PHENO 2020

FROM THE INFRARED TO THE ULTRAVIOLET

Physics at the Electron-Ion Collider
QCD at a Fermi Scale

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Acknowledgement:
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TMD Collaboration

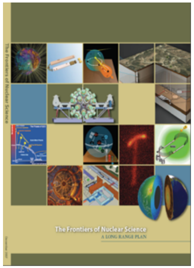
U.S. DEPARTMENT OF ENERGY | Office of Science

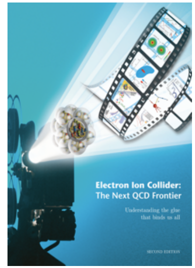
JSA

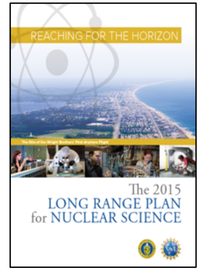
U.S. - based Electron-Ion Collider

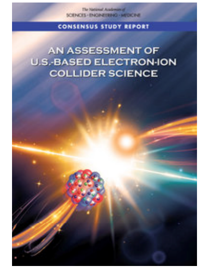
- A long journey, a joint effort of the full community:

…









…

"… 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?

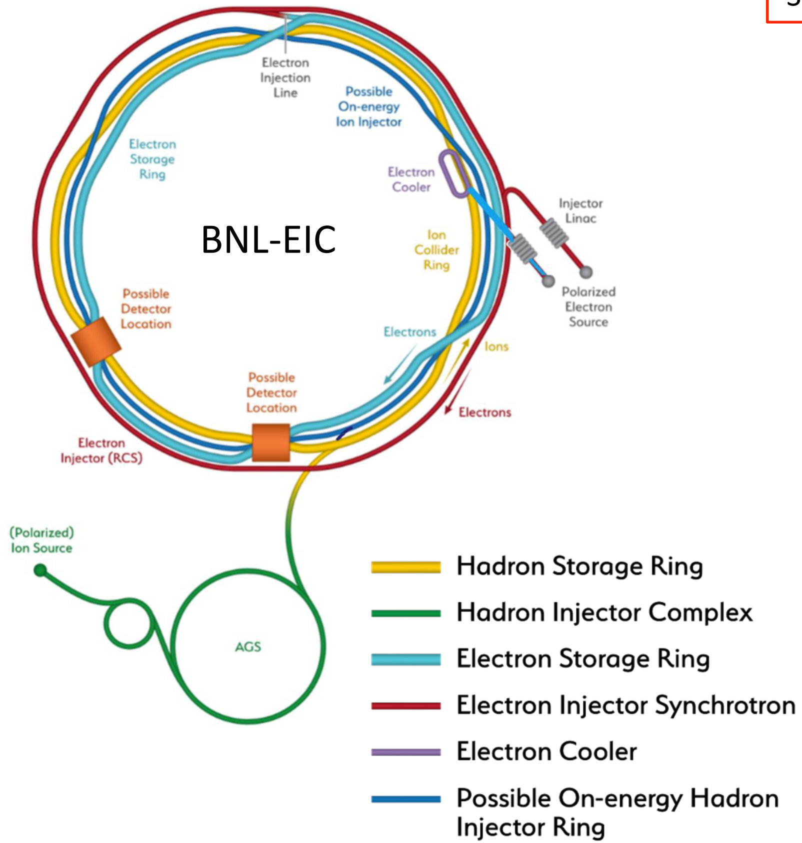
- On January 9, 2020:

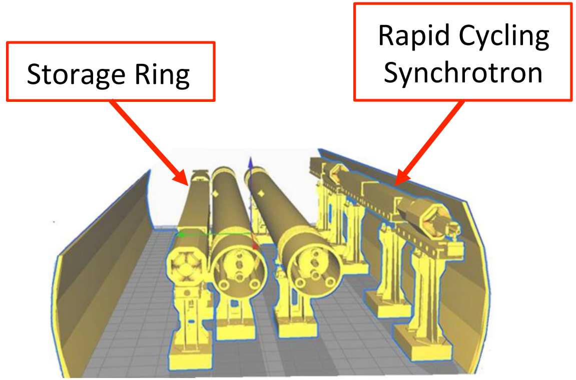
The U.S. DOE announced the selection of BNL as the site for the Electron-Ion Collider

→ *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

Outline of the Rest of My Talk

- **Frontiers of QCD and strong interaction:**

  To understand where did we come from?
  To understand the visible world at 3ºK – what are we made of?

- **QCD at a Fermi scale – Nuclear Femtography:**

  Great intellectual challenge: can't see quarks and gluons in isolation
  Quantify hadron internal structure as quantum correlation functions

- **Why do we need an Electron-Ion Collider (EIC)?**

  Why do we need a lepton-hadron collider?
  Why is the difference between a US-EIC and the HERA at DESY?

- **What an EIC can do, but, why other machine cannot do?**

  Major nuclear science issues to be studied at an EIC
  EIC is an international effort

- **Summary and outlook**

Frontiers of QCD and Strong Interaction

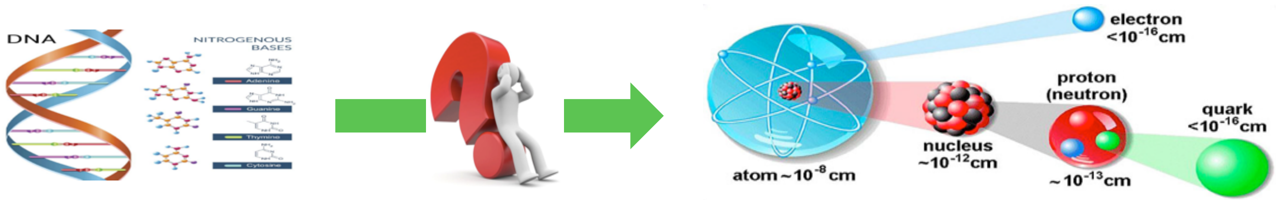
- **Understanding where did we come from?**

Global Time: →

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

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

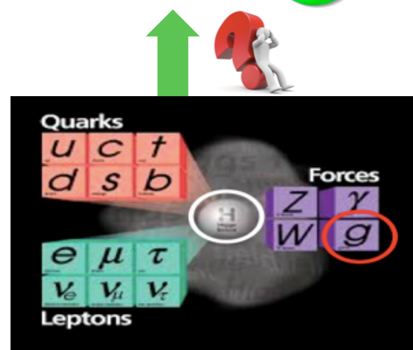
- **Understanding the visible world at 3°K – what are we made of?**



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?



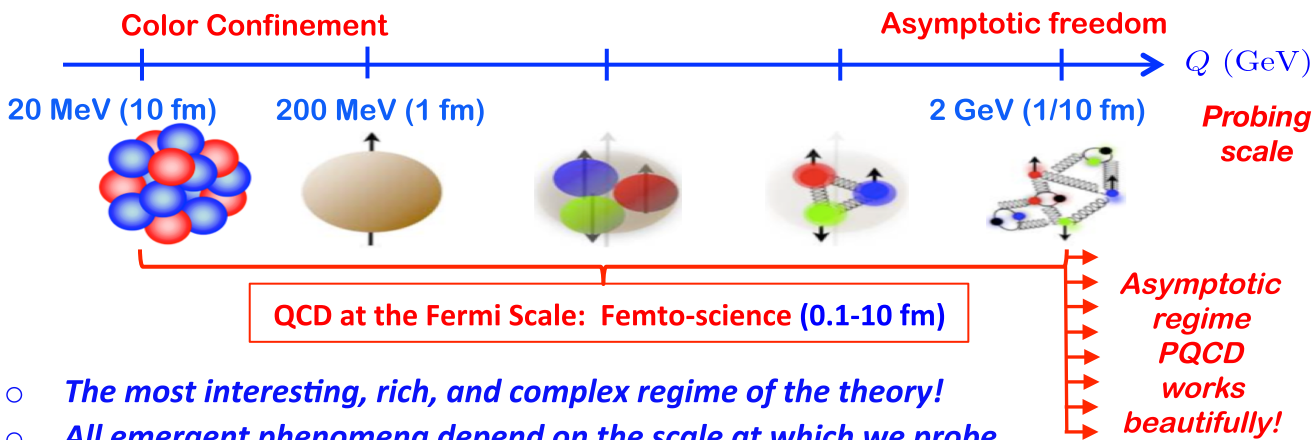
Facilities – EIC: *Search for answers to these*

Nuclear Femtography *questions at a Fermi scale!*

QCD at a Fermi Scale – Nuclear Femtography

❑ QCD – Color Confinement:

- *Do not see any quarks and gluons in isolation*
- *The structure of nucleons and nuclei – emergent properties of QCD*



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

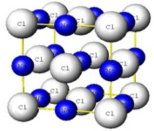
❑ QCD – Asymptotic Freedom:

- *Force becomes weaker at a shorter-distance – Controllable "Probes"*
- *Explore the structure of nucleons and nuclei indirectly by using "local", "sharp", and "controllable" probes, …*

"See" the Structure of Nucleons and Nuclei

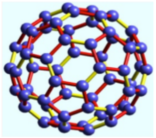
- **Structure – "a still picture":**

Crystal Structure:



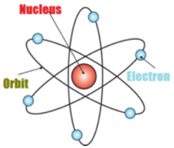
NaCl, B1 type structure

Nano-material:



Fullerene, C60

Atomic structure



Quantum orbits

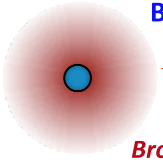
Motion of nuclei is so much slower than the speed of light, neutral photon!

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

  Quarks and gluons are moving relativisticaly, color is fully entangled!

  Partonic structure = "Quantum Probabilities": $\langle P, S | \mathcal{O}(\overline{\psi}, \psi, A^{\mu}) | P, S \rangle$

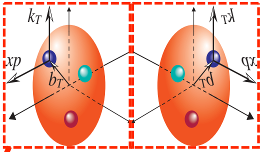
B-meson

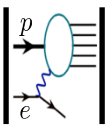
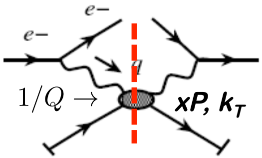
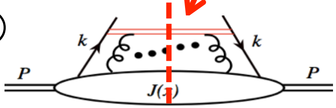


$B^{+}(u\bar{b})$

Brown-Muck

- **Need a probe to "see" quarks and gluons!**



$\sigma_{\rm DIS}(x, Q^2) = \Big|$  $\Big|^2 \approx$  $\otimes$  $+\, O\left(\frac{1}{QR}\right)$

Factorization

Hard-part Probe

Parton-distribution Structure

Power corrections Approximation

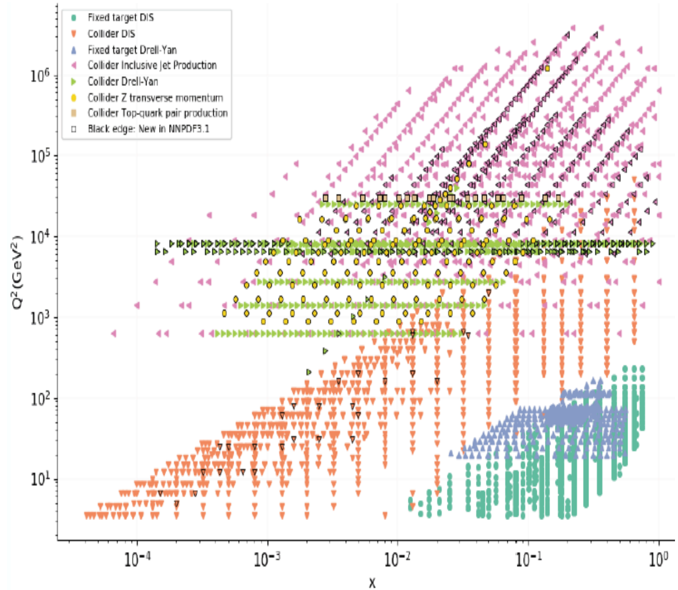
QCD Factorization Works to the Precision

❑ 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	$0.01 \lesssim x \lesssim 0.5$
	$p\bar{p} \to (W^\pm \to \ell^\pm \nu) + X$	$ud \to W^+, \bar{u}\bar{d} \to W^-$	$u,d,\bar{u},\bar{d}$	$x \gtrsim 0.05$
	$p\bar{p} \to (Z \to \ell^+\ell^-) + X$	$uu, dd \to Z$	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

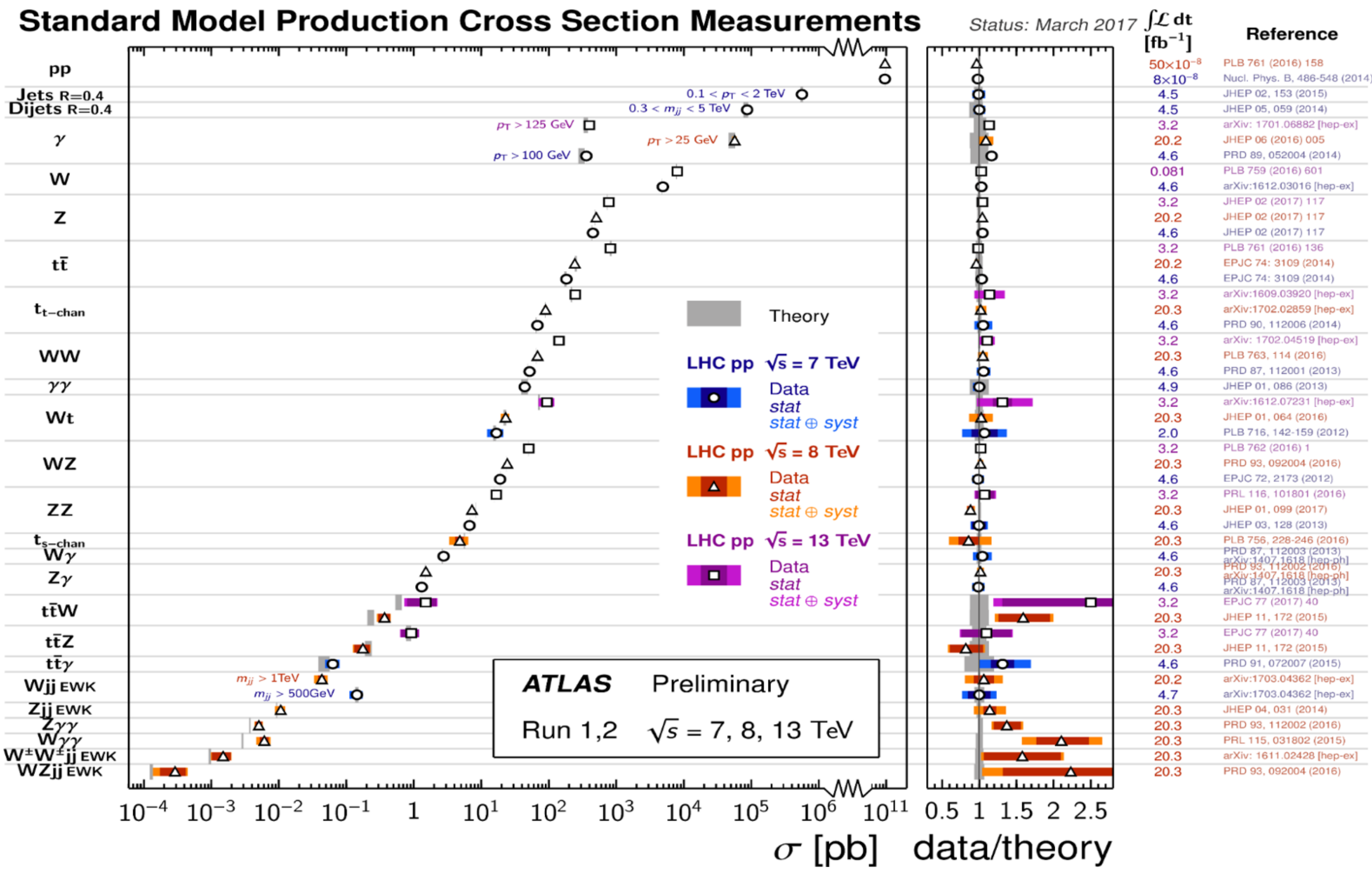


❑ Fit Quality:

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

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

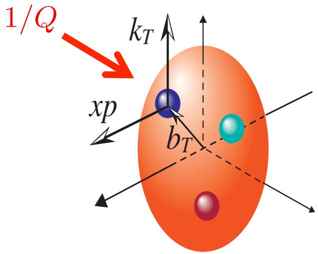
Unprecedent Success of QCD and Standard Model



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

Need New-Type Probes for 3D Hadron Structure

- Single scale hard probe is too "localized":



  - It pins down the particle nature of quarks and gluons
  - But, not very sensitive to the detailed structure of hadron ~ fm
  - Transverse confined motion: k_T ~ 1/fm << Q
  - Transverse spatial position: b_T ~ fm >> $1/Q$

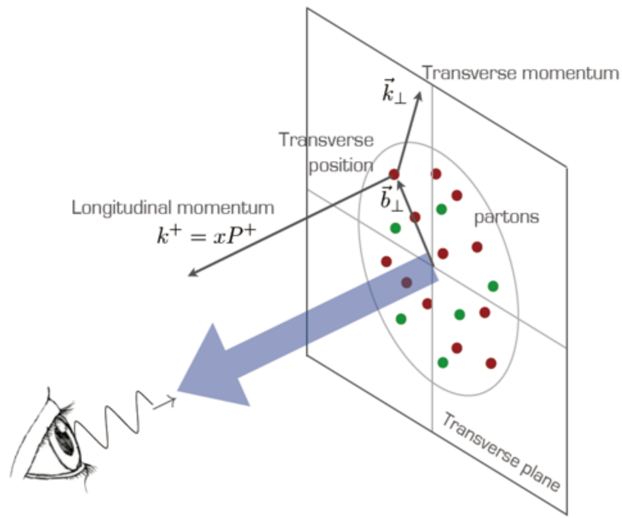
- Need new type of "Hard Probes" – Physical observables with TWO Scales:

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

Hard scale: Q_1 To localize the probe
particle nature of quarks/gluons

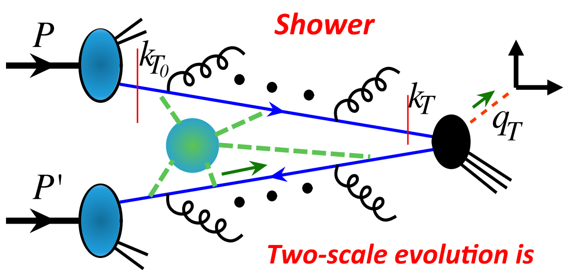
"Soft" scale: Q_2 could be more sensitive to the
hadron structure ~ 1/fm

Hit the hadron "very hard" without breaking it,
clean information on the structure!



Unprecedent Challenge - "True" Hadron Structure

- Challenge to separate "true" hadron structure from "collision effects":



Two-scale evolution is often Non-perturbative!

- Drell-Yan type (W/Z, H^0): Q >> q_T (two scales)
- Parton *shower* develops when hadron broken
- *Parton k_T probed at the hard collision is NOT the same as "confined motion" in a hadron*
- The difference is encoded in QCD evolution
- Two-scale evolution *is different* from DGLAP!

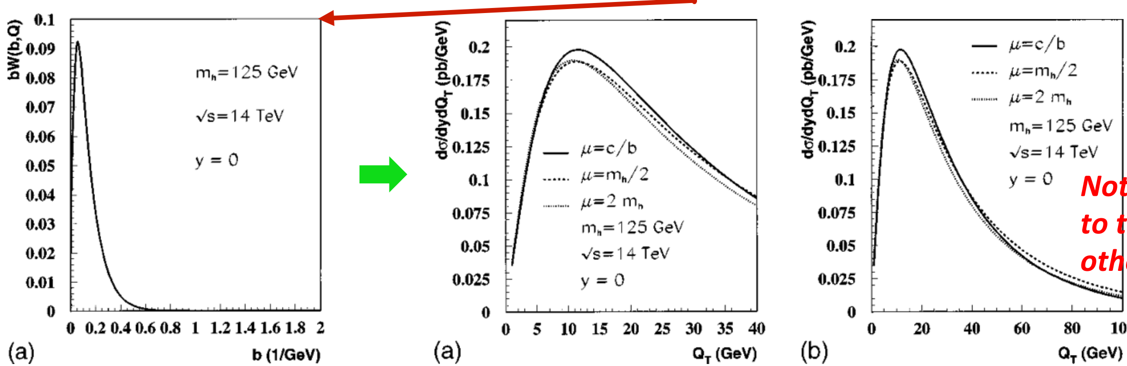
- Structure information could be easily washed out in high energy collisions:

e.g., Higgs production at the LHC:

$$f(x_b, k_T, \mu, \zeta_b)$$

F.T.

$$\frac{d\sigma(Q,q_T)}{dy\,dq_T} = \int_0^\infty \frac{db_T}{2\pi}\, b_T J_0(q_T b_T) H(Q,\mu) f(x_a, b_T, \mu, \zeta_a) f(x_b, b_T, \mu, \zeta_b) + \mathcal{O}\left(\frac{q_T^2}{Q^2}\right)$$

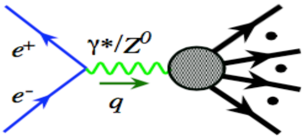


Not sensitive to the structure other than PDFs!

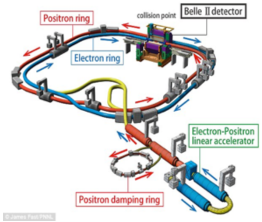
Berger, Qiu PRD67 (2003) 034026

QCD & Hadron Structure needs Lepton-Hadron Collider

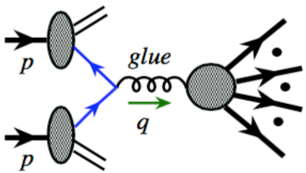
❑ Lepton colliders – e+e- collisions:



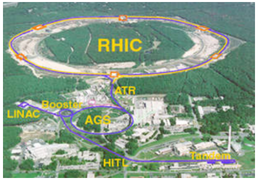
- *No hadron to start with*
- *Emergence of hadrons from the energy!*



❑ Hadron-hadron colliders:

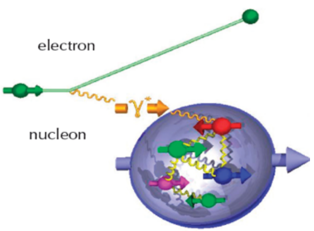


- *Colliding hadrons are broken*
- *Partonic structure - challenge*
- *Emergence of hadrons*
- *Heavy ion target or beam(s)*



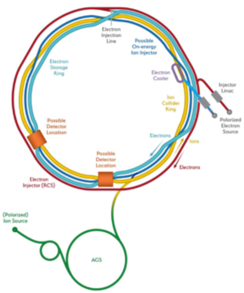
Also the LHC

❑ Lepton-hadron colliders:



One facility covers all!

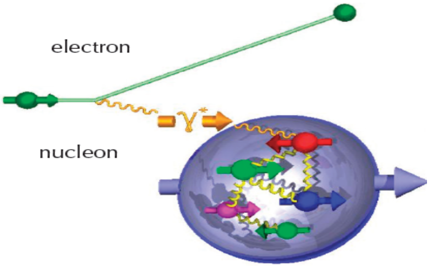
- *Colliding hadron can be broken or stay intact!*
- *Imaging partonic structure*
- *Emergence of hadrons*
- *Polarized beams*
- *Heavy ion beams*



Also CEBAF, COMPASS

Many Complementary Probes at One Facility

❑ A new generation of the "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(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)

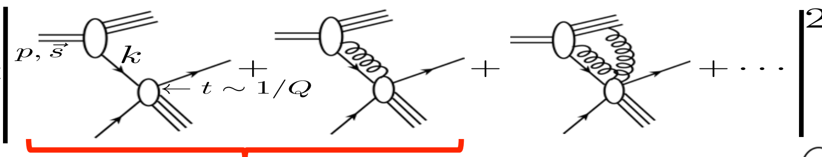
(Initial hadron is NOT broken – tomography! – almost impossible for h-h collisions)

US-EIC can do what HERA could not do

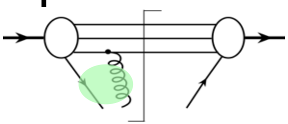
- **Quantum imaging:**
  - ✧ **HERA discovered: 15% of e-p events is diffractive – Proton not broken!**
  - ✧ **US-EIC: 100-1000 times luminosity – *Critical for 3D tomography!***

- **Quantum interference & entanglement:**
  - ✧ **US-EIC: Highly polarized beams – *Origin of hadron property: Spin, …***
    Direct access to chromo-quantum interference!

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



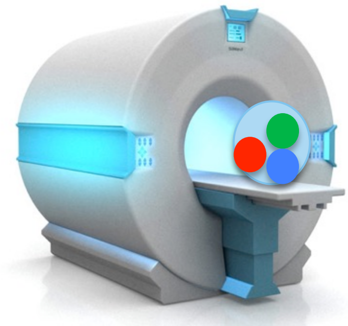
$\sigma(s) - \sigma(-s)$ ➡ **Quantum interference** ➡ $T^{(3)}(x, x) \propto$



- **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 (ions as femtometer size detectors!),
    – "a new controllable knob" – Atomic weight of nuclei

US-EIC can do what HERA could not do

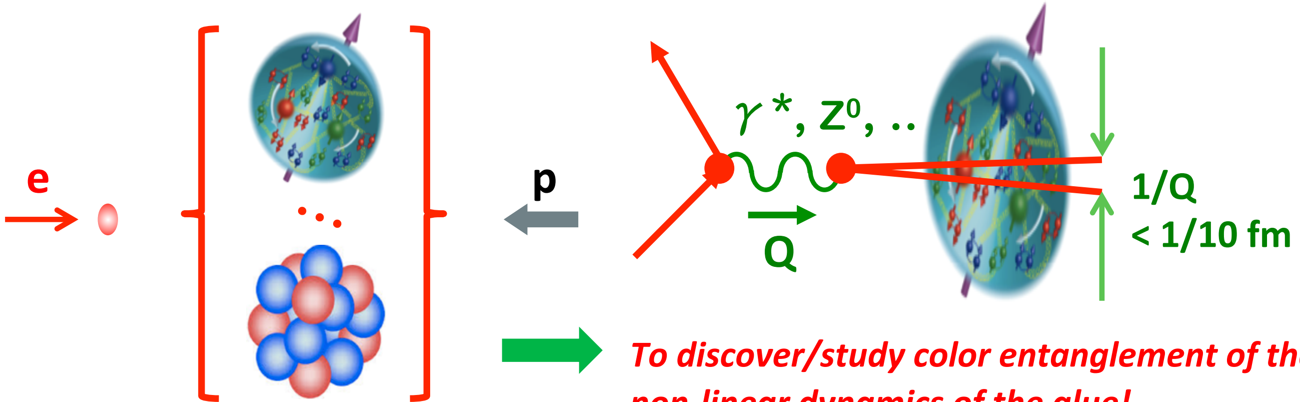
- ❑ Be a sharpest "CT" – "imagine" quark/gluon structure without breaking the hadron



  - ○ "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!*

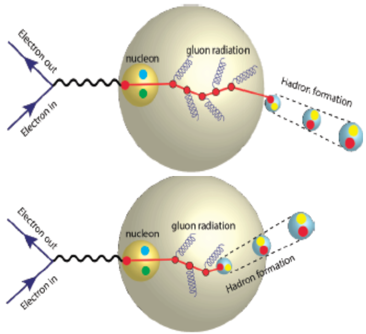
- ❑ Be a giant "Microscope" – "see" quarks and gluons by breaking the hadron



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

How Hadrons are Emerged from Quarks and Gluons?

- **Ions as femtometer sized detectors:**

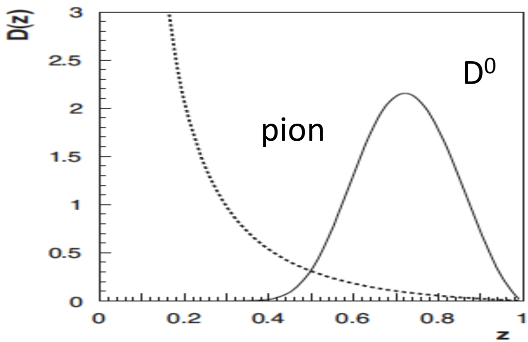


The Control of photon energy
v
medium length!

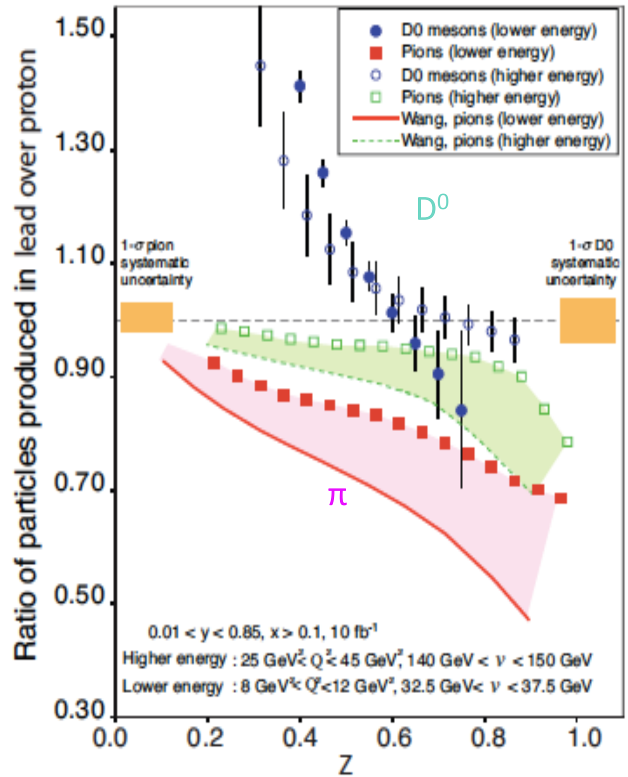
$$\nu = \frac{Q^2}{2mx}$$

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:**

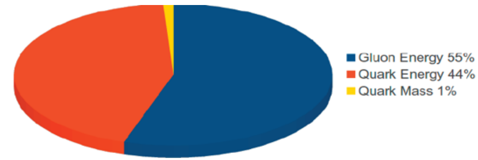
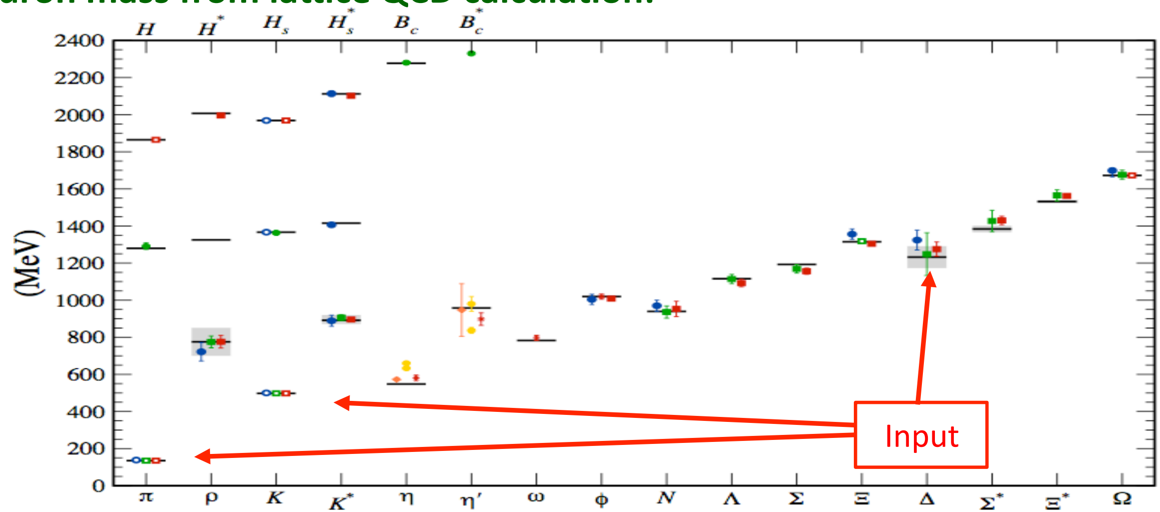


Fig. 2.1 NAS Report

Higgs mechanism is far from enough!!!

"Mass without mass!"

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

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

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

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

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

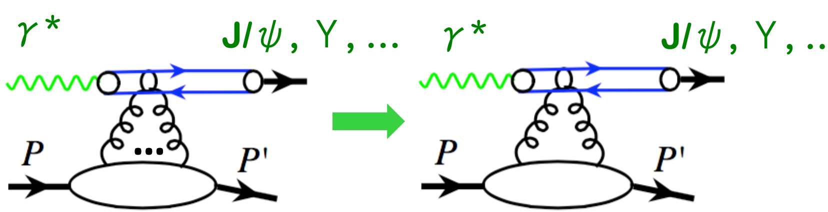
Relativistic motion ($E_q + E_g$); Quark Energy (E_q); Gluon Energy (E_g); χ Symmetry Breaking and Quark Mass (χ_{m_q}); Quantum fluctuation and Trace Anomaly (T_g)

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: Decomposition

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

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

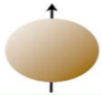
(Postponed due to COVID-19)

A true international effort!

How does the Spin of the Nucleon Arise?

❑ An incomplete story:

Jaffe-Manohar, 90, Ji, 96, …



Proton Spin

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

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

$\sim 30\%$

Quark helicity
Best known

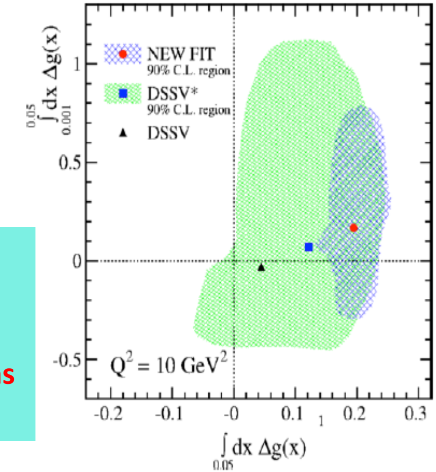
$$\Delta G = \int dx \Delta g(x)$$

$\sim 40\%$

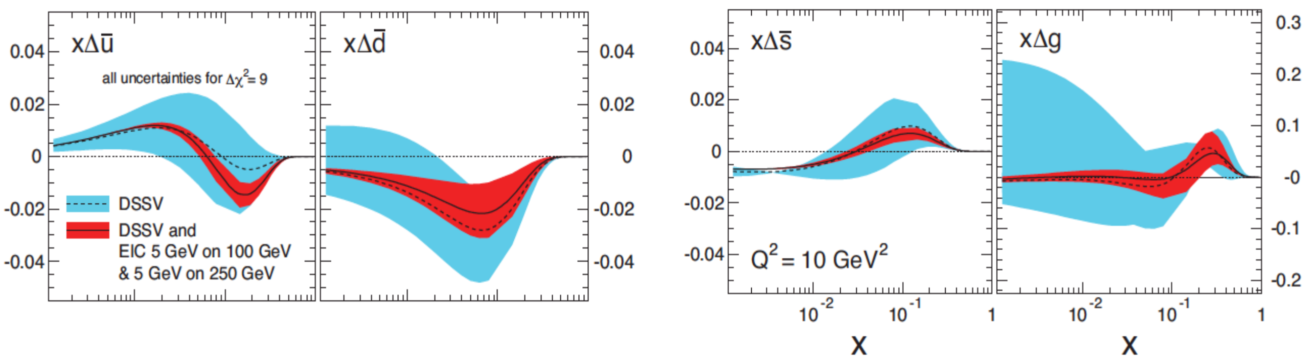
With RHIC data

Gluon helicity
Start to know

Orbital Angular Momentum of quarks and gluons
Little known

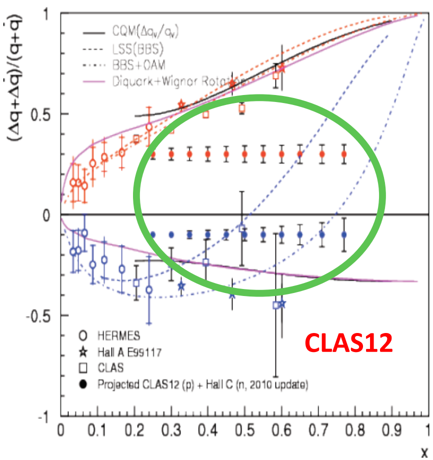


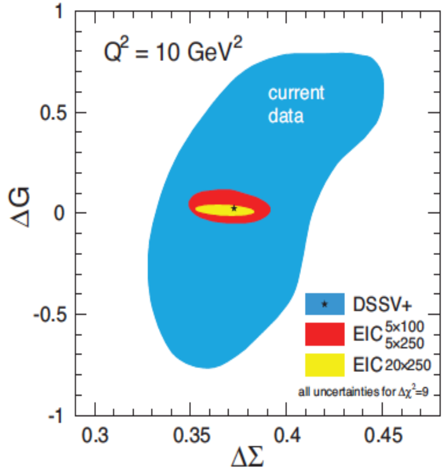
❑ What an EIC could help:

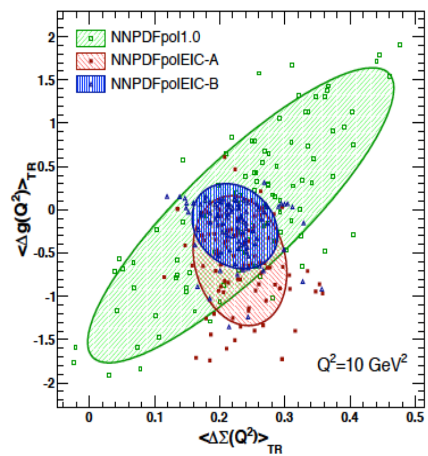


The Proton Spin: from JLab12 to EIC

❑ Complementary between JLab12 and EIC:







No other machine in the world can achieve this!

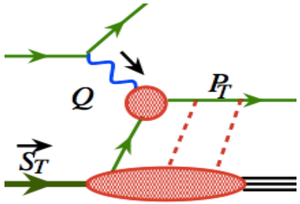
❑ Critical Tests of the emergence of hadron properties in QCD:

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

"See" Nucleon's Internal Landscape

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

✧ **Semi-inclusive DIS:**

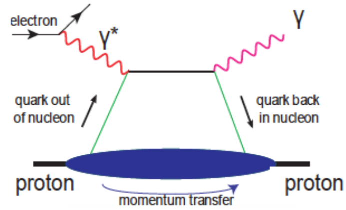


+ …

SIDIS: $Q >> P_T$

Parton's confined motion encoded into TMDs

✧ **Exclusive DIS:**



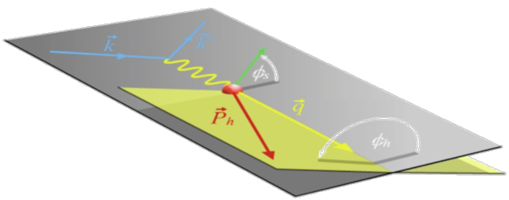
+ …

Imaging quarks

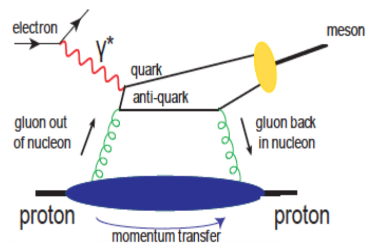
DVCS: $Q^2 >> |t|$

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

✧ **Two scales + Two planes:**



Angular modulation provides the best way to separate TMDs



J/Ψ, Φ, …

Imaging gluons

Heavy quarkonium: $Q^2+M^2 >> |t|$

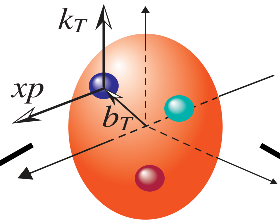
Gluon's spatial imaging only at EIC

Theory is Solid – Unified Description

- Wigner distributions in 5D (or GTMDs):

Momentum Space
TMDs
Confined motion

$\int d^2b_T$



$\int d^2k_T$

Coordinate Space
GPDs
Spatial distribution

$f(x,k_T)$ | Two-scales observables | $f(x,b_T)$

- 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:

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

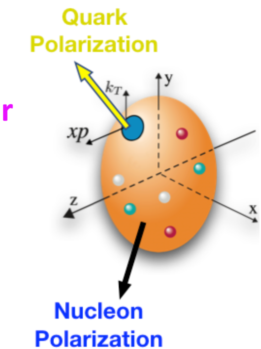
  - P_{hT} Integrated - Collinear factorization:

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

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

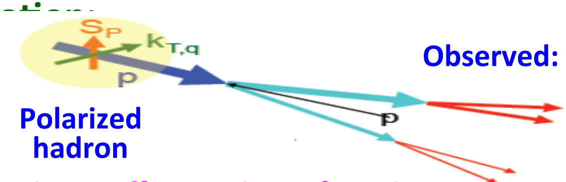
$$\sigma_{\rm SIDIS}(Q,P_{h\perp},x_B,z_h)=\sum_{abc}\hat{H}_{ab\to c}\otimes\phi_{\gamma\to a}\otimes\phi_b\otimes D_{c\to h}+\mathcal{O}\left(\frac{1}{Q},\frac{Q}{P_{h\perp}}\right)$$

Explore the Flavor-Spin-Motion Correction



- ❑ **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, ..

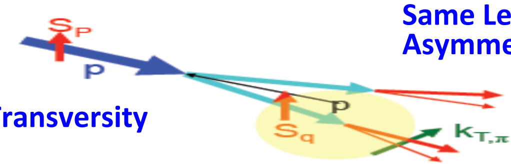
- ❑ **Quantum correlation between hadron spin and parton motion:**



  - ✧ 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 hadron

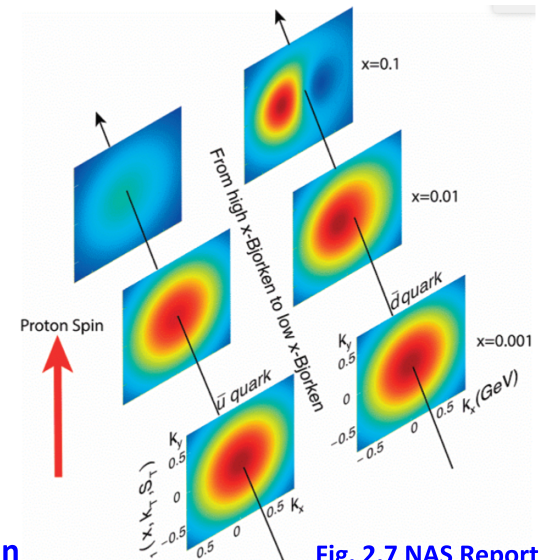
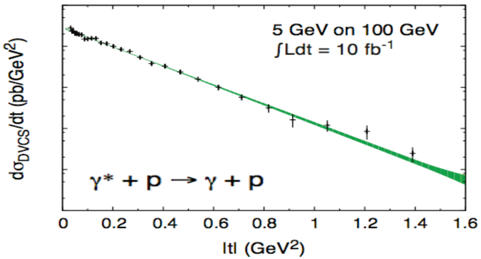
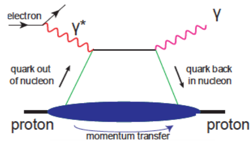


Fig. 2.7 NAS Report

Flavor Dependence of Spatial Imaging

❑ DVCS at EIC:

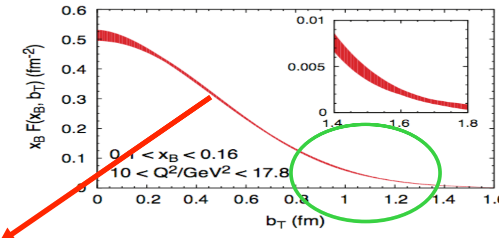




Factorization

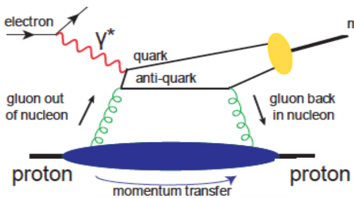
GPDs

F.T.



Proton radius of quark dist.(x)!

❑ "Seeing" the glue at EIC:

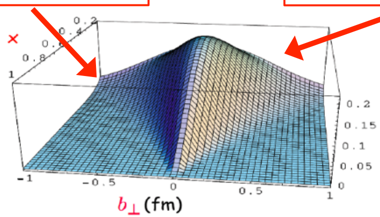


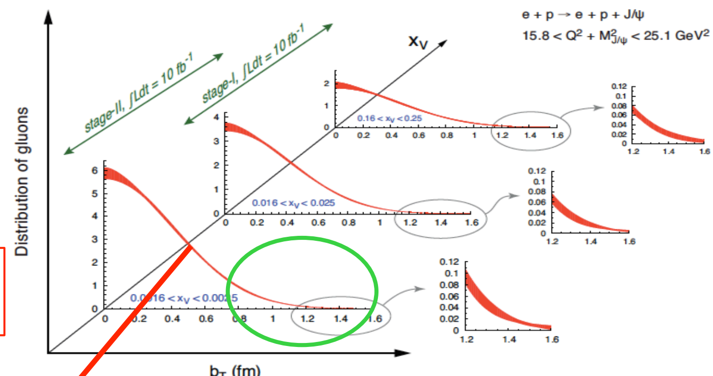
J/Ψ, Φ, …

F.T. t-dep

How far does glue density spread?

How fast does glue density fall?

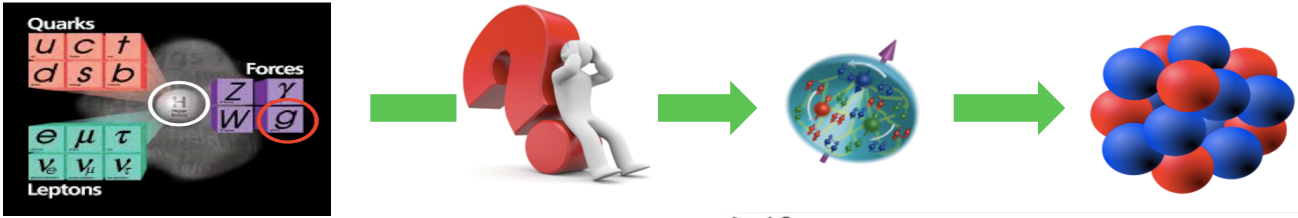




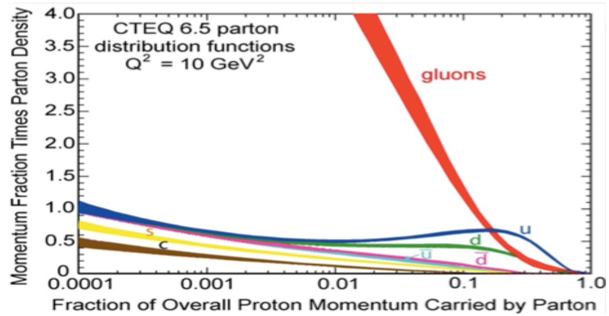
Proton radius of gluons (x)!

Only possible at EIC!

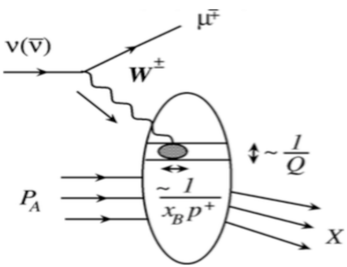
How QCD Glue Holds us Together?



- **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

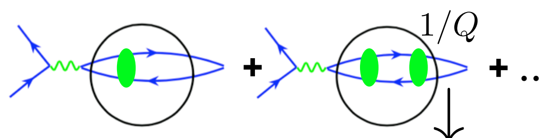
Longitudinal probing size

> 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:



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

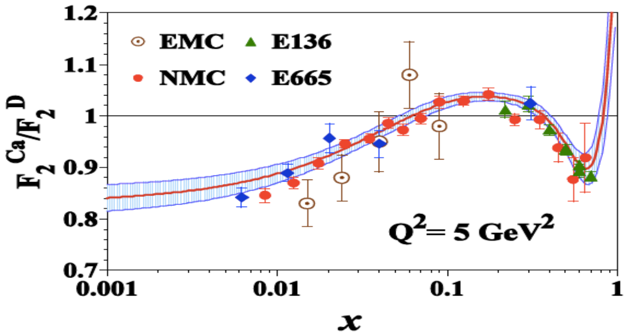
Color entangled between two active partons

Nuclear Landscape – Nuclear Force

- ❑ **EMC discovery:**

  Nuclear landscape

  ≠ Superposition of nucleon landscape



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

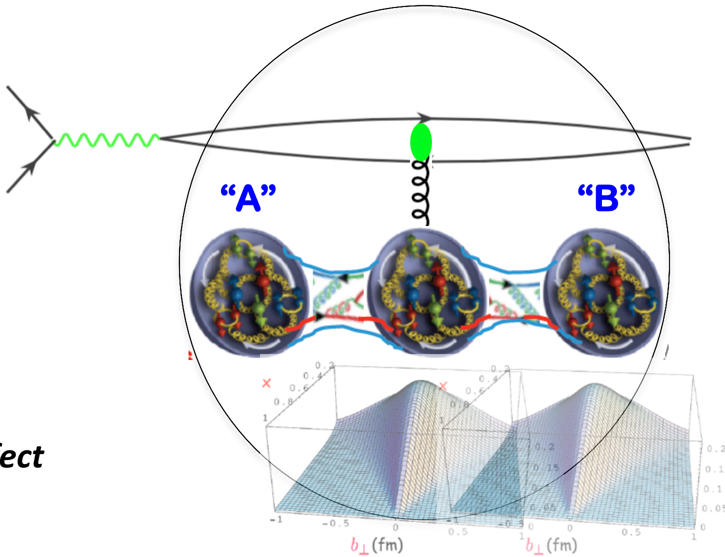
  ✧ What does a nucleus look like *if we only see quarks and gluons ?*

  ✧ 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!

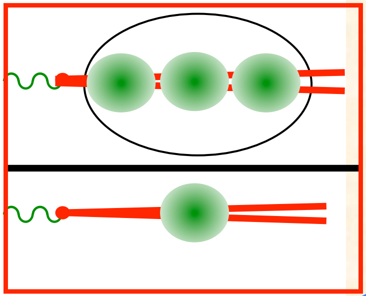
  IF NOT, Observed nuclear effect in cross-section is a coherent collision effect

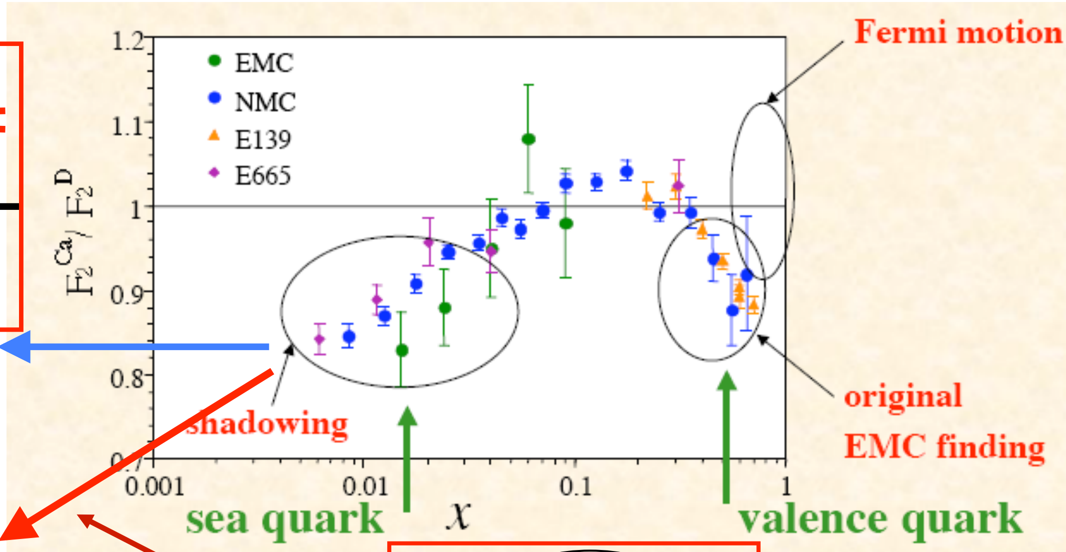
  EIC can tell !



Coherent Length of the Color

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

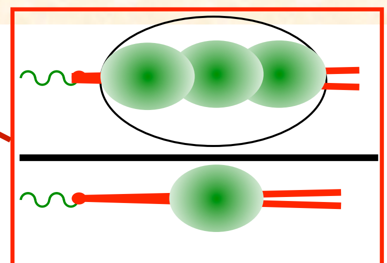




Color localized
Inside nucleons

Nucleus as a
bigger proton

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

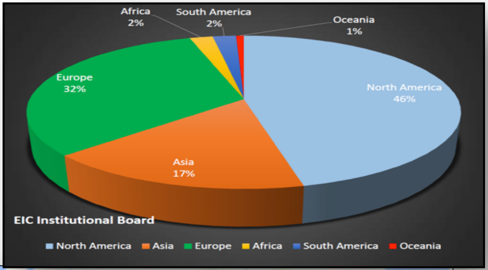


EIC can tell !

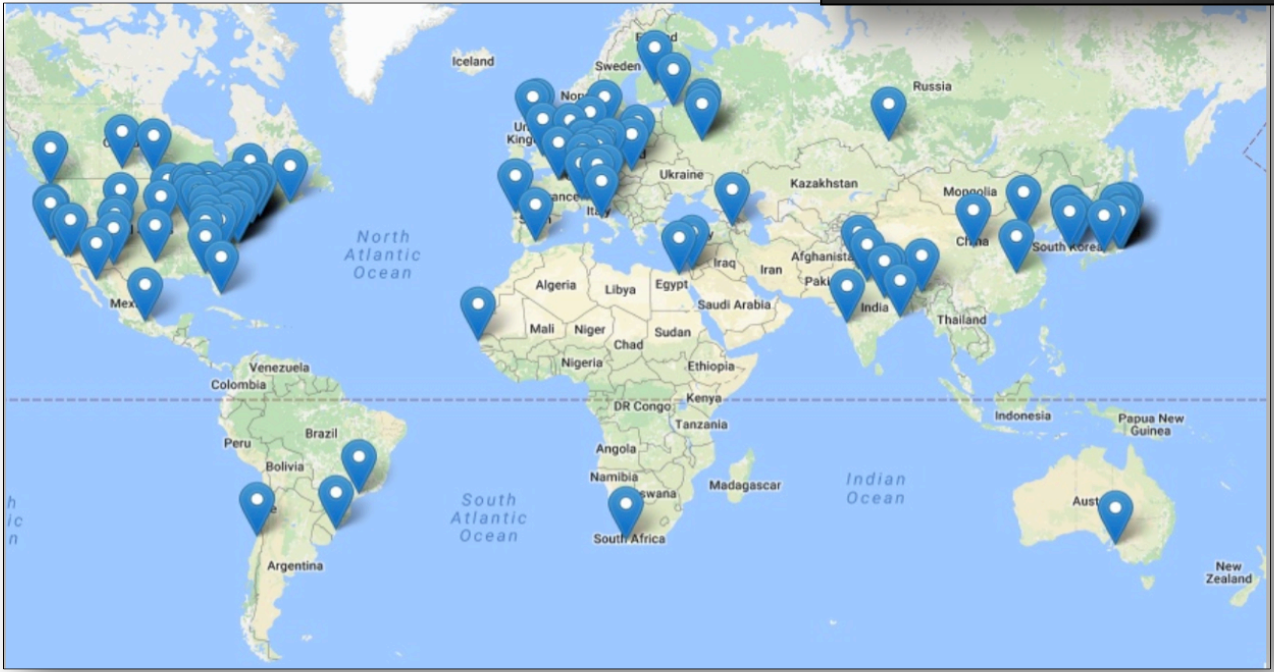
US EIC – An International Effort

❑ **EIC Users Group – *EICUG.ORG*:**

>1000 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!

Backup Slides

Internal Structure of Hadrons

1933: Proton's magnetic moment

Nobel Prize
In Physics 1943

Otto Stern

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

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

1960: Elastic e-p scattering

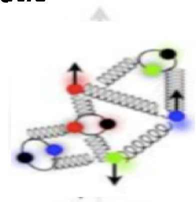
Nobel Prize
In Physics 1961

Robert Hofstadter

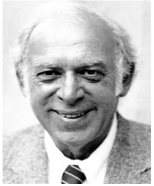
"for … for his discoveries concerning the structure of the nucleons"

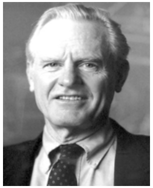
Form factor – charge distribution

"Proton Radius"



1969: Deep inelastic e-p scattering

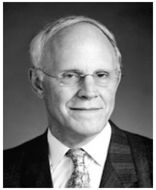


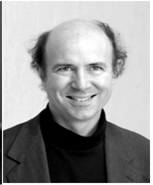


Nobel Prize in Physics 1990
Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor

"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".

US EIC – Luminosity & Kinematic Coverage