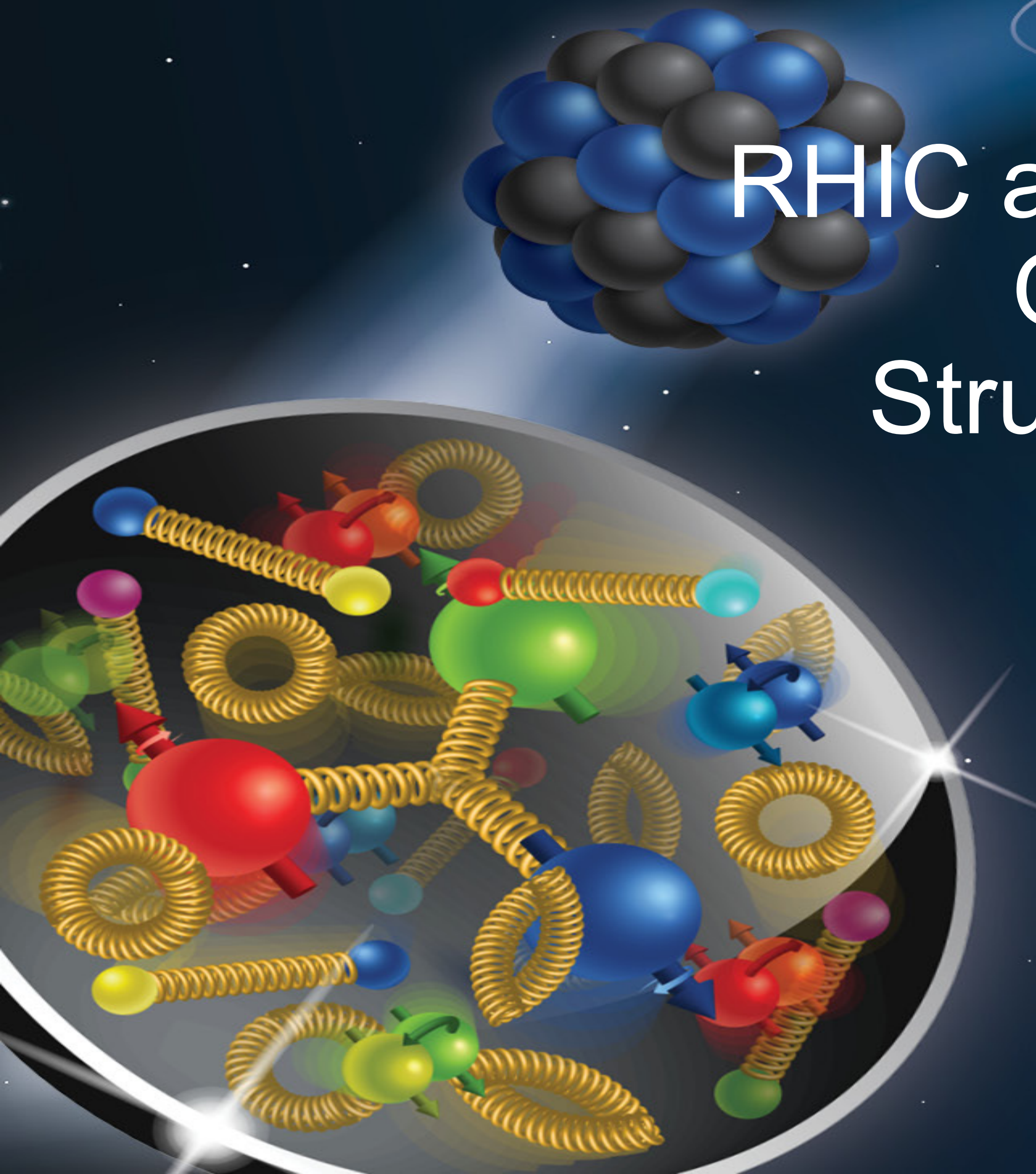
RHIC and the Electron-Ion Collider: Our Quest to Understand the Structure of Visible Matter in our Universe



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NuSTEAM/NuPUMAS @ BNL

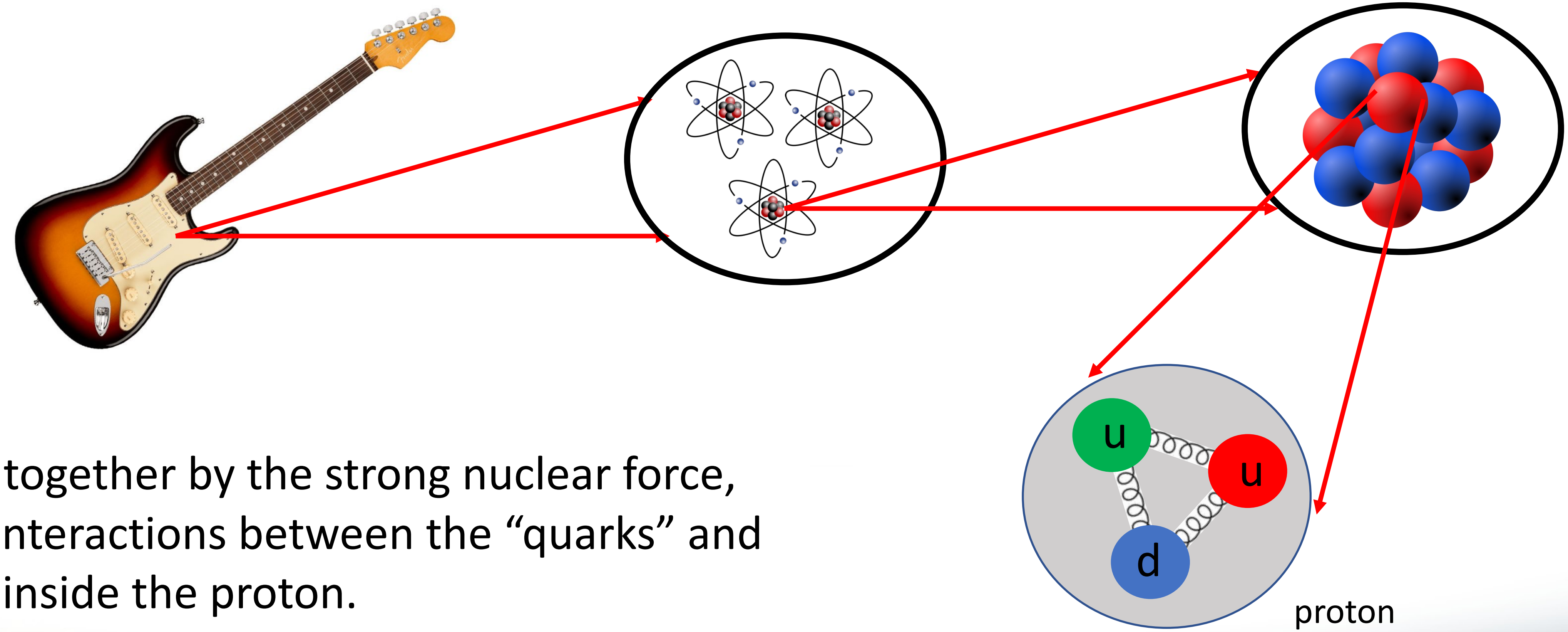
July 5^{th}, 2023

Electron Ion Collider

BROOKHAVEN NATIONAL LABORATORY · Jefferson Lab · U.S. DEPARTMENT OF ENERGY Office of Science

Visible Matter

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

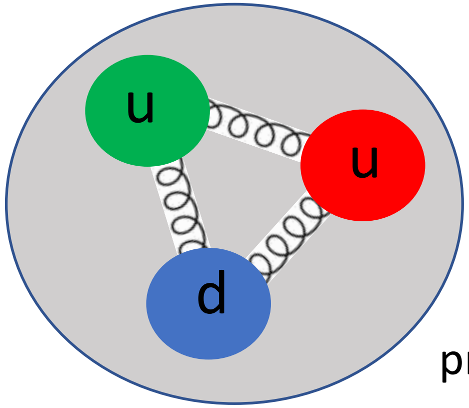


- Nuclei are held together by the strong nuclear force, which governs interactions between the “quarks” and “gluons” found inside the proton.
- Quarks and gluons collectively called “**partons**”.

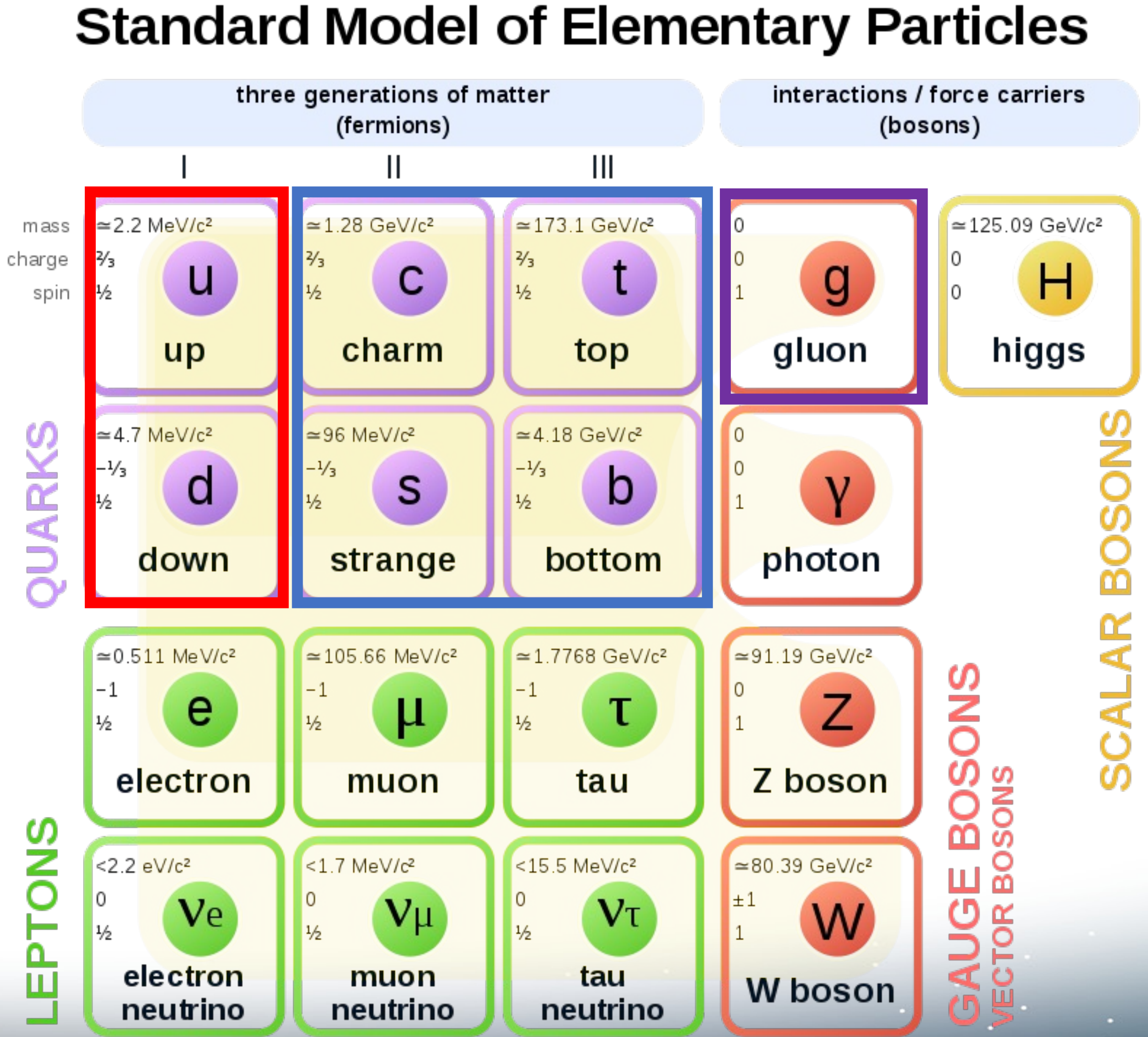
Visible Matter

- Some fundamental questions we can ask:
  - What are the properties of the proton?

  → Spin, mass, charge.
  - How do these properties manifest?



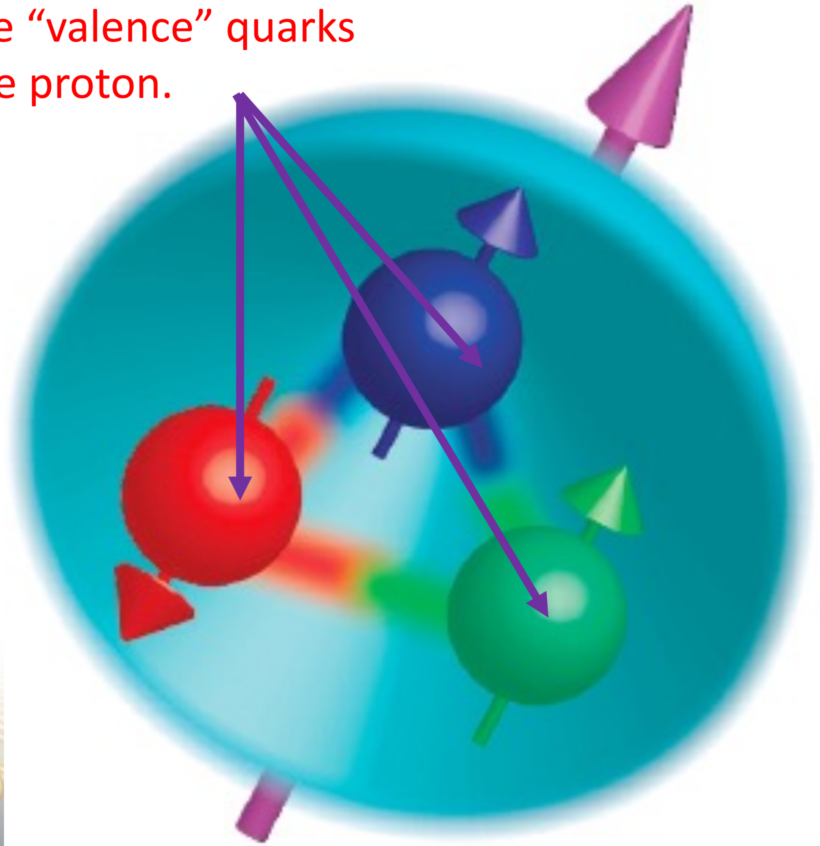
proton



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

The proton gets even more complicated

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



The Proton Spin Puzzle

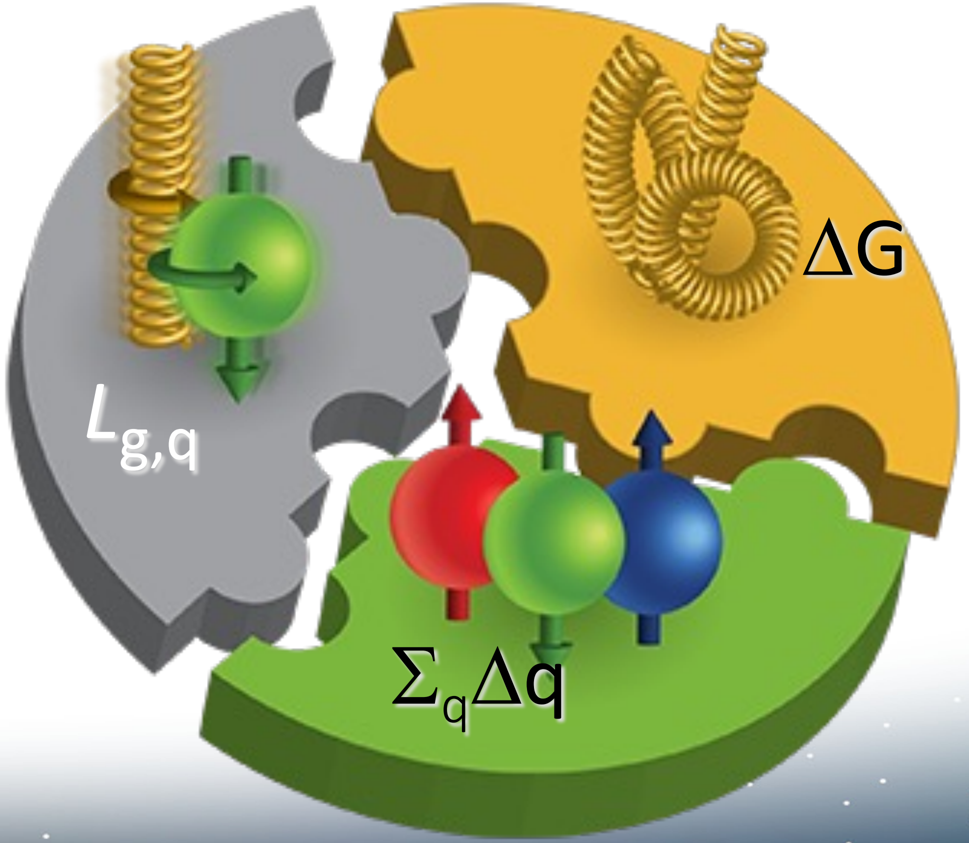
Spin structure – the three “valence” quarks do not account for the total spin of the proton!

quarks gluons

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

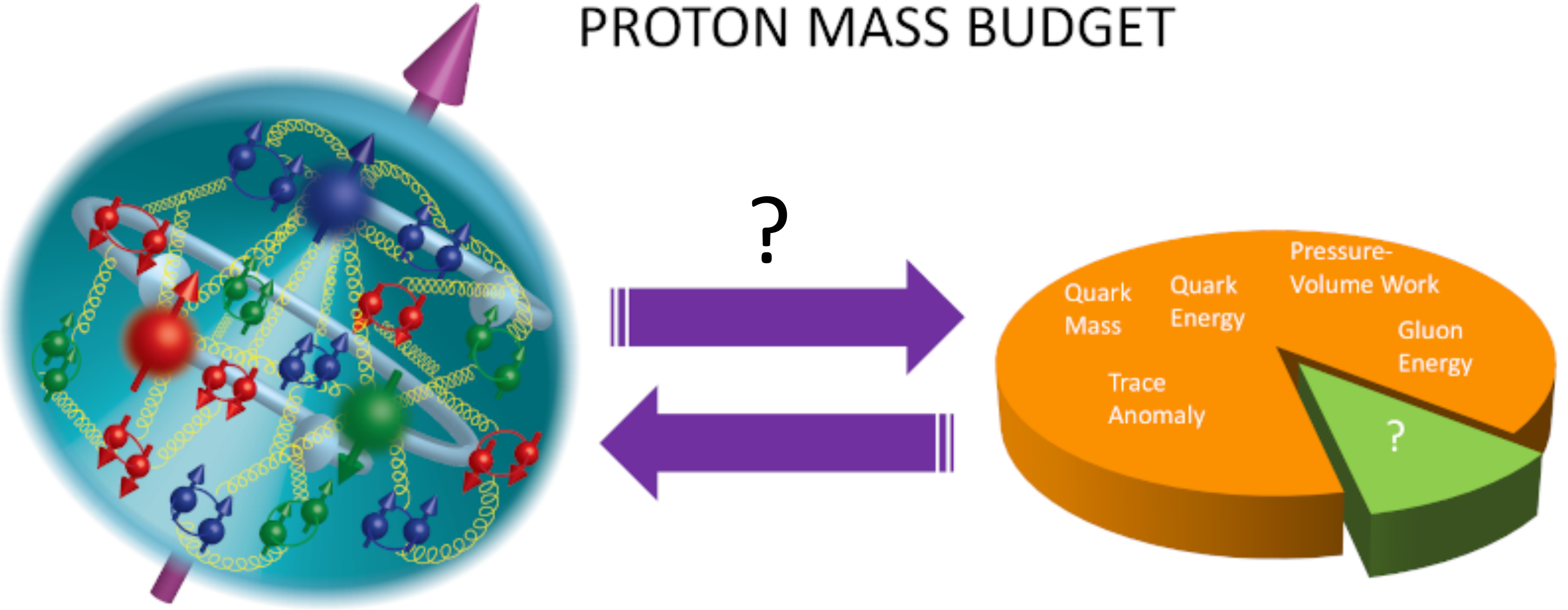
Orbital angular momentum

Only 20-30% comes from the quarks!



The Proton Mass

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

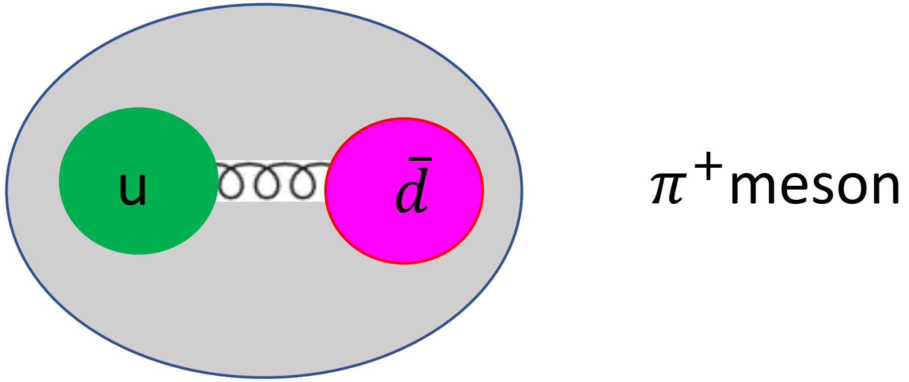


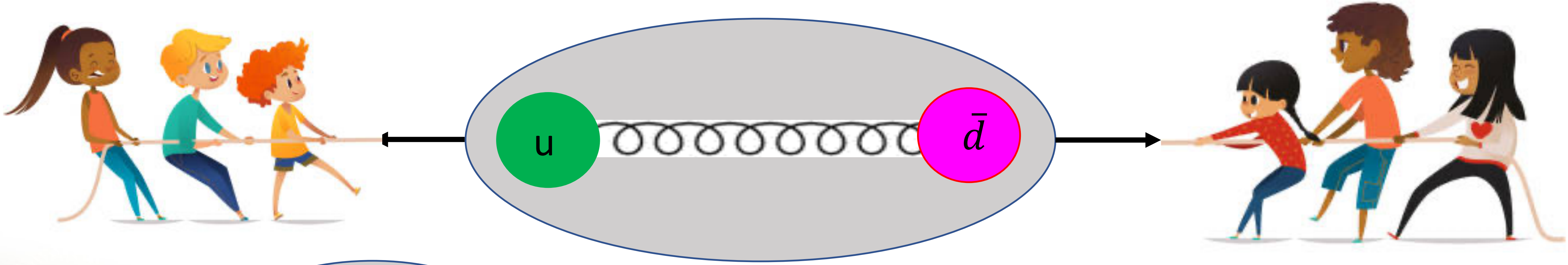
- Mass does not arise as simple sum of quark masses!
- ~ 99% of the mass is driven by quark and gluon dynamics!

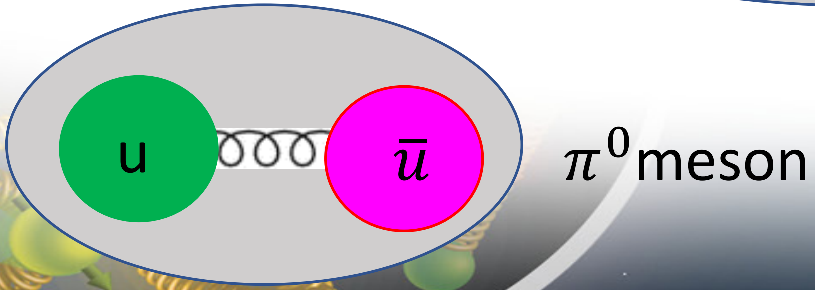
Some QCD Peculiarities

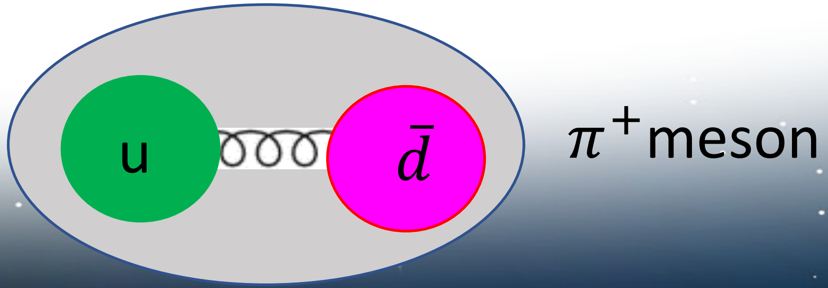
Another peculiar thing about QCD: <u>confinement</u>.

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









Some QCD Peculiarities

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

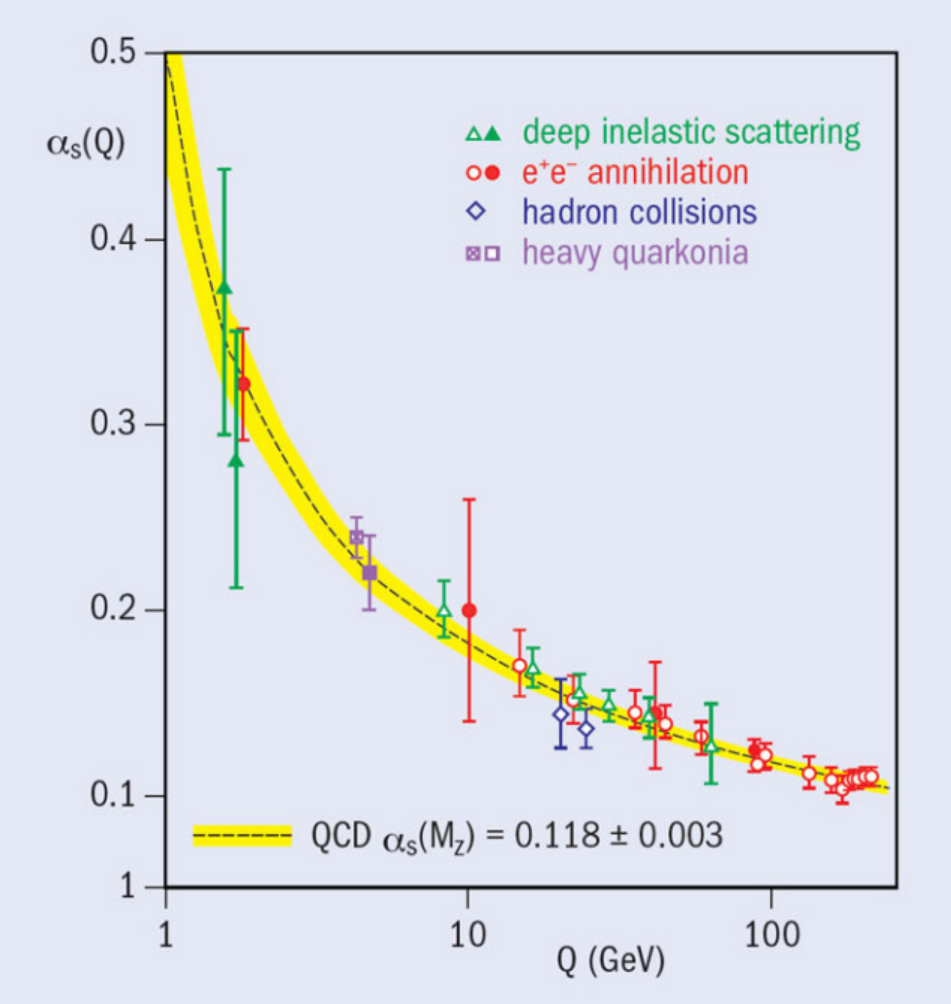
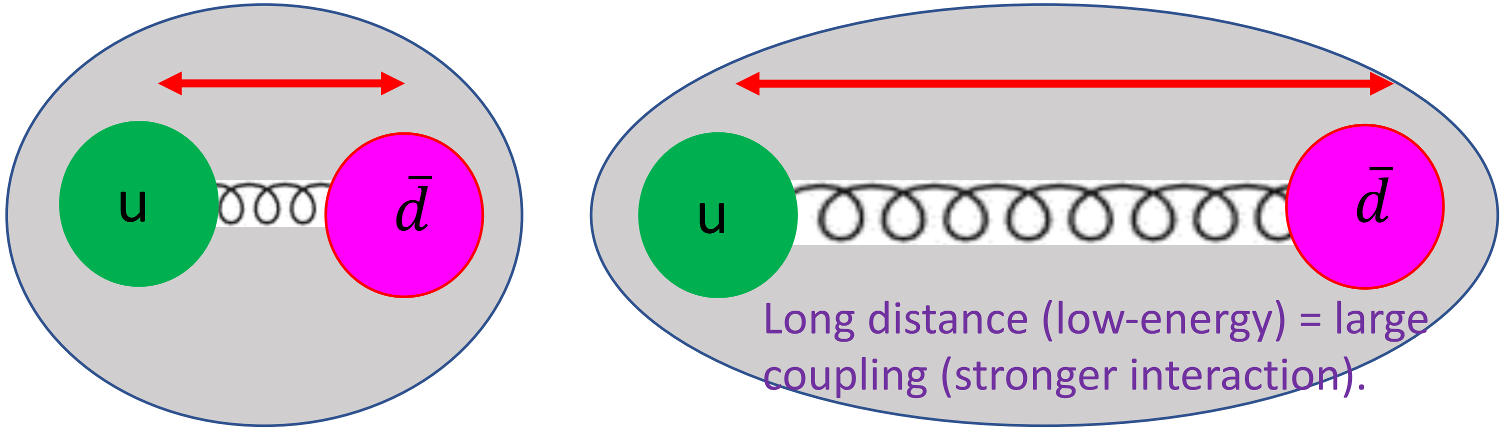


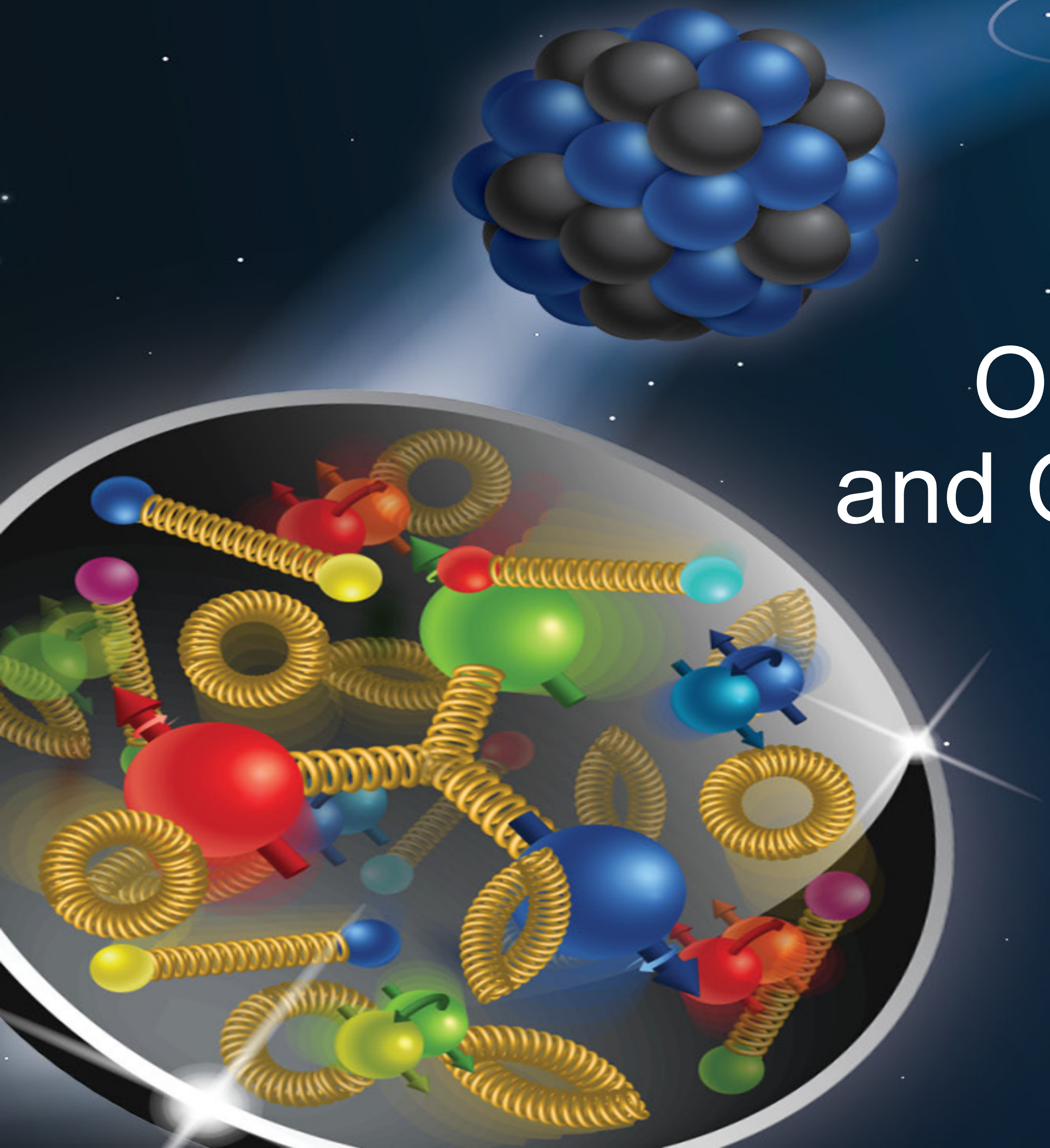
Image credit: From figure 5 in Siegfried Bethke and Peter Zerwas 2004 *Physik Journal* **3** 12 31.

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



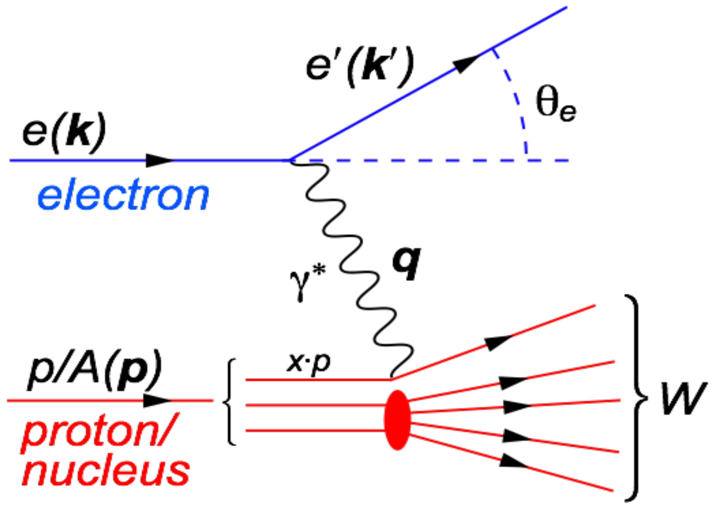
- Opposite of the EM force and gravity, which decrease as a function of $\frac{1}{(distance)^2}$.
- <u>Consequences:</u>
  - QCD calculations become non-perturbative (exceedingly hard) when the coupling constant is large (i.e. at low energy).

QCD requires experimental data to make progress!



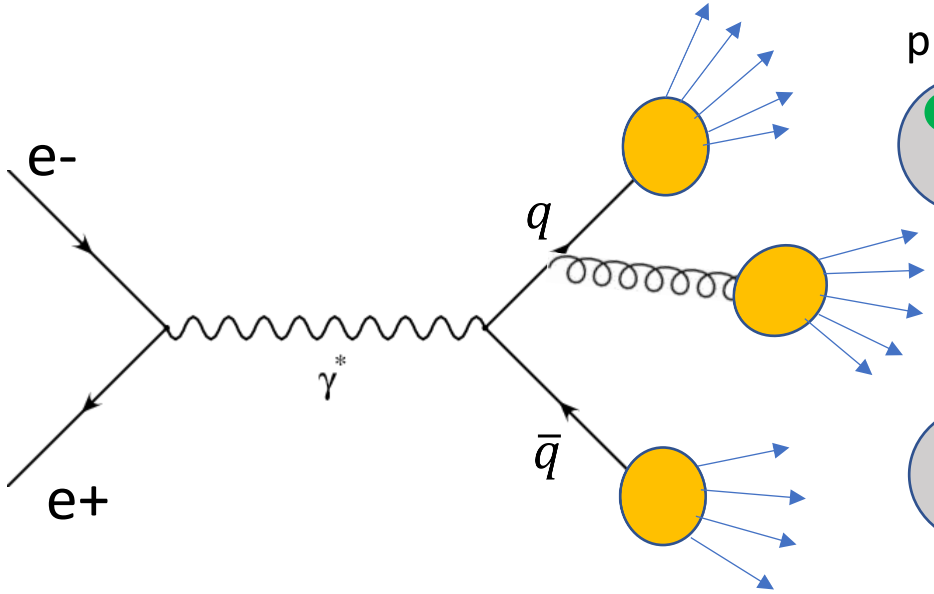
Okay, so the structure of matter and QCD seem complicated…how can we study them?

Different kinds of interactions (just a few)



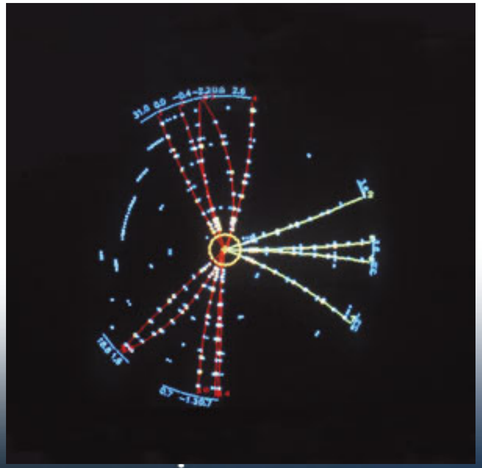
Deep-Inelastic Scattering:
electron + proton (or nucleus) collisions

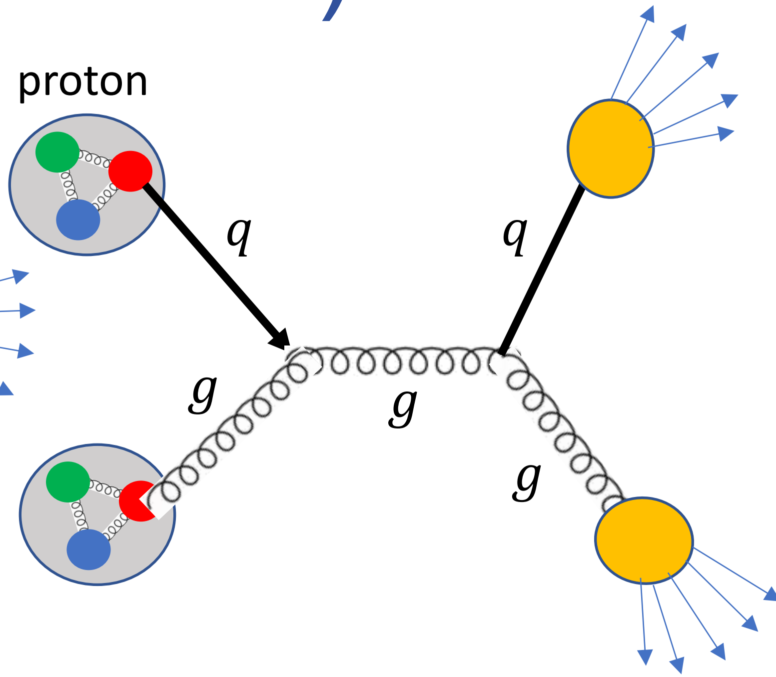
Led to discovery of the quark! (SLAC)



Electron + positron annhiliation:
electron + positron collisions

Led to discovery of the gluon! (PETRA)

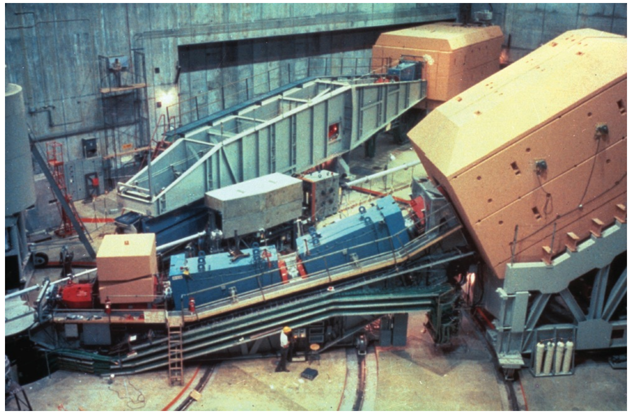




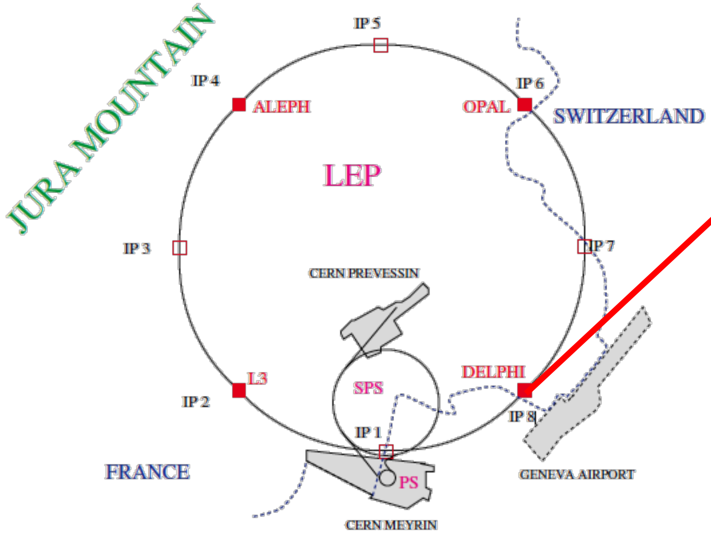
Hadronic interactions:
Proton + proton collisions

Discovery of the Higgs! (LHC)

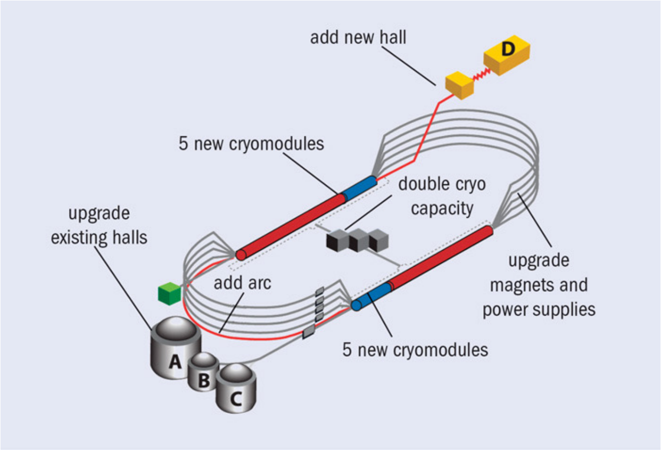
Building our microscope!



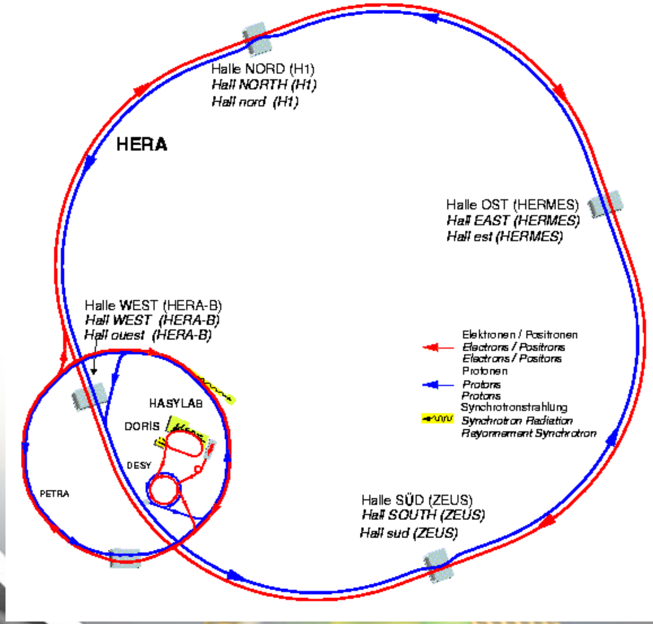
SLAC 1969: e + p (fixed)



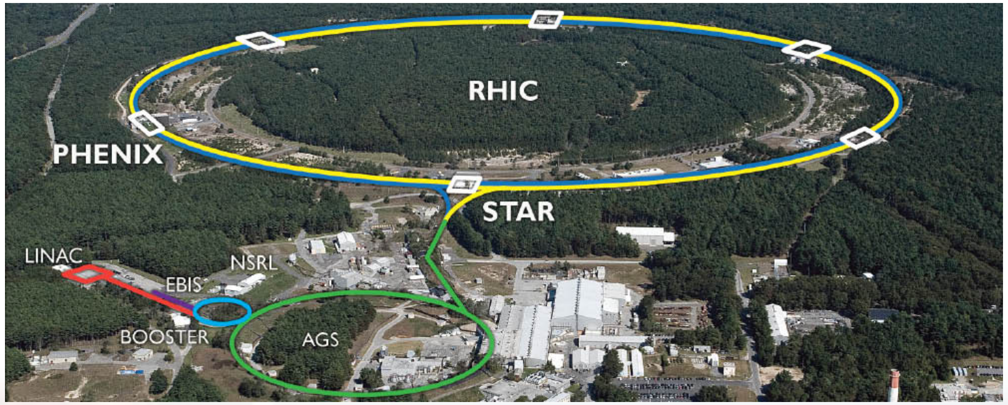
LEP @ CERN: 1989-2001: e+e-



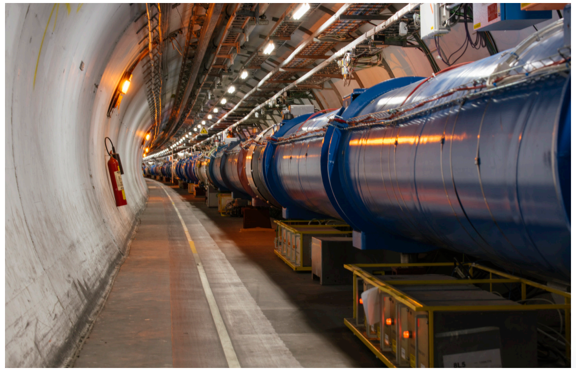
JLAB/CEBAF: 1984 – present: e + p (fixed)



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

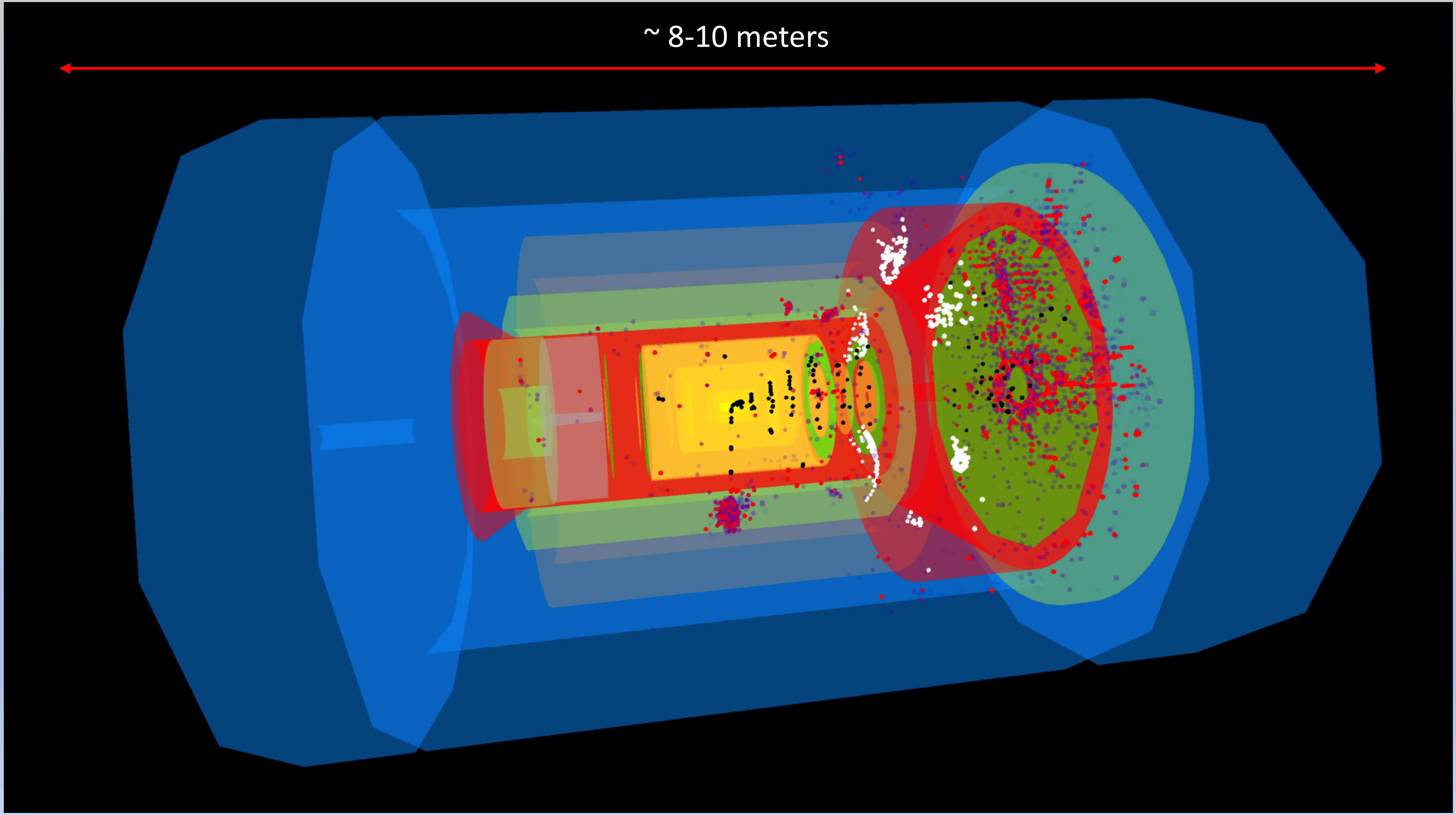


RHIC: 2000 – present: p+p, p+A, A+A, polarized protons



LHC: 2008 – present: p+p, p+A, A+A

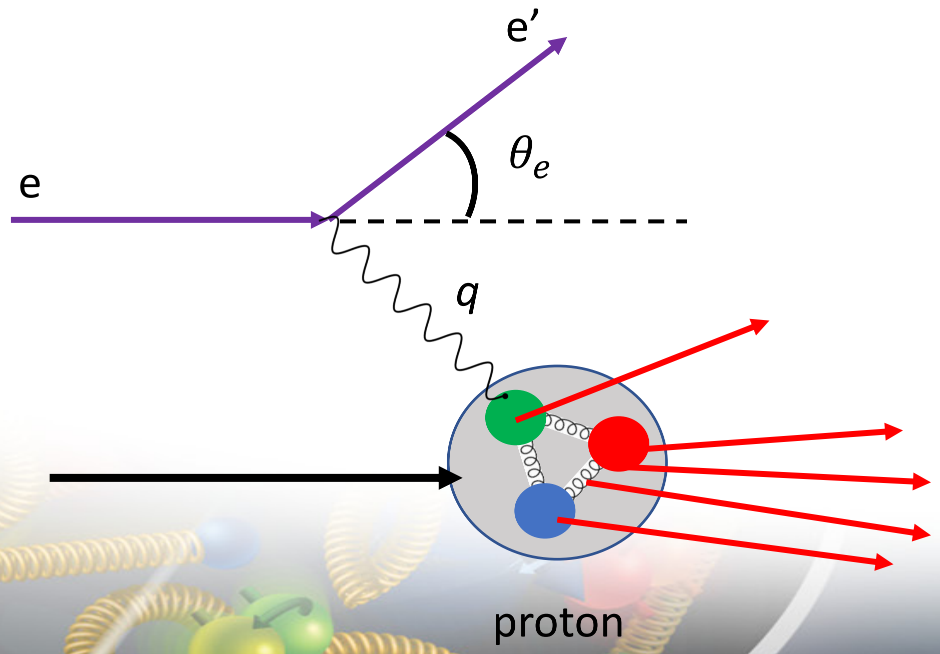
Building our microscope!



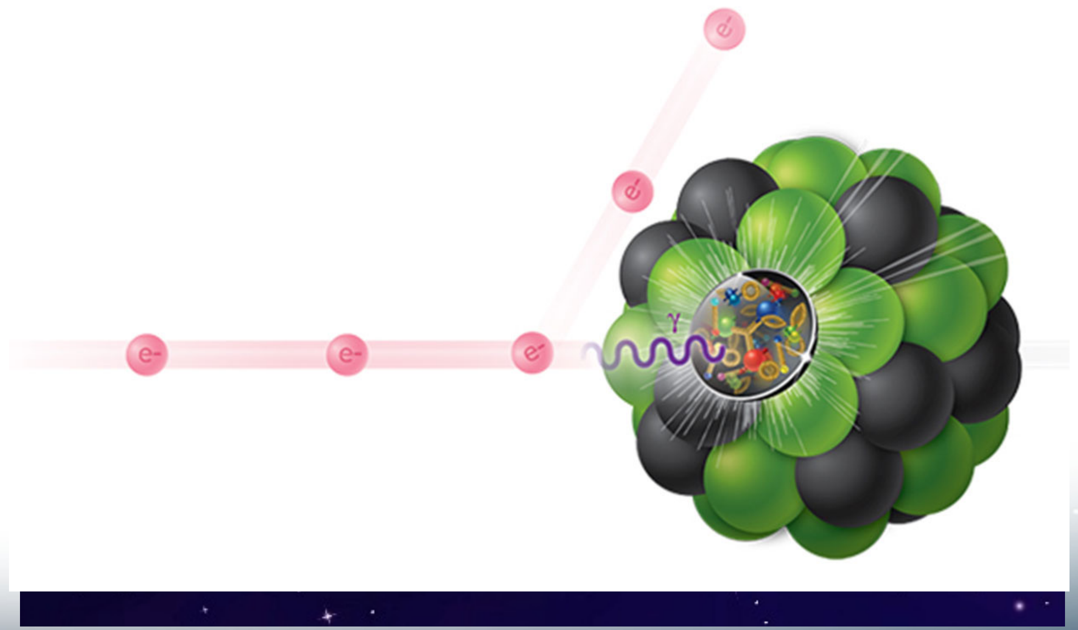
"Illuminating" the Structure of Matter

- **<u>Use Deep-Inelastic Scattering (DIS)</u>**
  - 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

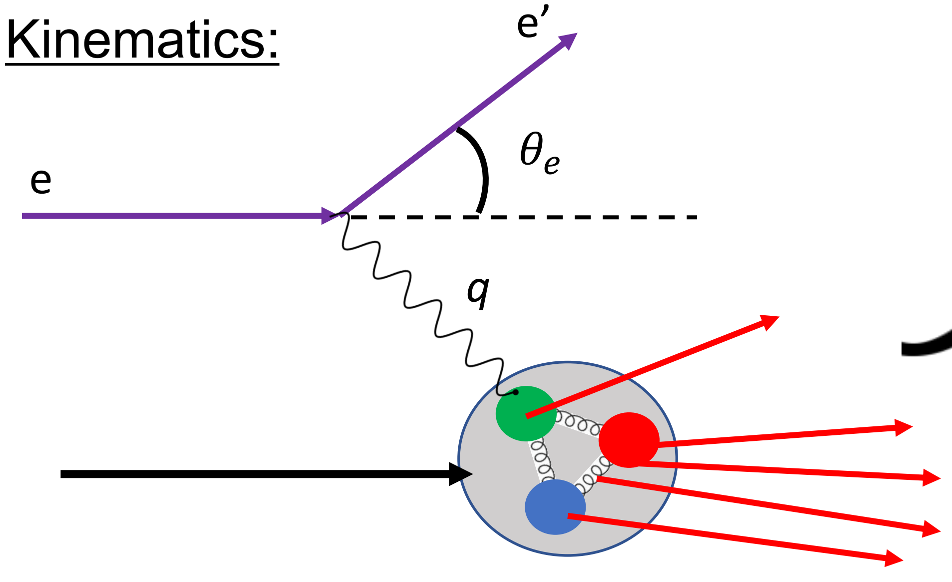


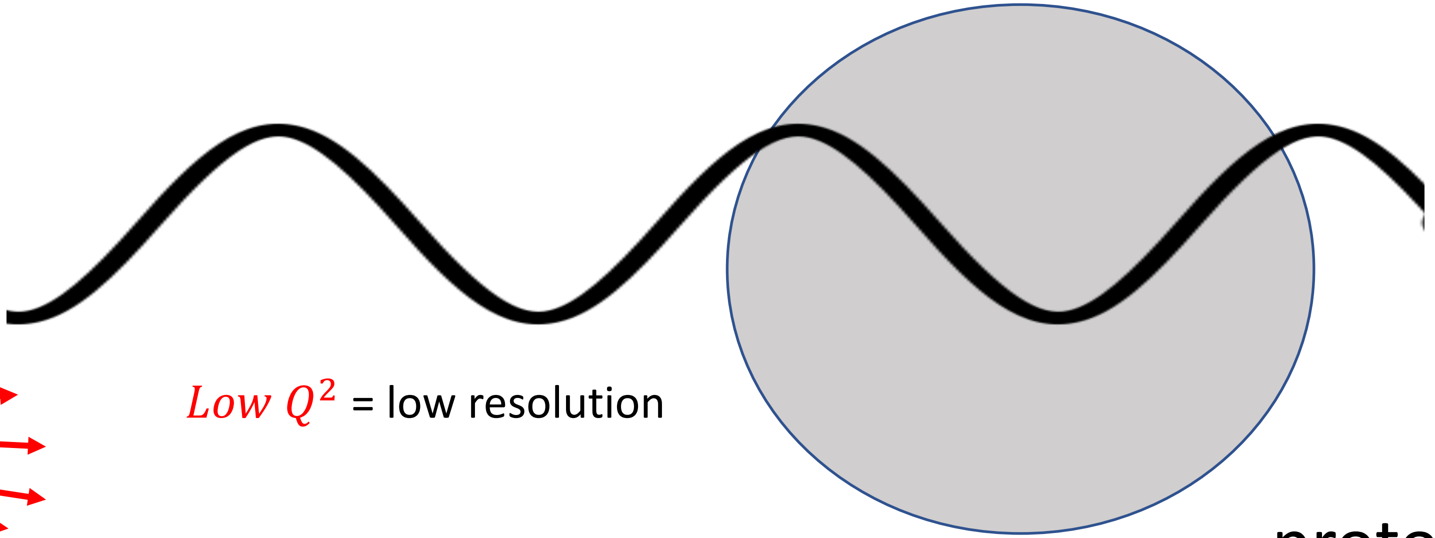
“Illuminating” the Structure of Matter

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

Measure of resolution power

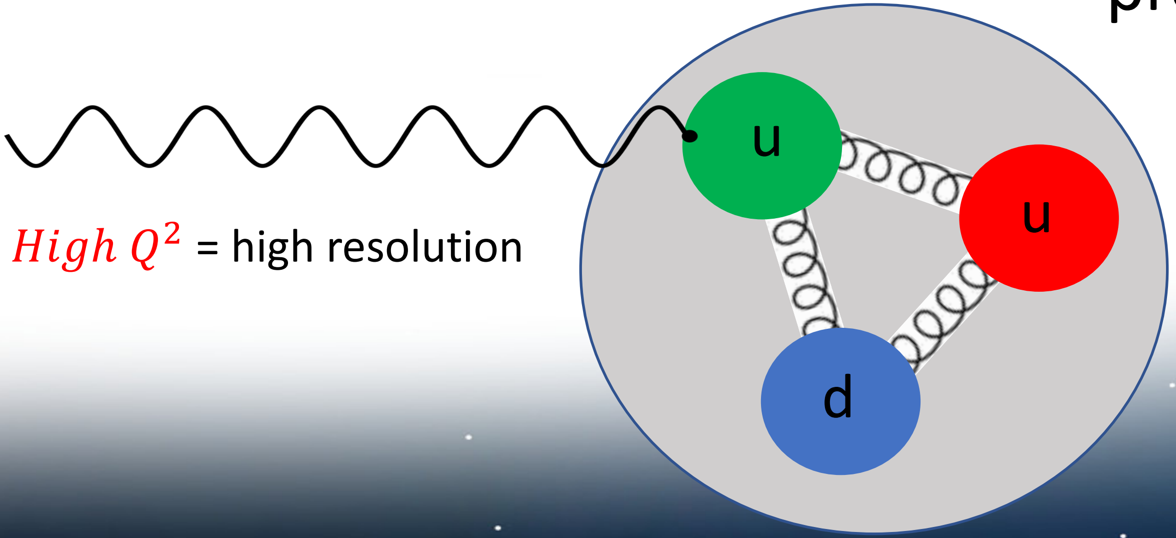
Kinematics:





$Low\ Q^2$ = low resolution

proton



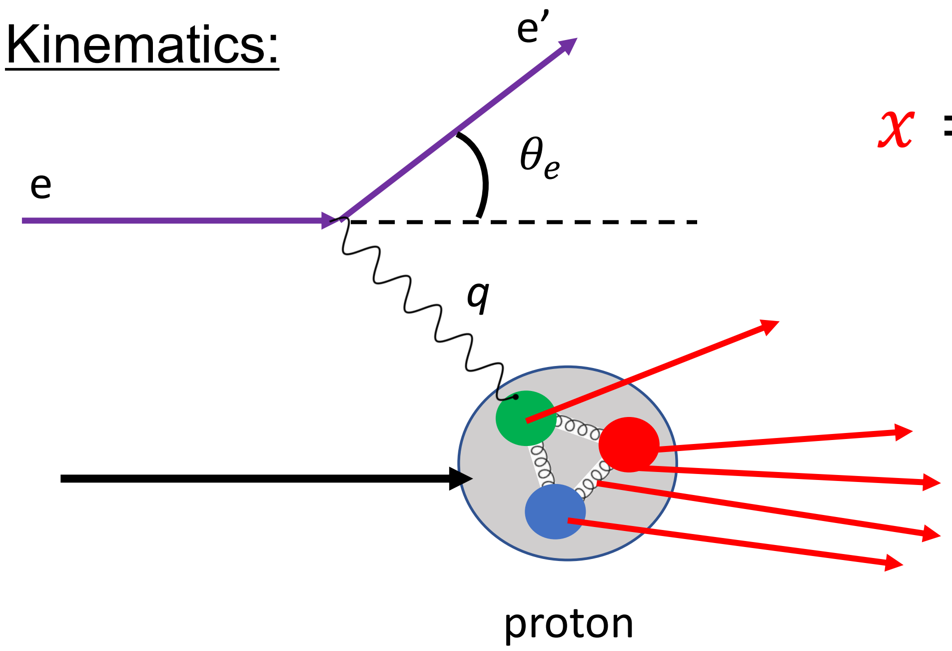
$High\ Q^2$ = high resolution

“Illuminating” the Structure of Matter

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

Measure of resolution power

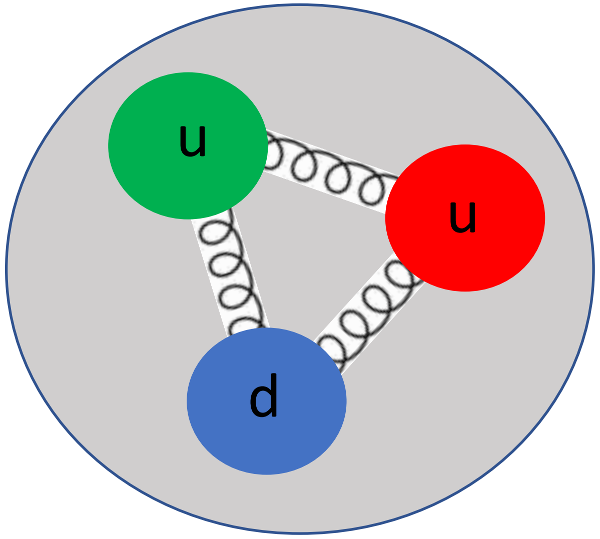
Kinematics:



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

Measure of momentum fraction of struck parton

“Bjorken-x”



x ~ 1/3 for just the “valence” quarks.

“Illuminating” the Structure of Matter

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

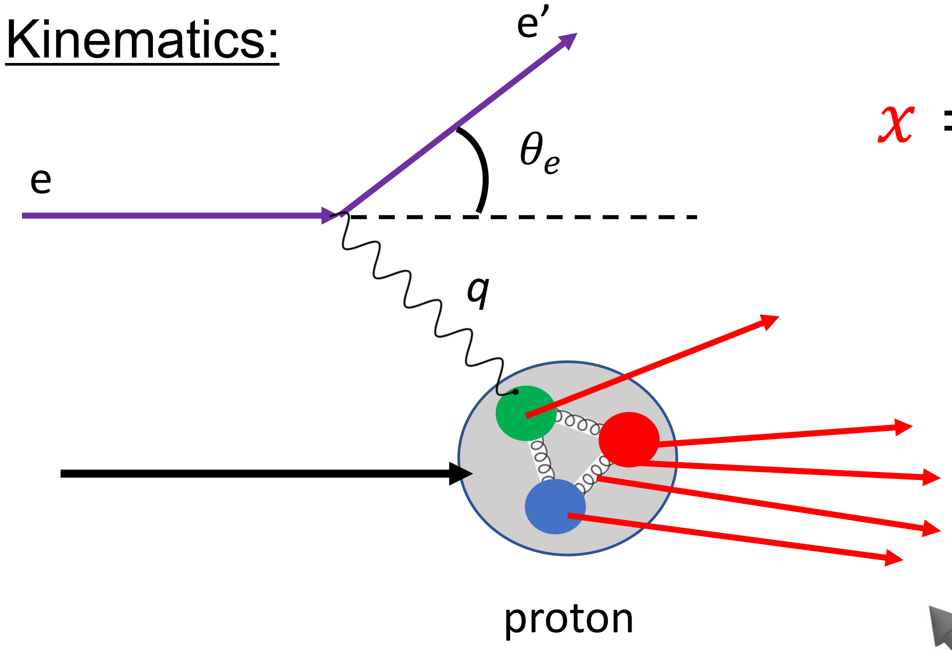
Measure of resolution power

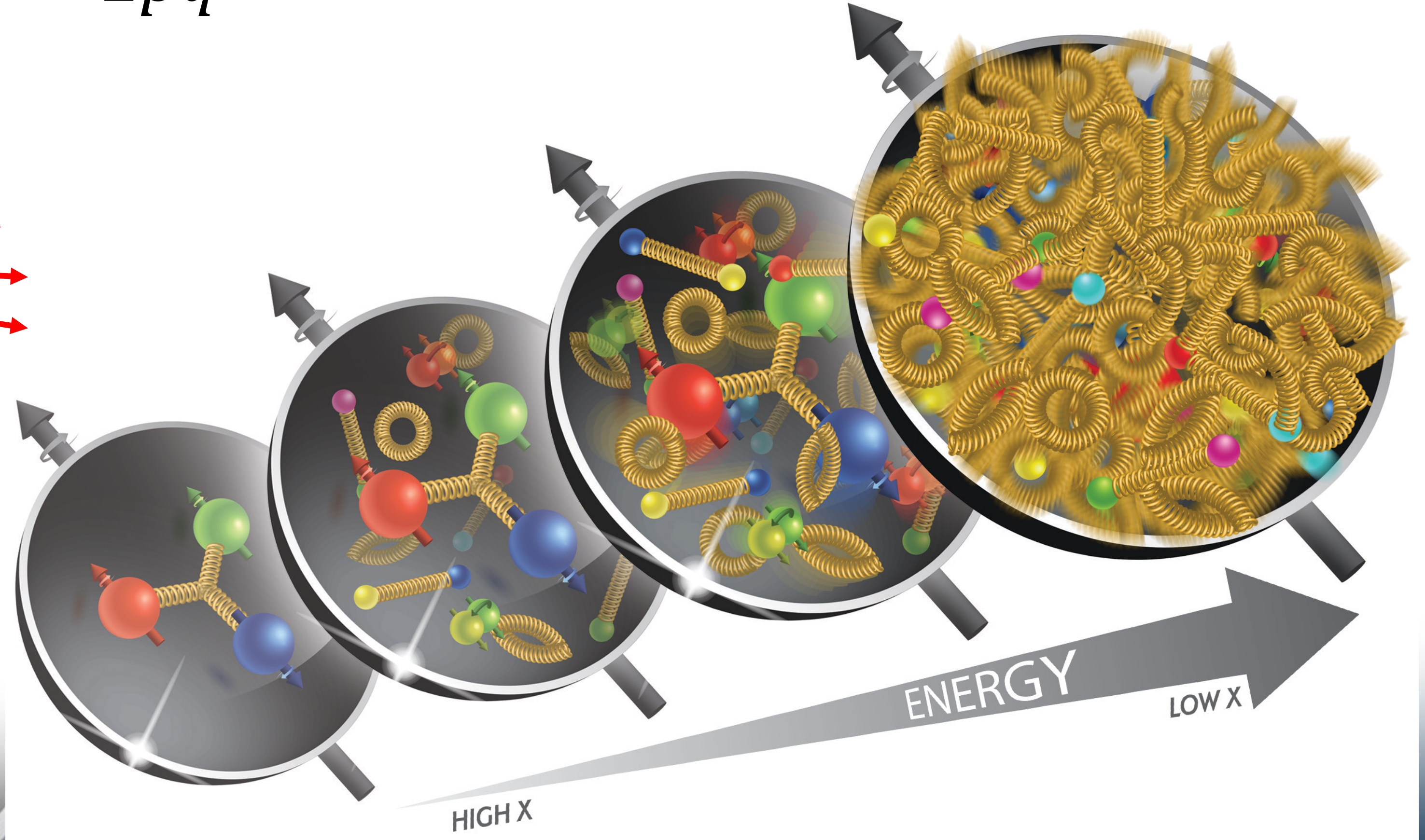
$$x = \frac{Q^2}{2pq}$$

Measure of momentum fraction of struck parton

“Bjorken-x”

Kinematics:



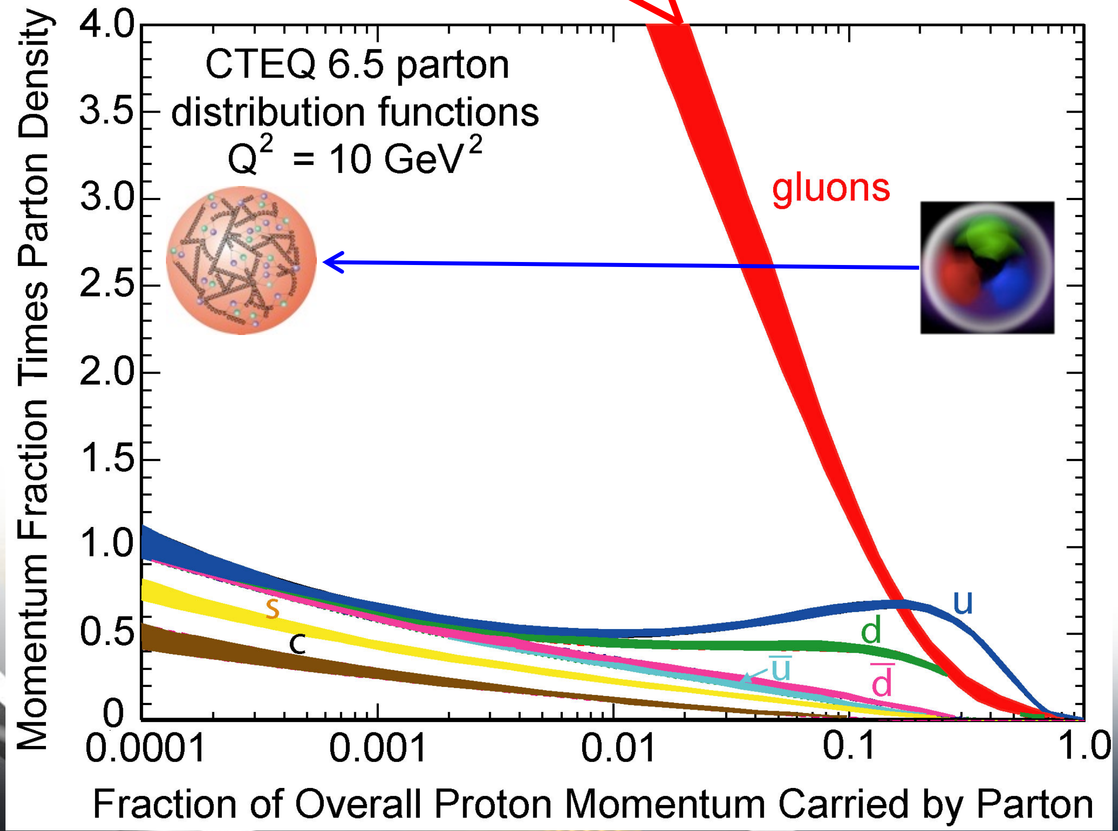


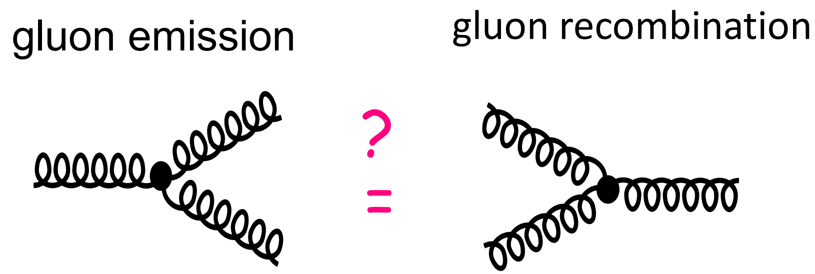
Physics aside: Exotic QCD state at low-x

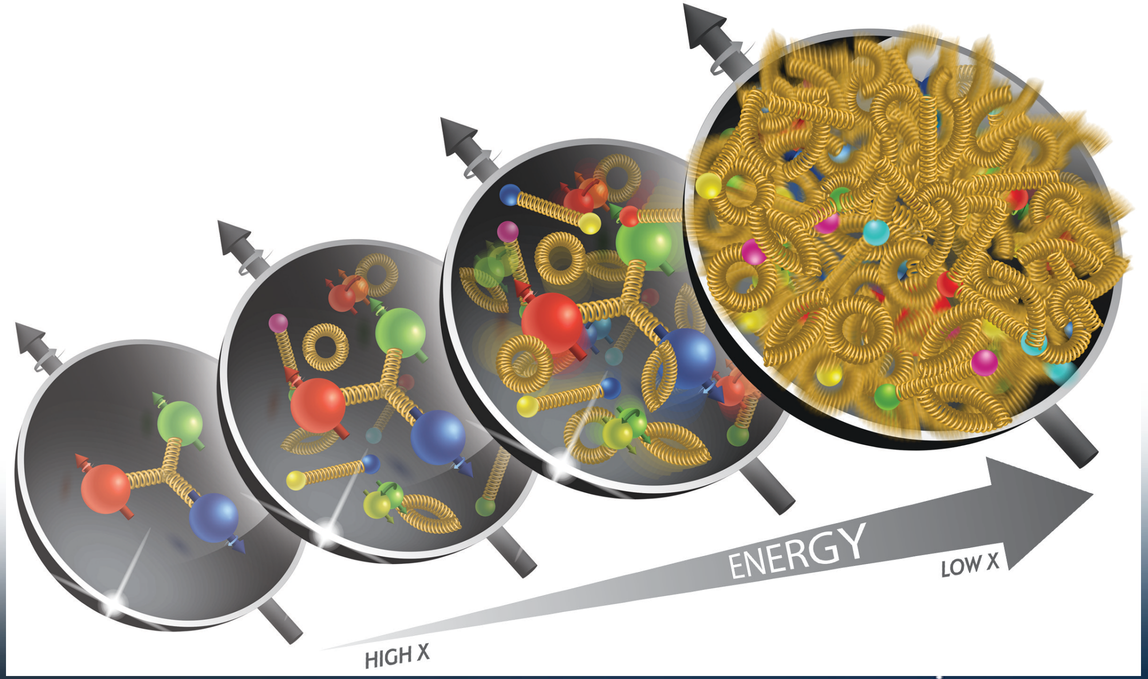
Saturation – gluon density increases drastically at low-x! At some point, does the density saturate? **New state of matter?**

?

Parton Distribution Function (PDF)

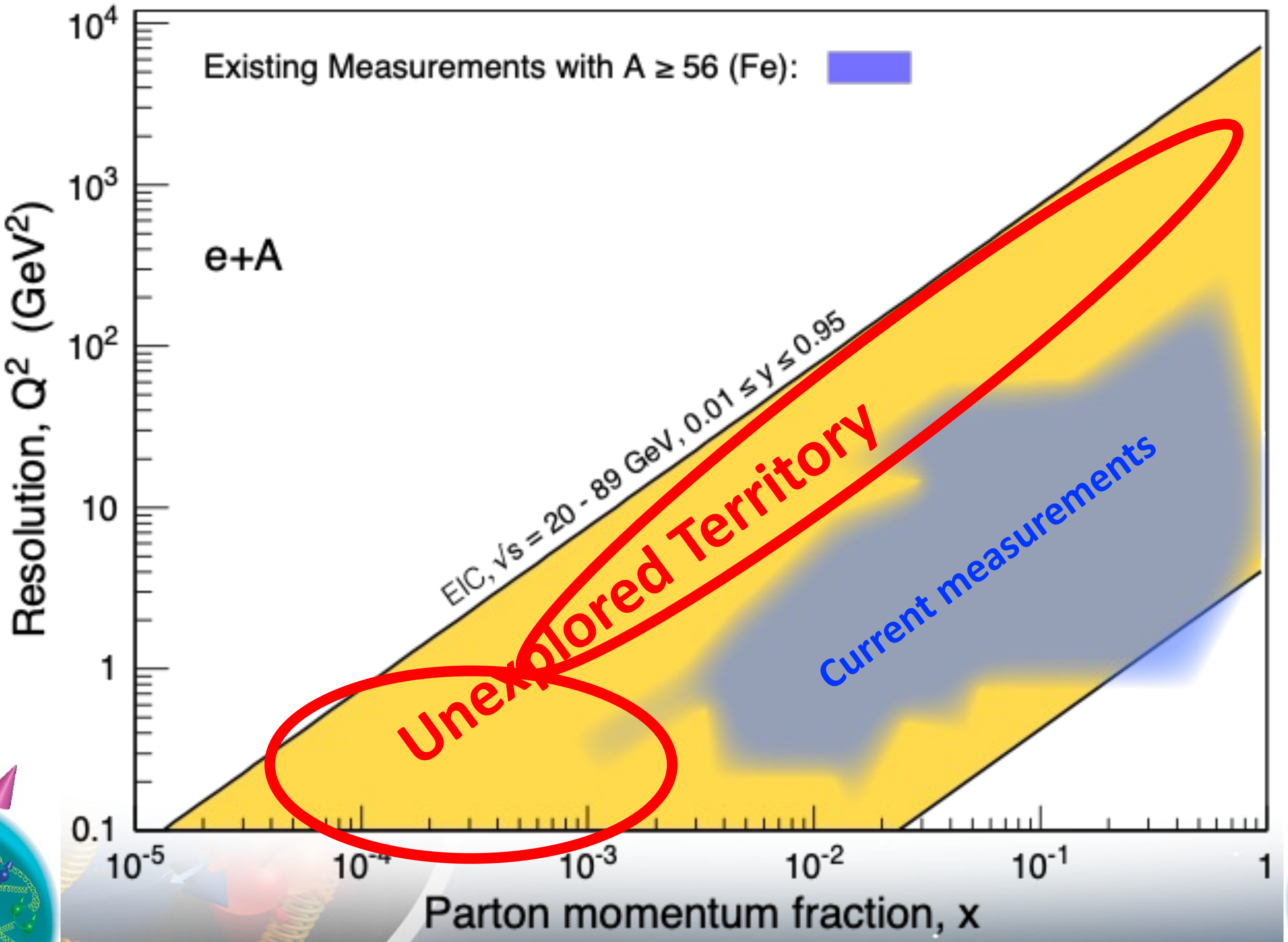


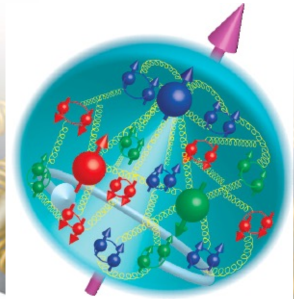




What is needed experimentally?

EIC Yellow Report, Fig. 2.1



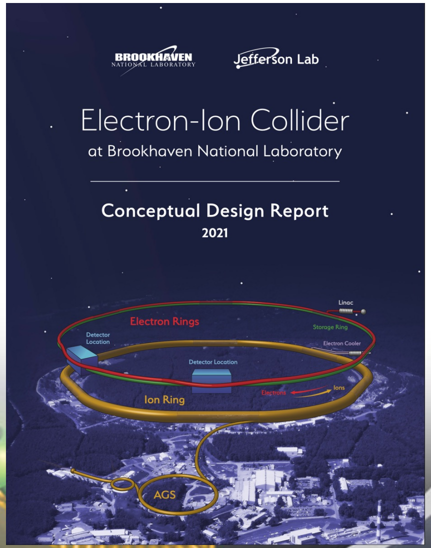


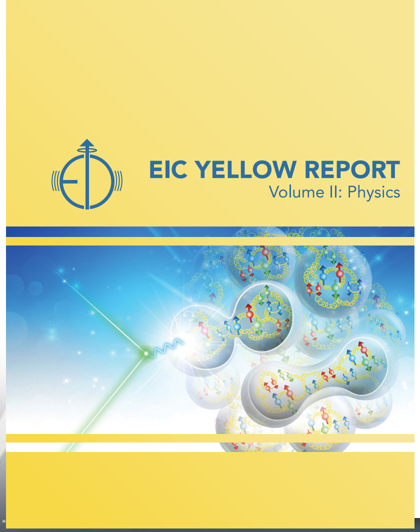
Lots of microscopes…and still unanswered questions?

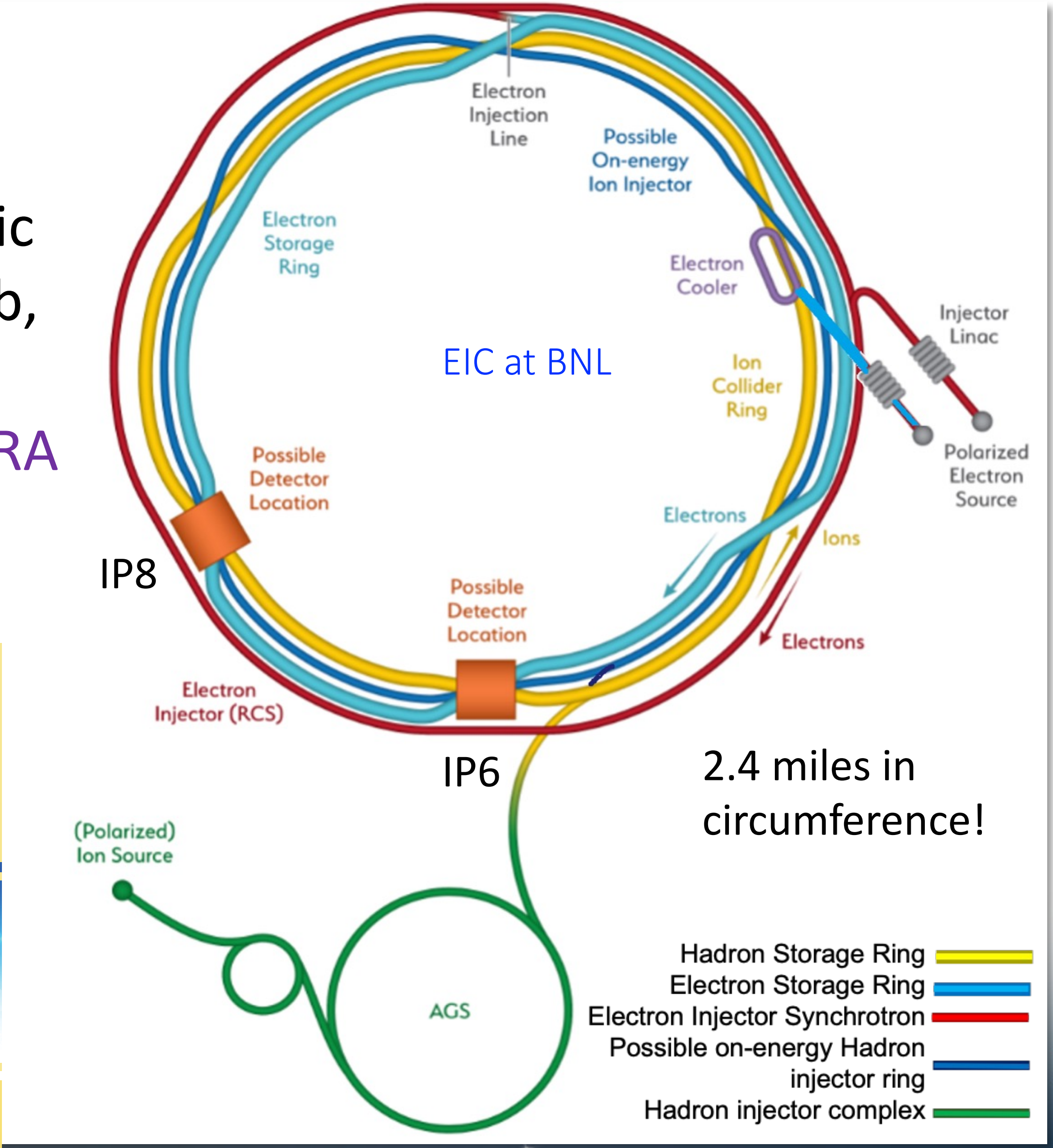
Is there a machine that can help?

The Electron-Ion Collider (EIC)

- Deep-Inelastic Scattering machine → 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.







2.4 miles in circumference!

The Electron-Ion Collider (EIC)

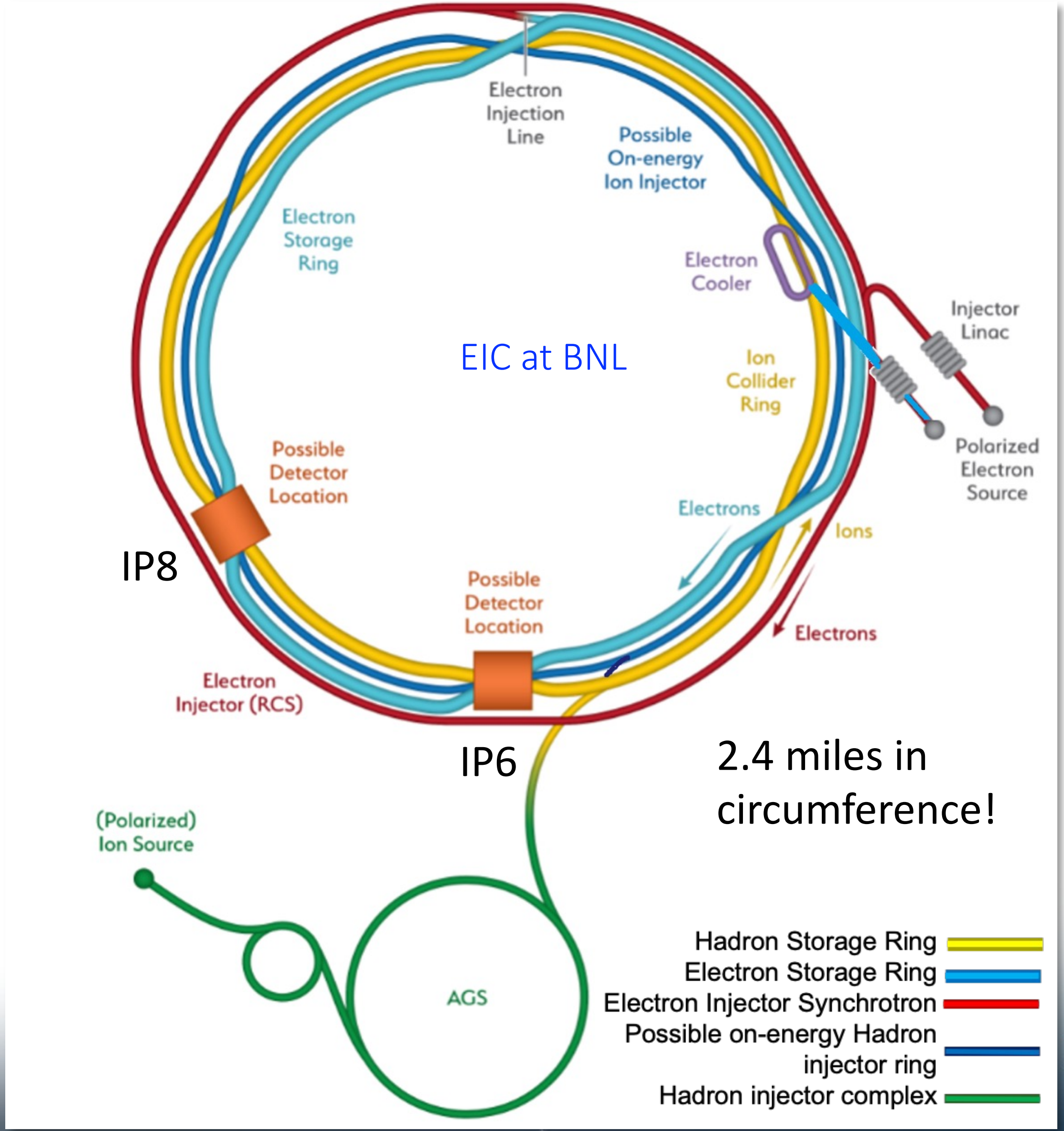
What is the EIC:

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!



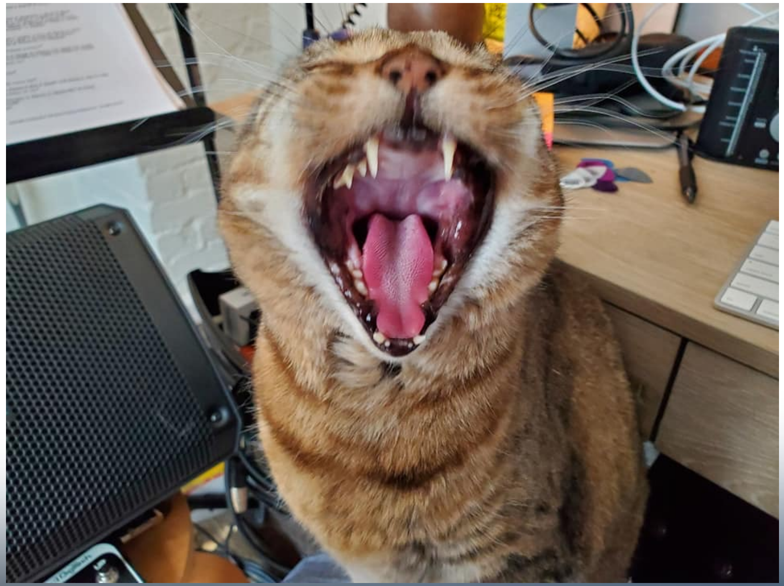
2.4 miles in circumference!

Intermission: Cute Animals

Julep

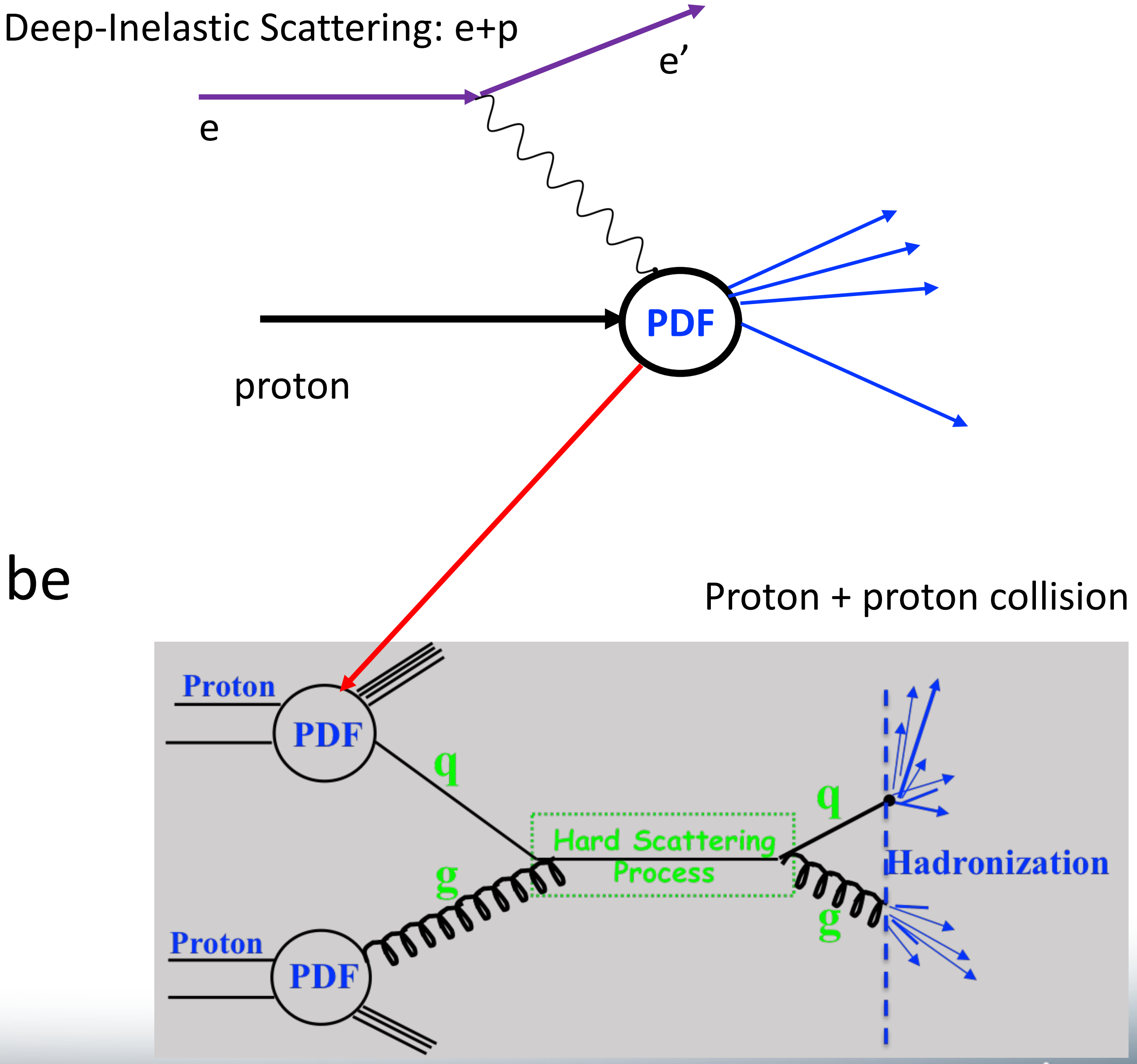
They (mostly) get along.

Lilu



She's in a death metal band.

More about QCD



Universality

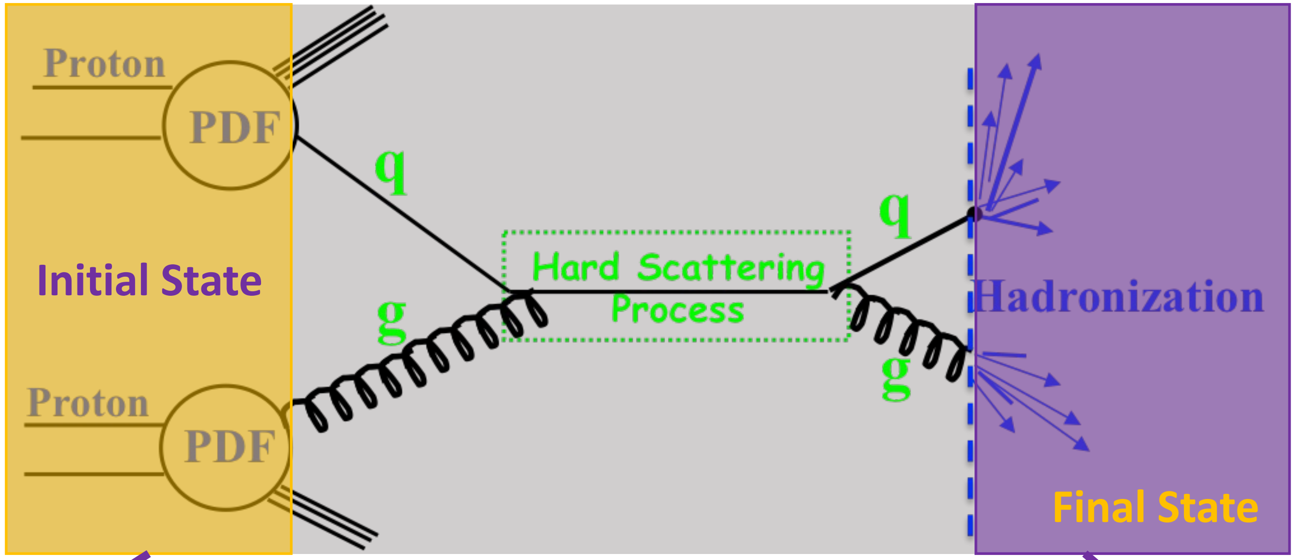
- QCD interactions arising from different collision systems should be *universal*.

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

More about QCD

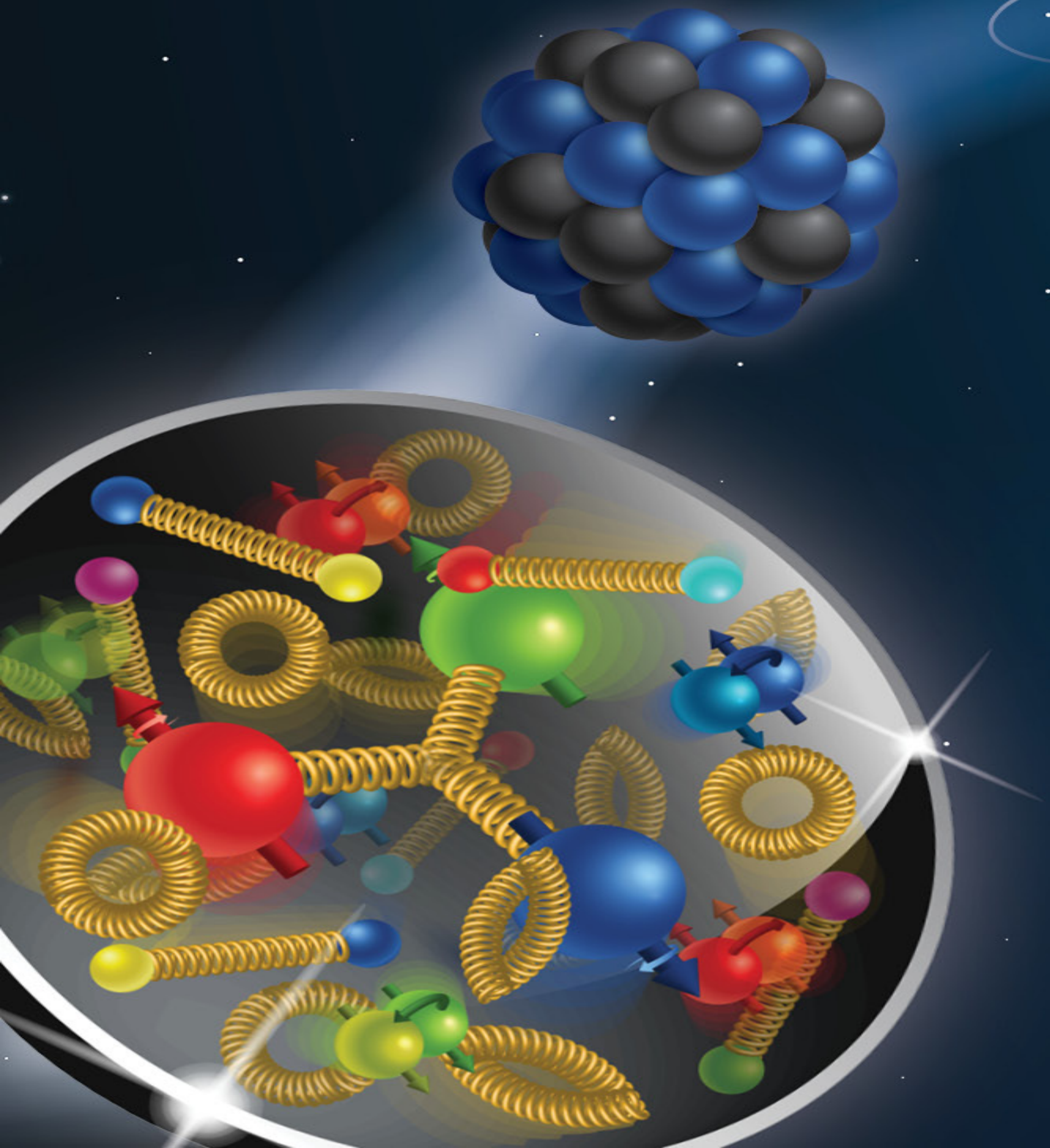
QCD Interactions ~ PDF ⊗ high-energy parton interaction ⊗ Hadronization

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.

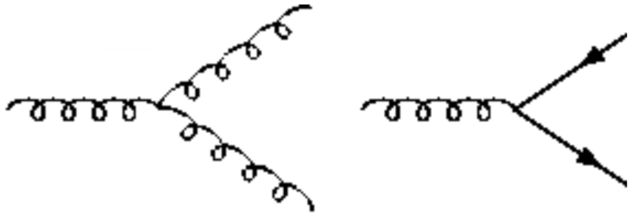
$$\boldsymbol{DIS\ cross\ section \times luminosity = DIS\ event\ rate}$$

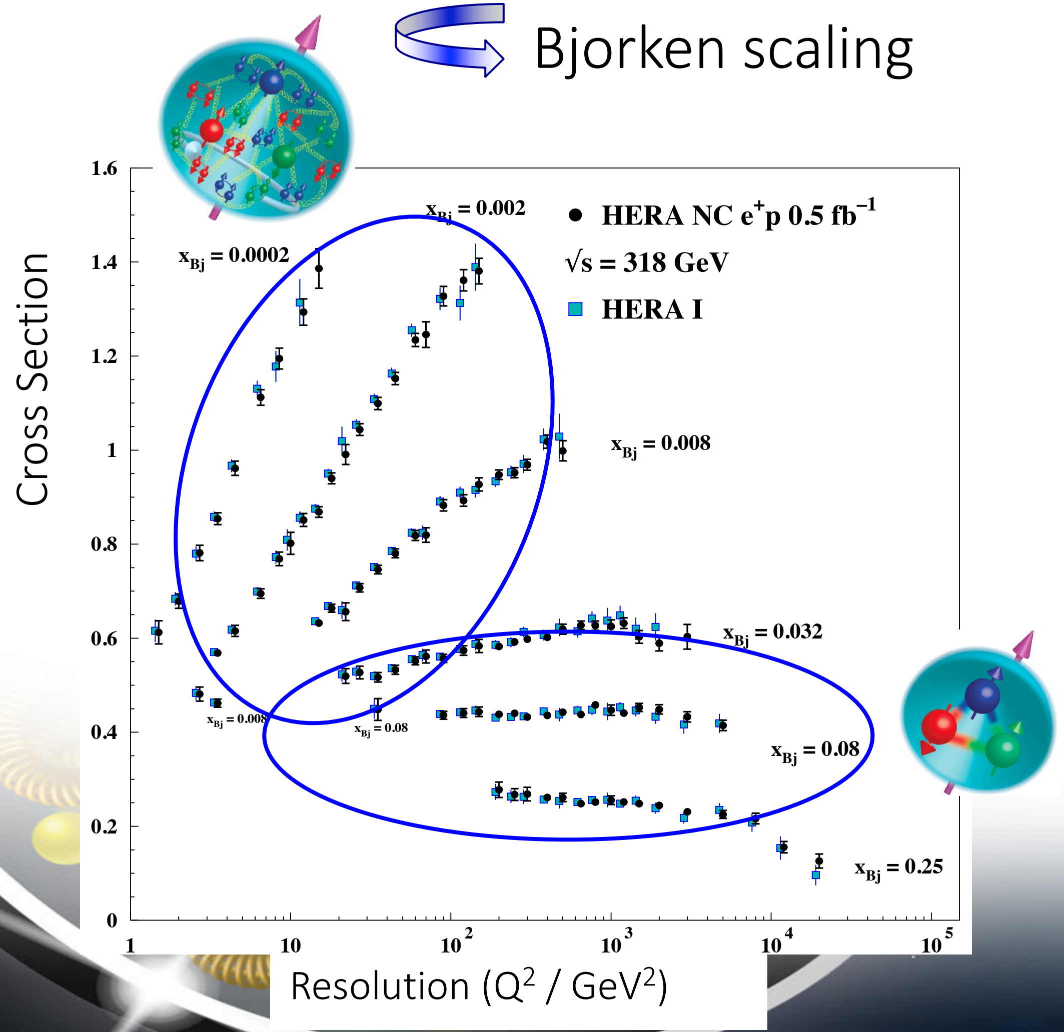
$\mathbf{(e.g.\ number\ of\ collisions\ per\ second)}$

BUT:

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

Because of gluon-initiated processes



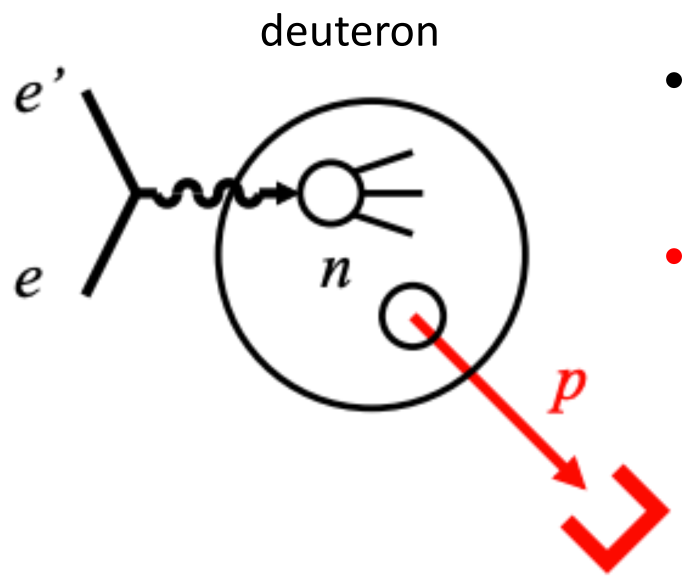


EIC:

- **How are the structure functions modified in nuclei?**
- **Spin dependence?**
- **Protons vs. neutrons?**

Neutron Structure Functions

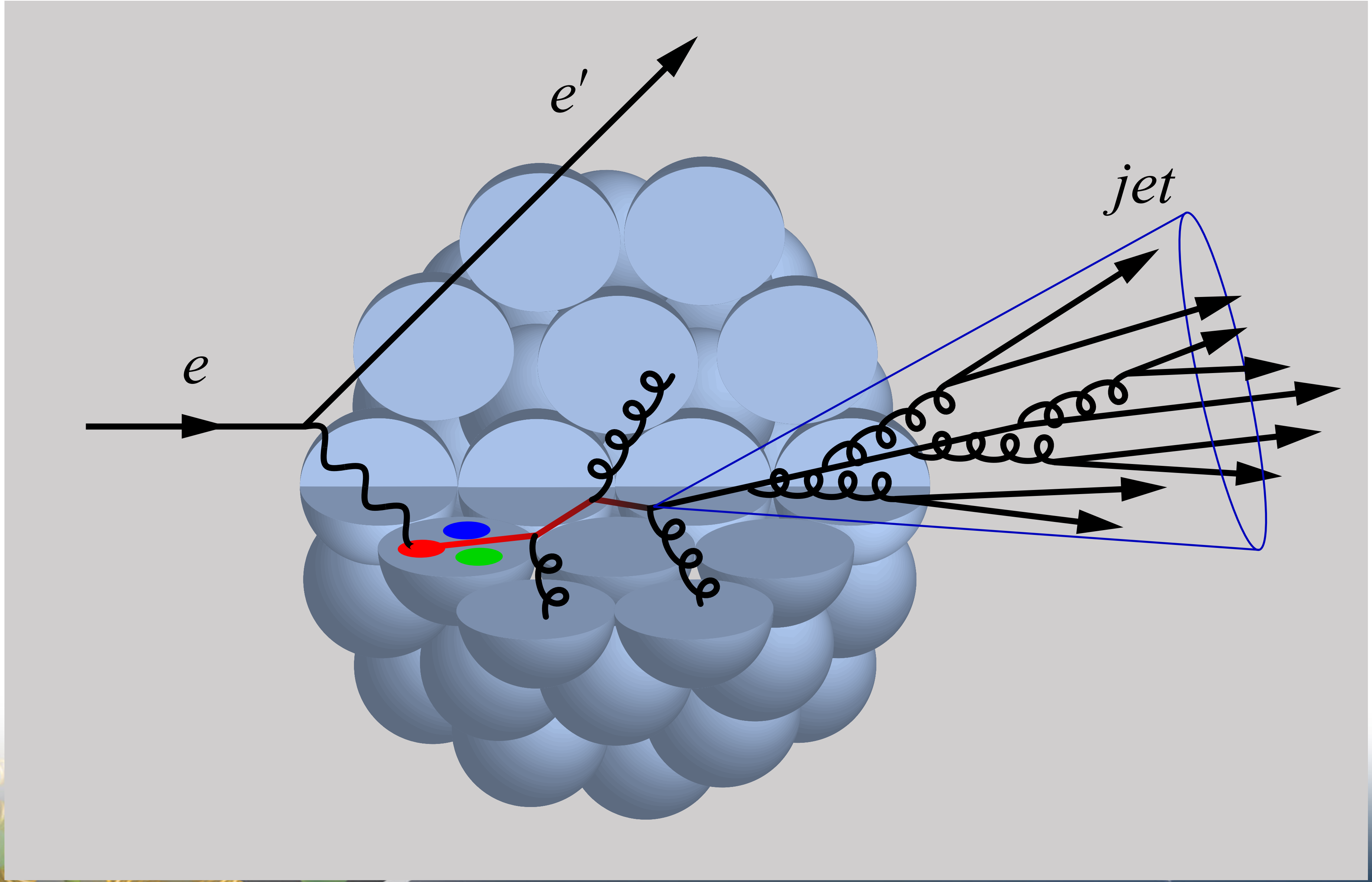
EIC enables use of deuteron beams → the next best thing to a beam of neutrons!



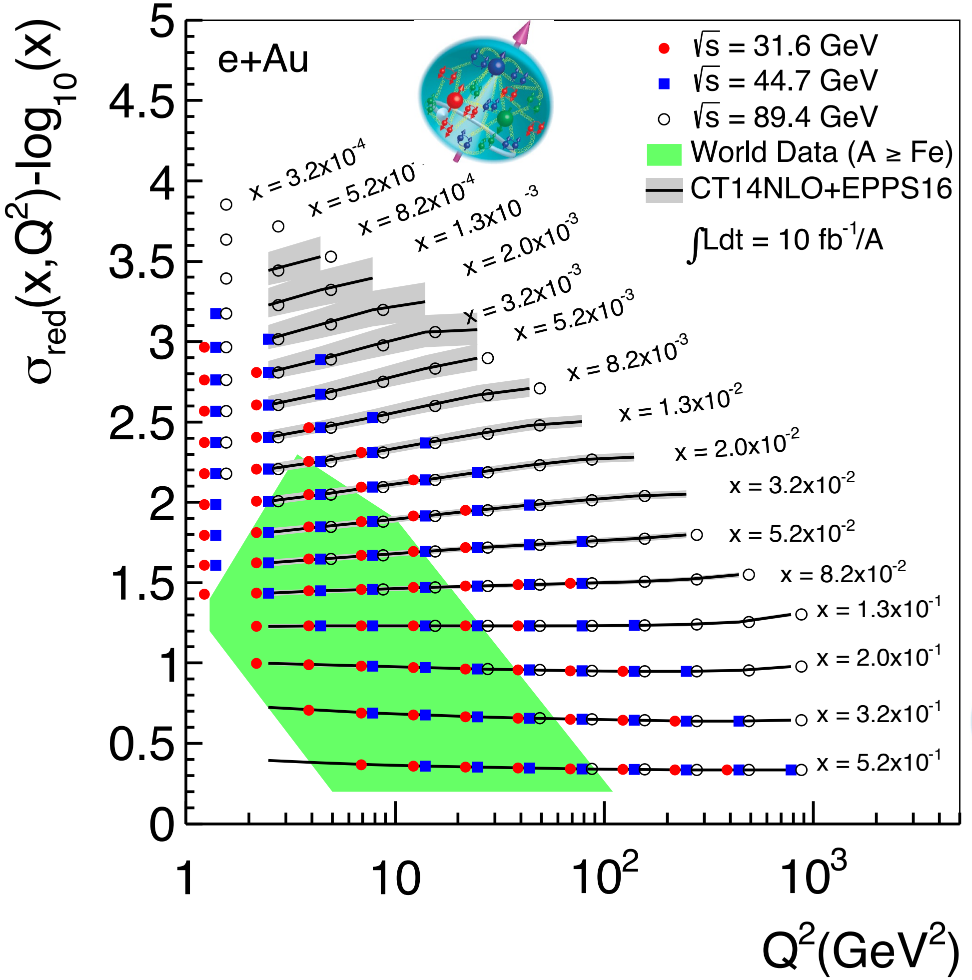
- Measurements on unpolarized deuterons[1] (or polarized He-3)[2] at the EIC.
- Spectator proton momentum → enables selection of nuclear (p/n) configurations.
  - Extract free neutron structure function[3] → Not possible elsewhere!
  - Study nuclear modifications of both nucleons in the deuteron (study 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?



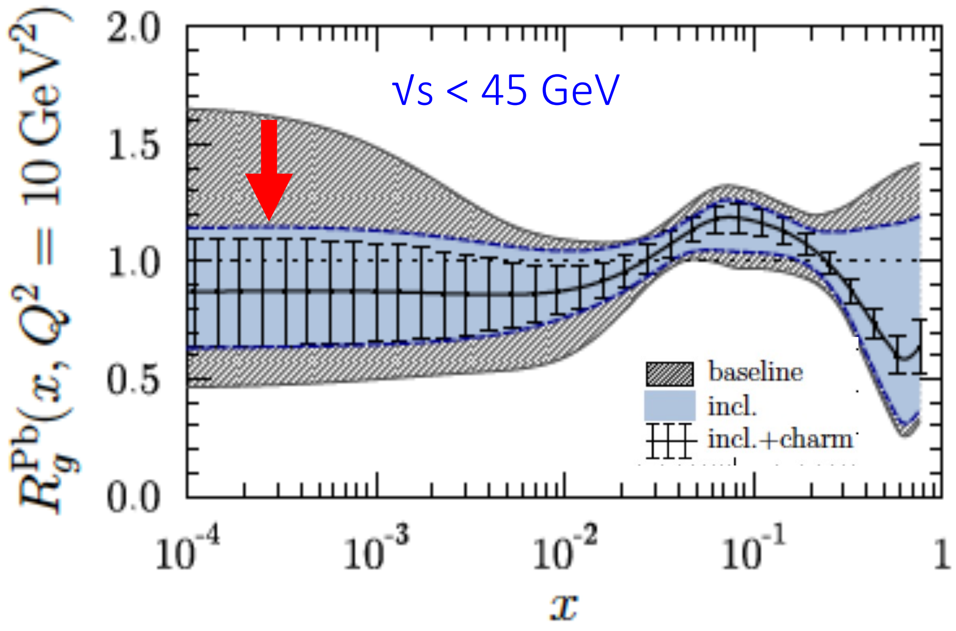
Nuclear Parton Distribution Functions

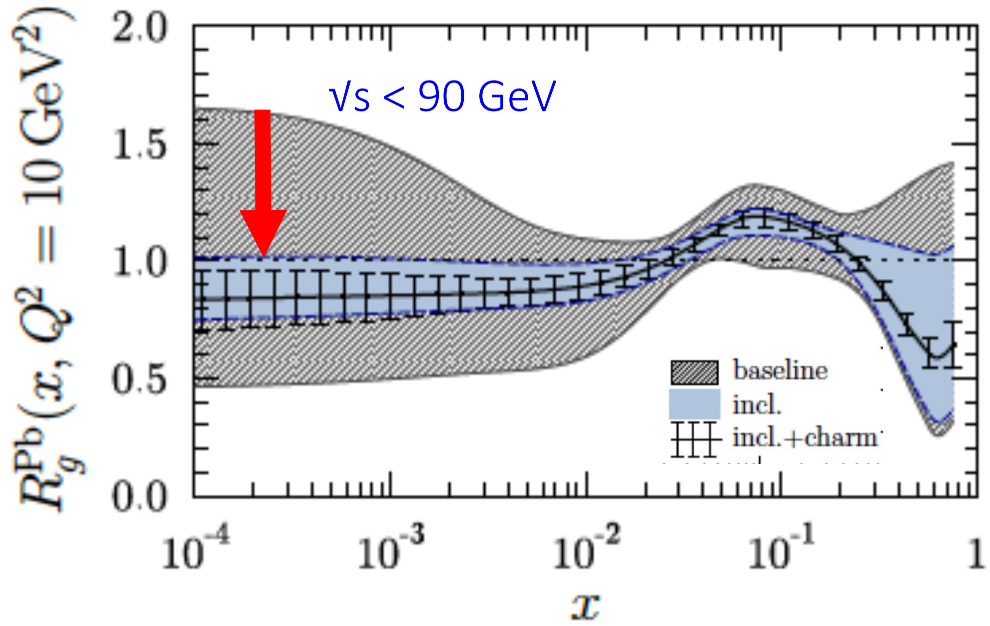


More data from EIC

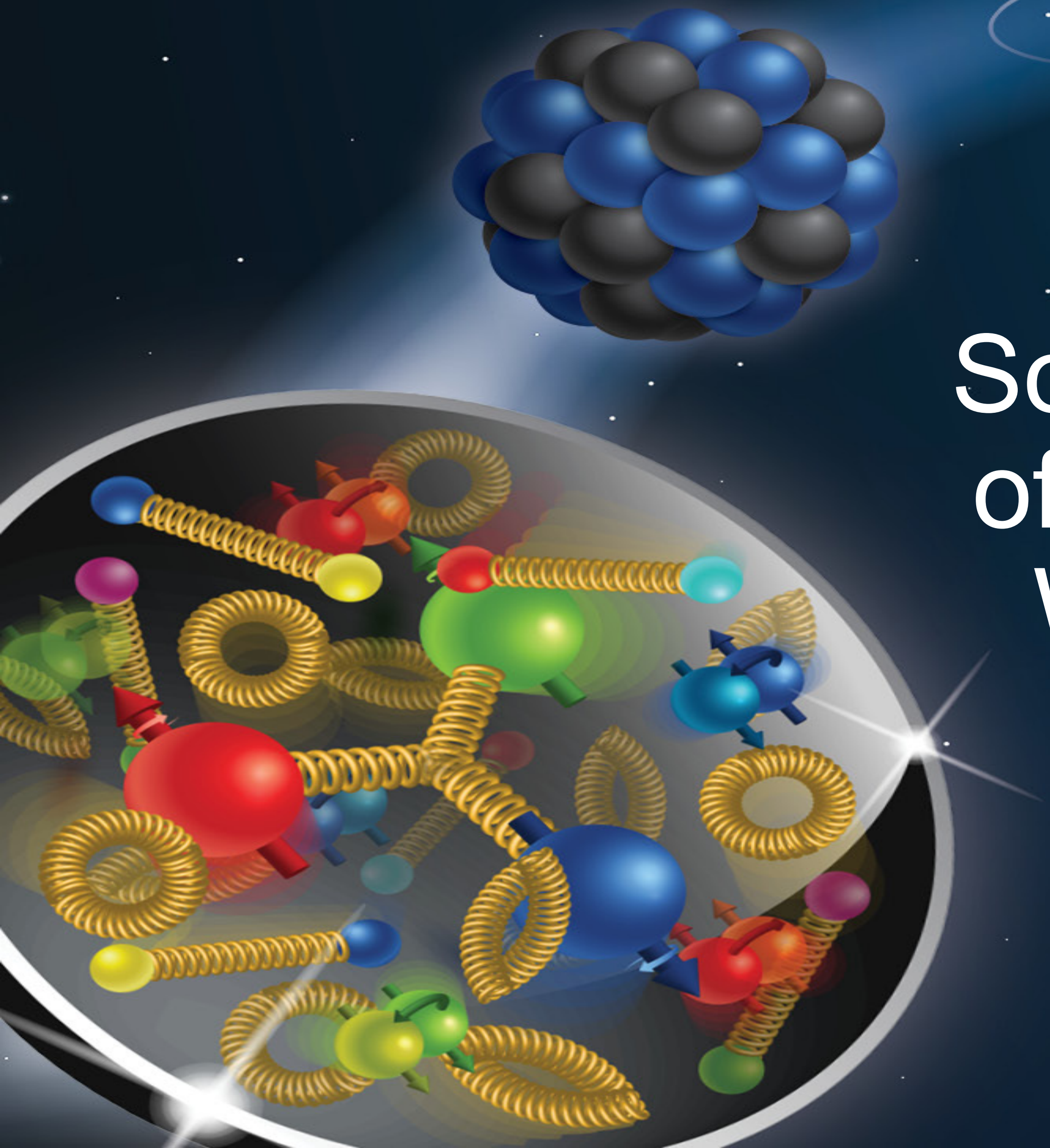
=

Better constraints on nPDFs





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

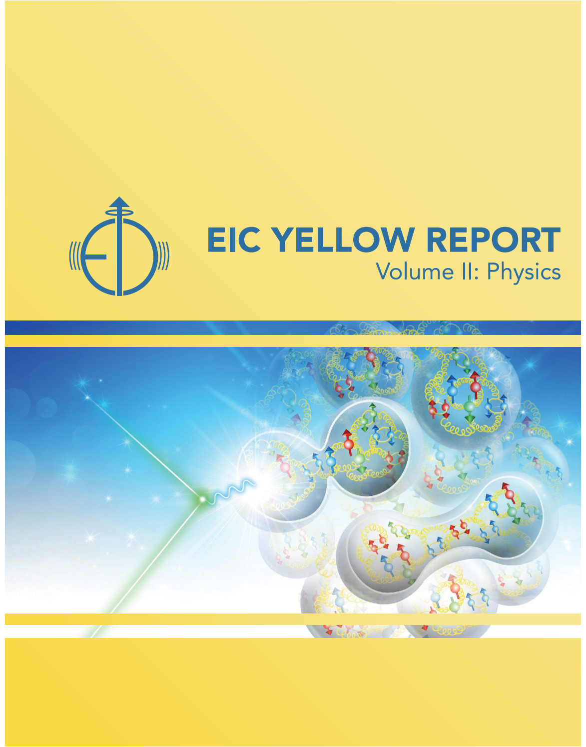


So, how do we take pictures of the collisions at the EIC? What is our *microscope*?

Defining the Requirements: Yellow Report Initiative

The EIC Users Group: EICUG.ORG
Report: https://arxiv.org/abs/2103.05419

Physics Topics → Processes → Detector Requirements



Physics Working Group:

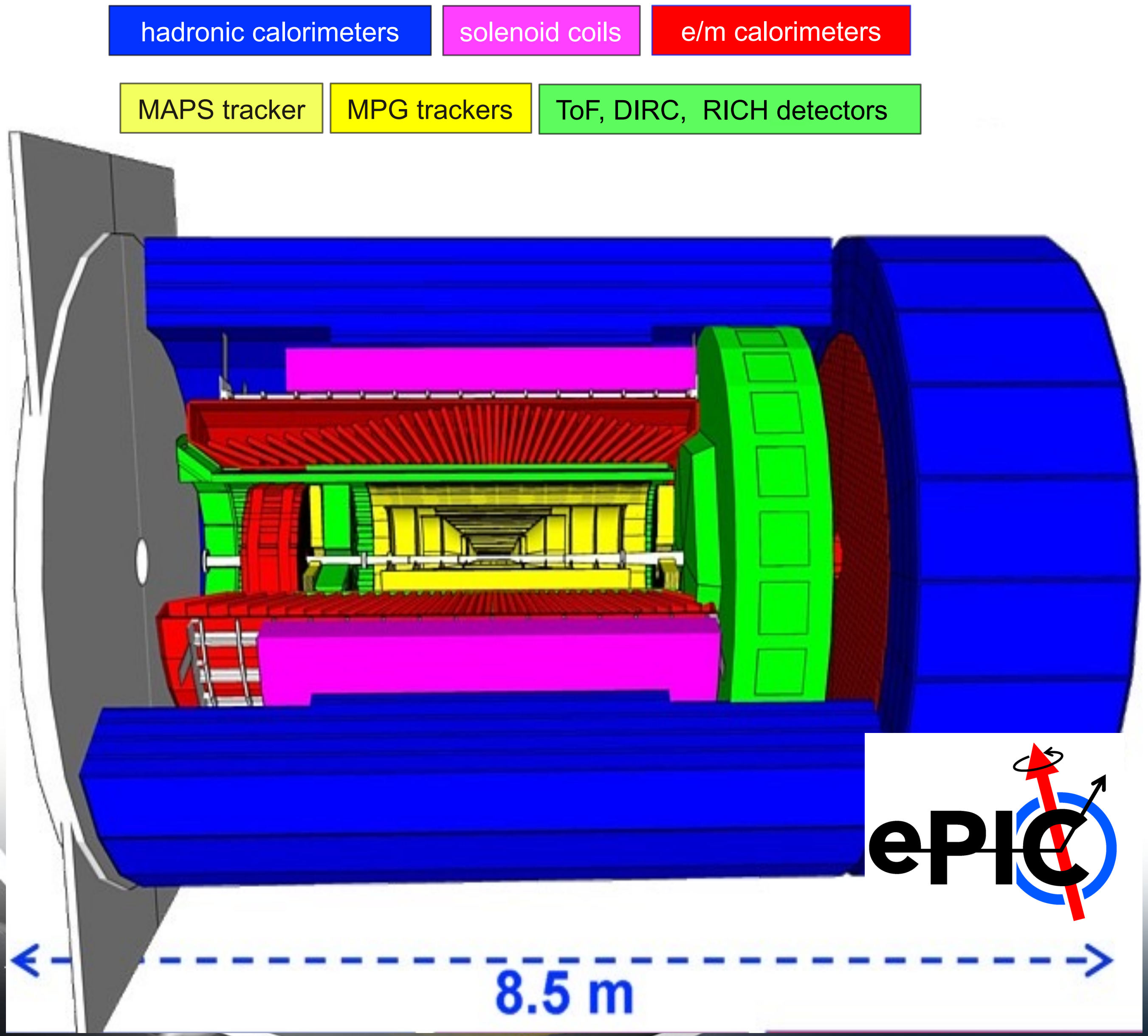
- Inclusive Reactions
- Semi-Inclusive Reactions
- Jets, Heavy Quarks
- Exclusive Reactions
- Diffractive Reactions & Tagging

⟷

Detector Working Group:

- Tracking + Vertexing
- Particle ID
- Calorimetry
- DAQ/Electronics
- Polarimetry/Ancillary Detectors
- Central Detector: Integration & Magnet
- Far- Forward Detector & IR Integration

3 Years Later: The ePIC Collaboration



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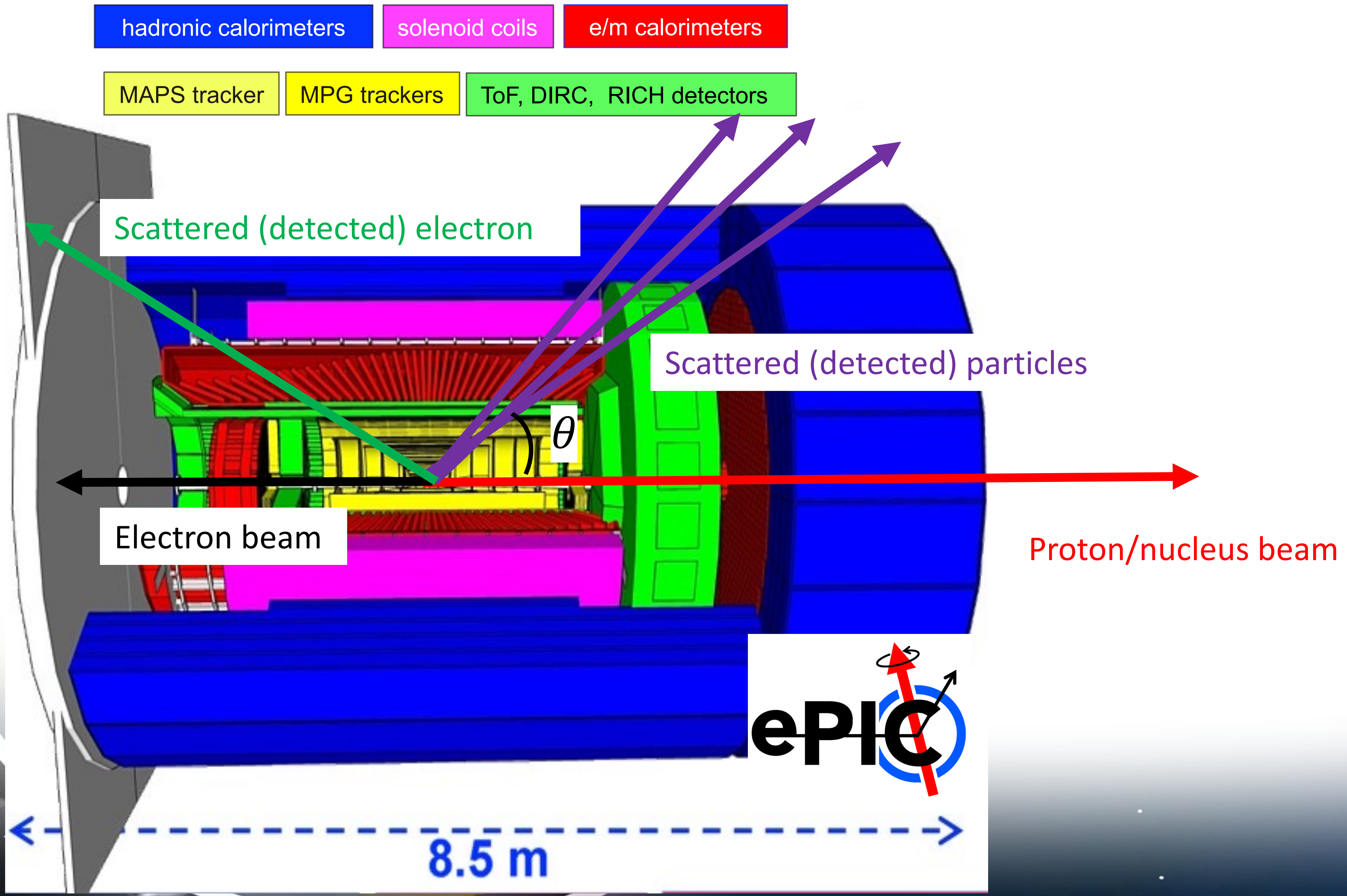

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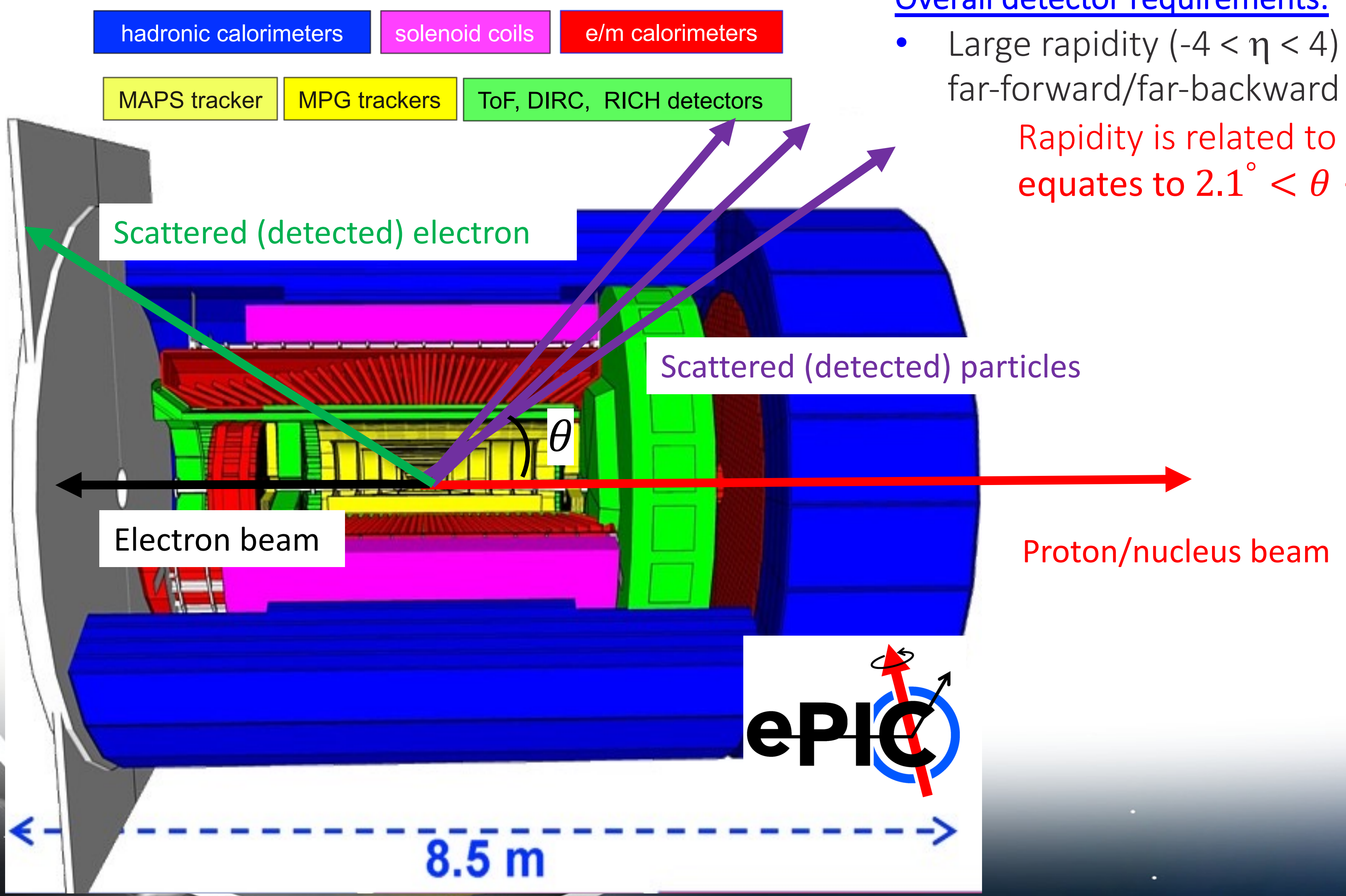

Overall detector requirements:

- 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 $2.1^\circ < \theta < 90^\circ$

$$\eta = -ln(tan(\theta/2))$$

pseudorapidity

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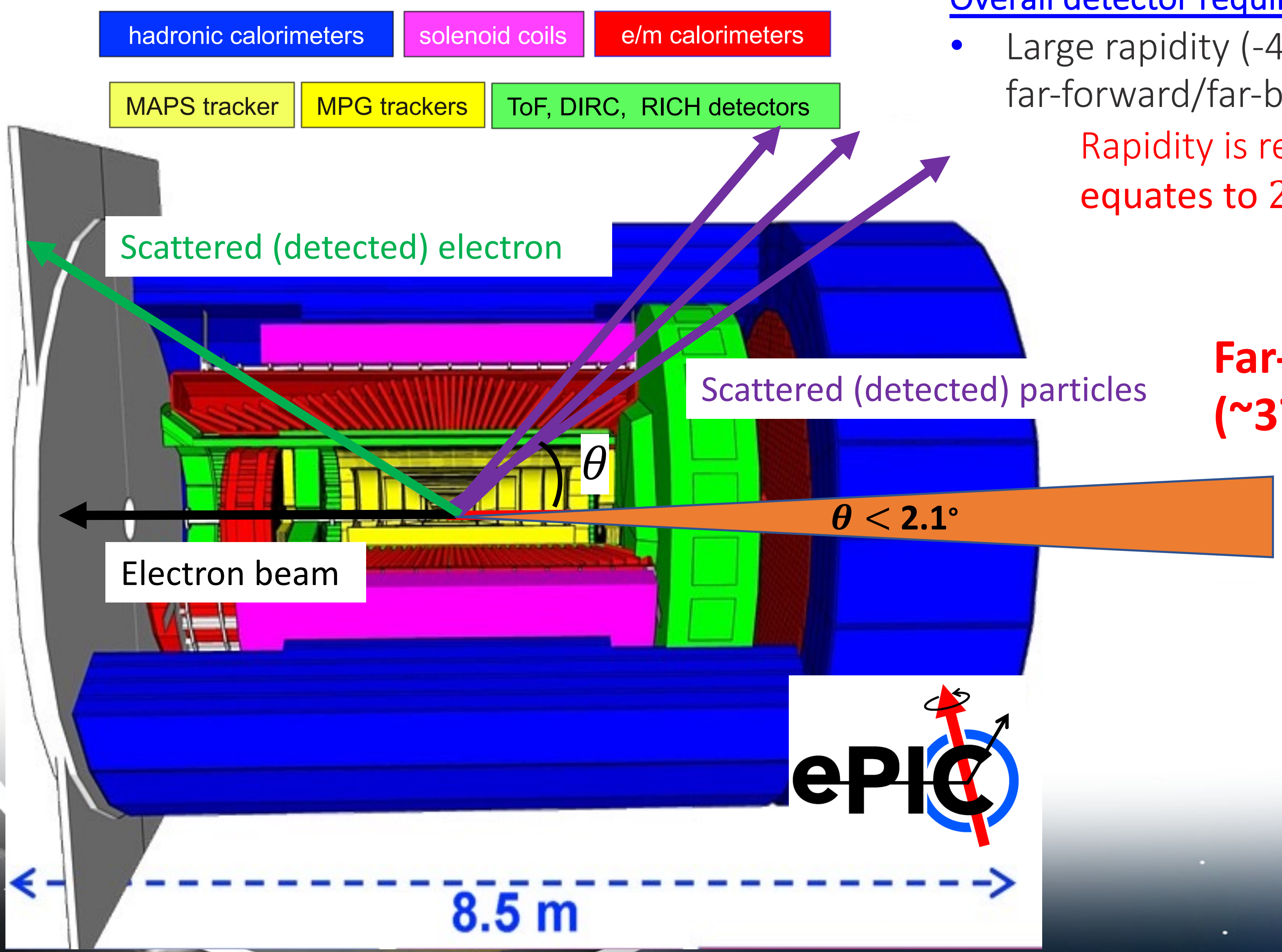

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Far-forward here means $\theta < 2.1°$ (~37 mrad)

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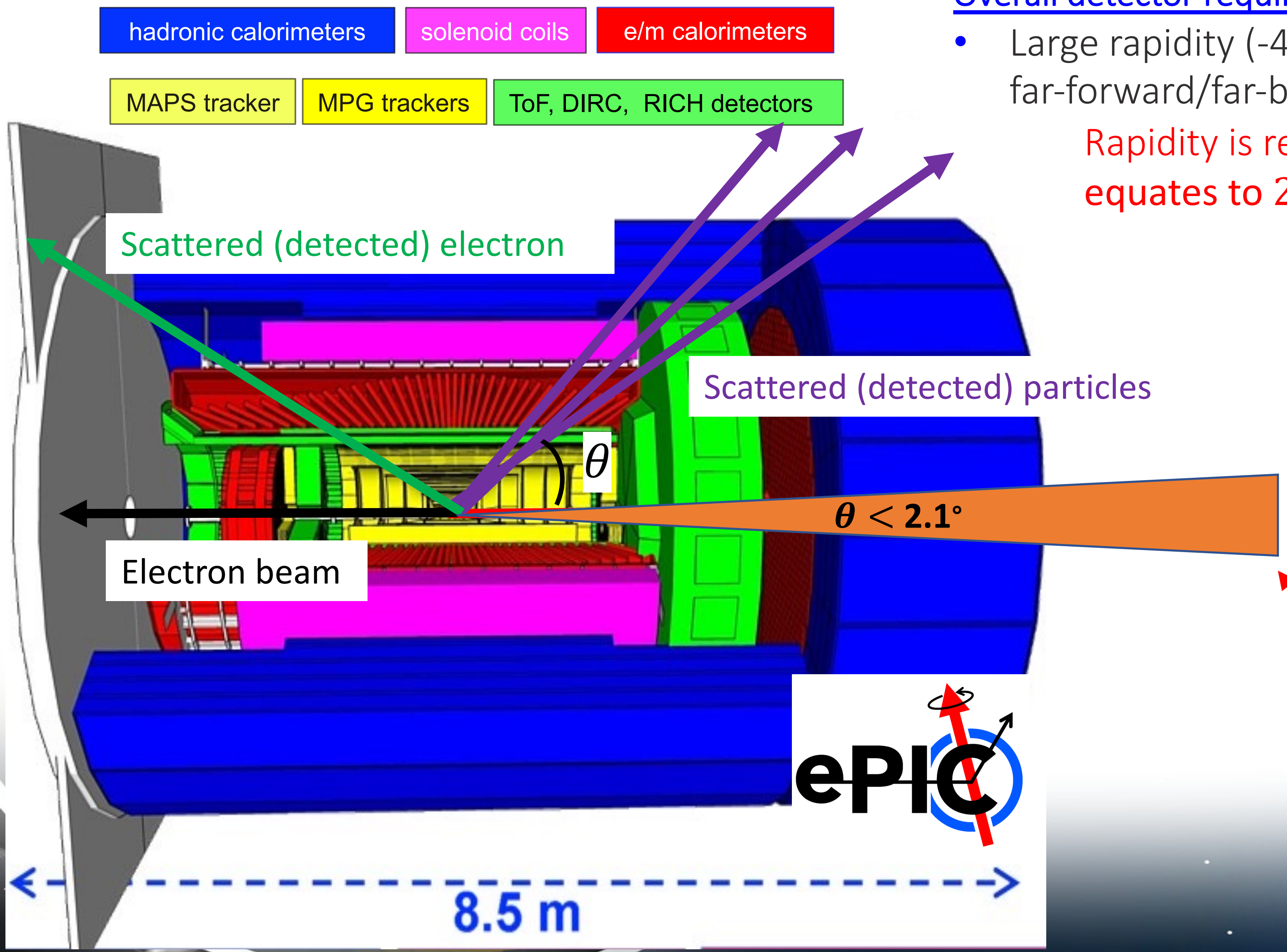

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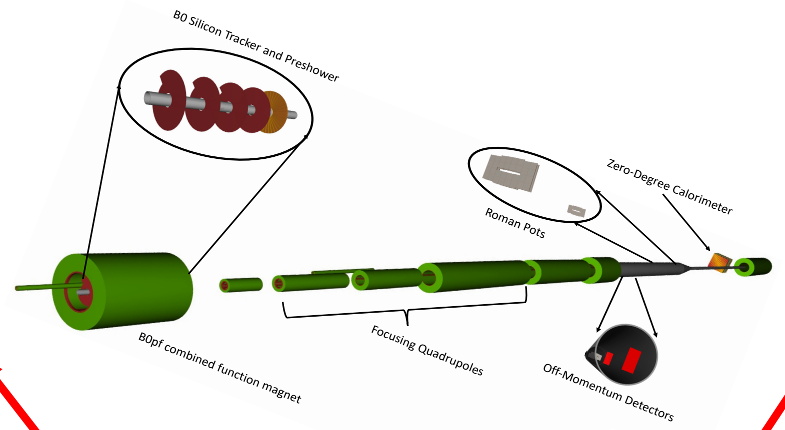
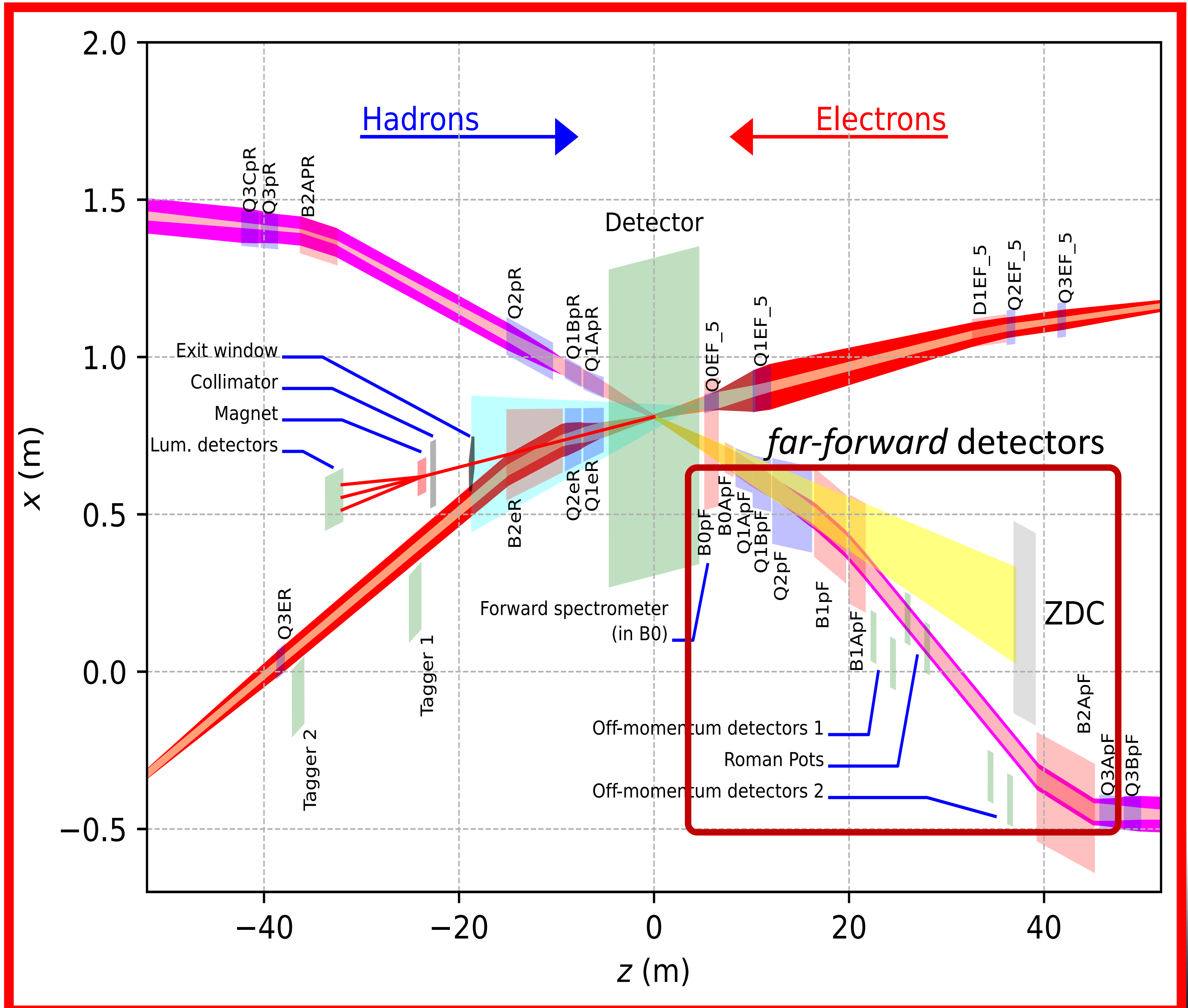
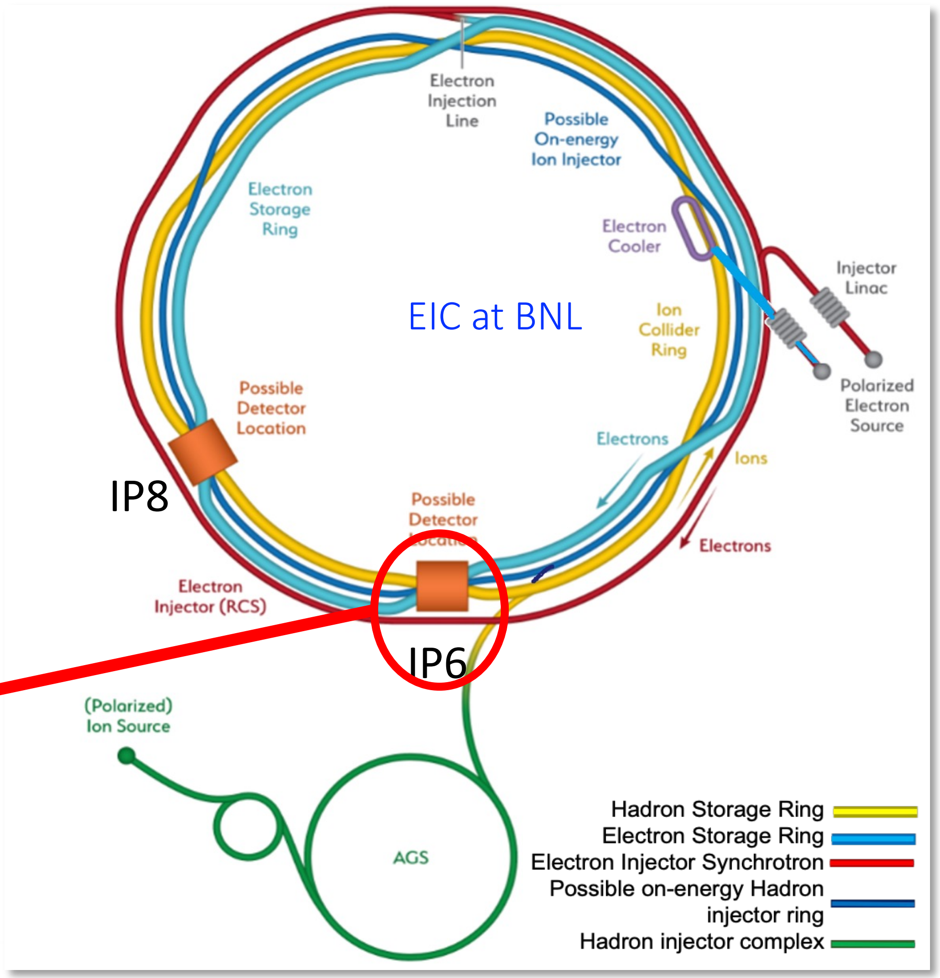


Need detectors here!!

The Interaction Region (IR6)



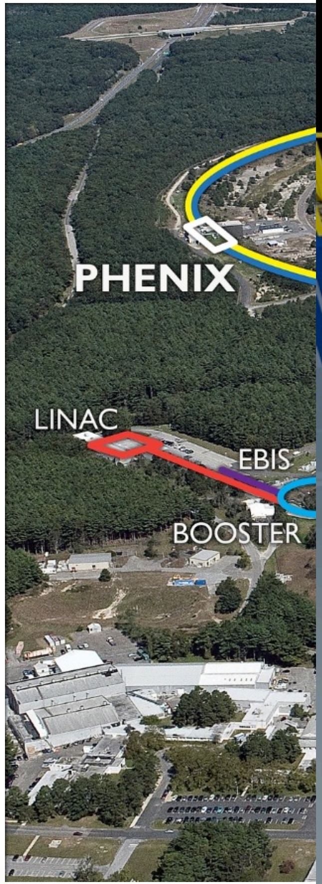


Intermission: fun animal facts

- Live primarily in desert regions in North Africa and Arabian peninsula.
- Their bat-like ears radiate body heat and help keep the foxes cool.
- They have been known to jump in the air 2 feet (.6 meters) high from a standing position, and they are able to leap a distance of 4 feet (1.2 meters).
- Live in adorable colonies of around 10 foxes.
- They are omnivorous, but they prefer Tex-Mex and craft beer.
  - Okay, maybe not, but if they tried it, they'd like it.

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

Relativ



species

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p, p+Au

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• Located

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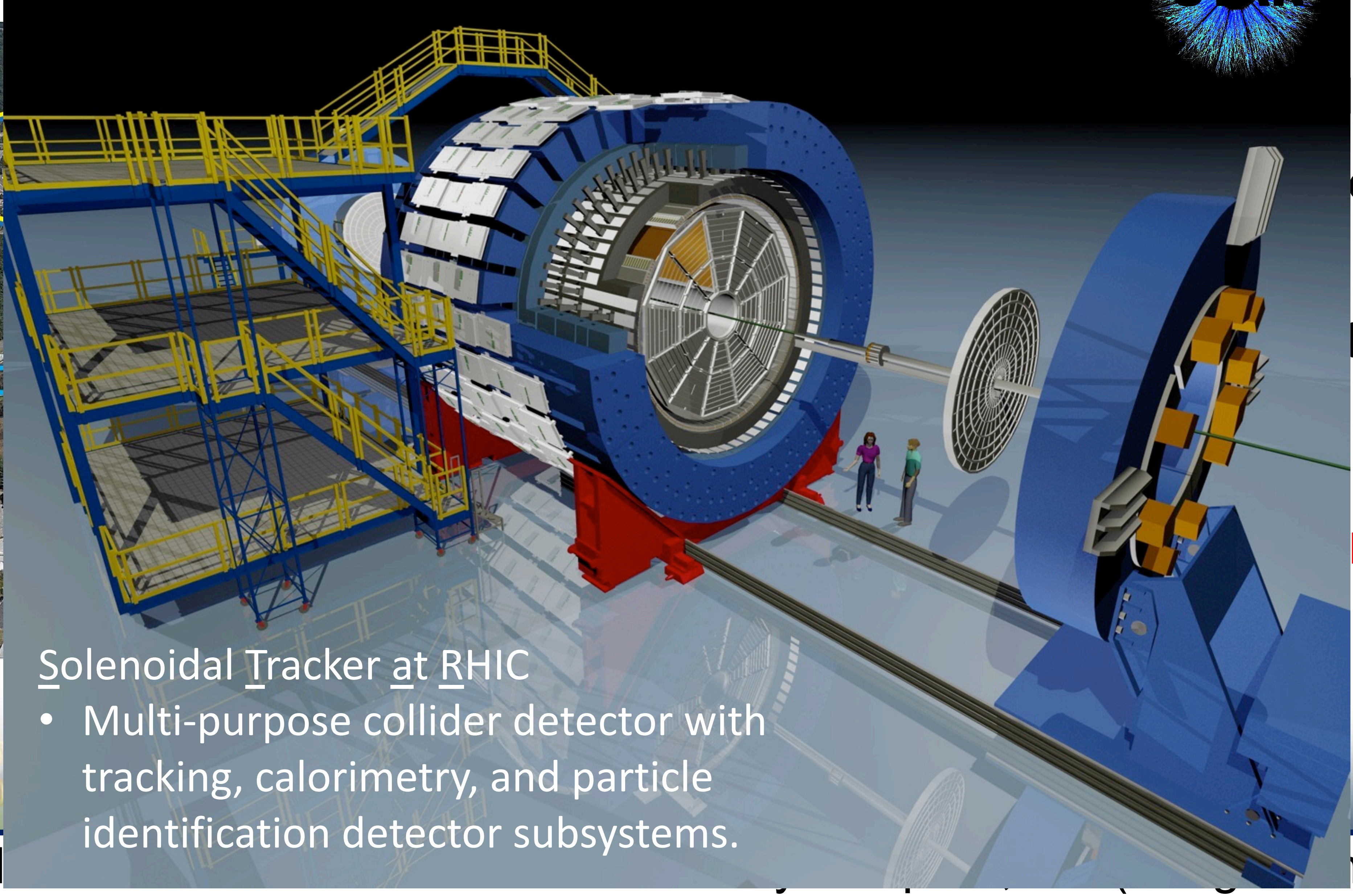
The STAR Detector



Solenoidal Tracker at RHIC

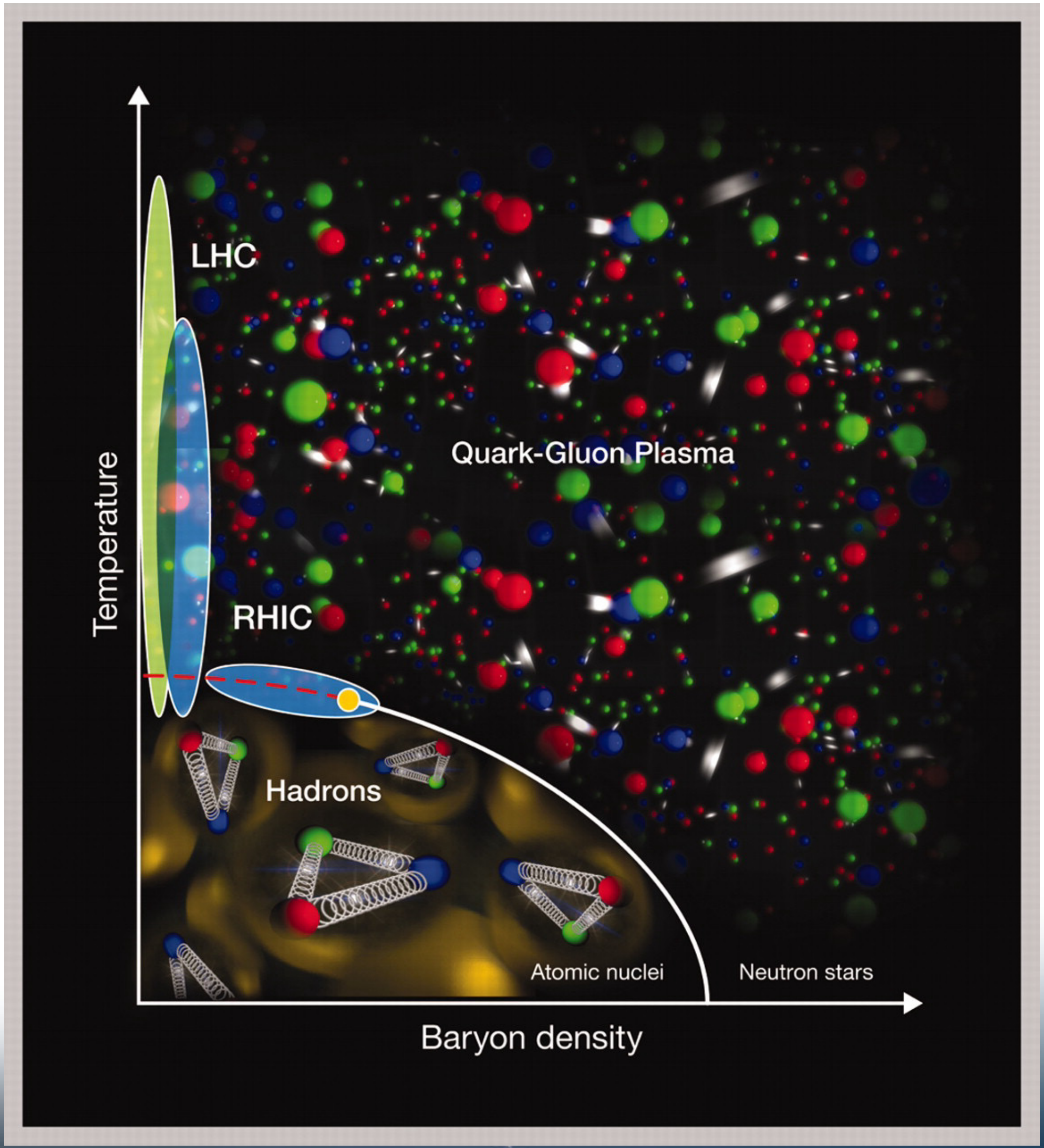
- Multi-purpose collider detector with tracking, calorimetry, and particle identification detector subsystems.

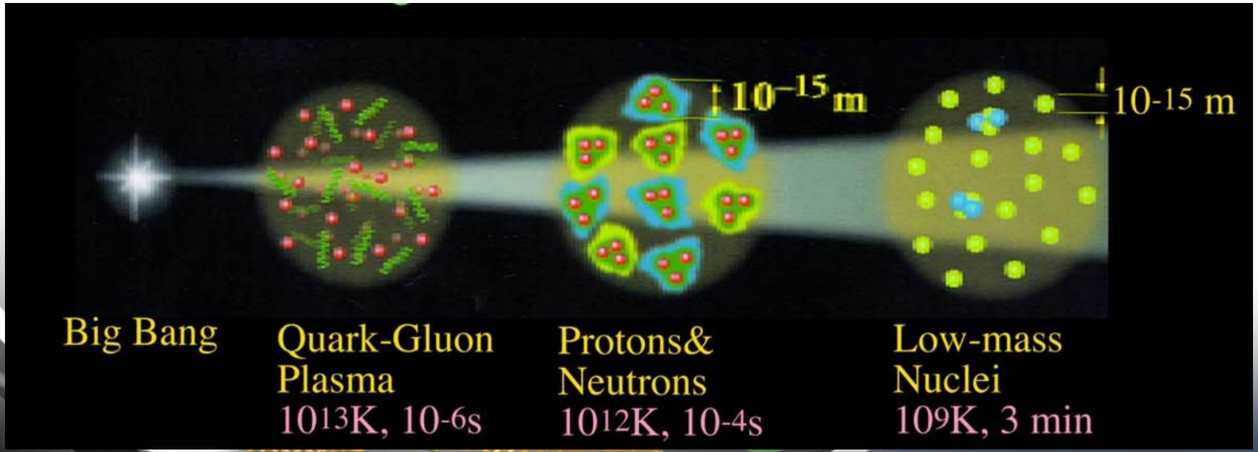
Physics of RHIC – Hot and Cold QCD

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

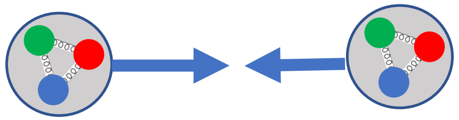
"Cold" QCD

RHIC Cold QCD ⟺ EIC physics

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

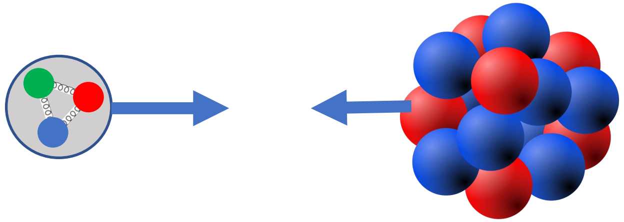
Lots of un-analyzed RHIC Cold QCD data (e.g. 2017 data), and more datasets being collected NOW!

Polarized proton + proton collisions



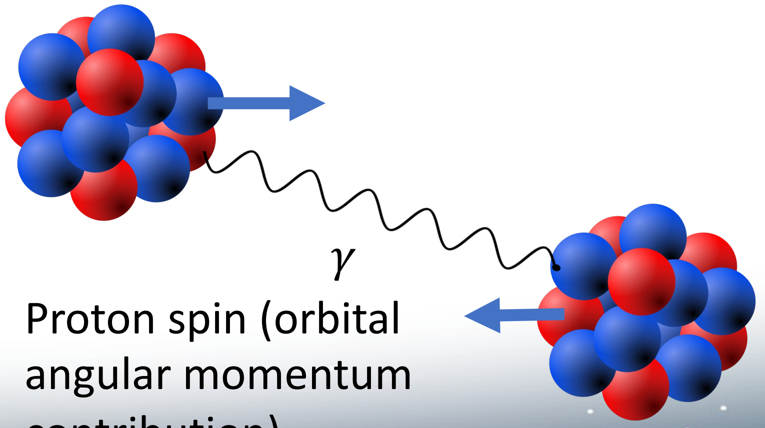
- Proton spin (gluon contribution).

proton + nucleus collisions



- Hints of saturation?
- Nuclear PDFs.

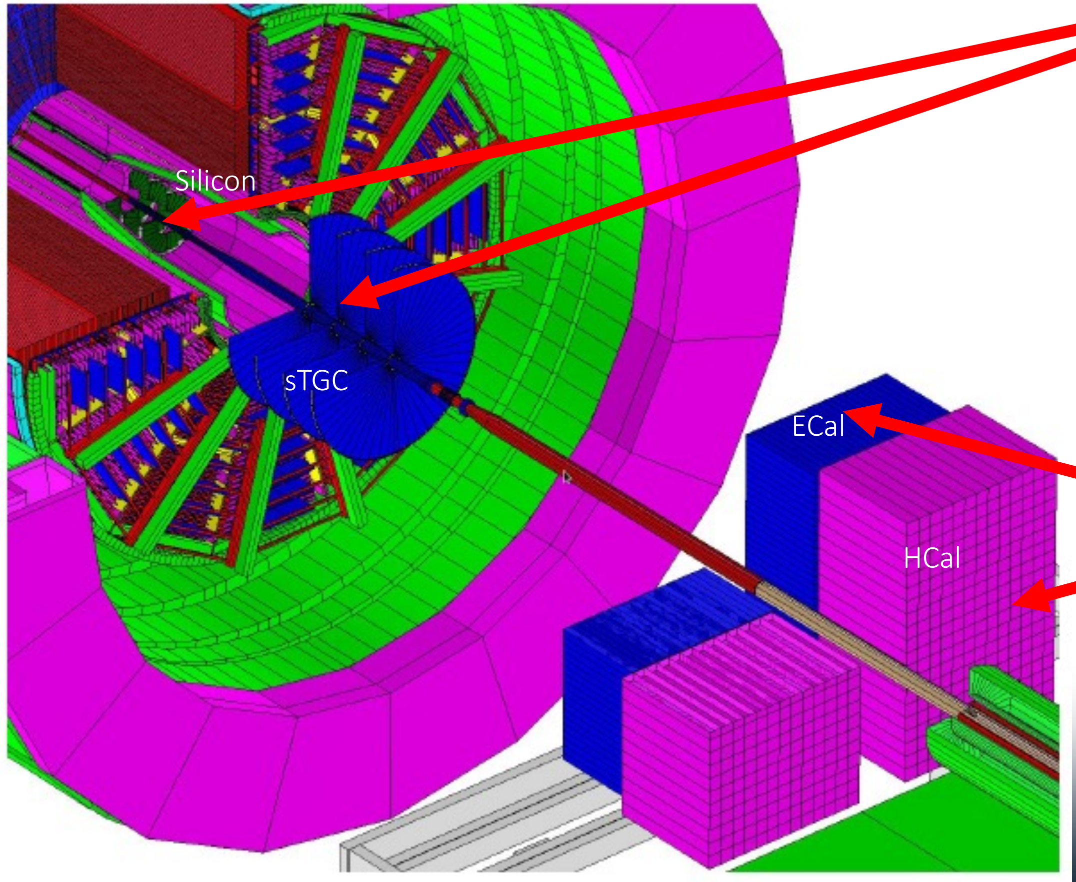
Ultra-Peripheral Au + Au (or p+p, p+A) collisions



- Proton spin (orbital angular momentum contribution).

Looking Forward: The STAR Forward Upgrade

- Addition of silicon tracking system and EM and hadronic calorimetry $\rightarrow$ 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)

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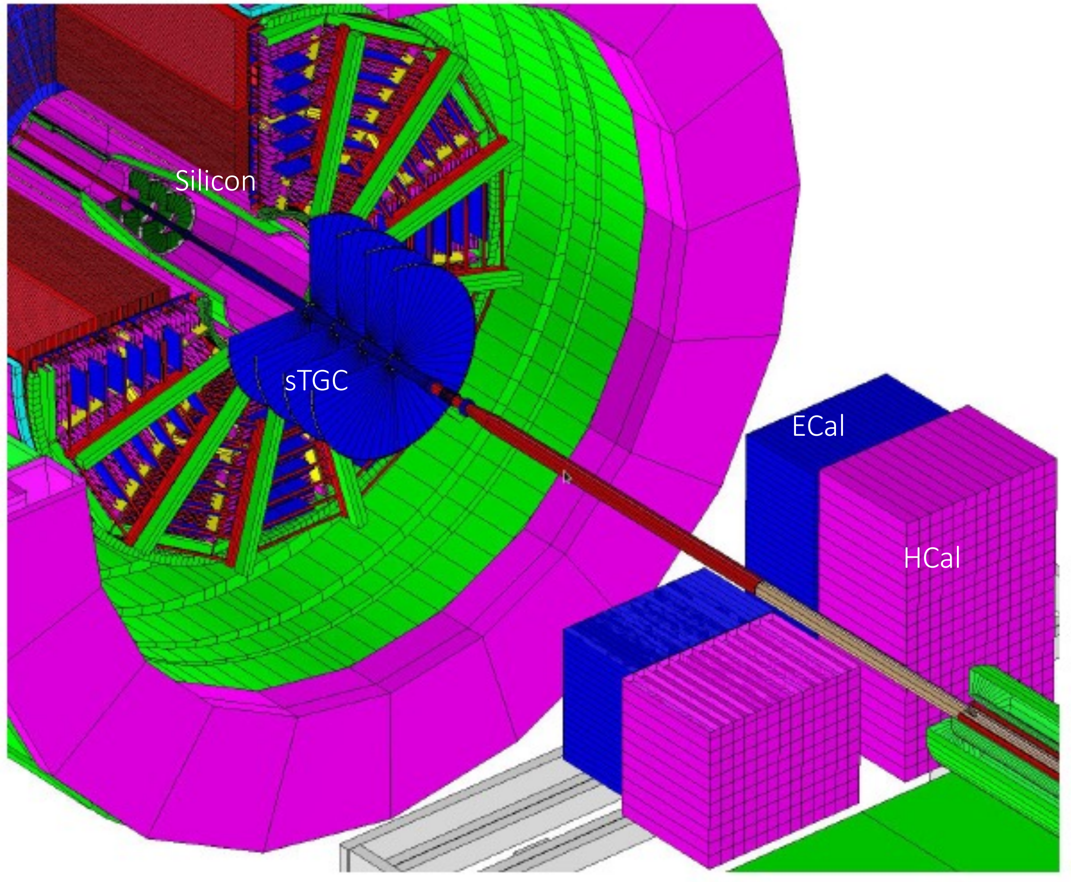


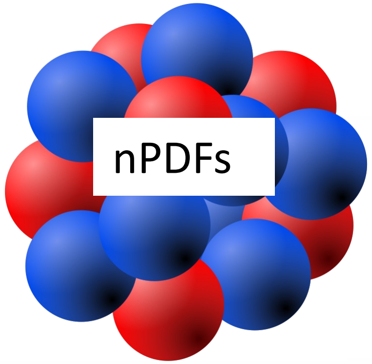
Collecting Data Now + next 3 years

- **<u>STAR Forward Upgrade</u>**

quarks gluons

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

Orbital angular momentum

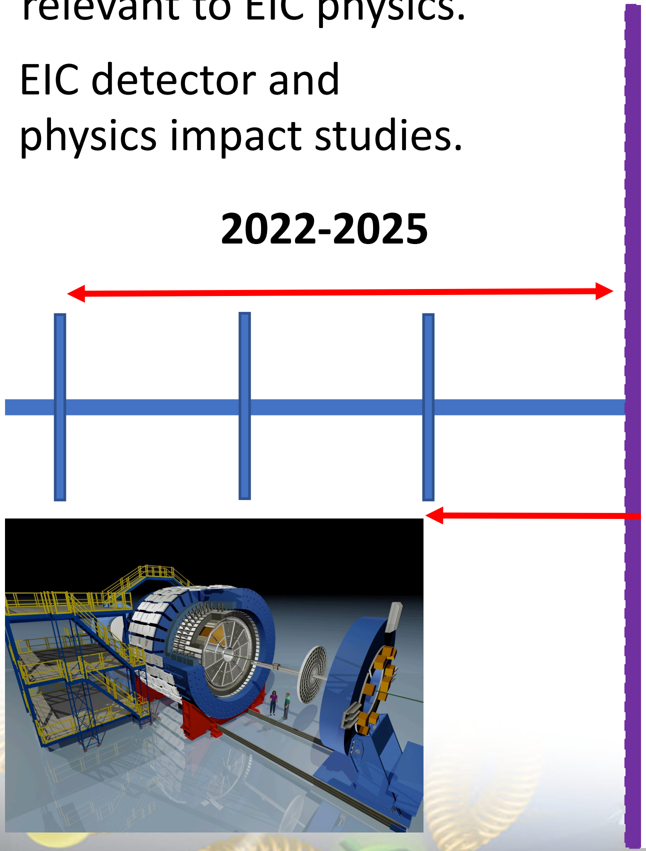


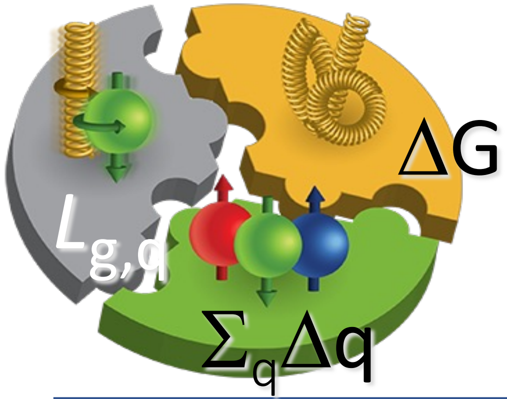
Lots of overlap with EIC topics!

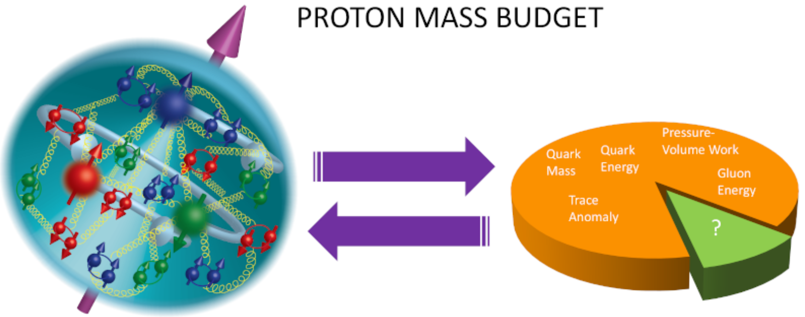
EIC Timeline

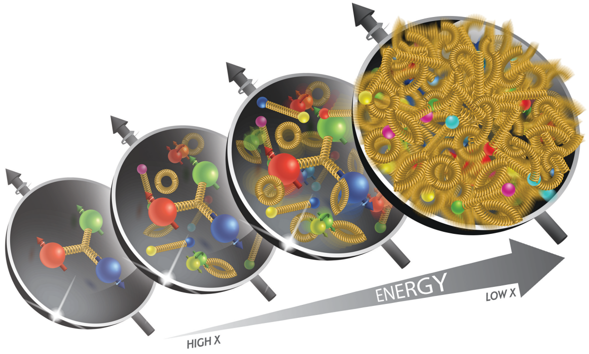
- Leverage STAR Cold QCD program and perform studies relevant to EIC physics.
- EIC detector and physics impact studies.

2022-2025

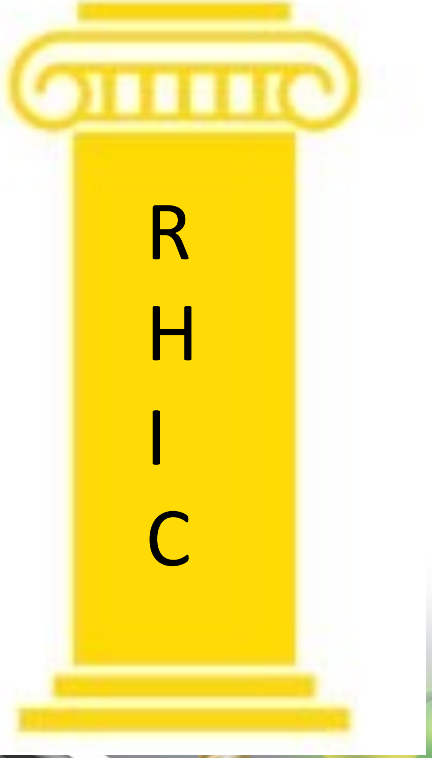








Our understanding of the structure of visible matter in the universe!



Thank you!