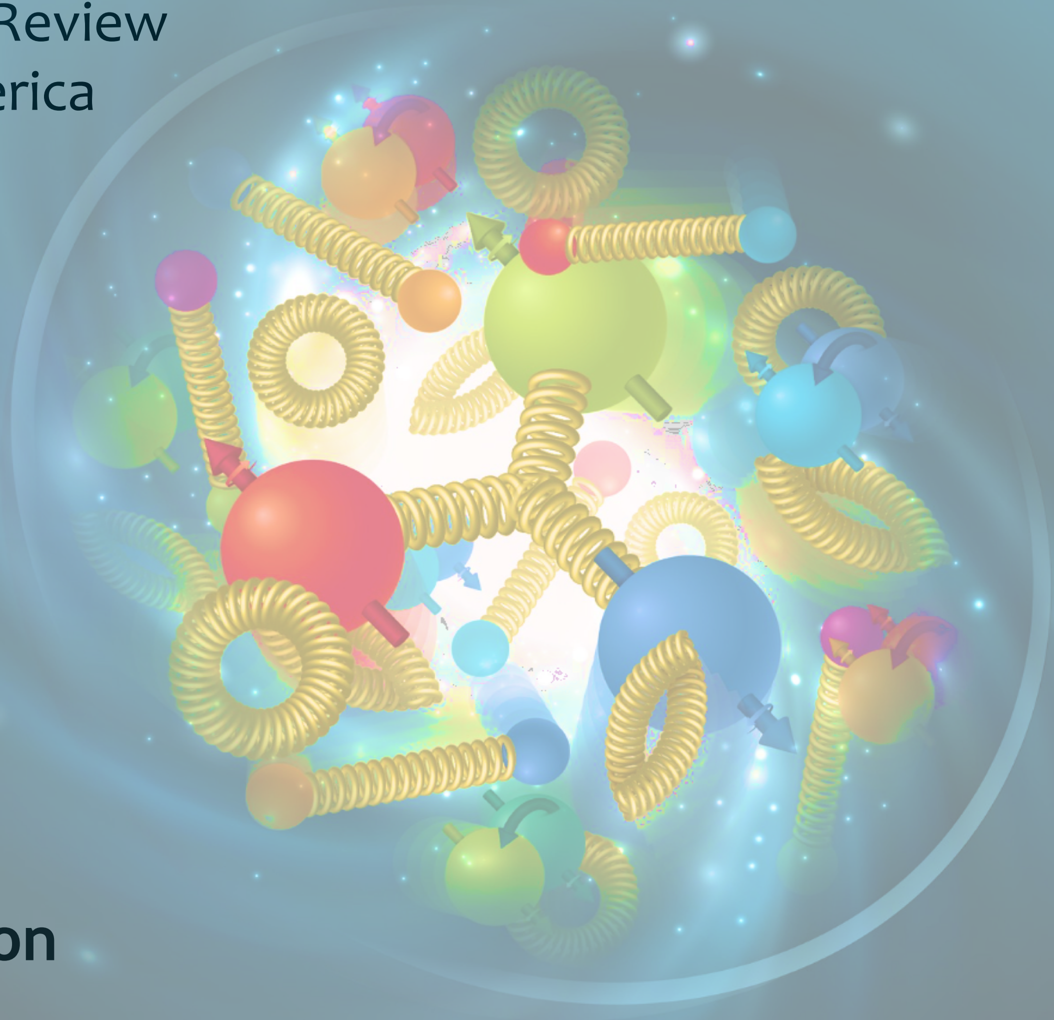
The EIC and the ePIC Detector: *Getting to the heart of matter*

ePIC Computing & Software Review
Catholic University of America
26-27 September 2024

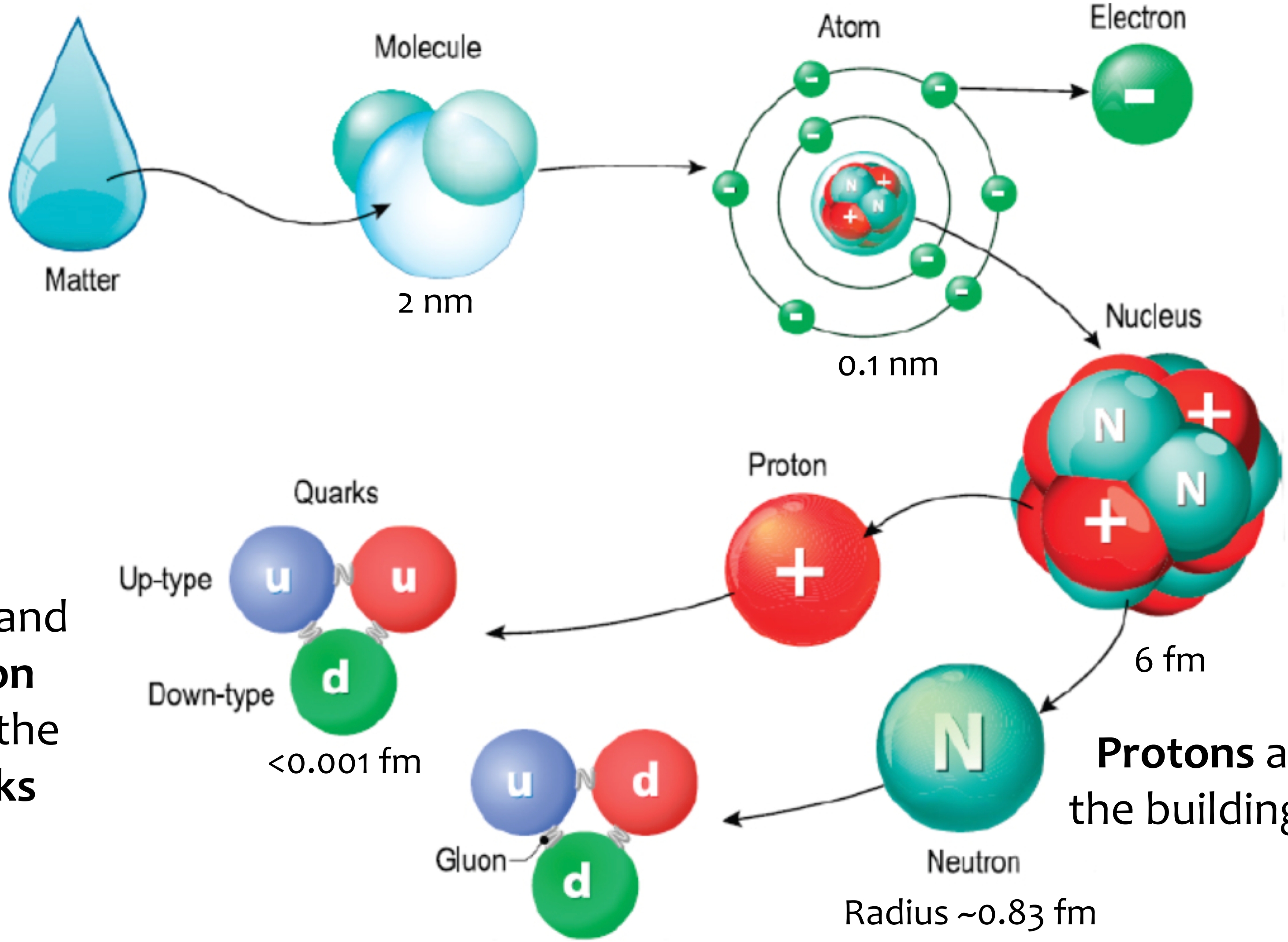


Holly Szumila-Vance
(Florida International University)
On behalf of the Collaboration

Brookhaven National Laboratory
Jefferson Lab

How does visible matter emerge from its elementary constituents?

Nucleons provide ~99% of the mass of the visible universe!



How does the structure and properties of the **proton** and **neutron** arise from the dynamics of their **quarks** and **gluons**?

Protons and **neutrons** are the building blocks of nuclei.

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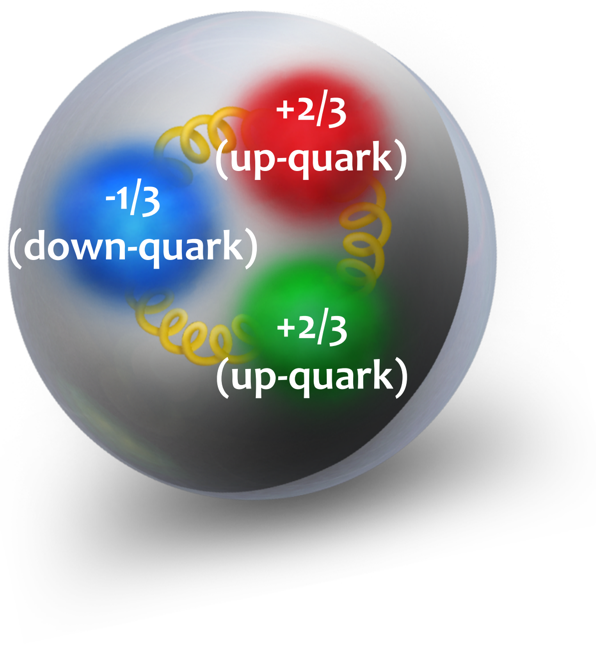
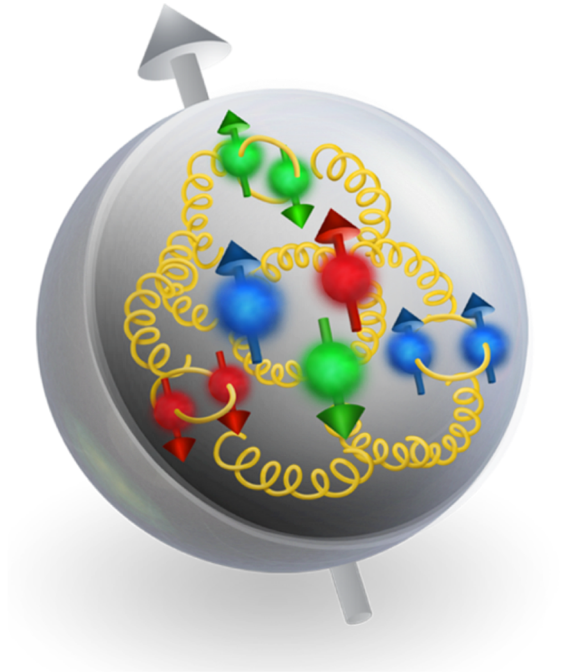
The proton: QCD at work!

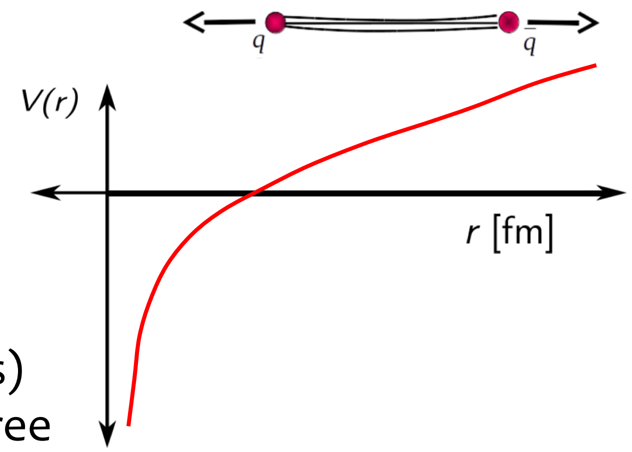


$$|p\rangle = |uud\rangle + |uudq\bar{q}\rangle + |uudg\rangle + \ldots$$

Properties of nucleons and nuclei emerge from this complex system of interacting quarks and gluons



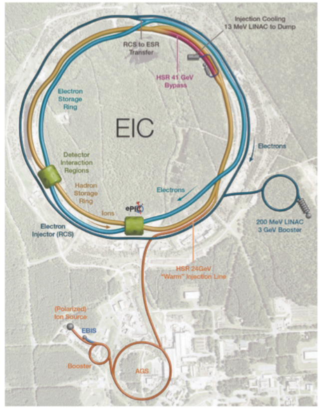
Quantum Chromodynamics (QCD) governs the strong force interaction between quarks and gluons

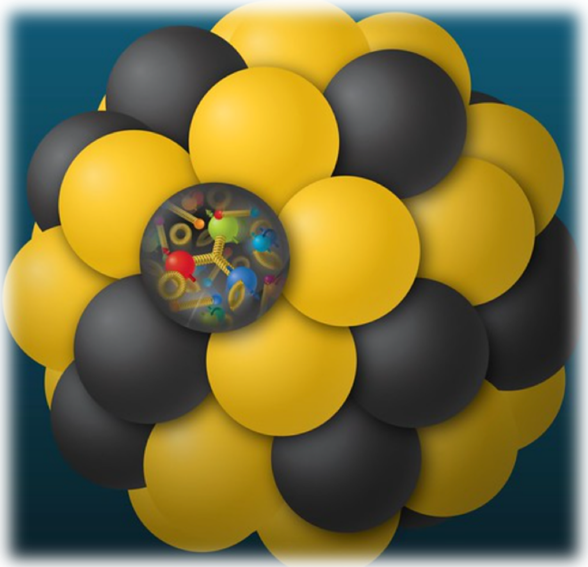


Color force increases at large distances → quarks and gluons can not be found in isolation

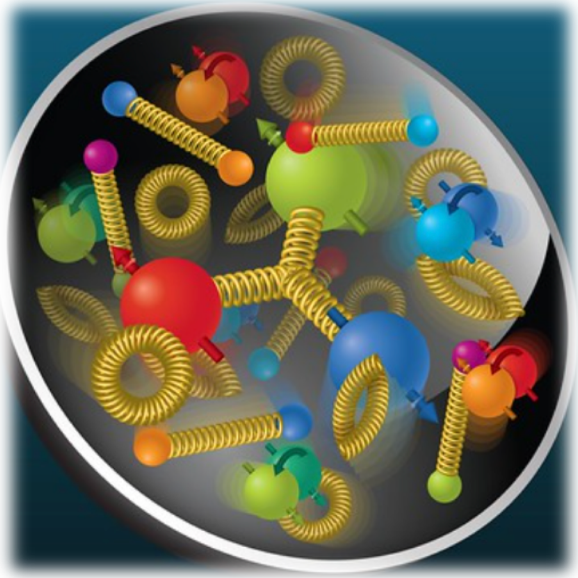
At very small distances (large energies) quarks interact weakly and are nearly free

EIC will explore the nucleon structure and observed properties in terms of the quark & gluon *dynamics!*



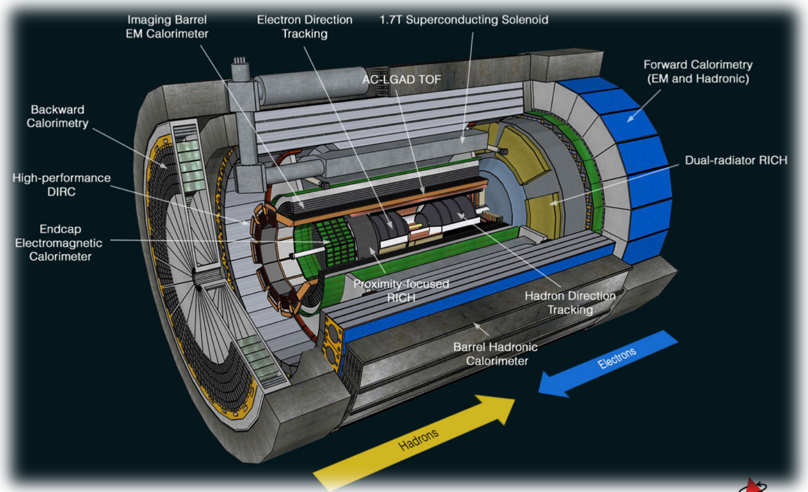


Detailed mapping of the quark & gluon dynamics that account for > 99% of the mass of our visible universe!



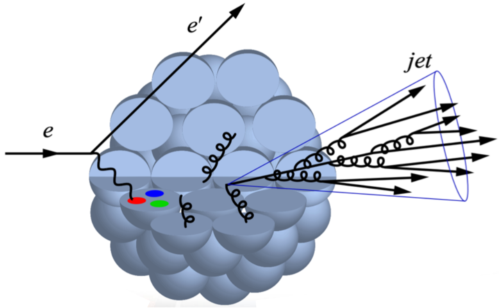
EIC will provide transformational insights into the heart of matter

Development of cutting-edge technologies to build a state-of the art detector and beamline leveraging new readout capabilities!

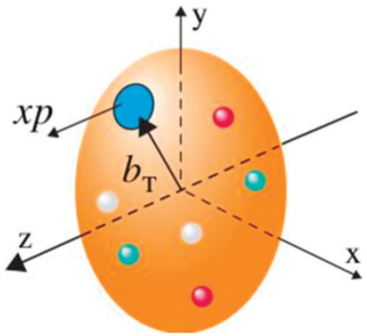


The EIC will explore the heart of matter

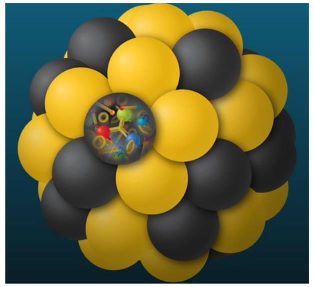
How do the **nucleonic properties** such as **mass** and **spin** emerge from partons and their underlying interactions?



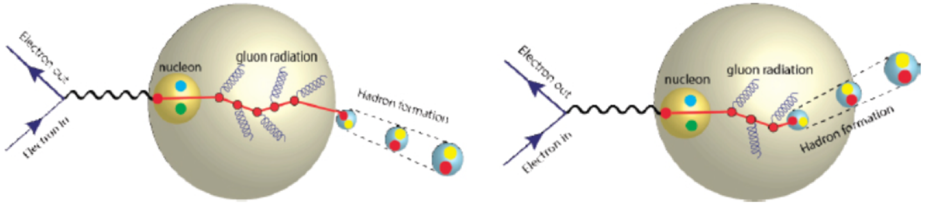
How are **partons** inside the nucleon **distributed** in both **momentum** and **position** space?



How do color-charged quarks and gluons, and 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**?

Yellow Report : 2103.05419

Exploring the internal landscape of nucleons

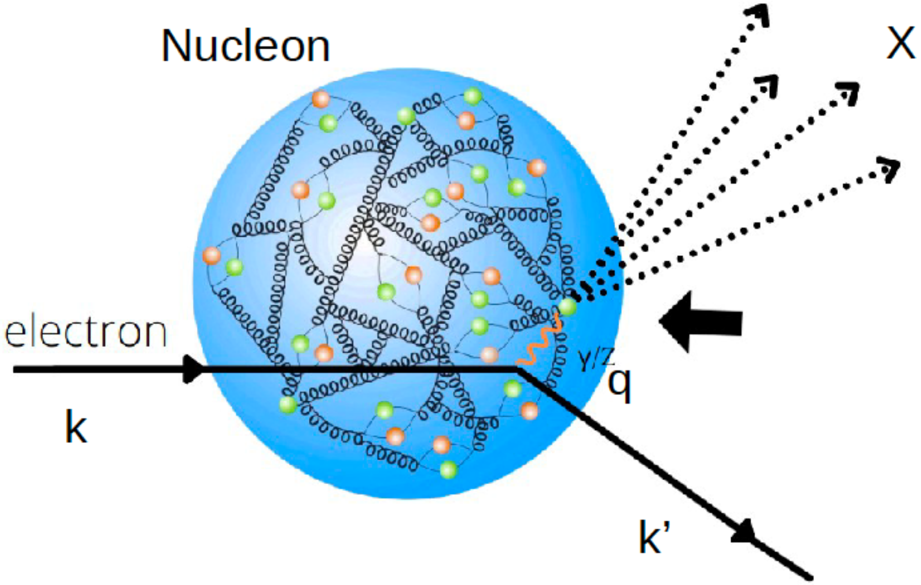
Resolution power, Q^2

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

$s \equiv$ center-of-mass energy, squared

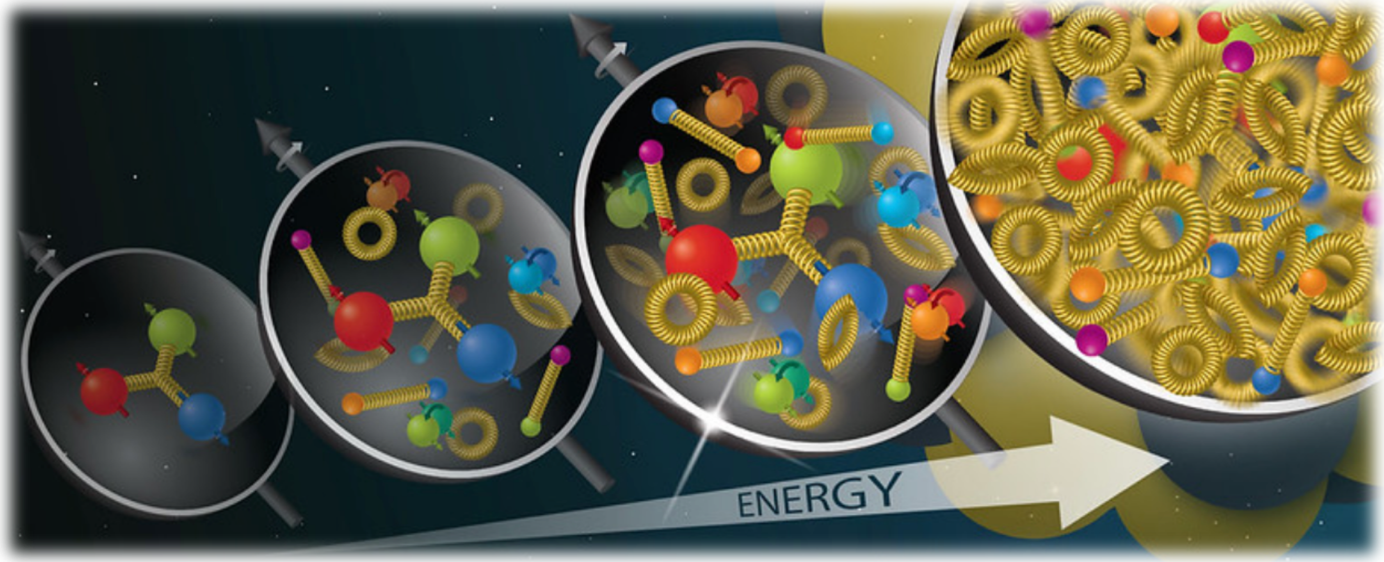
$x \equiv$ fraction of the nucleon's momentum that the struck quark carries

$y \equiv$ inelasticity



Deep inelastic scattering: $e + p \rightarrow e' + X$

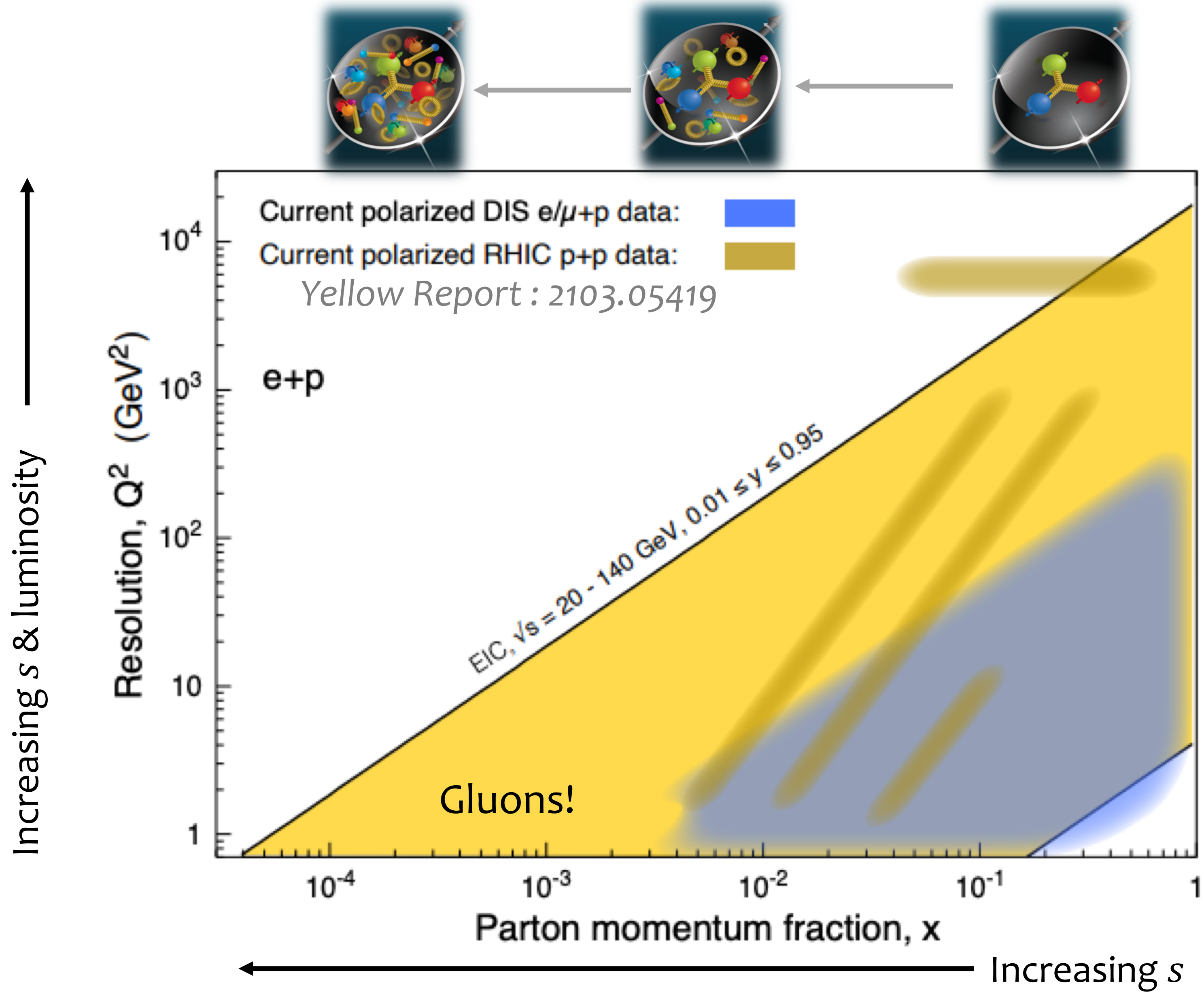
Quark/gluon density, $1/x$



High x

Low x

EIC is uniquely designed to explore gluons & sea quarks!



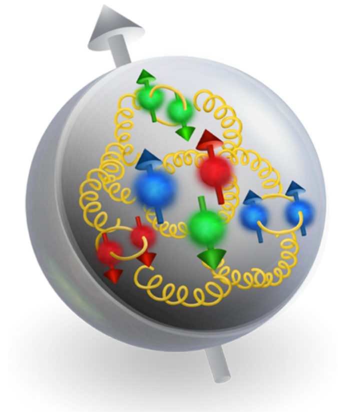
EIC parameter space

- Connect and extend existing measurements
- Heavy nuclei to access high density gluon matter

Spin contributions in nucleons

Overall proton spin ½, how does this arise from its components?

Small fraction of spin is carried by valence quarks

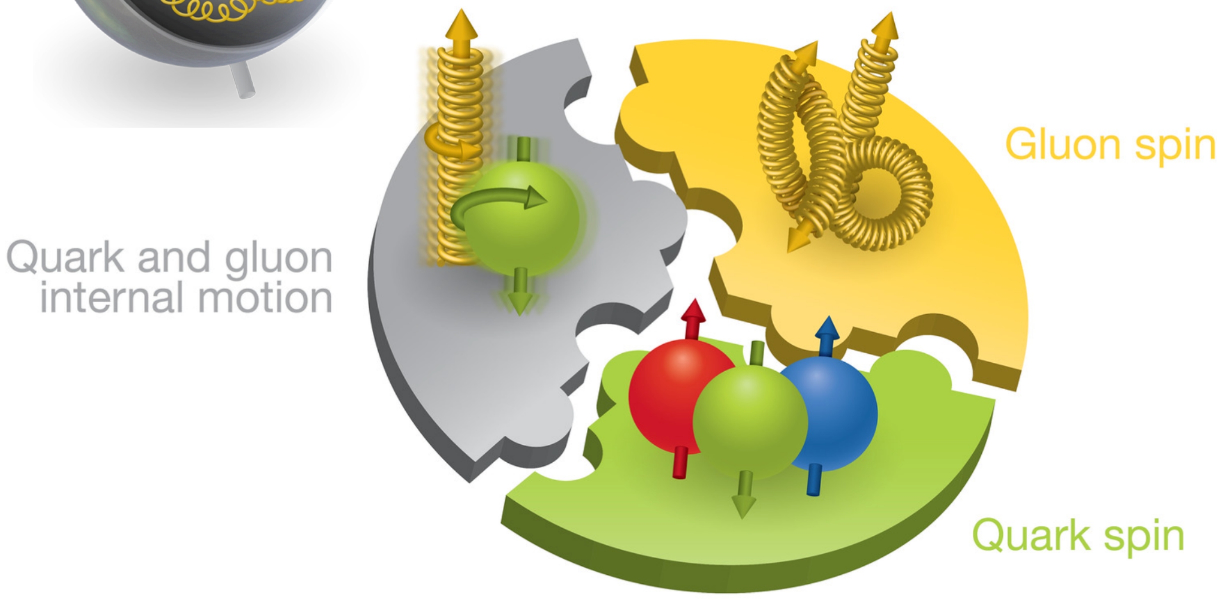


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + \Delta G(\mu) + L_{Q+G}(\mu)$$

Quark spin

Gluon spin

Orbital angular momentum



Quark spins contribute ~30% to the proton spin

EIC can explore:

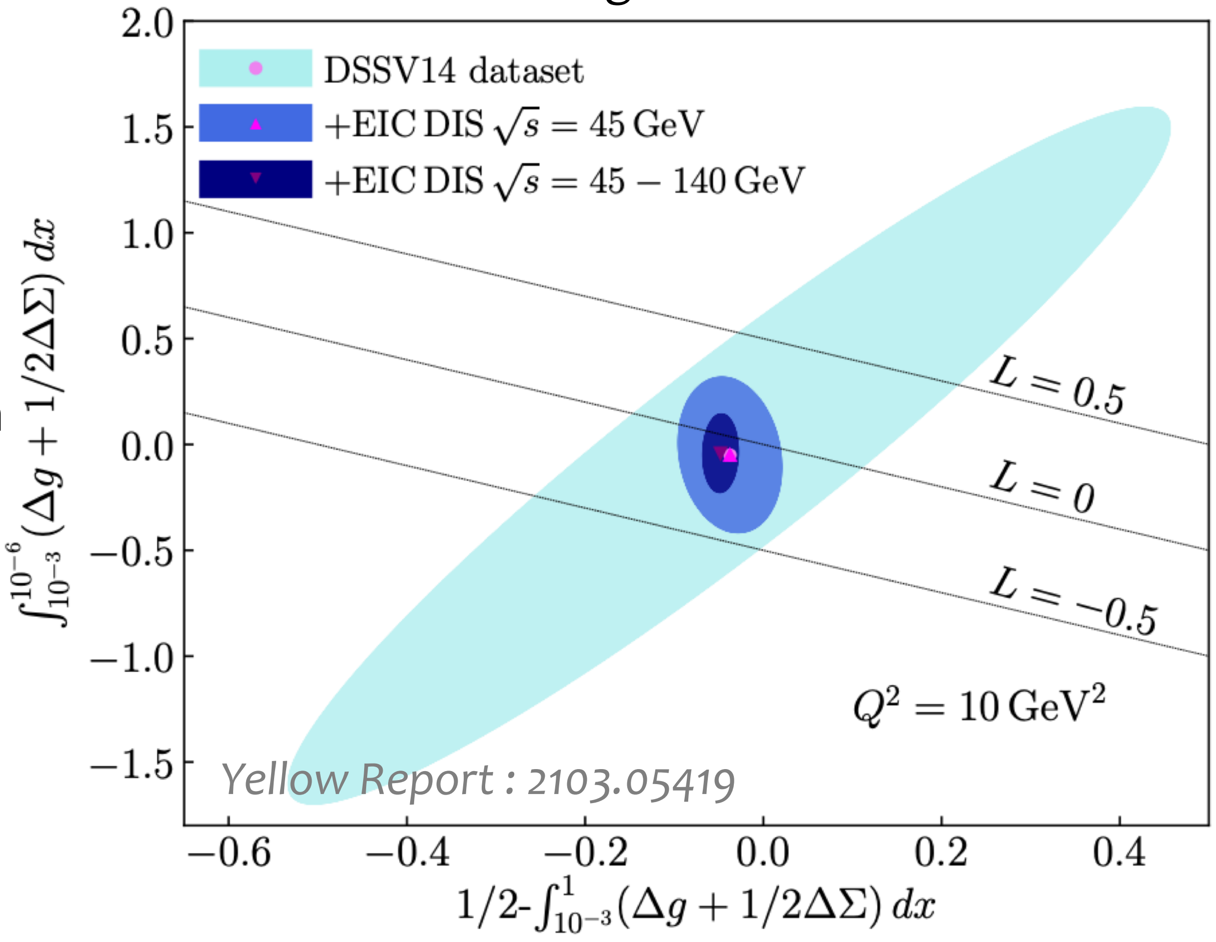
- Gluon spin
- Orbital angular momentum
- Improve existing quark spin measurements

i.e. How do sea quarks contribute?

Spin contributions in nucleons

Orbital angular momentum

Spin contribution from partons with x = (10^{-6} - 10^{-3})



OAM contributions to the proton spin from partons with x > 0.001

Access to **gluon spin** with the measurement of the g_1 structure function through difference of cross-sections with different longitudinal spin orientation of electron and proton

Access to **quark contribution** to orbital angular momentum through exclusive processes

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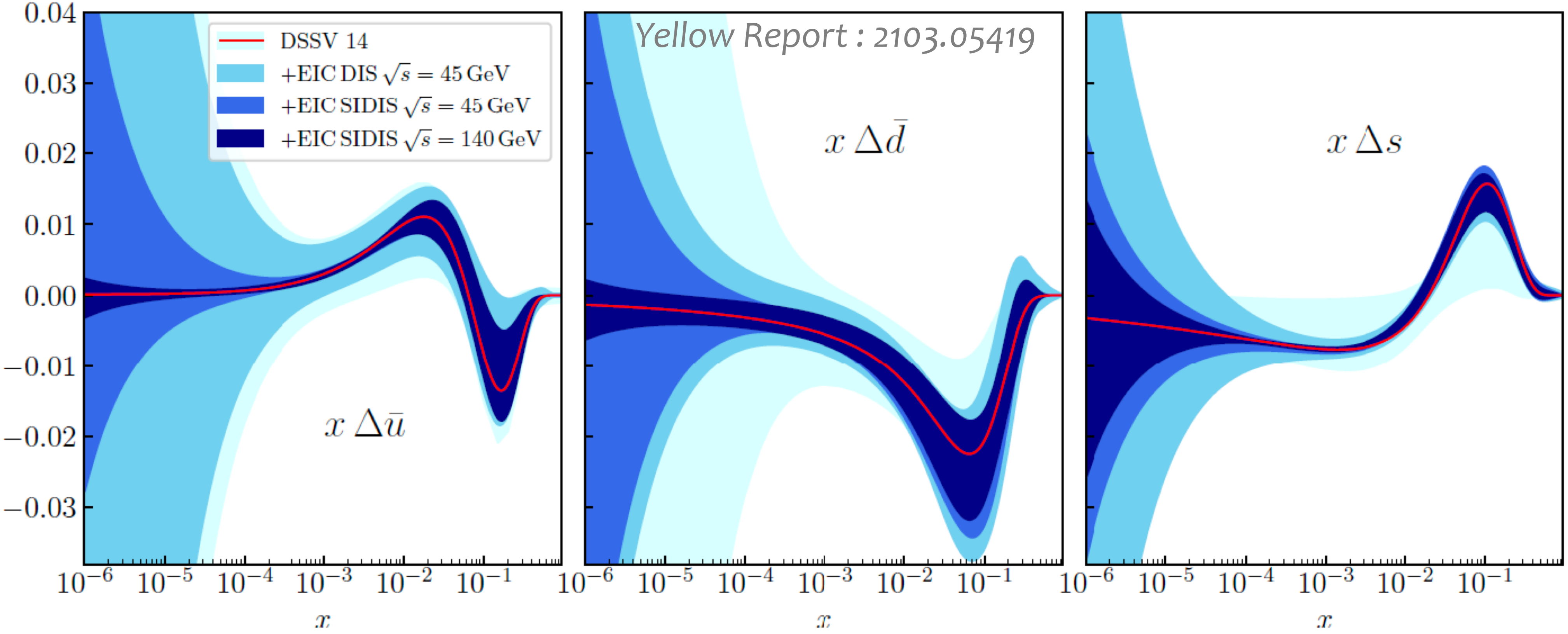
Flavor-separated Helicity distributions of proton sea



Access flavor through Semi-Inclusive Deep Inelastic Scattering measurements of identified charged pions and kaons.

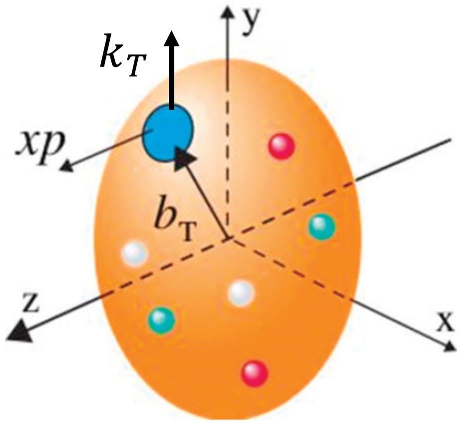
EIC can tell us how sea quark helicities contribute to the spin sum rule

Tomography: Imaging of Quarks & Gluons

Wigner Function

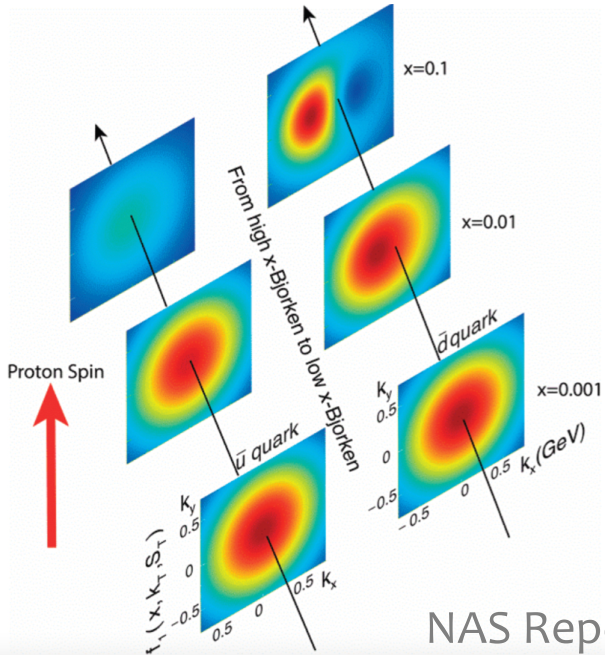
$W(x, b_T, k_T)$

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



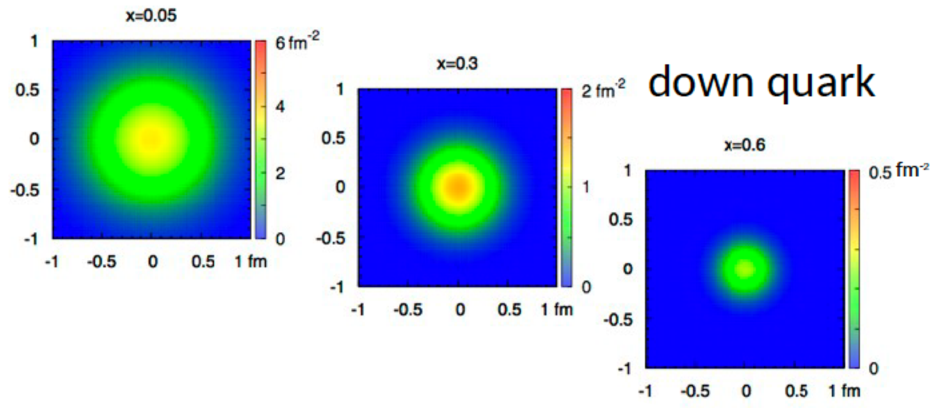
$f(x, k_T)$

Spin-dependent 3D momentum space



$f(x, b_T)$

Spin-dependent 2+1D coordinate space



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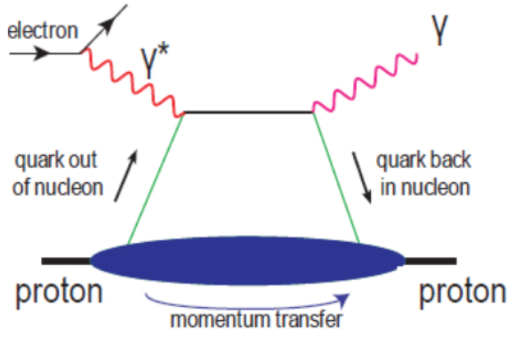
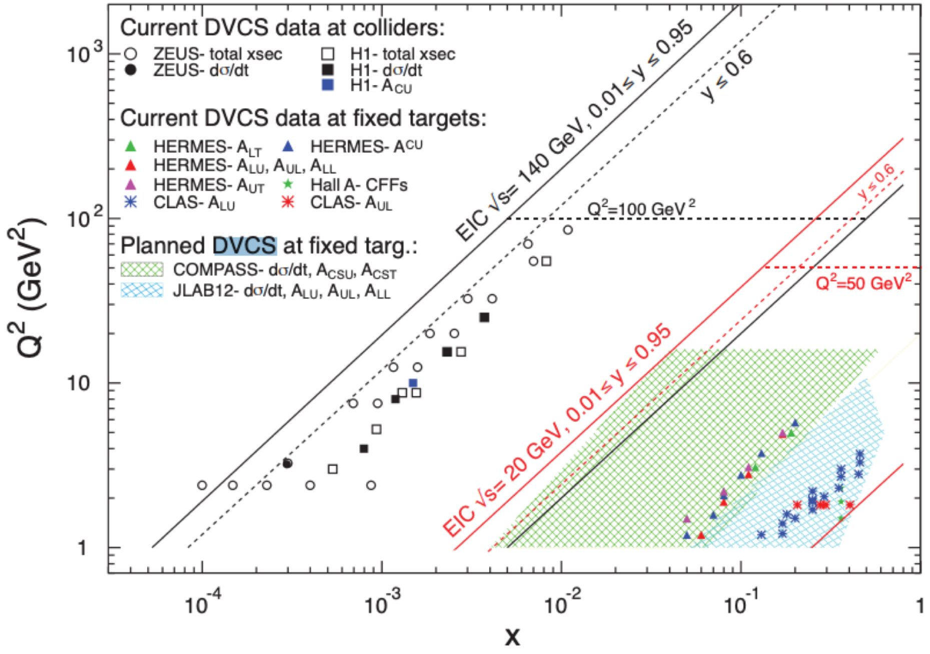
2+1D imaging in coordinate space

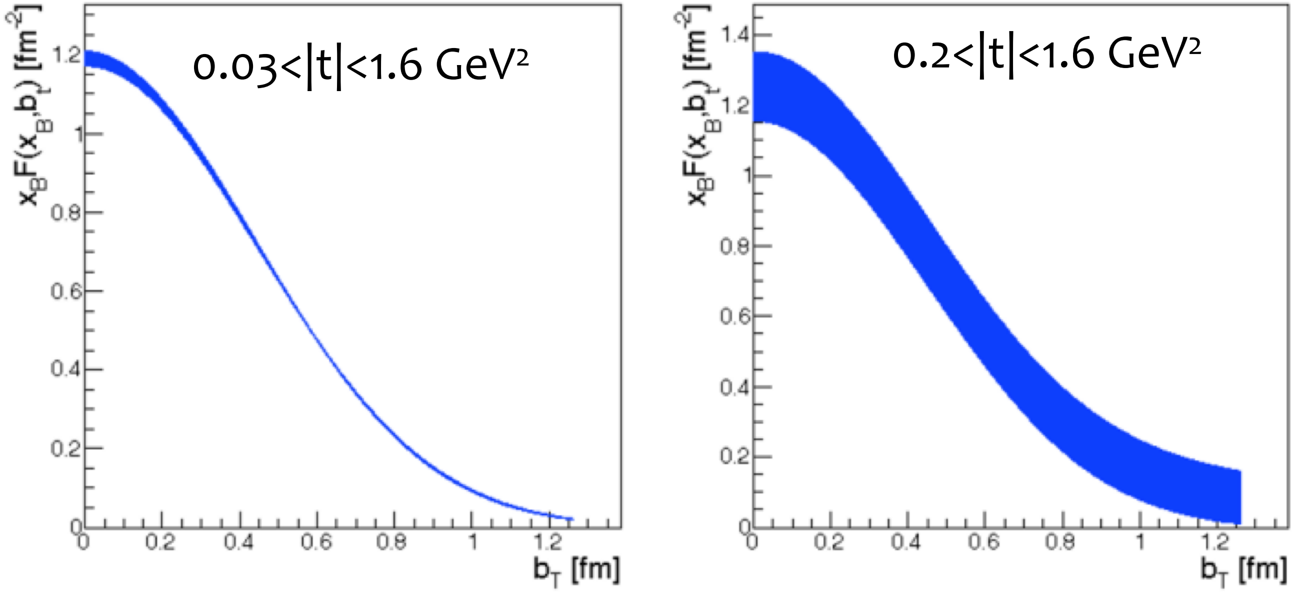
High precision imaging at EIC at low and high x to constrain Generalized Parton Distributions

Deeply Virtual Compton Scattering (DVCS)





Partonic densities,
Fourier Transform of DVCS cross section



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Transverse spin structure of the proton

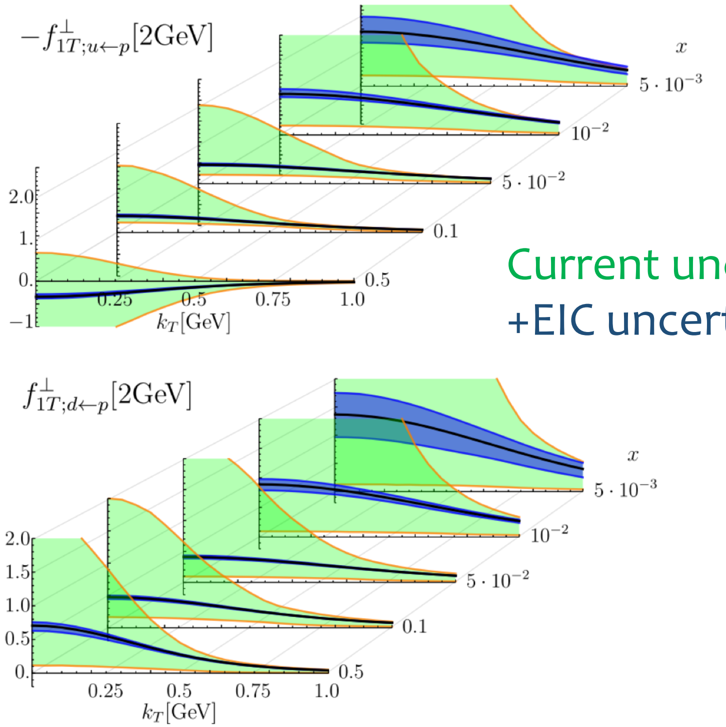
Sivers TMD PDF x unpolarized FF

- How is the parton k_T correlated with proton spin?
- Limited subset of existing data that satisfies factorization conditions.
- Uncertainties reduced by > ×10 for all flavors.
- EIC will obtain a wide range of hadron p_T facilitating k_T mapping

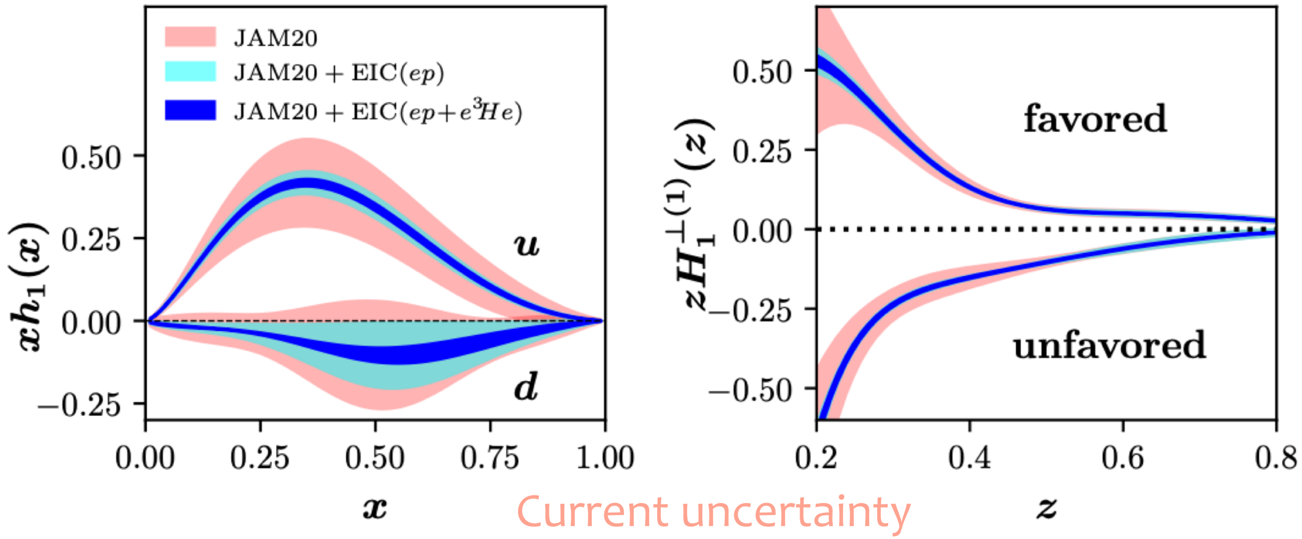
Transversity PDF x Collins TMD FF

- How is the parton spin correlated with the spin of the proton?
- Correlation of fragmenting parton k_T and spin
- Benefits from polarized ^{3}He beams

u and *d* quark Sivers distributions



Current uncertainty
+EIC uncertainty



Current uncertainty
+EIC uncertainty

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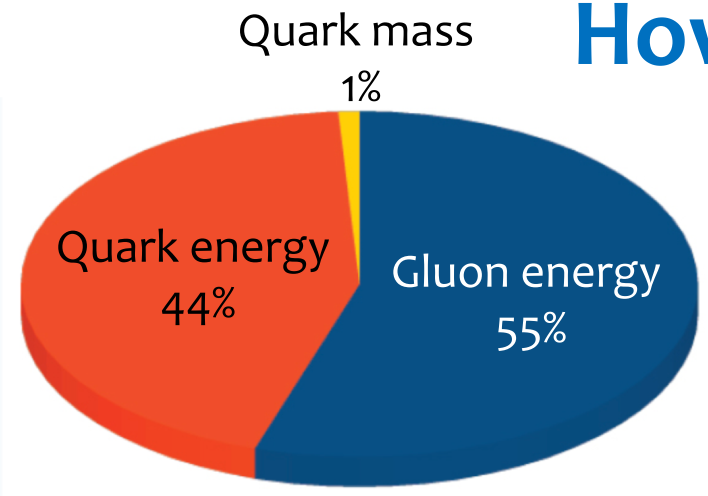
How do nucleons acquire mass?



Mass contributions to the total mass of the nucleon

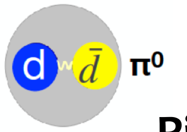
Mass of the proton >
100x the the sum of the 3 constituent quark masses!

Mass emerges from the complex dynamics of the proton structure:

- Gluons are massless
- Quarks have very small masses

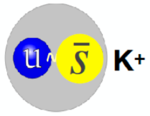
QCD trace anomaly can be determined through exclusive reactions at the EIC!

What about the mass of **light mesons**?



Pions, 140 MeV

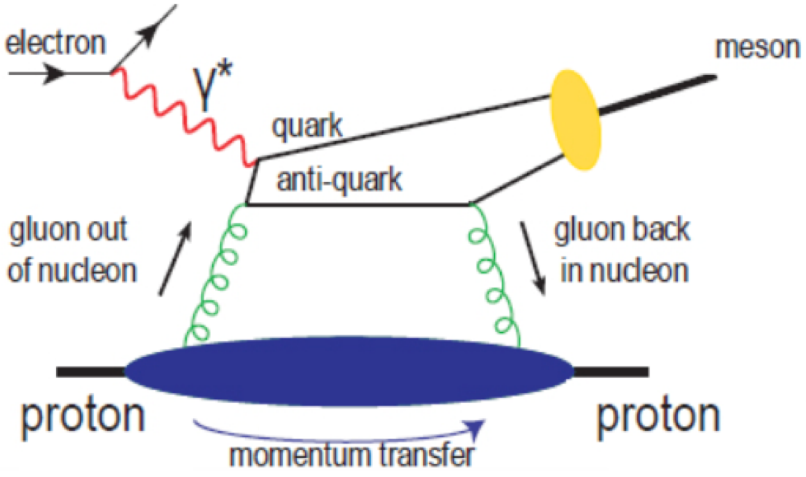
Emergent mechanism
Gluons?

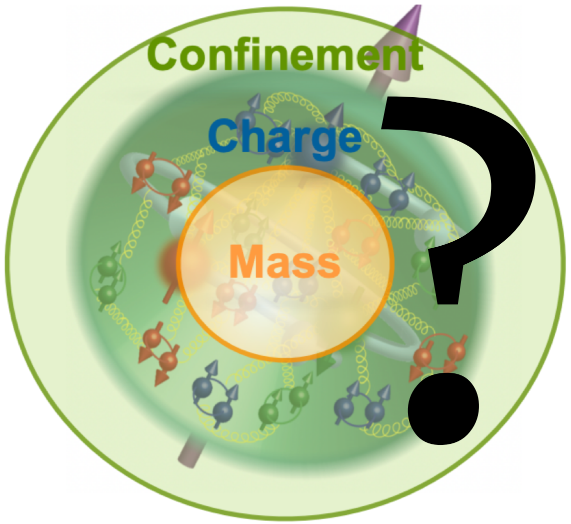


Kaons, 490 MeV

Emergent vs Higgs-mass mechanisms
Gluons?

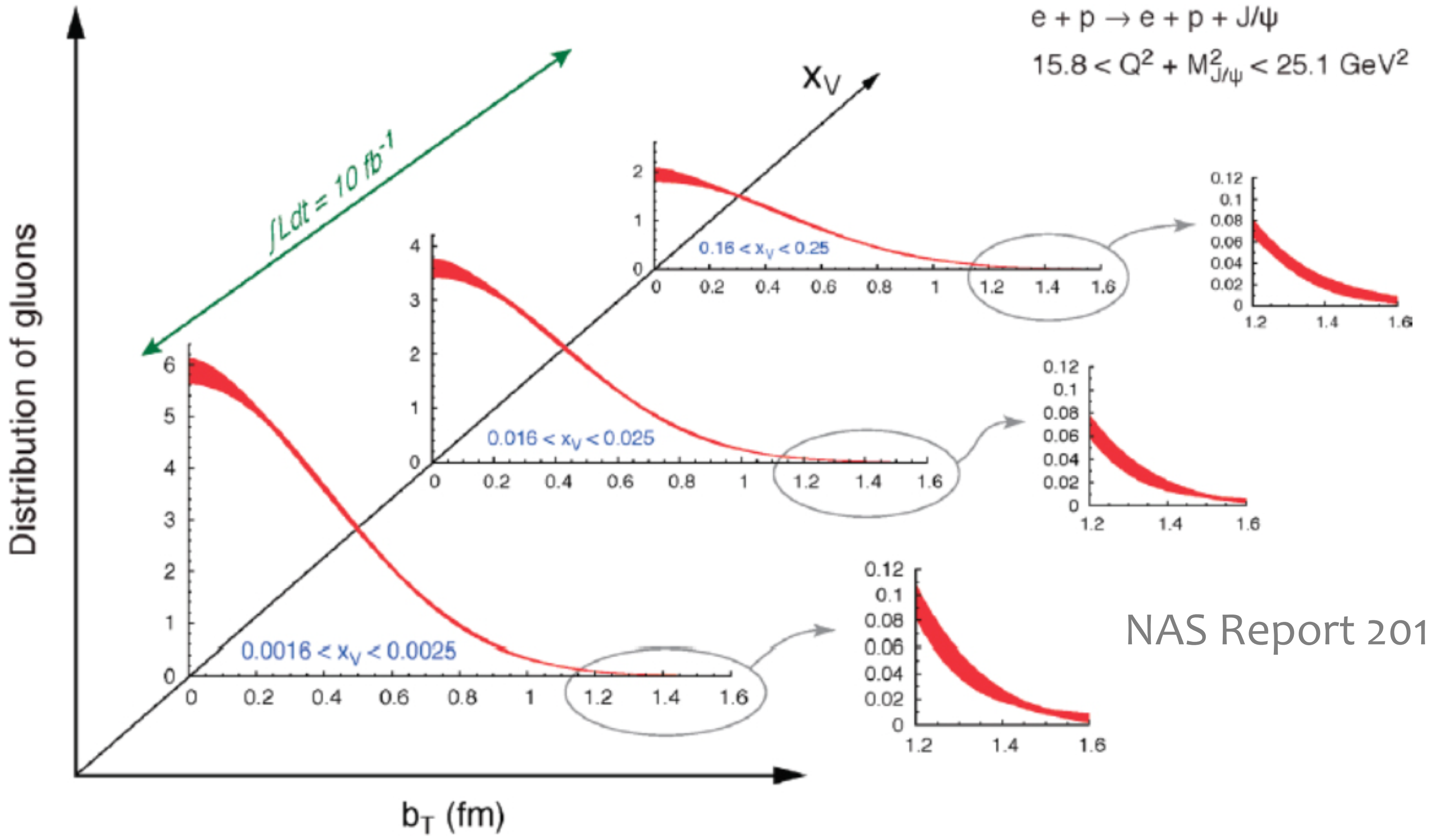
Accessing the gluonic distribution, J/ψ





How are gluons distributed in nucleons? Mesons?

Projected gluon spatial densities from real meson production at the EIC



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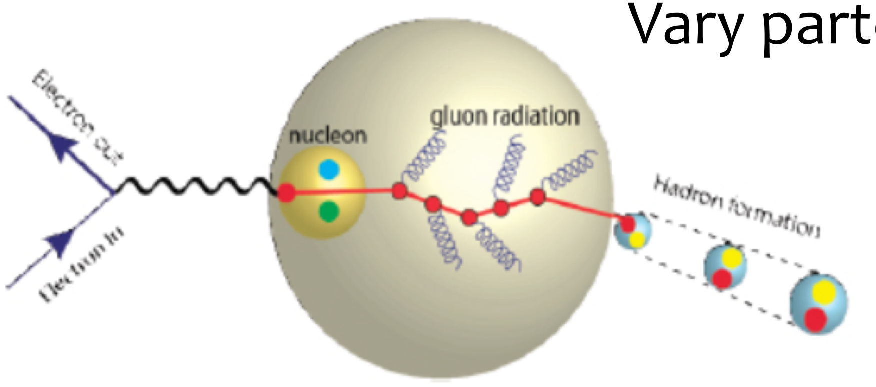
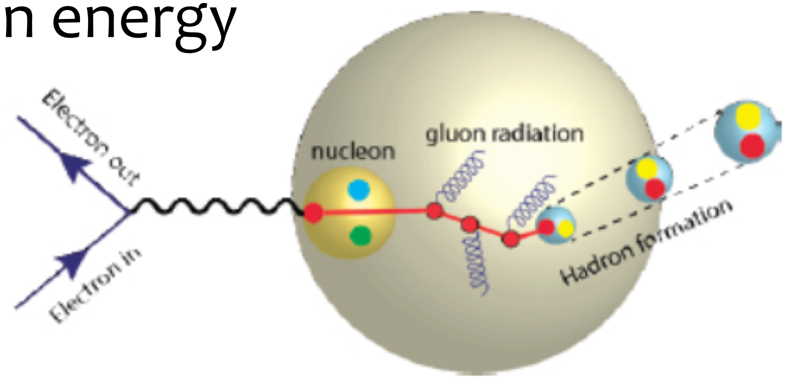
Hadronization at the EIC will tell us about QCD bound states

Range of small to large nuclei are femto-scale detectors for hadronization!

Vary parton energy



Hadronization outside the nucleus

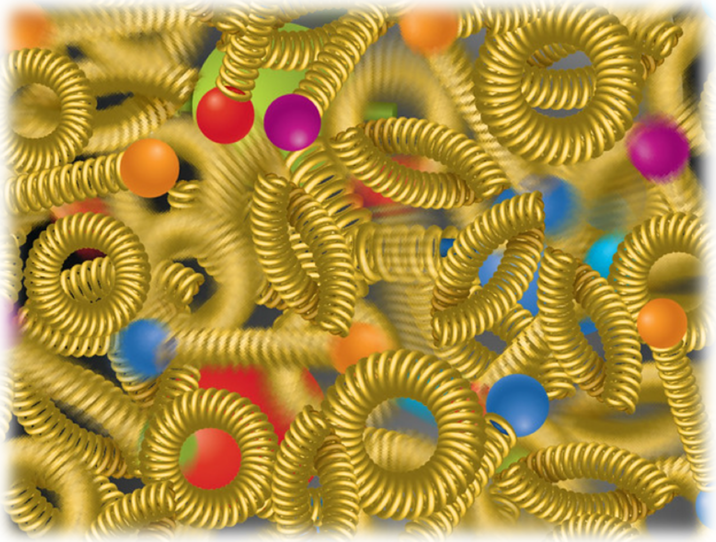


Hadronization inside the nucleus

How do the degrees of freedom of QCD, quarks and gluons, relate to the hadronic degrees of freedom we observe in nature?

How does a color charge convert to a hadron?

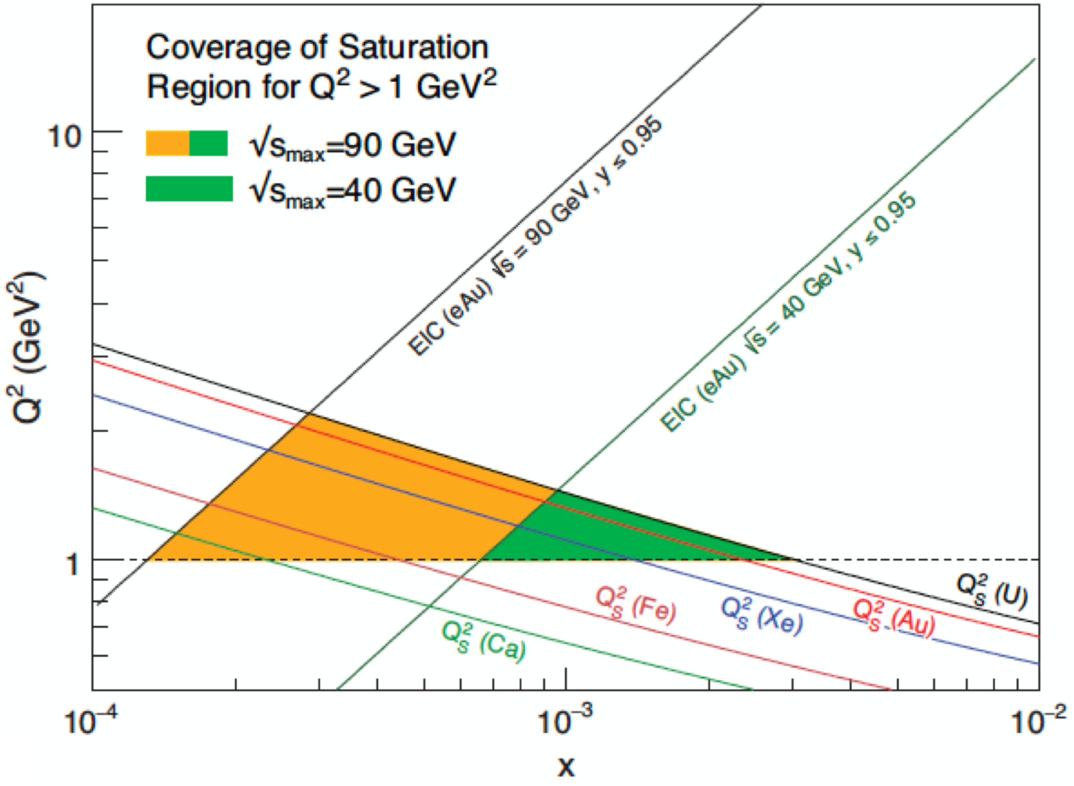
What are the time scales for color neutralization and hadron formation?

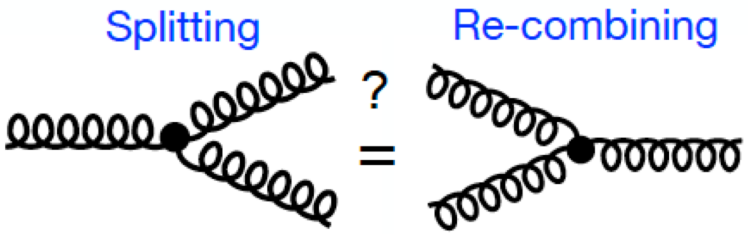


Into New Gluon Territory

What happens to the **gluon density** in nuclei?

- Number of gluon grows in the low-x limit
- At some point the density becomes so large that gluons lose their individual identity and are strongly overlapping (Q_s)



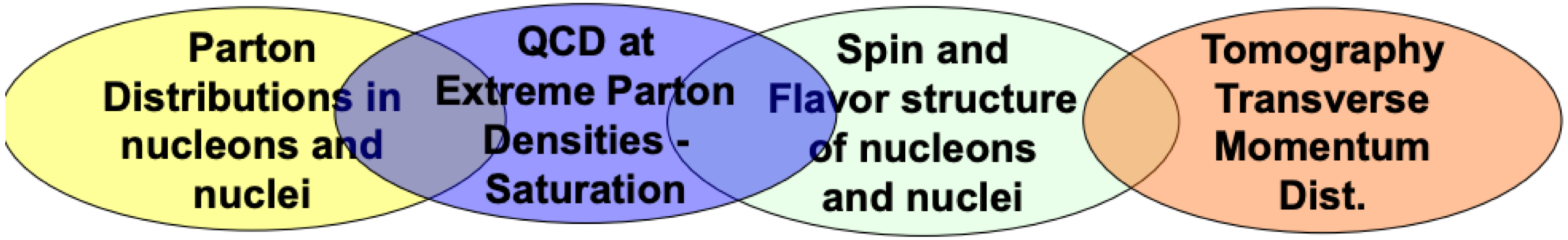


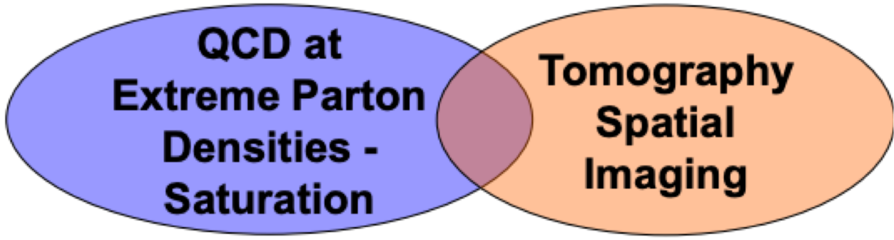
EIC can study very high gluon densities
i.e. $e + Pb$ collisions

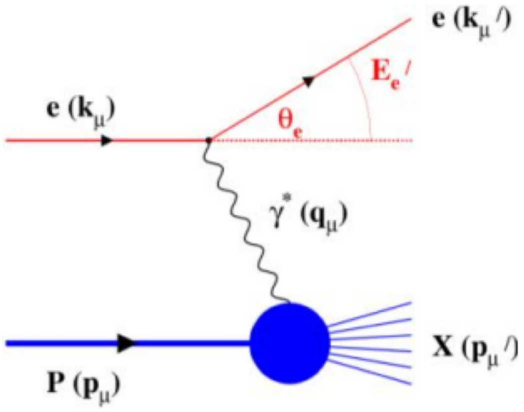
EIC will map the transition from the non-saturated to the saturated regime!

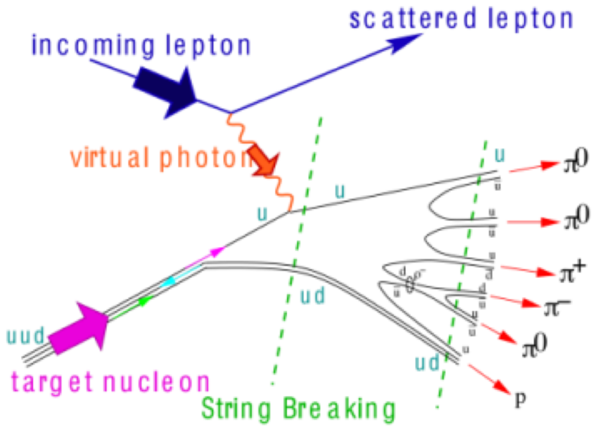
ePIC

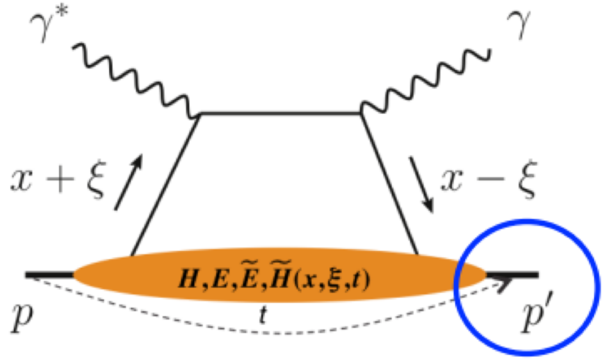
From physics to machine and detector requirements











Inclusive DIS

- measure scattered lepton
- multi-dimensional binning: x, Q2

→ reach to lowest x, Q^2 impacts Interaction Region design

Semi-Inclusive DIS

- measure scattered lepton and hadrons in coincidence
- multi-dimensional binning: x, Q^2 , z, pT , θ

→ particle identification over entire region is critical

Exclusive processes

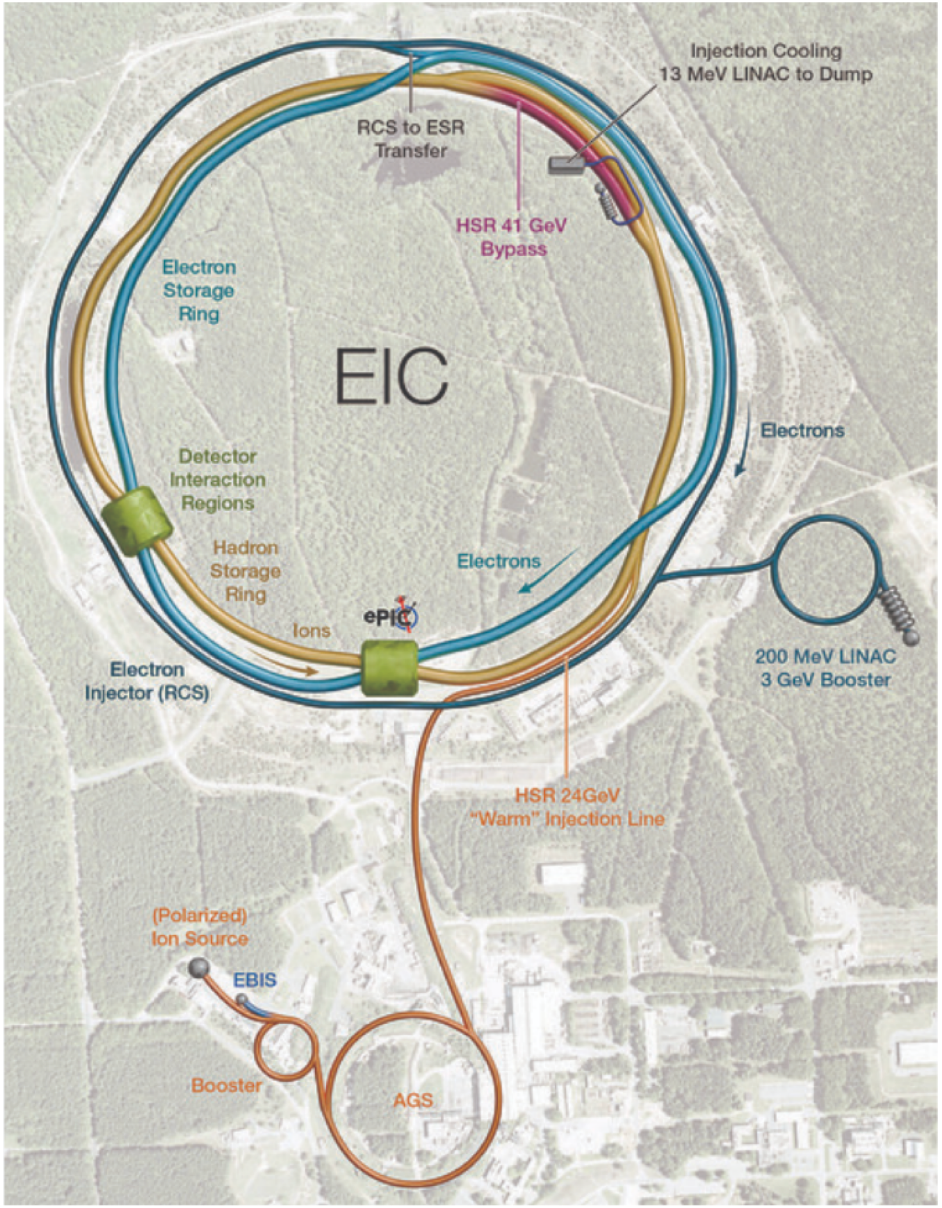
- measure all particles in event
- multi-dimensional binning: x, Q^2, t, θ
- proton p_t : 0.2 - 1.3 GeV

→ cannot be detected in main detector

→ strong impact on Interaction Region design

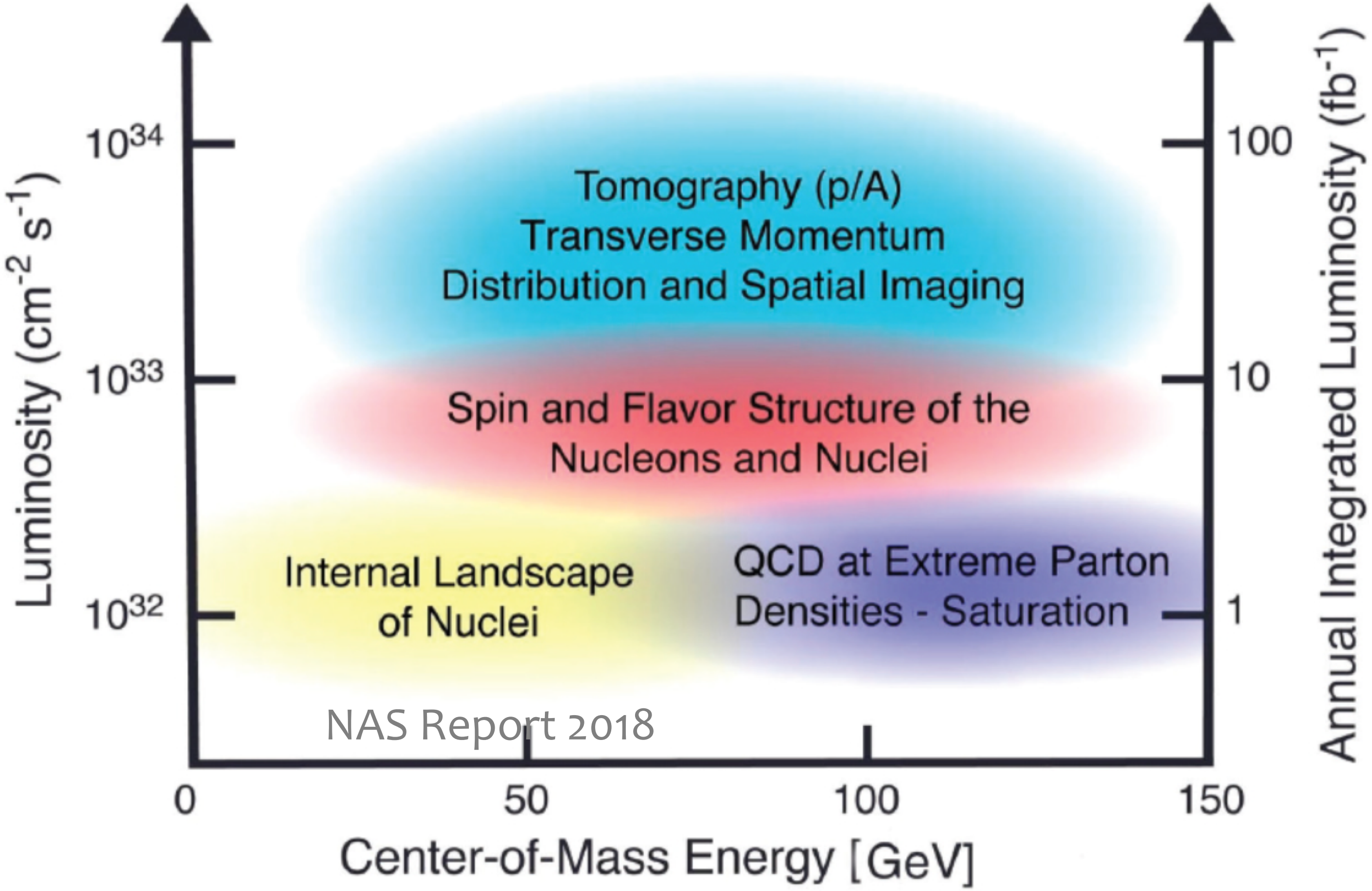
$\int L\,dt =$ 1 fb^{-1} → 10 fb^{-1} → 10-100 fb^{-1}

EIC: the machine of the future!



- EIC:
  - High luminosity (10^{33} - 10^{34} $cm^{-2}s^{-1}$) polarized electron proton/ion collider
  - center-of-mass energies $20 < \sqrt{s} < 140$ GeV
- First of its kind:
  - 100x-1000x higher luminosity than HERA
  - High spin polarized beams: 70%
  - Ranging from protons, light nuclei, up to uranium
- ePIC and beam line detectors to reconstruct all particles with high precision

EIC physics requires high luminosity and a wide range of center-of-mass energies



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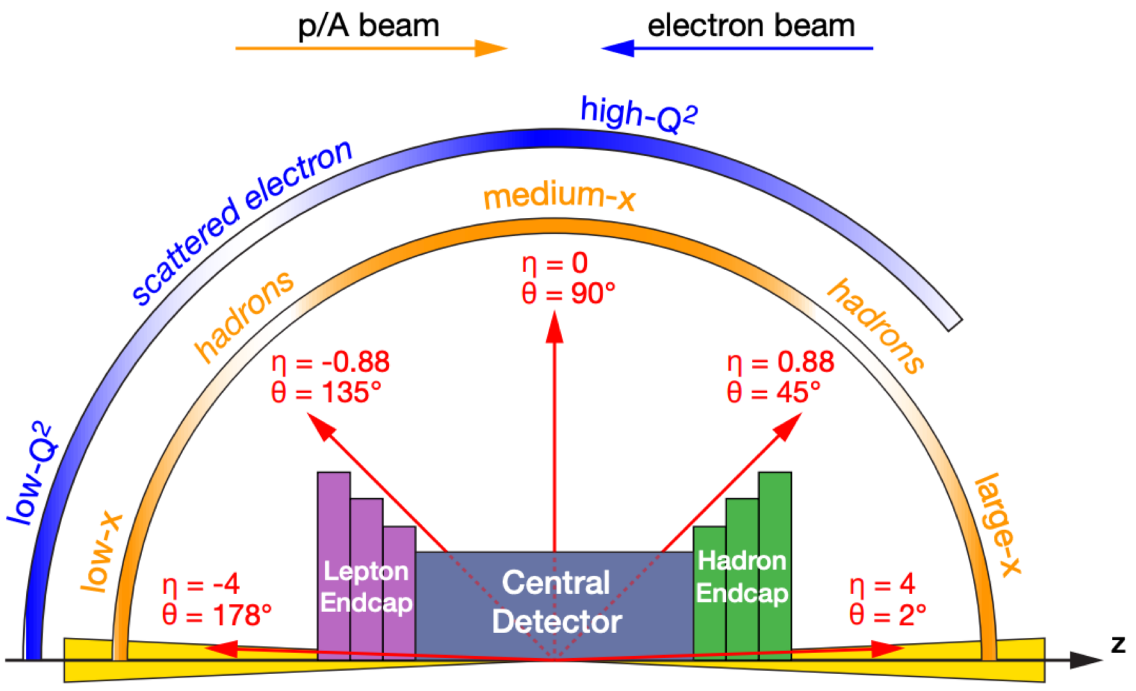
Physics determines the requirements of detector



Inclusive DIS requires fine multidimensional binning in x,Q^2:

- Large coverage ($-3.5<\eta<3.5$) for wide phase-space reach
- Excellent EM-calorimetry with PID support for e/π separation
- Fine resolution tracking with low mass

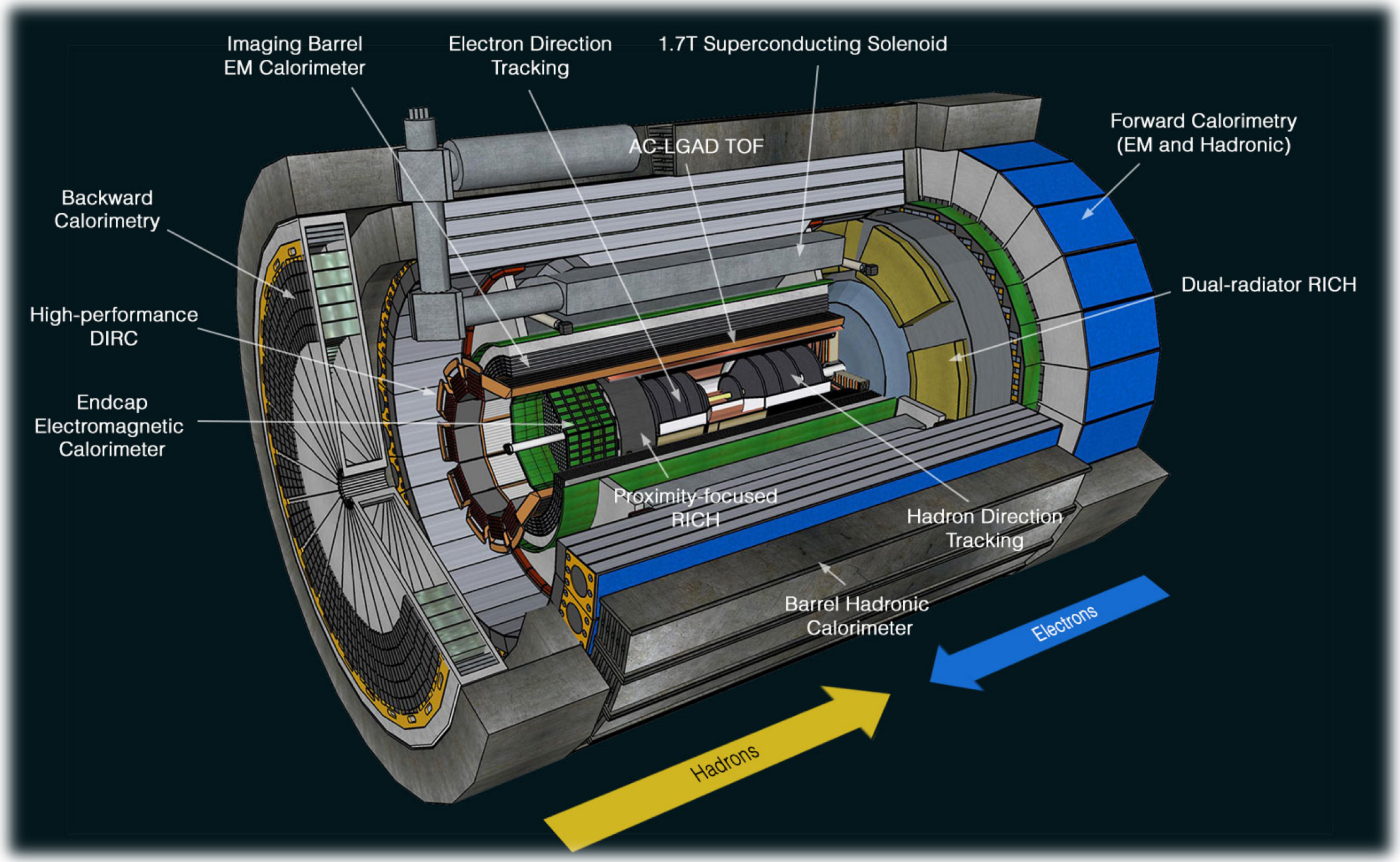
Semi-inclusive DIS requires five-dimensional binning in $x,Q^2,z,p_{T,}\theta$:

- Fine p_T resolution
- Extended PID systems for hadron identification
- H-calorimetry to attempt TMD assessment with jets (new world-wide)

Exclusive processes require four-dimensional binning in x,Q^2,t,θ:

- Extend acceptance at extremely small scattering angles by far forward detectors
- Fine vertex resolution by tracking

ePIC Central Detector design

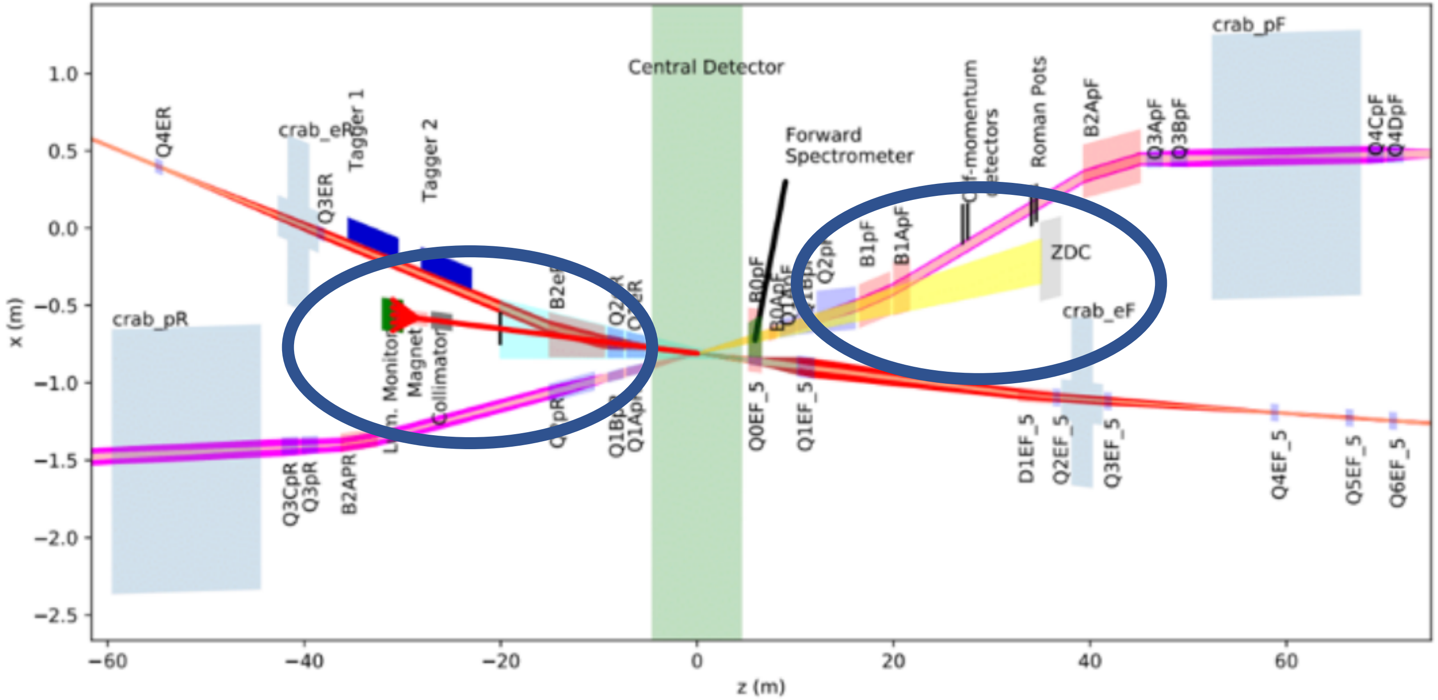


Tracking:
- New 1.7T (2.0T) solenoid
- Si MAPS Tracker
- MPGDs (µRWELL/µMegas)

PID:
- high-performance DIRC
- proximity-focused RICH
- dual-radiator RICH
- AC-LGAD (~30ps TOF)

Calorimetry:
- Imaging Barrel EMCal
- $PbWO_4$ EMCal (backwards)
- Finely segmented EMCal +Hcal in forward direction
- Outer HCal (sPHENIX re-use)
- Backwards HCal (tail-catcher)

Far-forward and far-backward detectors

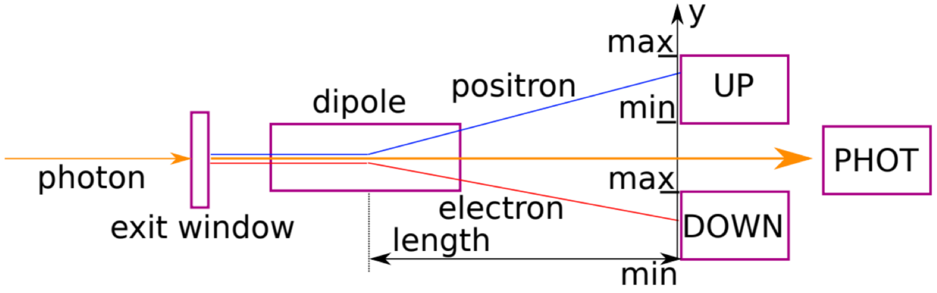


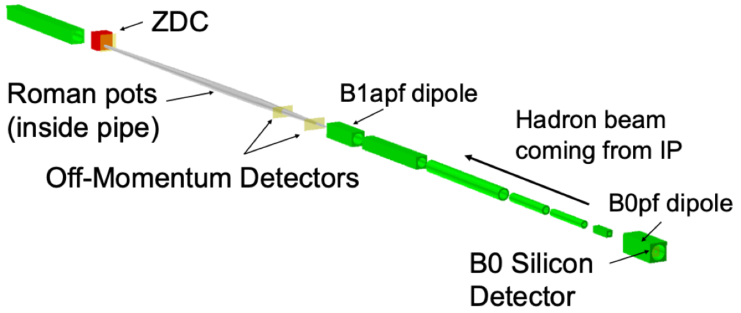
Far-Backward Detectors

- Luminosity monitor
- Low-Q2 Tagging Detectors

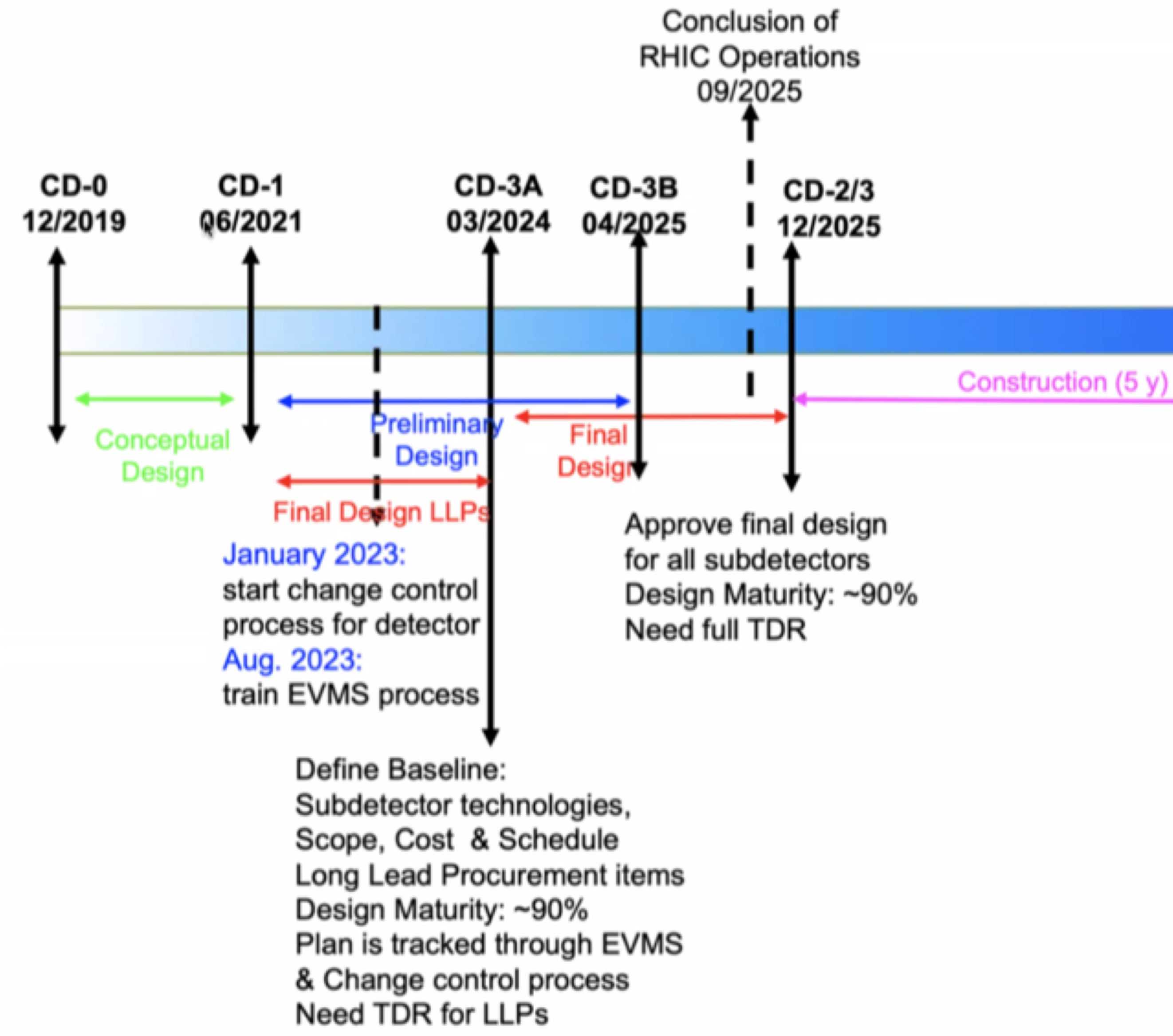
Far-Forward Detectors

- B0 Tracking and Photon Detection
- Roman Pots and Off-Momentum Detectors
- Zero-Degree Calorimeter





EIC schedule

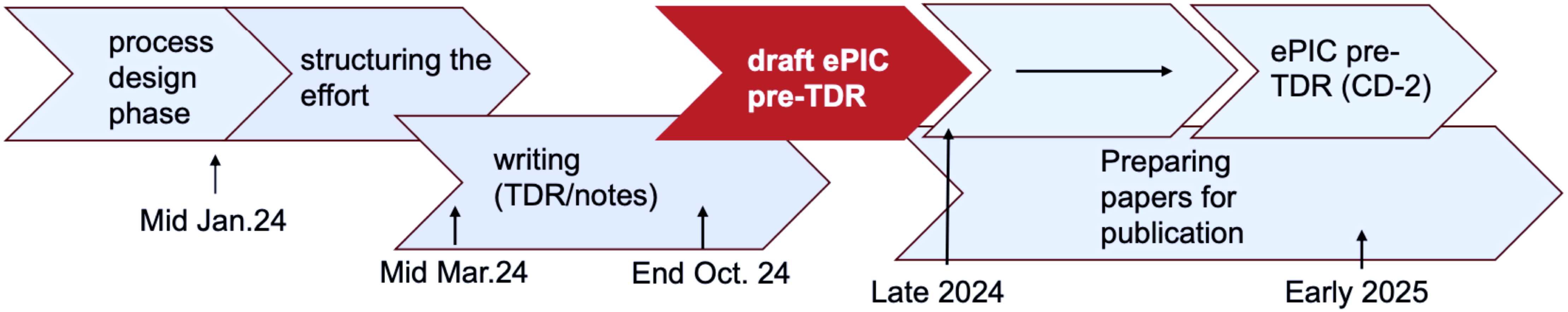


EIC Critical Decision Plan

CD-0/Site Selection	December 2019 ✓
CD-1	June 2021 ✓
CD-3A	ESAAB March 25th 2024
CD-3B Review	**January 7-9 2025**
CD-2/3	**December 2025**
CD-4 early finish	Oct 2032
CD-4	**Oct 2034**

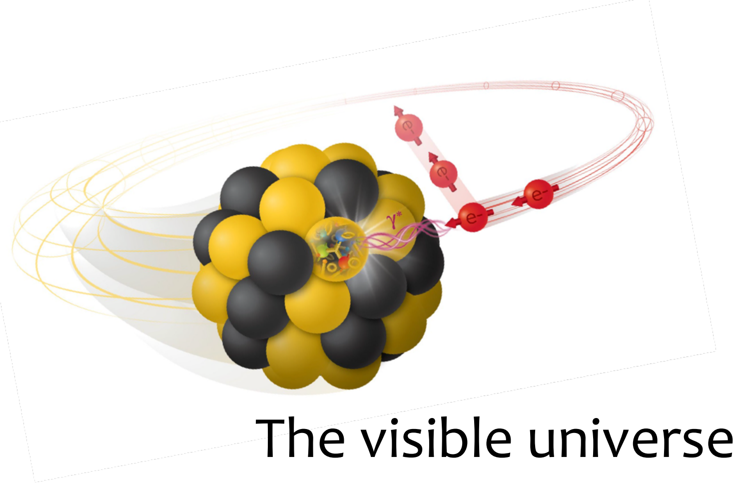
Implemented in P6 presented at CD-3A review

ePIC Computing Technical Design Report (TDR)



ePIC Software & Computing is essential to the TDR, providing advanced software and simulation productions that are the input for detector and physics studies

- The EIC (pre)TDR is the top priority for the ePIC Collaboration, with the timeline driven by the EIC Project (CD-2/CD-3).
- Extended versions of the sections on the detector, physics performance, and software & computing will be published in scientific journals.



Summary

The visible universe is governed by gluons and the dynamics of the strong interaction

- EIC will get to the heart of matter to study the strong interaction in a novel and comprehensive way

Access to EIC Physics using the ePIC detector via:

- Large kinematic coverage
- Polarized electron and hadron beams and unpolarized nuclear beams with high luminosities
- Detector setup fulfilling specific requirements of the polarized e-p/A collider

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

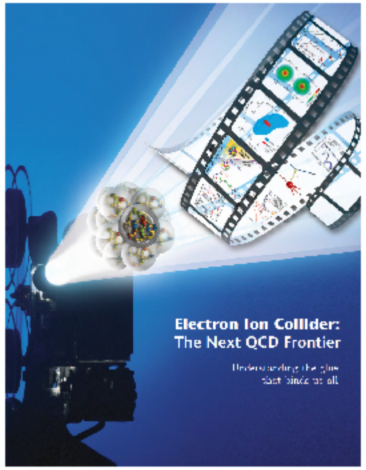
Thank you!

Thank you to my ePIC Collaborators!

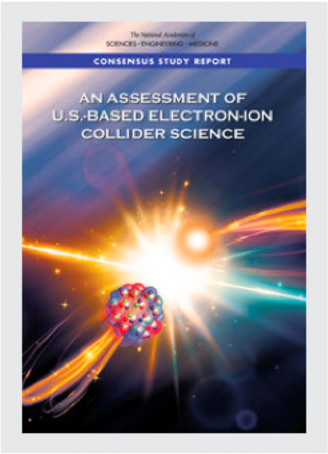
This includes: previous slides from *M. Żurek (ANL), R. Montgomery (UGlasgow), E.C. Aschenauer (BNL), C. Aidala (UMichigan)*

Images and studies showcasing the science are from the reports below

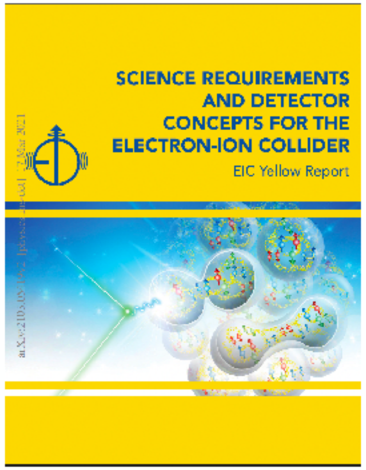
EIC-related images are from BNL



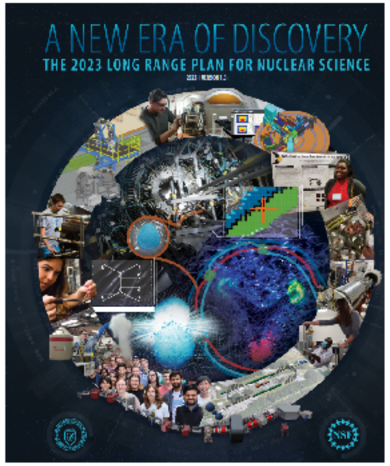
White Paper
arXiv:1212.1701 [nucl-ex]



NAS Report
DOI 10.17226/25171



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



NSAC LRP