U.S. DEPARTMENT OF ENERGY | Office of Science | JSA

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Electron-Ion Collider: The Ultimate QCD Machine

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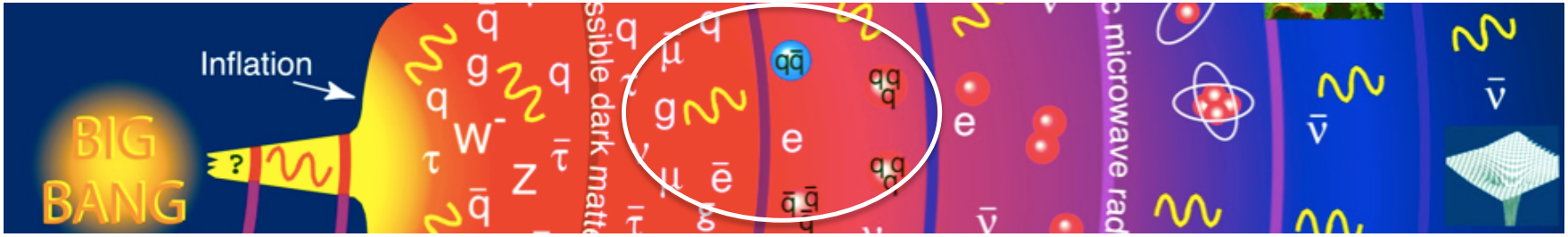
Acknowledgement: Much of the physics presented here are based on the work of EIC White Paper Writing Committee put together by BNL and JLab managements, …

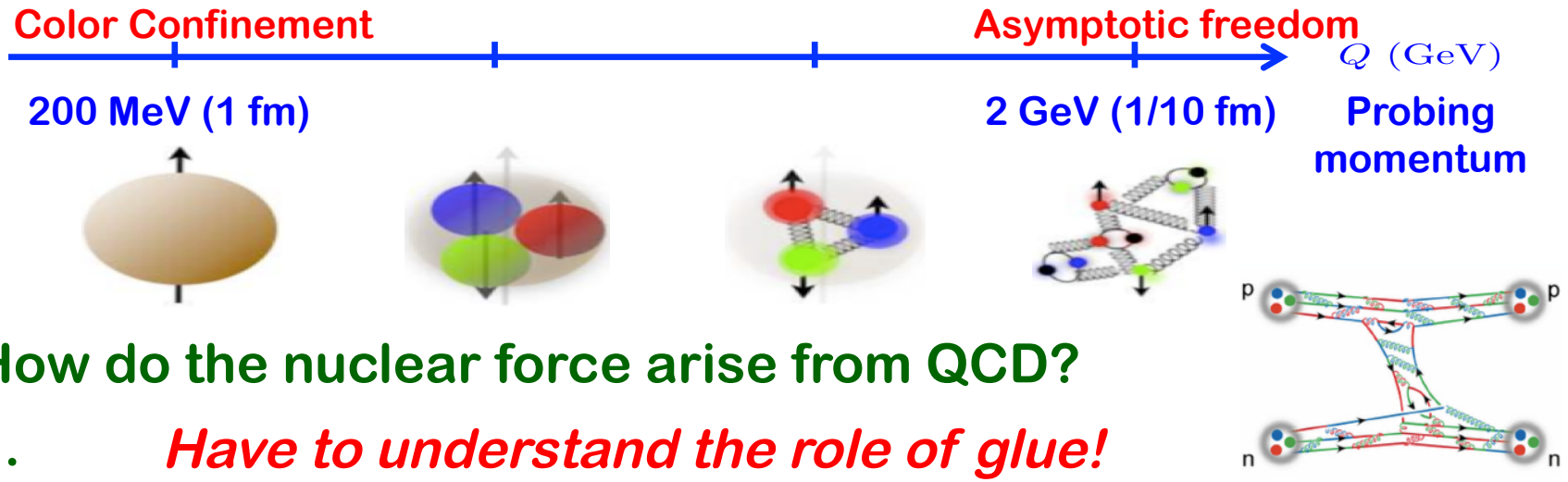
21st Century Nuclear Science

- What is the role of QCD in the evolution of the universe?



- How hadrons are emerged from quarks and gluons?
- How does QCD make up the properties of hadrons?

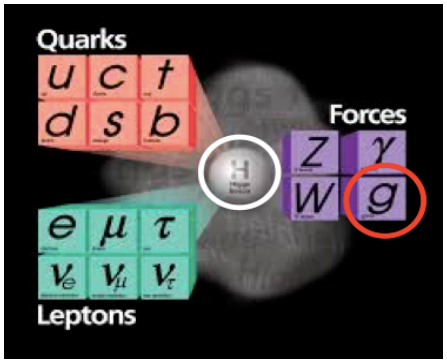
  Their mass, spin, magnetic moment, …
- What is the QCD landscape of nucleon and nuclei?

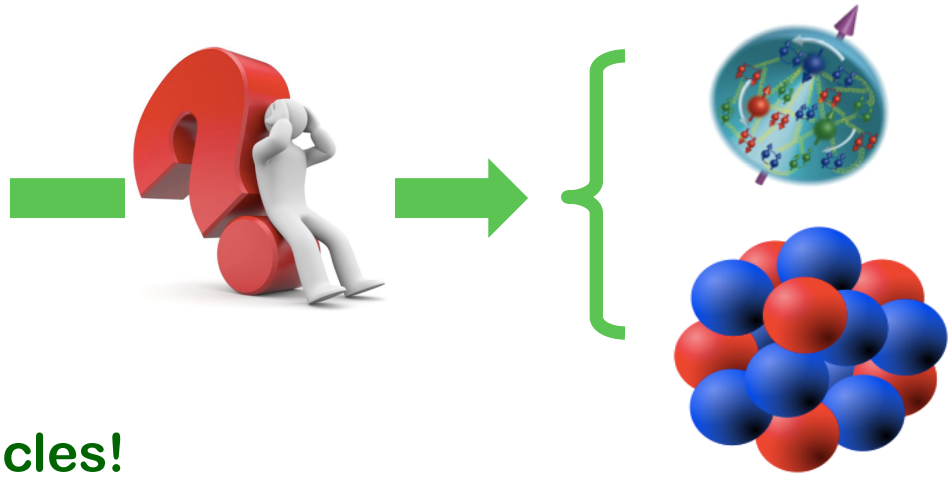


- How do the nuclear force arise from QCD?
- … *Have to understand the role of glue!*

The next QCD frontier

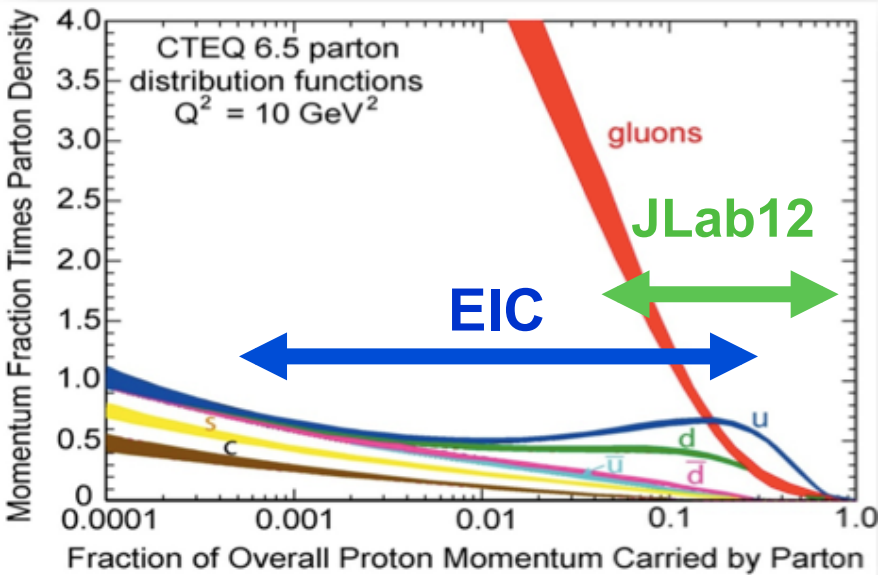
- Understanding the glue that binds us all – the Next QCD Frontier!





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

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



Unprecedented Intellectual Challenge!

- **Facts:**

  Gluons are dark!

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

- **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?

- **Answer to the challenge:**

  Theory advances:

  QCD factorization – matching the quarks/gluons to hadrons with controllable approximations!

  Experimental breakthroughs:

  Jets – ***Footprints of energetic quarks and gluons***

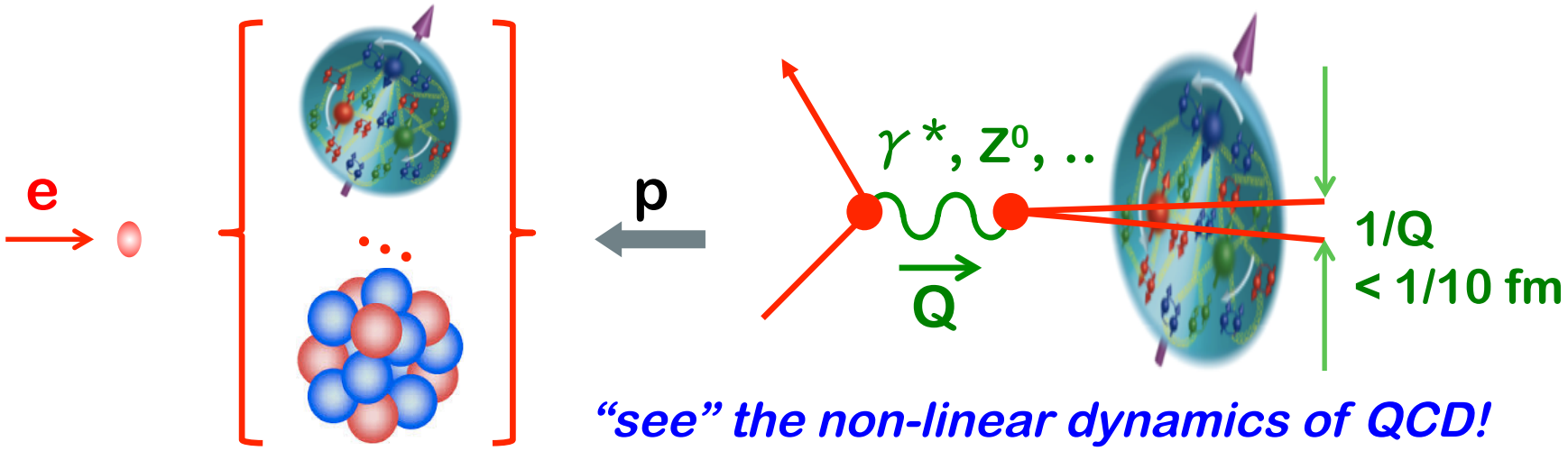
  Quarks – ***Need an EM probe to "see" their existence, …***

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

Energy, luminosity and measurement – Unprecedented resolution, event rates, and precision probes, especially EM probes, …

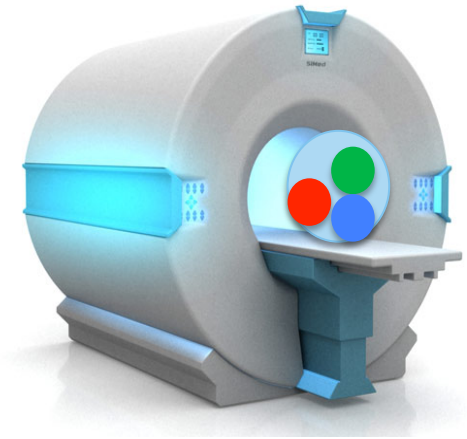
Electron-Ion Collider (EIC)

- "see" quarks and gluons by breaking the hadron/nuclei



"see" the non-linear dynamics of QCD!

- "Imagine" quark/gluon without breaking the hadron/nuclei
  - A sharpest "CT"
  - "cat-scan" the nucleon and nuclei with better than 1/10 fm resolution
  - "see" the proton "radius" of quark density and gluon density: vs. the charge radius?



→ *To discover the color confining radius!*

EIC: the World Wide Interest

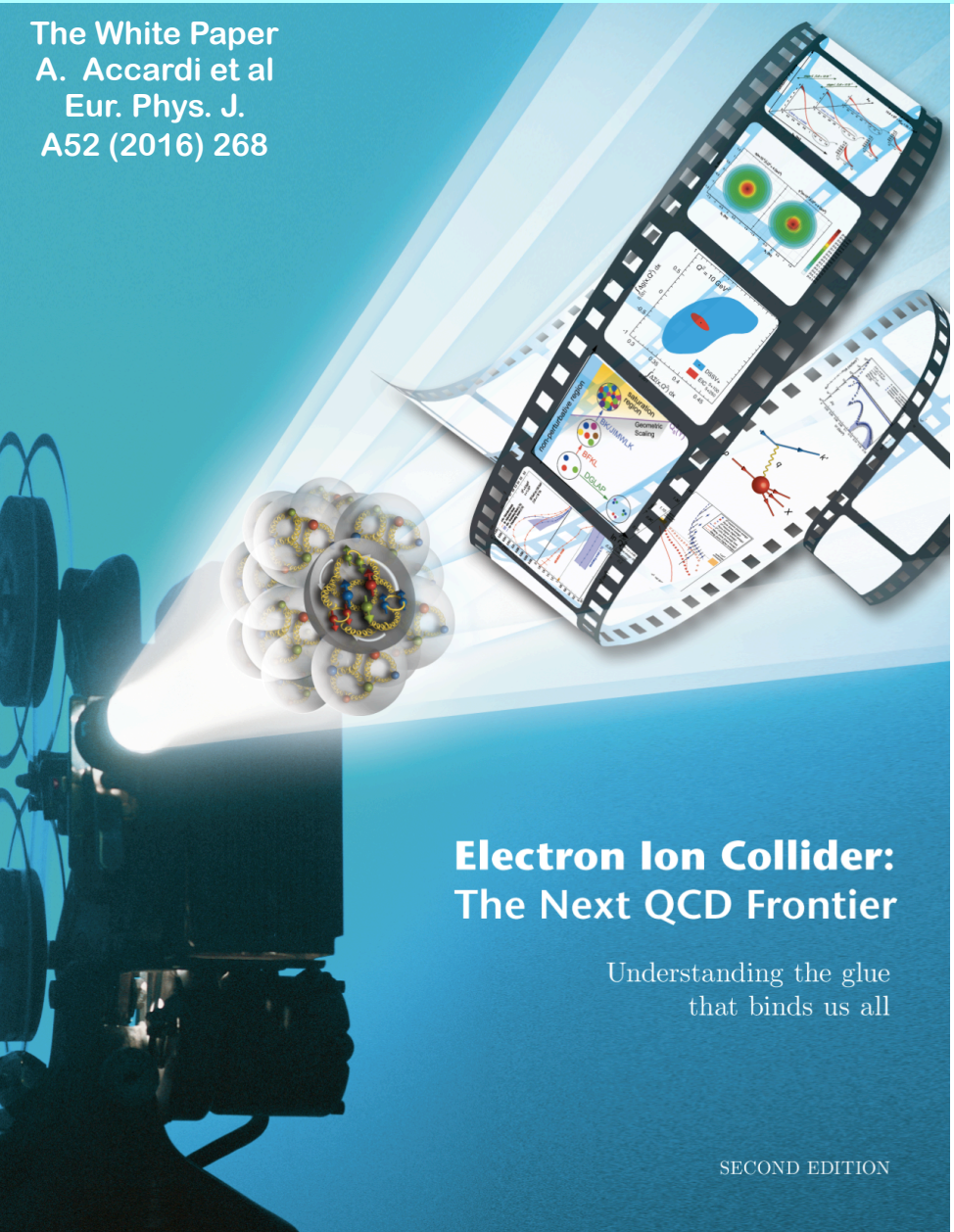
	HERA@DESY	LHeC@CERN	eRHIC@BNL	JLEIC@JLab	HIAF@CAS	ENC@GSI
E_{CM} (GeV)	320	800-1300	45-175	12-140	12 → 65	14
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-5}	5×10^{-5}	$7 \times 10^{-3} \rightarrow 3 \times 10^{-4}$	5×10^{-3}
ion	p	p to Pb	p to U	p to Pb	p to U	p to ~ ^{40}Ca
polarization	-	-	p, ^{3}He	p,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

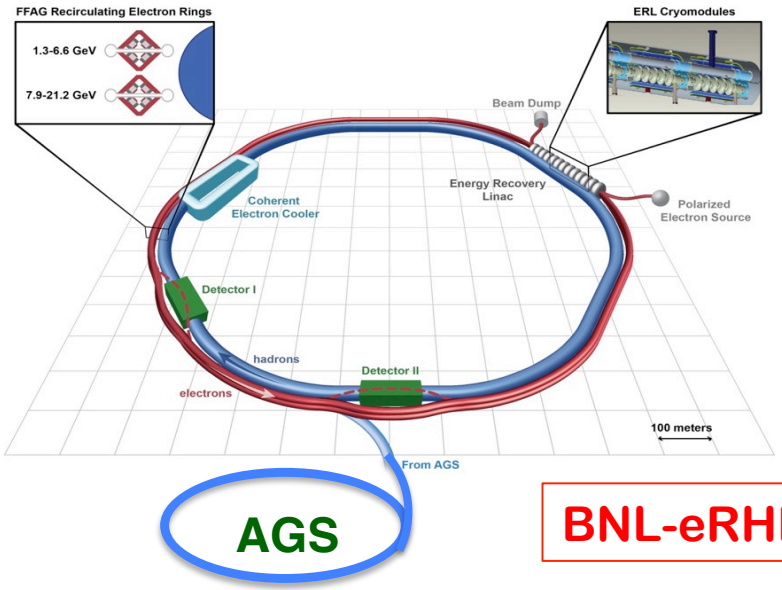
The past

Possible future

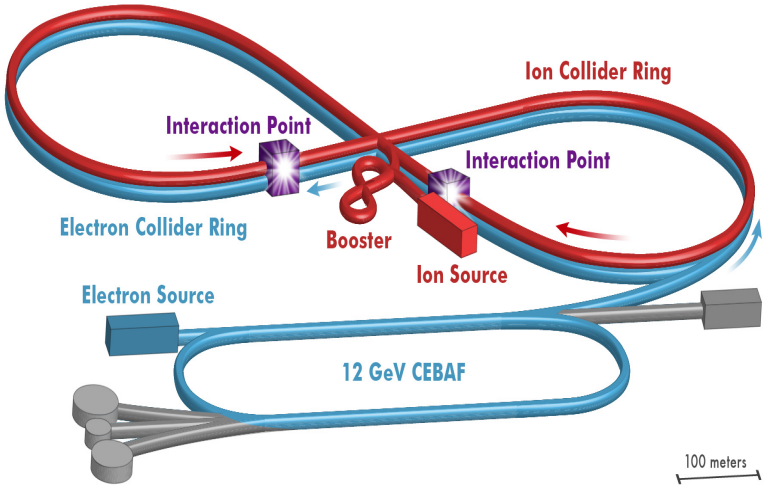
US EIC – two options of realization

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





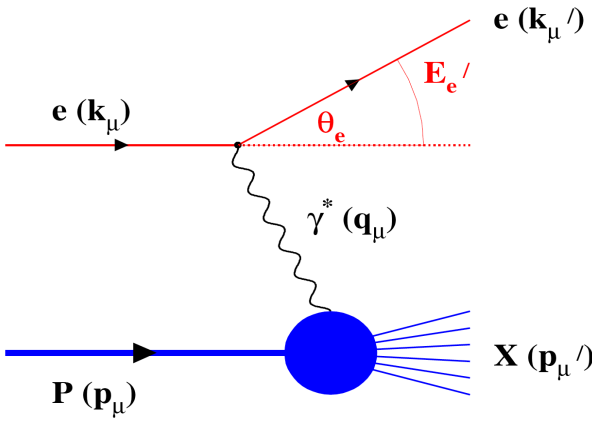
BNL-eRHIC



JLab-JLEIC

Many complementary probes at one facility

- High energy and luminosity Lepton-hadron facility:



Q^2 →Measure of resolution

y → Measure of inelasticity

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

$Q^2 = S \times y$

Inclusive events: e+p/A → e'+X

Detect only the scattered lepton in the detector

(Modern Rutherford experiment!)

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

Detect the scattered lepton in coincidence with identified hadrons/jets

(Initial hadron is broken – confined motion!)

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!)

The key deliverables & opportunities

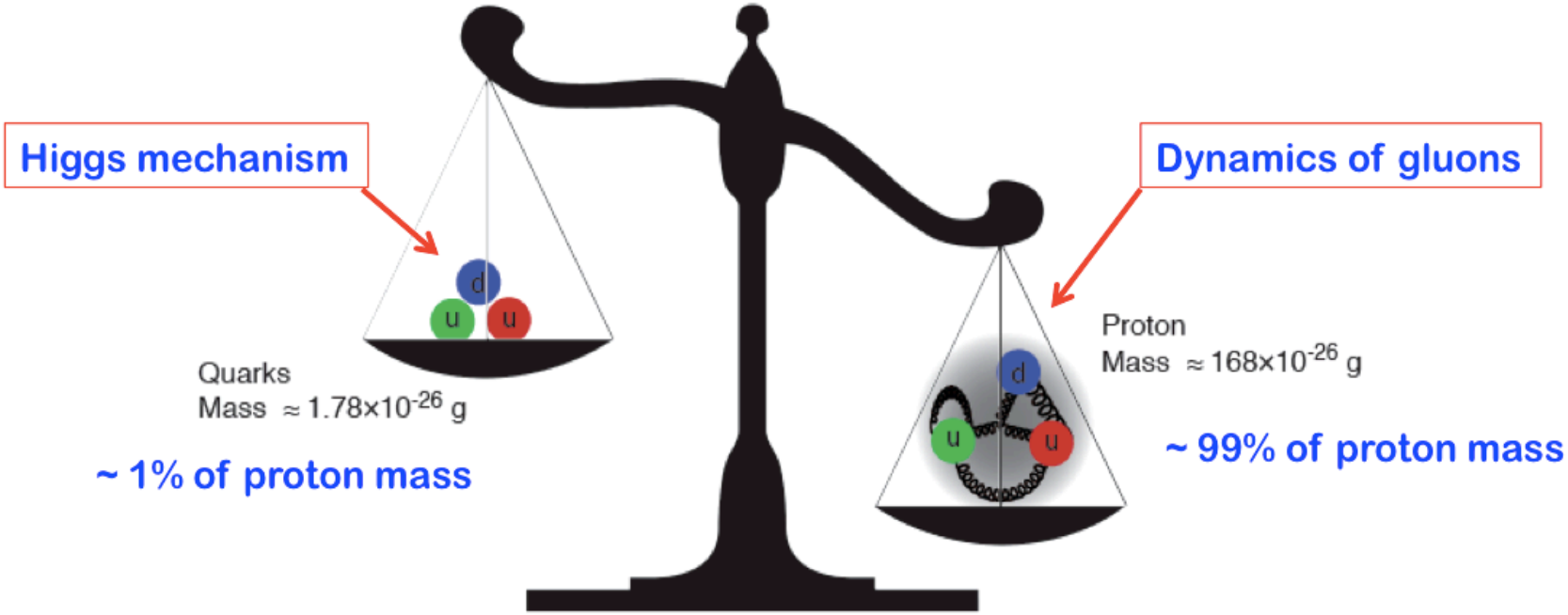
Why existing facilities, even with upgrades, cannot do the same?

The proton mass?

- How does QCD generate the nucleon mass?

  "… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …" *The 2015 Long Range Plan for Nuclear Science*

- Higgs mechanism is not relevant to hadron mass!



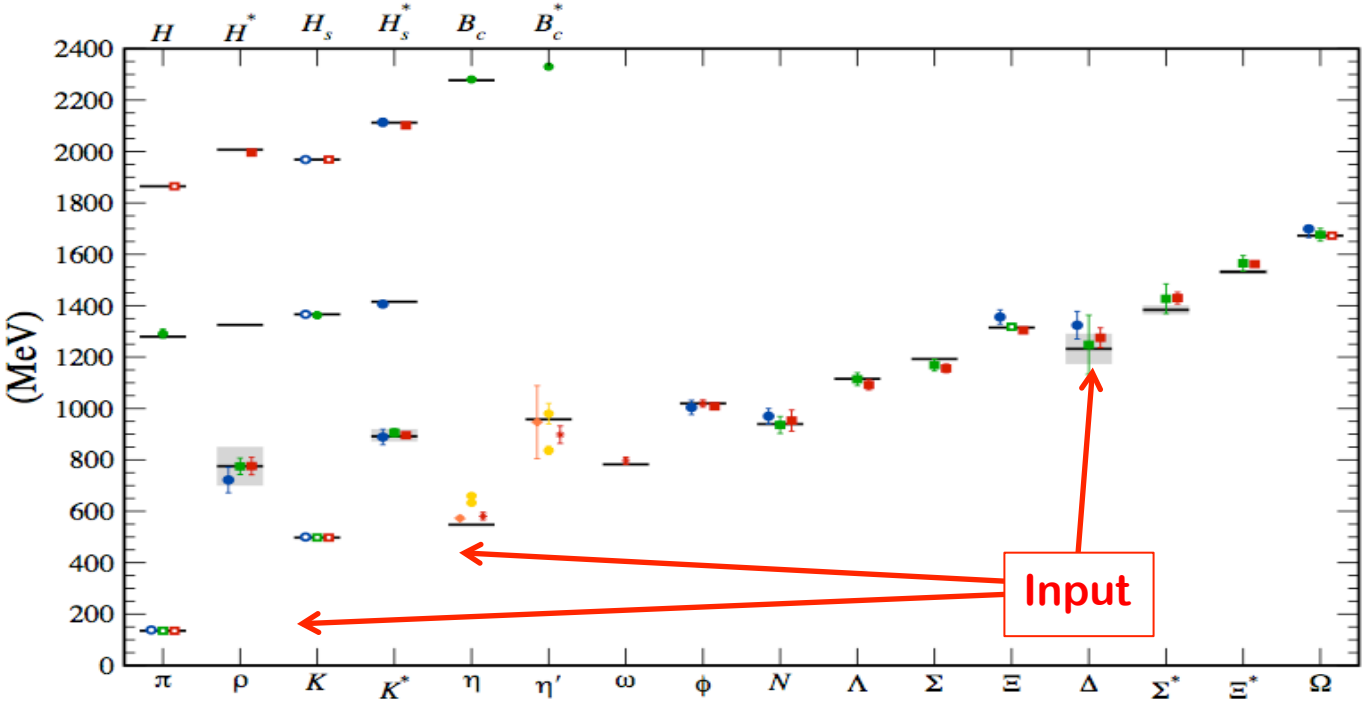
"Mass without mass!"

The proton mass?

- **How does QCD generate the nucleon mass?**

  "… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …" *The 2015 Long Range Plan for Nuclear Science*

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



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

If we do not understand proton mass, we do not understand QCD

How to answer the "big" questions?

❑ How does QCD generate the nucleon mass?

"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …" *The 2015 Long Range Plan for Nuclear Science*

❑ Role of quarks and gluons?

✧ QCD energy-momentum tensor:

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

✧ Trace of the QCD energy-momentum tensor:

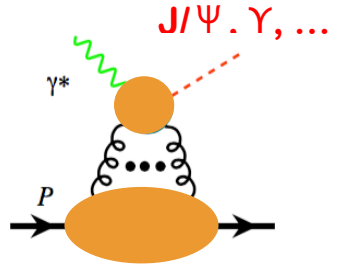
$$T^{\alpha}_{\alpha} = \underbrace{\frac{\beta(g)}{2g}F^{\mu\nu,a}F^{a}_{\mu\nu}}_{\text{QCD trace anomaly}} + \sum_{q=u,d,s} m_q(1+\gamma_m)\overline{\psi}_q\psi_q$$

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

✧ Mass, trace anomaly, chiral symmetry break, and …

$$m^2 \propto \langle p|T^{\alpha}{}_{\alpha}|p\rangle \quad \Rightarrow \quad \frac{\beta(g)}{2g}\langle p|F^2|p\rangle$$

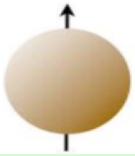
at the chiral limit!



⇒ Heavy quarkonium production near the threshold, from JLab12 to EIC

The proton spin?

- How does QCD generate the nucleon's spin?



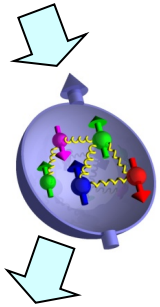
Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g) = \sum \langle P,S|\hat{J}^z_f(\mu)|P,S\rangle$$

Quark helicity
Best known

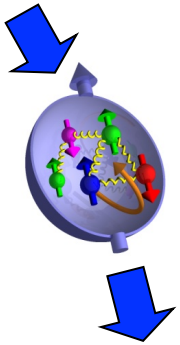
$$\frac{1}{2}\int dx\left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$
$$\sim 30\%$$

Spin "puzzle"



Gluon helicity
Start to know

$$\Delta G = \int dx \Delta g(x)$$
$$\sim 20\% (\text{with RHIC data})$$

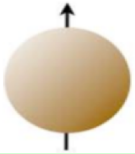


Orbital Angular Momentum of quarks and gluons
Little known

If we do not understand proton spin, we do not understand QCD

How to answer the “big” questions?

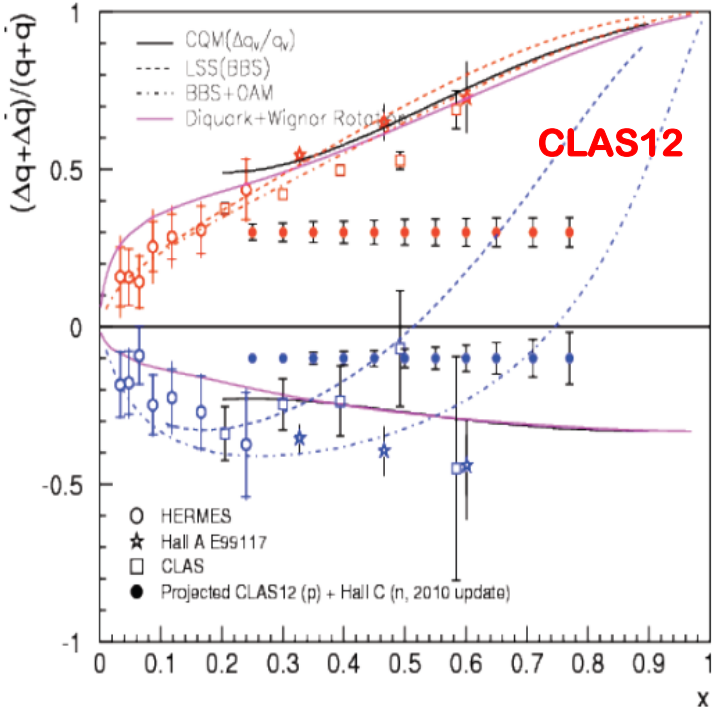
- How does QCD generate the nucleon’s spin?

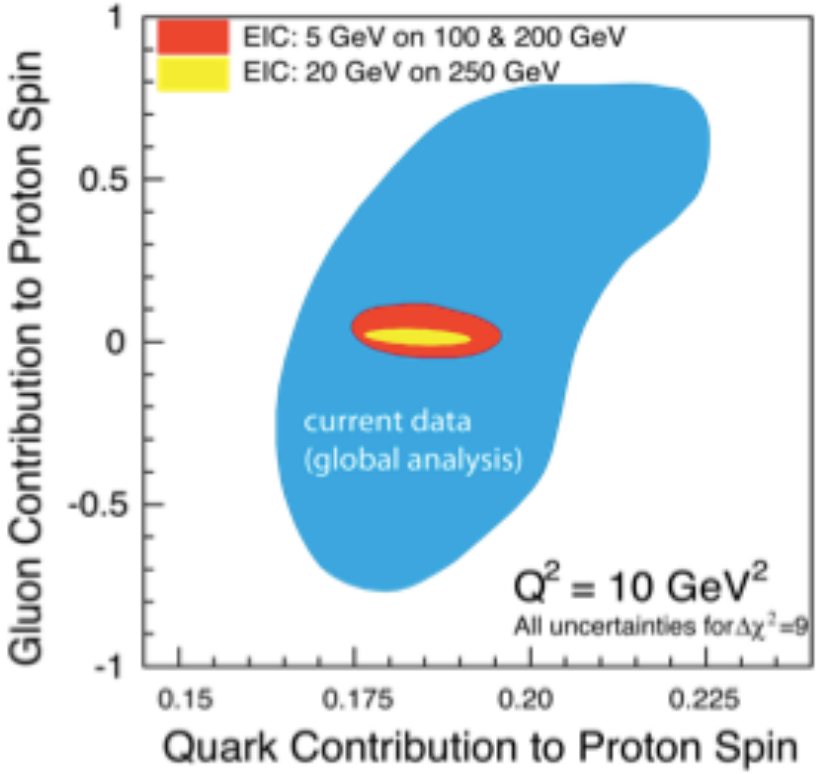


Proton Spin

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

- What can JLab12 and EIC do?

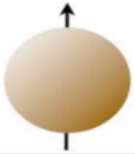




Plus many more JLab12 experiments – flavor

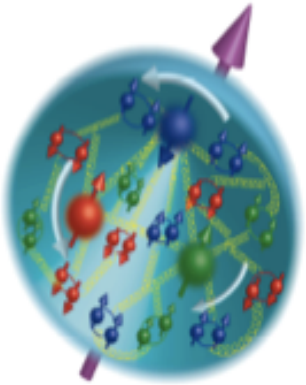
How to answer the "big" questions?

- How does QCD generate the nucleon's spin?



Proton Spin

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



To understand the proton spin,
fully, we need to understand
the distribution and confined motion of
quarks and gluons inside the proton in QCD,

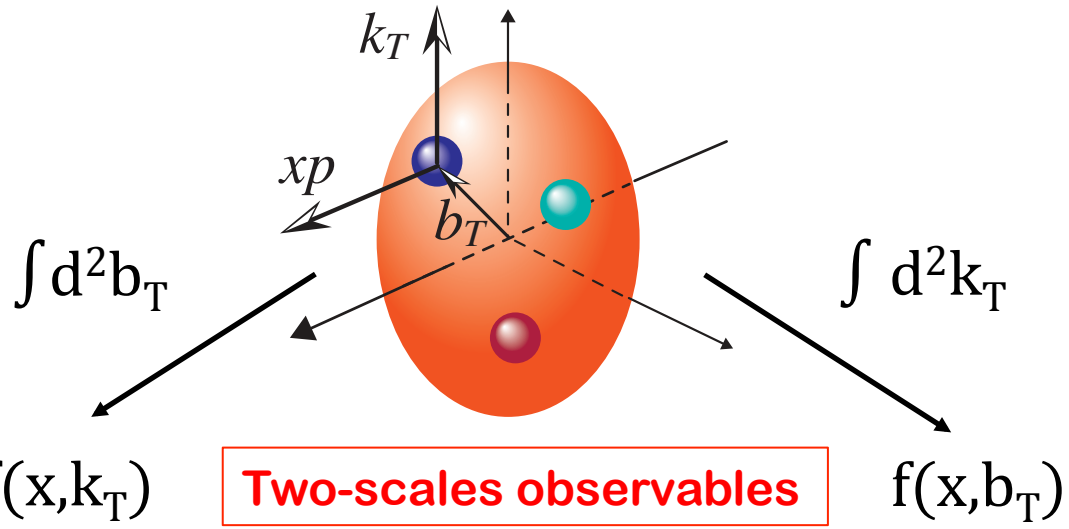
encoded in GPDs, TMDs, GTMDs, …

Need new "probes"
with two distinctive momentum scales!

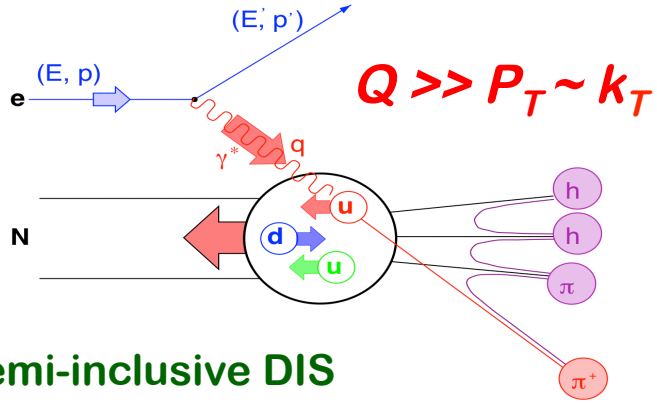
Hard scale – to "see" the particle nature of quarks and gluons
Soft scale – to "be" sensitive to the QCD confinement ~ 1/fm ~ 200 MeV

The 3D confined distribution and motion?

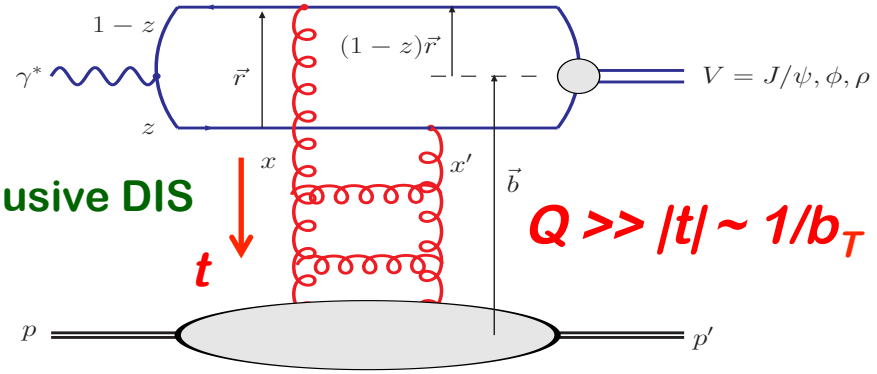
- **3D boosted partonic structure:**



3D momentum space images



2+1D coordinate space images



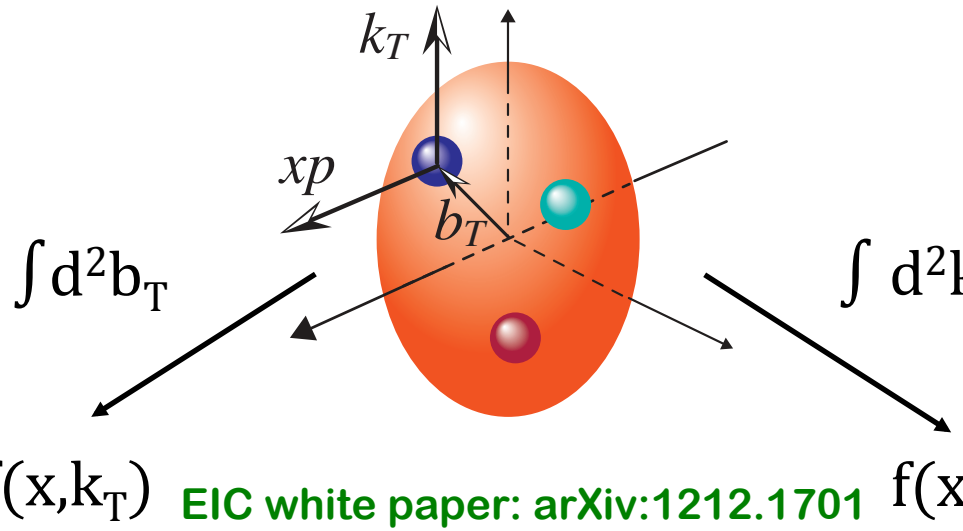
JLab12 – valence quarks, EIC – sea quarks and gluons

How to answer the “big” questions?

- **3D boosted partonic structure:**

Momentum Space

TMDs



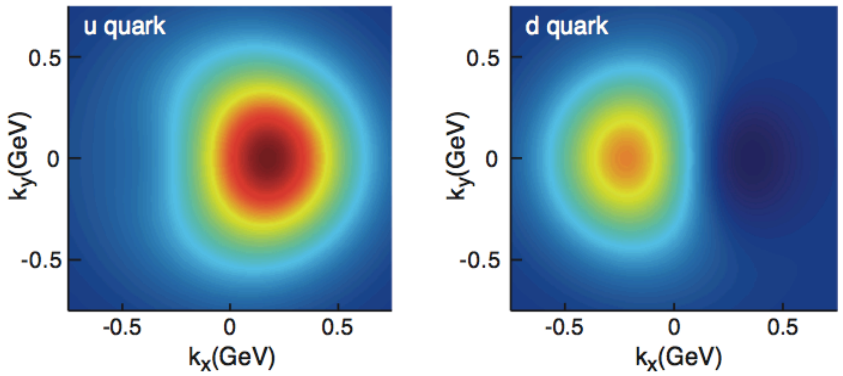
Coordinate Space

GPDs

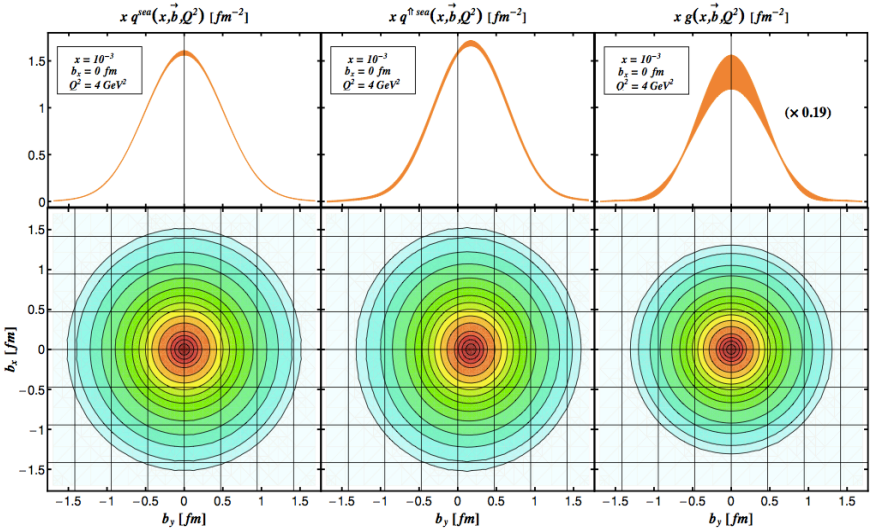
Sivers Function

Imaging

EIC white paper: arXiv:1212.1701



Density distribution of an unpolarized quark in a proton moving in z direction and polarized in y-direction



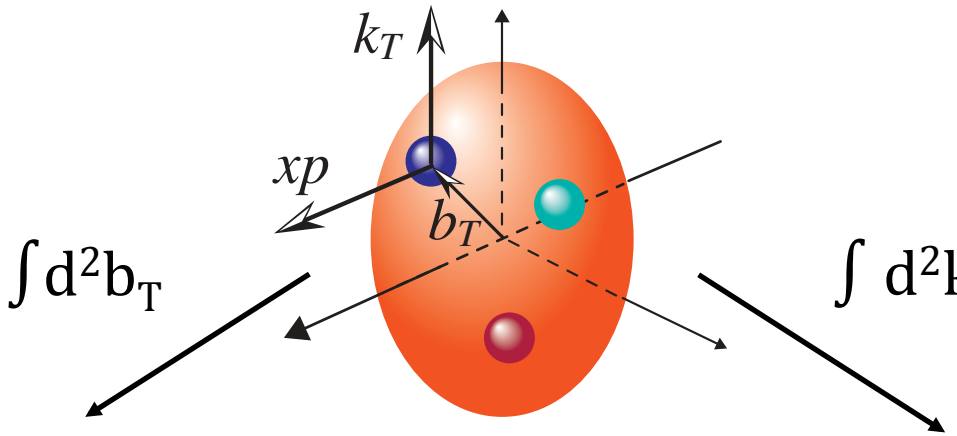
Spatial density distributions – “radius”

How to answer the “big” questions?

- **3D boosted partonic structure:**

Momentum Space

TMDs



Coordinate Space

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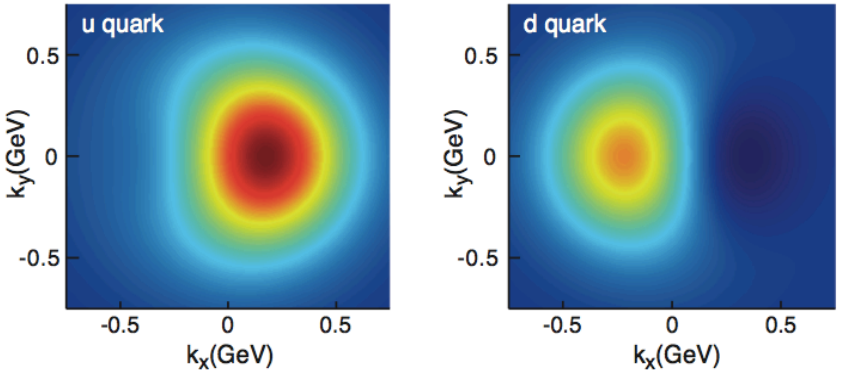
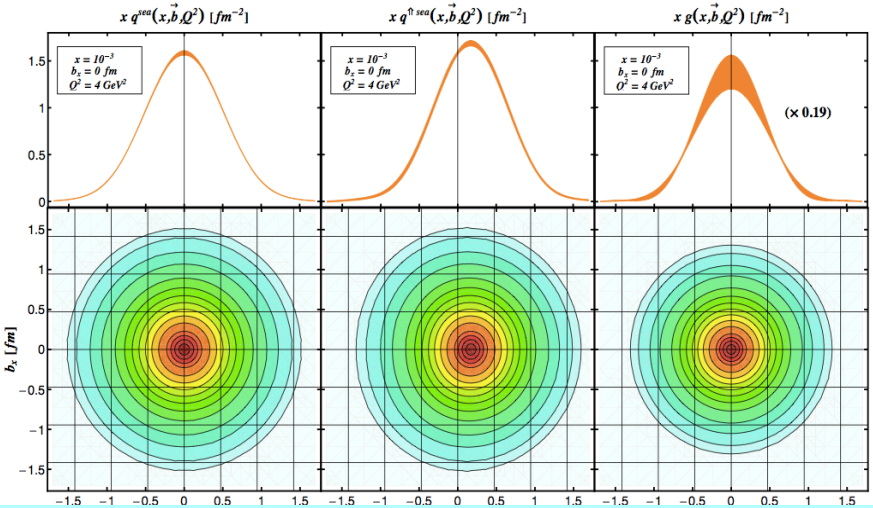
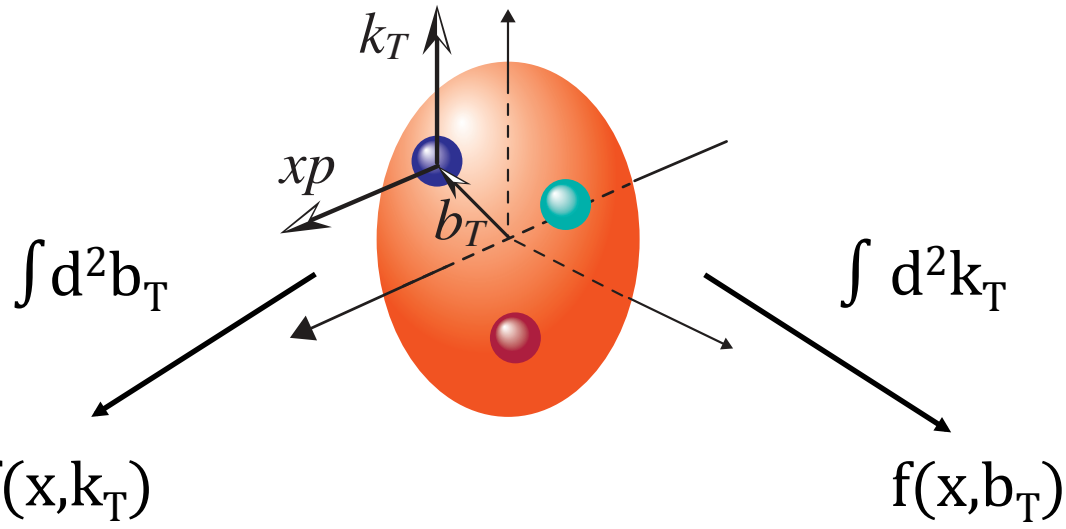




Position *r* x Momentum *p* → Orbital Motion of Partons

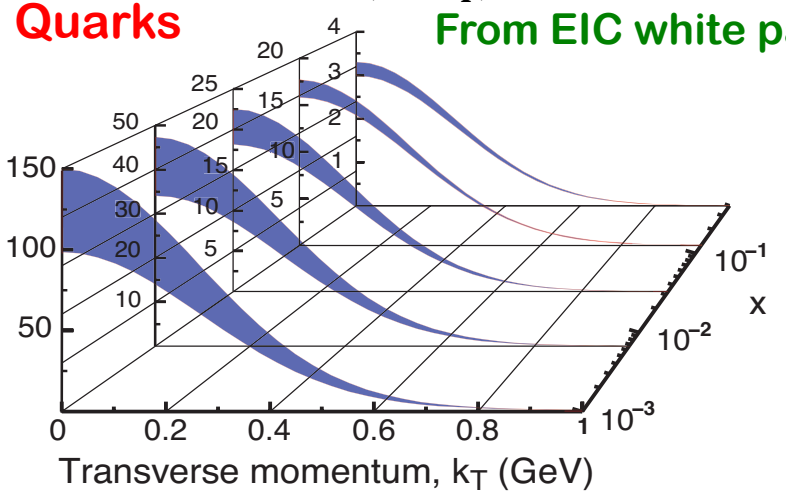
How to answer the “big” questions?

- **3D boosted partonic structure:**

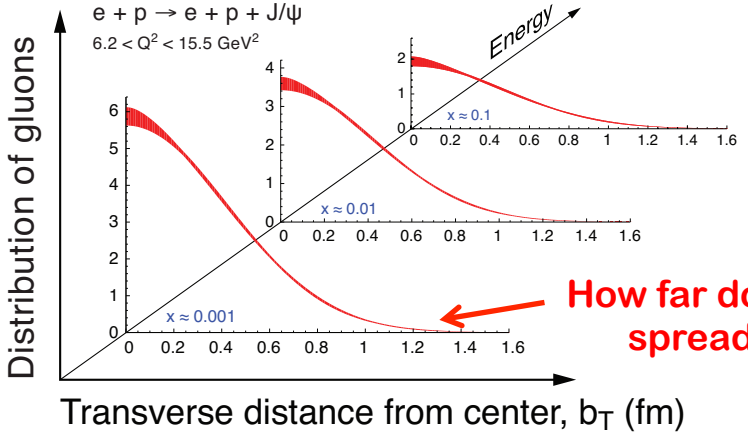


Quarks

From EIC white paper: arXiv:1212.1701



Gluons



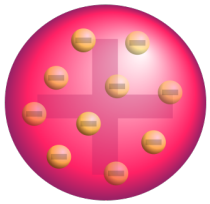
How far does it spread?

Role of momentum fraction -“x”, and nature of pion cloud?

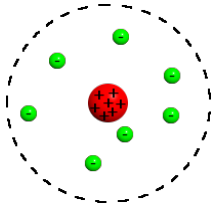
Why 3D nucleon structure?

❑ Rutherford's experiment – atomic structure (100 years ago):

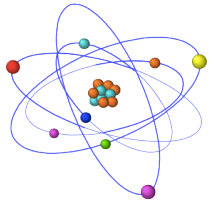
Atom:



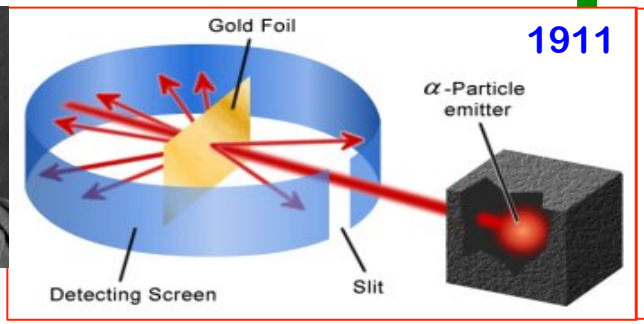
J.J. Thomson's
plum-pudding model



Rutherford's
planetary model



Modern model
Quantum orbitals



Discovery of nucleus
A localized
charge/force center
A vast
"open" space

Discovery of
Quantum Mechanics,
and
the Quantum World!

❑ Completely changed our "view" of the visible world:

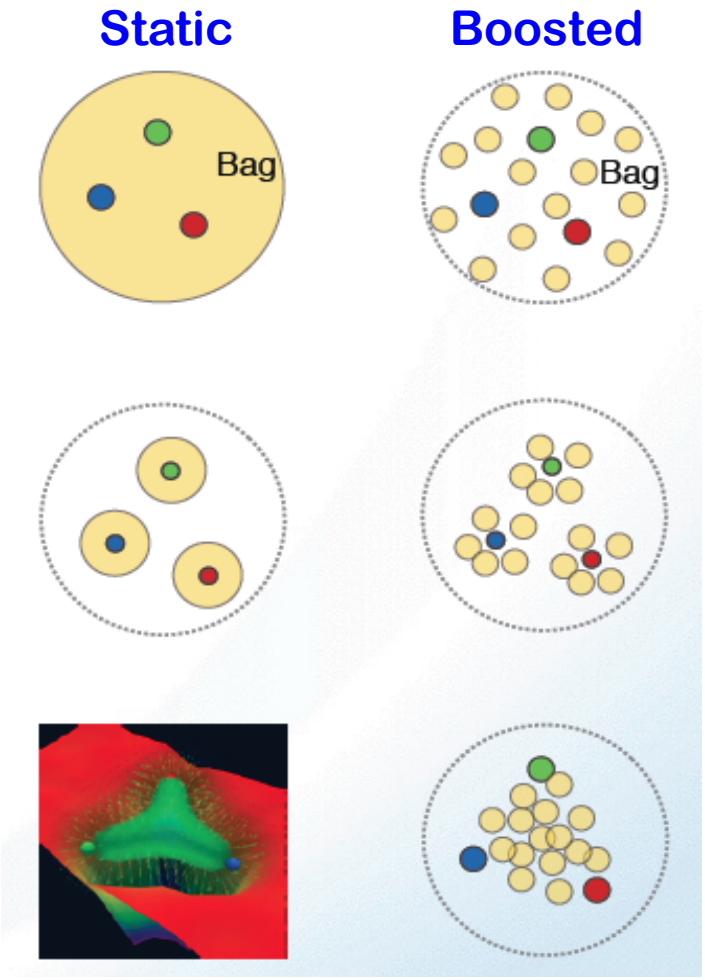
- ✧ Mass by "tiny" nuclei – *less than 1 trillionth in volume of an atom*
- ✧ Motion by quantum probability – *the quantum world!*

❑ Provided infinite opportunities to improve things around us:

- ✧ Gas, Liquid, Solid, Nano materials, Quantum computing, …

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

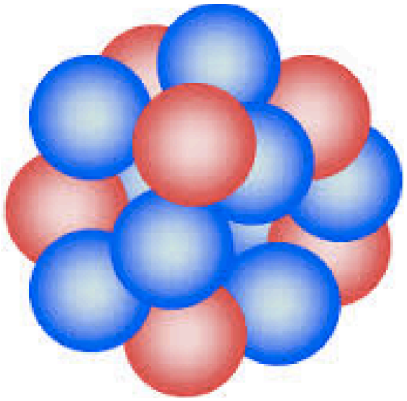
Gluon radius < Charge Radius

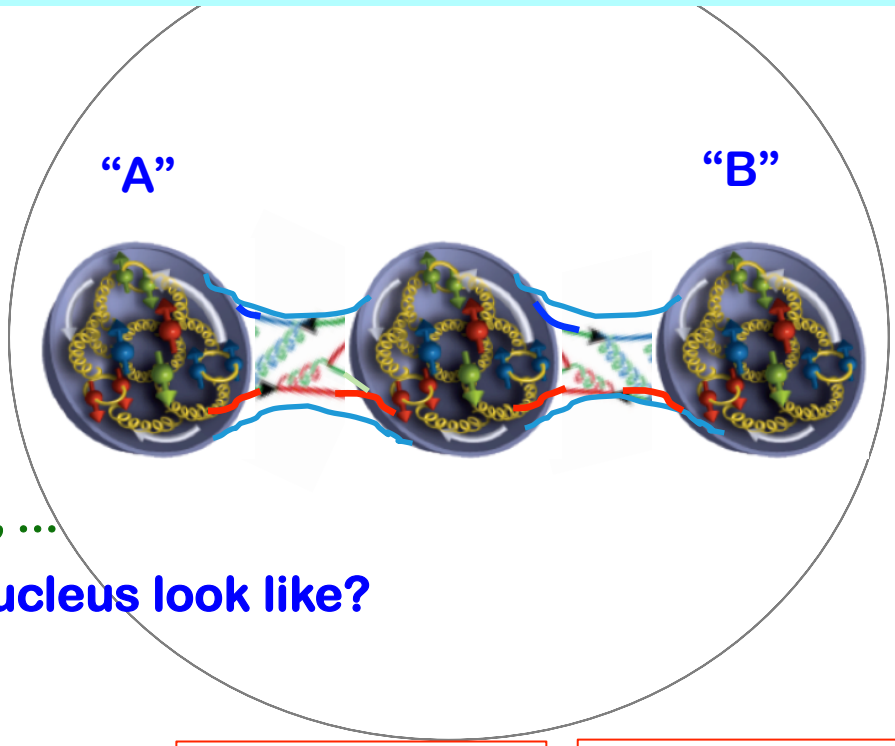
3D Confined Motion (TMDs) + Spatial Distribution (GPDs)

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

Why 3D nucleon structure?

❑ Nature of nuclear force:





If we only see quarks and gluons, …

What does the nucleus look like?

❑ Range of color force:

Does the color of nucleon "A" correlated with the color of nucleon "B"?

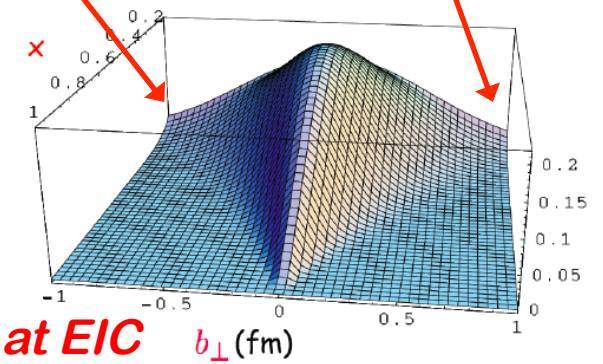
If it does, what is the strength of such correlation?

Can a large nucleus look like a big proton at small-x? the range of color correlation?

How far does glue density spread?

How fast does glue density fall?

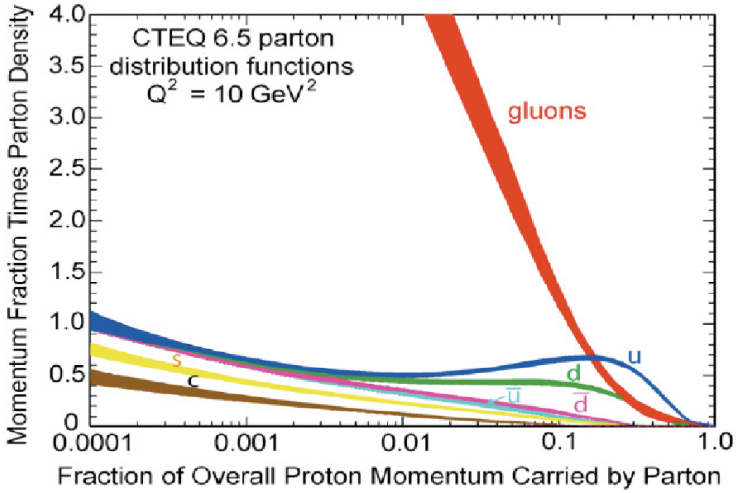
Imagine of gluon density



Only possible at EIC

Non-linear interaction – dynamical mass scale?

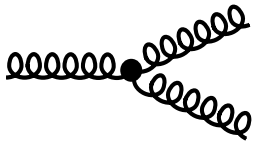
❑ Run away gluon density at small x?



What causes the low-x rise?

gluon radiation

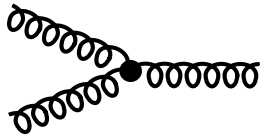
– non-linear gluon interaction



What tames the low-x rise?

gluon recombination

– non-linear gluon interaction



❑ QCD vs. QED:

QCD – gluon in a proton:

$$Q^2\frac{d}{dQ^2}xG(x,Q^2) \approx \frac{\alpha_s N_c}{\pi}\int_x^1 \frac{dx'}{x'}x'G(x',Q^2)$$

QED – photon in a positronium:

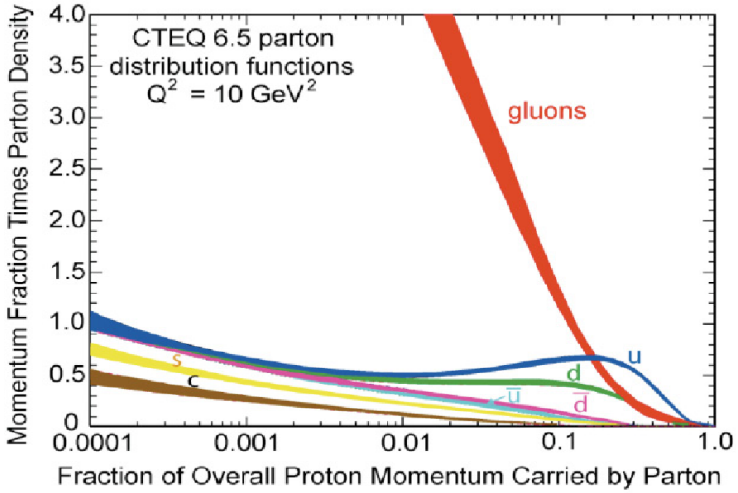
$$Q^2\frac{d}{dQ^2}x\phi_\gamma(x,Q^2) \approx \frac{\alpha_{em}}{\pi}\left[-\frac{2}{3}x\phi_\gamma(x,Q^2) + \int_x^1 \frac{dx'}{x'}x'[\phi_{e+}(x',Q^2)+\phi_{e-}(x',Q^2)]\right]$$

✧ At very small-x, proton is "black", positronium is still transparent!

✧ Recombination of large numbers of glue could lead to saturation phenomena

How to answer the "big" questions?

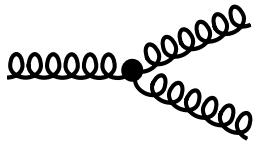
❑ Run away gluon density at small x?



What causes the low-x rise?

gluon radiation

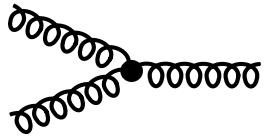
– non-linear gluon interaction



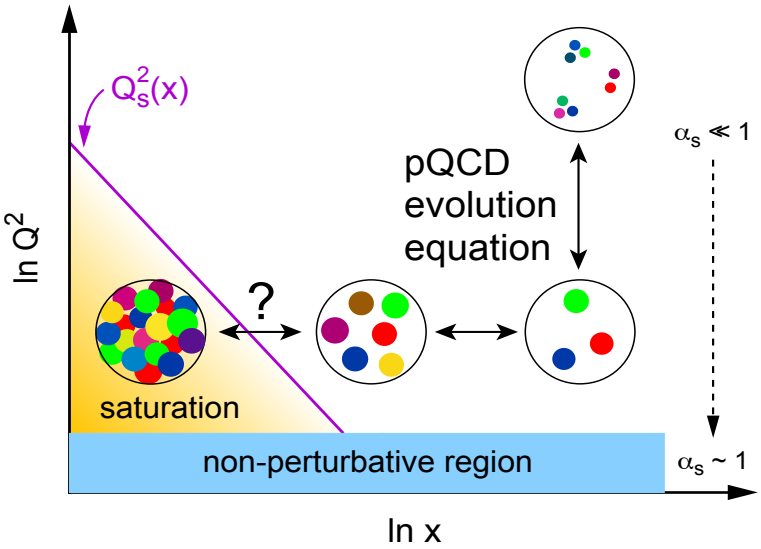
What tames the low-x rise?

gluon recombination

– non-linear gluon interaction

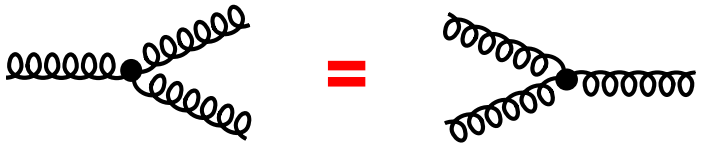


❑ Particle vs. wave feature:



Gluon saturation – Color Glass Condensate

Radiation = Recombination



at Q_s

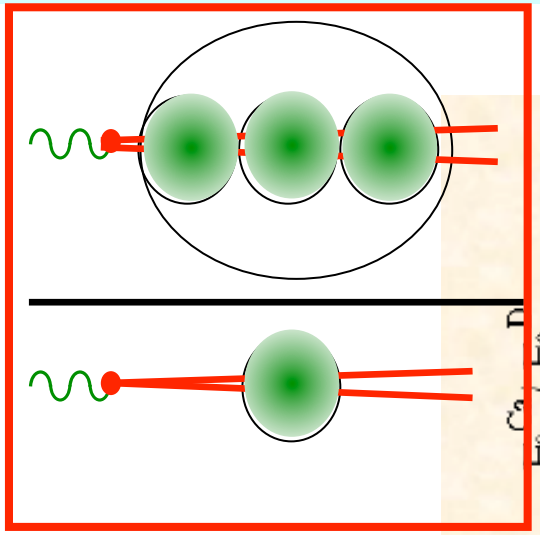
Leading to a collective gluonic system?

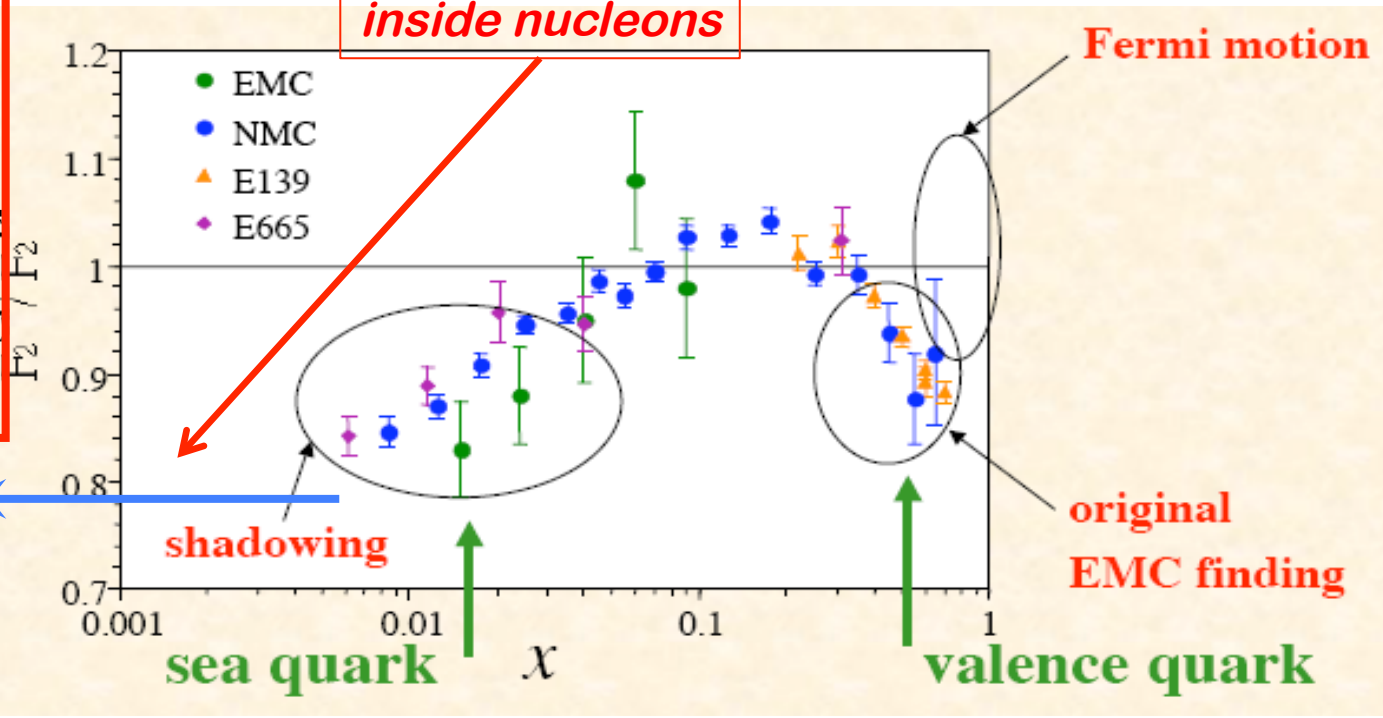
with a universal property of QCD?

new effective theory QCD – CGC?

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

True structure – separation of collision effect?





Saturation in RF_2

=

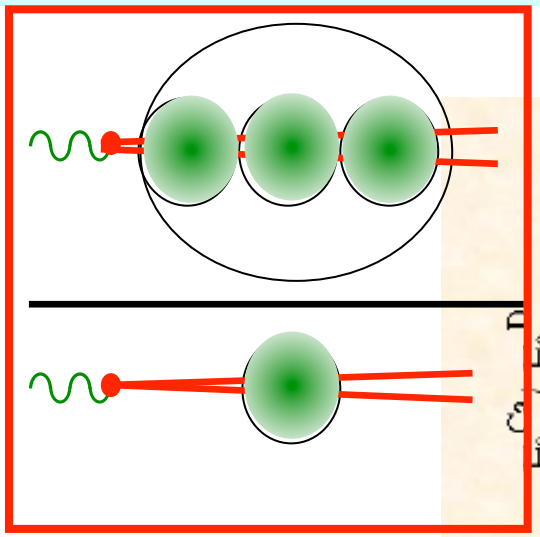
No saturation in F_2^A

Collision effects

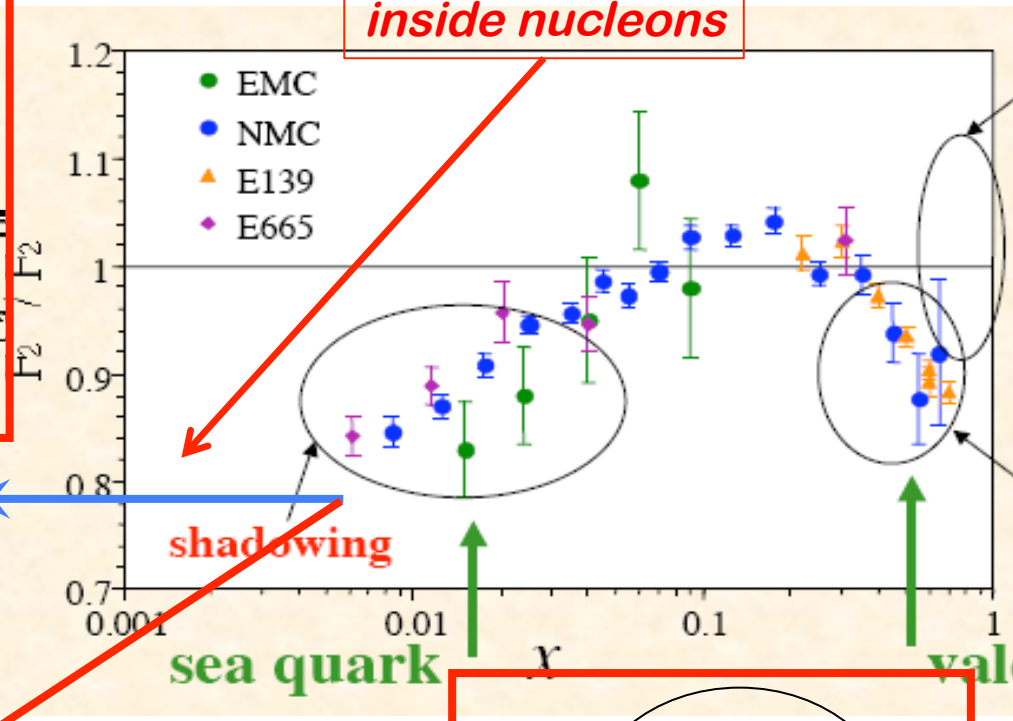
❑ A simple question:

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

Color confining radius?



Color localized inside nucleons



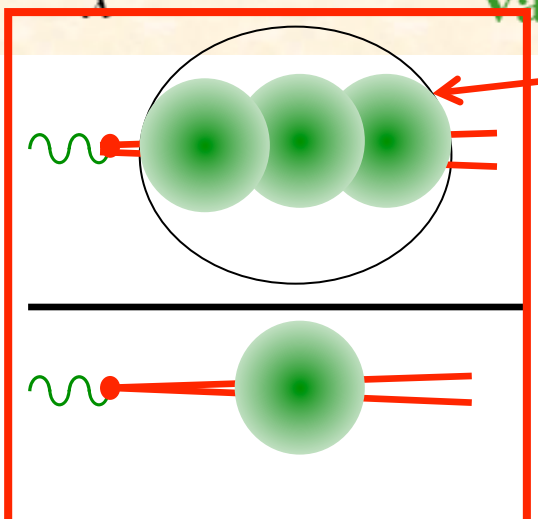
Saturation in RF_2

=

No saturation in F_2^A

Collision effects

Saturation in nucleon



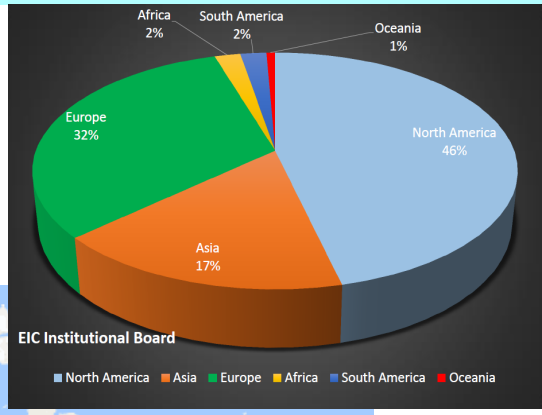
Color leaks outside nucleons Soft gluon radius is larger

❑ **A simple question:**

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

The EIC Users Group: *EICUG.ORG*

(no students included as of yet)



670 collaborators, 28 countries, 150 institutions... (December, 2016)

Map of institution's locations

EICUG MEETING – July 18-22
TRIESTE

eicug2017.ts.infn.it

Summary

- 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 and nuclei with a resolution better than 1/10 fm

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

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

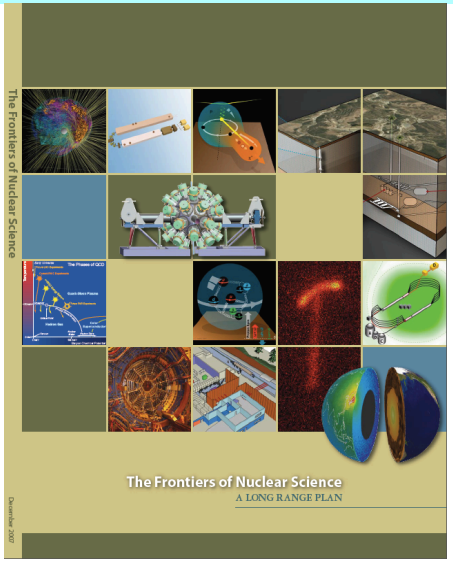
Thanks!

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:

Last public committee meeting: April 19-21

Expect to have the committee report late this year!

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

How to answer the "big" questions?

- **How does QCD generate the nucleon mass?**

  "… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …" *The 2015 Long Range Plan for Nuclear Science*

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

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

  - ✧ Mass = energy of the hadron when it is at the rest

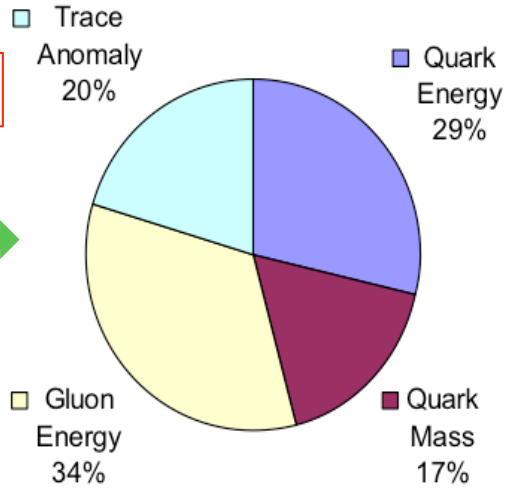
$$m = \frac{\langle p|\int d^3x\, T^{00}\,|p\rangle}{\langle p|p\rangle} \sim \mathrm{GeV}$$

when proton is at rest!

Relativistic motion | χ Symmetry Breaking | Quantum fluctuation

$$m = E_q + E_g + \chi_{m_q} + T_g$$

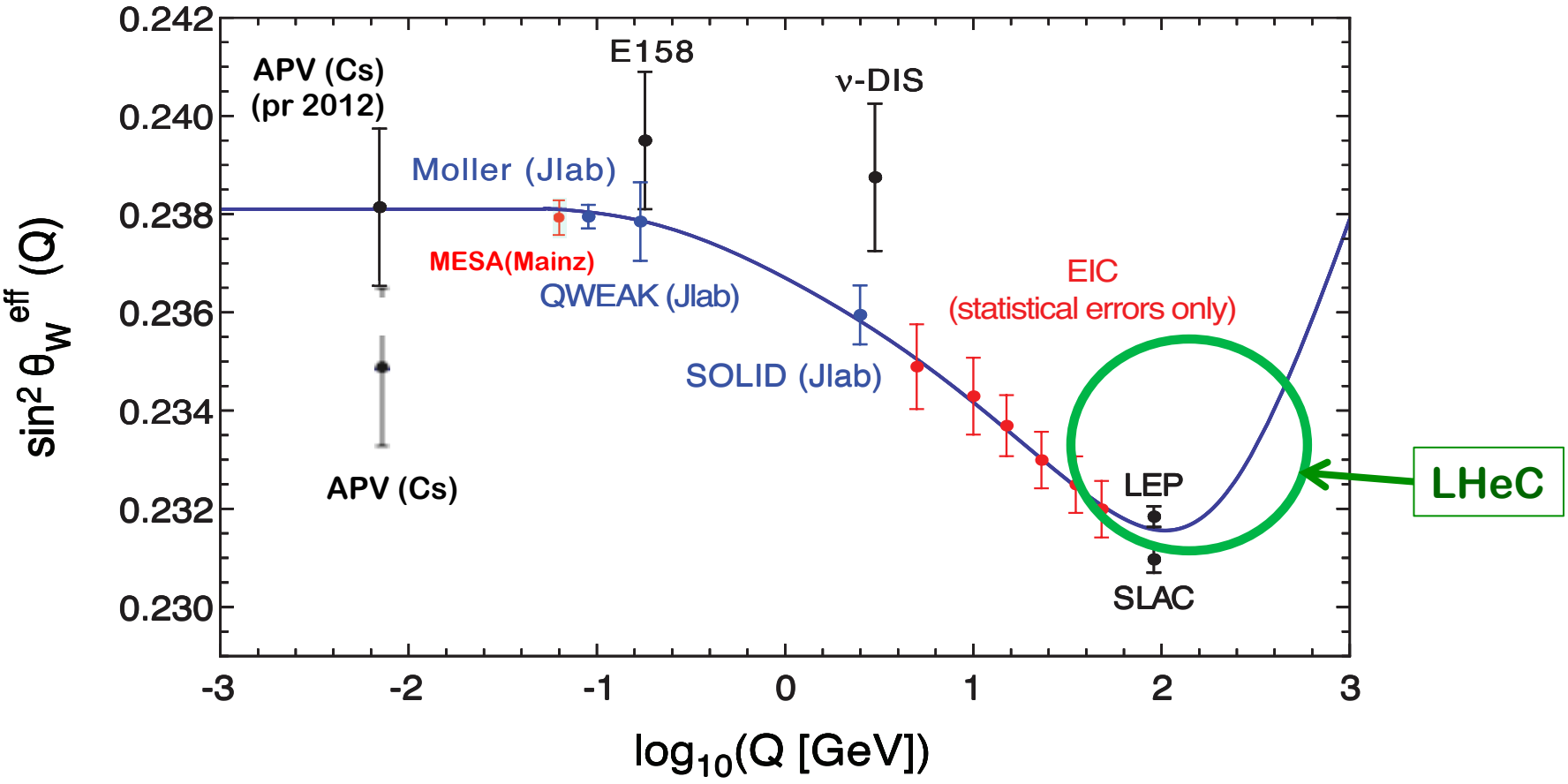
Quark Energy | Gluon Energy | Quark Mass | Trace Anomaly



Decomposition is not unique!

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***

Emergence of hadrons/Jets – A puzzle?

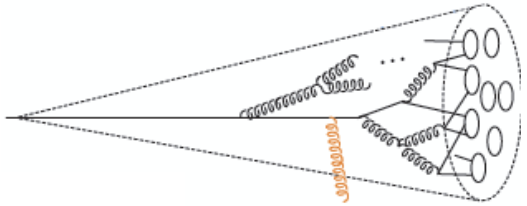
- **Emergence of hadrons:**

  How do hadrons emerge from a created quark or gluon?
  How is the color of quark or gluon neutralized?

- **Need a femtometer detector or "scope":**

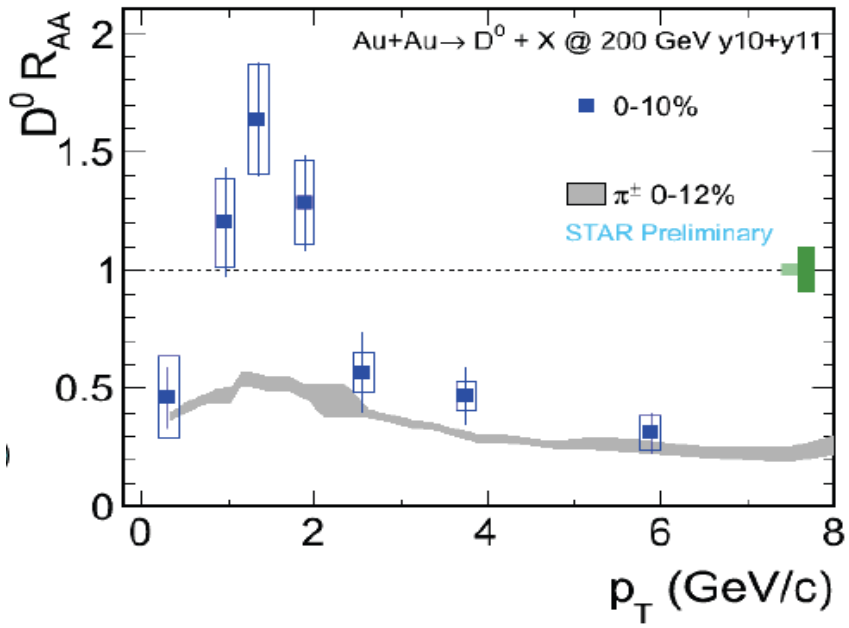
  Nucleus, a laboratory for QCD
  A "vertex" detector: Evolution of hadronization

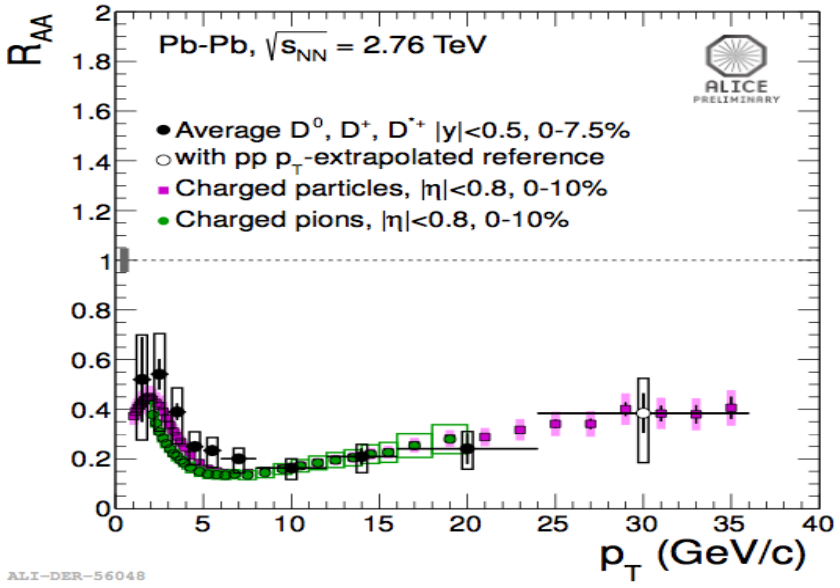
Jet substructure



Boosted hadronization

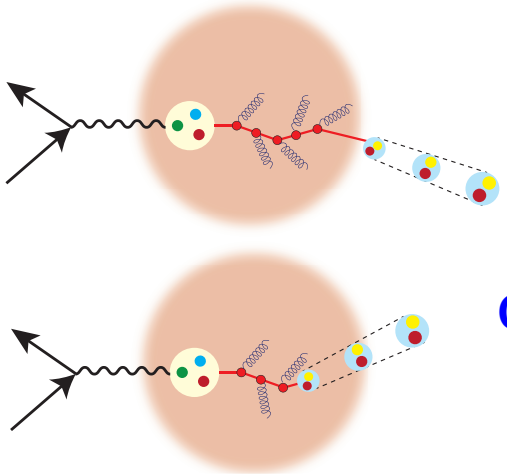
- **Strong suppression of heavy flavors in AA collisions:**





How to answer the "big" questions?

❑ Emergence of a hadron?

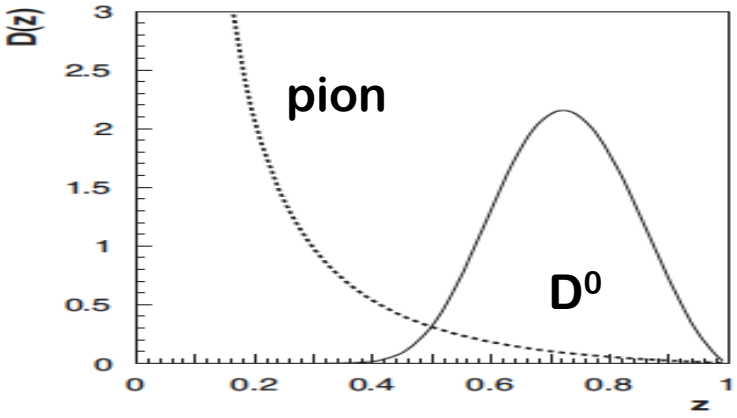


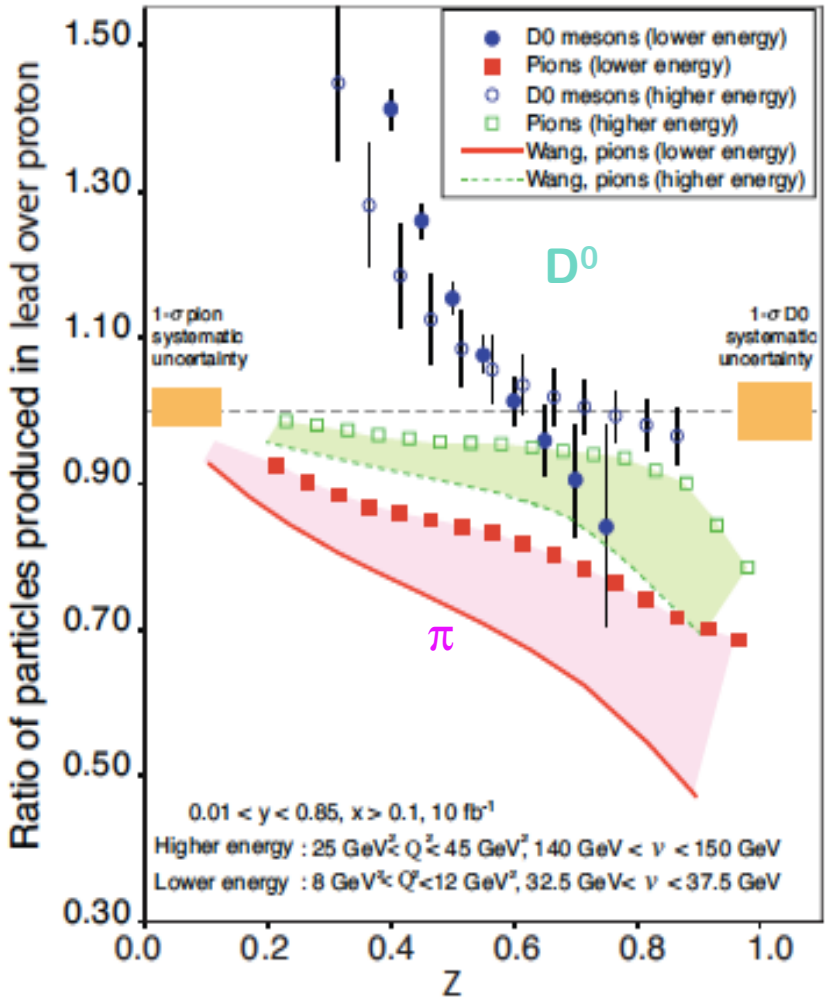
$$\nu = \frac{Q^2}{2mx}$$

Control of ν and medium length!

❑ Heavy quark energy loss:

- **Mass dependence of fragmentation**



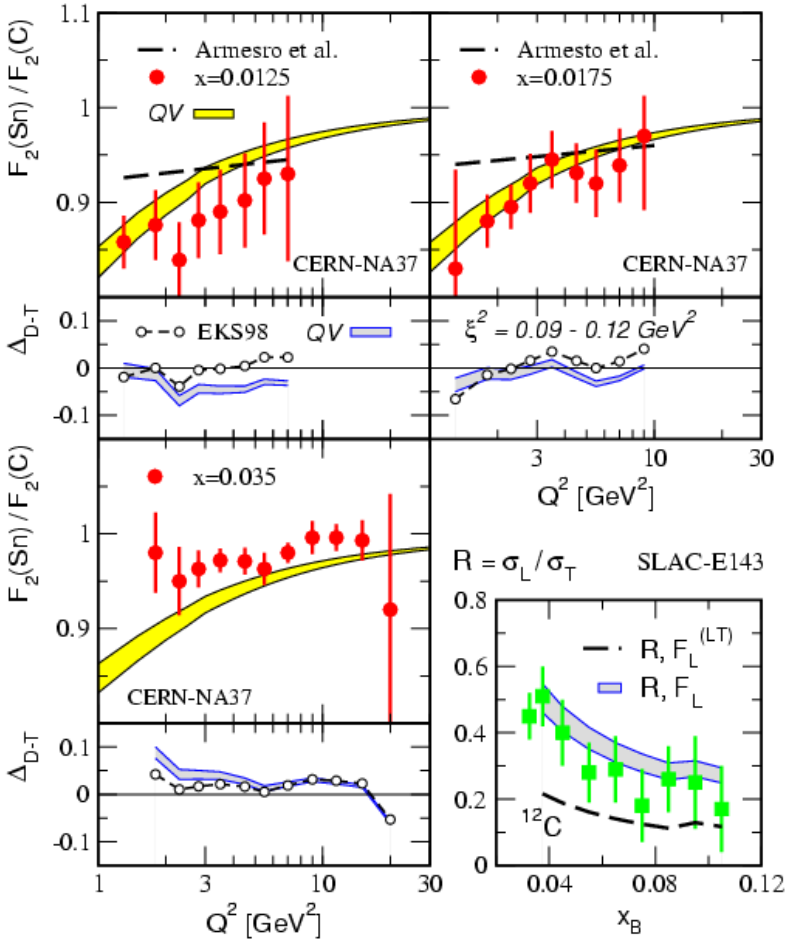


Need the collider energy of EIC and its control on parton kinematics

DIS on a large nucleus

- If the color is localized inside nucleon, … Qiu, Vitev, PRL2004

$\xi^2 = 0.09 - 0.12\ \mathrm{GeV}^2$



One number for all x_B, Q, and A dependence !