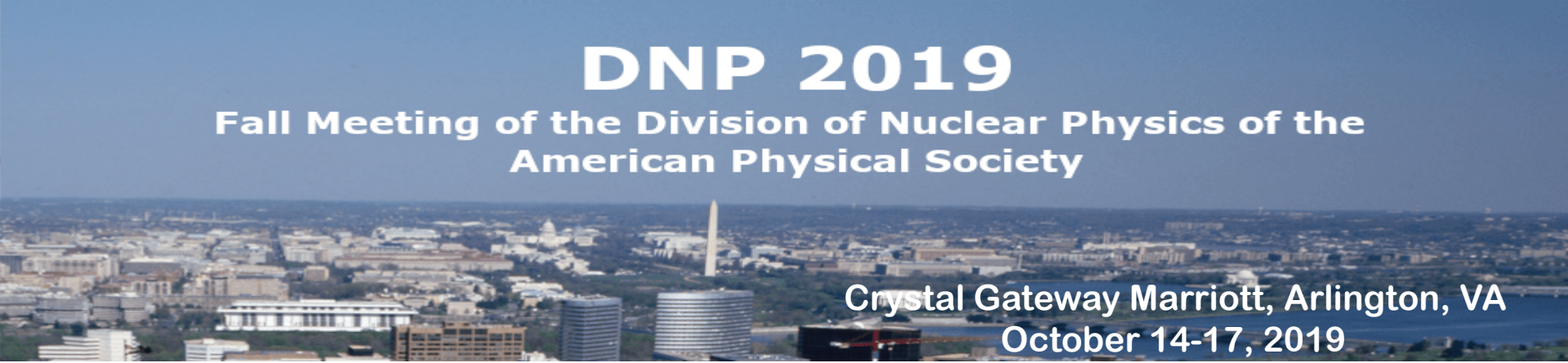


Critical Tests of QCD at the EIC

Jianwei Qiu

Theory Center, Jefferson Lab

Also at this DNP:
see talks at the workshop on
"Physics Opportunities with EIC"

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

Jefferson Lab

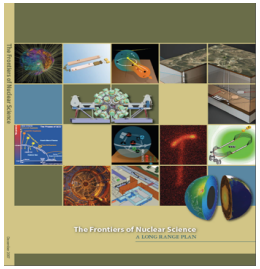
TMD Collaboration

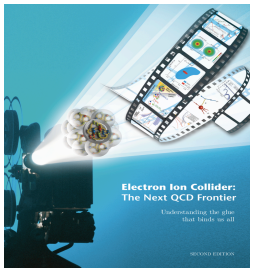
U.S. DEPARTMENT OF ENERGY | Office of Science

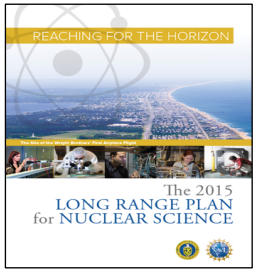
JSA

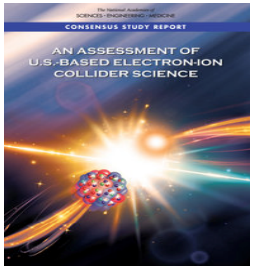
U.S. - based Electron-Ion Collider

- **A long journey, a joint effort of the full community:**

… 


The EIC Science case: a report on the joint BNL/INT/JLab program
Gluons and the quark sea at high energies: distributions, polarization, tomography
Institute for Nuclear Theory, University of Washington, USA
September 13 to November 19, 2010
Editors:
Brookhaven National Laboratory, Upton, NY
Institute for Nuclear Theory, Seattle, WA
Thomas Jefferson National Accelerator Facility, Newport News, VA






…

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

… 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?

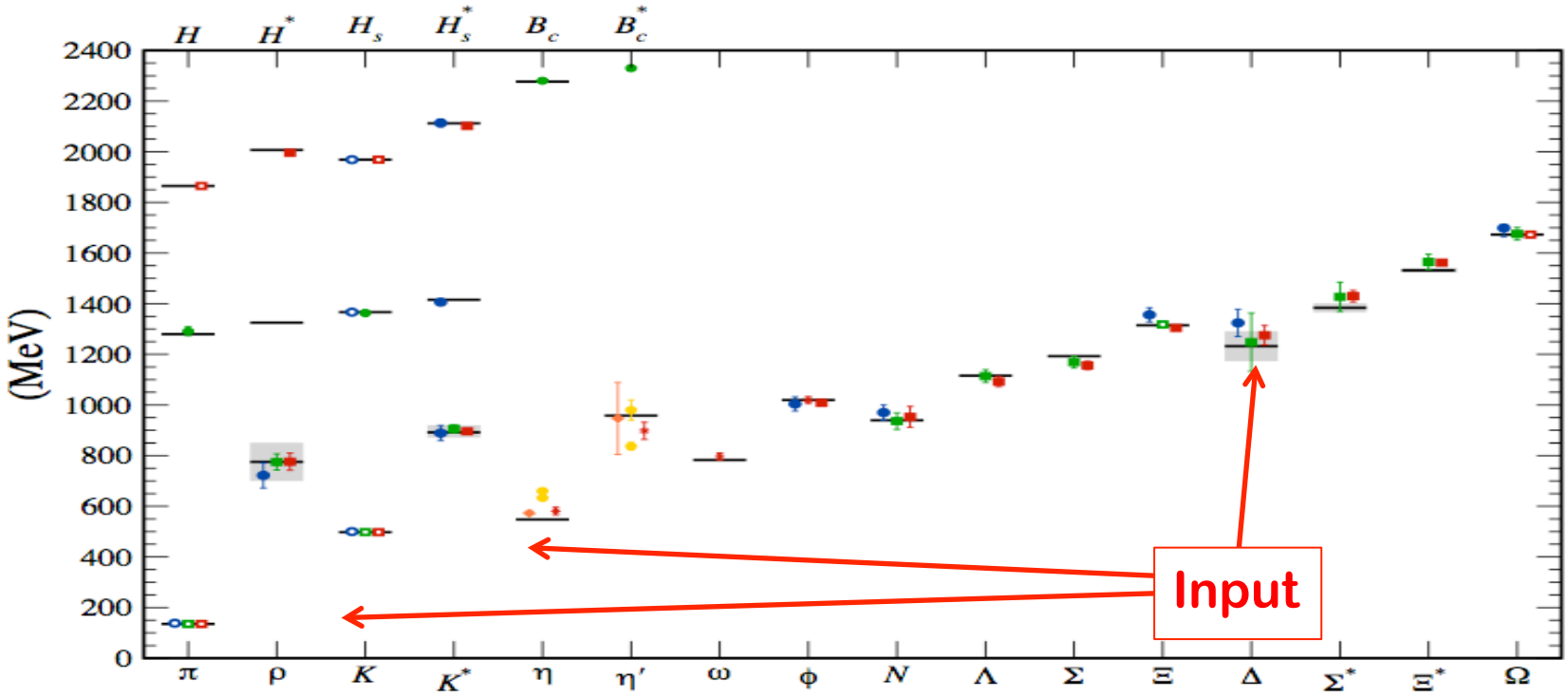
Explore the emergent phenomena of QCD!

Part I

How QCD has been tested?

QCD is the right theory, …

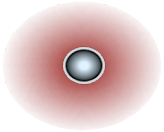
- **Hadron mass from lattice QCD calculations:**



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

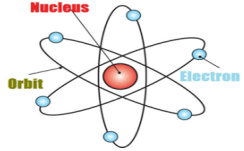
QCD – Unprecedented intellectual challenge

- **No modern detector has seen any quark or gluon in isolation:**
  - **Gluons are dark, but, carry color:**
    NO separation between color charges!
    Color is fully entangled!



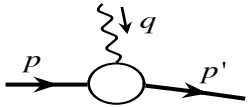
$B^+(u\bar{b})$

Brown-Muck

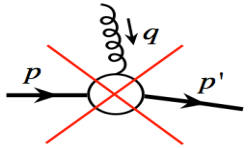


Quantum orbits

  - **No "color" radius of proton:**
    NO elastic "color" form factor!



Proton radius

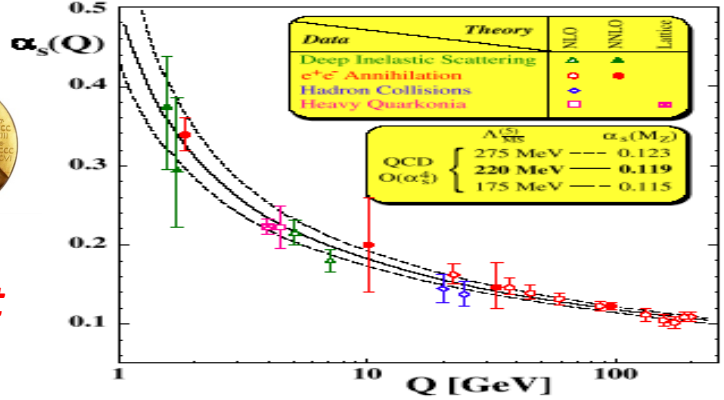


  - **The *challenge*:**
    How to test a theory, its dynamics, without seeing the players?

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

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

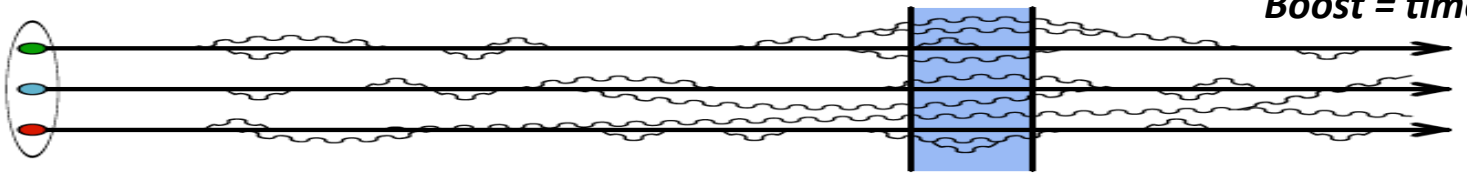
2004



➡ *Controllable perturbative QCD calculations at HIGH ENERGY* ➡ *Controllable "probe"?*

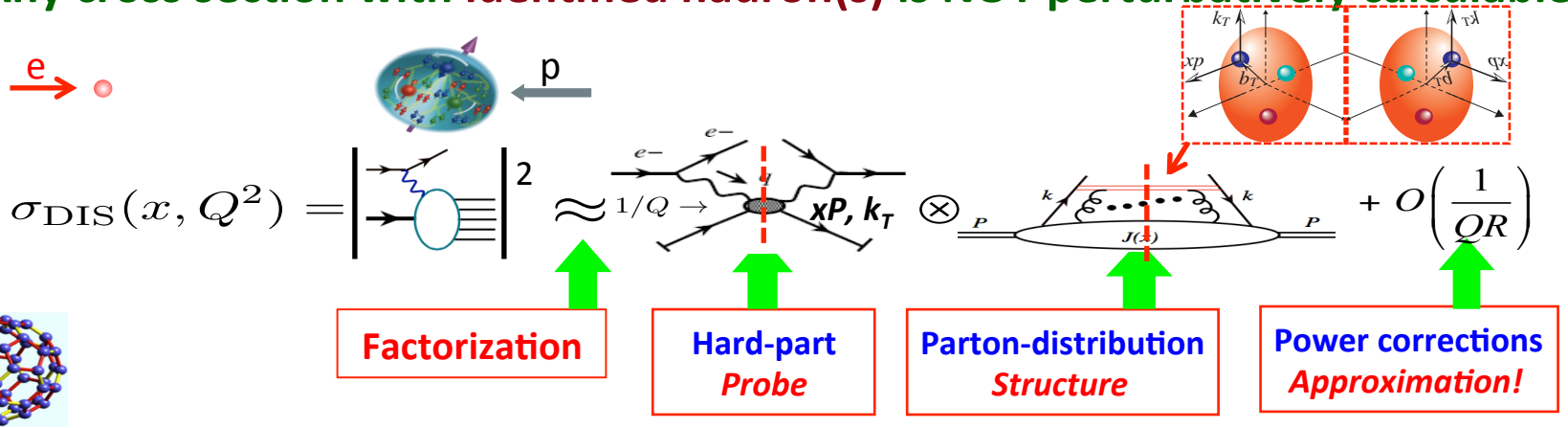
QCD has been tested in the asymptotic regime

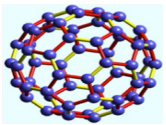
- **Hard probes to "catch" the quantum fluctuation:**



Hard probe (t ~ 1/Q < fm) → *Probability to "catch" the parton!*

- **Any cross section with identified hadron(s) is NOT perturbatively calculable!**

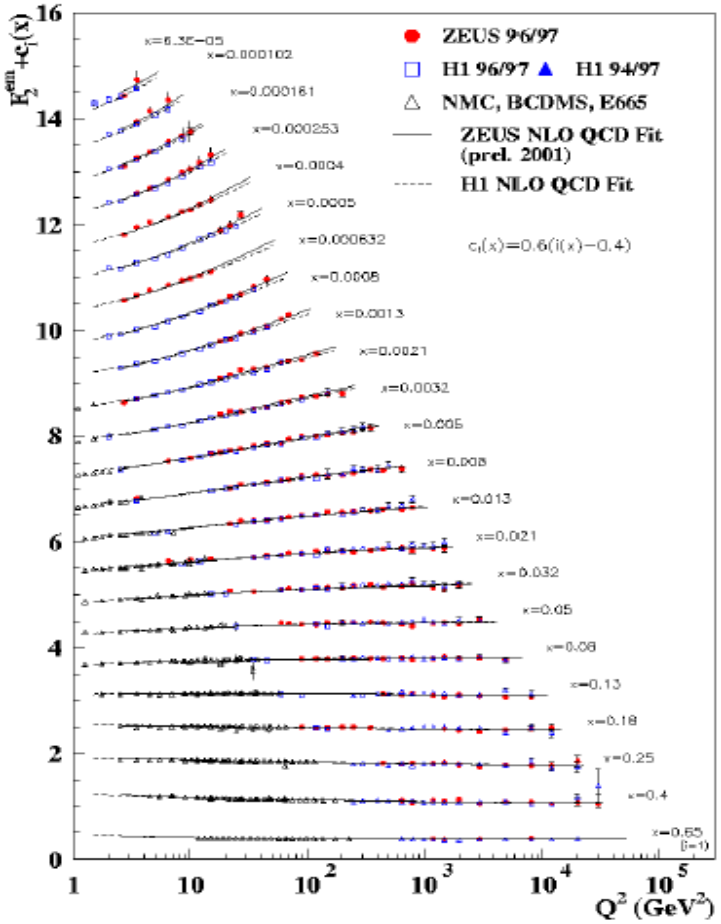




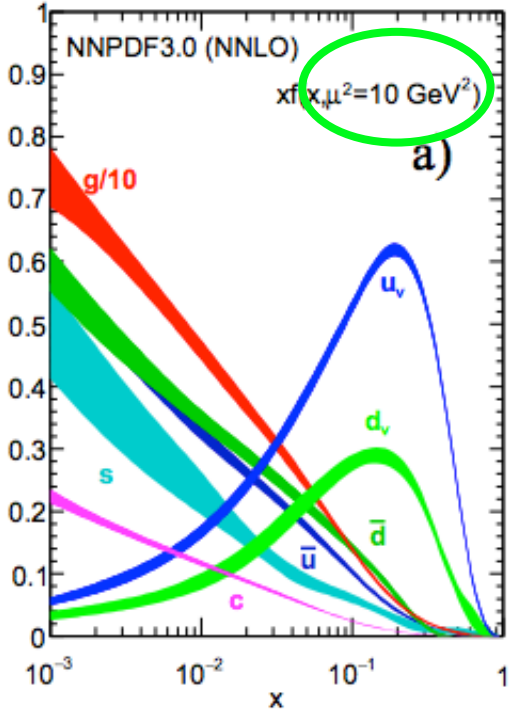
→ *NO "still picture" for hadron structure!* $f_{q/p}(x, k_T; \mu^2)$ – Quantum correlations!

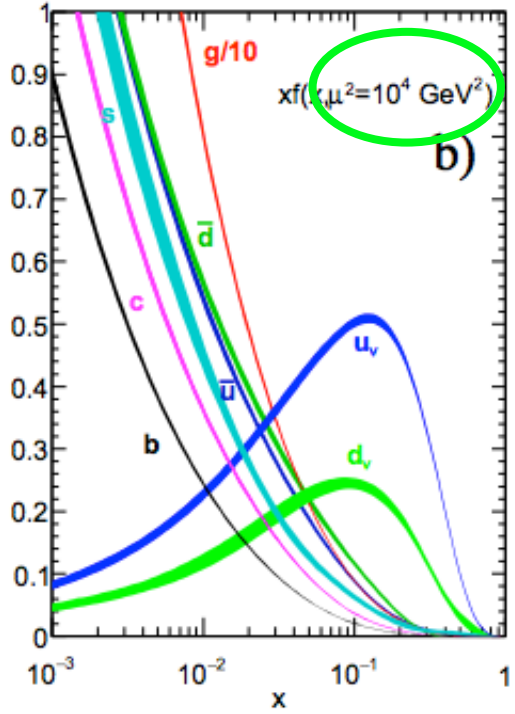
QCD is tested: factorization + probe + universality of the quantum correlations!

Unprecedented success of QCD and QCD factorization



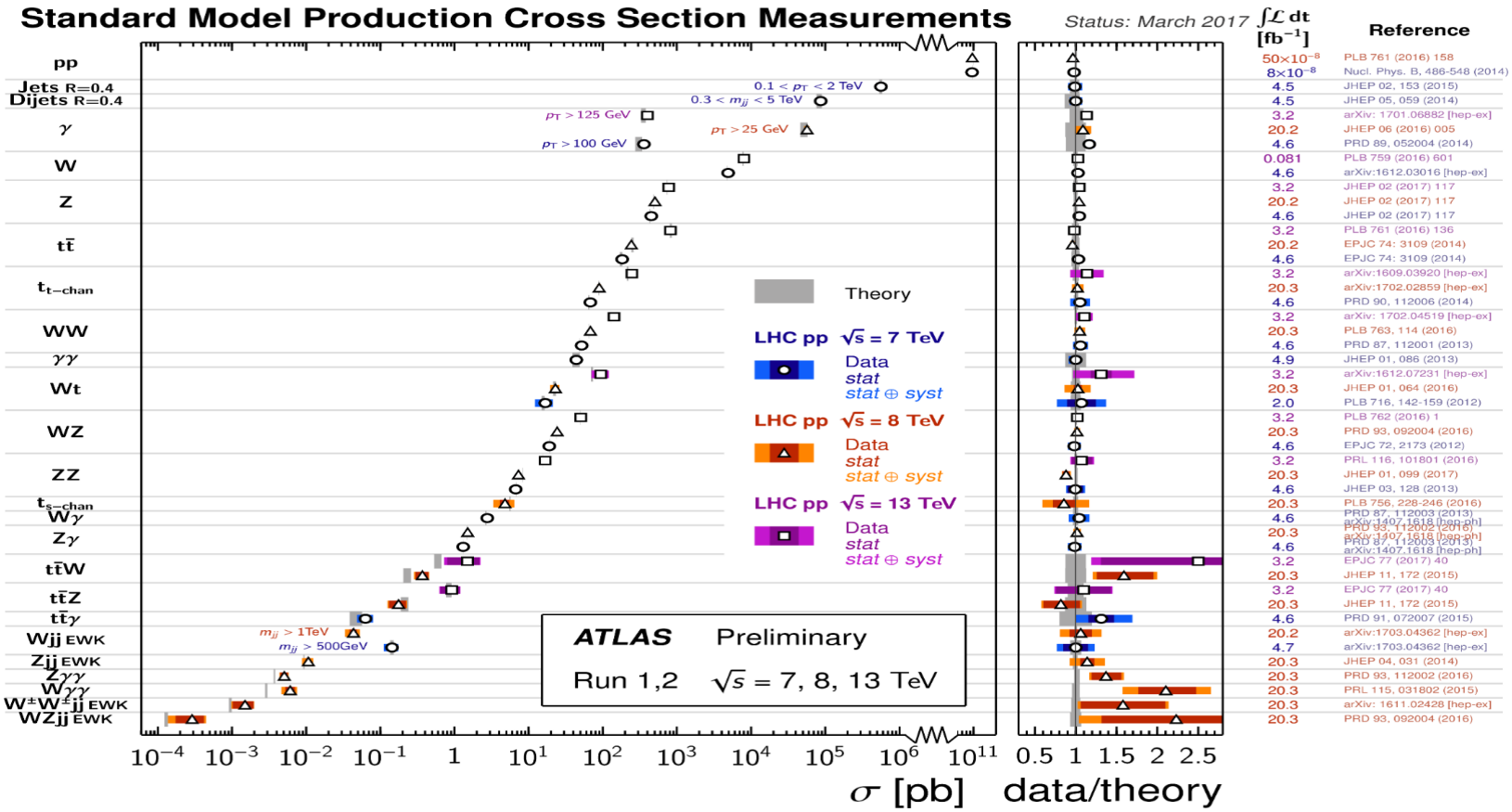
❑ **Universal Parton Distributions:**





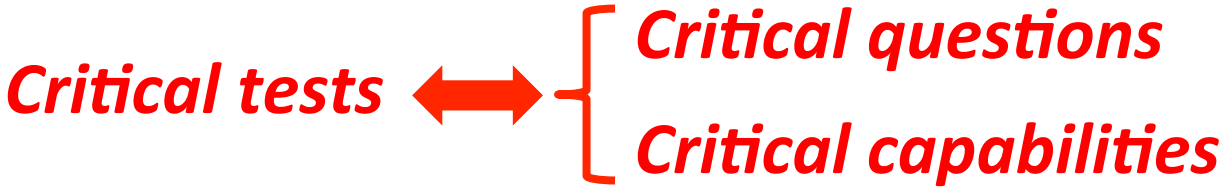
$$q(x) = \left| \{ \; P,+ \;\; xP \;\; + \; \} X \right|^2 + \left| \{ \; P,+ \;\; xP \;\; - \; \} X \right|^2$$

Unprecedented success of QCD and Standard Model



SM: Electroweak processes + QCD perturbation theory + PDFs works!

Part II


Critical tests
Critical questions
Critical capabilities

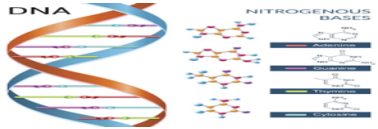
Eternal Questions we have been asking …

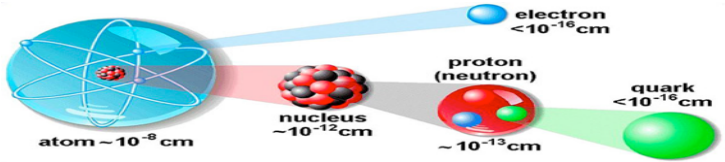
- **Where did we come from?**

Global Time: →

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

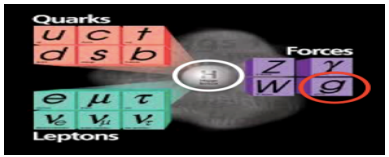
- **What are we made of?**

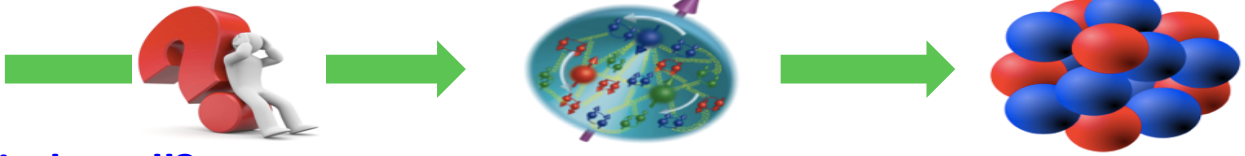




What is the internal structure and dynamics of hadrons?

- **What holds us together?**



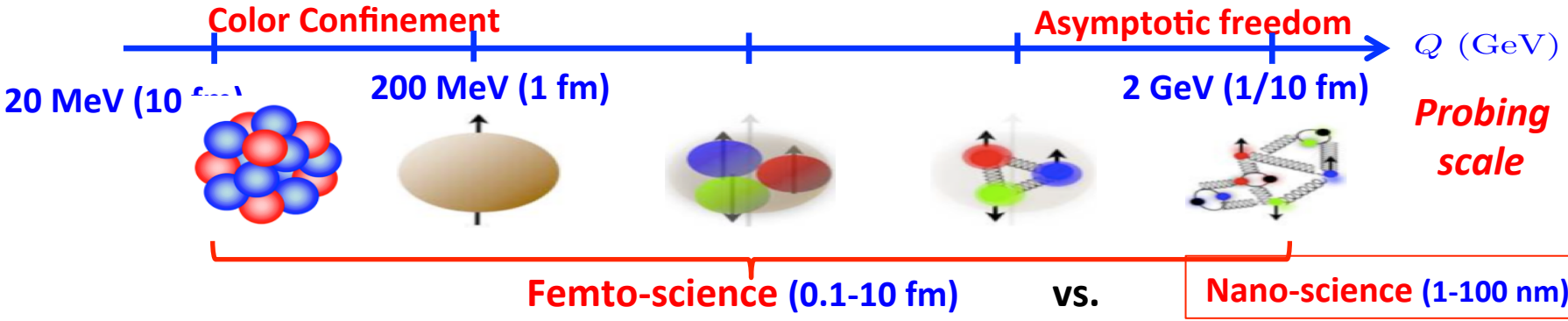


How does the glue bind us all?

EIC: a single facility being able to address all these questions, emergent phenomena of QCD, with the precision and the uniqueness, …

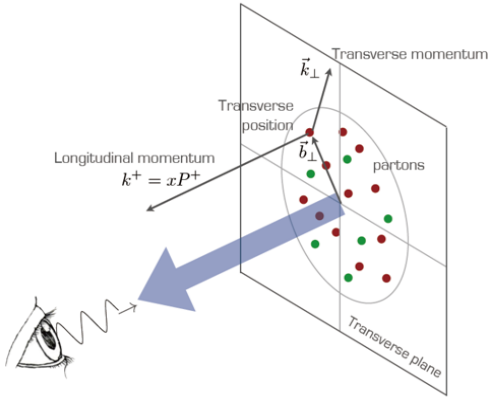
Exploring emergent phenomena of QCD

- QCD landscape of nucleon and nuclei?



- Need observables with two-momentum scales:

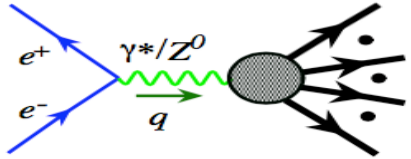
$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$



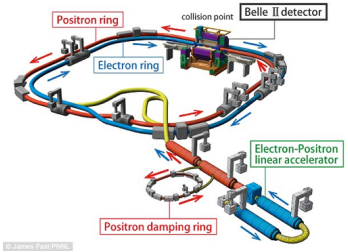
- ✧ Hard scale: localizes the probe
  particle nature of quarks/gluons
- ✧ "Soft" scale: could be more sensitive to the
  hadron structure ~ 1/fm
- ✧ Hit the hadron "very hard" without breaking it, clean information on the structure!

QCD needs lepton-hadron facilities

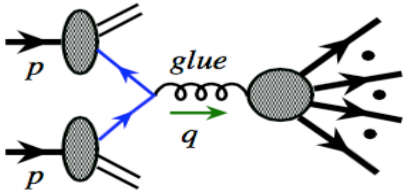
- **Hadrons are produced from the energy in e+e- collisions:**



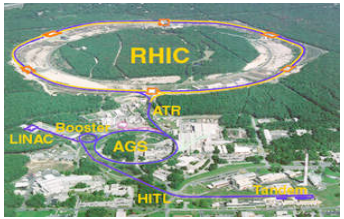
  - *No hadron to start with*
  - *Emergence of hadrons*



- **Hadrons are produced in hadron-hadron collisions:**

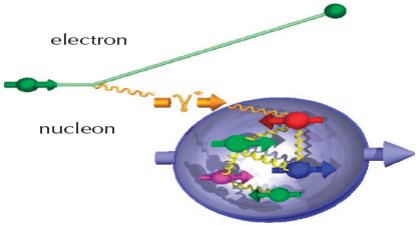


  - *Partonic structure*
  - *Emergence of hadrons*
  - *Heavy ion target or beam(s)*



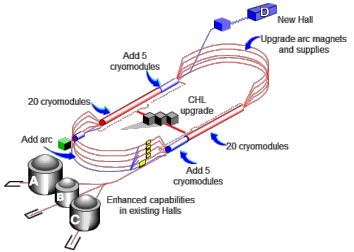
Also at the LHC

- **Hadrons are produced in lepton-hadron collisions:**



One facility covers all!

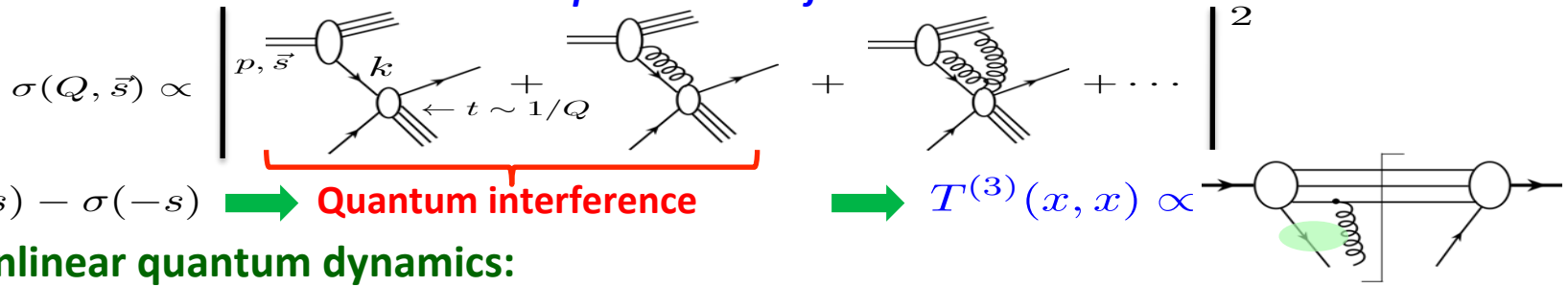
  - *Colliding hadron can be broken or stay intact!*
  - *Imaging partonic structure*
  - *Emergence of hadrons*
  - *Heavy ion target or beam*



Also at COMPASS & future EIC

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!



- **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

Part III

US-EIC: *Why existing facilities, even with upgrades, cannot do the same?*

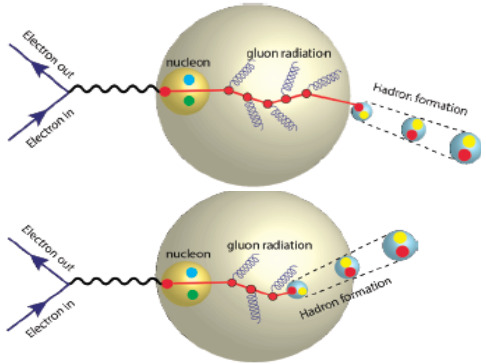
- ✧ **Emergence of hadrons**
- ✧ **Hadron properties:**
  mass, spin, …
- ✧ **Hadron's 3D partonic structure:**
  confined motion, spatial distribution,
  color correlation, fluctuation,
  saturation, …
- ✧ **Quantum correlation between**
  hadron properties and parton dynamics, …

…

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

How did hadrons be emerged from quarks and gluons?

❑ Ions as femtometer sized detectors:

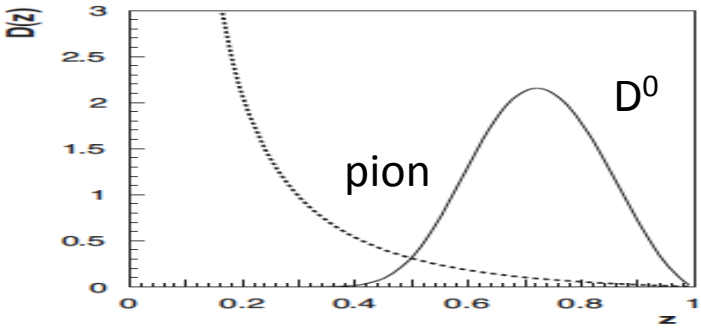


The Control of ν & medium length!

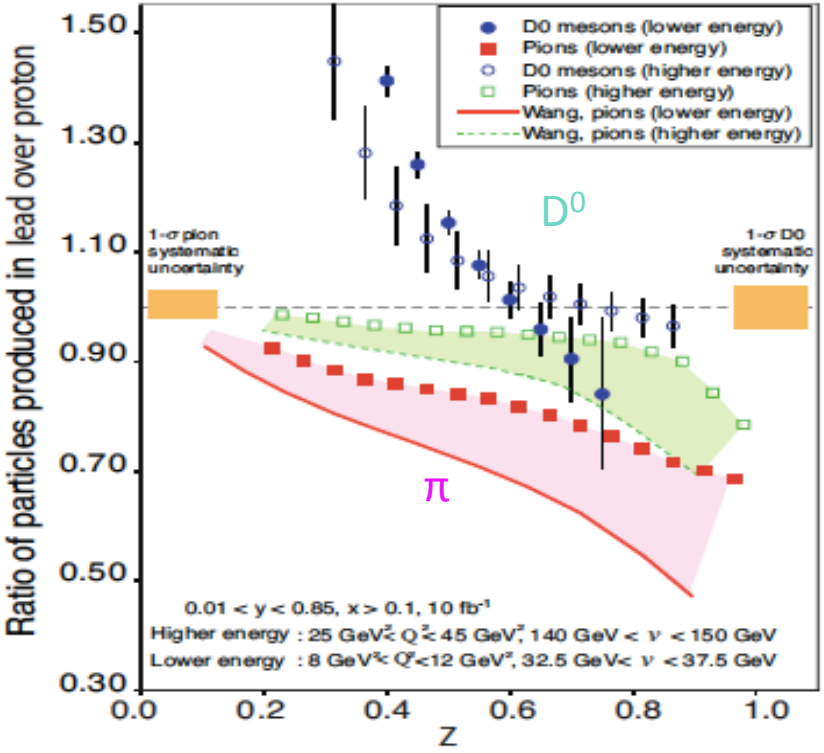
$$\nu = \frac{Q^2}{2mx}$$

Beyond HERA & pA!

❑ Mass dependence of hadronization:



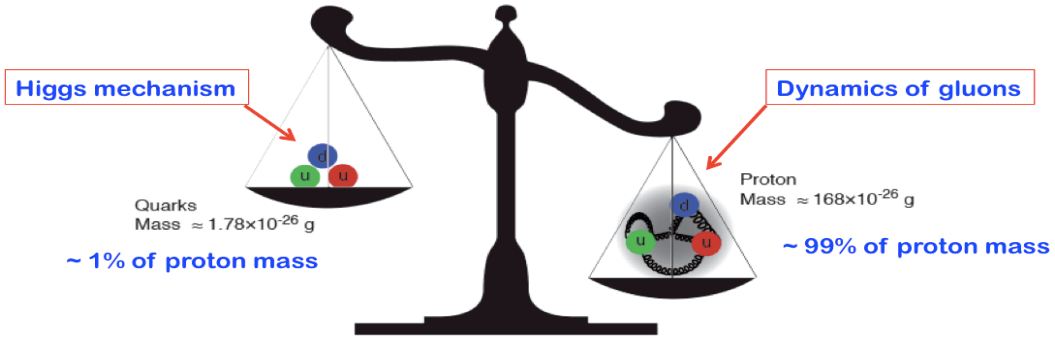
❑ *Critical test of QCD hadronization!*



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

How does the mass of the nucleon arise?

- **Nucleon mass – dominates the mass of visible world:**



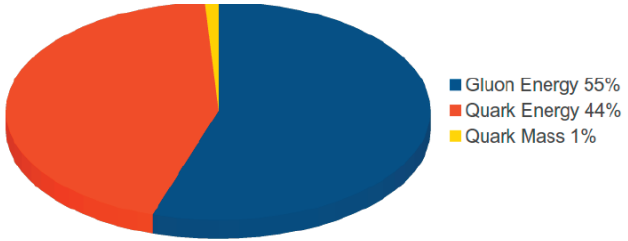


Fig. 2.1 NAS Report

Higgs mechanism is far from 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: decomposition

- **Role of quarks and gluons?**
  - **Trace of the QCD energy-momentum tensor:**

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

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

  - **Hadron mass:** ***Gluon quantum effect + Chiral symmetry breaking!***
- **Decomposition or sum rules – could be frame dependent!**

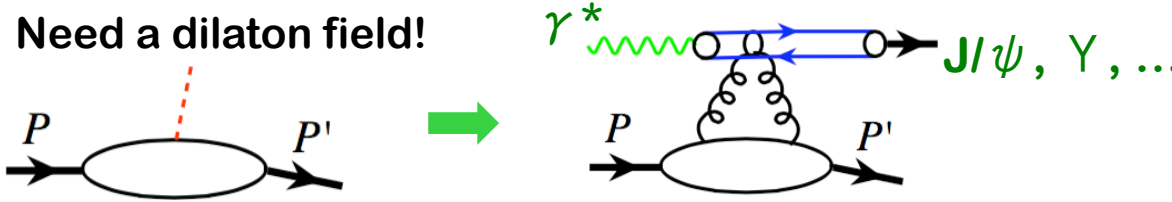
$$M_p = \left.\frac{\langle P| \int d^3x\, T^{00} |P\rangle}{\langle P|P\rangle}\right|_{\text{at rest}} = E_q + E_g + \chi_{m_q} + T_g$$

Relativistic motion; χ Symmetry Breaking; Quantum fluctuation; Trace Anomaly; Quark Energy; Gluon Energy; Quark Mass

Sum Rule is useful if individual terms can be measured independently

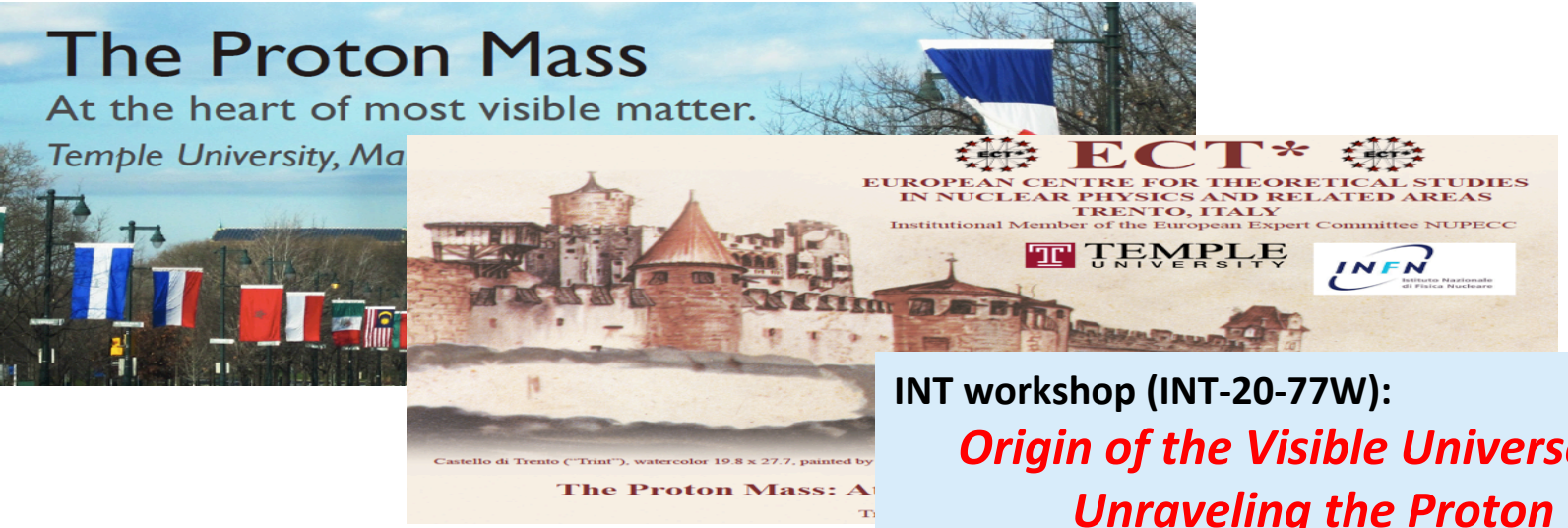
- **Critical test of QCD mass generation:**

Probe the distribution of mass inside the proton?



The Proton Mass: renewed world effort

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



A true international effort!

INT workshop (INT-20-77W):

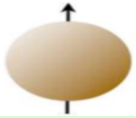
Origin of the Visible Universe:
Unraveling the Proton Mass

May 4-8, 2020,
I. Cloet, Z.-E. Meziani, B. Pasquini

How does the spin of the nucleon arise?

❑ An incomplete story:

Jaffe-Manohar, 90, Ji, 96, …



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

Proton Spin

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

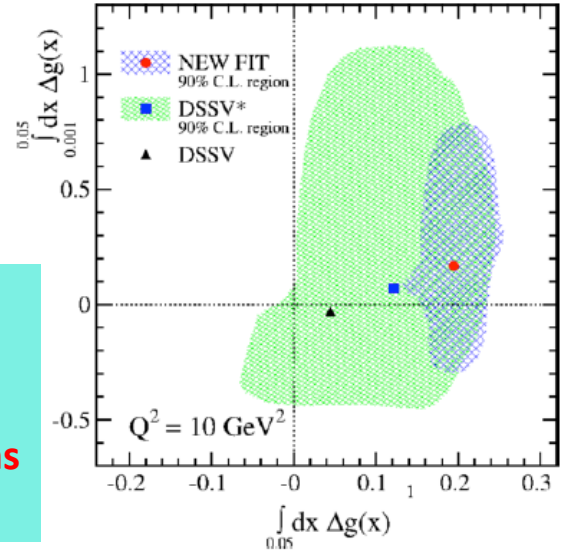
Quark helicity
Best known

$$\Delta G = \int dx \Delta g(x) \sim 40\%$$

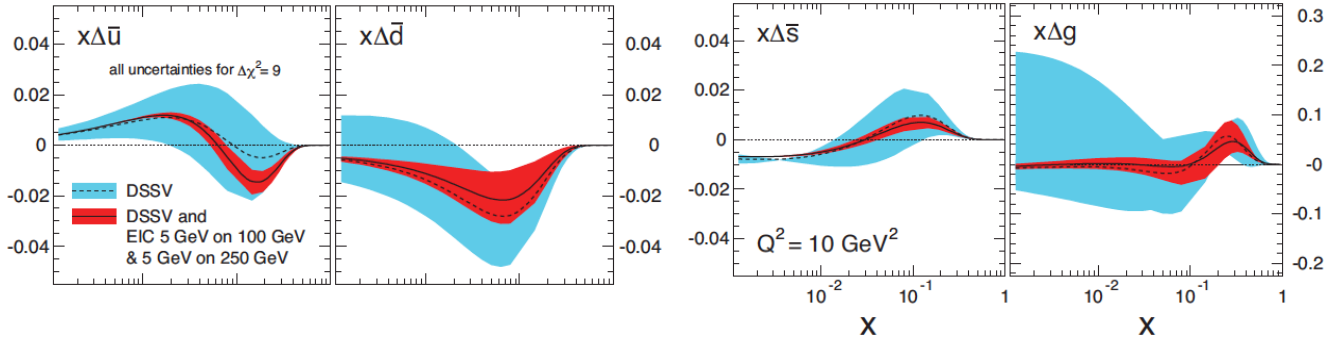
With RHIC data

Gluon helicity
Start to know

Orbital Angular Momentum of quarks and gluons
Little known

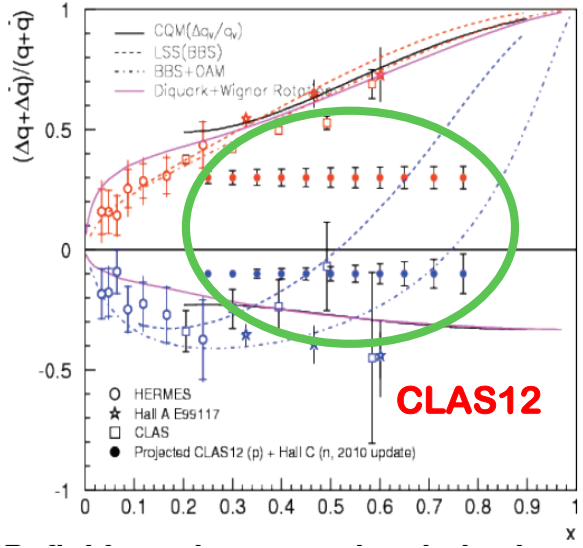


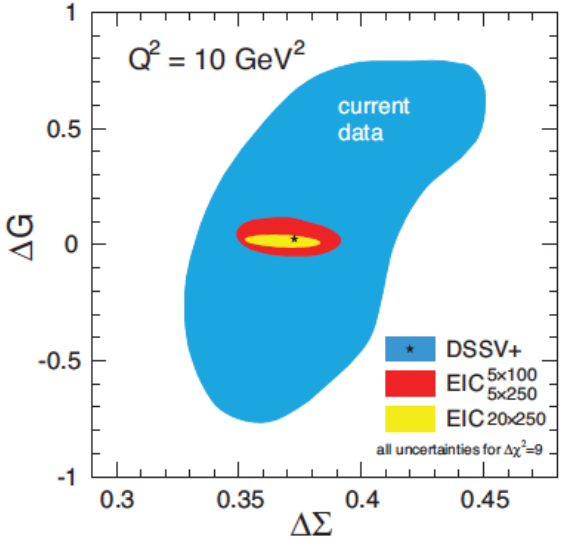
❑ What an EIC could help:

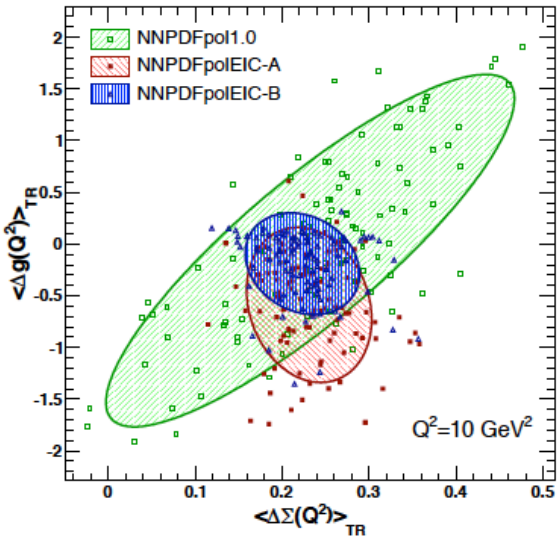


The Proton Spin: from JLab12 to EIC

❑ Complementary between JLab12 and EIC:







No other machine in the world can achieve this!

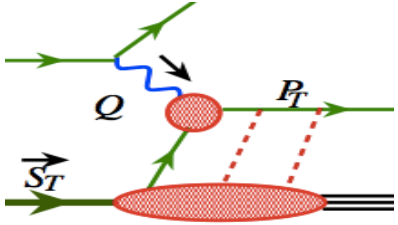
❑ Critical Tests of the emergence of hadron properties in QCD:

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

“See” nucleon’s internal landscape

❑ **Two-scale observables are natural in lepton-hadron collisions:**

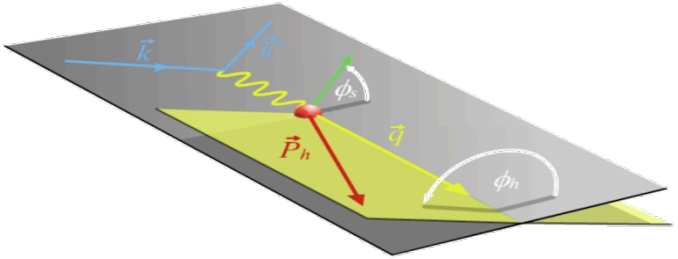
✧ **Semi-inclusive DIS:**



+ …

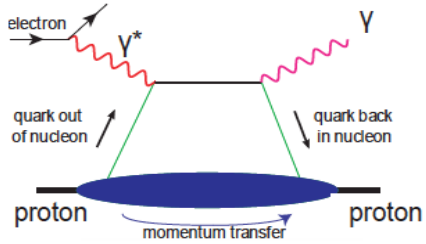
SIDIS: $Q \gg P_T$

Parton’s confined motion encoded into TMDs



Two scales, two planes, Angular modulation, …

✧ **Exclusive DIS:**

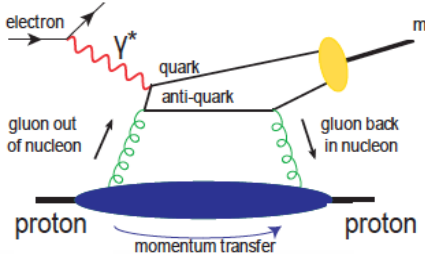


+ …

Imaging quarks

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

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



J/Ψ, Φ, …

Imaging gluons

Heavy quarkonium: $Q^2+M^2 \gg |t|$

Imaging the glue only at EIC

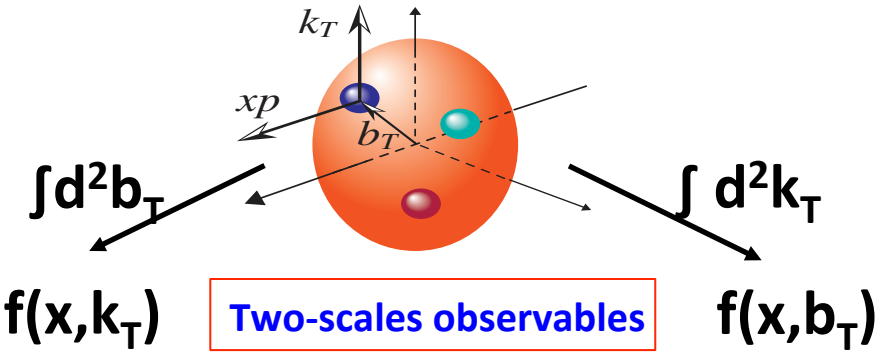
Theory is solid – unified description

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

Momentum Space

TMDs

Confined motion



Coordinate Space

GPDs

Spatial distribution

- **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:**

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

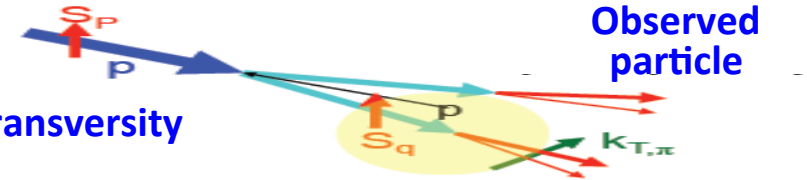
Critical tests of the flavor-spin-motion correlation

❑ **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

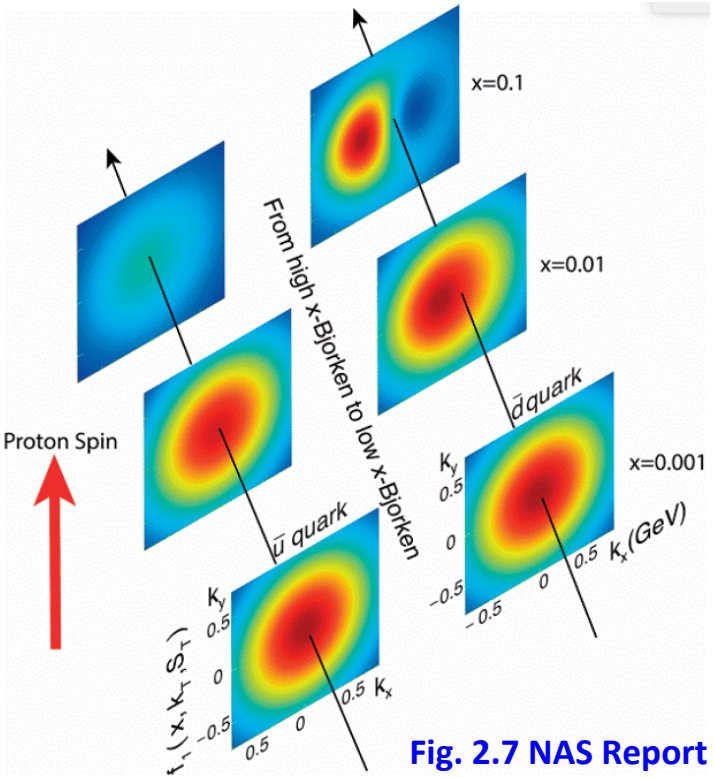
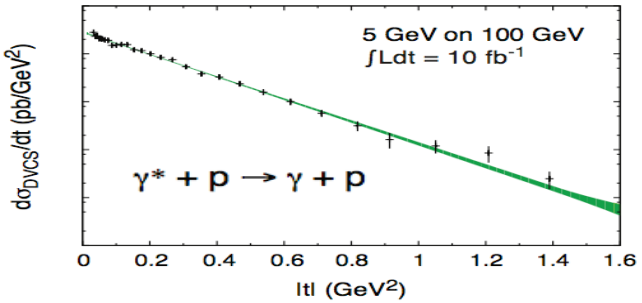
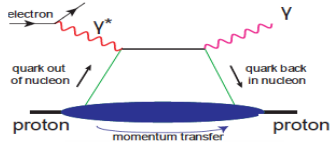


Fig. 2.7 NAS Report

Critical tests of the flavor-dependent spatial imaging

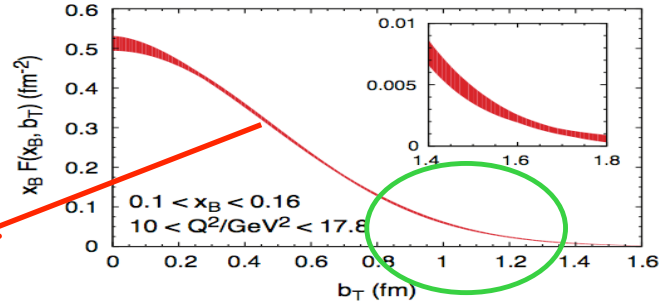
❑ DVCS at EIC:



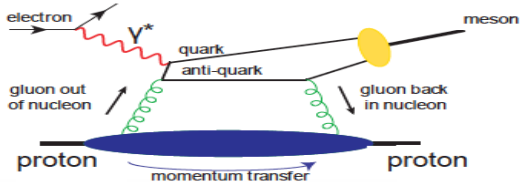


Factorization → **GPDs** → **F.T.**

Proton radius of quarks (x)!



❑ "Seeing" the glue at EIC:

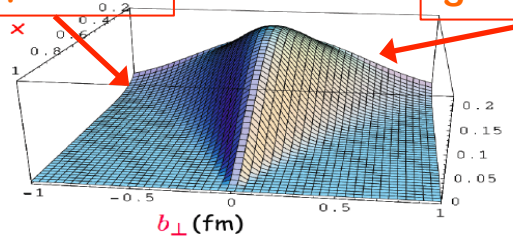


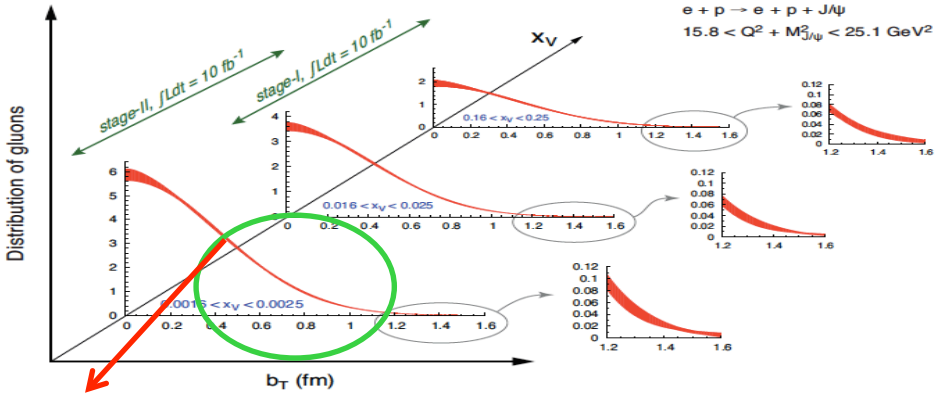
J/Ψ, Φ, …

F.T. **t-dep** →

How far does glue density spread?

How fast does glue density fall?

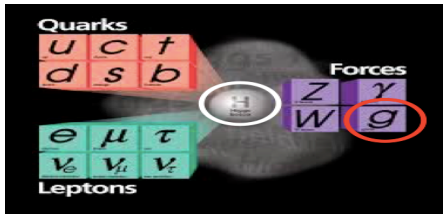


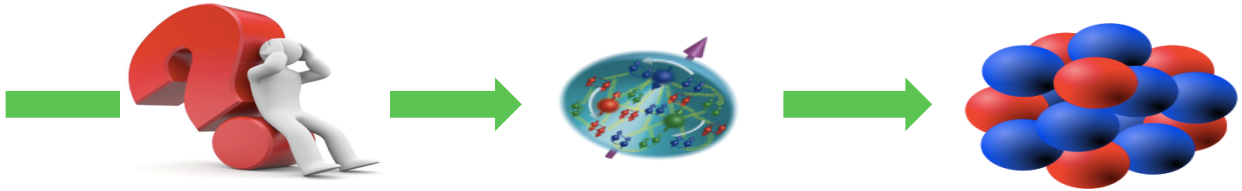


Proton radius of gluons (x)!

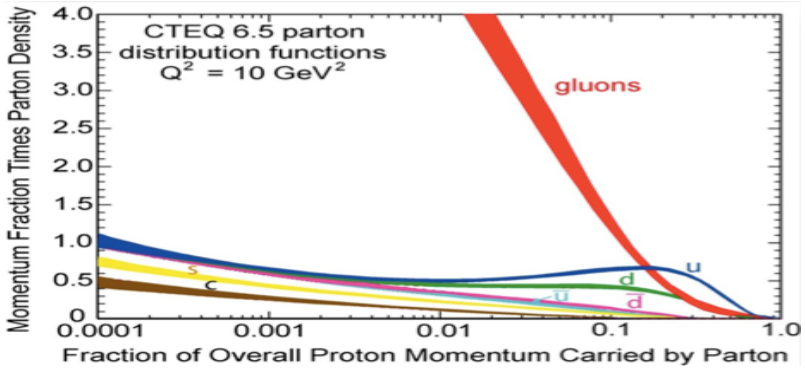
Only possible at EIC!

QCD glue holds us together!

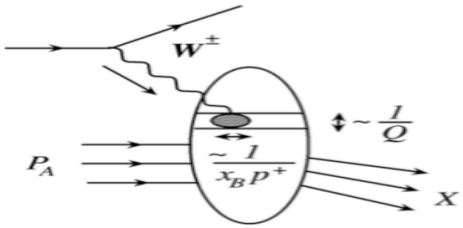




- **Another HERA discovery:**
  - **What are the emergent properties of dense systems of gluons, when the occupation number is ~ O(1)?**



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



in c.m. frame

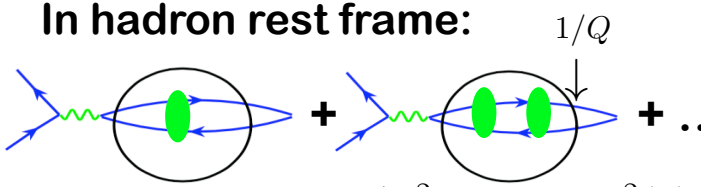
Longitudinal probing size

> **Lorentz contracted nucleon**

if $\frac{1}{xp} > 2R\frac{m}{p}$ or $x < 0.1$

Saturation in proton: x ~ 10^{-5}

In hadron rest frame:



$$\frac{1/R^2}{Q^2}\langle g(x)\rangle \sim \frac{Q_s^2(x)}{Q^2}$$

Color entangled between two active partons

Nuclear landscape – nuclear force

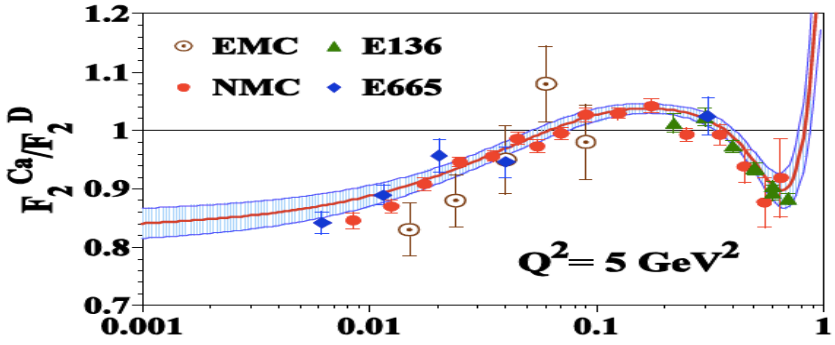
- **EMC discovery:**

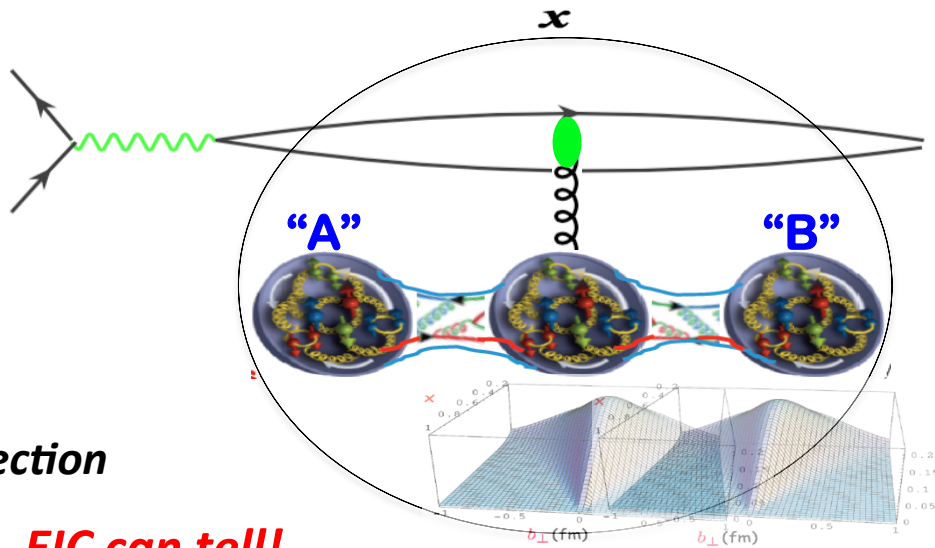
  Nuclear landscape
  ≠ Superposition of nucleon landscape

- **Simple, but fundamental, questions:**
  - **What does a nucleus look like?**
    if we only see quarks and gluons
  - **Does the color of nucleon "A" know the color of nucleon "B"?**

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

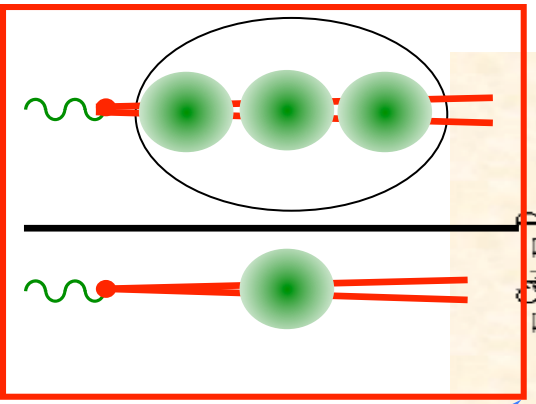
    IF NOT, Observed nuclear effect in x-section is a coherent collision effect

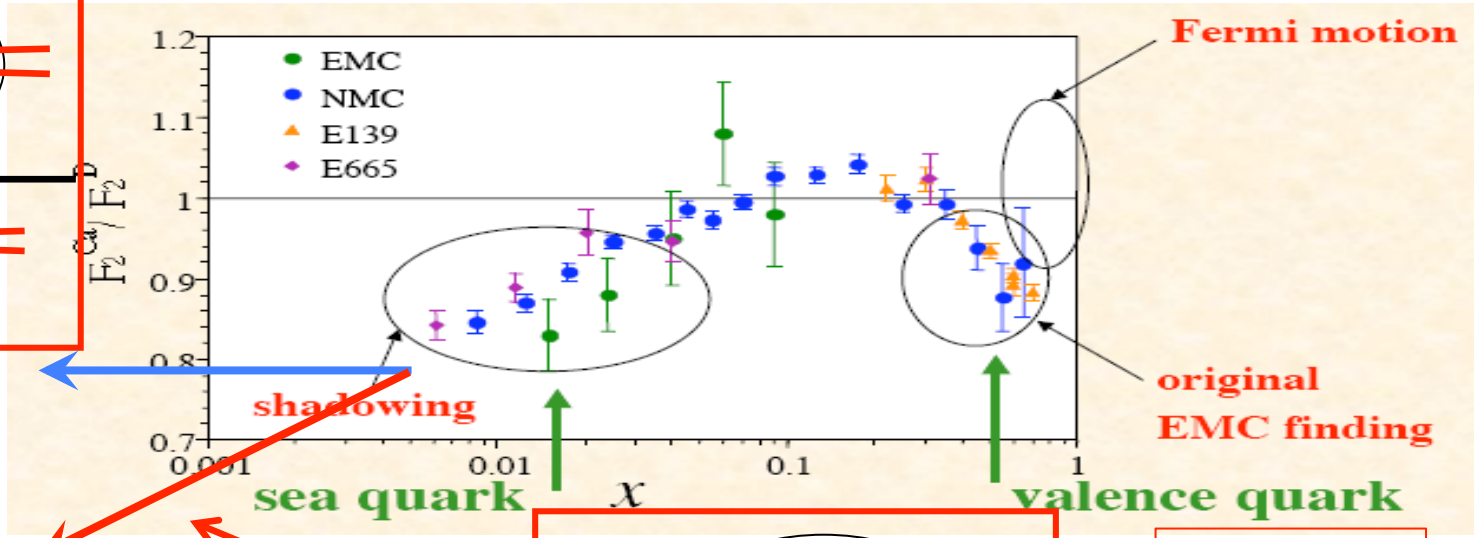




EIC can tell!

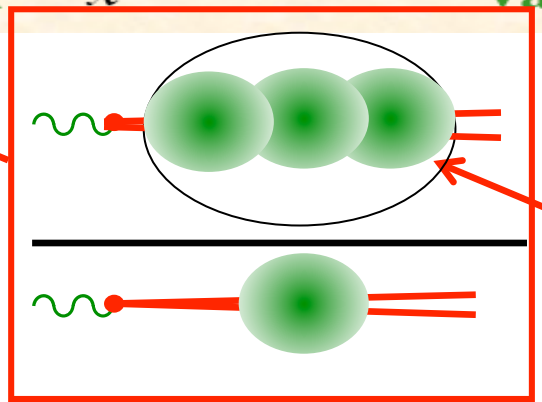
Critical test: coherence length of the color





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?

Summary and outlook

- QCD has been very successful in describing the short-distance dynamics owing to its “Asymptotic Freedom”, a defining property of QCD
- QCD’s another defining property, “Confinement”, makes the QCD and its emergent phenomena extremely rich, opening up a new femto-science
- EIC is a ultimate QCD machine and a facility, capable of discovering and exploring the emergent phenomena of QCD, and the role of color and glue
- US-EIC is sitting at a sweet spot for rich QCD dynamics, capable of taking us to the next frontier of Nuclear Science!

Thanks!

Hadron structure

1933: Proton's magnetic moment

Nobel Prize In Physics 1943

Otto Stern

"for … and for his discovery of the magne moment of the proton".

$g \neq 2$ **Proton is NOT point-like**

1960: Elastic e-p scattering

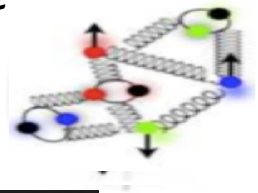
Nobel Prize In Physics 1961

Robert Hofstadter

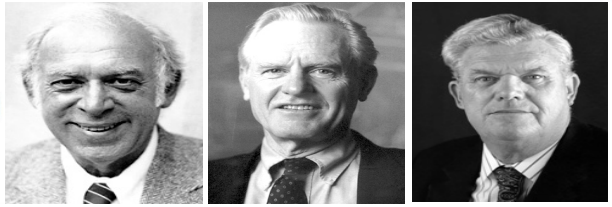
"for … for his discoveries concerning the structure of the nucleons"

Form factor – charge distribution

"Proton Radius"



1969: Deep inelastic e-p scattering



Nobel Prize in Physics 1990

Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor

"for their pioneering investigations concerning deep inelastic scattering of electrons on protons…".

1974: QCD Asymptotic Freedom

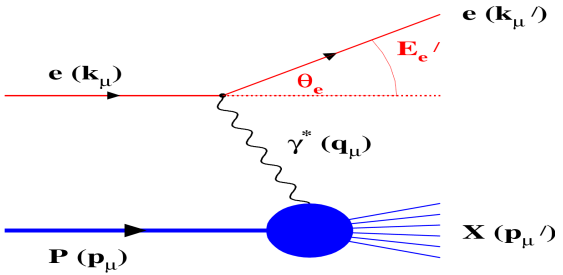
Nobel Prize in Physics 2004

David J. Gross, H. David Politzer, Frank Wilczek

"for the discovery of asymptotic freedom in the theory of the strong interaction".

Mary 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(p,K,p,jet)+X

Detect the scattered lepton in coincidence with identified hadrons/jets

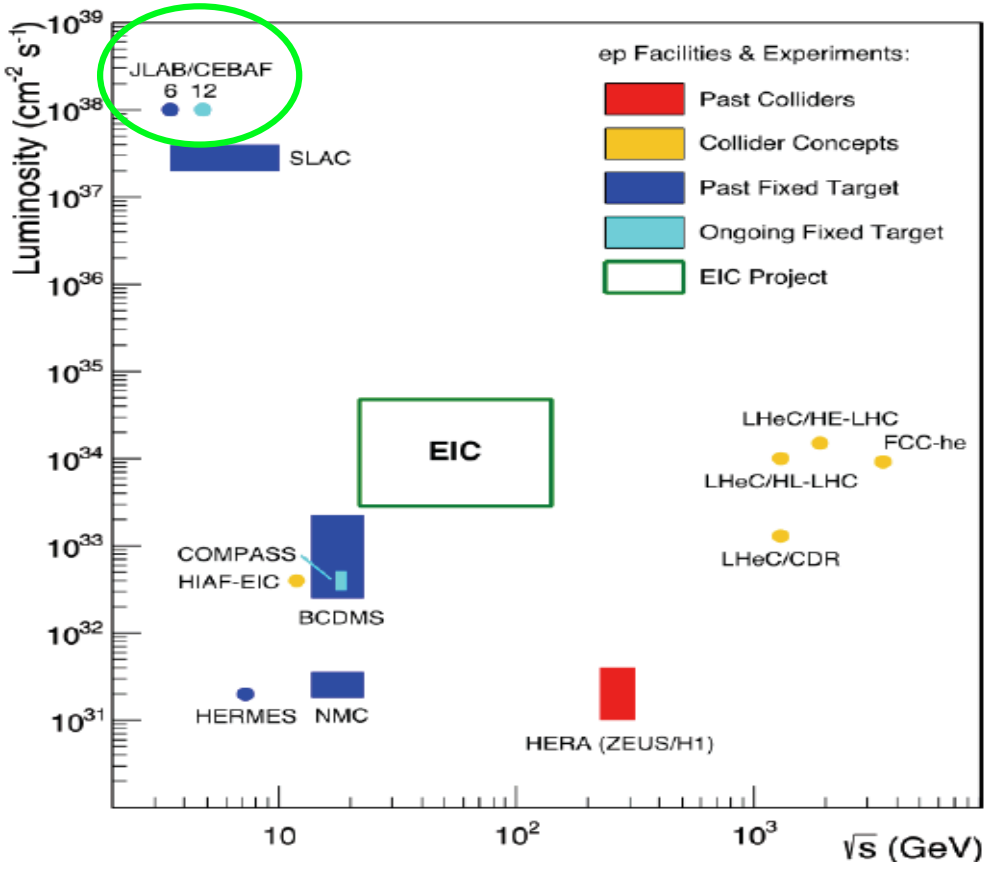
(Initial hadron is broken – confined motion! – cleaner than h-h collisions)

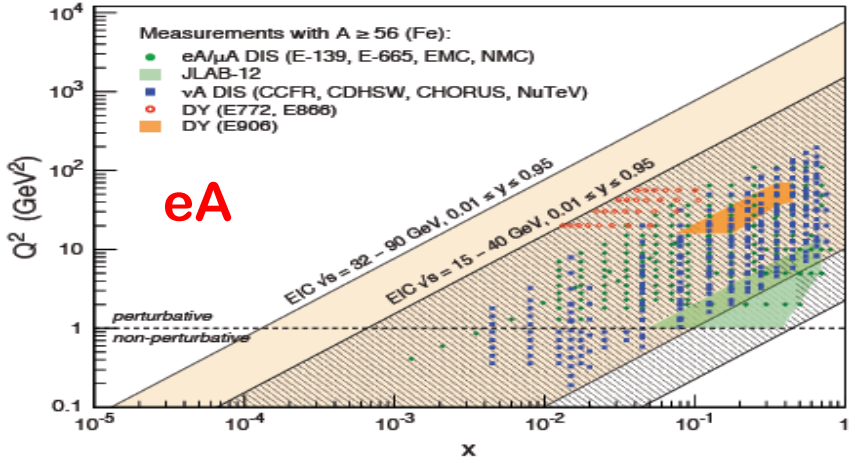
Exclusive events: e+p/A → e'+ p'/A'+ h(p,K,p,jet)

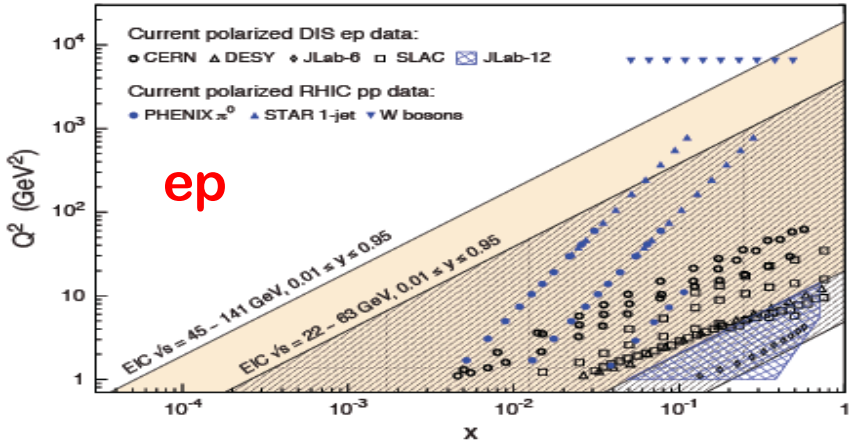
Detect every things including scattered proton/nucleus (or its fragments)

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

US-EIC: Luminosity and kinematic coverage





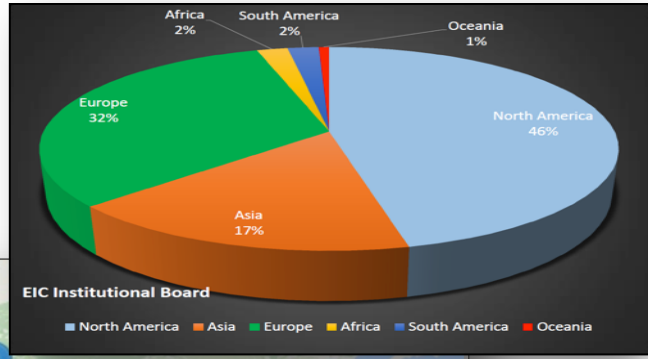


US-EIC: an International Effort

❑ EIC Users Group – *EICUG.ORG*:

732 collaborators, 29 countries,
169 institutions... (growing, ...)

(no students included yet!)



Map of institution's locations