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U.S. DEPARTMENT OF ENERGY

The Electron-Ion Collider – the Next QCD Frontier

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Nuclear and Particle Physics, BNL

May 23-27, 2022

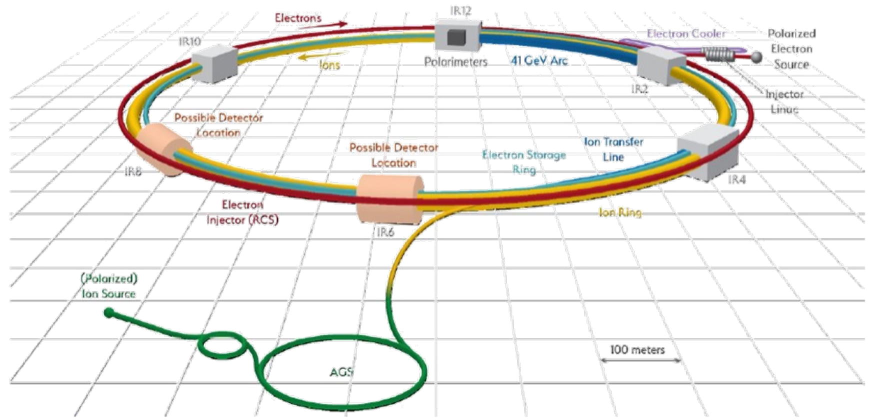
Transversity 2022

The Electron-Ion Collider

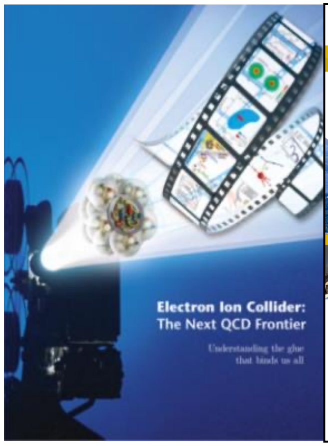
Project Design Goals

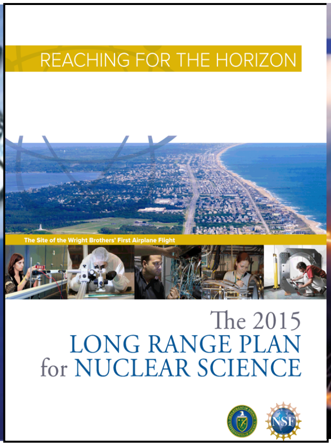
- High Luminosity: L= 10^{33}–10^{34} $cm^{-2}sec^{-1}$, 10–100 fb^{-1}/year
- Highly Polarized Beams: ~70%
- Large Center of Mass Energy Range: E_{cm} = 20–140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)

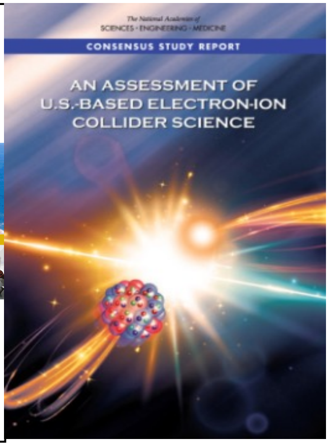
Conceptual design scope and expected performance meet or exceed NSAC Long Range Plan (2015) and the EIC White Paper requirements endorsed by NAS (2018)



Double Ring Design Based on Existing RHIC Facility







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Major milestones: CD-0 December 2019; DOE EIC site (BNL) selection on Jan 9, 2020; CD-1 June 2021; EIC project detector reference design selected in March 2022

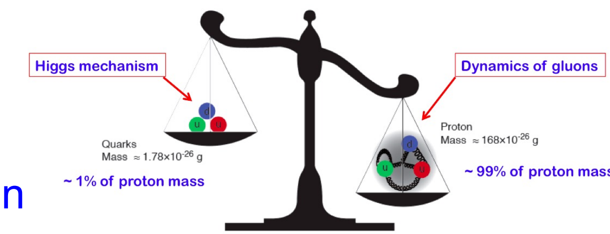
BNL/TJNAF Special Partnership

BNL/JLab partnership established in early 2020

Serve together as hosts for the EIC experimental program

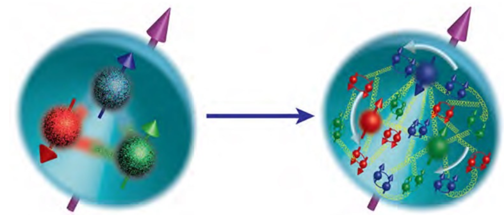
Integrated project scope responsibilities have been defined

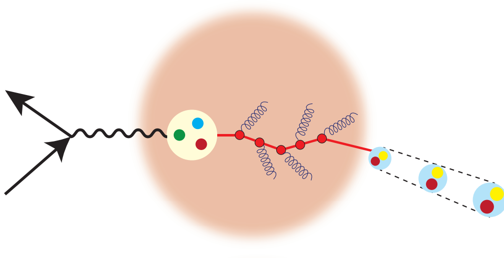
EIC Physics at-a-Glance



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?





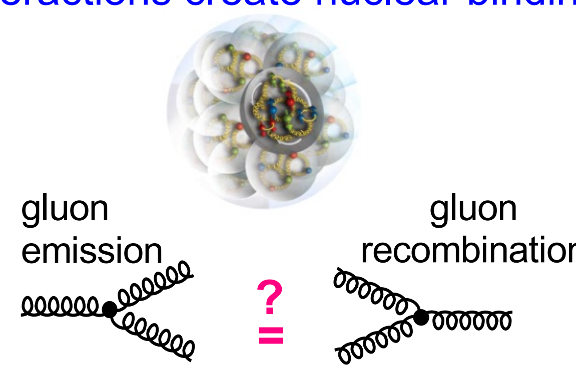
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

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?



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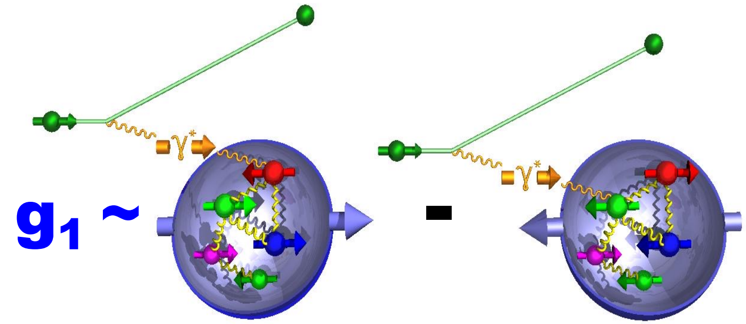
Nucleon Spin: Precision with EIC

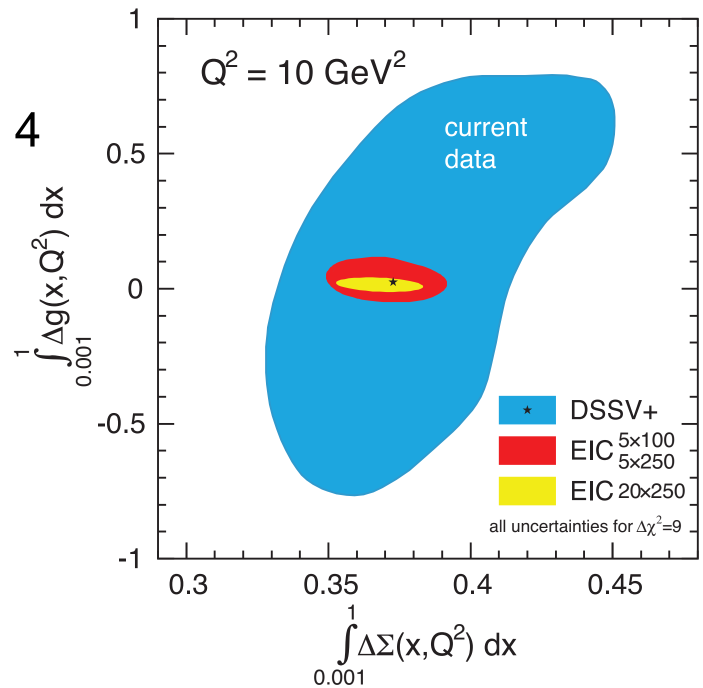
$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

$\Delta\Sigma/2$ = 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 about the magnitude of $L_Q+L_G = L$



A. Accardi *et al.*, EPJA **52**, 268 (2016)

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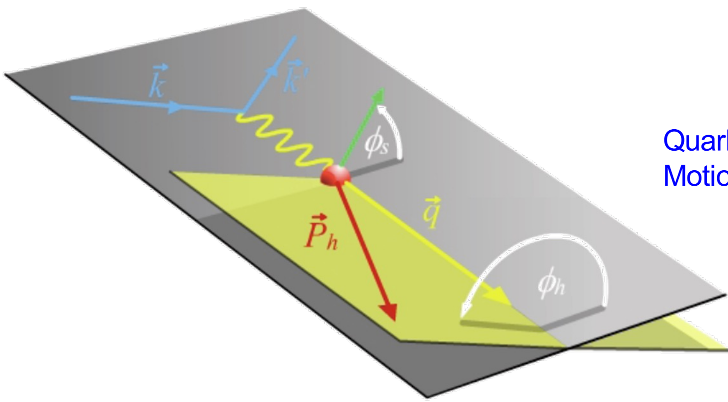
3D partonic image of the nucleon with the EIC

Spin-dependent 3D momentum space images from semi-inclusive scattering (SIDS)

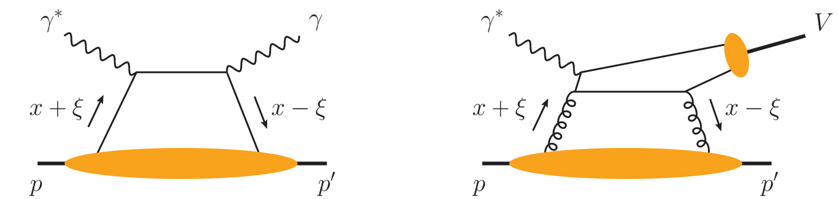
Transverse Momentum Distributions



Quarks Motion

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

Transverse Position Distributions

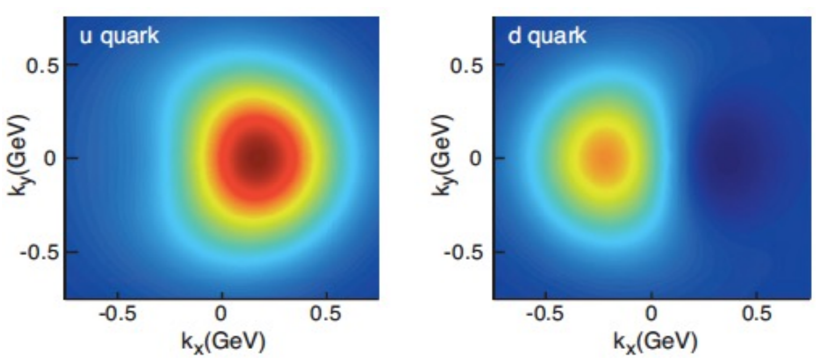


Gluons: Only @ Collider

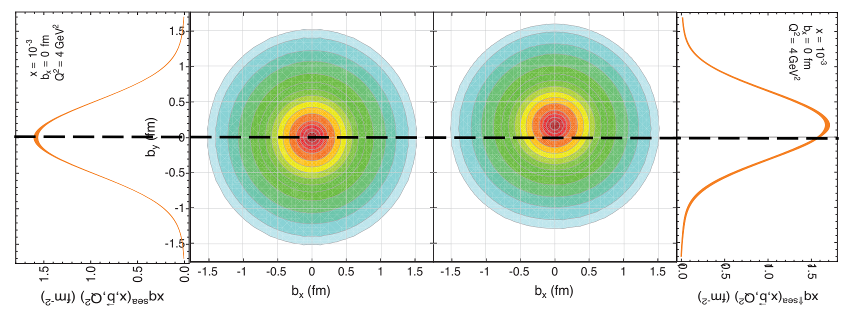
Deeply Virtual Compton Scattering
Measure all three final states
e + **p** → e'+ **p'**+ γ

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

Possible measurements of K (s) and D (c)



2D position distribution for sea-quarks
unpolarized polarized



A. Accardi *et al*., EPJA **52**, 268 (2016)

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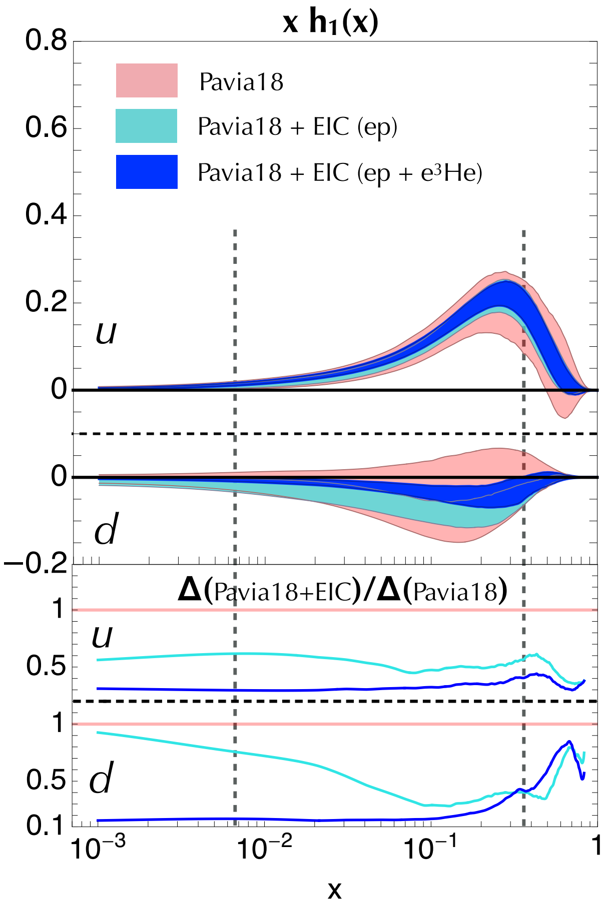
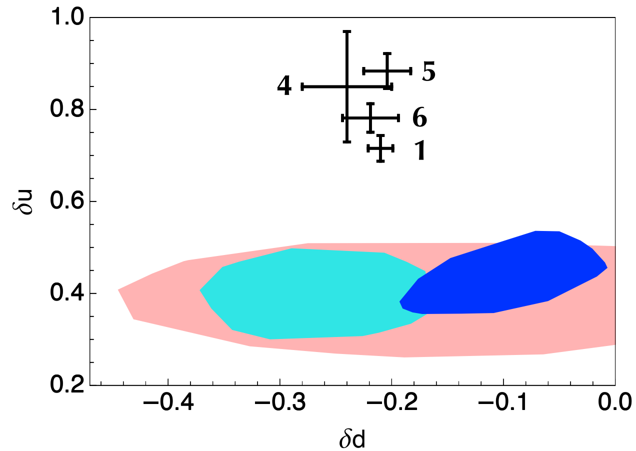
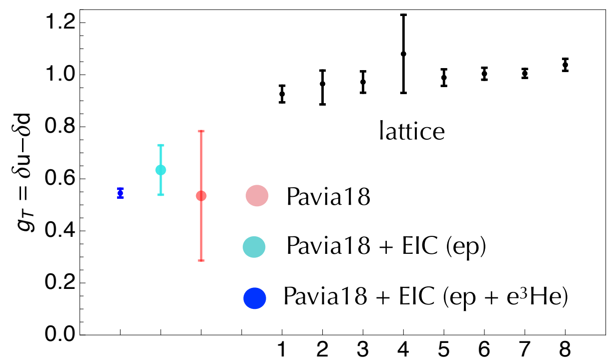
EIC impact on transversity and tensor charge







YR Fig 7.54

10 GeV x 100 GeV (10 fb^{-1} each e-p, e-3He beam configuration)

Q^2 = 2.4 GeV^2

M. Radici and A. Bacchetta, PRL 120,192001 (2018)

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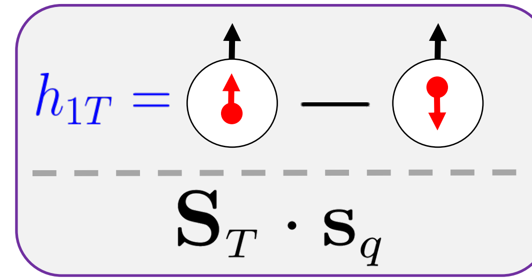
Transversity



- h_{1T} (h_1) = g_1 (no relativity)
- h_{1T} → tensor charge (lattice QCD calculations)
- neutron beta decay and EDM

[1] C. Alexandrou et al., PRD102 (5) 2020 054517

[2] T. Haris et al., PRD 100 (3) 2019 034513

[3] N. Hasan et al., PRD 99 (11) 2019 114505

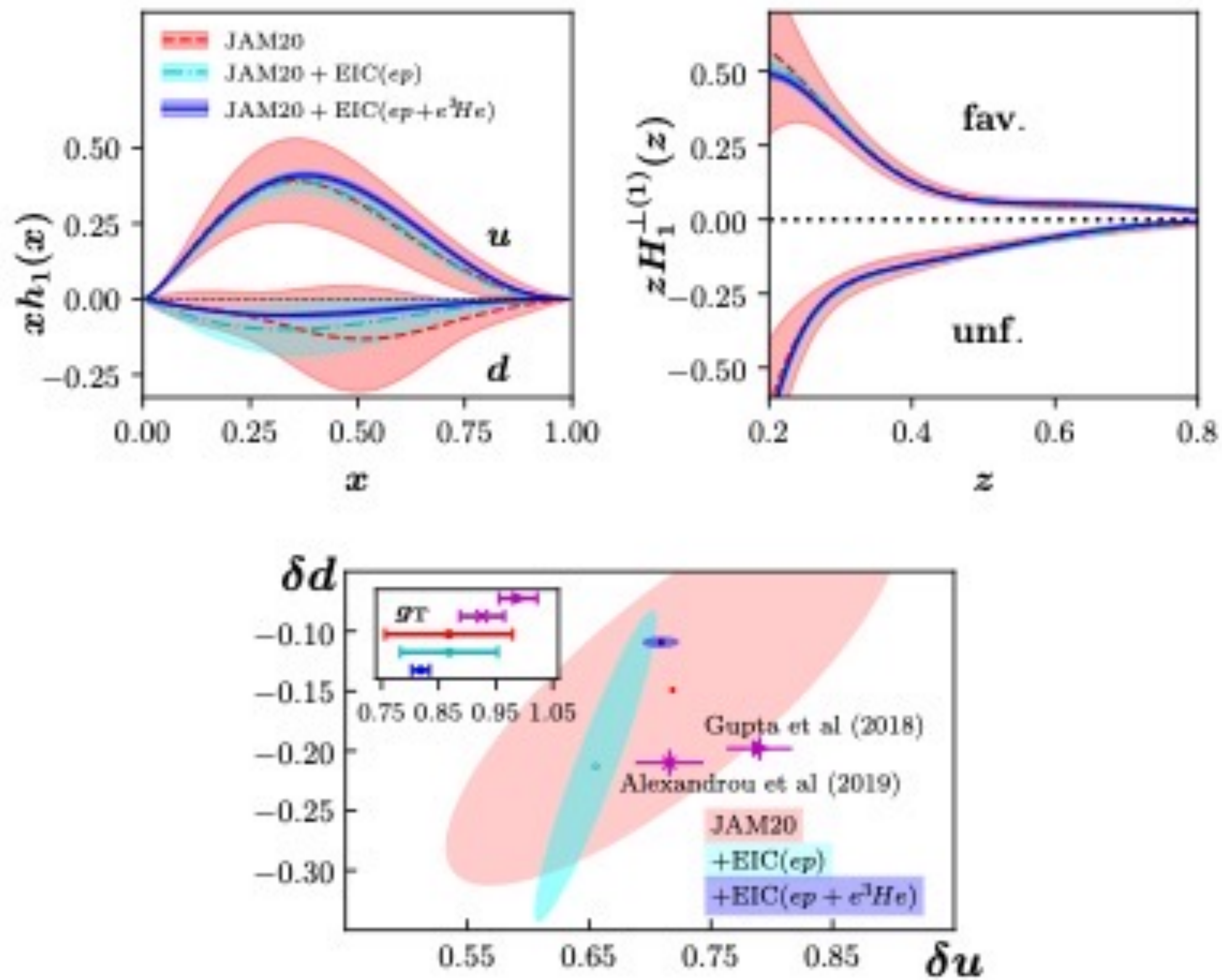
[4] N. Yamanaka et al., PRD 98 (5) 2018 054516

[5] R. Gupta et al., PRD98 (2018) 034503

[6] C. Alexandrou et al., PRD95 (11) (2017) 114514

[7] G.S. Bali et al., PRD91 (5) 2015 054501

[8] J.R.Green et al., PRD86 (2012) 114509



NB: JAM20+EIC includes all energy configurations (18x275, 10x100, 5x100, 5x41 for ep and 18x100, 5x100, 5x41 for eHe3) = 8223 points after data cuts

10 fb^{-1} each e-p, e-3He beam configuration (70 fb^{-1} total)

Gamberg, Kang, Pitonyak, Prokudin, Sato, Reidl, PLB 816, 136255 (2021)

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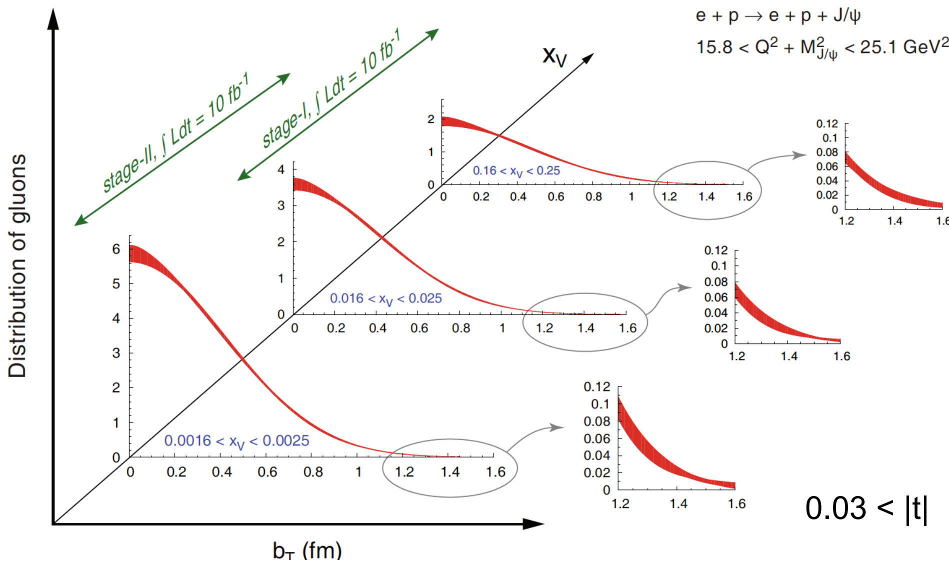
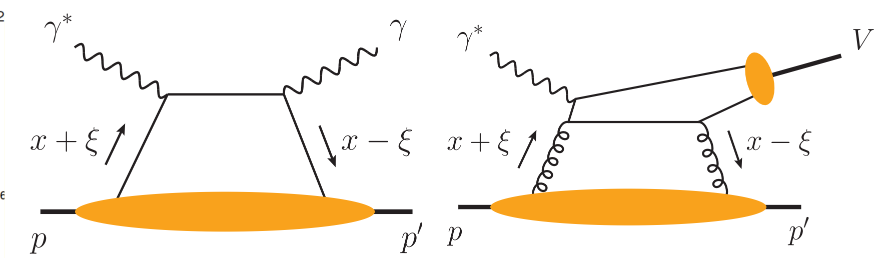
Spatial distribution of quarks and gluons: GPDs via DVCS & DVVM





Fourier transform of momentum transferred = |t| = p-p' → Spatial distribution

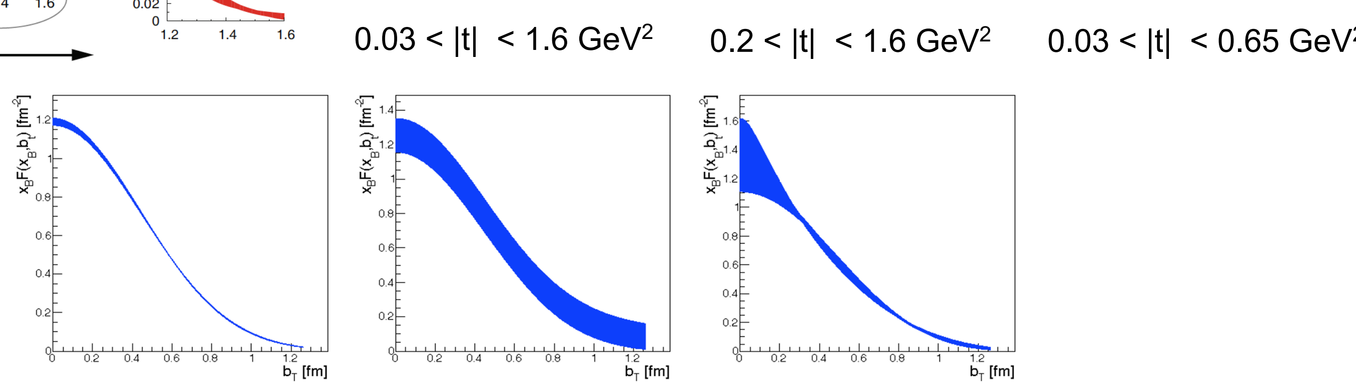


Figure 7.48: Fourier transform of the DVCS cross section as a function of the impact parameter b_T. The cross sections are for different $|t|$ acceptance and an integrated luminosity of $10\,\mathrm{fb}^{-1}$. The bands represent the parametric errors in the fit and the uncertainty from different extrapolations to the regions of unmeasured (very low and very high) $|t|$. Left: $0.03\,\mathrm{GeV}^2 < |t| < 1.6\,\mathrm{GeV}^2$, middle: $0.2\,\mathrm{GeV}^2 < |t| < 1.6\,\mathrm{GeV}^2$, right: $0.03\,\mathrm{GeV}^2 < |t| < 0.65\,\mathrm{GeV}^2$.

Proton Mass and Quantum Anomalous Energy

- **Nucleon mass is the total QCD energy in the rest frame (QED contribution small)**

$$H_{QCD} = H_q + H_m + Hg + H_a$$

$H_q =$ Quark energy $\int d^3x \, \psi^\dagger (-i\mathbf{D} \cdot \alpha) \psi$

$H_m =$ Quark mass $\int d^3x \, \bar{\psi} m \psi$

$H_g =$ Gluon energy $\int d^3x \, \frac{1}{2} (\mathbf{E}^2 + \mathbf{B}^2)$

$H_a =$ Quantum Anomalous energy $\int d^3x \, \frac{9\alpha_s}{16\pi} (\mathbf{E}^2 - \mathbf{B}^2)$

Sets the scale for the hadron mass!

X. Ji PRL 74 1071 (1995),
X. Ji & Y. Liu, arXiv: 2101.04483

C. Lorce', EPJC 78 (2018) 2; C. Lorce', H. Moutarde and A. Trawińsk, EPJC79 (2019)

Metz, Pasquini and Rodini, PRD102, 114042(2021);
Lorce, Metz, Pasquini, Rodini, JHEP 11 (2021) 121
Rodini, Metz, Pasquini, JHEP 09 (2020) 067

- **Measuring quantum anomalous energy contribution in experiments is an important goal in the future** accessed through heavy quarkonium threshold (J/psi & Upsilon) production

D. Kharzeev, Proc. Int. Sch. Phys. Fermi 130, 105 (1996);

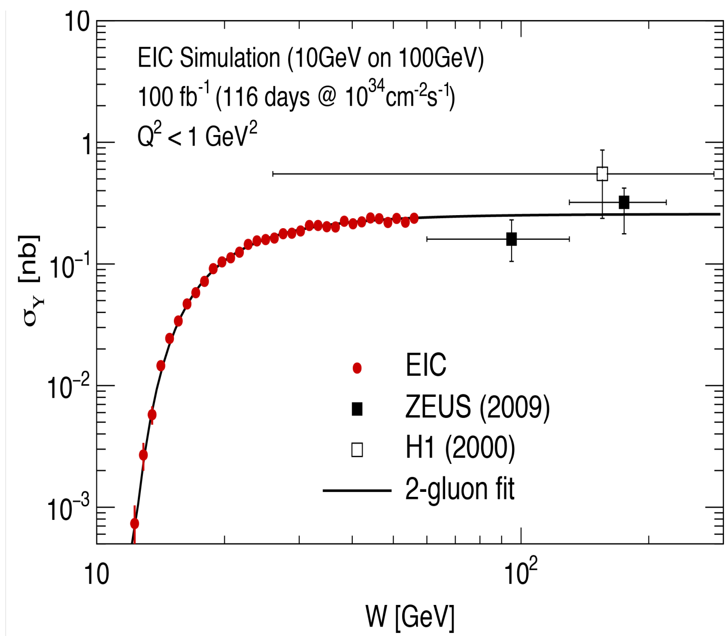
R. Wang et al, Eur. Phys. J.C 80 (2020) 6, 507

Gryniuk, Joosten, Meziani, and Vanderhaeghen,

PRD 102, 014016 (2020)

First three contributions in H_{QCD} can be determined from PDFs and pi-N sigma term & from lattice QCD

C. Alexandrou et al., (ETMC), PRL 119, 142002 (2017)
Y.-B. Yang *et al.*, (χQCD), PRL 121, 212001 (2018)



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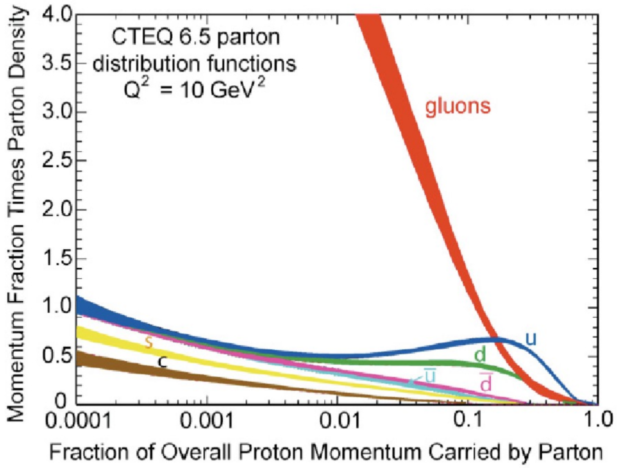
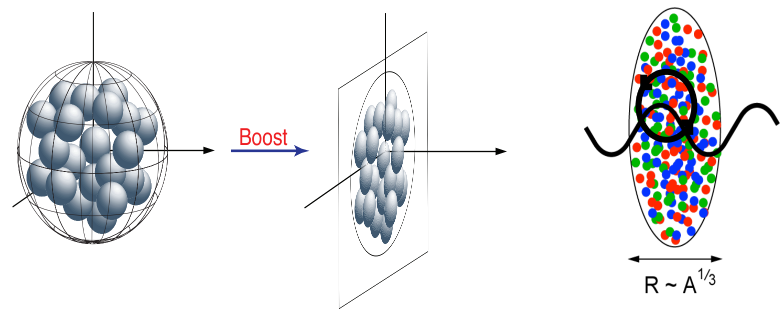
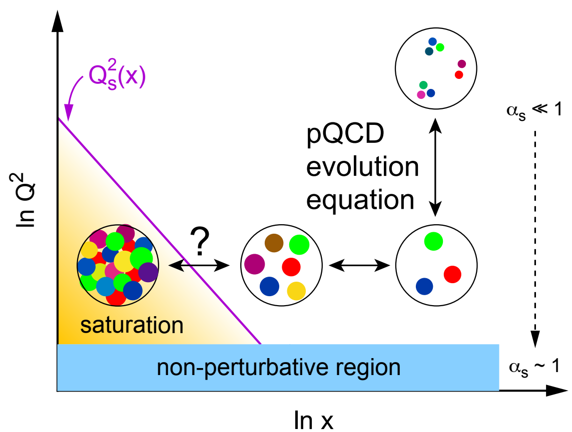
Low x physics with nuclei

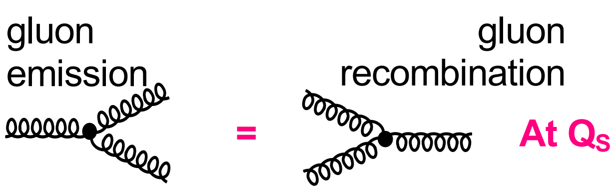




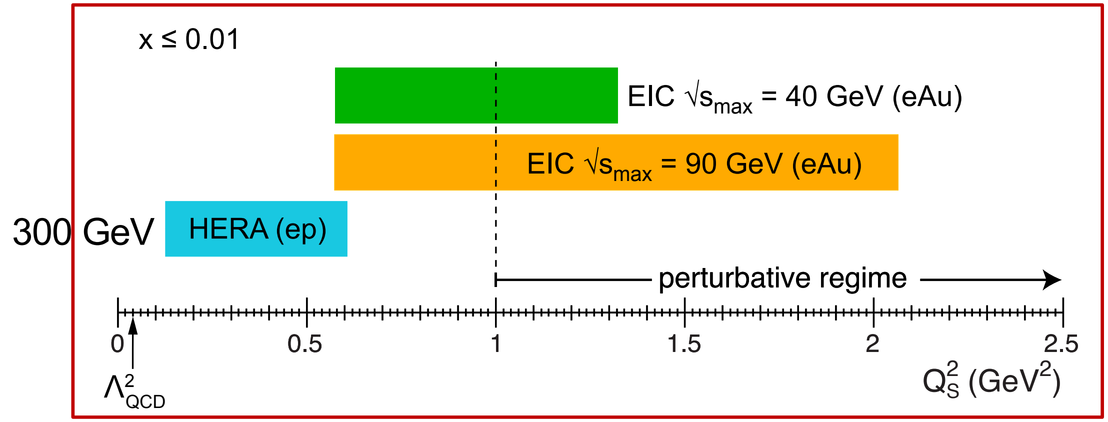
$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

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





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



A. Accardi *et al.*, EPJA **52**, 268 (2016)

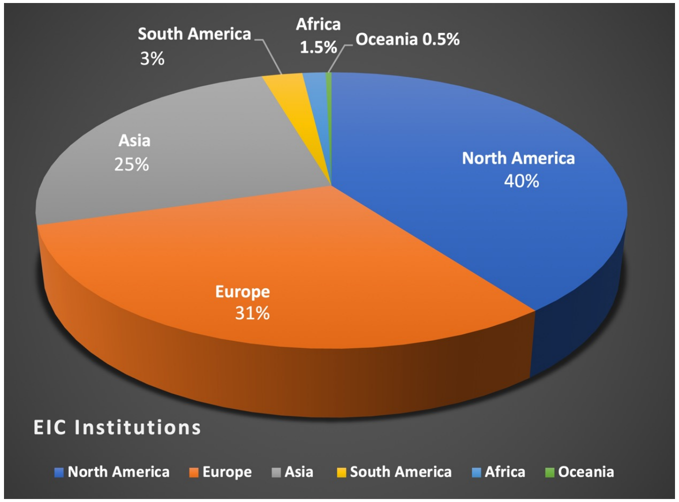
World-Wide Interest in EIC Physics

The EIC Users Group: EICUG.ORG

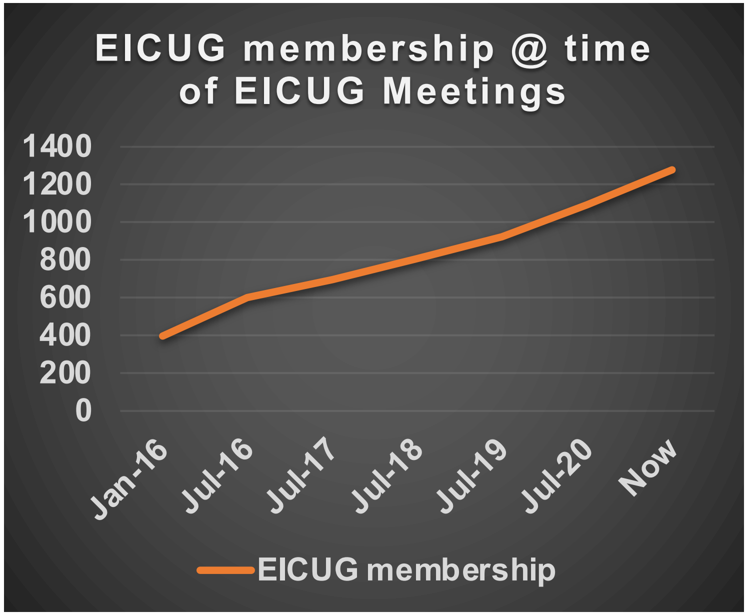
Formed in 2016, Current Status

1307 collaborators, 36 countries, 265 institutions
(Experimentalists 810, Theory 325, Acc. Sci. 159)

- EICUG has continuously grown since its formation, notably after CD-0 and site-selection
- Growth will continue as EIC project moves into construction



Location of Institutions

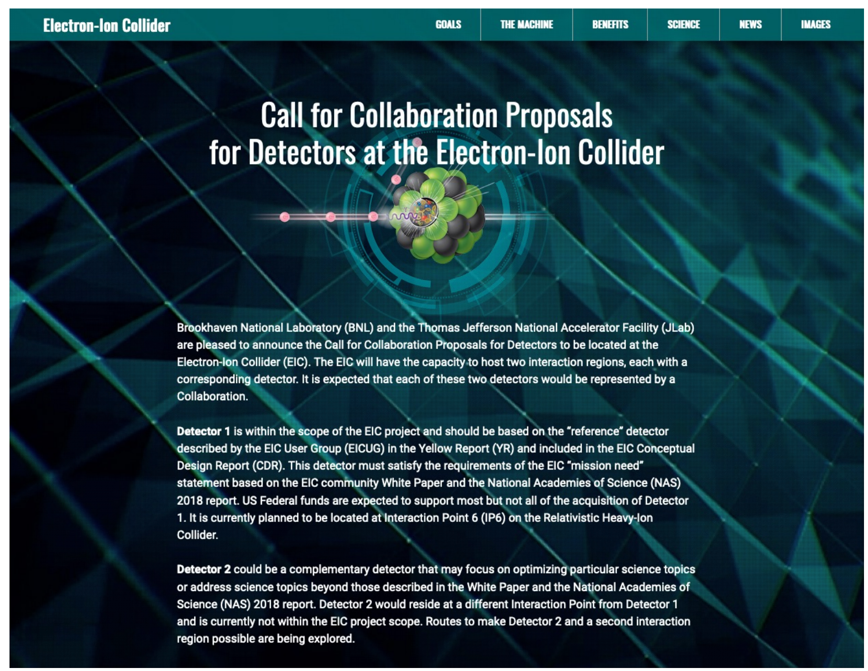


Yellow Report

"Yellow report" laying out physics case, detector requirements, and evolving detector concepts arXiv:2103.05419

Call for Proposals

Issued jointly by BNL and JLab in March 2021 with input from DOE and the EIC User Group.
Proposals due December 1, 2021



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EIC Detector Proposal Advisory Panel (DPAP)

A scientific-technical committee of renowned and independent experts was jointly appointed by BNL and JLab, and reviewed the proposals

Patricia McBride, co-chair	FNAL
Rolf Heuer, co-chair	CERN, Former CERN Director General
Sergio Bertolucci	INFN Sezione di Bologna, Former CERN Research Dir.
Daniela Bortoletto	Oxford Univ.
Markus Diehl	DESY
Ed Kinney	U. Colorado EIC DAC Chair
Fabienne Kunne	Paris-Saclay
Andy Lankford	UC Irvine
Naohito Saito	KEK, Former J-PARC Director
Brigitte Vachon	McGill Univ. EIC DAC Member
Tom Ludlam, Scientific Secretary	BNL

Three proposals received: ATHENA, CORE and ECCE
December 1, 2021

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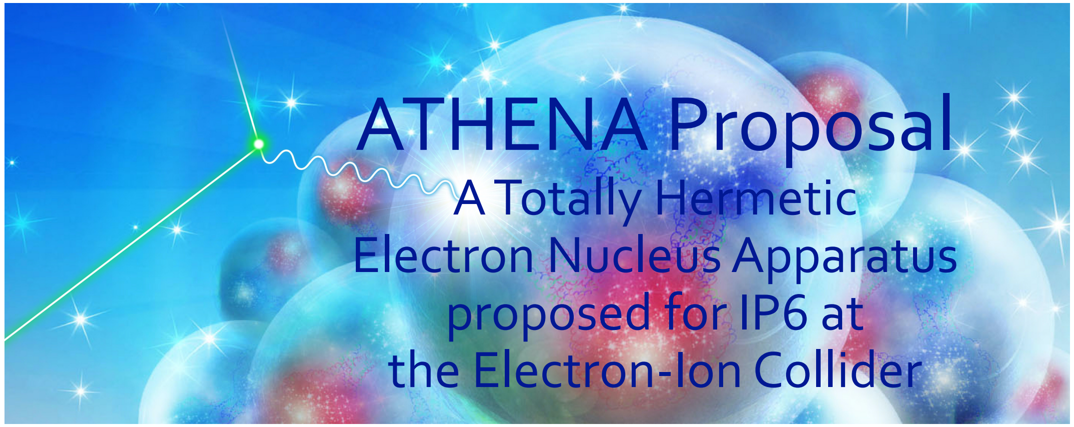
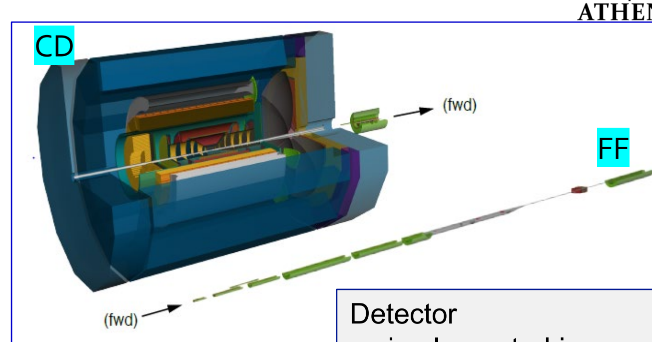


What characterizes ATHENA: **DETECTOR**

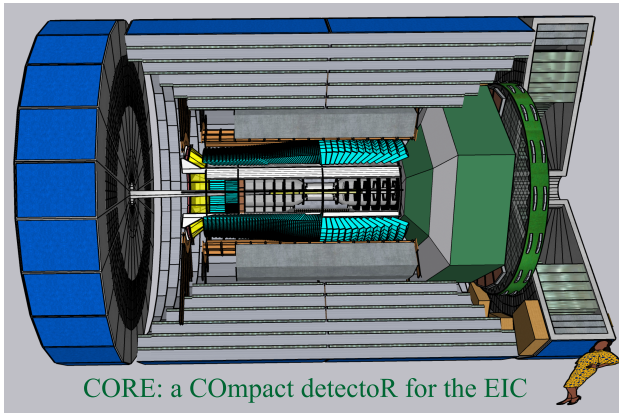
- INCLUDES
  - **CENTRAL DETECTOR** (CD)
  - **Far Forward** (FF) & **Far Backward** (FB) subdetectors



Detector
as implemented in
GEANT4 the FullSim

- **ATHENA DETECTOR matches ALL REQUIREMENTs** for EIC physics program by
  - Light, large-bore 3-T solenoid
  - Fully exploiting the IP6 potentialities (longitudinal and transversal space)
  - Careful choice of technologies, **several innovations since CDR/YR "reference"**
  - acceptance and hermeticity in CD:
    - ✓ careful integration of support structures and detector services to minimize gaps
- **Robust and realistic Detector**
  - careful balance between cutting-edge and mature technologies
  - Largely newly-built detectors that guarantee reliability over 10 y and more
  - Detector and support/services principle allowing for assembly/maintenance interventions

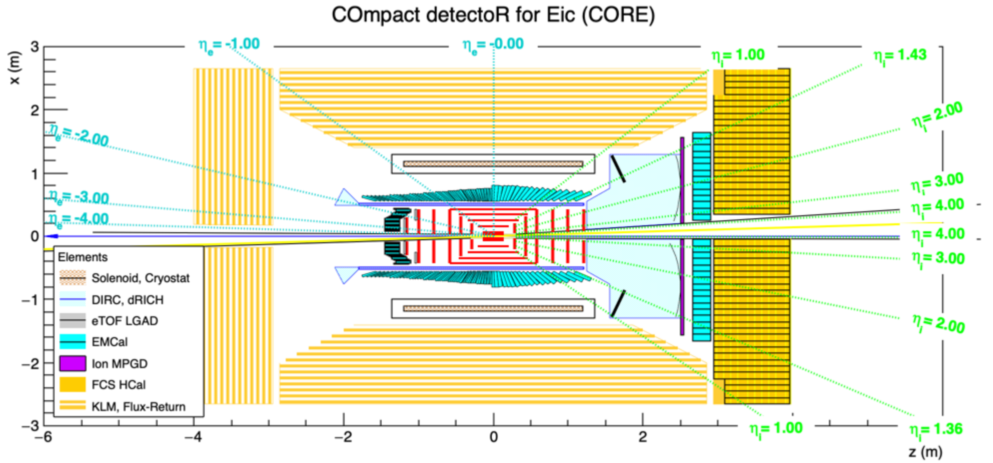
Included part in this talk, part in Thomas Ullrich's talk (tomorrow)



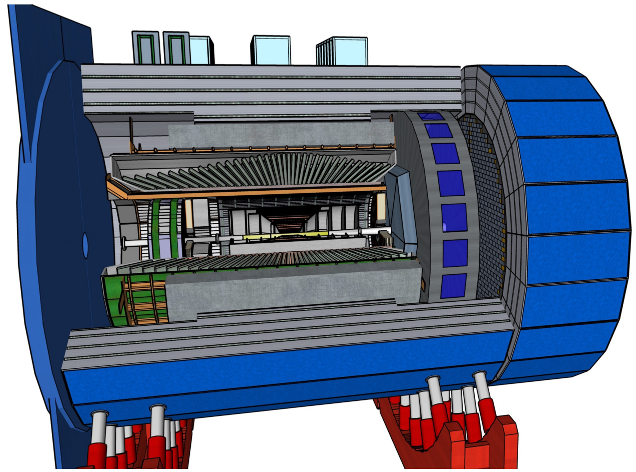
COmpact detectoR for the Eic (CORE)

CORE design philosophy

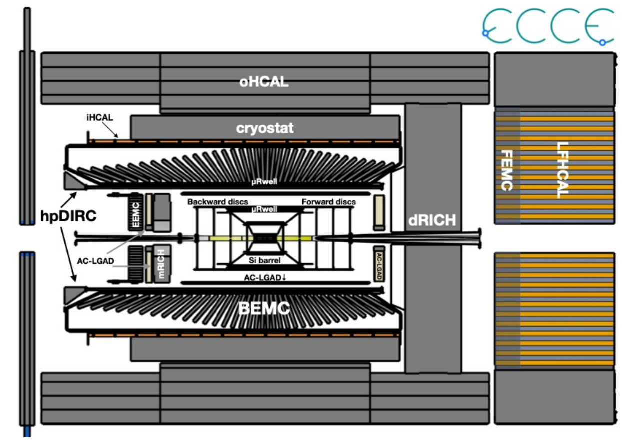
- A short 3 T solenoid enables high-resolution tracking and a higher luminosity
  - Synergetic with an IR with a 2nd focus, which provides the best far-forward acceptance at the lowest β^*



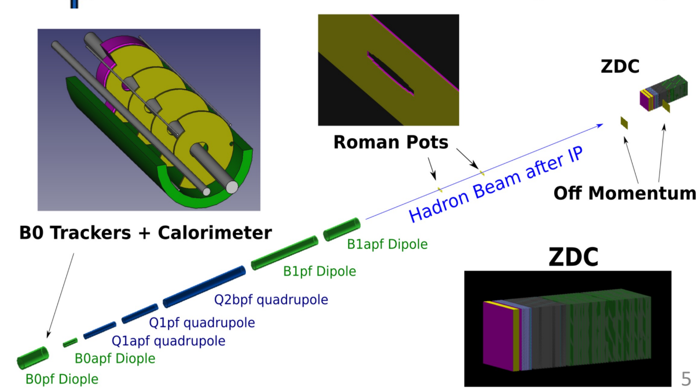
- A compact core of subsystems around a high-resolution all-silicon tracker inside a spacious flux return, makes the detector cost-effective and provides ample space for supports and services.
- In particular, the compact core makes it affordable to use the best possible EM calorimetry in the barrel, enabling new physics (*e.g.,* tomography of nuclei).
- CORE is a fully hermetic detector with 4π tracking, calorimetry, and PID.
- Since EIC jets generally have low energies and multiplicities, and are best reconstructed from the individual particles, the KLM in the barrel and electron endcap of CORE emphasizes measurement of the position of neutral hadrons and identification of muons.



EIC Comprehensive Chromodynamics Experiment (ECCE)



- Integrated design for physics performance:
  - AI optimized tracking,
  - Excellent calorimetry ($PbWO_4$; SciGlass; …),
  - Comprehensive PID (TOF + Cerenkov + Calo),
  - Reuse BaBar Magnet & sPHENIX HCal,
  - Optimized far-forward / back detectors.
- Established physics reach with Geant4 simulations
- Low-risk design to ensure on-time on-budget project completion:
  - Use advanced yet low-risk technologies,
  - Minimize number of technologies,
  - Magnet design contingency.



Recommendations from DPAP

- "The panel unanimously recommends ECCE as Detector 1. The proto-collaboration is urged to openly accept additional collaborators and quickly consolidate its design so that the Project Detector can advance to CD2/3a in a timely way."

- "The panel supports the case for a second EIC detector, however, given the current funding and available resources, the committee finds that a decision on Detector 2 should be delayed until the resources and schedule for the Project detector (Detector 1) are more fully realized."

Physics Performance; Detector Concept and Feasibility; Electronics, DAQ, Offline; Infrastructure, Magnet, and Machine Detector Interface; Management and Collaboration

Strength of Collaboration

"The three proto-collaborations are led by experienced, strong leadership teams. ATHENA and ECCE also have expert and experienced international collaborators, as demonstrated by the well-developed state of the proposed conceptual designs prepared in a relatively short period of time, and by the organization of the effort to produce these designs and of the proposals. This accomplishment is truly impressive."

Development following DPAP recommendations

A Key Point from DPAP

"In order to ensure that the EIC has a maximally optimal Detector 1, the proto-collaboration for a concept selected for Detector 1 must be open to: (1) integrating new collaborators in a manner that enables them to make contributions that impact the capabilities and success of the experiment in significant ways, including some new collaborating individuals and groups into positions of responsibility and leadership; and (2) integrating new experimental concepts and technologies that improve physics capabilities without introducing inappropriate risk."

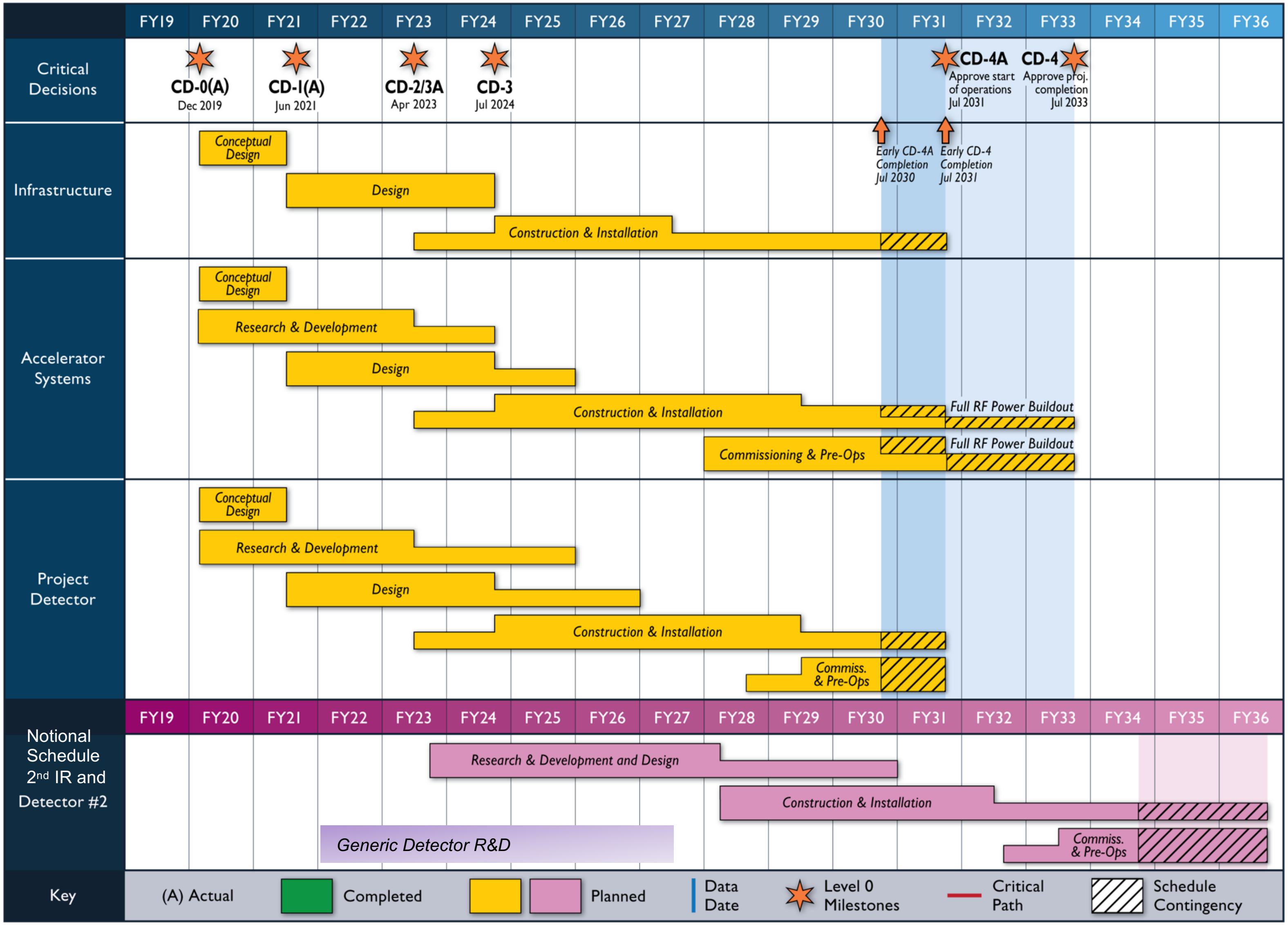
- Priority goal is to establish collaboration for project detector and consolidate the design – ongoing and being coordinated by the EIC project team

- A joint leadership team has formed between ATHENA and ECCE with detector and physics working groups

- Detector 1 first General Meeting took place April 29th, 2022: https://indico.bnl.gov/event/15371/

- Pursuing a path forward towards the 2nd detector with the highest priority on the project detector

Reference Schedule at CD-1



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Jim Yeck, Oct 2021 at EICUG Quarterly Meeting

This schedule is being revised

Summary

- EIC is the next QCD frontier with compelling science
- A strong international EIC user community continues to grow
- Major progress has been made with the EIC project in the last year
  - CD-1 approval in June 2021
  - EIC project detector reference design was selected in March 2022
  - Next major milestone for the EIC: CD2/3a
- The EIC community presented a strong case for a second EIC detector, supported by the DPAP; pursuing a path forward towards the 2nd detector with the highest priority on the project detector

Acknowledgement: DPAP, DAC, proto-collaborations E. Aschenauer, M. Chamizo Llatas, D. Dean, A. Deshpande, R. Ent, T. Ludlam, R. McKeown, R. Tribble, and J. Yeck.

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