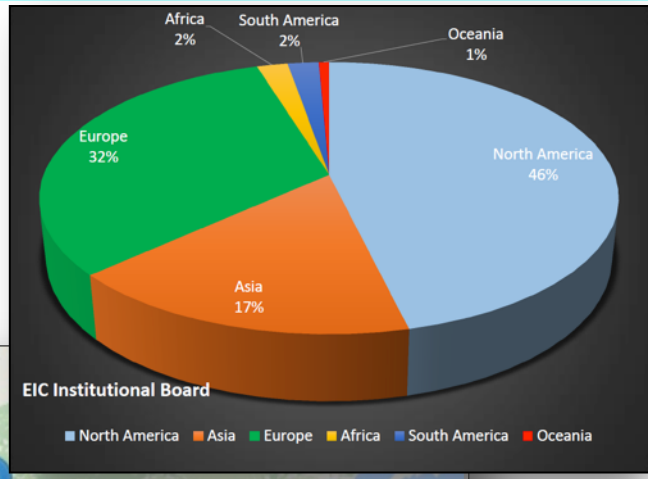
Will the suppression/shadowing continue to fall as x decreases?

US EIC – An International Effort

❑ EIC Users Group – *EICUG.ORG*:

732 collaborators, 29 countries, (no students included yet!)
169 institutions… (growing, …)

Map of institution's locations



Summary and outlook

- 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/nuclei (1/10 fm resolution) – necessarily for exploring nuclear femtography

- EIC could study major Nuclear Science issues that other existing facilities, even with upgrades, cannot do

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

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

Thanks!