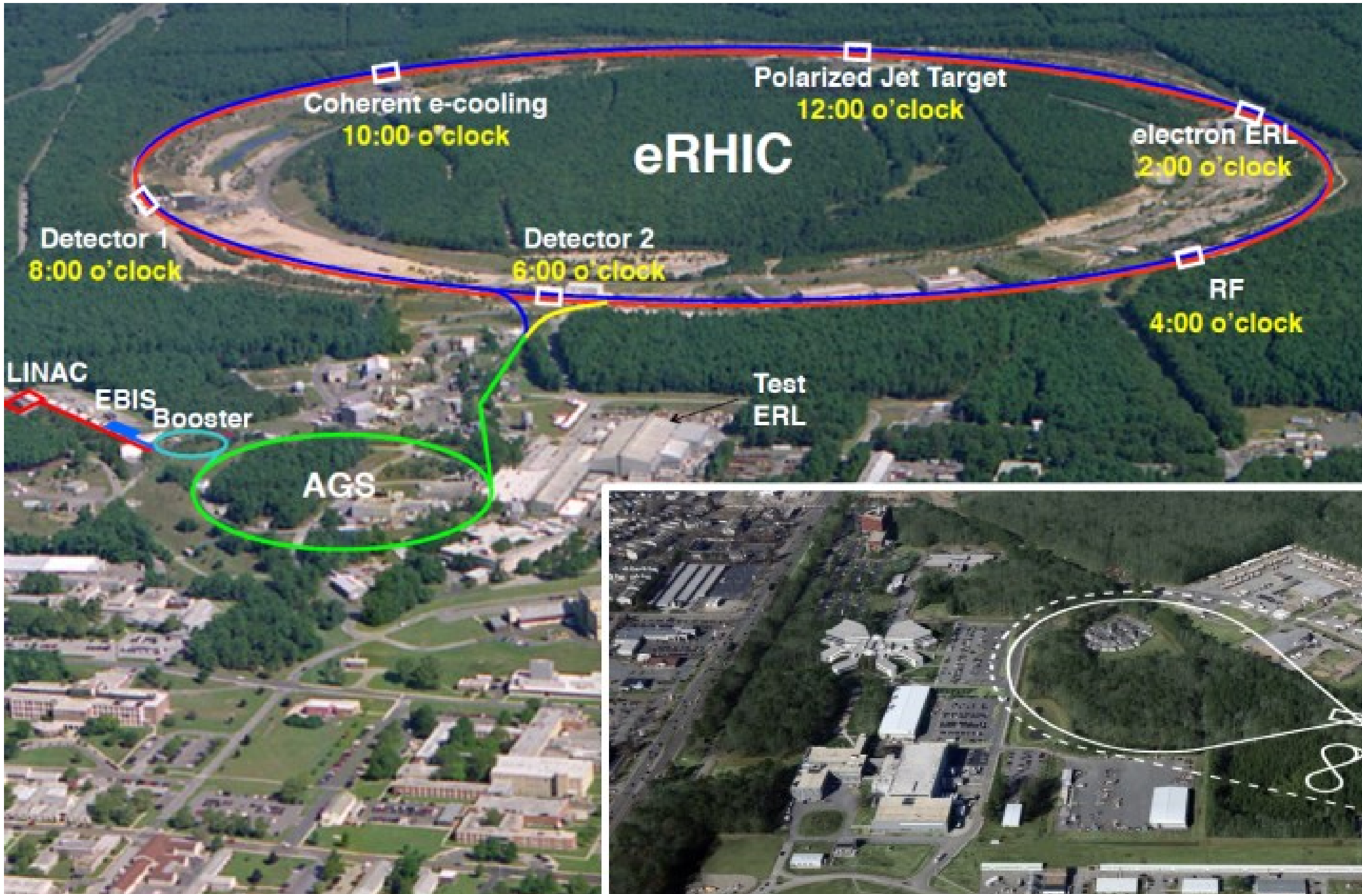
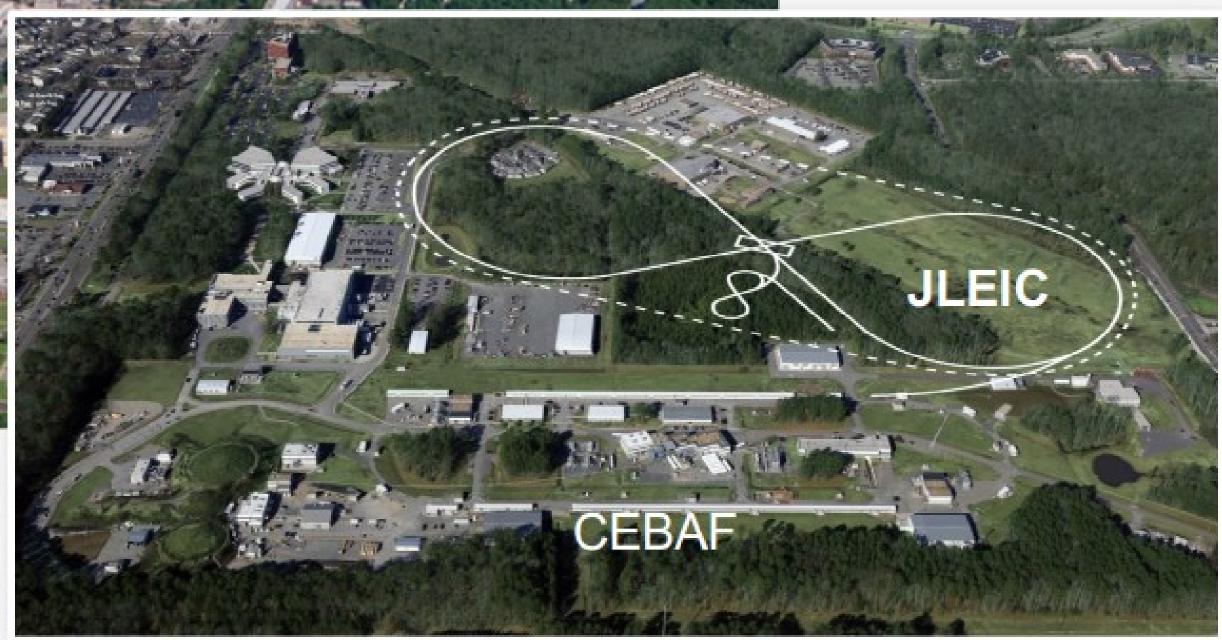
New physics opportunities with an Electron-Ion Collider



Outline:
- Open questions in QCD
- Physics case for an EIC
- Designs for an EIC in USA
- Detector developments
- Timeline



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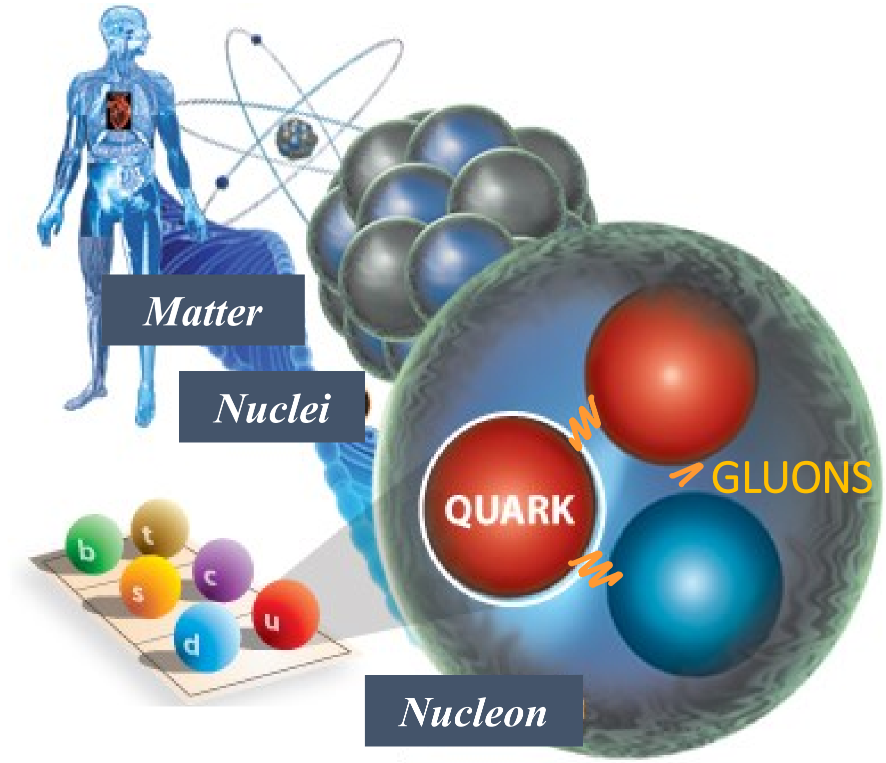
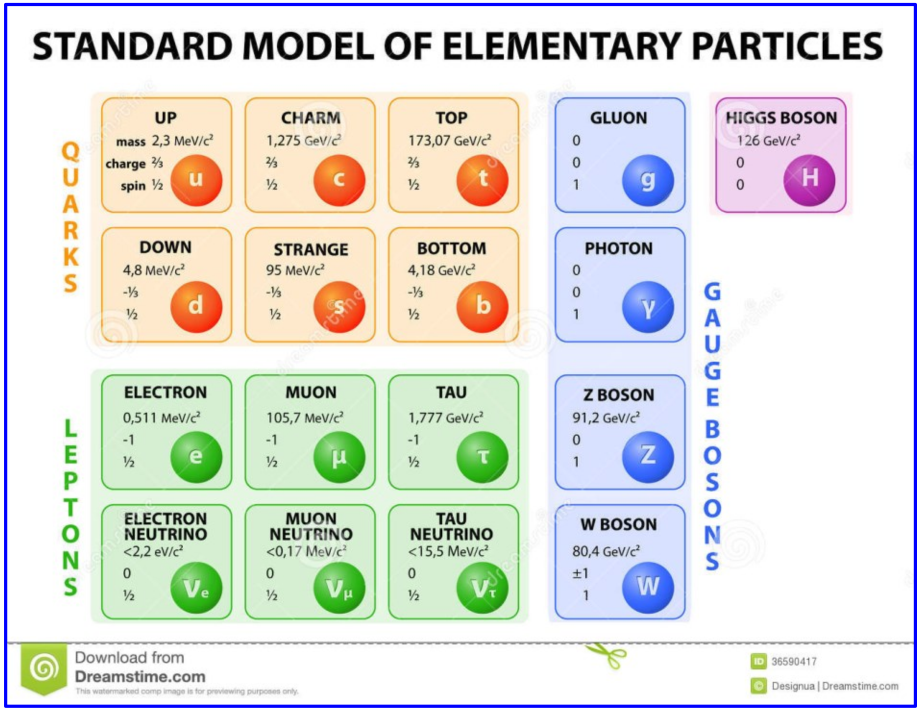
IPHC Strasburg, 15/12/2017

QCD at the heart of matter

- **Protons and neutrons** are the building blocks of atomic **nuclei**
- **Nucleons** provide **~99% of the mass** of the visible universe
- **~99% of nucleon mass** arises from the **dynamics** and **interactions** between its constituents (**quarks** and **gluons**)

→ **Quantum Chromodynamics (QCD)**

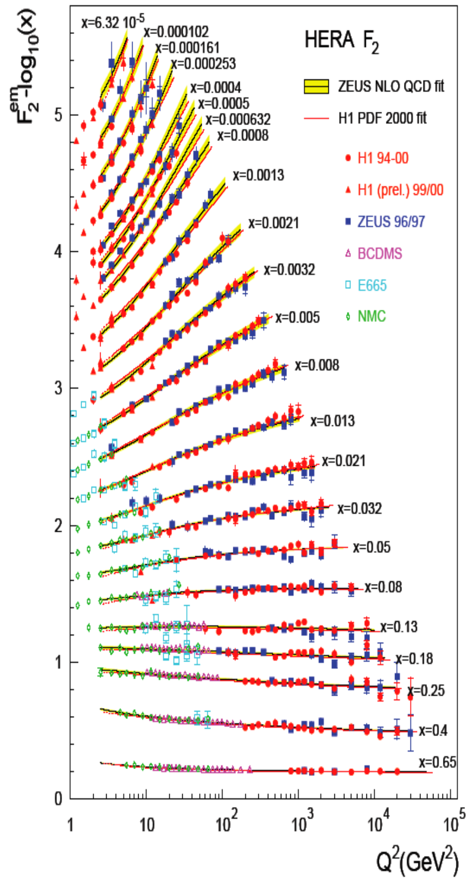




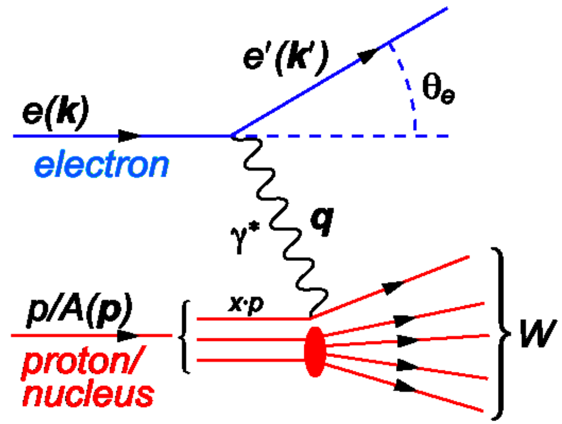
Properties of QCD:

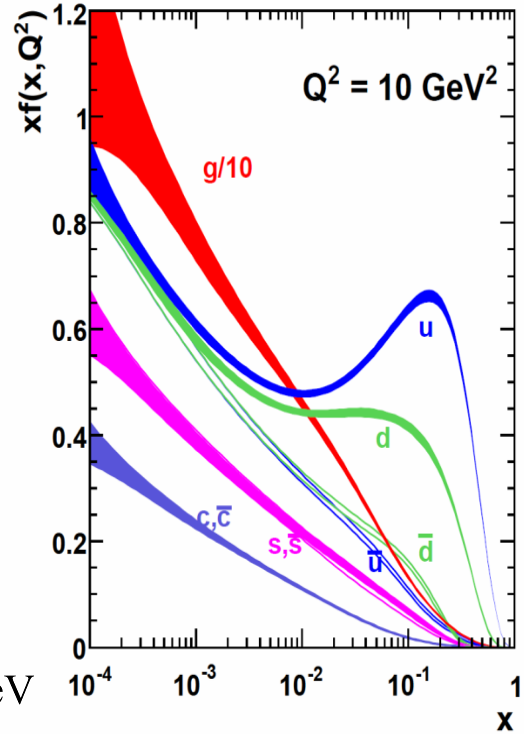
- **Confinement, at long distances:** unlike in QED, we cannot observe the individual constituents
- **Asymptotic freedom, at short distances**: the effective coupling constant α_s becomes very small (<1) at small distances (<0.2 fm)
- **Chiral simmetry breaking**: mass of the *u* and *d* quarks, very small → generates nucleon mass
- **Non-linearity**: **self-interaction of gluons**

Successes of QCD

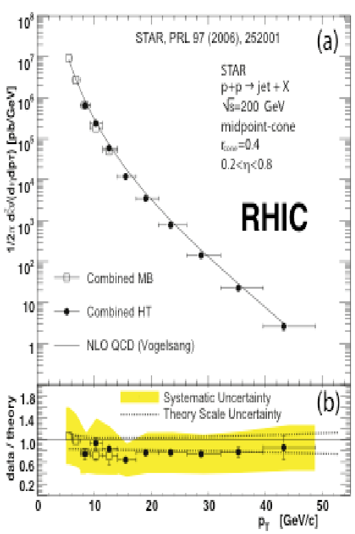


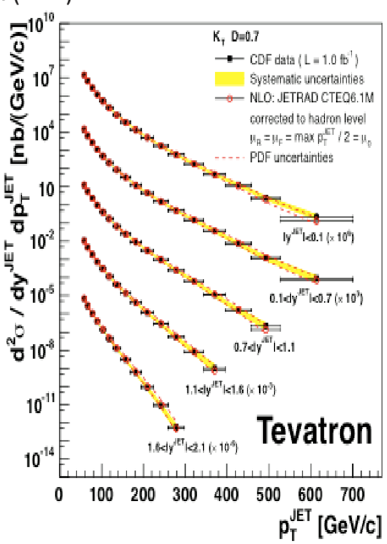
$$F_2 = \sum_q x\, q(x, Q^2)$$

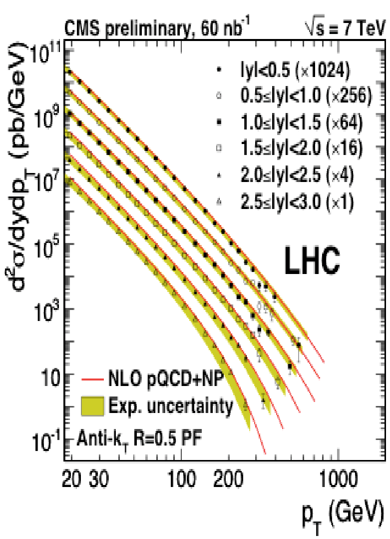




Measurements of F_2 in e-p at 0.3 TeV (HERA)
→ extraction quark and gluon PDFs
→ pQCD fits for p-p and p-$\bar{p}$ at 0.2, 1.96, and 7 TeV





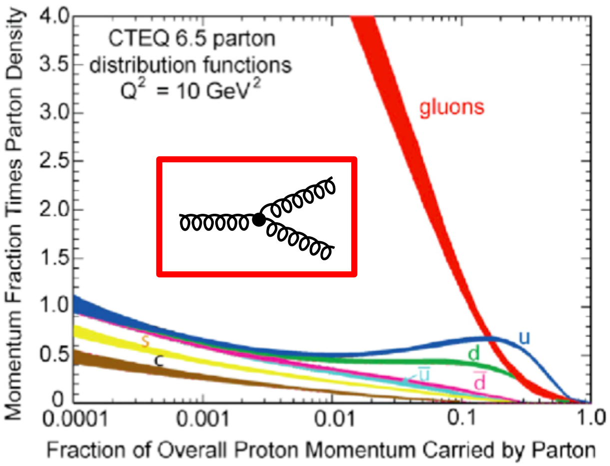


BUT…

QCD is still unsolved in non-perturbative regions

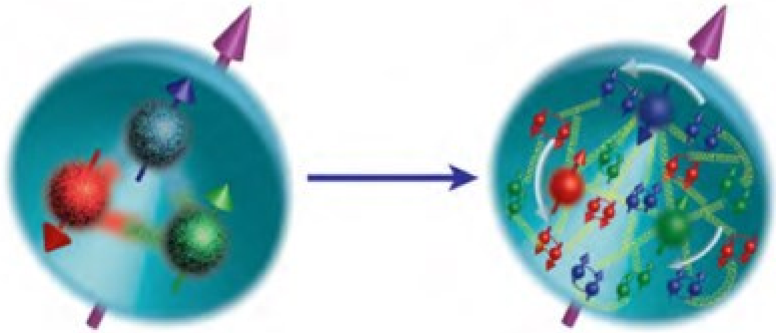
Insights into soft phenomena exist through qualitative **models** and quantitative **numerical calculations** (lattice)

Open questions in QCD



Saturation: a new state of hadronic matter?

What happens to the **gluon density** in nuclei at high energies?
It cannot grow infinetely…
Is there a **saturation** in some sort of gluonic matter with universal properties (« color glass condensate »)?

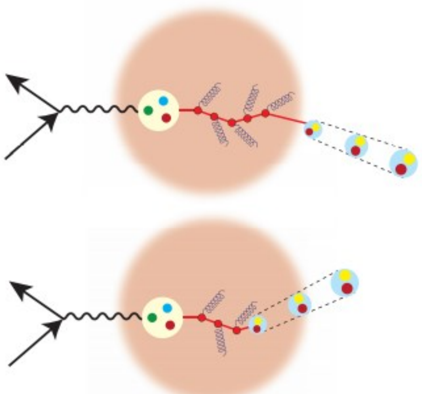


Exploring the partonic structure of nucleons and nuclei

How do the **spin** and the **mass** of the nucleon emerge from the dynamics of its constituents?
What are the position, momentum and spin distributions of **sea quarks and gluons** in the nucleon and in light nuclei?
What is the role of orbital momentum?

The role of gluons in nuclear medium

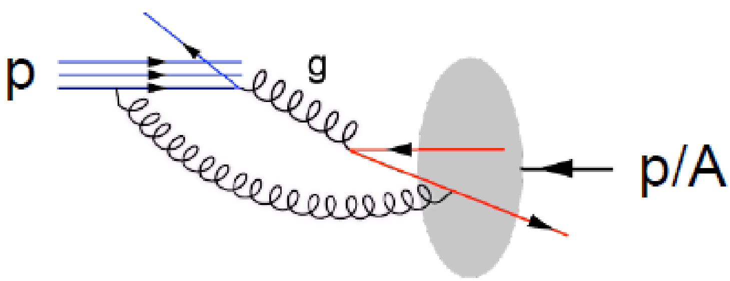
How do gluons and sea quarks contribute to nucleon-nucleon force? How does nuclear matter react when a colored charge passes through it?
How does nuclear matter affect quark and gluon distributions and their interactions in nuclei?



All of this (and more!) can be studied at the EIC

Why do we need an electron-ion collider?

Hadron-hadron

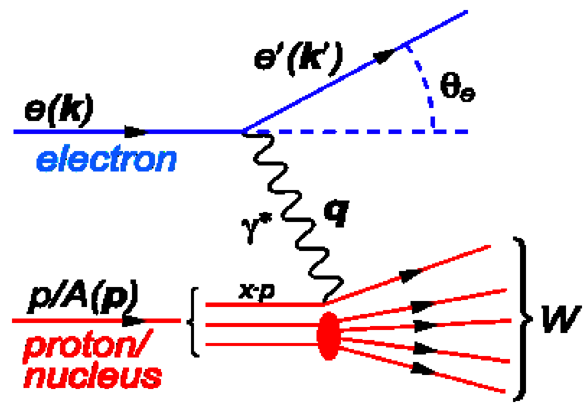


Probe and target have a complex strucure

Soft interactions before collisions can destroy factorization

Kinematics imprecisely determined

Electron-hadron (DIS)



Point-like probe

No initial-state soft interactions, factorization preserved

Kinematics precisely determined

Kinematic variables:

$Q^2 = -(k-k')^2$
(Resolution)

$x = Q^2/2M\nu = Q^2/(2pq)$
(mom. fraction)

$\nu = E_e - E_{e'}$

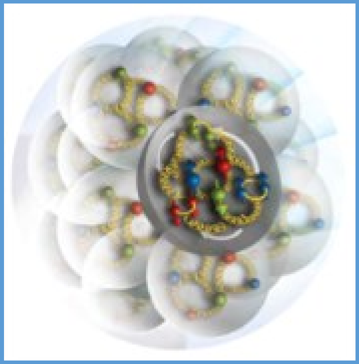
$s = (p+k)^2 = 4E_eE_p$

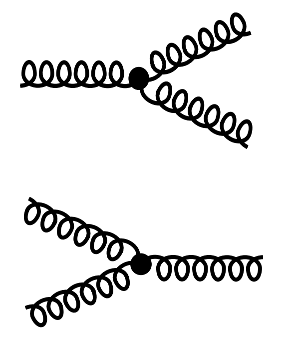
An EIC, with **high luminosity,** versatile beam **species** and beam **polarizations**, covering $0.1<Q^2<1000$ GeV^2, $10^{-4}<x<10^{-1}$ is needed to:

- explore both the region of **non-perturbative** effects and the **gluon dominated** region
- precisely image the **sea quarks and gluons** in nucleons and nuclei
- resolve outstanding issues in understanding nucleons and nuclei in terms of fundamental building blocks of QCD

EIC: the world's first electron-nucleus collider

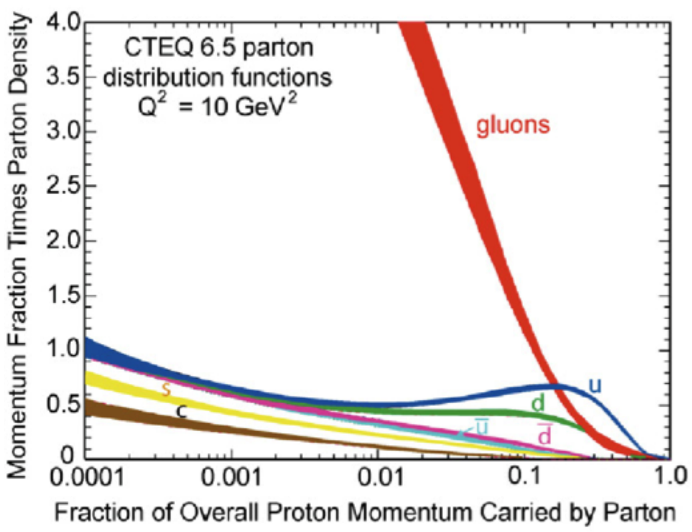
The nucleus as a laboratory for QCD

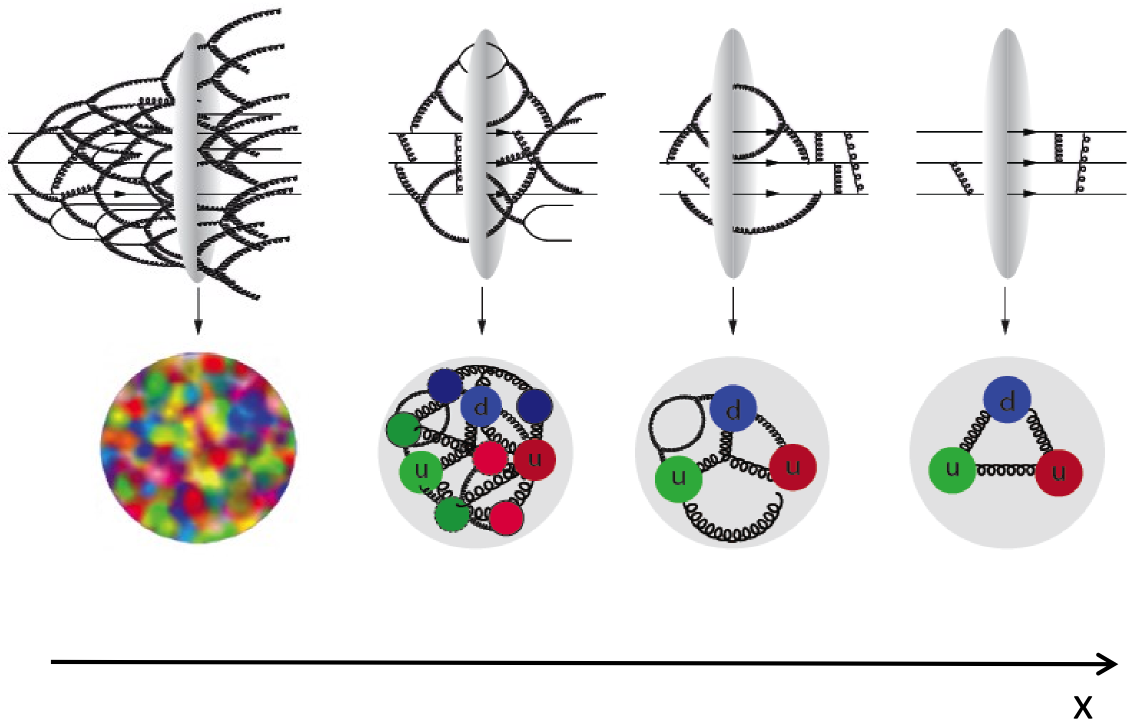




- What happens to the *gluon density in nuclei*? Does it *saturate at high energy*, giving rise to a **gluonic matter** with *universal properties* in all nuclei, even the proton?
- How does a *dense nuclear environment* affect the quarks and gluons, their correlations, and their interactions?
- How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

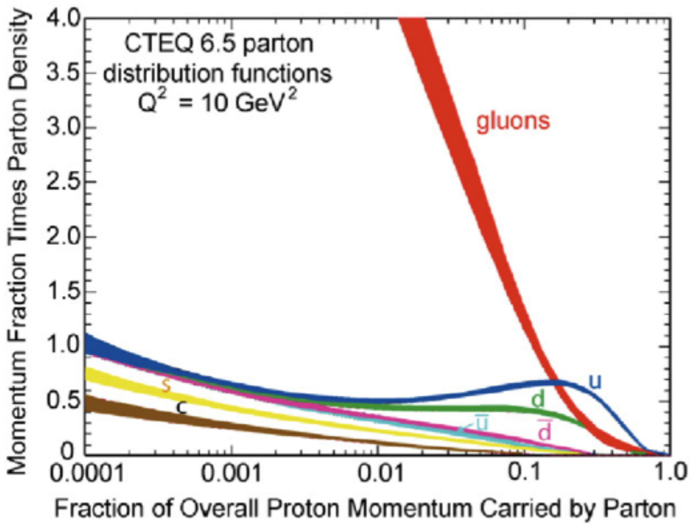
Gluon saturation at low x (→high energy)





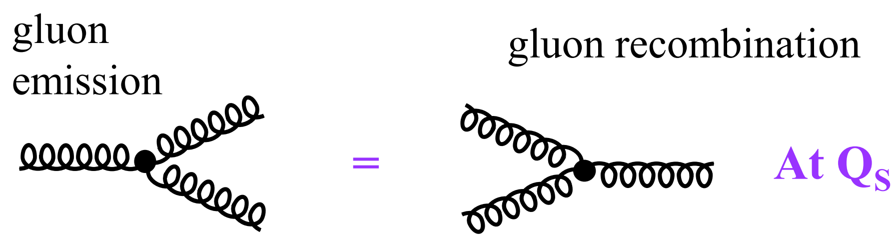
At small x the accelerated nucleon is saturated by gluons
« **Color glass condensate** »

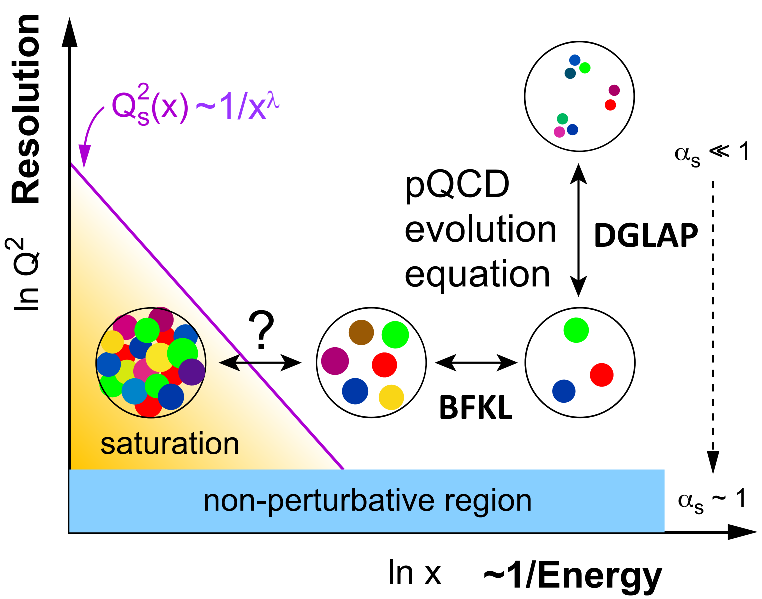
Gluon saturation at low x (→high energy)



What tames the low-x rise?

- Evolution equations at low x and moderate Q^2 are used to understand the onset of the **high gluon-density phase**
- "Black disk limit": unitarity bound on cross section
- **Saturation scale $Q_S(x)$:** where gluon emission and recombination become comparable (BK-JIMWLK evolution, non linear)





- **Saturation occurs when recombination becomes relevant**

– Gluon recombination leads to a **collective gluonic system**

– It is a **universal** phenomenon, for both nucleons and nuclei

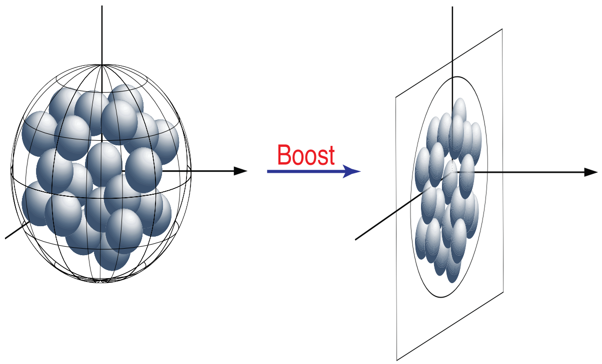
– Its presence has been hinted in many heavy-ion experiments

→ High potential for discovery and study at an EIC

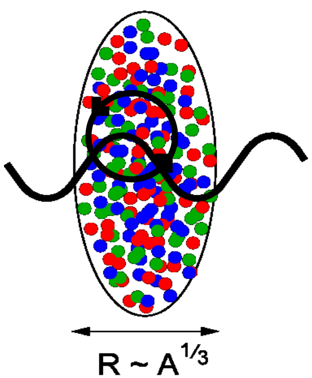
How to explore/study this new phase of matter?

(multi-TeV) e-p collider (LHeC) OR **a (multi-10s GeV) e-A collider**

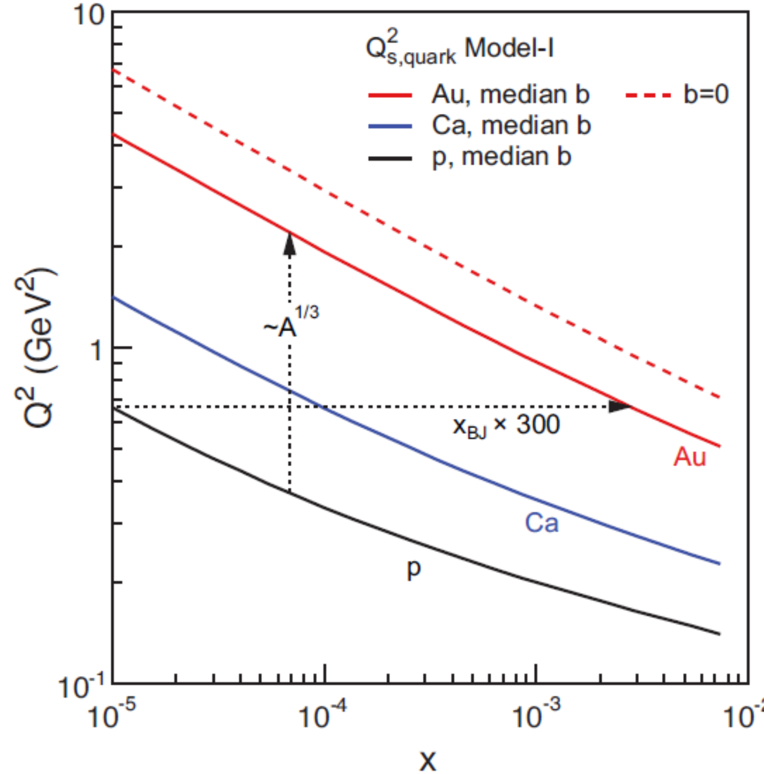
Advantage of nucleus →



Boosted nucleus:
High parton density in the transverse plane



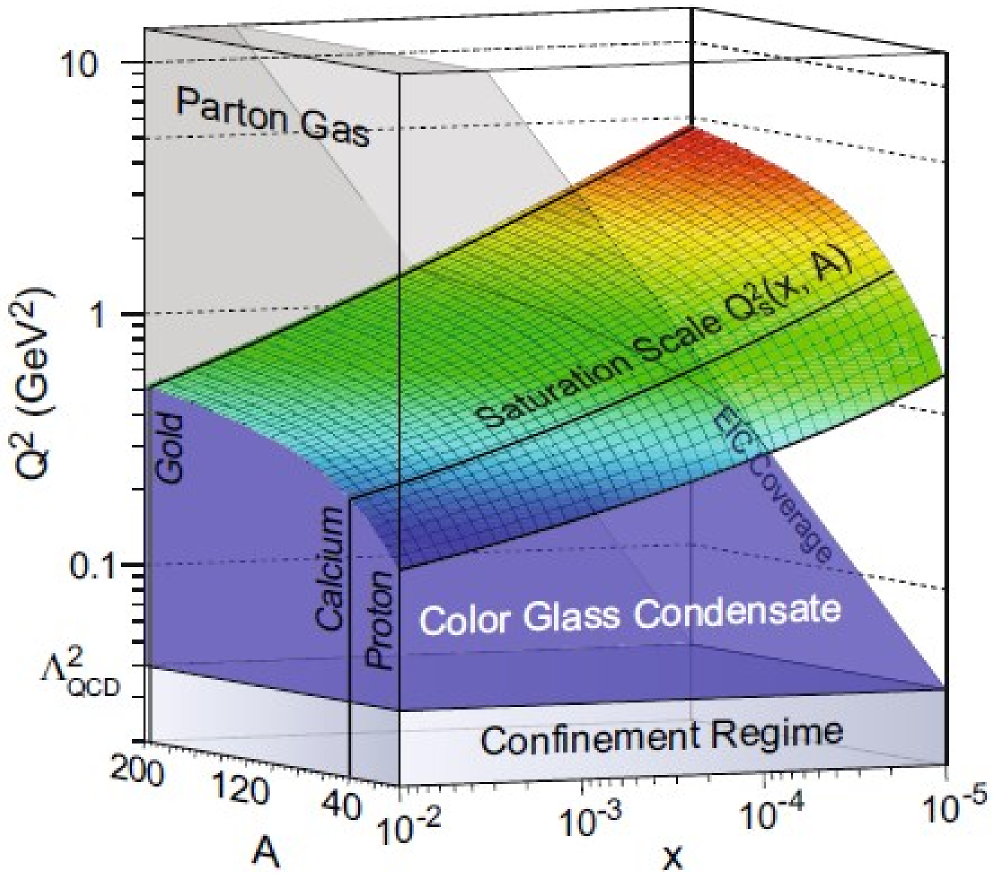
$$(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x}\right]^{1/3}$$



Enhancement of **Q_S with A** ("nuclear *oomph* factor"):
Saturation regime reached at significantly lower energy (=cost) in nuclei than for the proton
→ **need for ion beams at EIC**

How to explore/study this new phase of matter?

(multi-TeV) e-p collider (LHeC) OR **a (multi-10s GeV) e-A collider**



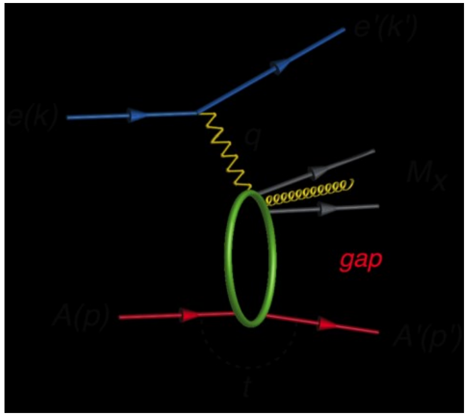
Enhancement of $\mathbf{Q_S}$ **with A** ("nuclear *oomph* factor"):
Saturation regime reached at significantly lower energy (=cost) in nuclei than for the proton
→ need for ion beams at EIC

Diffraction as a tool to study gluon densities

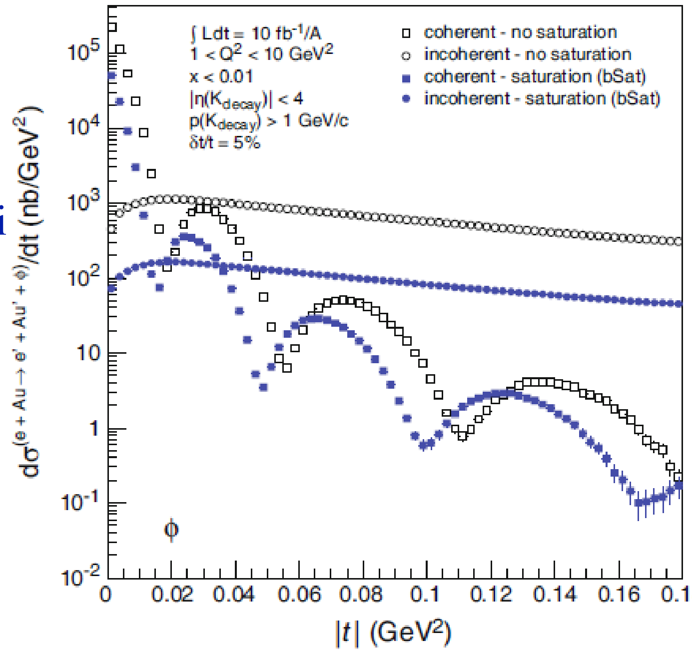
Diffraction cross-sections have strong discovery potential:

High sensitivity to gluon density in linear regime: $\sigma \sim [g(x,Q^2)]^2$

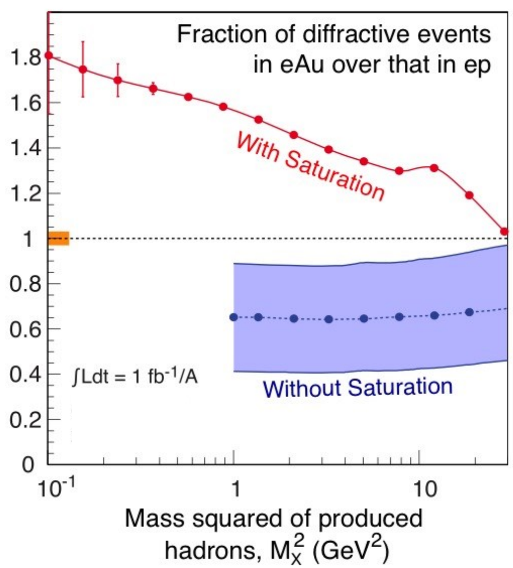
Dramatic changes in cross-sections with onset of non-linear strong color fields



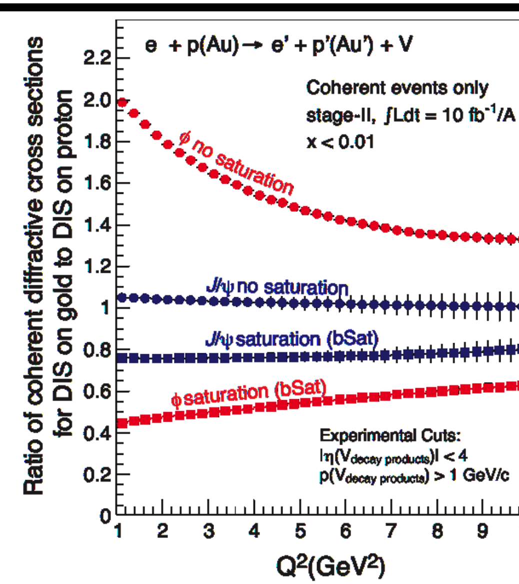
Extraction of the gluon distribution $\rho(b_T)$ of nuclei via Fourier transform of $d\sigma/dt$ in diffractive J/ψ and ϕ production



Probing gluon saturation through measuring $\sigma_{diffractive}/\sigma_{tot}$

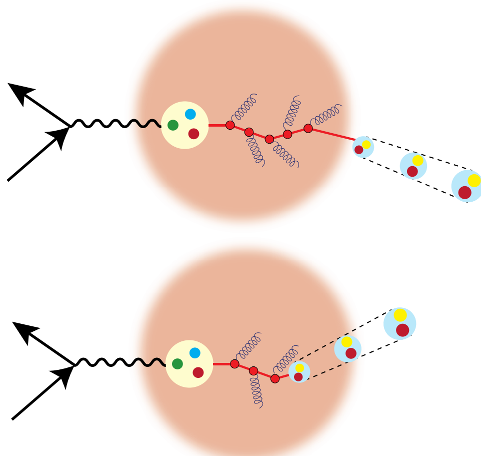


Probing Q^2 dependence of gluon saturation in diffractive vector meson production



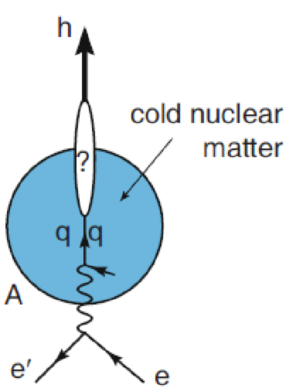
Emergence of hadrons from partons

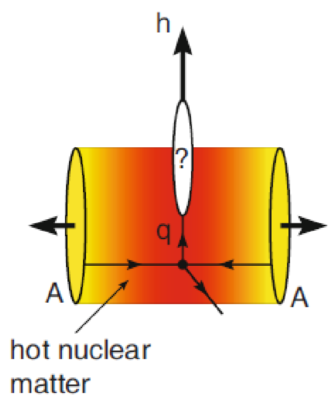
Unprecedented ν, the virtual photon energy range at EIC : *precision & control* on kinematics to study **hadronization**



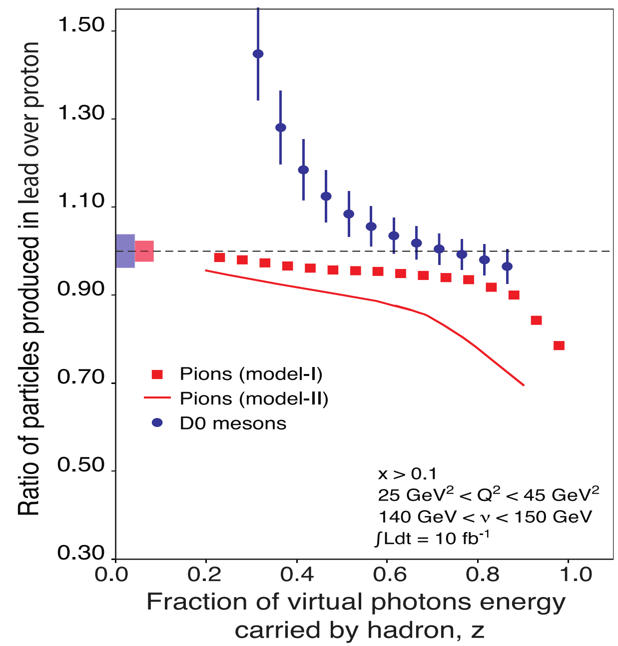
$$\nu = \frac{Q^2}{2mx}$$

Colored quark emerges as color neutral hadron ➔ What is the impact of colored media on confinement?





Energy loss by light vs. heavy quarks: Multiplicity ratios



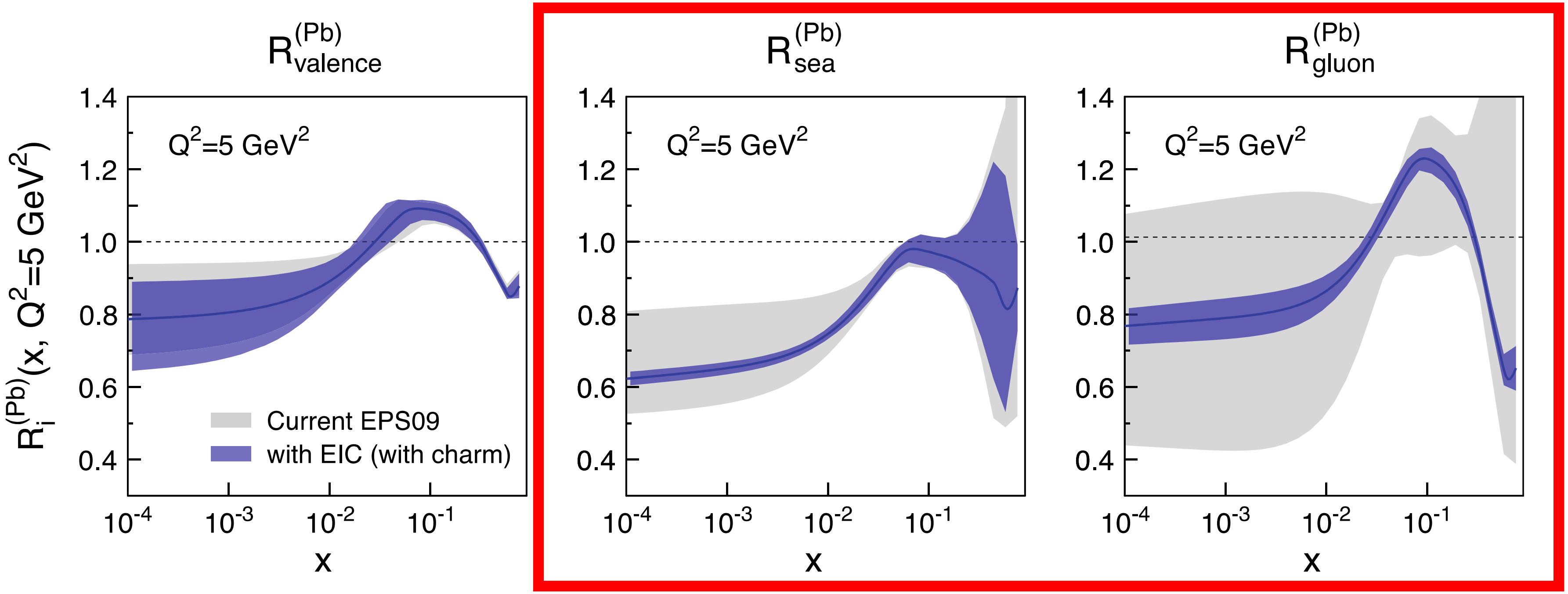
$z = E_h/\nu$

Identify light vs. charm hadrons in **e-A** (**SIDIS**): Understand **energy loss** of light vs. heavy quarks in **cold nuclear matter**

Provides insight into energy loss in Quark-Gluon Plasma

SIDIS at collider energies enables control of parton/event kinematics

Effect of the nuclear environment on partons
→ impact of the EIC on the knowledge of nPDFs

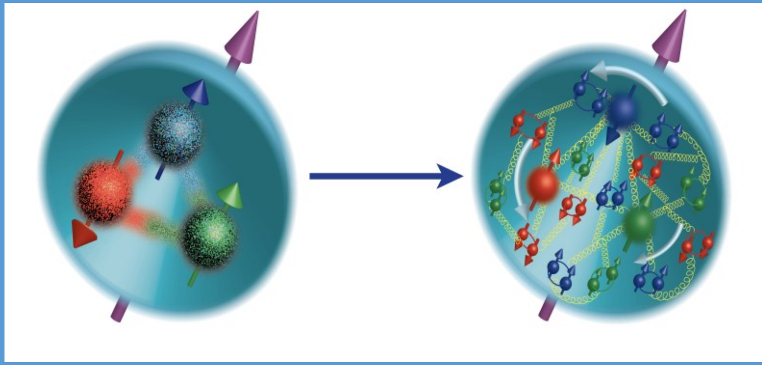


Ratio of Parton Distribution Functions of Pb over Proton:

- Without EIC, large uncertainties in **nuclear sea quarks and gluons**
- EIC significantly reduces uncertainties
- Impossible to achieve for current and future pA data at RHIC & LHC

EIC: the world's first polarized electron-proton collider

Polarized proton as a laboratory for QCD



- How are the sea quarks and gluons, and their spins, *distributed in space and momentum* inside the nucleon?
- How do the *nucleon properties such as **spin and mass emerge*** from them and their interactions?

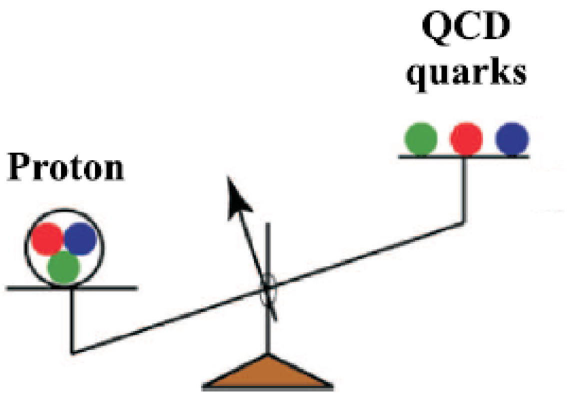
The proton: QCD at work!

What we know about the content of the proton:

- 2 *up* quarks (q_u = *2/3 e*) + 1 *down* quark (q_d = *-1/3 e*)
- Any number of quark-antiquark pairs (sea)
- Any number of gluons

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

Fundamental questions:



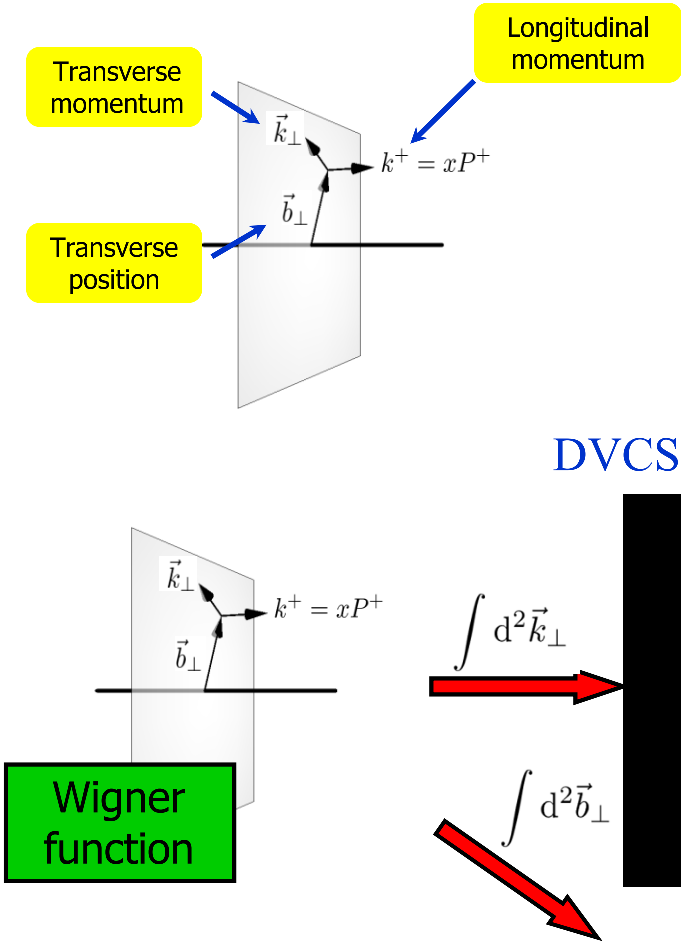
- Origin of proton **mass**?

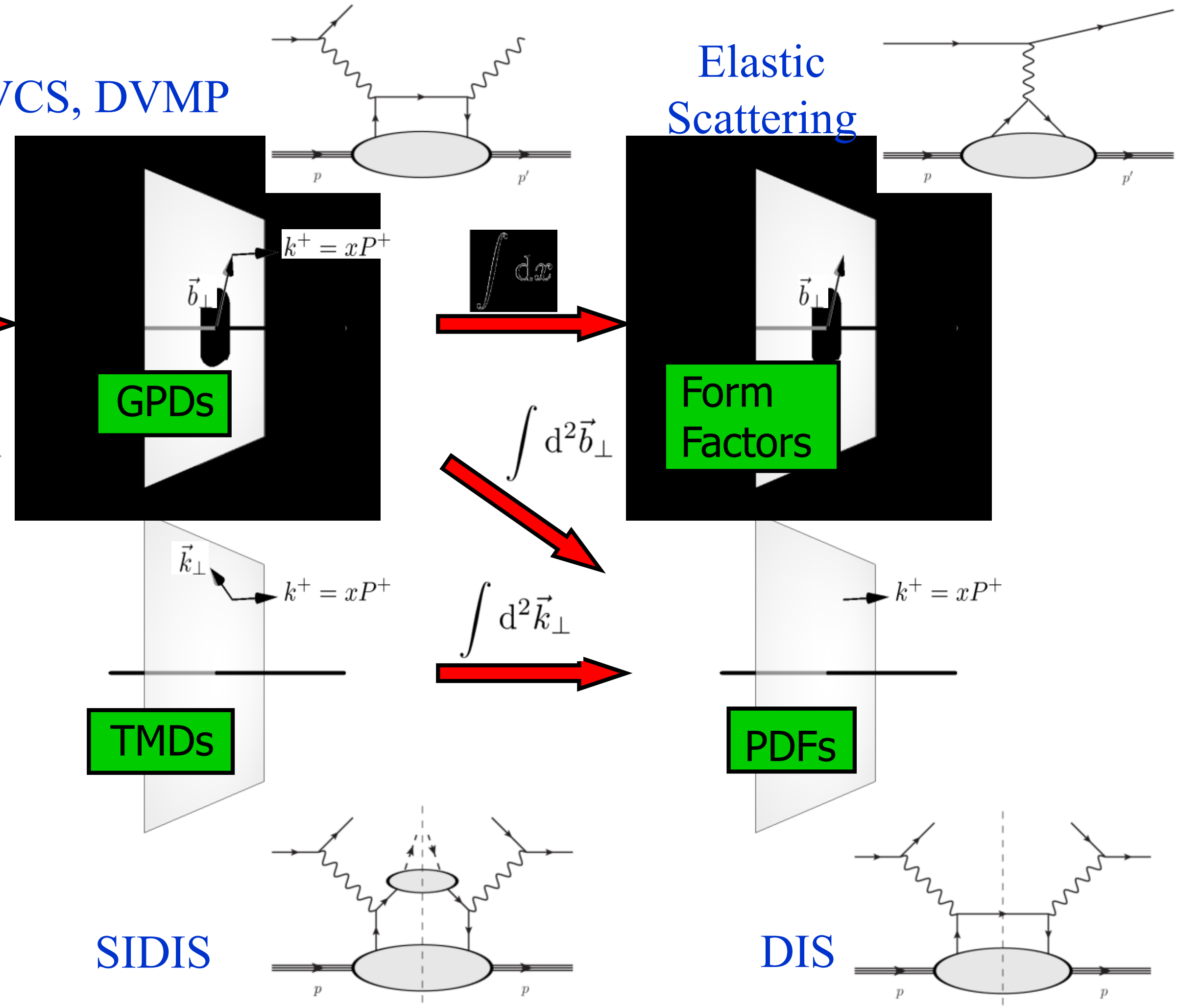
→ Only a small fraction comes from the actual quark masses
→ Most of it comes from the ***motion of quarks and gluons***

- Origin of proton **spin**?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

Multi-dimensional mapping of the nucleon



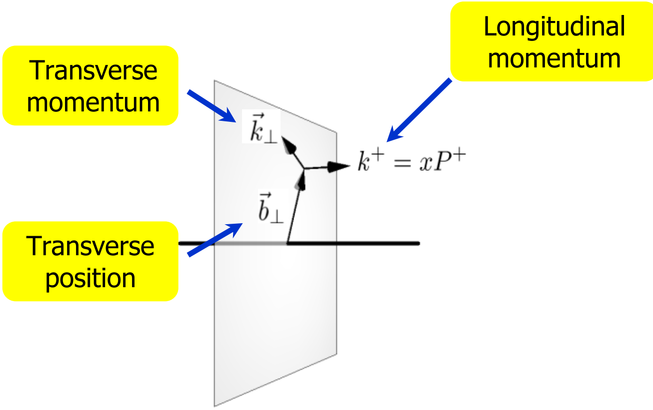


Legend:

GPDs: Generalized Parton Distributions
TMDs: Transverse Momentum Dependent Distributions
PDFs: Parton Distribution Functions

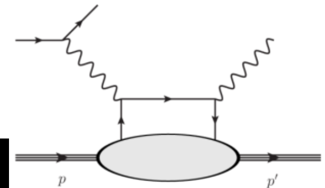
DVCS: deeply Virtual Compton scattering
DVMP: deeply Virtual meson production
SIDIS: semi-inclusive DIS

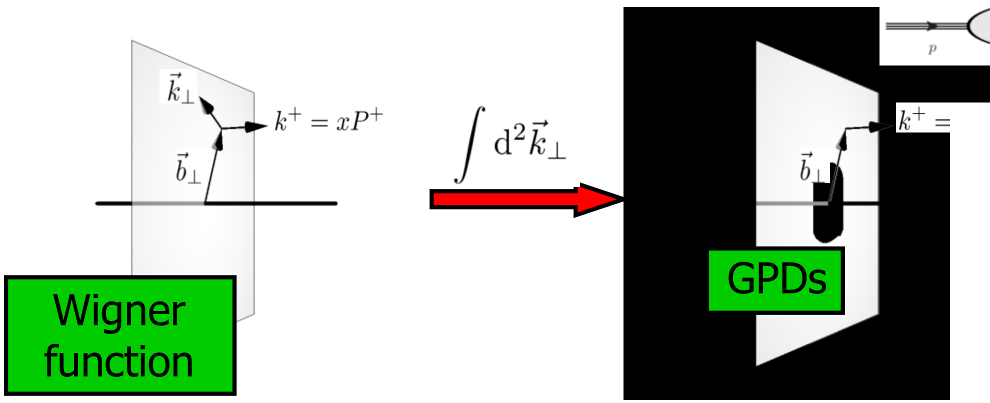
Multi-dimensional mapping of the nucleon

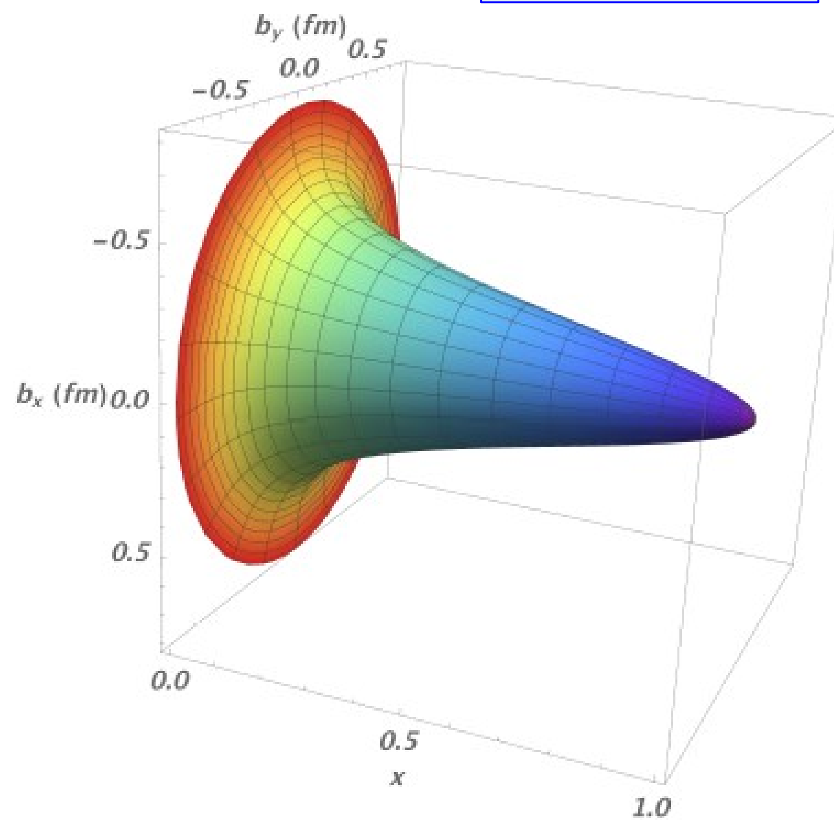


Proton tomography from JLab data at 6 GeV on DVCS

DVCS, DVMP







Ongoing intense research effort at **JLab** and **COMPASS** in the valence (and sea) quark regimes

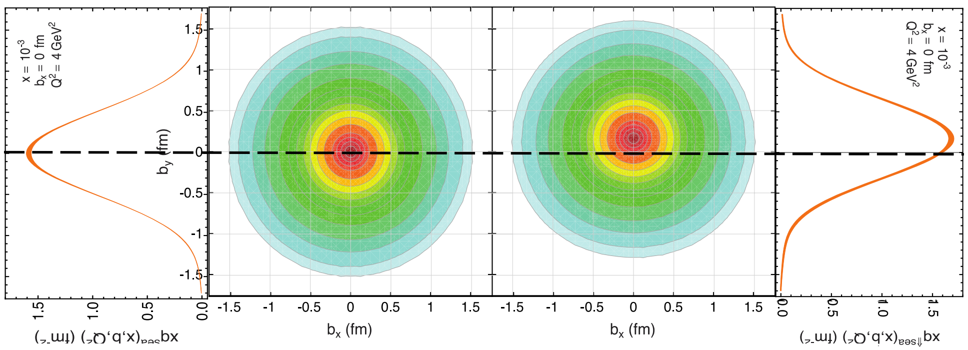
Multi-D partonic image of the nucleon with the EIC

Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum)

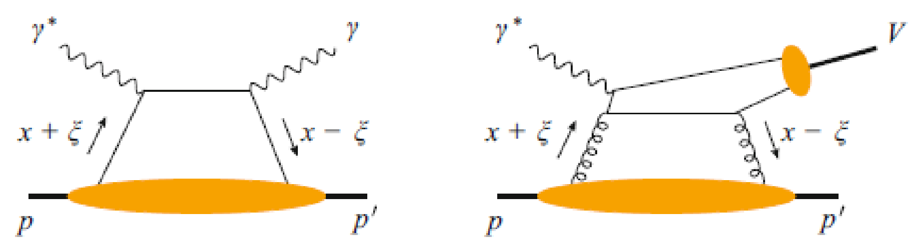
Measurable via **exclusive scattering**

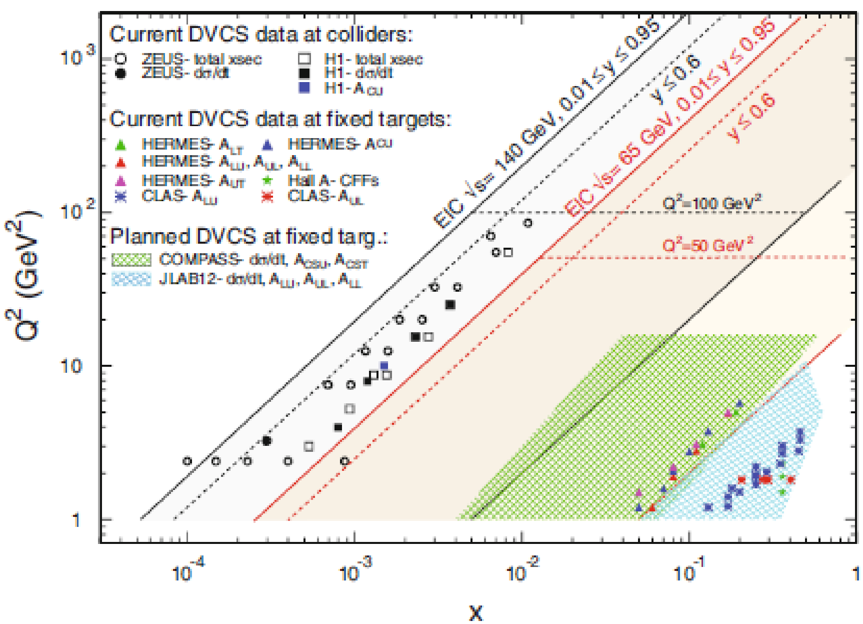
Sea quarks

unpolarized polarized

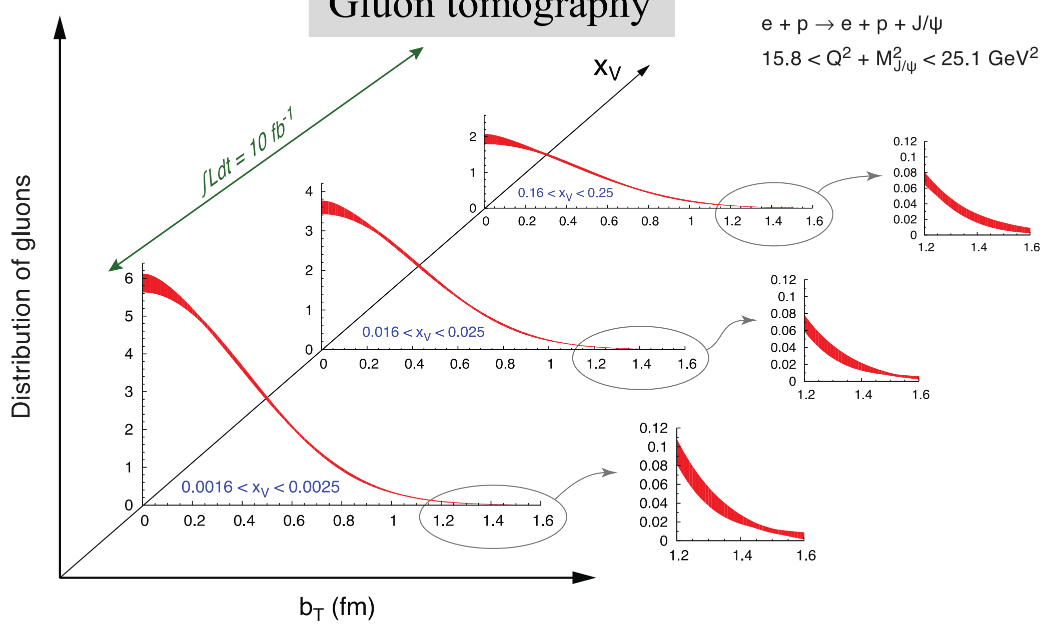


Generalized Parton Distributions





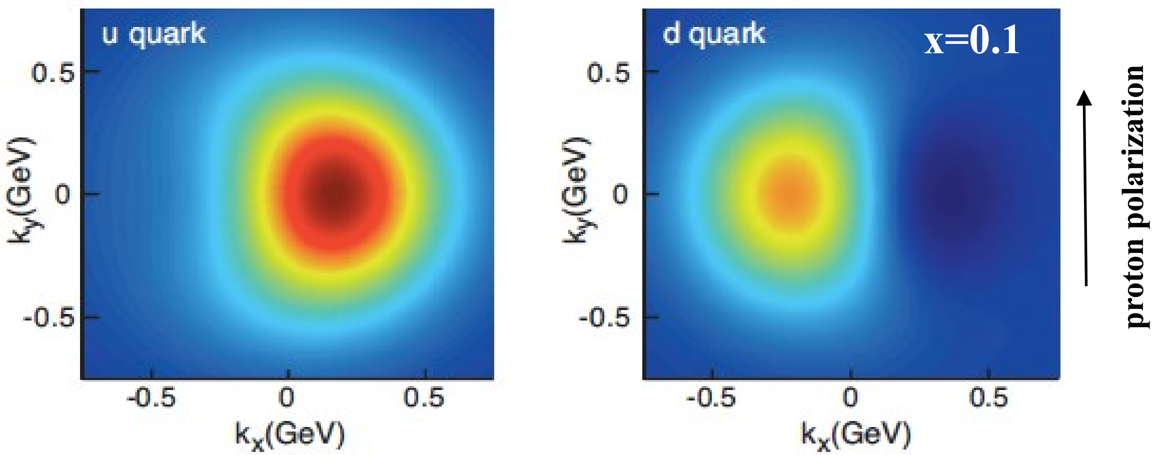
Gluon tomography

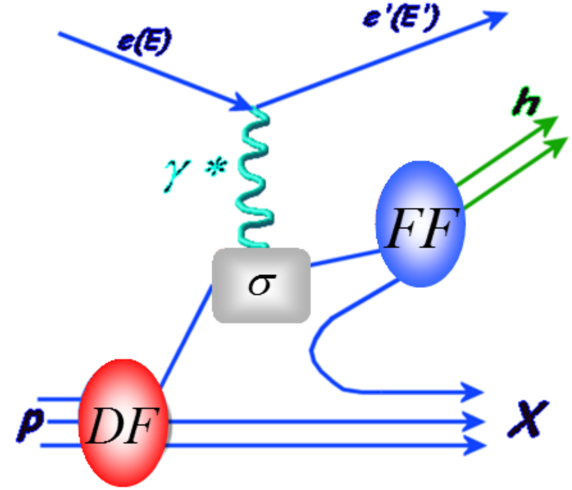


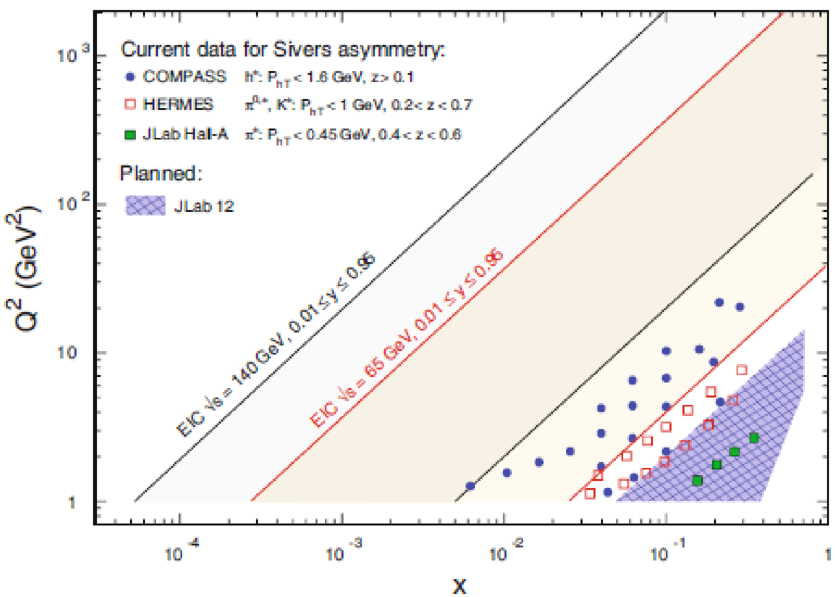
Multi-D partonic image of the nucleon with the EIC

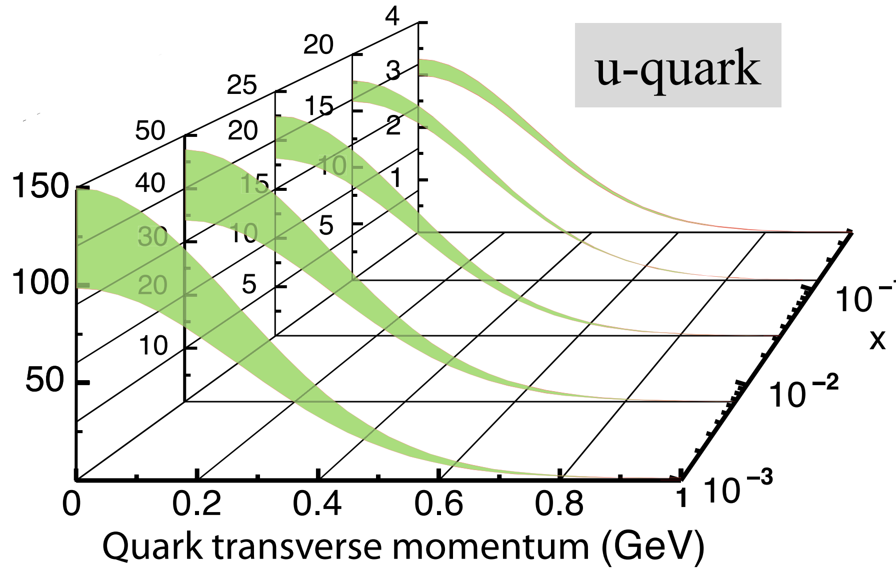
Spin-dependent 3D momentum space – Measurable in **semi-inclusive scattering**

Transverse Momentum Distributions

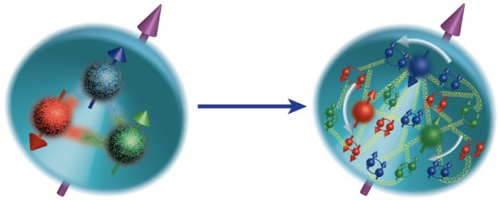








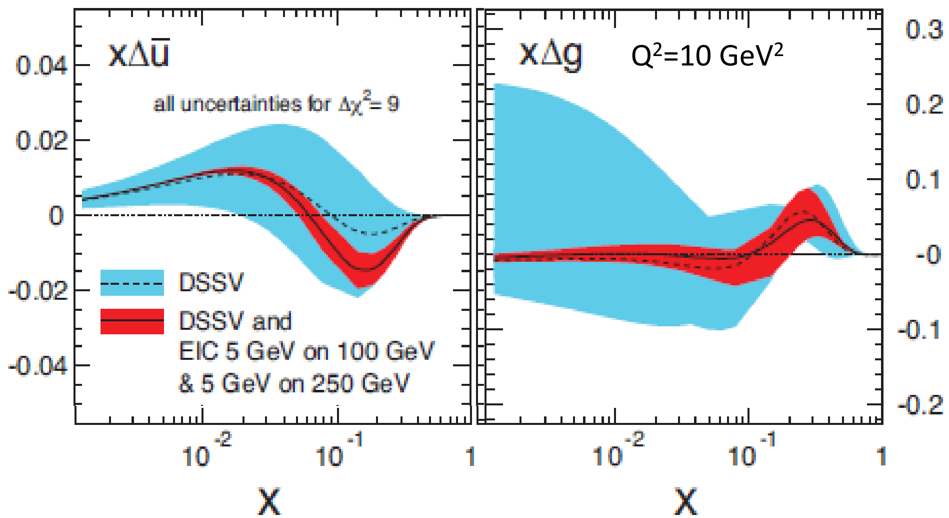
Understanding nucleon spin

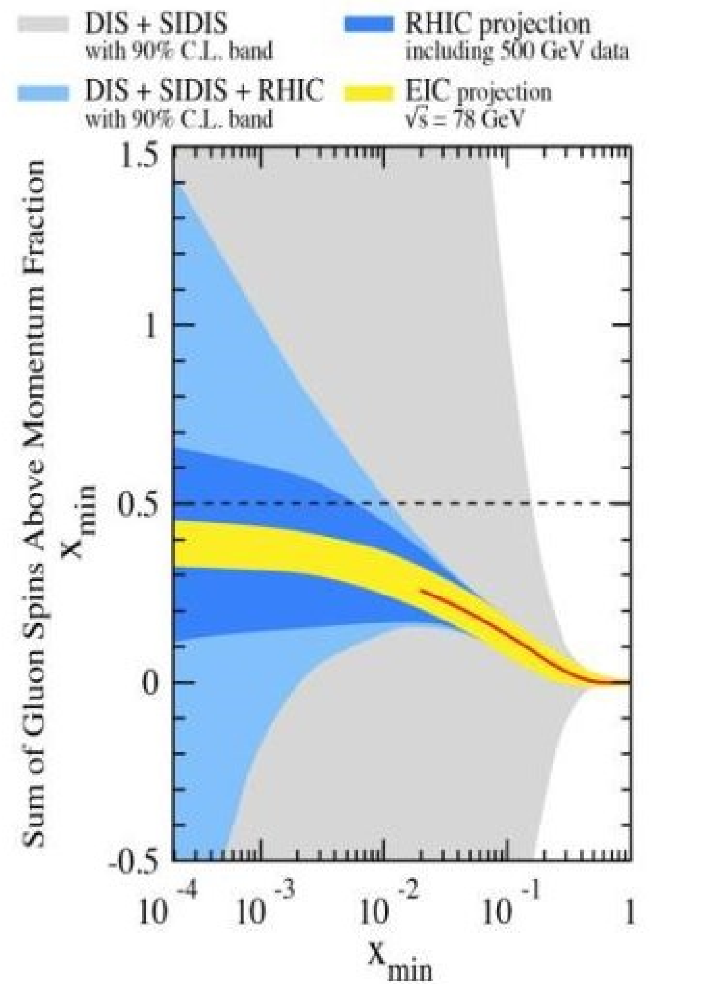


"Helicity sum rule"

$$\frac{1}{2}\hbar = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{quark contribution}} + \underbrace{\Delta G}_{\text{gluon contribution}} + \underbrace{\sum_q L_q^z + L_g^z}_{\text{orbital angular momentum}}$$

EIC projected measurements:
precise determination of polarized PDFs of quark sea and gluons ➔ precision ΔG and ΔS
→ A clear idea of the magnitude of $\sum L_q + L_g$

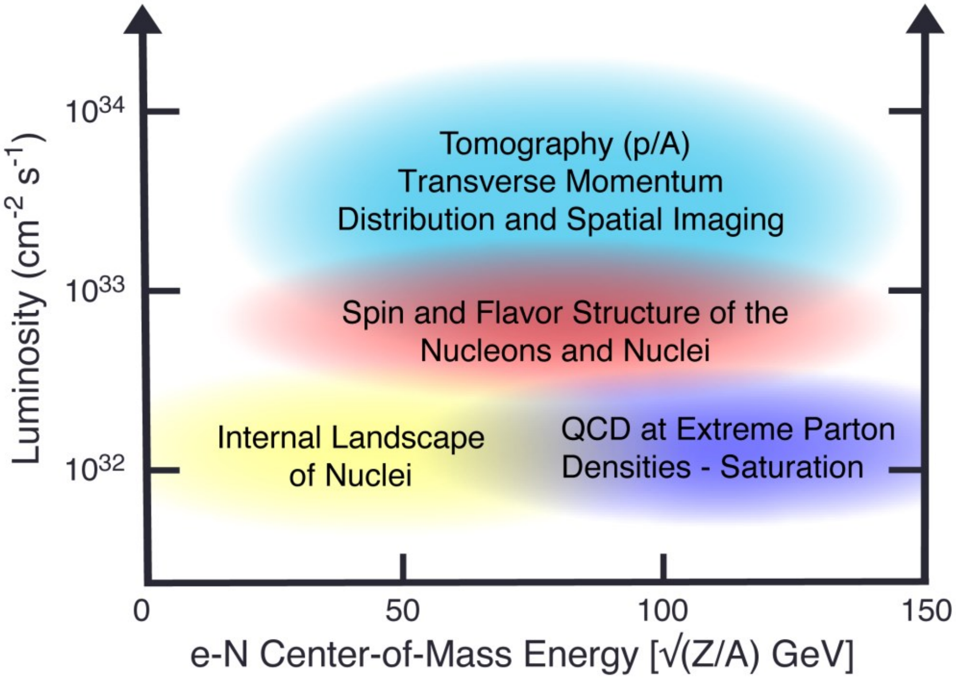




Spin and Lattice: Recent Activities

- ❑ **Gluon's spin contribution on Lattice: $S_G = 0.5(0.1)$**
  Yi-Bo Yang et al. PRL **118**, 102001 (2017)
- ❑ **J_q calculated on Lattice QCD:**
  χQCD Collaboration, PRD91, 014505, 2015

What EIC do we need?

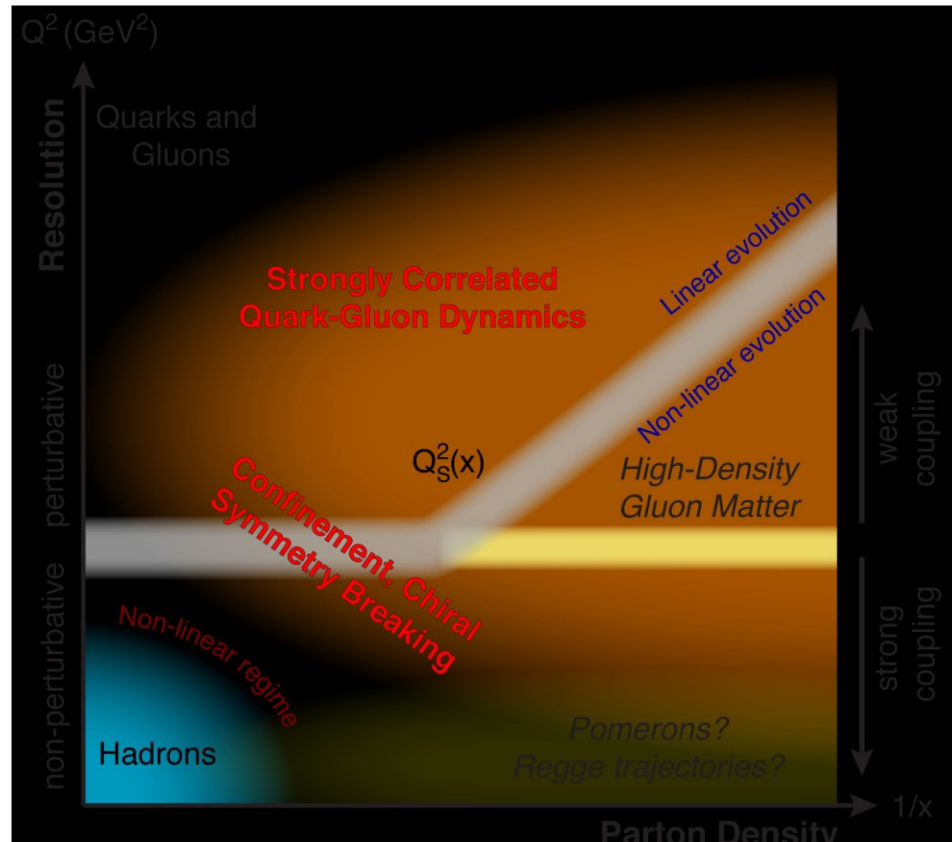


From **inclusive** to fully **exclusive** reactions

→ High energy and luminosity

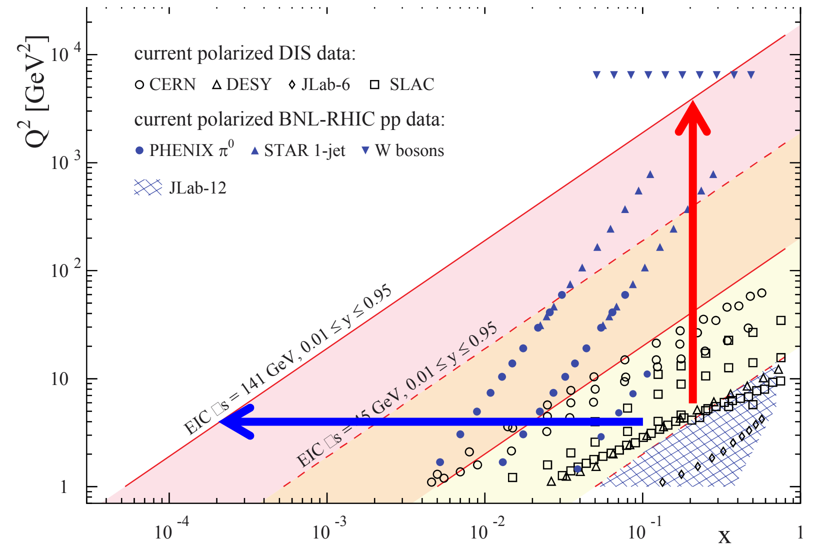
Various physical regimes to explore

→ Wide coverage in Q^2 and x



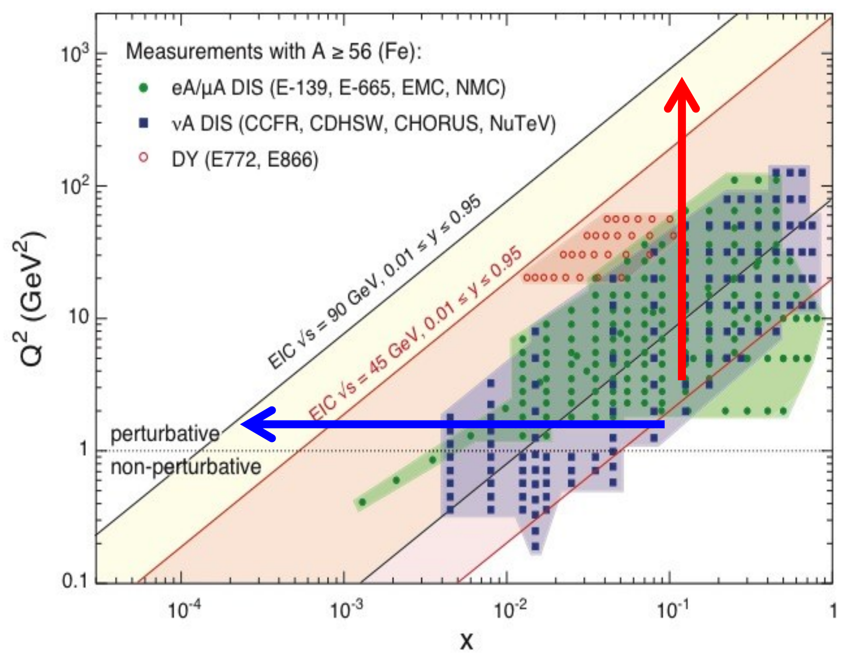
Electron-Ion Collider: specs

First collider in the world in $\vec{e}$-$\vec{p}$/$\overrightarrow{light\ nuclei}$ mode
+ electron-nuclei mode



For e-p/n collisions:
- Polarized e, p, deuteron or ^{3}He beams
- Electron beam energy ~ 5-20 GeV
- Proton beam energy up to ~50 - 250 GeV
- Luminosity L_{ep} ~ $10^{33\text{-}34}$ $cm^{-2}sec^{-1}$
- Center of mass energy s ~ sqrt($4E_pE_e$) ~ 30 – 140 GeV

For e-A collisions (use the same collider ring…):
- Wide range in nuclei (proton-to-uranium)
- Luminosity per nucleon (scaled) by the one for e-p
- Variable CM energy (scaled by A)



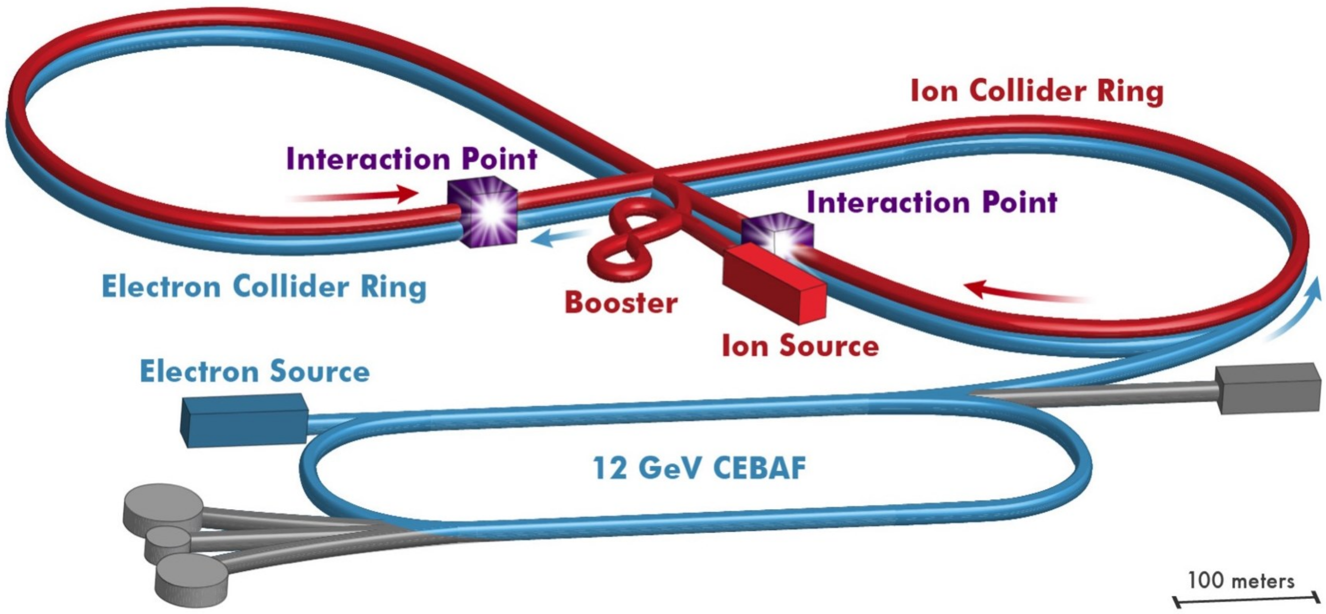
Two designs, at two US national lab, are currently under consideration:

Jefferson Lab

BROOKHAVEN NATIONAL LABORATORY

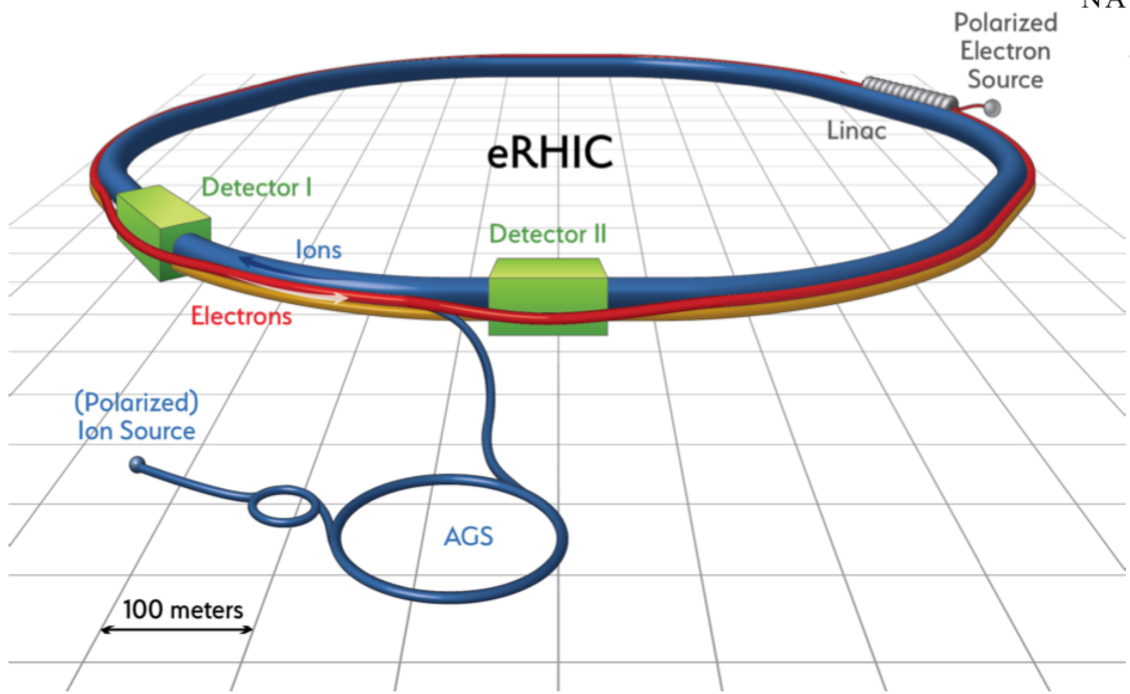
JLEIC realization

Jefferson Lab



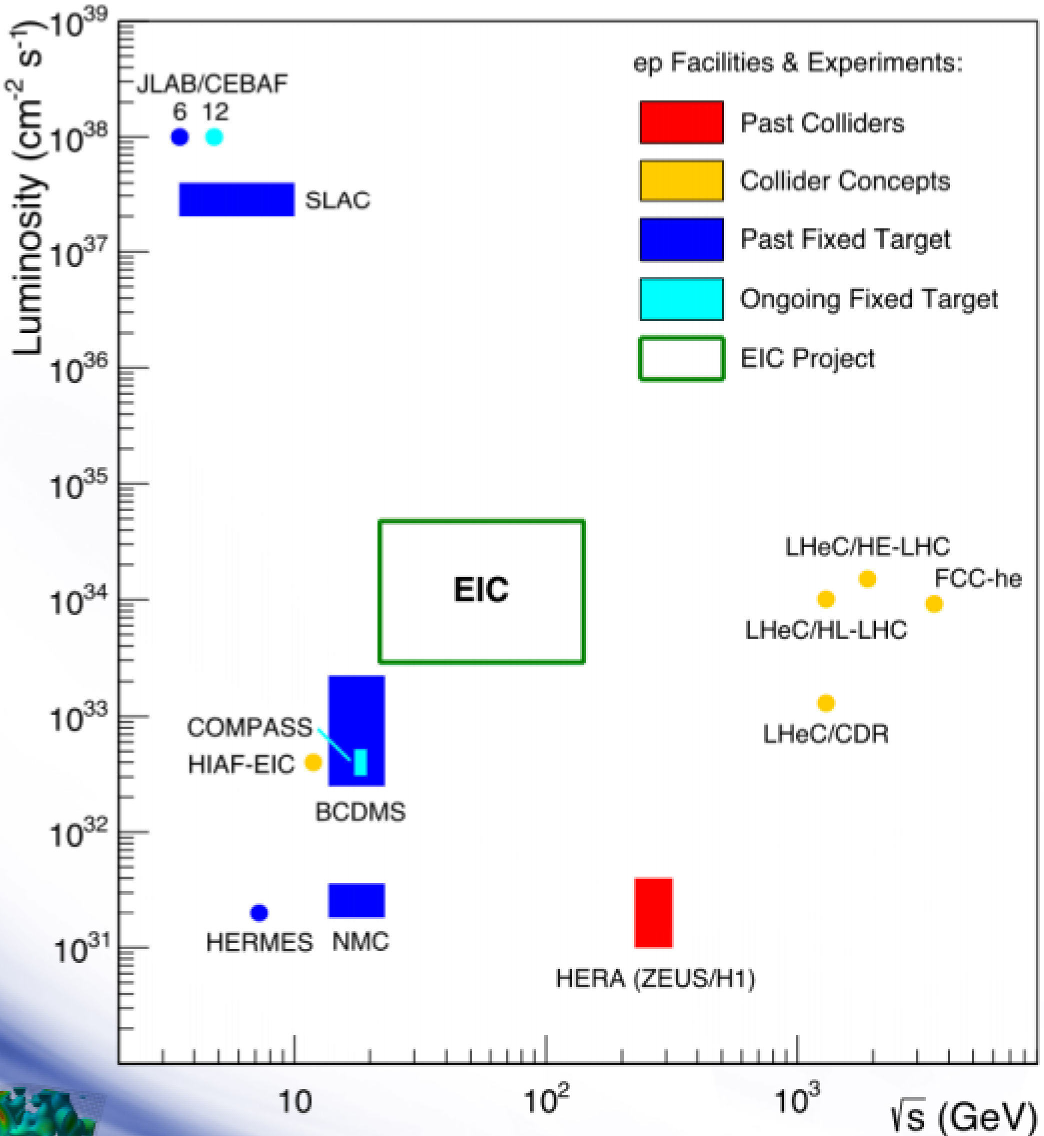
- Use existing CEBAF for polarized electron injector
- Figure 8 Layout: Optimized for high ion beam polarization ➔ polarized deuterons
- Energy Range: $\sqrt{s}$: 20 to 65 - 140 GeV (magnet technology choice)
- Fully integrated detector/IR
- JLEIC achieves initial high luminosity, with technology choice determining initial and upgraded energy reach

BROOKHAVEN NATIONAL LABORATORY



- Use existing RHIC
  - Up to 250-GeV protons, 15 GeV electrons
  - Existing: tunnel, detector halls & hadron injector complex
- Add 18-GeV electron accelerator in the same tunnel
  - Use either high intensity Electron Storage Ring or Energy Recovery Linac
- Achieve high luminosity, high energy e-p/A collisions with full acceptance detector
- Luminosity and/or energy staging possible

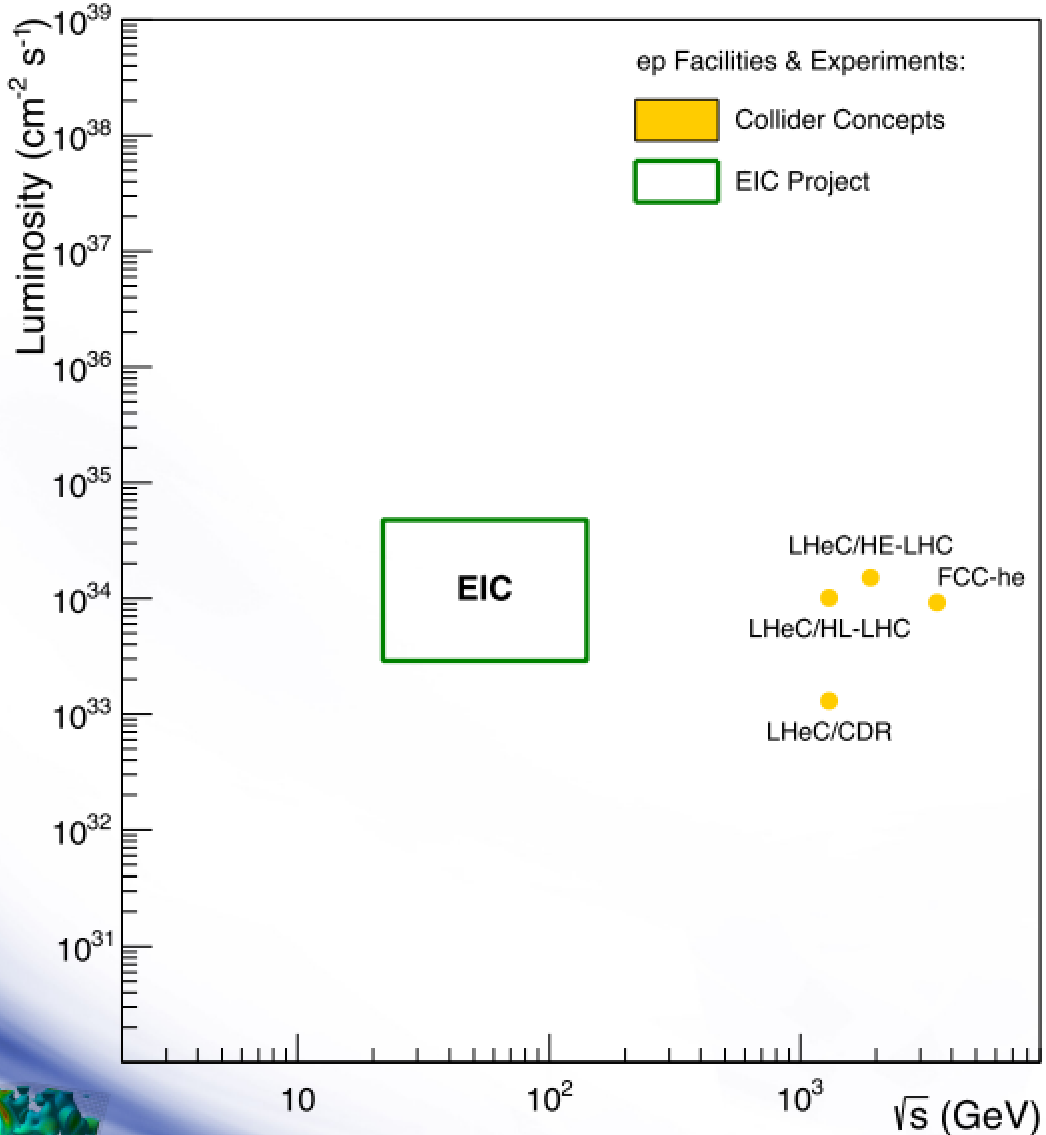
Uniqueness of EIC among all DIS facilities



All DIS facilities in the world.

However, if we ask for:

Uniqueness of EIC among all DIS facilities

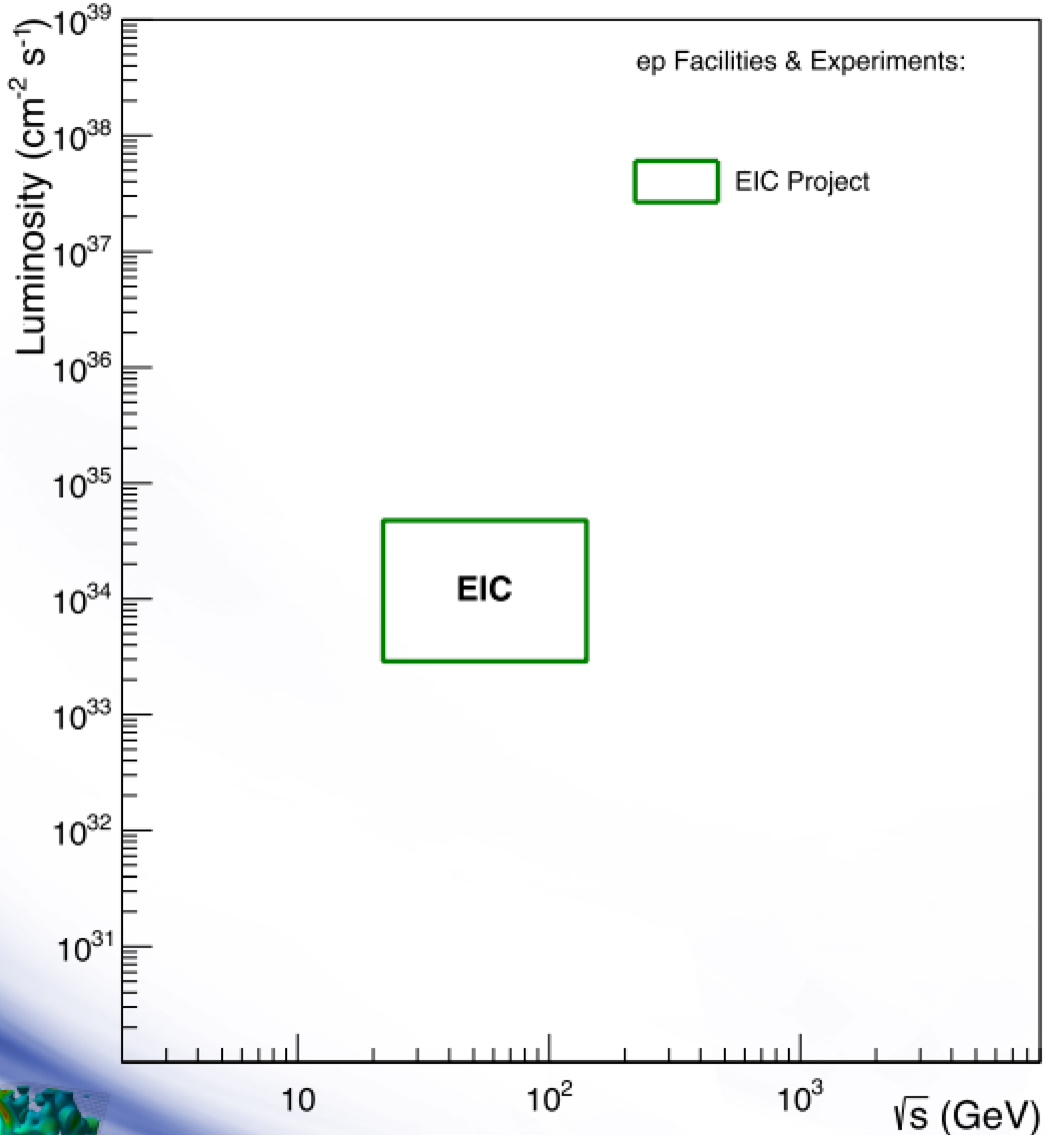


All DIS facilities in the world.

However, if we ask for:

- **High luminosity and wide reach in $\sqrt{s}$**

Uniqueness of EIC among all DIS facilities



All DIS facilities in the world.

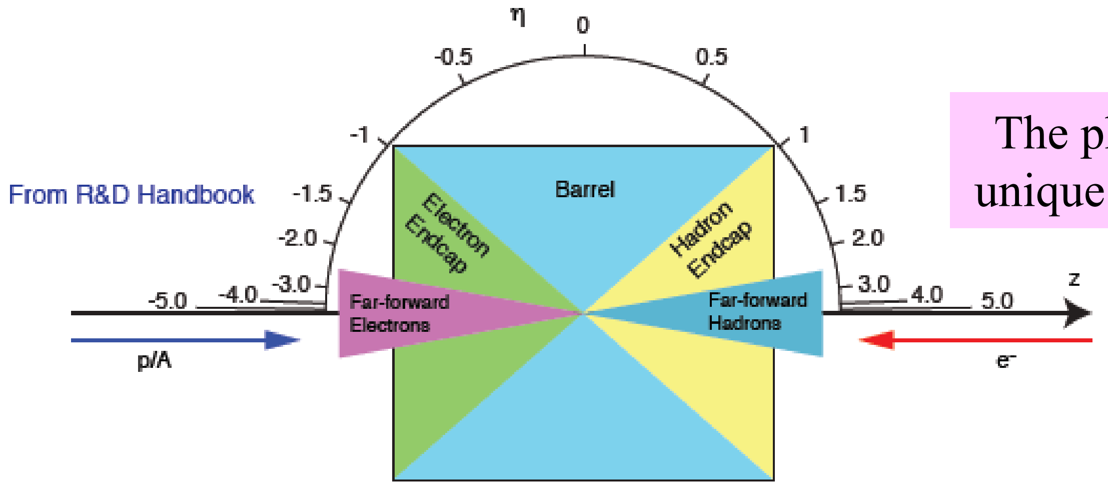
However, if we ask for:

- **High luminosity and wide reach in $\sqrt{s}$**
- **Polarized lepton and hadron beams**
- **Nuclear beams**

EIC stands out as a unique facility…

EIC detector requirements

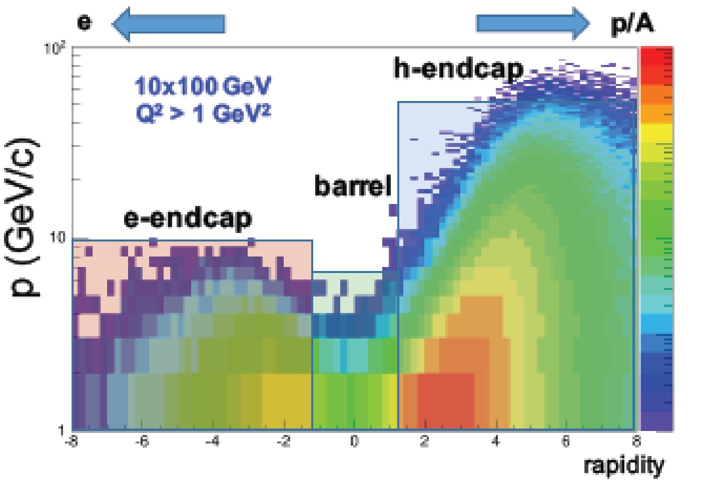
Detector requirements are mostly **site-independent**, with some slight differences in the forward region (IR integration)



The physics characteristics bring unique challenges to EIC detectors

General requirements:

- Hermetic detector
- Low mass inner tracking, good PID (e, π/K/p) at wide angle, calorimetry, forward and backwards tracking
- Moderate radiation hardness requirements, low pile-up, low multiplicity

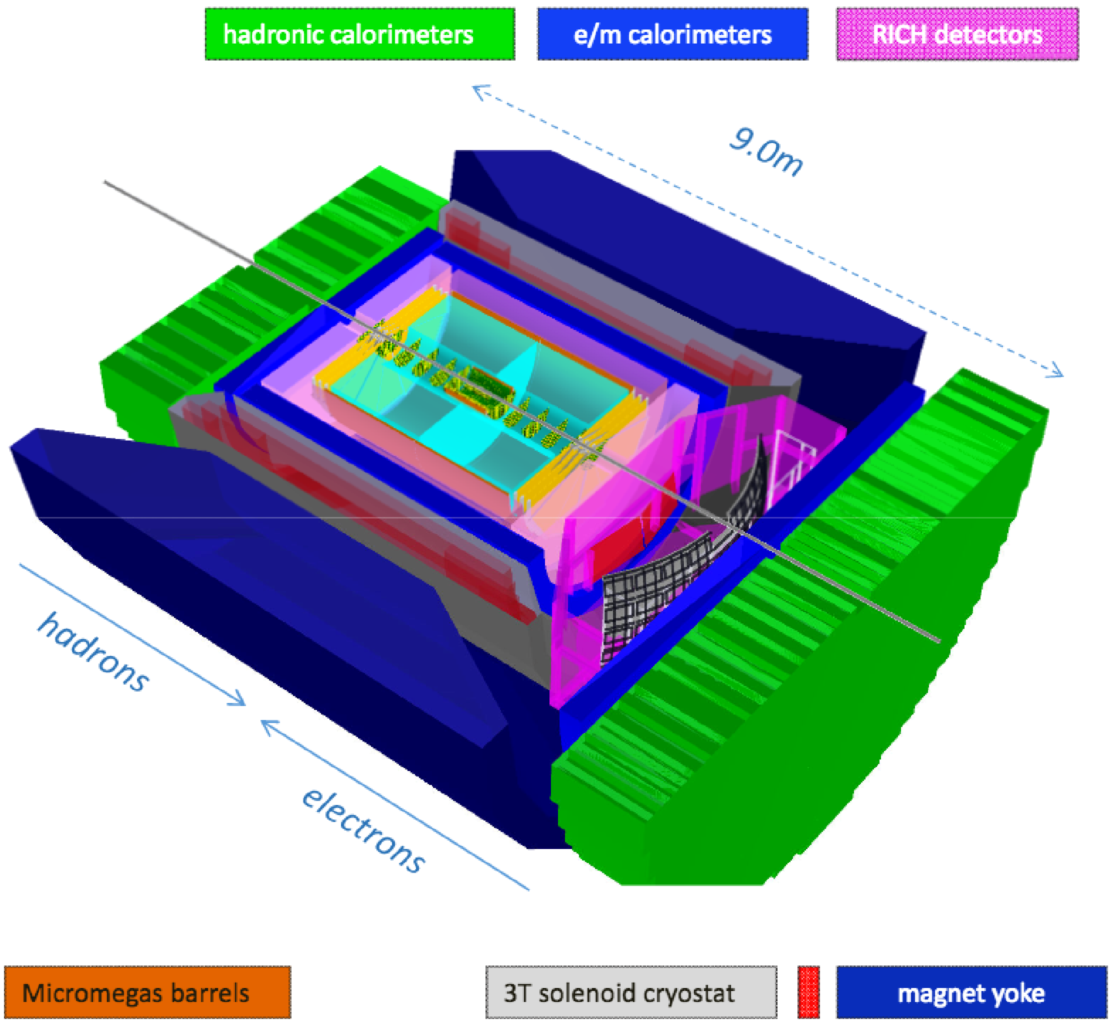


EIC Detector Concepts: BNL

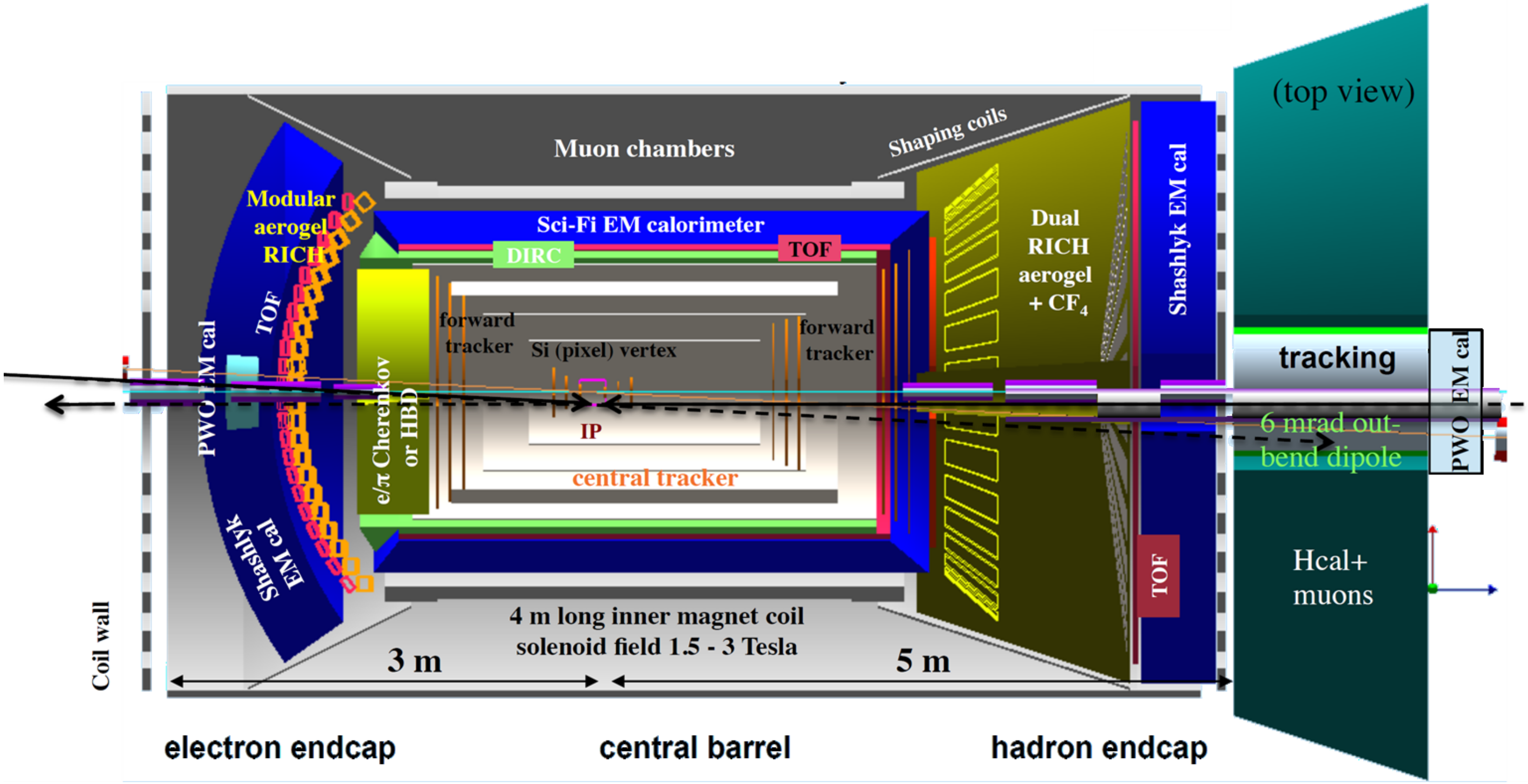
BeAST (Brookehaven eA Solenoidal Tracker)

- **From the center outwards:**
  - ✓ Silicon vertex in the center
  - ✓ Trackers
  - ✓ Cerenkov detectors
  - ✓ EM and hadronic calorimeters
  - ✓ Solenoid

- **Detectors are standard collider designs, using latest technologies**
  - ✓ Very similar to RHIC or LHC detectors, with emphasis on PID capabilities
  - ✓ Asymmetry between the hadron and electron sides, with different PID requirements



EIC Detector Concepts: JLab



- **Similar concept to BNL**

✓ With lots of room devoted to RICH detectors

✓ The low multiplicity expected in e-A allows for better Particle ID

- **Low angle capabilities**

✓ Critical for many processes

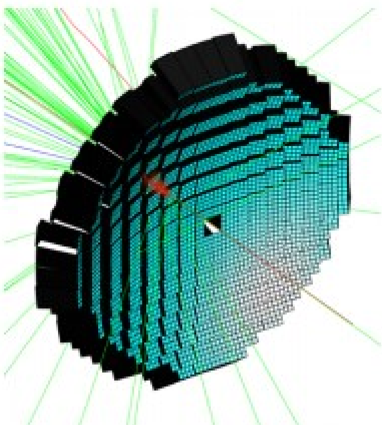
  ➢ Coherent scatterings

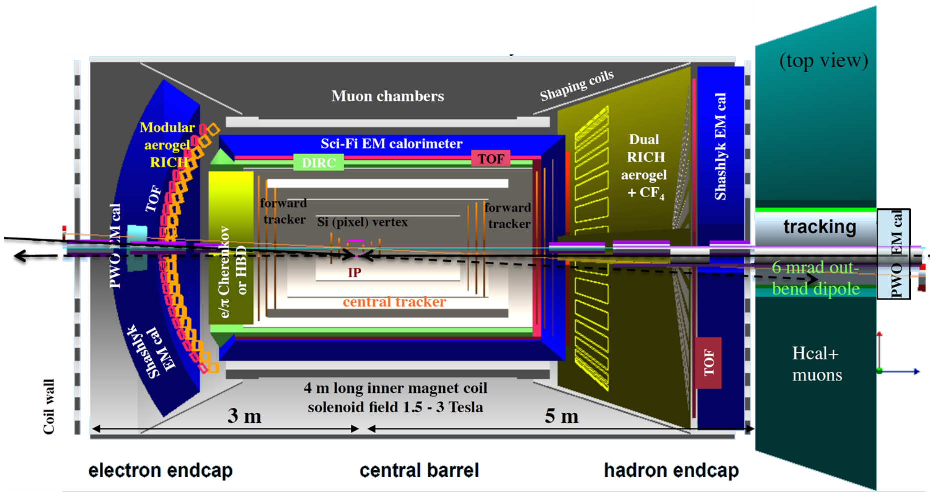
  ➢ Centrality measurements

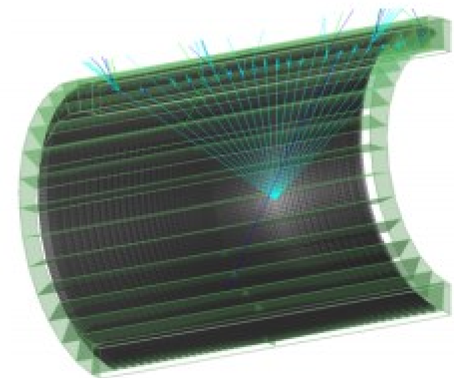
✓ Unique in comparison to the many fixed target facilities performing e-A

Calorimetry for EIC

- **IPNO part of Consortium on Calorimetry at EIC since 2014**
- **Calorimetry activity at IPNO has been financed by BNL funds since 2015**







JLEIC detector concept

- Electron identification and trigger (e-EMC, barrel EMC)
- Measurement of electron kinematics (e-EMC, barrel EMC), high resolution is needed
- Jets, DIS: kinematics and trigger for hadronic final states (barrel EMC/Hcal, h-MC/Hcal)
- Photon ID for DVCS
- Diffractive ID via rapidity gap (h-HCal)
- Measurement of the energy of high-energy particles (h-Hcal)

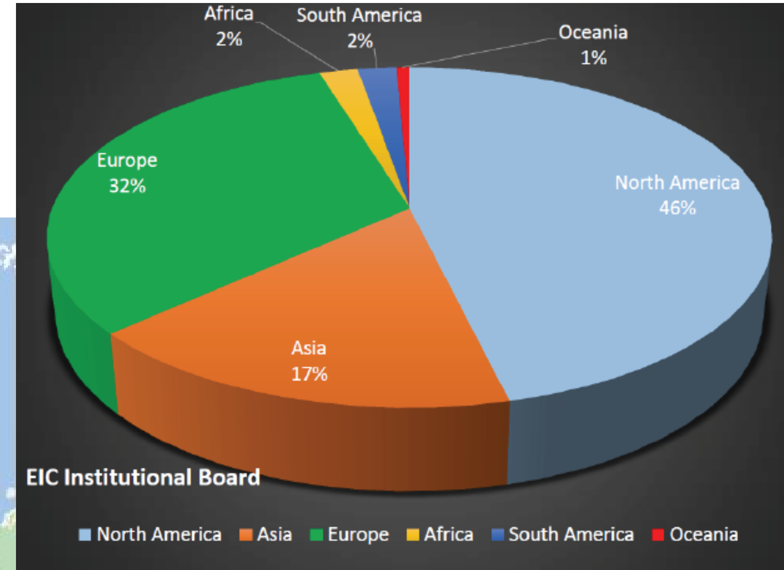
R&D studies ongoing at IPNO on:

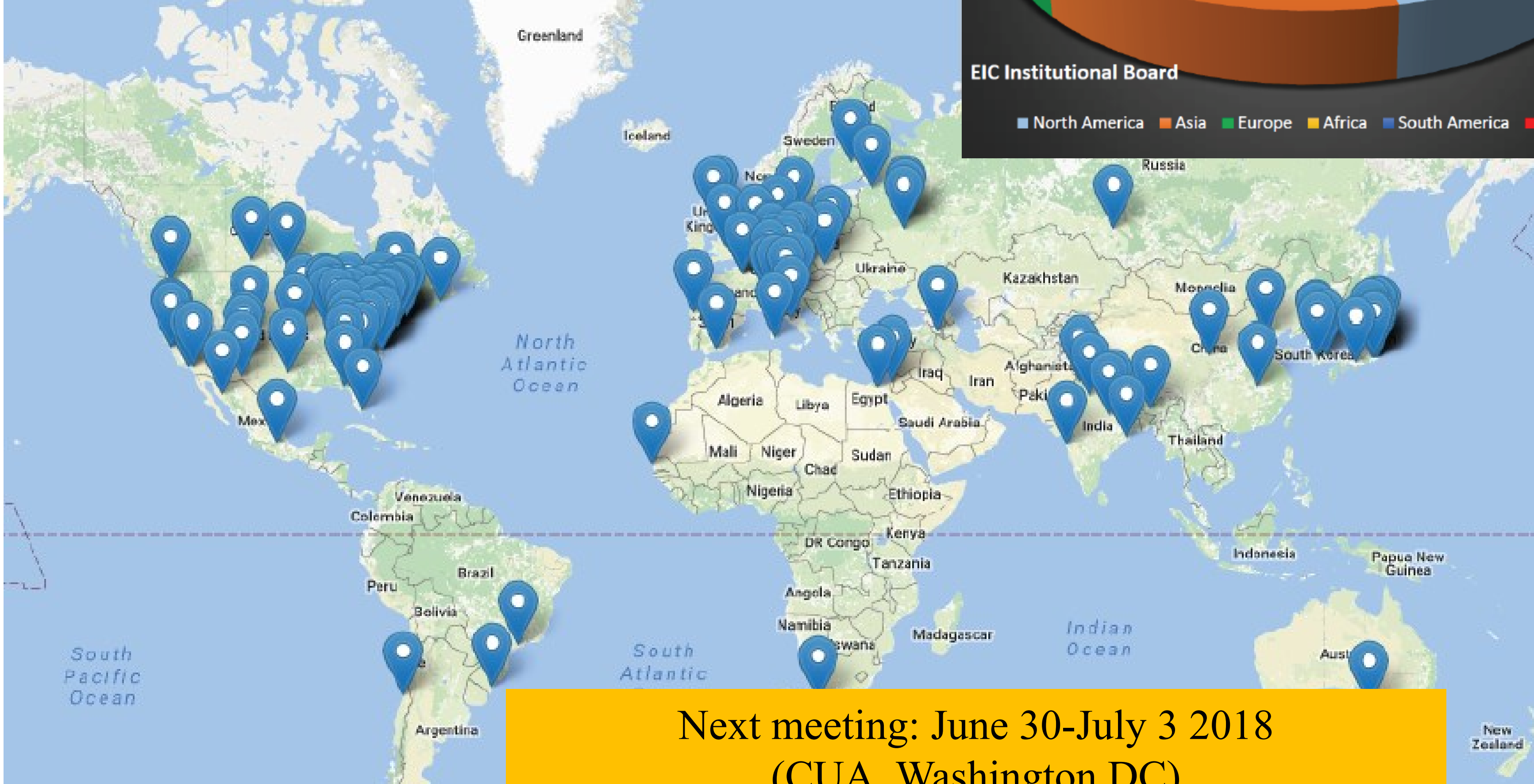
- Crystals-based EMCal at small angles: high resolution and PID are required
- Photo-sensors: SiPM & APDs, radiation damage effects

EIC Users Group

697 scientists (+students & engineers), 29 countries, 160 institutions

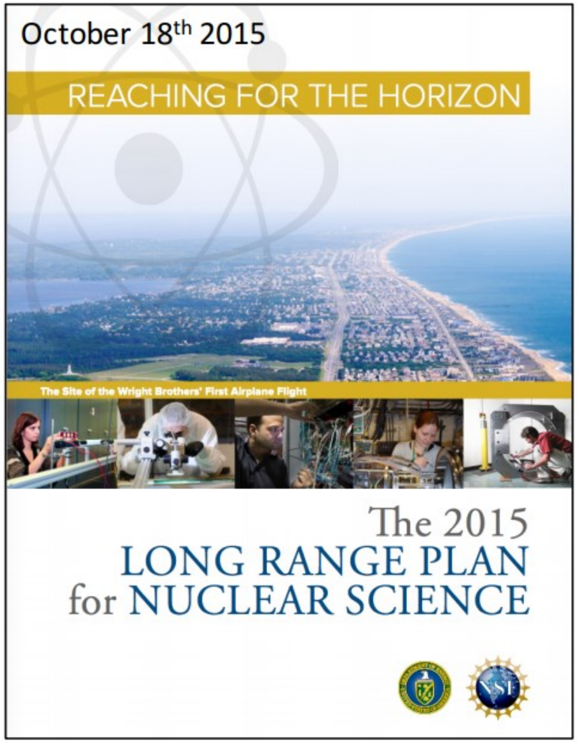
Strong European involvement, still low from France





Next meeting: June 30-July 3 2018
(CUA, Washington DC)

It is the ideal time to get involved in the EIC!



1. **The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.**
   - **12 GeV** – unfold quark & gluon structure of hadrons and nuclei
   - **FRIB** – understanding of nuclei and their role in the cosmos
   - **Fundamental Symmetries Initiative** – physics beyond the SM
   - **RHIC** – properties and phases of quark and gluon matter

   The ordering of these four bullets follows the priority ordering of the 2007 plan
2. **We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.**

4. **We recommend increasing investment in small and mid-scale projects and initiatives that enable forefront research at universities and laboratories.**

- A review by the National Academy of Sciences has begun. The Charge is: *"Assess the scientific justification for a U.S. domestic electron ion collider facility"* (report expected for June 2018)
- DOE project "CD0" (*Establish Mission Need*) after NAS review: 2018
- EIC construction must start after FRIB is completed, which will not happen before 2020.
- Most optimistic scenario: start EIC construction (CD3) in FY20. More realistic: FY22-23
- According to the NSAC/LRP recommendations, the best estimate for construction completion of EIC is 2025-2030

New Users → New Physics → Lots of activities

- Jet studies at the EIC:
  - Systematic investigations of general issues in jet-finding at an EIC
  - Understanding of "micro-jets" – jets with only few hadrons
  - Understanding the jet structure modifications in nuclei vs. protons
  - Energy loss in cold QCD matter (Nuclei) vs. hot QCD matter at RHIC and LHC
- Precision measurements of the "initial state" for collisions leading to the QGP being studied at RHIC and LHC
- Precision PDF measurements in proton, neutron & photons at the EIC:
  - Study the free neutron PDFs through tagging and on-shell extrapolation
  - Study the gluon PDFs at large Bjorken x through evolution and open-charm production
  - Study of gluons TMDs
  - Study the potential impact on Higgs studies in the High-Luminosity LHC era
  - Study the impact of TMDs @ EIC on W-production at the LHC
  - Polarized and unpolarized photon PDFs
- Measurements of PDFs in pions and kaons through the Sullivan process
  - Theoretical studies of the equivalence of near-off-shell and on-shell pions and kaons
  - Study the extraction of, and expected differences of, quark and gluon PDFs in pions, kaons and nucleons, and the relation to their physical masses
- Nucleon structure with electroweak probes, and precision BSM physics (i.e. Sin^2Q_W)
- Heavy quark & quarkonia production with 100-1000 times HERA luminosity
- In view of new discoveries of multi-quark XYZ states: what could EIC contribute?

New Users → New Physics → Lots of activities

Programs related to EIC

Highly Active EIC Community in evolution

Conclusions and outlook

- The EIC is the **optimal future facility** for the study of **QCD**
- This **future is approaching fast** (start ~2030) and requires an involvement from **today**
- This could be a **unifying project for the hadronic physics community** in France:
  - ✓ The whole **JLab team** is getting involved in the **detector conception** phase and the definition of the **physics program,** in parallel to the ongoing research work with JLab@12 GeV
  - ✓ Many **French theoreticians** are strongly interested in EIC
  - ✓ Strong interest and **commitment from IRFU** (a new staff member was recently hired to work explicitly on EIC)
  - ✓ Potential interest from the **ALICE community** in France
- Possible contributions in the **development of the accelerator**

For more details on the physics case, refer to the EIC White Paper: Electron-Ion Collider: The next QCD frontier, EPJA 52 (2016)

Contact us at IPNO if interested! niccolai@ipno.in2p3.fr ☺