UCLA College | Physical Sciences Physics & Astronomy

Nuclear Femtography

A new frontier of Science and Technology

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Acknowledgement: Some of the physics 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

Congratulation!

The Nobel Prize in Physics 2020

Congratulations to Professor Andrea Ghez

on the 2020 Nobel Prize in Physics

for the discovery of a supermassive compact object

at the center of our galaxy!

Frontiers of QCD and Strong Interaction

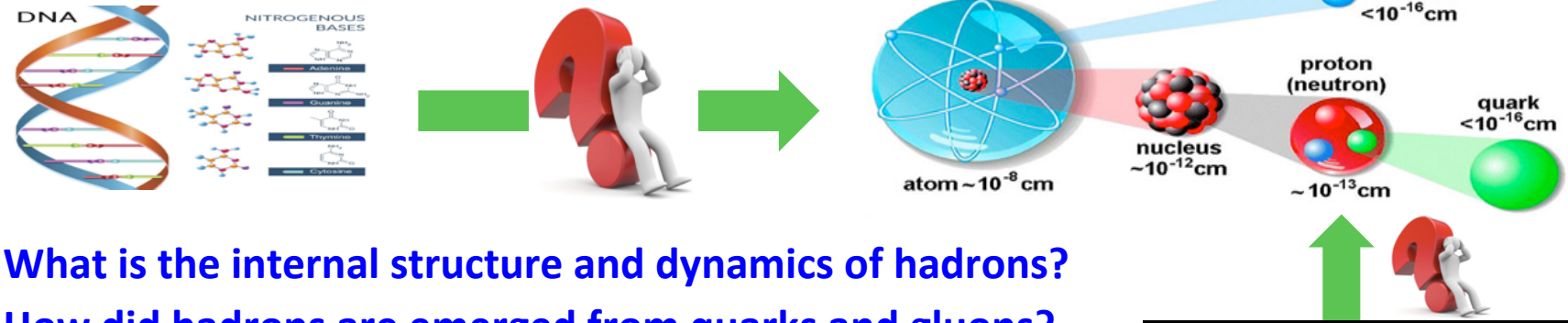
- **Understanding where did we come from?**

Global Time: ⟶

QCD at high temperature, high densities, phase transition, …

Facilities – Relativistic heavy ion collisions: SPS, RHIC, the LHC, …

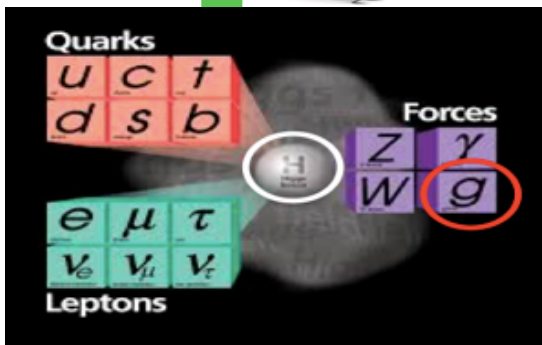
- **Understanding the visible world at 3°K – what are we made of?**



What is the internal structure and dynamics of hadrons?

How did hadrons are emerged from quarks and gluons?

How does the glue bind us all?



Facilities – CEBAF, EIC, …

Nuclear Femtography

Search for answers to these questions at a Fermi scale!

Outline 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?**

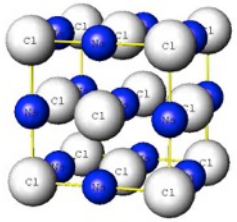
  Major Nuclear Science issues to be studied at an EIC
  EIC is an international effort

- **Summary and outlook**

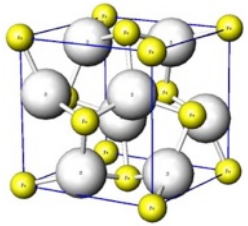
Atomic structure

- **Structure – "a still picture"**

Crystal Structure:

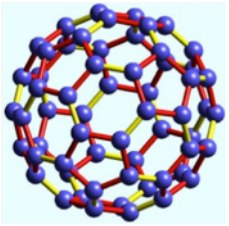


NaCl,
B1 type structure



FeS2,
C2, pyrite type structure

Nano-material:



Fullerene, C60

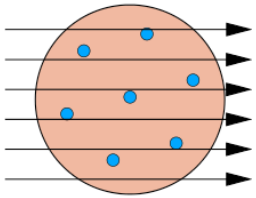
Motion of nuclei is much slower than the speed of light!

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

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

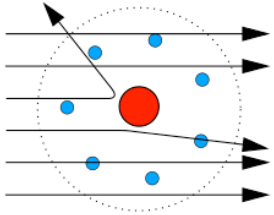
Over 100 years ago

Atom:



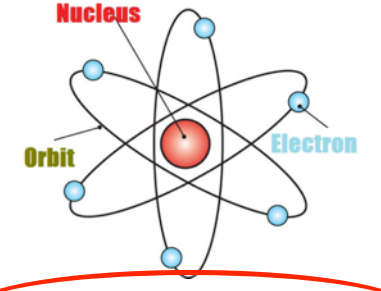
J.J. Thomson's
plum-pudding model

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 … !

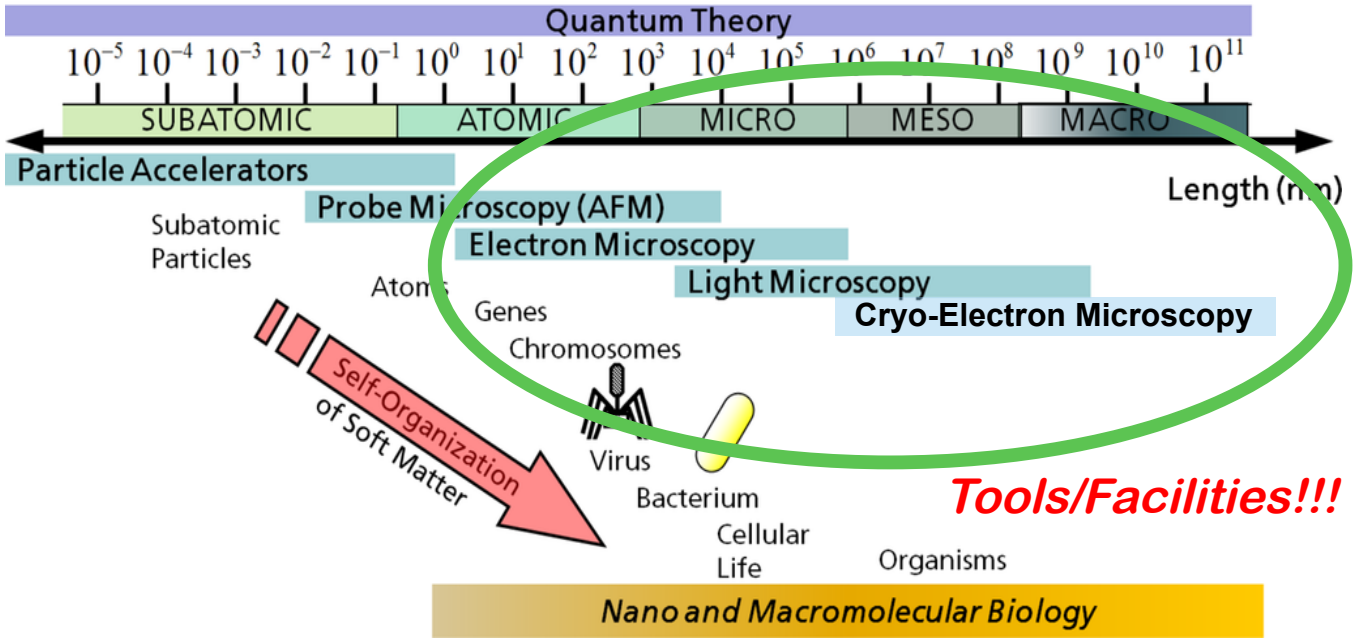
Nano-Science and Technology

❑ The idea:

"There's plenty of room at the bottom"

Feynman, APS meeting at Caltech, December 29, 1959

❑ New technology/facilities to advance:



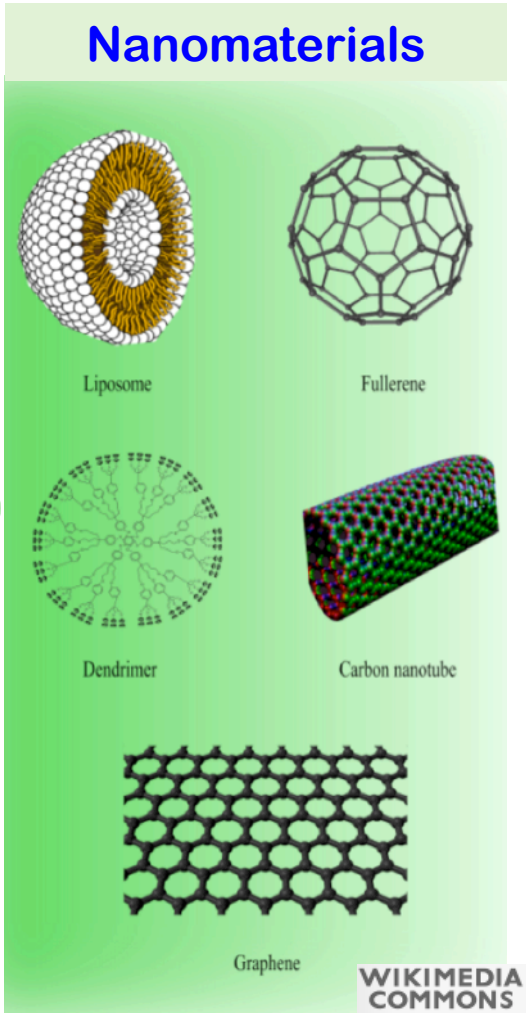
Tools/Facilities!!!

❑ The Support:

National Nanotechnology Initiative

Nano-science (1-100 nm)

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



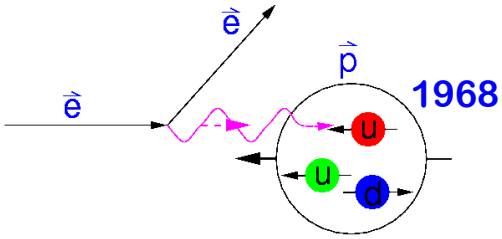
Ensure the role of quantum physics

Hadron structure

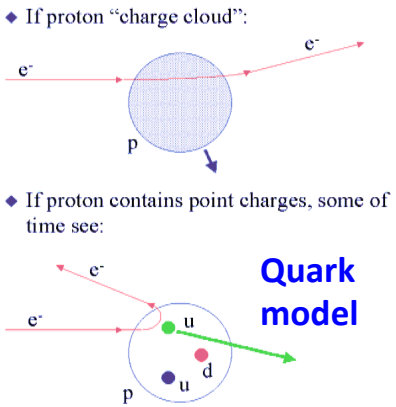
- A modern "Rutherford" experiment (about 50 years ago):

Nucleon: ***The building unit of all atomic nuclei***

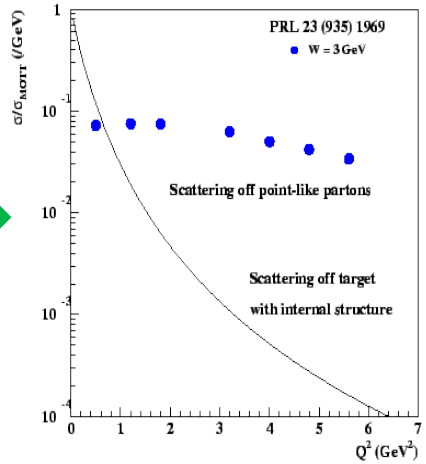
$e + p \rightarrow e + X$



Prediction



Discovery

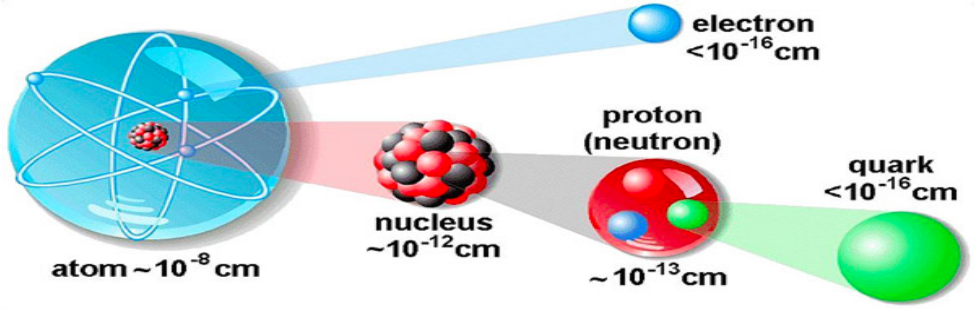


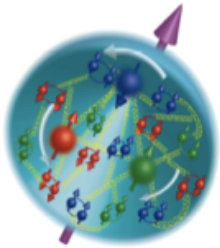
Discovery: ✧ Partons/Quarks – *moving relativistically*

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

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

Atomic world:





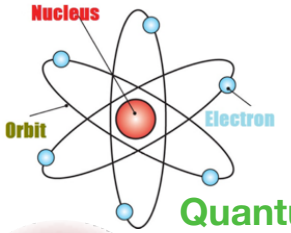
Birth of Quantum Chromodynamics (QCD) – gluons & color force!

Unprecedented intellectual challenge!

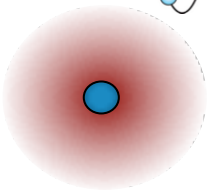
❑ The *challenge*:

✧ *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

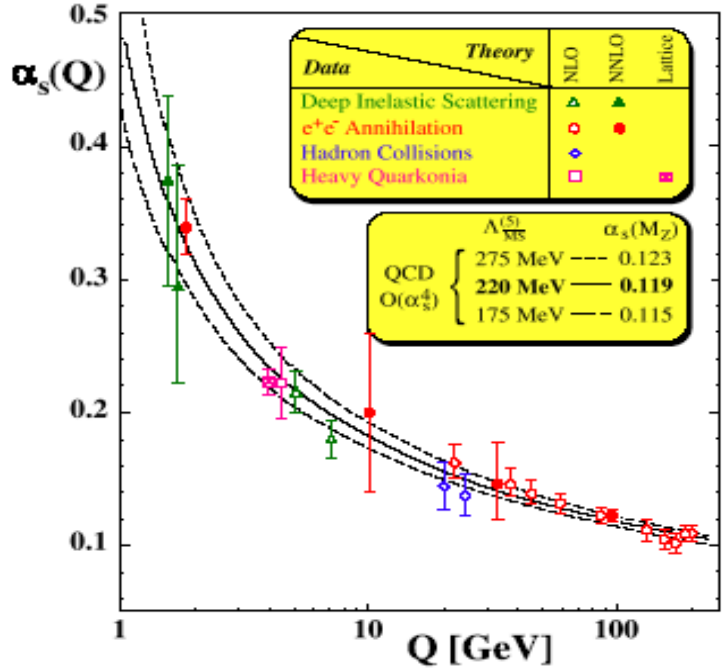


$B^+(u\bar{b})$

Brown-Muck

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

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



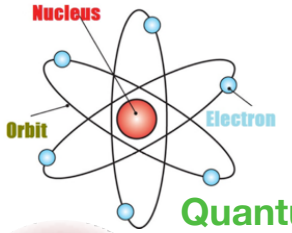
✧ *Interaction strength:* **Nobel Prize, 2004**

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

➡ *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!*



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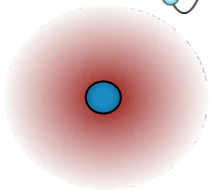


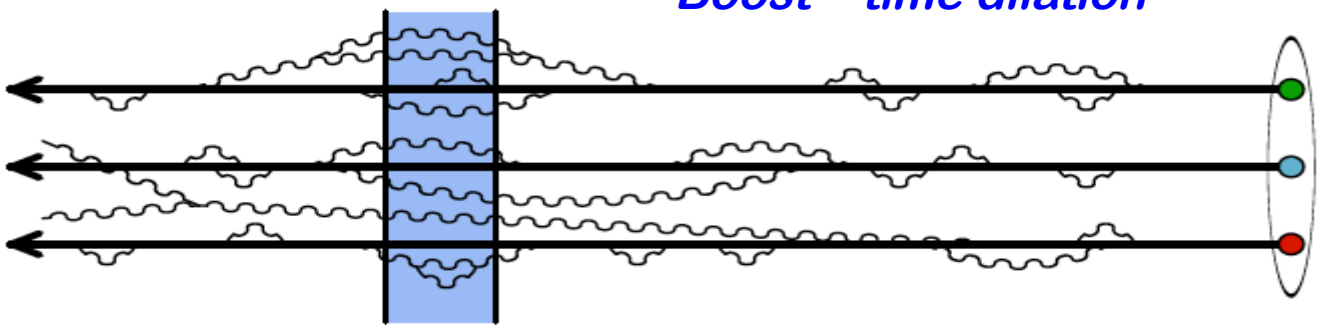
$B^+(u\bar{b})$

Brown-Muck

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

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

Boost = time dilation



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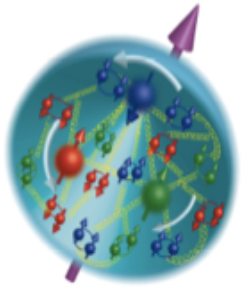

Hard probe (t ~ 1/Q << fm) ➡ *Probability to "catch" the parton!*

or "catch" the quantum fluctuation

Feynman:

At t ~ 1/Q << fm, the probe is only sensitive to the momentum fraction of the probed quark (or gluon) xP ~ Q and the probability f(x)

Unprecedented intellectual challenge!

- The *challenge*:
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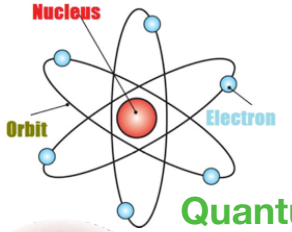
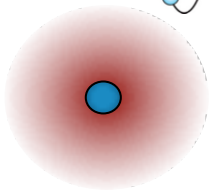


Quantum orbits



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

Brown-Muck

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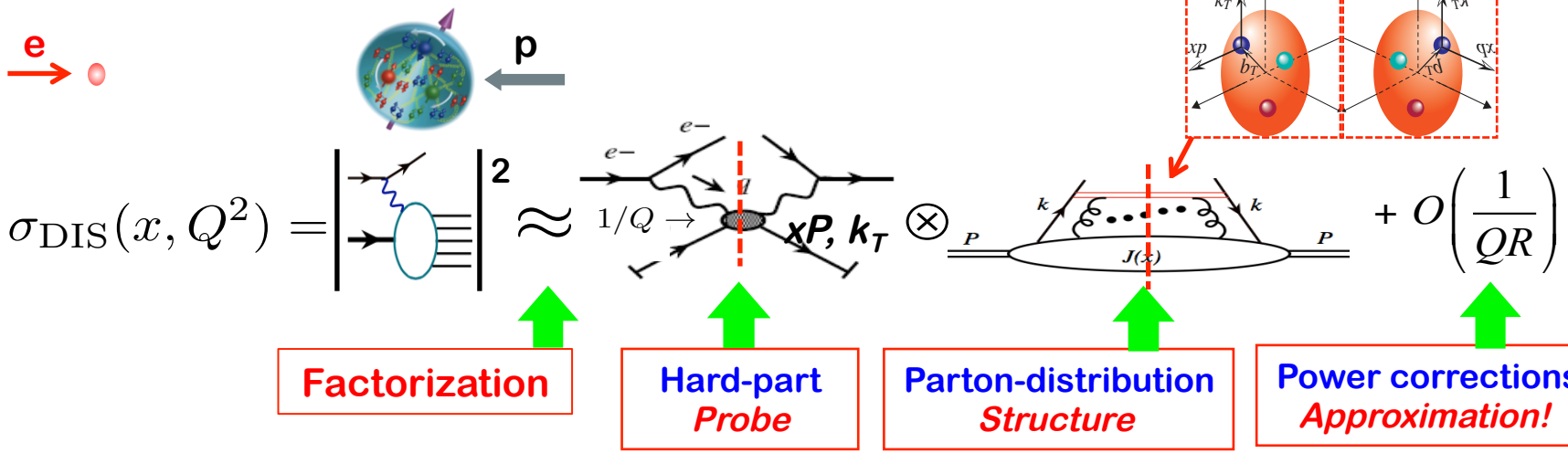
- The *need* – a probe to "see" quarks and gluons:



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

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

Measurement ⟺ Factorization ⟺ Quantum probabilities!

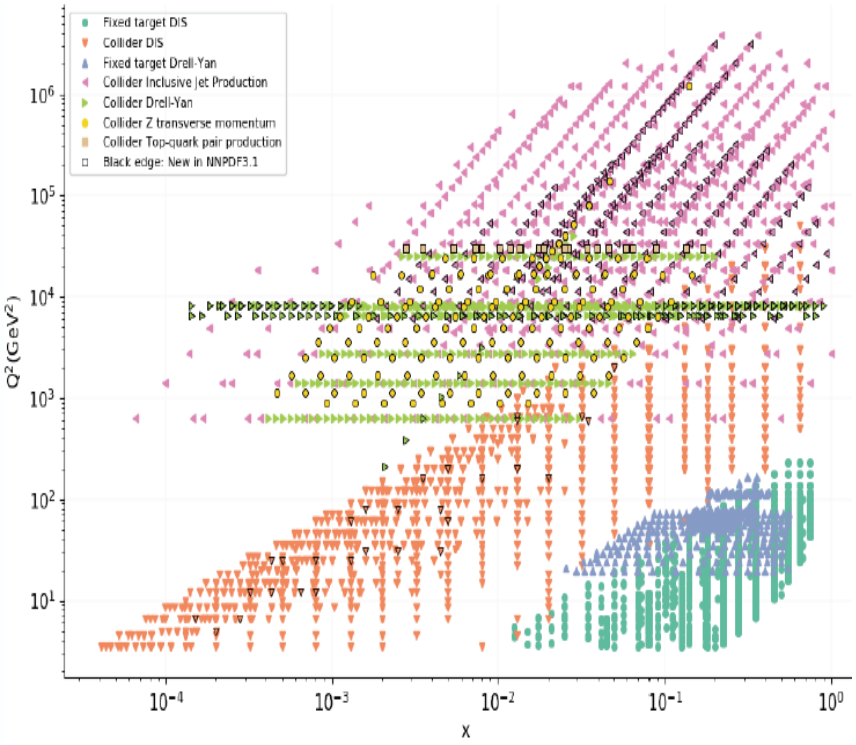
Unprecedented success of QCD and SM!

❑ Data sets for Global Fits:

	Process	Subprocess	Partons	x range
Fixed Target	$\ell^\pm\{p,n\} \to \ell^\pm + X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
	$\ell^\pm n/p \to \ell^\pm + X$	$\gamma^* d/u \to d/u$	d/u	$x \gtrsim 0.01$
	$pp \to \mu^+\mu^- + X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
	$pn/pp \to \mu^+\mu^- + X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
	$\nu(\bar{\nu})N \to \mu^-(\mu^+) + X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
	$\nu N \to \mu^- \mu^+ + X$	$W^* s \to c$	s	$0.01 \lesssim x \lesssim 0.2$
	$\bar{\nu} N \to \mu^+ \mu^- + X$	$W^* \bar{s} \to \bar{c}$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
Collider DIS	$e^\pm p \to e^\pm + X$	$\gamma^* q \to q$	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
	$e^+ p \to \bar{\nu} + X$	$W^+\{d,s\} \to \{u,c\}$	d, s	$x \gtrsim 0.01$
	$e^\pm p \to e^\pm c\bar{c} + X$	$\gamma^* c \to c, \gamma^* g \to c\bar{c}$	c, g	$10^{-4} \lesssim x \lesssim 0.01$
	$e^\pm p \to e^\pm b\bar{b} + X$	$\gamma^* b \to b, \gamma^* g \to b\bar{b}$	b, g	$10^{-4} \lesssim x \lesssim 0.01$
	$e^\pm p \to \text{jet} + X$	$\gamma^* g \to q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$
Tevatron	$p\bar{p} \to \text{jet} + X$	$gg, qg, qq \to 2j$	g, q	$0.01 \lesssim x \lesssim 0.5$
	$p\bar{p} \to (W^\pm \to \ell^\pm \nu) + X$	$u\bar{d} \to W^+, \bar{u}d \to W^-$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
	$p\bar{p} \to (Z \to \ell^+\ell^-) + X$	$uu, dd \to Z$	u, d	$x \gtrsim 0.05$
	$p\bar{p} \to t\bar{t} + X$	$qq \to t\bar{t}$	q	$x \gtrsim 0.1$
LHC	$pp \to \text{jet} + X$	$gg, qg, q\bar{q} \to 2j$	g, q	$0.001 \lesssim x \lesssim 0.5$
	$pp \to (W^\pm \to \ell^\pm \nu) + X$	$u\bar{d} \to W^+, d\bar{u} \to W^-$	$u, d, \bar{u}, \bar{d}, g$	$x \gtrsim 10^{-3}$
	$pp \to (Z \to \ell^+\ell^-) + X$	$q\bar{q} \to Z$	$q, \bar{q}, g$	$x \gtrsim 10^{-3}$
	$pp \to (Z \to \ell^+\ell^-) + X, p_\perp$	$gq(\bar{q}) \to Zq(\bar{q})$	$g, q, \bar{q}$	$x \gtrsim 0.01$
	$pp \to (\gamma^* \to \ell^+\ell^-) + X$, Low mass	$q\bar{q} \to \gamma^*$	$q, \bar{q}, g$	$x \gtrsim 10^{-4}$
	$pp \to (\gamma^* \to \ell^+\ell^-) + X$, High mass	$q\bar{q} \to \gamma^*$	$\bar{q}$	$x \gtrsim 0.1$
	$pp \to W^+\bar{c}, W^-c$	$sg \to W^+c, \bar{s}g \to W^-\bar{c}$	$s, \bar{s}$	$x \sim 0.01$
	$pp \to t\bar{t} + X$	$gg \to t\bar{t}$	g	$x \gtrsim 0.01$
	$pp \to D, B + X$	$gg \to c\bar{c}, b\bar{b}$	g	$x \gtrsim 10^{-6}, 10^{-5}$
	$pp \to J/\psi, \Upsilon + pp$	$\gamma^*(gg) \to c\bar{c}, b\bar{b}$	g	$x \gtrsim 10^{-6}, 10^{-5}$
	$pp \to \gamma + X$	$gq(\bar{q}) \to \gamma q(\bar{q})$	g	$x \gtrsim 0.005$

❑ Kinematic Coverage:

NNPDF3.1

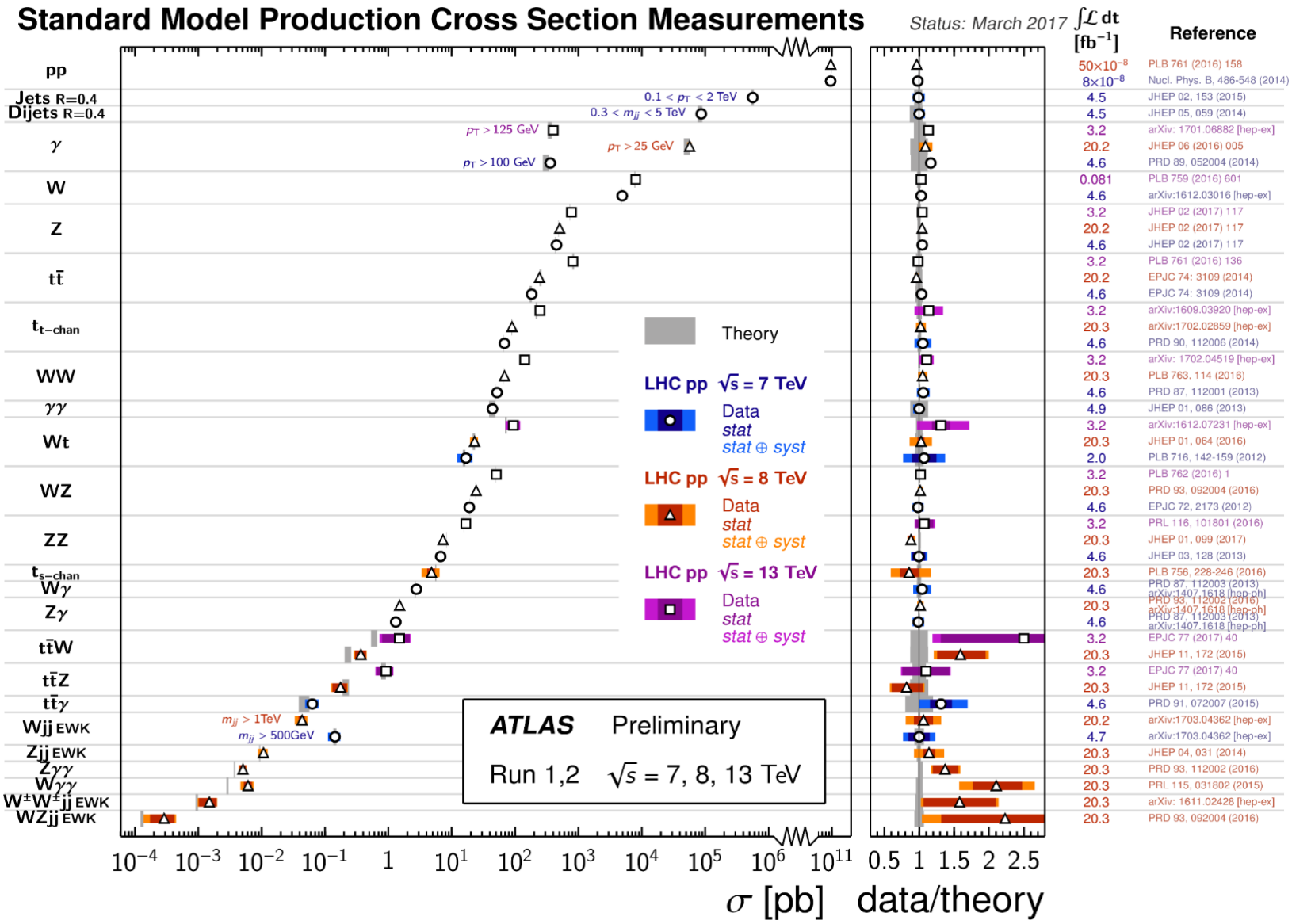


❑ Fit Quality:

$\chi^2/\text{dof} \sim 1 \Rightarrow$ Non-trivial check of QCD

All data sets	3706 / 2763	3267 / 2996	2717 / 2663
	LO	NLO	NNLO

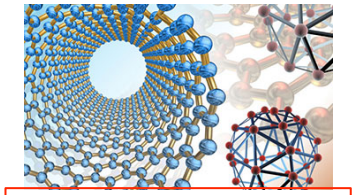
Unprecedented success of QCD and SM!



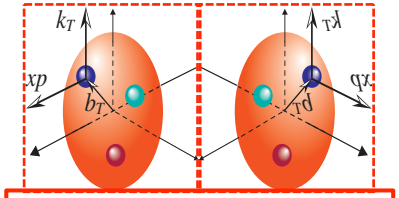
SM: Electroweak processes + QCD perturbation theory works!

From nano-science to femto-science

❑ The idea:



Nano-science
(1-100 nm)



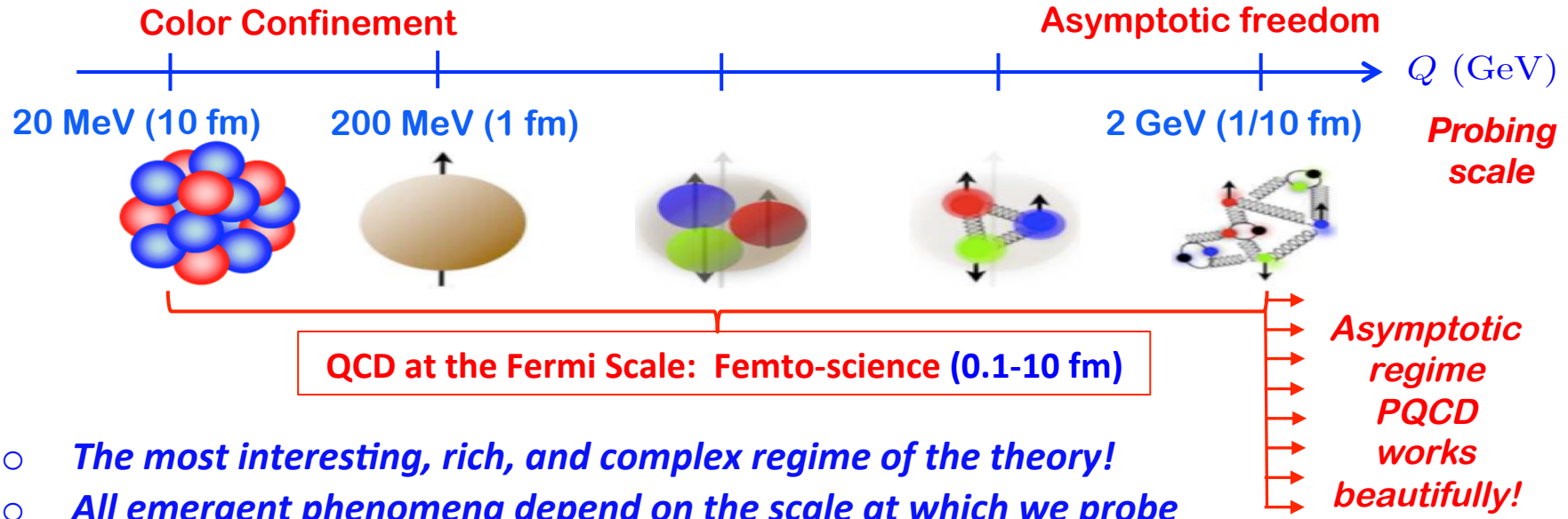
Femto-science
(0.1-10 fm)

Quantum Probability

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

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

❑ QCD landscape of nucleons and nuclei:

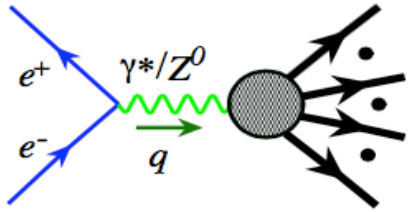


- *The most interesting, rich, and complex regime of the theory!*
- *All emergent phenomena depend on the scale at which we probe them!*

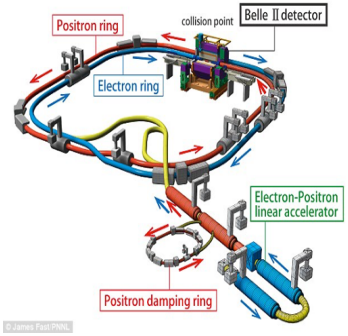
Need new facility capable of exploring this!

Why do we need lepton-hadron facilities?

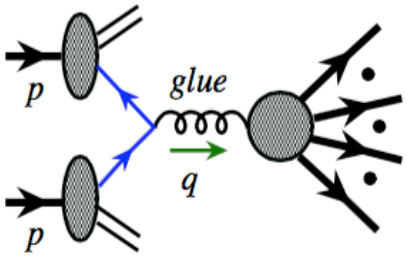
- **Hadrons are produced from the energy in e+e- collisions:**



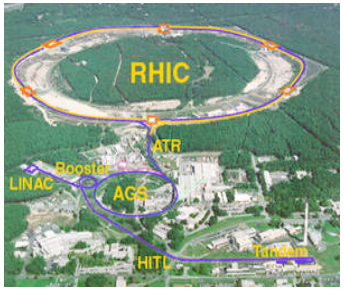
- *No hadron to start with*
- *Emergence of hadrons*



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

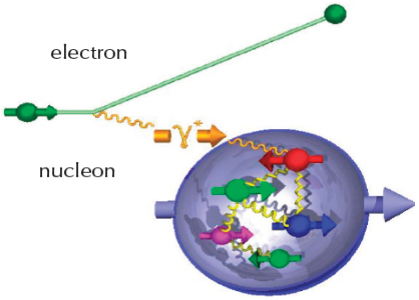


- *Partonic structure*
- *Emergence of hadrons*
- *Heavy ion target or beam(s)*



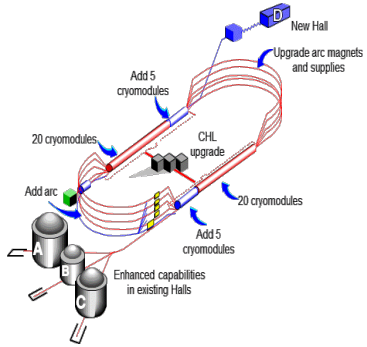
Also at the LHC

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



One facility covers all!

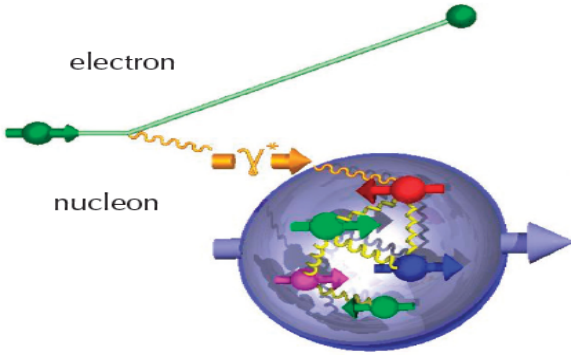
- *Colliding hadron can be broken or stay intact!*
- *Imaging partonic structure*
- *Emergence of hadrons*
- *Heavy ion target or beam*



Also at COMPASS & future EIC

Many complementary probes at one facility

- The new generation of "Rutherford" experiment:



- A controlled "probe" – virtual photon
- Can either break or not break the hadron

One facility covers all!

- **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)

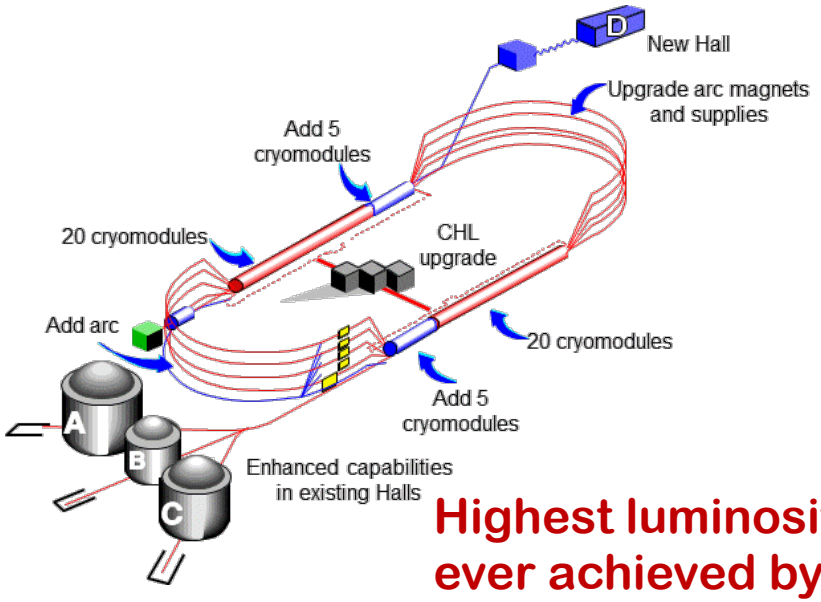
  Detect every things including scattered proton/nucleus (or its fragments)

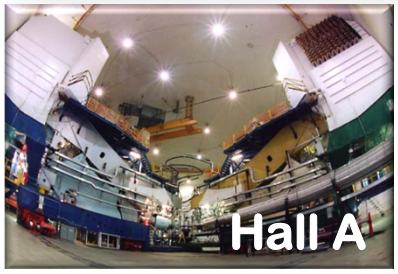
  (Initial hadron is NOT broken – tomography! – almost impossible for h-h collisions)

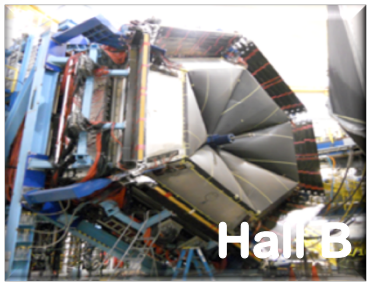
Jefferson Lab @ 12 GeV

❑ Lepton-hadron facility in the US now:

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







Highest luminosity ever achieved by a lepton-hadron facility

10^{38} (cm^{-2} s^{-1})

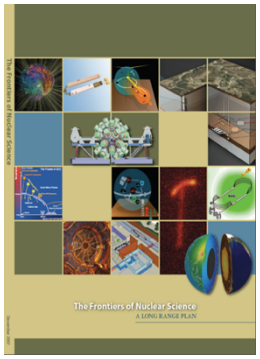
Future: MOLLER SoLID Detector

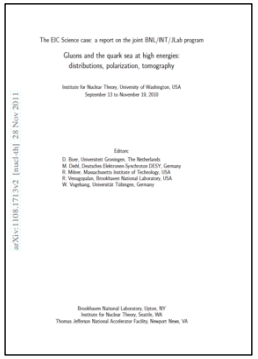
- Search for exotic hadrons, …
- Explore for 3D hadron structure, …
- Search for dark matter, photon, …
- Advance accelerator technology, …
- …

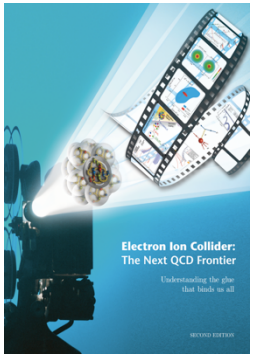
U.S. - based Electron-Ion Collider

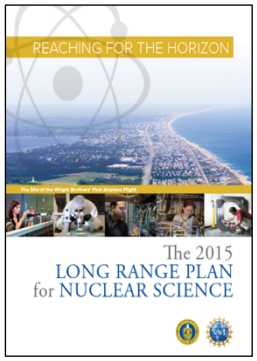
- A long journey, a joint effort of the full community:

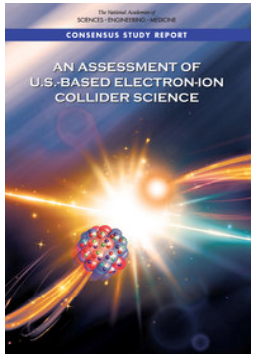
...











...

"... 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?

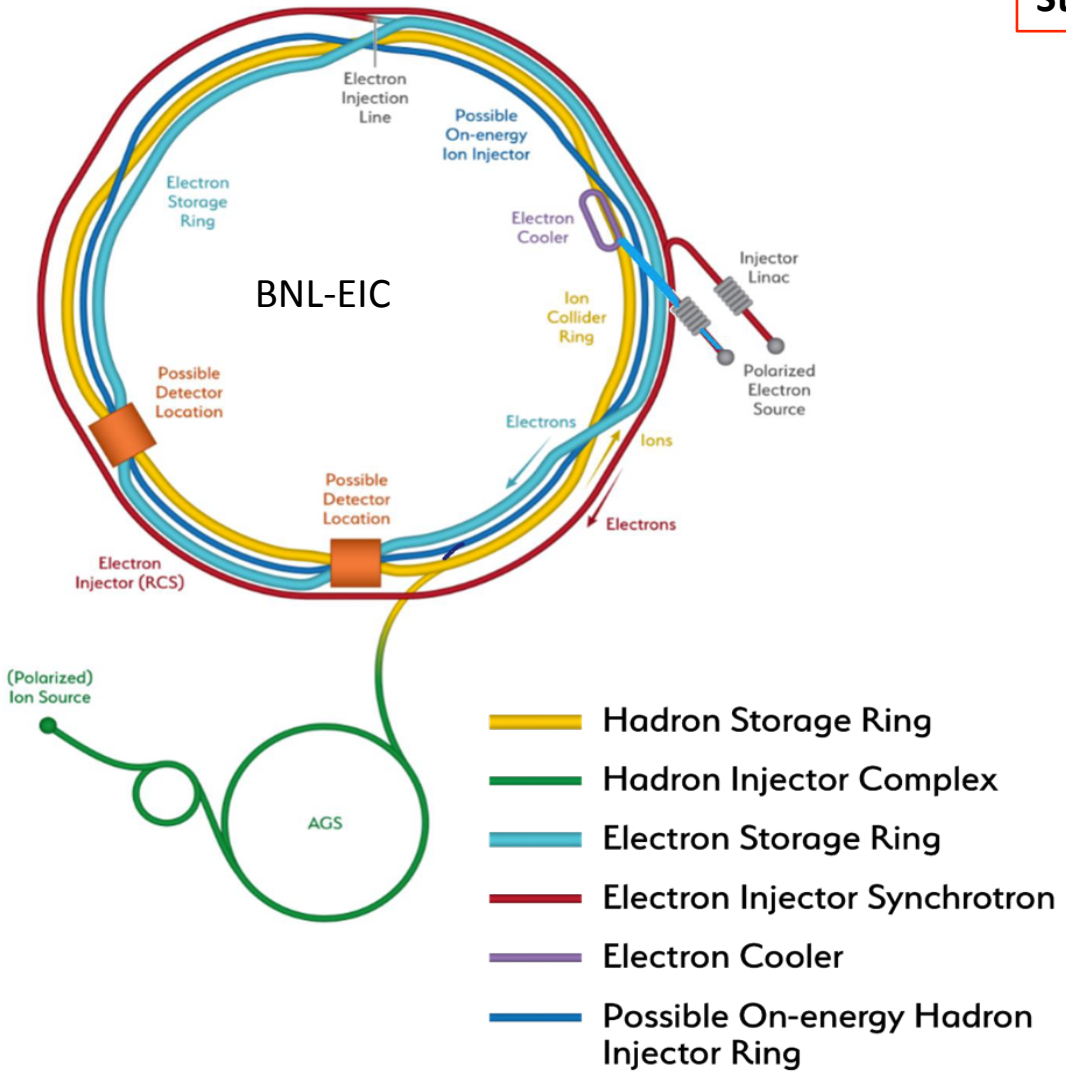
- On January 9, 2020:

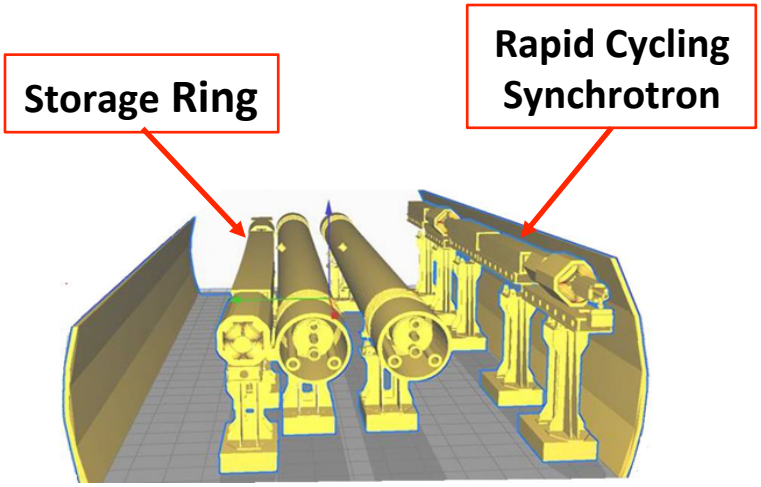
The U.S. DOE announced the selection of BNL as the site for the Electron-Ion Collider

→ ***A new era to explore the emergent phenomena of QCD!***

U.S. - based Electron-Ion Collider

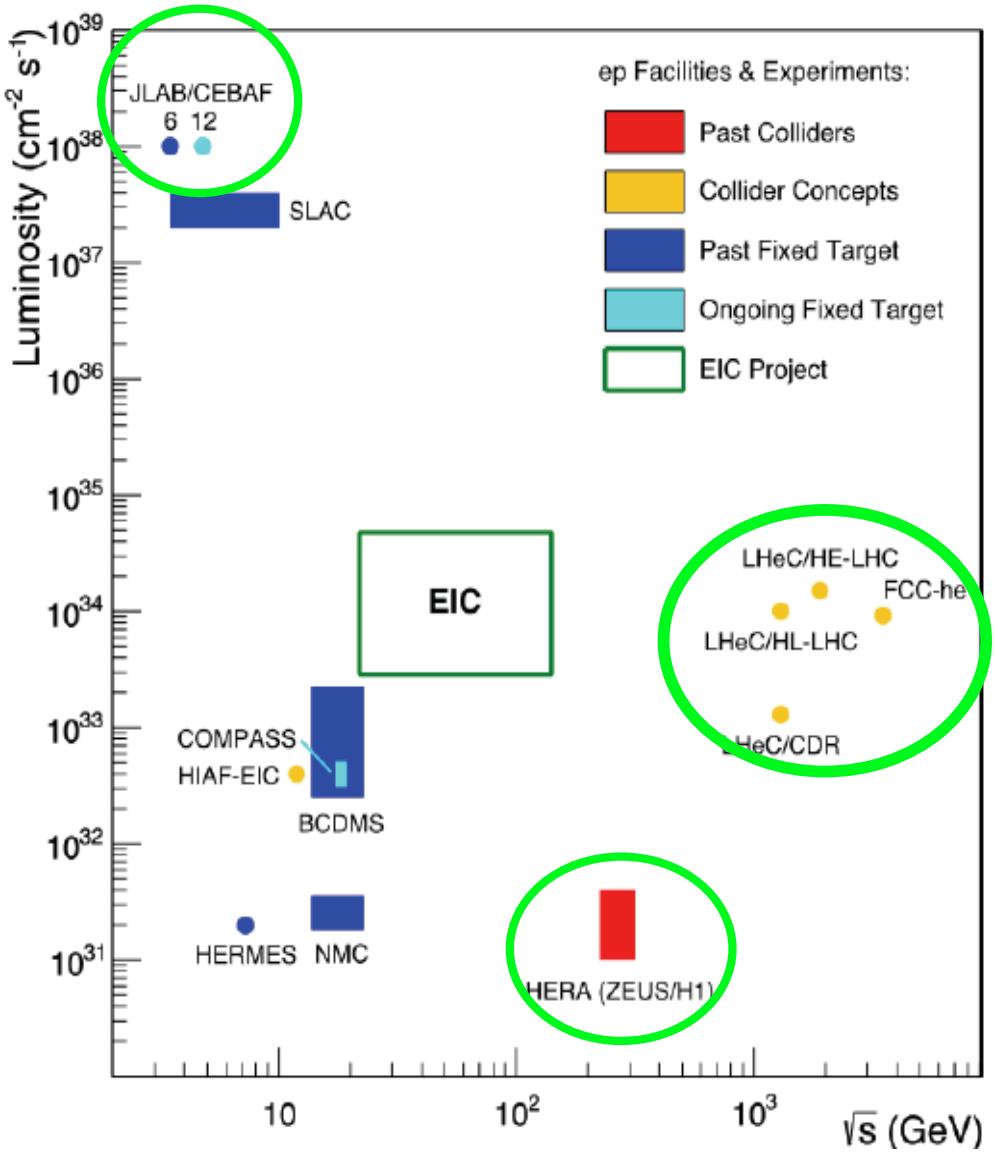
❑ The winning design - BNL:

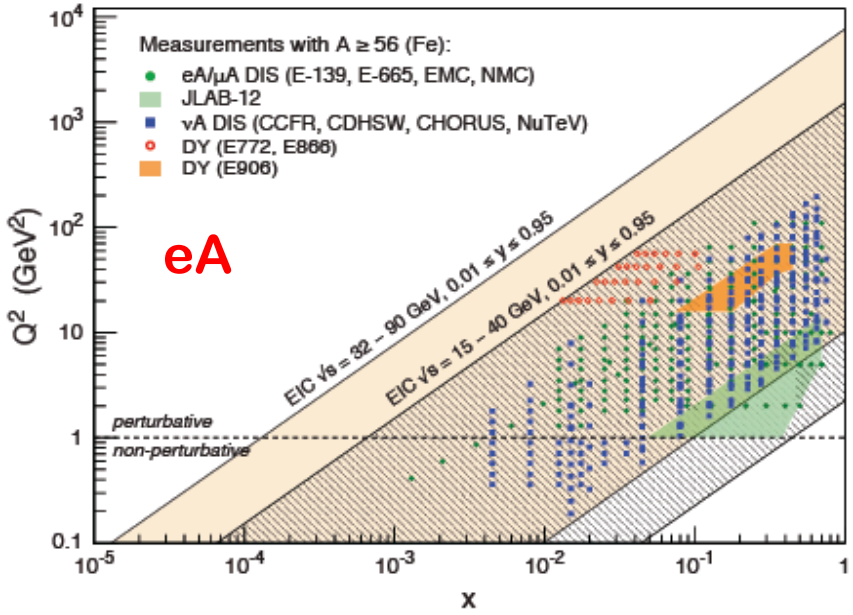


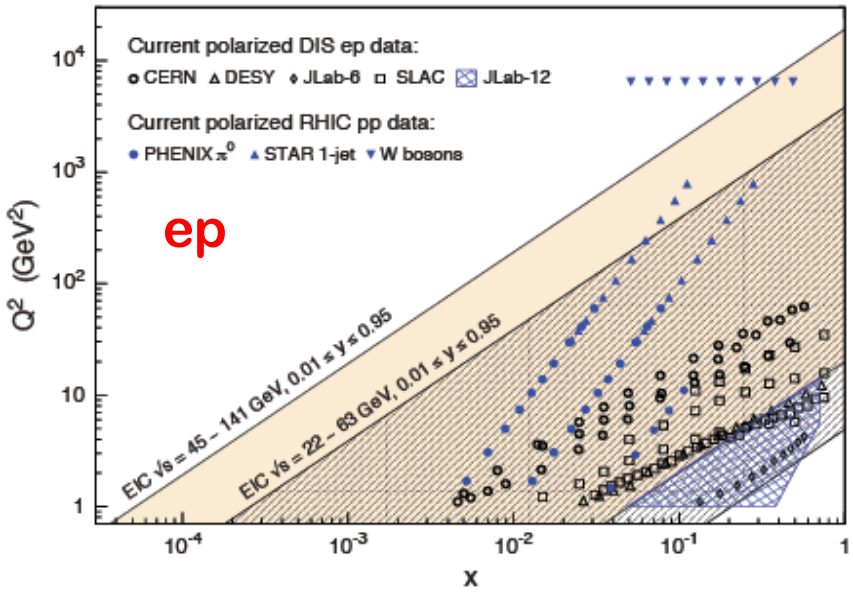


- **Center of Mass Energies:**
  20 GeV – 141 GeV
- **Required Luminosity:**
  10^{33} - 10^{34} $cm^{-2}s^{-1}$
- **Hadron Beam Polarization:**
  80%
- **Electron Beam Polarization:**
  80%
- **Ion Species Range:**
  p to Uranium
- **Number of interaction regions:**
  up to two

EIC – the World Wide Interest

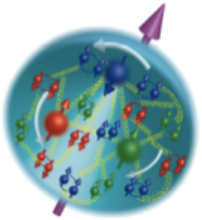






How EIC answer these questions and more?

❑ Nucleon Mass – dominates the Mass of visible world!

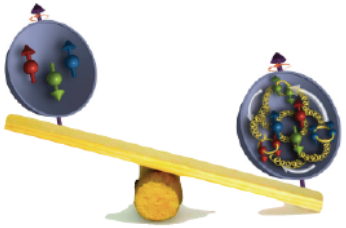


Nucleon – a relativistic bound state of quarks and gluons

Mass is the Energy of the nucleon when it is at the Rest!

Mass = Rest Mass of quarks and gluons + Their Energy

❑ Higgs mechanism is NOT enough – mass without mass!

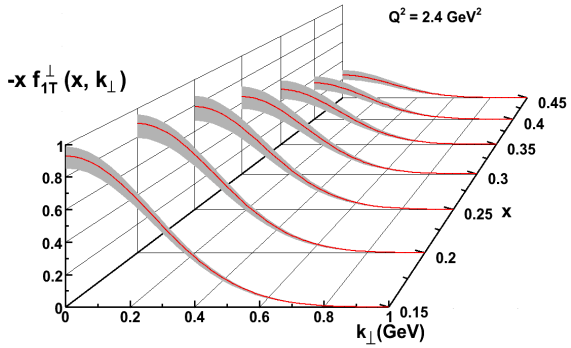


It is the Energy of Confined Motion of quarks and gluons in nucleon's rest frame!!!

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 $K+T$: $M_p \sim \frac{4}{R} \sim \frac{4}{0.84\text{fm}} \sim 938\ \text{MeV}$

❑ Confined motion of quarks and gluons – how to "see" it?



Transverse motion of quarks/gluons inside a colliding nucleon

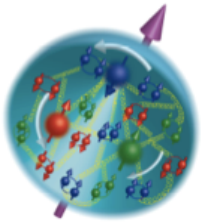
$$f(x) \longrightarrow f(x, k_T)$$ – the TMDs

Gives much needed information on the Confined Motion!

➡ *Need probes to "see" 3D partonic motion!*

How EIC answer these questions and more?

- **Nucleon Spin – without it, our visible world would not be the same!**

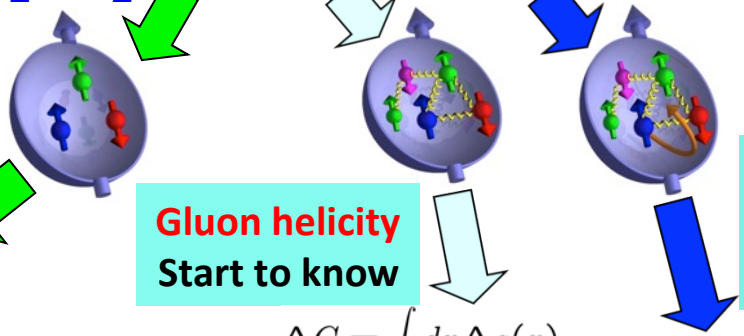


Spin is the Angular Momentum of the nucleon when it is at the Rest!

Spin = Spin of quarks and gluons + Orbital Angular Momentum

Helicity = Helicity of quarks and gluons + Their transverse motion

- **An incomplete story:** $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$



Quark helicity
Best known

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

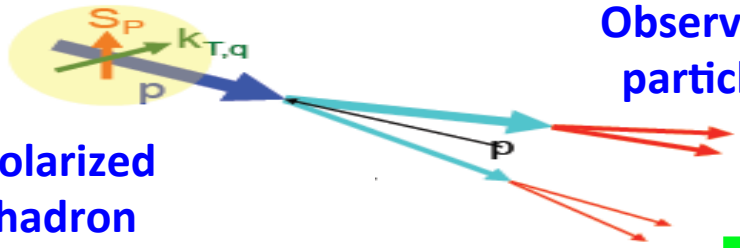
Gluon helicity
Start to know

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

Orbital Angular Momentum of quarks and gluons
Little known

Net effect of partons' transverse motion?

- **Correlation between hadron spin and parton motion within it?**



Polarized hadron

Observed particle

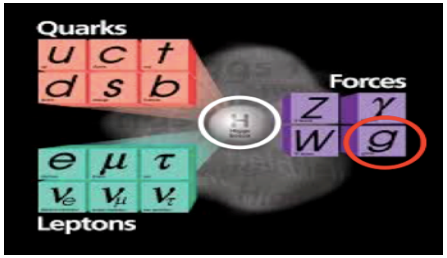
Sivers effect – Sivers function

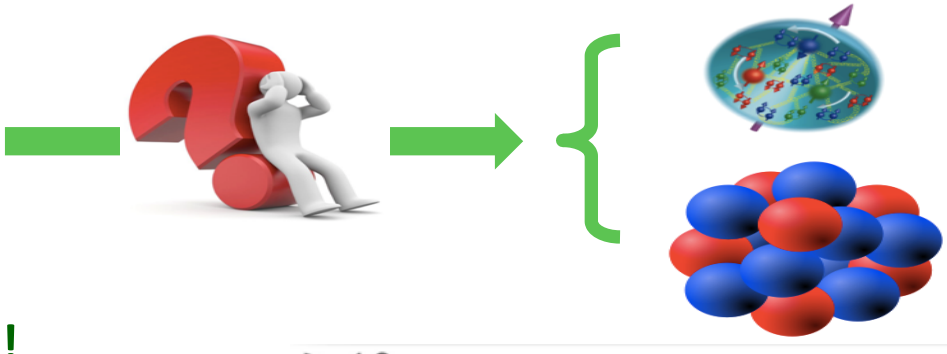
Hadron spin influences parton's transverse motion

Need probes to "see" 3D partonic motion!

How EIC answer these questions and more?

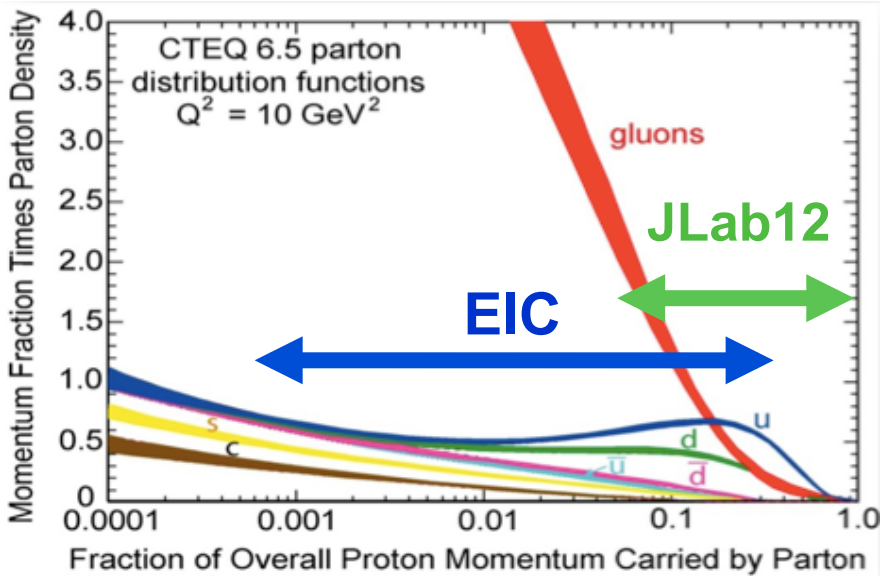
❑ Understanding the Glue that binds us all:





❑ Gluons are weird particles!

- ✧ Massless, yet, responsible for a lot of visible mass
- ✧ Carry color charge, unlike photon, responsible for color confinement but, also for asymptotic freedom, as well as the abundance of glue!



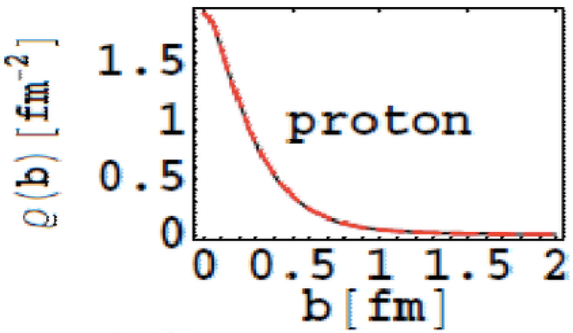
Without gluons, there would be NO nucleons, NO atomic nuclei… NO visible world!

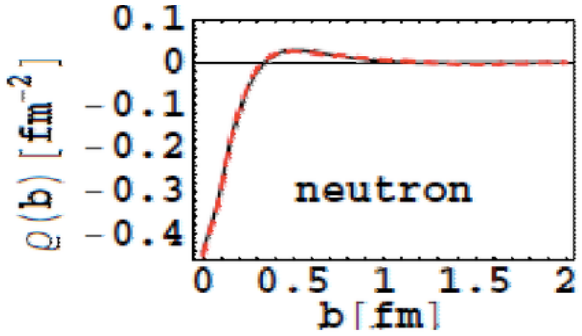
- ***What are the emergent properties of dense systems of gluons?***
- ***What does a nucleus look like if we only see quarks and gluons?***
- ***What is the coherent length of color force? …***

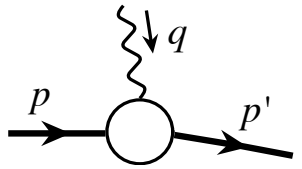
How EIC answer these questions and more?

- How Color Charge is distributed inside a nucleon (clue for color confinement?

  Elastic electric form factor ➡ Charge distributions







➡ Proton Radius

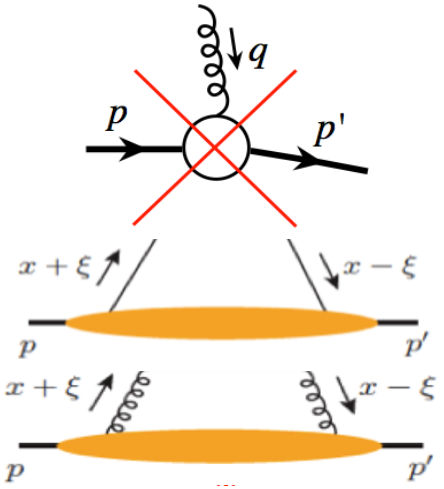
- But, there is NO elastic "color" form factor!

  Generalized form factor for quarks and gluons

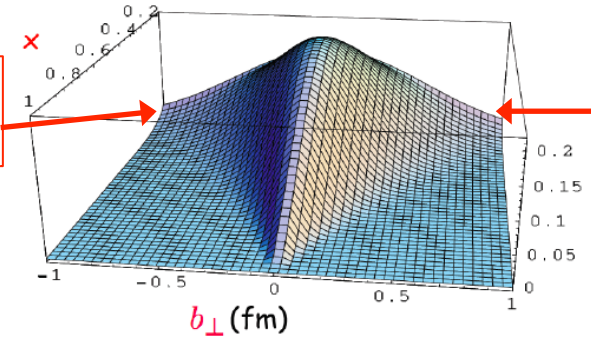
  Generalized PDFs (GPDs) – without breaking the proton

  Fourier transform of momentum transfer: p-p'

  ➡ Special parton density distributions



How far does glue density spread?

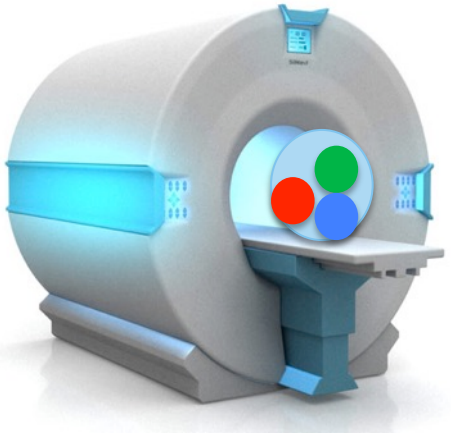


How fast does glue density fall?

Need to measure these GPDs?

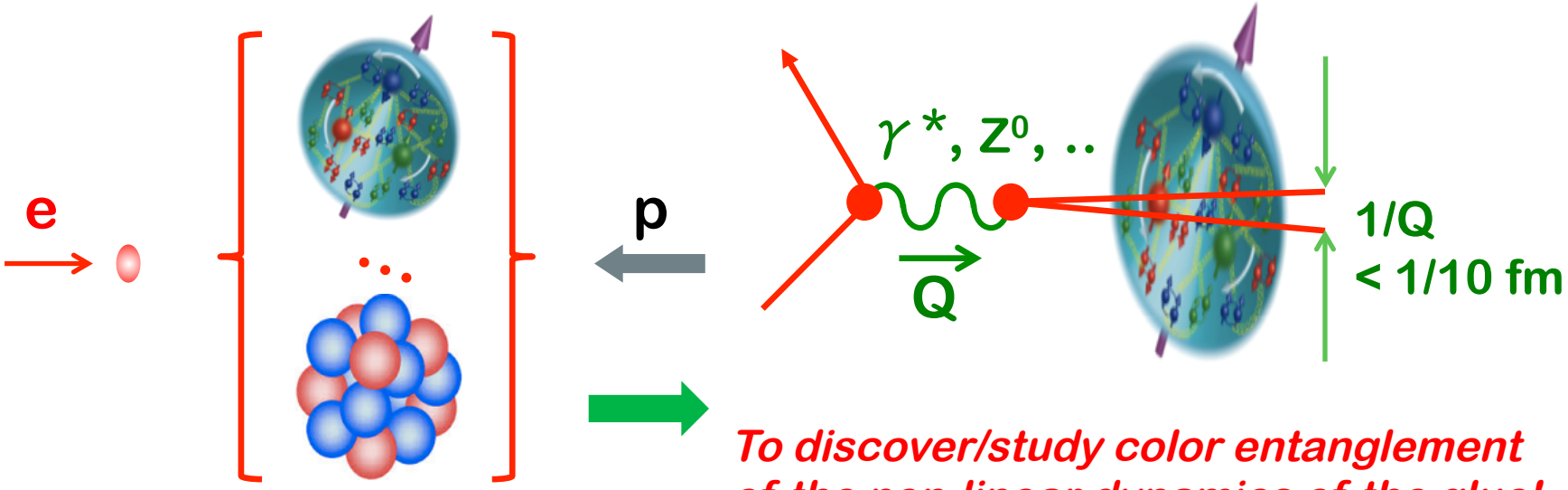
The Electron-Ion Collider (EIC) – the Future!

- 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!*

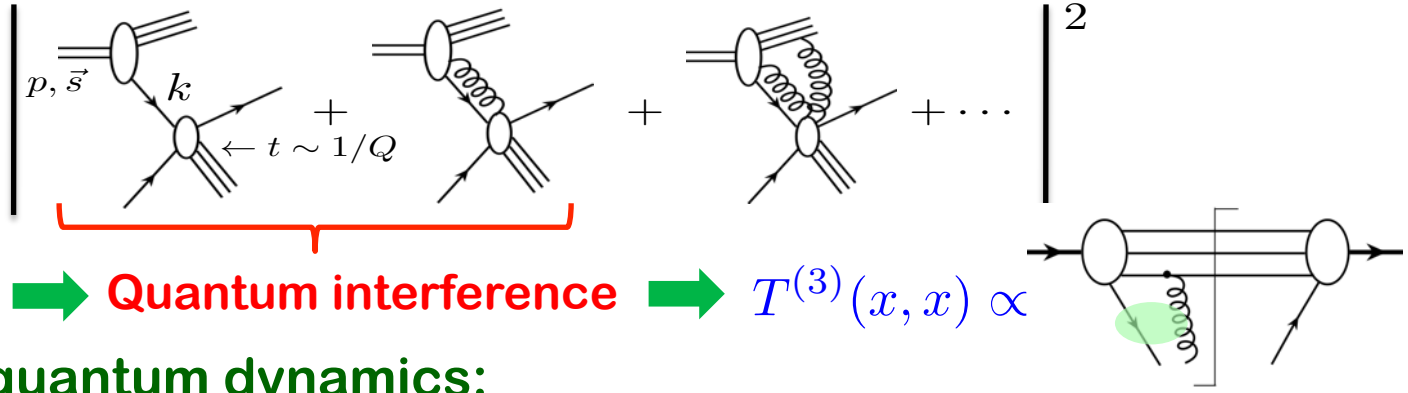
- A giant "Microscope" – "see" quarks and gluons by breaking the hadron



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

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!

$\sigma(Q,\vec{s}) \propto$ 

$\sigma(s) - \sigma(-s)$ ➡ **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?

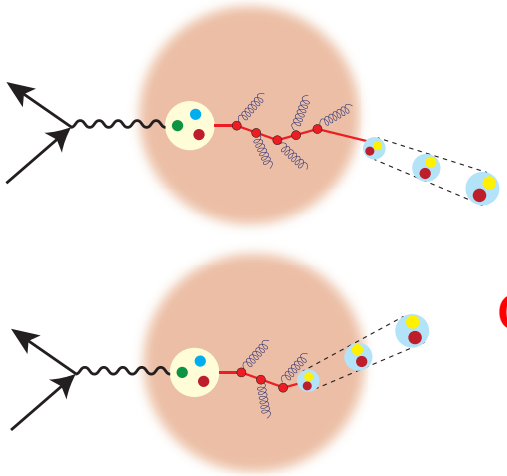
- ✧ Emergence of hadrons
- ✧ Hadron properties:
  mass, spin, …
- ✧ Hadron's 3D partonic structure:
  confined motion, spatial distribution,
  color correlation, fluctuation,
  saturation, …
- ✧ Quantum correlation between
  hadron properties and parton dynamics, …

…

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

Emergence of Hadrons from quarks & gluons

- **Femtometer sized detector:**

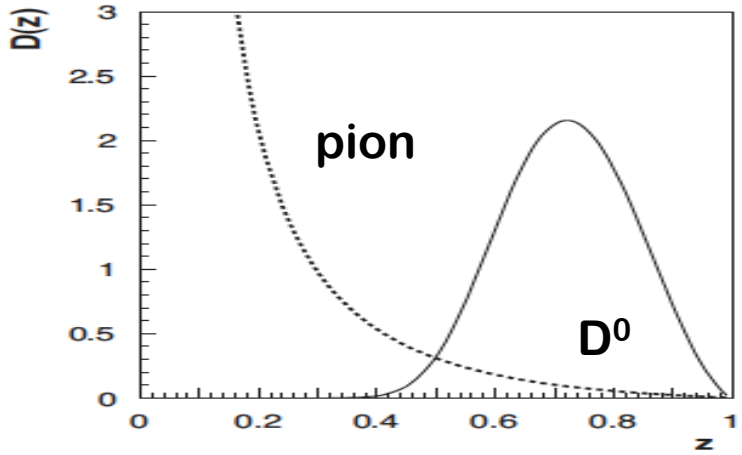


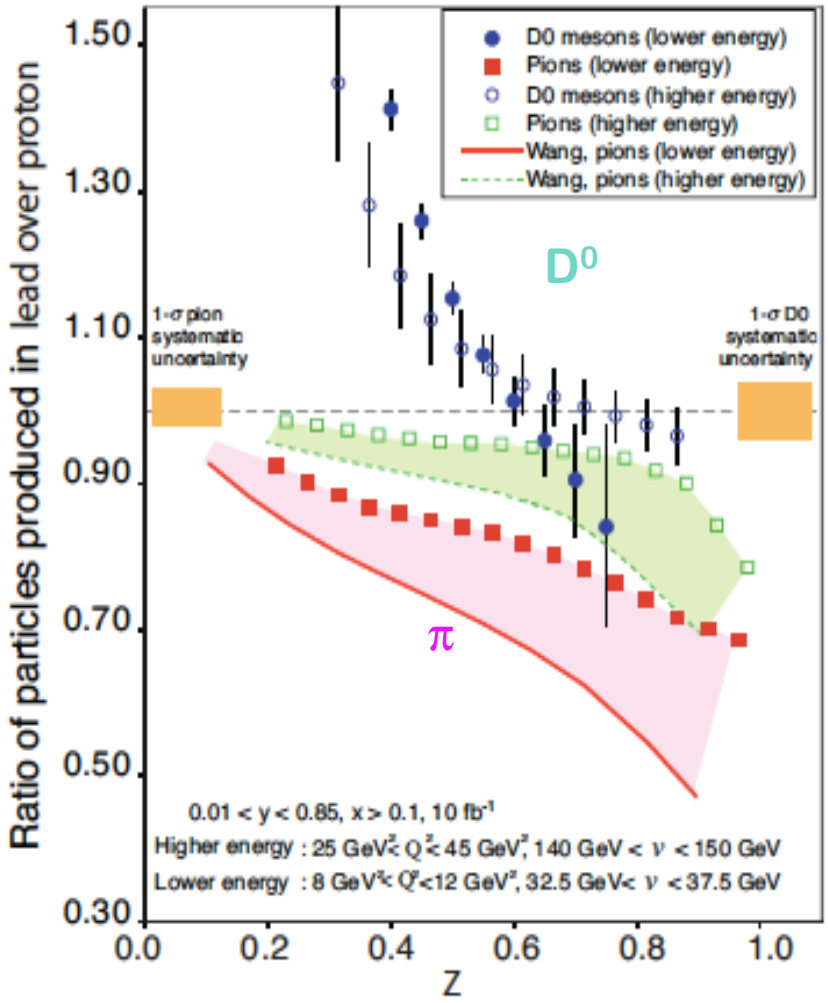
$$\nu = \frac{Q^2}{2mx}$$

Control of ν and medium length!

Mass dependence of hadronization

- **Heavy quark energy loss:**





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

Who ordered the hadron mass scale?

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

Higgs mechanism is far from enough!!!

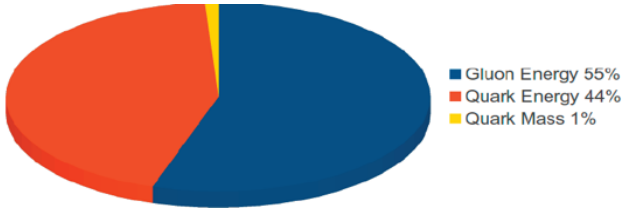
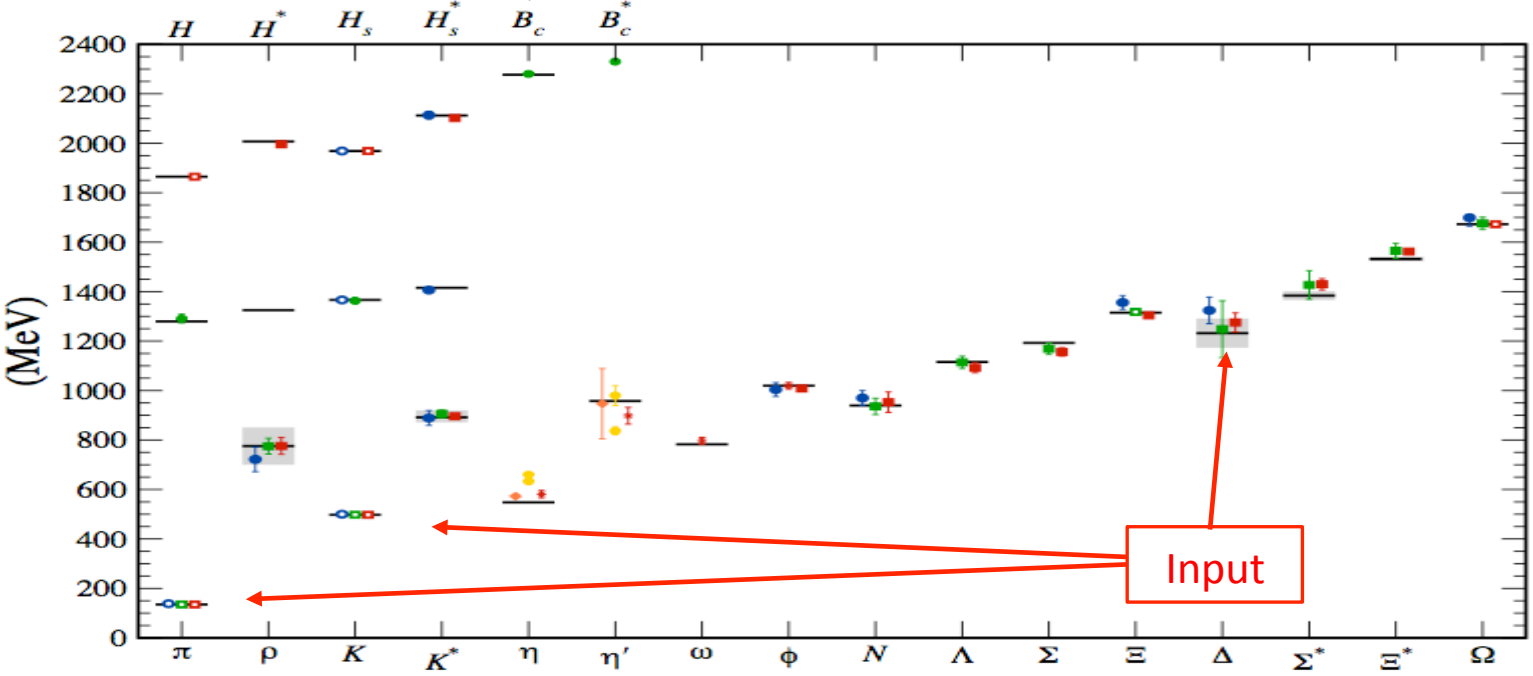


Fig. 2.1 NAS Report

"Mass without mass!"

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



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

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

  - **Hadron mass:** ***Gluon quantum effect + Chiral symmetry breaking!***

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

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

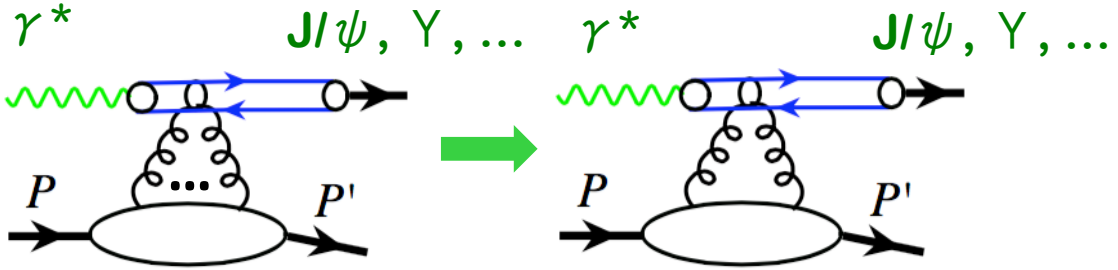
Relativistic motion; χ Symmetry Breaking; Quantum fluctuation; Trace Anomaly; Quark Energy; Gluon Energy; Quark Mass

Sum Rule is useful iff ALL individual terms can be measured independently!

- **Critical test of QCD:**

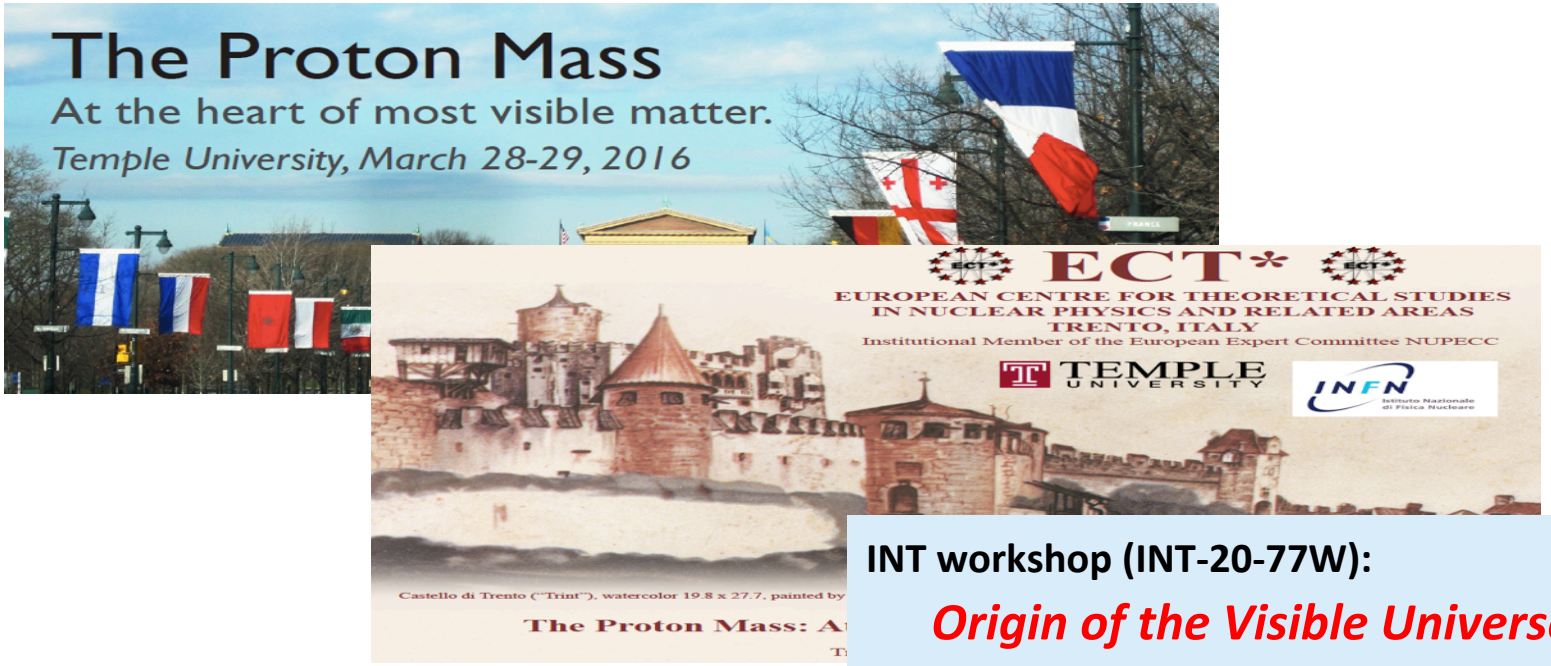
Probing Trace anomaly:

Probe parton energy distribution inside the proton?



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**



A true international effort!
A focused meeting is planned for coming January

INT workshop (INT-20-77W):

Origin of the Visible Universe:
Unraveling the Proton Mass

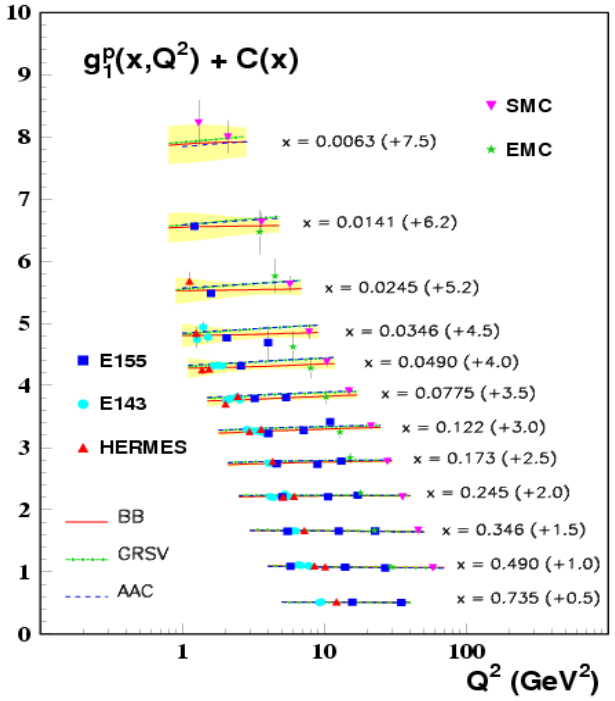
May 4-8, 2020,

I. Cloet, Z.-E. Meziani, B. Pasquini

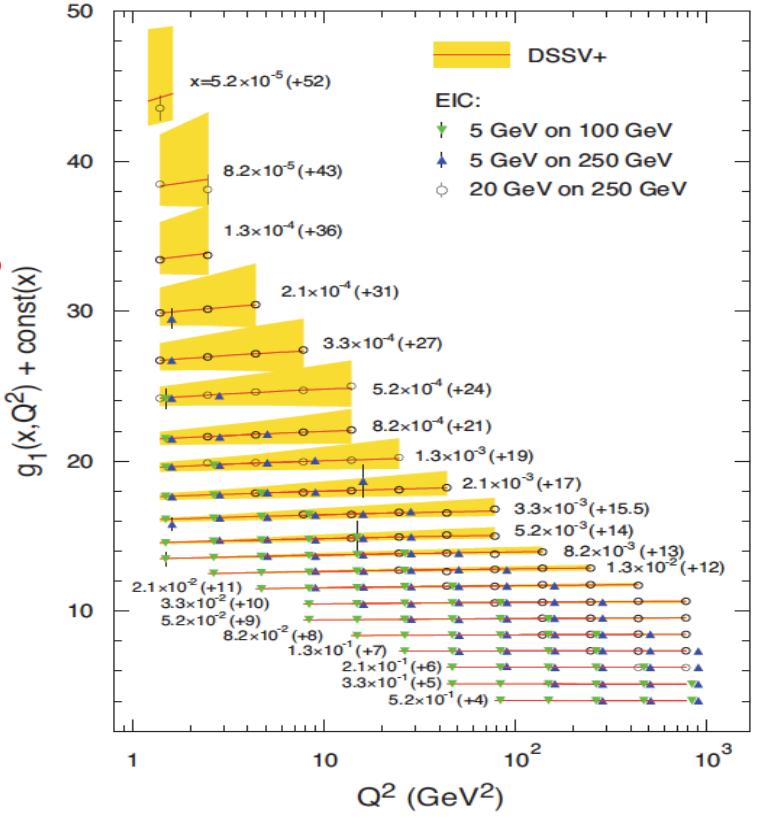
(Postponed due to COVID-19)

The Proton Spin: from JLab12 to EIC

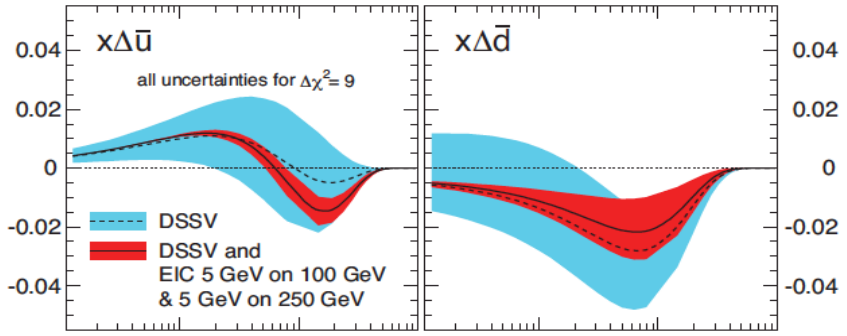
❑ The power & precision of EIC:

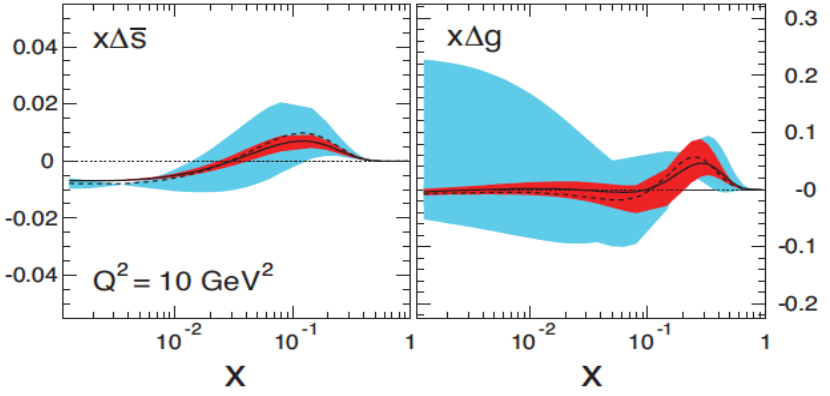


Polarized DIS at EIC



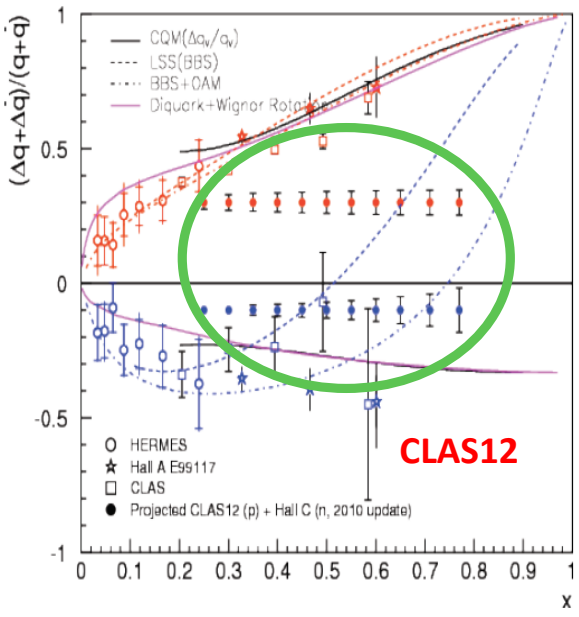
❑ What an EIC could help:

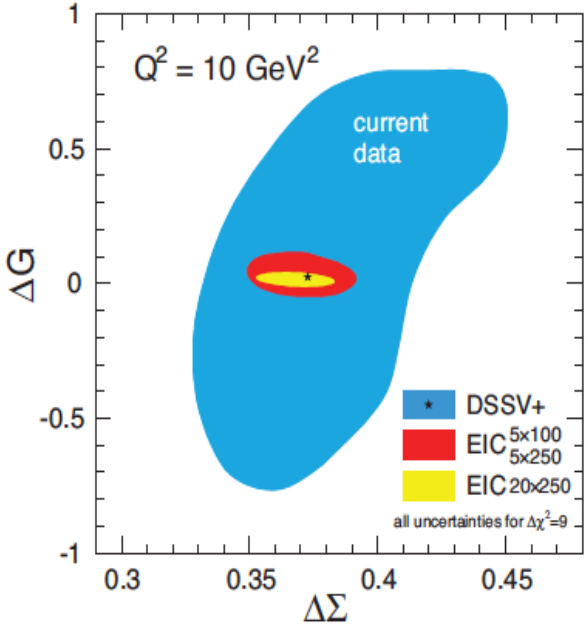


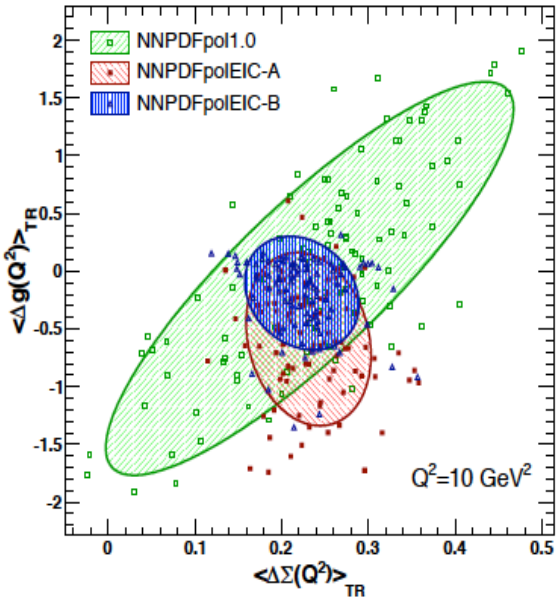


The Proton Spin: from JLab12 to EIC

❑ 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 Δg(x) – extends to smaller x regime***
- ✧ ***Orbital angular momentum contribution – measurement of TMDs & GPDs!***

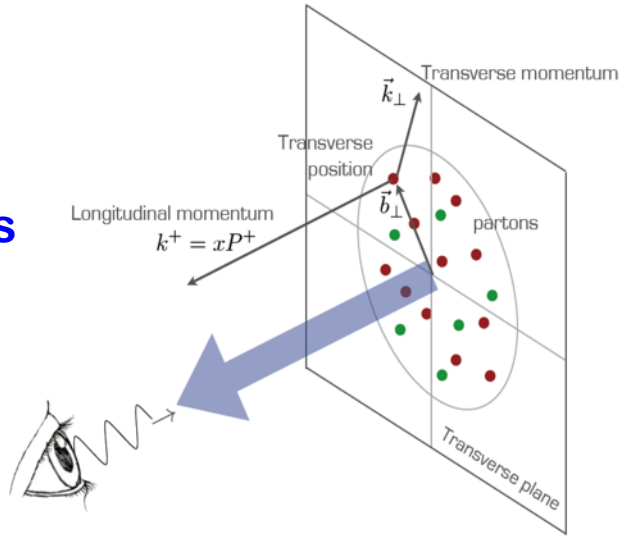
Hadron's 3D partonic structure

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

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

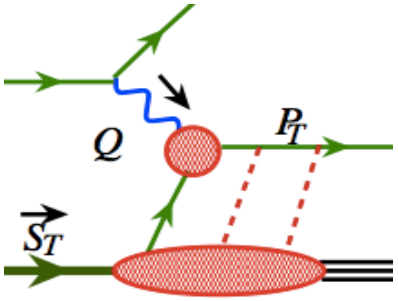
✧ **Hard scale:** Q_1 **localizes the probe particle nature of quarks/gluons**

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



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

✧ **Semi-inclusive DIS:**

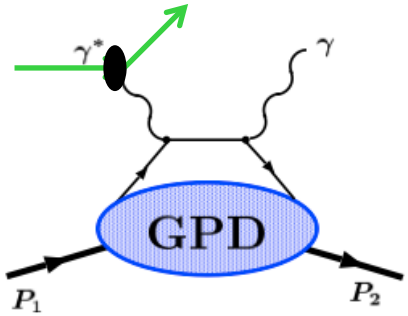


+ …

SIDIS: $Q \gg P_T$

Parton's confined motion encoded into TMDs

✧ **Exclusive DIS:**



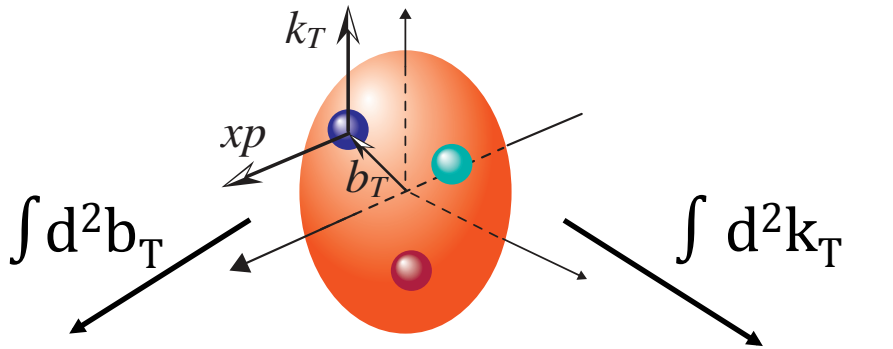
+ …

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

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

Theory is solid – A 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:**

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

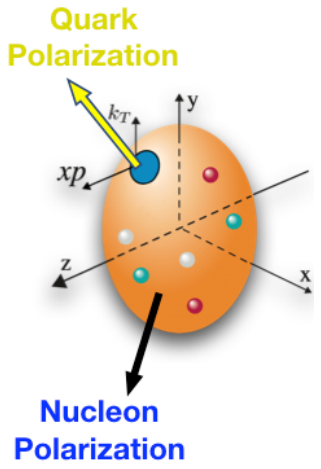
  - **Very high P_{hT} >> Q – Collinear factorization:**

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

Explore the Flavor-Spin-Motion Correlation

❑ **Intrinsic & confined parton motion:**

- ✧ Fundamental information sensitive to how partons are bound together
- ✧ Responsible for dynamical contribution to emergent hadron properties, such as spin, mass, ..



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

Polarized hadron

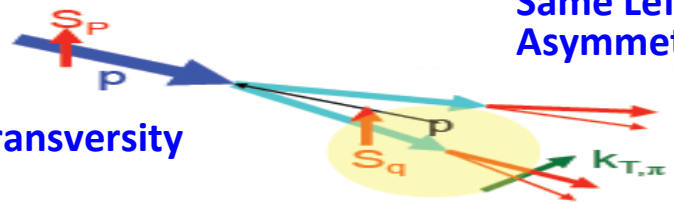
Observed: Left-Right Asymmetry

- ✧ Sivers effect – Sivers function

Hadron spin influences parton's transverse motion

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

Same Left-Right Asymmetry



Transversity

- ✧ Collins effect – Collins function

Parton's transverse polarization influences its hadron

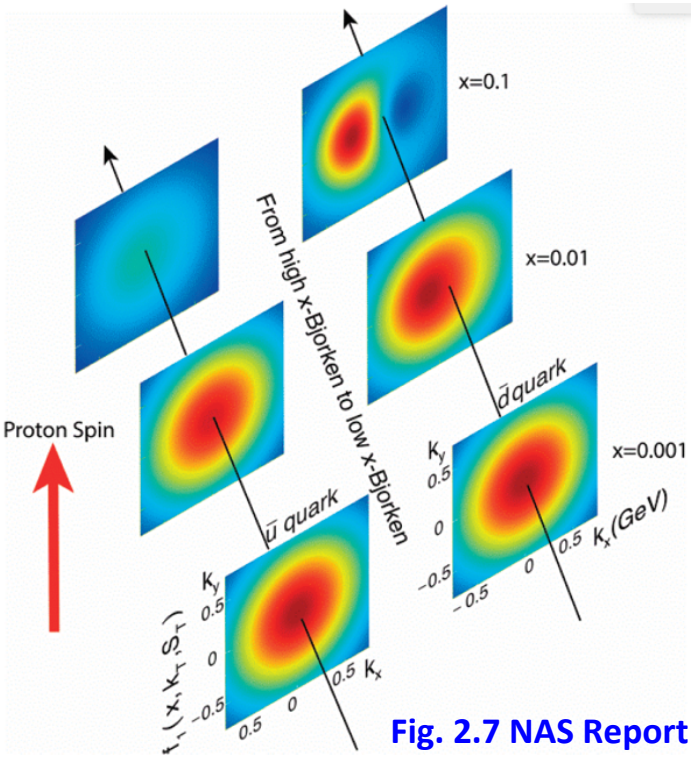
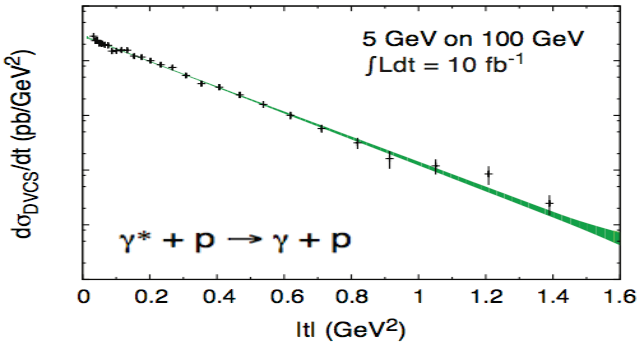
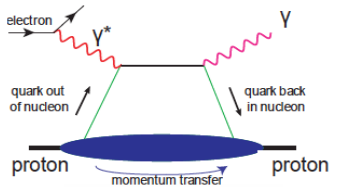


Fig. 2.7 NAS Report

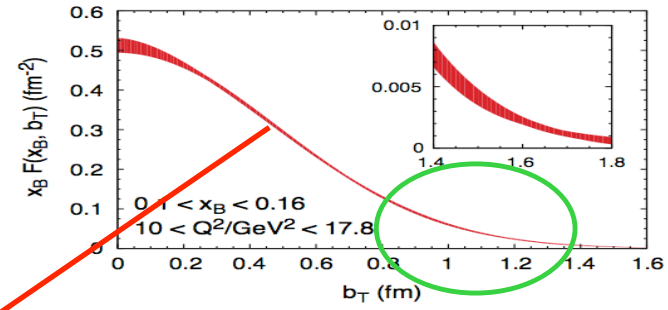
Flavor Dependence of Spatial Imaging

❑ DVCS at EIC:



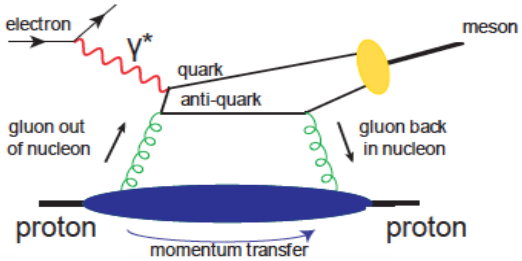


Factorization → **GPDs** → **F.T.**



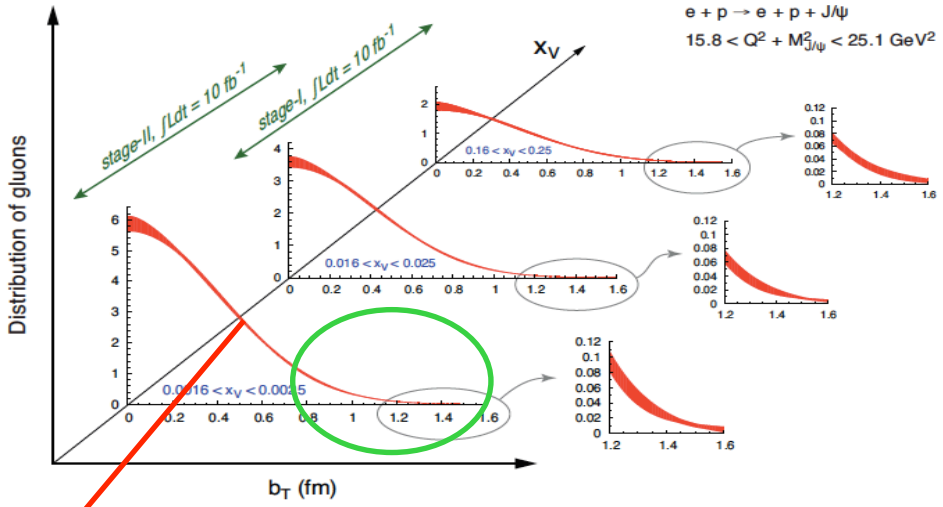
Proton radius of quark dist.(x)!

❑ "Seeing" the glue at EIC:



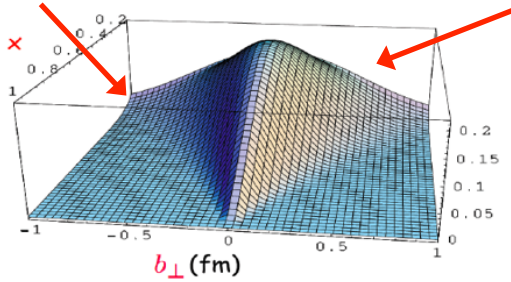
J/Ψ, Φ, …

F.T. **t-dep** →



How far does glue density spread?

How fast does glue density fall?

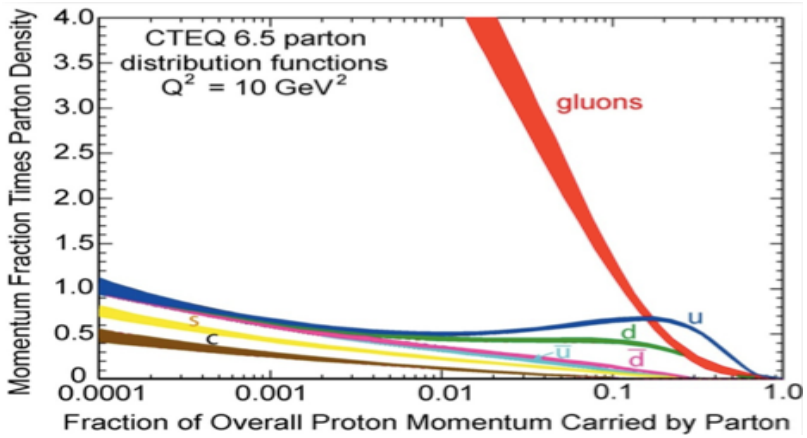


Proton radius of gluons (x)!

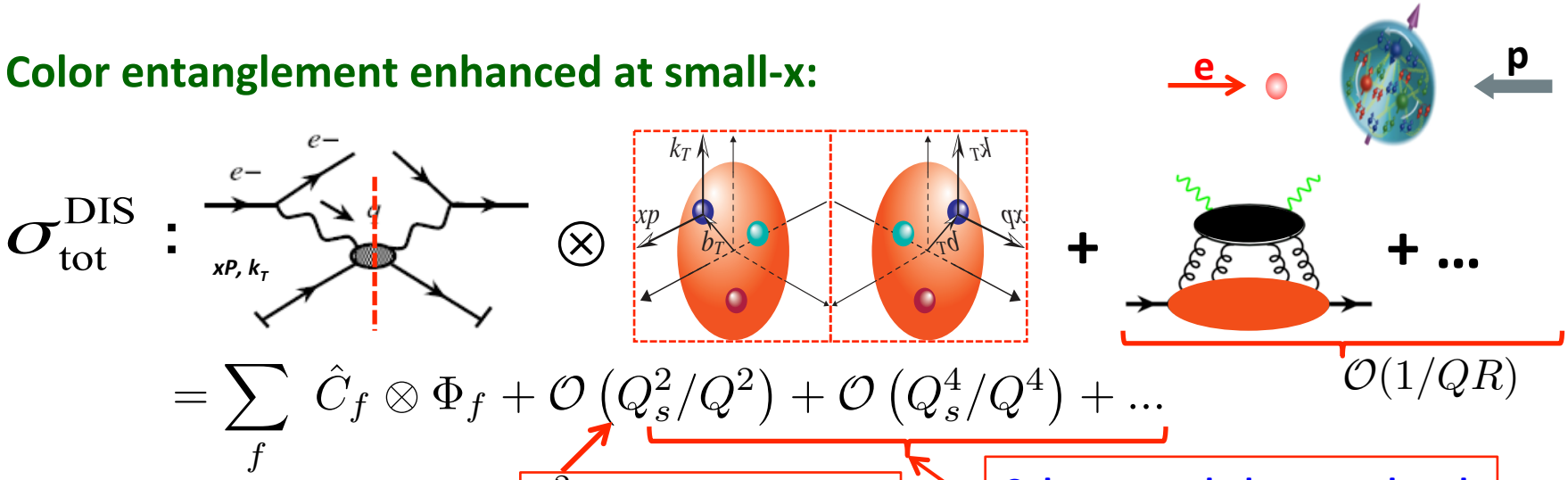
Only possible at EIC!

Emergent properties of dense gluons

- **Run away gluon density at small-x?**
  - ✧ **What are the emergent properties of dense systems of gluons, when the occupation number is ~ O(1)?**



- **Color entanglement enhanced at small-x:**



- **Saturation:**

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

➡ ***Color Glass Condensate (CGC)***

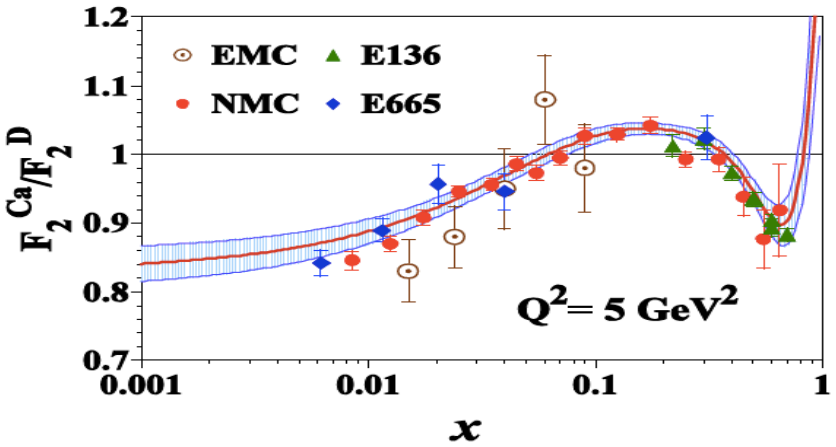
It is a part of QCD, where to find it?

Nuclear Landscape – Nuclear Force

❑ **EMC discovery:**

Nuclear landscape

≠ Superposition of nucleon landscape



❑ **Simple, but fundamental, questions:**

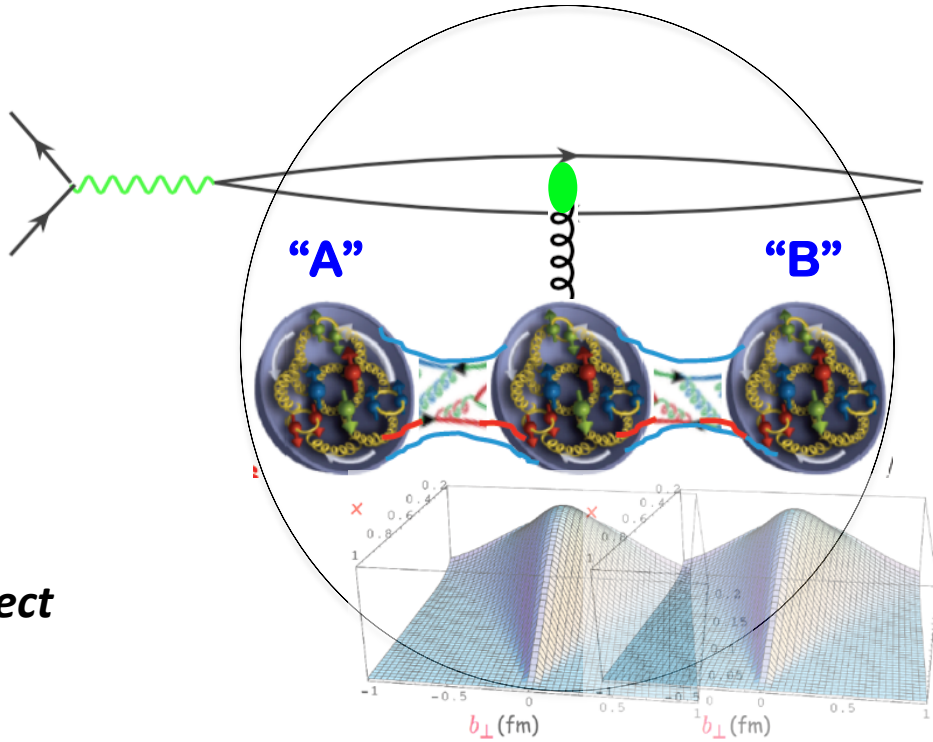
✧ **What does a nucleus look like *if we only see quarks and gluons ?***

✧ **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!**

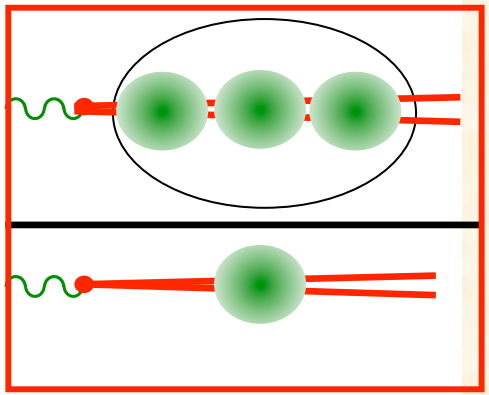
***IF NOT,* Observed nuclear effect in cross-section is a coherent collision effect**

EIC can tell !

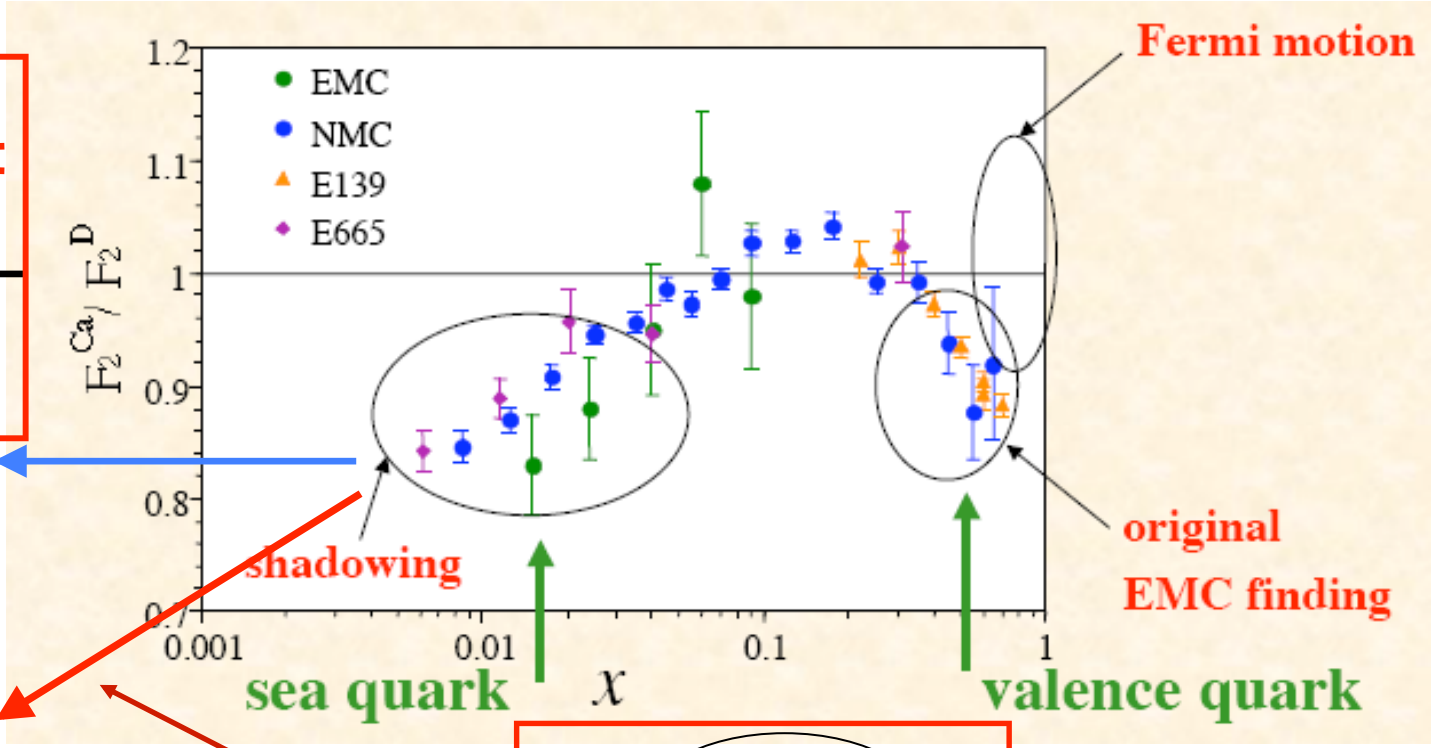


Coherent Length of the Color

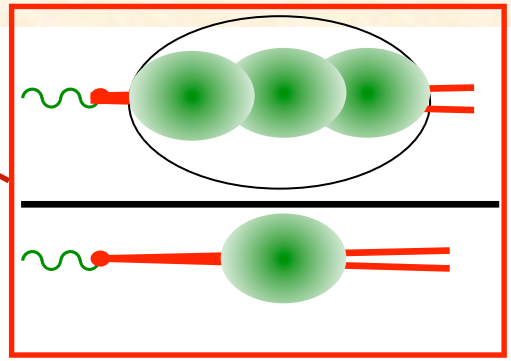
- **A simple experiment to address a "simple" question:**
  Will the EMC suppression/shadowing continue to fall as x decreases?



Color localized Inside nucleons



Nucleus as a bigger proton

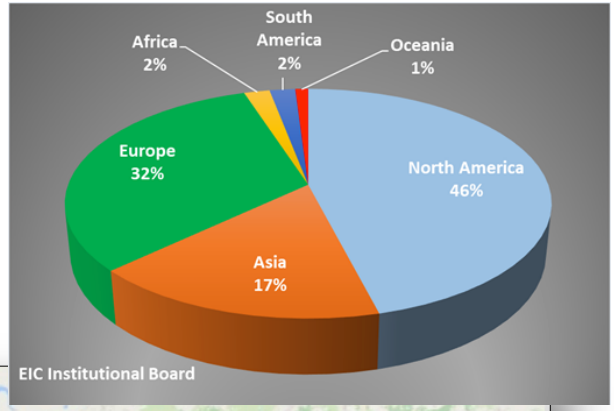


Color leaks outside nucleons
Proton radius of soft gluon is larger !

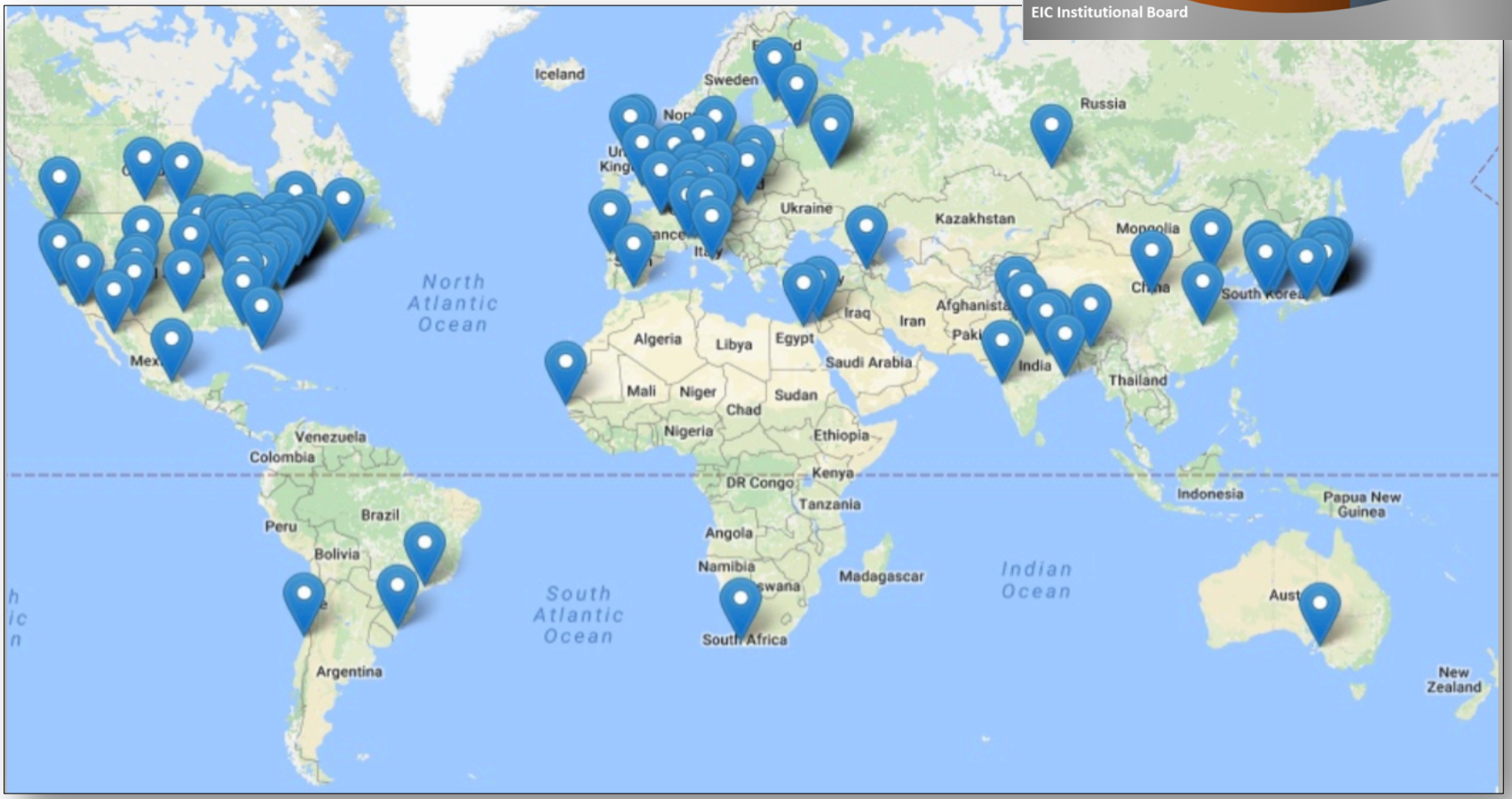
EIC can tell !

US EIC – An International Effort

- **EIC Users Group – *EICUG.ORG*:**
  - **>1100 collaborators, 30 countries,**
    205 institutions ... (since 2016 & growing)
    (no students included yet!)

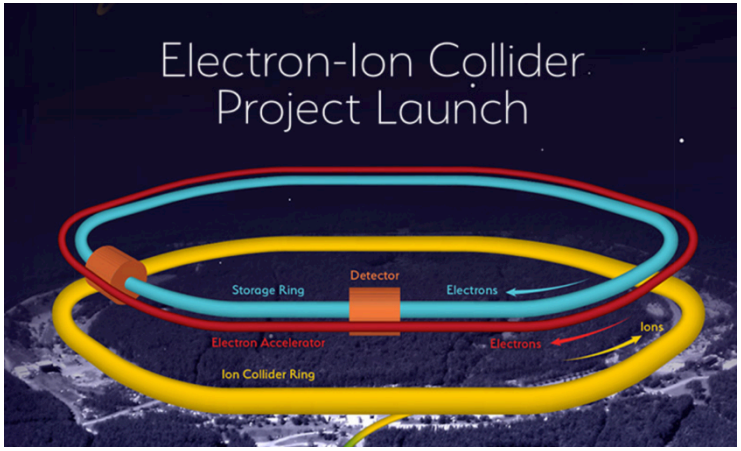


Map of institutions' locations



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!

September 18 2020

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:**

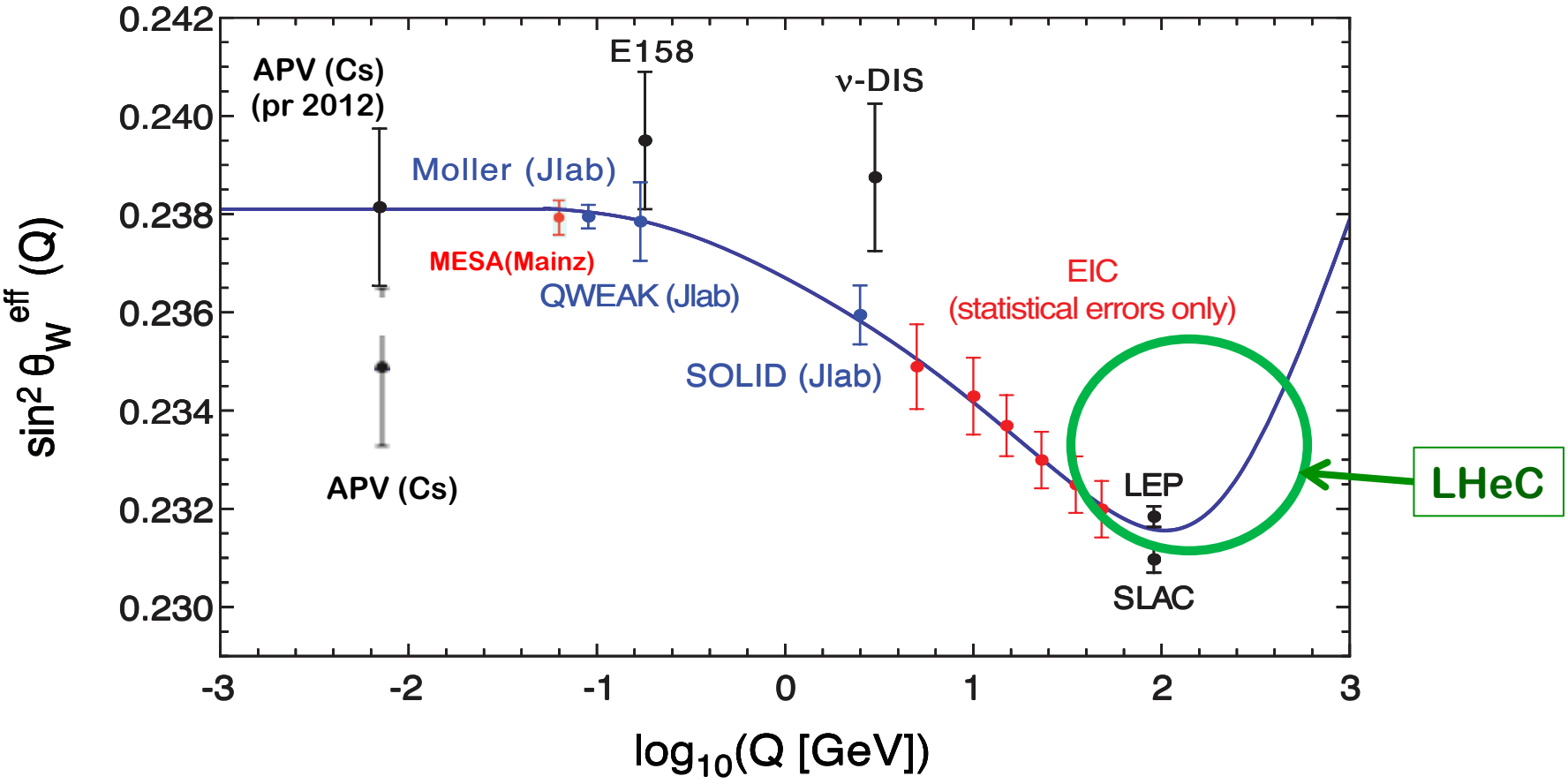
$$\mathcal{L}_{QED}(\phi, A) = \sum_f \overline{\psi}^f \left[(i\partial_\mu - eA_\mu)\gamma^\mu - m_f\right] \psi^f - \frac{1}{4}\left[\partial_\mu A_\nu - \partial_\nu A_\mu\right]^2$$

QCD is much richer in dynamics than QED

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

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***

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