2018 DIS

XXVI International Workshop on Deep Inelastic Scattering and Related Subjects

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Overview of EIC Physics Goals

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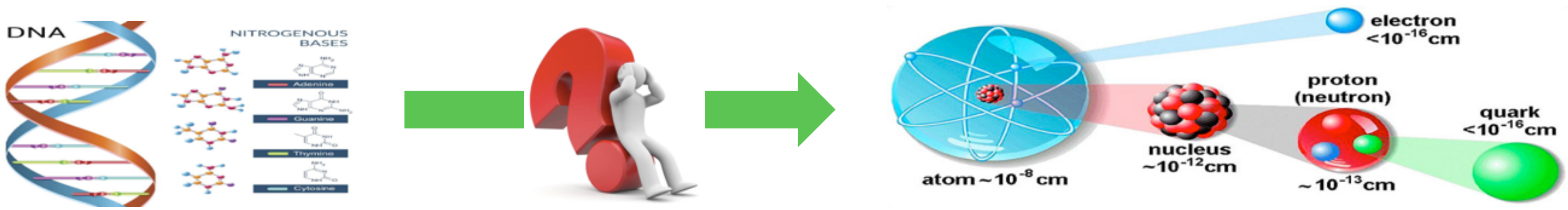
Eternal Questions we have been asking …

- **Where did we come from?**

Global Time: ⟶

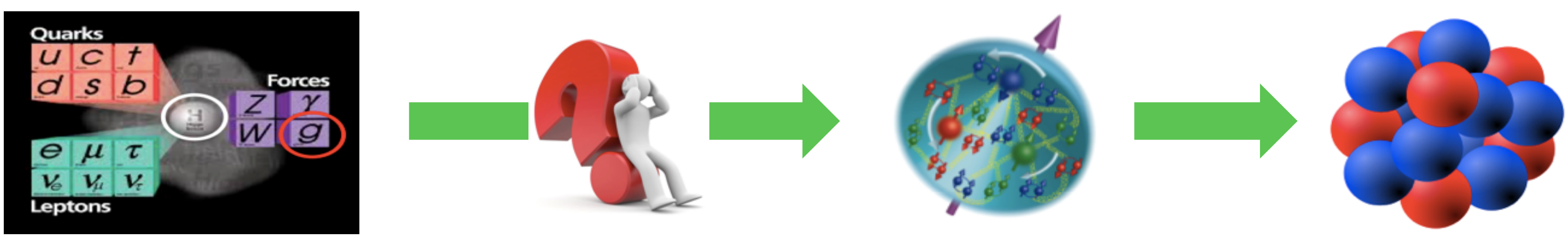
How did hadrons are emerged from the energy, the quarks and gluons?

- **What are we made of?**



What is the internal structure and dynamics of hadrons?

- **What holds us together?**

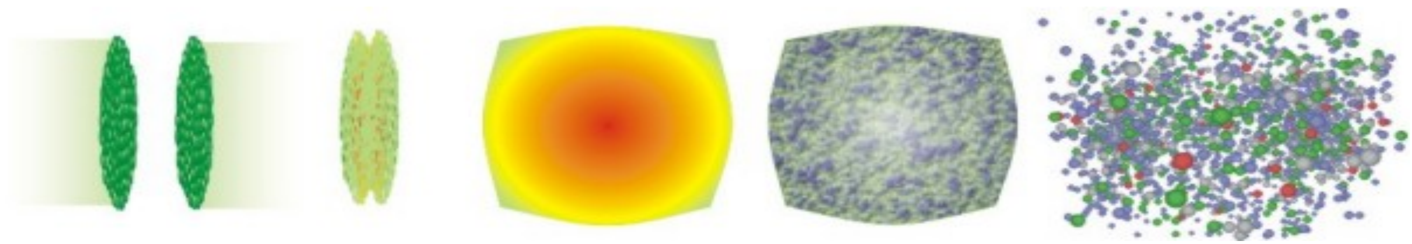


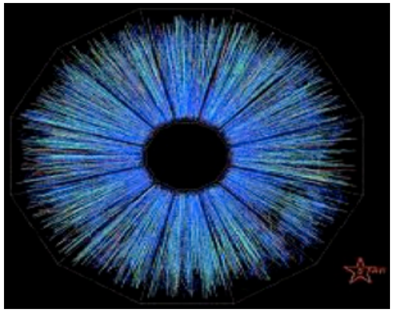
How does the glue bind us all?

Goals of EIC: to help search for answers of these questions in various stages!

Going back in time?

- Relativistic heavy-ion collisions - RHIC:





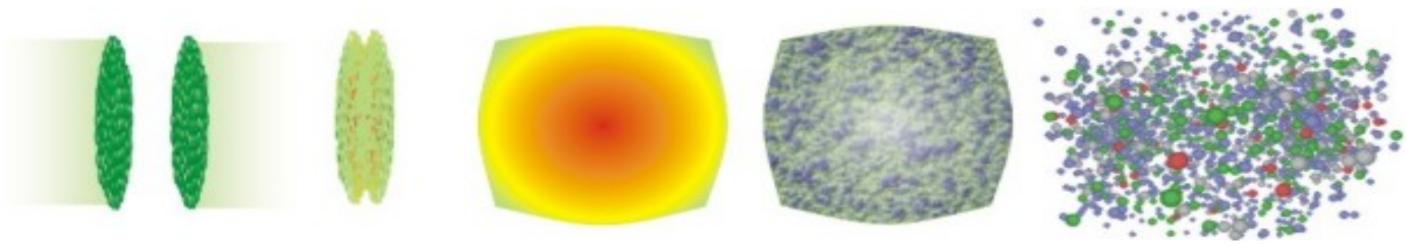
Lorentz contraction	Near collision	Quark-gluon plasma	Hadronization	Freeze-out	Seen in the detector
Visible!					**Visible!**

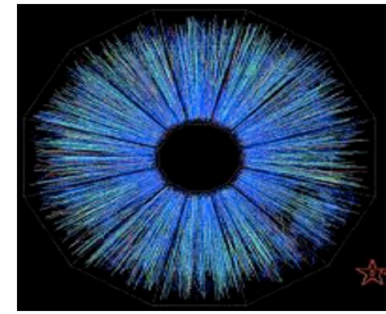
“Seeing” the unseen

A virtual journey of the visible matter!

A virtual journey of the visible matter

- Relativistic heavy-ion collisions - RHIC:

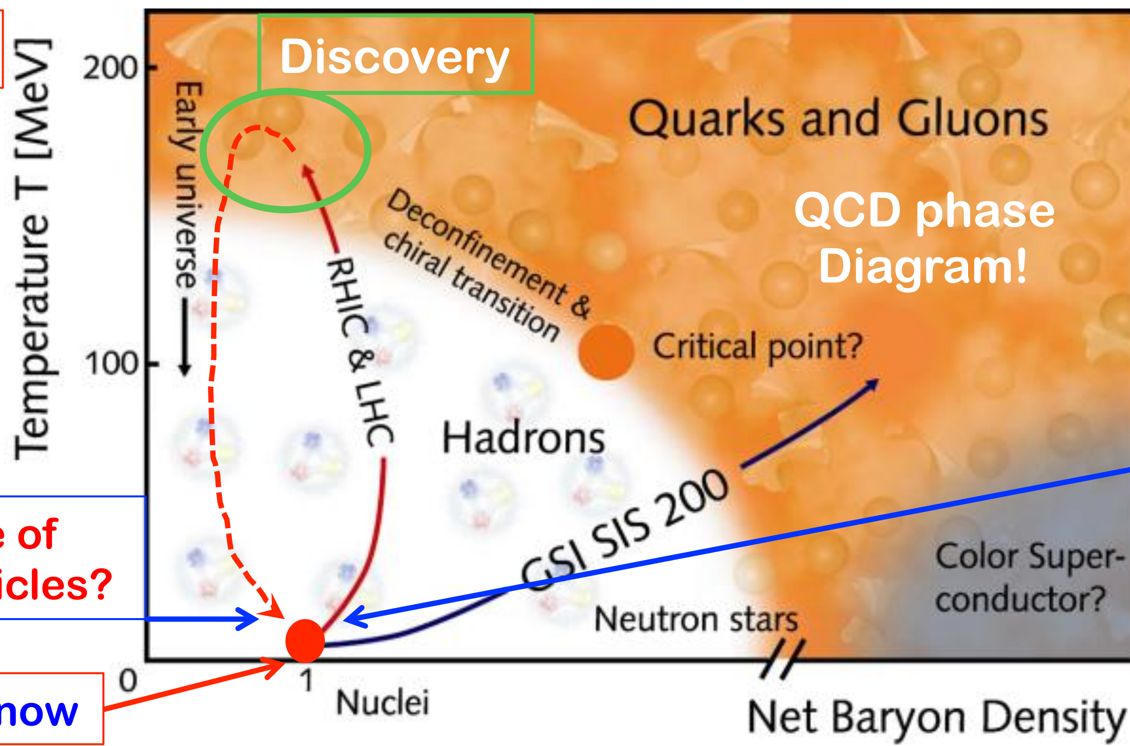




Lorentz contraction | Near collision | Quark-gluon plasma | Hadronization | Freeze-out | Seen in the detector

Visible!

Visible!



Emergence of hadronic particles?

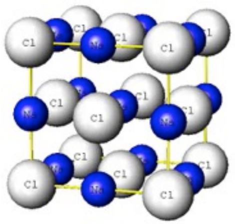
Where we are now

Structure of hadrons?
= initial conditions of RHIC?

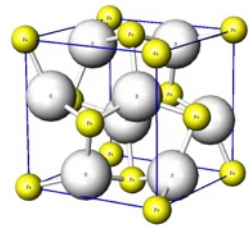
Hadron's partonic structure in QCD

- **Structure – "a still picture"**

Crystal Structure:

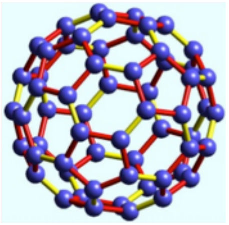


NaCl,
B1 type structure



FeS2,
C2, pyrite type structure

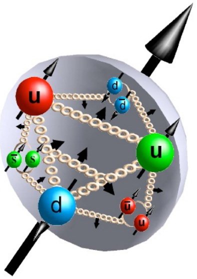
Nano-material:



Fullerene, C60

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

- **No "still picture" for hadron's partonic structure!**



Motion of quarks/gluons is relativistic!

Partonic Structure:

Quantum "probabilities" $\langle P, S | \mathcal{O}(\overline{\psi}, \psi, A^\mu) | P, S \rangle$

None of these matrix elements is a direct physical observable in QCD – color confinement!

- **Accessible hadron's partonic structure?**

= Universal quantum matrix elements of quarks and/or gluons

1) can be related to good physical cross sections of hadron(s) *with controllable approximation*,

2) can be calculated in lattice QCD, …

Intellectual challenge!

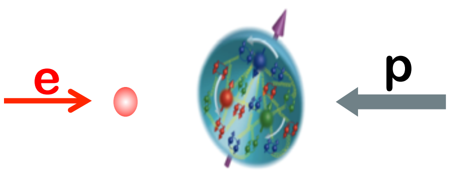
- The challenge:

  No modern detector has been able to see quarks and gluons in isolation!

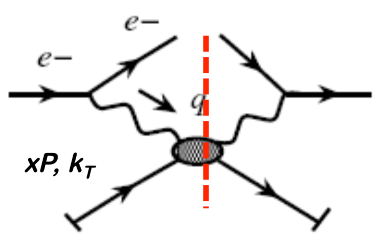
- Answer to the challenge:

  Theory advances: QCD factorization

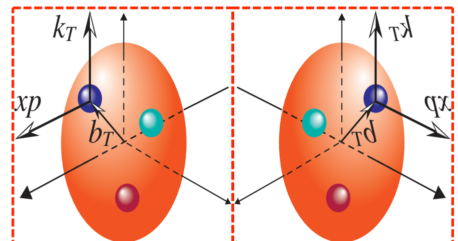
Color entanglement
Approximation



$\sigma_{\text{tot}}^{\text{DIS}}$:



$\otimes$



$+ \, O\left(\frac{1}{QR}\right)$

Physical
Observable

Controllable
Probe

Quantum Probabilities
Structure

Experimental tools:

Jets – *Footprints of energetic quarks and gluons*

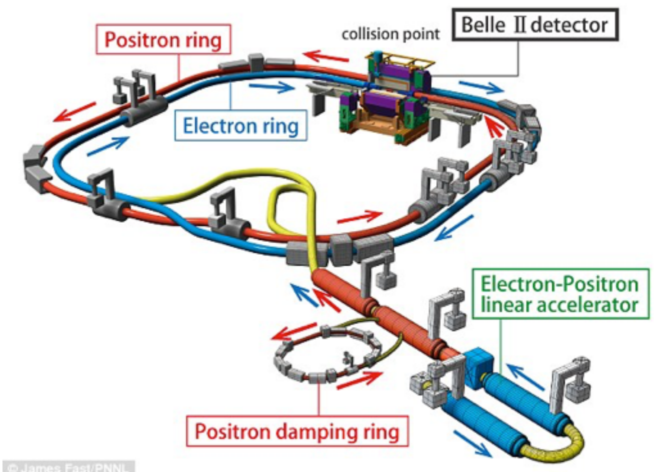
Quarks – *Need an EM probe to "see" their existence, …*

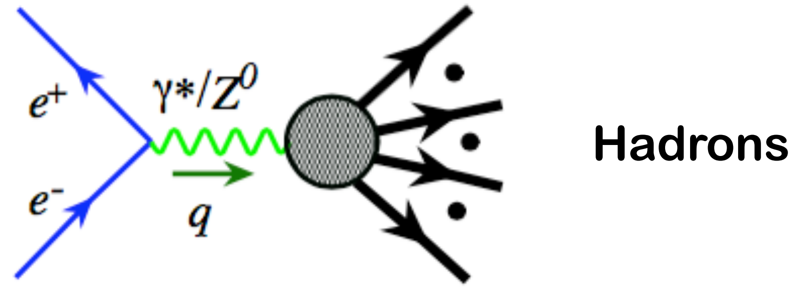
Gluons – *Varying the probe's resolution to "see" their effect, …*

Need probes with sub-femtometer resolution, and "see" the gluons!

Hard probes from high energy collisions

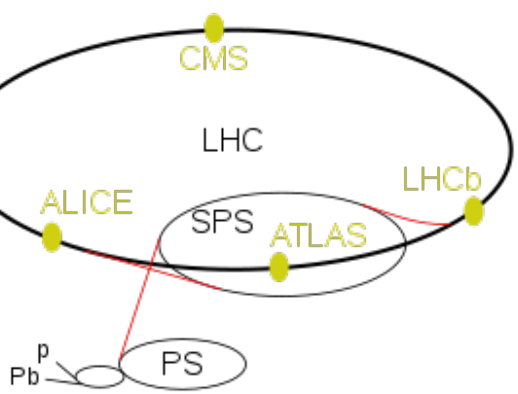
- Lepton-lepton collisions:

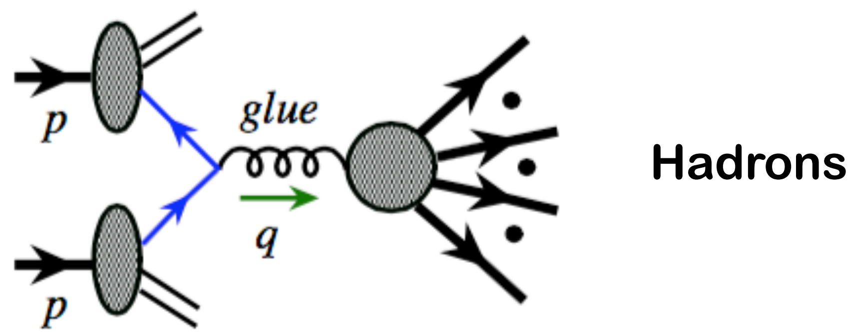




- ✧ No hadron in the initial-state
- ✧ Hadrons are emerged from energy
- ✧ Not ideal for studying hadron structure

- Hadron-hadron collisions:





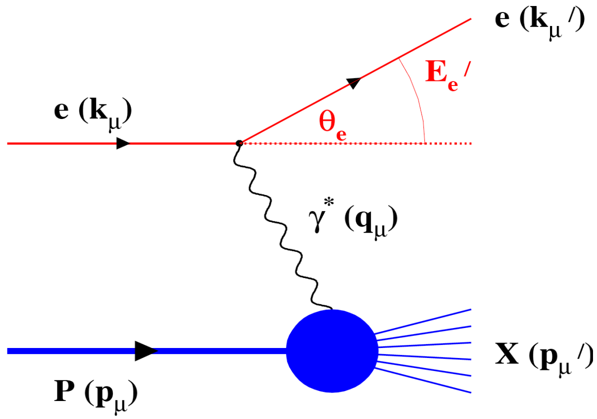
- ✧ Hadron structure – motion of quarks, …
- ✧ Emergence of hadrons, …
- ✧ Initial hadrons broken – collision effect, …

- Lepton-hadron collisions:

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

Why a lepton-hadron facility is special?

- Many complementary probes at one facility:



Q^2 → Measure of resolution

y → Measure of inelasticity

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

$$Q^2 = S\ x\ y$$

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!

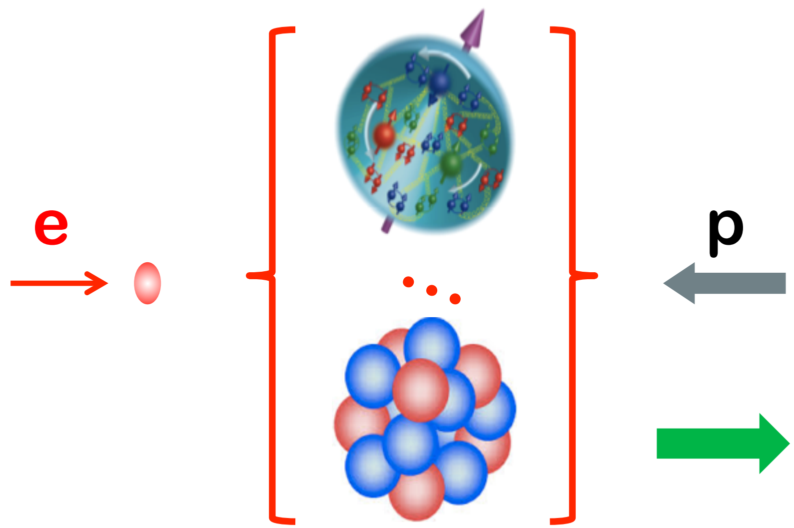
❑ **A sharpest "CT"** – "imagine" quark/gluon structure without breaking the hadron

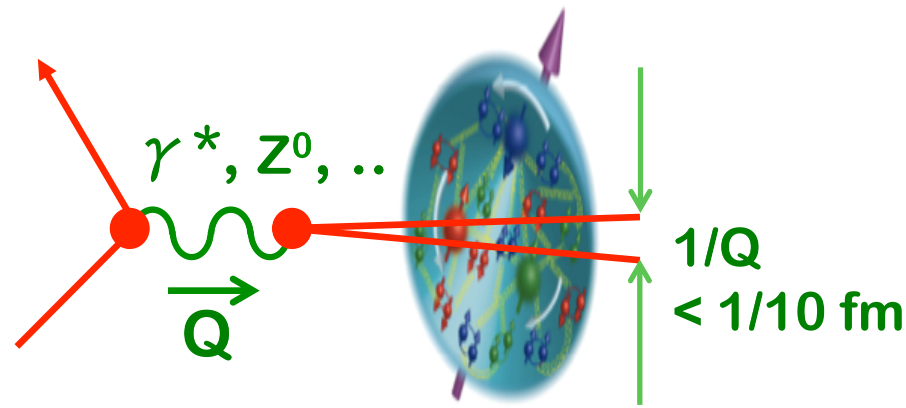
– "cat-scan" the nucleon and nuclei with a better than 1/10 fm resolution

– "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

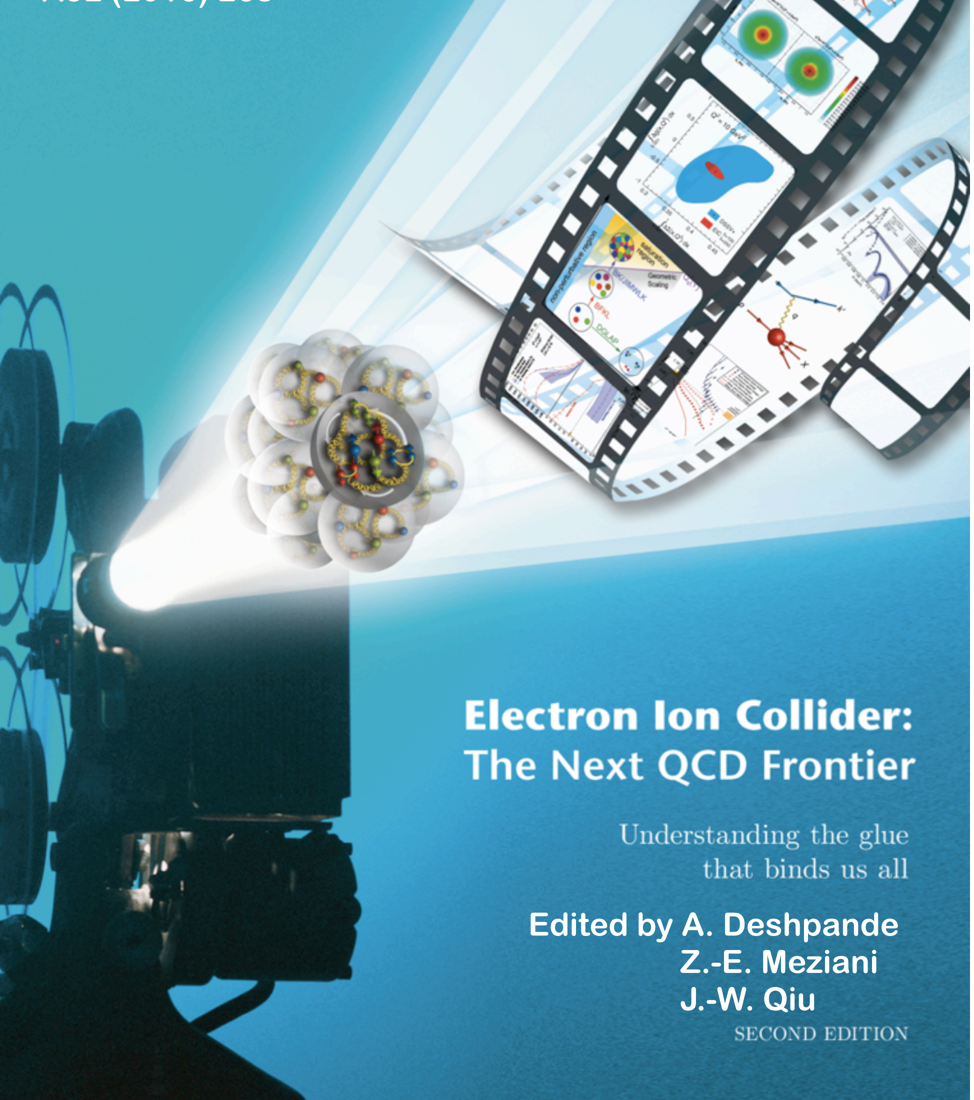
	HERA@DESY	LHeC@CERN	eRHIC@BNL	JLEIC@JLab	HIAF@CAS	ENC@GSI
E_{CM} (GeV)	320	800-1300	45-175	12-140	12 → 65	14
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-5}	5×10^{-5}	$7 \times 10^{-3} \rightarrow 3 \times 10^{-4}$	5×10^{-3}
ion	p	p to Pb	p to U	p to Pb	p to U	p to ~ ^{40}Ca
polarization	-	-	p, ^{3}He	p, 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

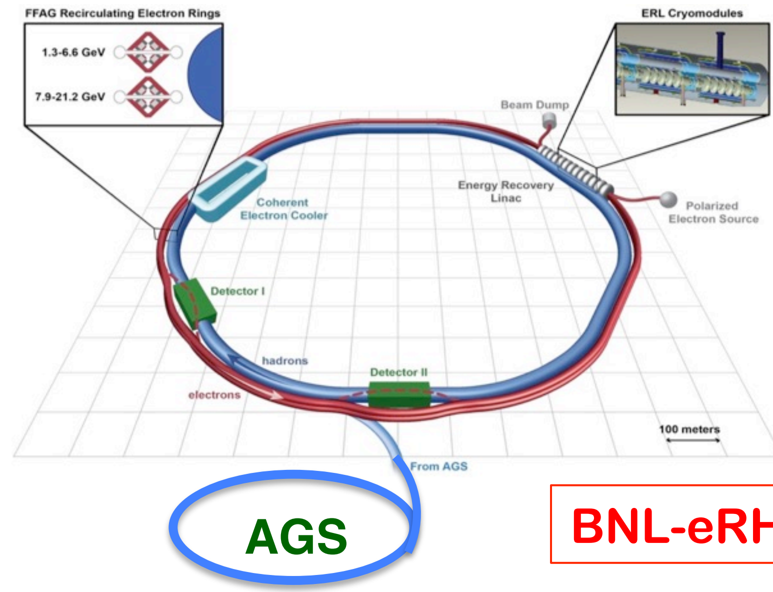
The past (HERA@DESY)

Possible future (LHeC@CERN to ENC@GSI)

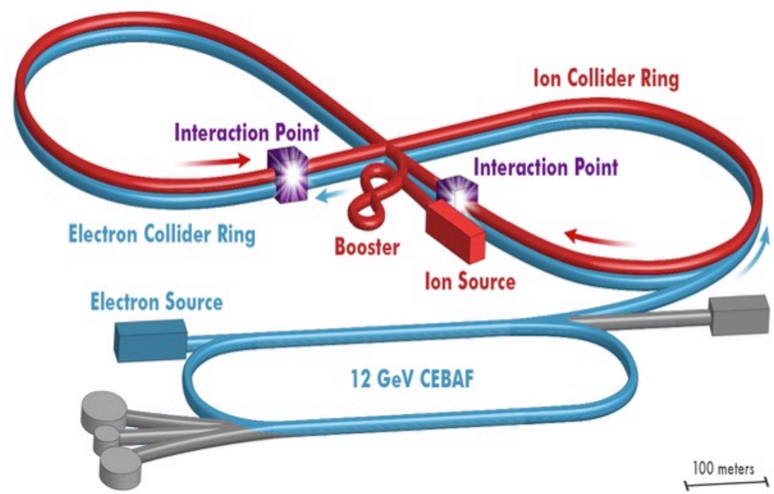
US EIC – Two Options of Realization

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



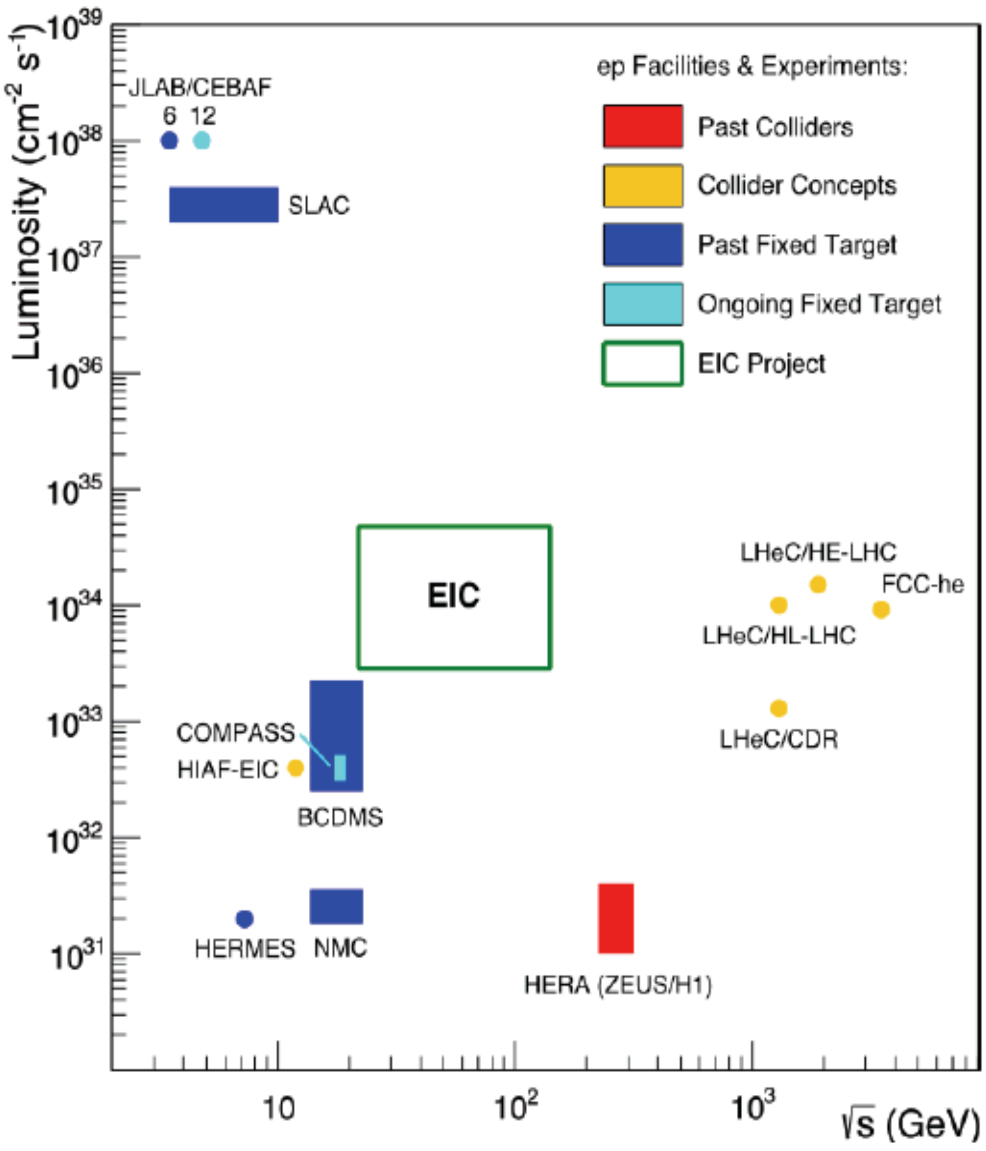


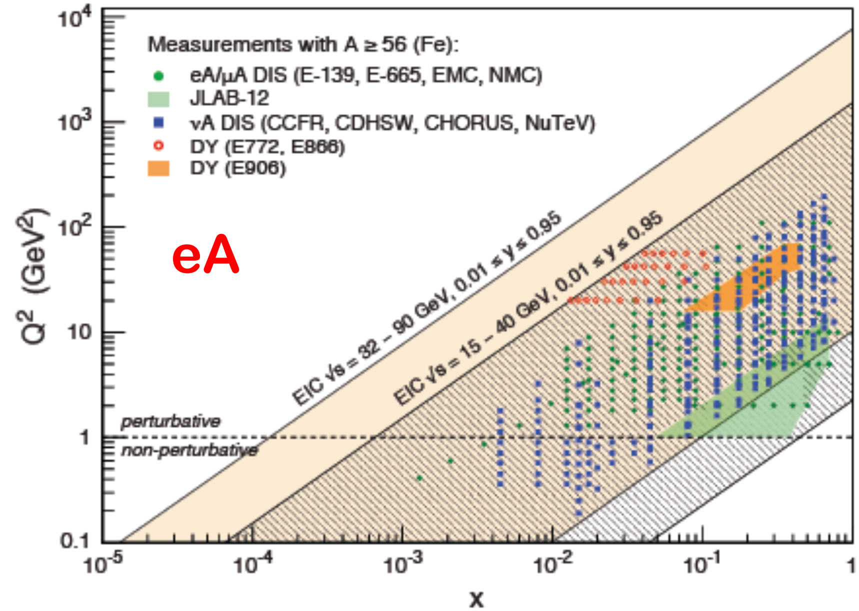
BNL-eRHIC

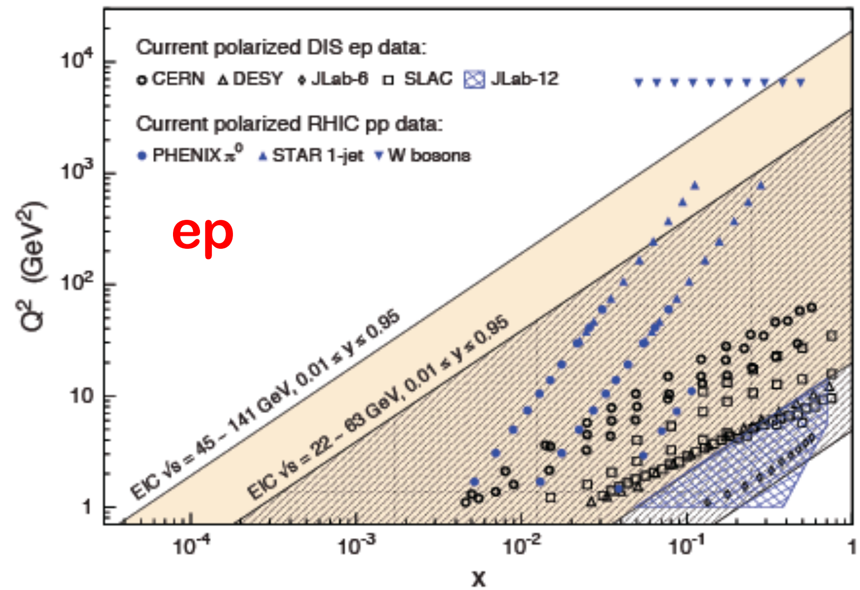


JLab-JLEIC

US EIC – Luminosity & kinematics coverage



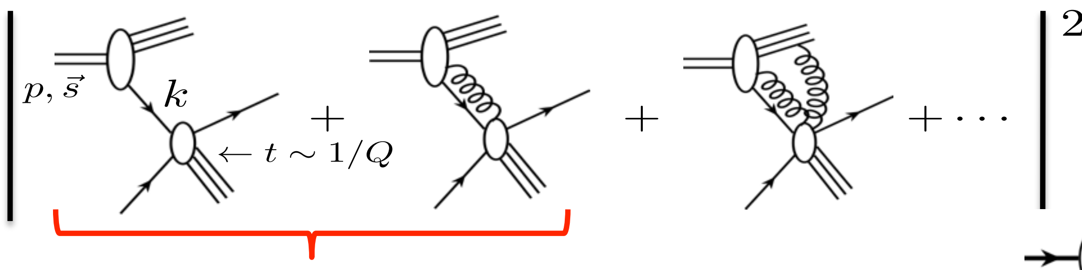




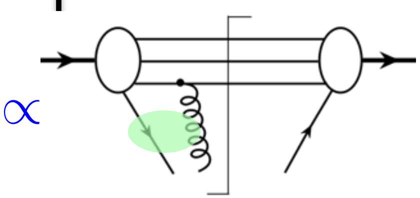
US-EIC – can do what HERA could not do

- **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!

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



$\sigma(s) - \sigma(-s)$ ➡ 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?

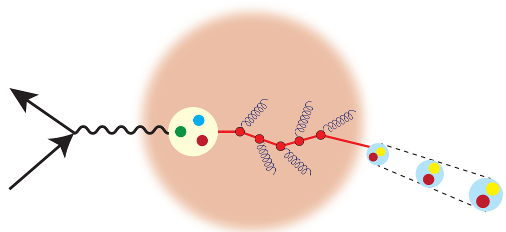
- ✧ **Emergence of hadrons**
- ✧ **Hadron properties:**
  mass, spin, …
- ✧ **Hadron's 3D partonic structure:**
  confined motion, spatial distribution,
  color correlation, fluctuation,
  saturation, …
- ✧ **Quantum correlation between**
  hadron properties and parton dynamics, …

…

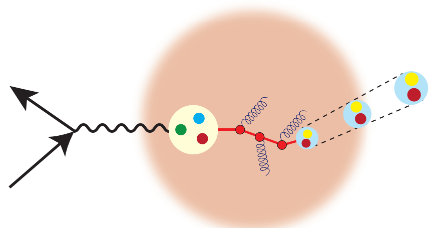
Due to the time, only a few examples to be presented in this talk!

Emergence of Hadrons from quarks & gluons

- ❑ **Femtometer sized detector:**



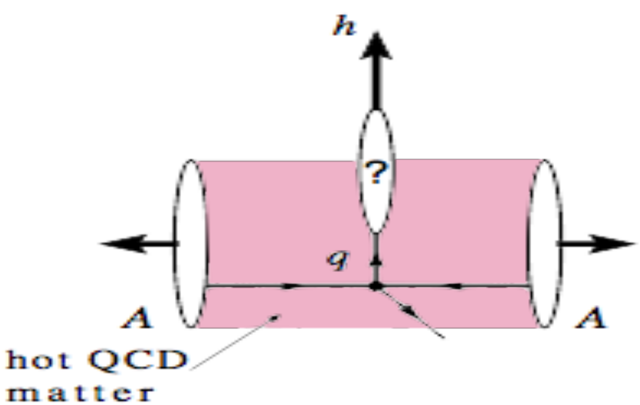
$$\nu = \frac{Q^2}{2mx}$$

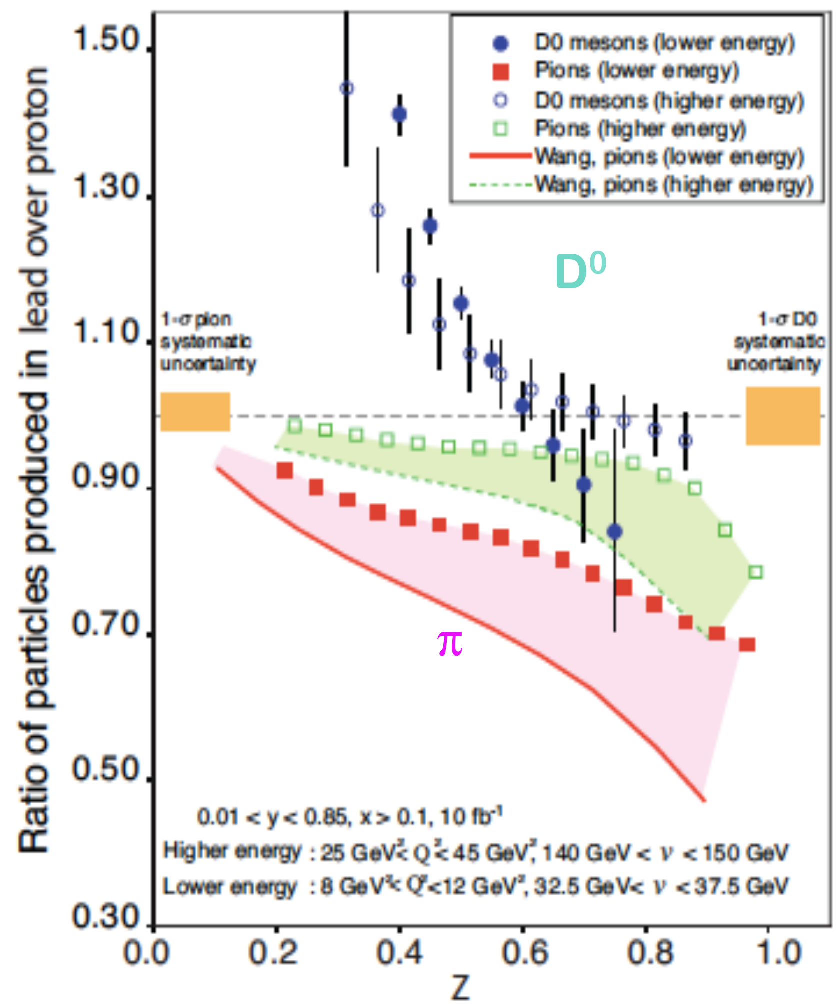


Control of ν and medium length!

Mass dependence of hadronization

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





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

Hadron Properties: Mass & Spin, …

- **Mass – intrinsic to a particle:**

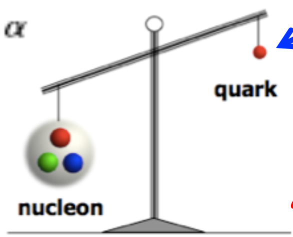
  = Energy of the particle when it is at the rest

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

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

  ✧ **Proton mass:**

$$m = \frac{\langle p|\int d^3x\, T^{00}\,|p\rangle}{\langle p|p\rangle} \sim \text{GeV}$$



Higgs Mech.

m_q ~ 10 MeV

m_N ~ 1000 MeV

"Mass without mass"

- **Spin – intrinsic to a particle:**

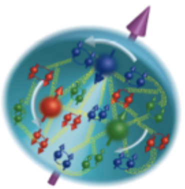
  = Angular momentum of the particle when it is at the rest

  ✧ **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:**

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



EMC found:

$$\sum_q (\Delta q + \Delta\bar{q}) \sim 0.12 \pm 0.17$$

"Proton spin puzzle"

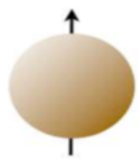
If we do not understand proton mass & spin, we do not understand QCD!

The Proton Spin

- **The sum rule:** $$S(\mu) = \sum_f \langle P, S | \hat{J}_f^z(\mu) | P, S \rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu)$$
  - **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

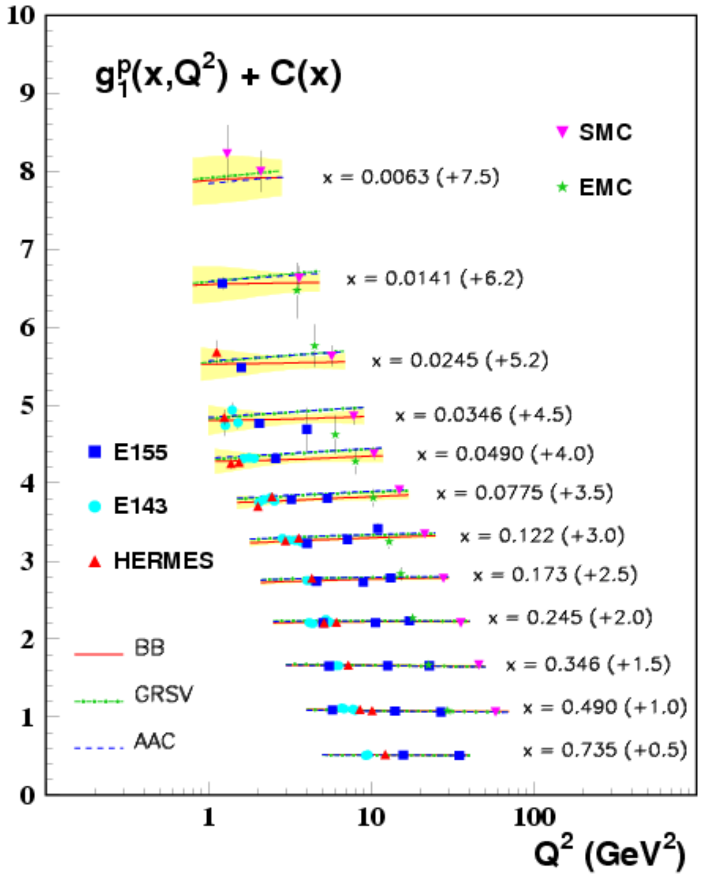
$$\Delta G = \int dx \Delta g(x)$$
$$\sim 40\% (\text{with RHIC data})$$

Orbital Angular Momentum
of quarks and gluons
Little known

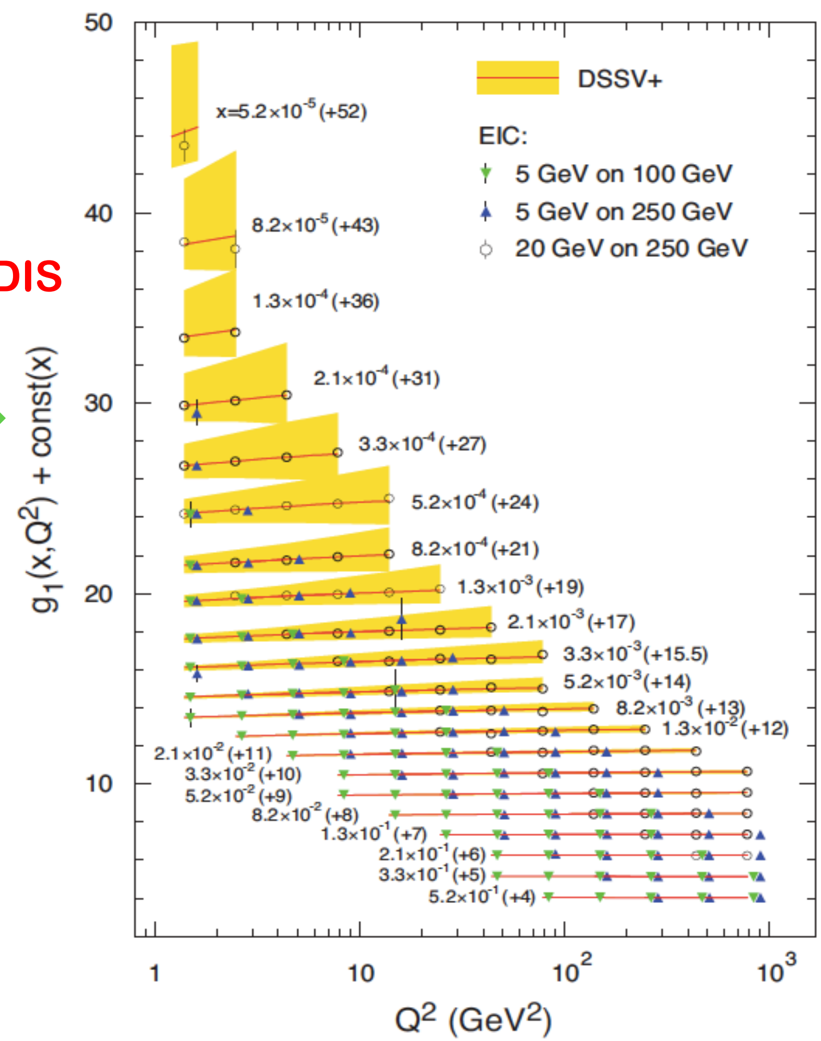
Net effect of partons' transverse motion?

The Proton Spin

- ❑ **The power & precision of EIC:**



Polarized DIS at EIC



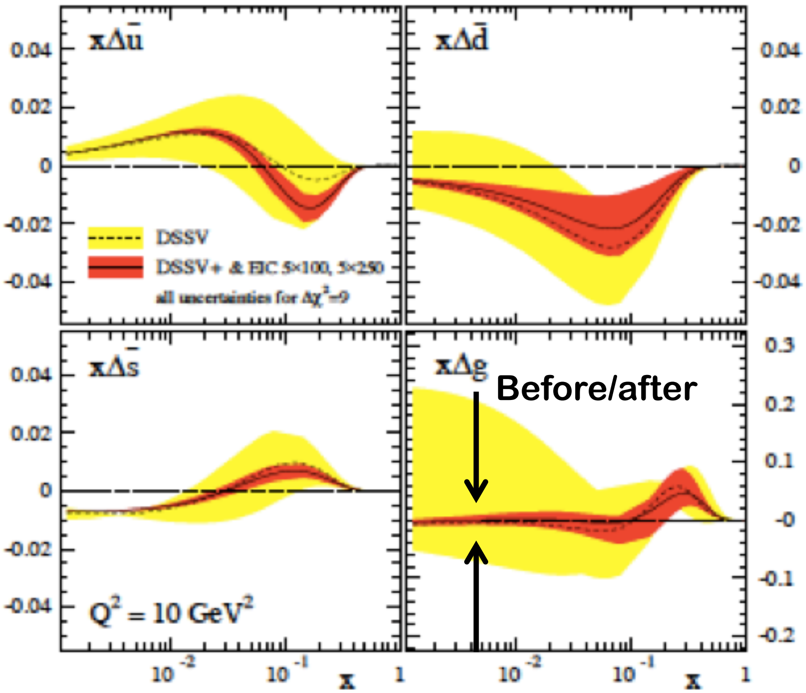
- ❑ **Reach out the glue:**

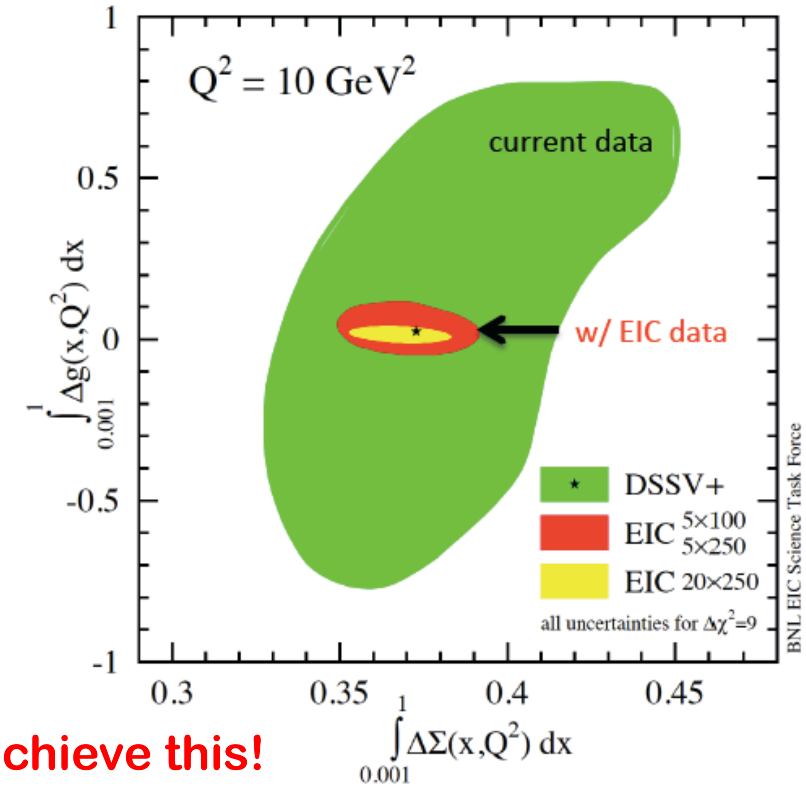
$$\frac{dg_1(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi} P_{qg} \otimes \Delta g(x,Q^2) + \cdots$$

The Proton Spin

- ❑ **One-year of running at EIC:**

Wider Q^2 and x range including low x at EIC!





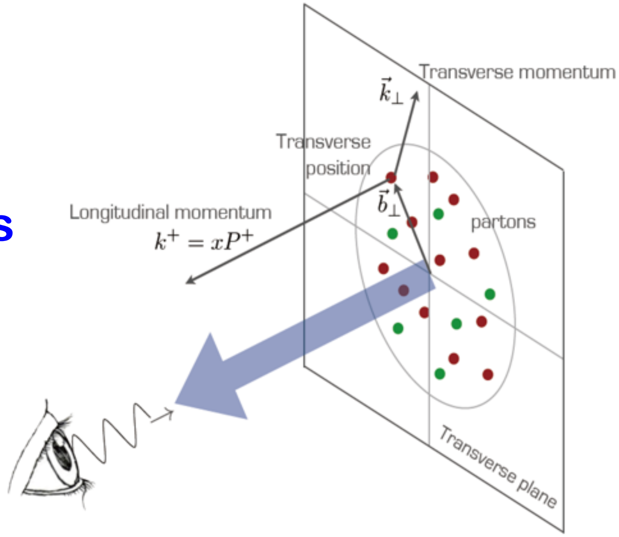
No other machine in the world can achieve this!

- ❑ **Ultimate solution to the proton spin puzzle:**
  - ✧ ***Precision measurement of $\Delta g(x)$ – 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:

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

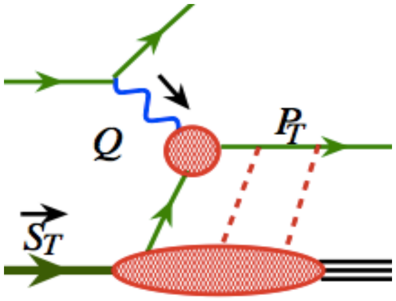


✧ Hard scale: Q_1 localizes the probe
particle nature of quarks/gluons

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

- Two-scale observables at the EIC:

✧ Semi-inclusive DIS:

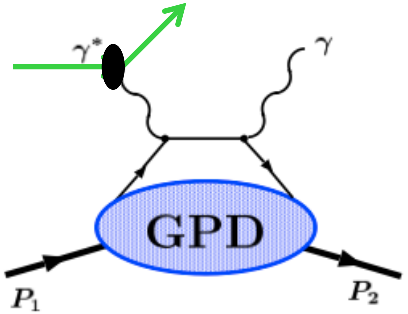


+ …

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

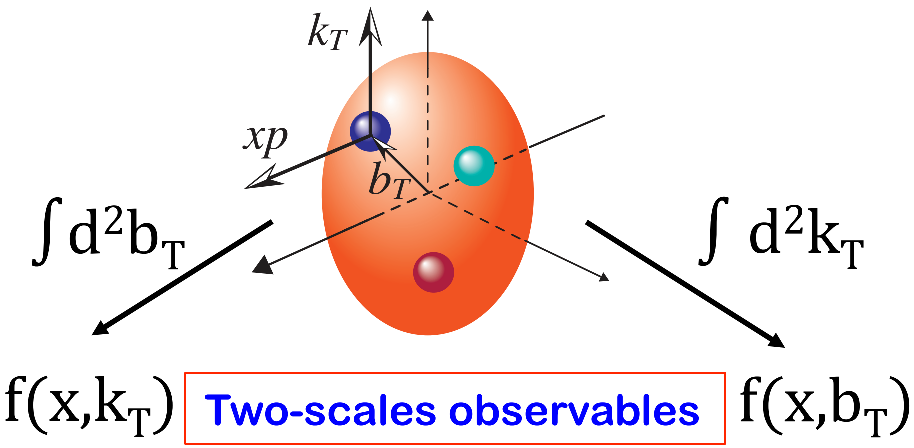
Theory is solid – unified description

❑ Wigner distributions in 5D (or GTMDs):

Momentum Space

TMDs

Confined motion



Coordinate Space

GPDs

Spatial distribution

❑ TMDs & SIDIS as an example:

✧ **Low P_{hT} (P_{hT} << Q) – TMD factorization:**

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

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

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

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

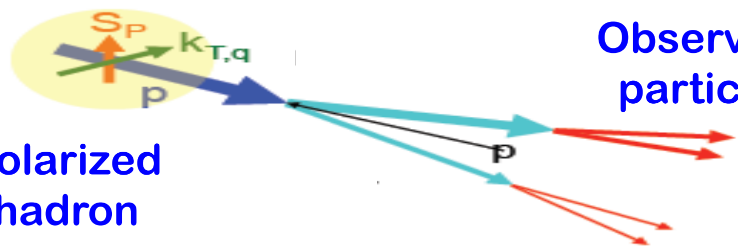
$$\sigma_{\text{SIDIS}}(Q, x_B, z_h) = \tilde{H}(Q, \alpha_s) \otimes \phi_f \otimes D_{f\to h} + \mathcal{O}\left(\frac{1}{Q}\right)$$

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

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

Confined motion of quarks & gluons

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



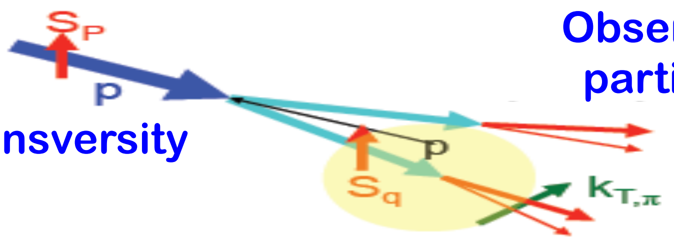
Polarized hadron

Observed particle

Sivers effect – Sivers function

Hadron spin influences parton's transverse motion

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



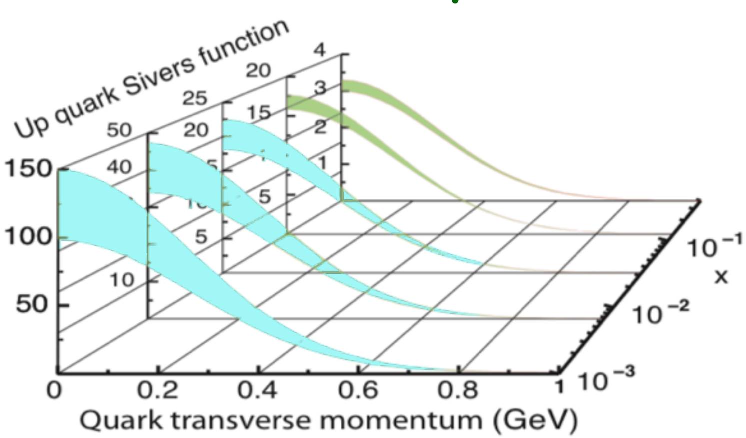
Transversity

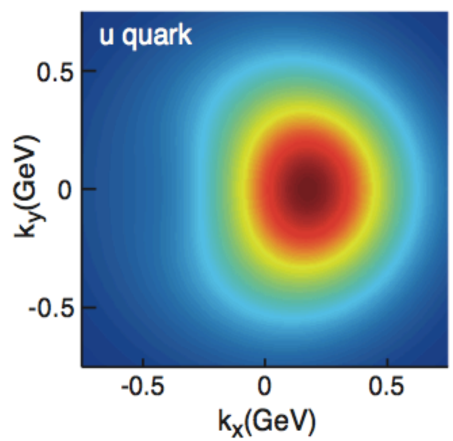
Observed particle

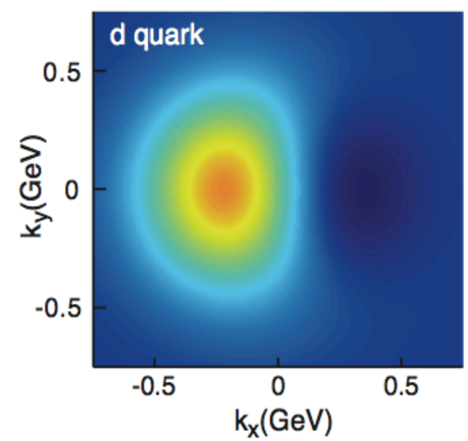
Collins effect – Collins function

Parton's transverse polarization influences its hadronization

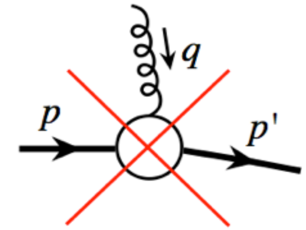
- **TMDs and their separation at EIC:**







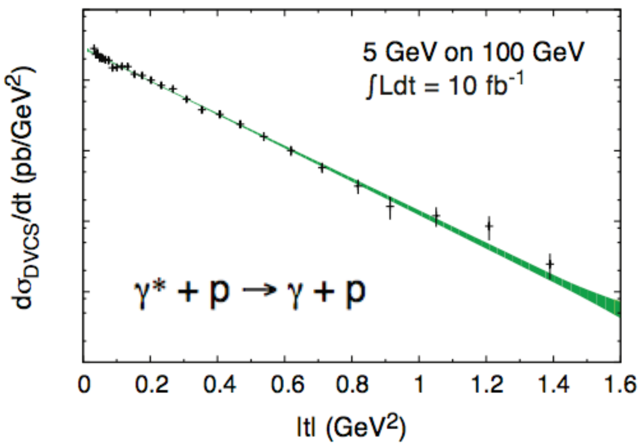
Spatial imaging of quarks & gluons



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

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

- **DVCS at EIC:**

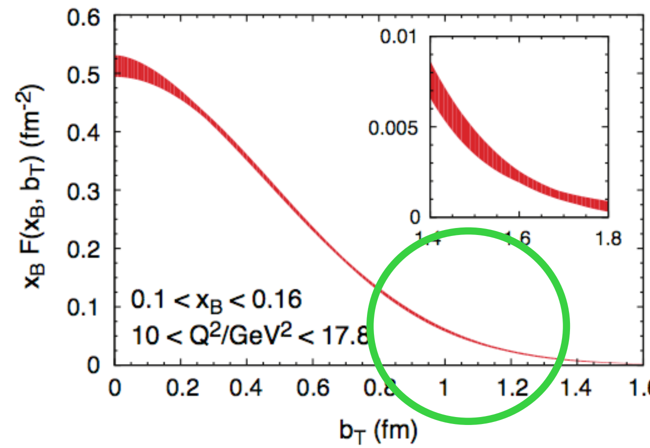


Factorization

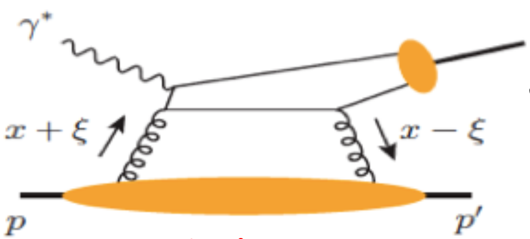
➡ **GPDs** ➡

F.T.

Proton radius of quarks (x)!



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



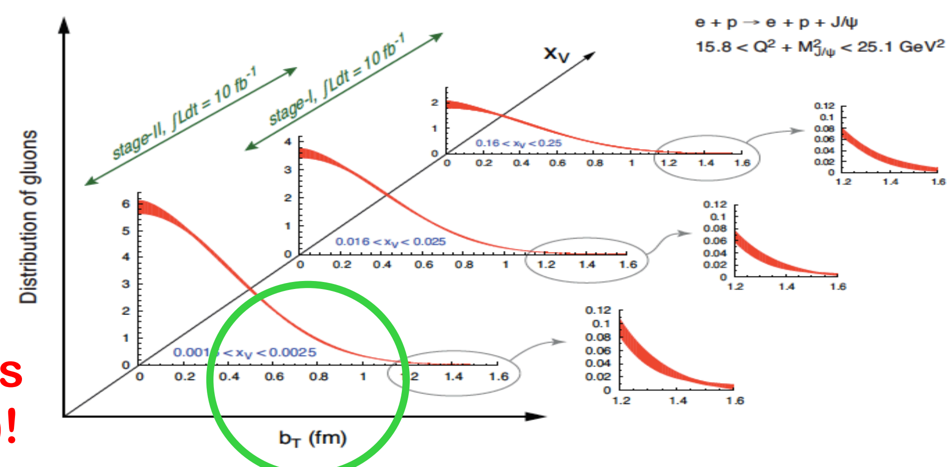
J/Ψ, Φ, …

t-dep

➡

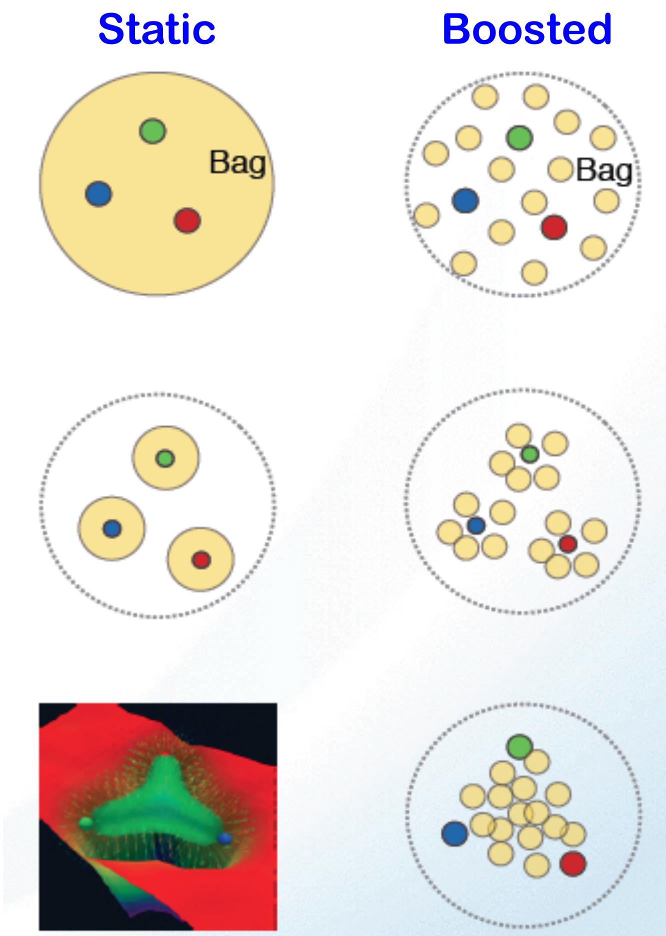
Only possible at EIC!

Proton radius of gluons (x)!



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

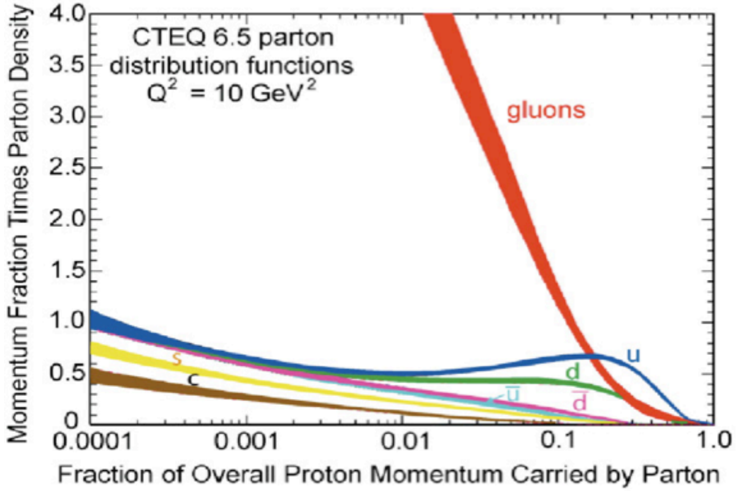
3D confined motion (TMDs) + spatial distribution (GPDs)

Hints on the color confining mechanism

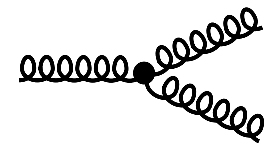
Relation between charge radius, quark radius (x), and gluon radius (x)?

Another HERA discovery

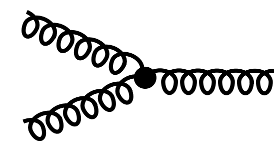
- **Run away gluon density at small-x?**



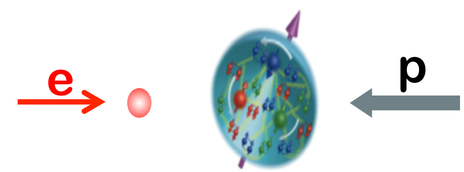
What causes the low-x rise?
gluon radiation
– non-linear gluon interaction



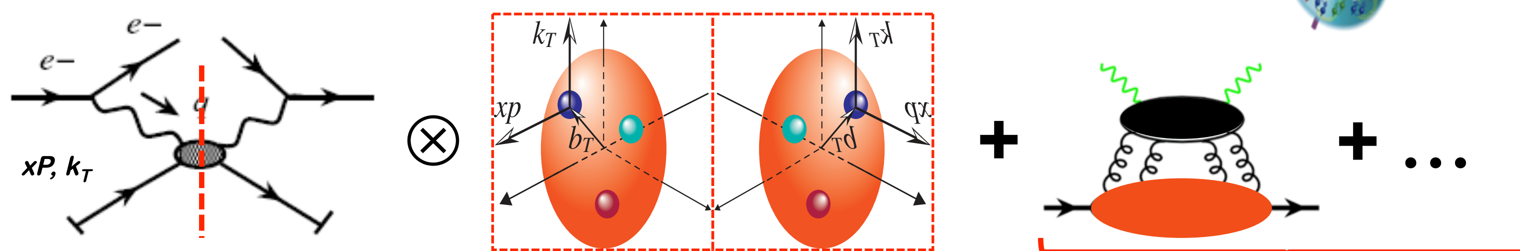
What could tame the low-x rise?
gluon recombination
– non-linear gluon interaction



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



$\sigma_{\text{tot}}^{\text{DIS}}$:



$$= \sum_f \hat{C}_f \otimes \Phi_f + \mathcal{O}\left(Q_s^2/Q^2\right) + \mathcal{O}\left(Q_s^4/Q^4\right) + \ldots \qquad \mathcal{O}(1/QR)$$

$Q_s^2 \propto$ parton density

Color entangled or correlated between two active partons

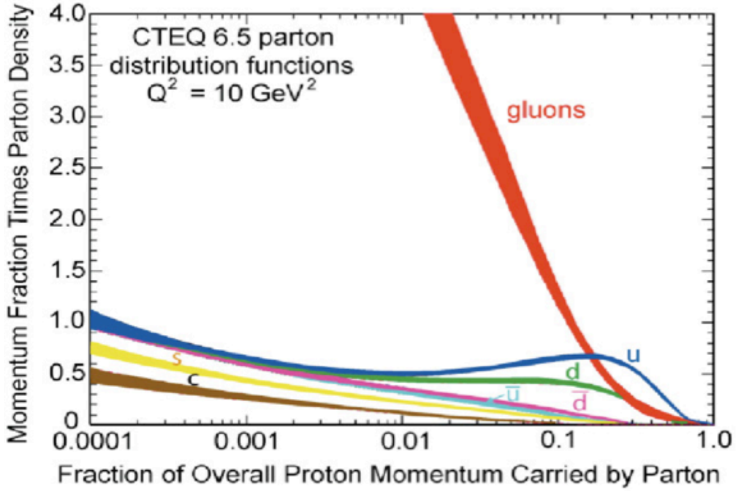
- **Saturation:**

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?



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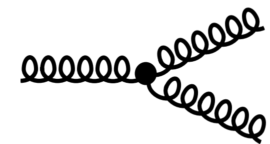

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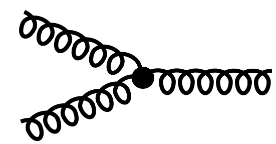
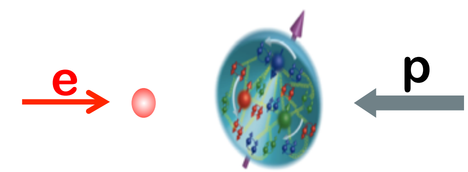
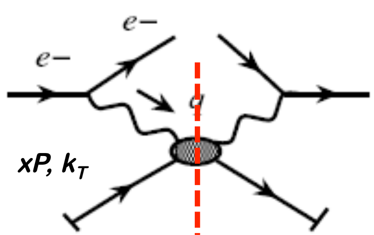


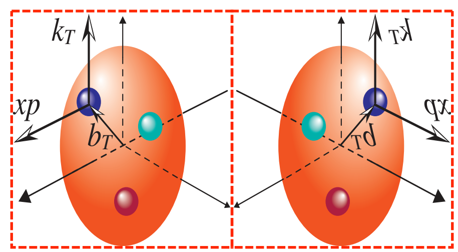
❑ Color entanglement enhanced at small-x:



$\sigma_{\rm tot}^{\rm DIS}$:



$\otimes$



+

+ . . .

$$= \sum_f \hat{C}_f \otimes \Phi_f + \mathcal{O}\left(Q_s^2/Q^2\right) + \mathcal{O}\left(Q_s^4/Q^4\right) + \ldots \qquad \mathcal{O}(1/QR)$$

$Q_s^2 \propto$ parton density

Color entangled or correlated between two active partons

❑ Saturation:

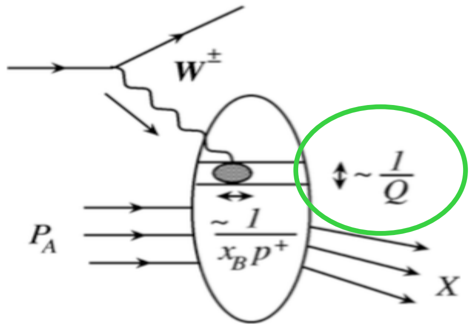
is a part of QCD!

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:

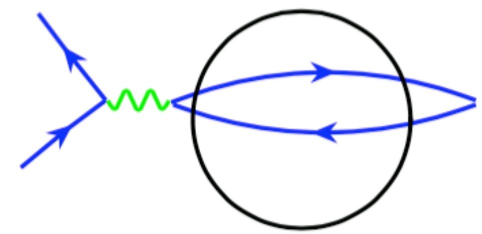


c.m. frame

Longitudinal probing size
> Lorentz contracted nucleon, if

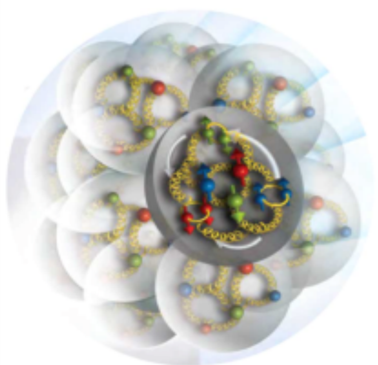
$$\frac{1}{xp} > 2R_A \frac{m}{p} \quad \text{or} \quad x \lesssim 0.01$$

Hadron rest frame



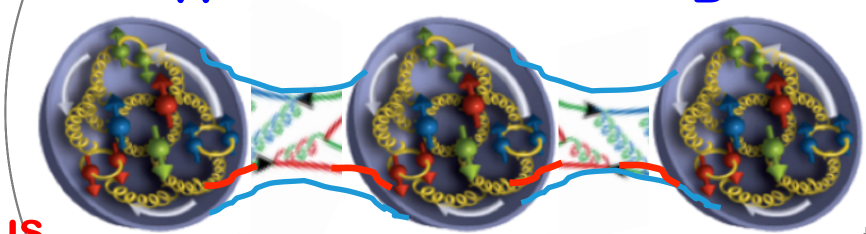
Hard probe can "see" gluons from all nucleons at the same impact parameter, coherently!

❑ Help explore the nature of nuclear force!



If we only see quarks and gluons, …

"A" "B"



What does a nucleus look like?

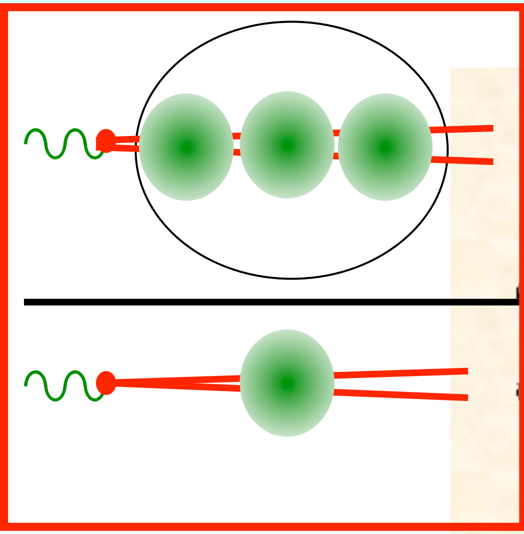
Does the color of "A" know the color of "B"?

✧ NO → Observed nuclear effect is a coherent collision effect

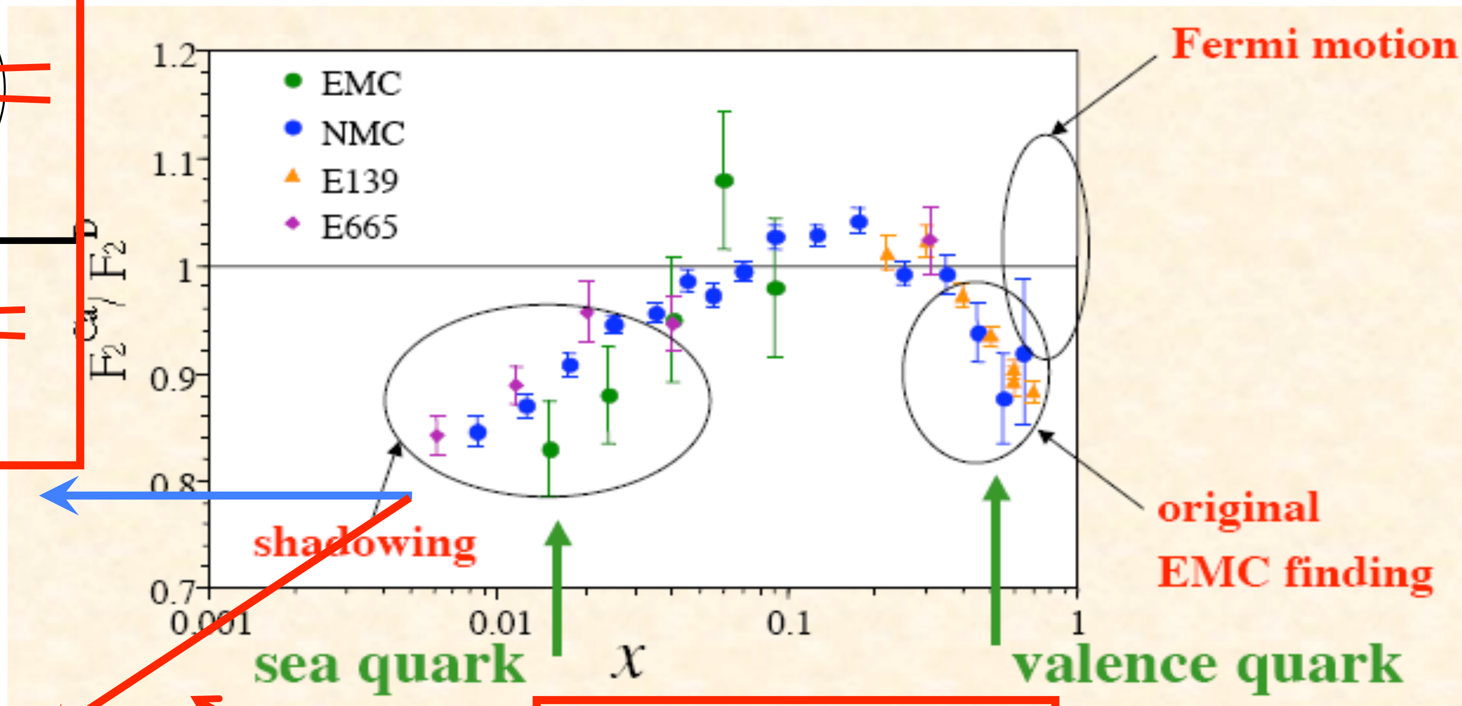
✧ YES → Nucleus could act like a bigger proton at small-x, and could reaching the saturation sooner!

EIC can tell!

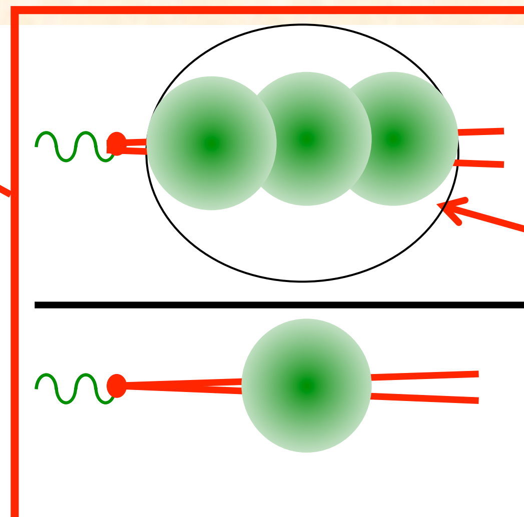
Role of color for nuclear force?



Color localized Inside nucleons



Nucleus as a bigger proton



Color leaks outside nucleons Soft gluon radius is larger

- A simple question:

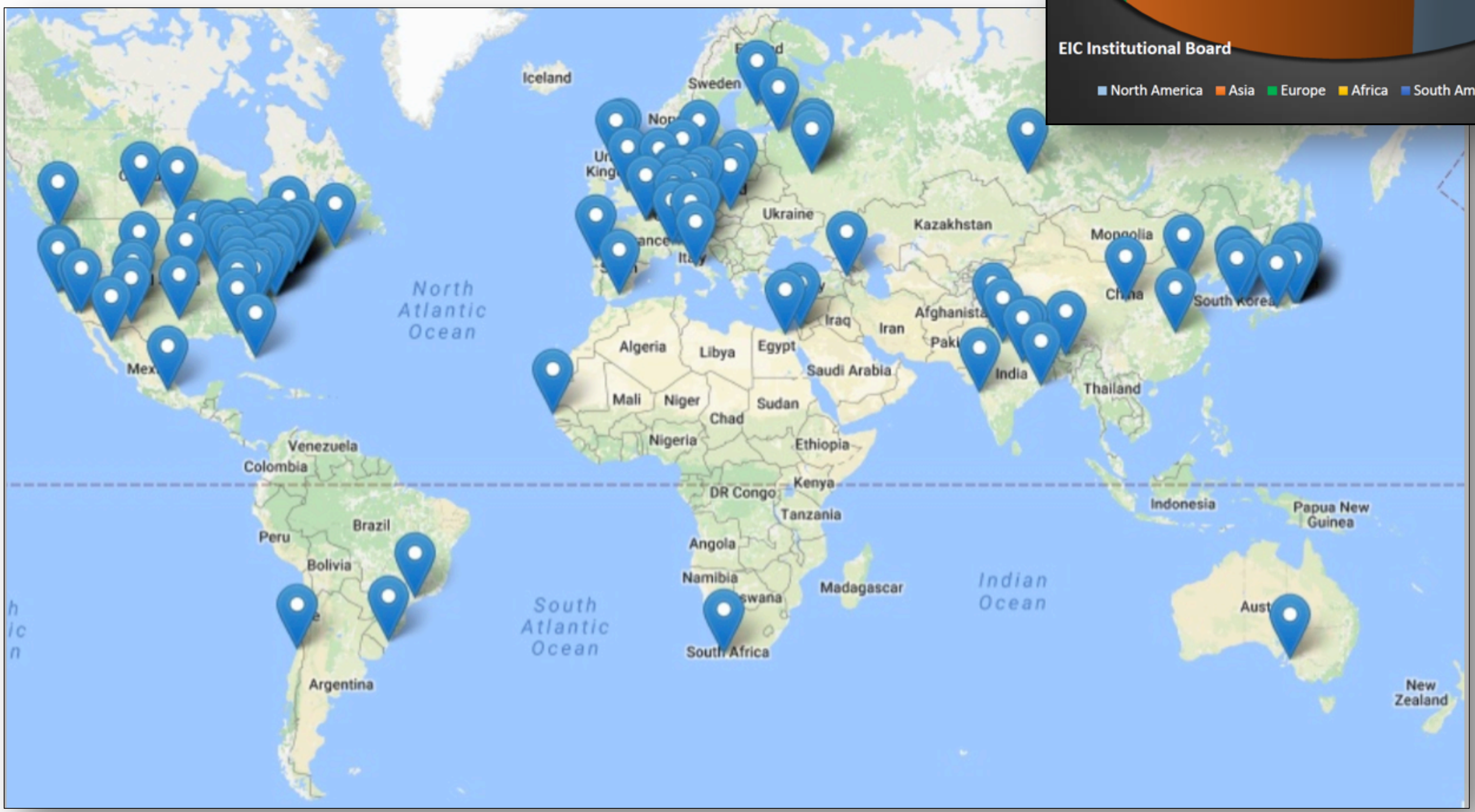
  Will the suppression/shadowing continue to fall as x decreases?

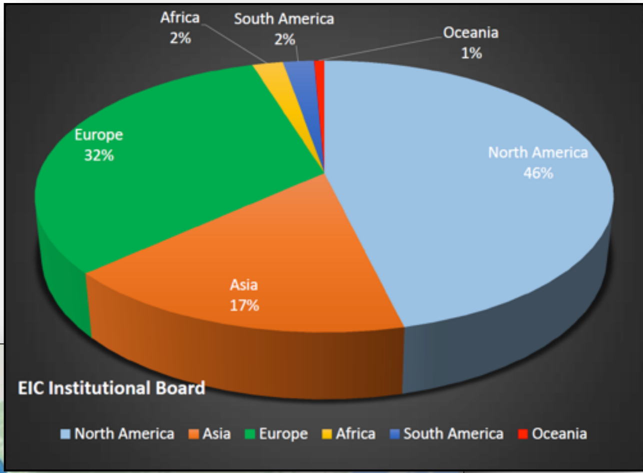
US EIC – An International Effort

❑ **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!

Backup slides

U.S. - based Electron-Ion Collider

- **NSAC 2007 Long-Range Plan:**

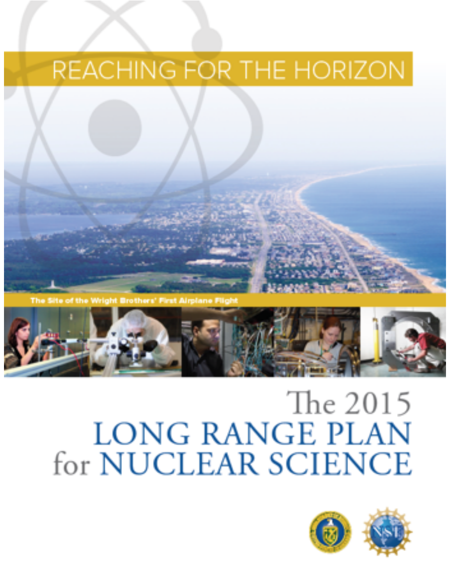
  "An Electron-Ion Collider (EIC) with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier."

- **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."



- **Under review of National Academy of Science:**

  Expect to have the committee report this year soon!

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/

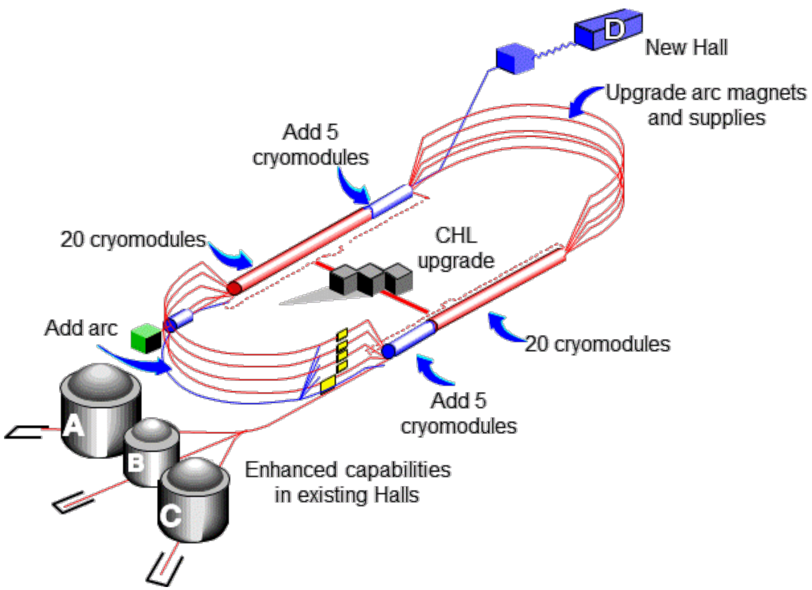
http://www.ectstar.eu/node/2218

A true international effort!

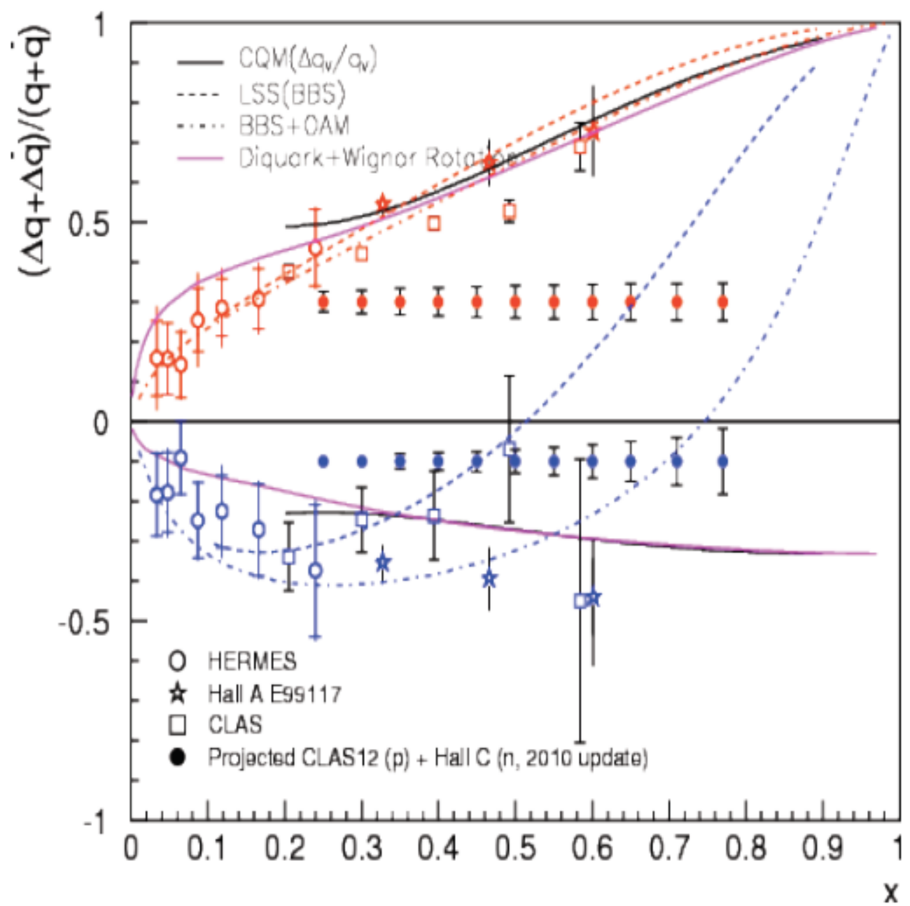
The Proton Spin

- JLab 12GeV – upgrade project just completed:

12 GeV CEBAF Upgrade Project
is just complete, and
all 4-Halls are taking data



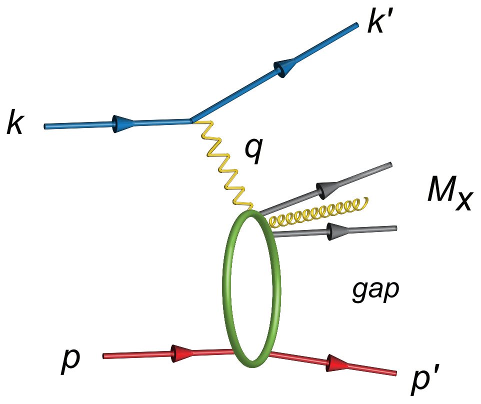
CLAS12



Plus many more JLab experiments,
COMPASS, Fermilab-fixed target expts
…

Best signature for gluon saturation

❑ Diffractive cross section:



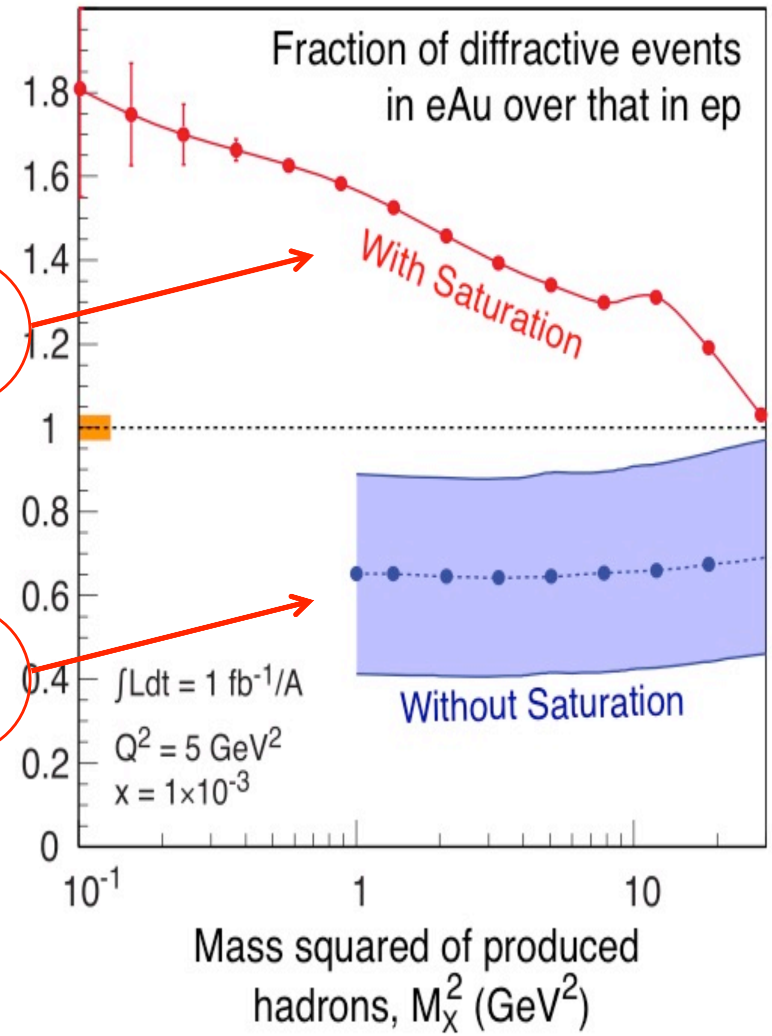
– off a coherent obj.

$$\frac{1}{\sigma_{\rm tot}^{eA}}\frac{d\sigma^{eA}_{diff}}{dM_x^2}\Big/\frac{1}{\sigma^{ep}_{\rm tot}}\frac{d\sigma^{ep}_{diff}}{dM_x^2} \sim \frac{25-30\%}{10-15\%} > 1$$

$$\sigma_{\rm diff} \propto [g(x,Q^2)]^2$$

– off a single hard, local interaction

$$\frac{1}{\sigma_{\rm tot}^{eA}}\frac{d\sigma^{eA}_{diff}}{dM_x^2}\Big/\frac{1}{\sigma^{ep}_{\rm tot}}\frac{d\sigma^{ep}_{diff}}{dM_x^2} \sim \left[\frac{g^p(x)}{g^A(x)}\right]_{\rm tot}\left[\frac{g^A(x)}{g^p(x)}\right]^2_{\rm diff} < 1$$



At HERA

ep: 10-15% diffractive

At EIC eA, if Saturation/CGC

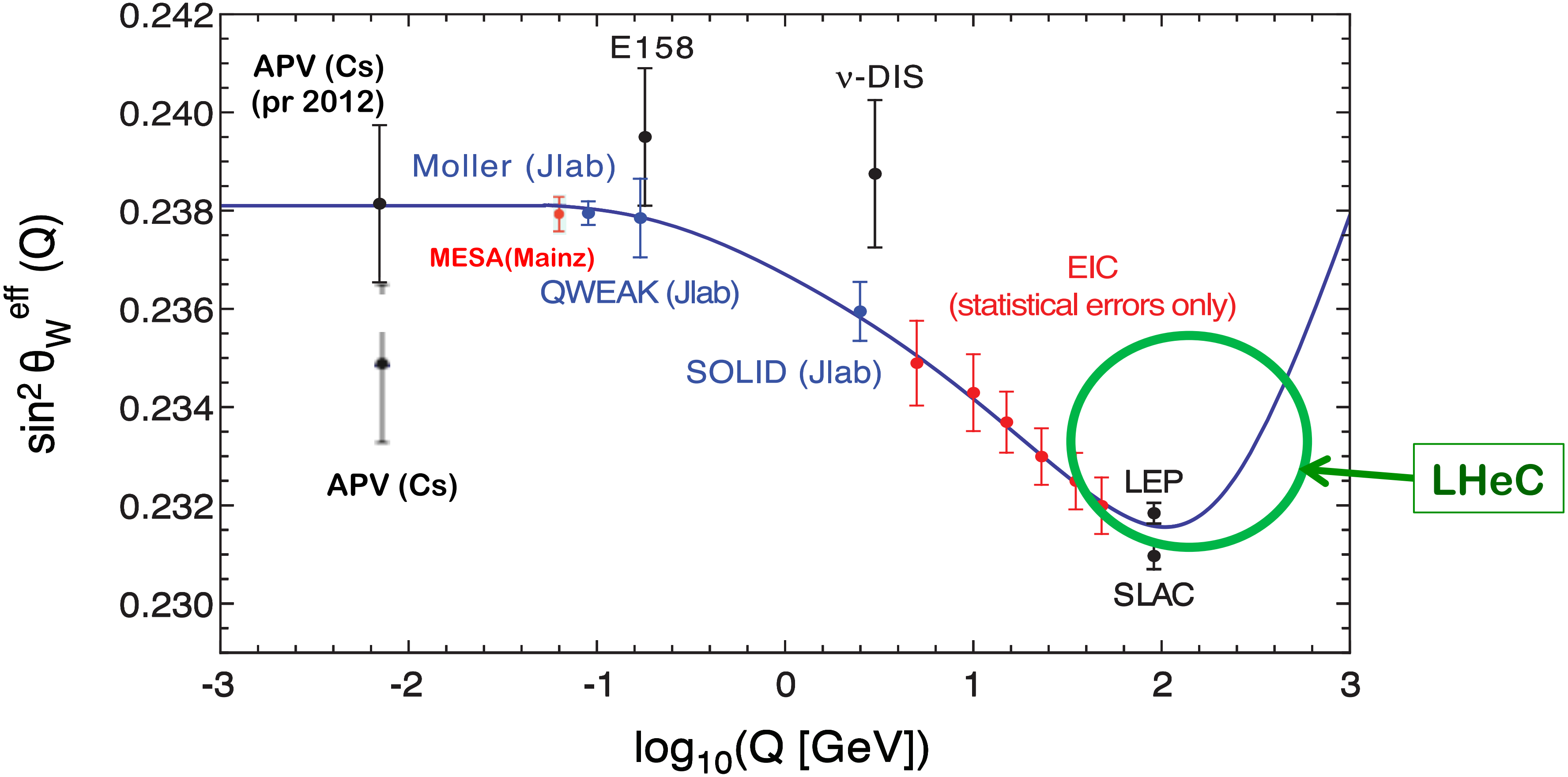
eA: 25-30% diffractive

Early work – E665 @ FNAL:

Nuclear shadowing, diffractive scattering and low momentum protons in μ Xe interactions at 490 GeV Z. Phys. C 65, 225–244 (1995)

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***