Exploring the fundamental properties of matter with an Electron-Ion Collider

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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, …

Eternal Questions

People have long asked

Where did we come from?

The Big Bang theory?

What is the world made of?

Basic building blocks?

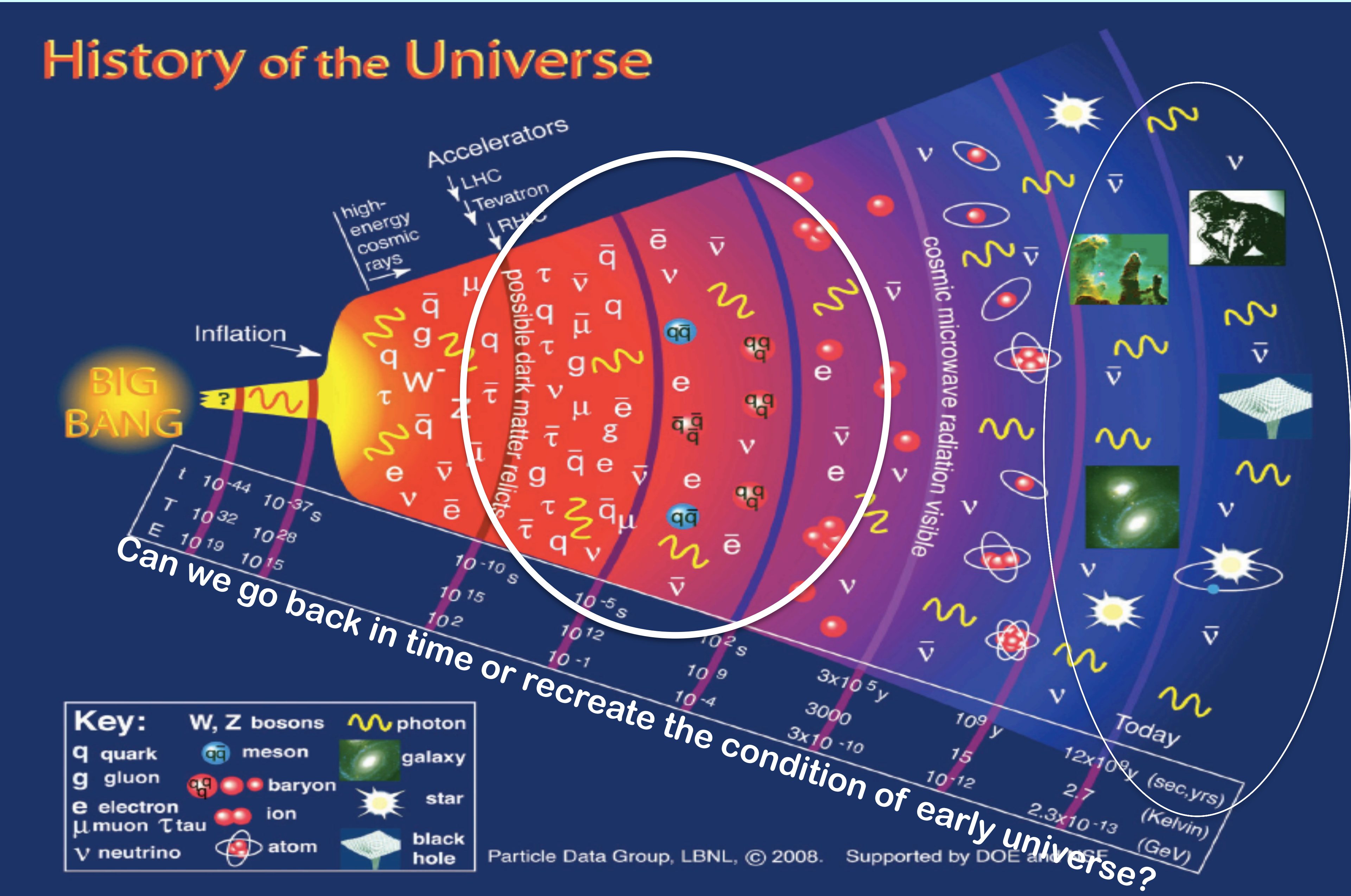
What holds it together?

Fundamental forces?

Where are we going to?

The future?

Where did we come from?



Going back in time?

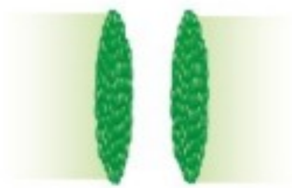
Expansion of the universe

Little Bang in the Laboratory

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

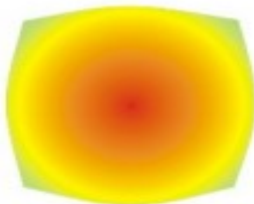
Relativistic heavy-ion collisions – the little bang

- A Virtual Journey of Visible Matter:

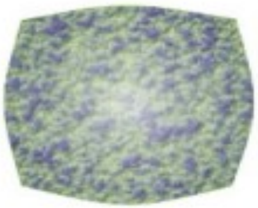


Lorentz contraction

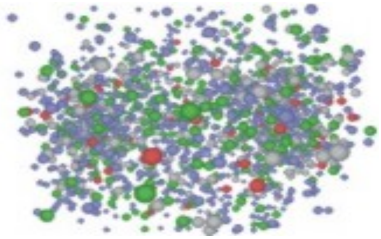
Near collision



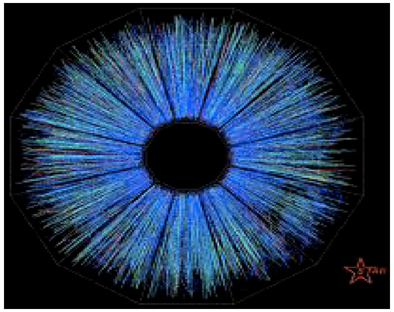
Quark-gluon plasma



Hadronization



Freeze-out



Seen in the detector

Visible!

"Seeing" the unseen

Visible!

Relativistic heavy-ion collisions – the little bang

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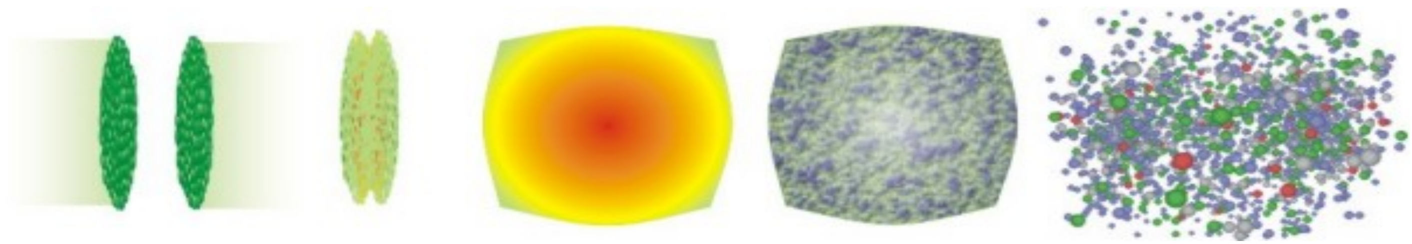
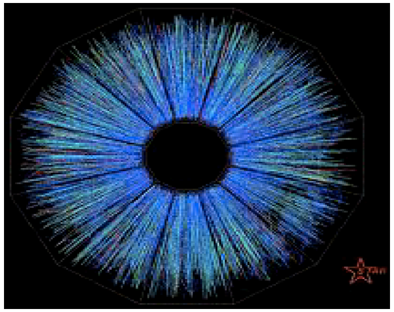
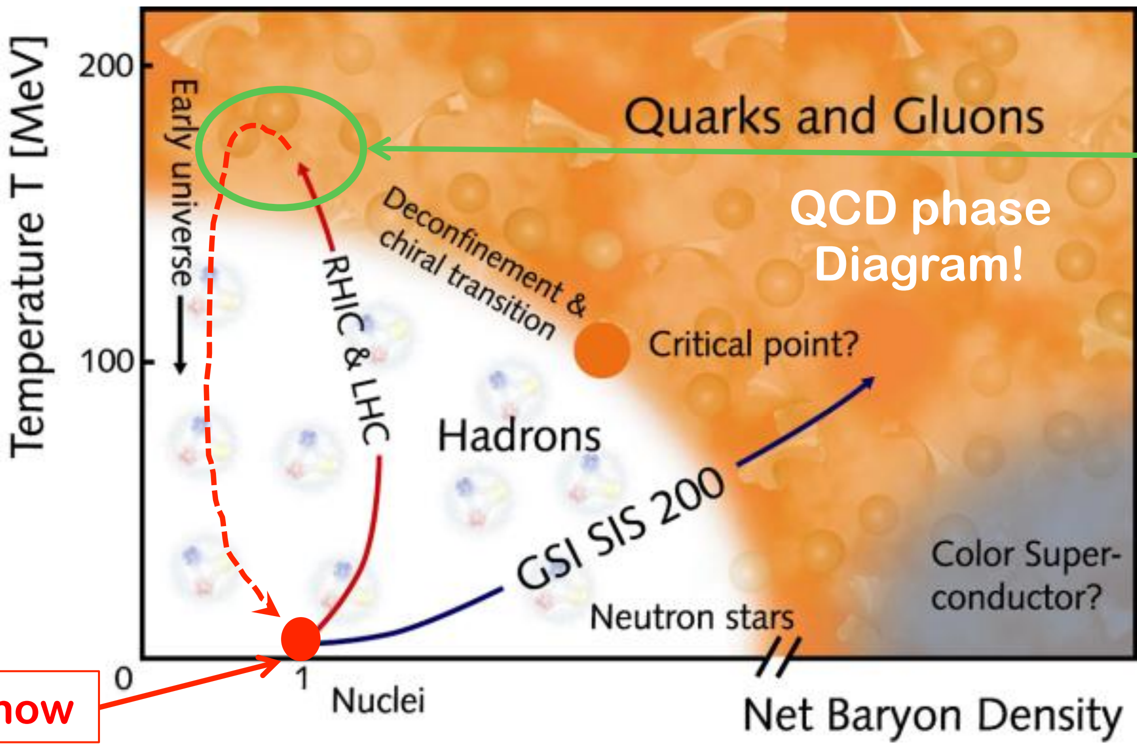




Lorentz contraction | Near collision | Quark-gluon plasma | Hadronization | Freeze-out | Seen in the detector

Visible!

Visible!

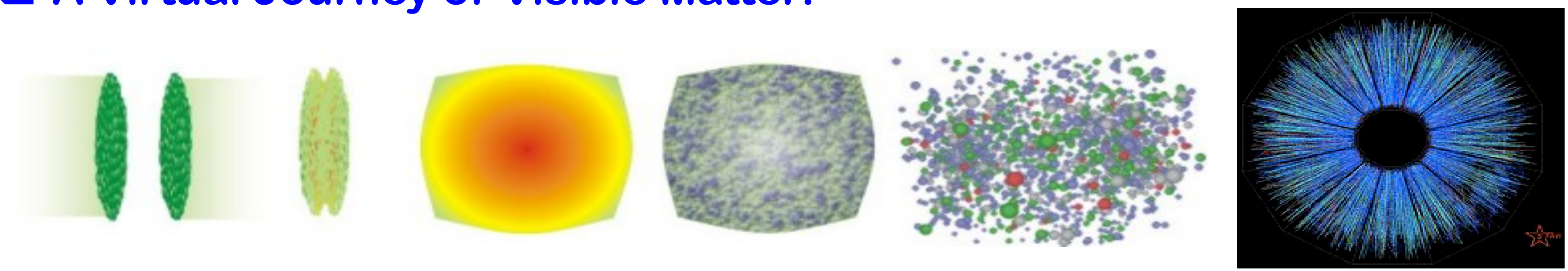


Discovery:
A nearly perfect quantum fluid (NOT a gas!) at 4 trillion degrees Celsius,
Not, at 10^{-5} K like ^{6}Li

Where we are now

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!

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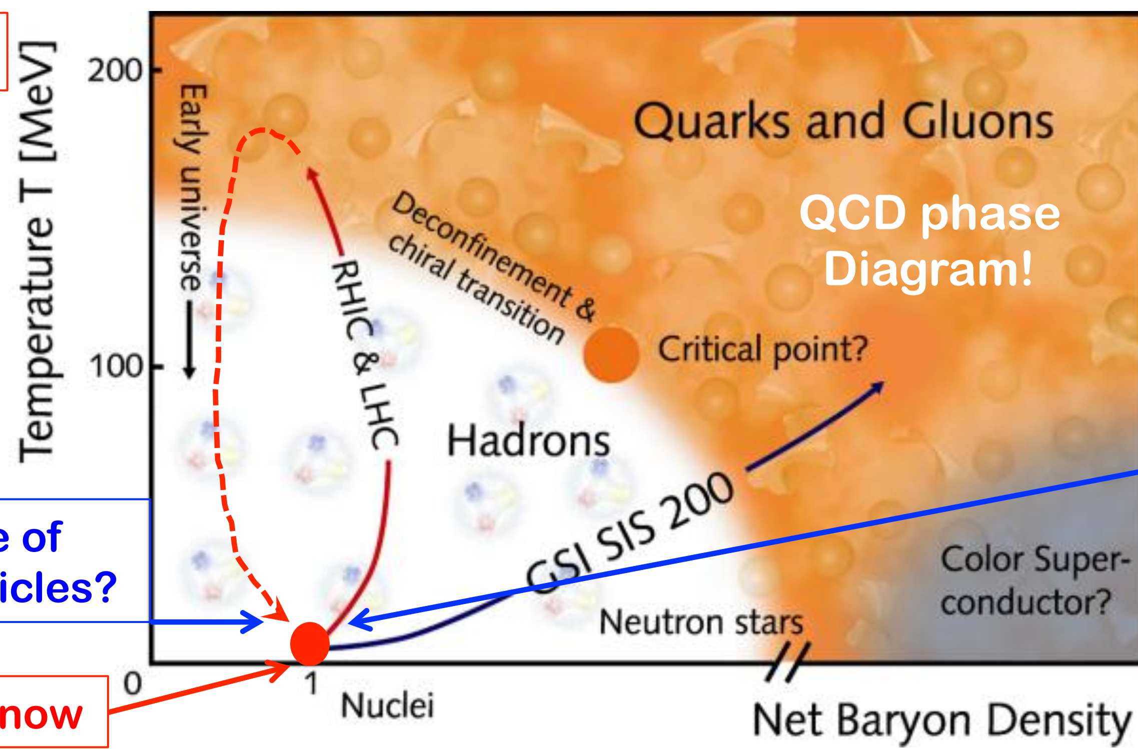
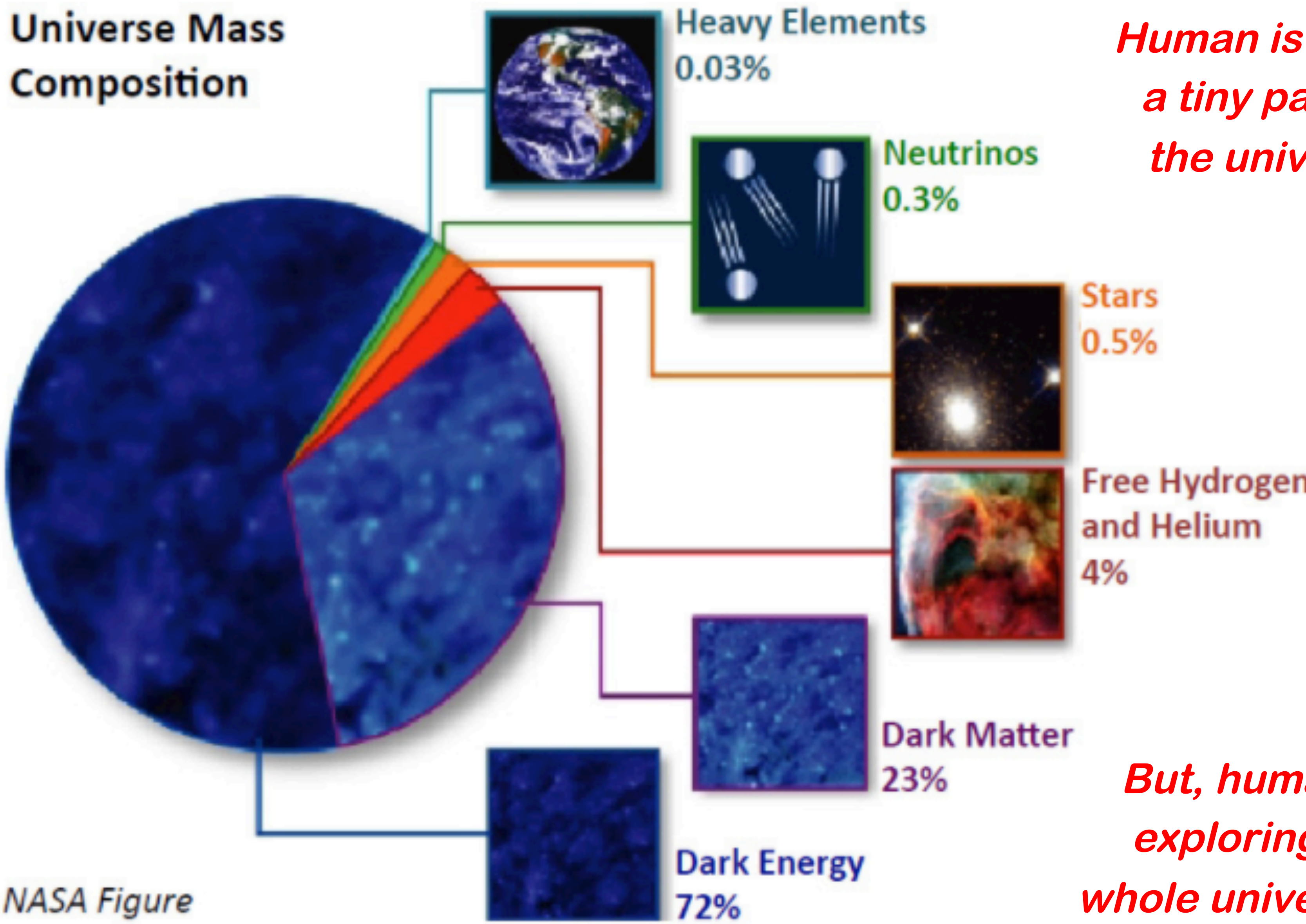


Emergence of hadronic particles?

Structure of hadrons? = initial conditions of RHIC?

Where we are now

What the world is made of?

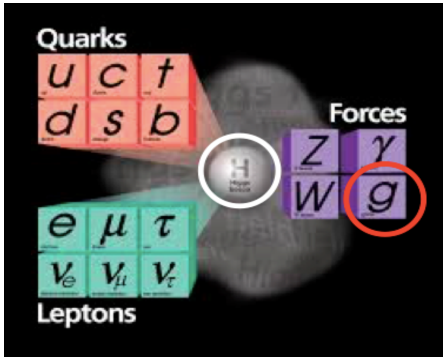


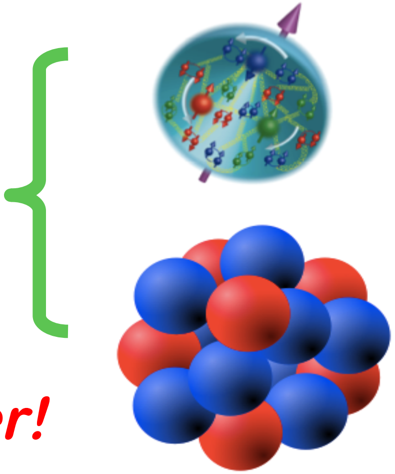
Human is only a tiny part of the universe

But, human is exploring the whole universe!

What hold it together?

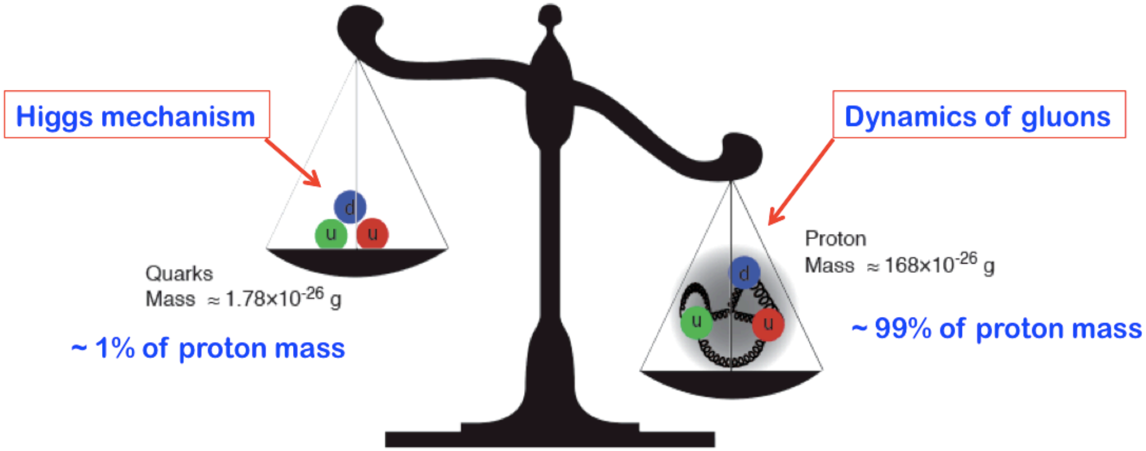
- ❑ Understanding the glue that binds us all:



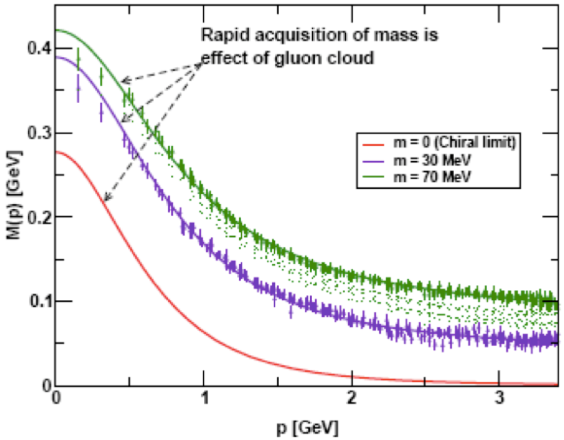


– the Next QCD Frontier!

- ❑ Gluons are weird particles!
  - ✧ Massless, yet, responsible for nearly all visible mass



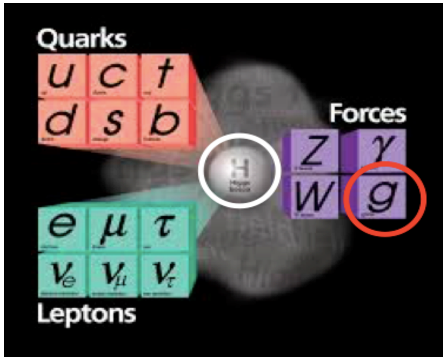
"Mass without mass!"

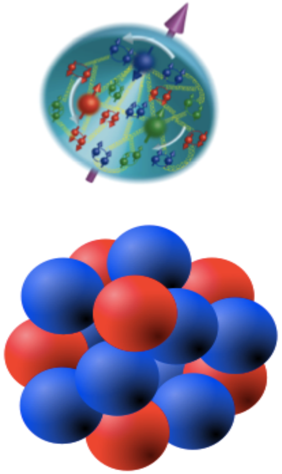


Bhagwat & Tandy/Roberts et al

What hold it together?

- **Understanding the glue that binds us all:**

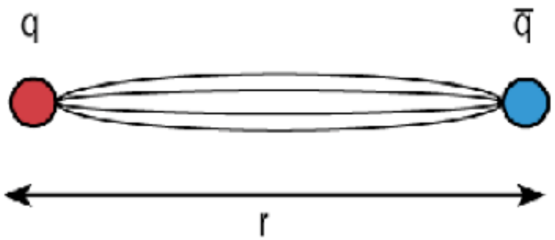




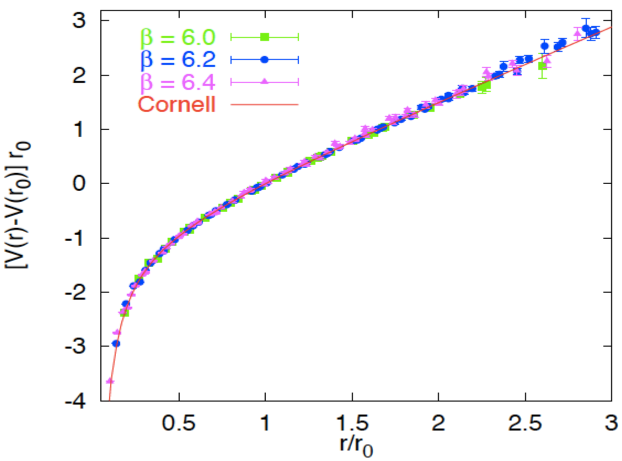
– the Next QCD Frontier!

- **Gluons are weird particles!**
  - ✧ **Massless, yet, responsible for nearly all visible mass**
  - ✧ **Carry color charge, responsible for color confinement and strong force**

Force between a heavy quark pair

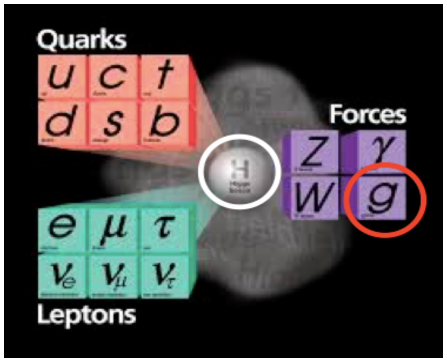


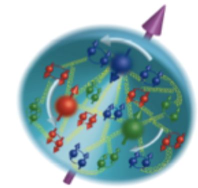
Heavy quarks experience a force of ~16 tons at ~1 Fermi (10^{-15} m) distance

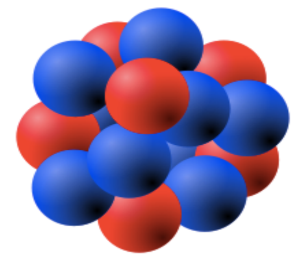


What hold it together?

- Understanding the glue that binds us all:







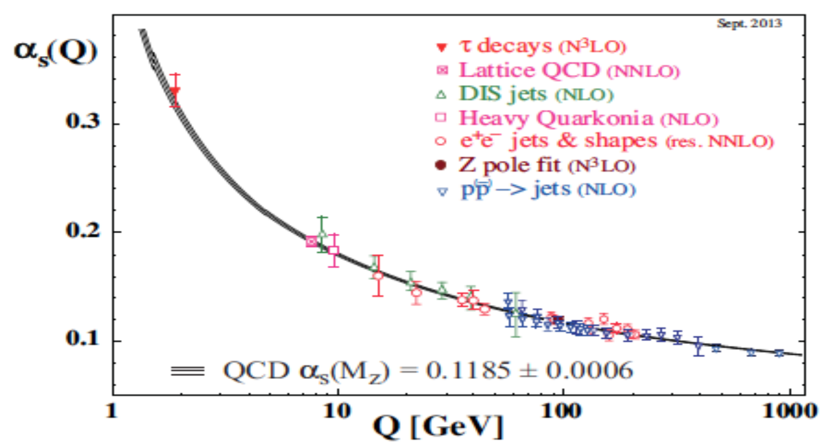
– the Next QCD Frontier!

- Gluons are weird particles!
  - ✧ Massless, yet, responsible for nearly all visible mass
  - ✧ Carry color charge, responsible for color confinement and strong force

    but, also for asymptotic freedom

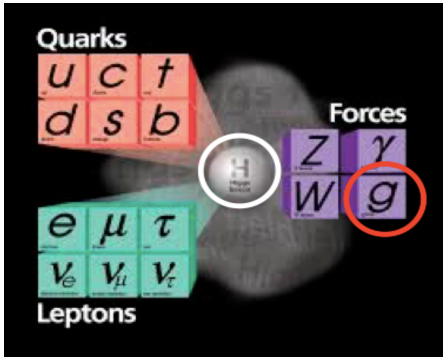
Nobel Prize, 2004

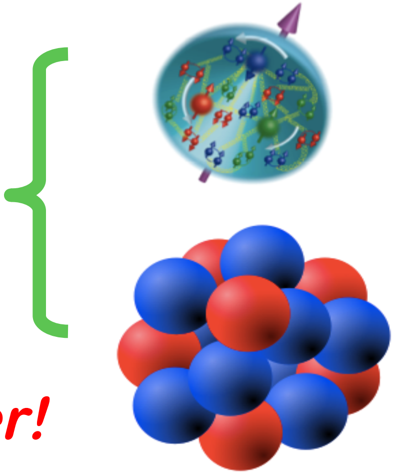
→ QCD perturbation theory



What hold it together?

❑ Understanding the glue that binds us all:





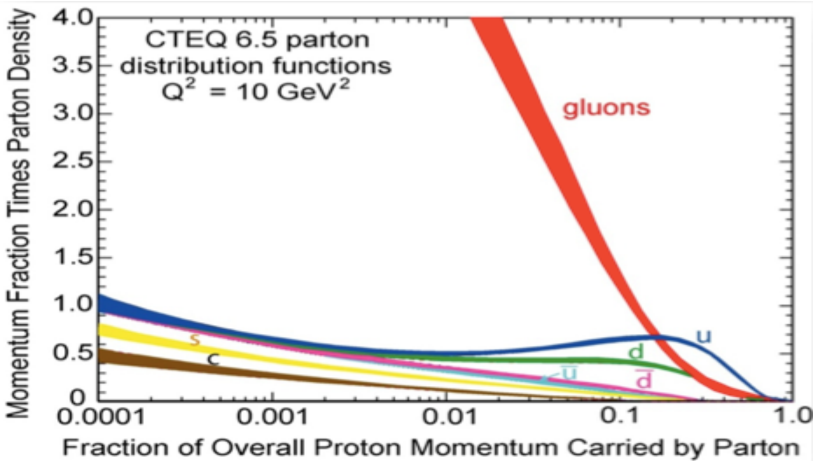
– the Next QCD Frontier!

❑ Gluons are weird particles!

- ✧ Massless, yet, responsible for nearly all visible mass
- ✧ Carry color charge, responsible for color confinement and strong force

  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***

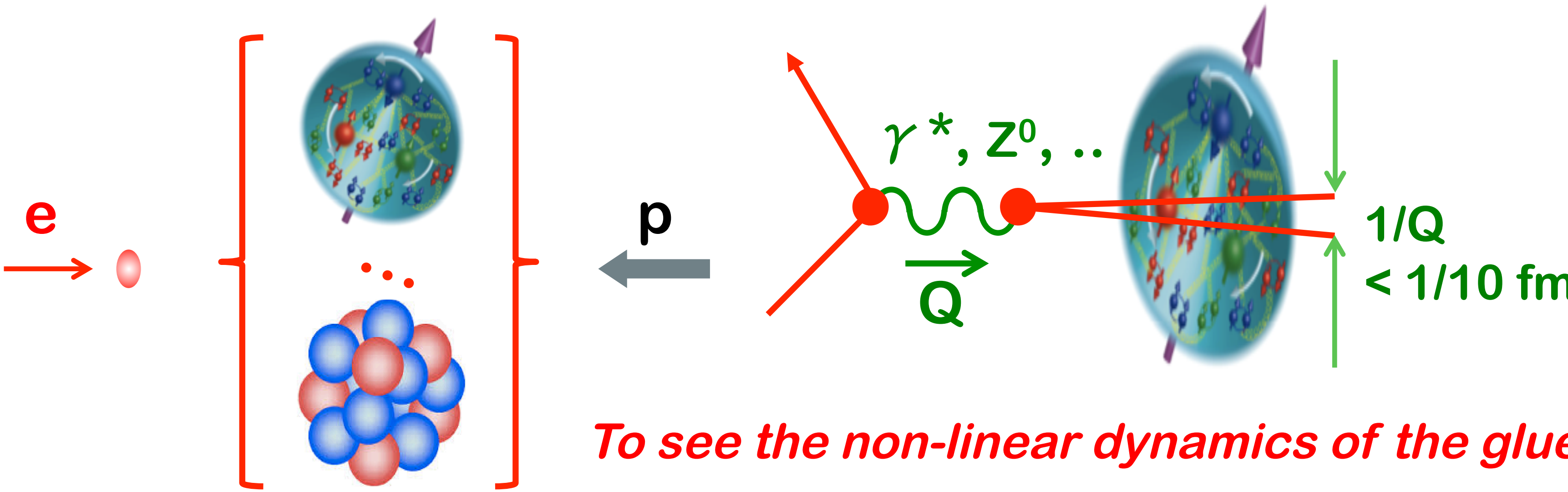
  Quarks – ***Need an EM probe to "see" their existence, …***

  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)

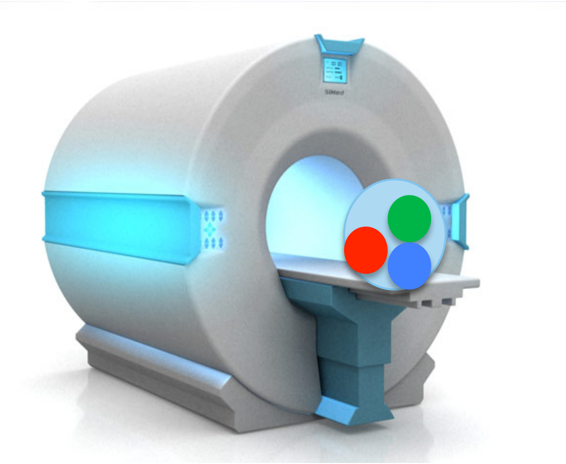
- A giant "Microscope" – "see" quarks and gluons by breaking the hadron



To see the non-linear dynamics of the glue!

- A sharpest "CT" – "imagine" quark/gluon without breaking the hadron
  - "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!



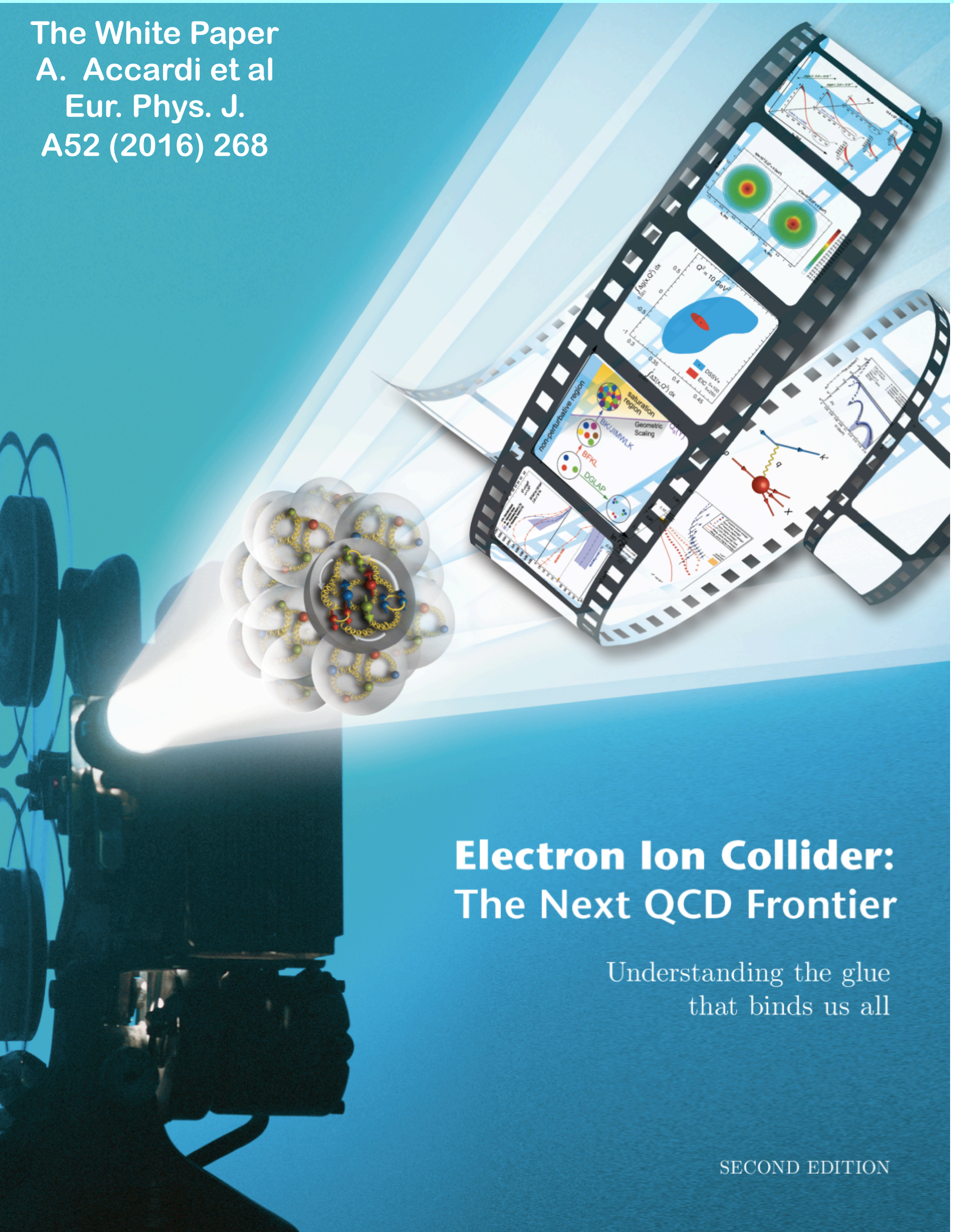
EIC: the World Wide Interest

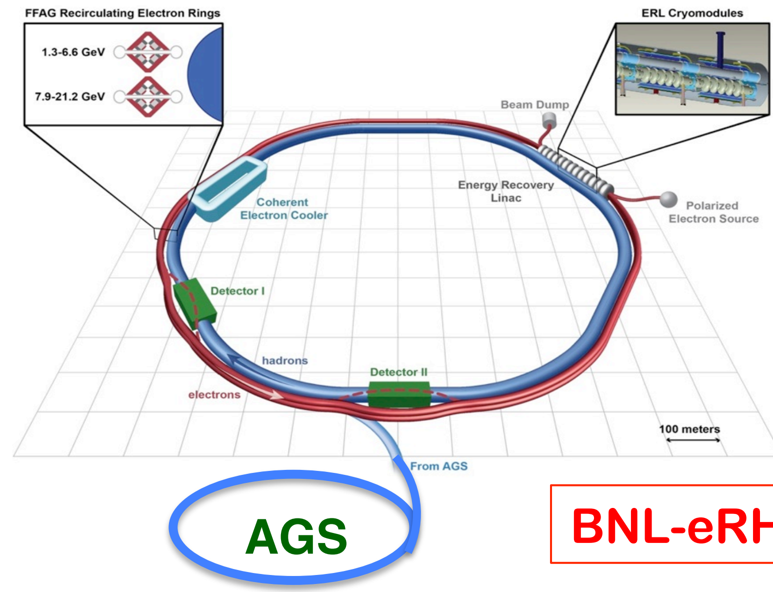
	HERA@DESY	LHeC@CERN	eRHIC@BNL	JLEIC@JLab	HIAF@CAS	ENC@GSI
E_{CM} (GeV)	320	800-1300	45-175	12-140	12 → 65	14
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-5}	5×10^{-5}	$7 \times 10^{-3} \rightarrow 3 \times 10^{-4}$	5×10^{-3}
ion	p	p to Pb	p to U	p to Pb	p to U	p to ~ ^{40}Ca
polarization	-	-	p, ^{3}He	p,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

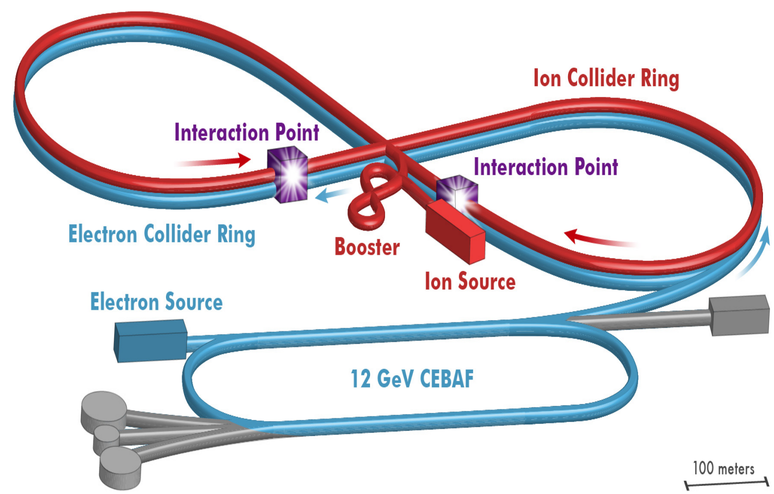
Possible future

US EIC – two options of realization





BNL-eRHIC



JLab-JLEIC

U.S. - based Electron-Ion Collider

❑ NSAC 2007 Long-Range Plan:

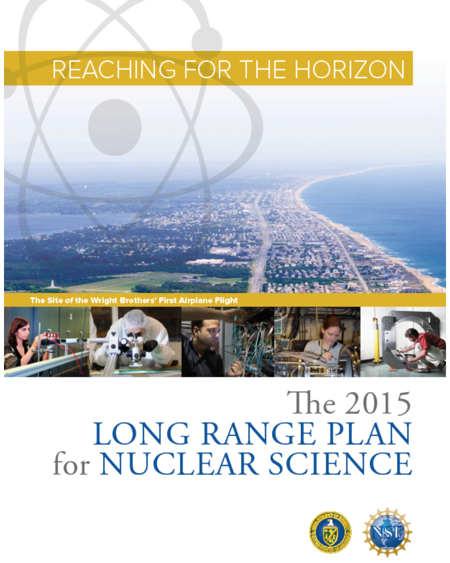
"An Electron-Ion Collider (EIC) with polarized beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**."

❑ 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**."

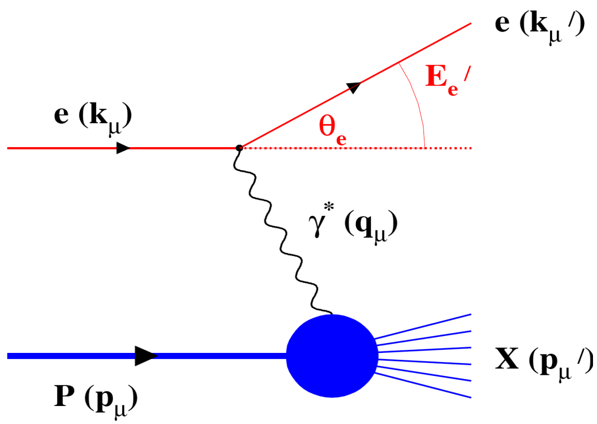


❑ Under review of National Academy of Science:

Last committee meeting: April 19-21
Expect to have the committee report late this year!

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

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

Inclusive events: e+p/A → e'+X

Detect only the scattered lepton in the detector

(Modern Rutherford experiment!)

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

Detect the scattered lepton in coincidence with identified hadrons/jets

(Initial hadron is broken – confined motion!)

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!)

US EIC

“Big” questions/puzzles about QCD, …

The key deliverables & opportunities

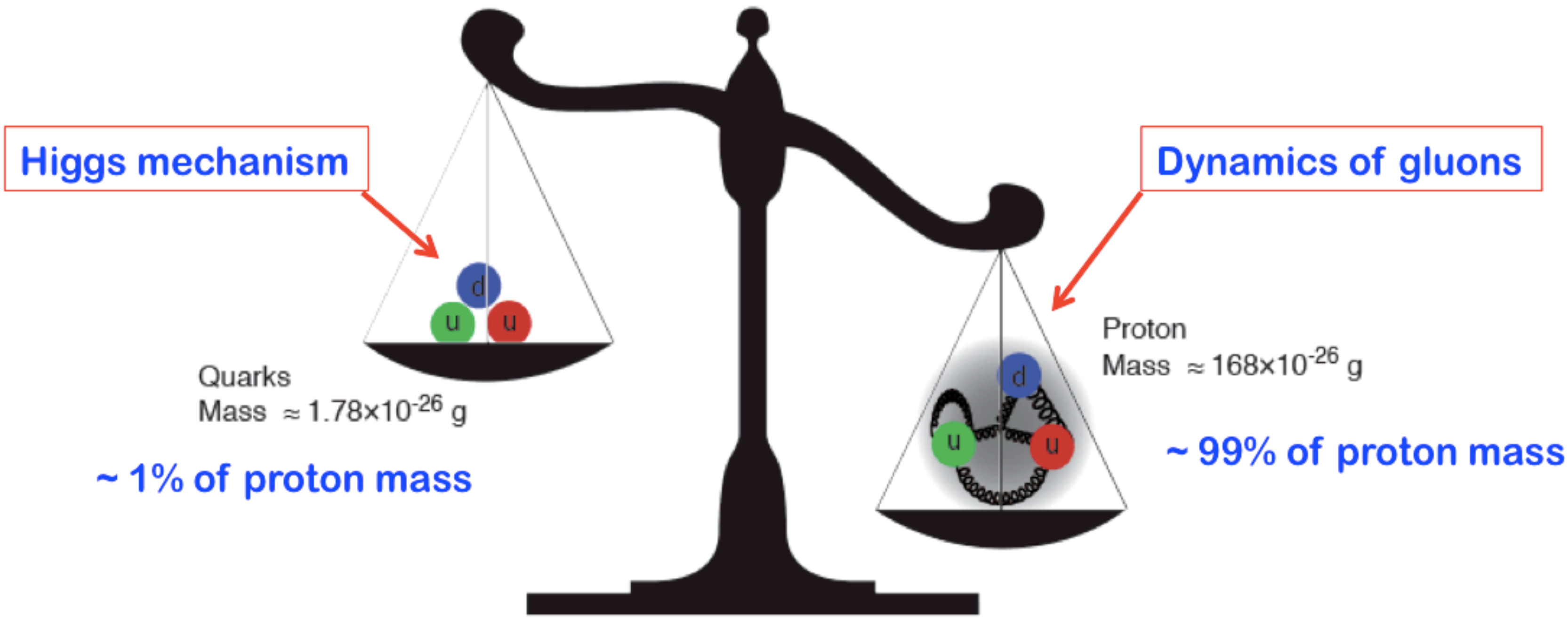
Why existing facilities, even with upgrades, cannot do the same?

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?**

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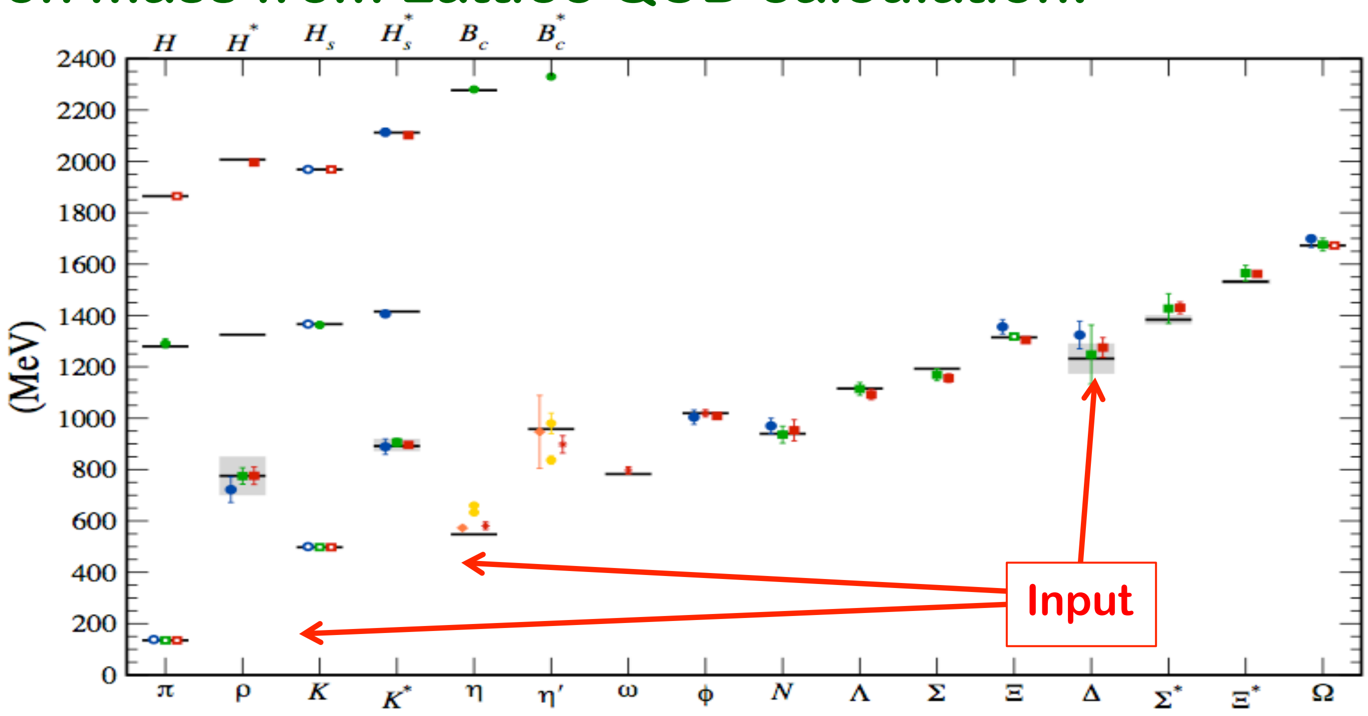
- ❑ **Hadron mass from Lattice QCD calculation:**

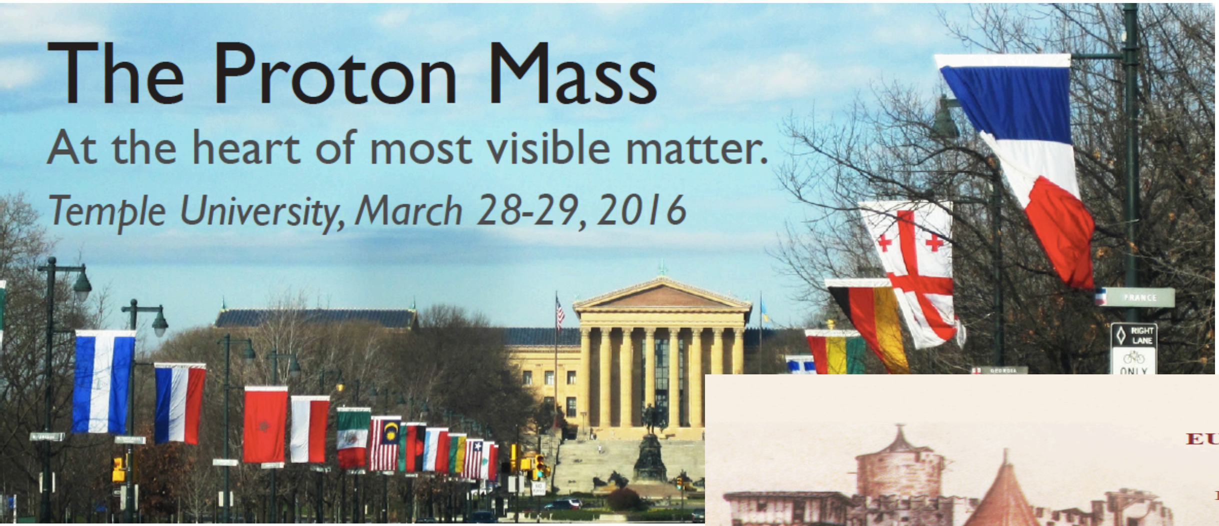


How does QCD generate this? The role of quarks vs that of gluons?

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

How to answer the “big” questions?

- 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

How to answer the "big" questions?

❑ How does QCD generate the nucleon mass?

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❑ Role of quarks and gluons?

✧ QCD energy-momentum tensor:

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

✧ Trace of the QCD energy-momentum tensor:

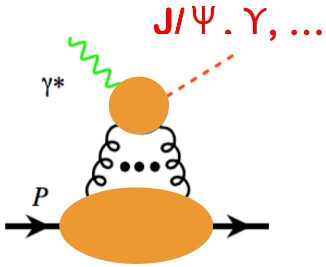
$$T^{\alpha}_{\ \alpha} = \underbrace{\frac{\beta(g)}{2g} F^{\mu\nu,a} F^{a}_{\mu\nu}}_{\text{QCD trace anomaly}} + \sum_{q=u,d,s} m_q (1+\gamma_m)\overline{\psi}_q \psi_q$$

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

✧ 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

How to answer the "big" questions?

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- **Role of quarks and gluons?**

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

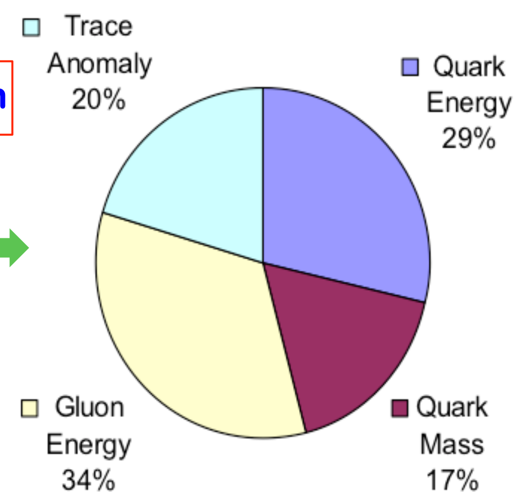
$$m = \frac{\langle p| \int d^3x\, T^{00}\, |p\rangle}{\langle p|p\rangle} \sim \mathrm{GeV}$$

when proton is at rest!

Relativistic motion | χ Symmetry Breaking | Quantum fluctuation

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

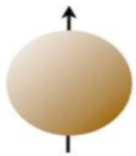
Quark Energy | Gluon Energy | Quark Mass | Trace Anomaly



Decomposition is not unique!

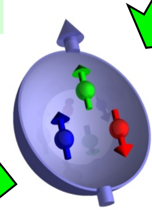
The proton spin?

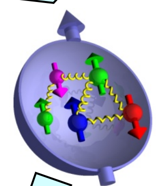
❑ **How does QCD generate the nucleon's spin?**

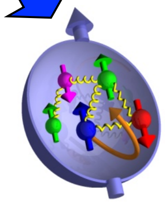


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g) = \sum \langle P, S | \hat{J}^z_f(\mu) | P, S \rangle$$

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

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

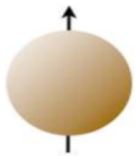
$$\sim 20\% (\text{with RHIC data})$$

Orbital Angular Momentum of quarks and gluons
Little known

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

How to answer the "big" questions?

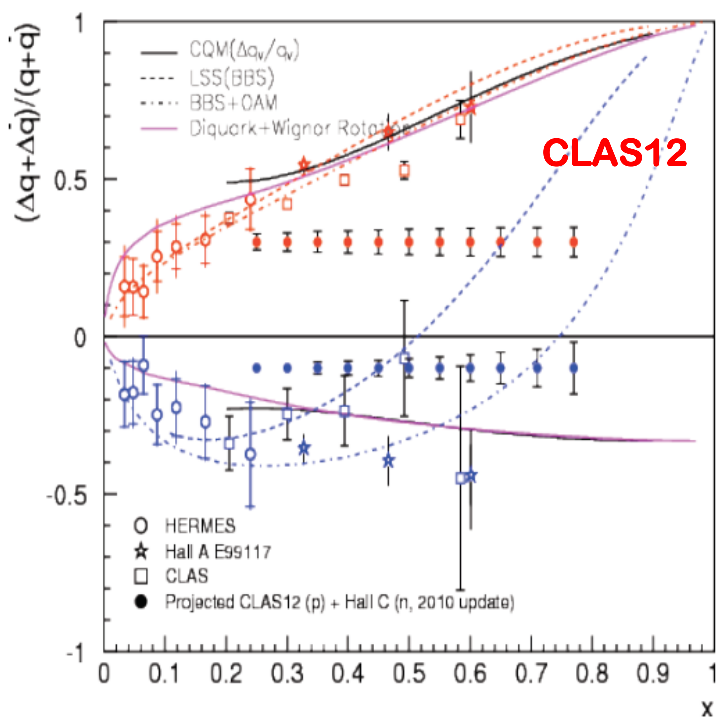
- How does QCD generate the nucleon's spin?

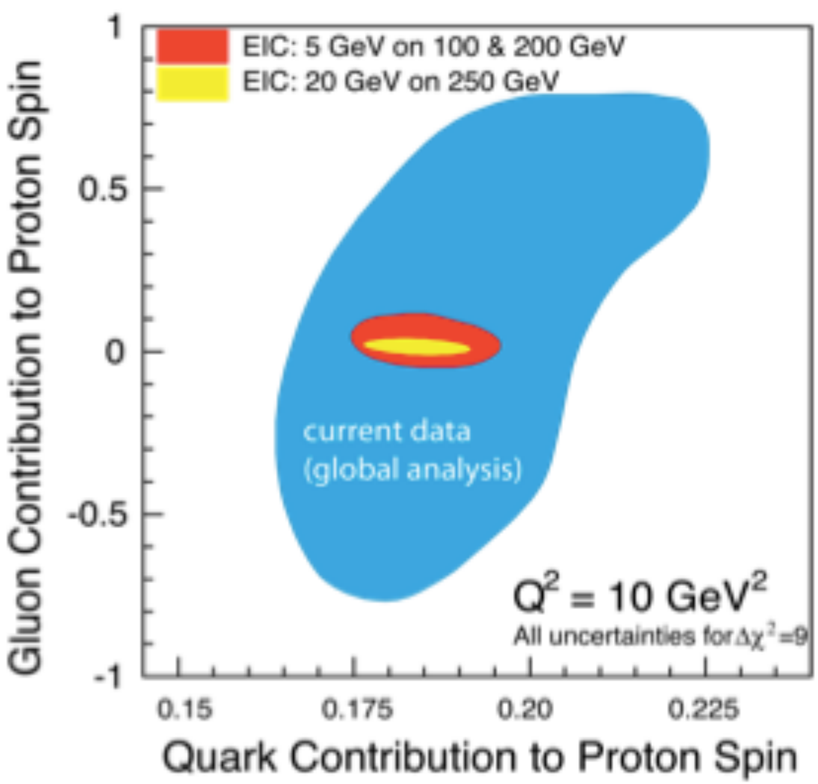


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

Proton Spin

- What can JLab12 and EIC do?

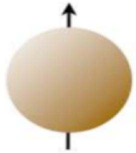




Plus many more JLab12 experiments – flavor

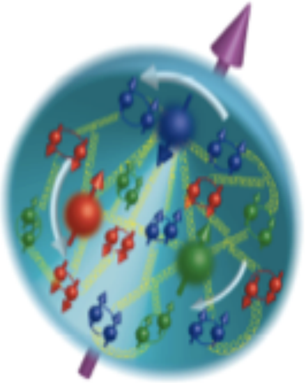
How to answer the "big" questions?

- 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!

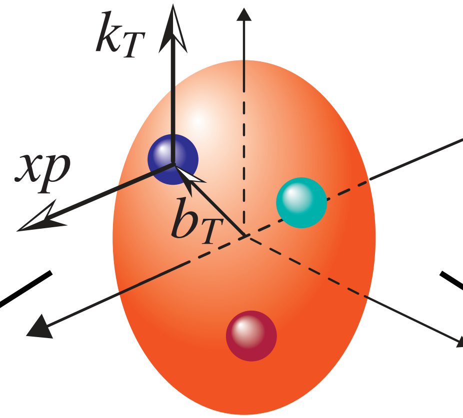
Hard scale – to "see" the particle nature of quarks and gluons
Soft scale – to "be" sensitive to the QCD confinement ~ 1/fm ~ 200 MeV

The 3D confined distribution and motion?

- 3D boosted partonic structure:

Momentum Space | *Coordinate Space*

TMDs | *GPDs*



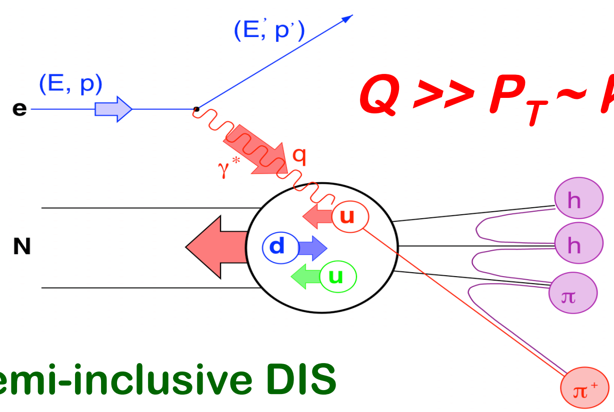
$\int d^2b_T$ $\qquad$ $\int d^2k_T$

Confined motion | Spatial distribution

$f(x,k_T)$ $\qquad$ **Two-scales observables** $\qquad$ $f(x,b_T)$

3D momentum space images

2+1D coordinate space images

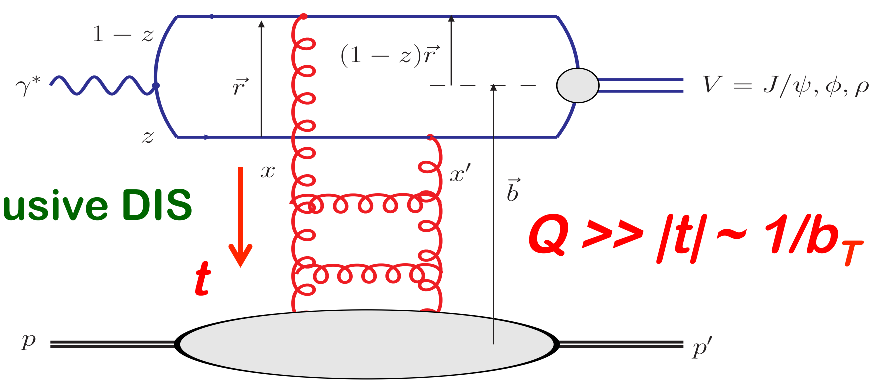


$Q >> P_T \sim k_T$

Semi-inclusive DIS

Exclusive DIS

t



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

JLab12 – valence quarks, EIC – sea quarks and gluons

How to answer the "big" questions?

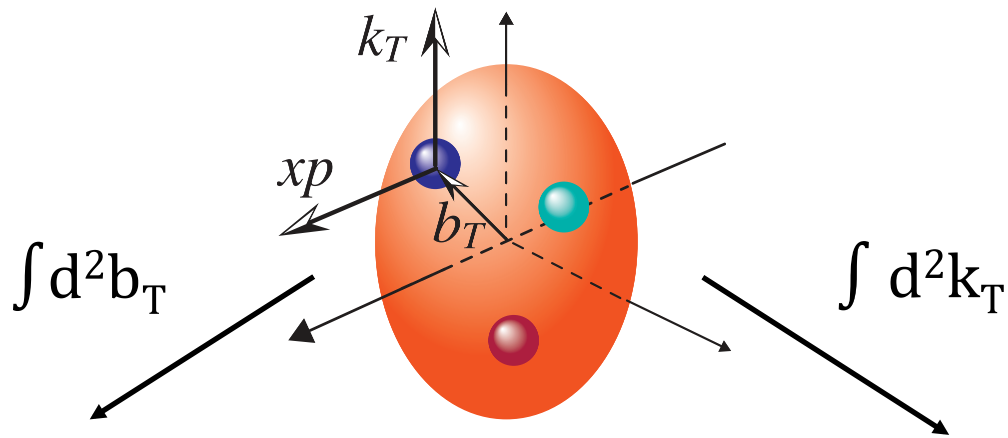
- **3D boosted partonic structure:**

Momentum Space

TMDs

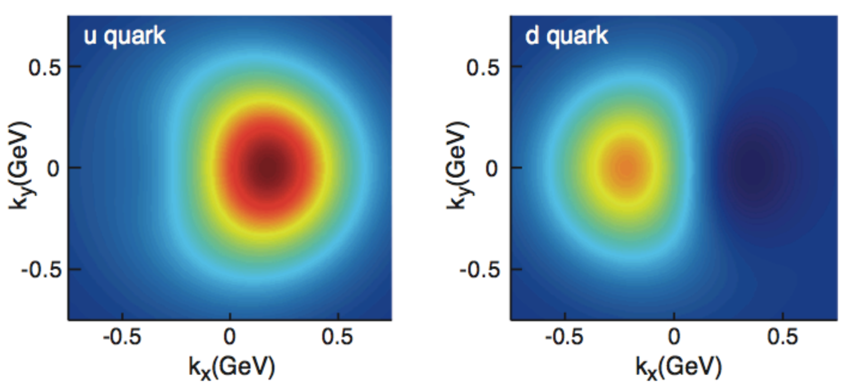
Coordinate Space

GPDs



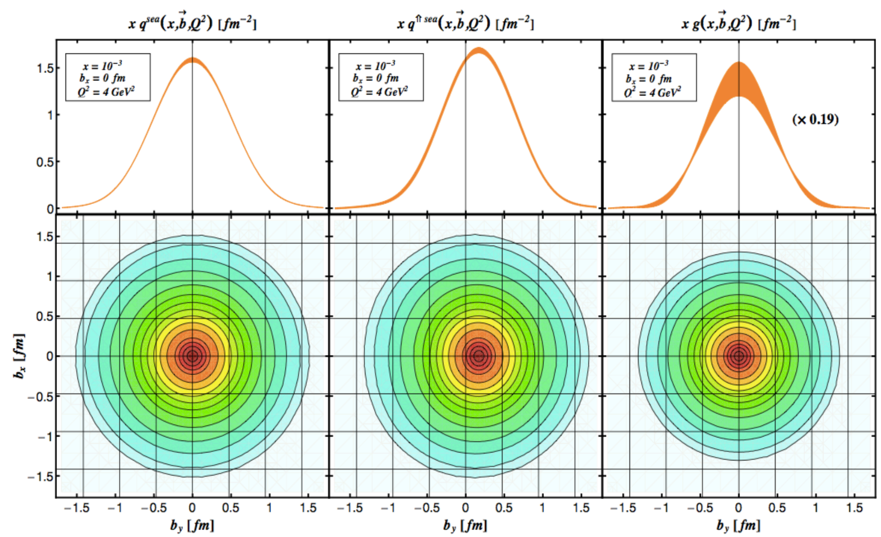
$f(x,k_T)$ EIC white paper: arXiv:1212.1701 $f(x,b_T)$

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"

How to answer the "big" questions?

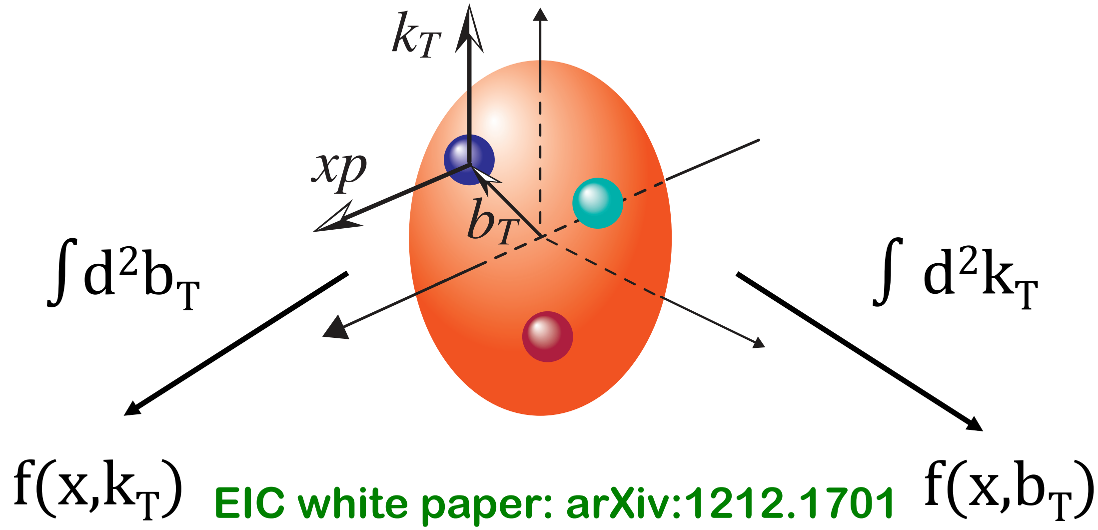
- **3D boosted partonic structure:**

Momentum Space

TMDs

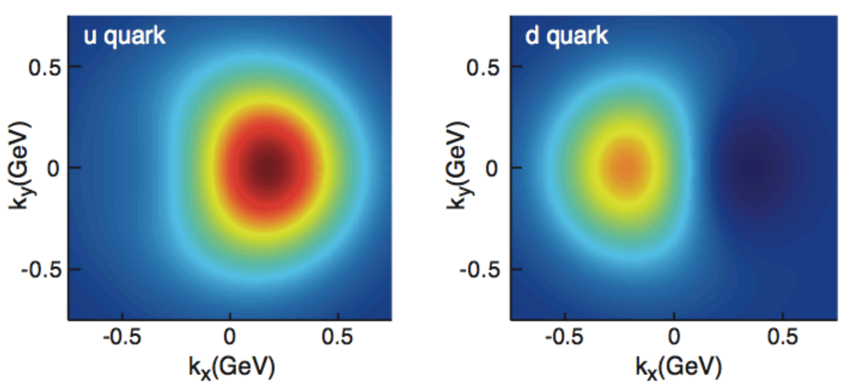
Coordinate Space

GPDs

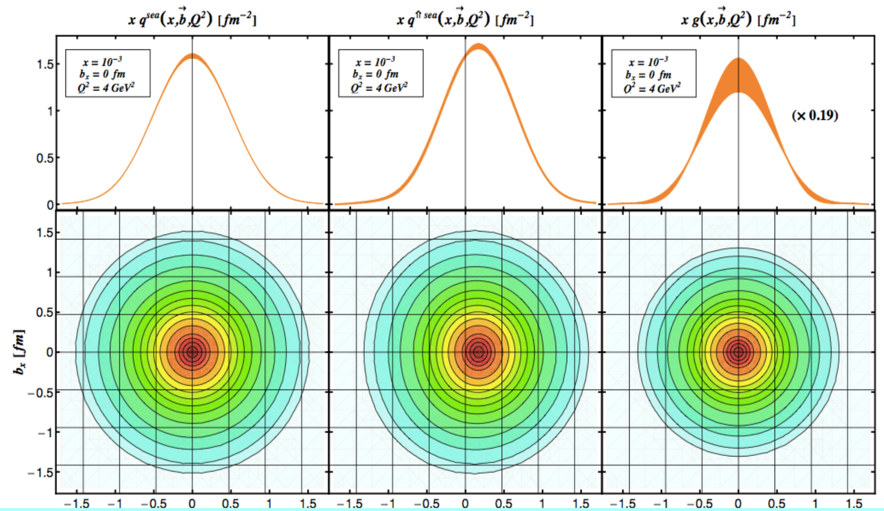


EIC white paper: arXiv:1212.1701

Sivers Function



Imaging



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

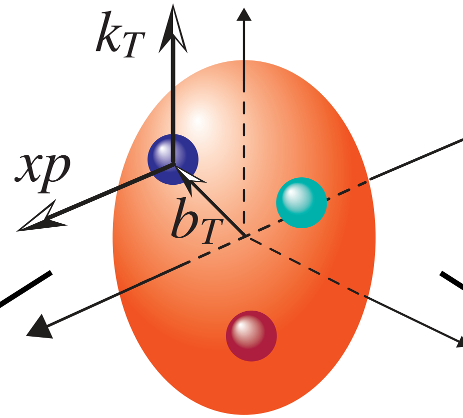
How to answer the "big" questions?

❑ 3D boosted partonic structure:

Momentum Space

TMDs

$\int d^2 b_T$



$\int d^2 k_T$

Coordinate Space

GPDs

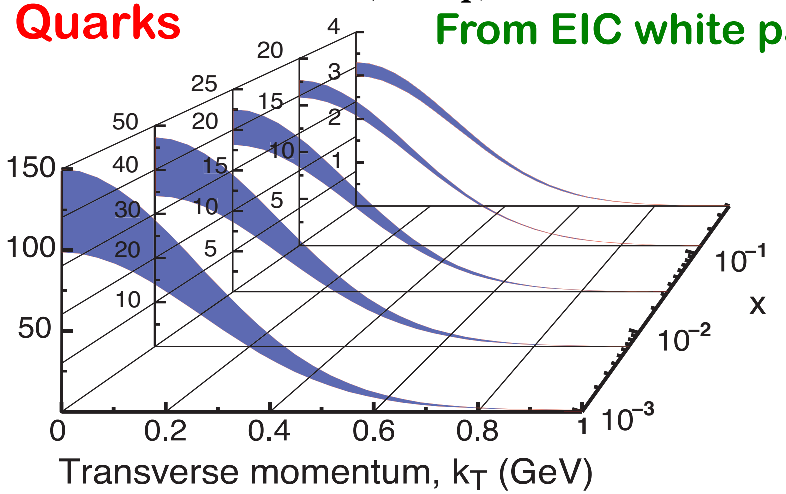
$f(x, k_T)$

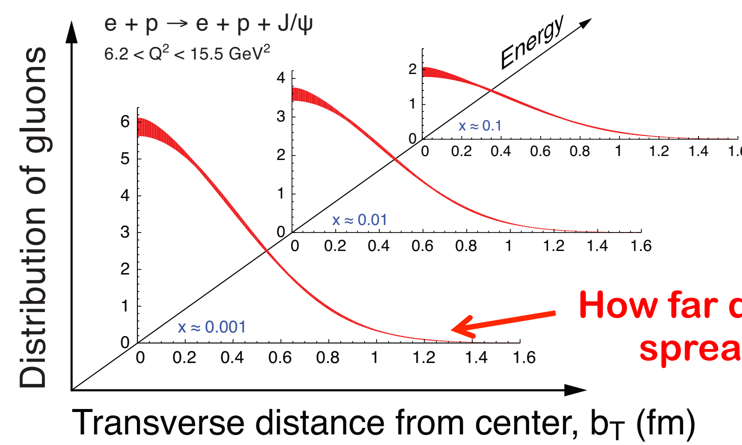
$f(x, b_T)$

Quarks

From EIC white paper: arXiv:1212.1701

Gluons





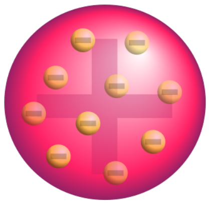
How far does it spread?

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

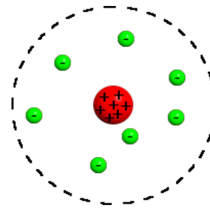
Why 3D nucleon structure?

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

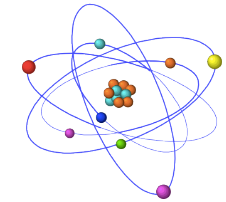
Atom:



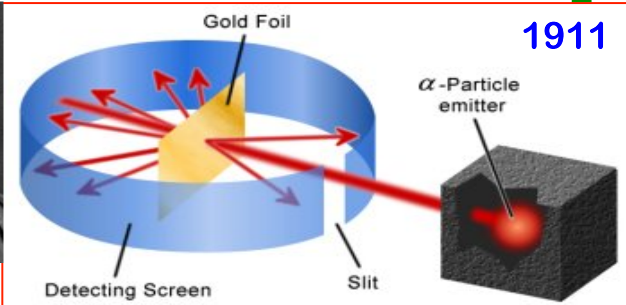
J.J. Thomson's
plum-pudding model



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:

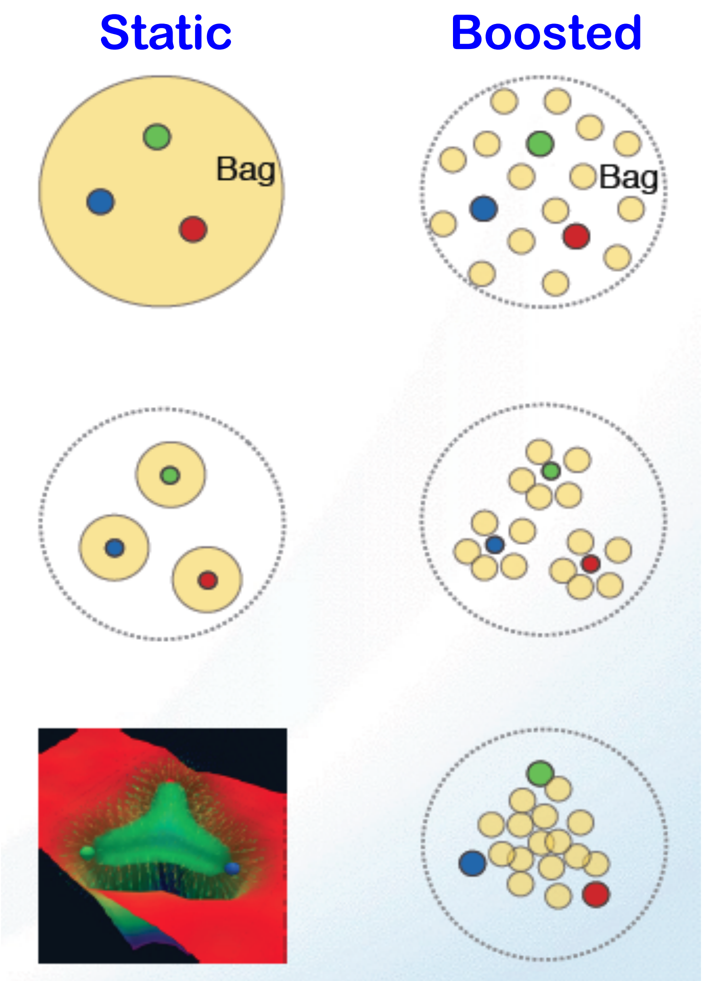
- ✧ Mass by "tiny" nuclei – *less than 1 trillionth in volume of an atom*
- ✧ Motion by quantum probability – *the quantum world!*

❑ 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

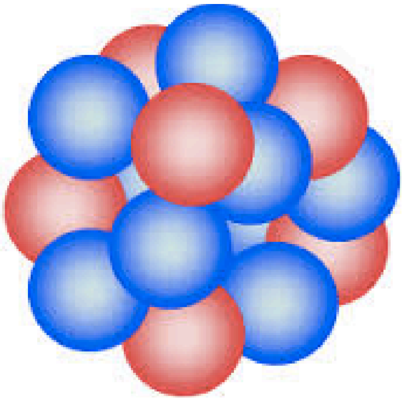
Lattice Gauge theory (with slow moving quarks):
Gluons more concentrated inside the quarks
Gluon radius < Charge Radius

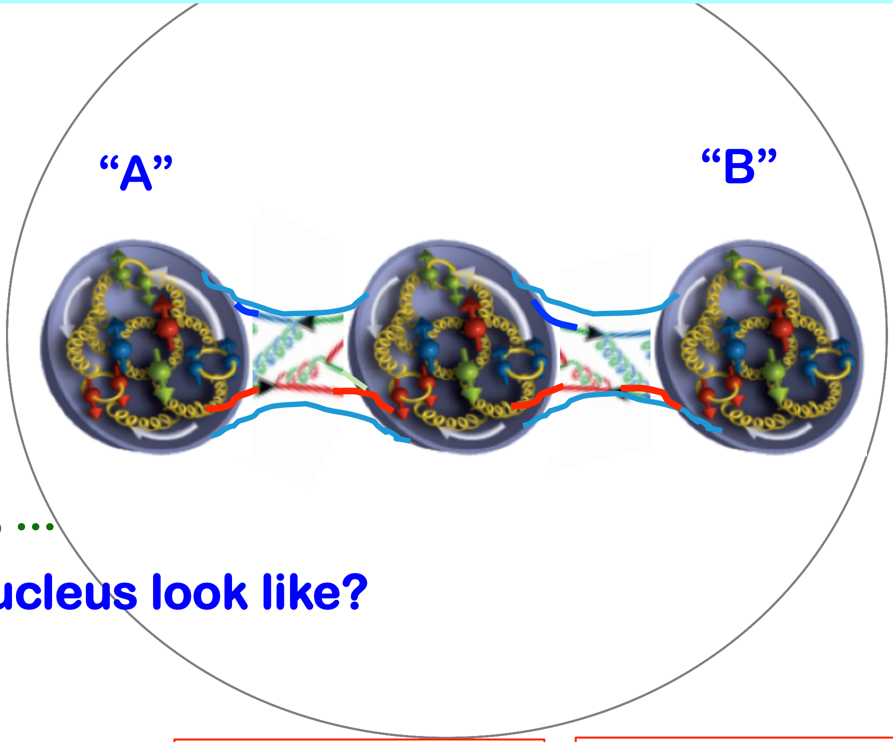
3D Confined Motion (TMDs) + Spatial Distribution (GPDs)

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"?

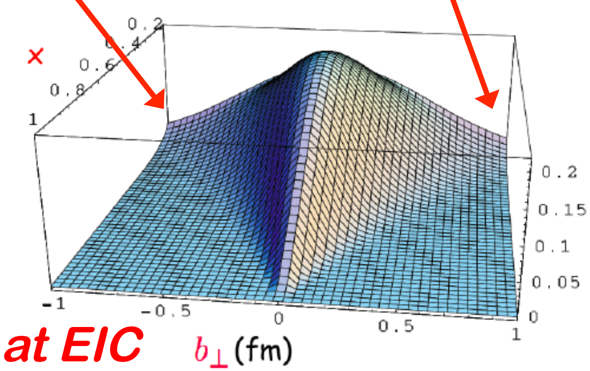
If it does, what is the strength of such correlation?

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



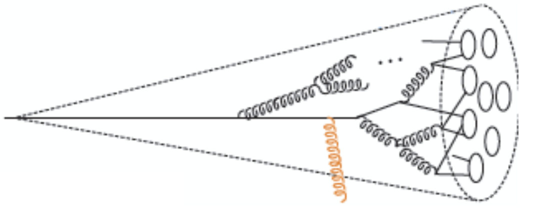
Only possible at EIC

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

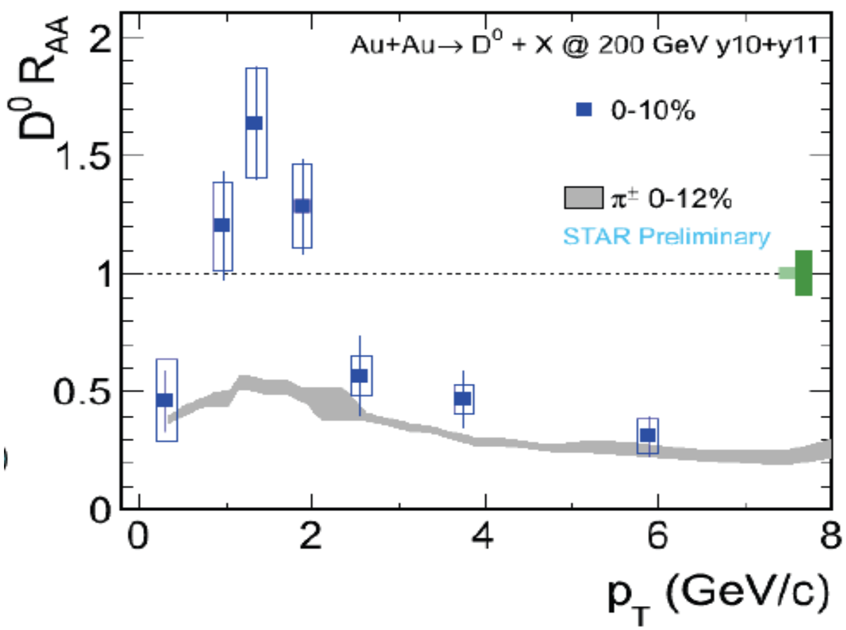


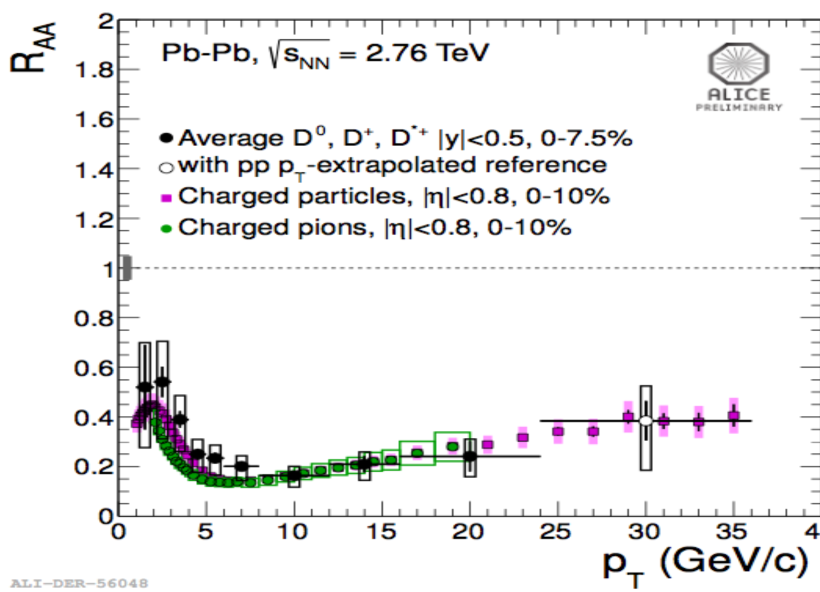
Boosted hadronization

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

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

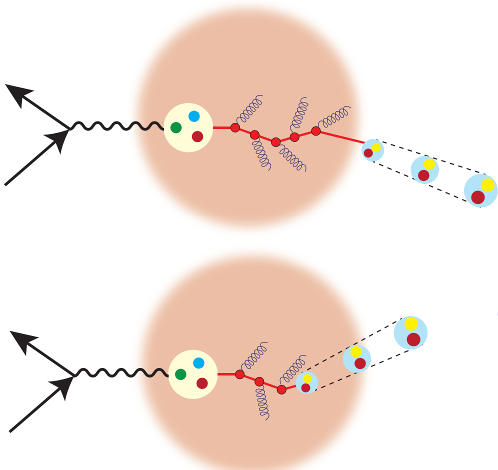
- **Strong suppression of heavy flavors in AA collisions:**





How to answer the “big” questions?

❑ Emergence of a hadron?

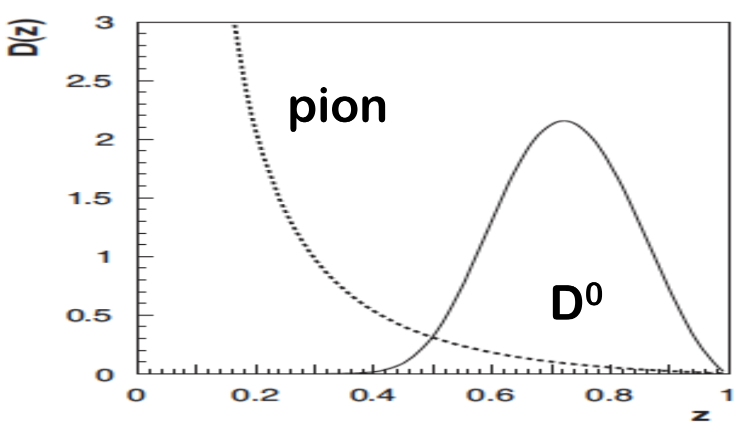


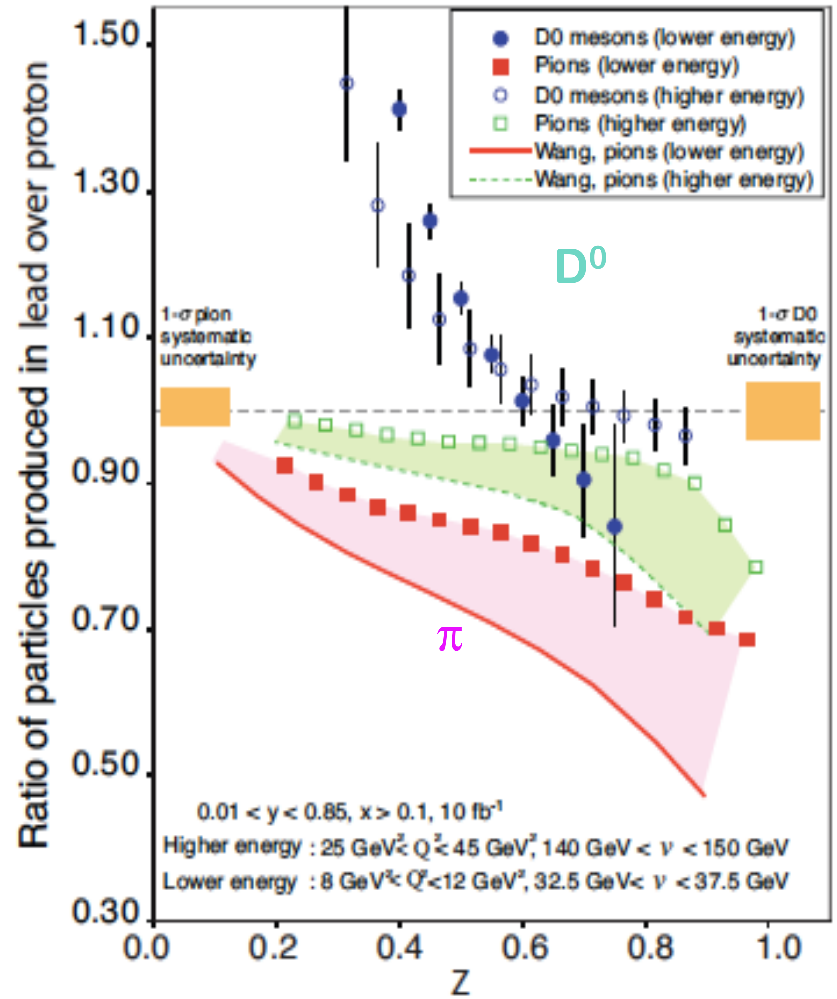
$$\nu = \frac{Q^2}{2mx}$$

Control of ν and medium length!

❑ Heavy quark energy loss:

– **Mass dependence of fragmentation**

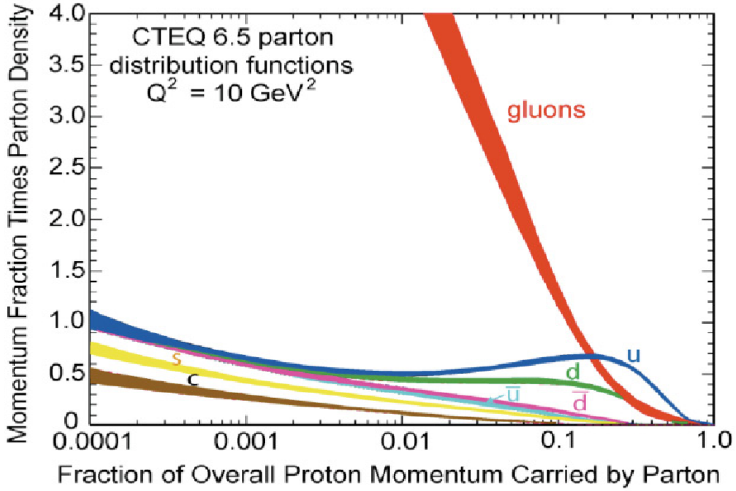




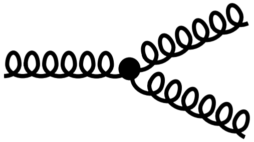
Need the collider energy of EIC and its control on parton kinematics

Non-linear interaction – dynamical mass scale?

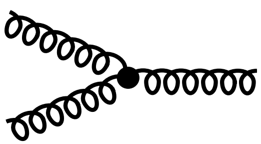
- Run away gluon density at small x?



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:

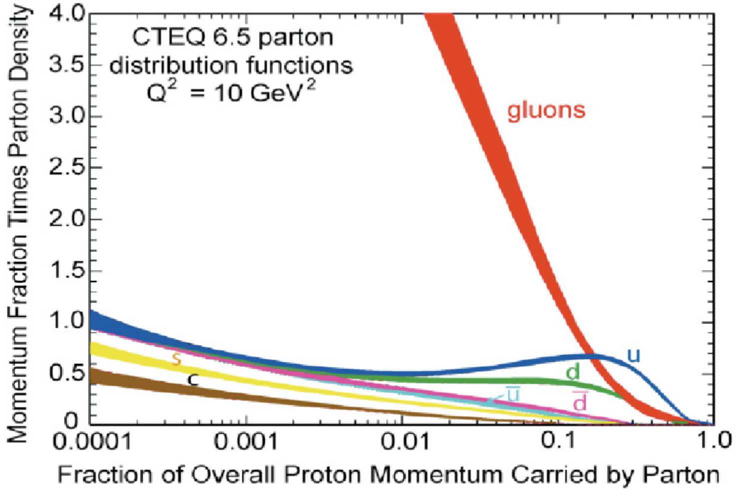
$$Q^2\frac{d}{dQ^2}x\phi_\gamma(x,Q^2)\approx\frac{\alpha_{em}}{\pi}\left[-\frac{2}{3}x\phi_\gamma(x,Q^2)+\int_x^1\frac{dx'}{x'}x'[\phi_{e^+}(x',Q^2)+\phi_{e^-}(x',Q^2)]\right]$$

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

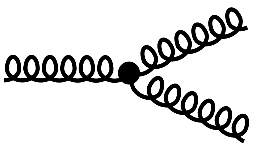
✧ Recombination of large numbers of glue could lead to saturation phenomena

How to answer the "big" questions?

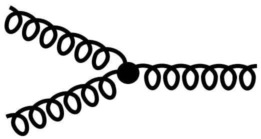
❑ Run away gluon density at small x?



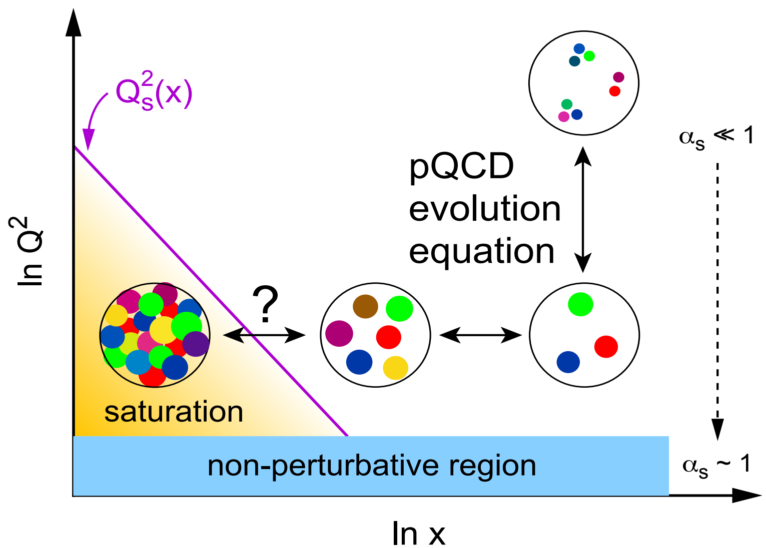
What causes the low-x rise?
gluon radiation
– non-linear gluon interaction



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

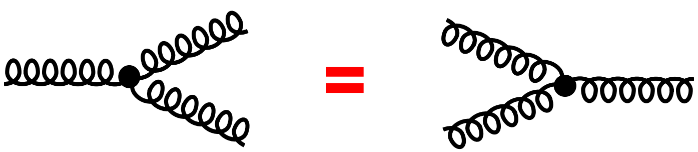


❑ Particle vs. wave feature:



Gluon saturation – Color Glass Condensate

Radiation = Recombination



at Q_s

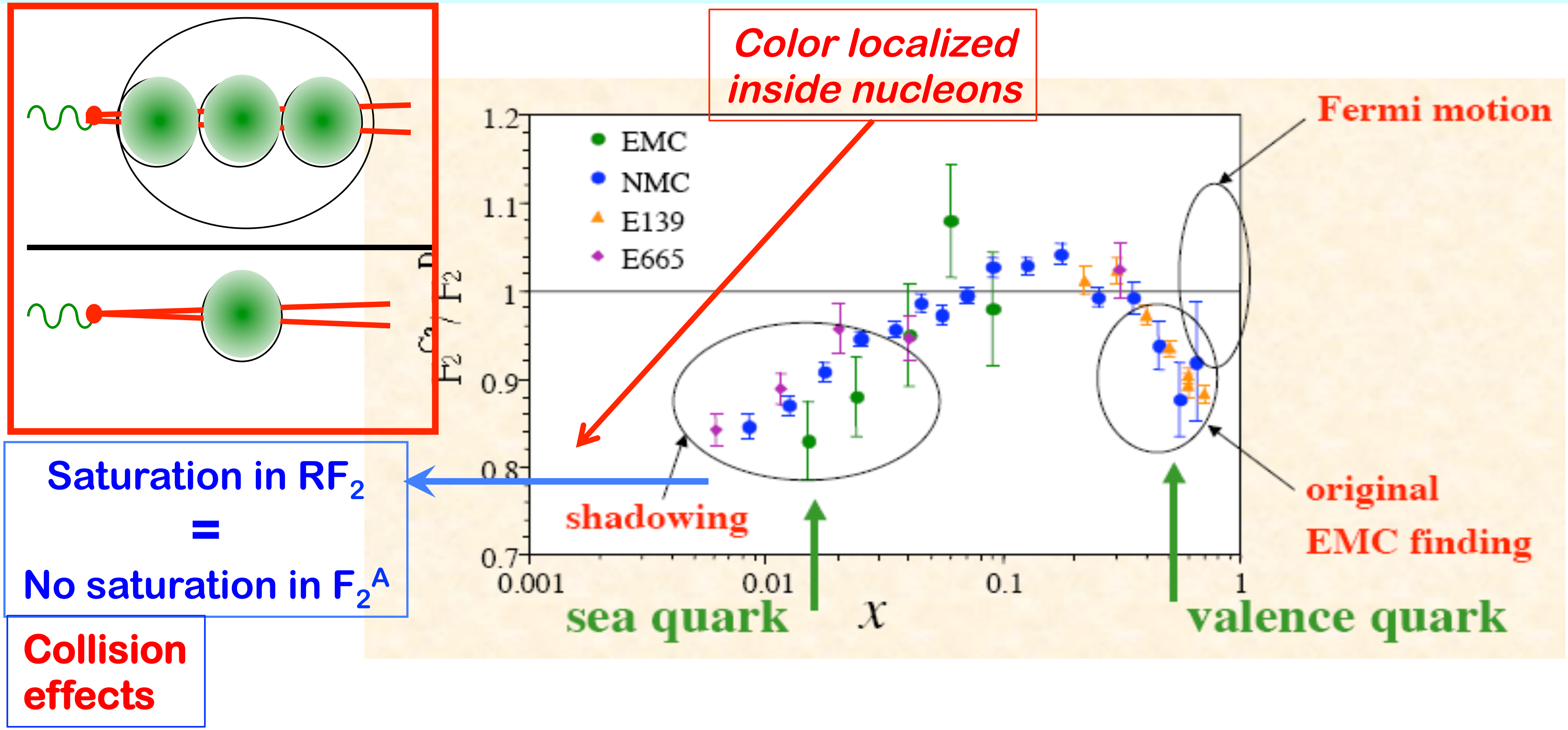
Leading to a collective gluonic system?

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?



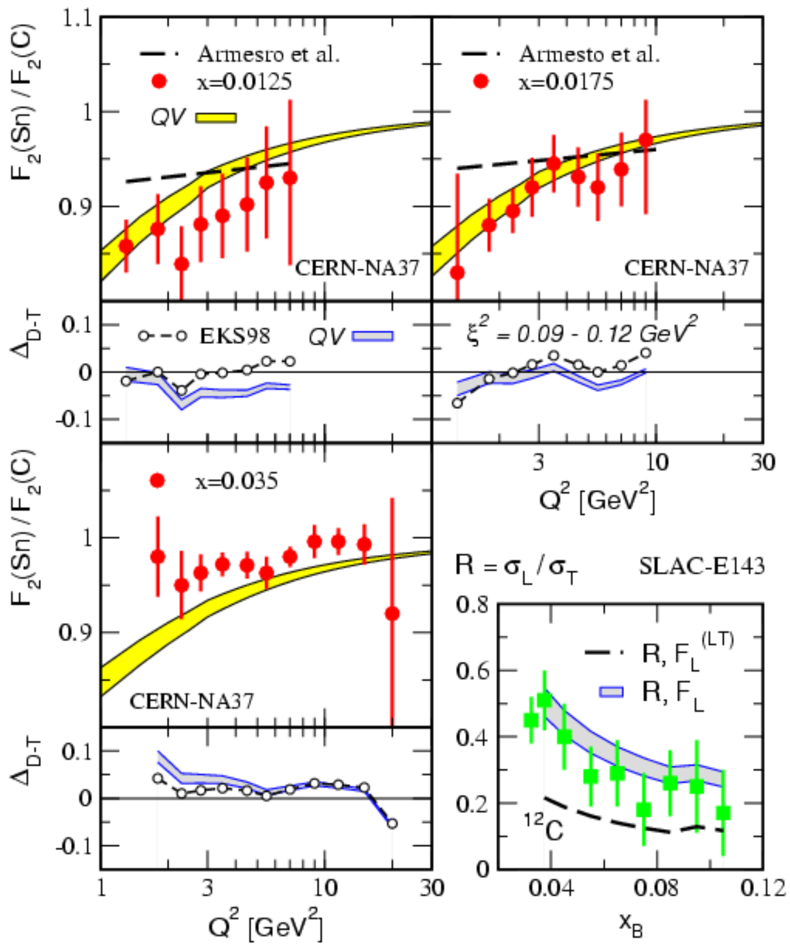
- A simple question:

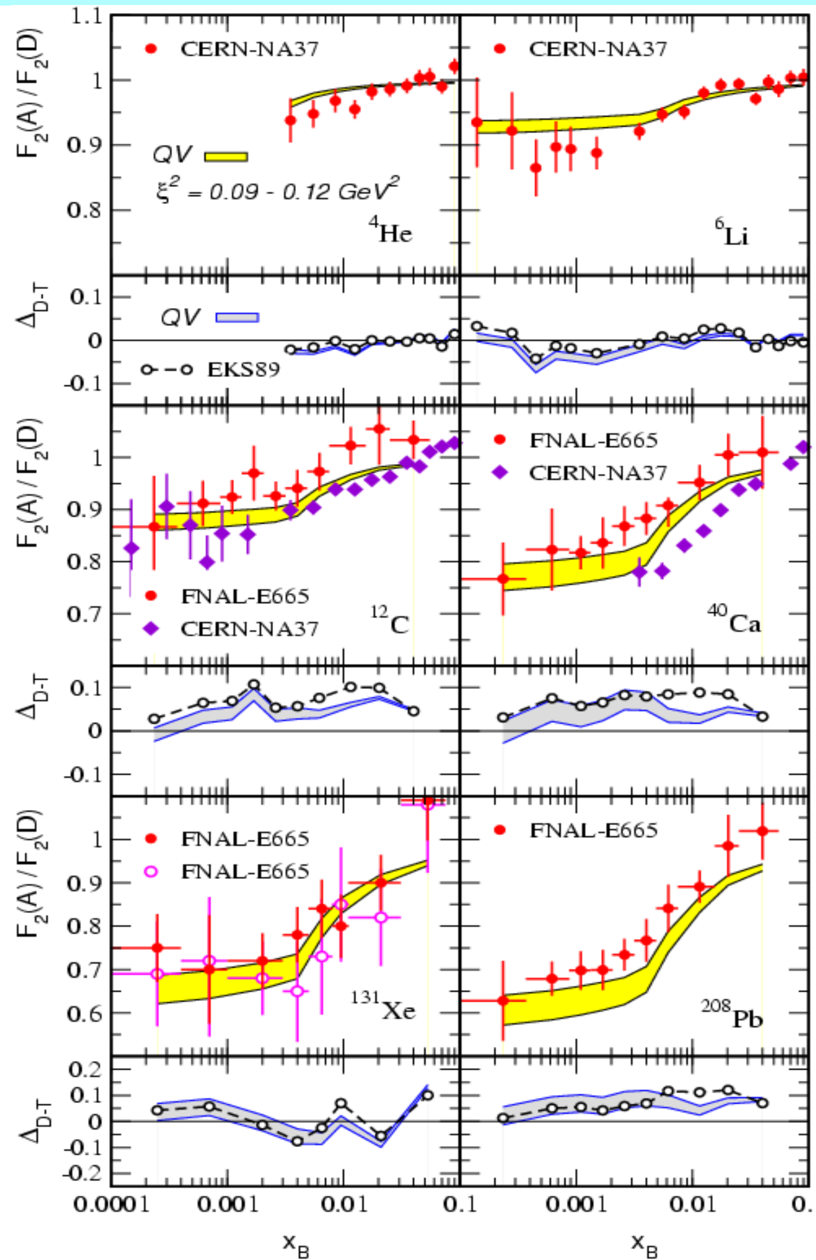
Will the suppression/shadowing continue to fall as x decreases?

DIS on a large nucleus

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

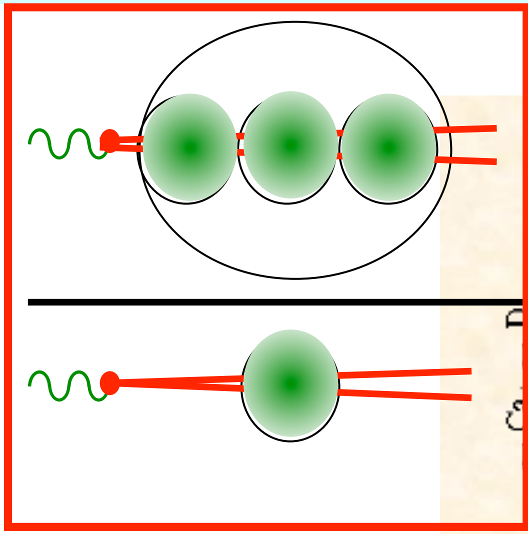
$\xi^2 = 0.09 - 0.12\ \mathrm{GeV}^2$



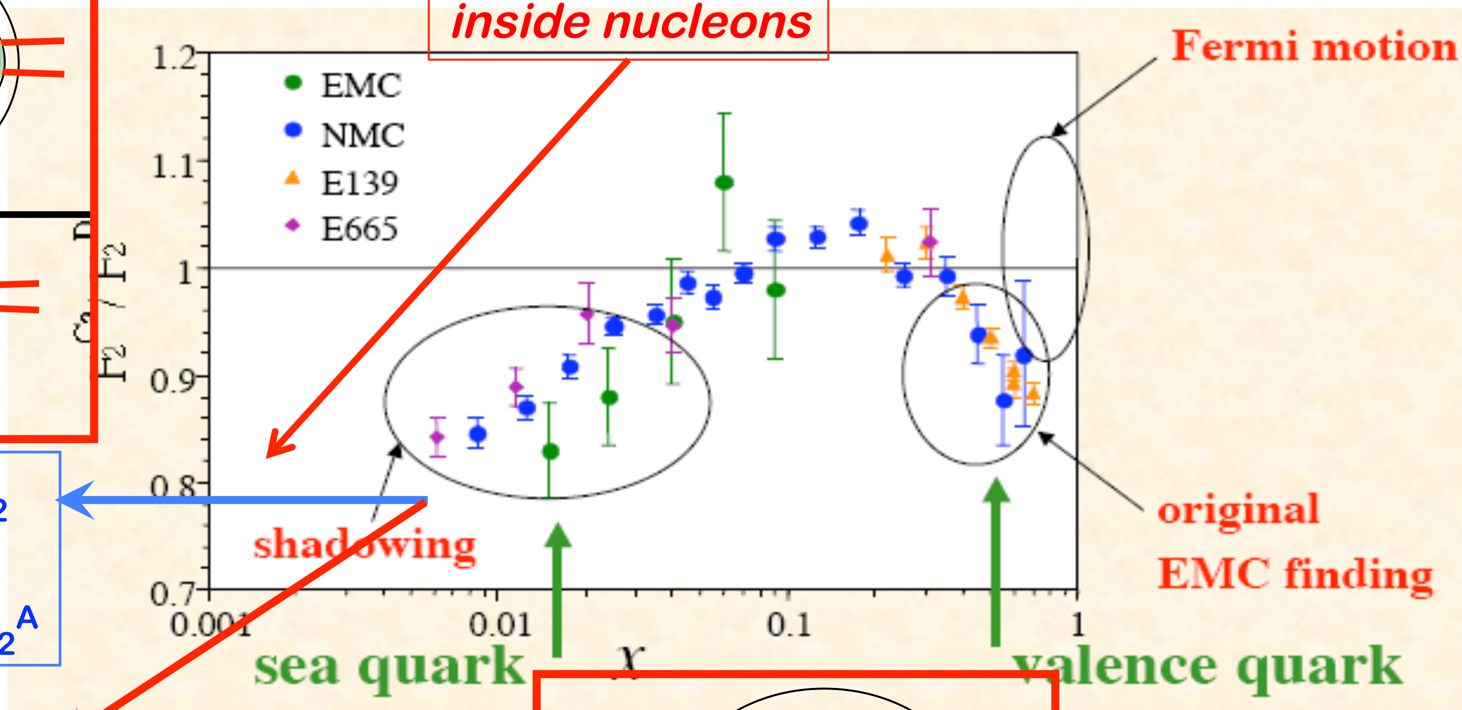


One number for all x_B, Q, and A dependence !

Color confining radius?



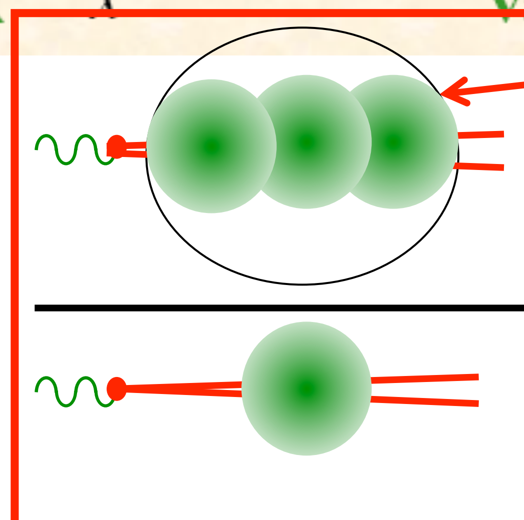
Color localized inside nucleons



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:**

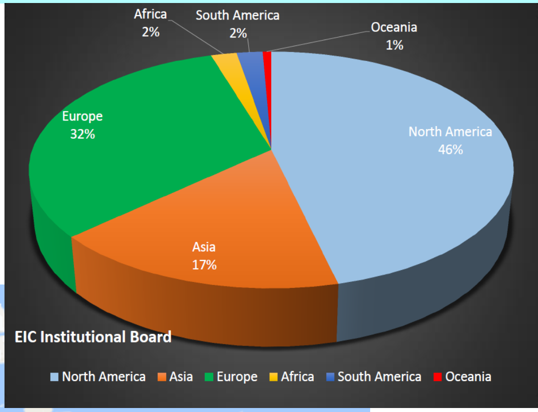
Will the suppression/shadowing continue to fall as x decreases?

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



The EIC Users Meeting at Stony Brook, June 2014:

→ *http://skipper.physics.sunysb.edu/~eicug/meeting1/SBU.html*

The EIC UG Meeting at University of Berkeley, January 6-9, 2016

http://skipper.physics.sunysb.edu/~eicug/meeting2/UCB2016.html

Recent EICUG Argonne National Laboratory July 7-10, 2016

http://eic2016.phy.anl.gov

Remote/Internet: meeting: March 16th : For NAS Review preparation

Next meeting:

July 18-22, 2017 Trieste, Italy

- **Registration opening by April 30**

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

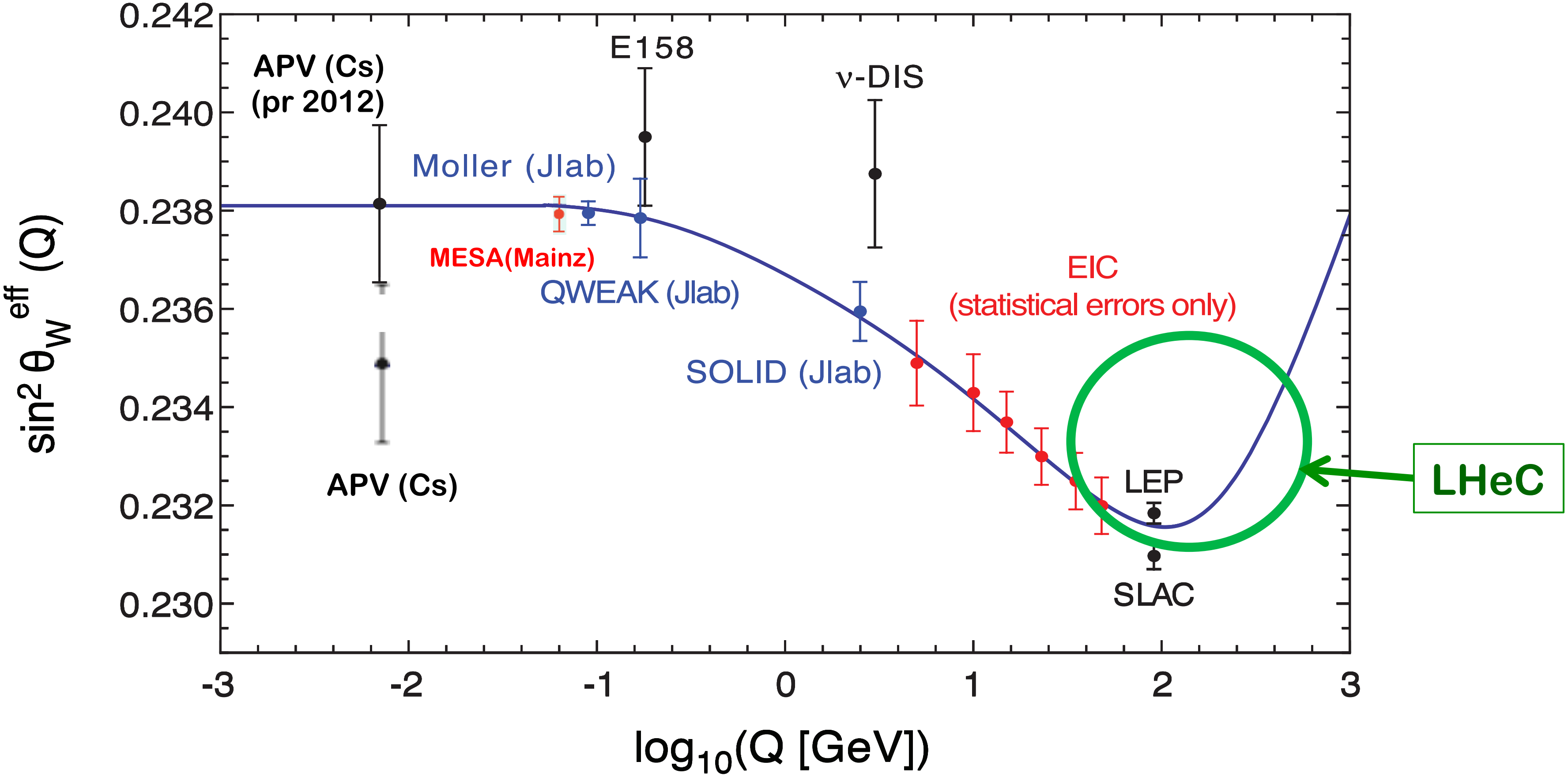
- EIC designs explore the polarization and intensity frontier, as well as the frontier of new accelerator/detector technology

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

Thanks!

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***