Status and Plans of the Electron-Ion Collider (EIC) Project

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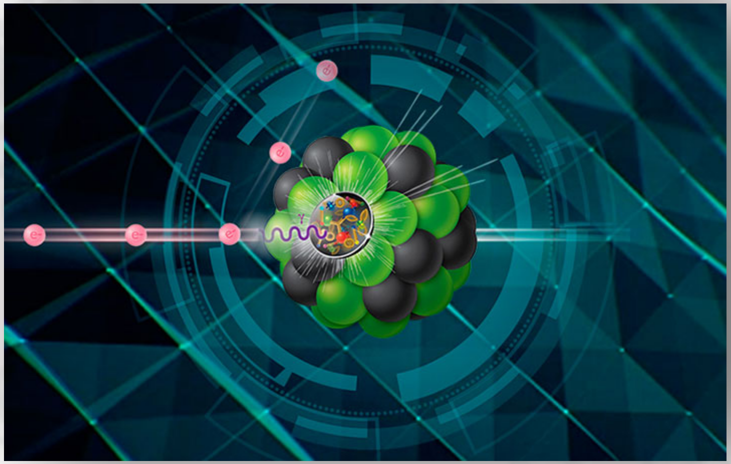
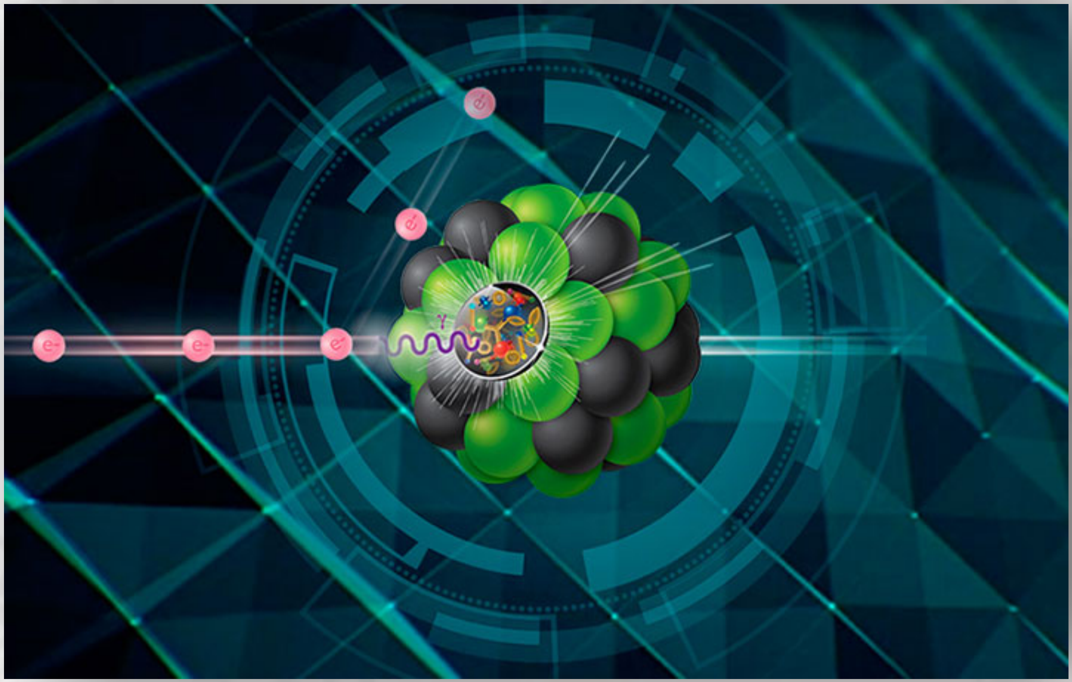


Outline

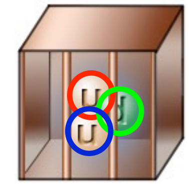
- Theoretical foundation
- EIC Physics Pillars
- EIC Project Development
- EIC Accelerator Design
- EIC Detector Requirements and R&D
- EIC Users Group
- EIC Current status and Next Steps
- Summary



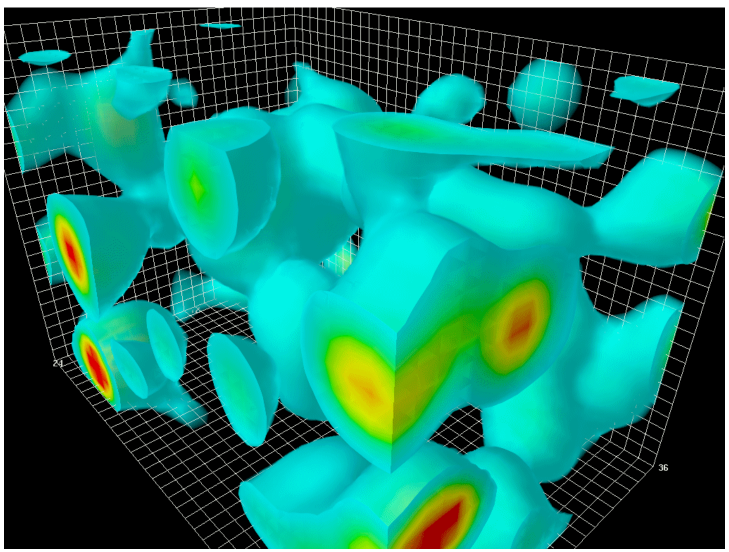
Theoretical foundation

- EIC - A QCD lab to explore the structure and dynamics of the visible world

$$\mathcal{L}_{QCD} = \sum_{j=1}^{n_f} \bar{\psi}_j \left(iD_\mu \gamma^\mu - m_j \right) \psi_j - \frac{1}{4} \mathrm{Tr}\, G^{\mu\nu} G_{\mu\nu}$$



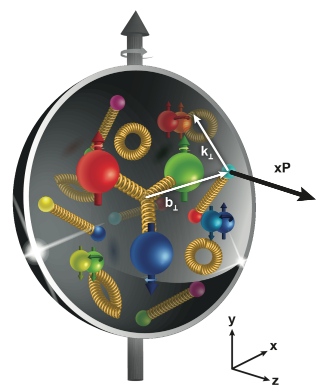
- Interactions arise from fundamental symmetry principles: $SU(3)_c$
- Properties of visible universe such as mass and spin (e.g. proton): Emergent through complex structure of the QCD vacuum



D. Leinweber: Quantum fluctuations in gluon fields

Major goal:

Understanding QCD interactions and emergence of hadronic and nuclear matter in terms of quarks and gluons



Essential elements looking forward:

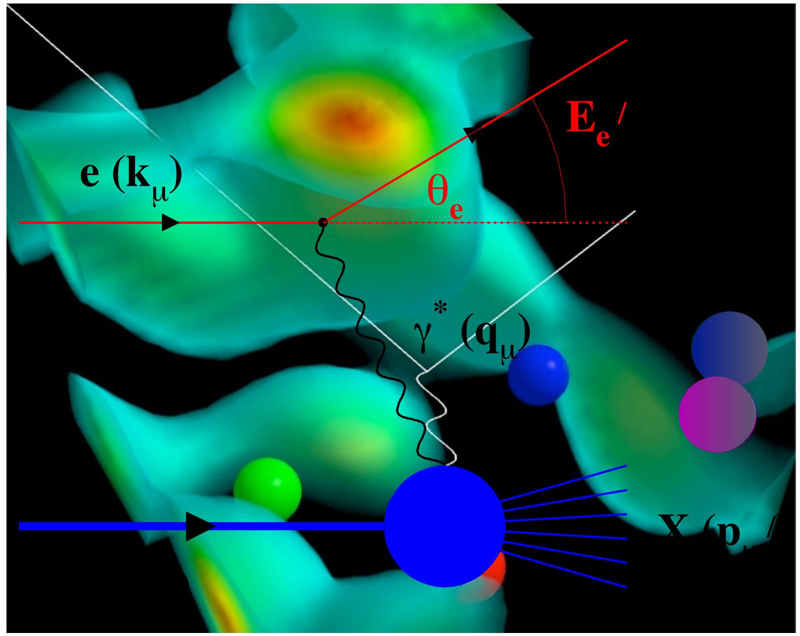
1) Tomography of hadrons and nuclear matter in terms of quarks and gluons
2) Synergy of experimental progress and theory

Theoretical foundation

- DIS - Kinematics

$$k = \begin{pmatrix} E_e \\ 0 \\ 0 \\ -E_e \end{pmatrix}$$

$$p = \begin{pmatrix} E_P \\ 0 \\ 0 \\ E_P \end{pmatrix}$$



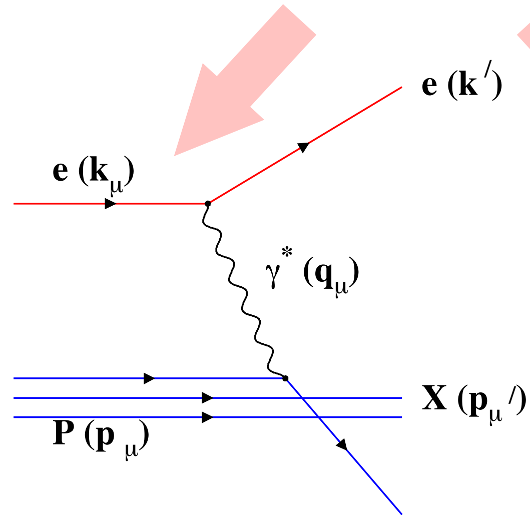
$$k' = \begin{pmatrix} E'_e \\ E'_e \sin\theta'_e \cos\phi'_e \\ E'_e \sin\theta'_e \sin\phi'_e \\ E'_e \cos\theta'_e \end{pmatrix}$$

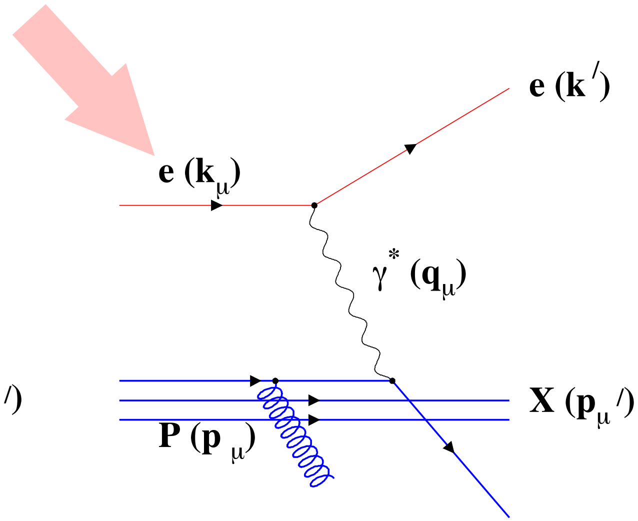
$$p' = \begin{pmatrix} \sum_h E_h \\ \sum_h p_{X,h} \\ \sum_h p_{Y,h} \\ \sum_h p_{Z,h} \end{pmatrix}$$

$$Q^2 = -(k-k')^2 = -q^2$$ Measure of resolution power

$$x = \frac{Q^2}{2(p \cdot q)}$$ Measure of momentum fraction by struck quark

$$y = \frac{p \cdot q}{p \cdot k}$$ Measure of inelasticity

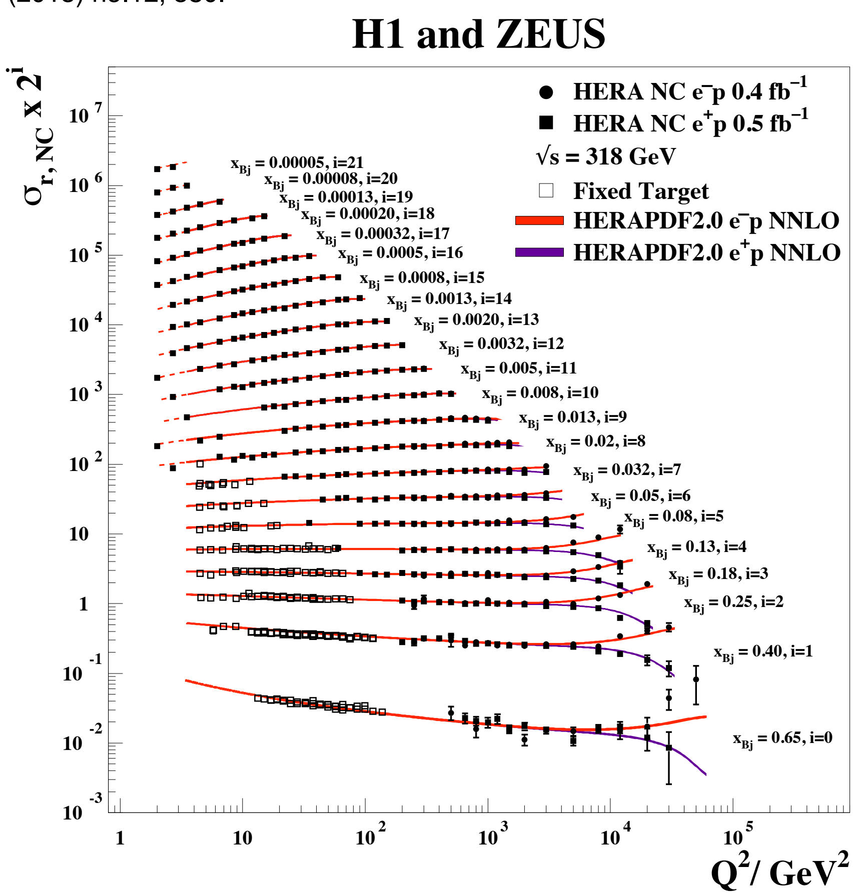




Theoretical foundation

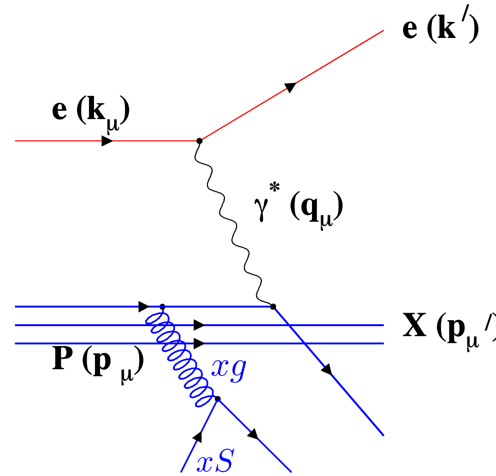
DIS - Parton structure: Unpolarized

H1 and ZEUS Collaborations (H. Abramowicz et al.), Eur.Phys.J. C75 (2015) no.12, 580.

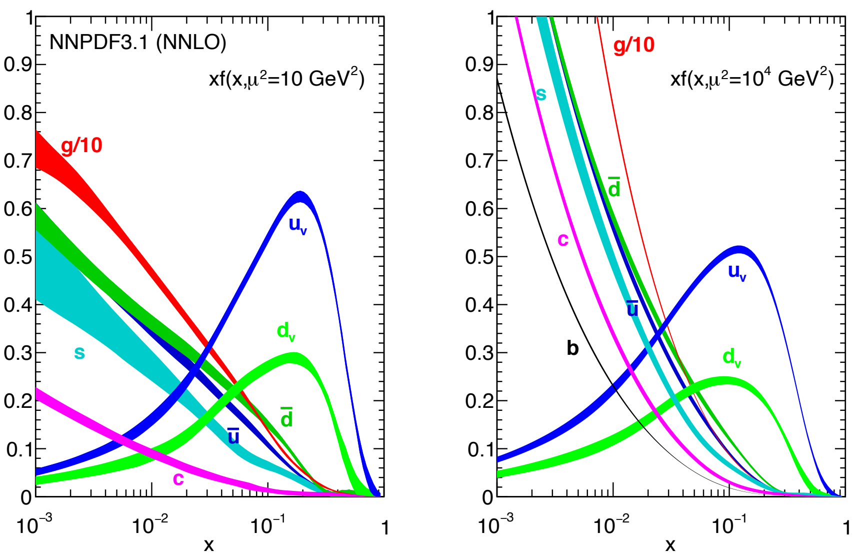


$$d\sigma_{eP} \propto F_2^P = \sum_i e_i^2\, x\, (q_i + \bar{q}_i)$$

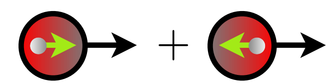
1990: J. I. Friedman, H. W. Kendall and R. E. Taylor: “for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics.”



R. D. Ball et al., EPJ C77 (2017) 663.



$f(x) =$



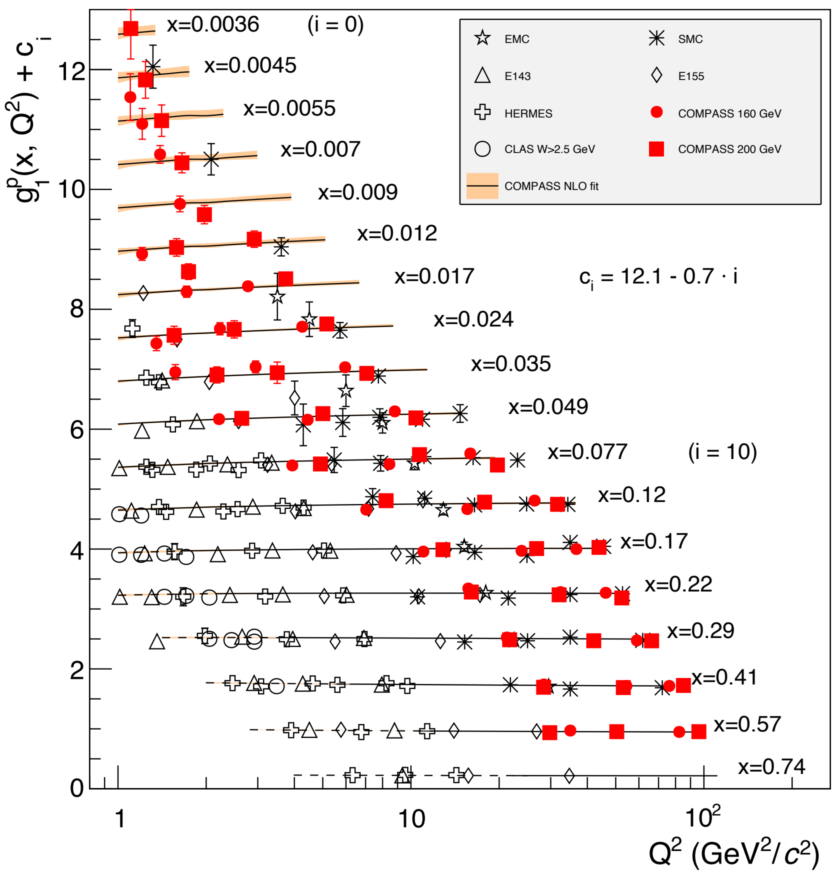
$f^+(x) + f^-(x)$

Measure of probability to find parton f with longitudinal momentum fraction x

Theoretical foundation

DIS - Parton structure: Polarized

COMPASS Collaboration (C. Adolph et al.), Phys.Lett. B753 (2016) 18.



$$g_1^P = \frac{1}{2}\sum_i e_i^2 \left(\Delta q_i + \Delta\bar{q}_i\right)$$

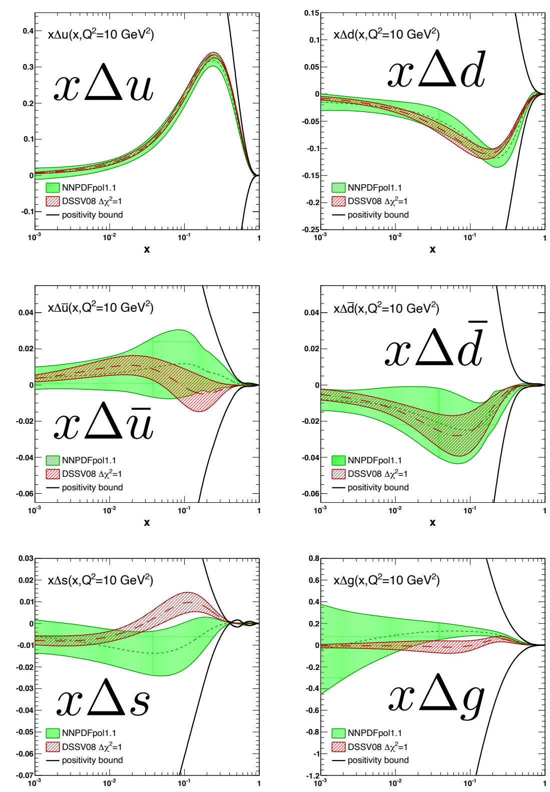
$$\overbrace{\frac{1}{2} = \langle S_q\rangle}^{\frac{1}{2}\Delta\Sigma} + \underbrace{\langle S_g\rangle}_{\Delta G} + \langle L_q\rangle + \langle L_g\rangle$$

(R.L. Jaffe and A. Manohar, Nucl. Phys. B337, 509 (1990))

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$

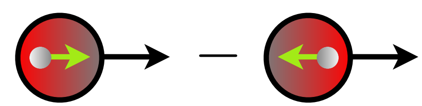
$$\Delta q_i(Q^2) = \int_0^1 \Delta q_i(x, Q^2)dx$$

$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2)dx$$



NNPDF Collaboration (Emanuele R. Nocera et al.), Nucl.Phys. B887 (2014) 276-308

$$\Delta f(x) =$$

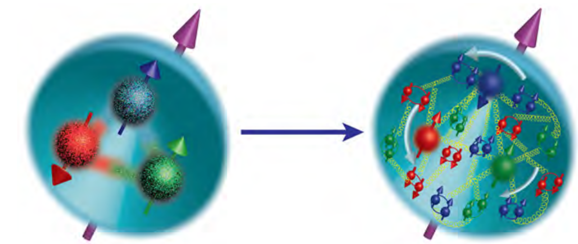


$$\underbrace{f^+(x) - f^-(x)}$$

Measure of probability to find parton f with spin aligned to anti-anti-aligned to proton spin at momentum fraction x

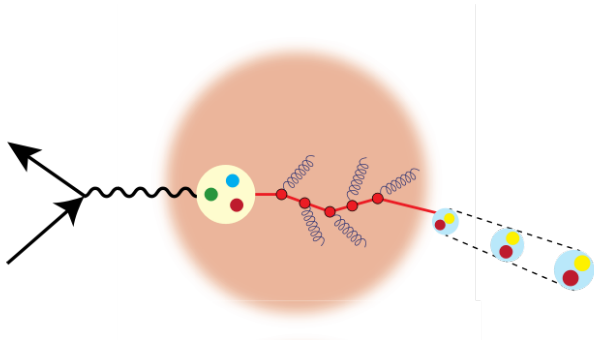
EIC Physics Pillars

Motivation - EIC program



How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?



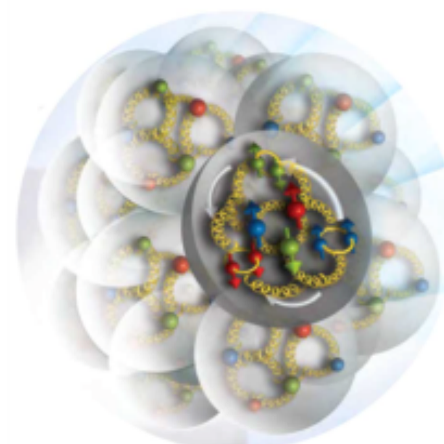
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

How do the confined hadronic states emerge from these quarks and gluons?

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?

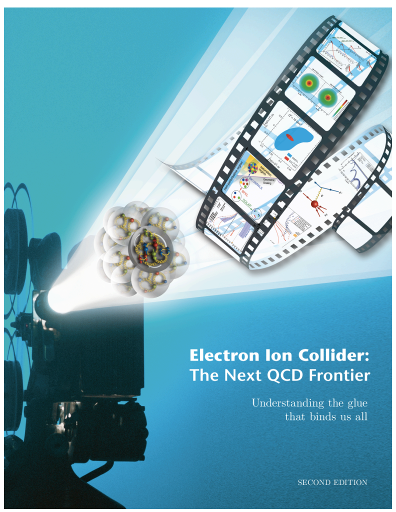
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?



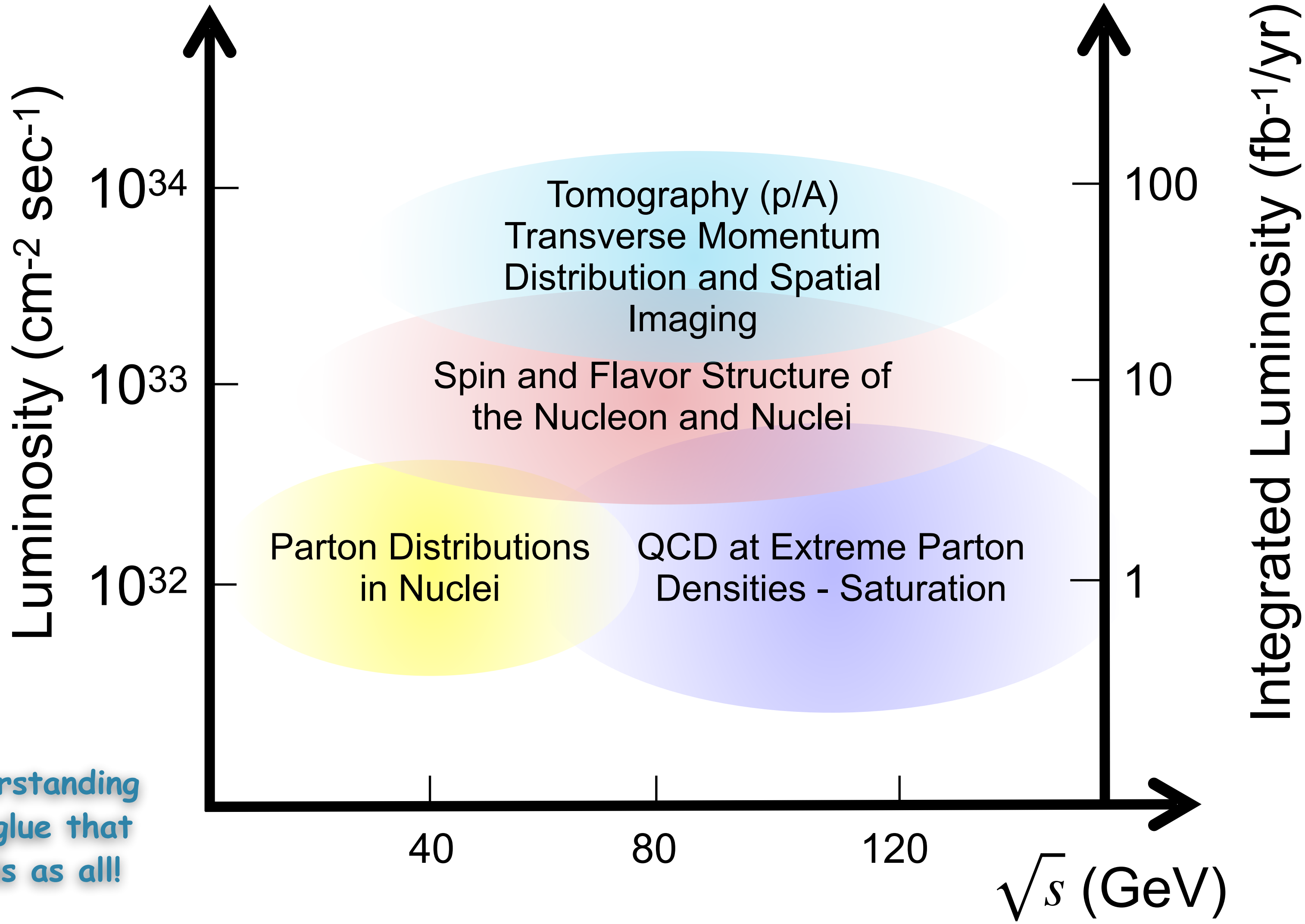
EIC Physics Pillars

- EIC: Study structure and dynamics of matter at high luminosity, high energy with polarized beams and wide range of nuclei
- Whitepaper:

arXiv:1212.1701

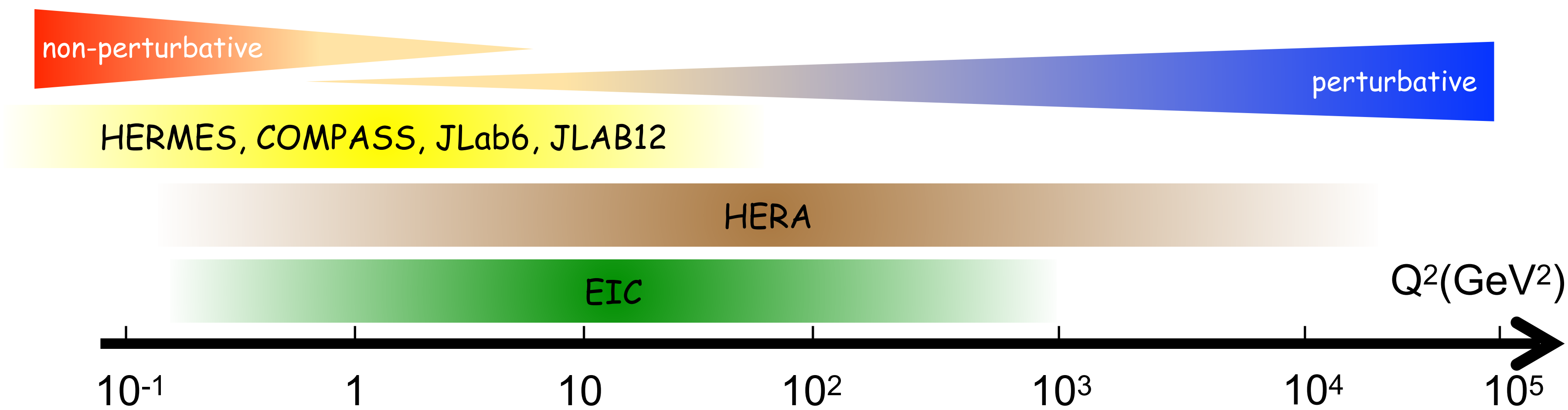


Understanding the glue that binds as all!



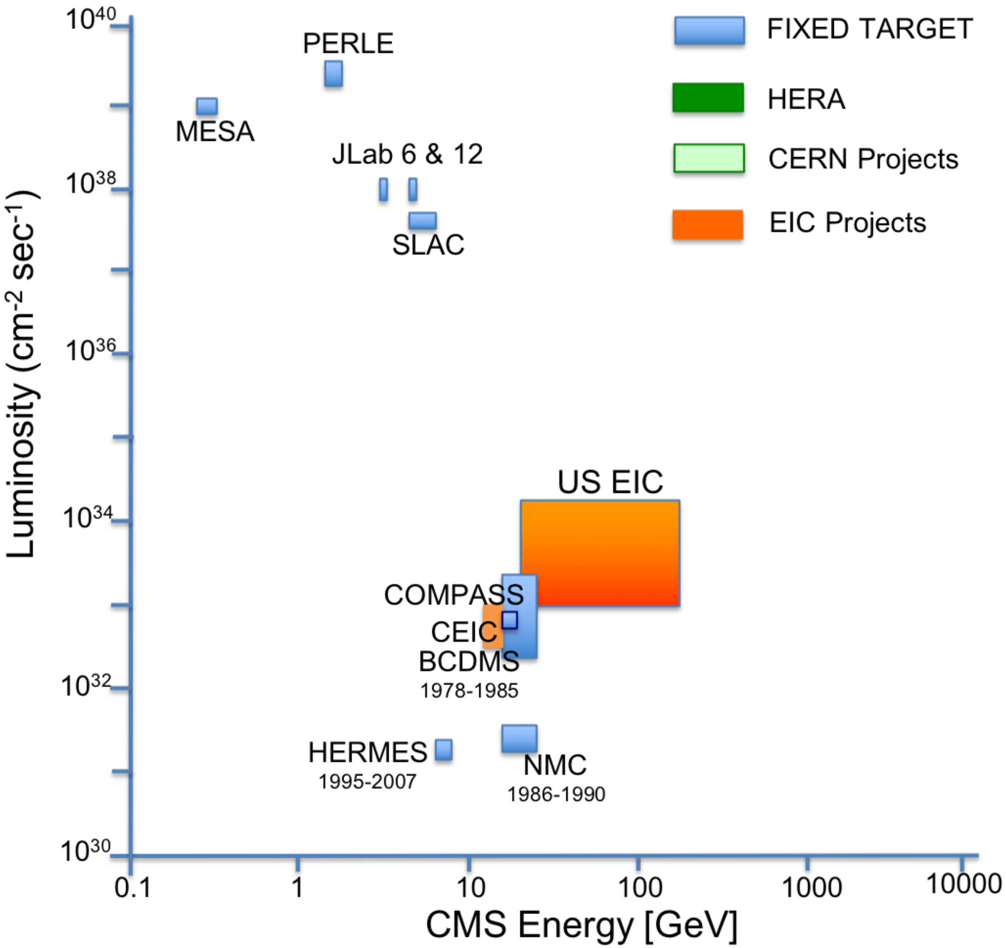
EIC Physics Pillars

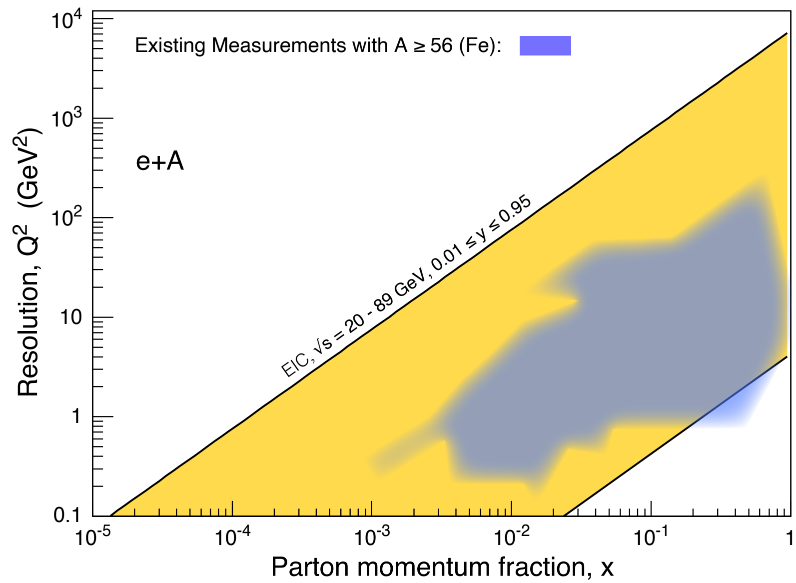
- Requirements
  - Machine:
    - High luminosity: $10^{33}cm^{-2}s^{-1}$ - $10^{34}cm^{-2}s^{-1}$
    - Flexible center-of-mass energy $\sqrt{s} = \sqrt{4\, E_e\, E_p}$: Wide kinematic range $Q^2 = s\, x\, y$
    - Highly polarized electron (0.8) and proton / light ion (0.7) beams: Spin structure studies
    - Wide range of nuclear beams (d to Pb/U): High gluon density
  - Detector:
    - Wide acceptance detector system including particle ID (e/h separation & π, K, p ID - flavor tagging)
    - Instrumentation for tagging of protons from elastic reactions and neutrons from nuclear breakup: Target / nuclear fragments in addition to low Q^2 tagger / polarimetry and luminosity (abs. and rel.) measurement



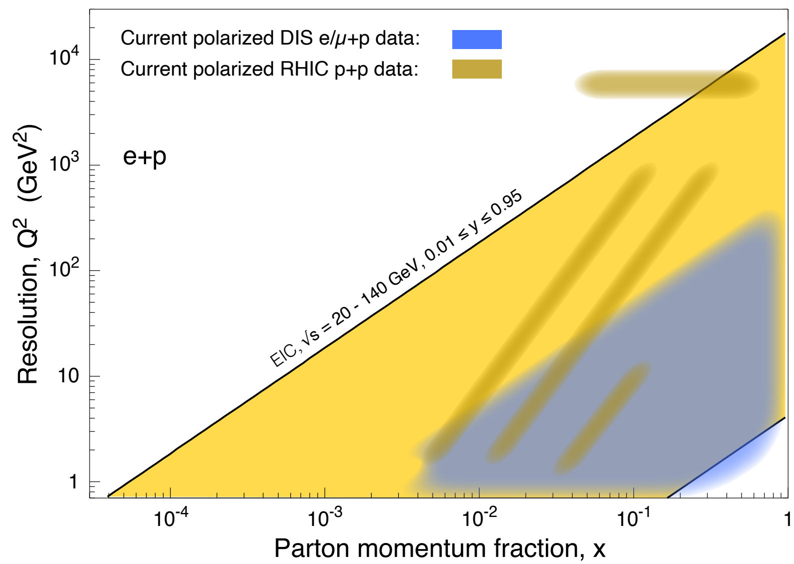
EIC Physics Pillars

- Luminosity / $\sqrt{s}$ / Kinematic coverage





eA

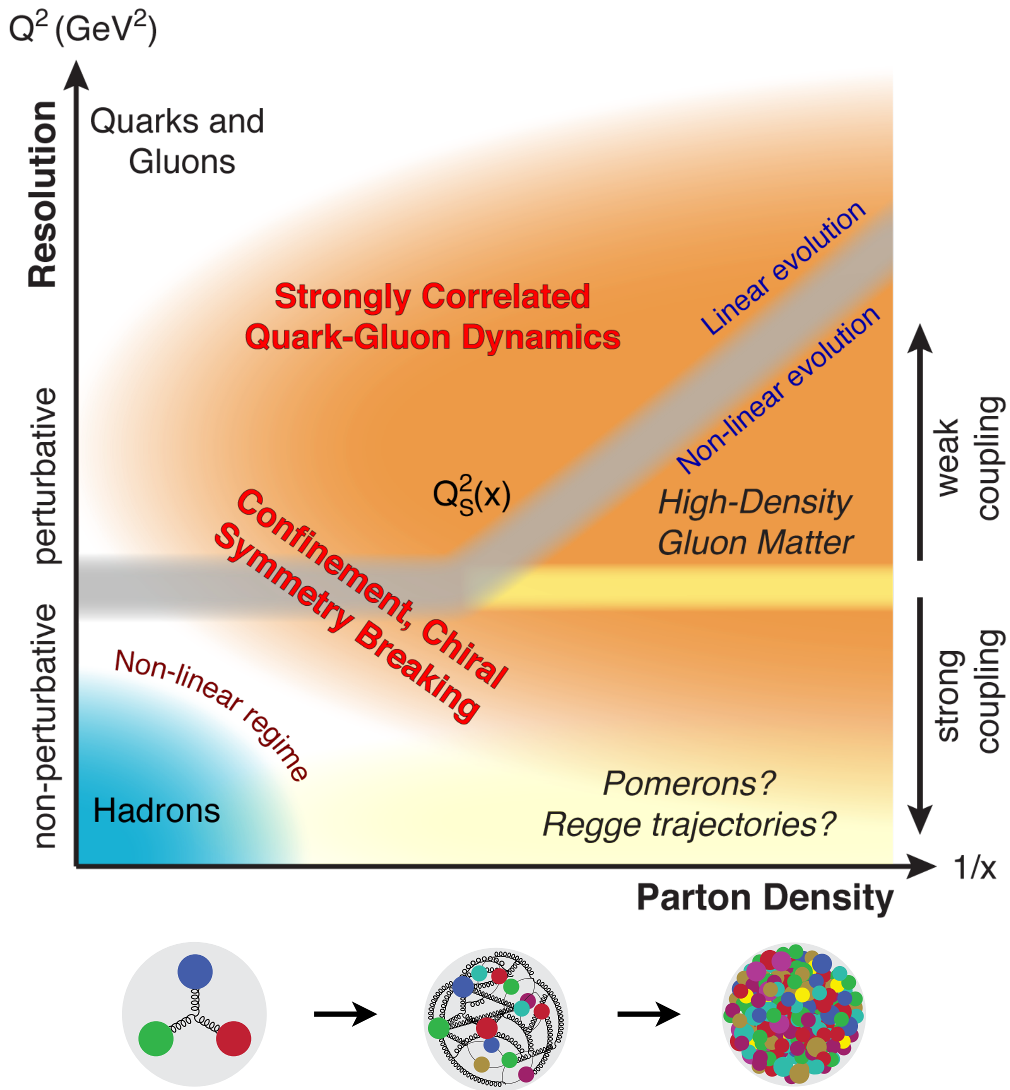


ep

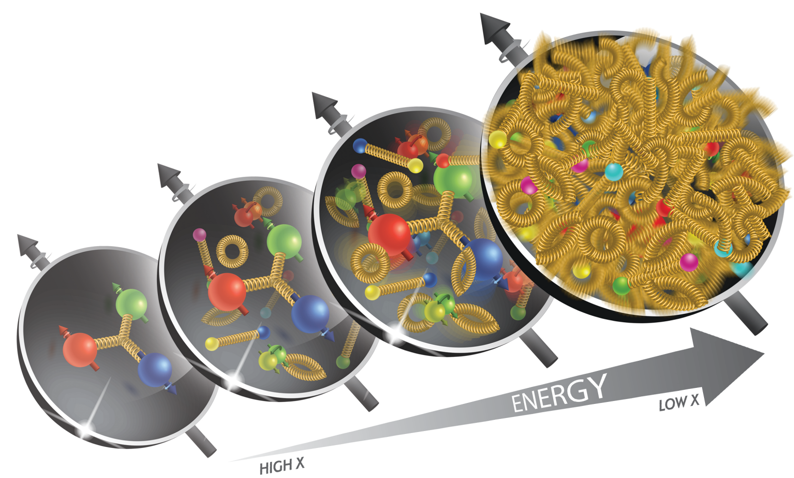
EIC Physics Pillars

- QCD dynamics

arXiv:1708.01527



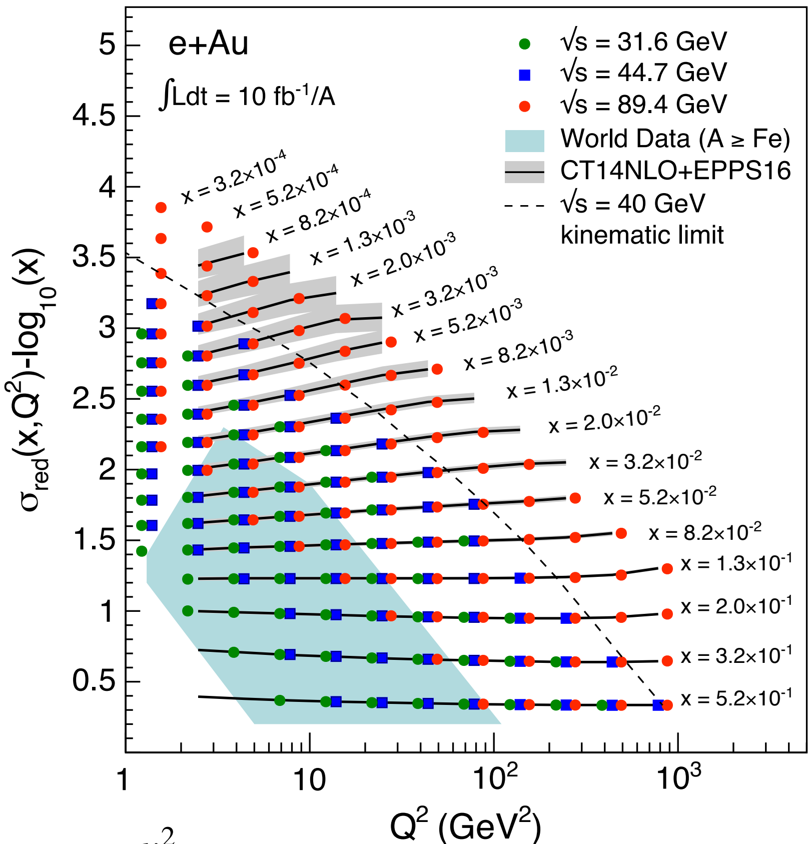
- Explore QCD landscape in various aspects over a wide range in x and Q^2
- Heavy nuclei at high energy critical to explore high-density gluon matter!

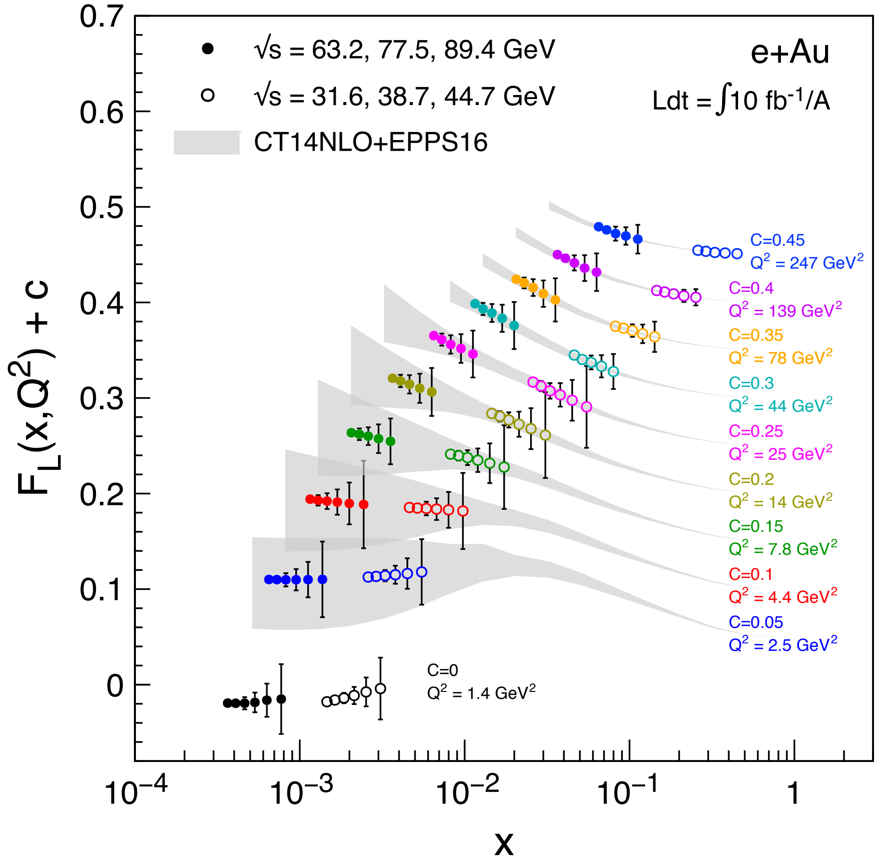


EIC Physics Pillars

- Inclusive eA scattering measurements

arXiv:1708.01527





$$\sigma_{\text{red}} = F_2 - \frac{y^2}{Y_+} F_L$$

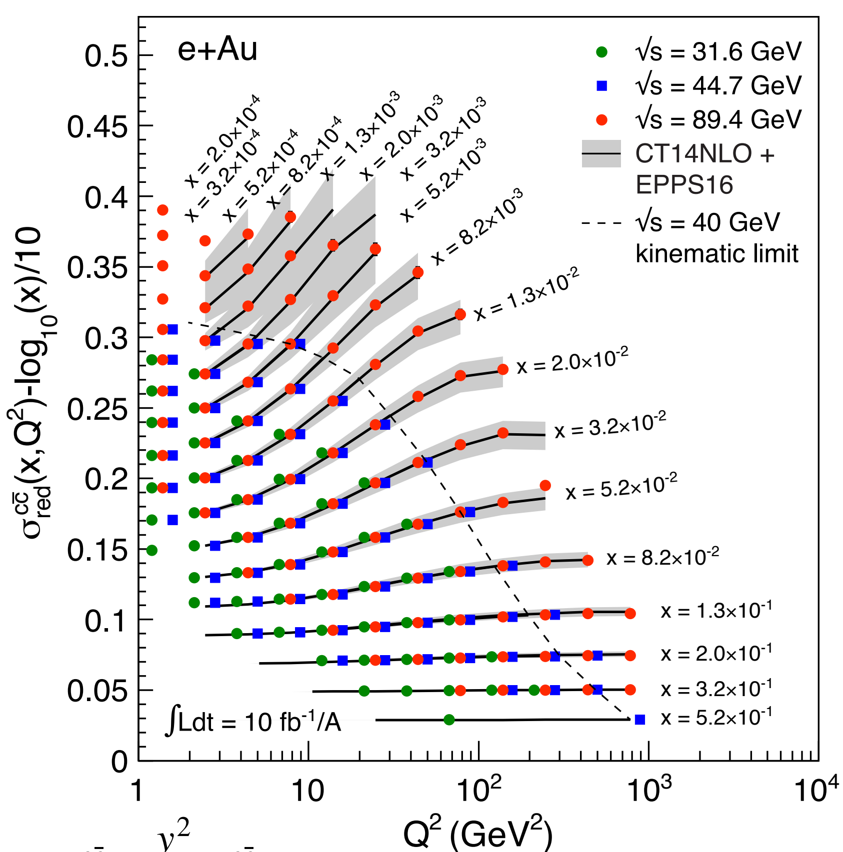
$$\left(\frac{d^2\sigma}{dx\,dQ^2}\right) = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L\right)$$

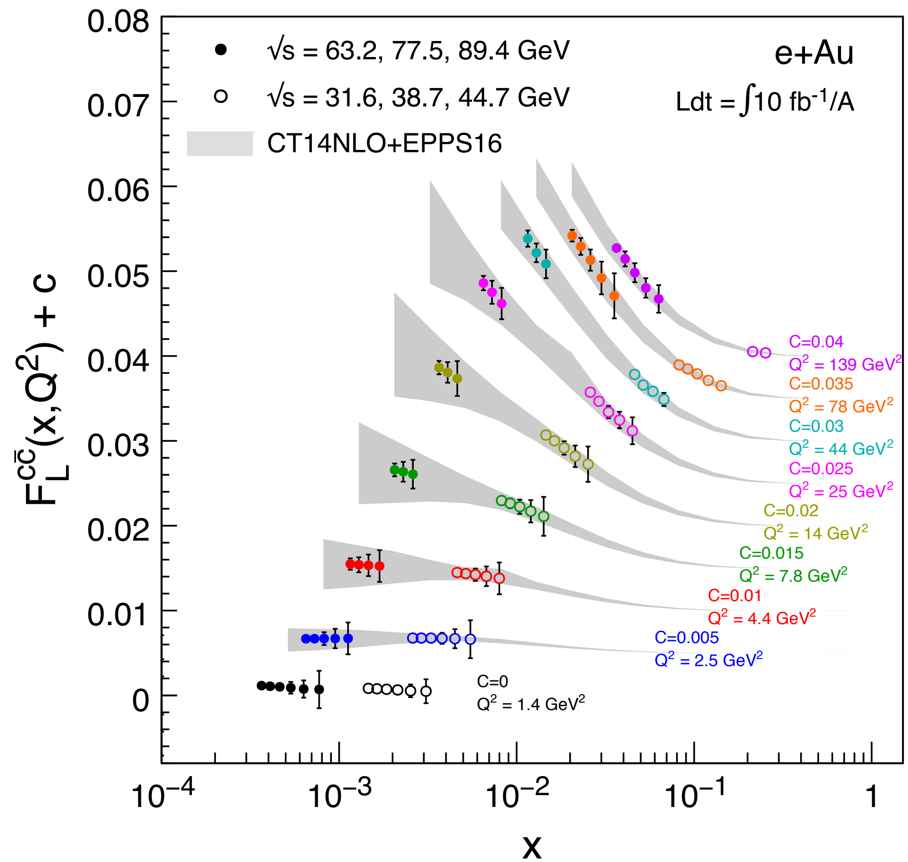
$$Y_+ = 1 + (1-y)^2$$

EIC Physics Pillars

- Charm-associated eA scattering measurements

arXiv:1708.01527





$$\sigma_{\text{red}}^{c\bar{c}} = F_2^{c\bar{c}} - \frac{y^2}{Y_+} F_L^{c\bar{c}}$$

$$\left(\frac{d^2\sigma}{dx\,dQ^2}\right)^{c\bar{c}} = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left(F_2^{c\bar{c}} - \frac{y^2}{Y_+}F_L^{c\bar{c}}\right)$$

$$Y_+ = 1 + (1-y)^2$$

EIC Physics Pillars

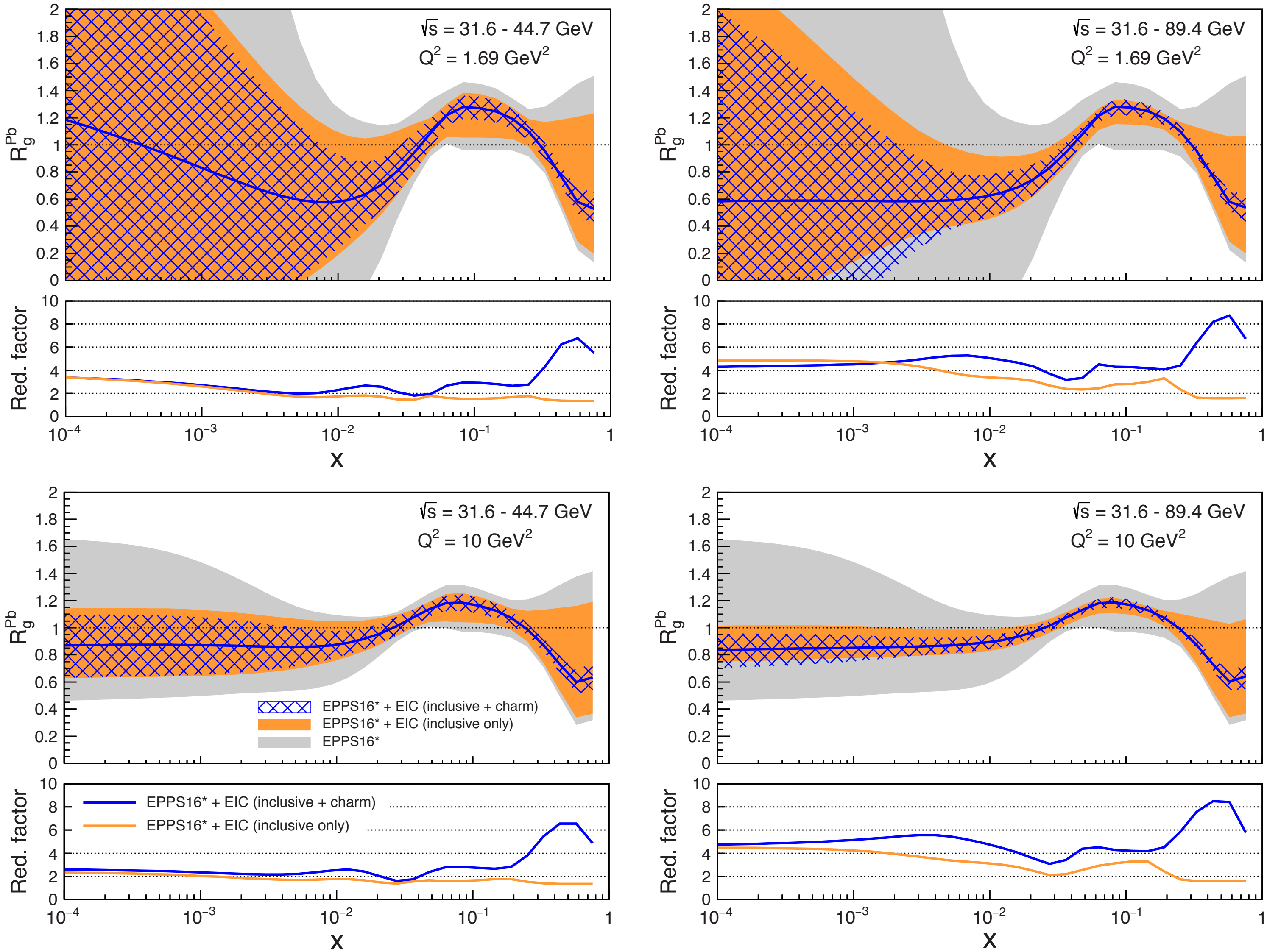
- Impact on nuclear gluon behavior in eA scattering

arXiv:1708.01527

Modifications of nuclear environment:

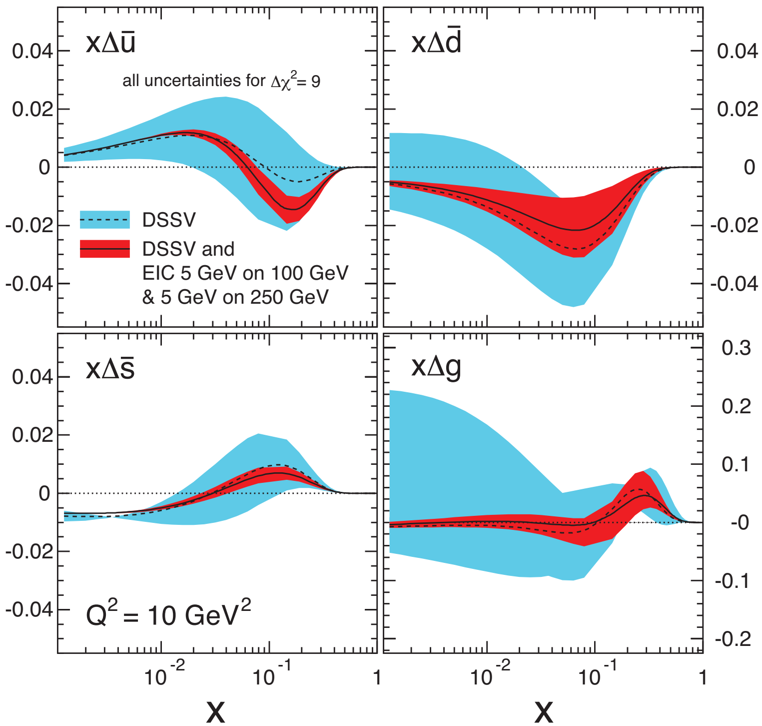
R_g^{Pb}

Ratio of gluon distribution in Pb compared to proton

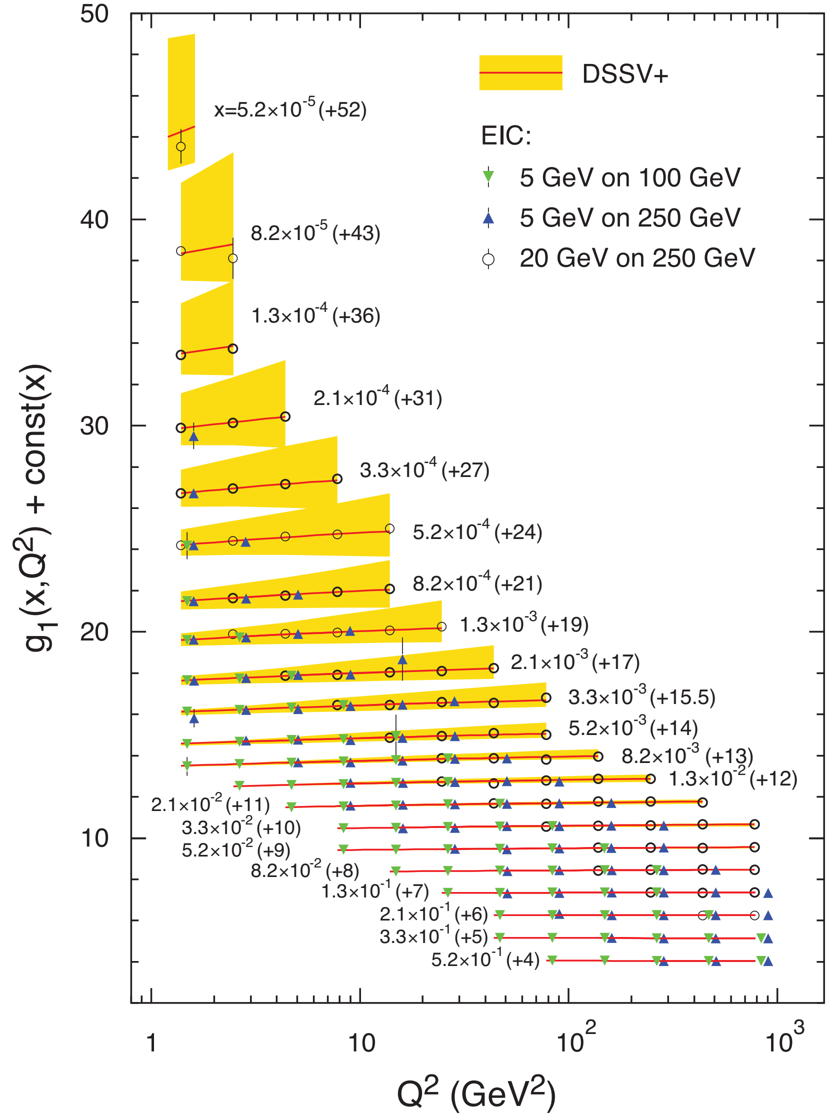


EIC Physics Pillars

- Spin and Flavor Structure of the Nucleon



arXiv:1212.1701

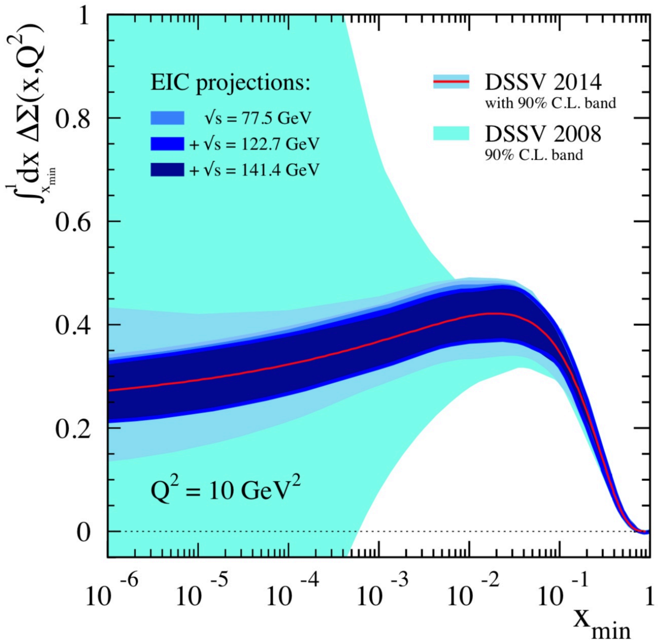


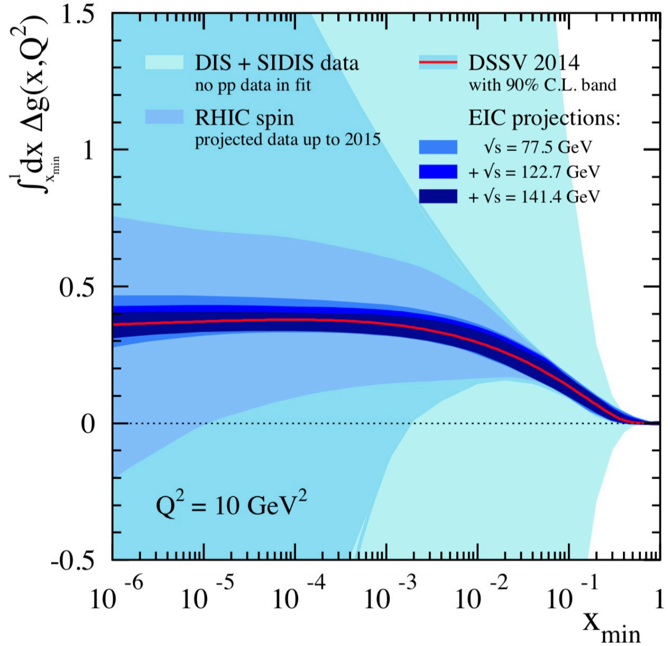
- g_1 stat. uncertainty projections for $10 fb^{-1}$ for range of CME in comparison to DSSV+ predictions incl. uncertainties
- EIC impact on helicity distributions of anti-u, anti-d and s quarks together with gluons

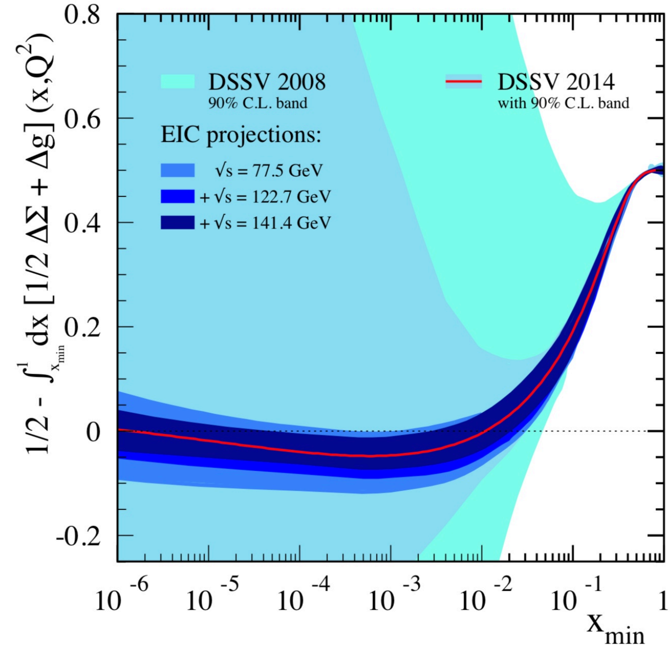
EIC Physics Pillars

- Impact on proton spin

E. Aschenauer, R. Sassot and M. Stratmann, Phys. Rev. D92 (2015) 094030.







Quark Spin

Gluon Spin

Orbital Angular Momentum

EIC Physics Pillars

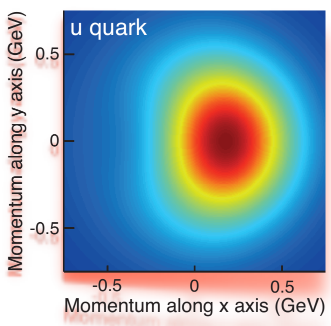
Transverse Momentum Distribution and Spatial Imaging

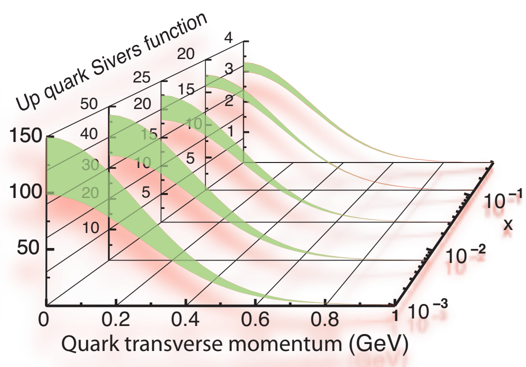
arXiv:1212.1701

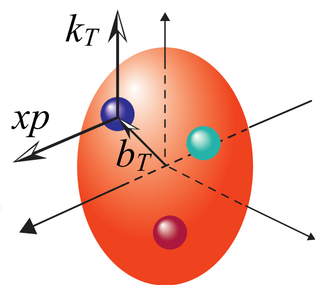
$f(x, k_T)$ 1+2D $\quad \int d^2 b_T \quad W(x, b_T, k_T) \quad \int d^2 k_T \quad$ $f(x, b_T)$ 1+2D

Transverse Momentum Distribution (TMD) — Wigner Distribution — Impact Parameter Distribution

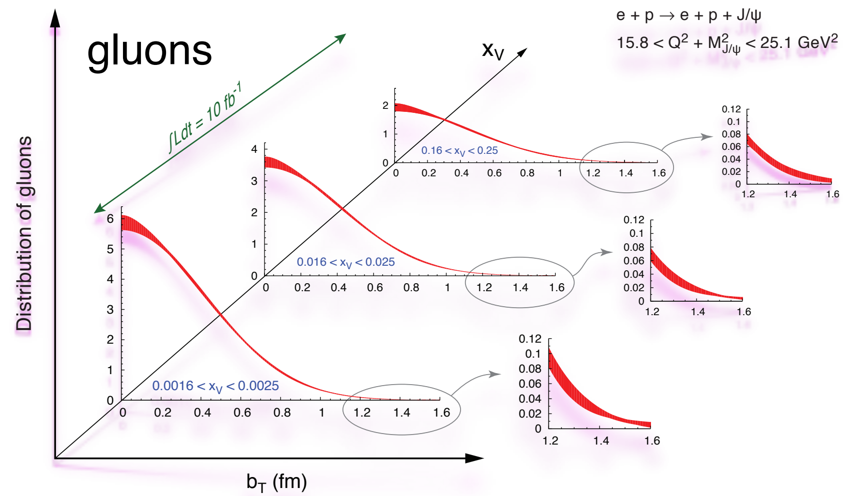
quarks







gluons



Fourier transf.

$b_T \longleftrightarrow \Delta$: $t = -\Delta^2$

$H(x, 0, t)$

$\xi = 0$

$H(x, \xi, t)$

Generalized Parton Distribution (GPD)

- Spin-dependent 1+2D momentum space (transverse) images from semi-inclusive scattering
- Spin-dependent 1+2D impact parameter (transverse) images from exclusive scattering

EIC project development

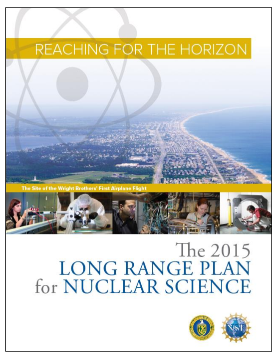
- Critical steps over the last couple of years - 1
  - INT Workshop series / Documentation of Physics Case - Whitepaper: "Understanding the glue that binds us all!"
    - INT Workshop: 2010
    - WP: 2012, updated in 2014 for LRP
  - 2015 Long-range plan (LRP):

T. Hallman

The 2015 Long Range Plan for Nuclear Science

Recommendations:

1. Capitalize on investments made to maintain U.S. leadership in nuclear science.
2. Develop and deploy a U.S.-led ton-scale neutrino-less double beta decay experiment.
3. Construct a high-energy high-luminosity polarized electron-ion collider (EIC) as the highest priority for new construction following the completion of FRIB.
4. Increase investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.



The FY 2018 Request supports progress in important aspects of the 2015 LRP Vision

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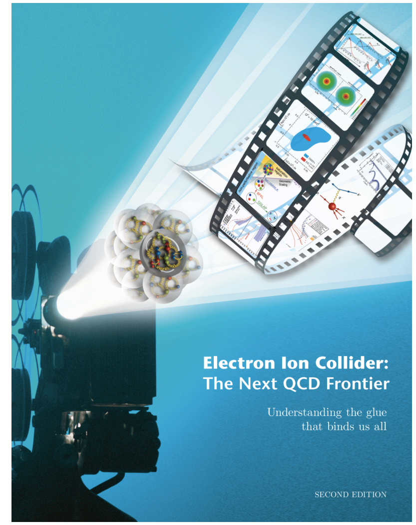
  - Request to review EIC Science Case by National Academy of Sciences, Engineering, and Medicine (NAS)

arXiv:1212.1701



Understanding the glue that binds as all!

T. Hallman

Next Formal Step on the EIC Science Case is Continuing

THE NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE
Division on Engineering and Physical Science
Board on Physics and Astronomy
U.S.-Based Electron Ion Collider Science Assessment

Summary
The National Academies of Sciences, Engineering, and Medicine ("National Academies") will form a committee to carry out a thorough, independent assessment of the scientific justification for a U.S. domestic electron ion collider facility. In preparing its report, the committee will address the role that such a facility would play in the future of nuclear science, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics. The need for such an accelerator will be addressed in the context of international efforts in this area. Support for the 18-month project in the amount of $540,000 is requested from the Department of Energy.

"U.S.-Based Electron Ion Collider Science Assessment" is now getting underway. The Chair will be Gordon Baym. The rest of the committee, including a co-chair, will be appointed in the next couple of weeks. The first meeting is being planned for January, 2017

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EIC project development

- NAS Webinar and NAS report release: 07/24/2018

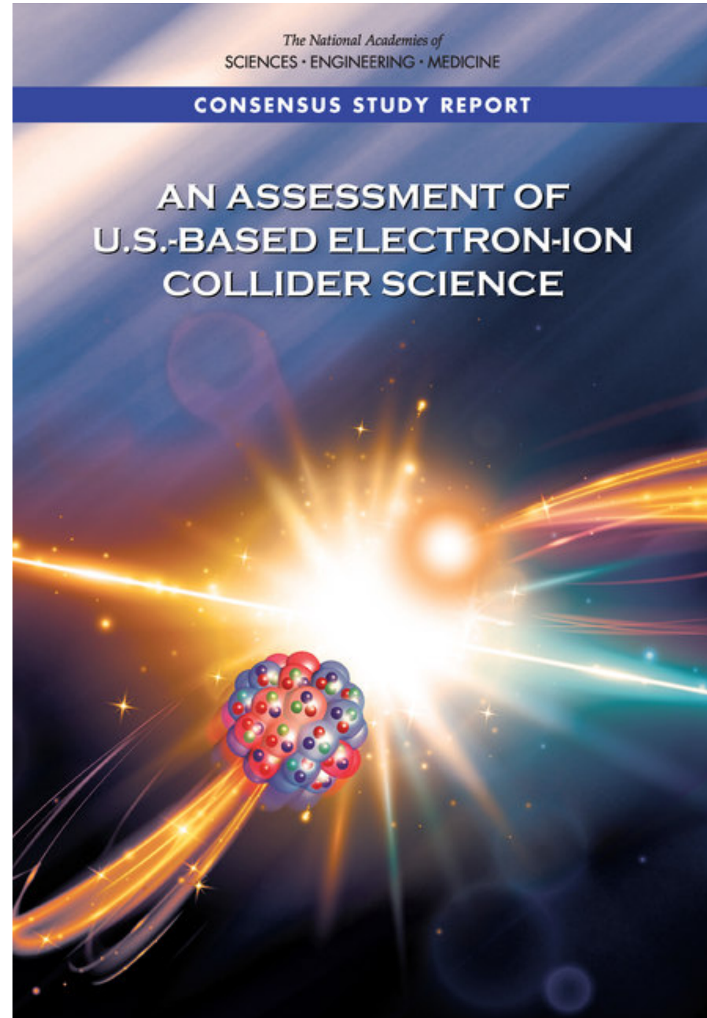
https://www.nap.edu/catalog/25171/an-assessment-of-us-based-electron-ion-collider-science

Download pdf-file of final report!

- Webinar on Tuesday, July 24, 2018 - Public presentation and report release
- Gordon Baym (Co-chair): Webinar presentation

"The committee finds that the science that can be addressed by an EIC is compelling, fundamental and timely."

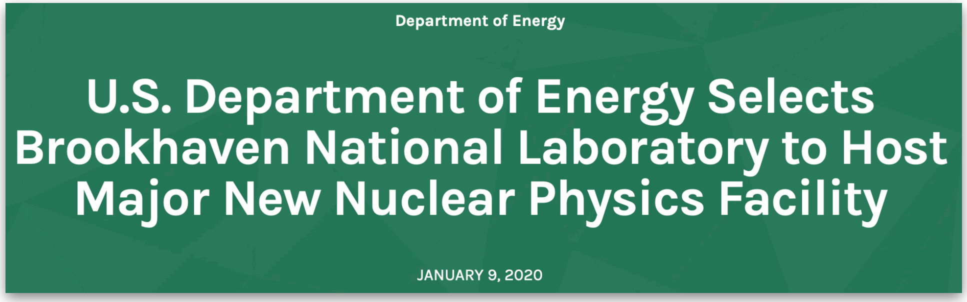
- Slides from Webinar: https://www.nap.edu/resource/25171/eic-public-briefing-slides.pdf
- Glowing" report on a US-based EIC facility!



EIC project development

- Announcement by the Department of Energy on January 9, 2020

https://www.energy.gov/articles/us-department-energy-selects-brookhaven-national-laboratory-host-major-new-nuclear-physics



WASHINGTON, D.C. – Today, the U.S. Department of Energy (DOE) announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility. The Electron Ion Collider (EIC), to be designed and constructed over ten years at an estimated cost between $1.6 and $2.6 billion, will smash electrons into protons and heavier atomic nuclei in an effort to penetrate the mysteries of the "strong force" that binds the atomic nucleus together.

EIC project development

- Press release by JLab and BNL

JEFFERSON LAB TO BE MAJOR PARTNER IN ELECTRON ION COLLIDER PROJECT

The Department of Energy announced that Jefferson Lab will collaborate on plans to build a future Electron Ion Collider in New York

NEWPORT NEWS, VA – The Department of Energy announced that it has taken the next step toward construction of an Electron Ion Collider (EIC) in the United States. DOE announced on Thursday that the collider will be sited at DOE's Brookhaven National Laboratory in Upton, N.Y. In addition, DOE's Thomas Jefferson National Accelerator Facility will be a major partner in realizing the EIC, providing key support to build this next new collider, which will be the most advanced particle collider of its type ever built.

https://www.jlab.org/news/releases/jefferson-lab-be-major-partner-electron-ion-collider-project

U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

January 9, 2020

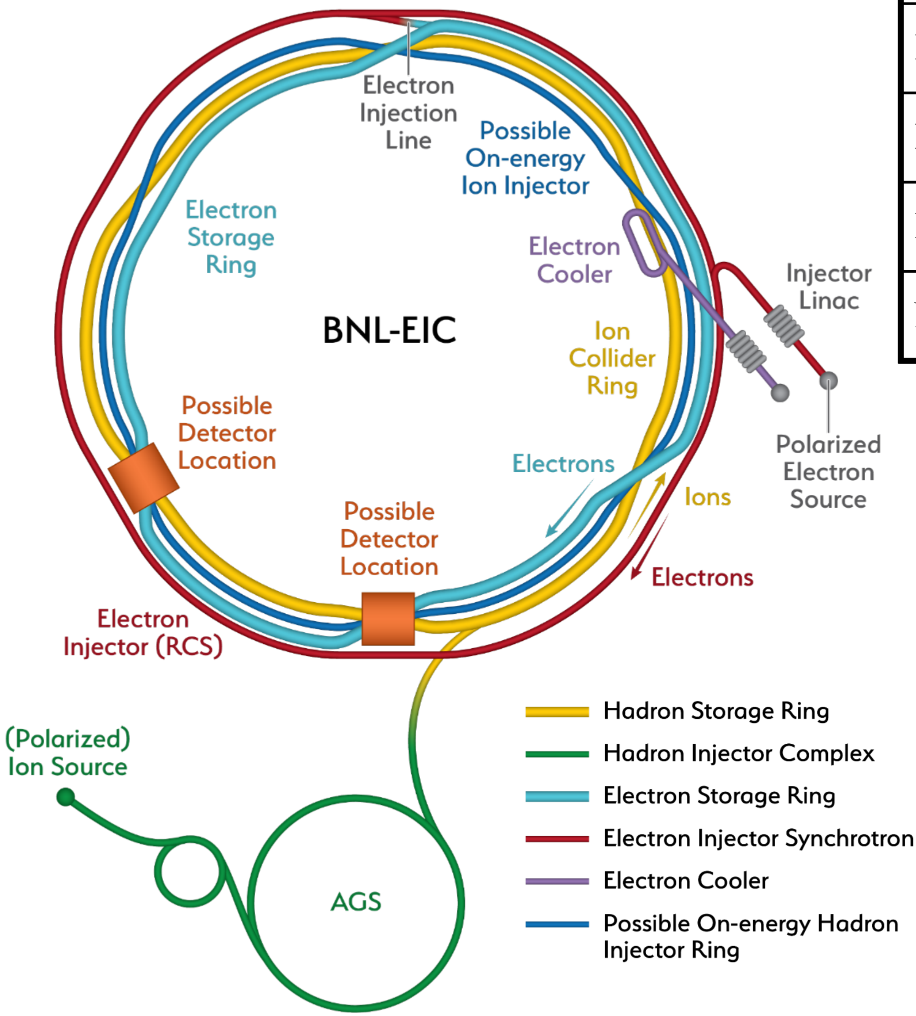
The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory will provide crucial infrastructure for the new Electron Ion Collider. + ENLARGE

WASHINGTON, D.C. – Today, the U.S. Department of Energy (DOE) announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

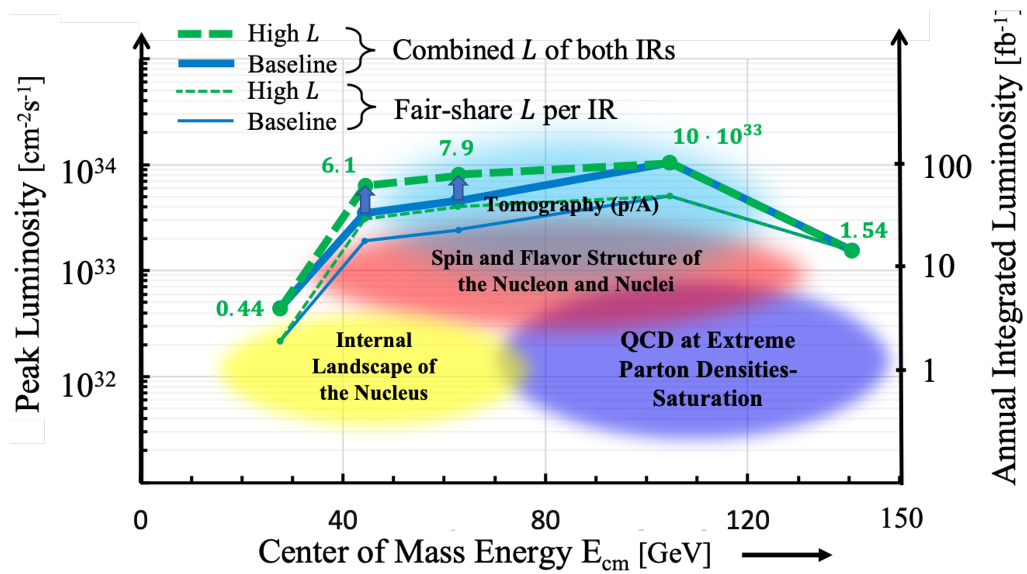
https://www.bnl.gov/newsroom/news.php?a=116996

EIC Accelerator Design

- EIC accelerator design



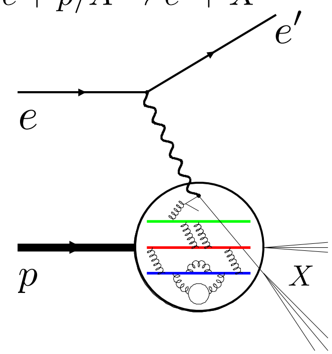
Center of Mass Energies:	20GeV - 140GeV
Luminosity:	10^{33} - 10^{34} cm^{-2}s^{-1} / 10-100fb^{-1} / year
Highly Polarized Beams:	70%
Large Ion Species Range:	p to U
Number of Interaction Regions:	Up to 2!



The EIC Detector Requirements and R&D

Overview of processes and final states

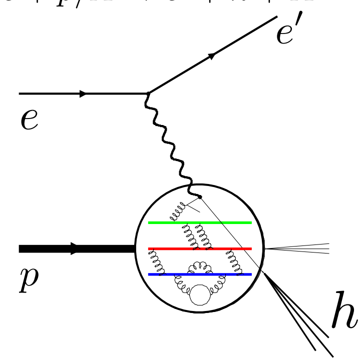
$e + p/A \rightarrow e' + X$

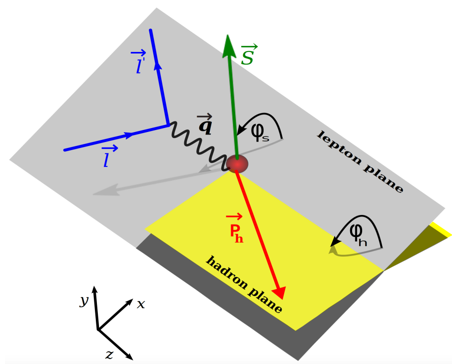


Inclusive DIS

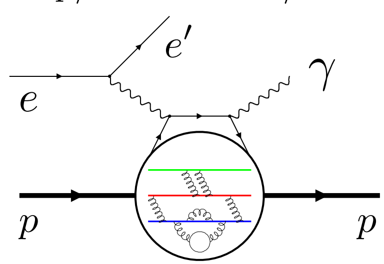
Semi-Inclusive DIS (SDIS)

$e + p/A \rightarrow e' + h + X$





$e + p/A \rightarrow e' + N'/A' + \gamma/m$



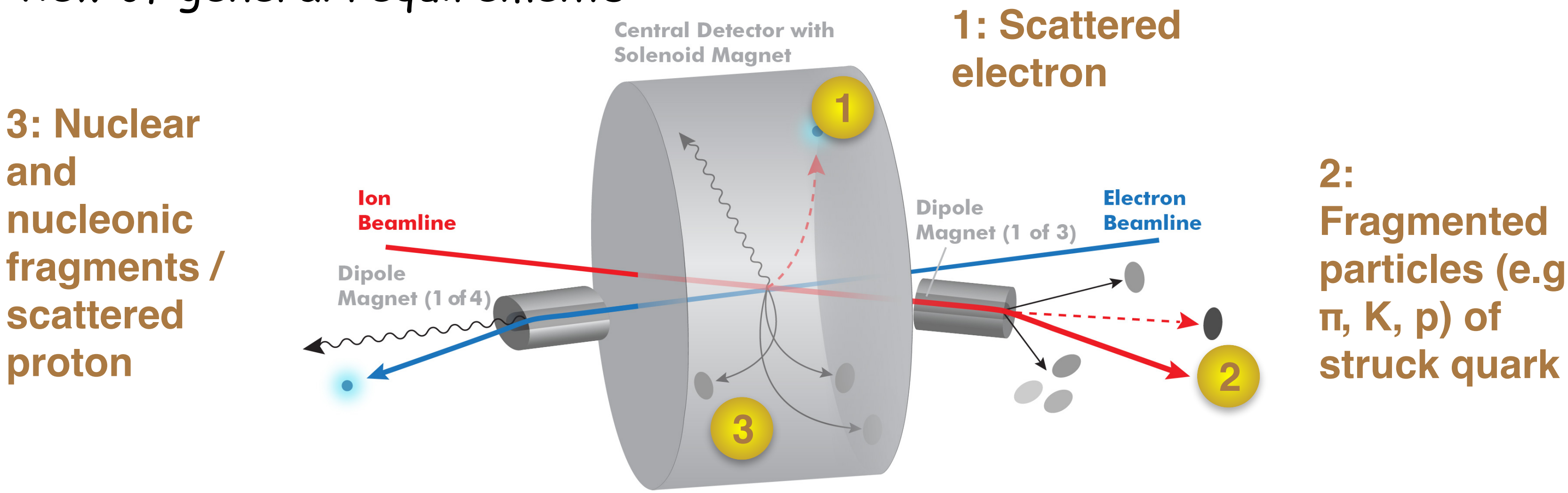
Deeply-Virtual Compton Scattering (DVCS)

- Inclusive: Unpolarized $f_i(x,Q^2)$ and helicity distribution $\Delta f_i(x,Q^2)$ functions through unpolarized and polarized structure function measurements (F_2, F_L, g_1)
- Define kinematics (x, y, Q^2) through electron (e-ID and energy+angular measurement critical) / hadron final state or combination of both depending on kinematic x-Q^2 region
- SDIS: Flavor tagging through hadron identification studying FF / TMD's (Transverse momentum, k_T, dependence) requiring azimuthal asymmetry measurement - Full azimuthal acceptance
- Heavy flavor (charm / bottom): Excellent secondary vertex reconstruction
- Exclusive: Tagging of final state proton using Roman pot system studying GPD's (Impact parameter, b_T, dependence) using DVCS and VM production
- eA: Impact parameter determination / Neutron tagging using Zero-Degree Calorimeter (ZDC)

The EIC Detector Requirements and R&D

Overview of general requirements

arXiv:1212.1701



- Acceptance: Close to 4π coverage with a η-coverage ($\eta = -\ln(\tan(\theta/2))$) of approximately $\eta < |3.5|$ combined calorimetry (EM CAL and hadron CAL at least in forward direction) and tracking coverage
- Low dead material budget in particular in rear direction (~5% X/X_0)
- Good momentum resolution $\Delta p/p$ ~ few %
- Electron ID for e/h separation varies with θ / η at the level of 1:10^4 / ~2-3%/√E for η<-2 and ~7%/√E for -2<η<1
- Particle ID for π/K/p separation over wide momentum range (Forward η up to ~50GeV/c / Barrel η up to ~4GeV/c / Rear η up to ~6 GeV/c)
- High spatial vertex resolution ~ 10-20μm for vertex reconstruction
- Low-angel taggers:
  - Forward proton / A fragment spectrometer (Roman pots)
  - Low Q^2 tagger
  - Neutrons on hadron direction
- Luminosity (Absolute and relative) and local polarization direction measurement

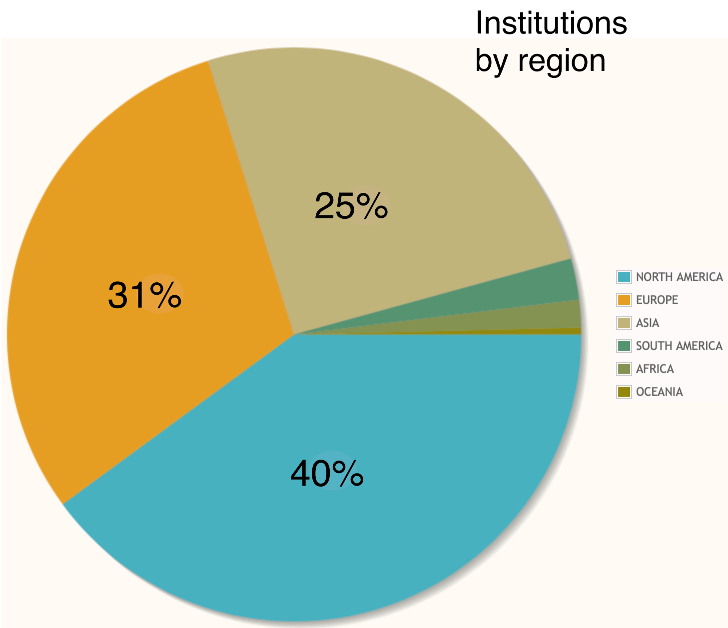
The EIC Detector Requirements and R&D

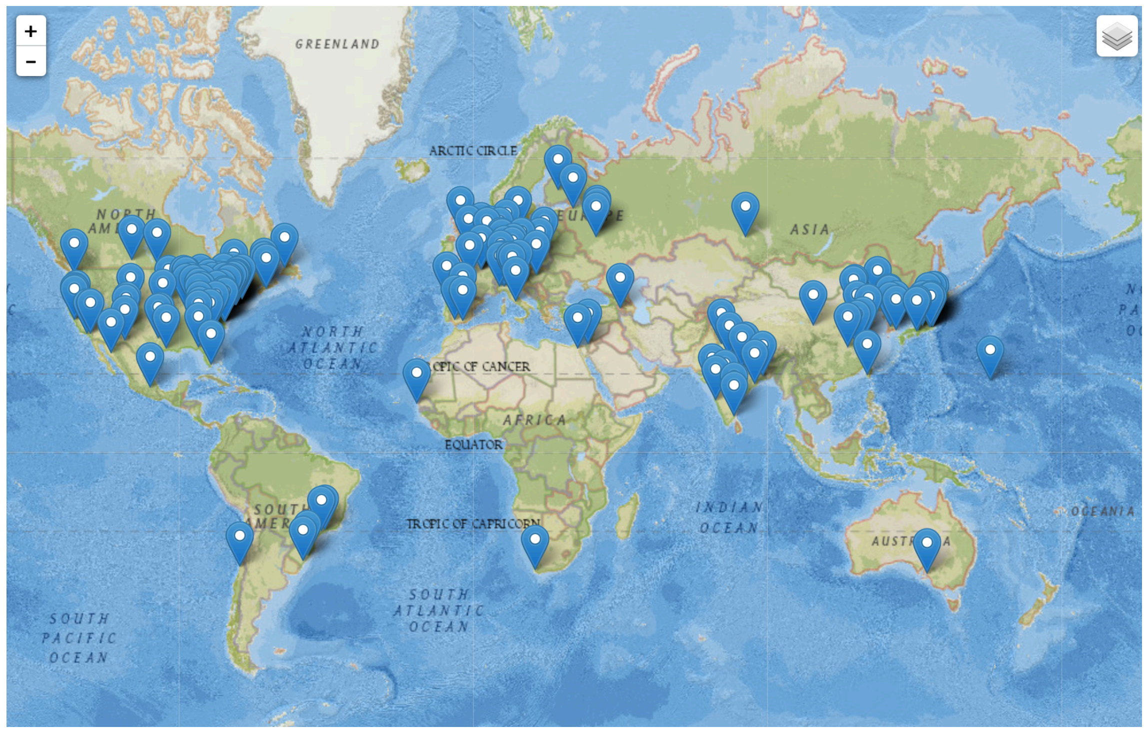
- Generic Detector R&D program for an EIC
  - In January 2011, BNL, in association with JLab and the DOE Office of NP, announced a generic detector R&D program to address the scientific requirements for measurements at a future EIC facility.
  - Goals:
    - Enable successful design and timely implementation of an EIC experimental program
    - Develop instrumentation solutions that meet realistic cost expectations
    - Stimulate the formation of user collaborations to design and build experiments
  - Peer-reviewed program funded by DOE and managed by BNL with $1M/year to $1.5M/year Initiated and coordinated by Tom Ludlam (BNL) until 2014 / Since 2014 coordinated by Thomas Ullrich (BNL)
  - Key to success: Standing EIC Detector Advisory Committee
    - Current members: Marcel Demarteau (ANL), Carl Haber (LBNL), Peter Krizan (Ljubljana), Ian Shipsey (Oxford), Rick van Berg (UPenn), Jerry Va'vra (SLAC) and Glenn Young (JLab)
    - Past members: Robert Klanner (Hamburg) and Howard Wieman (LBL)
  - Wide range of R&D programs: Calorimetry / Tracking (GEM, MicroMegas, TPC) incl. silicon / Particle ID (TRD, Dual-RICH, Aerogel RICH, DIRC, TOF) / Polarimetry / Background / Simulation Tools /

https://wiki.bnl.gov/conferences/index.php/EIC_R%25D

The EIC Users Group

- Size and demographics
  - EICUG organization established in summer 2016
  - In numbers....: 1298 members (Experimental scientists: 797 / Theory scientists: 327 / Accelerator scientists: 161 / Computer Scientists: 7 / Support: 4 / Other: 2), 263 institutions, 35 countries, 6 world regions
  - World map:





The EIC Users Group

- EICUG Formation
  - A user organization was formed in 2016 based on a charter stating:

Electron Ion Collider Users Group
Charter
June 9, 2016

PREAMBLE
With the recommendation by the U.S. nuclear physics community in the 2015 Long Range Plan that an Electron-Ion Collider (EIC) is the highest priority for new facility construction, it is timely for all the users of a future US-based EIC to organize more formally into an EIC Users Group (EICUG) with the goal of giving the future users community a stronger and more visible role in the process leading to the realization of an EIC.

  - Goal:
    - Enhance and refine the scientific case
    - Provide a forum for discussion and promote collaboration across the accelerator, experimental and theoretical communities to enhance the progress towards realization of the EIC
    - Represent the interests of the EIC users in discussions with laboratories and funding agencies
    - Serve as a point of contact for those across the globe with interest in participating in the EIC program
  - Membership: Open to individuals from all institutions that support the missions of the EIC User organization!

The EIC Users Group

- EIC community activities / Conferences and Workshops

Highly Active EIC Community!

Programs related to EIC

The EIC Users Group

- Major effort in 2019-2021: Yellow Report Activities
  - With the announcement of CD0 and site selection, EICUG announced the formation of a Yellow Report study in preparation of the EIC program:
    - Quantify physics measurements for existing or new physics topics and implications for detector design ("Physics WG")
    - Study detector concepts based on the requirements defined above, and quantify implications for physics measurements ("Detector WG")
    - Effort planned for 1 year with 4 dedicated workshops summarized in Yellow Report - Important input for conceptual and technical design report
      - 1st YR Workshop: March 19-21, 2020: Temple University, US
      - 2nd YR Workshop: May 22-24, 2020: INFN Pavia, Italy
      - 3rd YR Workshop: September 17-19, 2020, CUA, Washington DC, US
      - 4th YR Workshop: November 19-21, 2020: UCB, Berkeley, US
    - Formation of collaborations following Yellow Report effort in 2021
  - Strong international presence at both the leadership and participants of the Yellow Report studies!

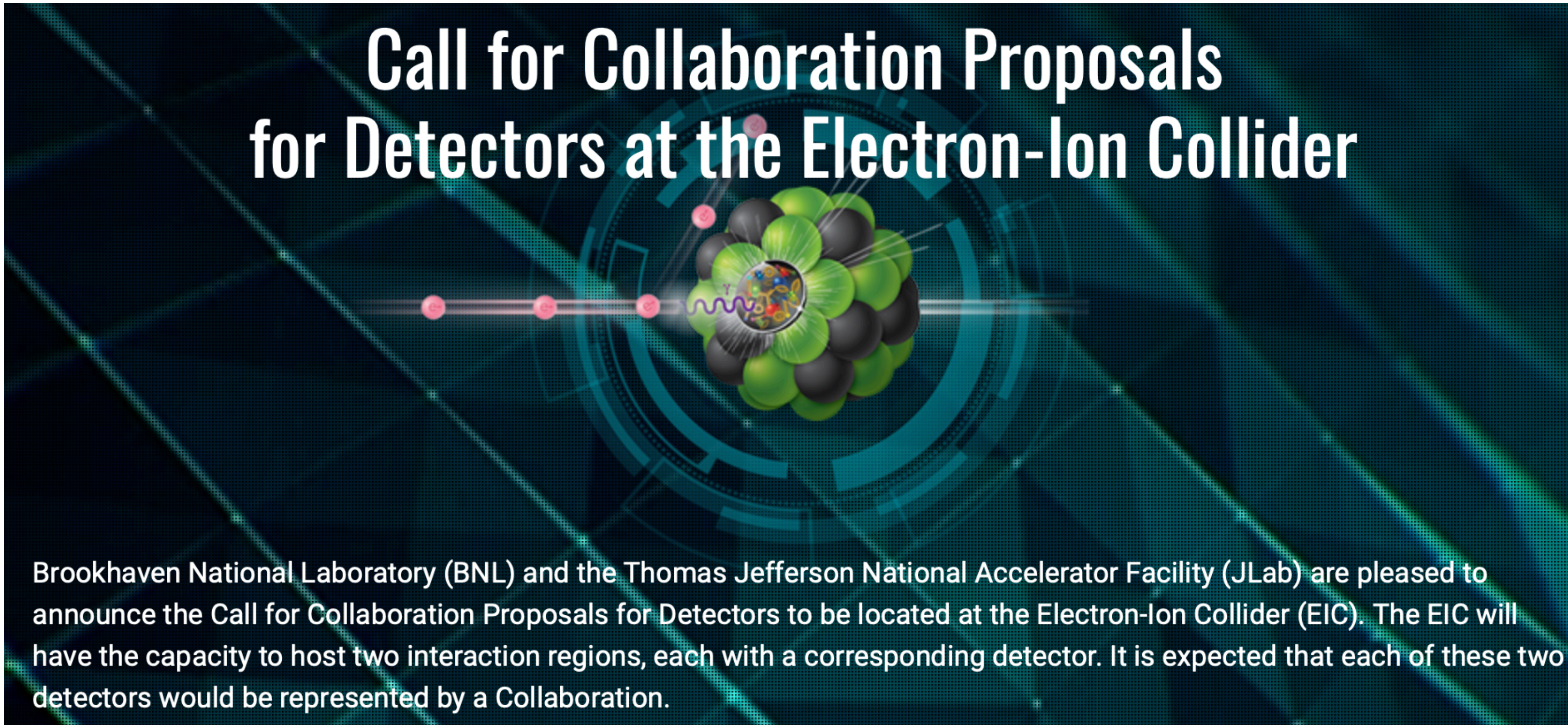
The EIC Users Group

- Volume 1-3: Executive Summary / Physics / Detector

- ~400 authors / ~150 institutions / ~900 pages with strong international contributions!
- Review: Community review within EICUG and external readers (~30) worldwide covering physics and detector expert fields!
- Editorial process completed / Available on archive: https://arxiv.org/abs/2103.05419

EIC Current Status and Next Steps

Open Call for Detector Proposals

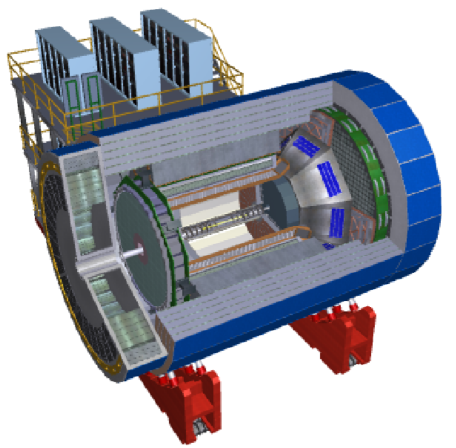


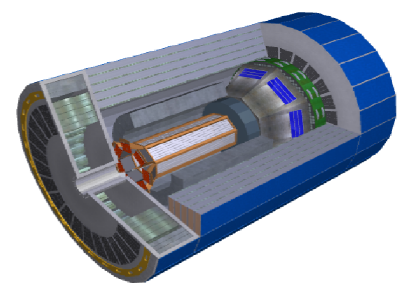
- Deadline for proposal submission: December 1, 2021
- Part 1 (40 pages): Science and performance estimation of conceptual detector design together with technology choices, R&D needs, and risks
- Part 2 (20 pages): Collaboration roster and structure, timescale, and cost

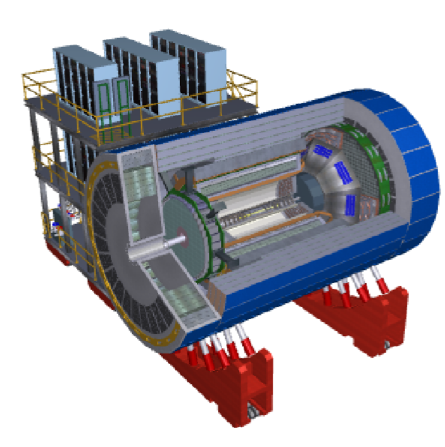
EIC Current Status and Next Steps

Known Detector Proposal Efforts: ATHENA / CORE / ECCE

- Three detector proposals efforts have emerged: ATHENA / CORE / ECCE
- Shown below a SketchUp implementation for integration studies







ATHENA: A Totally Hermetic Electron-Nucleus Apparatus

Concept: General purpose detector inspired by the YR studies based on a new central magnet of up to 3T

WWW-page: https://www.athena-eic.org

CORE: COmpact detectoR for the Eic

Concept: Nearly hermetic, general-purpose compact detector, 2T baseline

WWW-page: https://userweb.jlab.org/~hyde/EIC-CORE/

ECCE: EIC Comprehensive Chromodynamics Experiment

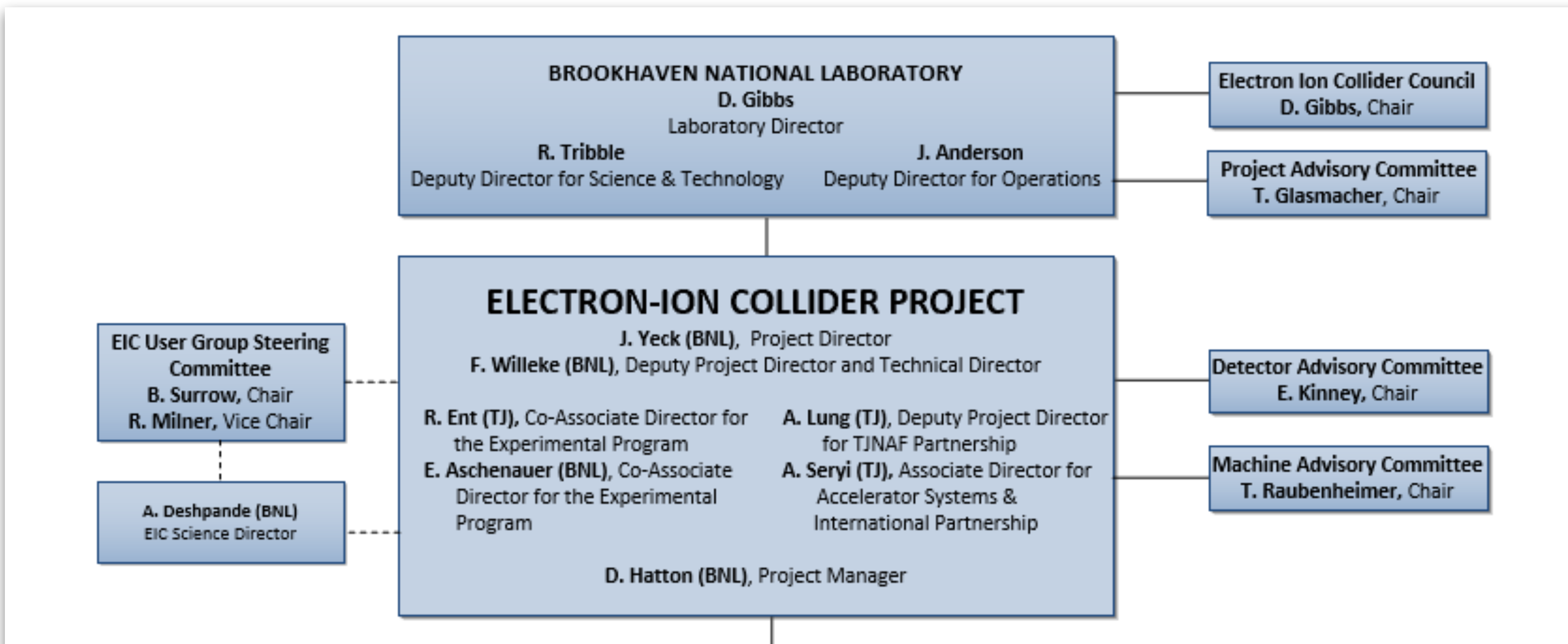
Concept: General purpose detector based on 1.5T BaBar magnet

WWW-page: https://www.ecce-eic.org

EIC Current Status and Next Steps

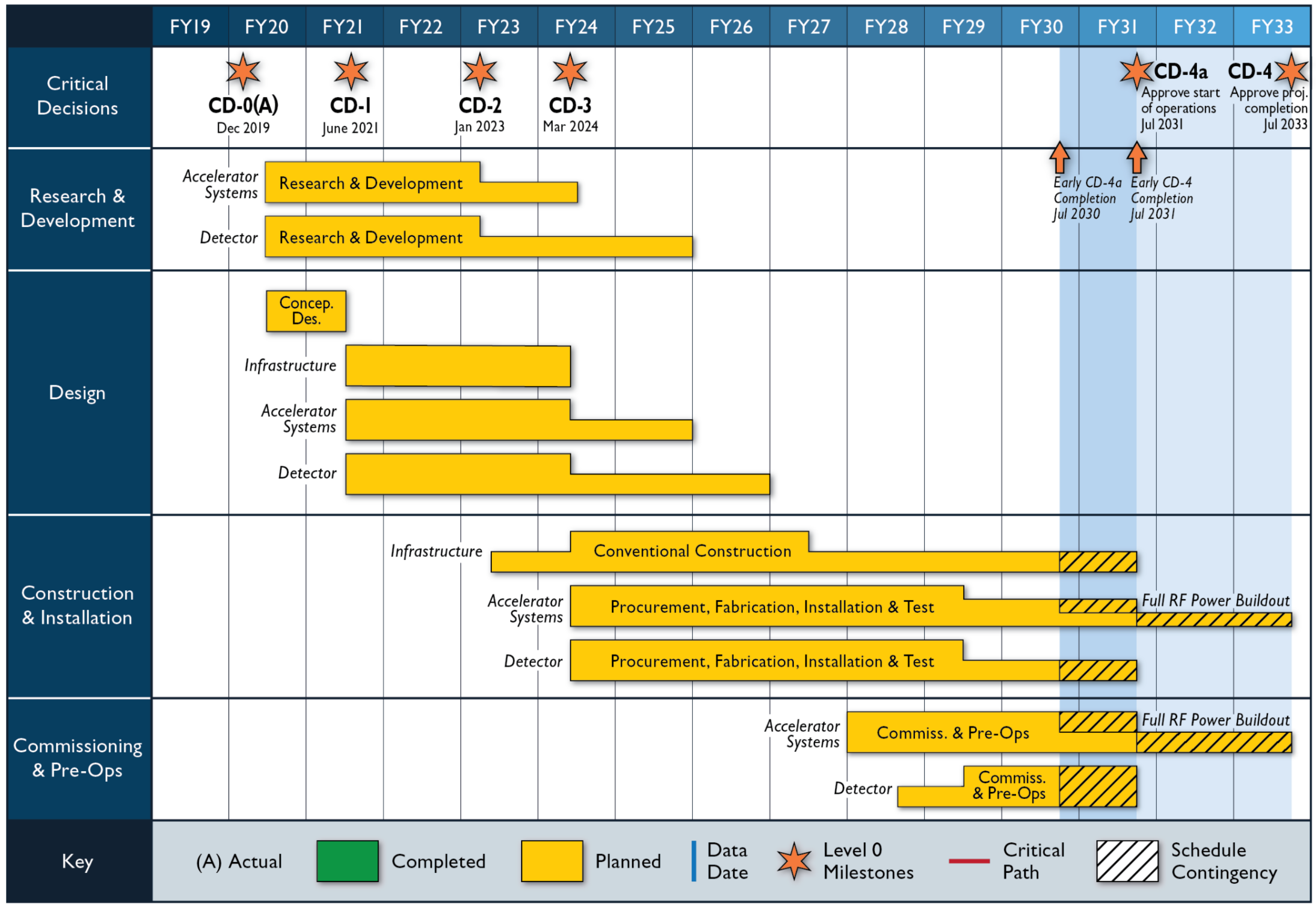
Project status

- EIC project is carried out in partnership between BNL and TJNAF / Partnering agreement signed in May 2020
- EIC Council, chaired by BNL Director, established in June 2020. TJNAF director is a founding member. Concept based on recent DOE Office of Science projects
- Executive Management Team integrates BNL and TJNAF project leadership roles:



EIC Current Status and Next Steps

- Milestones and Anticipated Next steps
  - Total Project Cost (TPC): $2,249M
  - CD1 approved!
  - CD2 preparations well underway!
  - DOE NP office together with BNL/JLab and EICUG engage in regular dialog with international funding agencies!



Summary

- Over two decades, the U.S. nuclear physics community has developed the scientific and technical case for the Electron-Ion Collider, to push the frontiers of human understanding of the fundamental structure of matter.
- Realization of EIC will demand that DOE NP, BNL and JLab lead the U.S. to the frontiers of collider technology.
- Enormously profit from diverse set of experiences in accelerator science, detector technology and theory at numerous institutions world-wide critical for a broad EIC scientific program.
- The recently completed Yellow Report activity brought together the EIC community even under restricted conditions and resulted in a 3 Volume Series: Executive Summary / Physics / Detector - Basis for Detector proposal efforts: ATHENA / CORE / ECCE with a deadline of December 1, 2021!
- Outstanding educational opportunities for multiple generations of students and postdoc world-wide: Physics studies / Detector technology / Accelerator technology

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Join us!