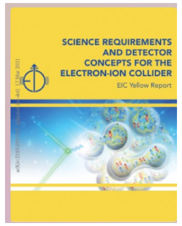
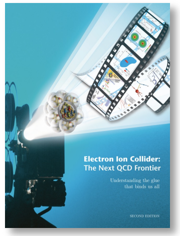
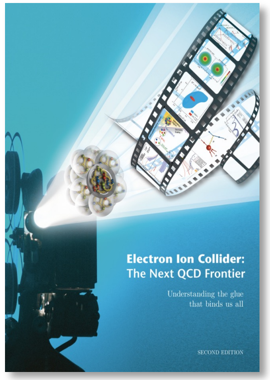
Center for Frontiers in Nuclear Science





Electron Ion Collider:
A new *tool* to study the glue that binds us all…

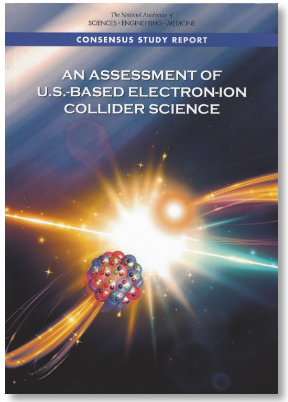
2015



2016

Physics of EIC

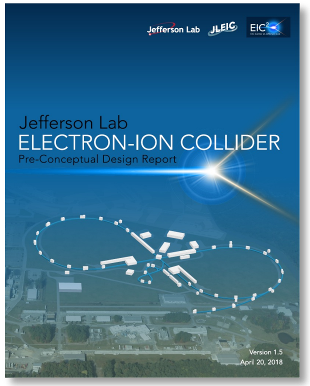
2018



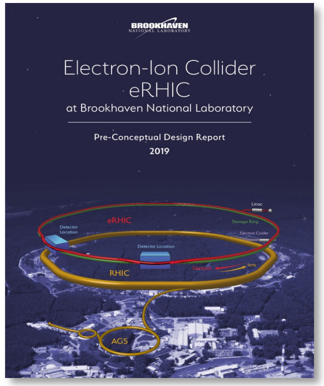
Evaluation

2019-present

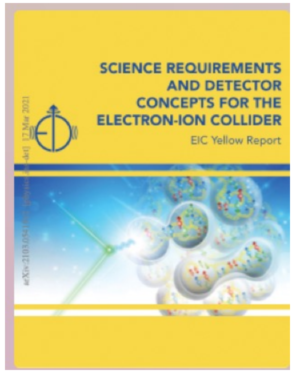
2019



machine

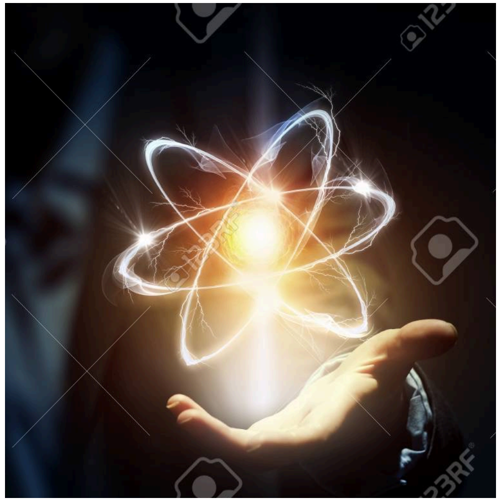


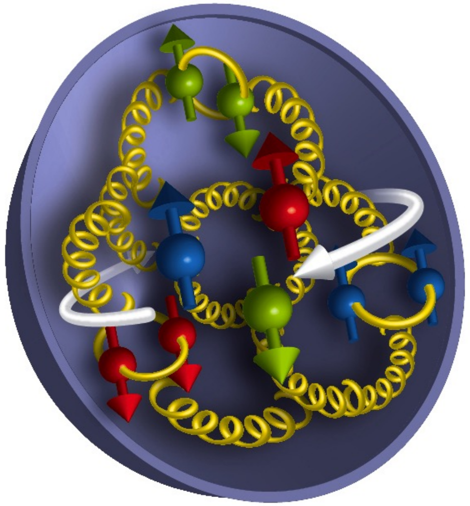
detector



Realization

About 100 years after the discovery of the atom and the proton





We know atomic structure so well, that we *define* "time" using electronic transitions:

Current accuracy
~1 sec in 220 Million years

However, the internal structure of the proton is
known to only about 20-30%
~20 minutes in an hour…!

WHY?

Because of the gluons

1974: QCD Asymptotic Freedom

Nobel Prize in Physics 2004

David J. Gross, H. David Politzer, Frank Wilczek

"for the discovery of asymptotic freedom in the theory of the strong interaction".

Quantum Chromodynamics (QCD)

Theory of strong interactions includes color confinement, asymptotic freedom

2004 Nobel Prize for explaining asymptotic freedom

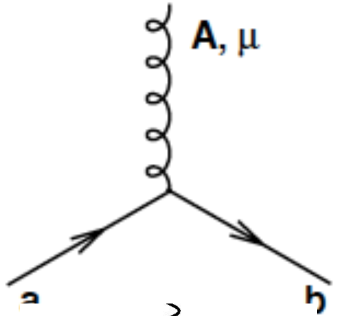
Confinement observed, but not quite understood….. Many facets to it…

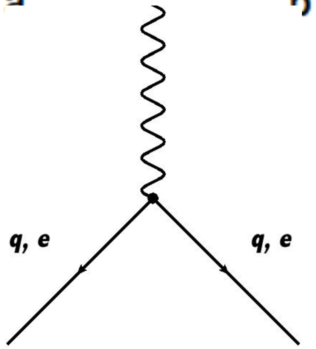
What distinguishes QCD from QED?

QED is mediated by photons (γ) which are charge-less (and couple to charged particles)

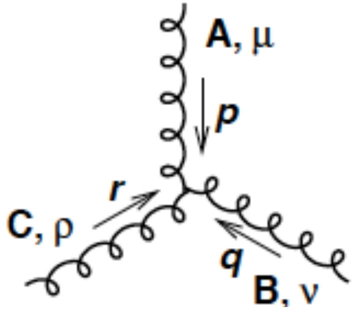
QCD is mediated by gluons (g), also charge-less but *are* colored! → can interact with themselves, and colored quarks

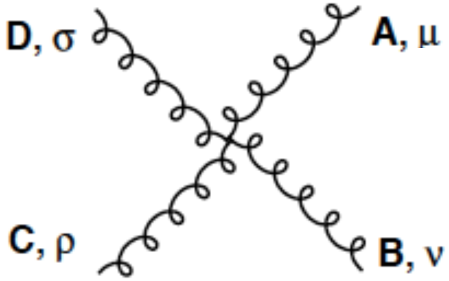
In QCD &
g → γ in QED





Only in QCD





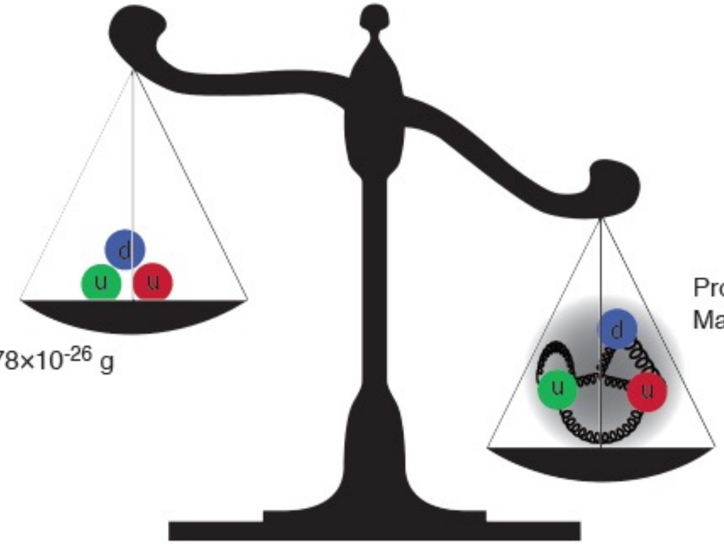
Nonlinear growth in g-g interactions…
Bring richness and complexity to QCD
Experimental guidance always needed

Proton mass puzzle

François Englert

Peter W. Higgs

Nobel 2013 With Francois Englert
"Higgs Boson" that gives mass to quarks, electrons,….



Add the masses of the quarks (HIGGS mechanism) together 1.78 x 10^{-26} grams

But the proton's mass is 168 x 10^{-26} grams

➔ **only 1% of the mass of the protons (neutrons)** ➔ Hence the Universe

➔ Where does the rest of the mass come from?

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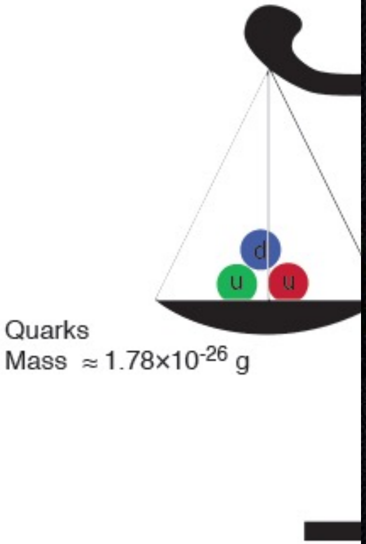

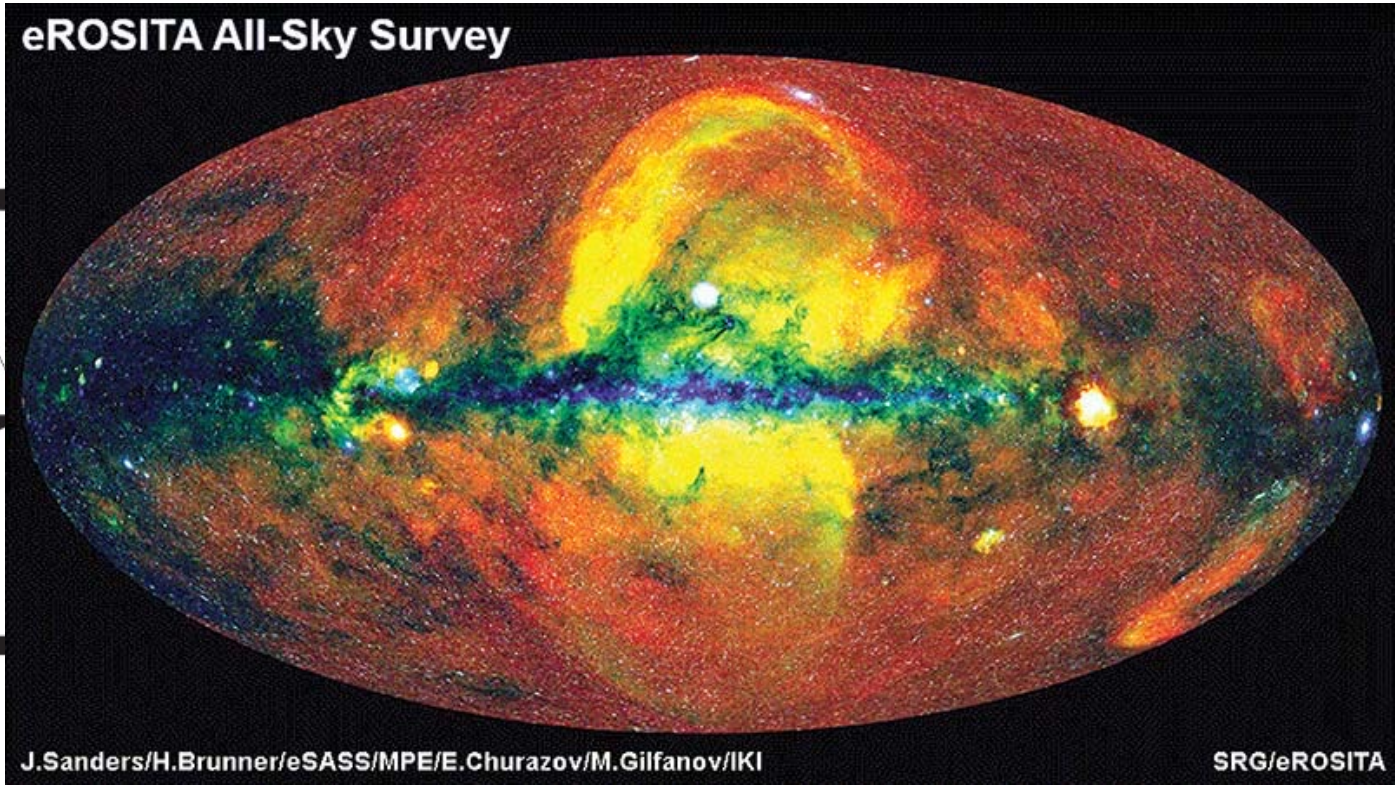

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Non-linear Dynamics of QCD has Fundamental Consequences

Emergence of spin, mass & confinement, gluon fields

- Quark (Color) confinement:
  - Unique property of the strong interaction
  - Consequence of nonlinear gluon self-interactions
- Strong Quark-Gluon Interactions:
  - Confined motion of quarks and gluons – Transverse Momentum Dependent Parton Distributions (TMDs)
  - Confined spatial correlations of quark and gluon distributions -- Generalized Parton Distributions (GPDs)

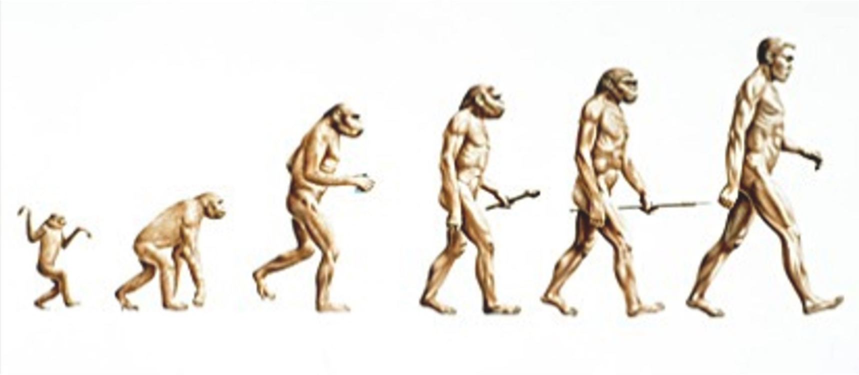
➔ Deeply connected to emergence of mass and spin of observed building blocks of nature

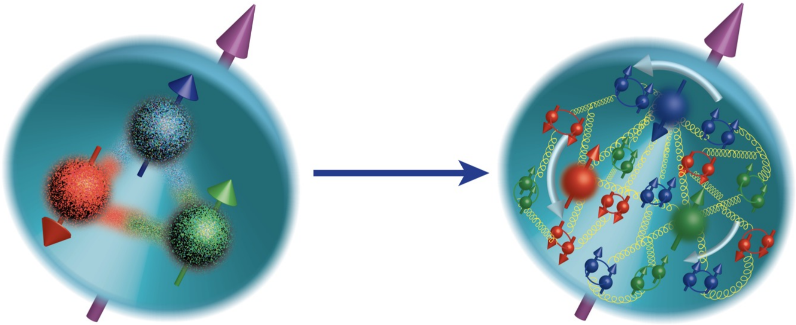
- Ultra-dense color (gluon) fields in all nucleons and nuclei?
  - Runaway growth in gluon number: Is it tamed by existing mechanisms in QCD?
  - Is there a universal many-body structure due to ultra-dense color fields?
  - Happens **in all** hadrons and nuclei? ➔ Universal?

A-A, p-A, e-A, p-p, e/μ-p/A and e-e collisions are all essential for fully understanding of QCD

Spin "Crisis" → Spin Puzzle

Discovered by EMC experiment at CERN





$$\frac{1}{2} = \underbrace{[Q_{\mathrm{spin}}}_{25\%} + \underbrace{Q_{\mathrm{ang.mom.}}]}_{?} + \underbrace{[G_{\mathrm{spin}}}_{25\%} + \underbrace{G_{\mathrm{ang.mom.}}]}_{?}$$

Transverse motion and finite size of the proton must create the orbital motion

Connected to the mass?

Nuclear Puzzle

Discovered by EMC experiment at CERN

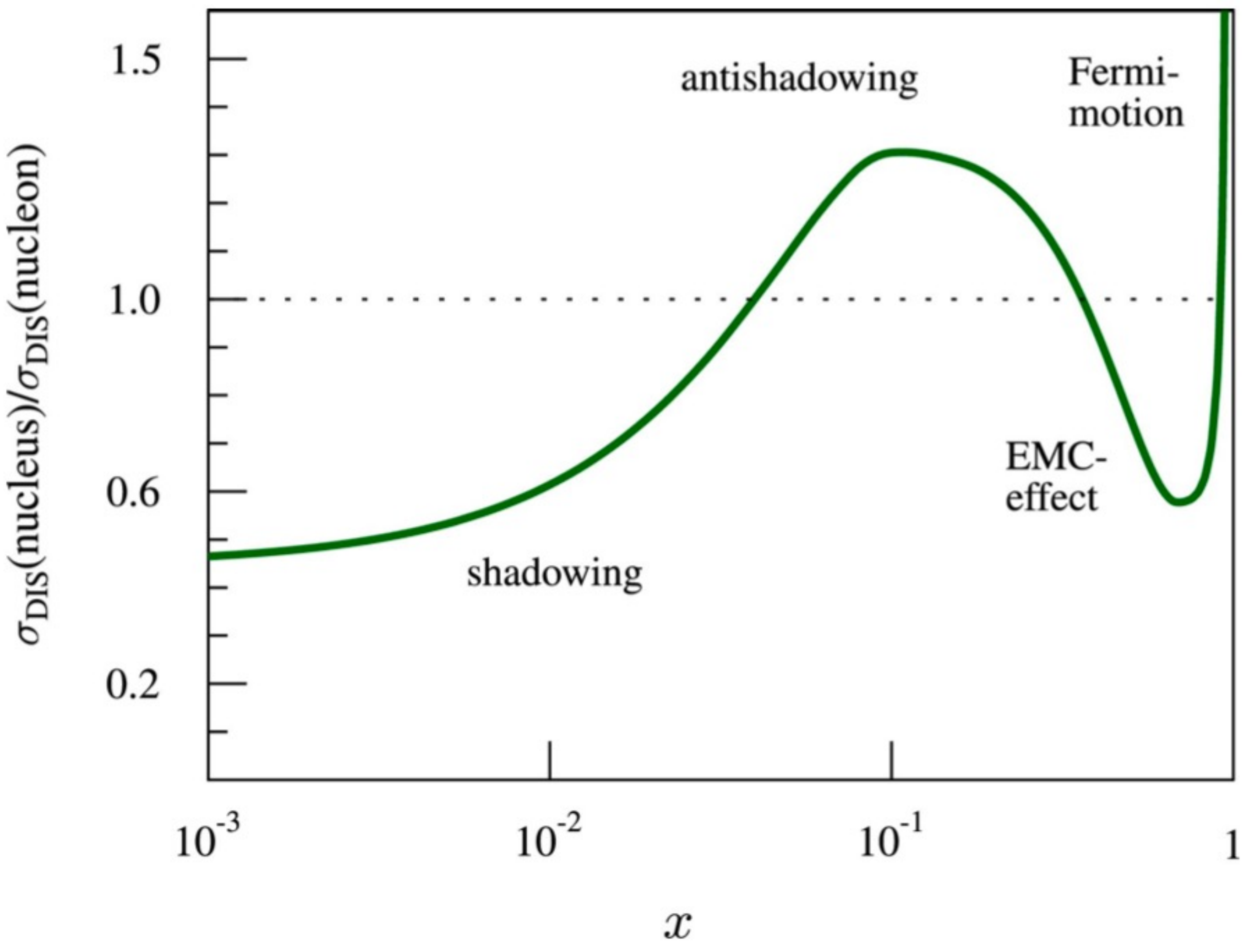
Nuclear EMC effect

Parton distributions are different in protons and nuclei

Exactly how do they get modified?

What happens in regions x < 0.001? Not quite known, and not predictable

However, low-x dynamics in protons and nuclei is of great interest, need to measure experimentally



DEEP INELASTIC SCATTERING (DIS)

The best technique to understand the internal structure of protons, neutrons and the nuclei.

Study of internal structure of a watermelon:

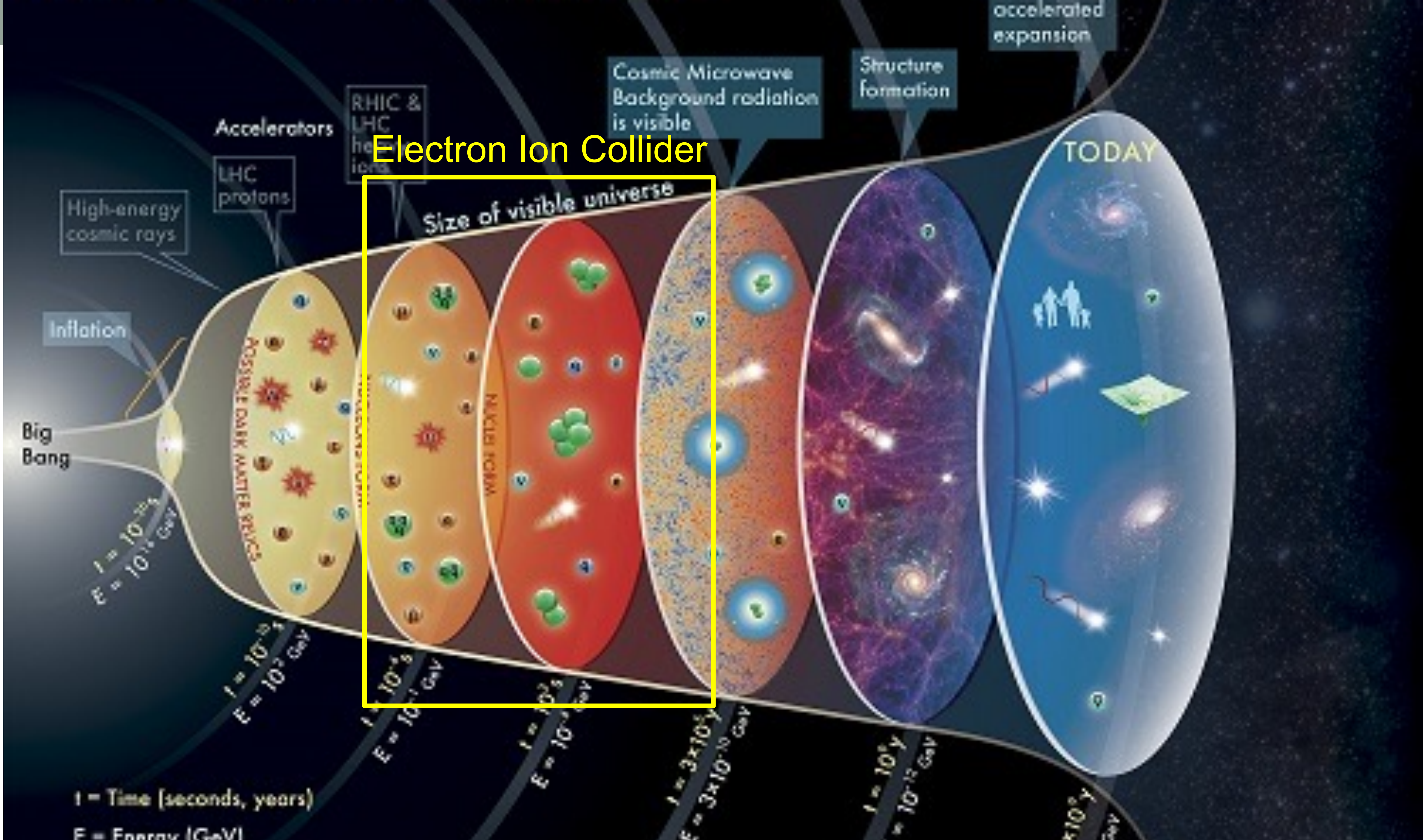
A-A (RHIC/LHC)

1) Violent collision of melons

2) Cutting the watermelon with a knife

Violent DIS e-A (EIC)

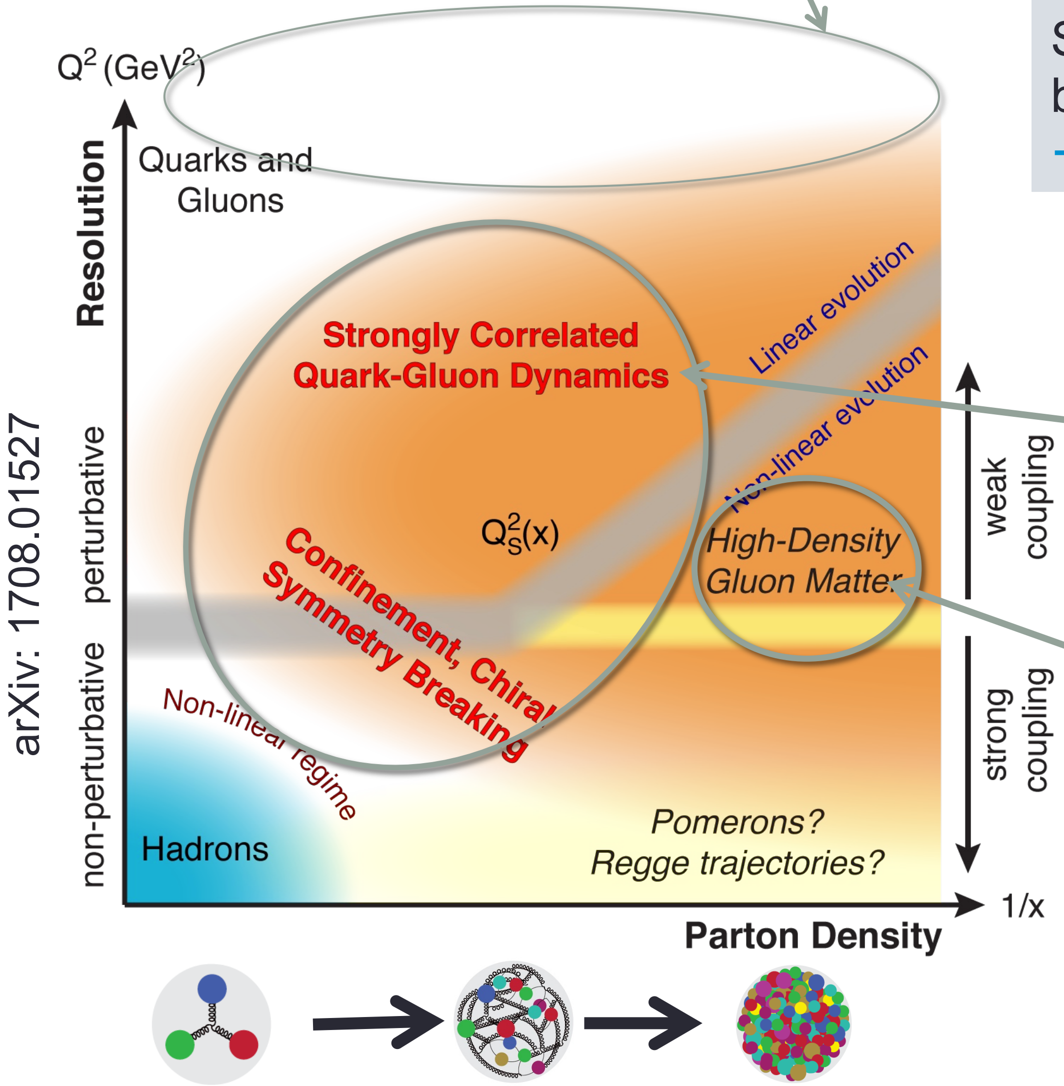
PHYSICS OF EIC


accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
RHIC & LHC
Accelerators
Electron Ion Collider
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEI FORM
t = Time (seconds, years)
E = Energy (GeV)

QCD Landscape to be explored by a new future facility

QCD at high resolution (Q^2) —weakly correlated quarks and gluons are well-described

Strong QCD dynamics creates many-body correlations between quarks and gluons
→ hadron structure emerges

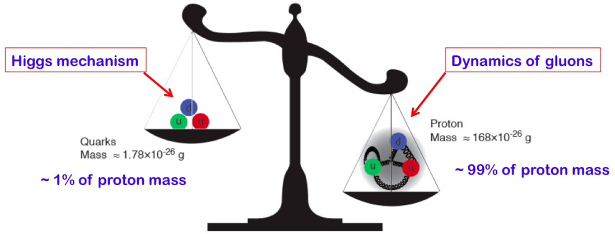


Systematically explore correlations in this region.

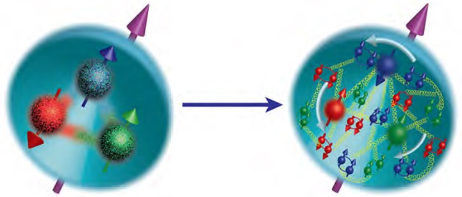
An exciting opportunity: Observation of a new regime in QCD of weakly coupled high-density matter

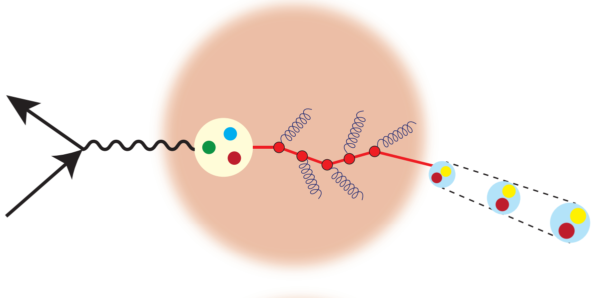
Need Precision and Control

EIC Physics at-a-Glance



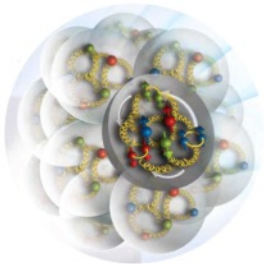
How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
How do the nucleon properties (mass & spin) emerge from their interactions?



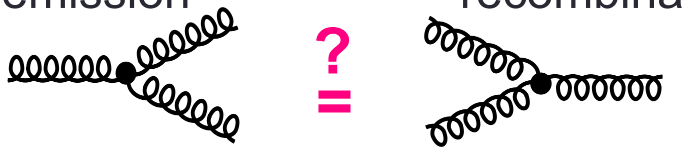


How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
How do the confined hadronic states emerge from these quarks and gluons?
How do the quark-gluon interactions create nuclear binding?

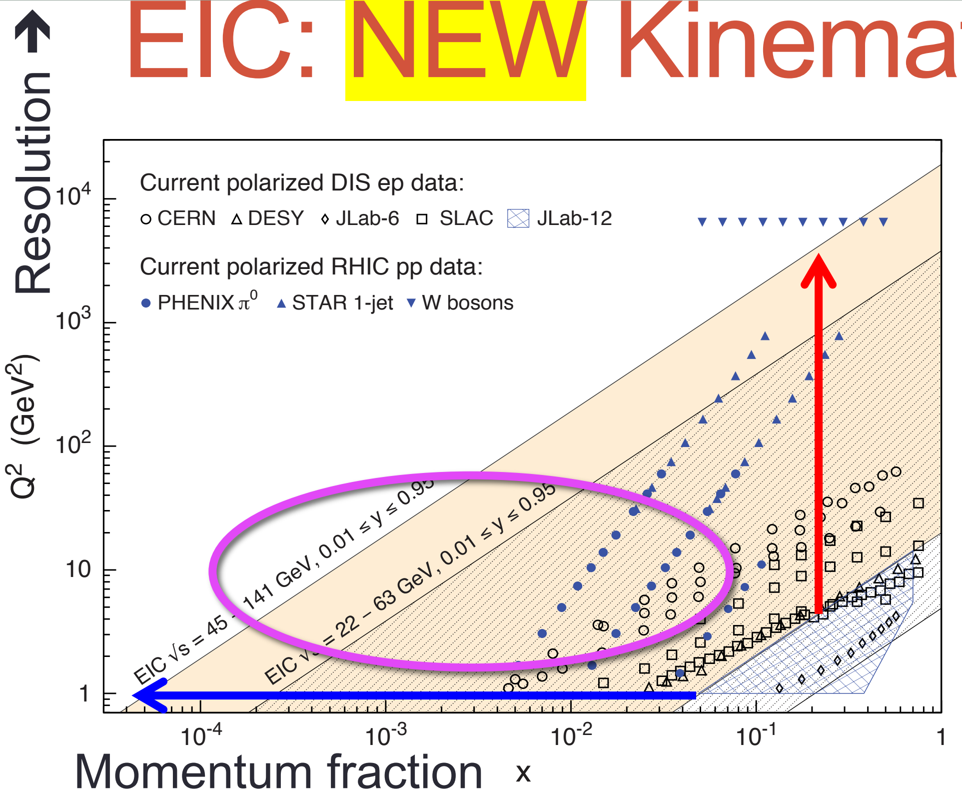
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

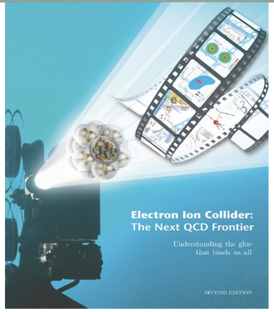


gluon emission ?= gluon recombination



EIC: NEW Kinematic reach & properties



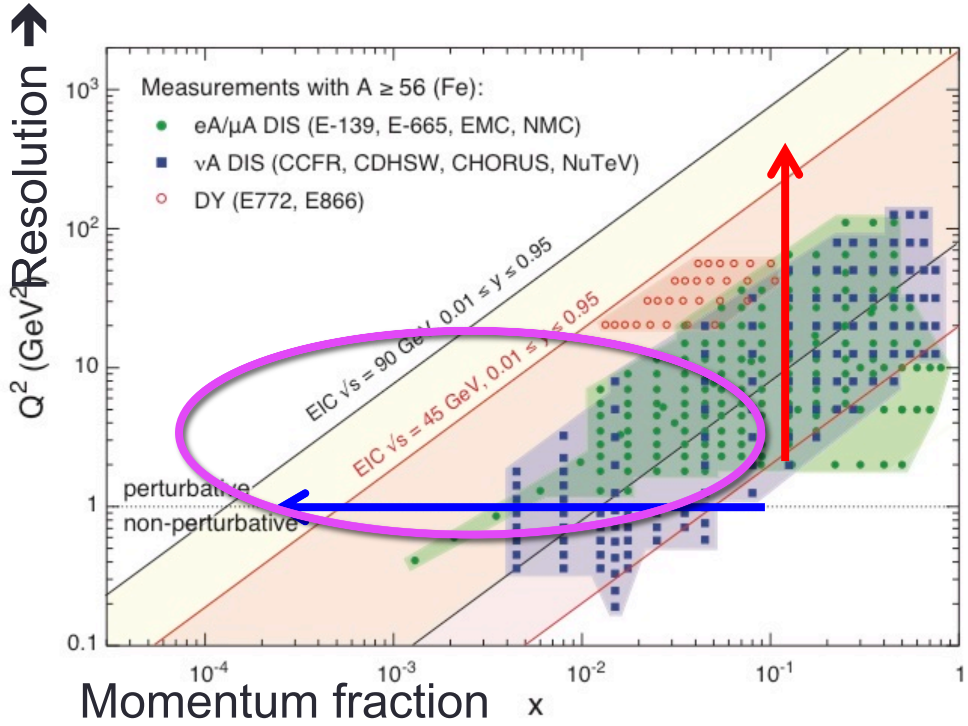


For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

For e-A collisions at the EIC:

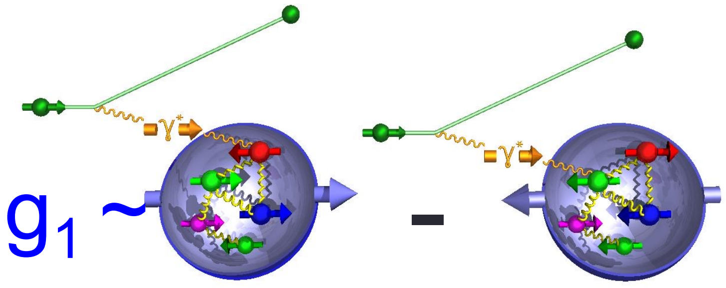
- ✓ Wide range in nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy
- ✓ Wide x range (evolution)
- ✓ Wide x region (reach high gluon densities)



Nucleon Spin: Precision with EIC

$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

$\Delta\Sigma/2$ = Quark contribution to Proton Spin
Δg = Gluon contribution to Proton Spin
L_Q = Quark Orbital Ang. Mom
L_G = Gluon Orbital Ang. Mom

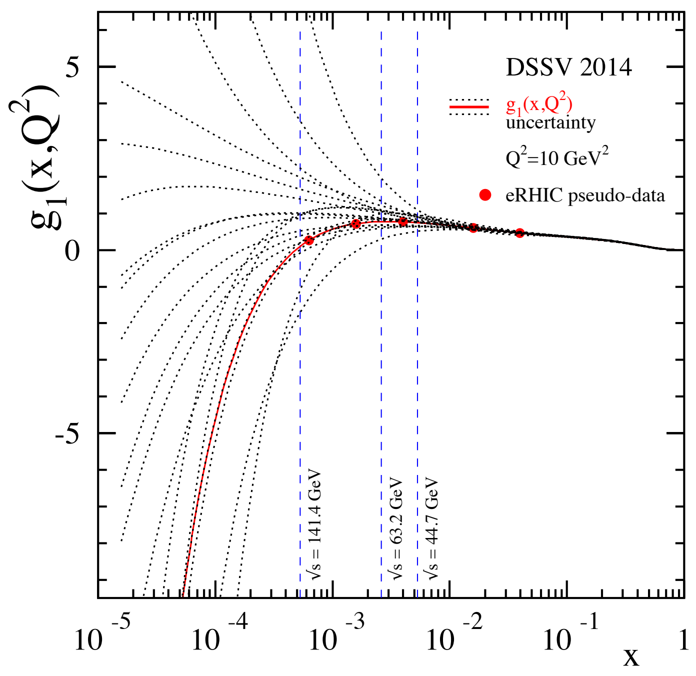


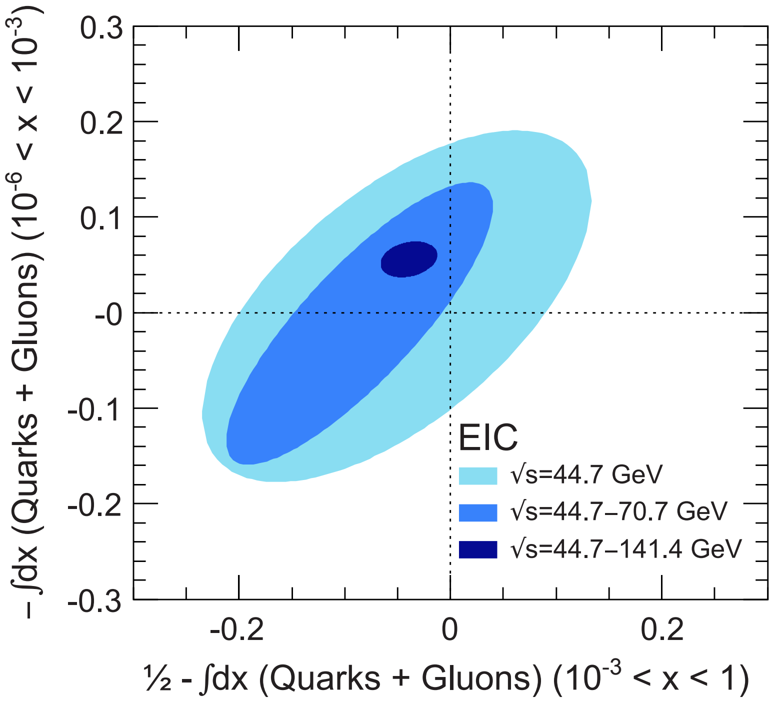
Spin structure function g_1 needs to be measured over a large range in x-Q^2

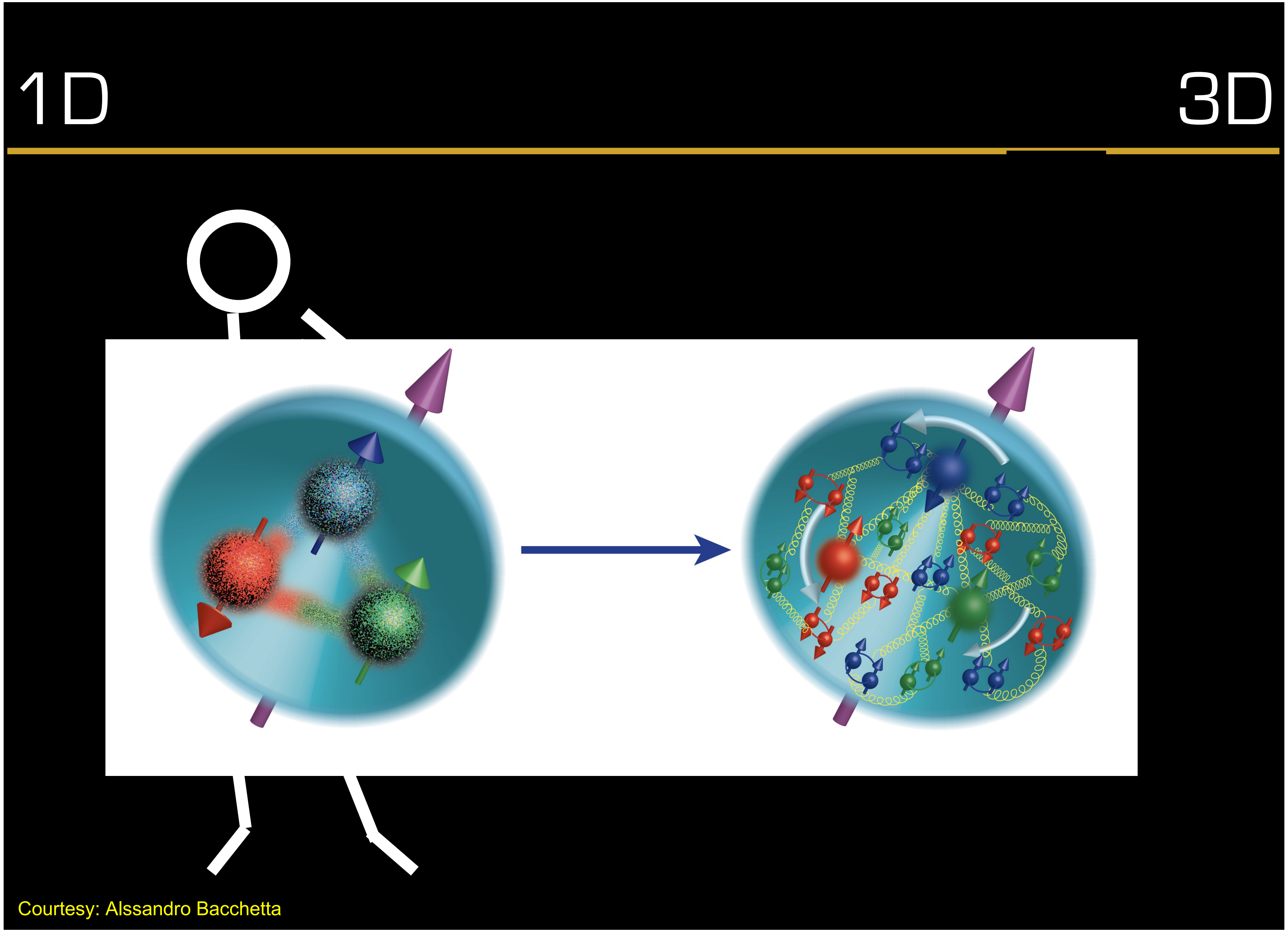
Precision in $\Delta\Sigma$ and Δg → A clear idea Of the magnitude of L_Q+L_G = L

Lattice Calculations : comparison

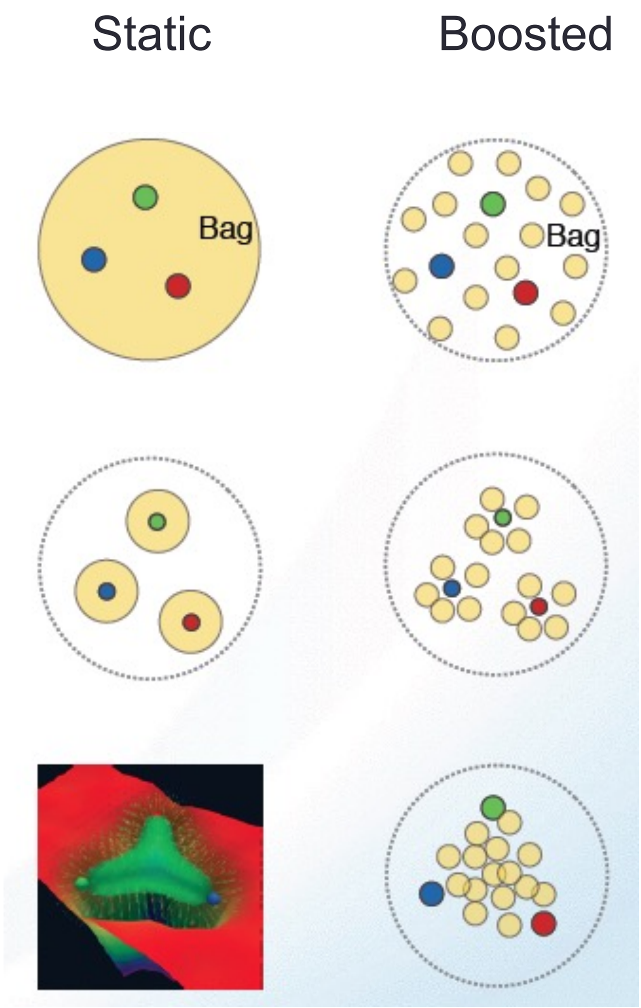
SIDIS: strange and charm quark spin contributions






1D
3D
Courtesy: Alssandro Bacchetta

What does a proton look like in "transverse" dimension?



Bag Model: Gluon field distribution is wider than the fast moving quarks. Color (Gluon) radius > Charge (quark) Radius

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

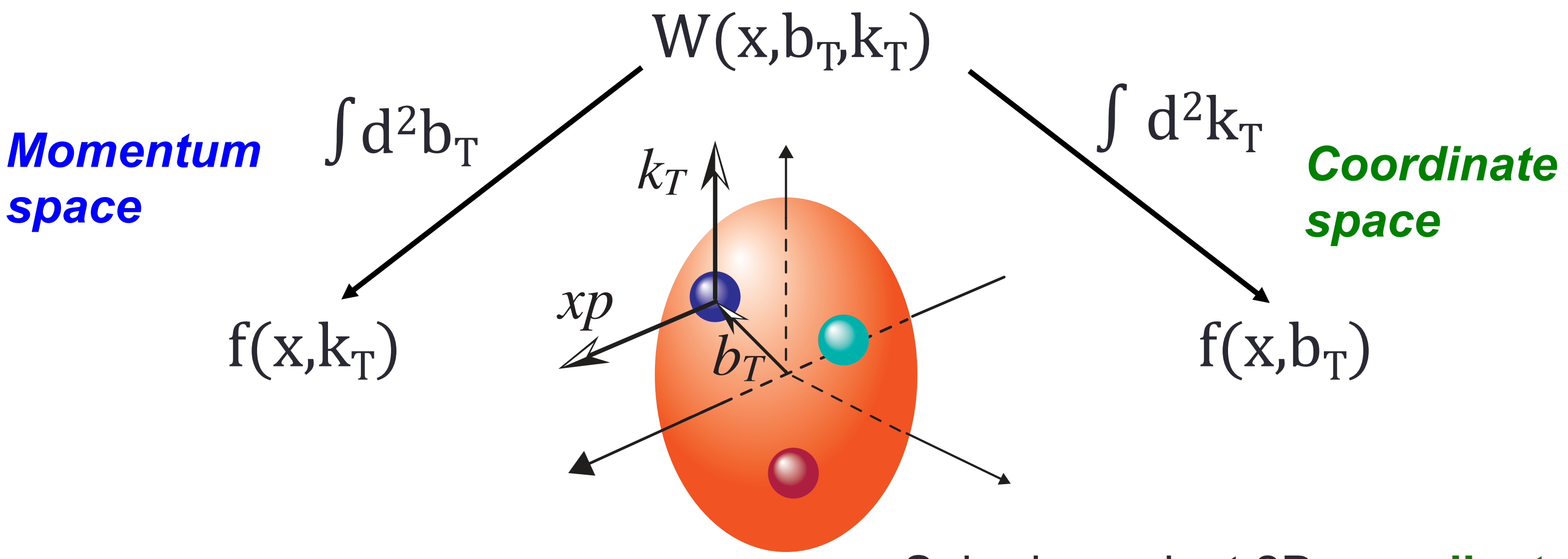
Lattice Gauge theory (with slow moving quarks), gluons more concentrated inside the quarks: Color (Gluon) radius < Charge (quark) Radius

Need *transverse* images of the quarks *and gluons* in protons

2+1-Dimensional Imaging Quarks and Gluons

Wigner functions **$W(x,b_T,k_T)$**

offer unprecedented insight into confinement and chiral symmetry breaking.



Near future promise of direct Comparison with lattice QCD

Spin-dependent 3D **momentum space** images from semi-inclusive scattering
→ **Transverse Momentum Distribution**

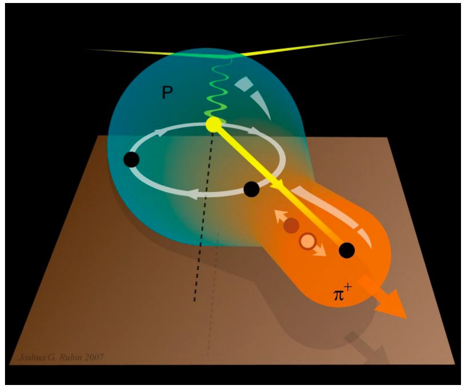
Spin-dependent 2D **coordinate space** (transverse) + 1D (longitudinal momentum) images from exclusive scattering (Deeply virtual Compton scattering and meson production)
→ **Generalized Parton Distributions**

momentum and position distributions → Orbital motion of quarks and gluons

2+1 D partonic image of the proton with the EIC

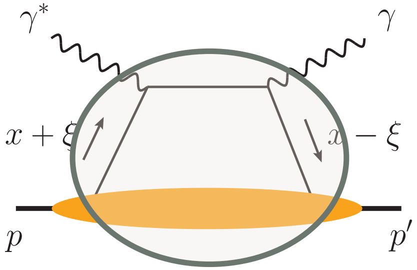
Spin-dependent (2+1)D momentum space images from semi-inclusive scattering (SIDS)

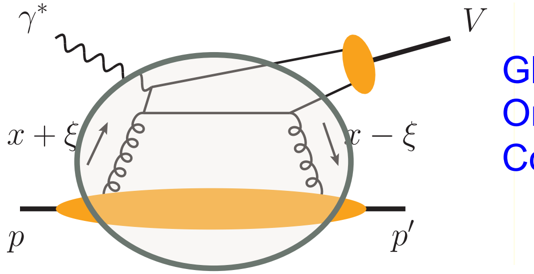
Transverse Momentum Distributions



Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering **Transverse Position Distributions**

Quarks Motion



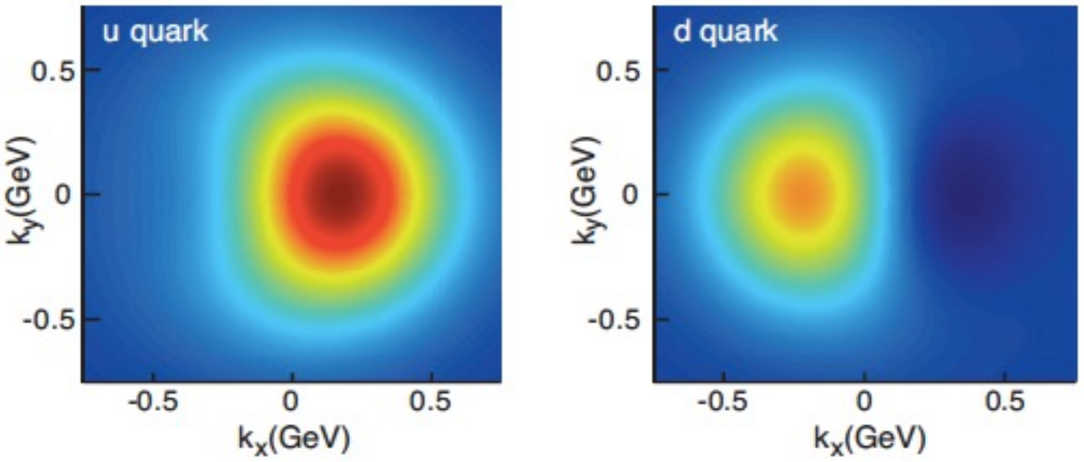


Gluons: Only @ Collider

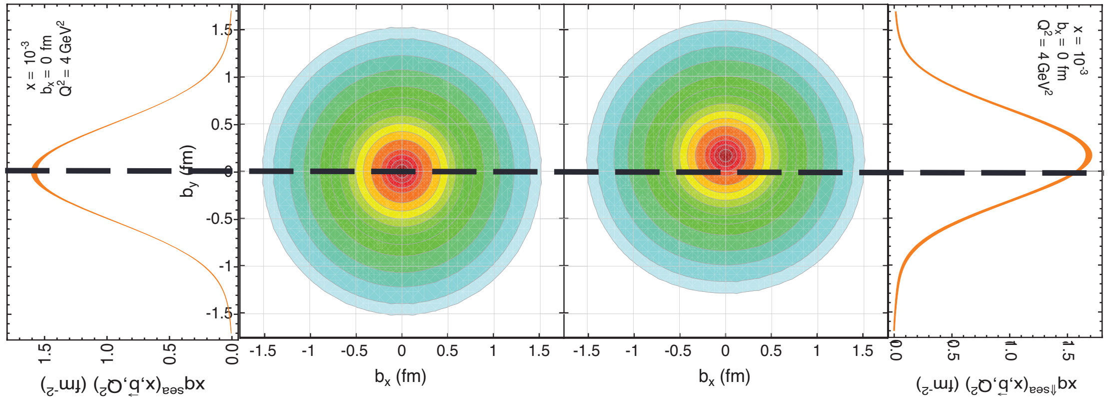
Deeply Virtual Compton Scattering
Measure all three final states
e + **p** → e'+ **p'**+ γ

Fourier transform of momentum transferred=(p-p') → Spatial distribution

Quark's 2D momentum distribution



Sea quark's 2D position distribution
unpolarized polarized



Study of internal structure of a watermelon:

A-A (RHIC)

1) Violent collision of melons

2) Cutting the watermelon with a knife

Violent DIS e-A (EIC)

3) MRI of a watermelon

Non-Violent e-A (EIC)

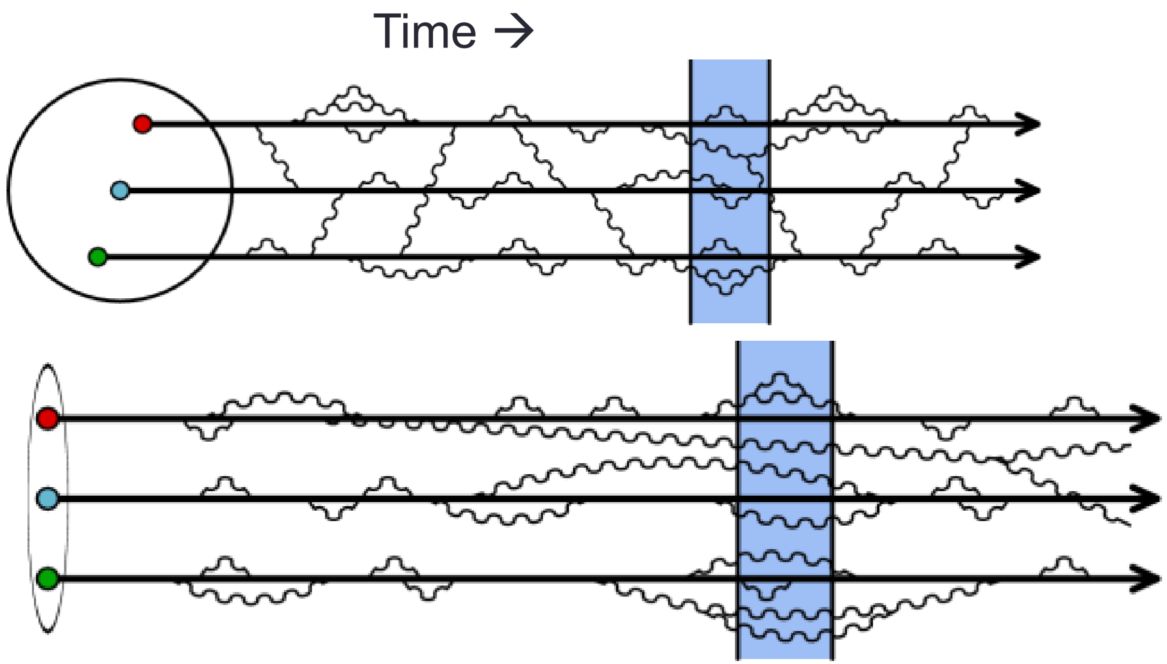
CONSEQUENCE OF GLUON SELF INTERACTIONS

Particularly at high energy (low-x)

How does a Proton look at low and very high energy?

Low energy: High x
Regime of fixed target exp.

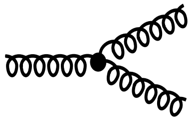
High energy: Low- x
Regime of a Collider



Cartoon of boosted proton

At high energy:

- Wee partons fluctuations are time dilated in strong interaction time scales
- Long lived gluons radiate smaller x gluons ➔ which in turn radiate more… a chain reaction leading to a **runaway growth?**



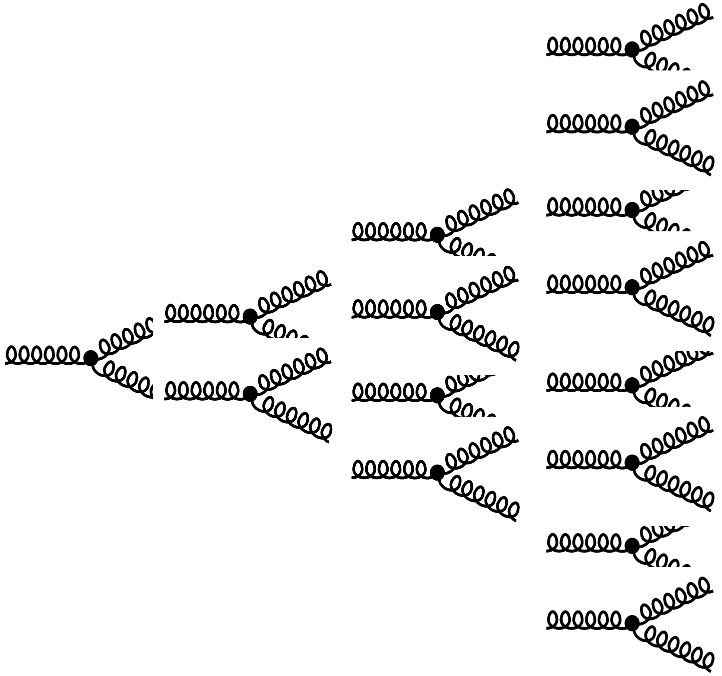
Gluon splitting

Gluon and the consequences of its interesting properties:

Gluons carry color charge ➔ Can interact with other gluons!

“…The result is a self catalyzing enhancement that leads to a runaway growth. A small color charge in isolation builds up a big color thundercloud….”

F. Wilczek, in “Origin of Mass”
Nobel Prize, 2004



?
Infinity?
No!

Gluon and the consequences of its interesting properties:

Gluons carry color charge ➔ Can interact with other gluons!

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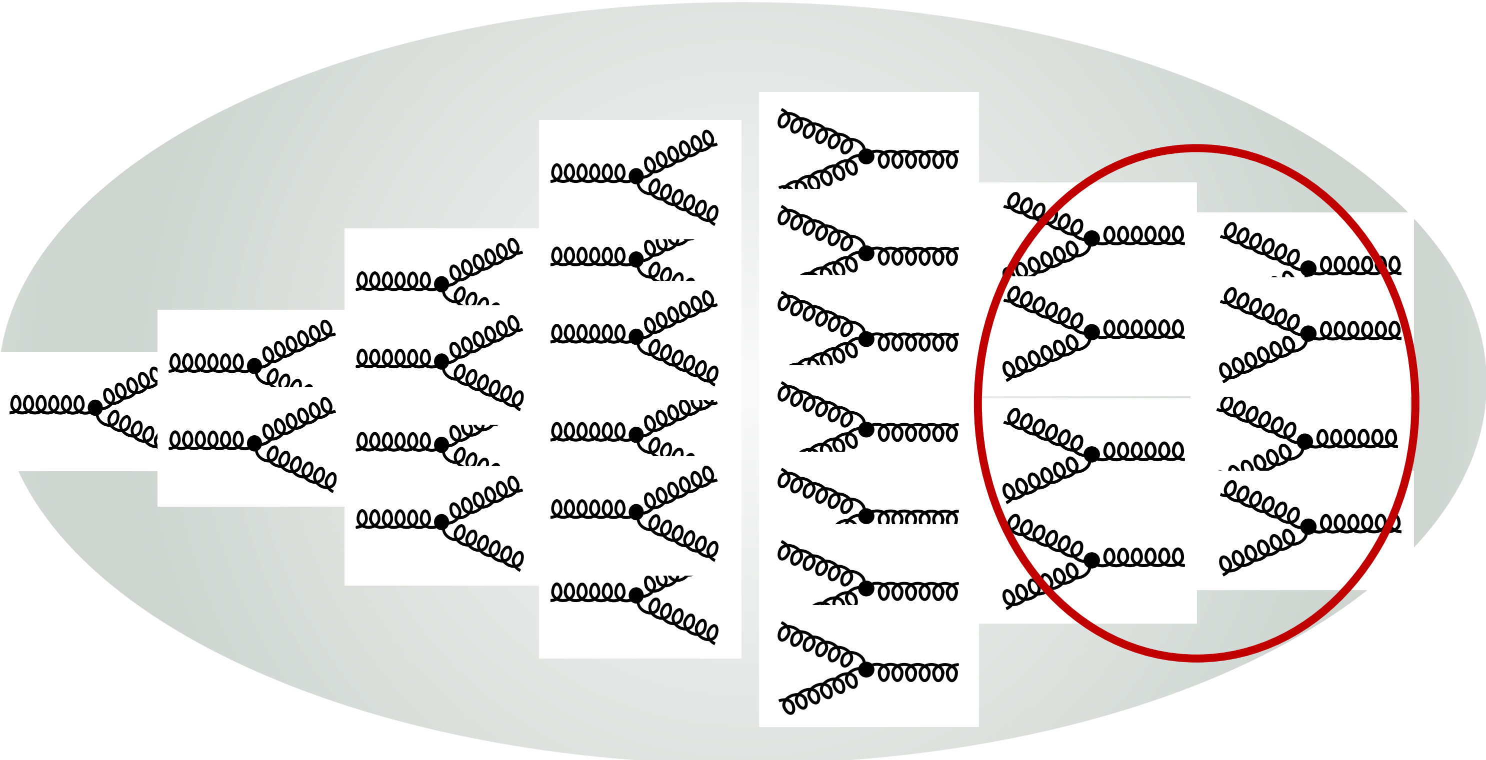
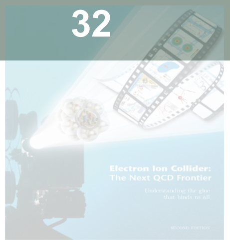
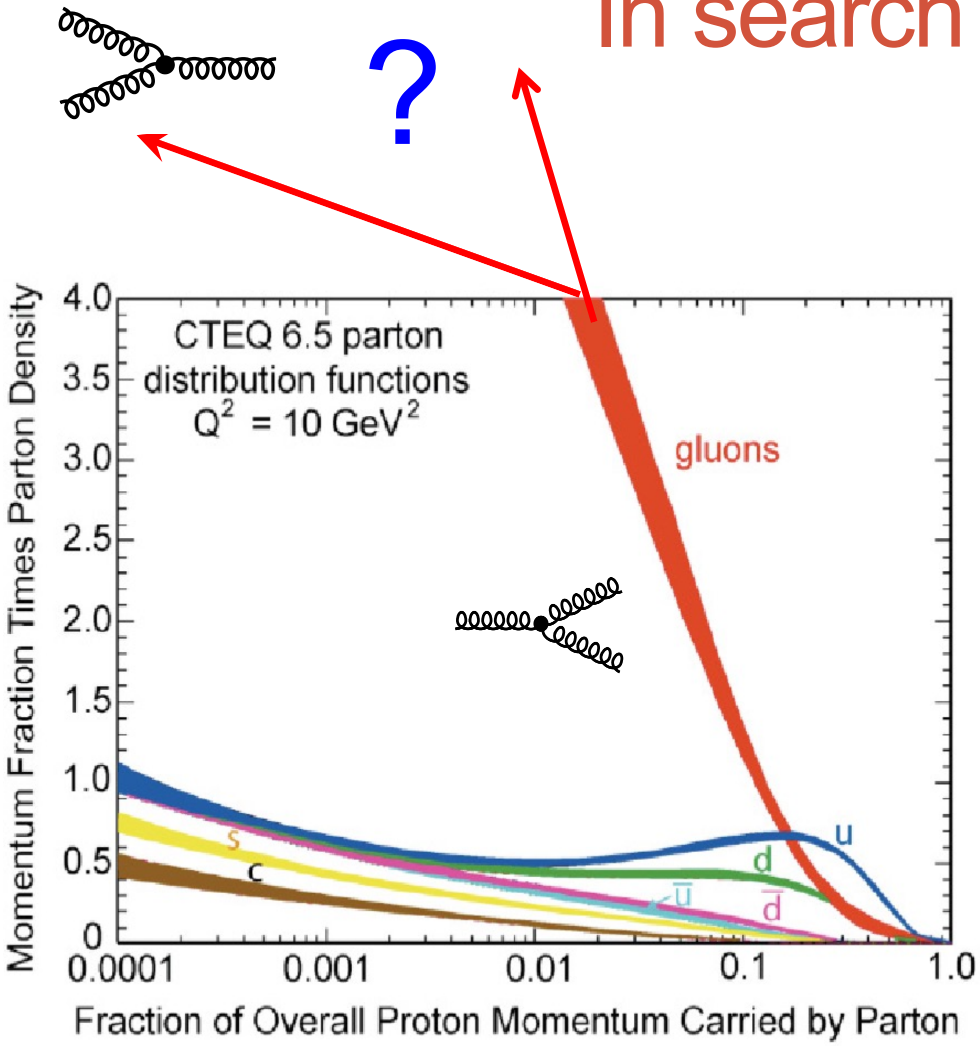


gluon emission

gluon recombination



In search of a new state of matter!

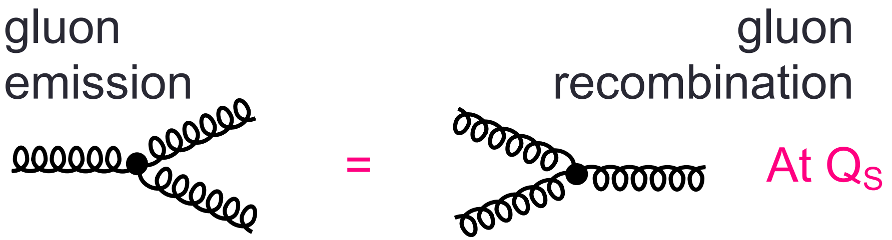


Experimental evidence needed

What could tame the low-x rise?

Can EIC access this region?

QCD inherently has the needed mechanism for this taming but we don't know when it gets triggered.



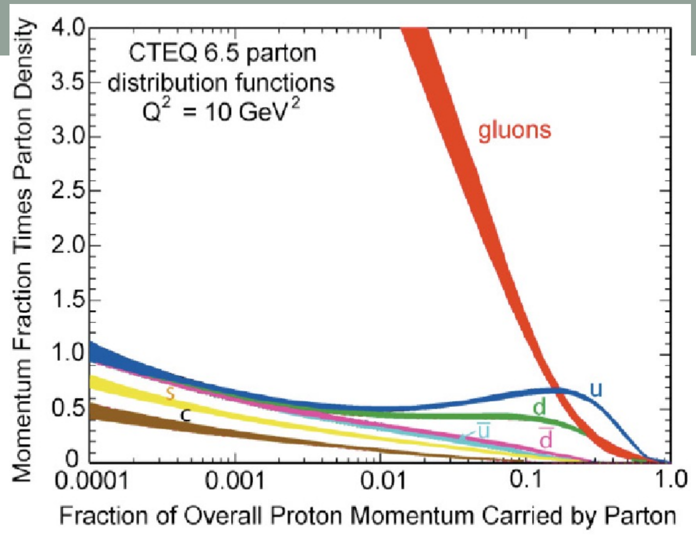
Observation of gluon recombination effects

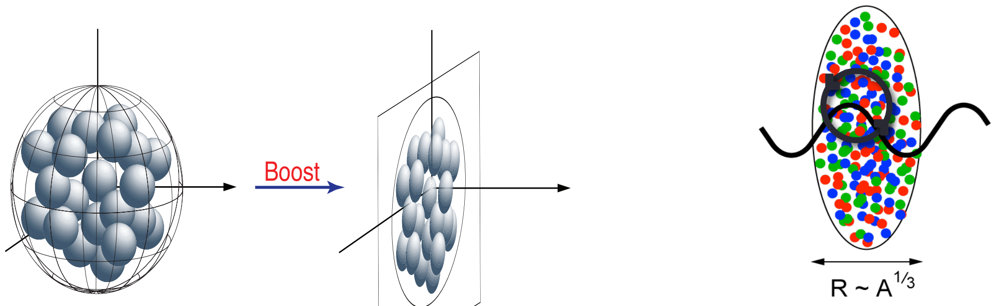
→Is there such new state of matter?

→ "Color Glass Condensate"

→ 50-100 times higher energy density than the core of the neutron star

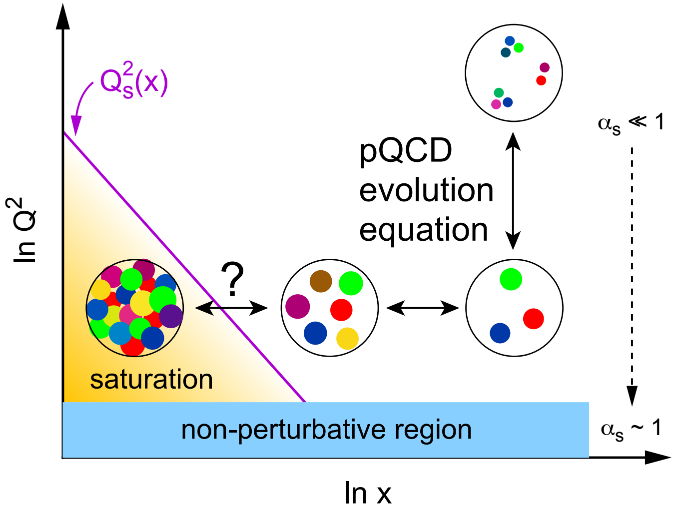
Low x physics with nuclei

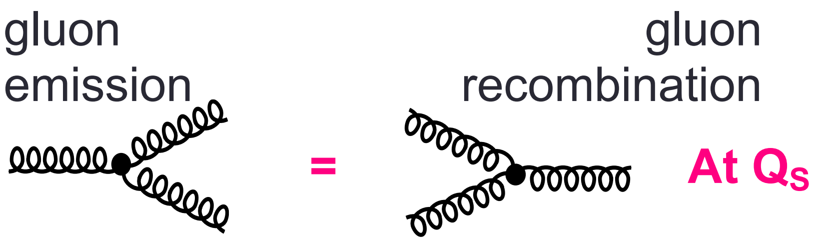




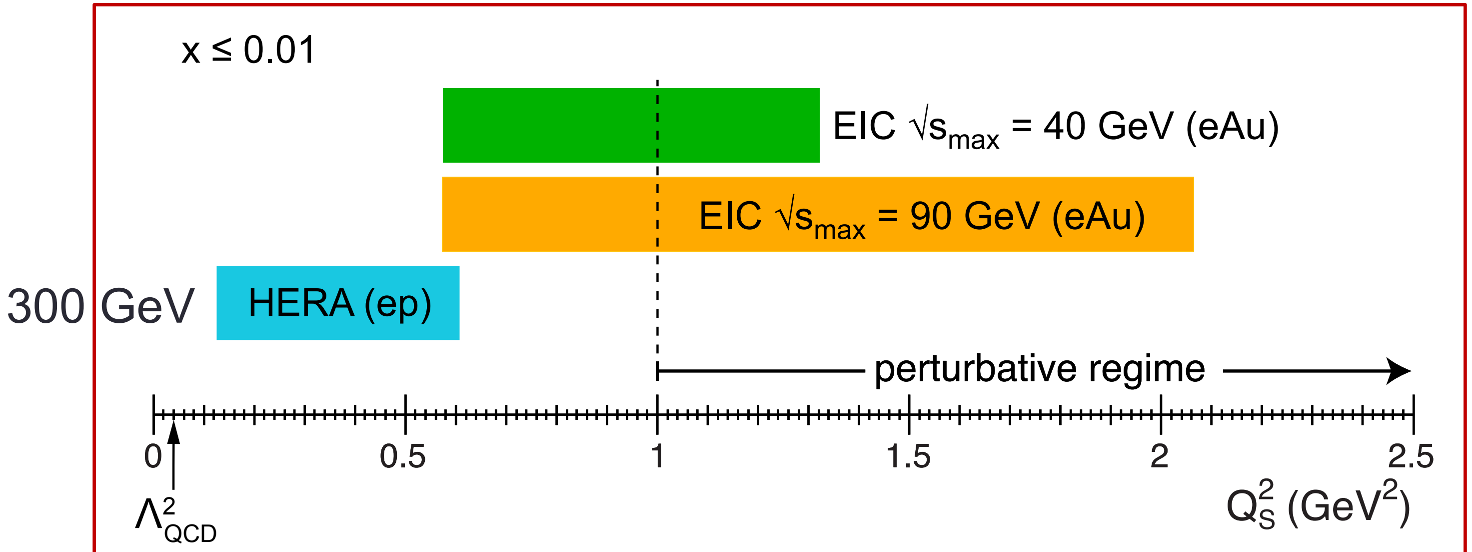
$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

L ~ $(2m_N x)^{-1}$ > 2 R_A ~ $A^{1/3}$





Accessible range of saturation scale $Q_s^{\,2}$ at the EIC with e+A collisions. arXiv:1708.01527

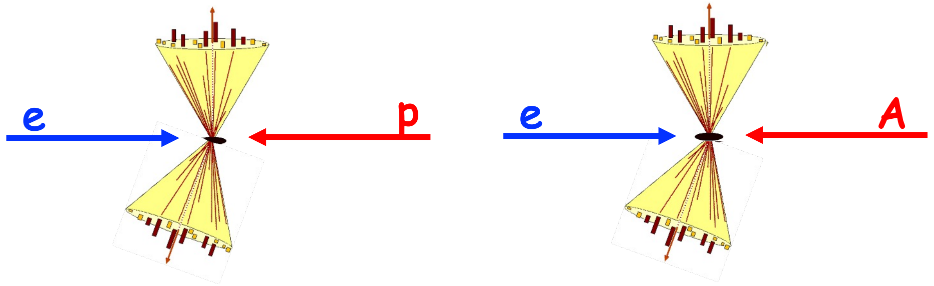


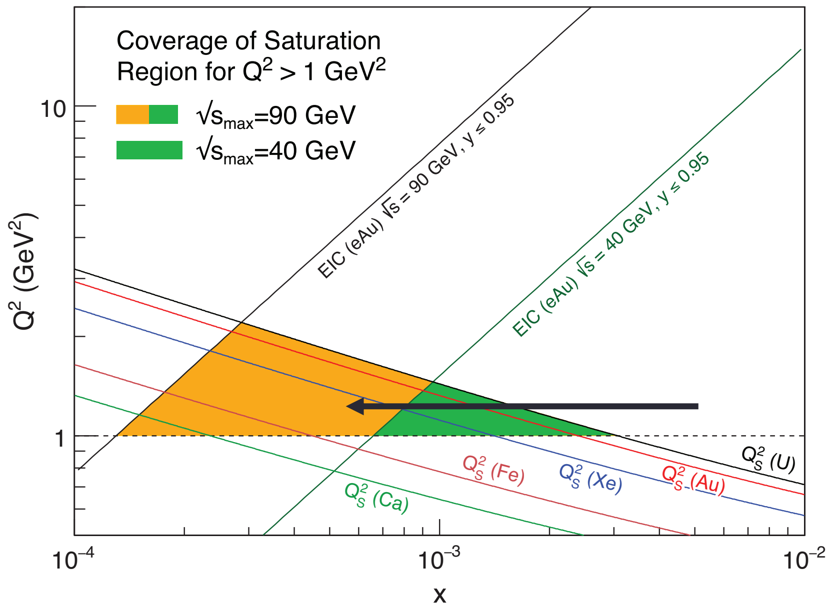
Can EIC discover a new state of matter?

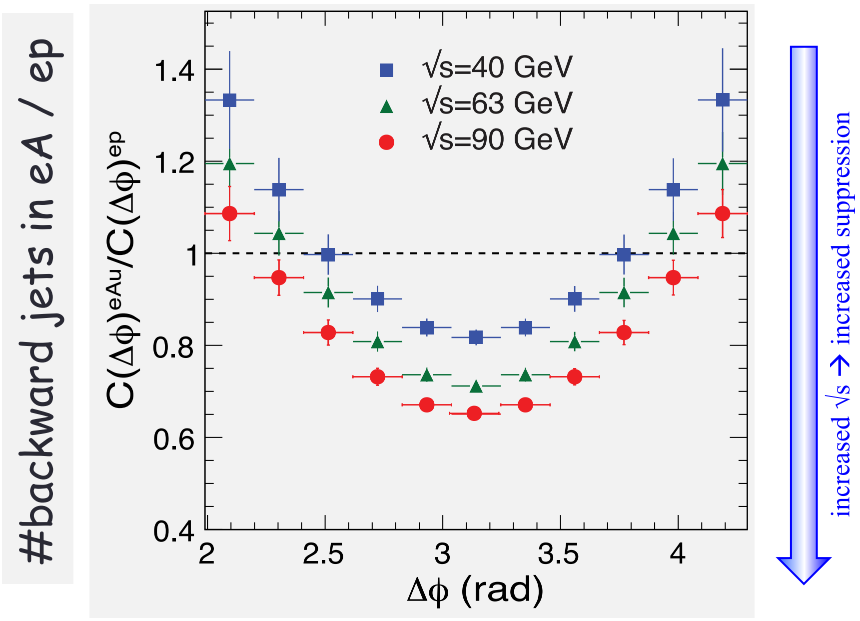
EIC provides an absolutely unique opportunity
to have very high gluon densities
→ electron – lead collisions
combined with an unambiguous observable

EIC will allow to unambiguously
map the transition from a non-saturated to
saturated regime

counting experiment of
Di-jets in ep and eA
Saturation:
Disappearance of backward jet in eA





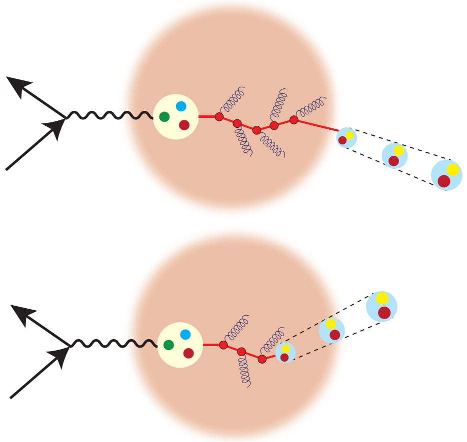


Emergence of Hadrons from Partons

Nucleus as a Femtometer sized filter

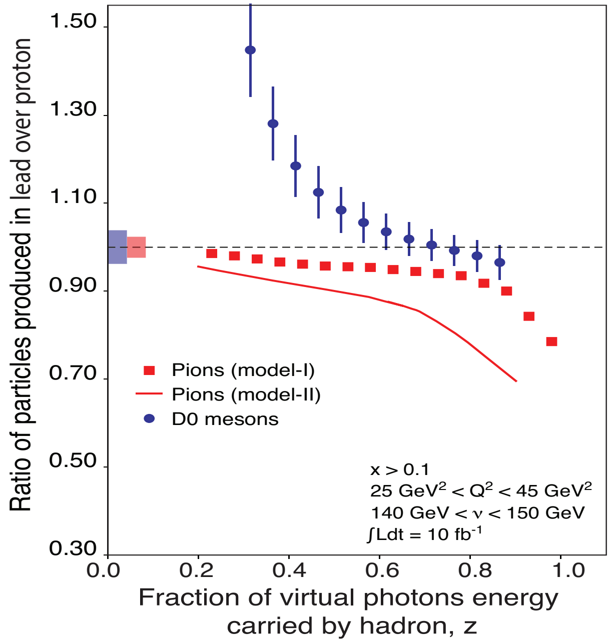
Unprecedented ν, the virtual photon energy range @ EIC : *precision & control*

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



Study in light quarks
vs.
heavy quarks

Energy loss by light vs. heavy quarks:



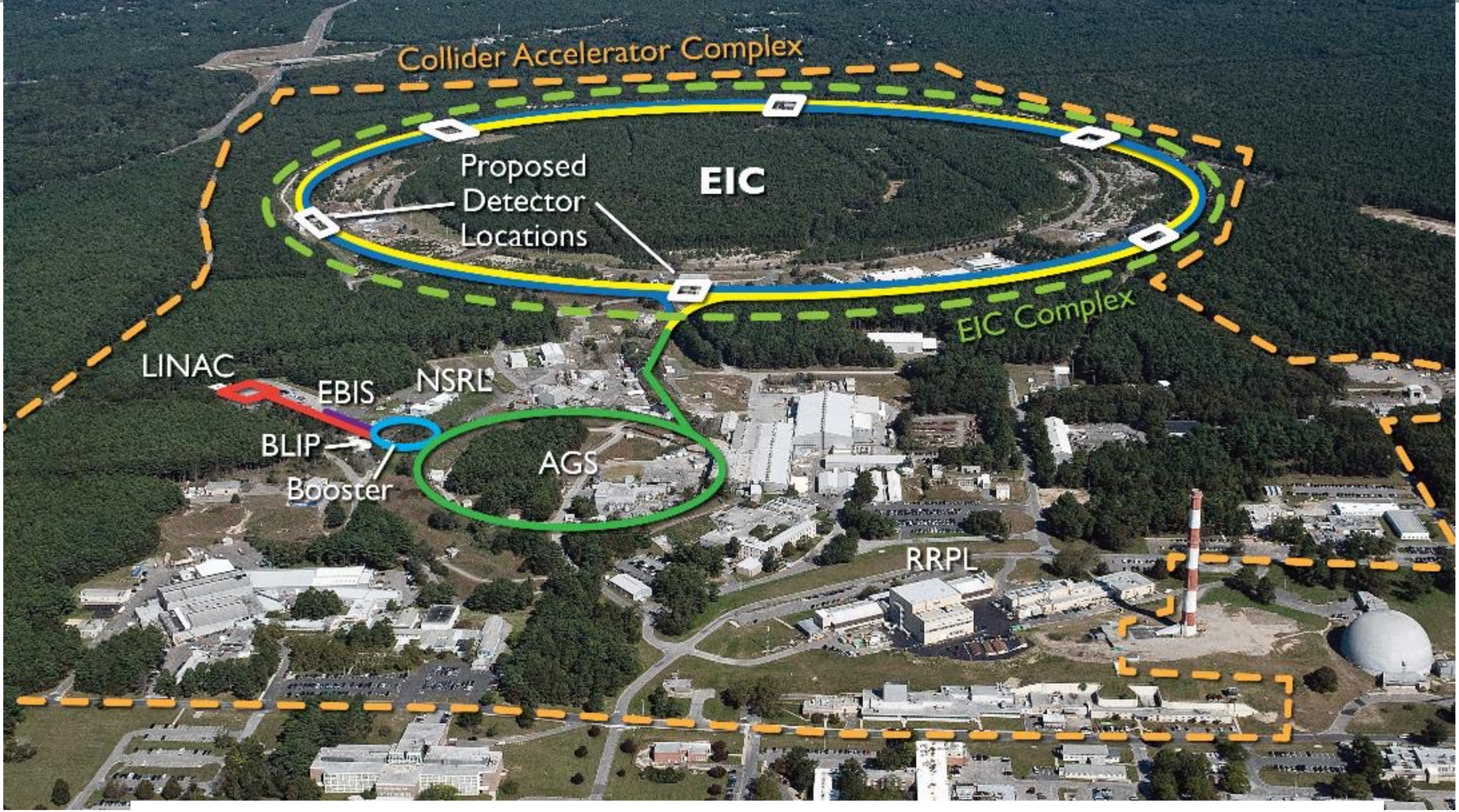
Control of ν by selecting kinematics;
Also under control the nuclear size.

Identify π vs. D^0 **(charm)** mesons in e-A collisions:

(colored) Quark passing through cold QCD matter emerges as color-neutral hadron ➔
Clues to color-confinement?

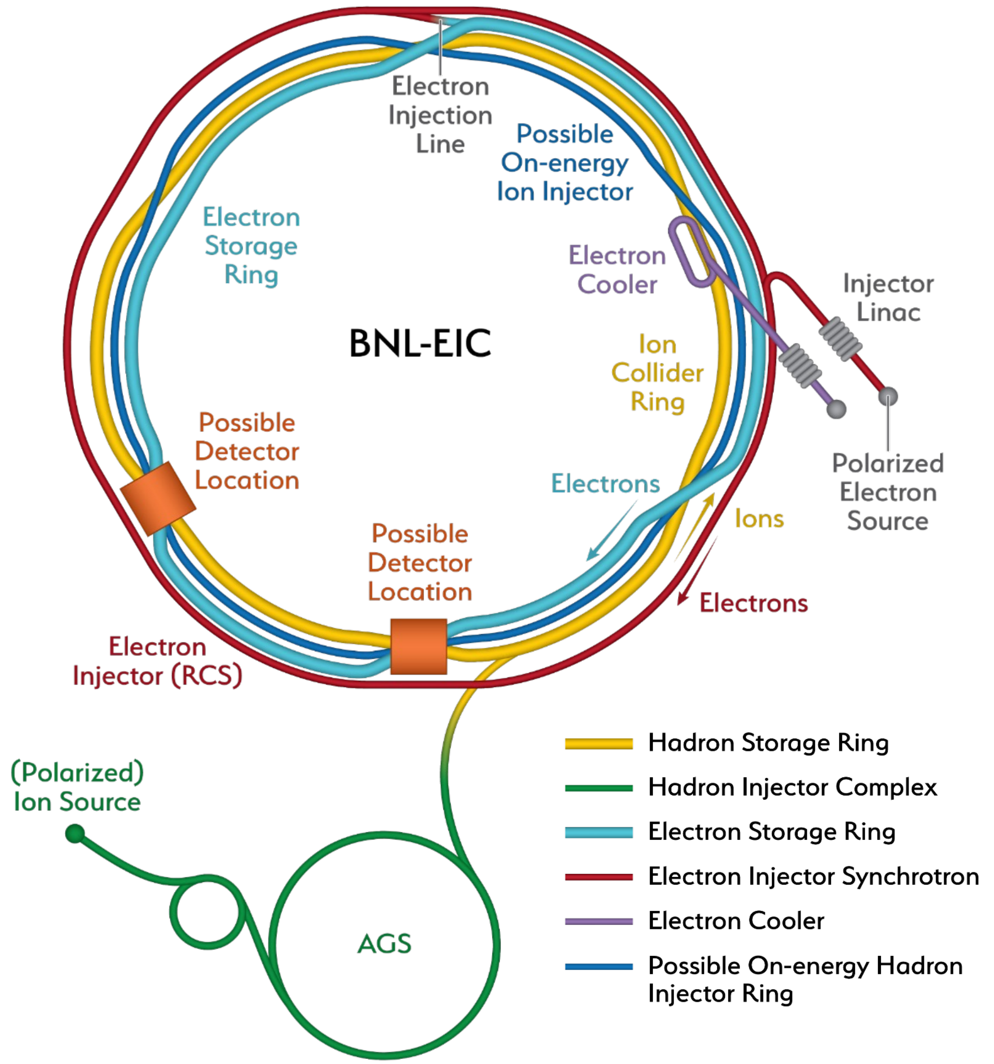
Understand energy loss of light vs. heavy quarks traversing the cold nuclear matter:
Connect to energy loss in Hot QCD

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

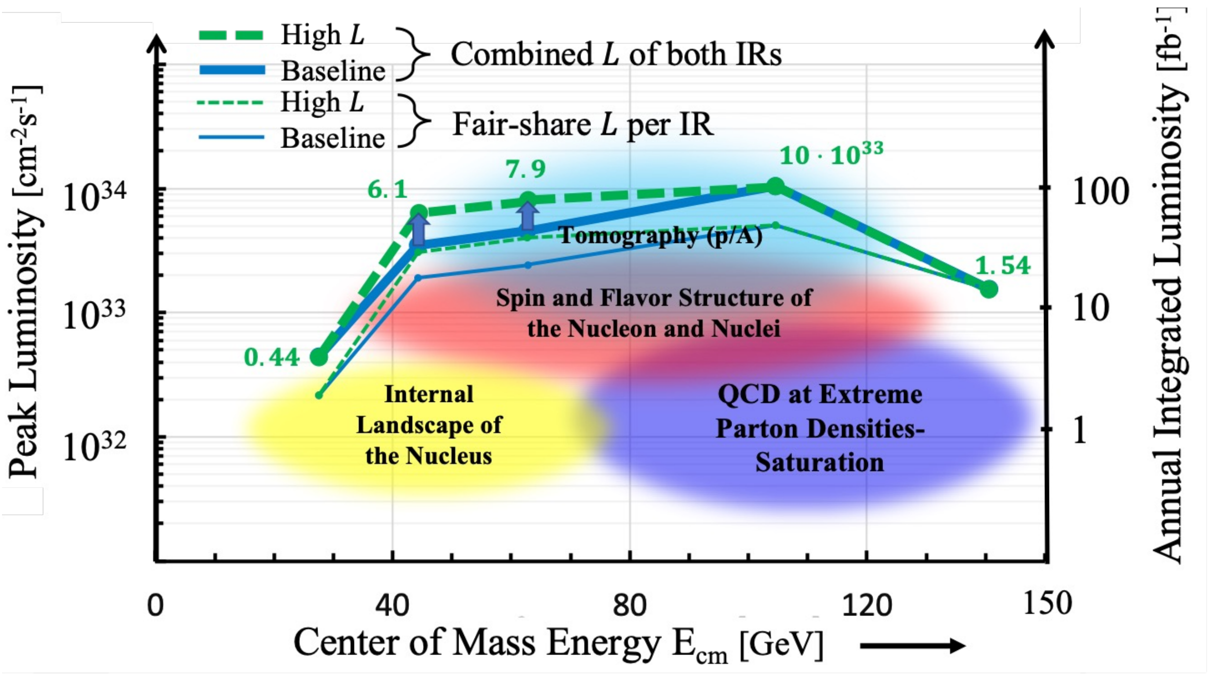


- EIC benefits from $B class investments at BNL and the highly successful RHIC program.

EIC Accelerator Design



Center of Mass Energies:	20GeV - 140GeV
Luminosity:	10^{33} - 10^{34} $cm^{-2}s^{-1}$ / 10-100fb^{-1} / year
Highly Polarized Beams:	70%
Large Ion Species Range:	p to U
Number of Interaction Regions:	Up to 2!



Physics @ the US EIC beyond the EIC's core science

Of HEP/LHC-HI interest to Snowmass 2021 (EF 05, 06, and 07 and possibly also EF 04)

Perhaps other intersections with LQCD?

New Studies with proton or neutron target:

- Impact of precision measurements of unpolarized PDFs at high x/Q^2, on LHC-Upgrade results(?)
- What role would TMDs in e-p play in W-Production at LHC? Gluon TMDs at low-x!
- Heavy quark and quarkonia (c, b quarks) studies with 100-1000 times lumi of HERA
- Does polarization of play a role (in all or many of these?)

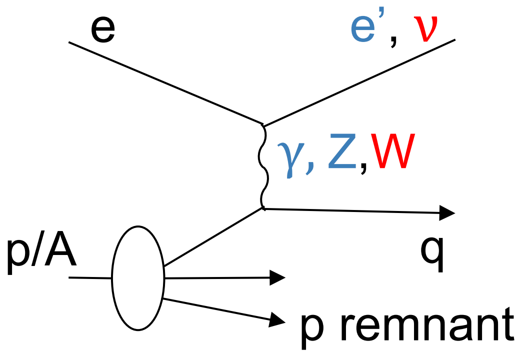
Physics with nucleons and nuclear targets:

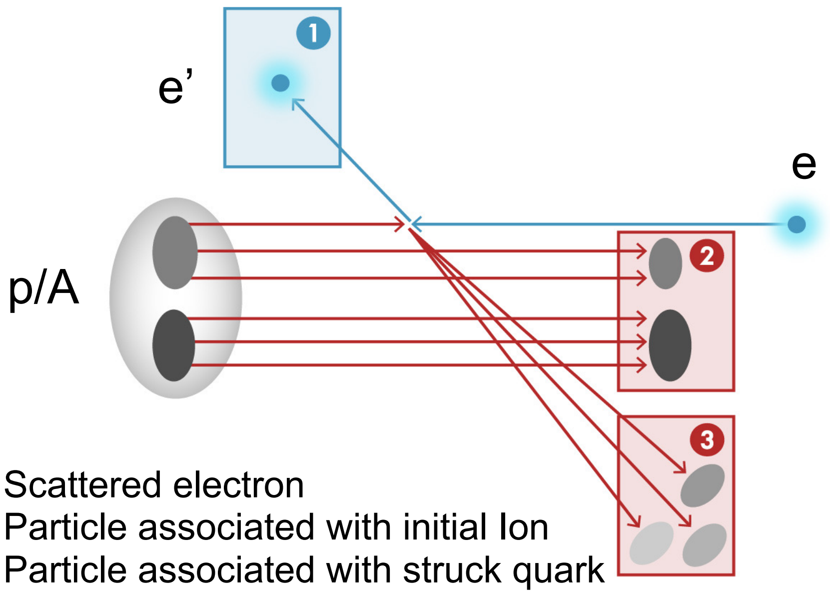
- Quark Exotica: 4,5,6 quark systems…? Much interest after recent LHCb led results.
- Physic of and with jets with EIC as a precision QCD machine:
  - Internal structure of jets : novel new observables, energy variability, polarization, beam species
  - Entanglement, entropy, connections to fragmentation, hadronization and confinement
  - Studies with jets: Jet propagation in nuclei… energy loss in cold QCD medium
- Connection to p-A, d-A, A-A at RHIC and LHC
- Polarized light nuclei in the EIC

Precision electroweak and BSM physics:

- Electroweak physics & searches beyond the SM: Parity, charge symmetry, lepton flavor violation

Detector Challenge of the EIC





1. Scattered electron
2. Particle associated with initial Ion
3. Particle associated with struck quark (or associated gluon)

Aim of EIC is 3D nucleon and nuclear structure beyond the longitudinal description.

This makes the requirements for the machine and detector different from all previous colliders.

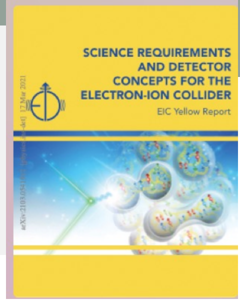
"Statistics"=Luminosity × Acceptance

EIC Physics demands ~100% acceptance for all final state particles (including particles associated with initial ion)

Ion remnant is particularly challenging

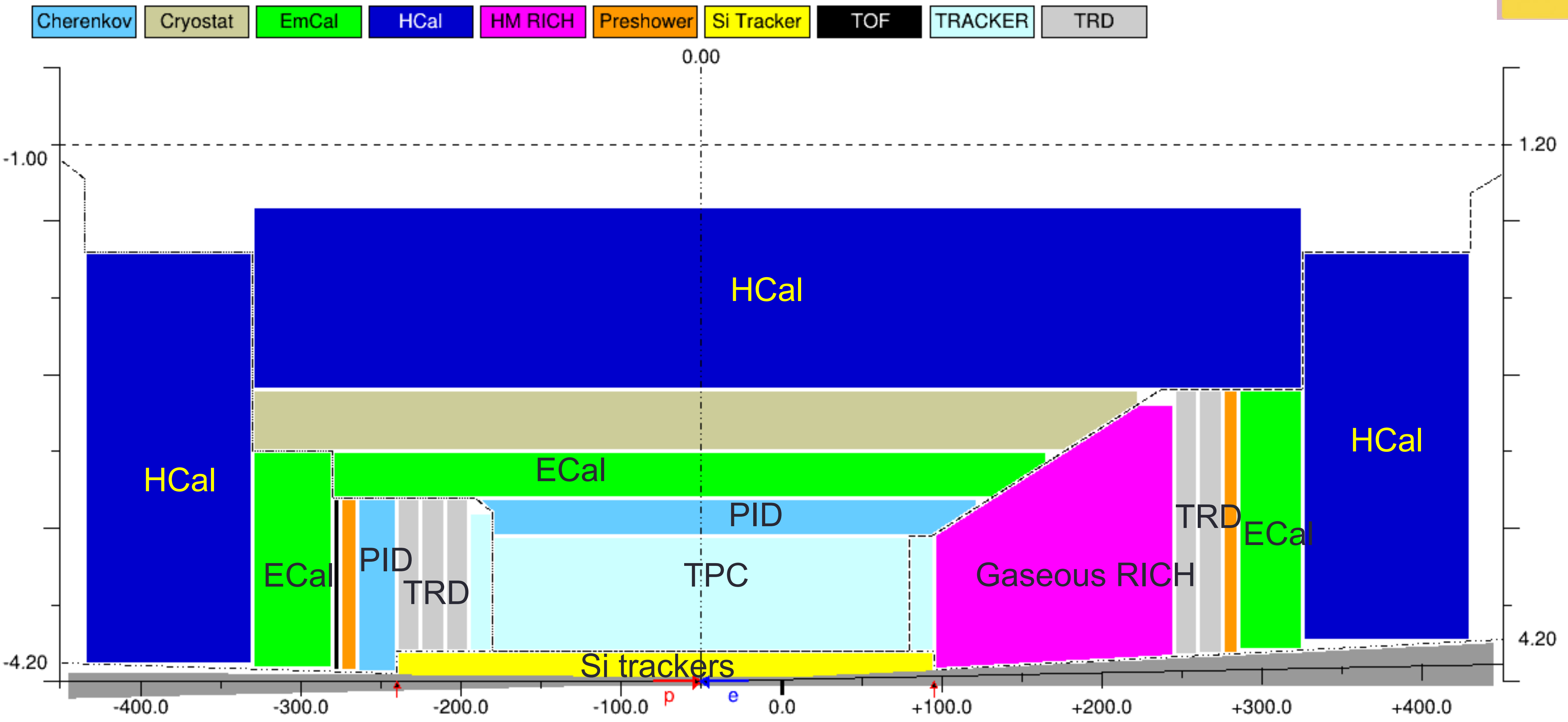
- not a usual concern at colliders
- at EIC integrated from the start with a highly integrated (and complex) detector and interaction region scheme.

Aschenauer/Ent



Concept DETECTOR

This detector concept was included in the EIC CDR prepared for the CD1 Review



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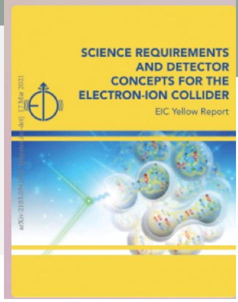
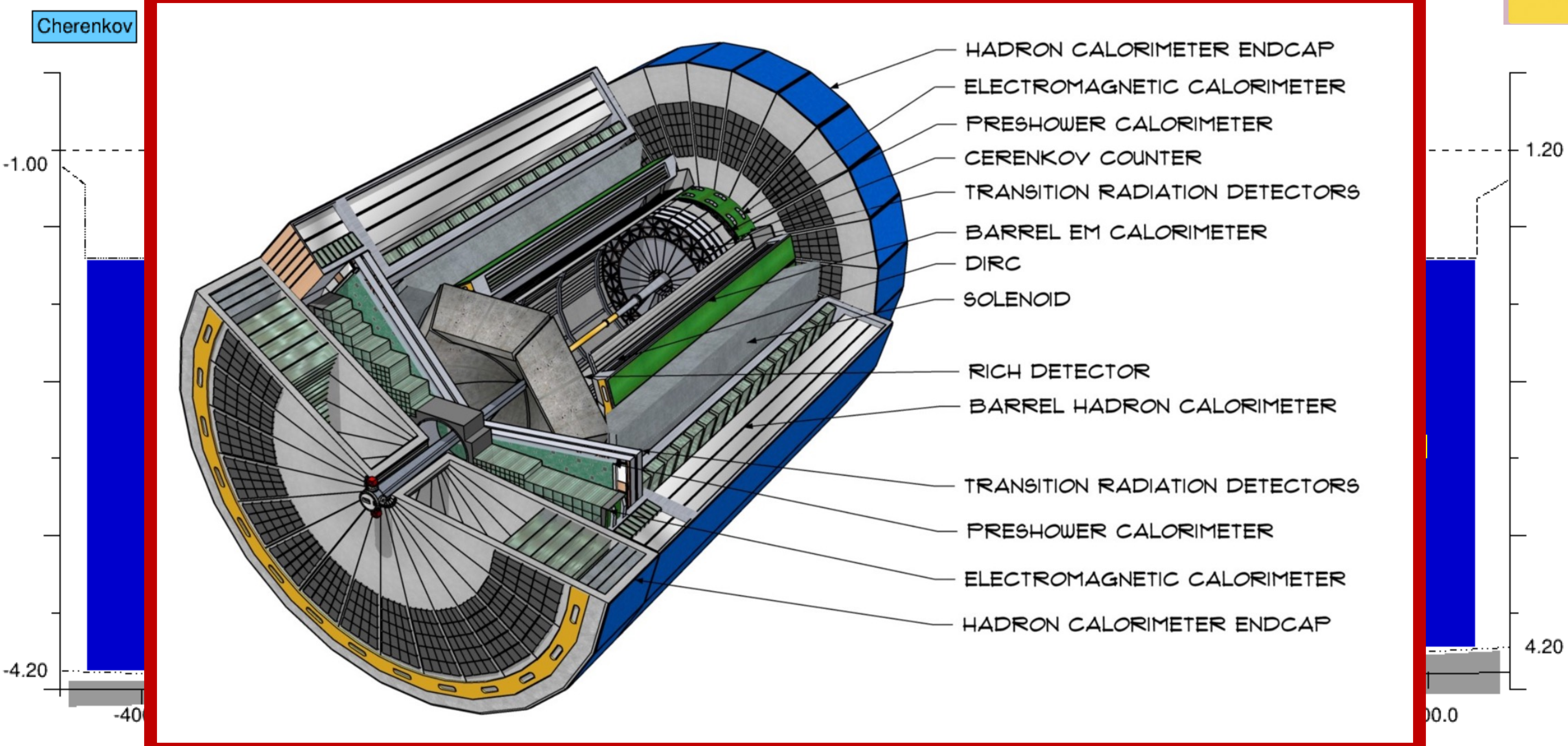
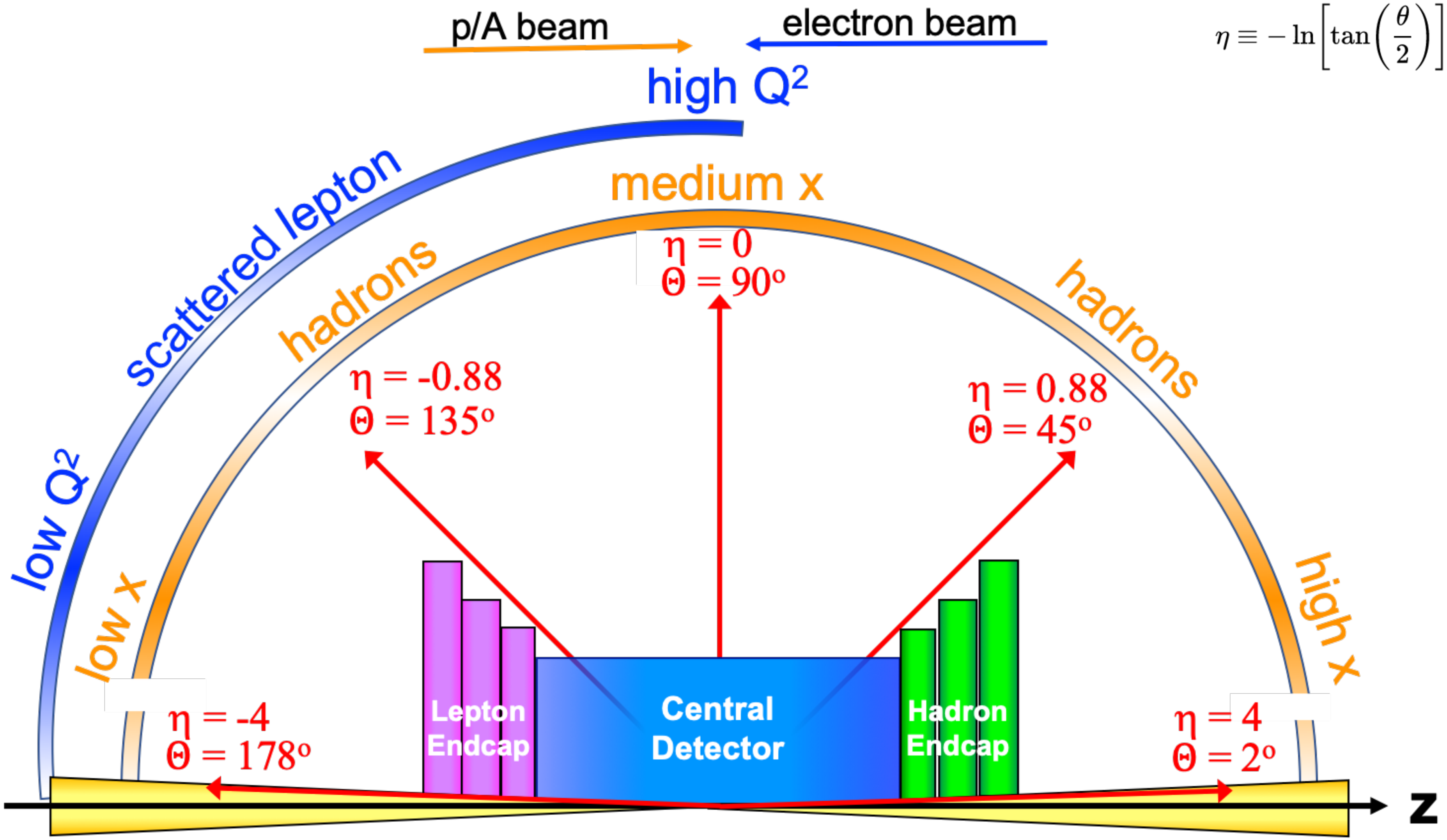


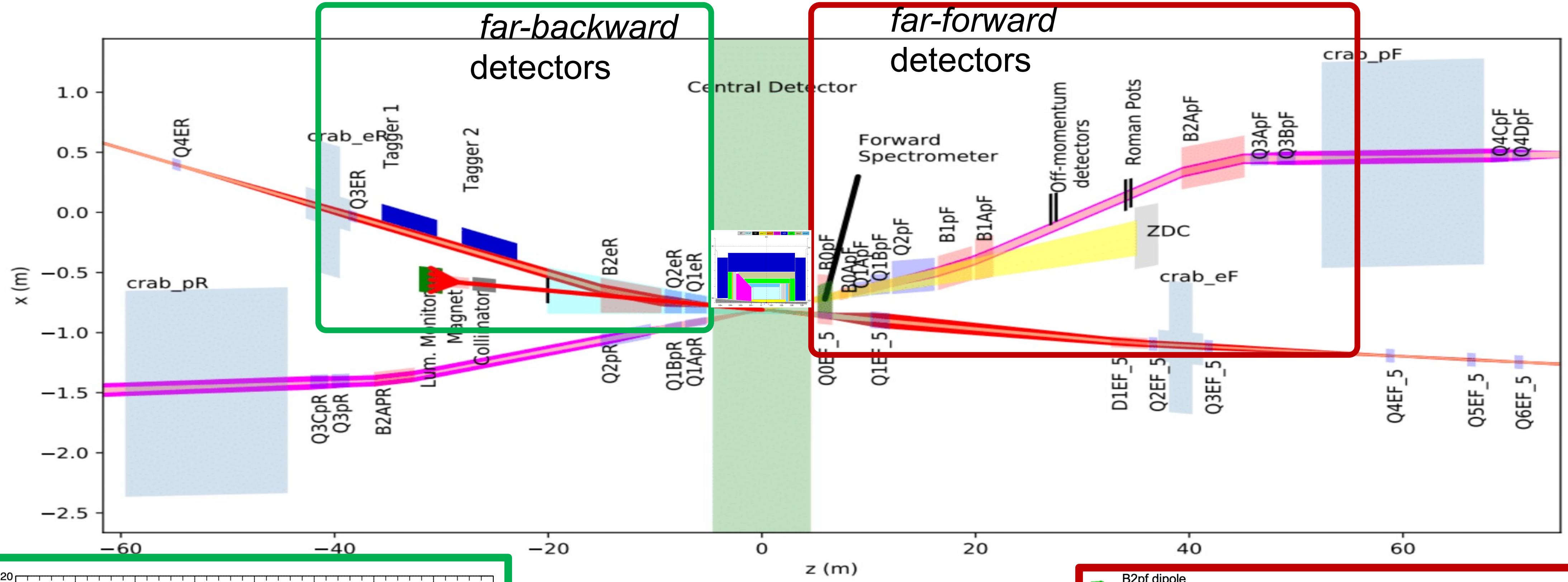


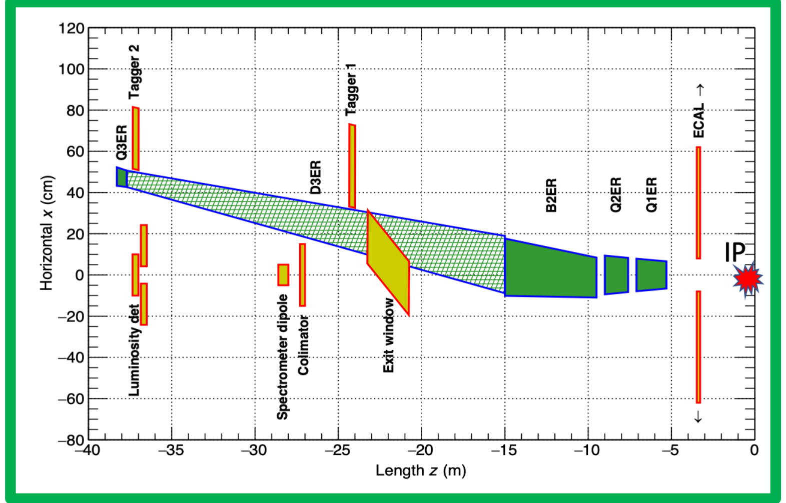
Detector polar angle / pseudo-rapidity coverage

$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$

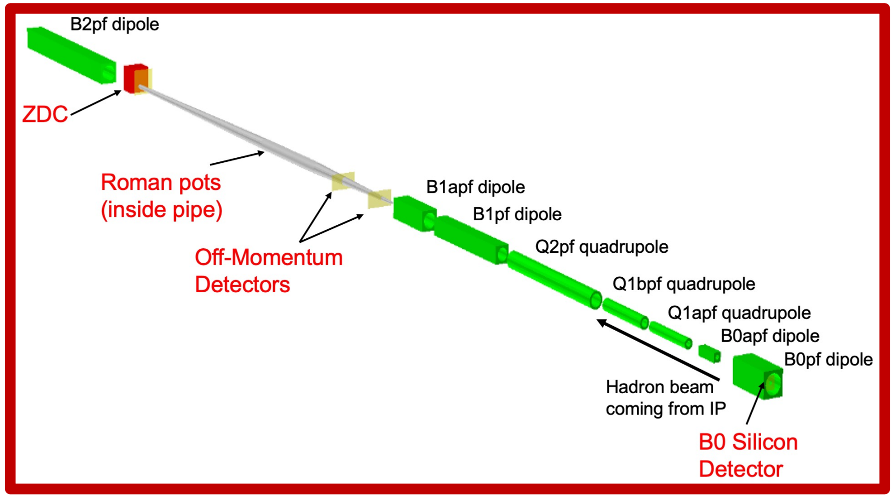


Reference Detector – Backward/Forward Detectors

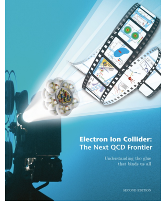




Extensive integration of forward and backward detector elements into the accelerator lattice

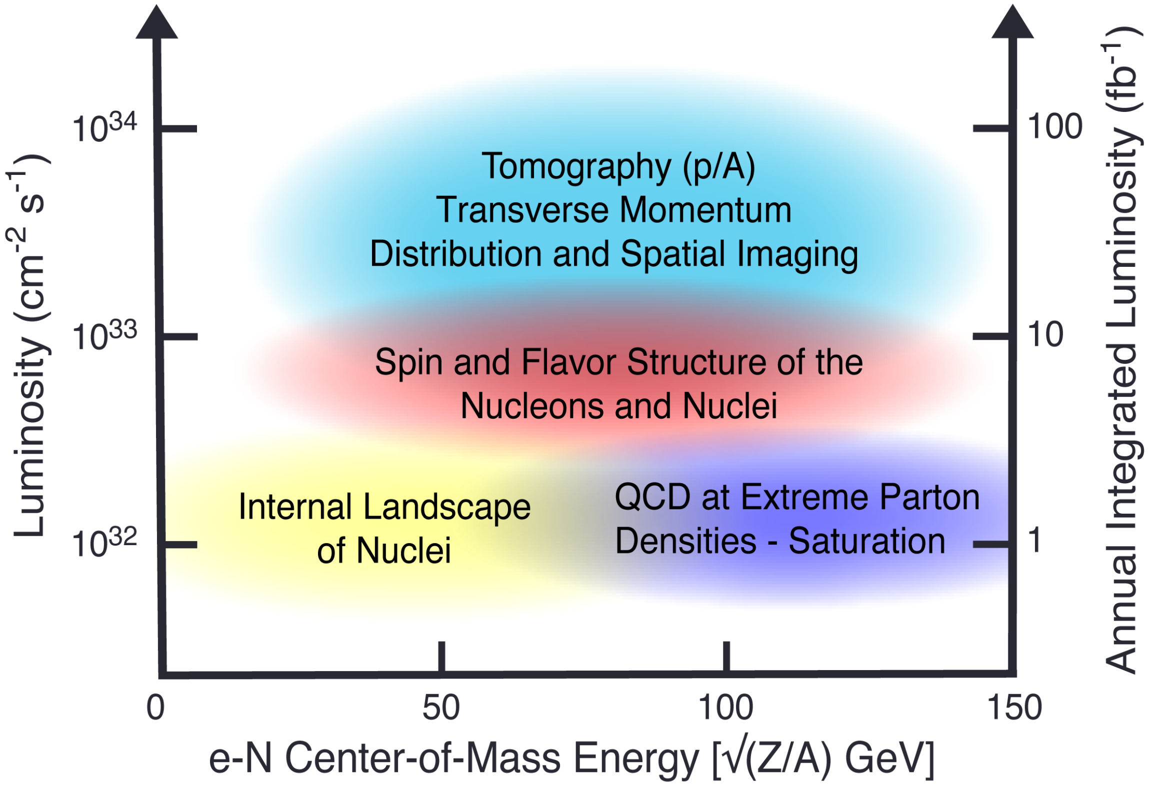


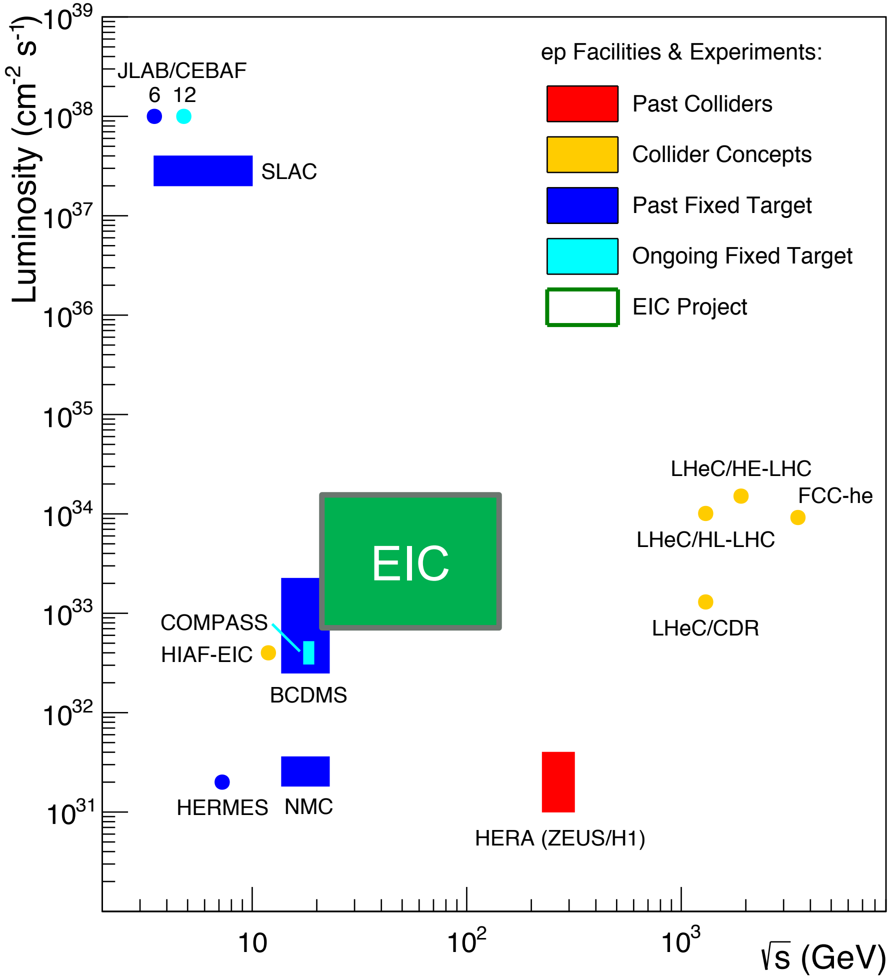

"New directions in science are launched by new tools much more often than by new concepts."
Freeman Dyson



EIC Physics and the machine parameters

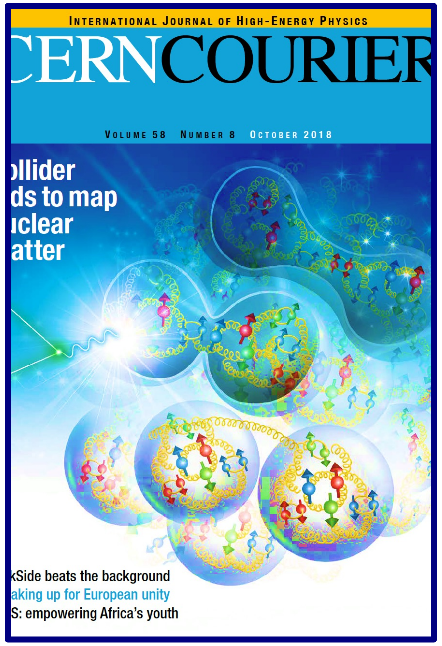
CM vs. Luminosity vs. Integrated luminosity





The US EIC with a wide range in $\sqrt{s}$, polarized electron, proton and light nuclear beams and luminosity makes it a unique machine in the world.

R. Ent, T. Ullrich, R. Venugopalan
Scientific American (2015)
Translated into multiple languages



E. Aschenauer
R. Ent
October 2018

A. Deshpande
& R. Yoshida
June 2019
Translated in to multiple languages