College of Arts and Sciences

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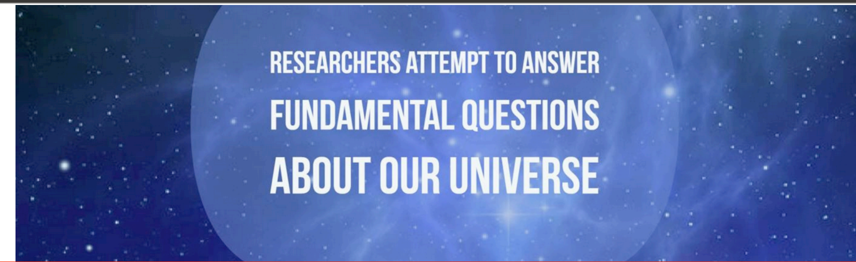

The Electron-Ion Collider:
– Exploring the Science of Nuclear Femtography

Jianwei Qiu

Theory Center, Jefferson Lab

December 1st, 2017

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, …

Theory Center

Jefferson Lab
EXPLORING THE NATURE OF MATTER

Eternal Questions

People have long asked

Where did we come from?

The Big Bang theory?

What is the world made of?

Basic building blocks?

What holds it together?

Fundamental forces?

Where are we going to?

The future?

The Role of 21st Century Nuclear Science
in addressing all these questions?

Eternal Questions

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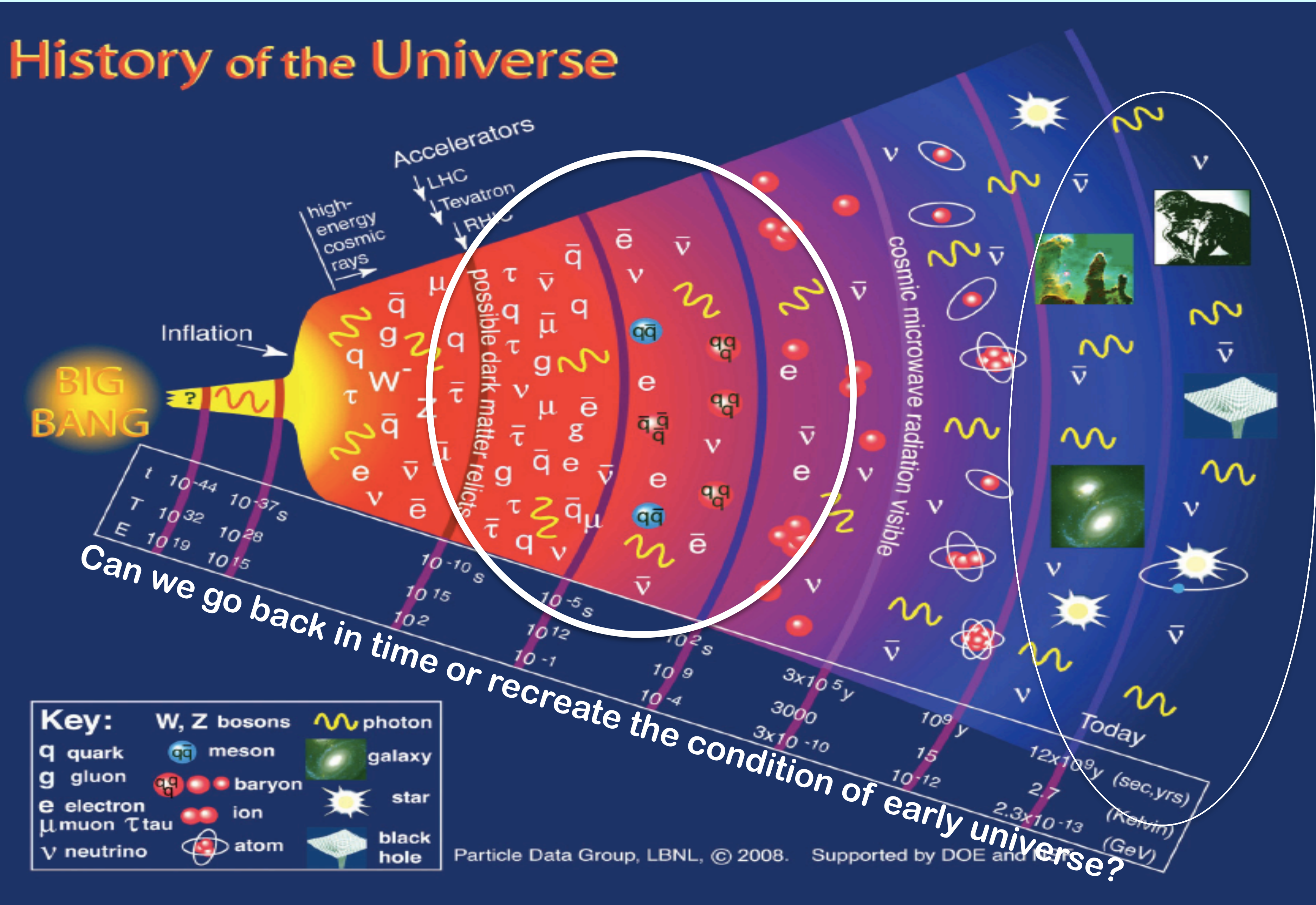
Fundamental forces?

Where are we going to?

The future?

2015 Long-Range Plan: Probing nuclear matter in all its forms, and Exploring their potential for applications

Where did we come from?



Going back in time?

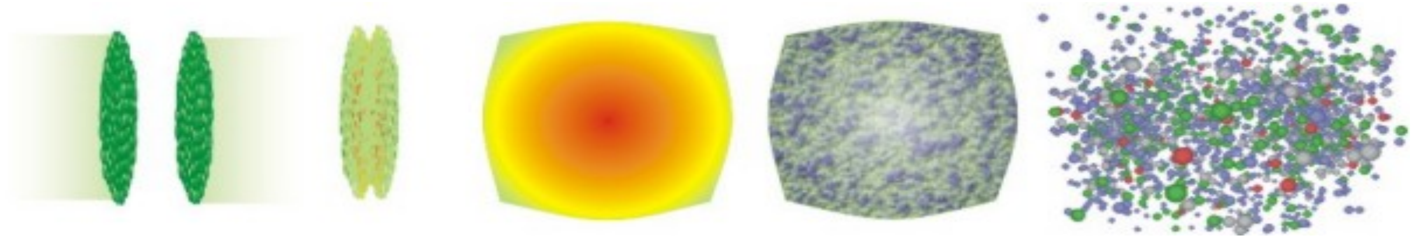
Expansion of the universe

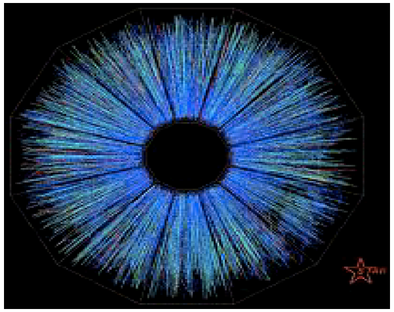
Little Bang in the Laboratory

Create a matter (QGP) with similar temperature and energy density

Relativistic heavy-ion collisions – the little bang

- **A Virtual Journey of Visible Matter:**





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

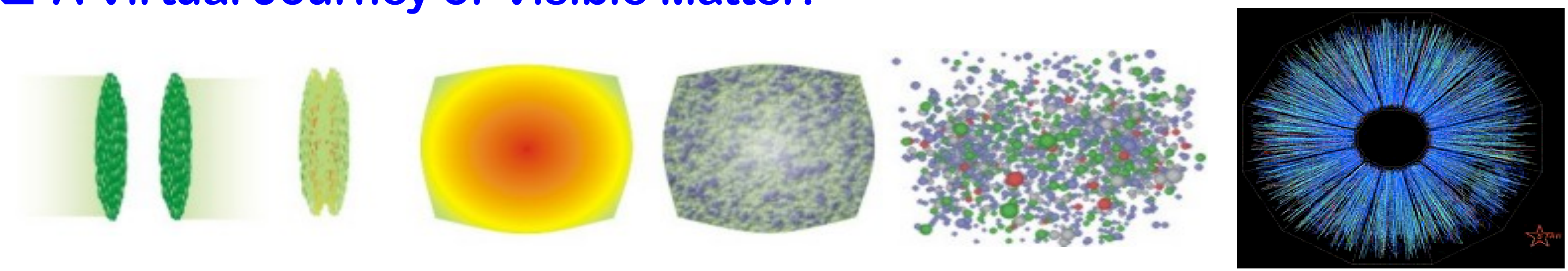
Visible!

"Seeing" the unseen

Visible!

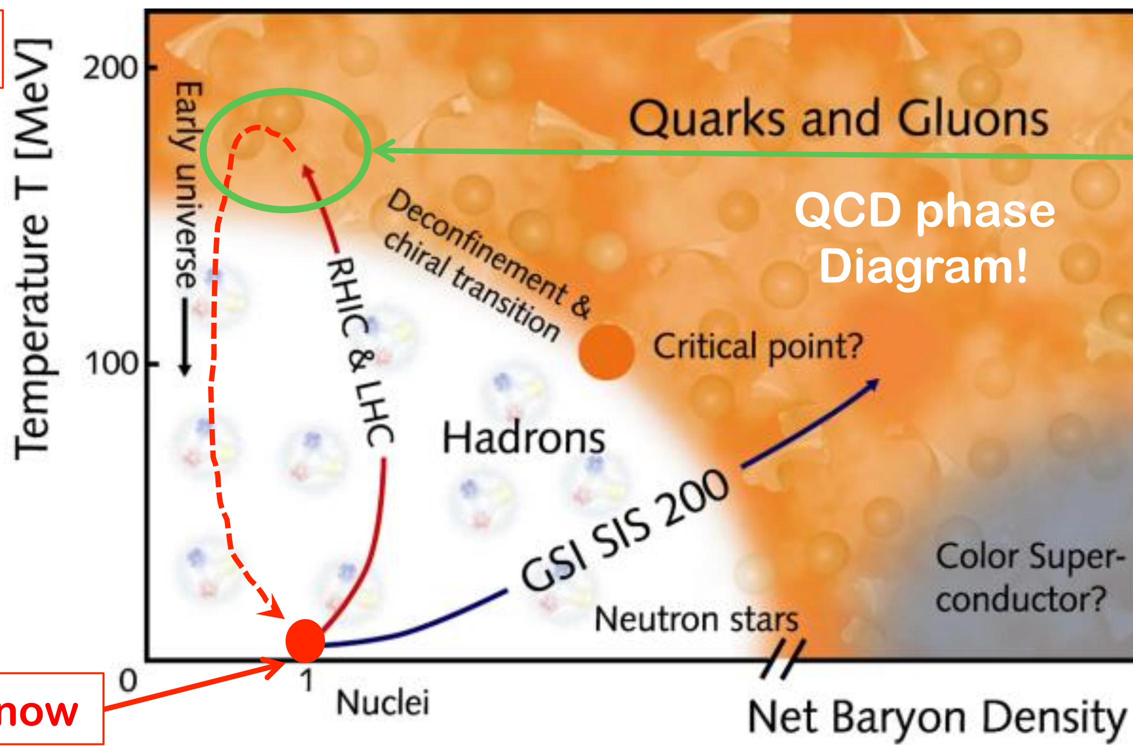
Relativistic heavy-ion collisions – the little bang

- A Virtual Journey of Visible Matter:



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

Visible! | Visible!



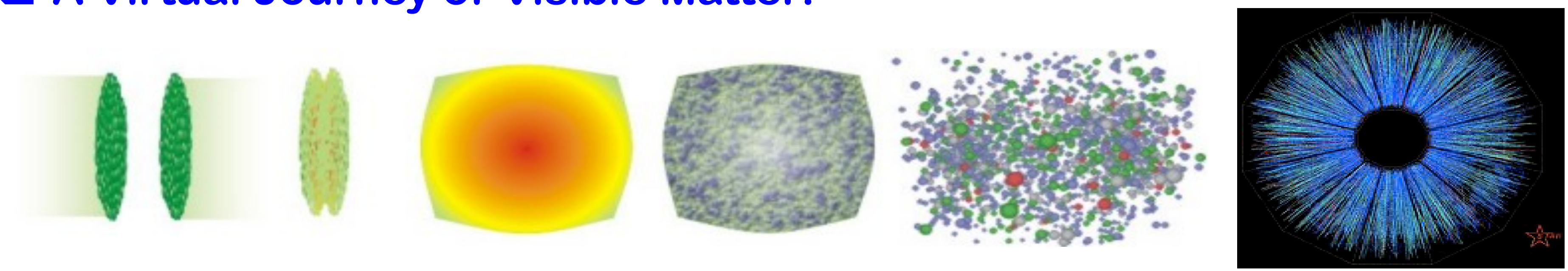
Discovery:

A nearly perfect quantum fluid (NOT a gas!) at 4 trillion degrees Celsius,

Not, at 10^{-5} K like ^{6}Li

Relativistic heavy-ion collisions – the little bang

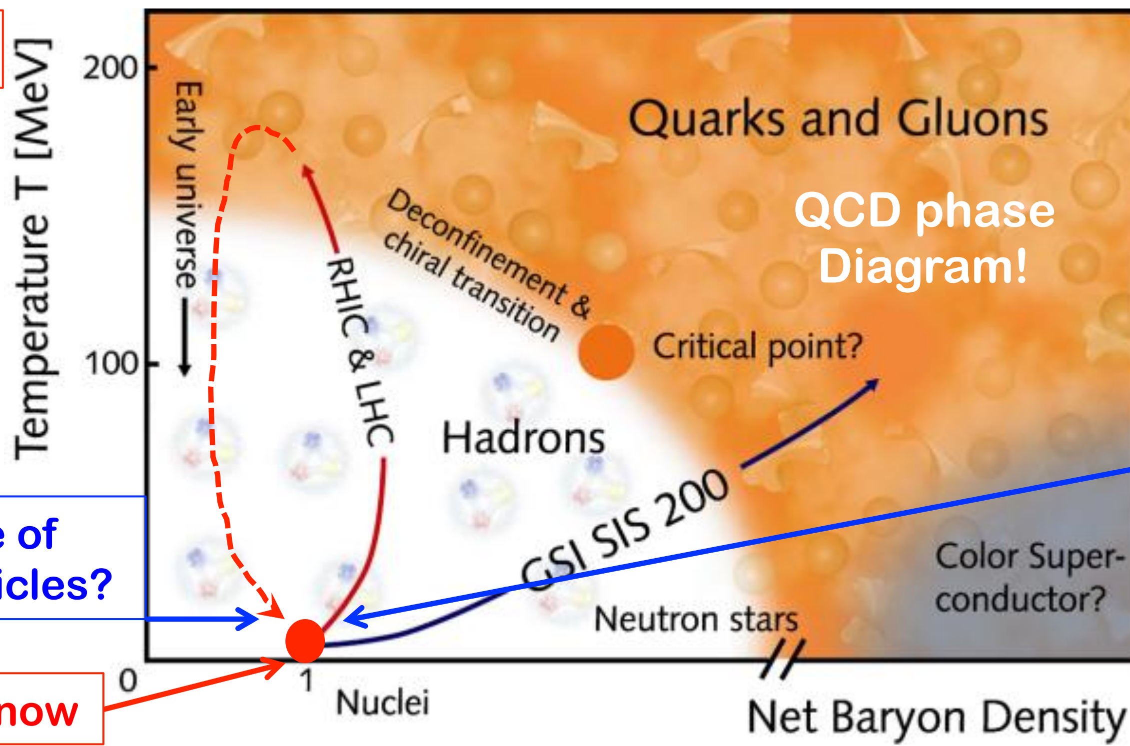
❑ **A Virtual Journey of Visible Matter:**



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

Visible!

Visible!

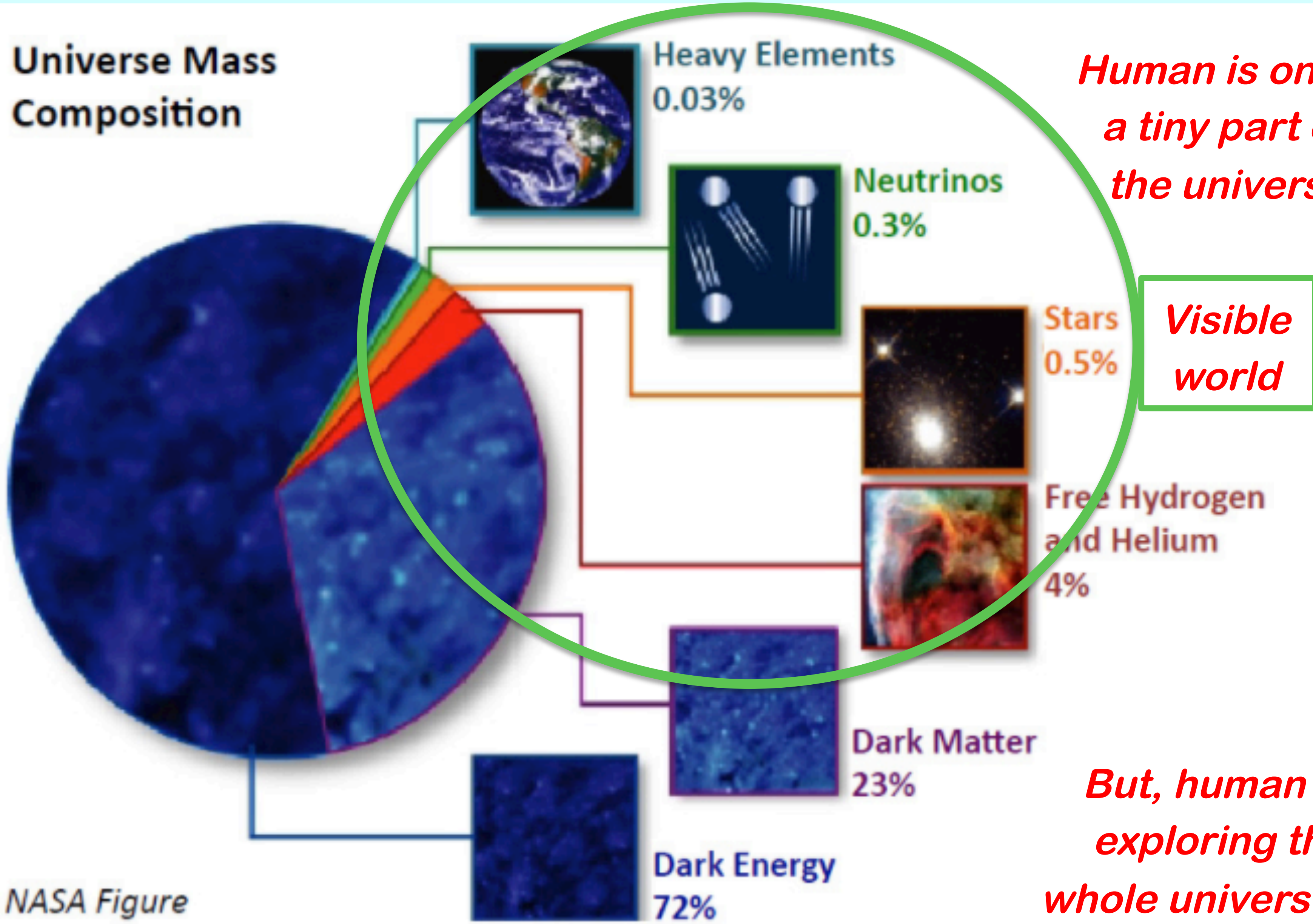


Structure of hadrons? = initial conditions of RHIC?

Emergence of hadronic particles?

Where we are now

What the world is made of?



Human is only a tiny part of the universe

But, human is exploring the whole universe!

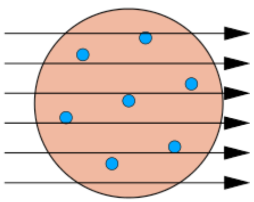
From atomic structure to quantum world, ...

❑ Atomic structure: dating back to Rutherford's experiment :

α + *Au* ➔ α + *X*

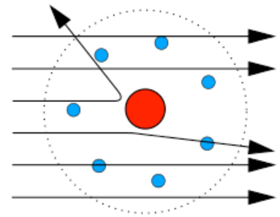
Over 100 years ago

Atom:



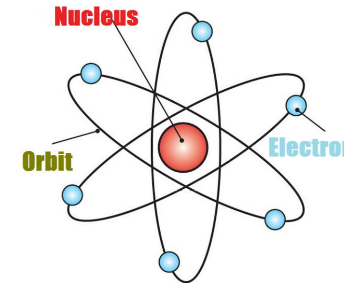
J.J. Thomson's plum-pudding model

Experiment



Rutherford's Experiment - Data

Theory



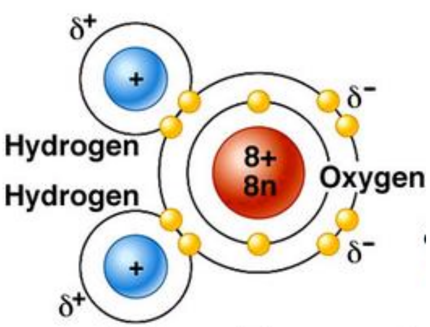
Quantum orbitals

Discovery: ✧ Tiny nucleus - *less than 1 trillionth in volume of an atom*

✧ Quantum probability *- the Quantum World!*

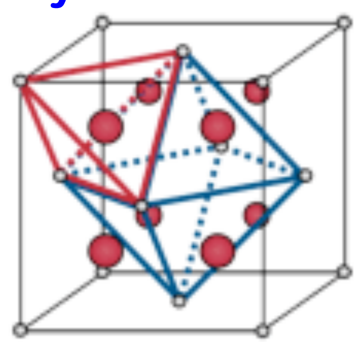
❑ Localized mass and charge centers – vast "open" space:

Molecule:



"Water"

Crystal:



Rare-Earth metal

Nanomaterial:

Carbon-based

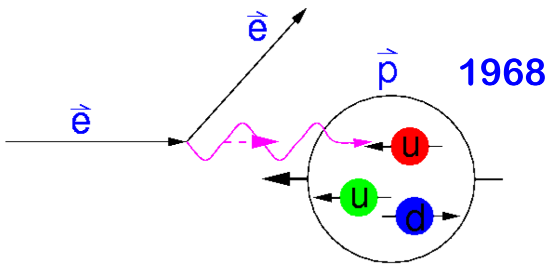
➔ *Infinite opportunities to create & improve ... !*

From nuclear structure to QCD, …

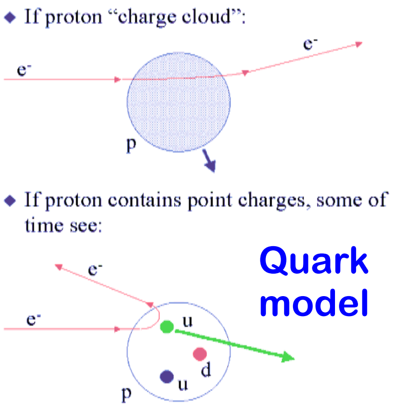
- A modern "Rutherford" experiment (about 50 years ago):

Nucleon: *The building unit of all atomic nuclei*

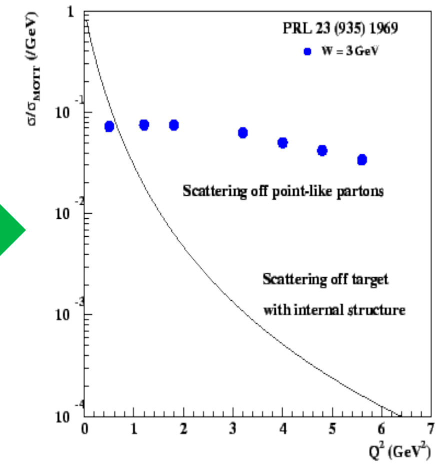
e + p ➔ e + X



Prediction

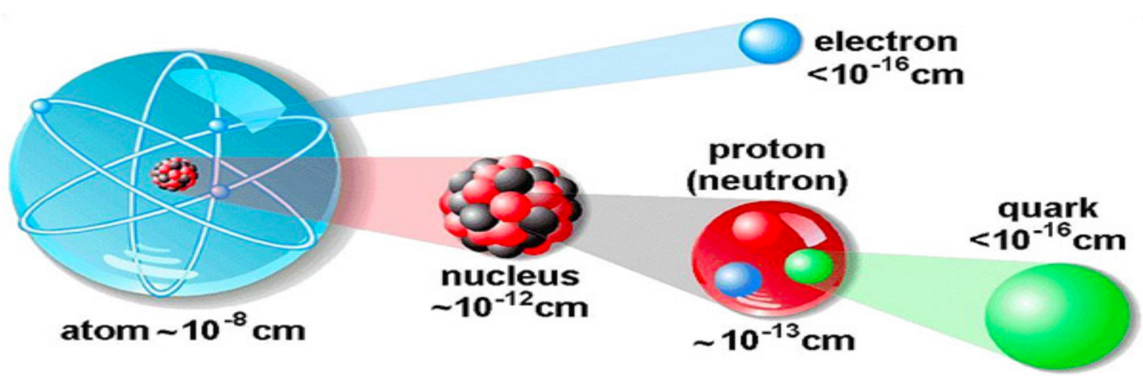


Discovery

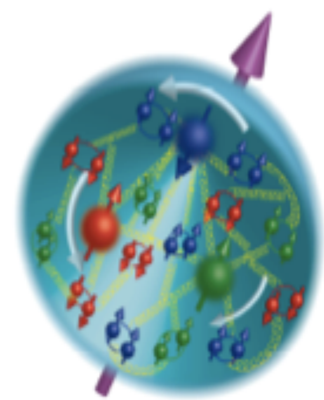


Discovery of quarks!

- Discovery of Quantum Chromodynamics (QCD):



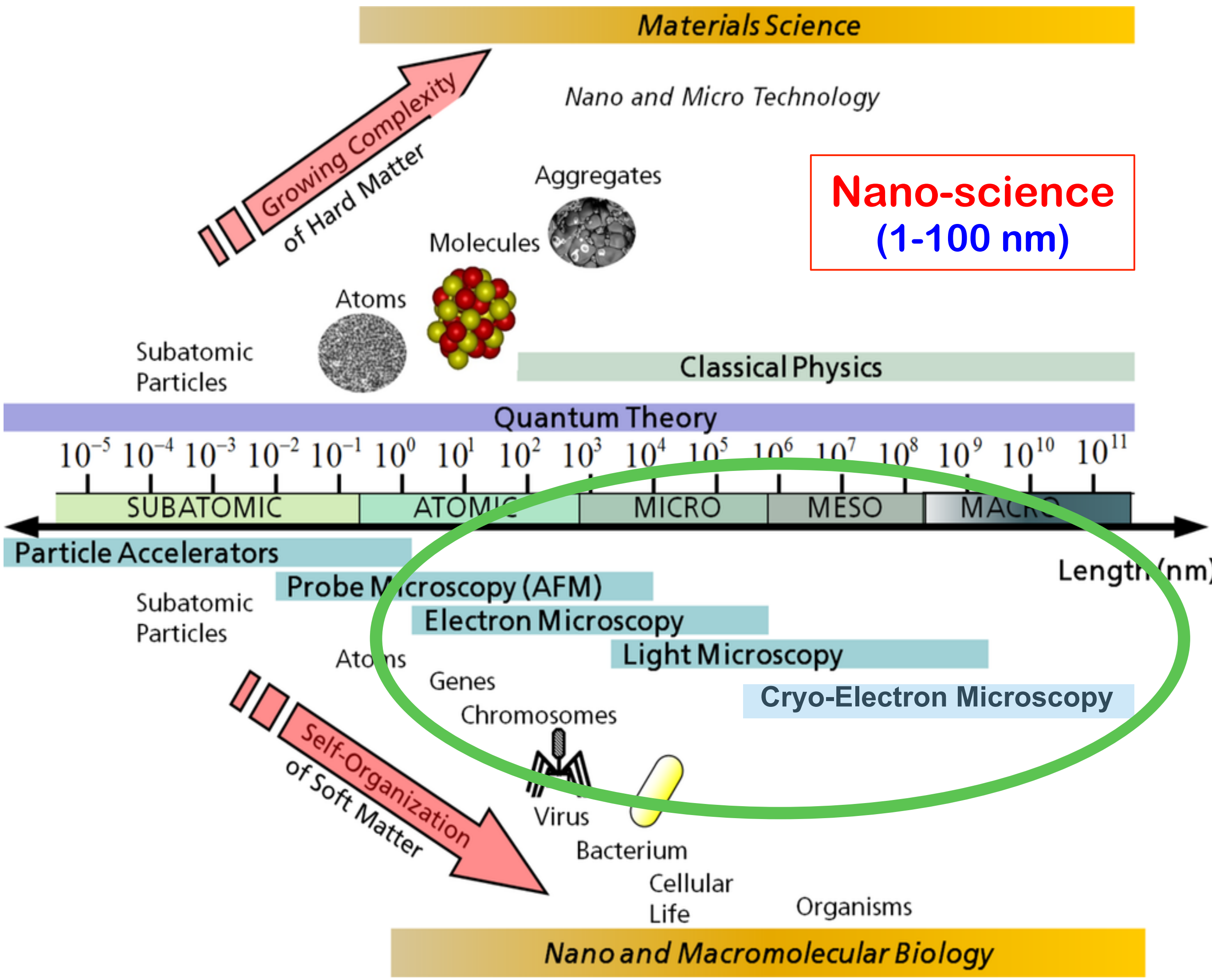
Gluons



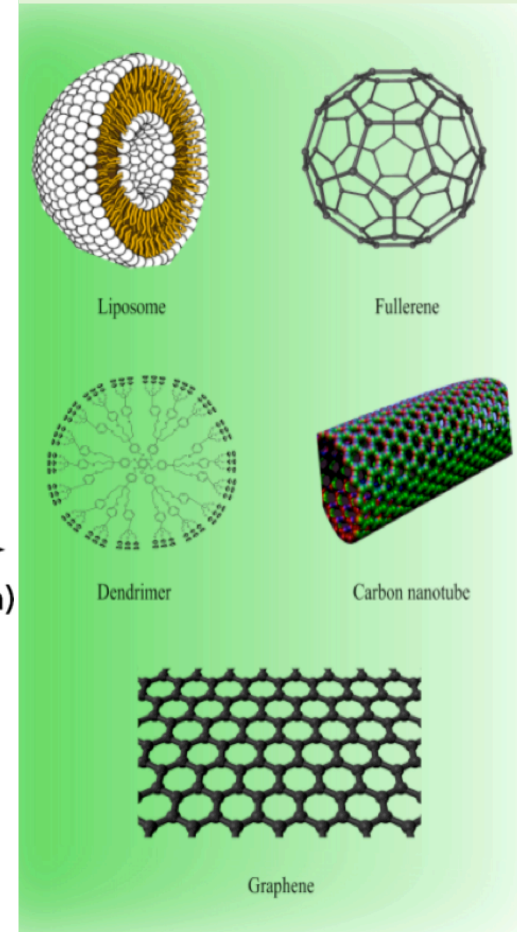
Nanometer *Femtometer* *Fluctuation*

From nano-science to femto-science

❑ Force, distance, complexity, & application:



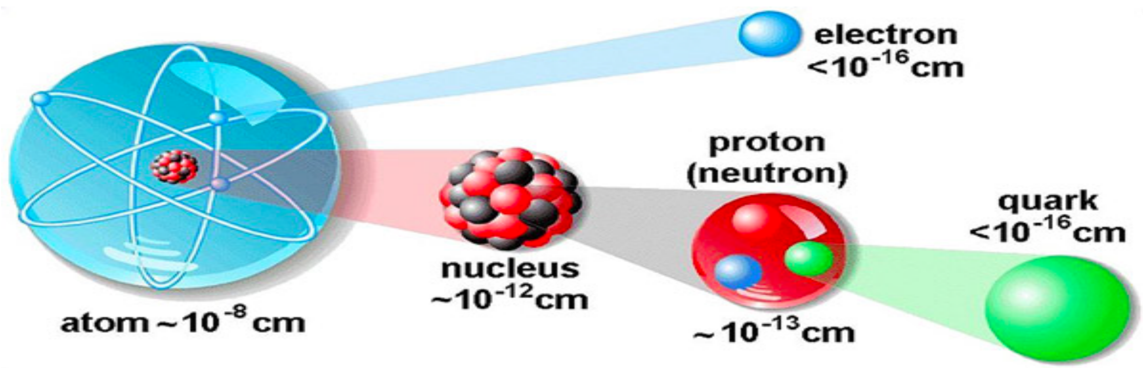
Nanomaterials



Ensure the role of quantum physics

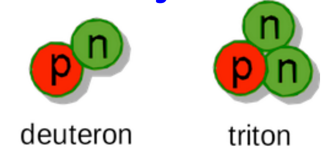
From nano-science to femto-science

- Force, distance, complexity, & application:

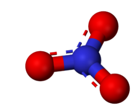


Femto-science
(0.1-10 fm)

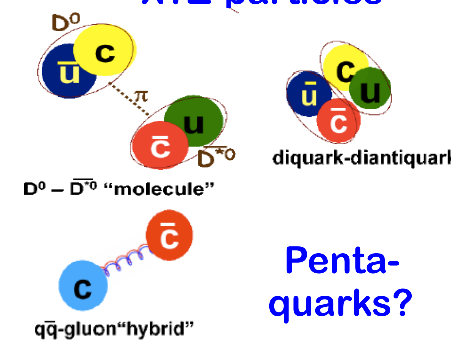
2-body force



3-body force



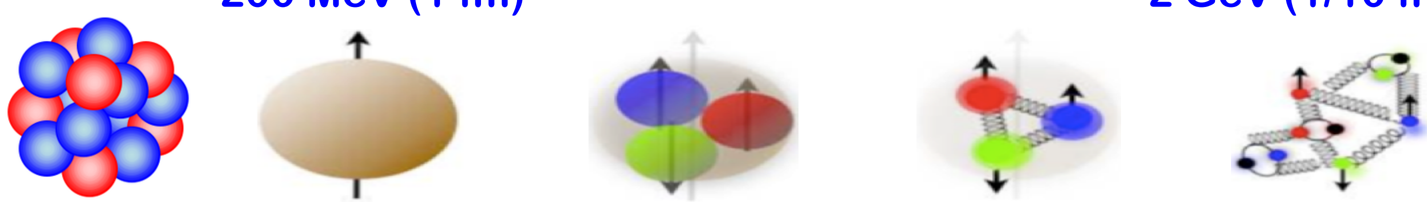
XYZ-particles



Penta-
quarks?

- QCD landscape of nucleon and nuclei?

Probing
scale



Need a facility to be able to explore/see the structure and dynamics !

Overarching questions, …

- How did hadrons, the building blocks of visible world, emerge from quarks and gluons?

  Necessary knowledge for understanding
  where and how did we come from?

- What is the internal structure of hadrons, and the dynamics behind the structure?

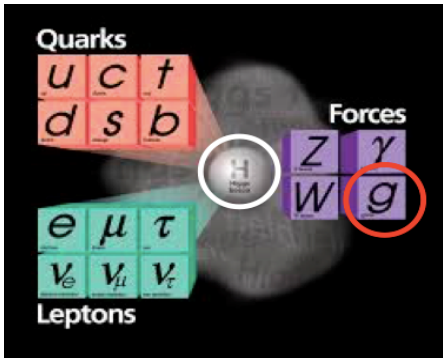
  Necessary knowledge for understanding
  what are we made of, and
  what hold us together, as well as
  how do we improve and move forward?

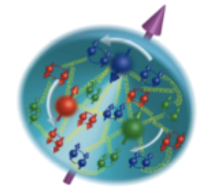
- What is the key for understanding color confinement?

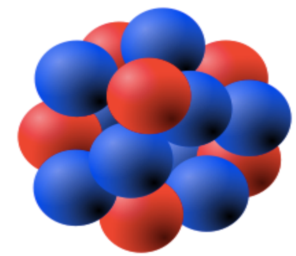
  Necessary knowledge for understanding
  What is the mother nature of the nonlinear,
  strongly interacting dynamics of color force?

What hold us together?

❑ Understanding the glue that binds us all – Next frontier of SM!





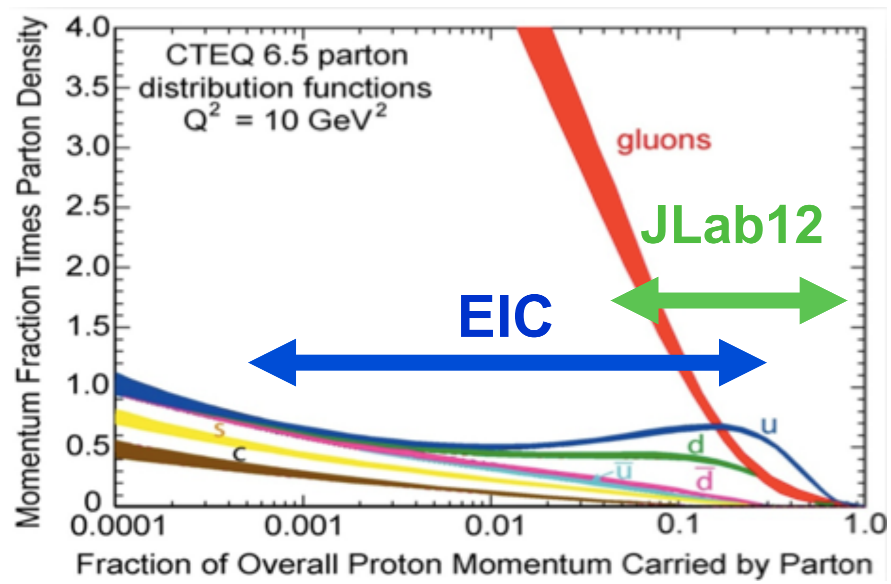


❑ Gluons are weird particles!

✧ 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, …***

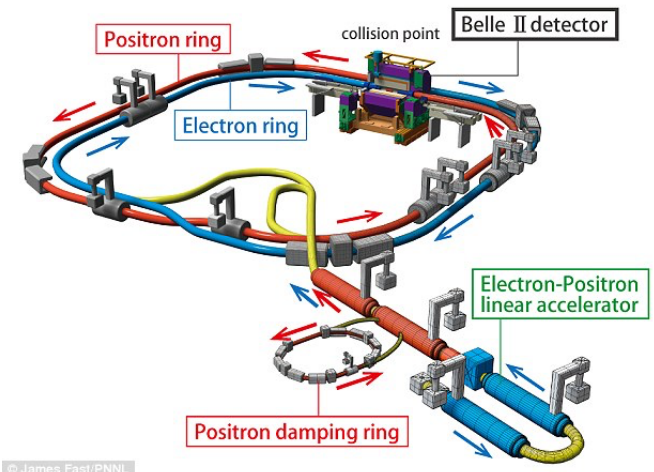
  Hadron "structure" – dynamical!

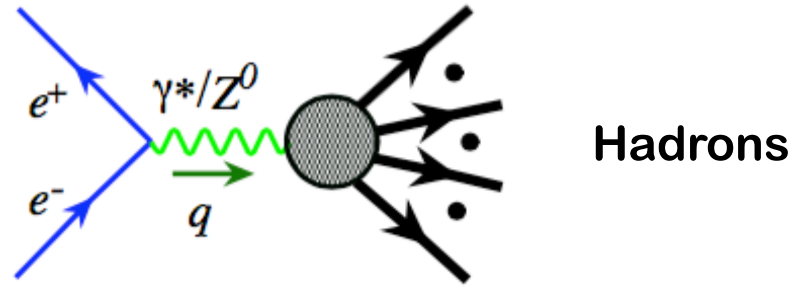
  No still picture of 3D structure!

  Need hard probes with the sub-femtometer resolution !

Hard probes from high energy collisions

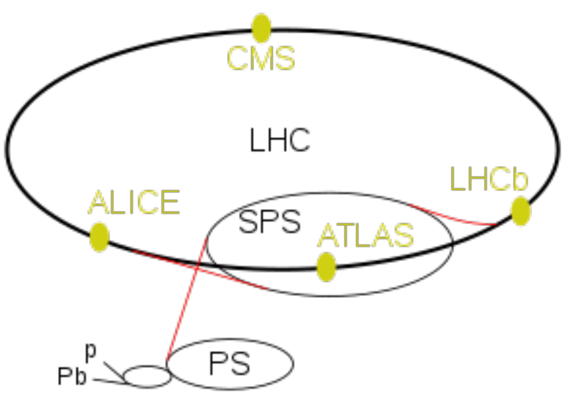
- Lepton-lepton collisions:

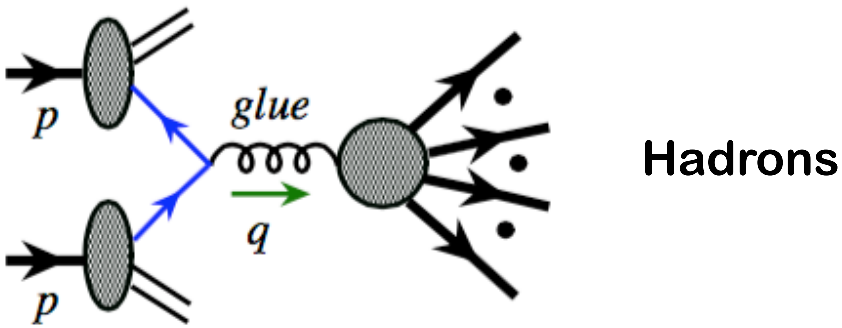




✧ No hadron in the initial-state
✧ Hadrons are emerged from energy
✧ Not ideal for studying hadron structure

- Hadron-hadron collisions:





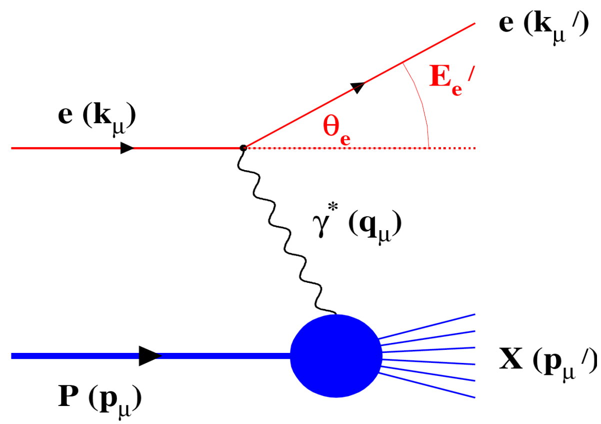
✧ Initial hadrons broken – collision effect, ...
✧ Hadron structure – motion of quarks, ...
✧ Emergence of hadrons, ...

- Lepton-hadron collisions:

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

Many complementary probes at one facility

- The future "Rutherford" experiment:



Q^2 → Measure of resolution

y → Measure of inelasticity

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

$Q^2 = S \times y$

Inclusive events: e+p/A → e'+X

Detect only the scattered lepton in the detector

(Modern Rutherford experiment!)

Semi-Inclusive events: e+p/A → e'+h(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)

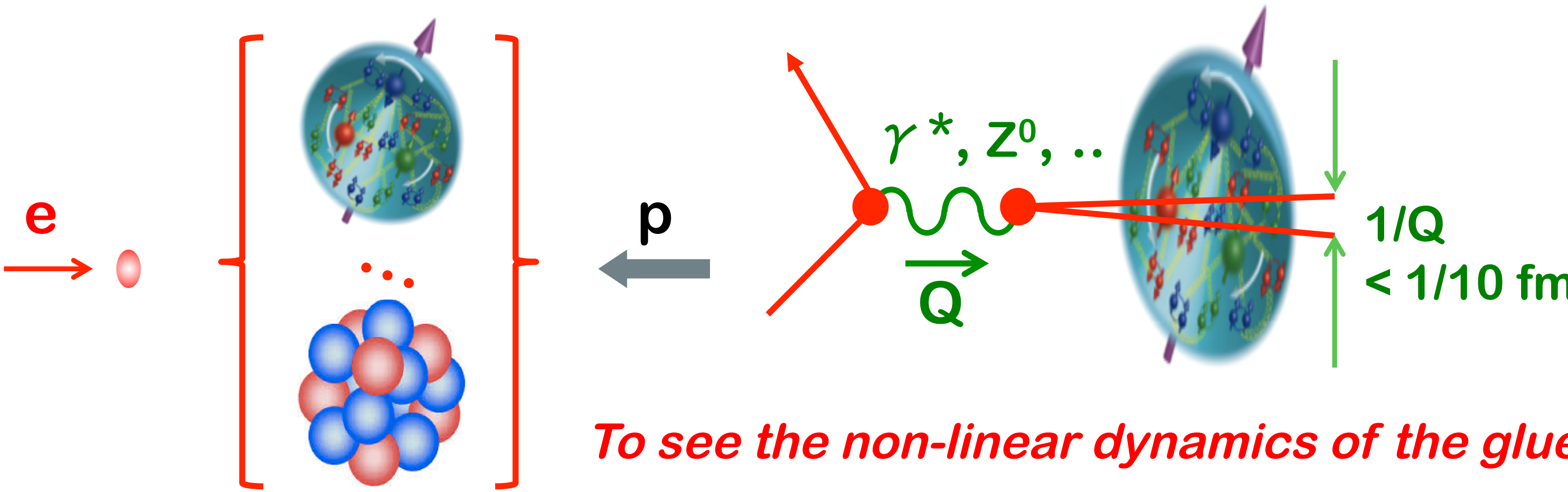
Exclusive events: e+p/A → e'+ p'/A'+ h(π,K,p,jet)

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

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

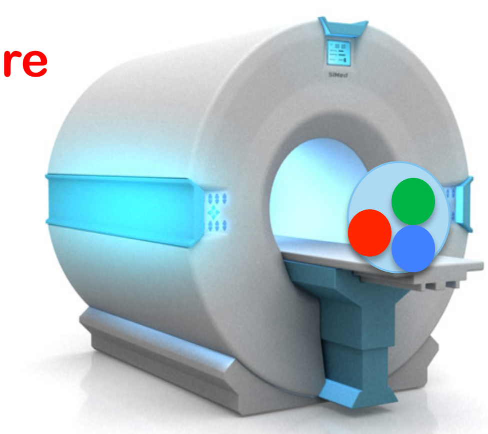
The Electron-Ion Collider (EIC)

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



To see the non-linear dynamics of the glue!

- 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



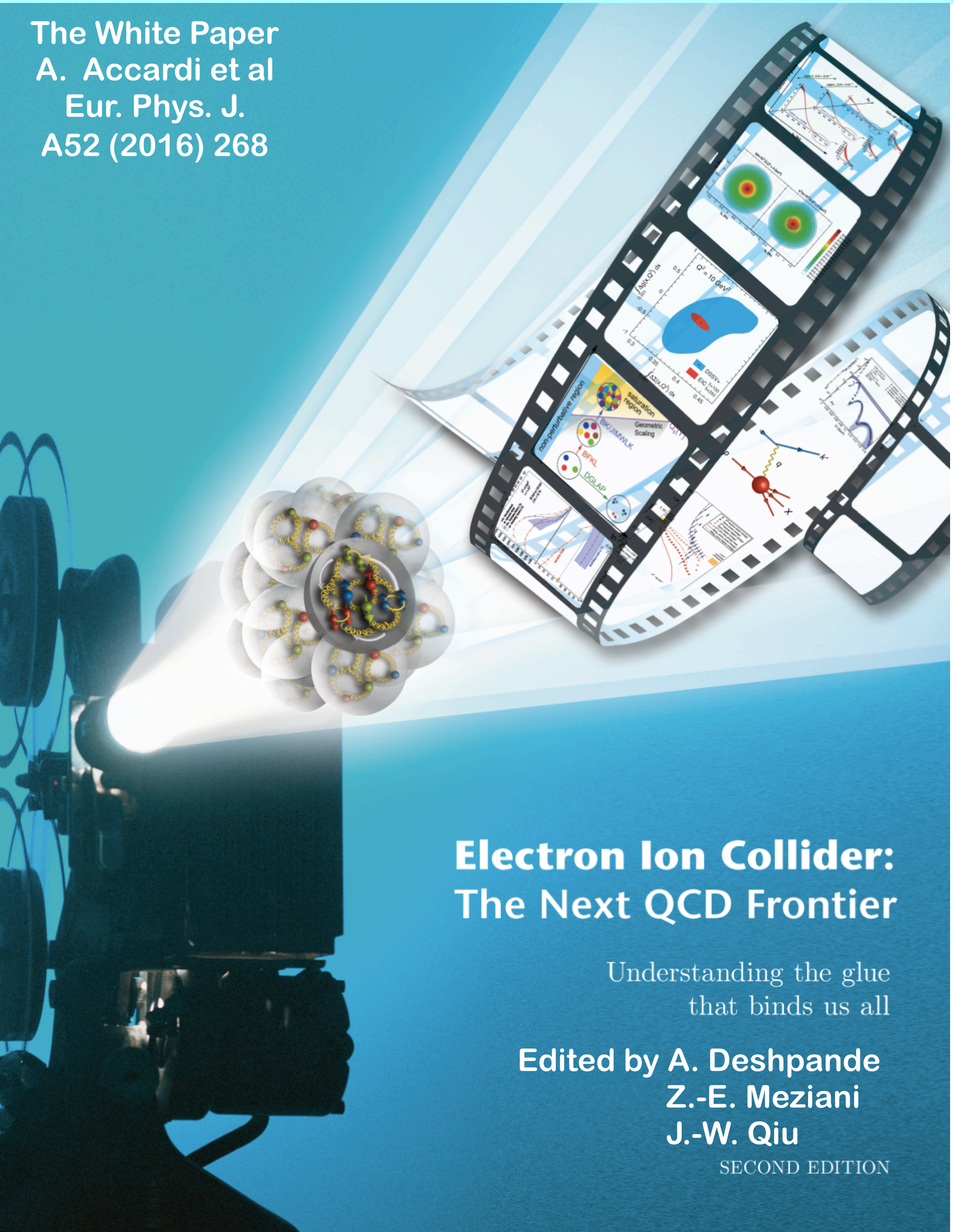
➡ *To discover color confining radius, hints on confining mechanism!*

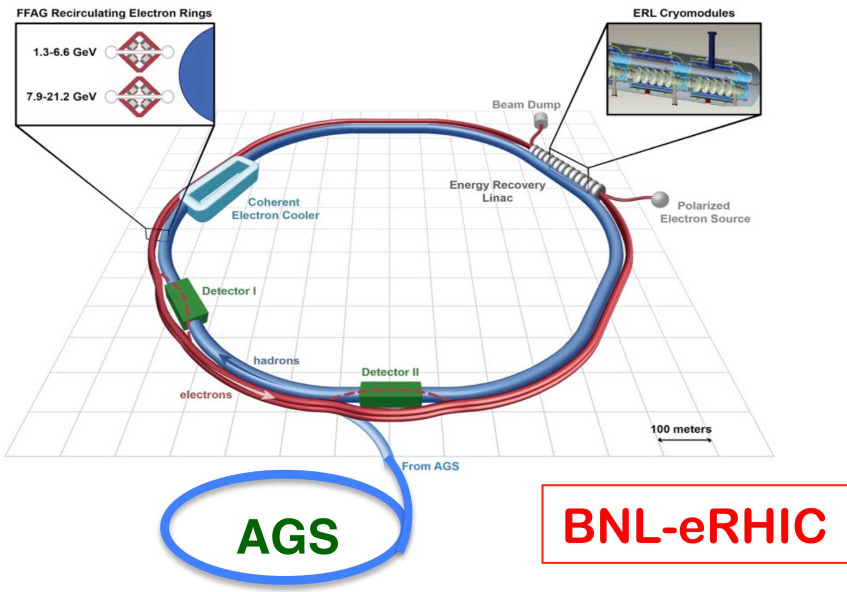
EIC: the World Wide Interest

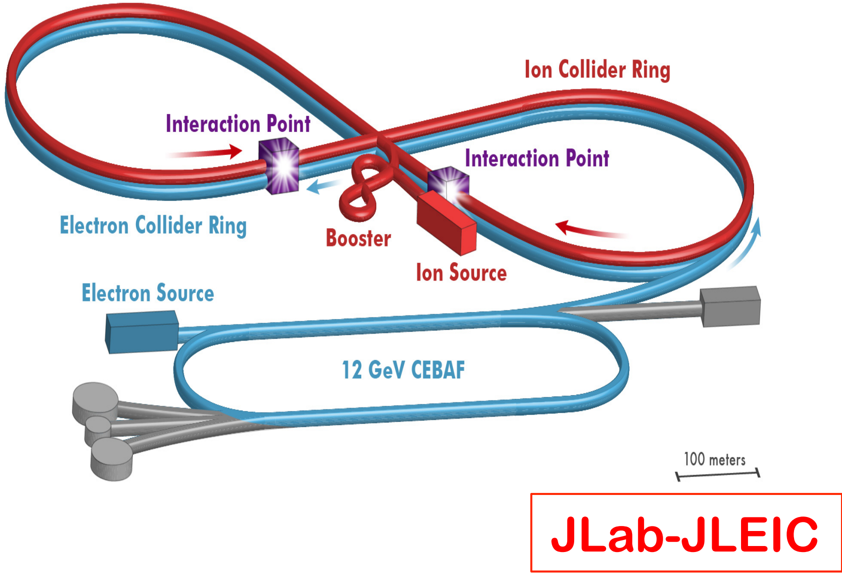
	HERA@DESY	LHeC@CERN	eRHIC@BNL	JLEIC@JLab	HIAF@CAS	ENC@GSI
E_{CM} (GeV)	320	800-1300	45-175	12-140	12 → 65	14
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-5}	5×10^{-5}	$7 \times 10^{-3} \rightarrow 3 \times 10^{-4}$	5×10^{-3}
ion	p	p to Pb	p to U	p to Pb	p to U	p to ~ ^{40}Ca
polarization	-	-	p, ^{3}He	p,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

US EIC – Two Options of Realization







U.S. - based Electron-Ion Collider

❑ NSAC 2007 Long-Range Plan:

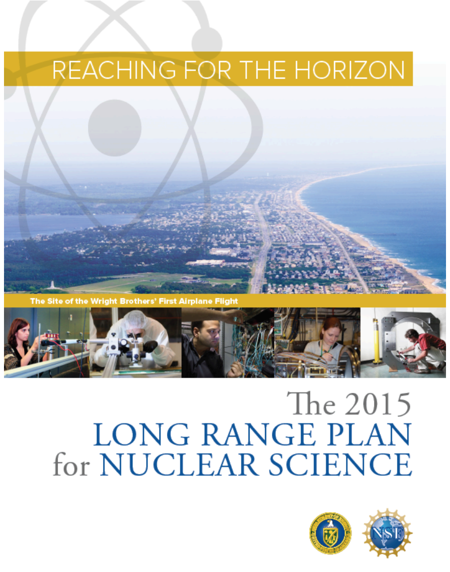
"An Electron-Ion Collider (EIC) with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier."

❑ 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."

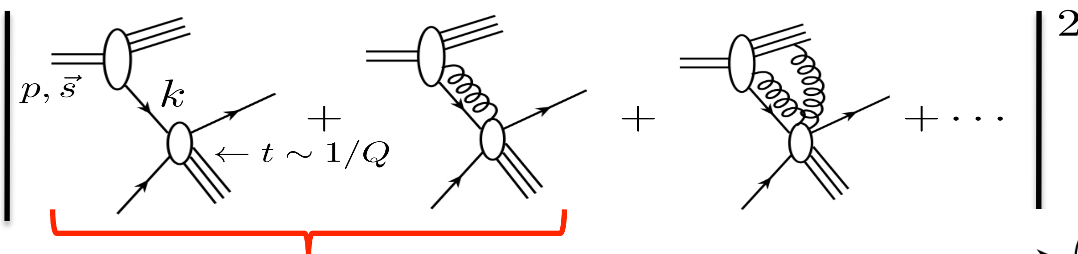


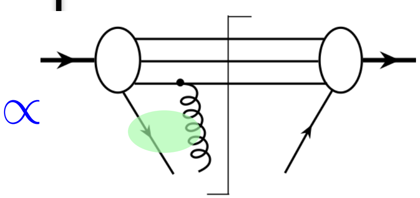
❑ Under review of National Academy of Science:

Expect to have the committee report early next year!

Why US-EIC can do what HERA can't 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

What can a US EIC do?

Major Nuclear Science issues to be studied at an EIC

or "Big" questions/puzzles about QCD, ...

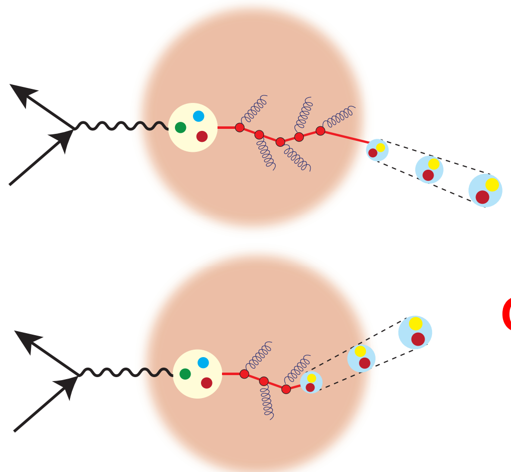
The key Deliverables & Opportunities

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

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

Emergence of hadrons from quarks & gluons

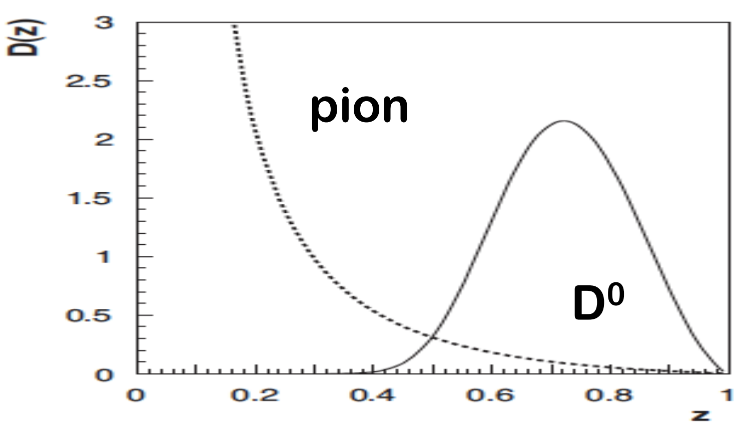
- **Femtometer sized detector:**

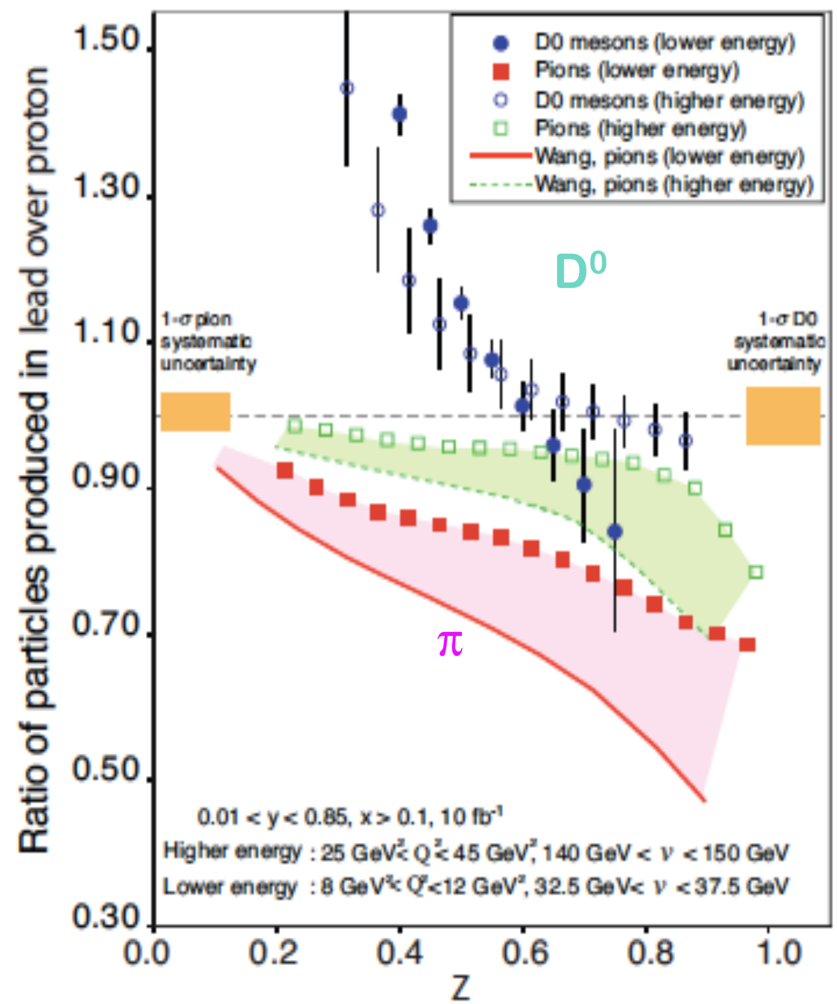


$$\nu = \frac{Q^2}{2mx}$$

Control of ν and medium length!

- **Heavy quark energy loss:**
  - **Mass dependence of fragmentation**





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:

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

❑ 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:

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

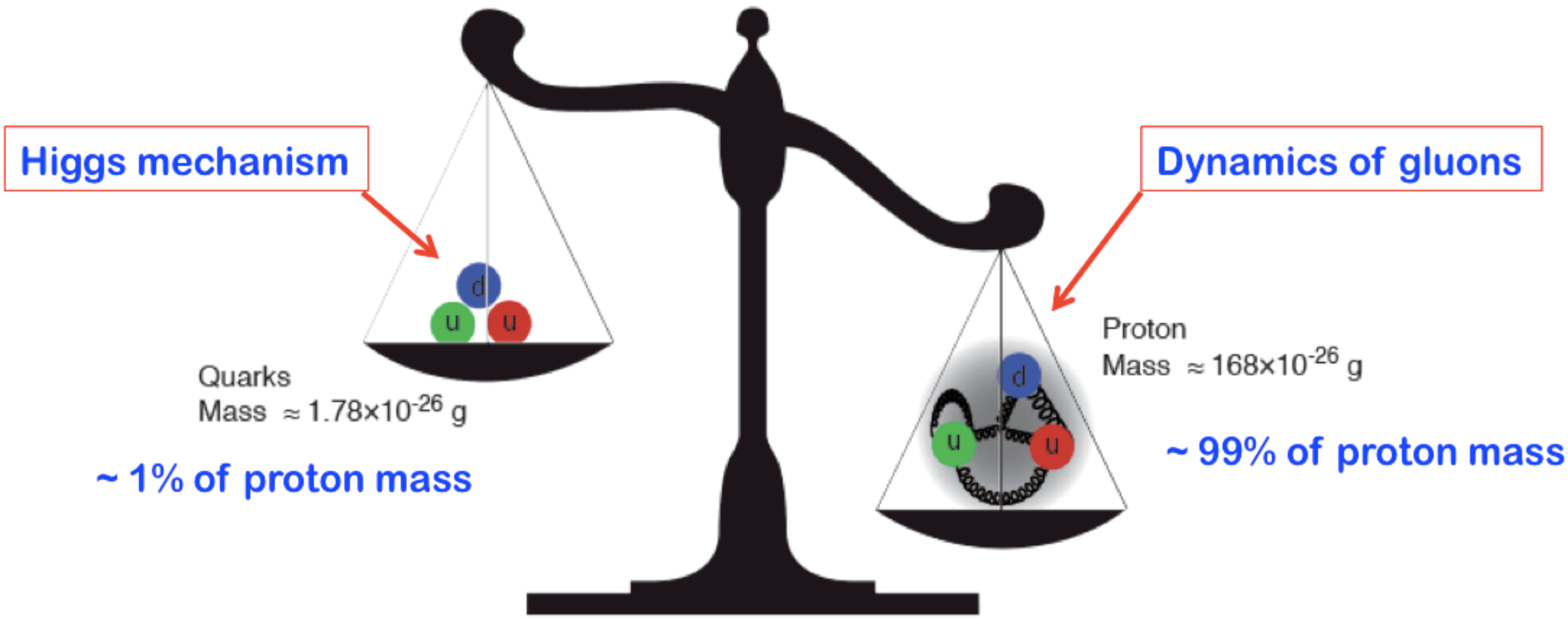
If we do not understand proton mass & spin, we do not understand QCD!

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*

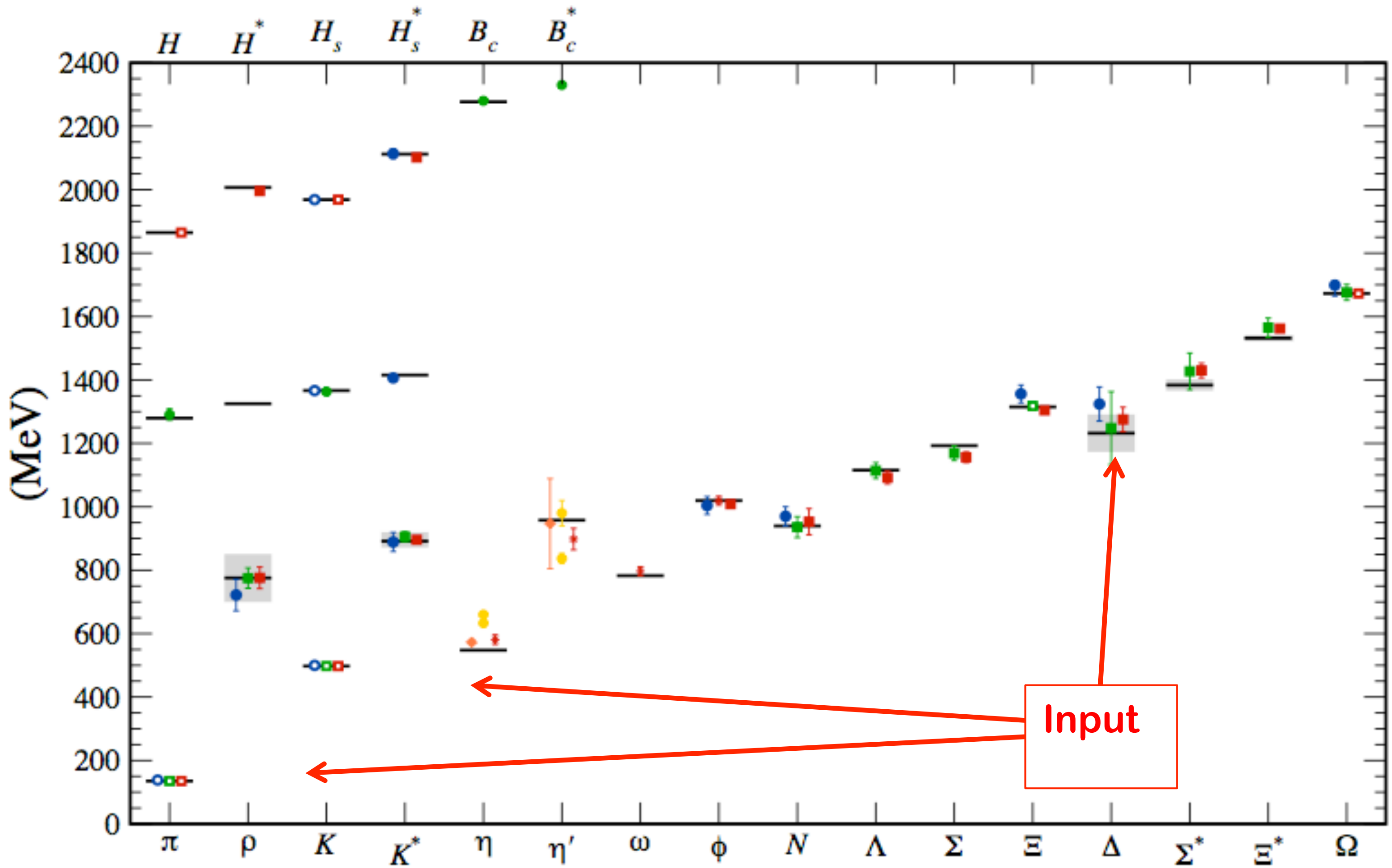
- ❑ **Higgs mechanism is not relevant to hadron mass!**



"Mass without mass!"

The Proton Mass?

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



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

The Proton Mass?

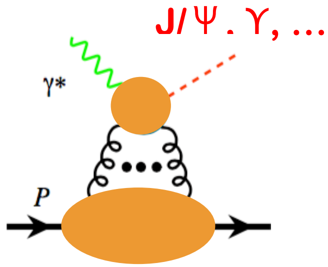
❑ Role of quarks and gluons?

✧ **Trace of the QCD energy-momentum tensor:** $\beta(g) = -(11 - 2n_f/3)\, g^3/(4\pi)^2 + \ldots$

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

✧ **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 chiral limit!***



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

❑ Decomposition or sum rules – could be frame dependent!

Relativistic motion

χ Symmetry Breaking

Quantum fluctuation

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

Quark Energy

Gluon Energy

Quark Mass

Trace Anomaly

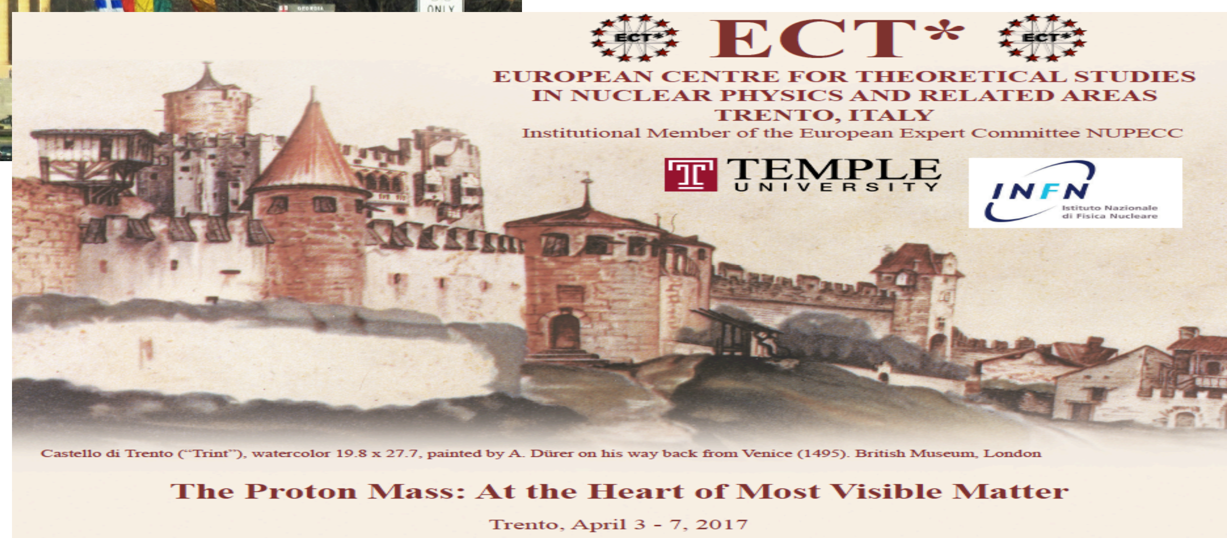
This is useful if only if individual terms can be measured independently

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**

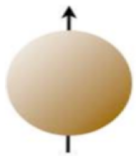
https://phys.cst.temple.edu/meziani
/proton-mass-workshop-2016/

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



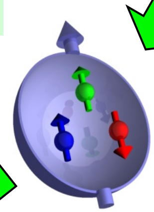
The Proton Spin?

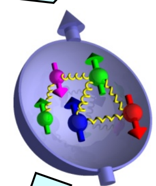
- ❑ **How does QCD generate the nucleon's spin?**

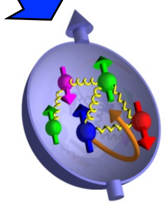


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

Proton Spin







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

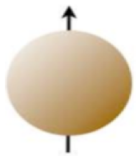
$$\Delta G = \int dx \Delta g(x)$$

$$\sim 20\% (\text{with RHIC data})$$

Orbital Angular Momentum of quarks and gluons
Little known

The Proton Spin?

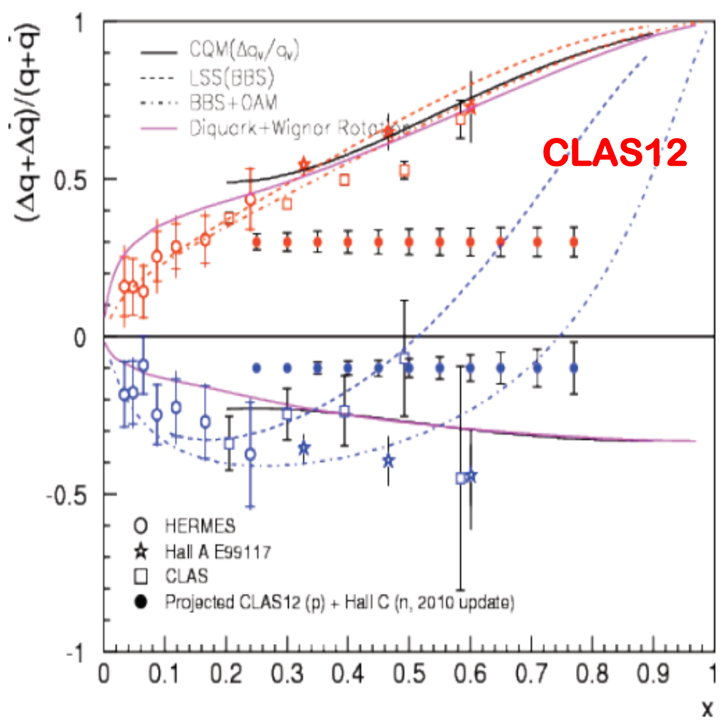
- How does QCD generate the nucleon's spin?

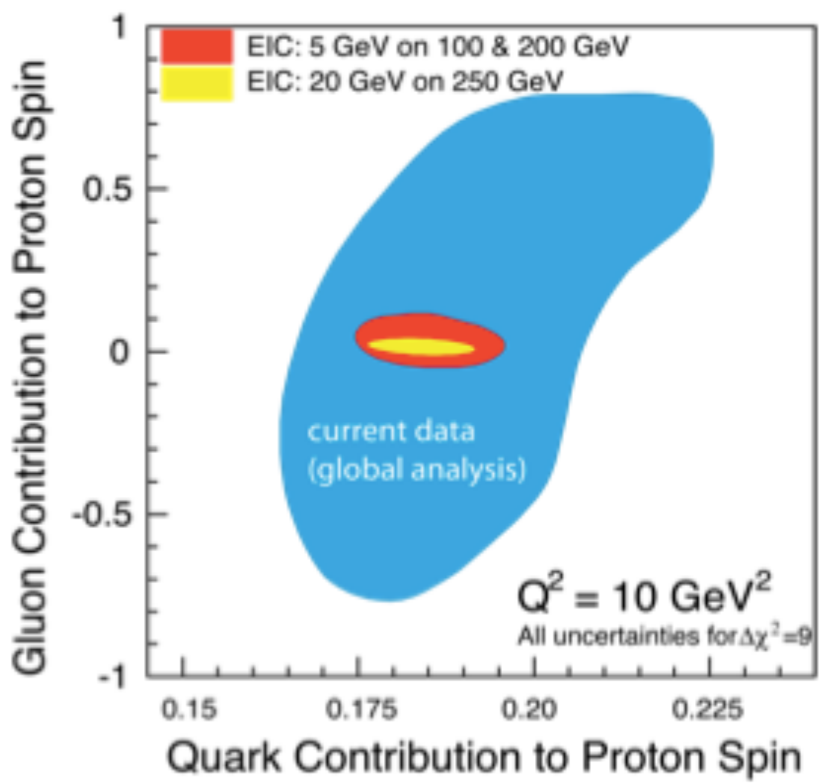


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

Proton Spin

- What can JLab12 and EIC do?

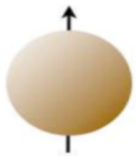




Plus many more JLab12 experiments – flavor

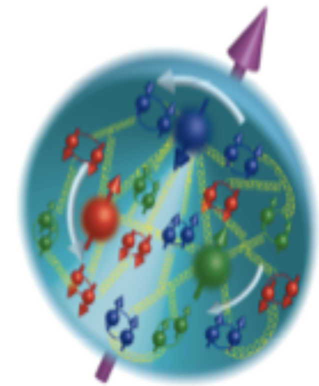
The Proton Spin?

- How does QCD generate the nucleon's spin?



Proton Spin

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



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

3D confined motion and spatial distribution

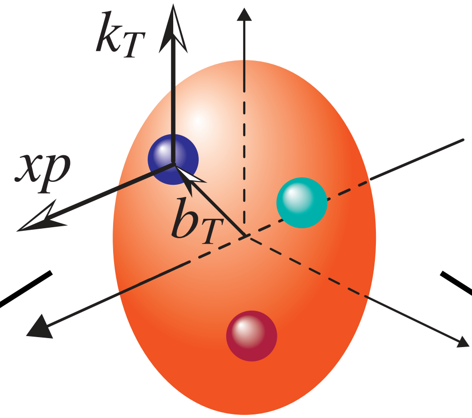
❑ **3D boosted partonic structure:**

Momentum Space

TMDs

Confined motion

$\int d^2b_T$



$\int d^2k_T$

Coordinate Space

GPDs

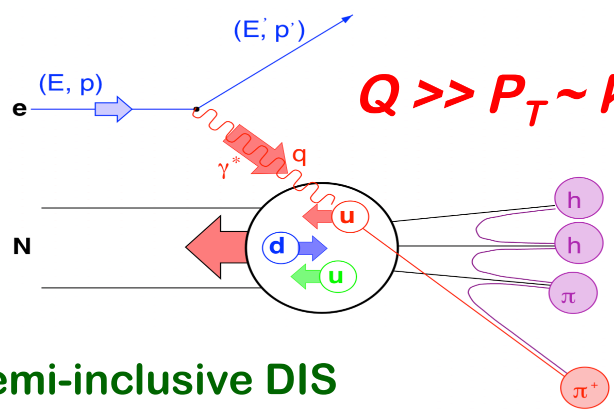
Spatial distribution

$f(x,k_T)$

Two-scales observables

$f(x,b_T)$

3D momentum space images

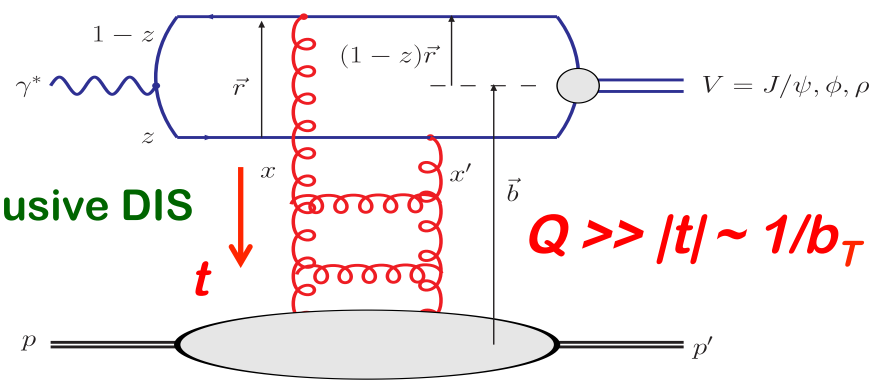


$Q >> P_T \sim k_T$

Semi-inclusive DIS

2+1D coordinate space images

Exclusive DIS



$Q >> |t| \sim 1/b_T$

3D confined motion and spatial distribution

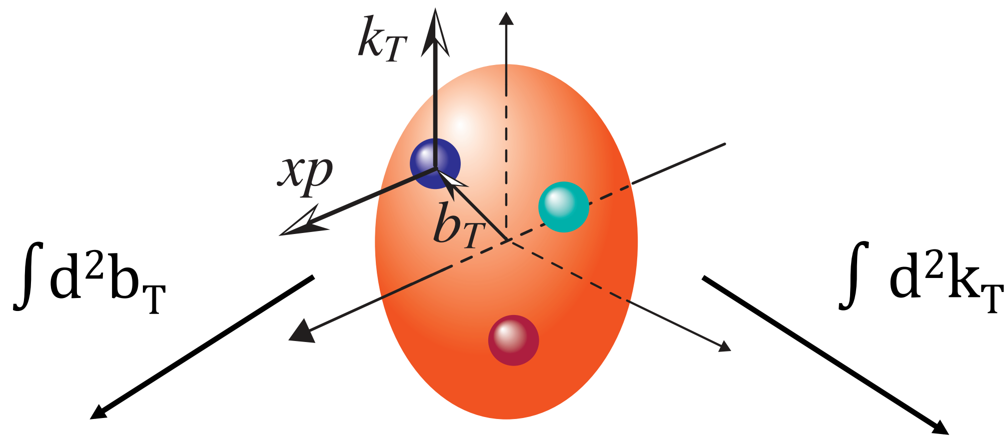
❑ 3D boosted partonic structure:

Momentum Space

TMDs

Coordinate Space

GPDs

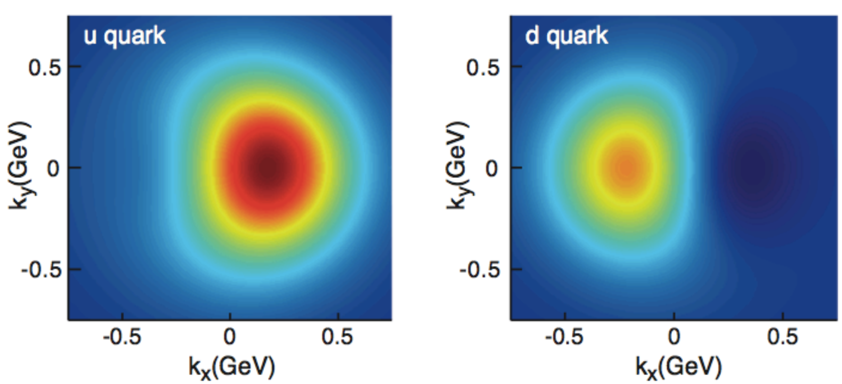


$f(x,k_T)$

EIC white paper: EPJ A52 (2016) 268

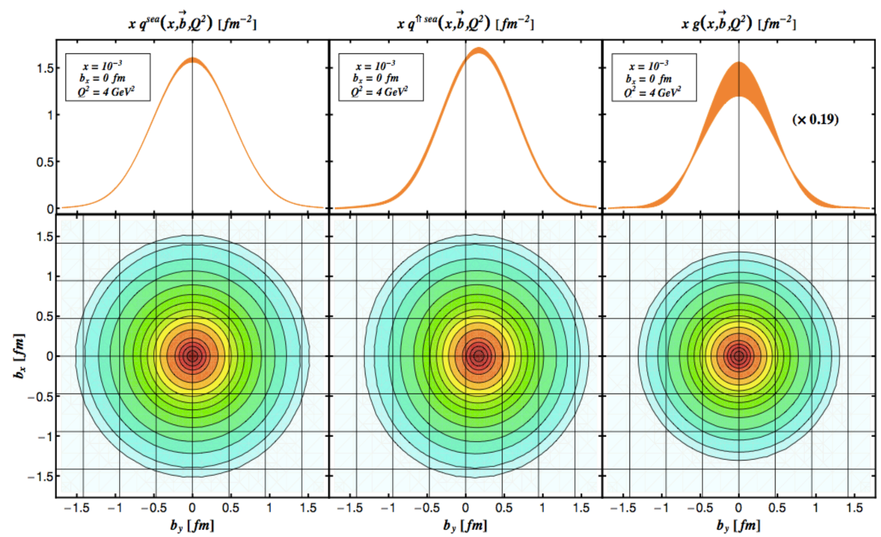
$f(x,b_T)$

Sivers Function



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

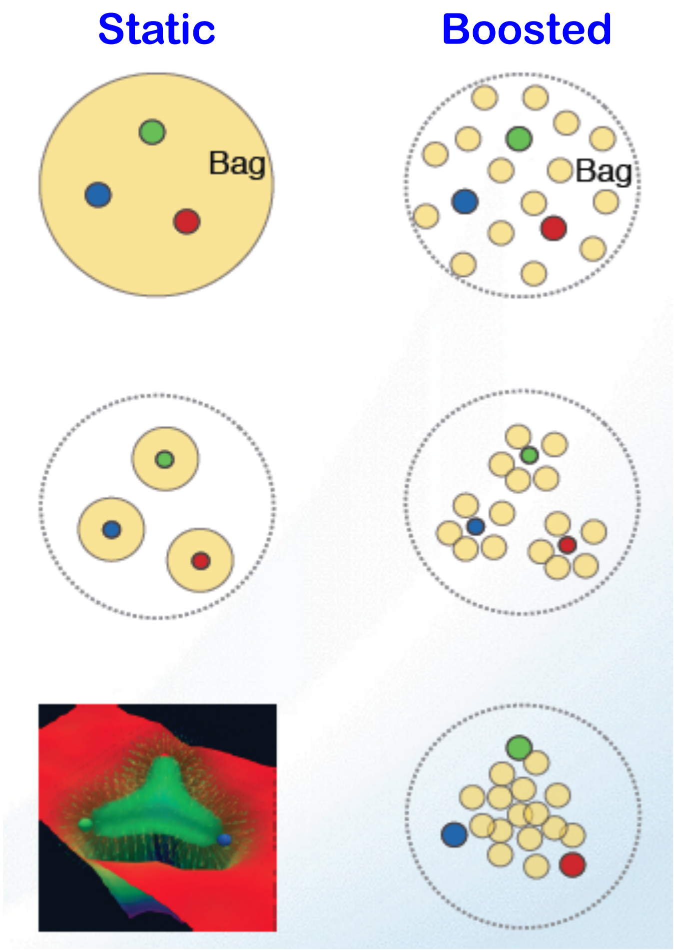
Imaging



Spatial density distributions – "radius"

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

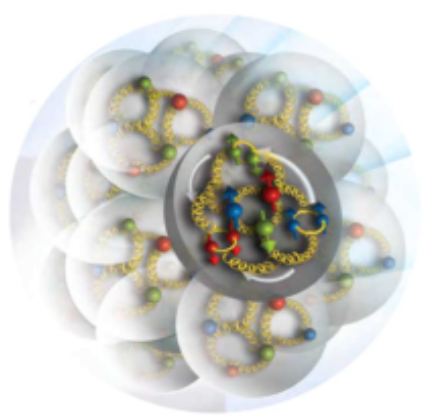
Constituent Quark Model:
Gluons and sea quarks hide inside massive quarks.
Gluon radius ~ Charge Radius

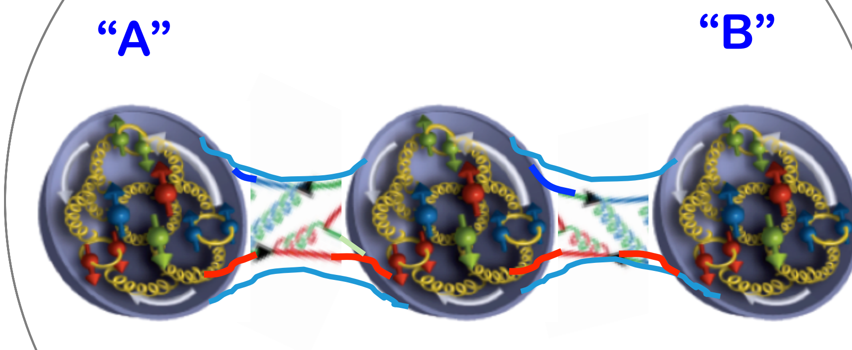
Lattice Gauge theory (with slow moving quarks):
Gluons more concentrated inside the quarks
Gluon radius < Charge Radius

3D confined motion (TMDs) + spatial distribution (GPDs)
Hints on the color confining mechanism
Relation between charge radius, quark radius (x), and gluon radius (x)?

The origin of nuclear force?

❑ 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"?

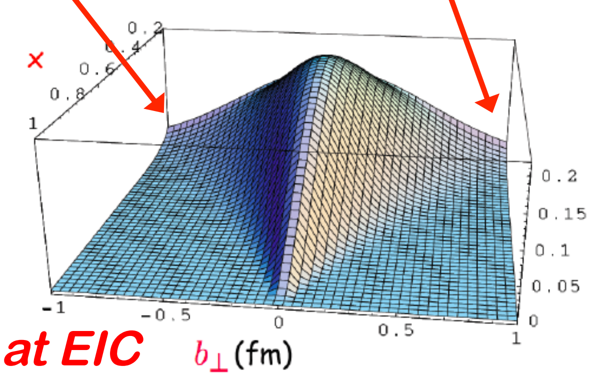
If it does, what is the strength of such correlation?

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

How far does glue density spread?

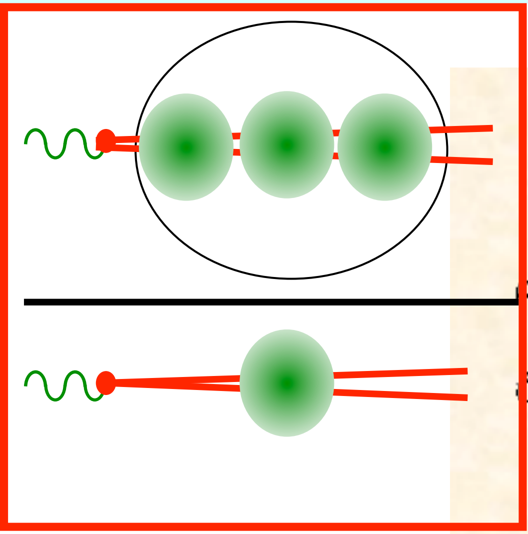
How fast does glue density fall?

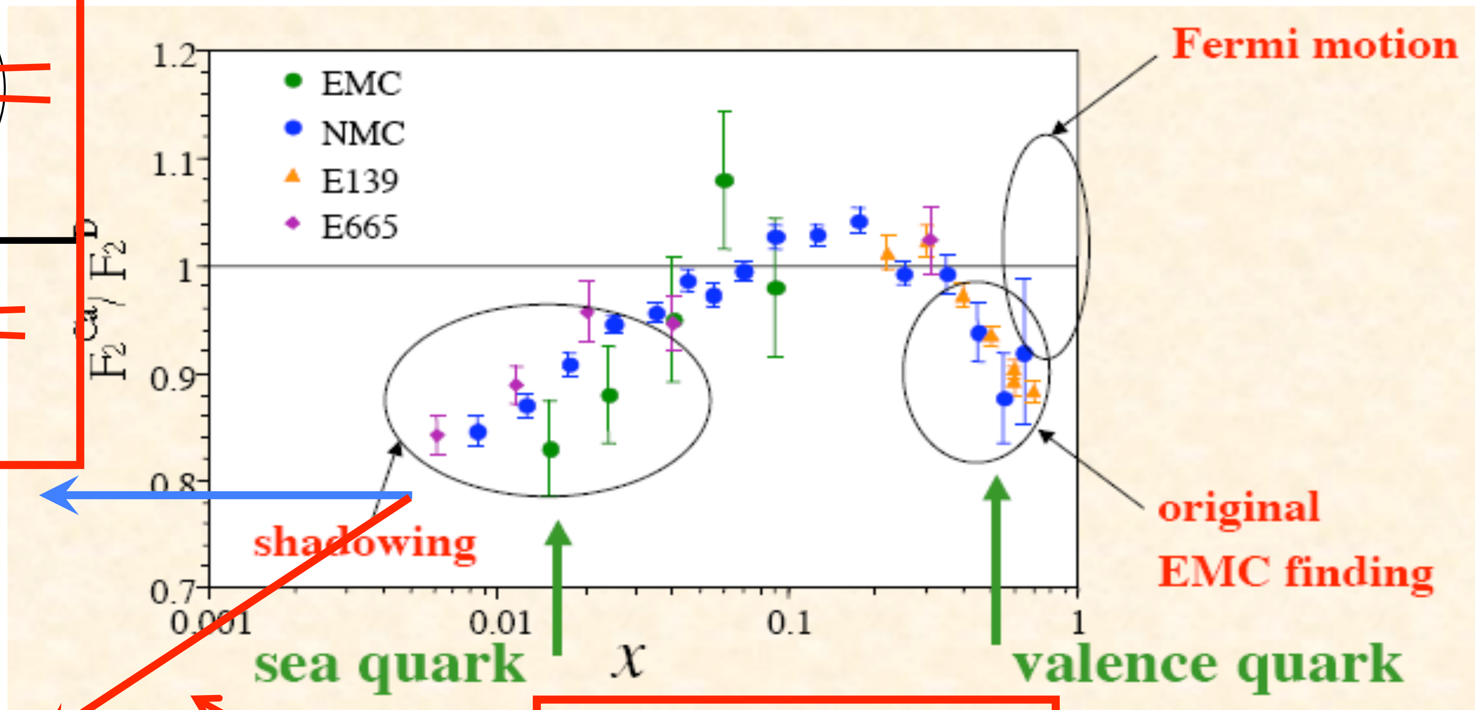
Imaging gluon density



Only possible at EIC

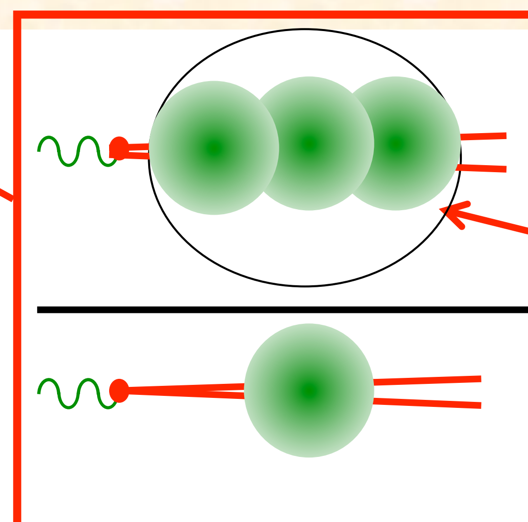
Simple test of color confining radius?





Color localized Inside nucleons

Saturation in nucleon



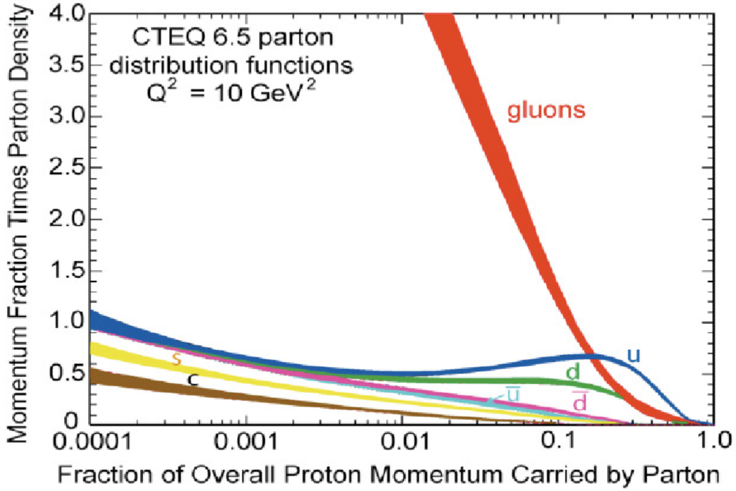
Color leaks outside nucleons Soft gluon radius is larger

- ❑ A simple question:

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

Another HERA discovery

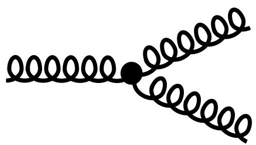
- **Run away gluon density at small x?**



What causes the low-x rise?

gluon radiation

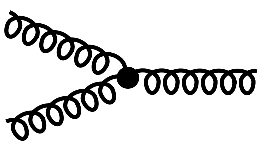
– non-linear gluon interaction



What could tame the low-x rise?

gluon recombination

– non-linear gluon interaction



- **QCD vs. QED:**

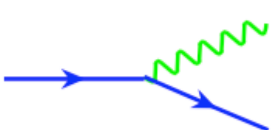
QCD – gluon in a proton:

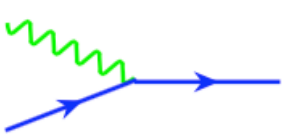
$$Q^2\frac{d}{dQ^2}xG(x,Q^2)\approx\frac{\alpha_s N_c}{\pi}\int_x^1\frac{dx'}{x'}x'G(x',Q^2)$$

QED – photon in a positronium:

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

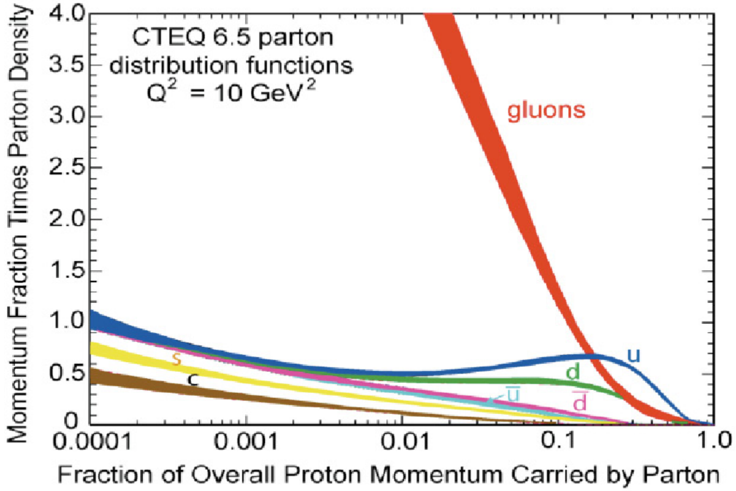
- **At very small-x, proton is "black", positronium is still transparent!**
- **Recombination of large numbers of glue could lead to saturation phenomena**





How to answer the "Big" questions?

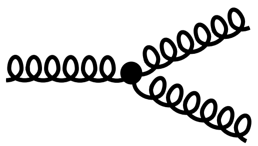
❑ Run away gluon density at small x?



What causes the low-x rise?

gluon radiation

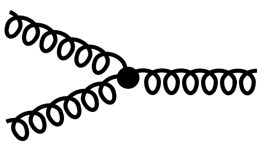
– non-linear gluon interaction



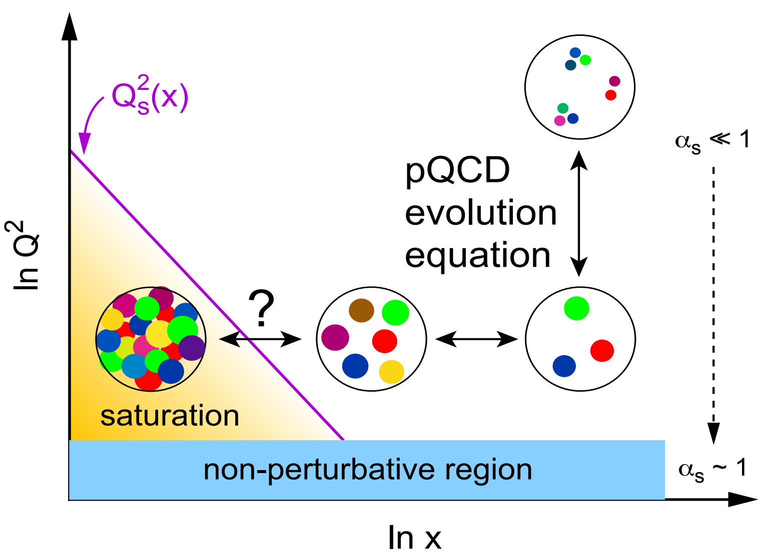
What could tame the low-x rise?

gluon recombination

– non-linear gluon interaction

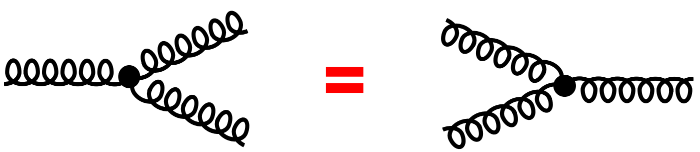


❑ Particle vs. wave feature:



Gluon saturation – Color Glass Condensate

Radiation = Recombination



at Q_s

Leading to a collective gluonic system?

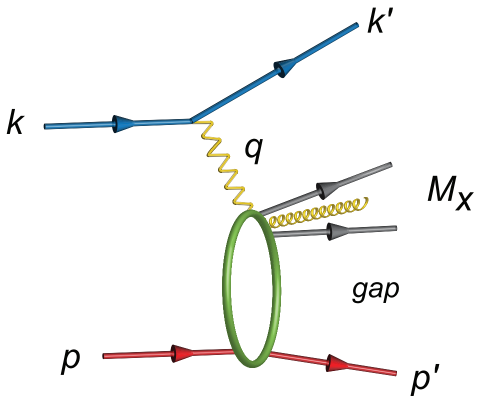
with a universal property of QCD?

new effective theory QCD – CGC?

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

Best signature for gluon saturation

❑ Diffractive cross section:



– off a coherent obj.

$$\frac{1}{\sigma_{\text{tot}}^{eA}}\frac{d\sigma_{diff}^{eA}}{dM_x^2}\Big/\frac{1}{\sigma_{\text{tot}}^{ep}}\frac{d\sigma_{diff}^{ep}}{dM_x^2}$$

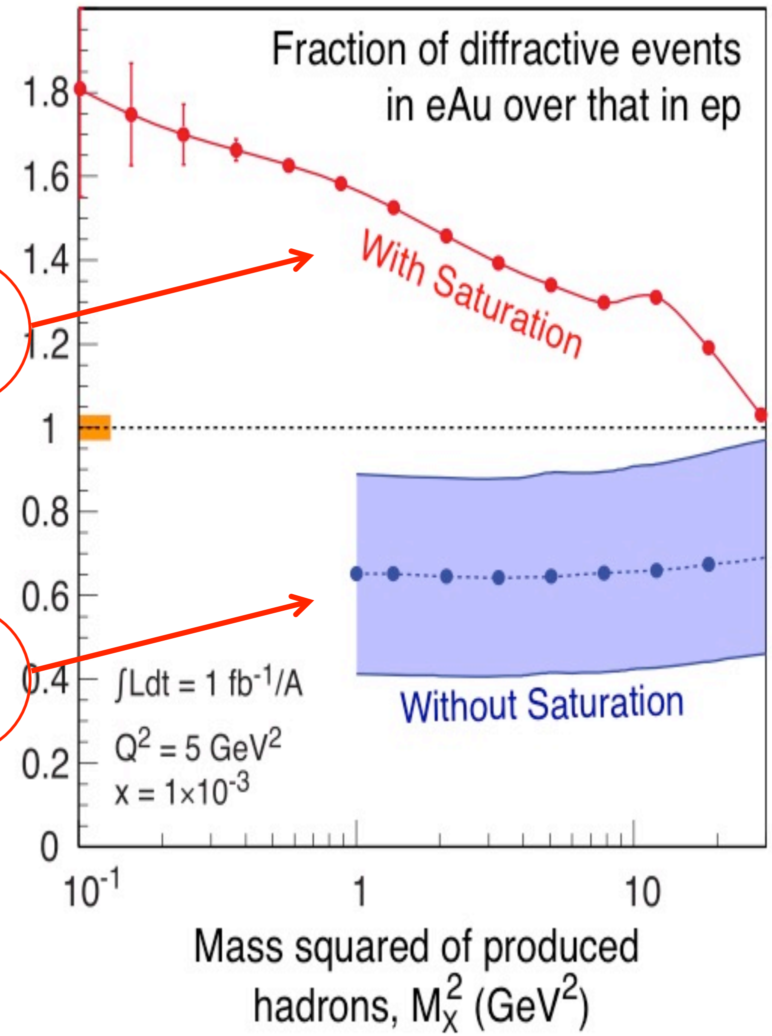
$$\sim\frac{25-30\%}{10-15\%}>1$$

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

– off a single hard, local interaction

$$\frac{1}{\sigma_{\text{tot}}^{eA}}\frac{d\sigma_{diff}^{eA}}{dM_x^2}\Big/\frac{1}{\sigma_{\text{tot}}^{ep}}\frac{d\sigma_{diff}^{ep}}{dM_x^2}$$

$$\sim\left[\frac{g^p(x)}{g^A(x)}\right]_{\text{tot}}\left[\frac{g^A(x)}{g^p(x)}\right]^2_{\text{diff}}<1$$



At HERA

ep: 10-15% diffractive

At EIC eA, if Saturation/CGC

eA: 25-30% diffractive

Early work – E665 @ FNAL:

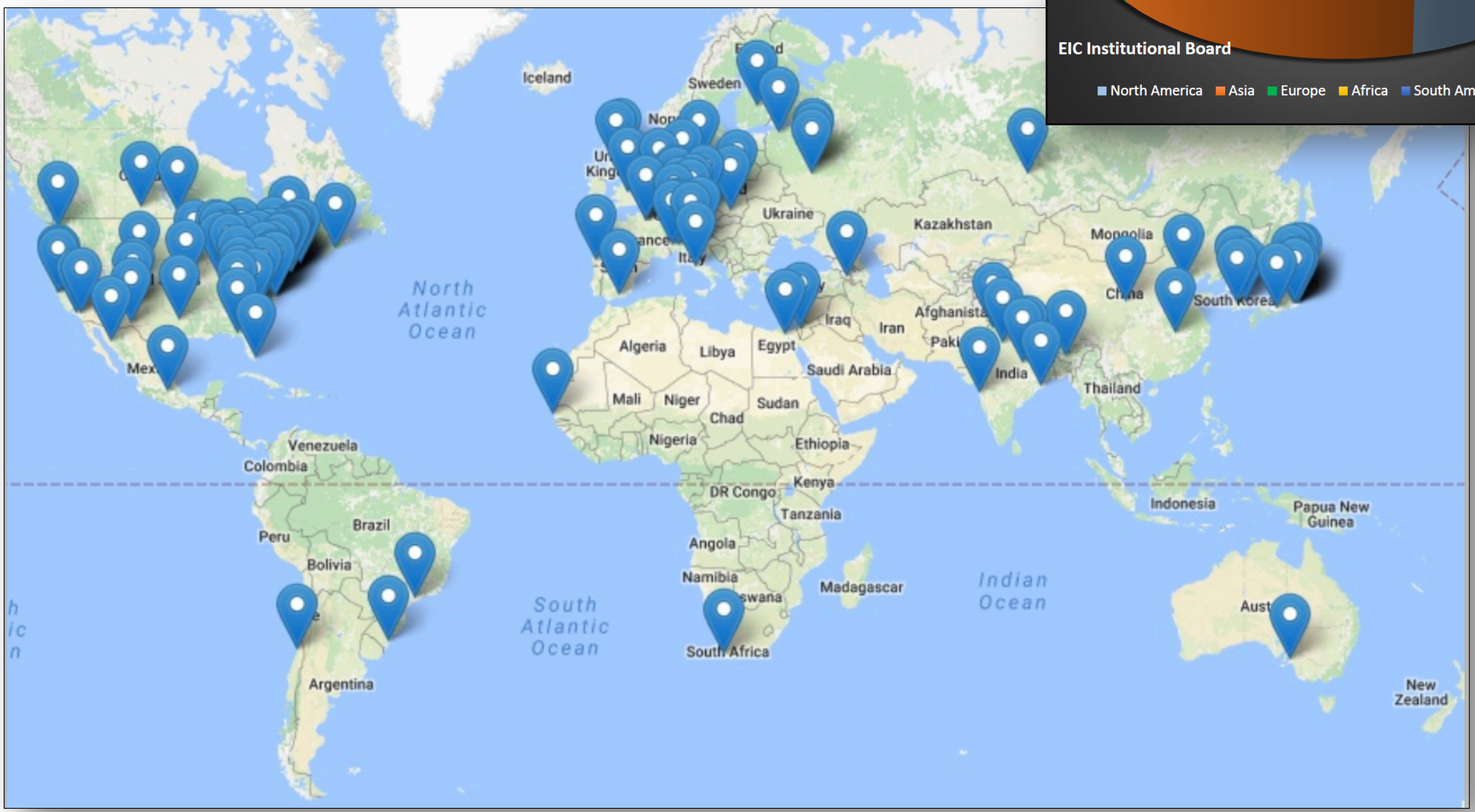
Nuclear shadowing, diffractive scattering and low momentum protons in μ Xe interactions at 490 GeV Z. Phys. C 65, 225–244 (1995)

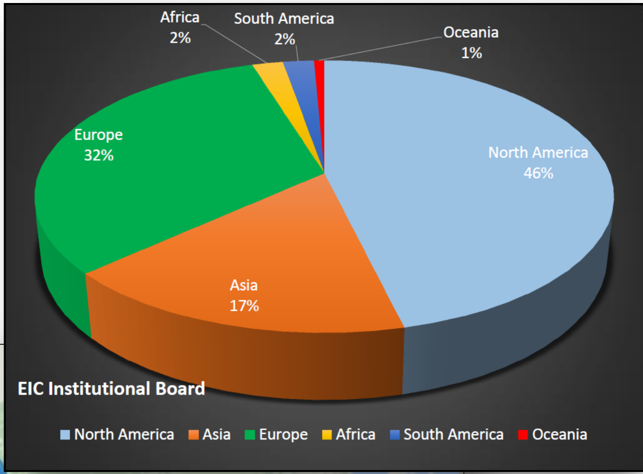
EIC – An International Effort

- **EIC Users Group – *EICUG.ORG*:**

  715 collaborators, 29 countries, (no students included as of yet)
  169 institutions… (September, 2017)

  Map of institution's locations





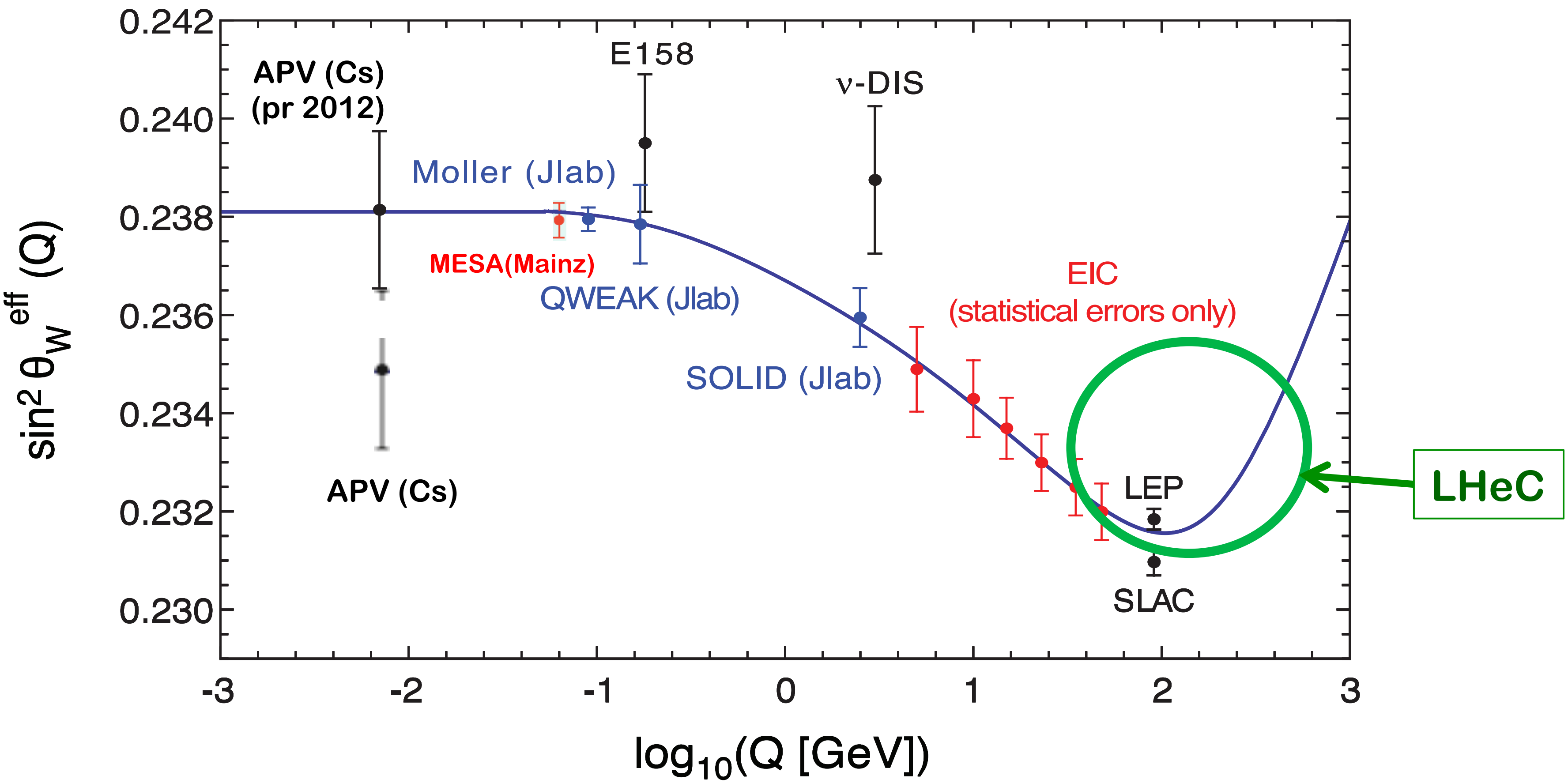
Summary and outlook

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

Electroweak physics at EIC

❑ Running of weak interaction – high luminosity:



✧ Fills in the region that has never been measured

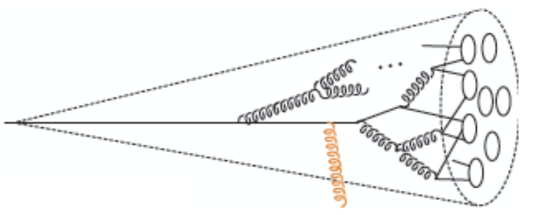
✧ *have a real impact on testing the running of weak interaction*

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?

Jet substructure



Boosted hadronization

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

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

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