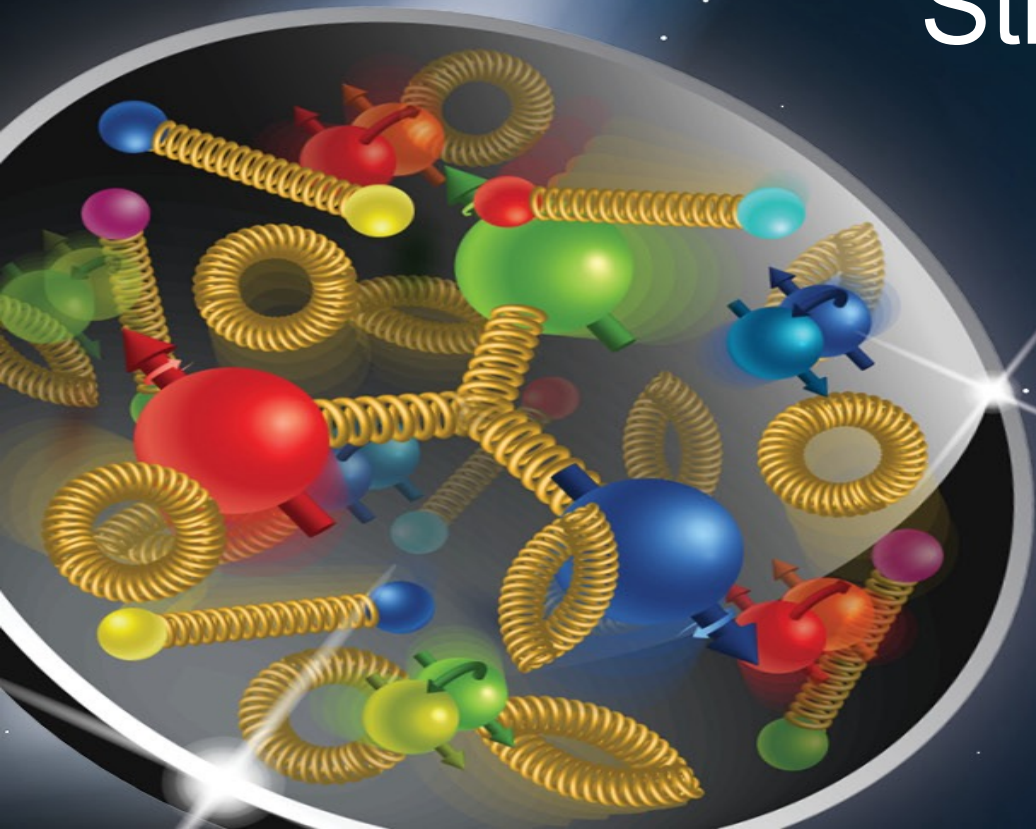# RHIC and the Electron-Ion Collider: Our Quest to Understand the Structure of Visible Matter in our Universe
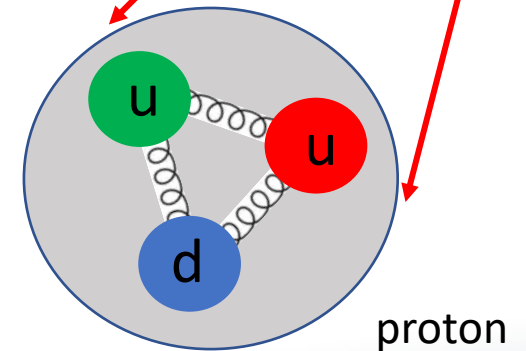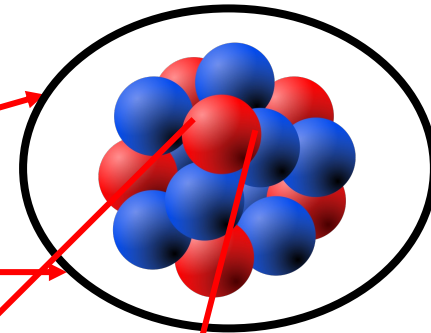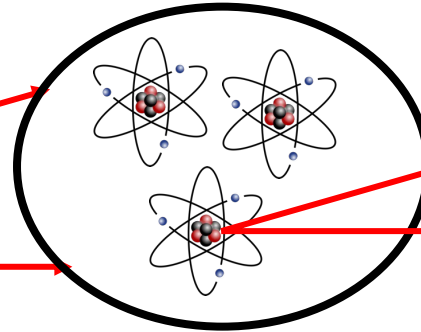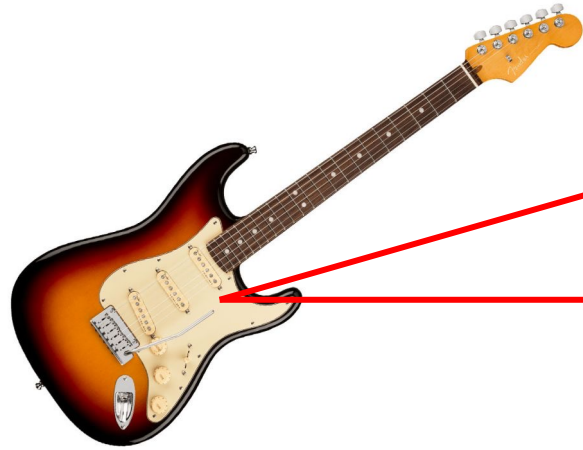
Alex Jentsch, *Brookhaven National Lab*

ajentsch@bnl.gov

NuSTEAM/NuPUMAS @ BNL

July 10th, 2024

Electron Ion Collider

Visible Matter

- All of the visible matter in the universe is comprised of atoms, which contain nuclei.
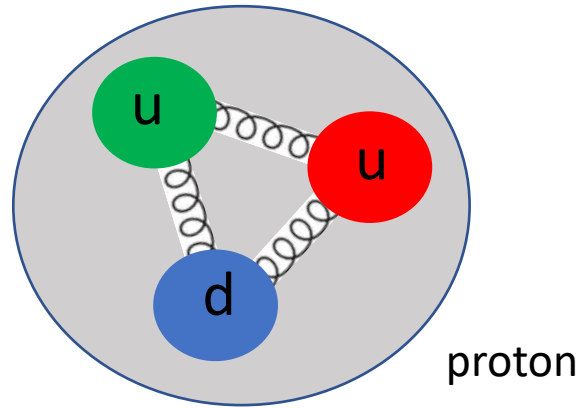

proton

- Nuclei are held together by the strong nuclear force, which governs interactions between the "quarks" and "gluons" found inside the proton.
- Quarks and gluons collectively called "**partons**".

Visible Matter

- Some fundamental questions we can ask:
  - What are the properties of the proton?
  - → Spin, mass, charge.
  - How do these properties manifest?

proton

- Quantum Chromodynamics (QCD) describes the interactions between the quarks and gluons (the strong force), and introduces the concept of "color", the strong force charge.

Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass charge spin	≈2.2 MeV/c² 2/3 ½ **u** up	≈1.28 GeV/c² 2/3 ½ **c** charm	≈173.1 GeV/c² 2/3 ½ **t** top	0 0 1 **g** gluon	≈125.09 GeV/c² 0 0 **H** higgs
QUARKS	≈4.7 MeV/c² −1/3 ½ **d** down	≈96 MeV/c² −1/3 ½ **s** strange	≈4.18 GeV/c² −1/3 ½ **b** bottom	0 0 1 **γ** photon	SCALAR BOSONS
LEPTONS	≈0.511 MeV/c² −1 ½ **e** electron	≈105.66 MeV/c² −1 ½ **μ** muon	≈1.7768 GeV/c² −1 ½ **τ** tau	≈91.19 GeV/c² 0 1 **Z** Z boson	GAUGE BOSONS VECTOR BOSONS
	<2.2 eV/c² 0 ½ **νe** electron neutrino	<1.7 MeV/c² 0 ½ **νμ** muon neutrino	<15.5 MeV/c² 0 ½ **ντ** tau neutrino	≈80.39 GeV/c² ±1 1 **W** W boson	

The proton gets even more complicated

- As you ramp up the energy, the proton becomes awash with more partons (quarks and gluons)!

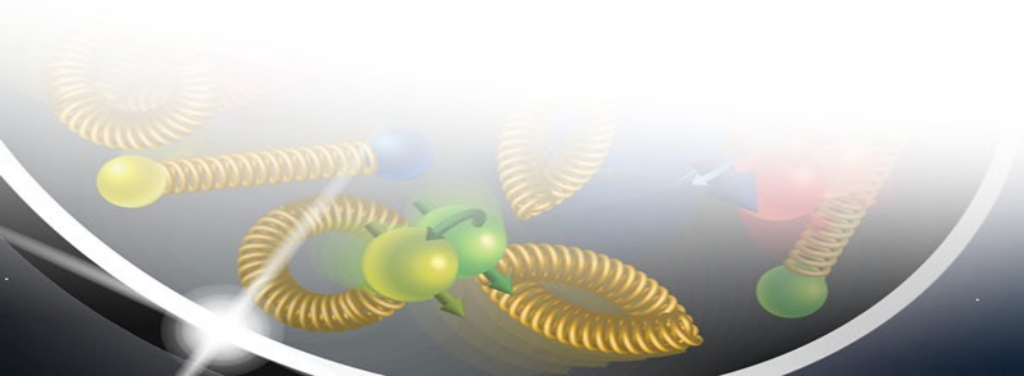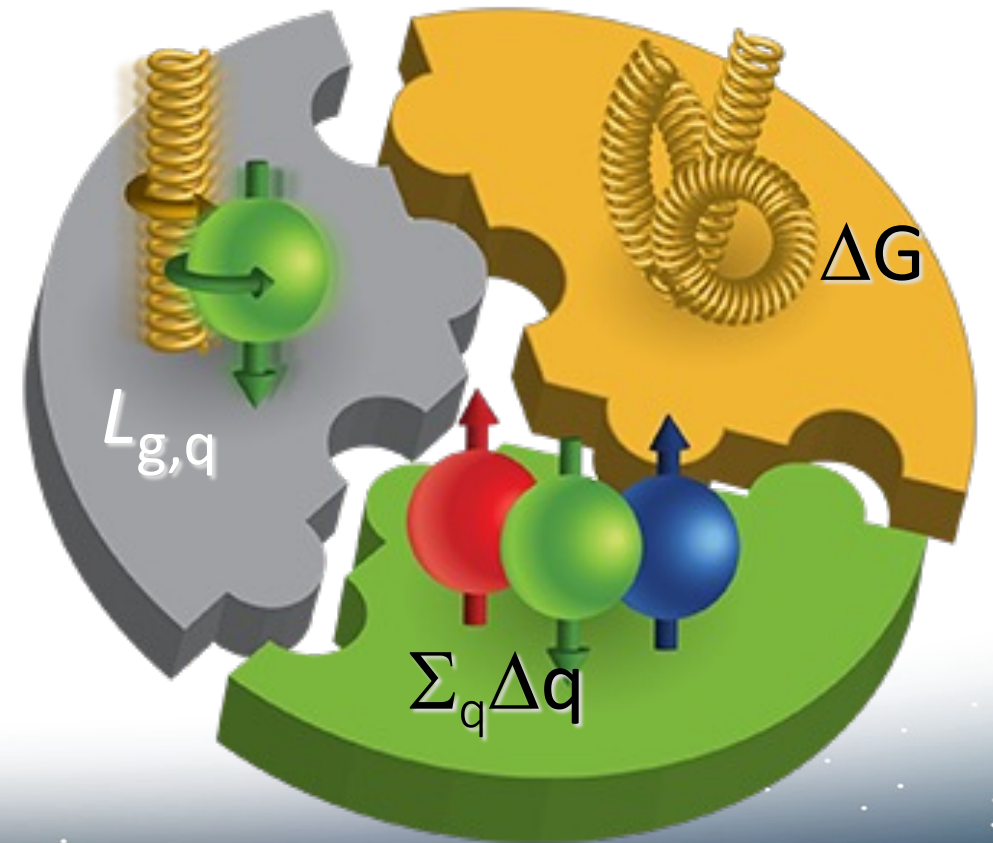Three "valence" quarks inside proton.
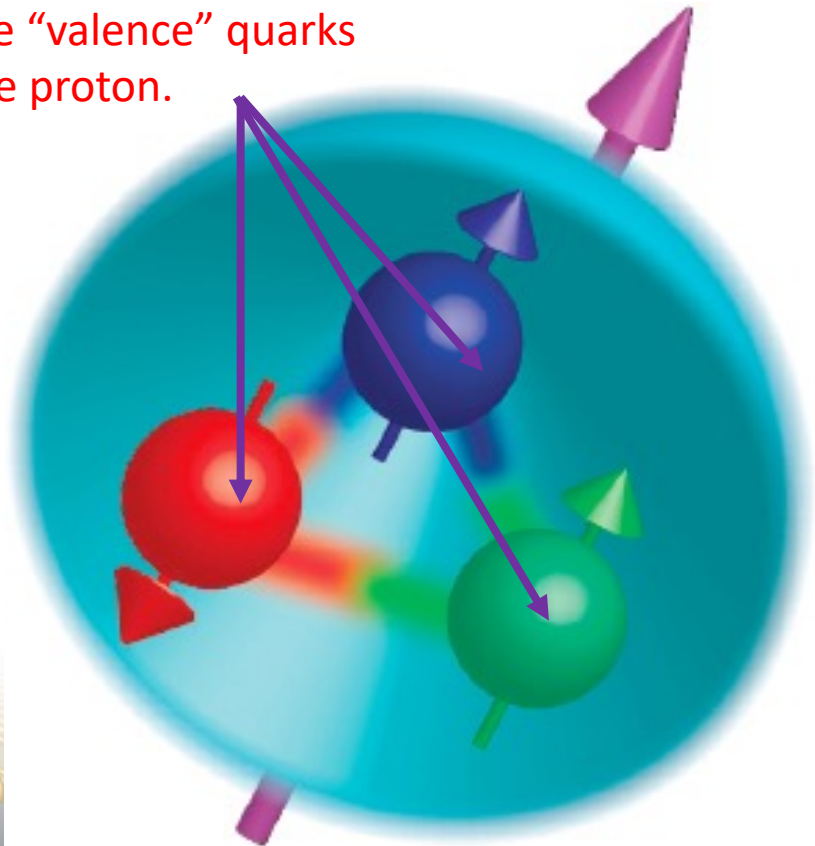
The Proton Spin Puzzle

Spin structure – the three "valence" quarks do not account for the total spin of the proton!

quarks   gluons

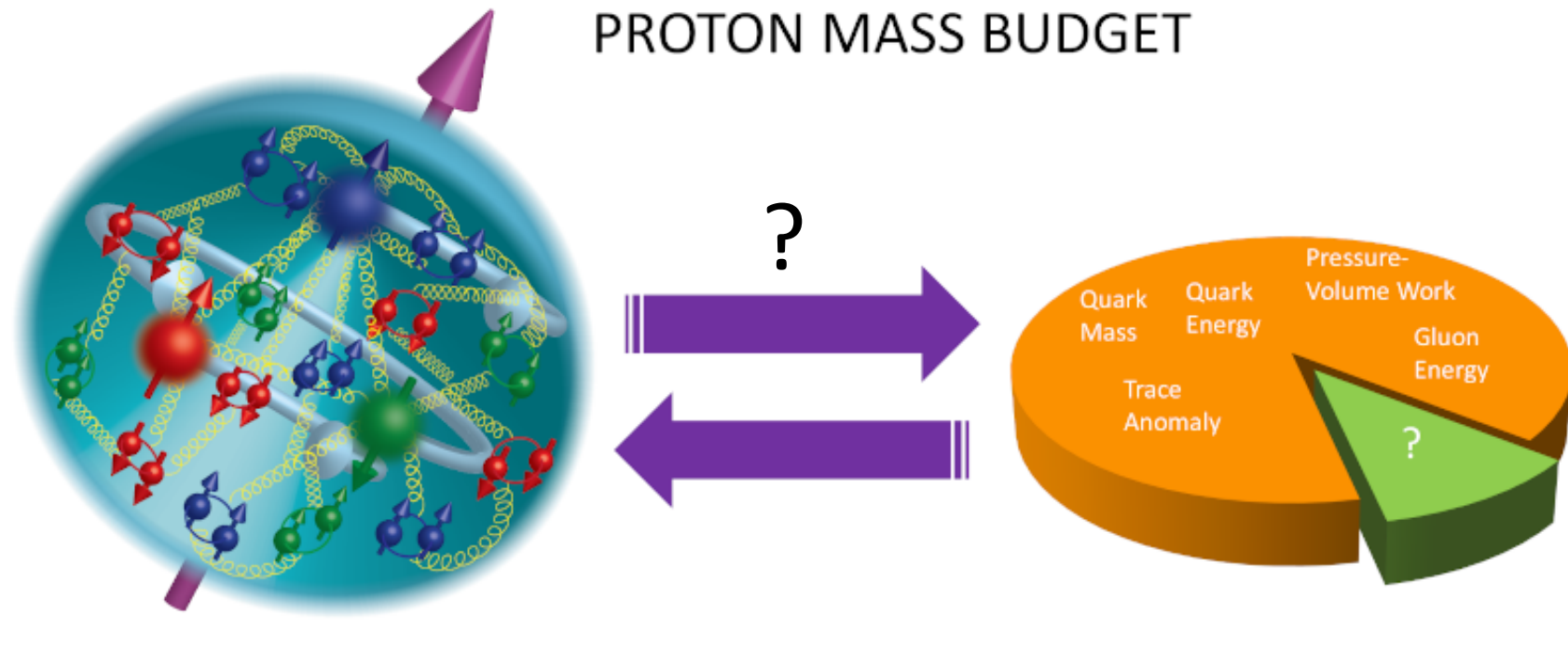Proton spin: $\frac{1}{2} = \frac{1}{2}\Sigma_q \Delta q + \Delta G + L_{g,q}$

Orbital angular momentum

Only 20-30% comes from the quarks!

ΔG

$L_{g,q}$

$\Sigma_q \Delta q$

The Proton Mass

- The proton mass composition is also rather complicated to pin-down!

PROTON MASS BUDGET

?

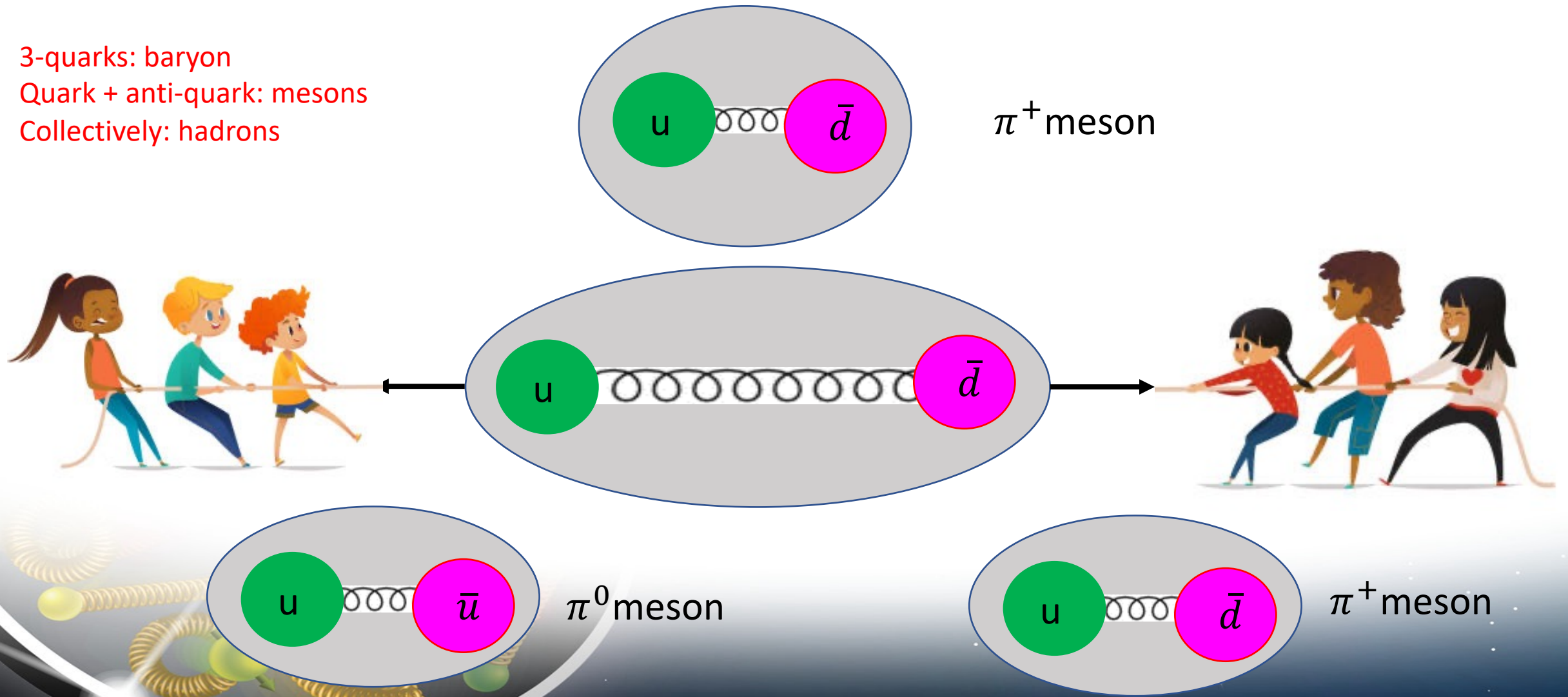Quark Mass   Quark Energy   Pressure-Volume Work   Gluon Energy   Trace Anomaly   ?

- Mass does not arise as simple sum of quark masses!
- ~ 99% of the mass is driven by quark and gluon dynamics!

Some QCD Peculiarities

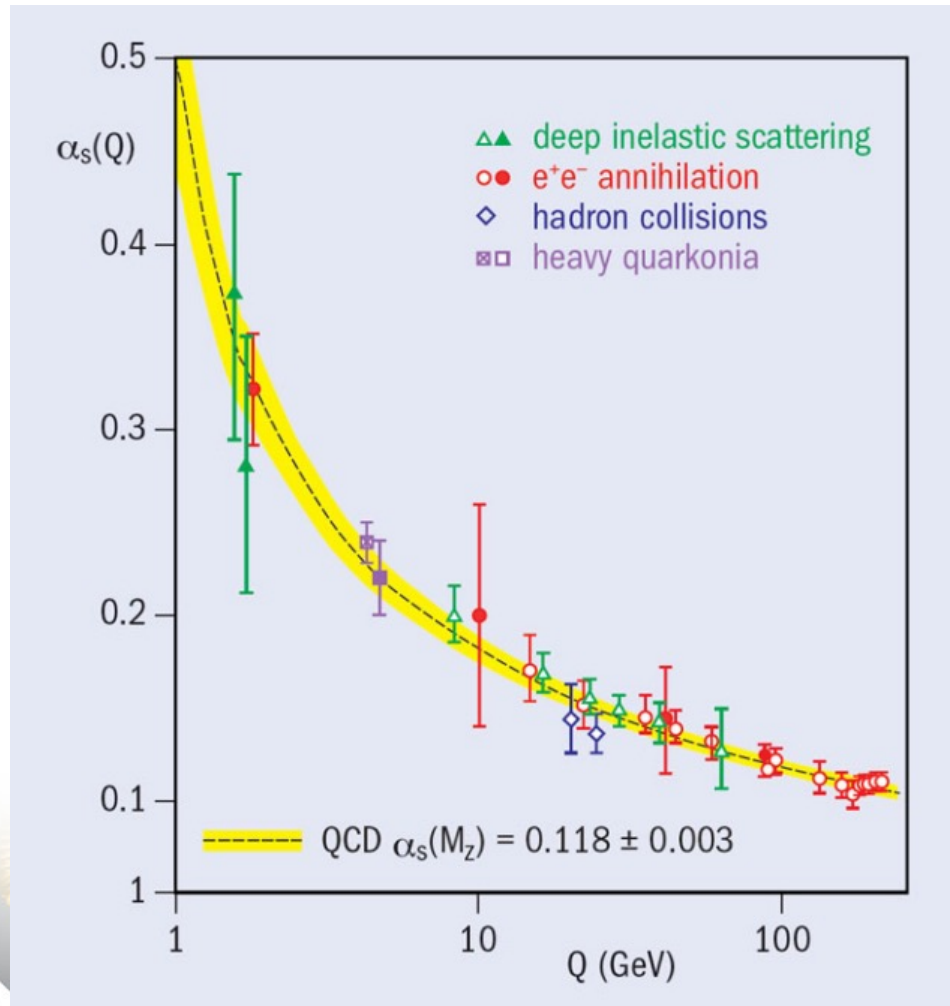Another peculiar thing about QCD: <u>confinement</u>.

3-quarks: baryon
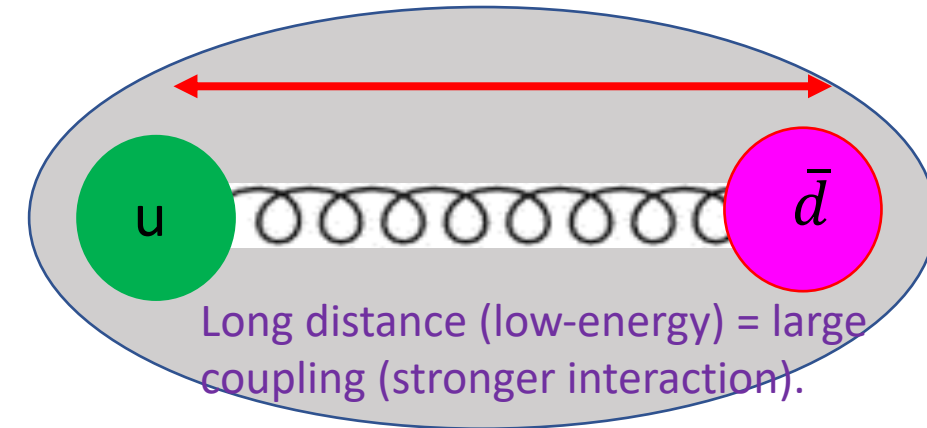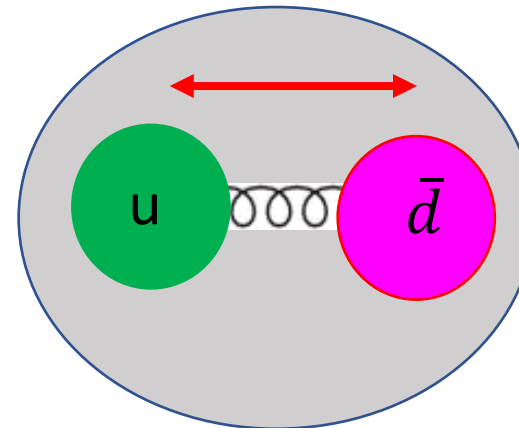Quark + anti-quark: mesons
Collectively: hadrons

π^+meson

π^0meson

π^+meson

Some QCD Peculiarities

An additional wrinkle in QCD → gluons can interact with *themselves.*

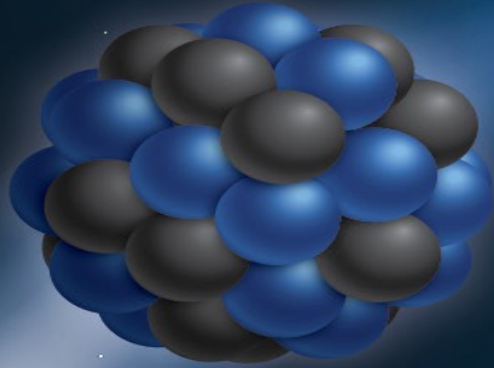Short distance (high-energy) = small coupling (weaker interaction).

Long distance (low-energy) = large coupling (stronger interaction).

- o Opposite of the EM force and gravity, which decrease as a function of $\frac{1}{(distance)^2}$.
- Consequences:
  - o QCD calculations become non-perturbative (exceedingly hard) when the coupling constant is large (i.e. at low energy).
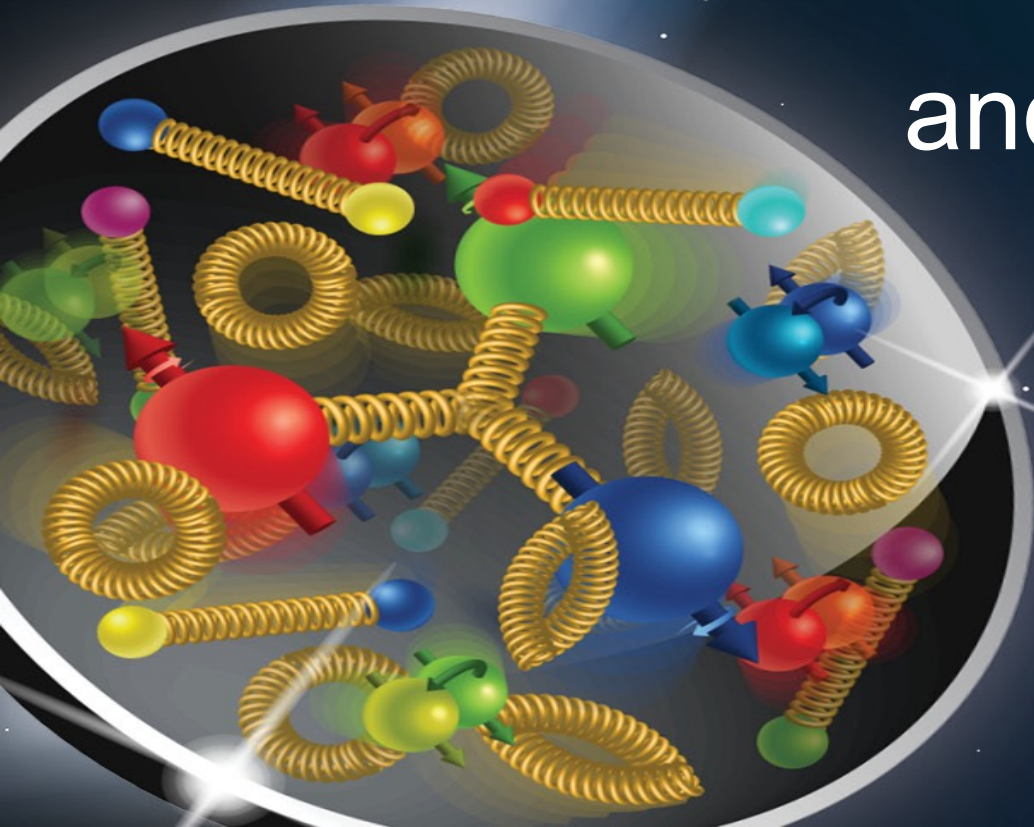
Image credit: From figure 5 in Siegfried Bethke and Peter Zerwas 2004 *Physik Journal* **3** 12 31.

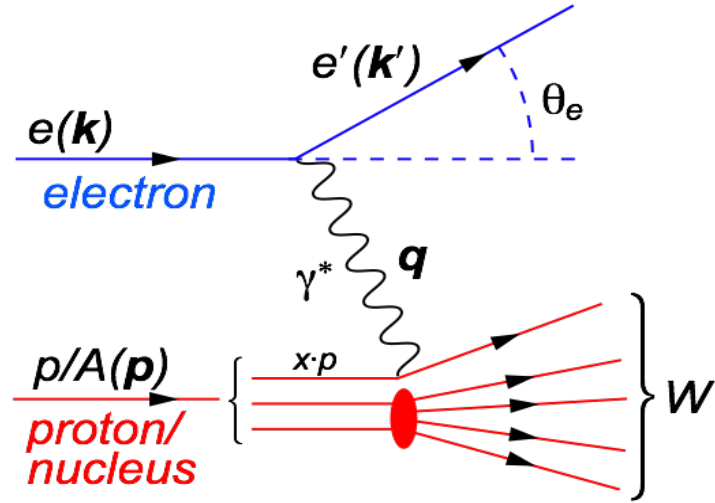**QCD requires experimental data to make progress!**

$\alpha_s(Q)$

- ▲△ deep inelastic scattering
- o● e^+e^- annihilation
- ◇ hadron collisions
- ⊠□ heavy quarkonia

QCD $\alpha_s(M_z) = 0.118 \pm 0.003$

Q (GeV)

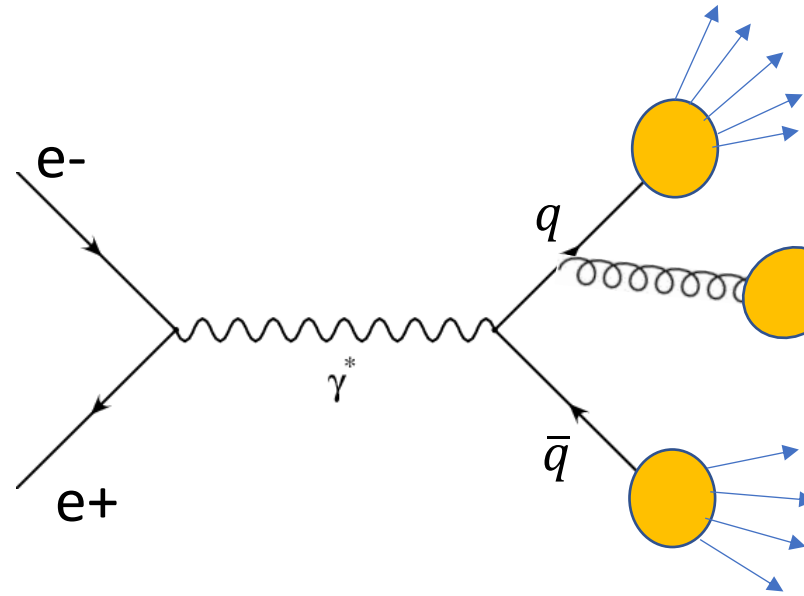Okay, so the structure of matter and QCD seem complicated…how can we study them?
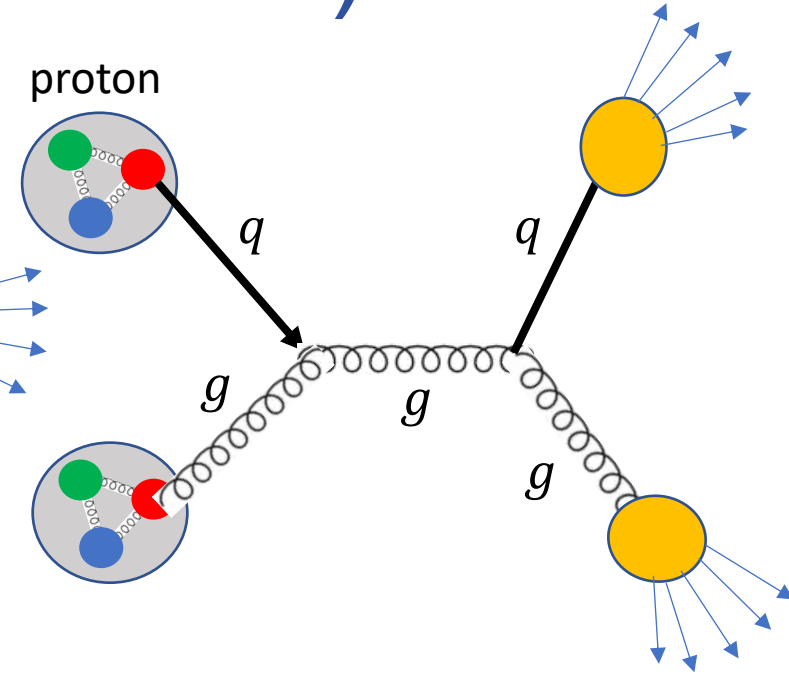
Different kinds of interactions (just a few)

Deep-Inelastic Scattering: electron + proton (or nucleus) collisions

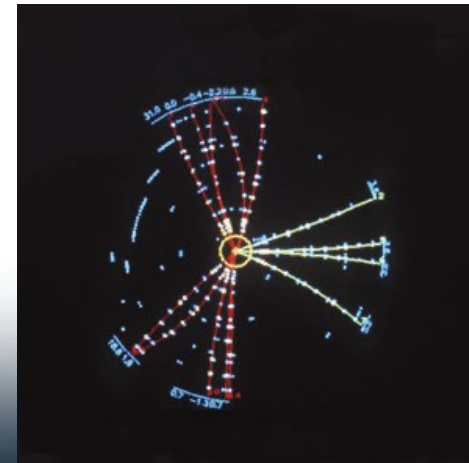**Electron + positron annhiliation:** electron + positron collisions

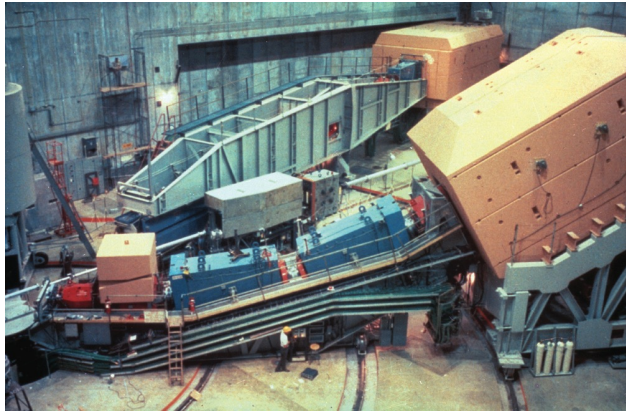**Hadronic interactions:** Proton + proton collisions

Led to discovery of the quark! (SLAC)
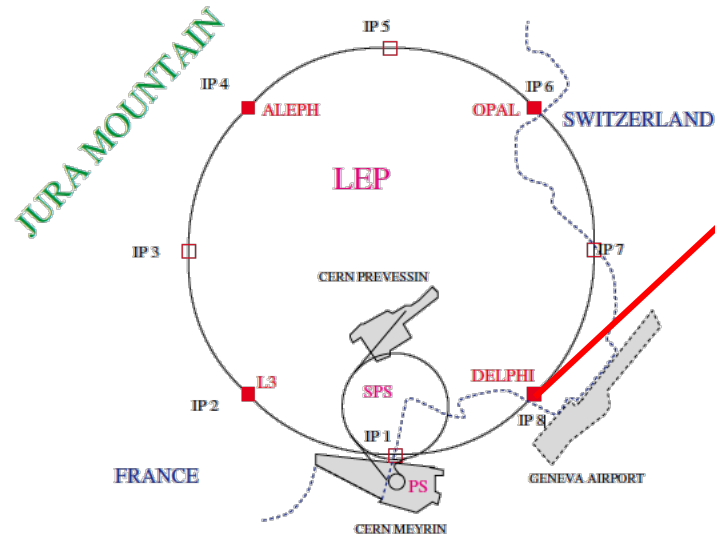
Led to discovery of the gluon! (PETRA)
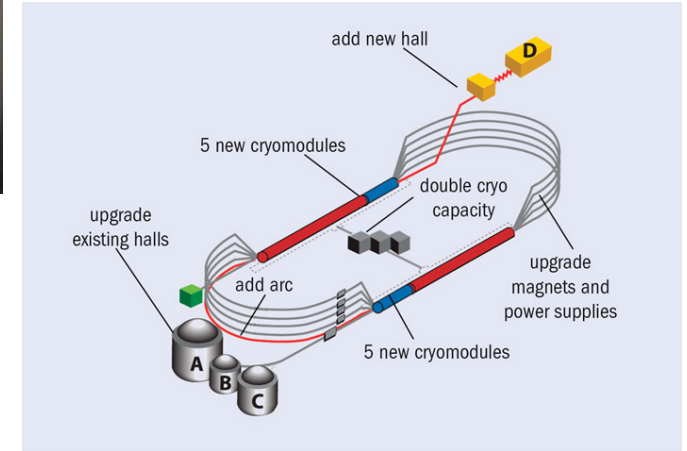
Discovery of the Higgs! (LHC)

Building our microscope!
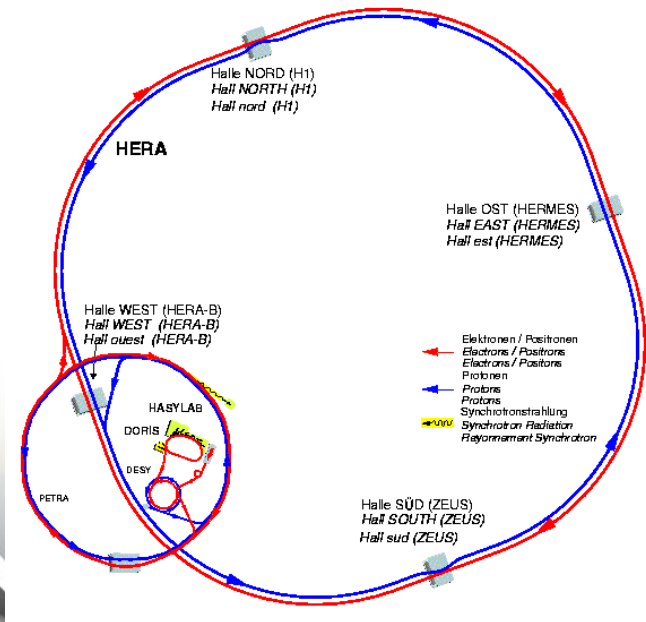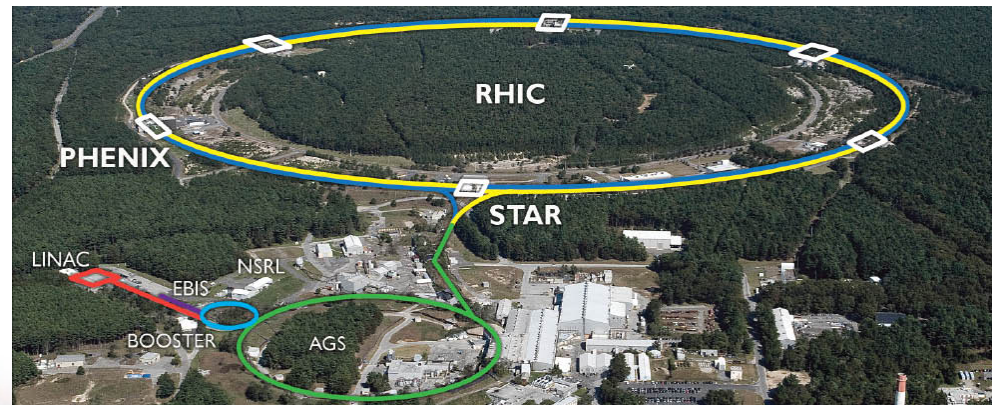

SLAC 1969: e + p (fixed)

LEP @ CERN: 1989-2001: e+e-
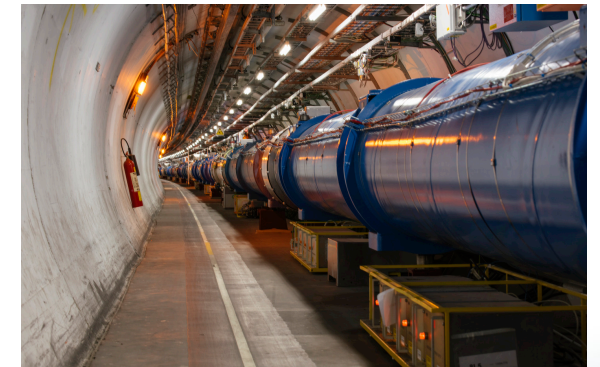

JLAB/CEBAF: 1984 – present: e + p (fixed)

HERA: 1998-2007: e + p (collider)

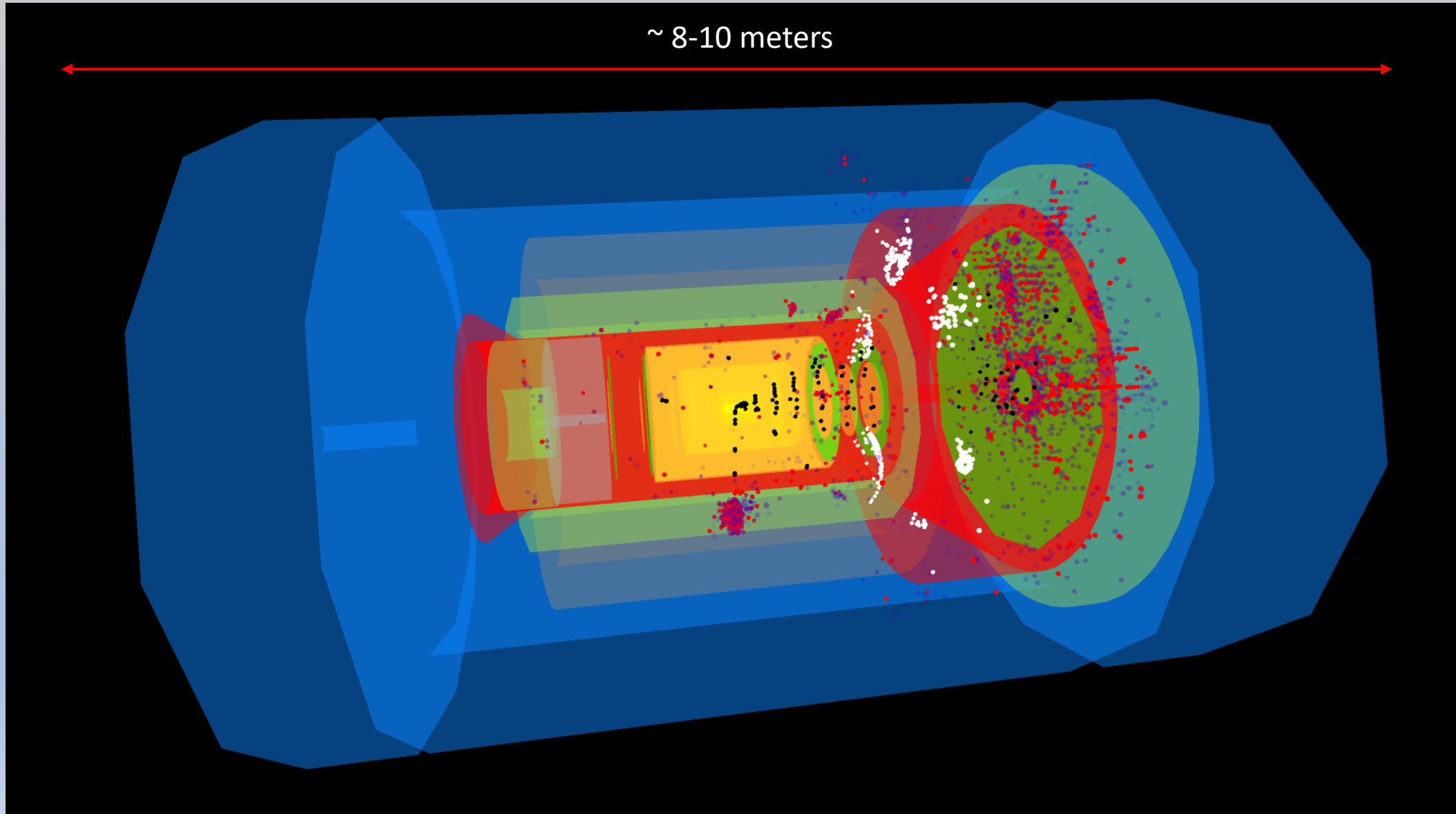RHIC: 2000 – present: p+p, p+A, A+A, polarized protons

LHC: 2008 – present: p+p, p+A, A+A
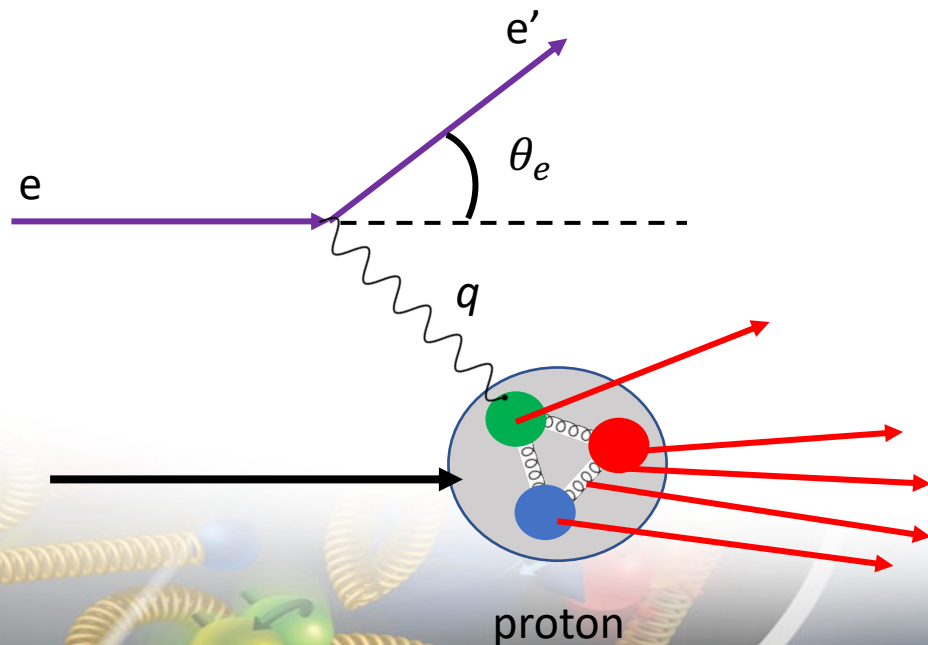
Building our microscope!

~ 8-10 meters

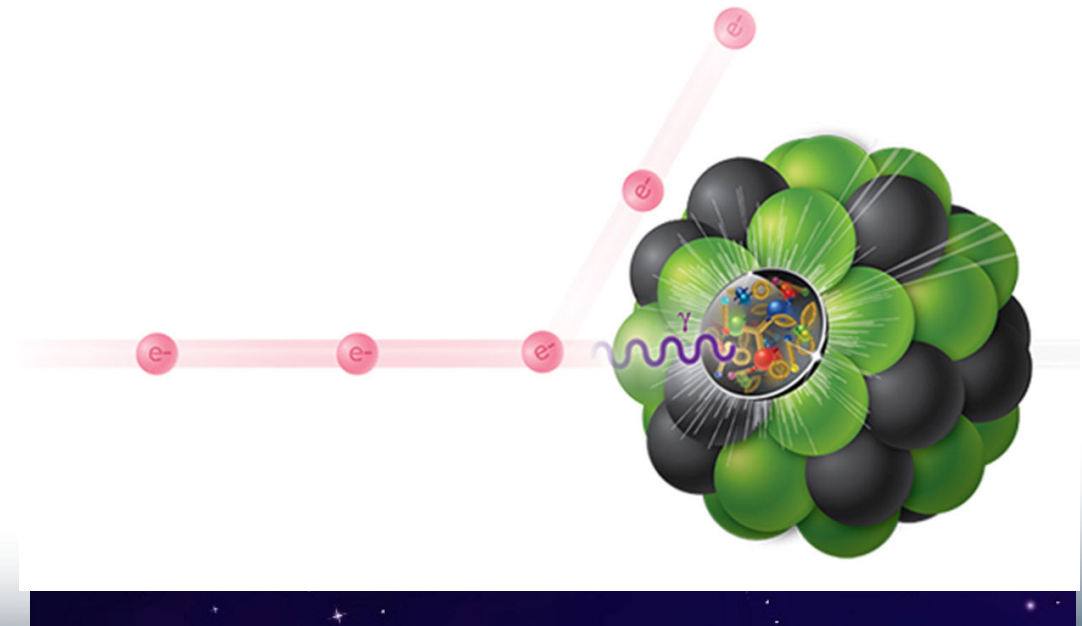# "Illuminating" the Structure of Matter

- **Use Deep-Inelastic Scattering (DIS)**
  - Collide electrons with protons or nuclei – the photon that is exchanged literally **illuminates** the target, allowing you to build a microscope of sorts to study the structure of matter!

electron + proton
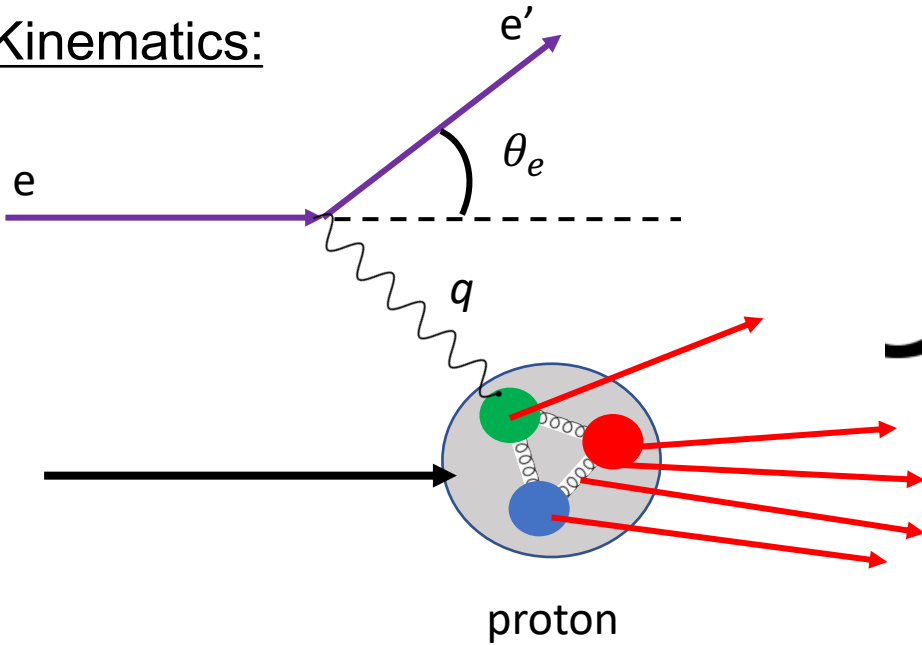
electron + nucleus

"Illuminating" the Structure of Matter

$$Q^2 = 2E_e E'_e (1 - cos\theta'_e) = -q^2$$

Kinematics:

e'

θ_e

e

q

proton

$Low \; Q^2$ = low resolution
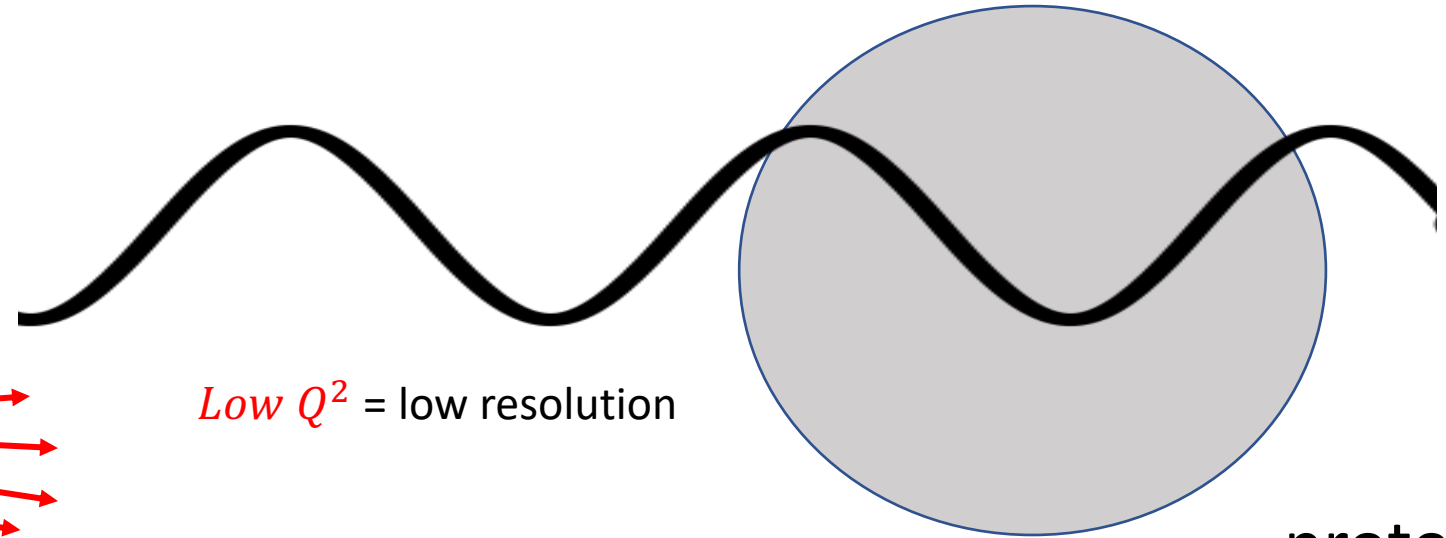
$High \; Q^2$ = high resolution

proton

u

u

d

"Illuminating" the Structure of Matter

$$Q^2 = 2E_e E_e'(1 - cos\theta_e') = -q^2$$

Kinematics:

$$x = \frac{Q^2}{2pq}$$

Measure of momentum fraction of struck parton

"Bjorken-x"

proton

x ~ 1/3 for just the "valence" quarks.

"Illuminating" the Structure of Matter

Kinematics:

$$Q^2 = 2E_e E'_e (1 - cos\theta'_e) = -q^2$$

Measure of resolution power

$$x = \frac{Q^2}{2pq}$$
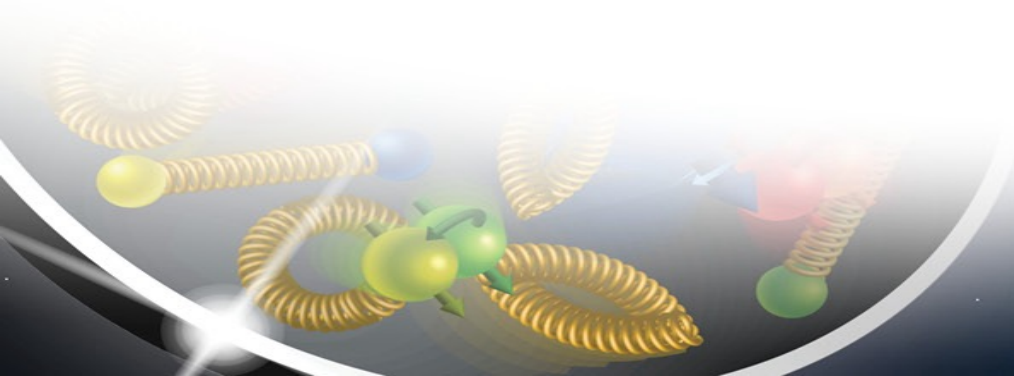
Measure of momentum fraction of struck parton
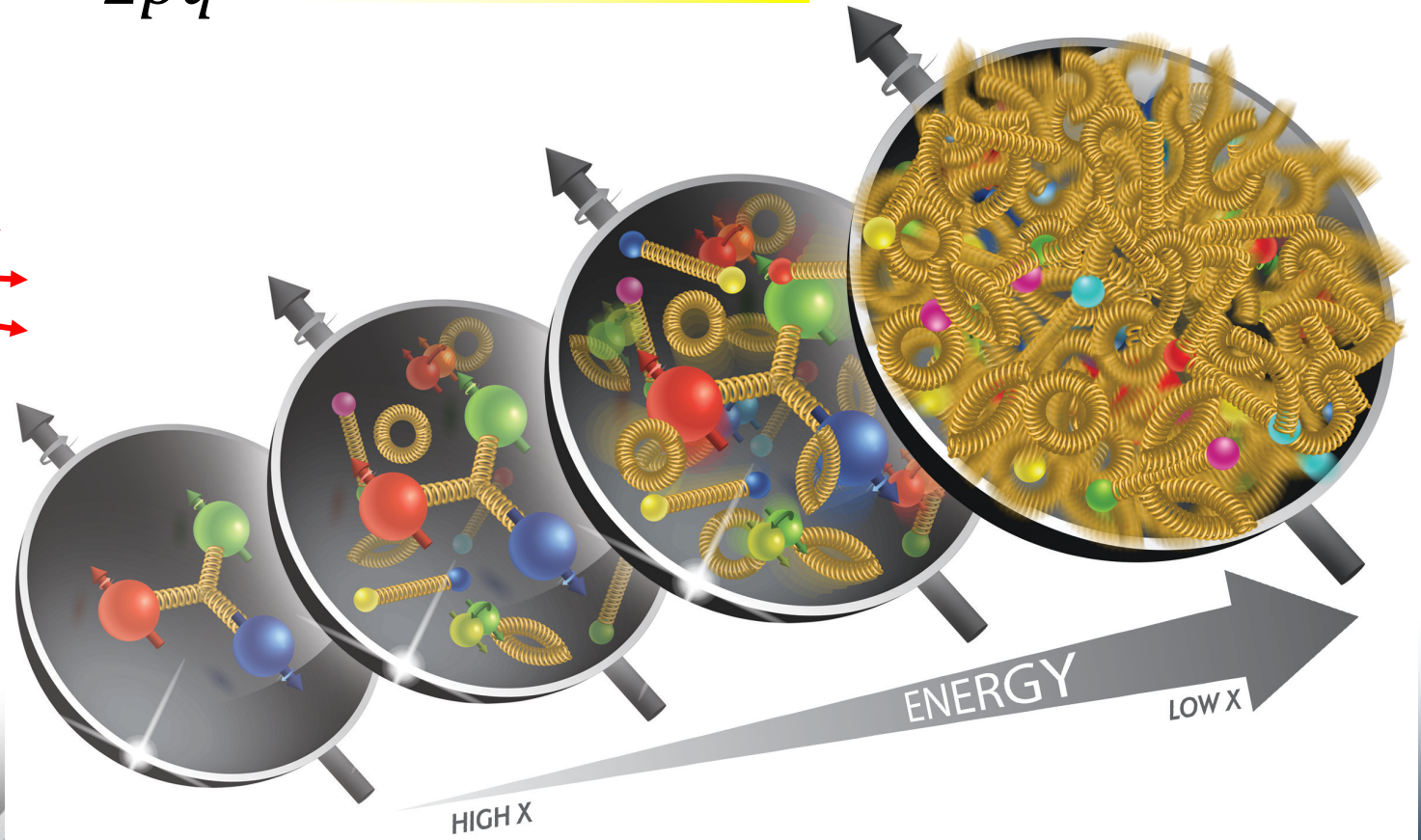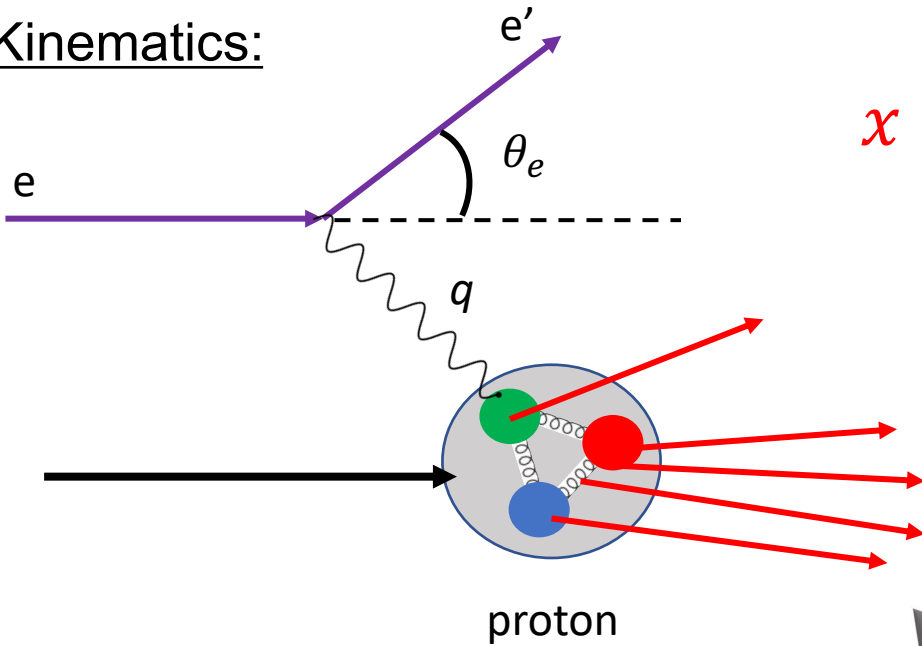
"Bjorken-x"

Saturation – gluon density increases drastically at low-x! At some point, does the density saturate? **New state of matter?**

Parton Distribution Function (PDF)

gluon emission   gluon recombination

CTEQ 6.5 parton distribution functions $Q^2 = 10\ GeV^2$

gluons

$\sim 1/k_T$

$k_T\ \phi(x,\ k_T^2)$

max. density

Momentum Fraction Times Parton Density

Fraction of Overall Proton Momentum Carried by Parton

ENERGY

LOW X

HIGH X
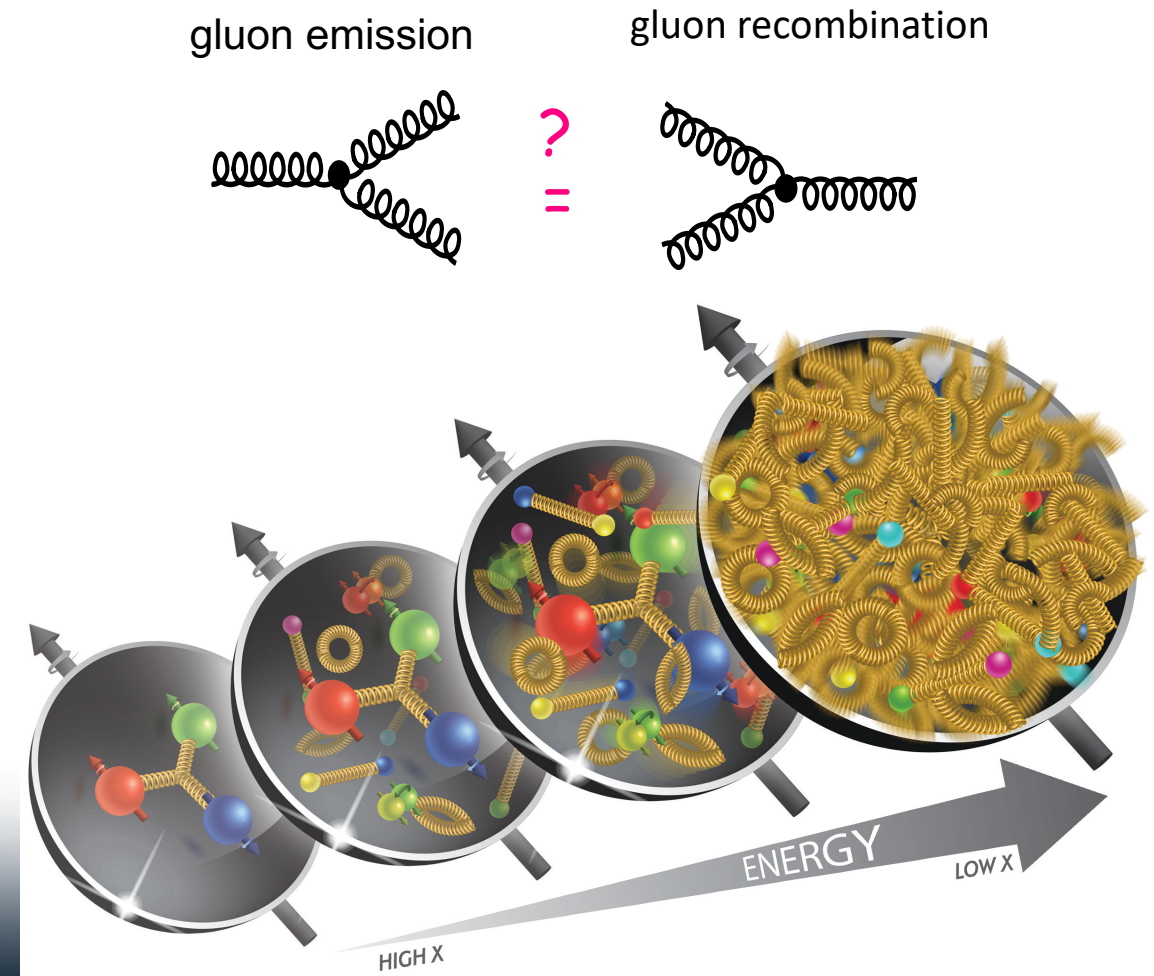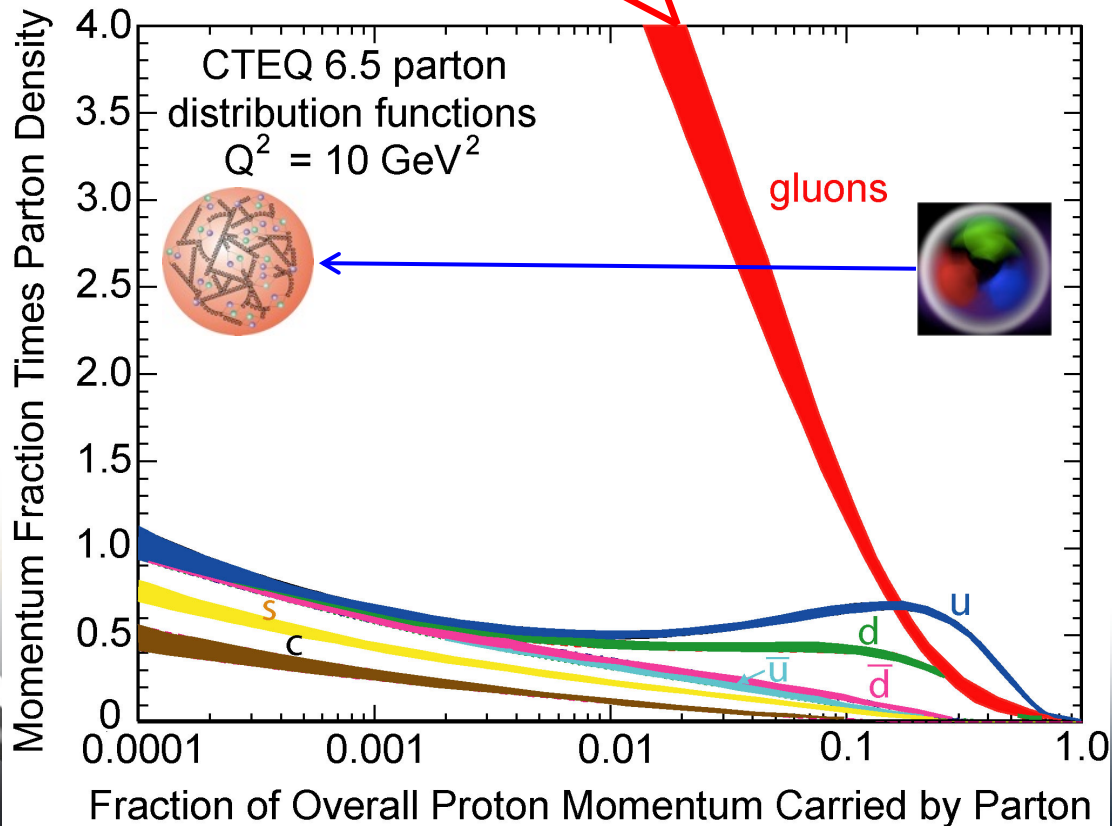
What is needed experimentally?

EIC Yellow Report, Fig. 2.1
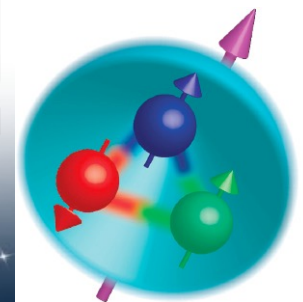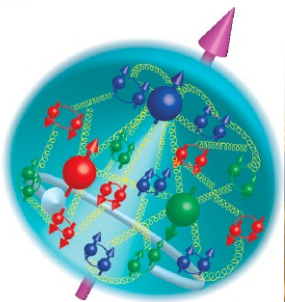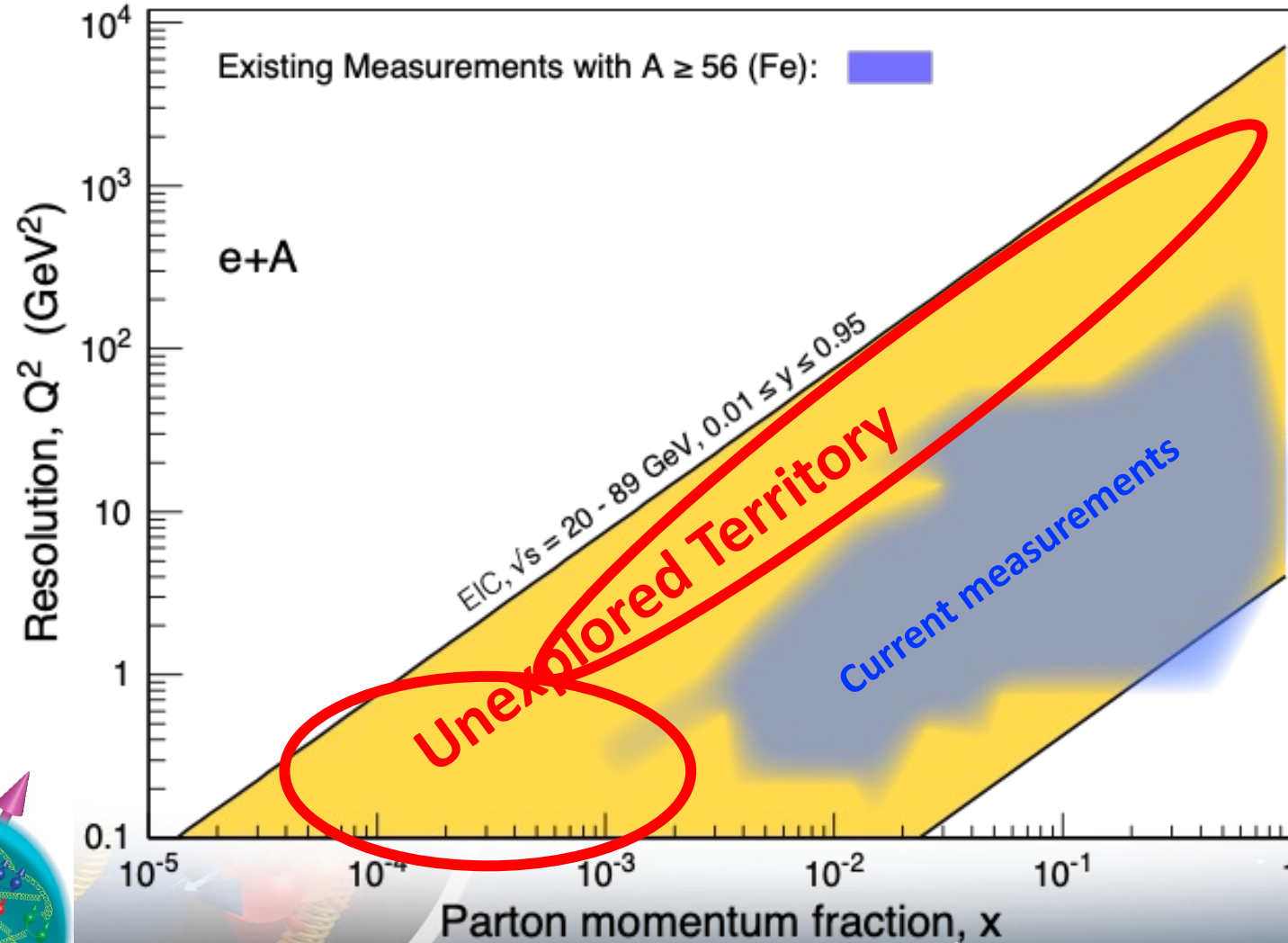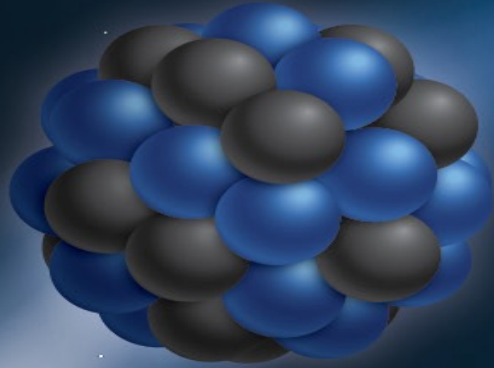
Lots of microscopes…and still unanswered questions?

Is there a machine that can help?
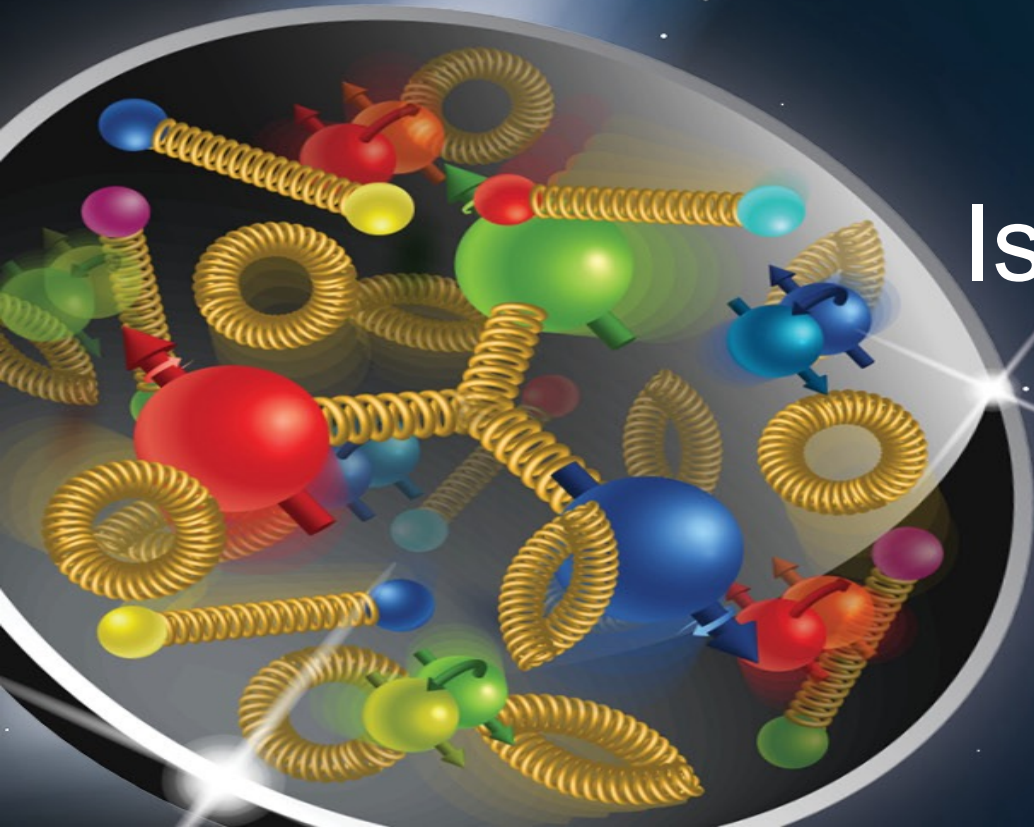
The Electron-Ion Collider (EIC)

- <u>Deep-Inelastic Scattering machine</u> → electron + proton (or nucleus) collisions.
- Built on the infrastructure of the existing Relativistic Heavy-Ion Collider (RHIC) facility at Brookhaven Lab, in partnership with Jefferson Lab.
  - This machine combines the functionality of HERA and RHIC.

EIC at BNL

IP8

IP6

2.4 miles in circumference!

Hadron Storage Ring	
Electron Storage Ring	
Electron Injector Synchrotron	
Possible on-energy Hadron injector ring	
Hadron injector complex	
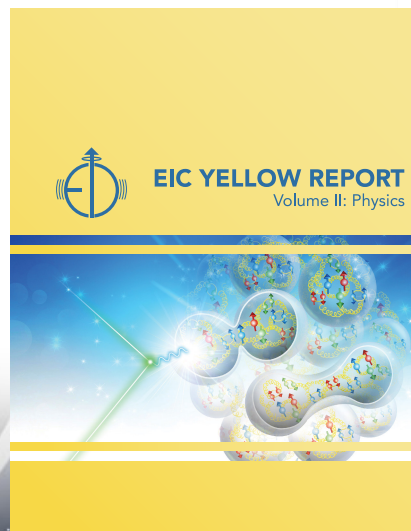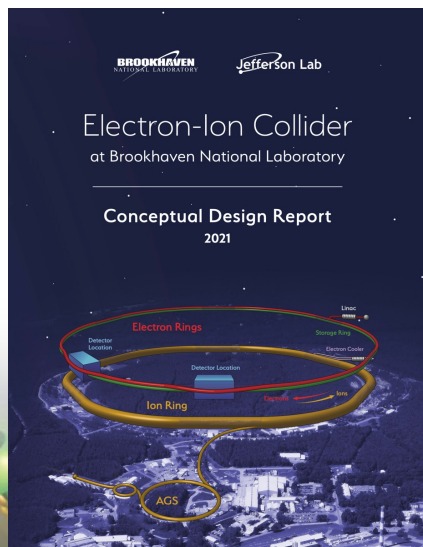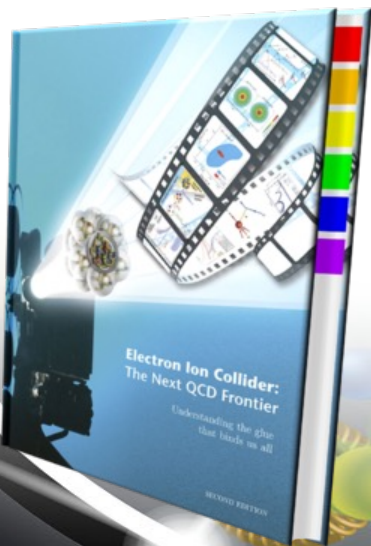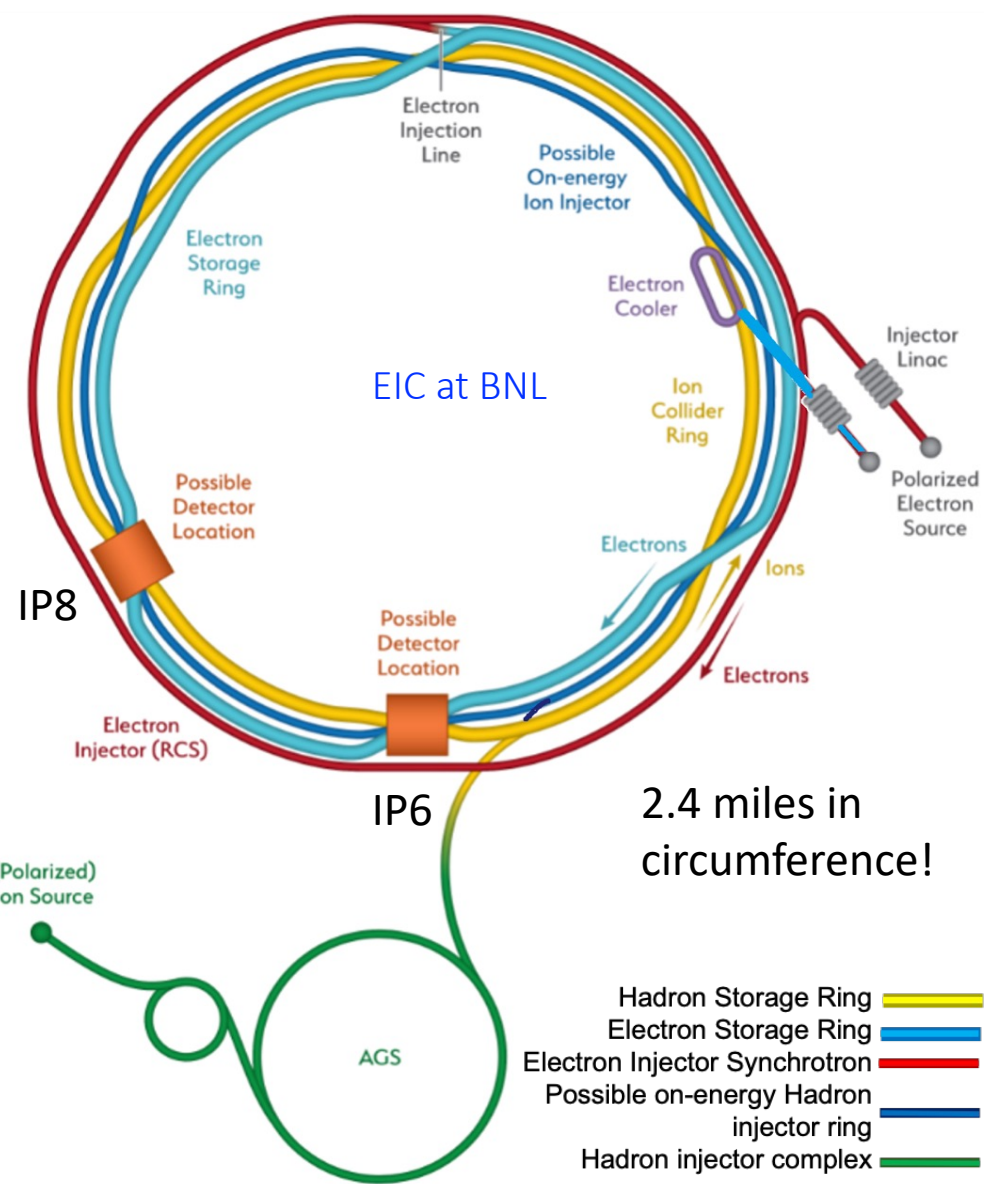
The Electron-Ion Collider (EIC)

What is the EIC:

A machine for colliding polarized electrons with polarized protons/light-nuclei, or unpolarized heavy-nuclei.

What is new/different:

- A factor of 100 - 1000 higher luminosity than HERA → more statistics, higher precision!
- Both electrons and protons / light nuclei polarized → spin-dependent observables!
- Nuclear beams: d to U → heavy-nuclei provide access to novel studies in QCD!

Data taking to start after 2030!

EIC at BNL

2.4 miles in circumference!

Hadron Storage Ring	(yellow)
Electron Storage Ring	(blue)
Electron Injector Synchrotron	(red)
Possible on-energy Hadron injector ring	(blue)
Hadron injector complex	(green)
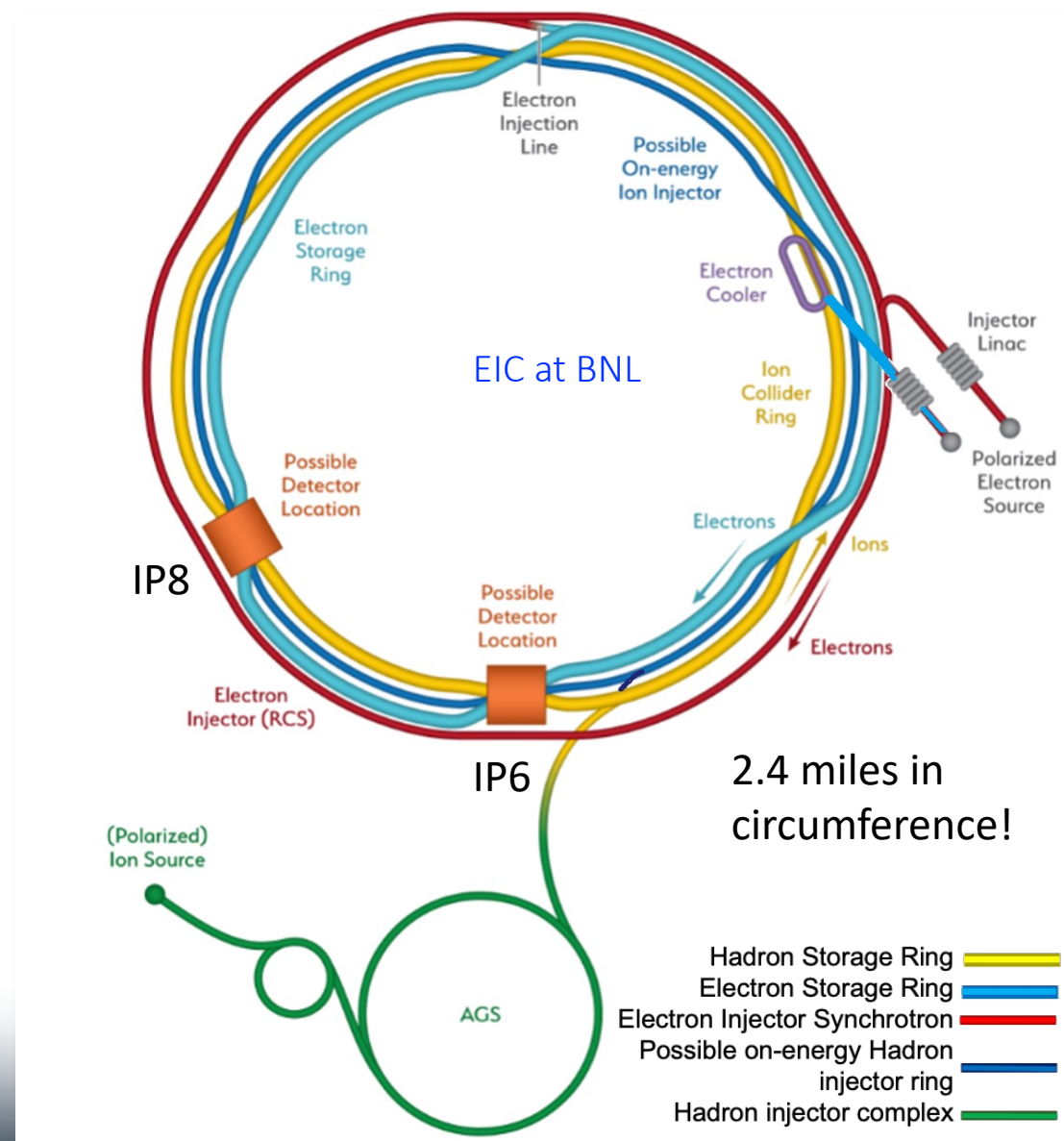
Intermission: Cute Animals

Julep
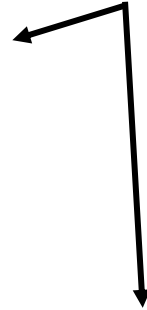
Lilu

They (mostly) get along.
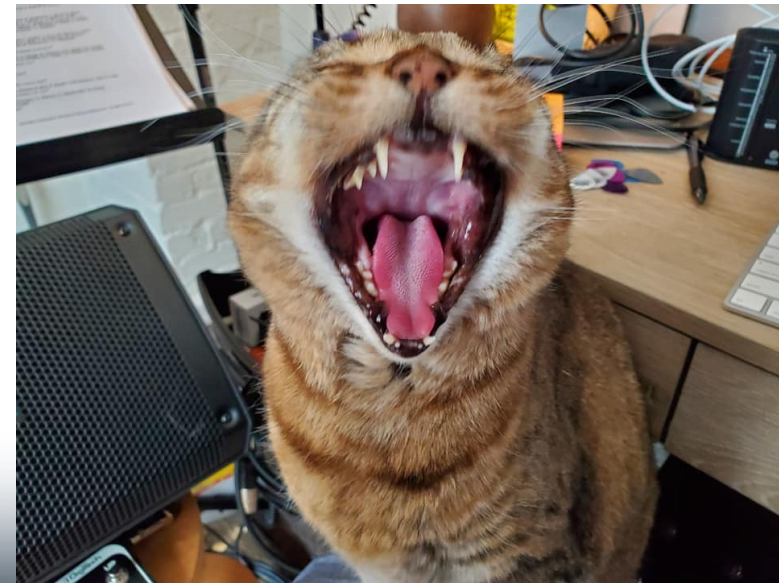
She's in a death metal band.

More about QCD

e'

e

proton

PDF

Universality

- QCD interactions arising from different collision systems should be *universal*.

Measurements from one collision system can inform studies on other systems!

Proton + proton collision

Proton

PDF

q

g

Hard Scattering Process

q

g

Hadronization

Proton

PDF

23
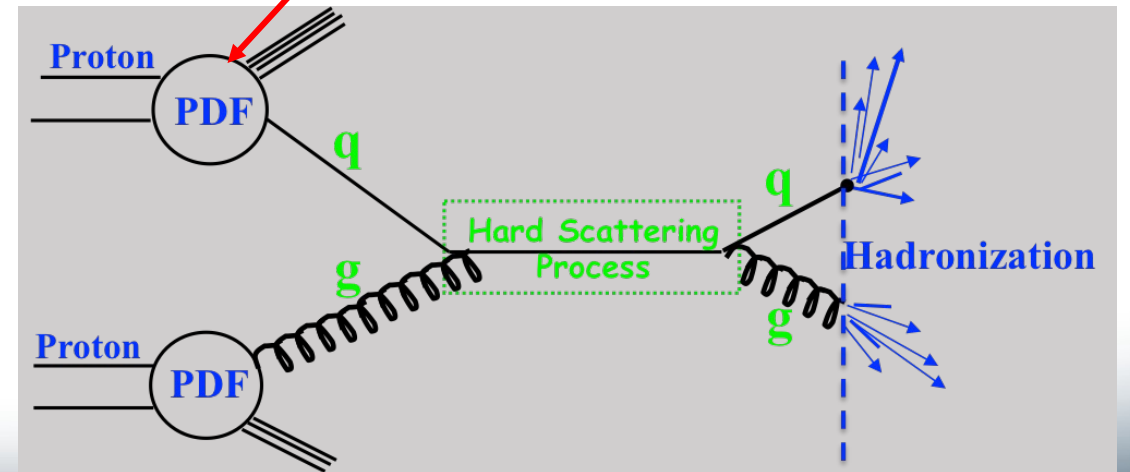
More about QCD

QCD Interactions ~ PDF $\otimes$ high-energy parton interaction $\otimes$ Hadronization

high-energy parton interaction : calculable in QCD
PDFs and Hadronization: **need to be determined experimentally**
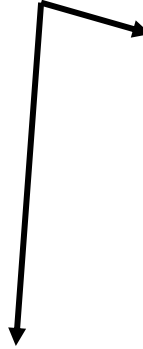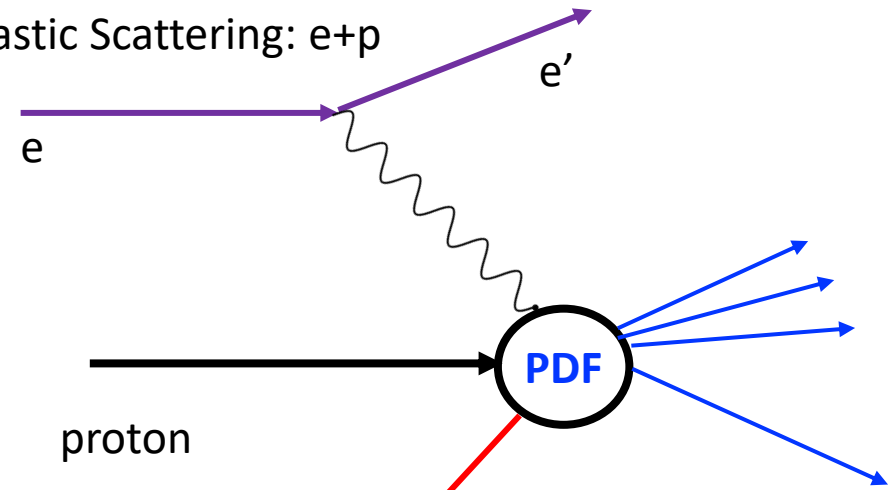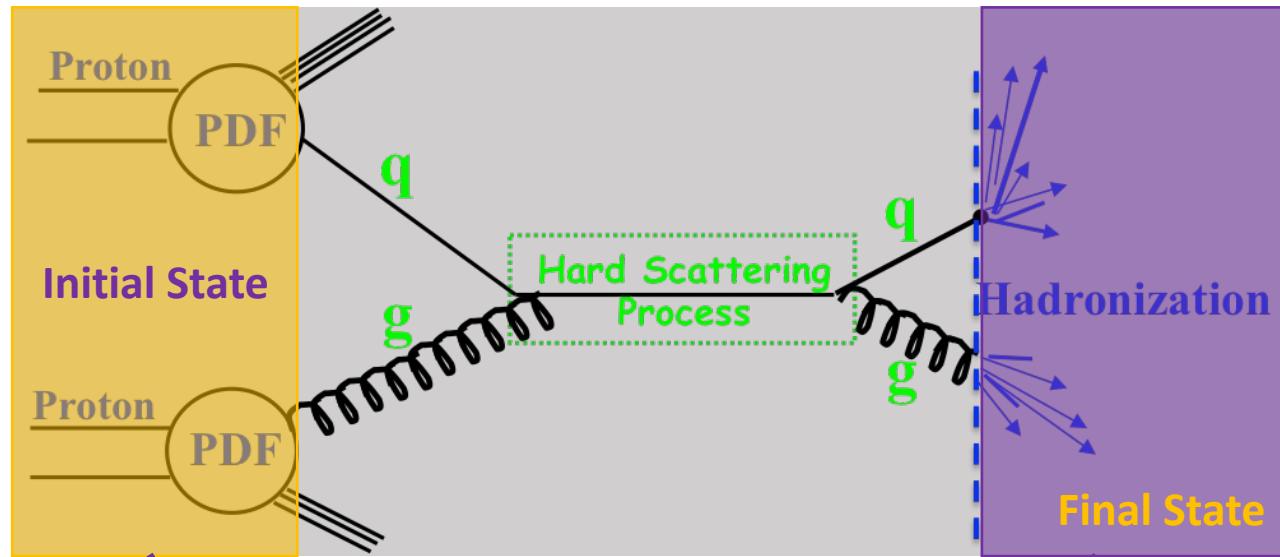

- Initial state: nuclear structure and parton distributions
  - How does the initial distribution of partons (PDF) affect the interaction?
    - Protons vs. nuclei?
  - How does polarization (spin) modfiy these distributions? → Proton spin puzzle!

- Final state: Fragmentation & Hadronization
  - How do the produced partons fragment and hadronize into the particles we measure?
  - Hadronization can aid in our understanding of confinement in QCD.
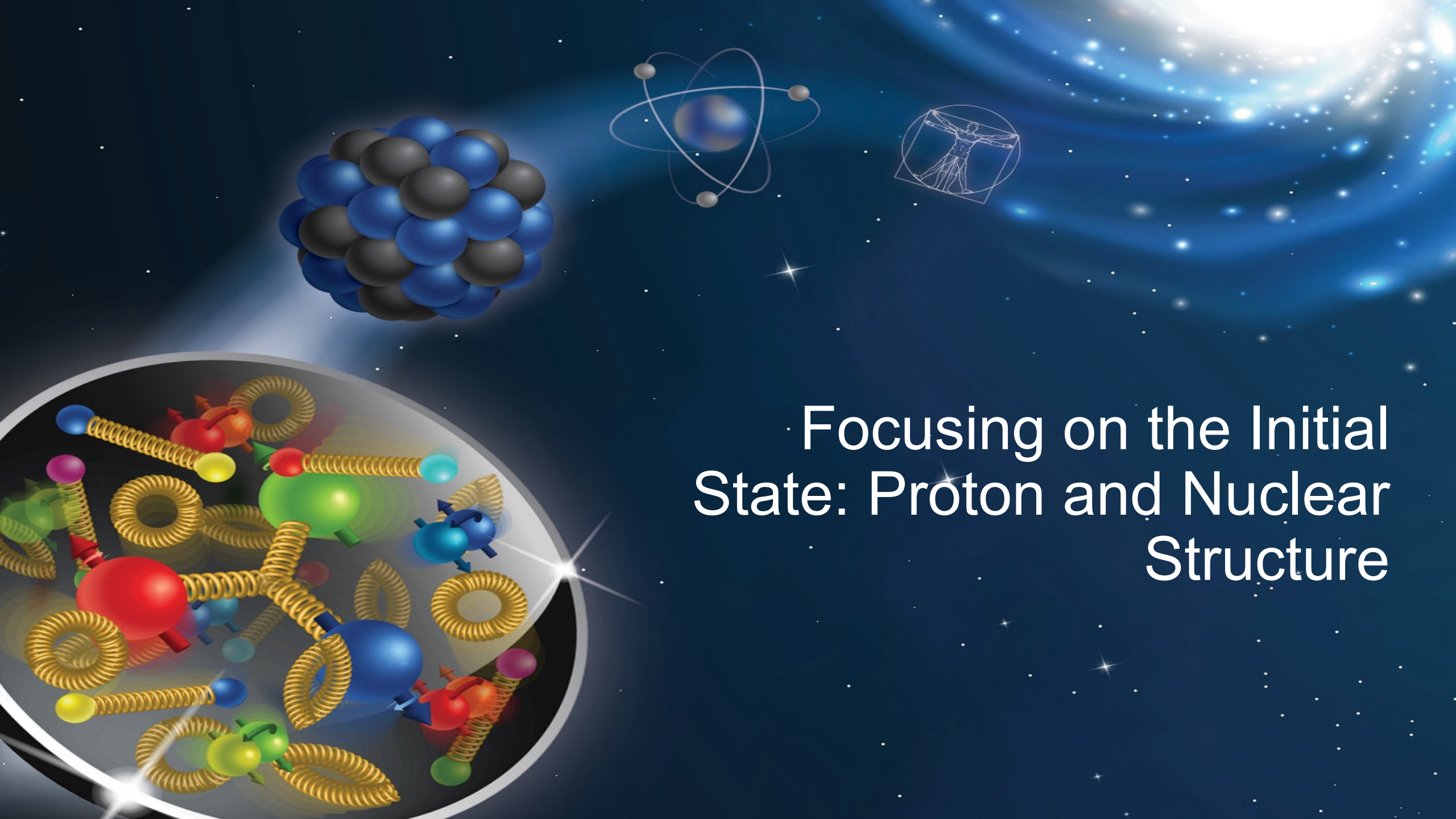
Focusing on the Initial State: Proton and Nuclear Structure

Quantifying proton structure – structure functions

Gluons manifest themselves through
➢ the behavior of the cross section as function of x and Q^2

without gluons the cross section depends only on
x, no dependence on Q^2 ➔ $F_2(x)$

Bjorken scaling

$$cross\ section \sim \alpha F_2(x, Q^2) + \beta F_L(x, Q^2)$$

quark+anti-quark
momentum distributions

gluon momentum
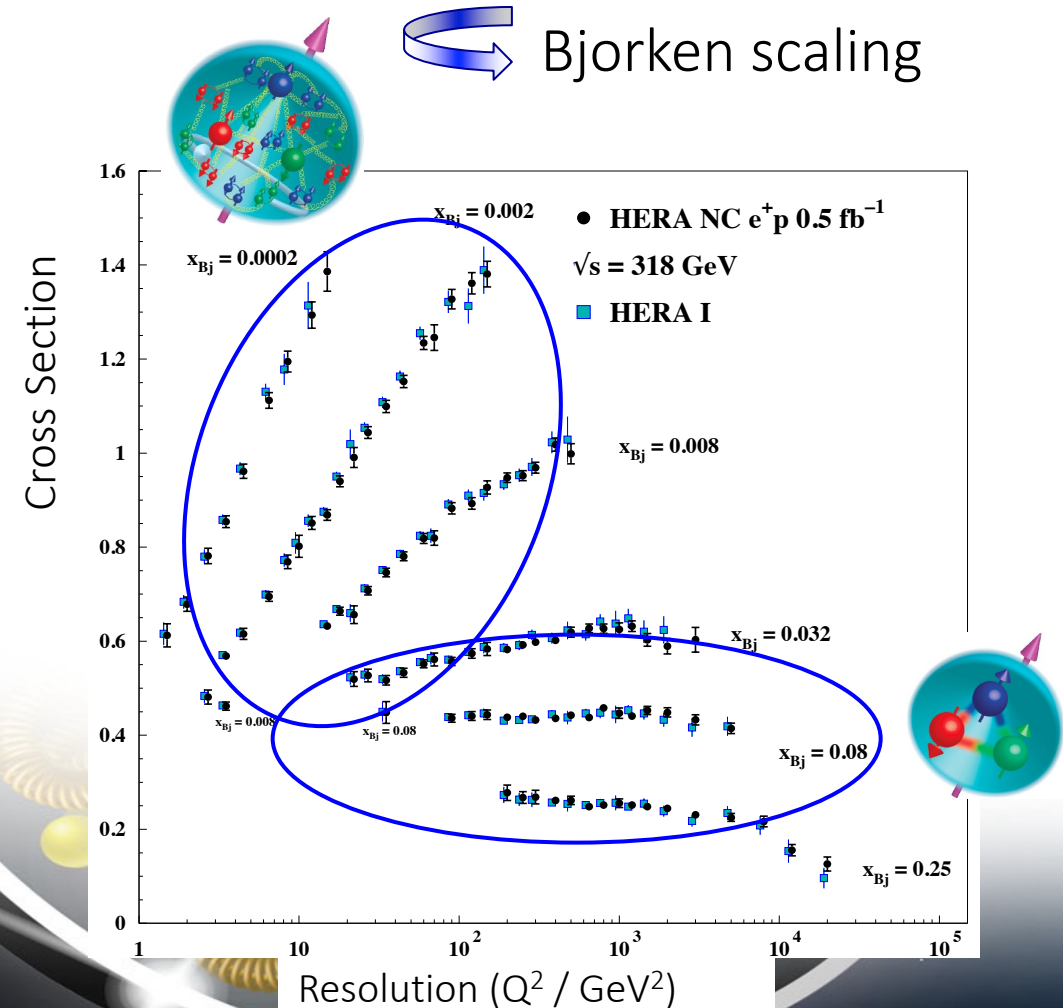distribution

F_2 and F_L - "structure functions"

"cross section" – essentially a probability for an event.

$$DIS\ cross\ section \times luminosity = DIS\ event\ rate$$
BUT:
$$(e.\,g.\ number\ of\ collisions\ per\ second)$$

Observe strong rise of cross section with both x and Q^2

Because of gluon-initiated processes
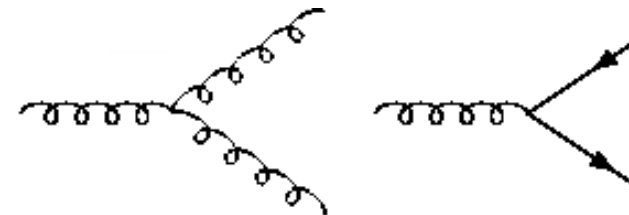
EIC:
* **How are the structure functions modified in nuclei?**
* **Spin dependence?**
* **Protons vs. neutrons?**

Cross Section

$x_{Bj} = 0.002$
$x_{Bj} = 0.0002$

● HERA NC e⁺p 0.5 fb⁻¹
√s = 318 GeV
■ HERA I

$x_{Bj} = 0.008$
$x_{Bj} = 0.032$
$x_{Bj} = 0.008$
$x_{Bj} = 0.08$
$x_{Bj} = 0.08$
$x_{Bj} = 0.25$

Resolution (Q^2 / GeV²)

Neutron Structure Functions

EIC enables use of deuteron beams → the next best thing to a beam of neutrons!

deuteron

e'

n

e

p
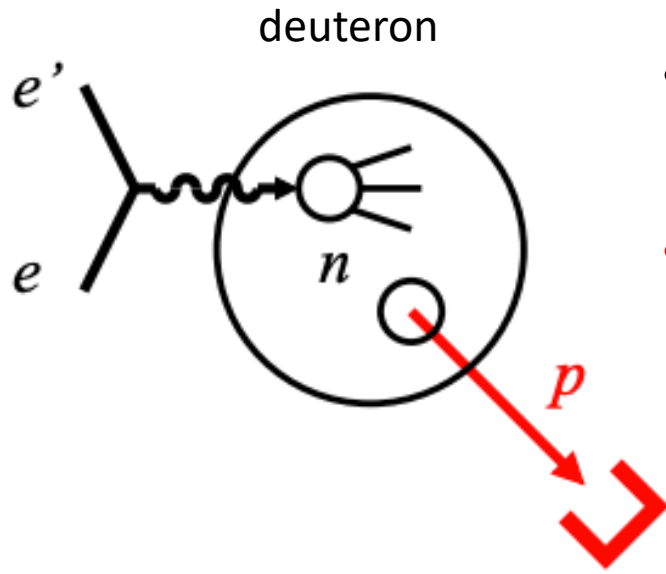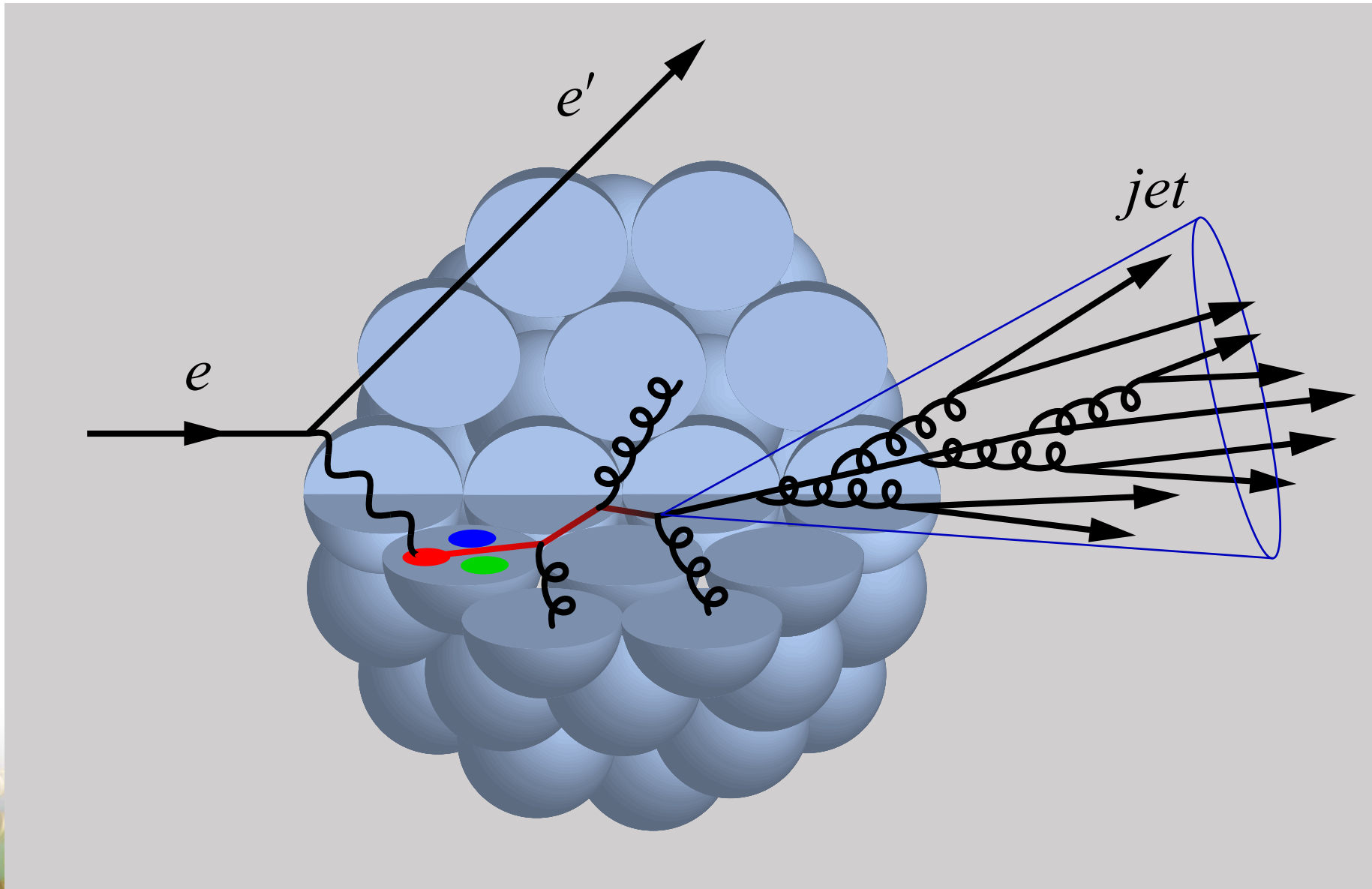
- Measurements on unpolarized deuterons[1] (or polarized He-3)[2] at the EIC.

- Spectator proton momentum → enables selection of nuclear (p/n) configurations.

  - Extract free neutron structure function[3] → Not possible elsewhere!
  - Study nuclear modifications of both nucleons in the deuteron (study in progress).

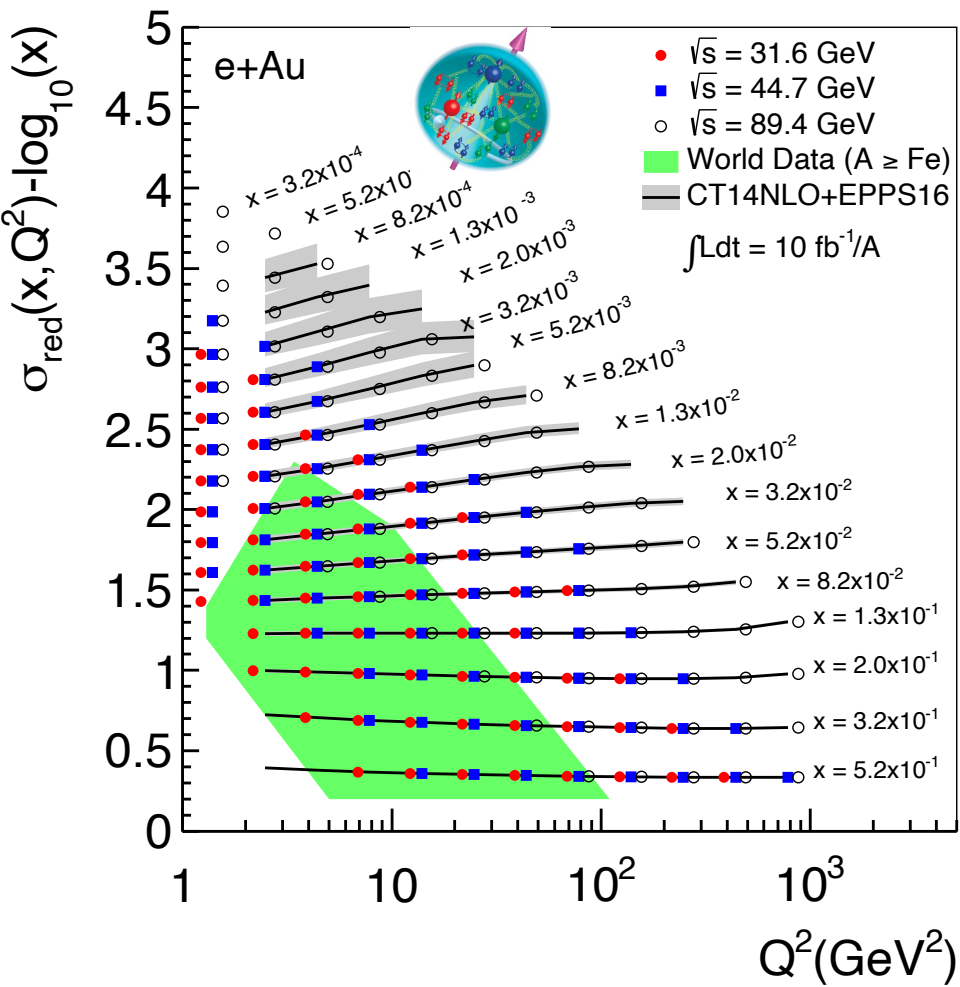[1] Z. Tu, A. Jentsch, et al., Physics Letters B, (2020)
[2] I. Friscic, D. Nguyen, J. R. Pybus, A. Jentsch, *et al.,* Phys. Lett. B, **Volume 823**, 136726 (2021)
[3] A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104,** 065205, (2021) **(Editor's Suggestion)**
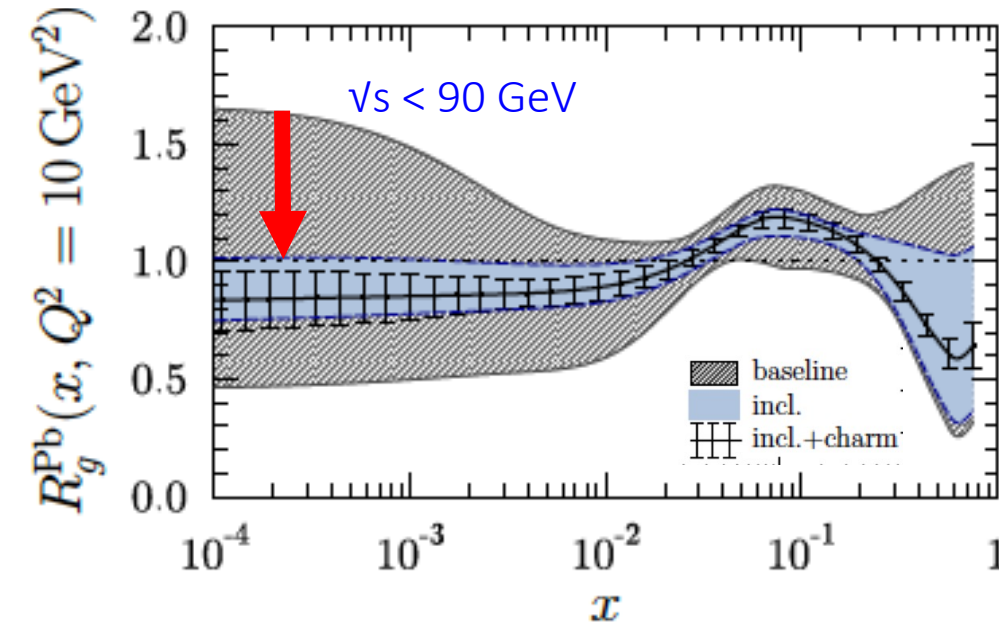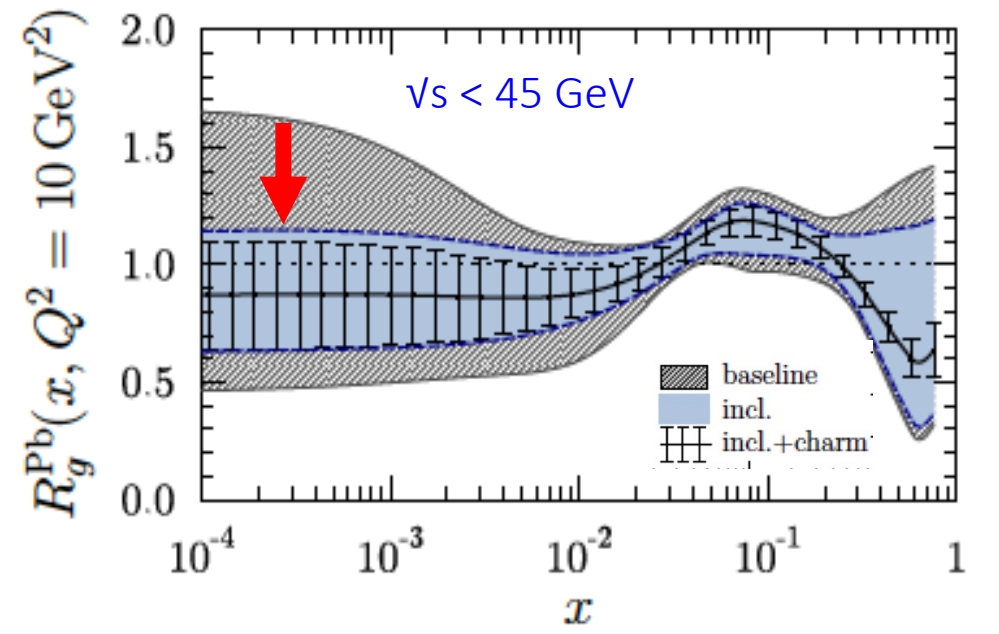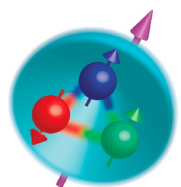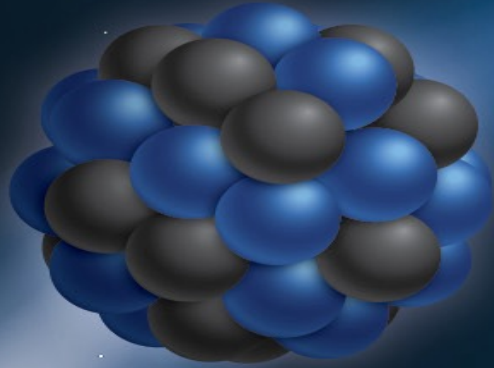
What about nuclei?

Nuclear Parton Distribution Functions

√s = 31.6 GeV
√s = 44.7 GeV
√s = 89.4 GeV
World Data (A ≥ Fe)
CT14NLO+EPPS16

∫Ldt = 10 fb⁻¹/A

e+Au

$x = 3.2 \times 10^{-4}$
$x = 5.2 \times 10^{-4}$
$x = 8.2 \times 10^{-4}$
$x = 1.3 \times 10^{-3}$
$x = 2.0 \times 10^{-3}$
$x = 3.2 \times 10^{-3}$
$x = 5.2 \times 10^{-3}$
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$x = 8.2 \times 10^{-2}$
$x = 1.3 \times 10^{-1}$
$x = 2.0 \times 10^{-1}$
$x = 3.2 \times 10^{-1}$
$x = 5.2 \times 10^{-1}$

More data from EIC

=

Better constraints on nPDFs

√s < 45 GeV

baseline
incl.
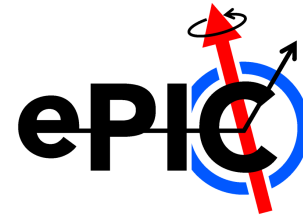incl.+charm

√s < 90 GeV

baseline
incl.
incl.+charm

E. C. Aschenauer, S. Fazio, M. A. C. Lamont, H. Paukkunen, and P. Zurita
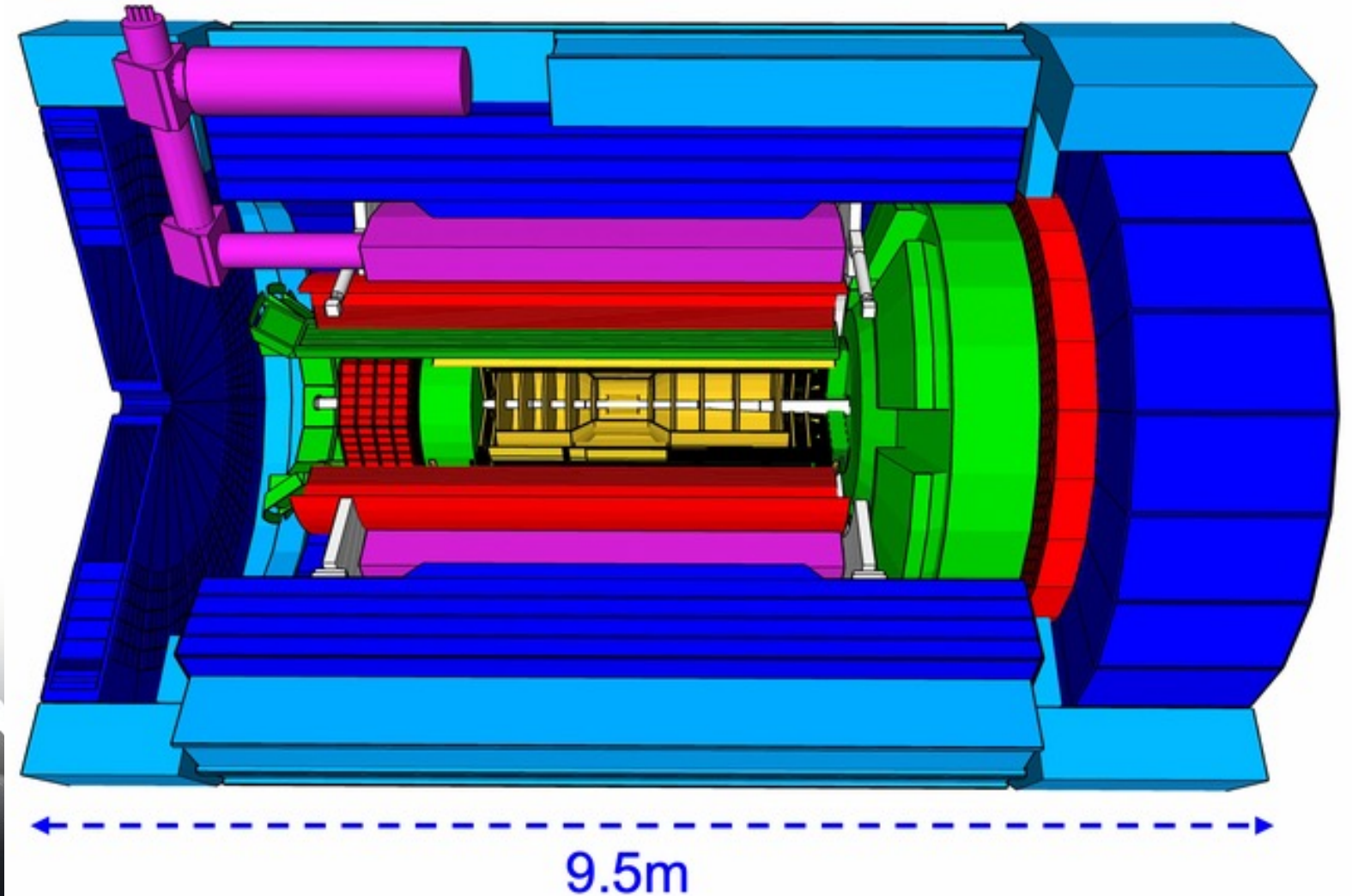Phys. Rev. D **96**, 114005 (2017)

So, how do we take pictures of the collisions at the EIC? What is our *microscope*?
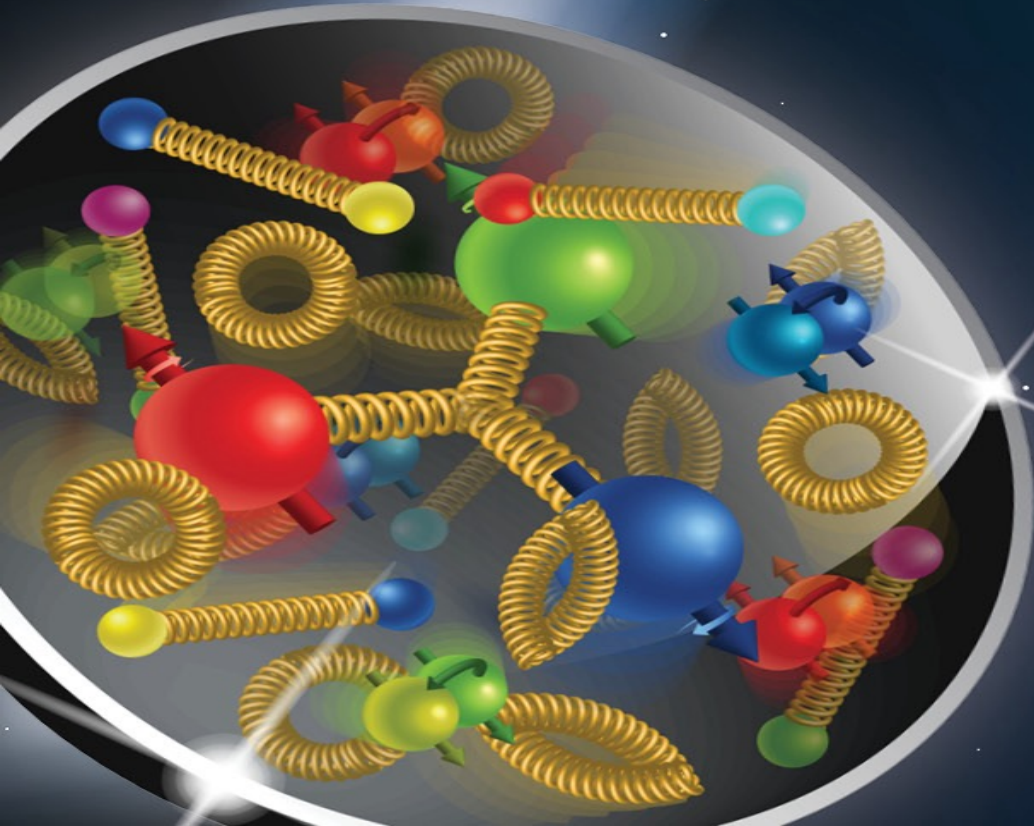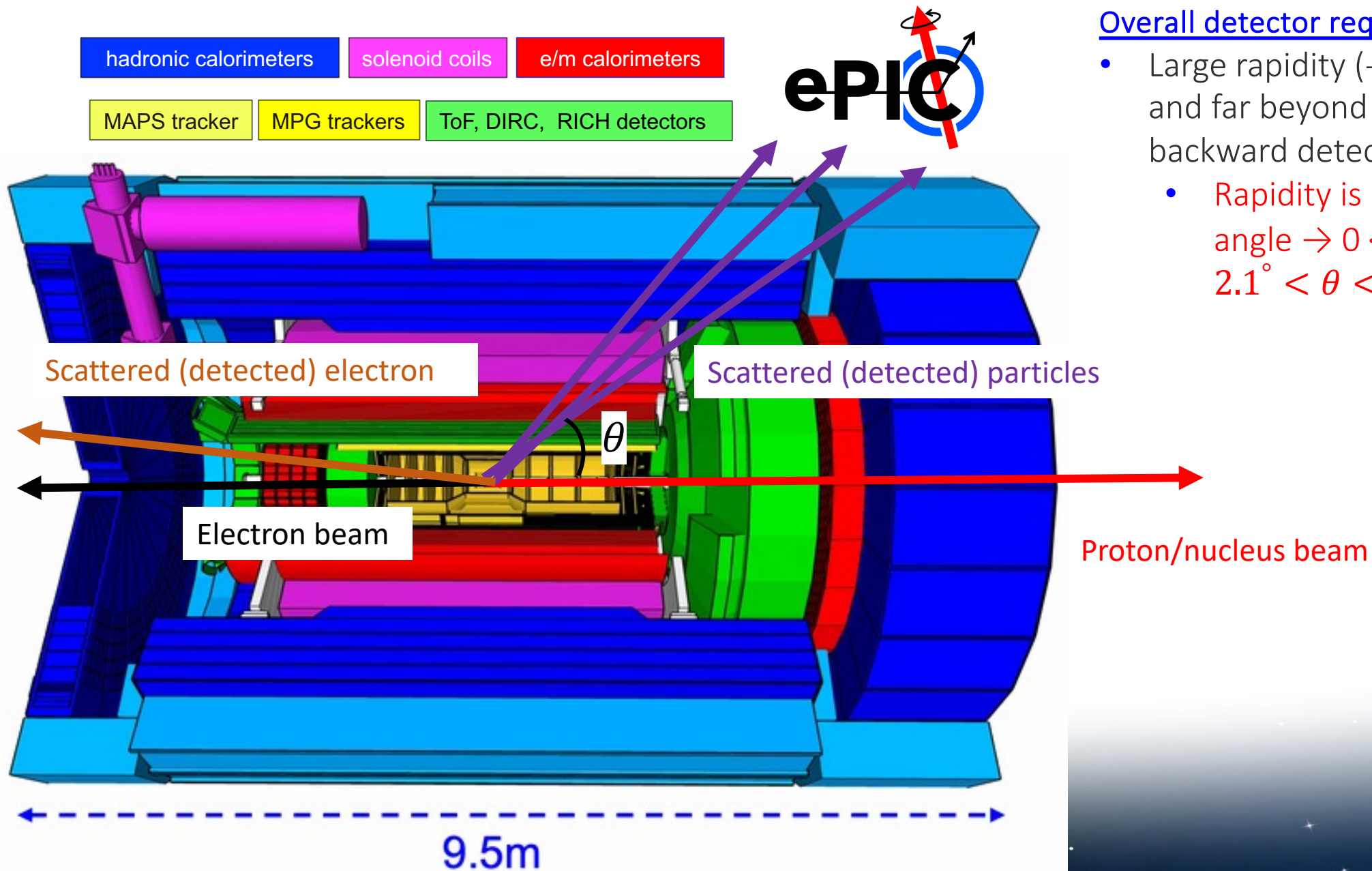
The ePIC Detector

hadronic calorimeters   solenoid coils   e/m calorimeters

MAPS tracker   MPG trackers   ToF, DIRC, RICH detectors

ePIC

9.5m

The ePIC Detector

hadronic calorimeters | solenoid coils | e/m calorimeters

MAPS tracker | MPG trackers | ToF, DIRC, RICH detectors

Scattered (detected) electron

Scattered (detected) particles
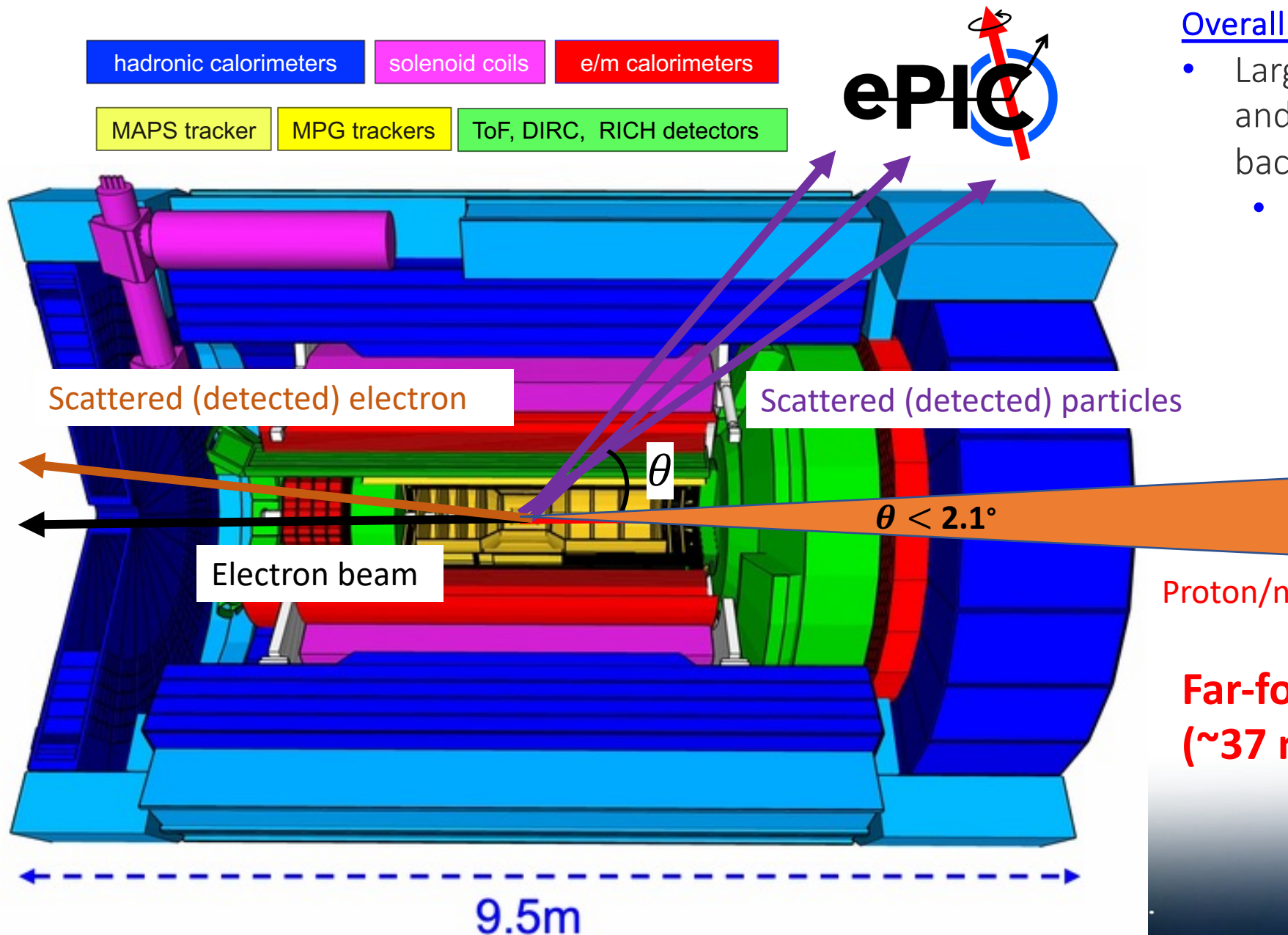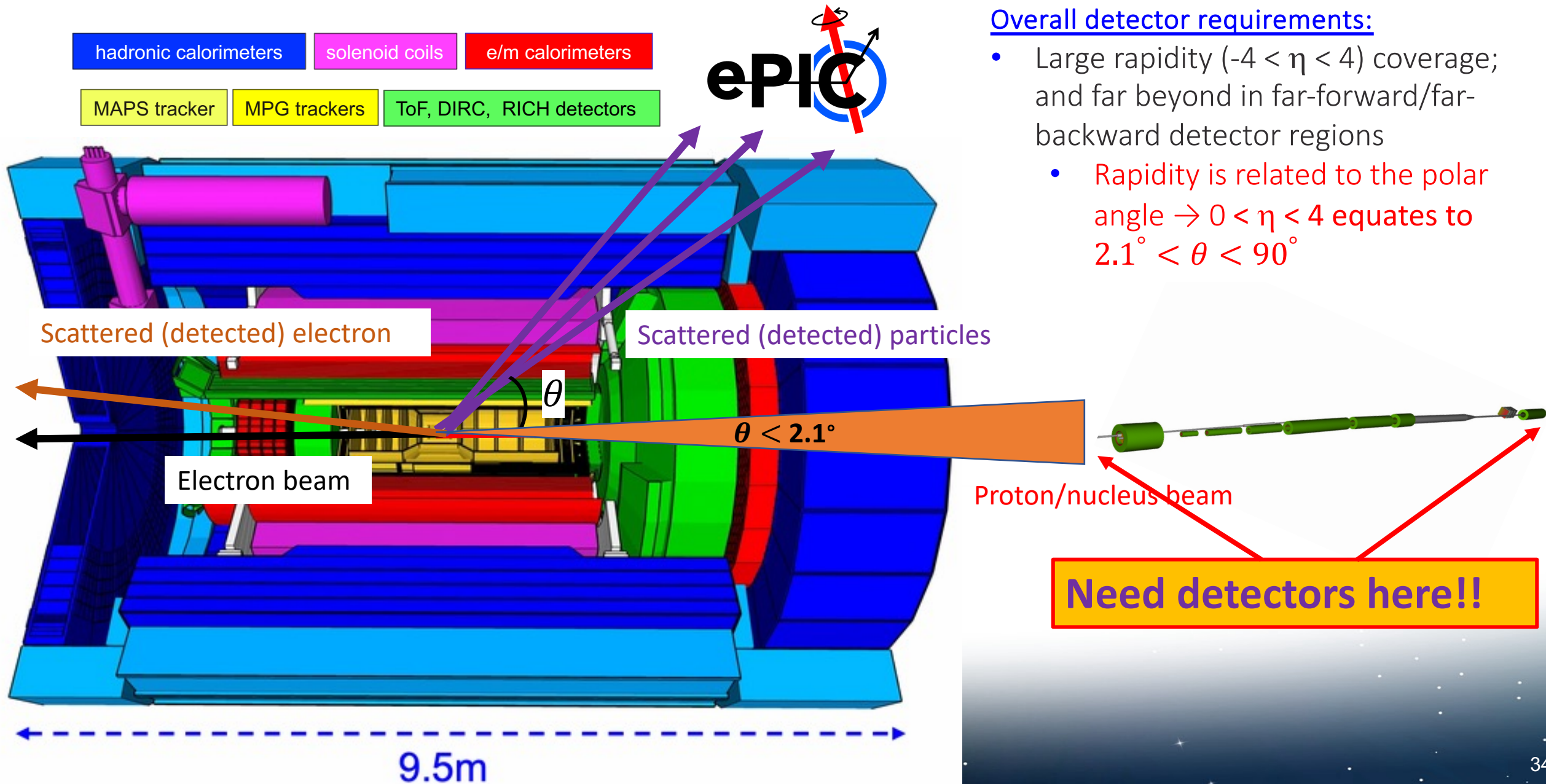
θ

Electron beam

Proton/nucleus beam

9.5m

Overall detector requirements:
- Large rapidity ($-4 < \eta < 4$) coverage; and far beyond in far-forward/far-backward detector regions
  - Rapidity is related to the polar angle $\rightarrow$ $0 < \eta < 4$ equates to $2.1° < \theta < 90°$

The ePIC Detector

hadronic calorimeters | solenoid coils | e/m calorimeters

MAPS tracker | MPG trackers | ToF, DIRC, RICH detectors

Scattered (detected) electron

Scattered (detected) particles

θ

$\theta < 2.1°$

Electron beam

Proton/nucleus beam

9.5m

**Overall detector requirements:**
- Large rapidity (-4 < η < 4) coverage; and far beyond in far-forward/far-backward detector regions
  - Rapidity is related to the polar angle → 0 < η < 4 equates to $2.1° < \theta < 90°$

Far-forward here means $\theta < 2.1°$ (~37 mrad)

The ePIC Detector

hadronic calorimeters | solenoid coils | e/m calorimeters

MAPS tracker | MPG trackers | ToF, DIRC, RICH detectors

Scattered (detected) electron

Scattered (detected) particles

θ

$\theta < 2.1°$

Electron beam

Proton/nucleus beam

Need detectors here!!

9.5m

Overall detector requirements:
- Large rapidity ($-4 < \eta < 4$) coverage; and far beyond in far-forward/far-backward detector regions
  - Rapidity is related to the polar angle $\to 0 < \eta < 4$ equates to $2.1° < \theta < 90°$
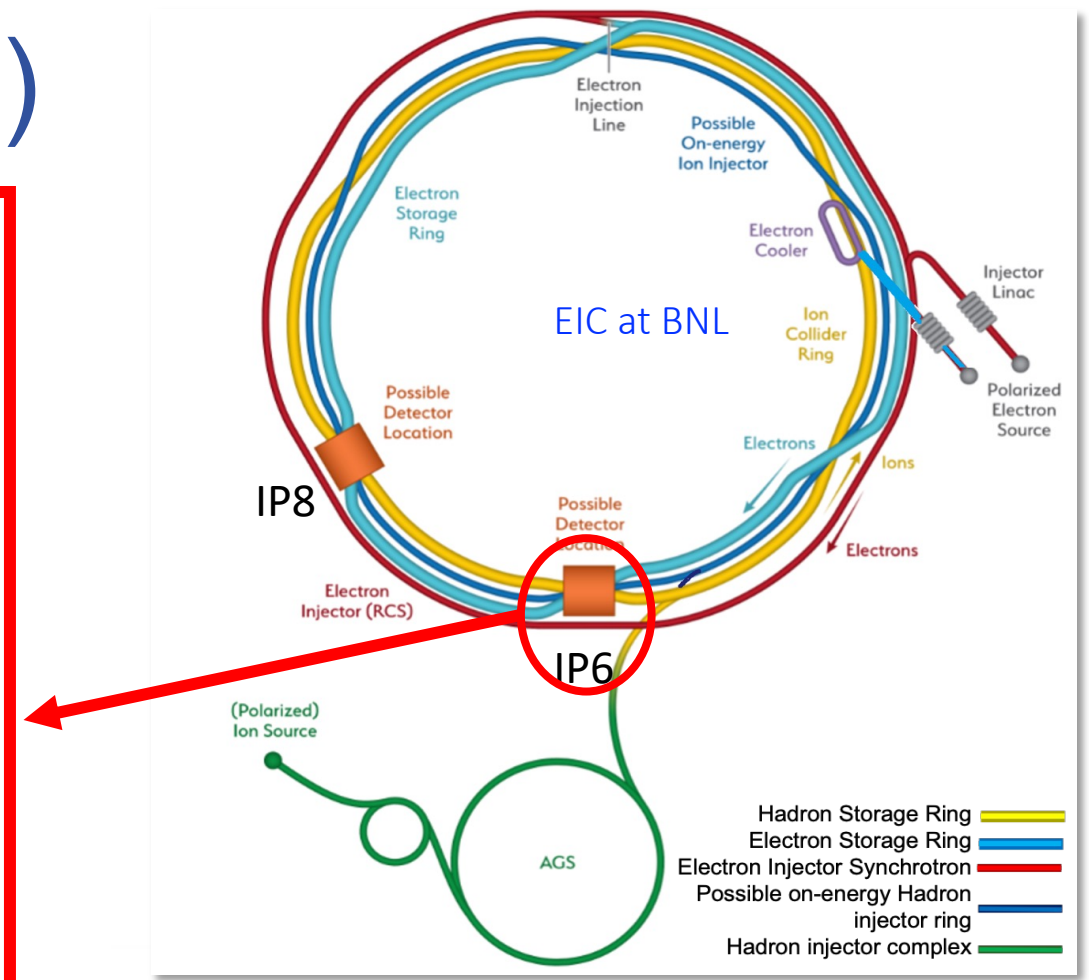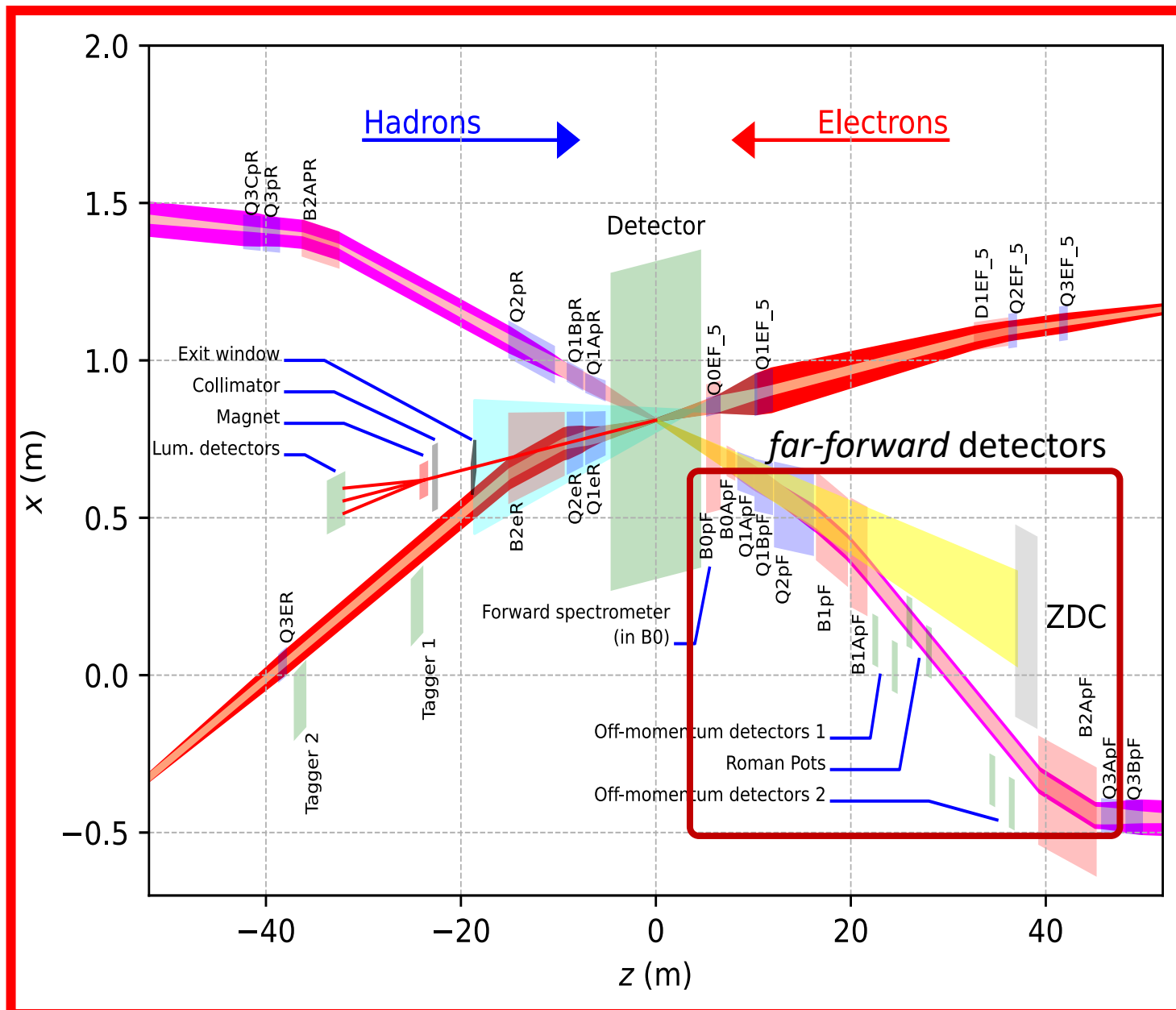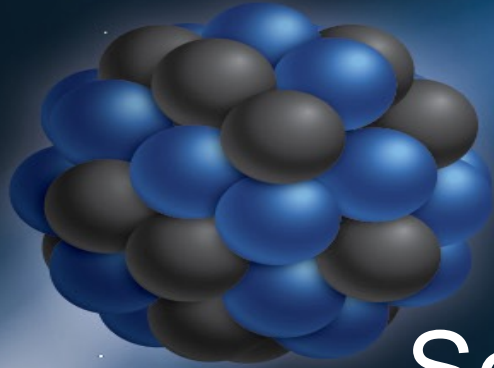
The EIC detector(s)
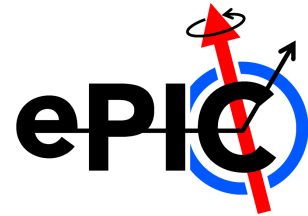
- Two interaction regions (IRs) for possible detector locations.
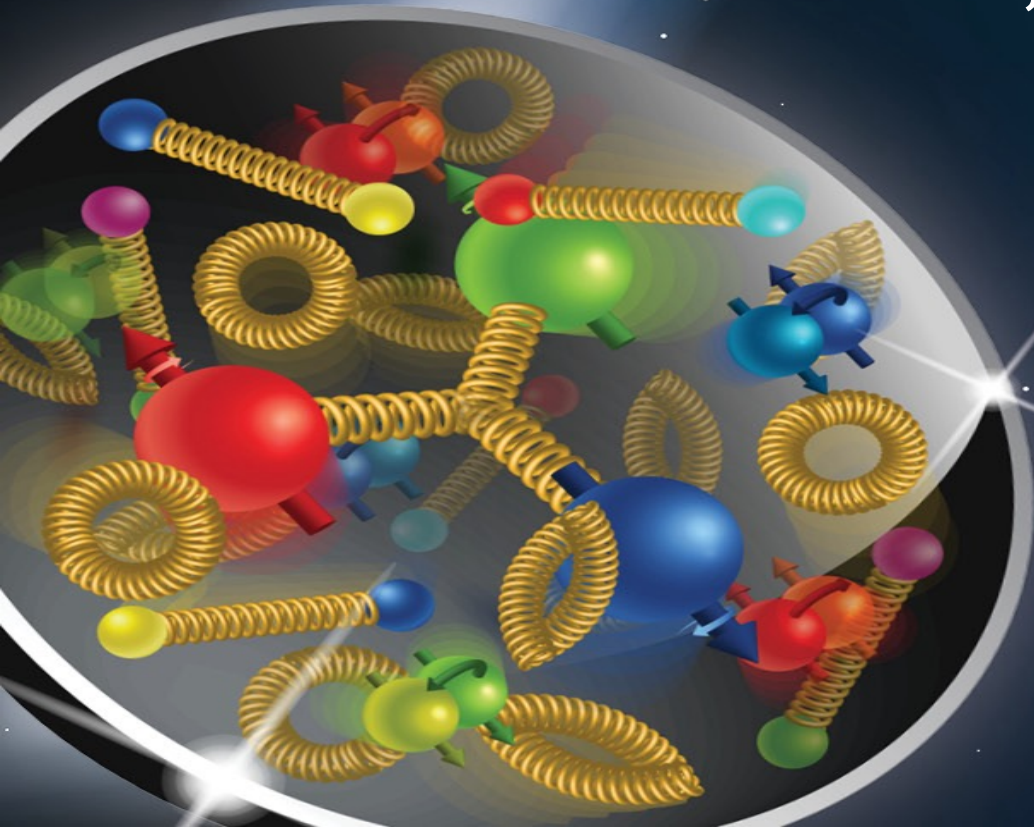 - Only one IR (IP6) part of the project scope.

9.5m
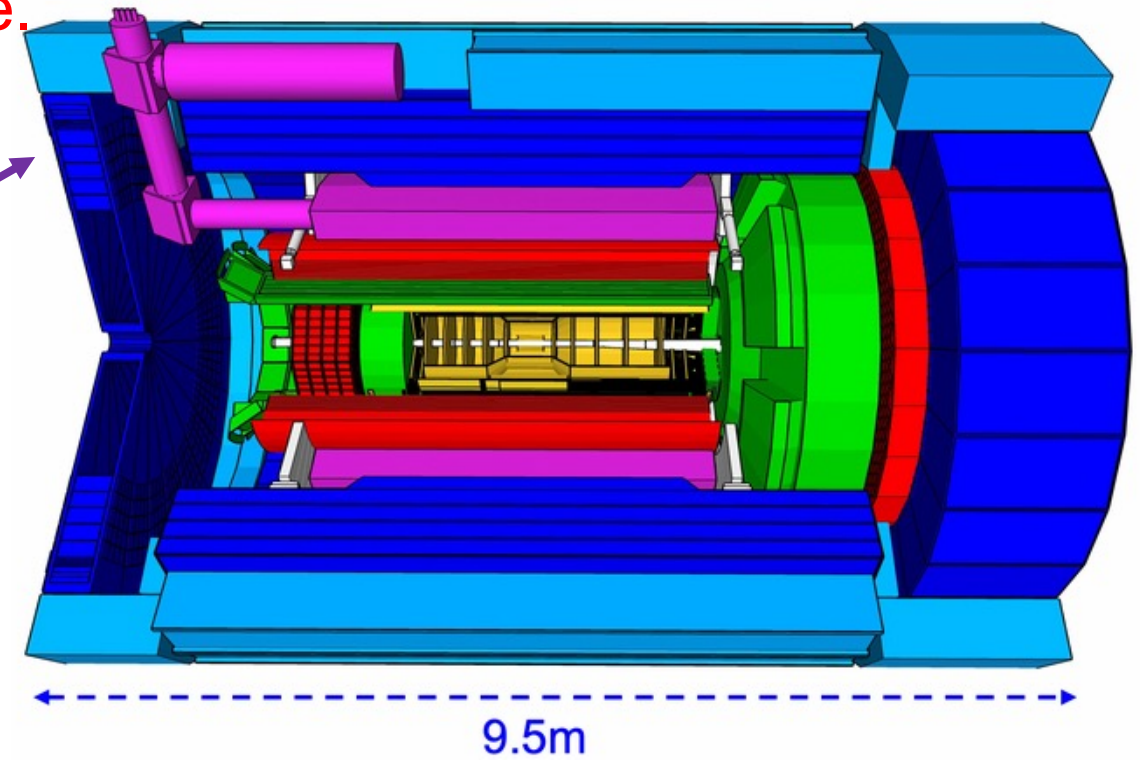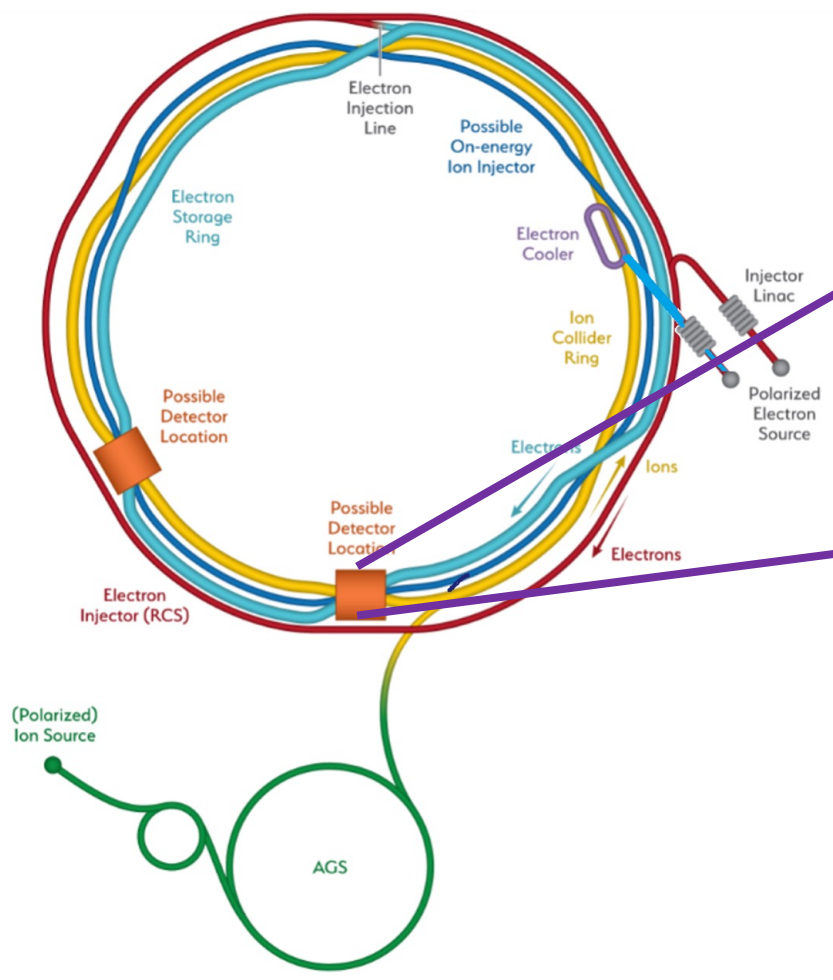
➢ ePIC detector based around a 1.7T solenoid magnet.
➢ Contains subdetectors for tracking, PID, and calorimetry.
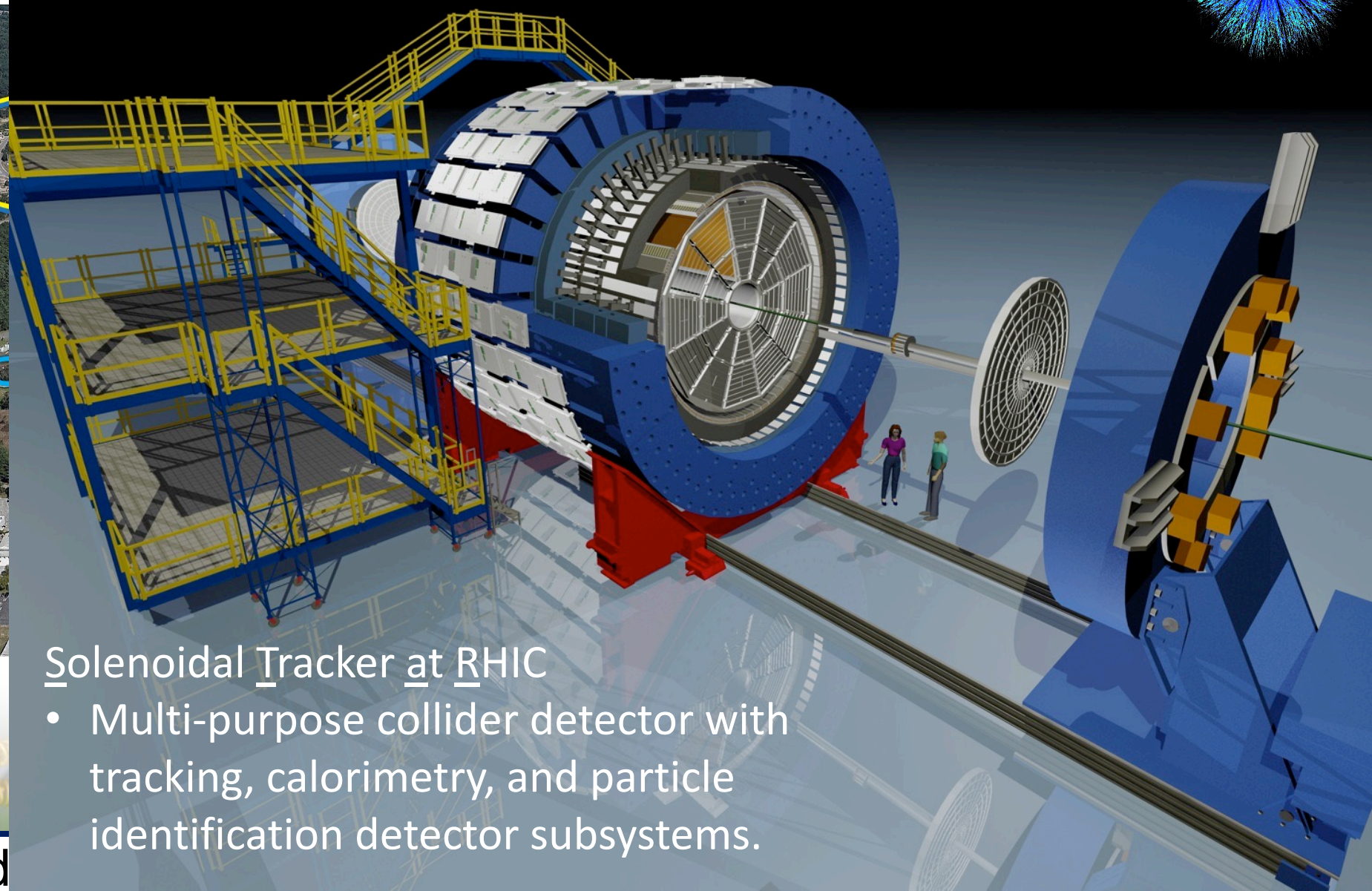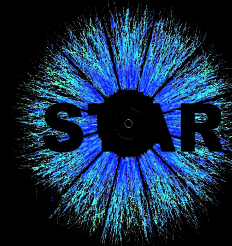
The Interaction Region (IR6)

So, the EIC seems far away…what else can we do NOW? (we are impatient, after all)

The STAR Detector

species

euteron,

p, p+Au

llider on

Solenoidal Tracker at RHIC
- Multi-purpose collider detector with tracking, calorimetry, and particle identification detector subsystems.

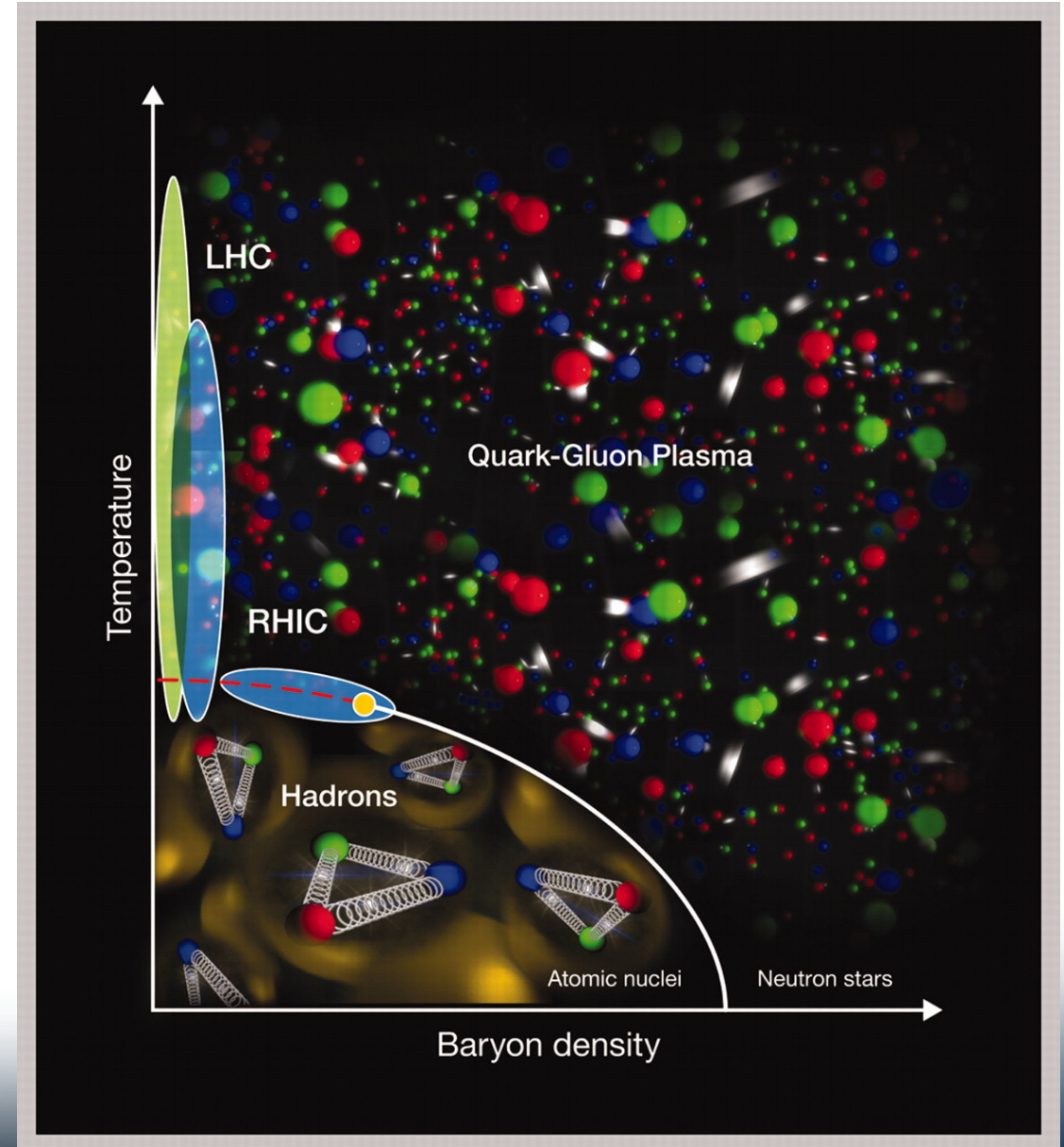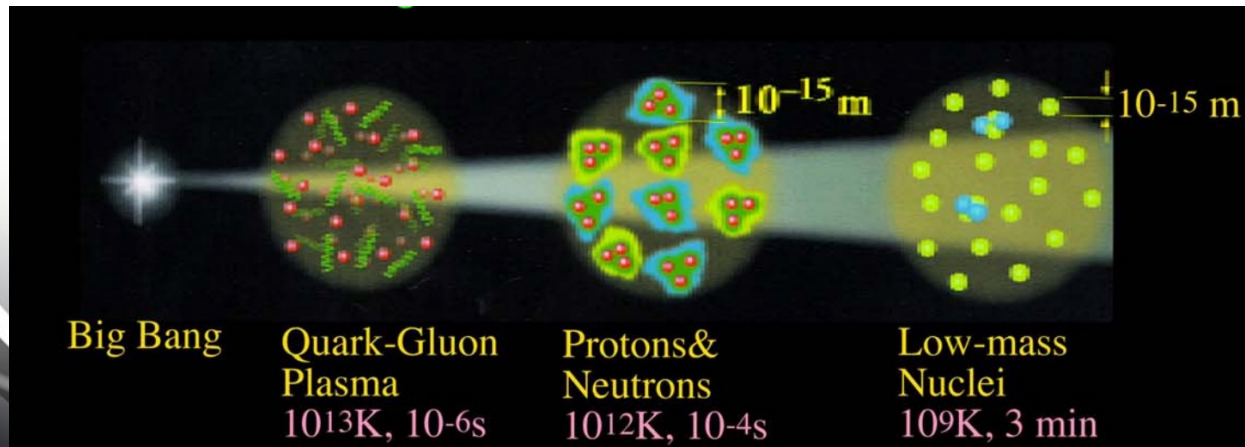PHENIX

LINAC

EBIS

BOOSTER

- Located nd).

Physics of RHIC – Hot and Cold QCD

Hot vs. Cold QCD – refers to temperature. All of the physics we have been talking about has been "cold".

"Hot" QCD

- Studies of hot, dense environment formed in heavy-ion (e.g. Au+Au) collisions!
- Extreme form of QCD matter → the Quark-Gluon Plasma → a "soup" of deconfined quarks and gluons.

Physics of RHIC – Hot and Cold QCD

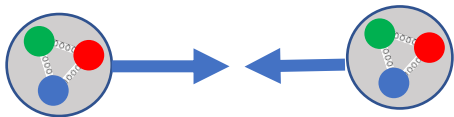## RHIC Cold QCD ⟺ EIC physics

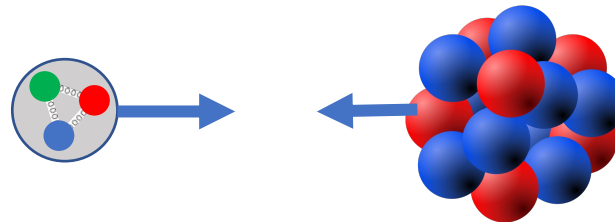**Universality!! – We are impatient, but we also need the RHIC data to fully utilize the EIC data!**

Lots of un-analyzed RHIC Cold QCD data (e.g. 2017 data), and more datasets being collected NOW!
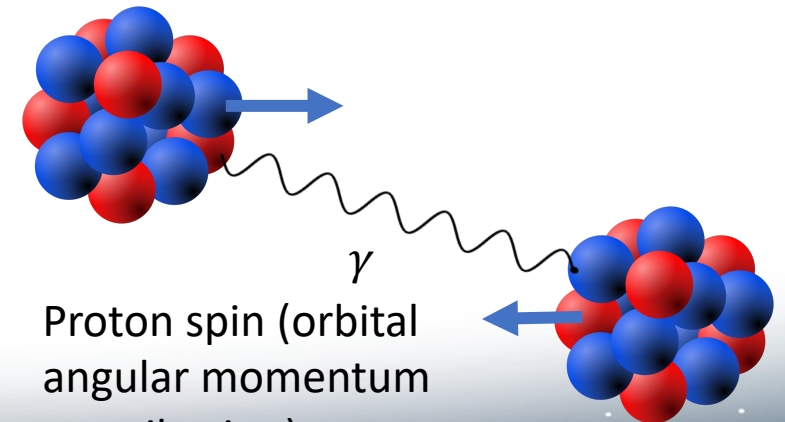
Polarized proton + proton collisions

proton + nucleus collisions

Ultra-Peripheral Au + Au (or p+p, p+A) collisions

- Proton spin (gluon contribution).

- Hints of saturation?
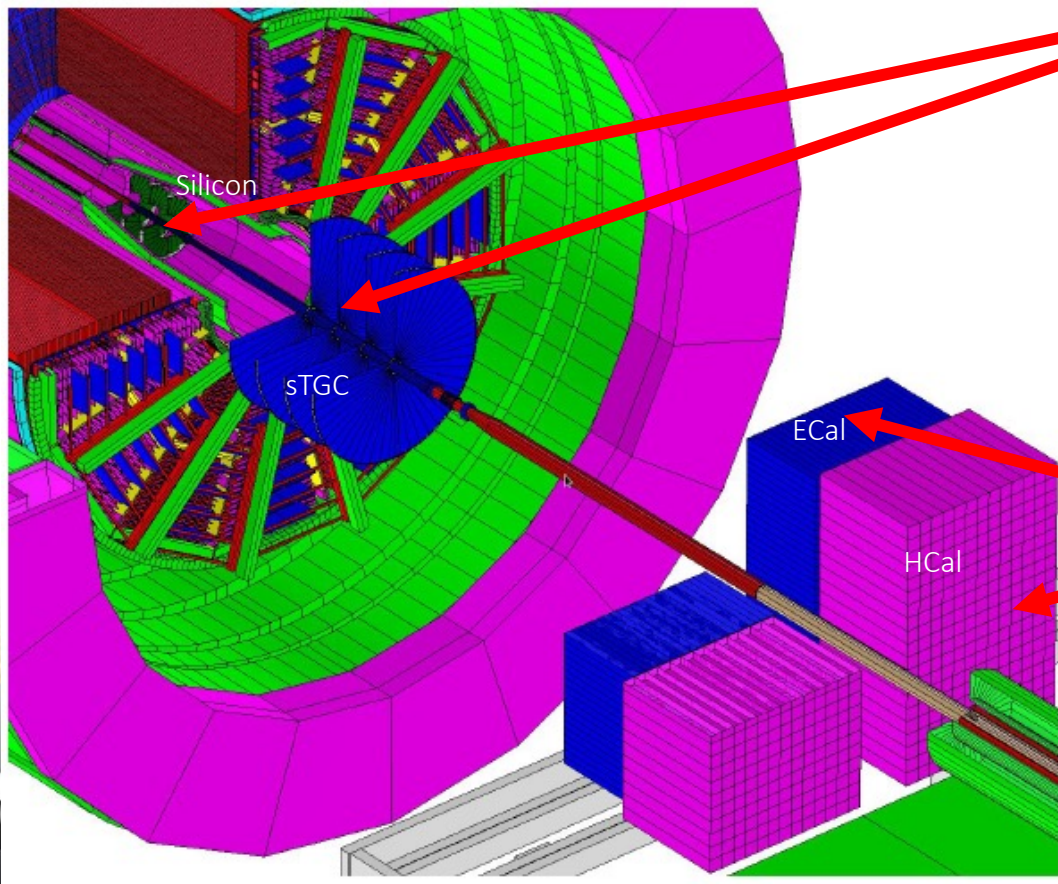- Nuclear PDFs.

- Proton spin (orbital angular momentum contribution).

γ

Looking Forward: The STAR Forward Upgrade

- Addition of silicon tracking system and EM and hadronic calorimetry → forward rapidity coverage.
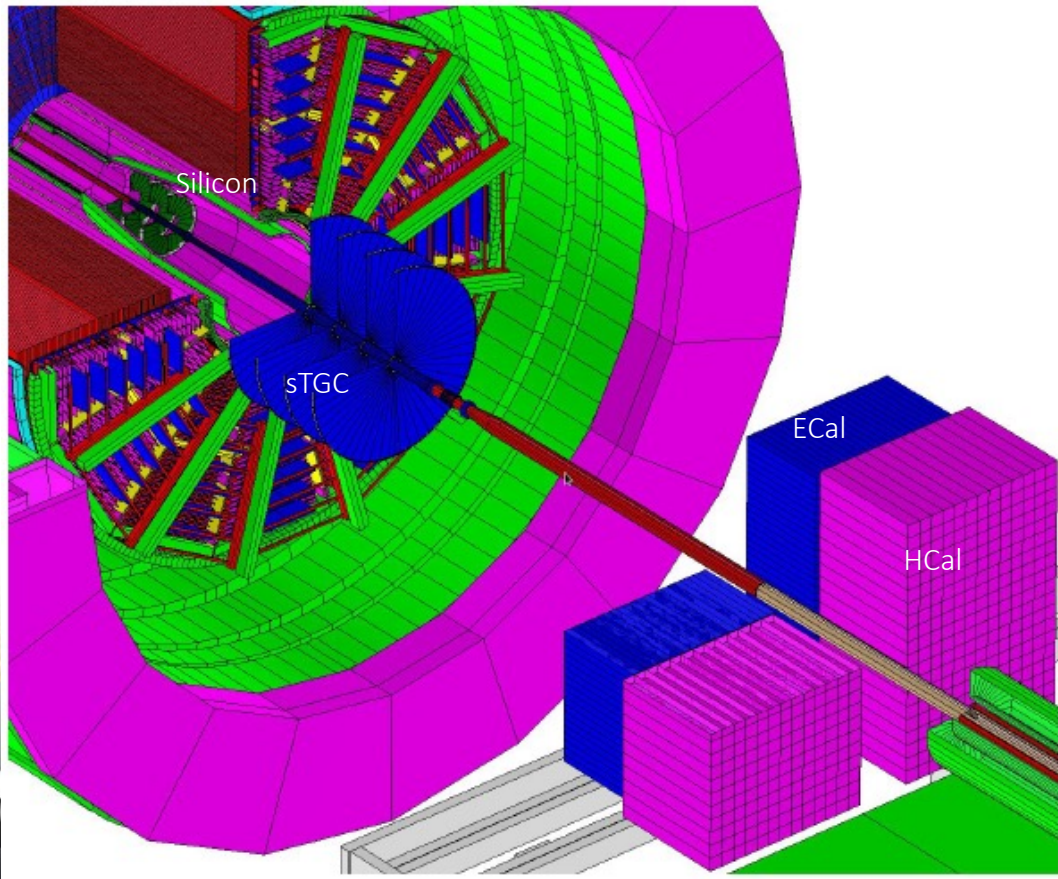 - **More coverage in x!**

Forward Silicon Tracker (FST)

First data-taking run with these new components happened in 2022 – data being produced now!

Forward Calorimeter System (FCS)

Looking Forward: The STAR Forward Upgrade

- Addition of silicon tracking system and EM and hadronic calorimetry → forward rapidity coverage.
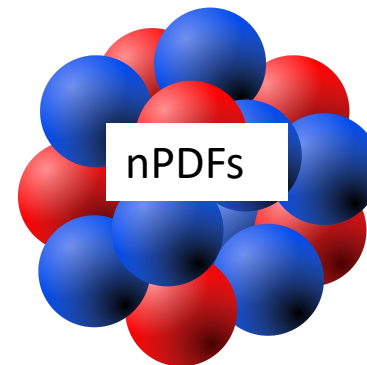 - **More coverage in x!**

Collecting Data Now!

- **STAR Forward Upgrade**

Proton spin: $\frac{1}{2} = \frac{1}{2}\Sigma_q \Delta q + \Delta G + L_{g,q}$
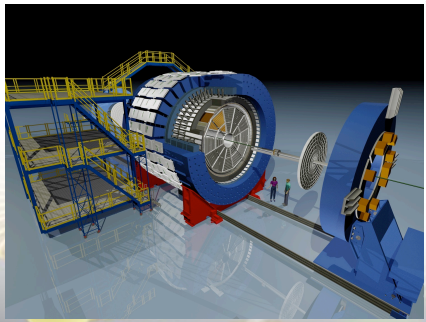
quarks   gluons
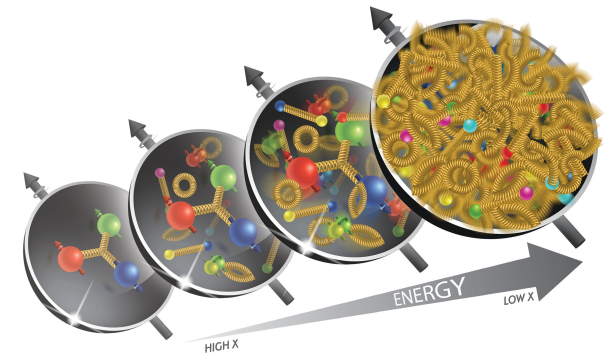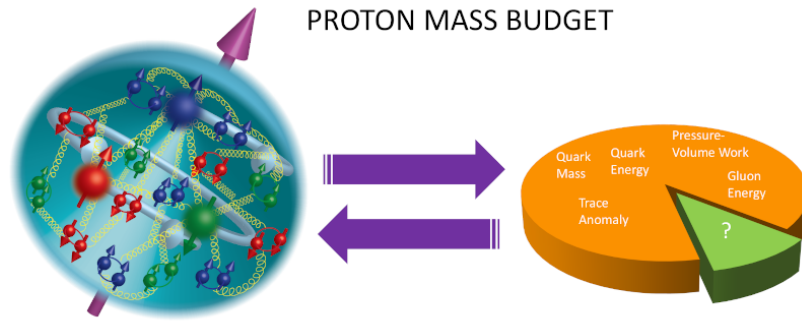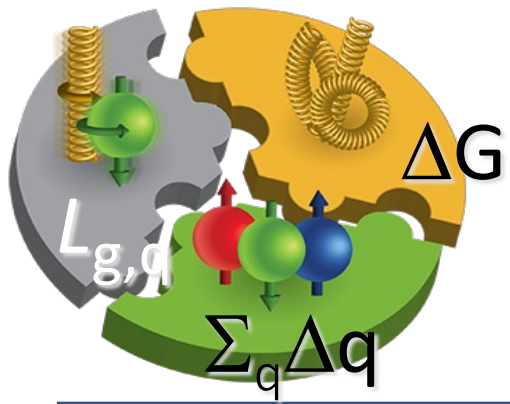
Orbital angular momentum

Lots of overlap with EIC topics!

EIC Timeline

- Leverage STAR Cold QCD program and perform studies relevant to EIC physics.

- EIC detector and physics impact studies.

2022-2025

PROTON MASS BUDGET

ΔG

$L_{g,q}$

$\Sigma_q \Delta q$

Our understanding of the structure of visible matter in the universe!

R H I C

E I C

Thank you!