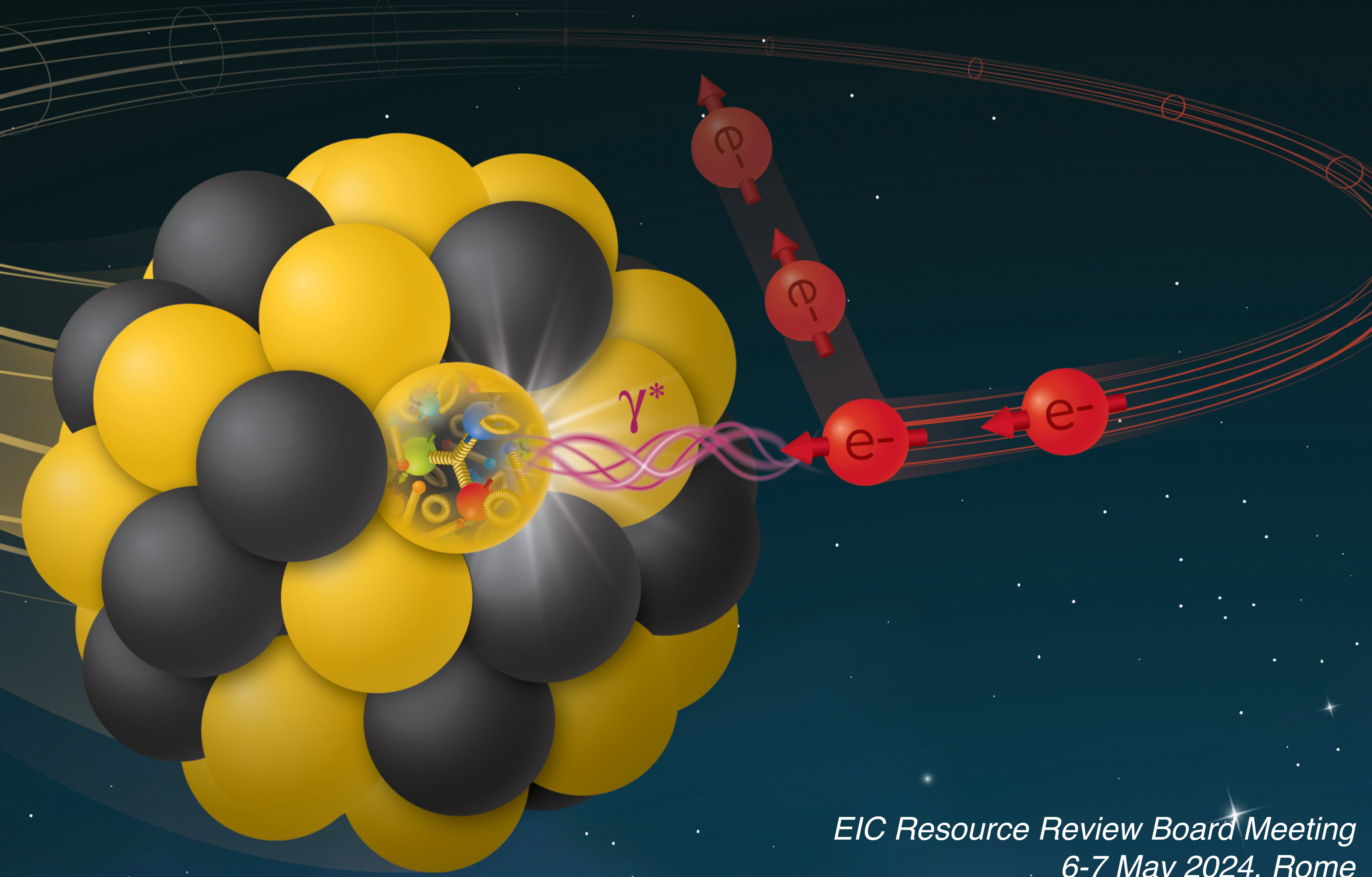
Glimpse into the Vast EIC Science: "Exploring the glue that binds us all"



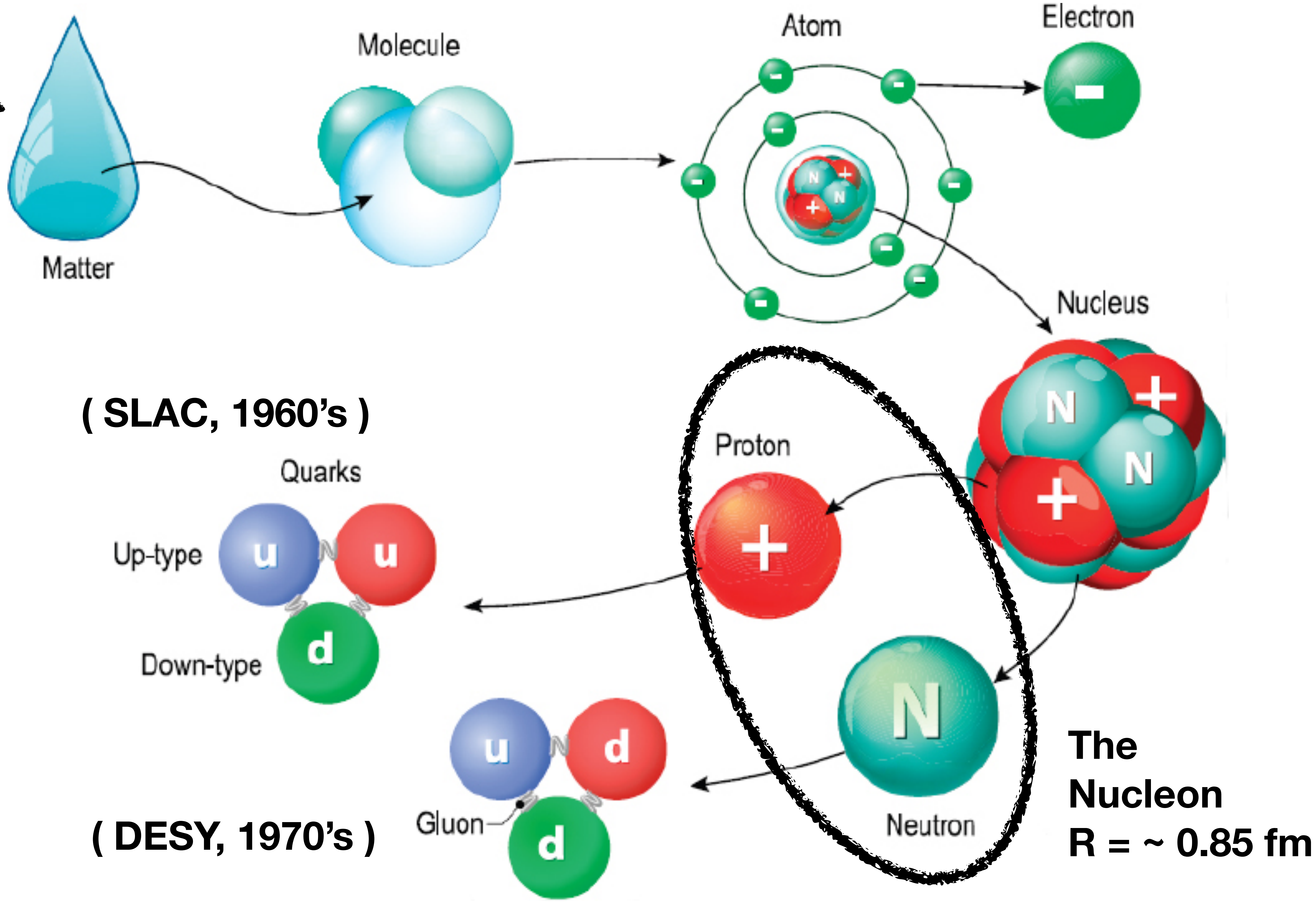
Rachel Montgomery

(UKRI STFC Ernest Rutherford Fellow, University of Glasgow, UK)

*on behalf of **many** …*

EIC Resource Review Board Meeting
6-7 May 2024, Rome

What are we made of?



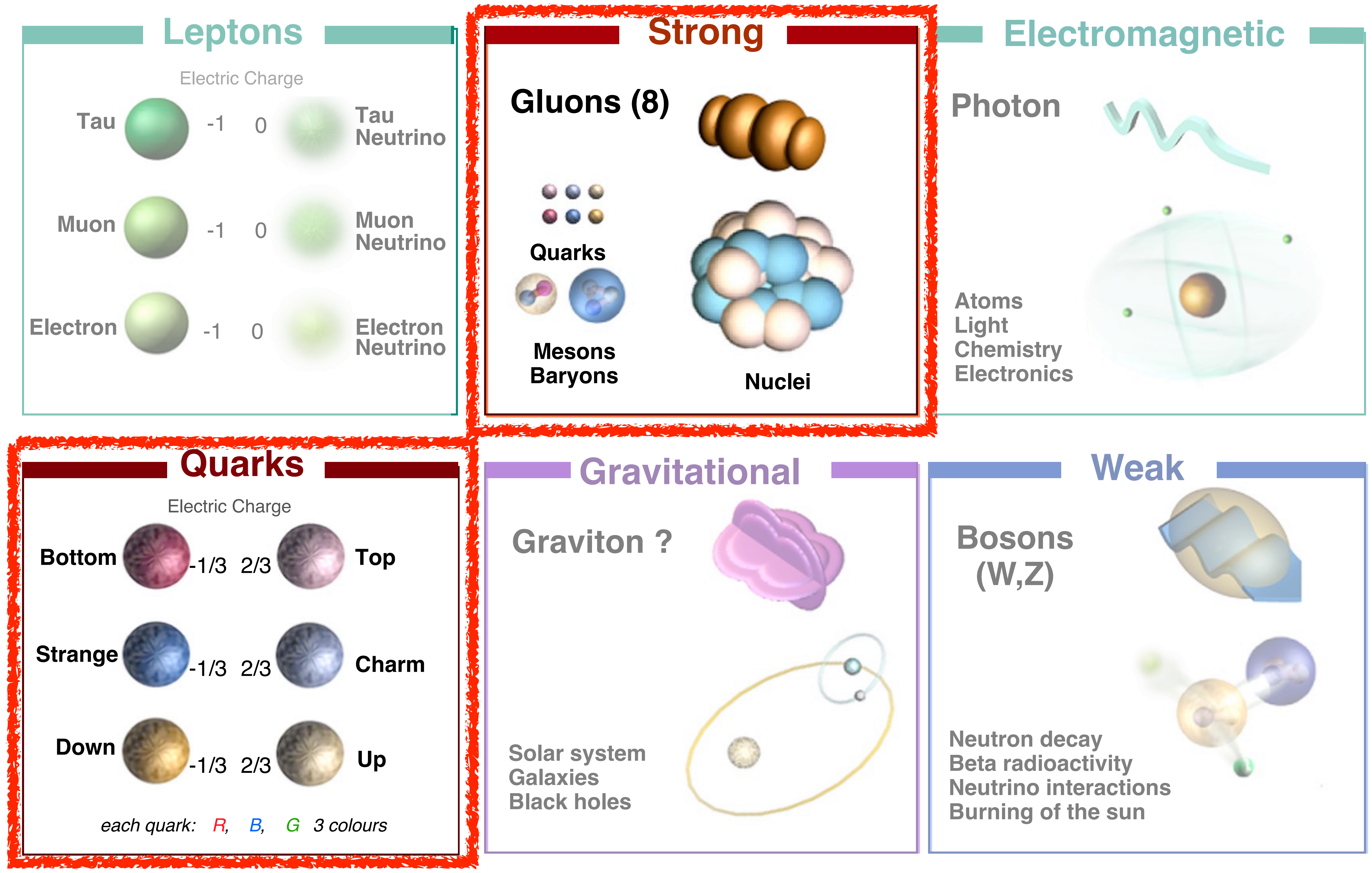
1 fm = 0.000 000 000 000 001 m

Nuclei are responsible for almost all visible matter in Universe

We still strive to fully understand how quarks and gluons are arranged inside the nucleon and nuclei

EIC will be like a powerful microscope to help us understand this further via nucleon "femtography"!

How Are We Held Together?



6 quark flavours
Each with different mass
and electrical charge

- We never observe free quarks and gluons
- Confined in nuclear matter by the strong force

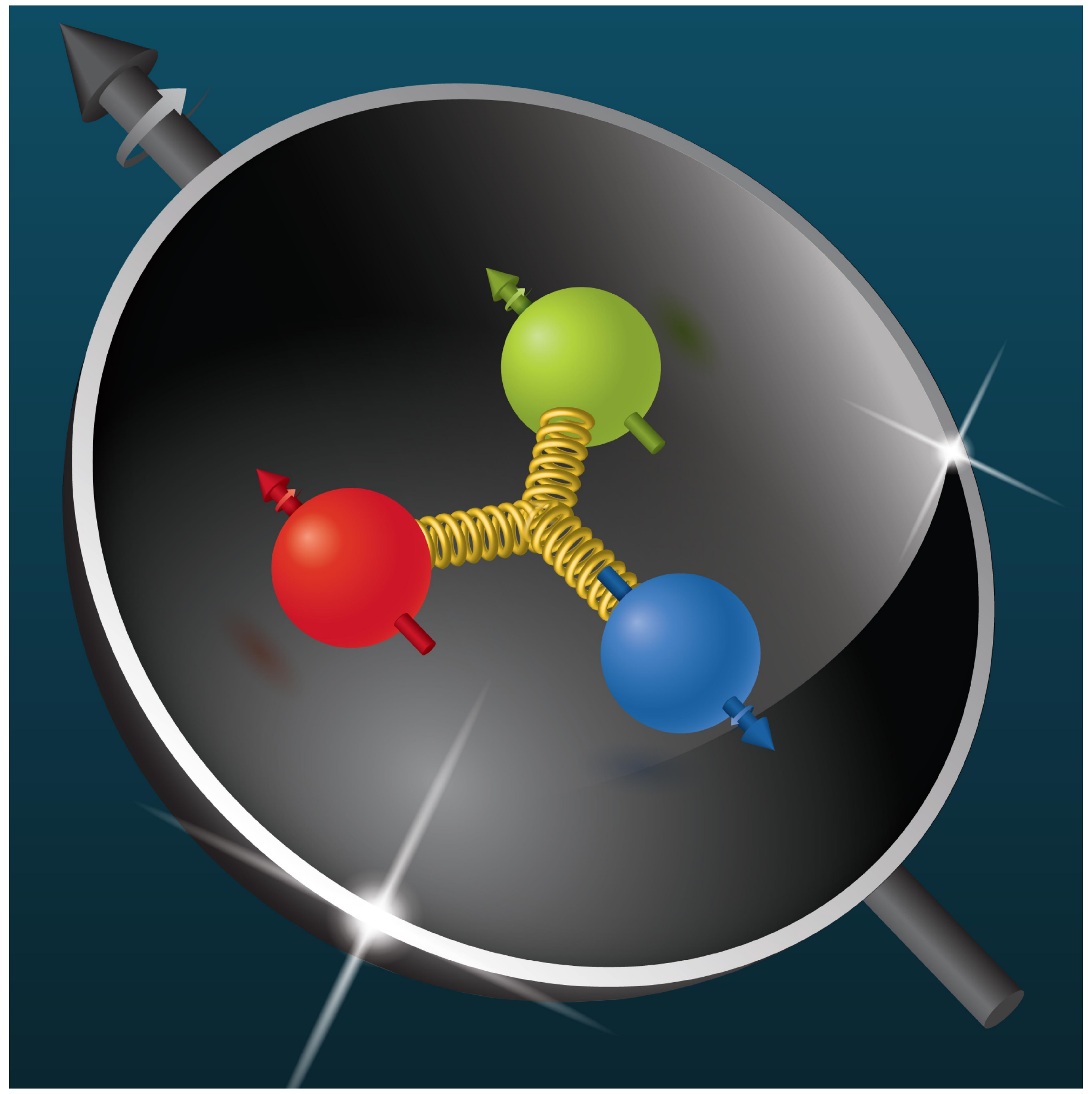
- Strong force acts on "colour" charge
- Gluons are the carrier of the strong force

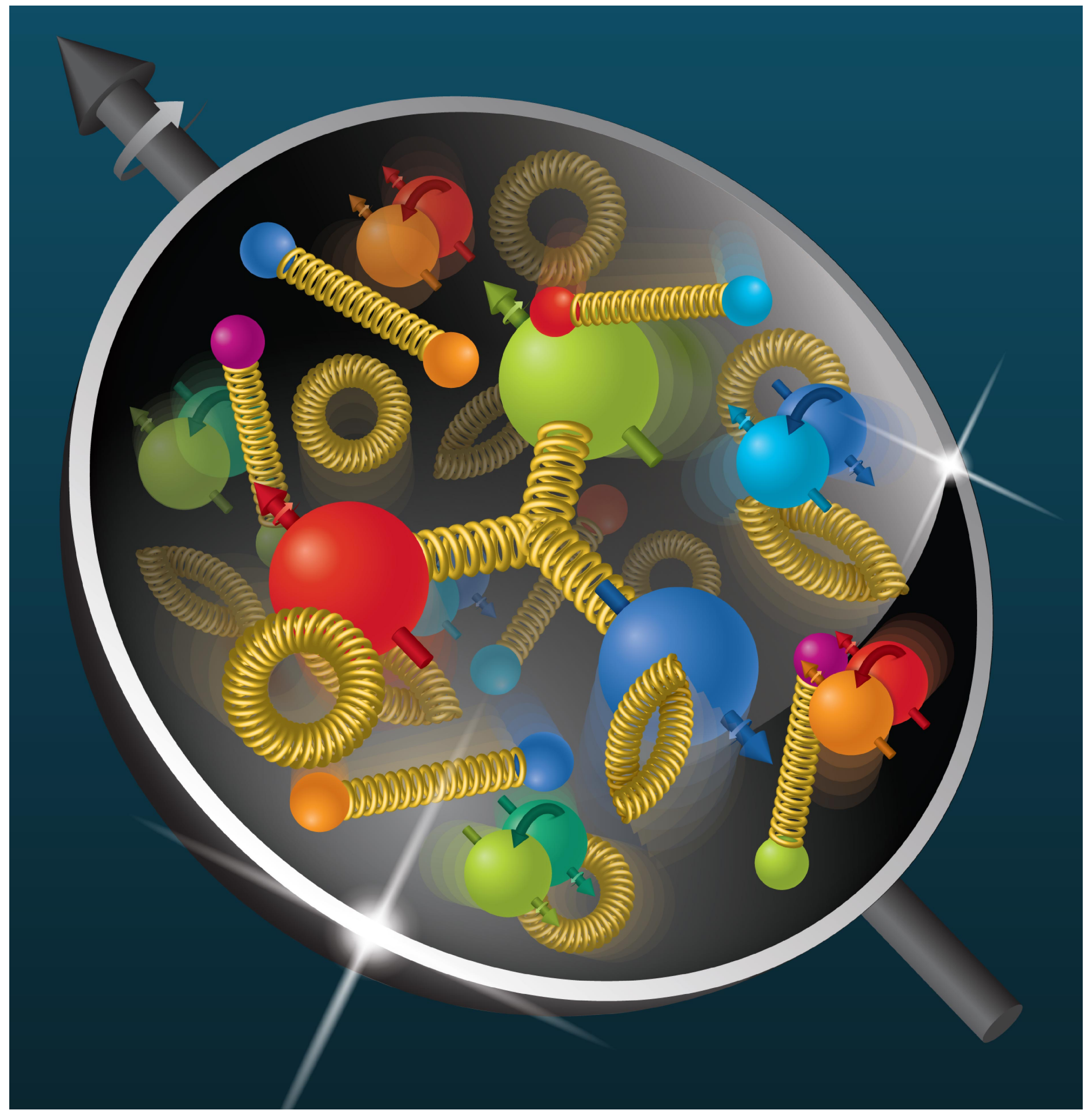
- Extremely complex
- Many aspects still not understood

- EIC will transform our understanding of the force keeping our visible world together!

Microcosm of the Nucleon

3 valence quarks
Proton = uud





Sea of transient quark/antiquark pairs and gluons

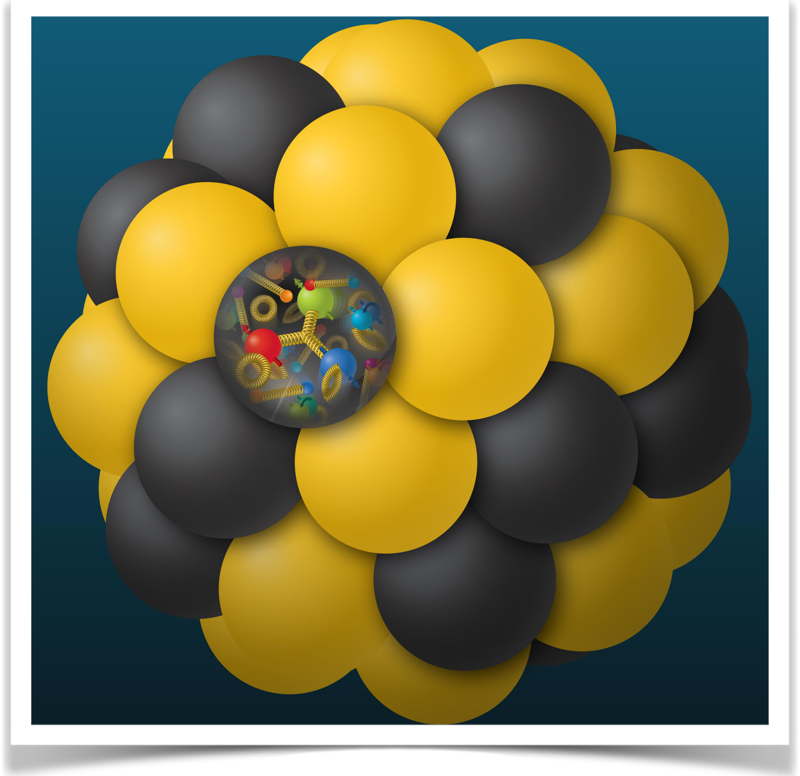
Proton = $uud + u\bar{u} + d\bar{d} + s\bar{s} + \ldots$

- Everyday properties emerge from the nature of the strong interaction
  - mass (mass spectrometry in pharmaceutics)
  - spin (magnetic moment in MRI machines)
- We exploit these properties, but don't fully understand them!
- We want to understand the nucleon structure and observed properties in terms of the quark/gluon *dynamics*
  - For this, we need the EIC

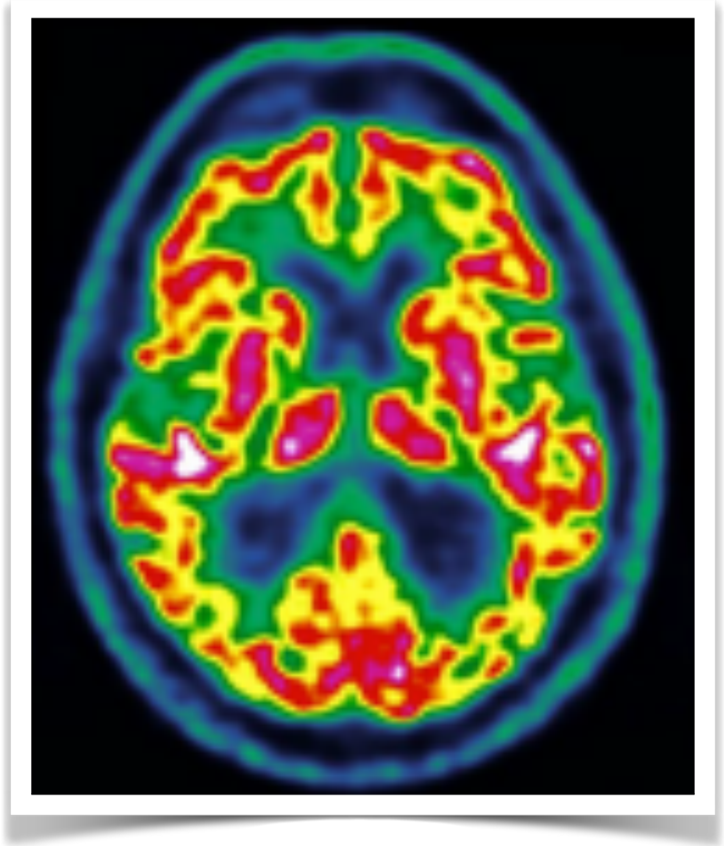
A Deep Dive into Nuclear Matter

EIC will be a revolutionary tool for nuclear physics, to push the frontier in our knowledge of nuclear matter

Understand better the building blocks of our visible Universe



Unlock discoveries and technologies which may benefit other sciences/society



https://doi.org/10.1038/s41598-022-18029-7

- Extensive scientific program which has been shaped by a wide international community, which is still growing!
- Example critical questions from the 2018 NAS Report (NAS Report (DOI 10.17226/25171):

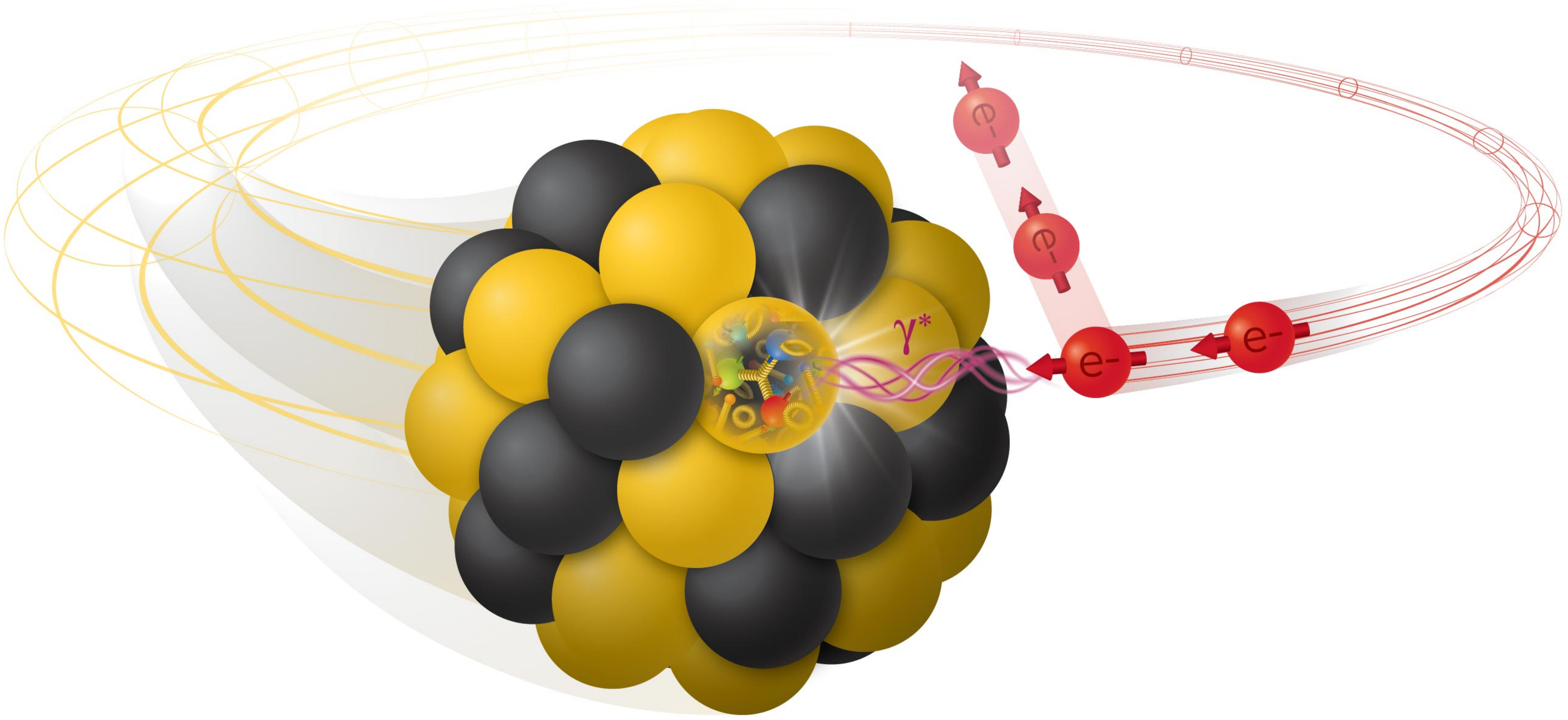
How does the mass of the nucleon arise?

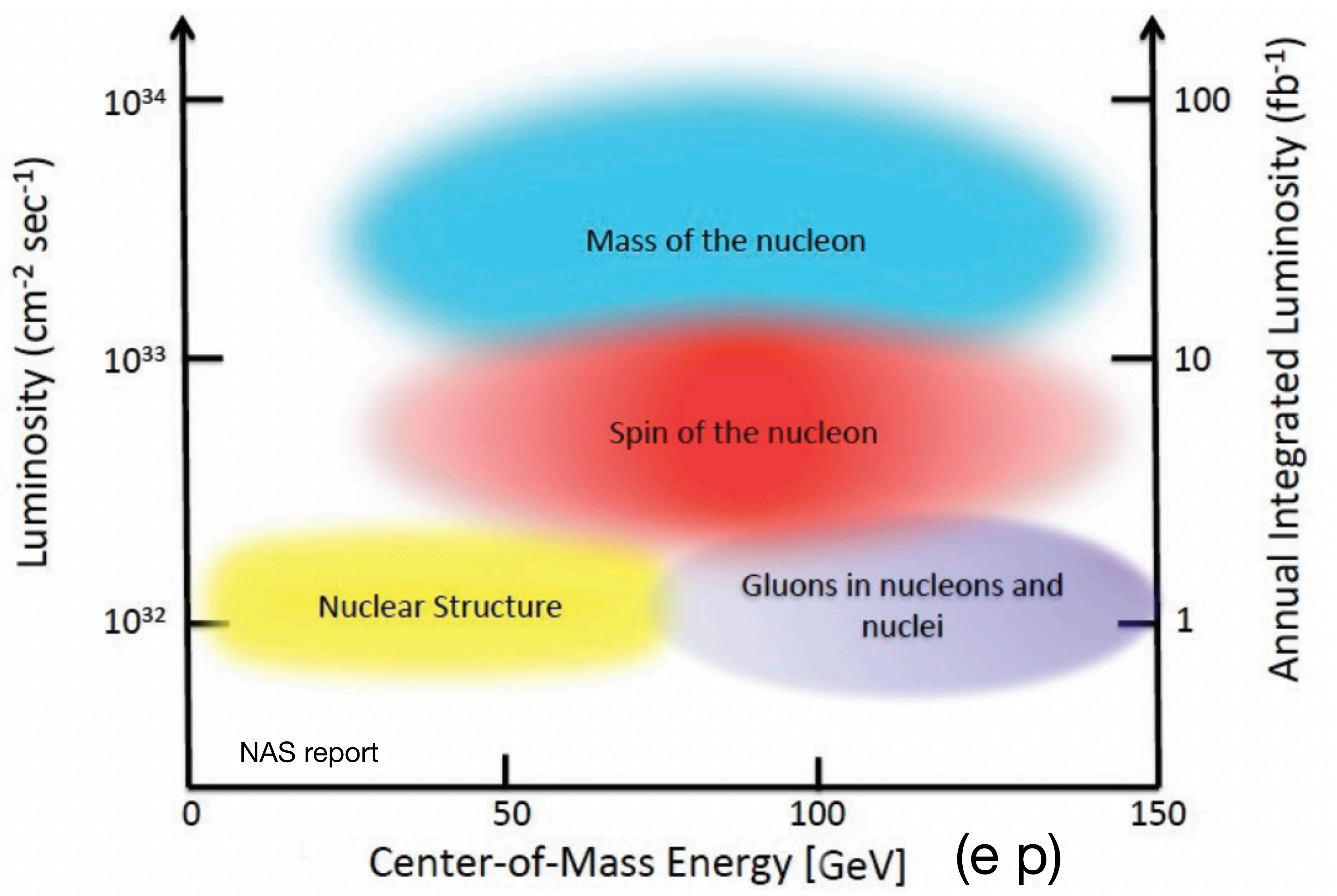
How does the spin of the nucleon arise?

What are the emergent properties of dense system of gluons?

How are quarks and gluons distributed *inside* nucleons and nuclei

First-Of-A-Kind Facility

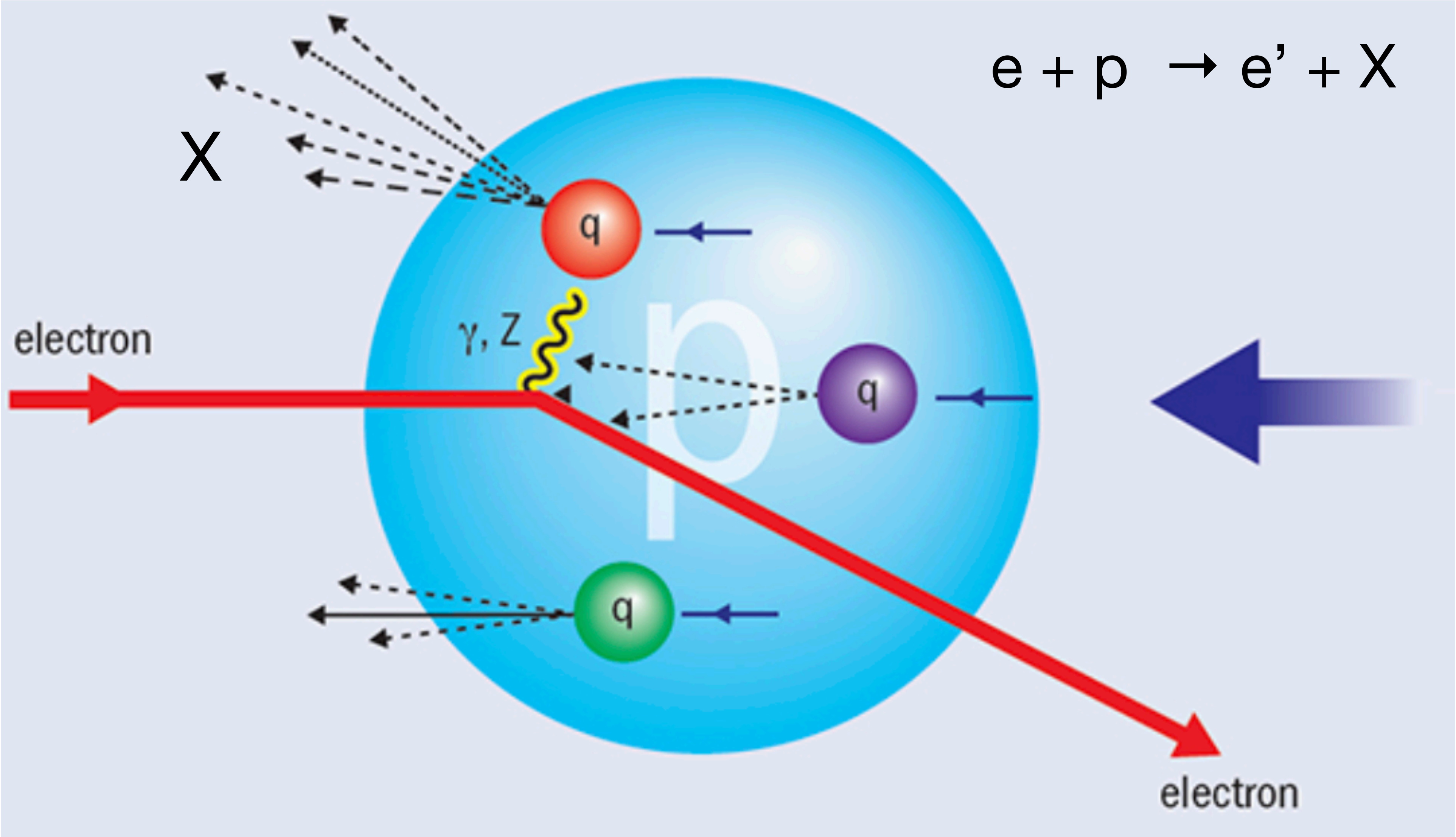


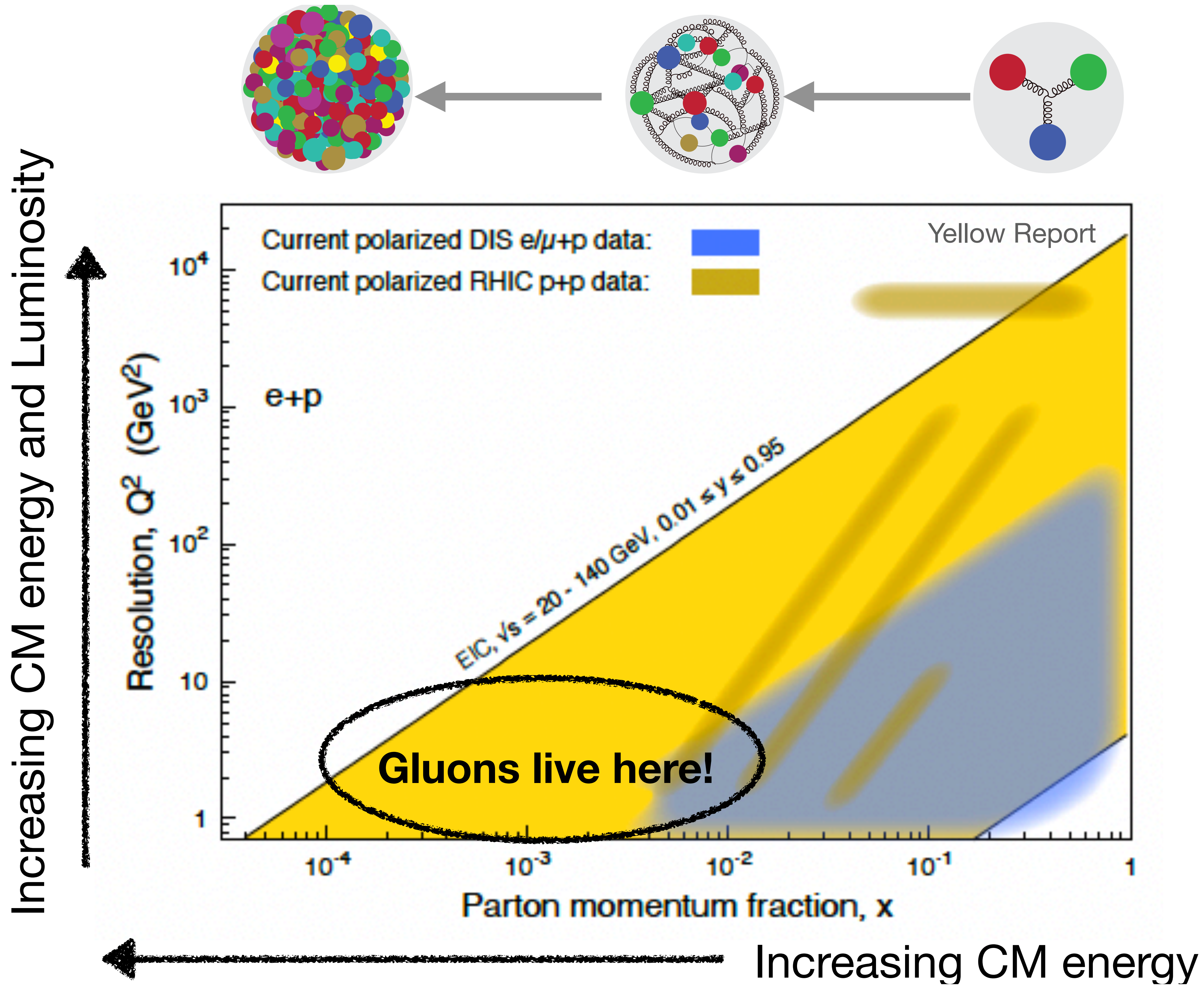


- World's first polarised electron-proton/light ion and electron-nucleus collider
  - Ranging from protons, light nuclei, up to uranium
- High-luminosities: 10^{33} - 10^{34} $cm^{-2}s^{-1}$; 10 - 100 fb^{-1}/year
- High spin polarised beams: 70%
- Large and variable centre of mass energy:
  - $20 < \sqrt{s} < 140$ GeV
- ePIC and beam line detectors to reconstruct all particles with high precision

☑ State-of-the-art, multi-purpose facility

Deep Inelastic Scattering (DIS) - the Golden Process





- Electrons → electromagnetic interaction → unmatched precision
- World first opportunity for a dedicated e+A DIS program

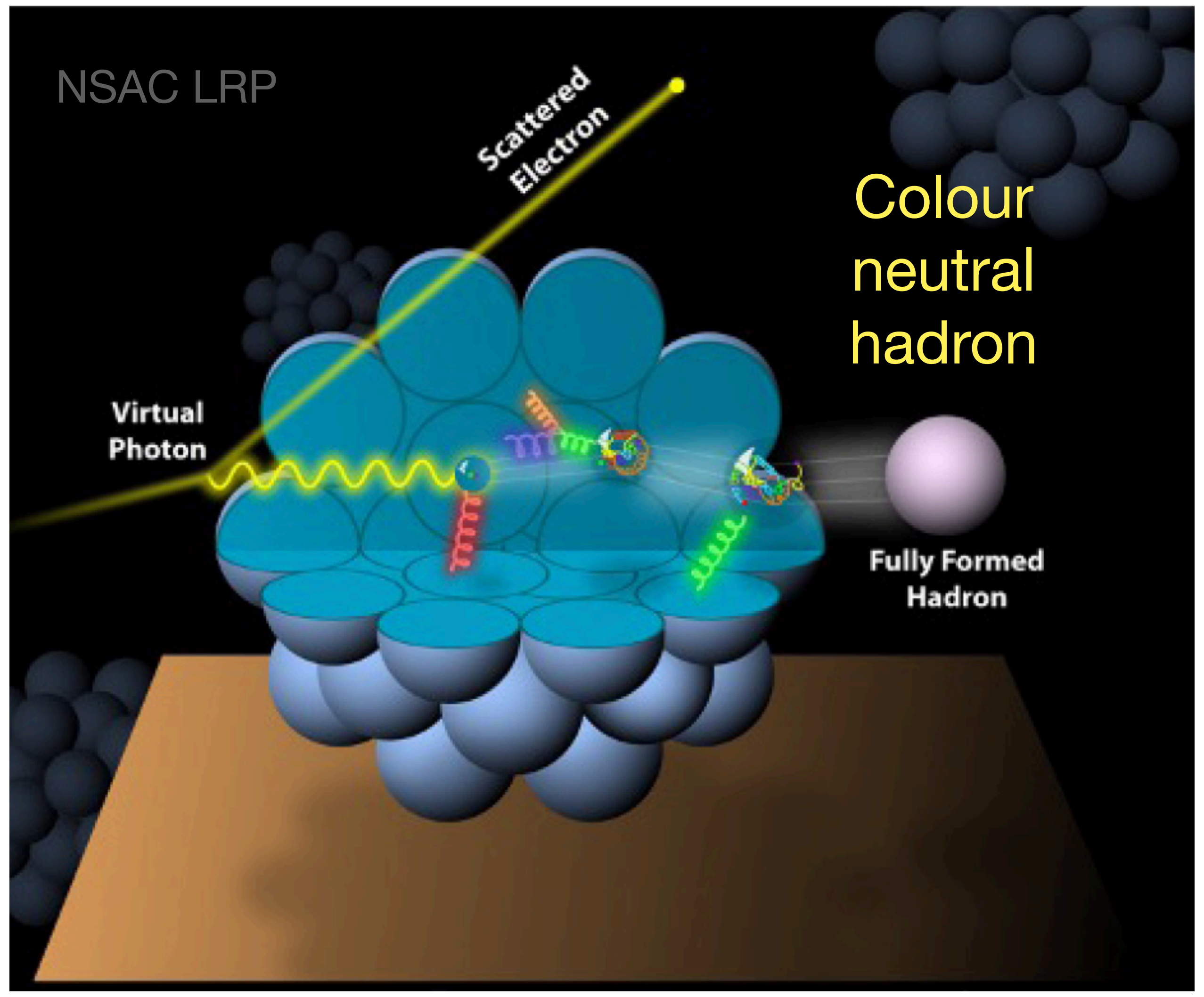
$$Q^2 = s \cdot x \cdot y$$

Q^2 = Resolution power
s = Centre-of-mass energy squared
x = Fraction of nucleon's momentum that the struck quark carries ($0<x<1$)
y = Inelasticity

Vastly expanded landscape over resolution (Q^2) and quark/gluon density (1/x)

The only facility in the world which is uniquely designed to probe the ocean of gluons and sea quarks!

Nuclei as a Laboratory for the Strong Force



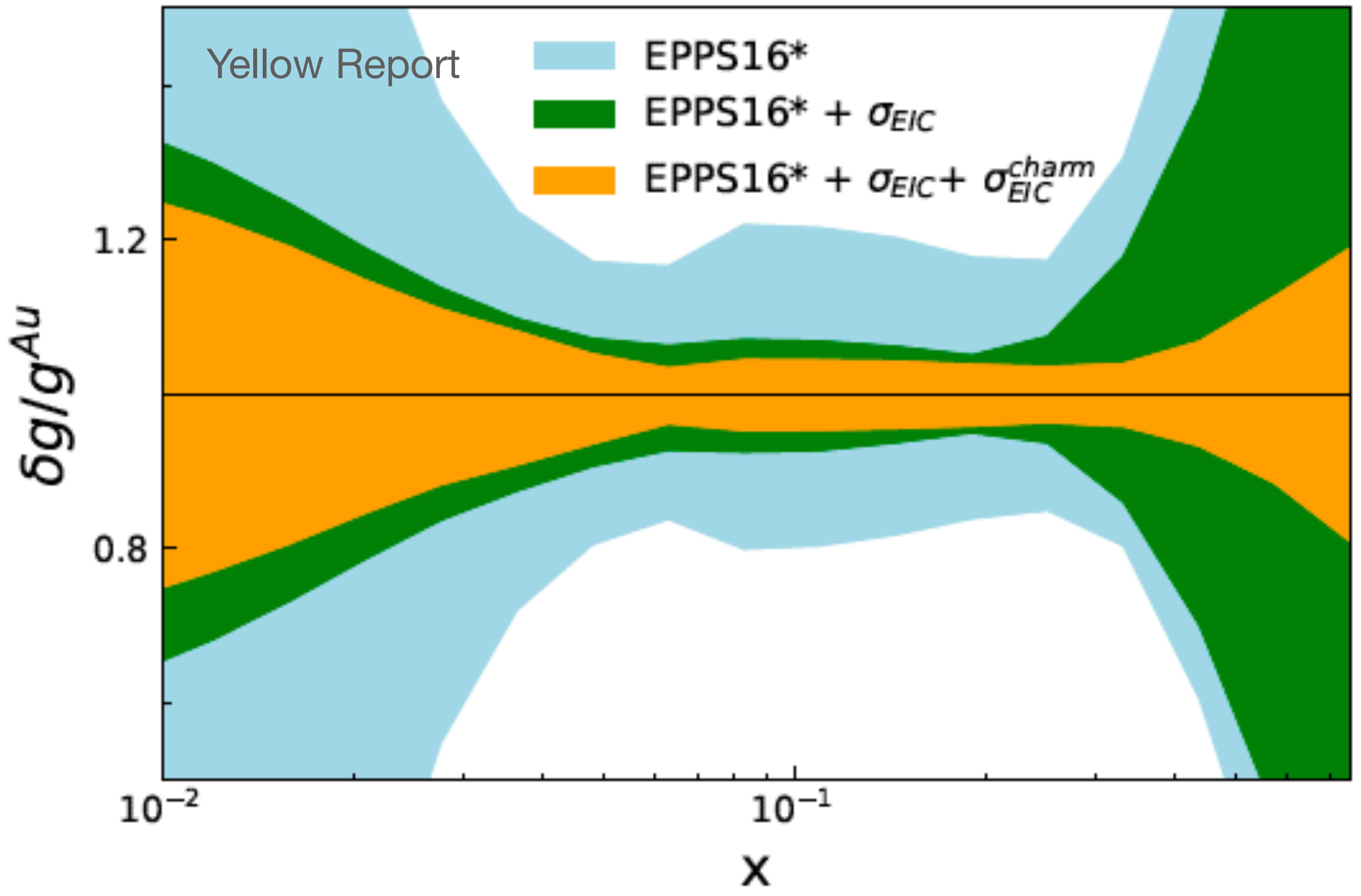
How do hadrons emerge? What's the nature of confinement?

How do colour charged quarks, gluons and colourless jets interact with nuclear medium?

EIC → ideal place to compare jets of particles created in e+p vs e+A

- Range of nuclei to study how different nuclear mediums affect different quarks types

Relative uncertainties of gluon densities in Au

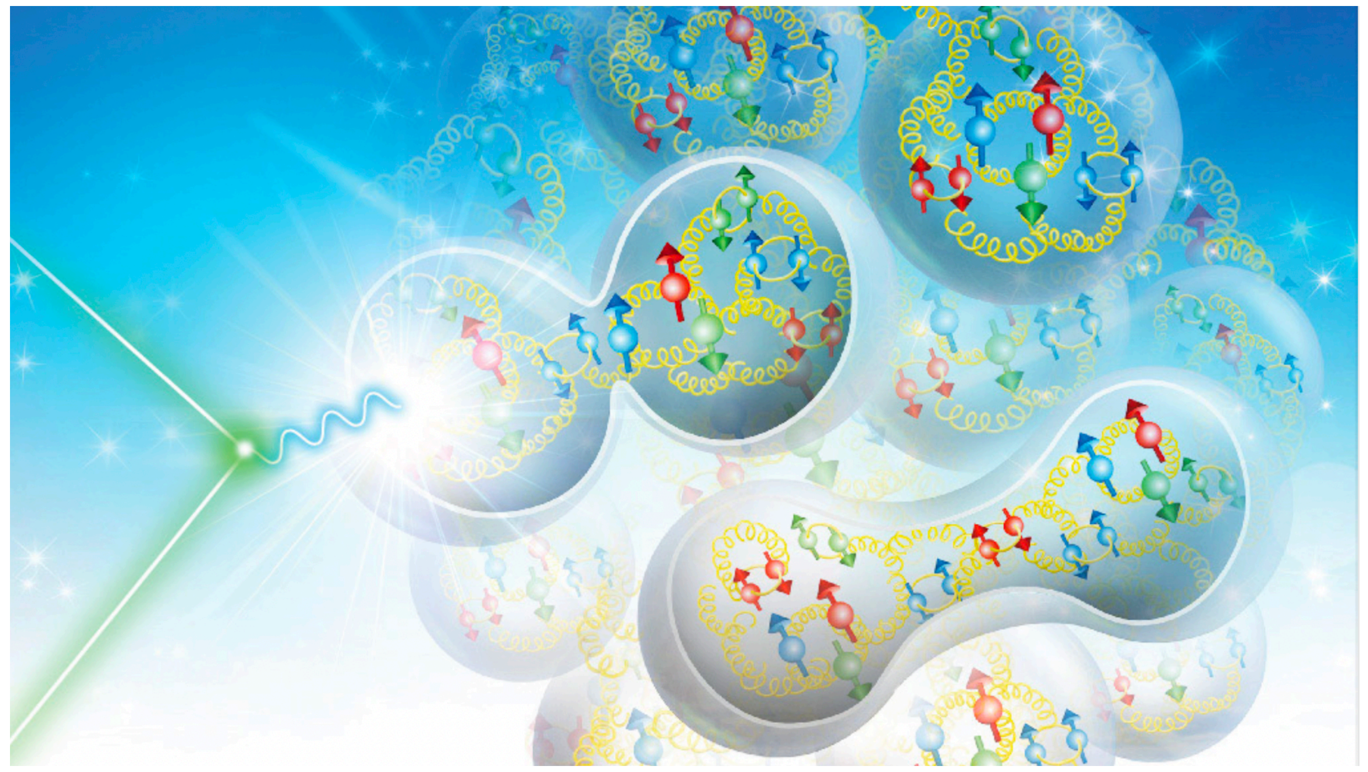


Access to heavy charm quarks will help pin down gluon contributions to nuclear modifications

Picture inside an un-bound proton changes when that proton is bound inside a nucleus. How? Why?

EIC will compare unbound protons versus protons bound in nuclei

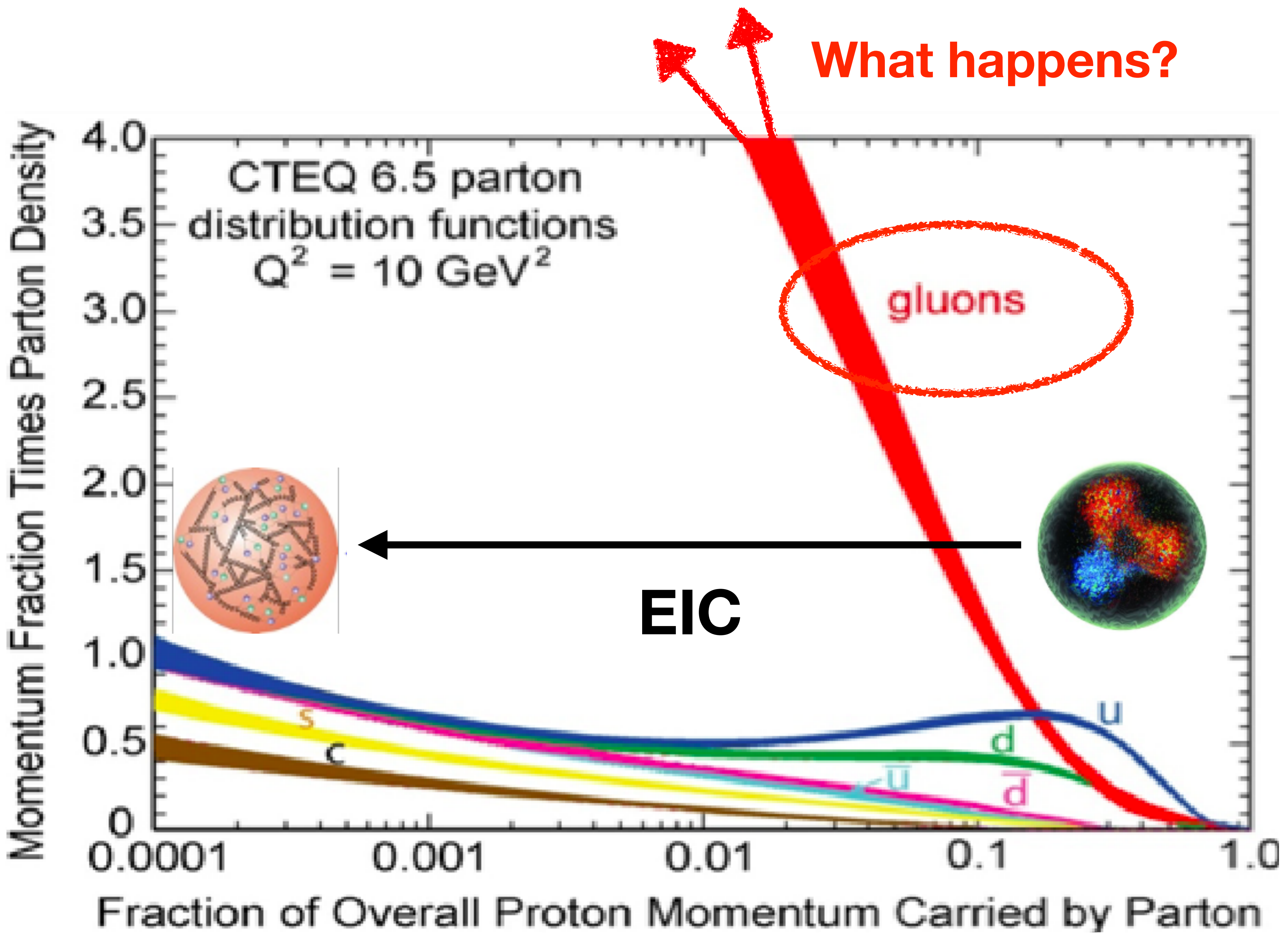
→ unrivalled precision over very wide landscape

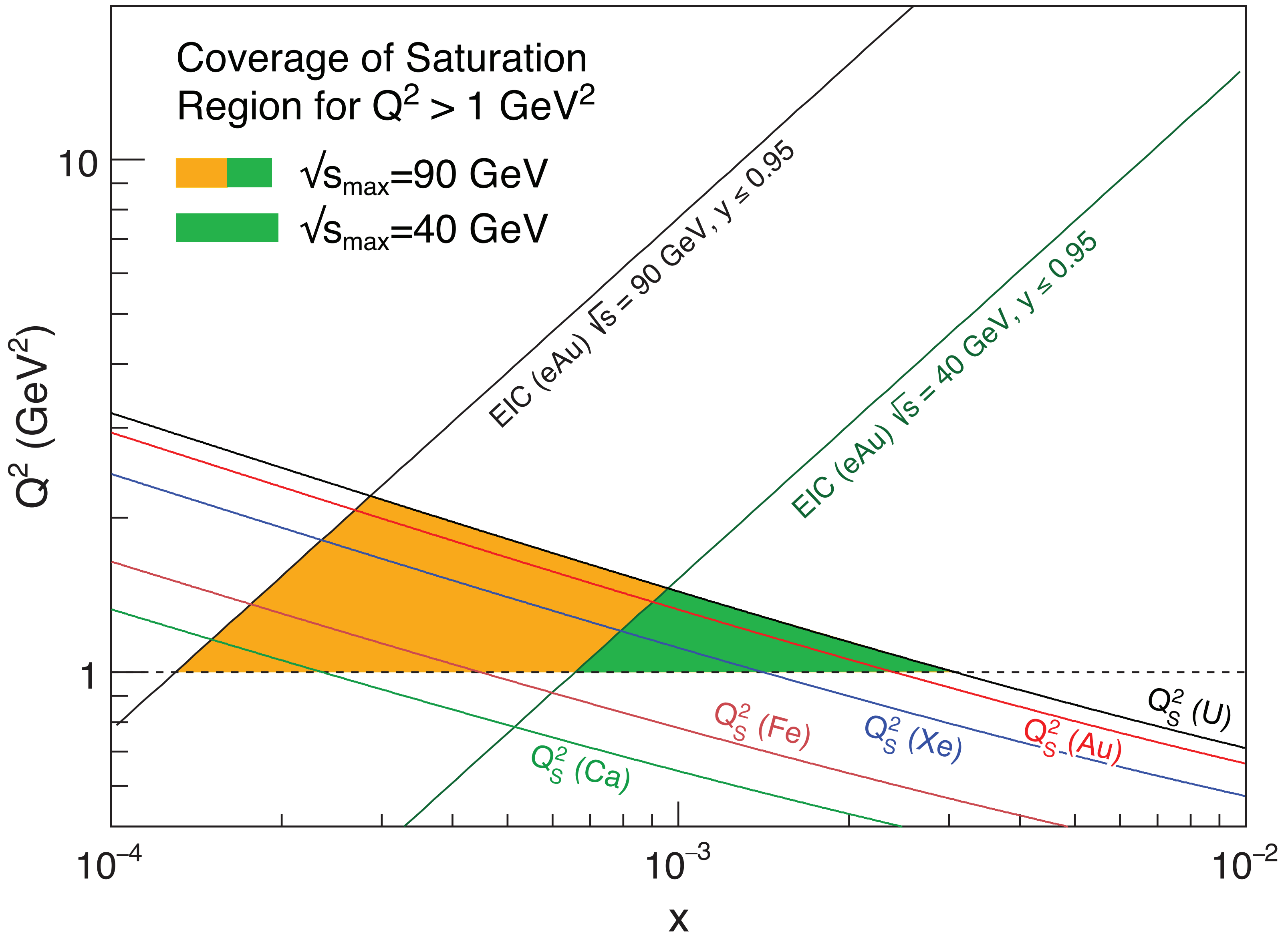


Measuring nucleons knocked out from light nuclei will shed light on how protons and neutrons interact with each other inside nuclei

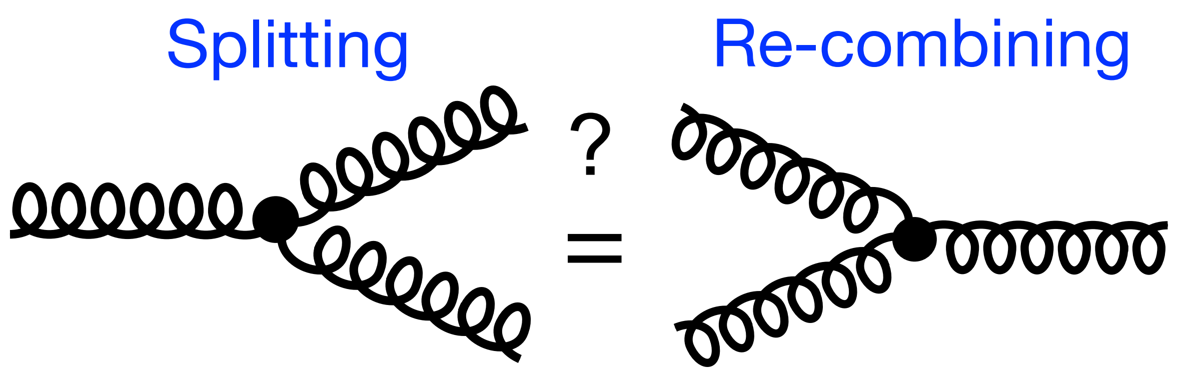
How does this influence nuclear binding?

Deep Dive into Unchartered Gluon Territory



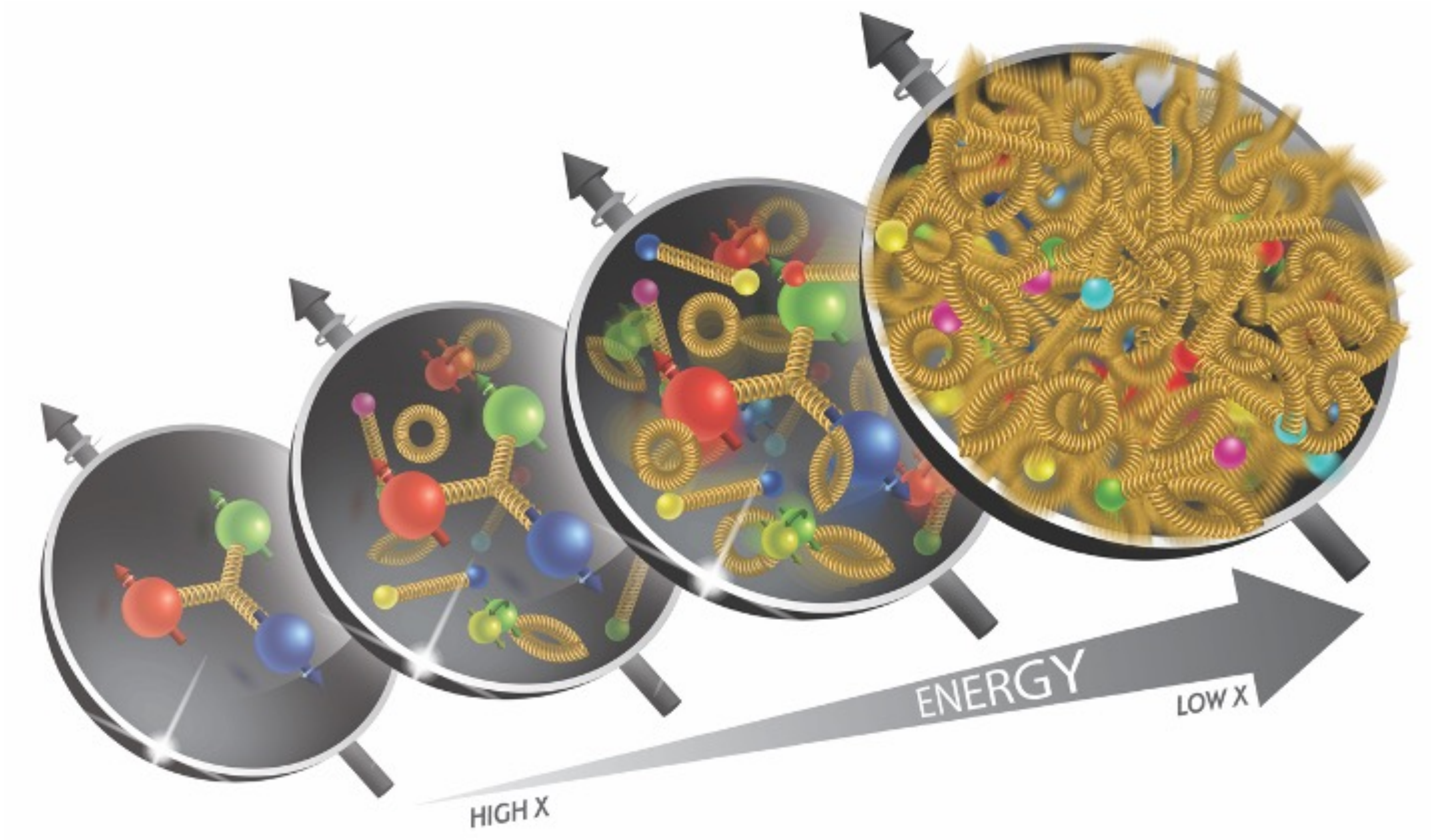


Gluons are self-interacting!



Saturation Scale Q_s

$$Q_S^2 \propto A^{\frac{1}{3}}$$



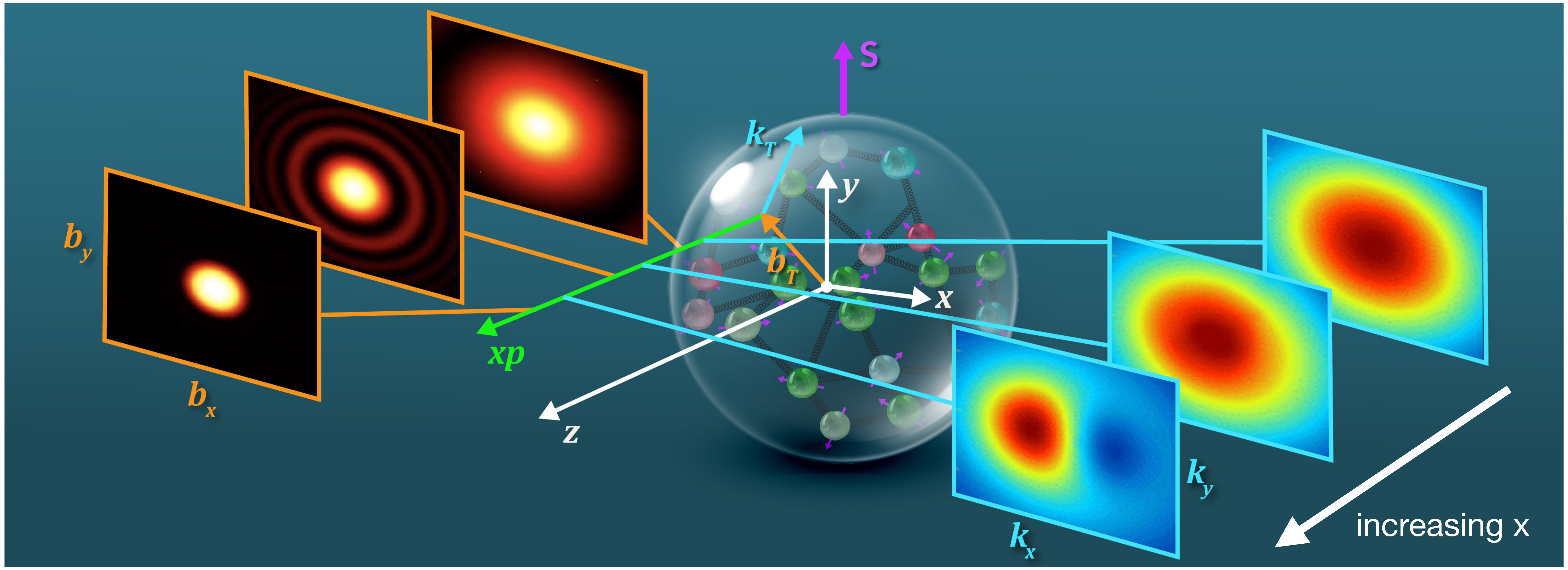
- Previous 1D studies show an explosion of gluon density
- Does it saturate? When?
- Does this give rise to a new phase of matter in nucleons/nuclei?

- EIC will provide a large suite of measurements to study the onset of saturation - multi-faceted approach
- e.g. angular correlations in the production of di-jets in e+p vs e+A
- EIC ideal for this:
  - high energies, low reach in x, range of nuclei
- Q_S can be reached at lower energies with heavier nuclei

Tomography for Multi-Dimensional Imaging

Coordinate Space

2D spatial images at different slices of momentum



Momentum Space

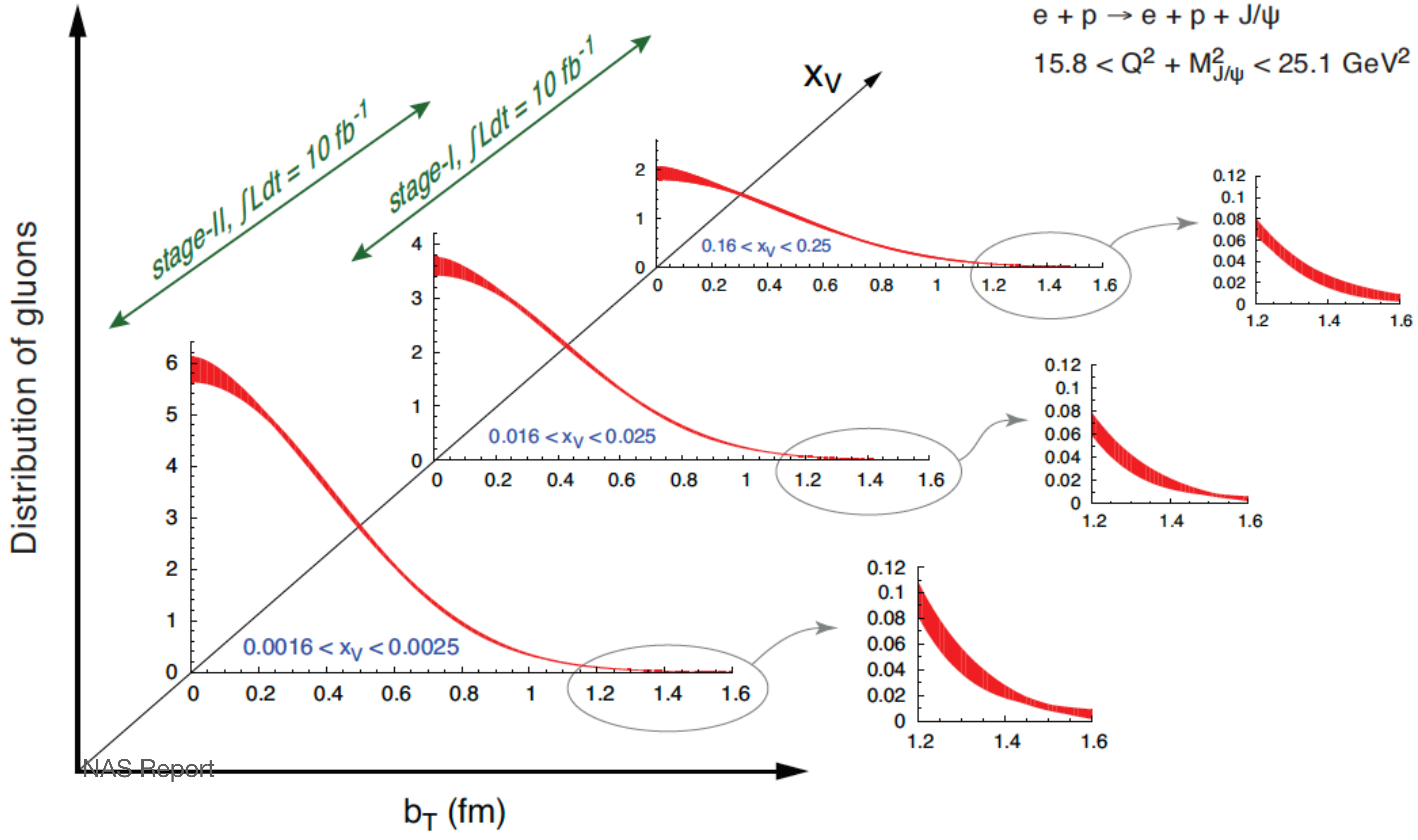
3D momentum images telling us about the motion confined inside the nucleon

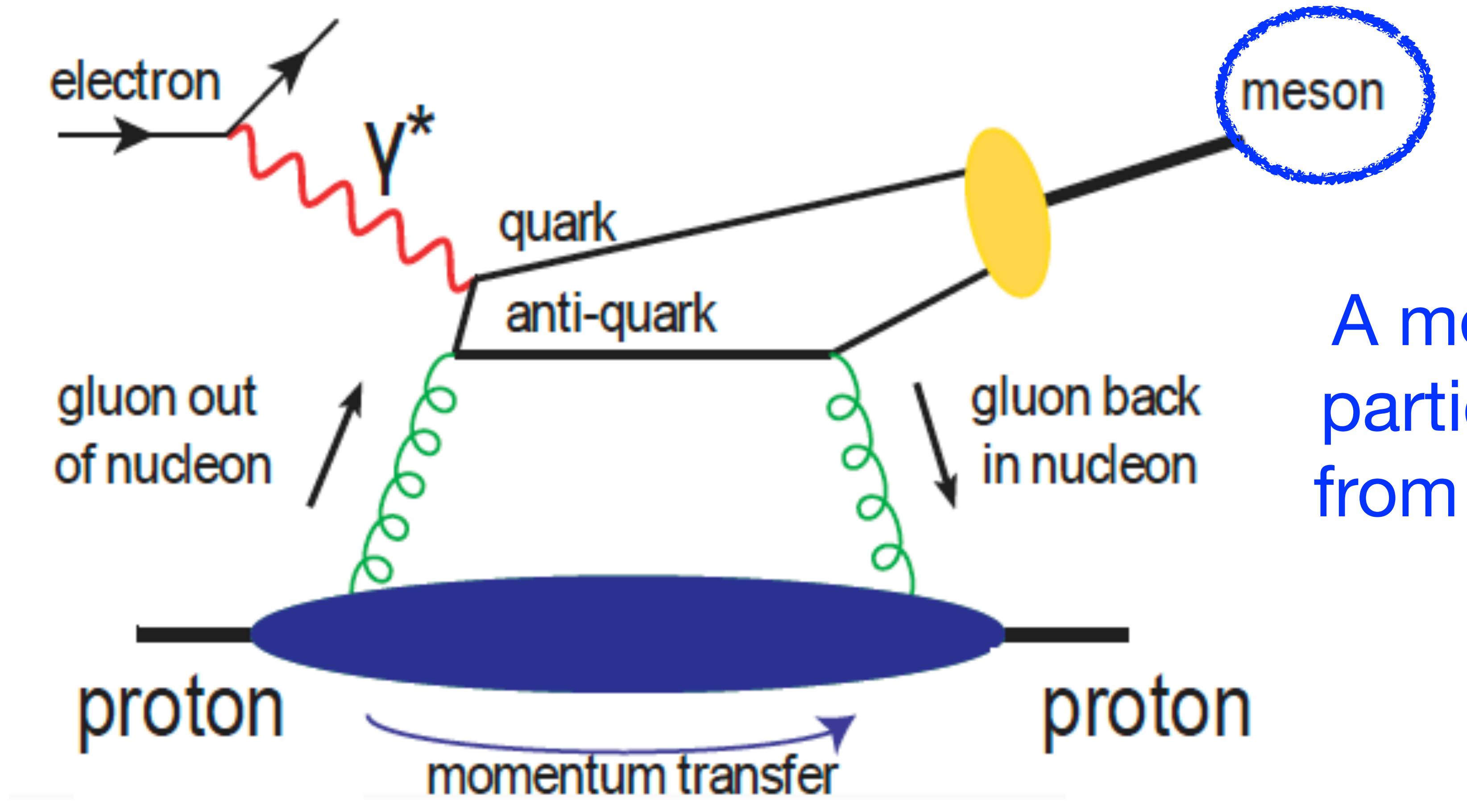
- How are the quarks/gluons distributed in space and momentum inside the nucleon?
- EIC will go beyond historical 1D picture to deliver a 3D imaging program:
  - collect “images” of position and momentum distributions for several x-slices (like in a CT)
  - build up multi-dimensional pictures
- Offers insights into properties like angular momentum, mass, and pressure inside the nucleon
- EIC will provide unrivalled precision in tomography, extending beyond the valence quark regime into sea quarks and gluons

Tomography of Gluons

Gluon spatial densities in proton for the first time!

Only possible at the EIC





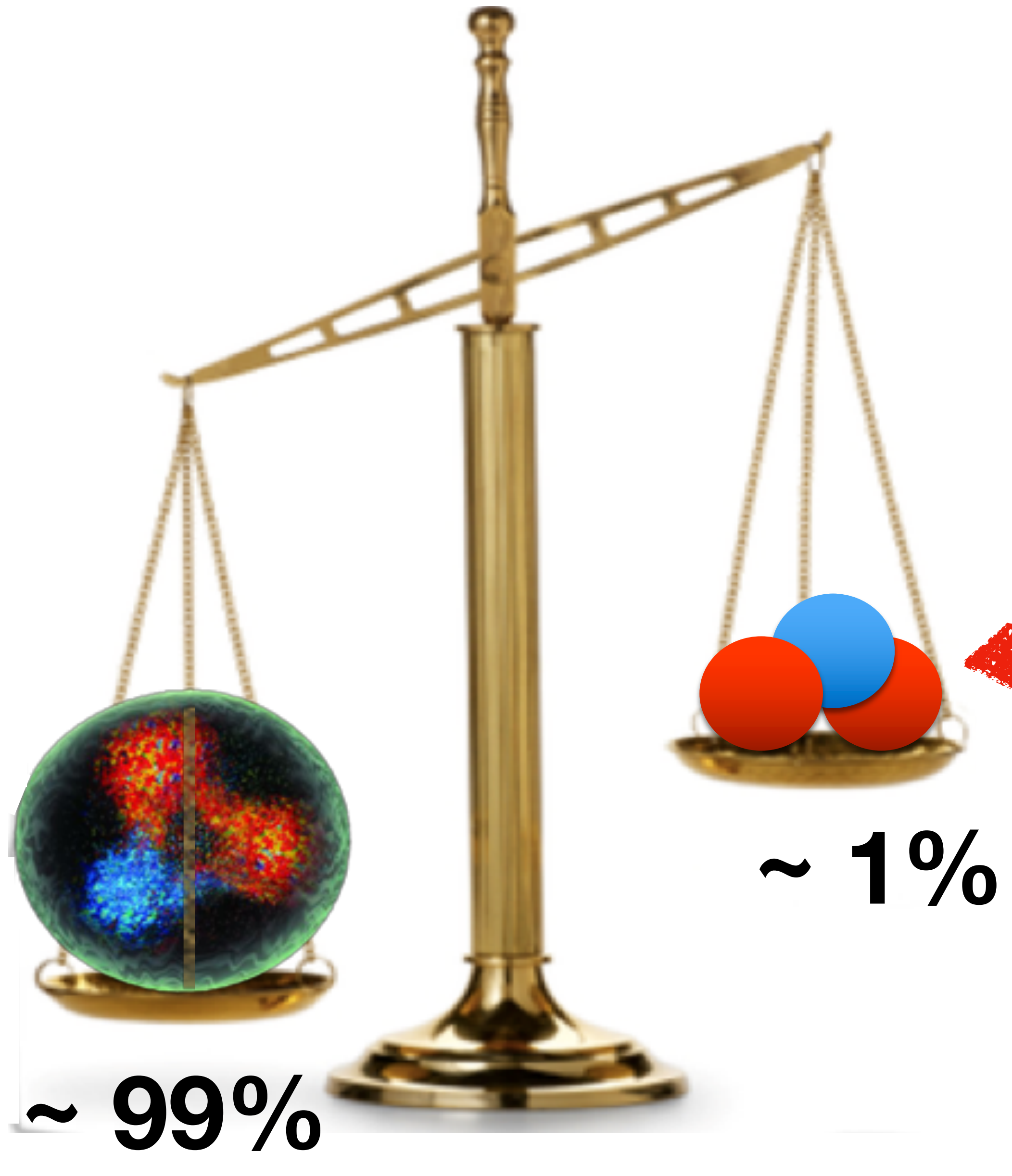
A meson is a particle made from a $q\bar{q}$ pair

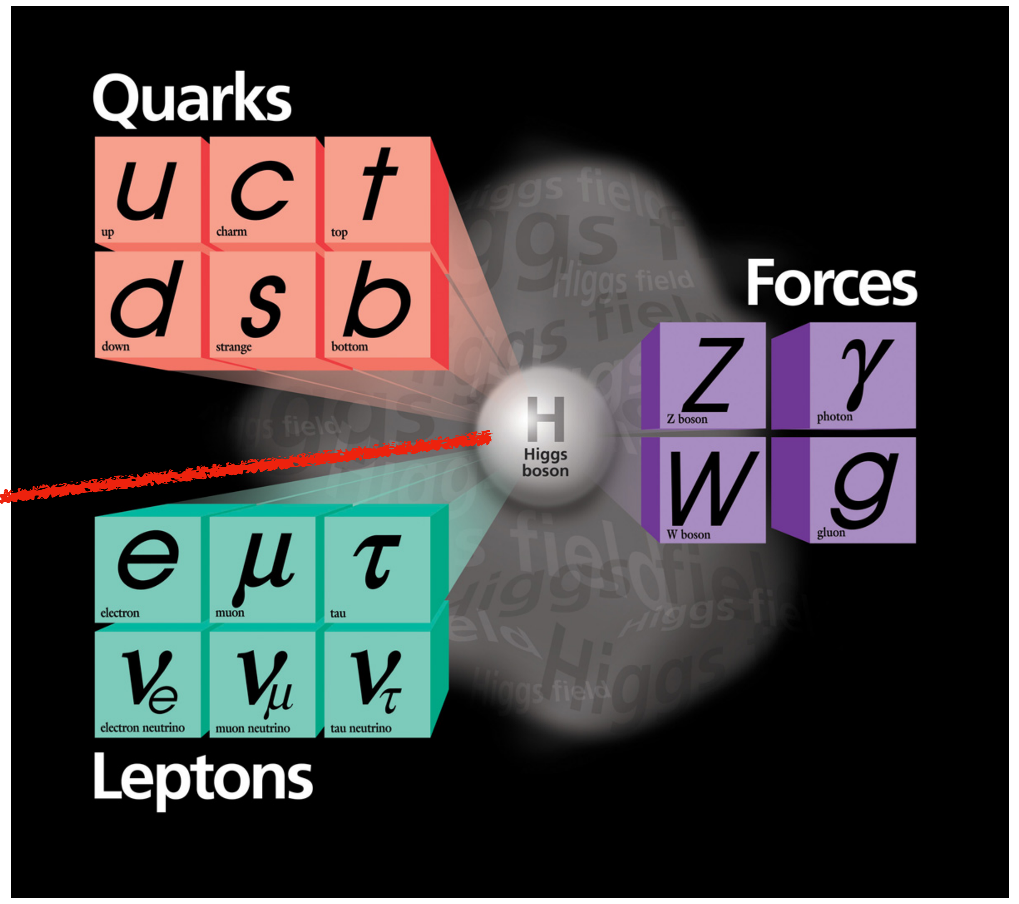
- Production of certain mesons in e+p at the EIC e.g. J/Ψ ($c\bar{c}$), will provide tomography of gluons in the nucleon

- In e + A scattering, ions scatter
  - coherently (ion stays in-tact)
  - incoherently (ion breaks apart)

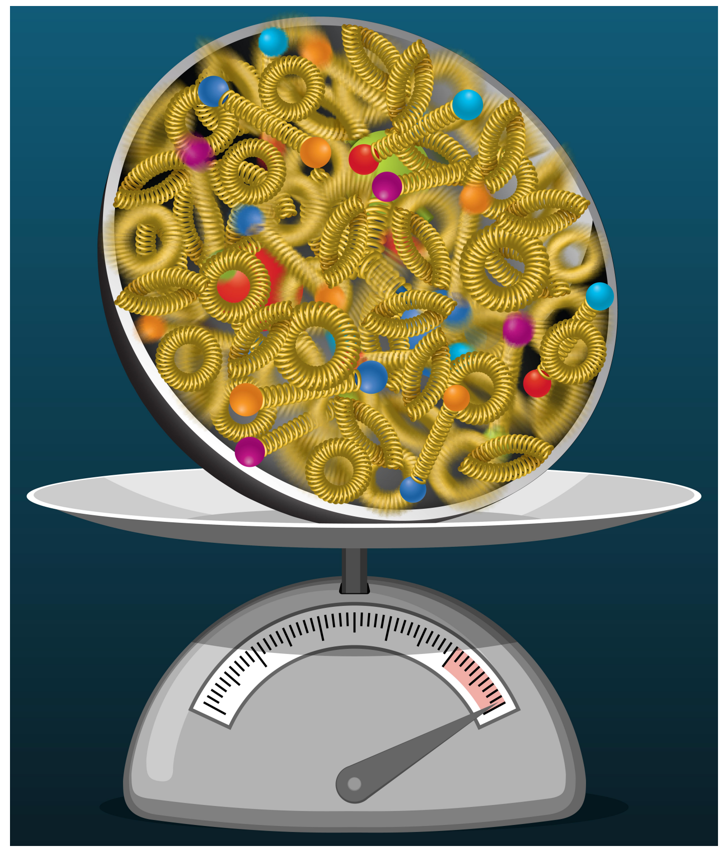
- Mesons produced in coherent scattering of ions can probe the gluon spatial distribution of a nucleus
- → might give hints about confinement

Nucleon Mass Enigma





	Observed Mass	Higgs Mass
Proton (uud)	~ 1000 MeV	~10 MeV



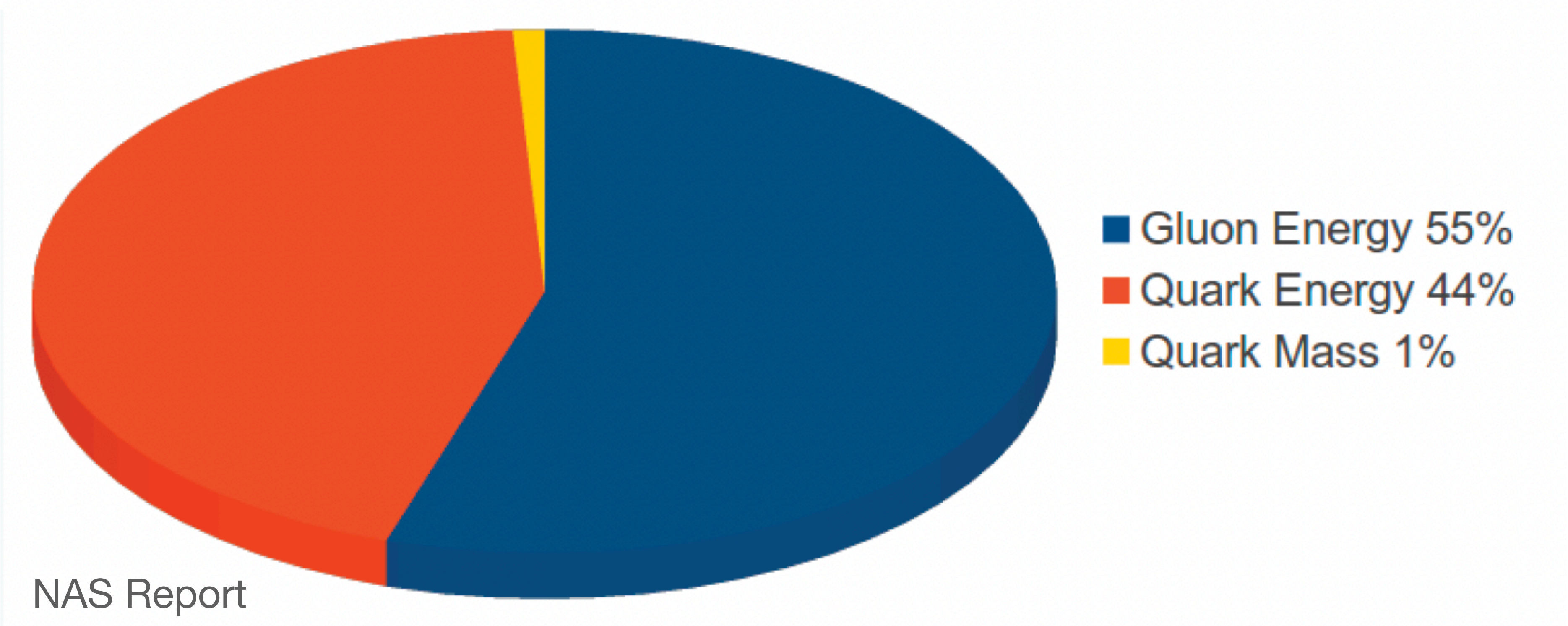
- Mass - intrinsic property of a particle

- Gluons are massless
- Quark masses generated by Higgs ~1% nucleon mass!
- Nucleon is unexpectedly *heavy*

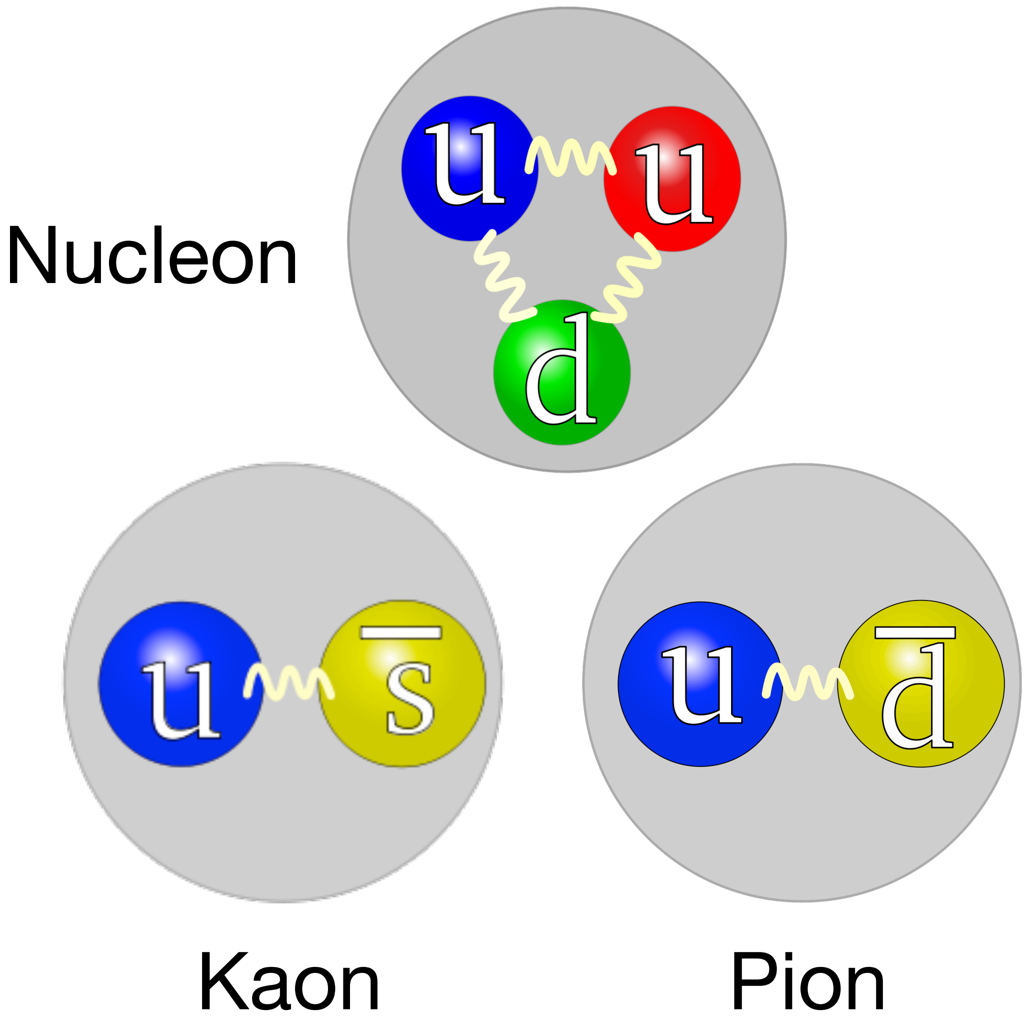
- Large coupling between u/d valence quarks and gluons
  - valence quarks in nucleon are surrounded by sea quarks ($q\bar{q}$) and gluons

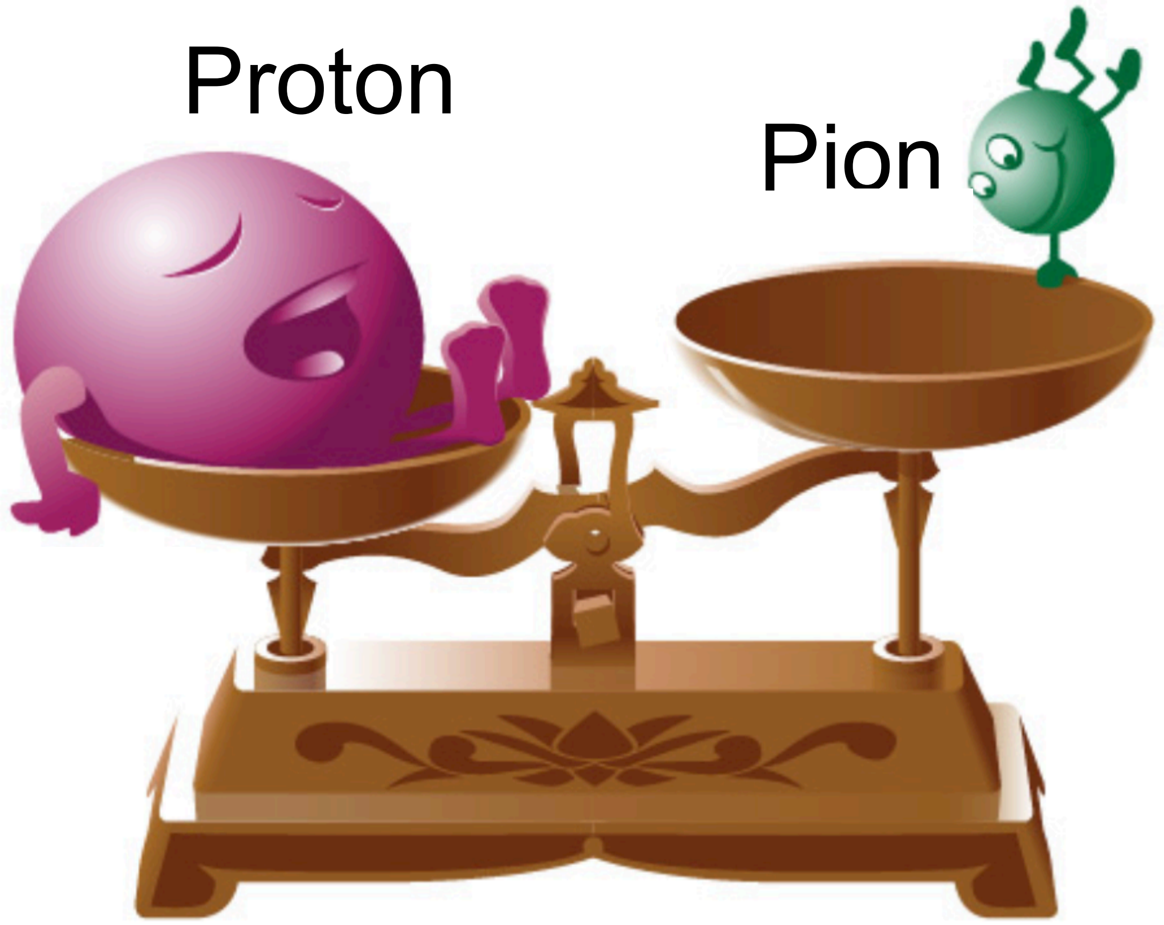
- *~99% of nucleon's mass is due to quantum fluctuations of $q\bar{q}$ pairs, gluons, and energy associated with quarks moving close to speed of light within it*

Nucleon mass budget



Nucleon Mass Enigma

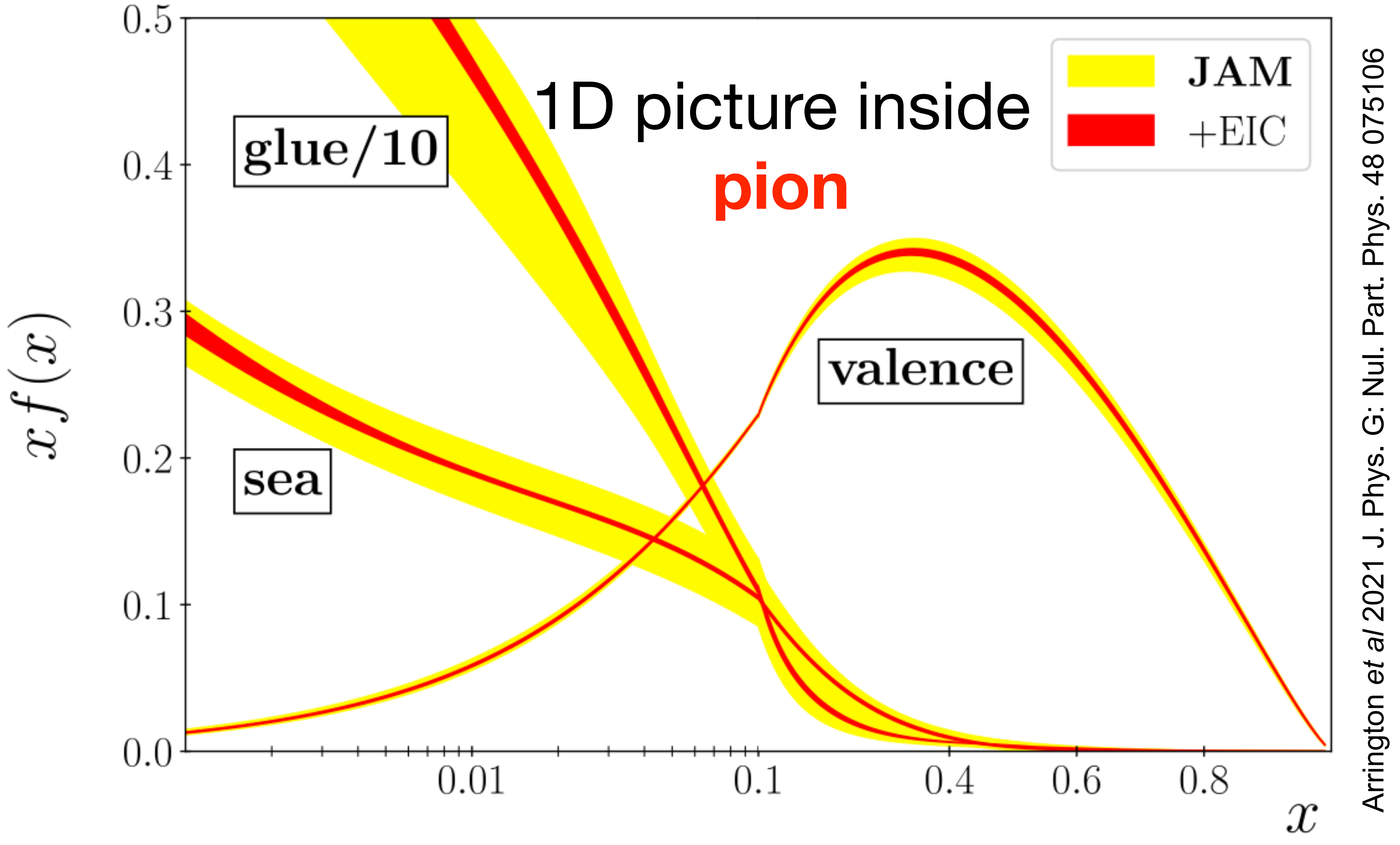




https://www.nobelprize.org/prizes/physics/2008/illustrated-information/

- Pion ($u\bar{d}$) and kaon ($u\bar{s}$) mesons appear unexpectedly light
- Gluon contents are expected to be different within pions, kaons and nucleon
- What can this tell us? We need more data!

- EIC will compare inner compositions of pions and kaons with the nucleon to shed light on mass enigma



EIC will get comparable data for pions/kaons compared to the proton

- Heavier mesons will also be measured
  - e.g. J/Ψ ($c\bar{c}$), ϒ ($b\bar{b}$)
  - These mesons interact primarily with gluons in the nucleon

- Tomography of J/Ψ and ϒ can be related to distribution of mass inside nucleon

Nucleon Spin Puzzle

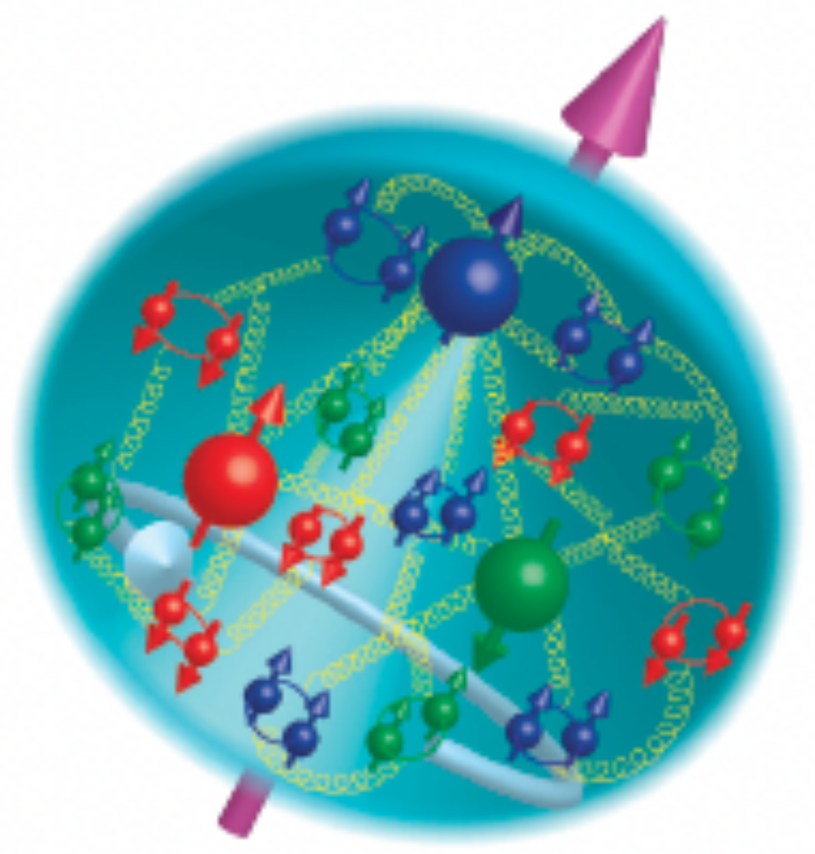
For proton with 3 valence quarks, is it
↑ = ↑ + ↑ + ↓?

- Inherent property of a particle (like mass or electrical charge)
- Allows a particle to behave like a tiny magnet (eg hydrogen nuclei in MRI)

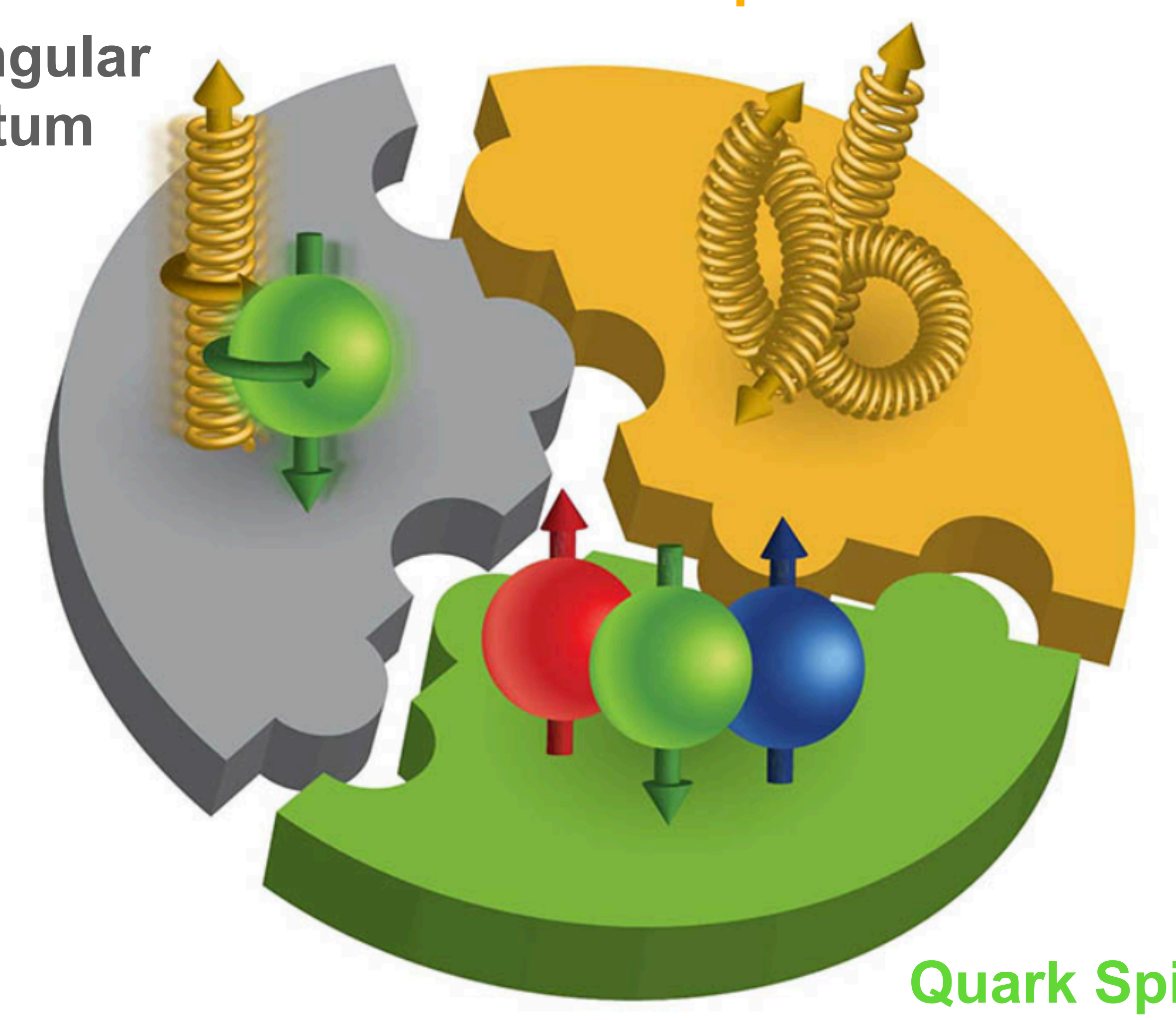
- Either integer or half integer, and aligned ↑ or anti-aligned ↓
- Proton spin appears as 1/2 - spins of its components should sum to this

- Only a small fraction is carried by valence quarks

- How does the nucleon's spin originate from quarks and gluons, and their interactions?



What about the sea?

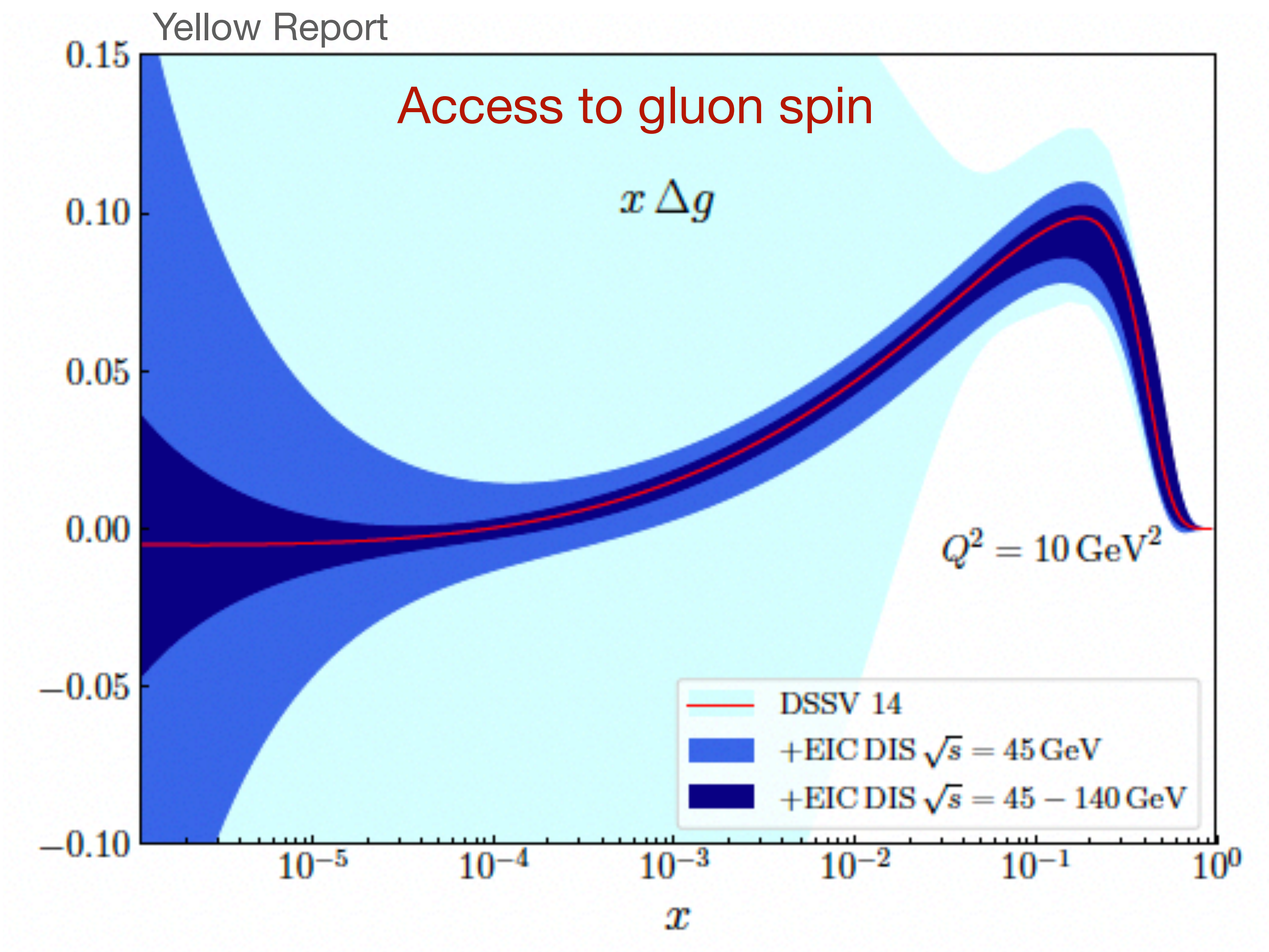


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \left(\sum L_q^z + L_g^z\right)$$

Quark Spin — Gluon Spin — Orbital Angular Momentum

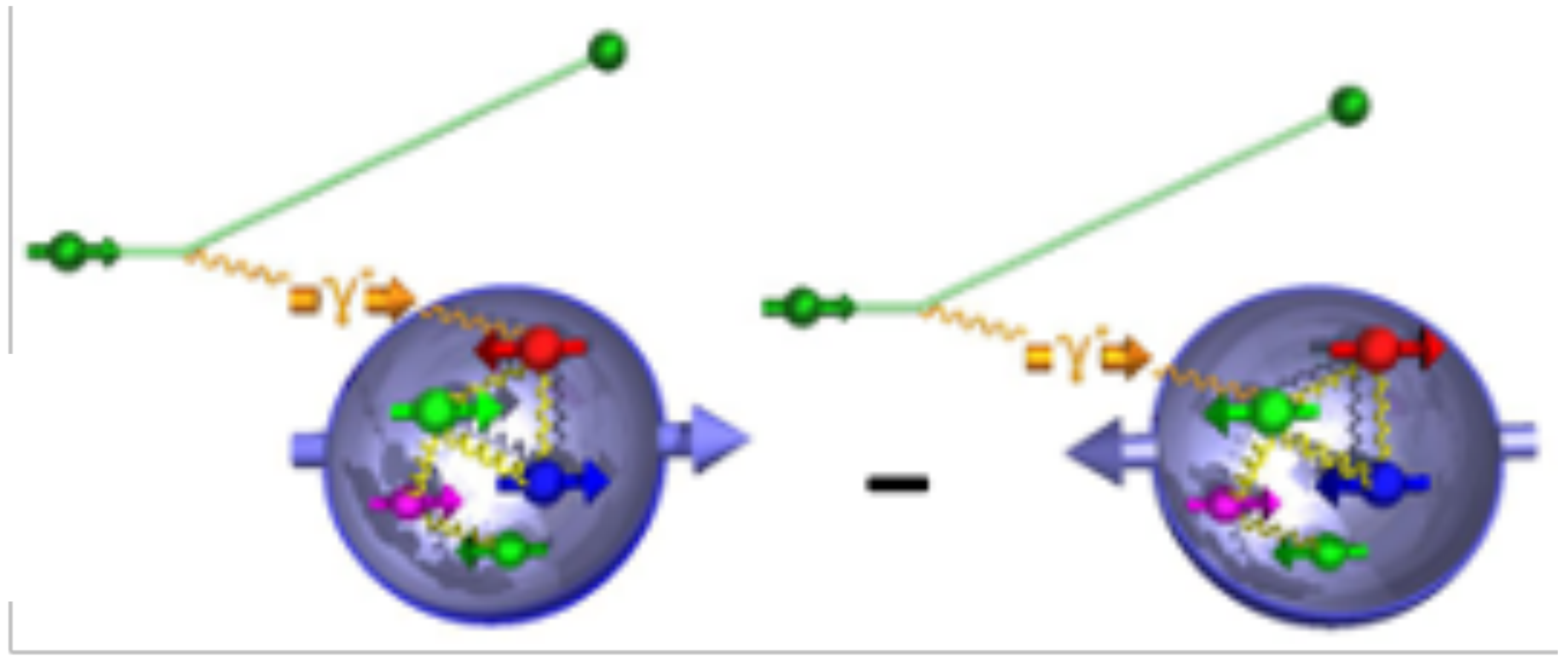
We need to pin down:
- Gluon spin
- Orbital angular momentum
- Improve existing quark spin measurements

Nucleon Spin Puzzle

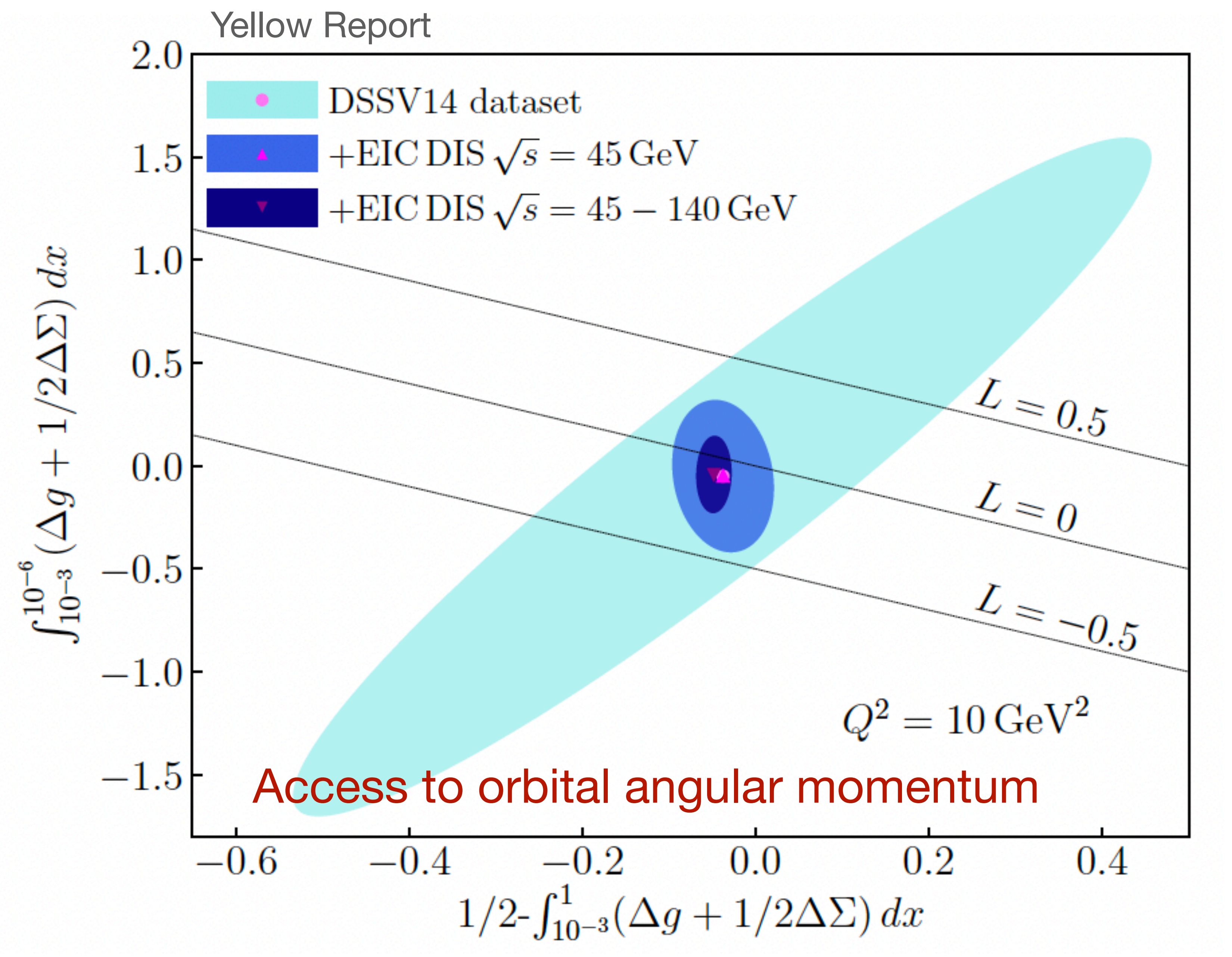


EIC:

- Unprecedented DIS program with spin polarised beams
- High precision mapping of different spin contributions across vast landscape
- Unchartered territory of high gluon densities
- Pioneering measurements of gluon contributions



EIC can align the spins of the beams to enable measurements like this for protons and light nuclei (ie neutrons)!



- Measurements of cross-section differences according to spin alignment

- Tomography will also offer new insights on:
  - Quark flavour contributions
  - Angular momentum

Summary

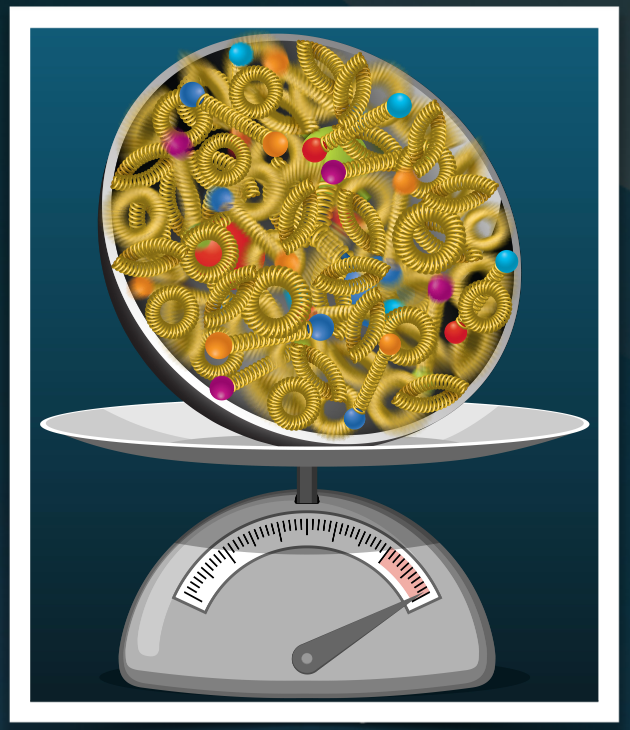
- Nuclear matter (what we are made of!) is governed by gluons and the dynamics of the strong interaction

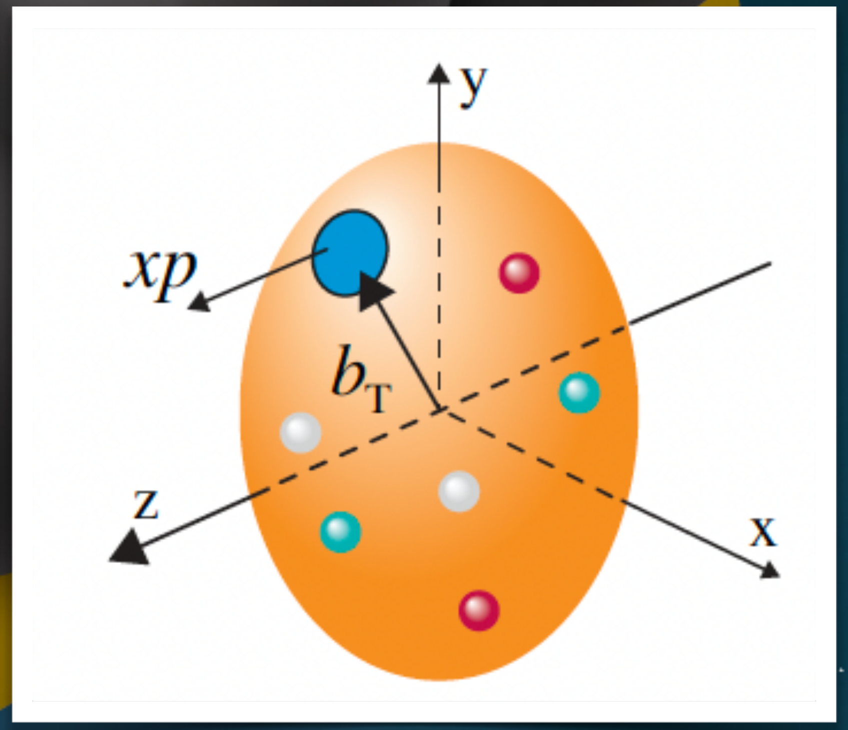
- EIC will delve deep into the building blocks of our visible Universe to revolutionise our understanding of the nucleon, nuclei and the strong interaction

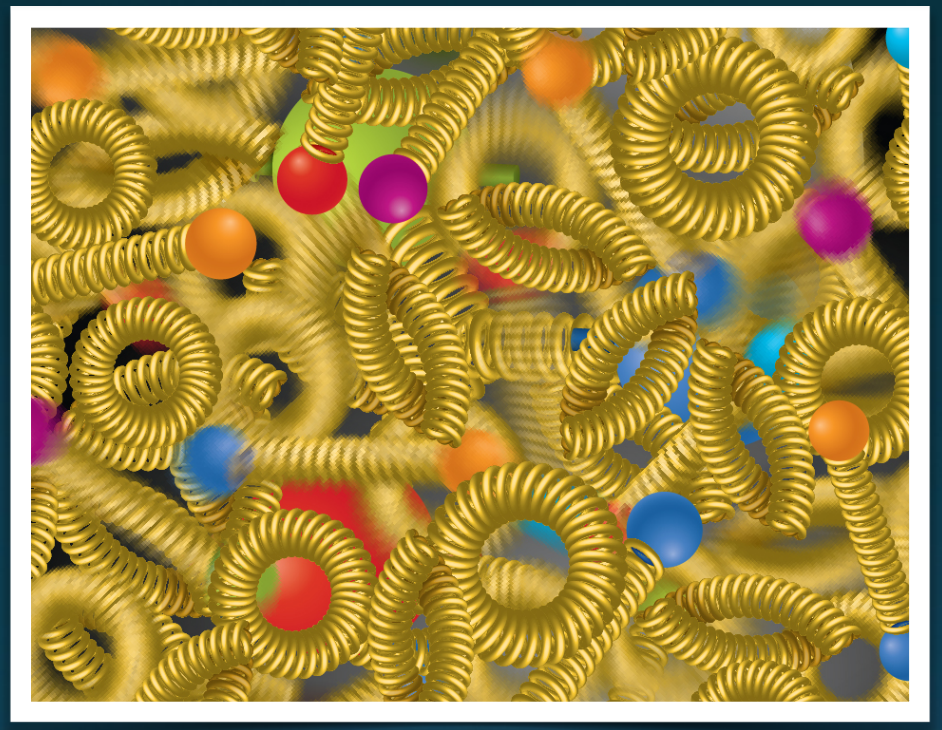
- The EIC will be one of the world's most sophisticated particle accelerators and use the cutting edge ePIC detector
- Its instrumentation is designed to realise this exciting science

- Specific physics topics include
  - Origins of mass and spin
  - Nucleon and nuclei tomography
  - Dense systems of gluons in the nucleon/nuclei
  - More…

- EIC will push the frontiers of nuclear science unlike anything before!







Thank you for your attention

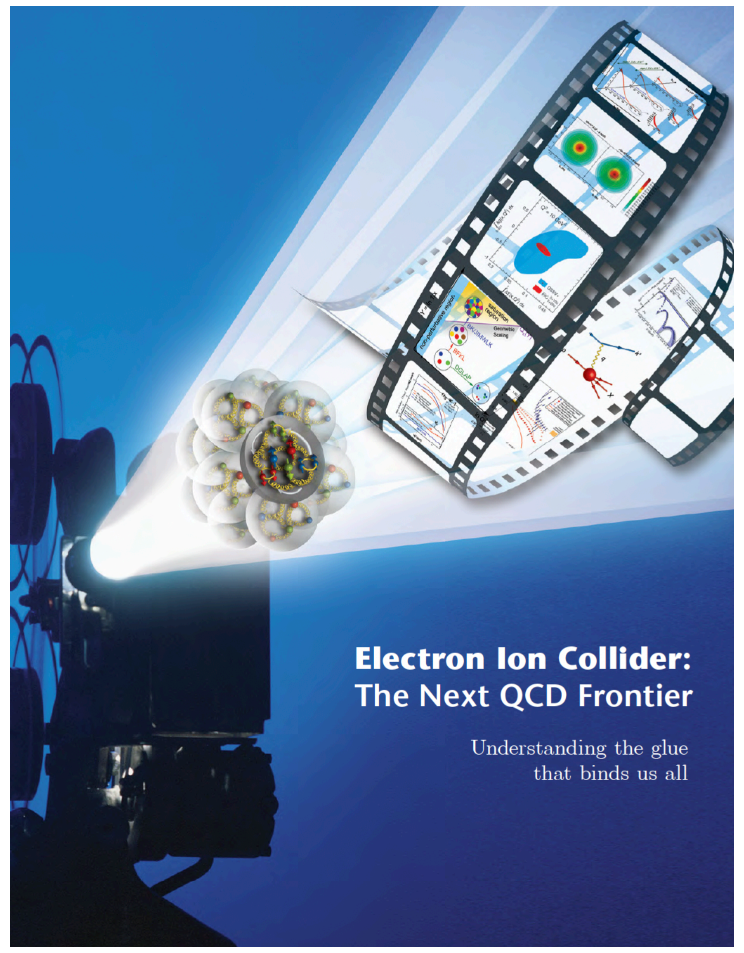
More Thanks

The physics case has been developed for >20 years and is **still growing** - these slides drew from a breadth of resources generated by numerous colleagues of EIC community

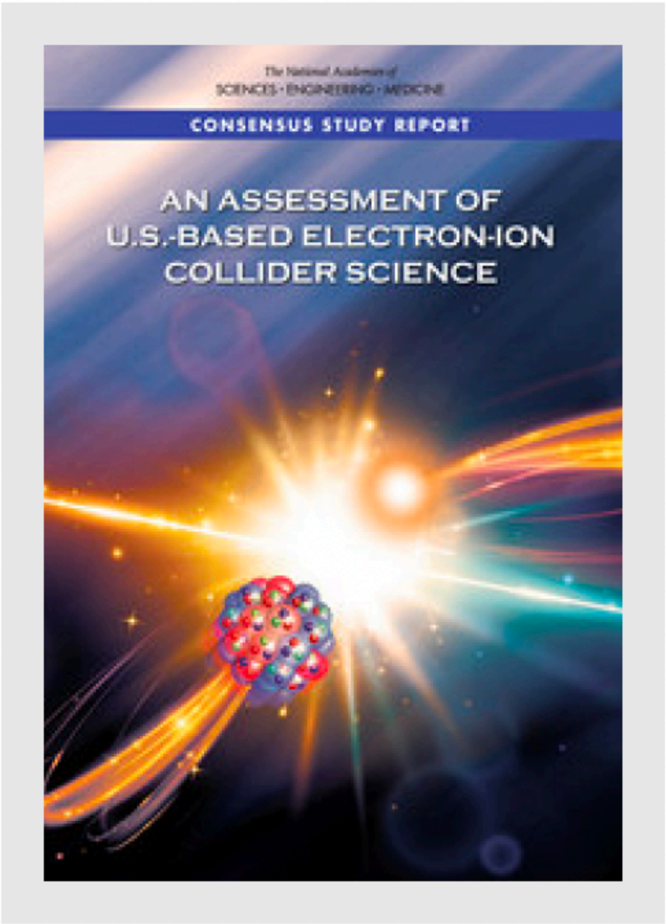
This includes: previous slides from *M. Żurek (ANL), R. Ent (JLab), E.C. Aschenauer (BNL)*

Images and studies showcasing the science have been taken from the reports below

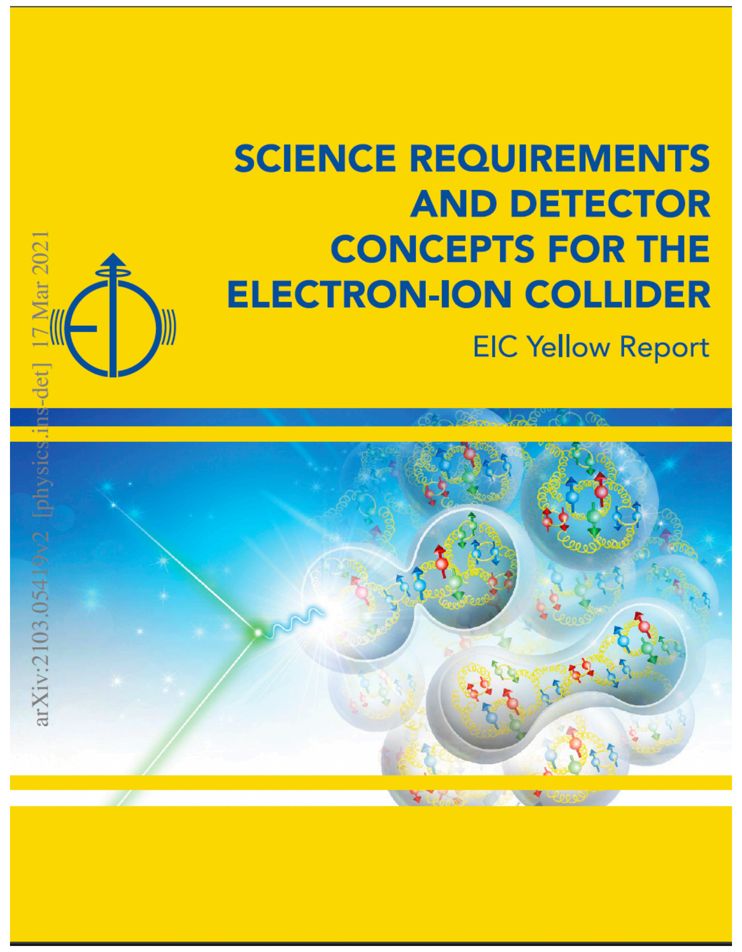
EIC-related images are from BNL



White Paper
arXiv:1212.1701 [nucl-ex]



NAS Report
DOI 10.17226/25171



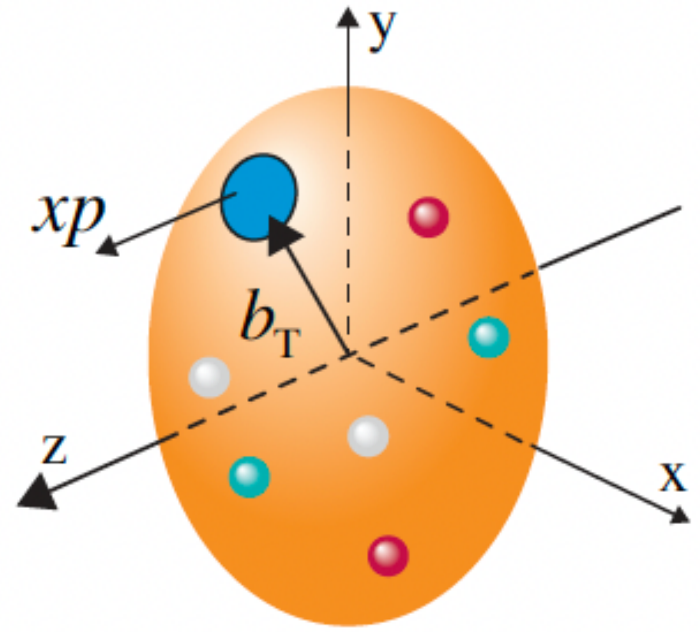
Yellow Report
arXiv:2103.05419v2 [physics.ins-det]

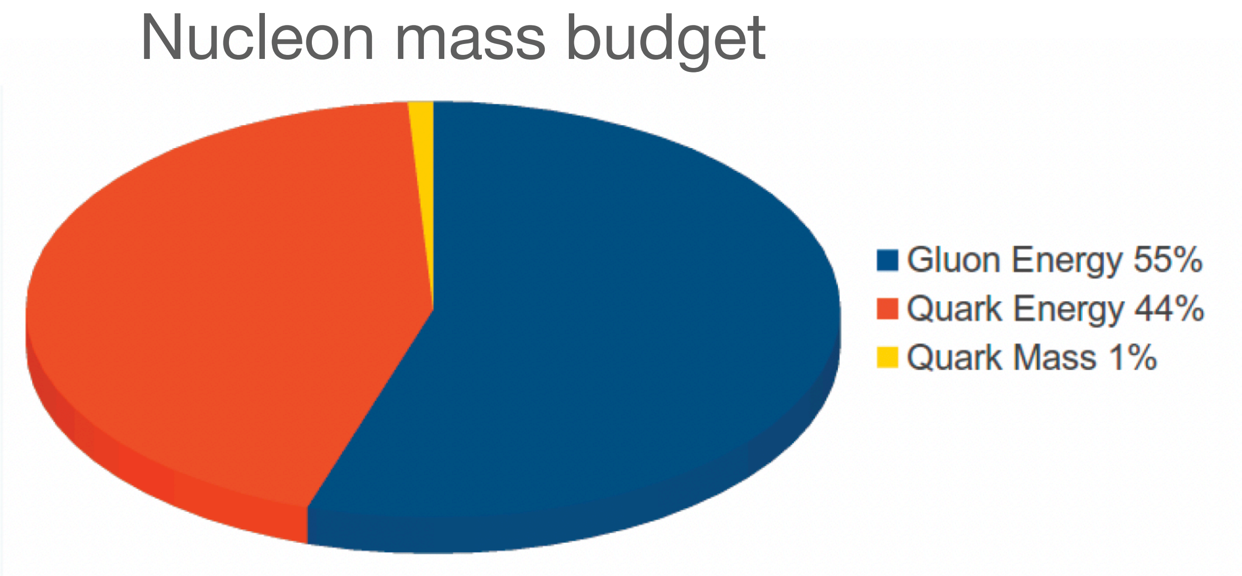
NSAC LRP

EIC - Reaching the next QCD Frontier

Back Up Slides Follow

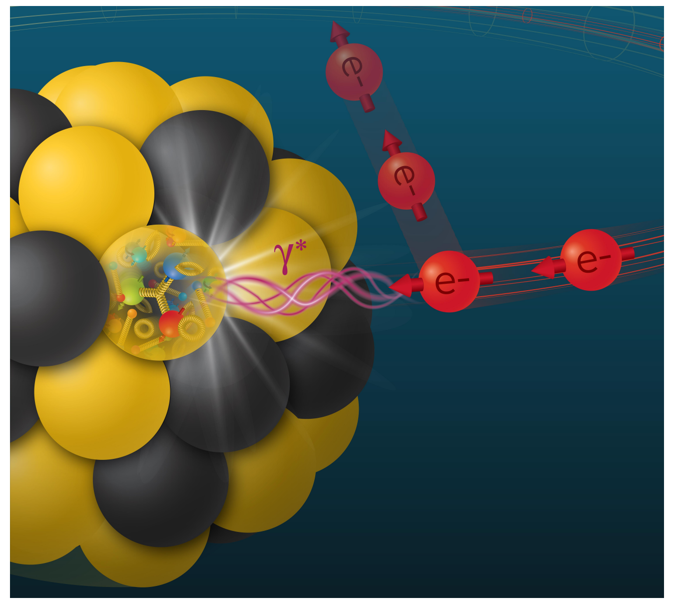
Fundamental Questions at the EIC

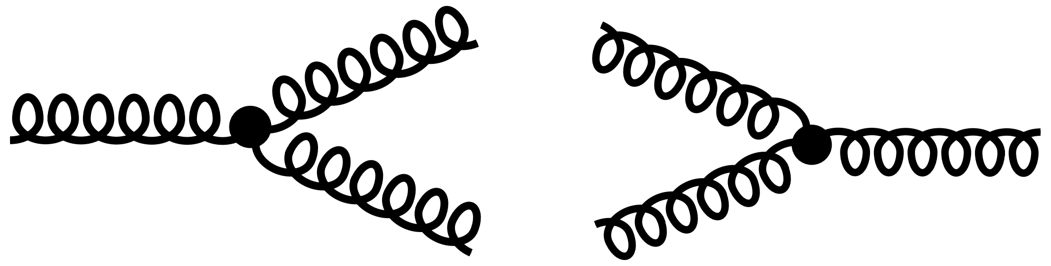




How are partons distributed inside the nucleon?

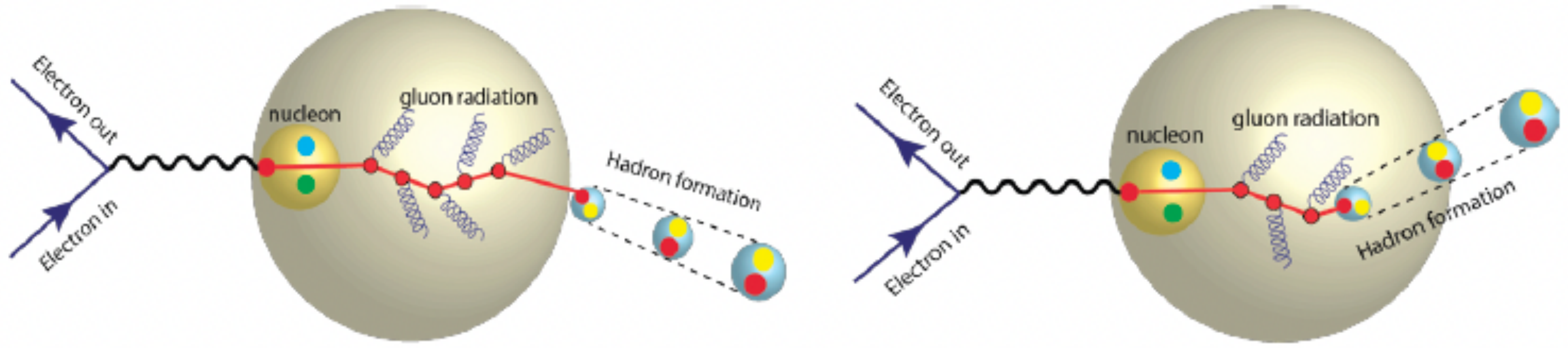
How do the nucleon’s mass and spin emerge from quarks and gluons and their dynamics?





How does a dense nuclear environment affect the dynamics of quarks and gluons and their interactions?

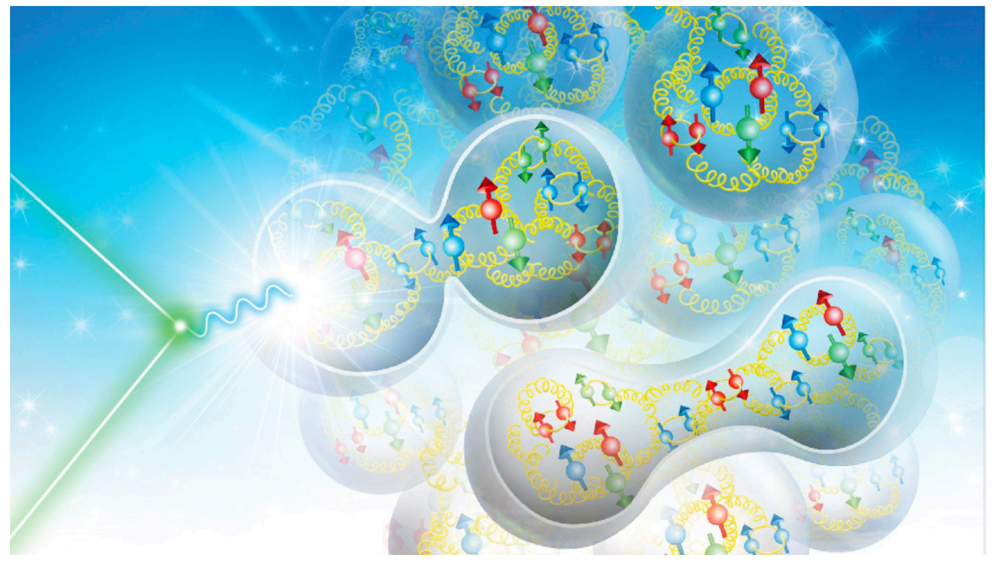
What happens to gluon density in nuclei? Does it saturate? When? Does this yield a new phase of matter with universal properties in nuclei and the nucleon?



How do colour charged quarks, gluons and colourless jets interact with the nuclear medium?

How do colourless hadrons emerge and what’s the nature of confinement?

How do quark-gluon interactions create nuclear binding?

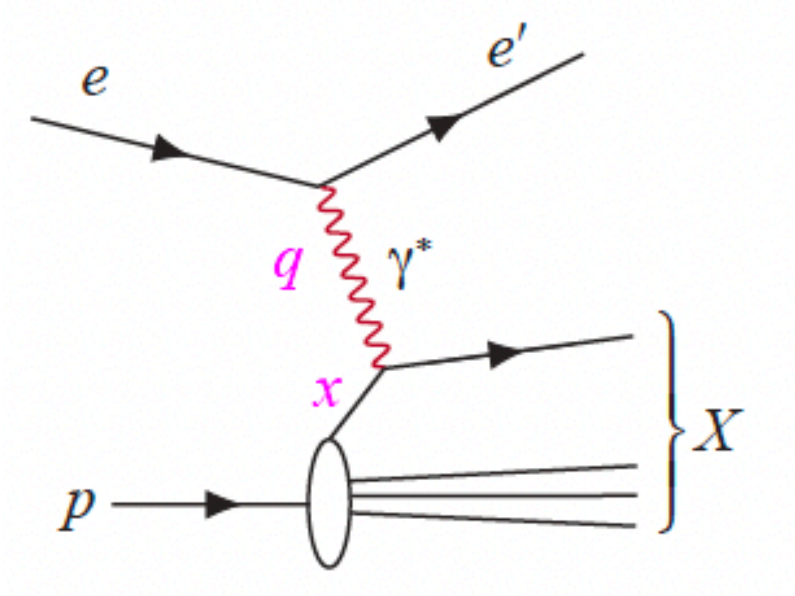


And more
(e.g. electroweak and beyond standard model)

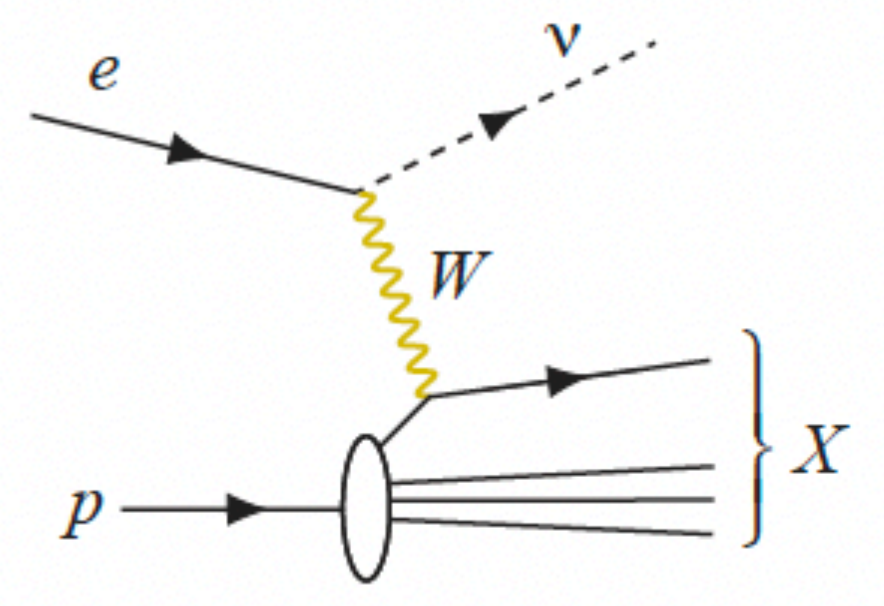
EIC physics case has evolved over the last 20 years and still growing

Tools to Unlock a Vast Scope of Physics

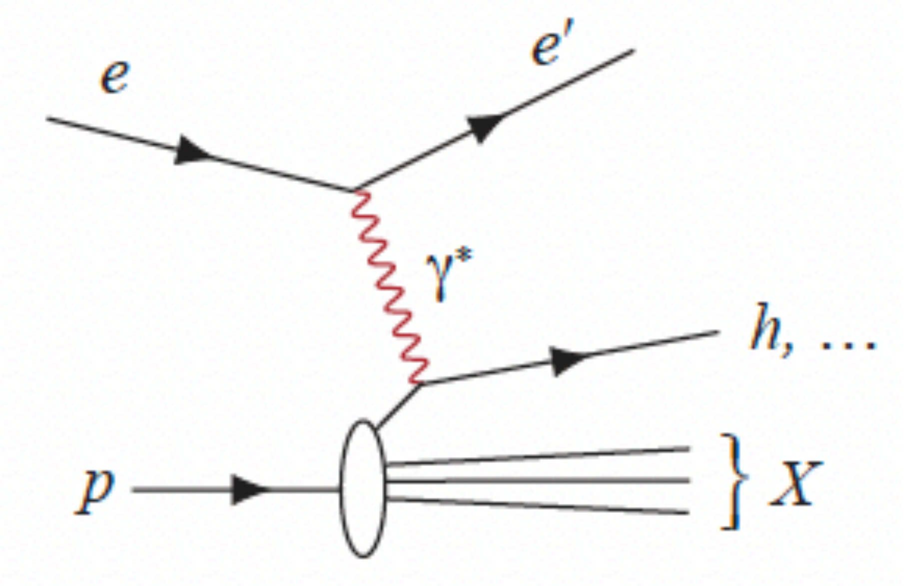
Neutral Current Inclusive



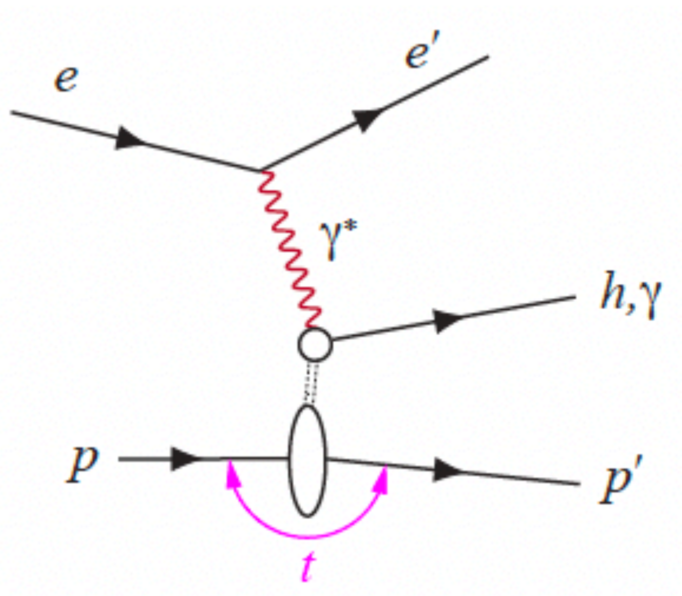
Charged current inclusive



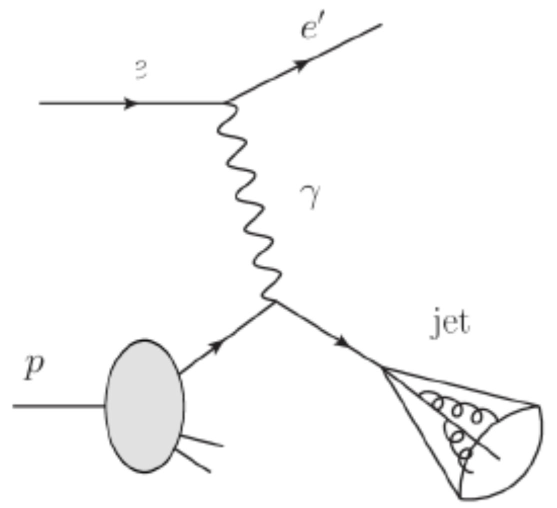
Semi-inclusive



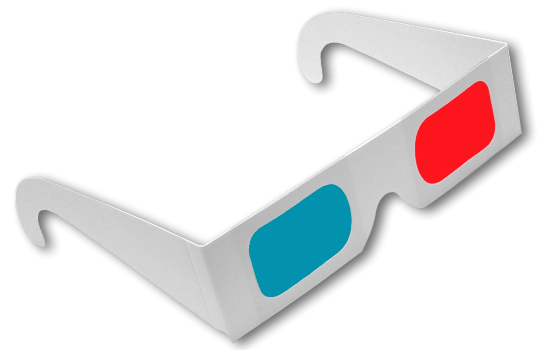
Exclusive

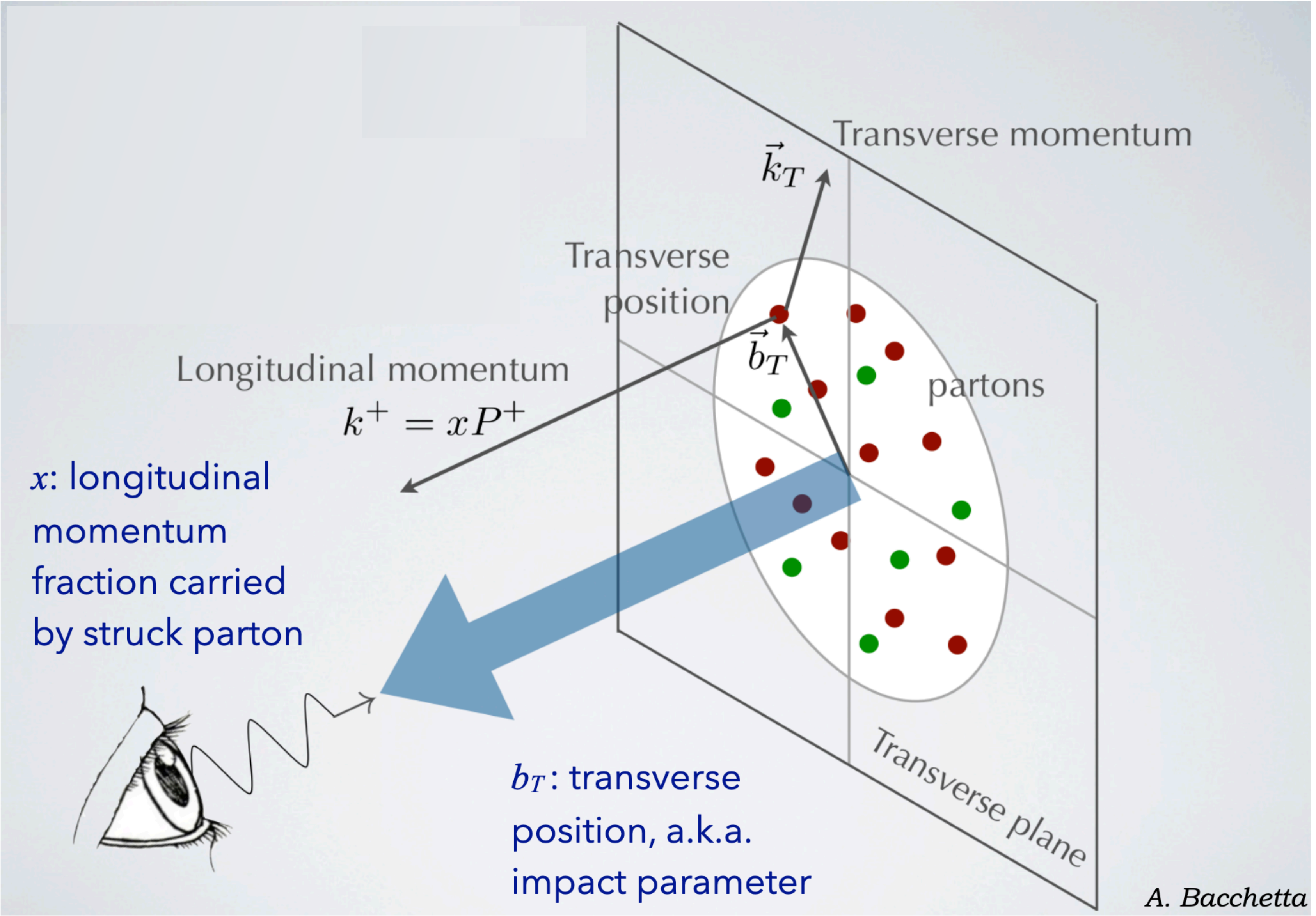


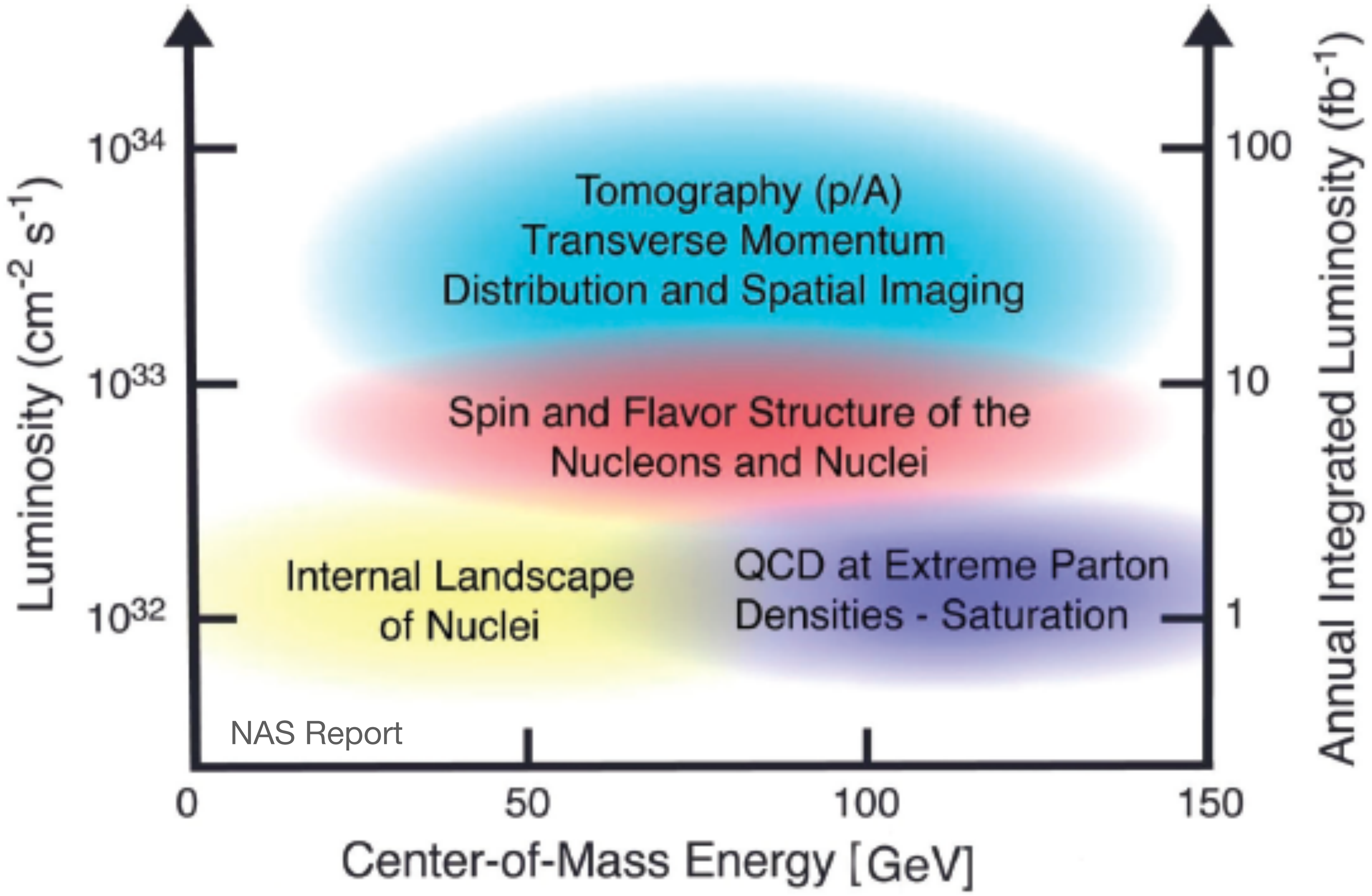
Jets



Many complimentary probes …

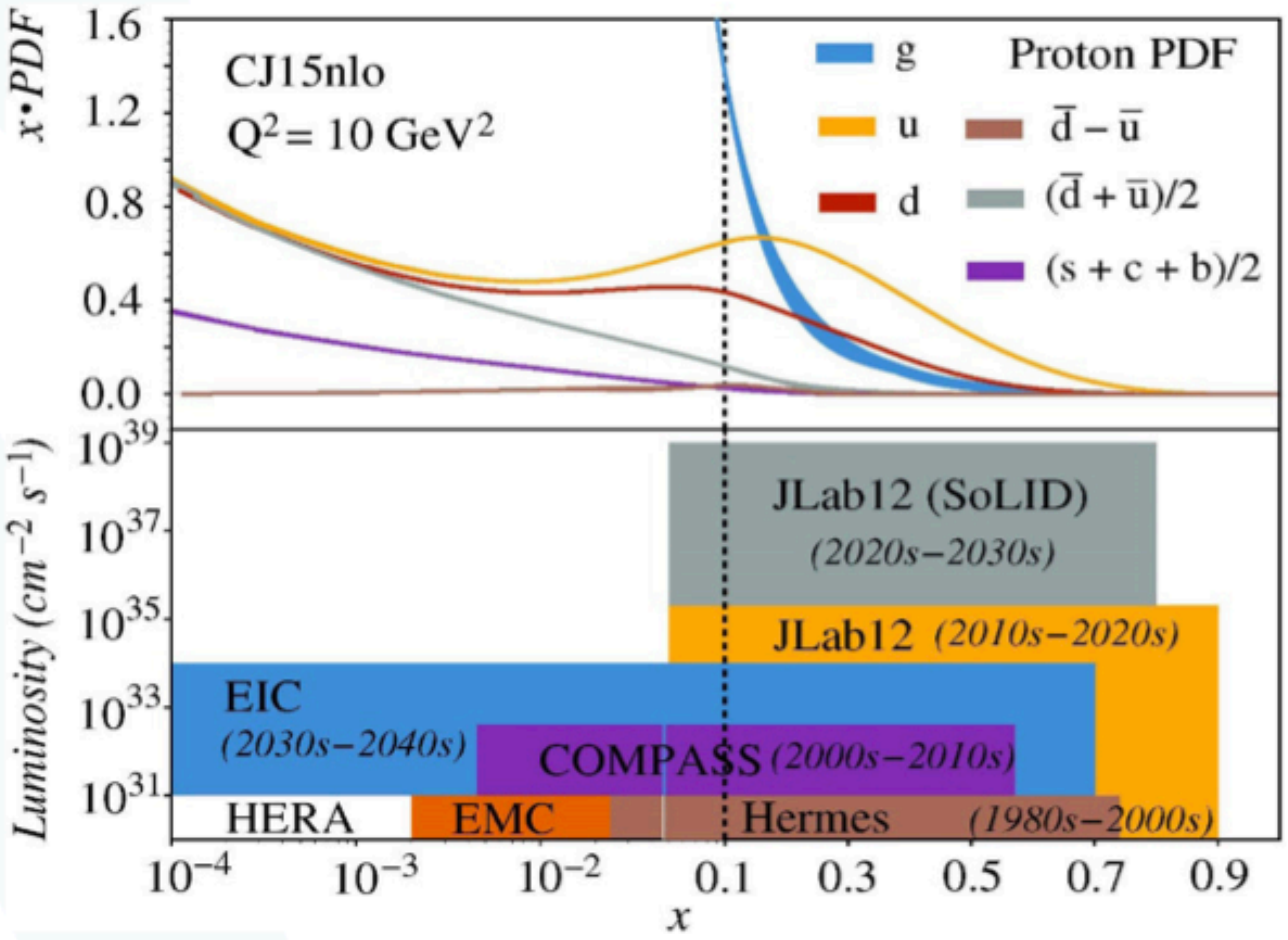




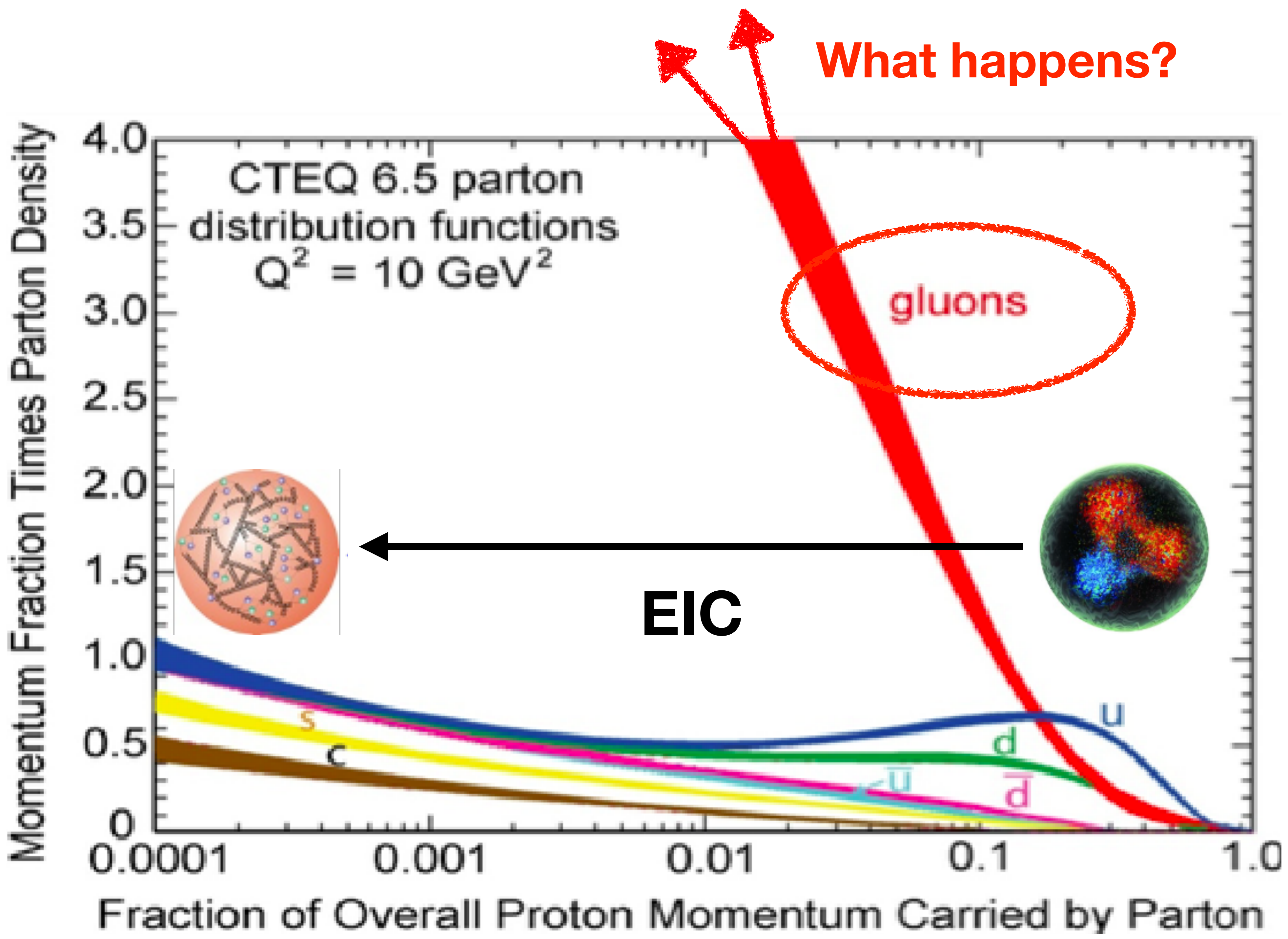


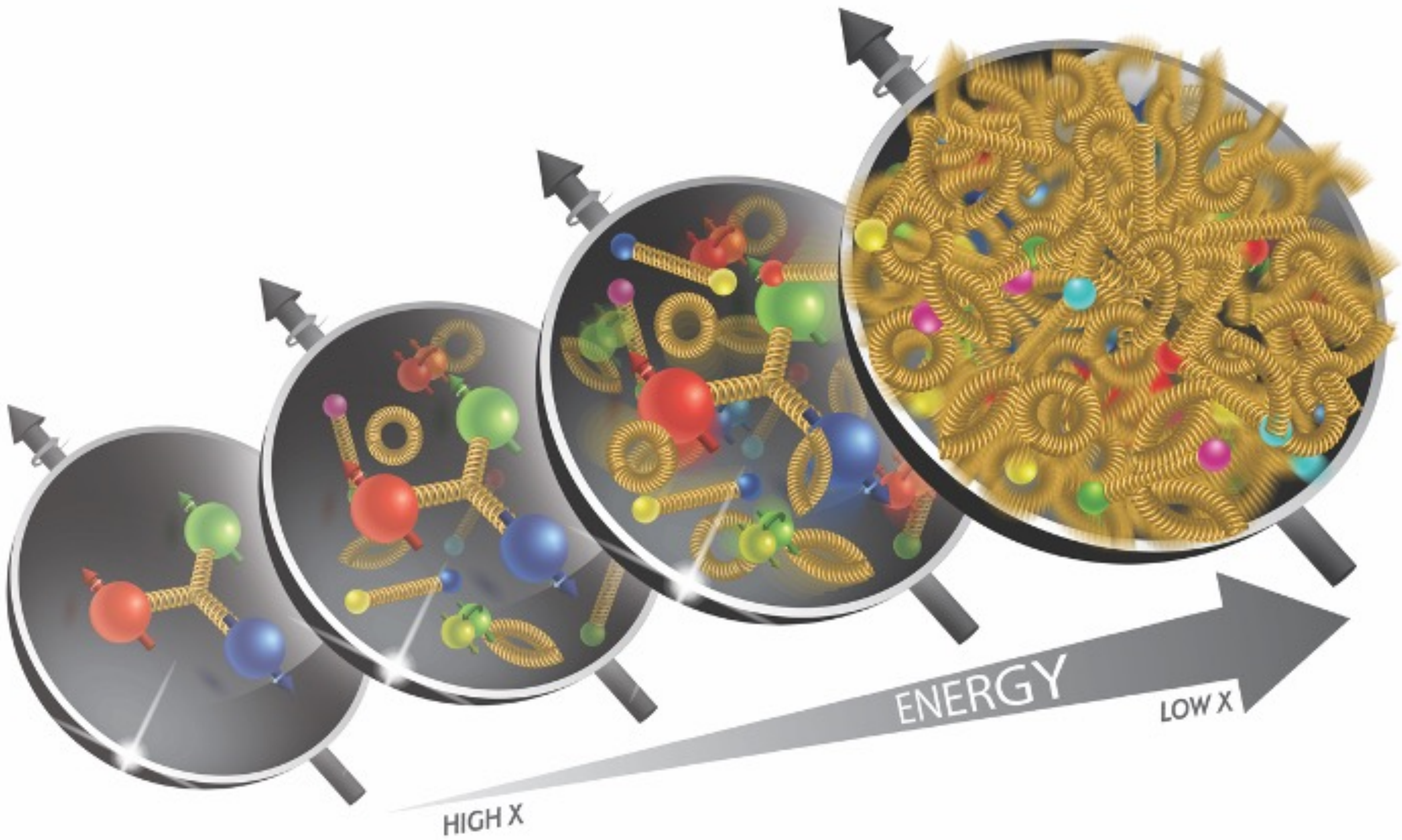
Different Facilities

Long range plan



Unchartered Territory of the Gluons





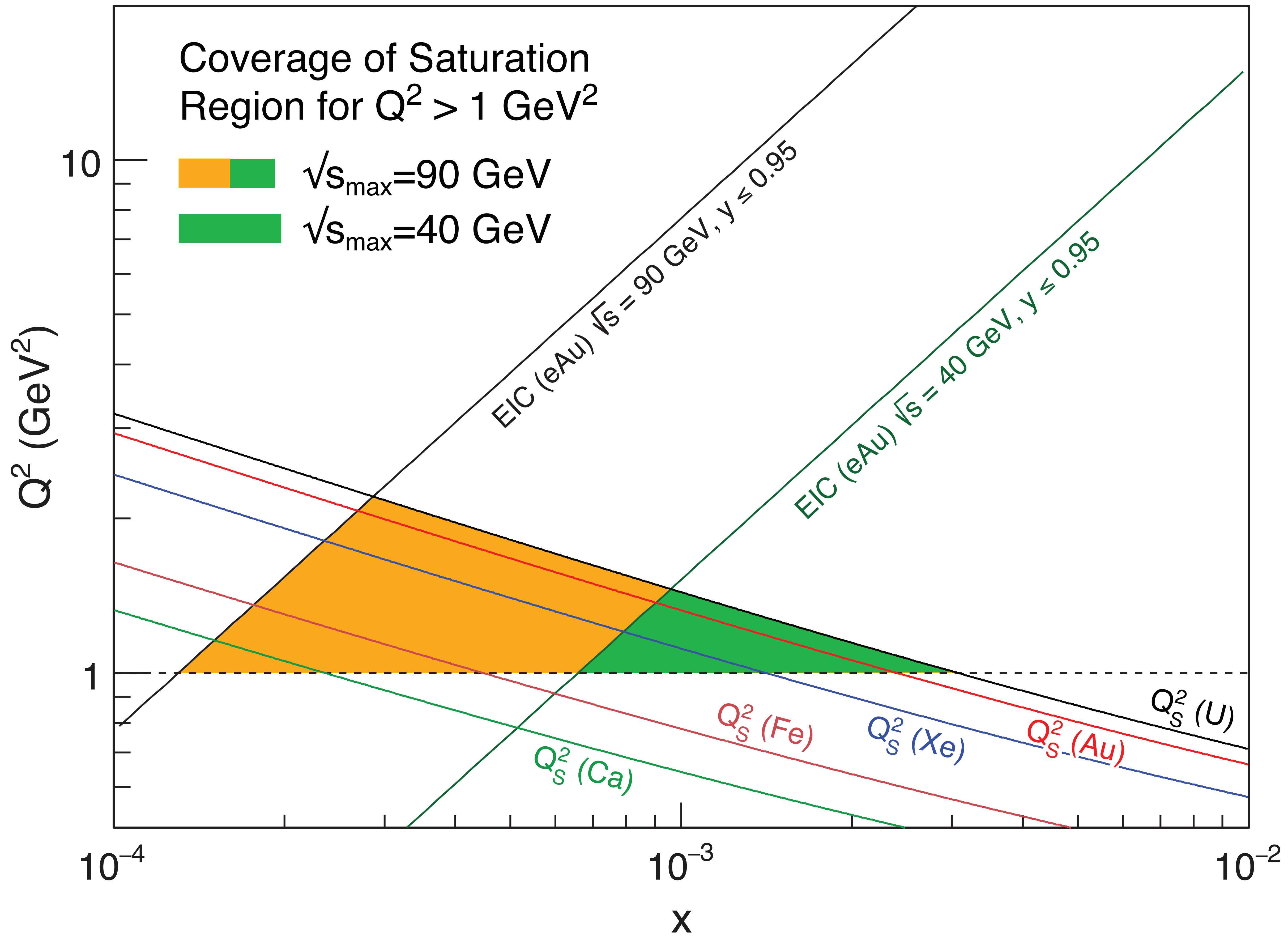
Is the proton a runaway popcorn machine?

Previous *1D* studies show an explosion of gluons
What happens to them?

Does gluon density start to saturate? When?

Does this give rise to a new phase of matter with universal properties in the nucleon and nuclei?

A New State of Matter?

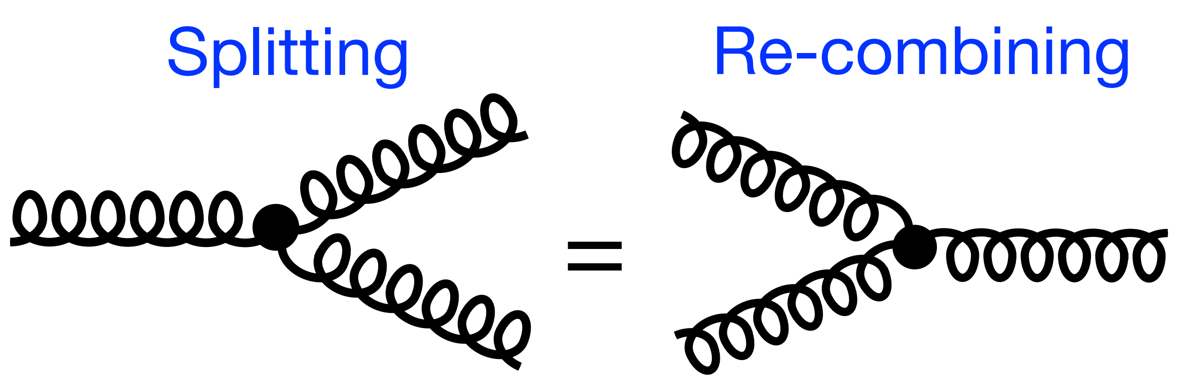


- EIC will provide a large suite of measurements to study the onset of saturation - multi-faceted approach

- EIC is ideal place for this due to its high energies, low reach in x, and its range of nuclei
- Saturation scale Q_S can be reached at lower energies with heavier nuclei

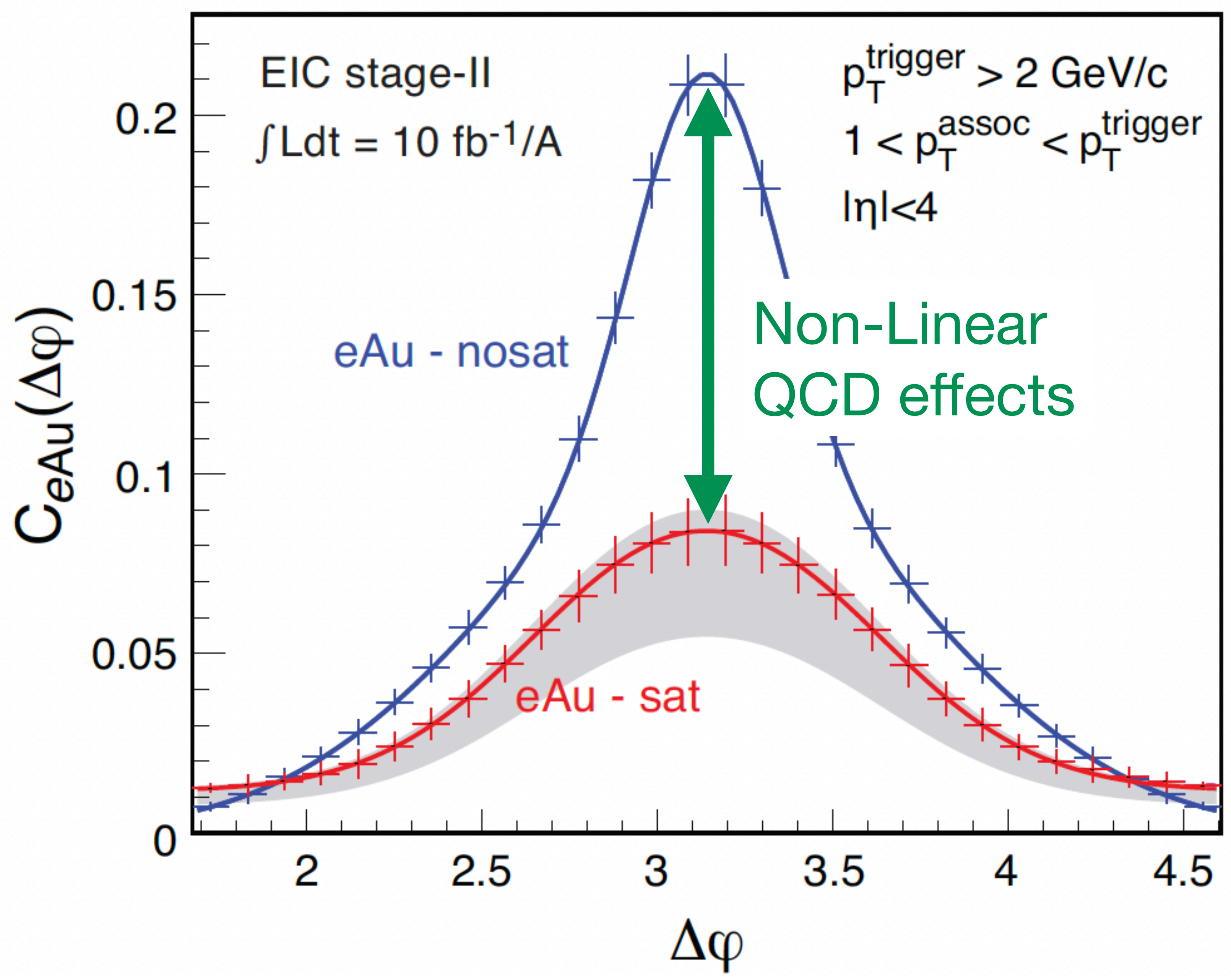
- e.g. angular correlations in the production of di-jets in e+p vs e+A

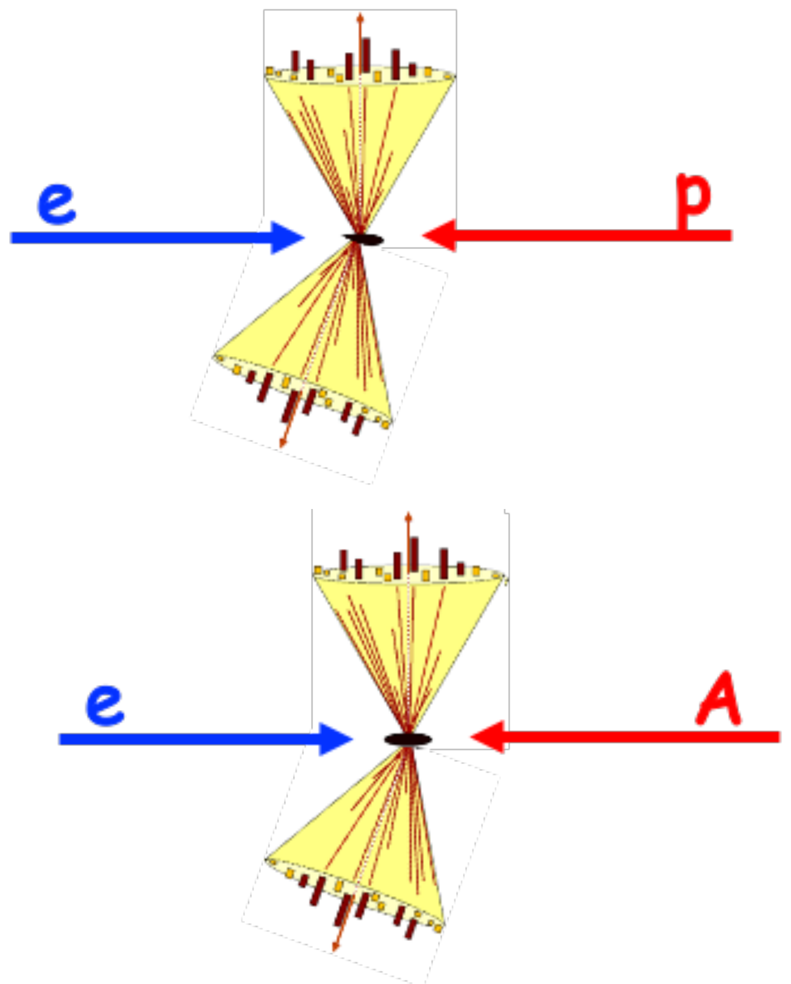
$$Q_S^2 \propto A^{\frac{1}{3}}$$

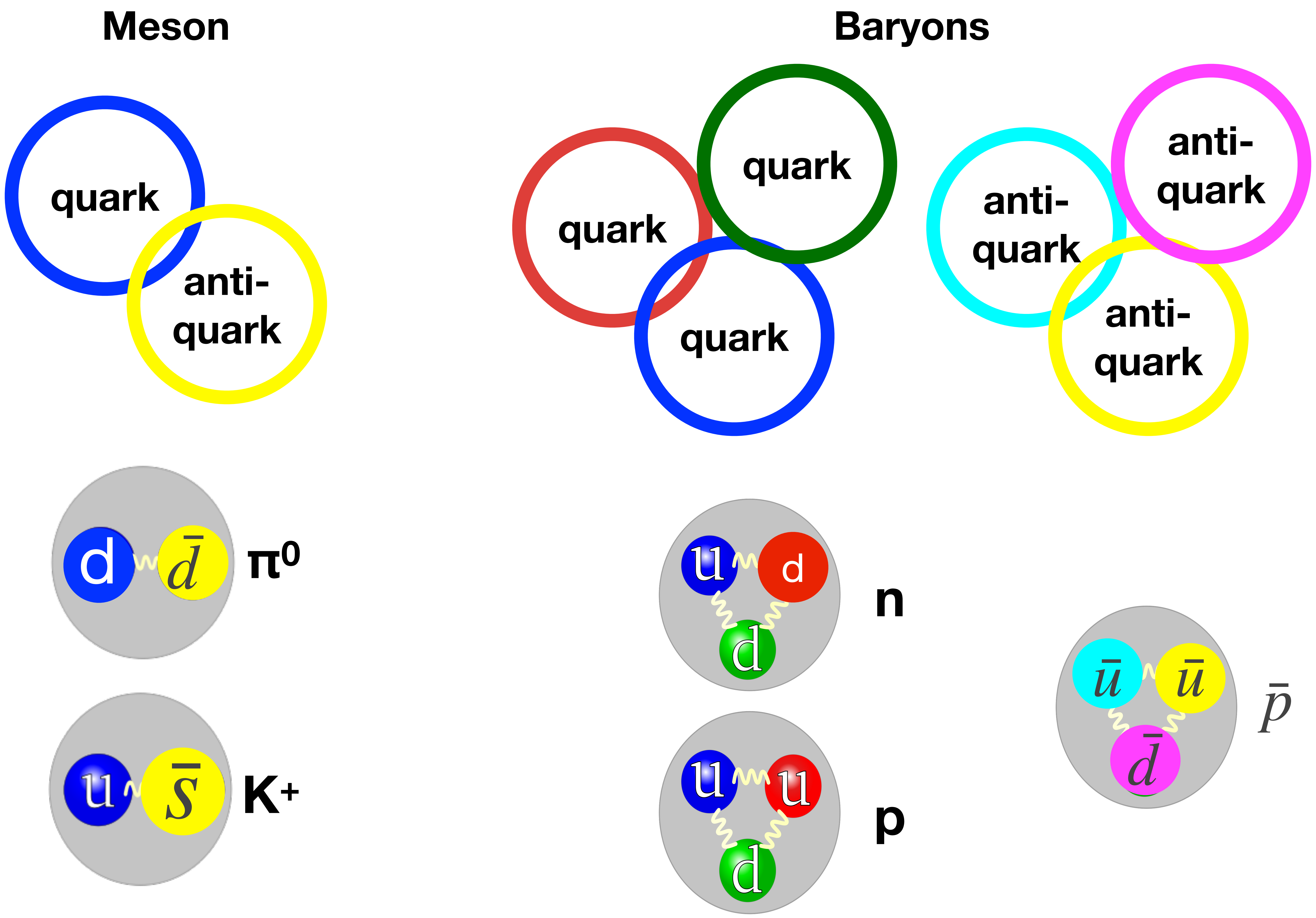


Gluons are self-interacting!

White Paper

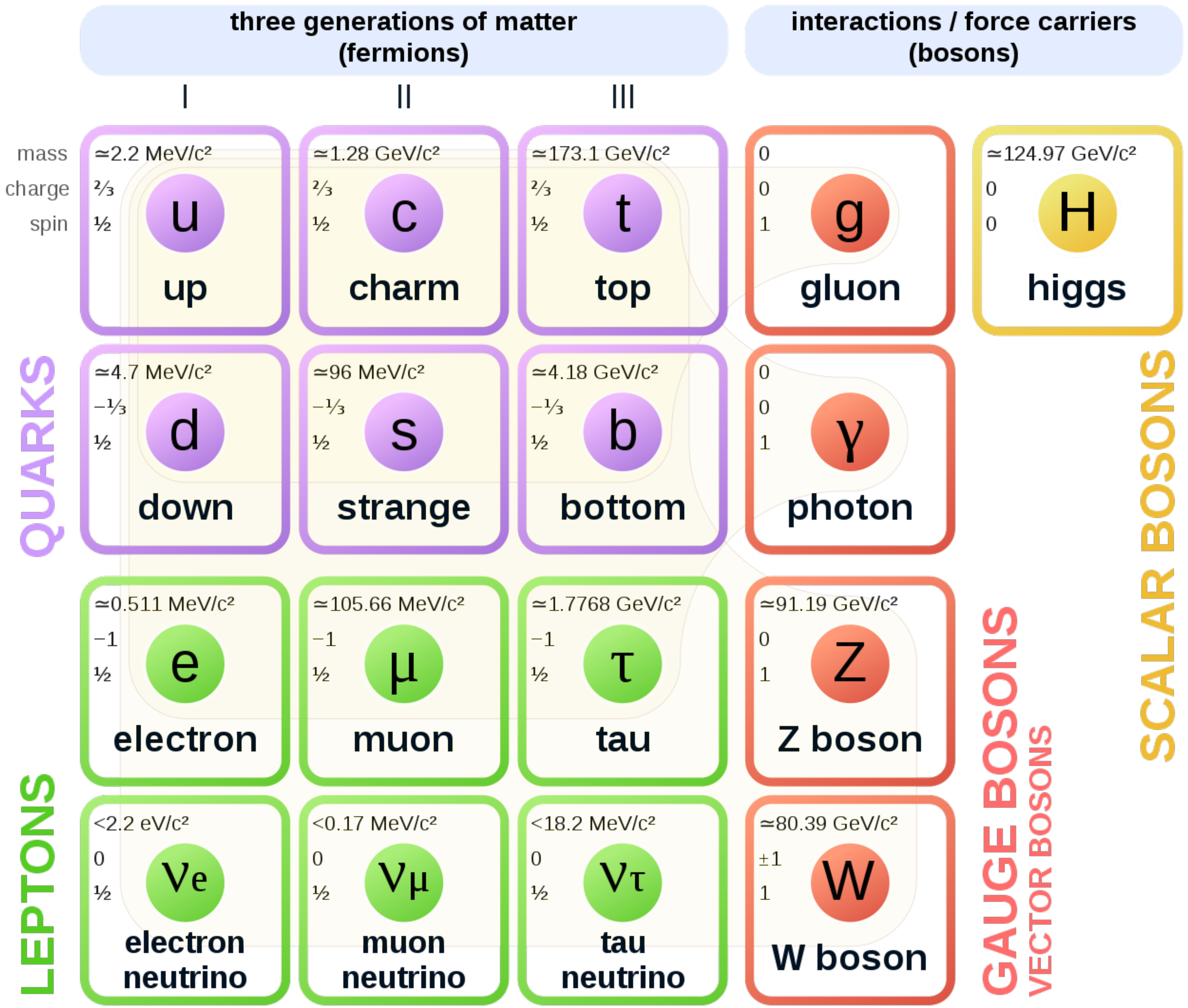


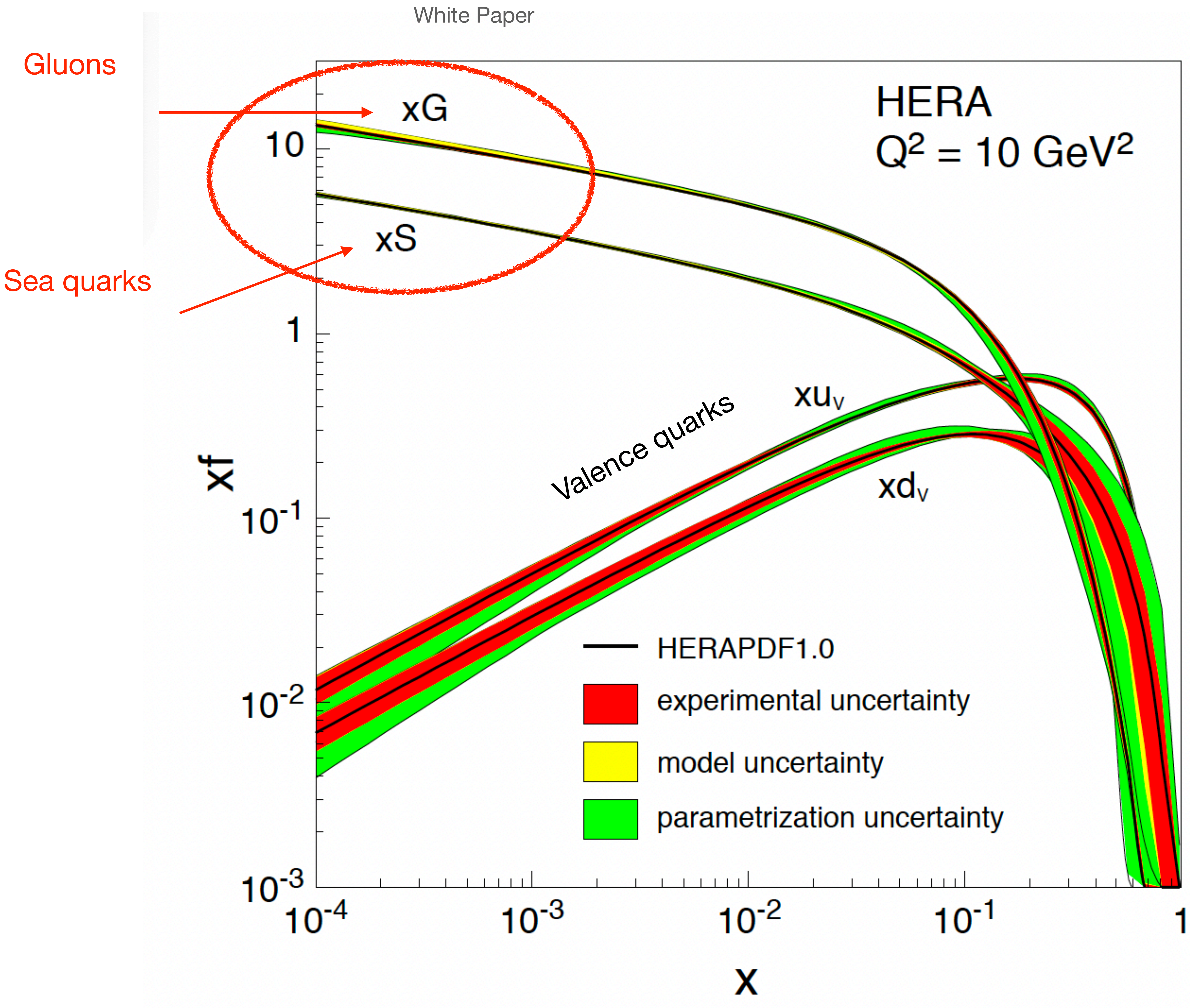




Different combinations of quark flavours define hadron properties
E.g. mass, charge, spin

The Universe’s Lego Bricks




White Paper
Gluons
Sea quarks
xG
xS
HERA
Q2 = 10 GeV2
Valence quarks
xuv
xdv
xf
x
10
1
10-1
10-2
10-3
10-4
10-3
10-2
10-1
1
HERAPDF1.0
experimental uncertainty
model uncertainty
parametrization uncertainty