The Electron-Ion Collider Update

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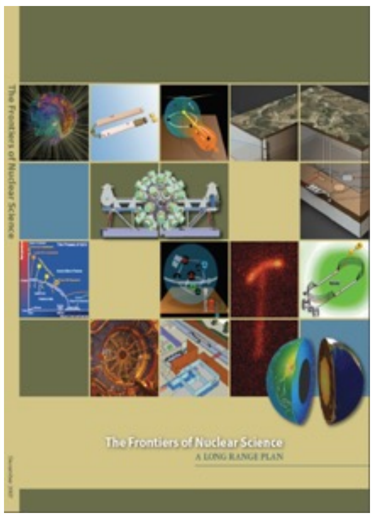
Nuclear and Particle Physics, BNL

June 2, 2023
IUPAP, WG.9 meeting

The Electron-Ion Collider – The Next QCD Frontier

2018 NAS Report : An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- How does the **mass** of the nucleon arise?
- How does the **spin** of the nucleon arise?
- What are the emergent properties of dense systems of gluons?



arXiv:1108.1713v2 [nucl-th] 28 Nov 2011

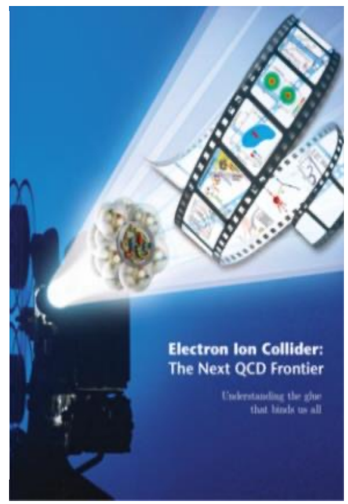
The EIC Science case: a report on the joint BNL/INT/JLab program

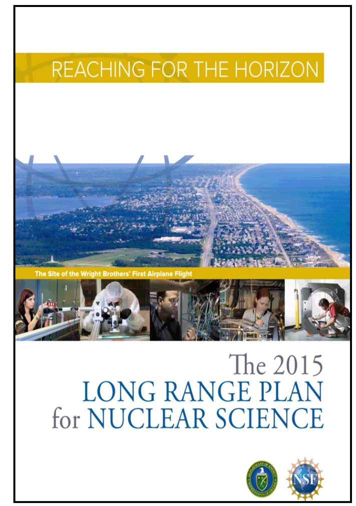
Gluons and the quark sea at high energies: distributions, polarization, tomography

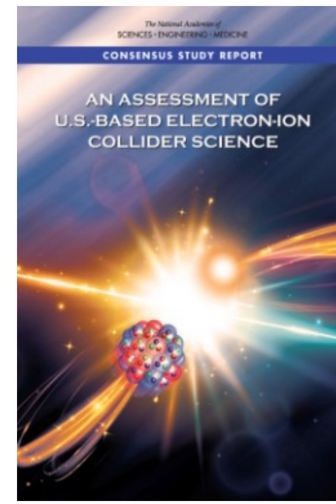
Institute for Nuclear Theory, University of Washington, USA
September 13 to November 19, 2010

Editors:
D. Boer, Universiteit Groningen, The Netherlands
M. Diehl, Deutsches Elektronen-Synchroton DESY, Germany
R. Milner, Massachusetts Institute of Technology, USA
R. Venugopalan, Brookhaven National Laboratory, USA
W. Vogelsang, Universität Tübingen, Germany

Brookhaven National Laboratory, Upton, NY
Institute for Nuclear Theory, Seattle, WA
Thomas Jefferson National Accelerator Facility, Newport News, VA







NSAC LRP 2007

EIC INT Report 2011

EIC White Paper 2015

NSAC LRP 2015

NAS Report 2018

CD-0 December 2019; DOE EIC site (BNL) selection Jan 2020; CD-1 June 2021; EIC project detector selected in March 2022; ePIC collaboration formed in July 2022 & spokesperson (John Lajoie) and deputy spokesperson (Silvia Dalla Torre) elected Feb 2023; EIC Resource Review Board (RRB) meeting April 2023

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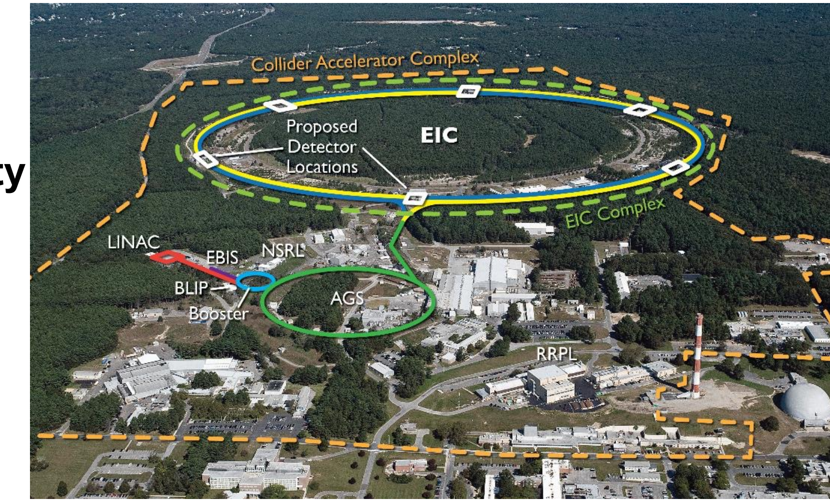
The Electron-Ion Collider

2015 NSAC LRP

“We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB."

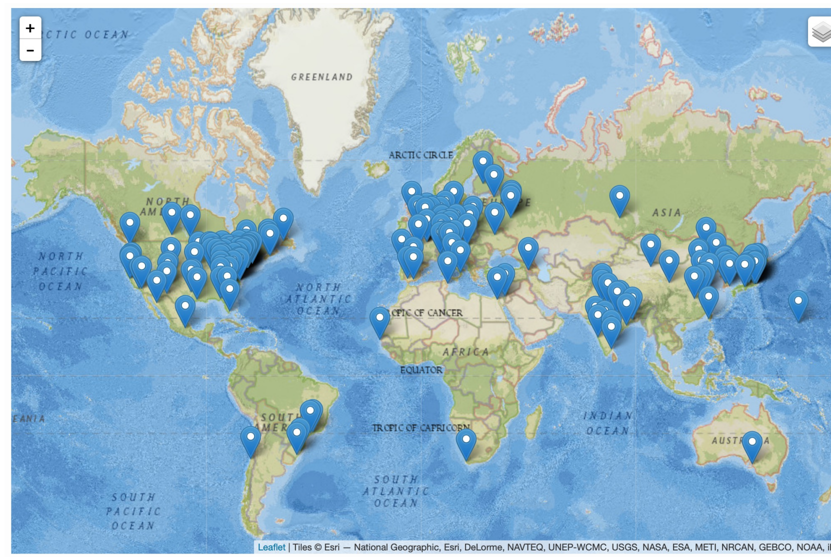


Double Ring Design Based on Existing RHIC Facility

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)



1362 collaborators, 36 countries, 267 institutions

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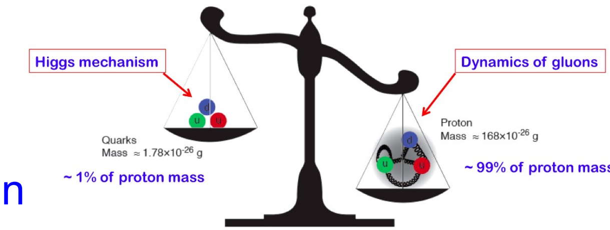
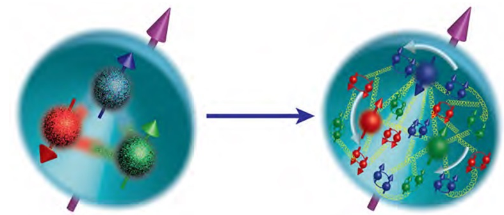
NSAC Long Range Plan (2023) expected to endorse EIC.

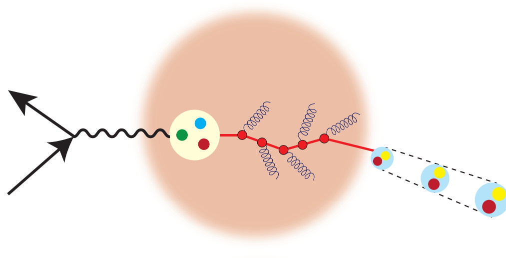
EIC Physics at-a-Glance



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?

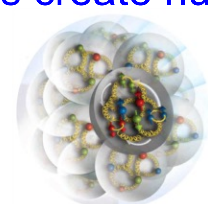




How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

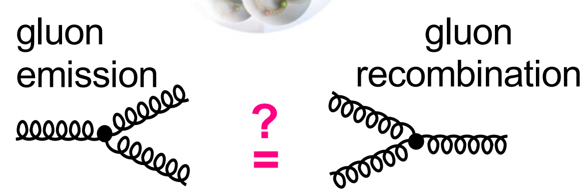
How do the confined hadronic states emerge from these quarks and gluons?

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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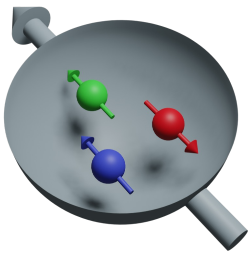
The incomplete nucleon: spin puzzle

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

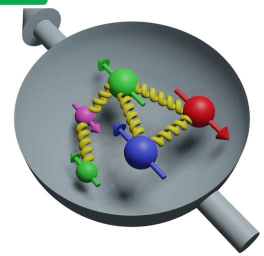
Jaffe-Manohar, 90
Ji, 96



Quark helicity
Best known

$$\frac{1}{2}\int dx\,(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s})$$

$$\sim 30\%$$

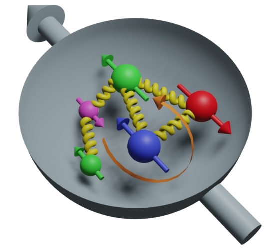


Gluon helicity
Start to know

$$\Delta G = \int dx \Delta g(x)$$

~40% -- RHIC Spin data at $Q^2 = 10\ GeV^2$

With larger uncertainty →



Orbital Angular Momentum of quarks and gluons
Little known

Net effect of partons' transverse motion?

Lattice QCD →

$$L_{u+d+s} = 0.207(64)_{stat}(45)_{syst}$$
$$J_{u+d+s} = 0.408(61)_{stat}(48)_{syst}$$
$$J_g = 0.133(11)_{stat}(14)_{syst}$$

$$J_N = 0.54(6)_{stat}(5)_{syst}$$
(MS = 2 GeV)

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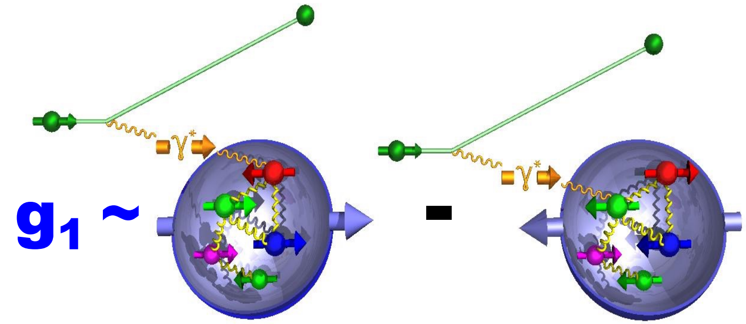
C. Alexandrou et al., PRL 119, 142002 (2017).

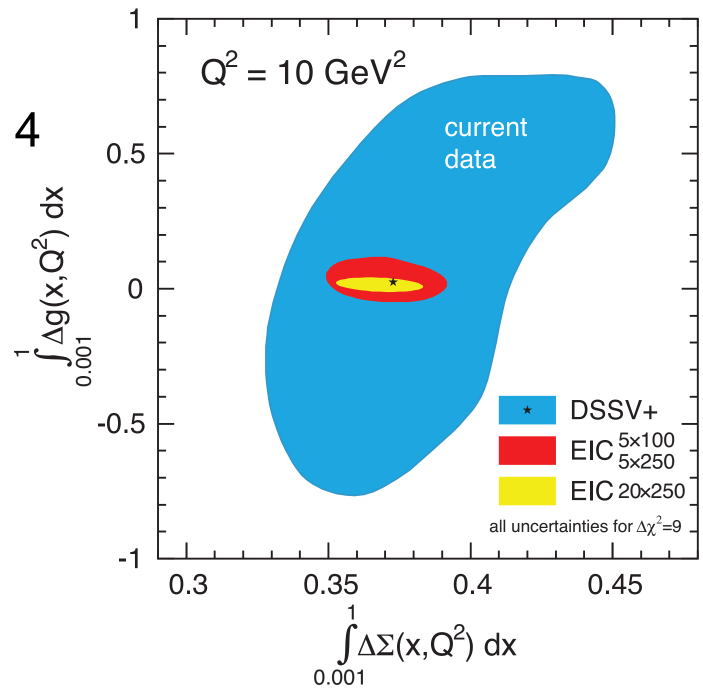
Y.-B. Yang et al., Phys. Rev. Lett. 118, 102001 (2017).

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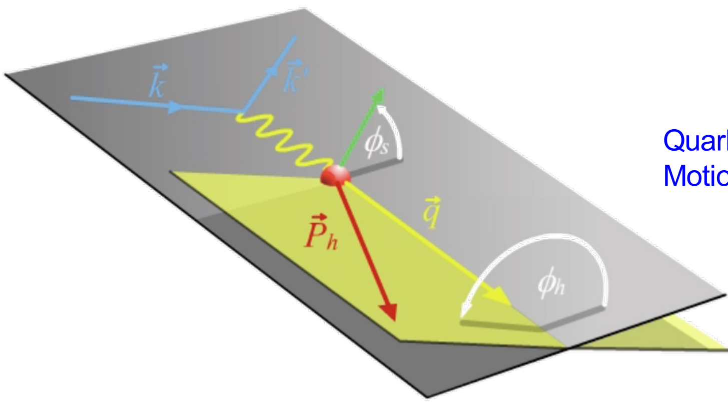
2+1 D partonic image of the nucleon with the EIC

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

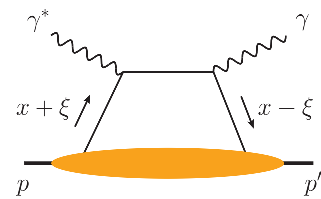
Transverse Momentum Distributions

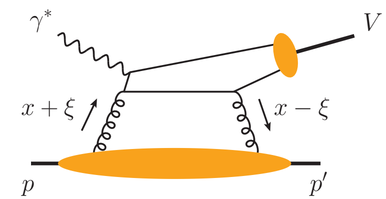


Quarks Motion

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

Transverse Position Distributions



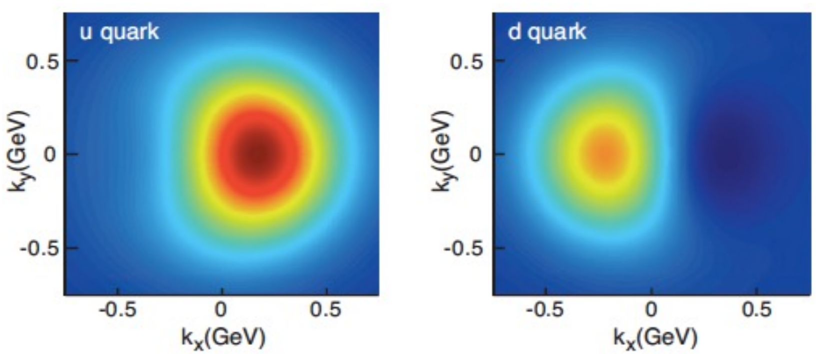


Gluons: Only @ Collider

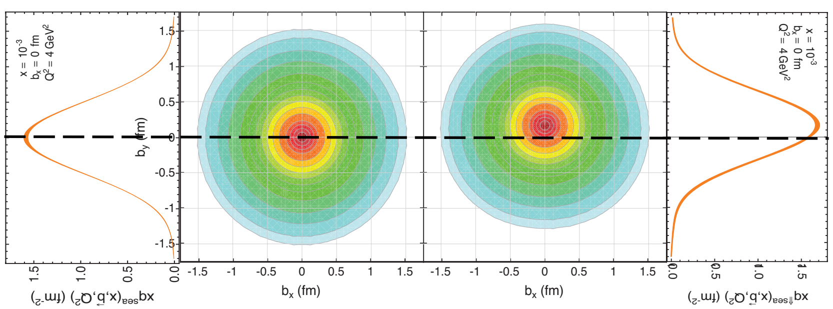
Deeply Virtual Compton Scattering
Measure all three final states
e + **p** → e' + **p'** + γ

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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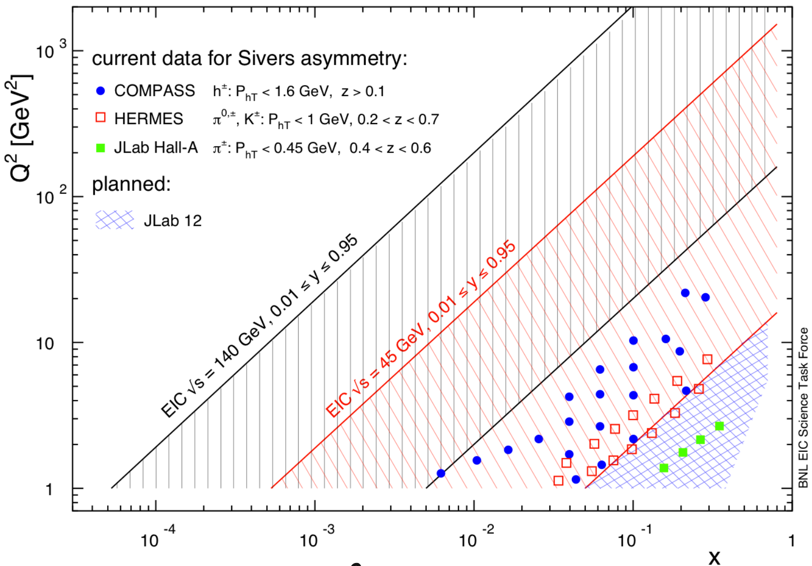
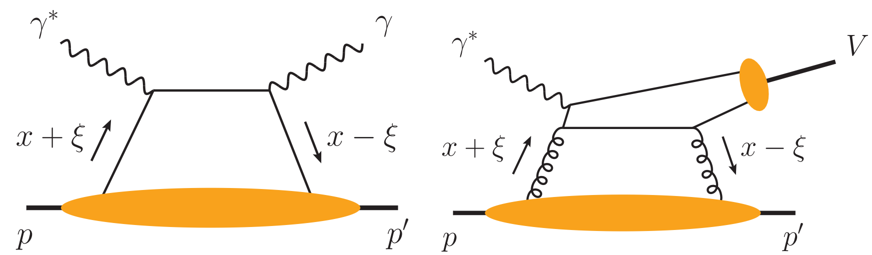
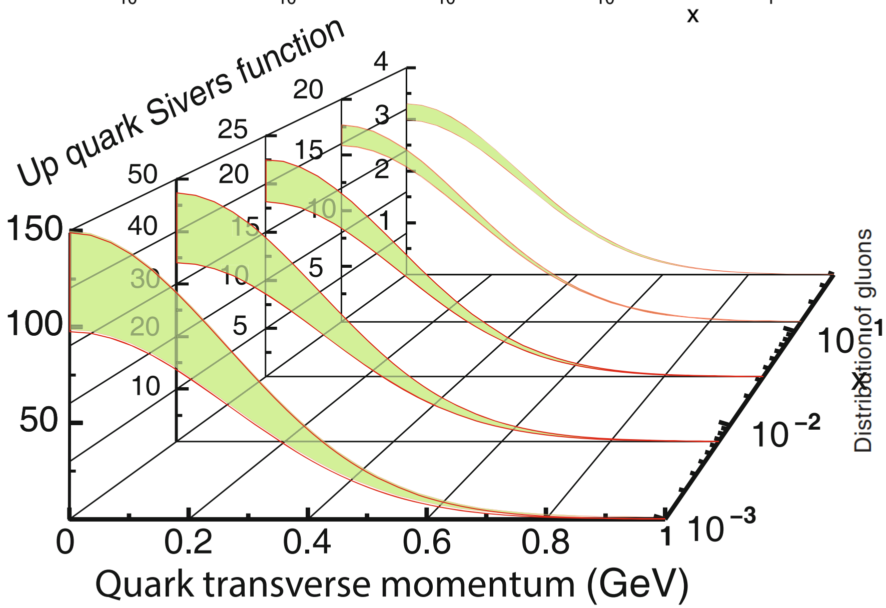
Tomography of the nucleon

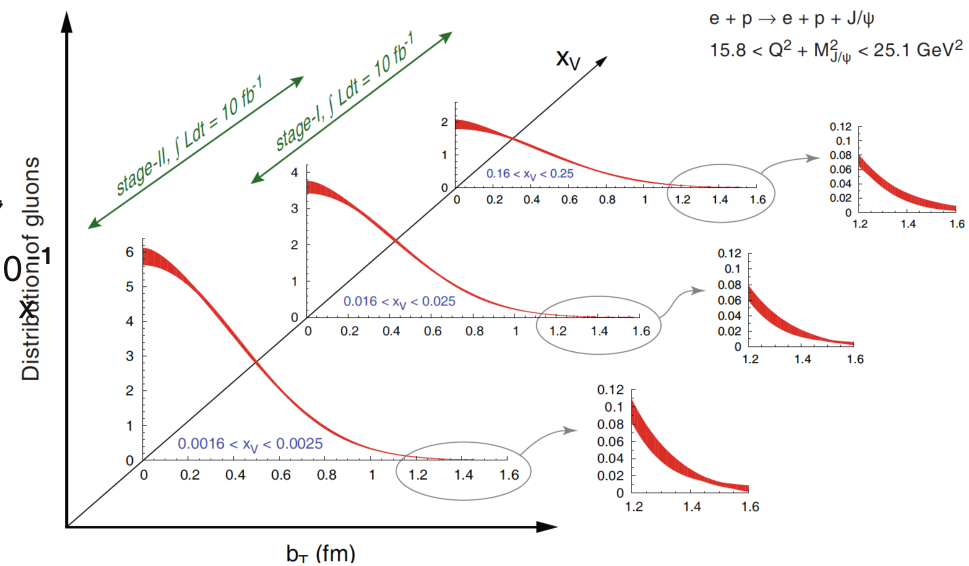




Fourier transform of momentum transferred = |t| = p-p' → Spatial distribution

0.03 < |t| < 1.6 GeV² 0.2 < |t| < 1.6 GeV² 0.03 < |t| < 0.65 GeV²





Proton Mass – Another Fascinating Story

Higgs discovery almost irrelevant to proton mass

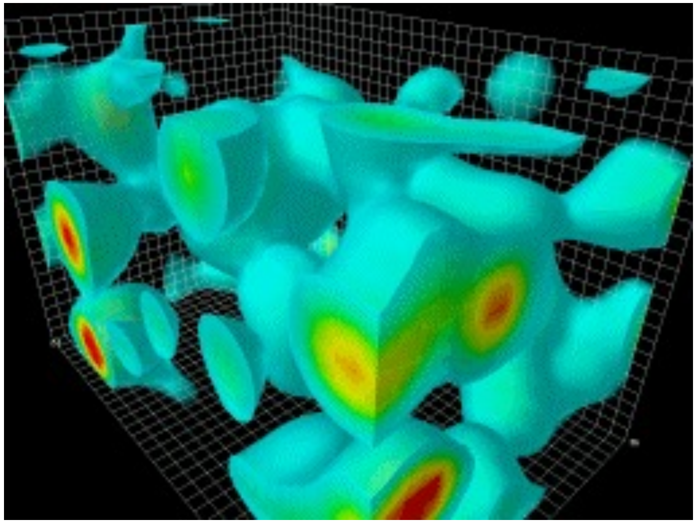
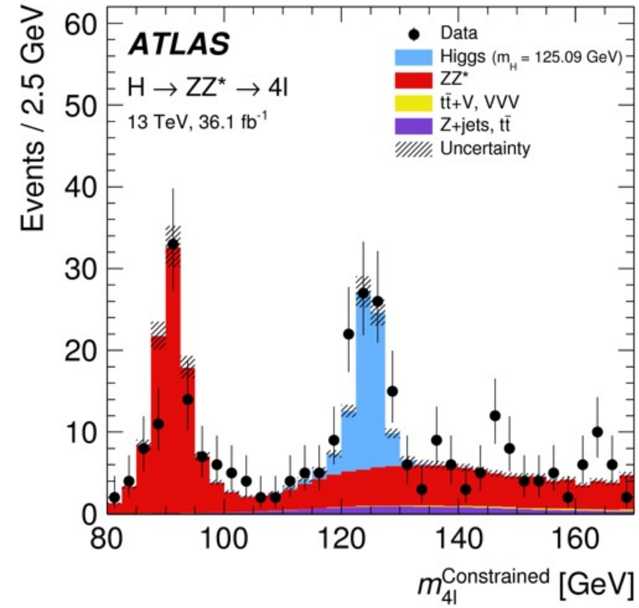


Image credit:
D. Leinweber



Proton mass decomposition in proton rest frame

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

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

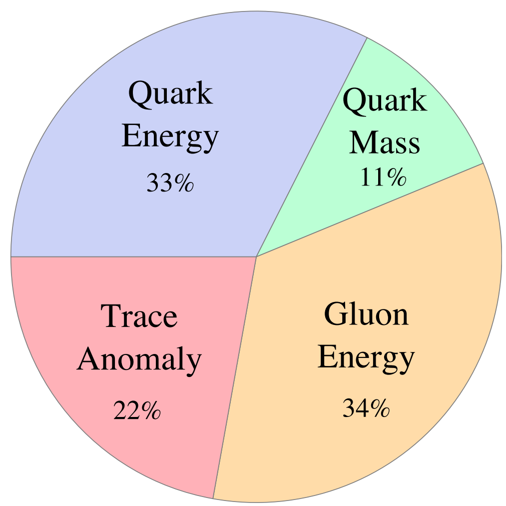
$H_m =$ Quark mass $\int d^3x\, \bar{\psi} m \psi$

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

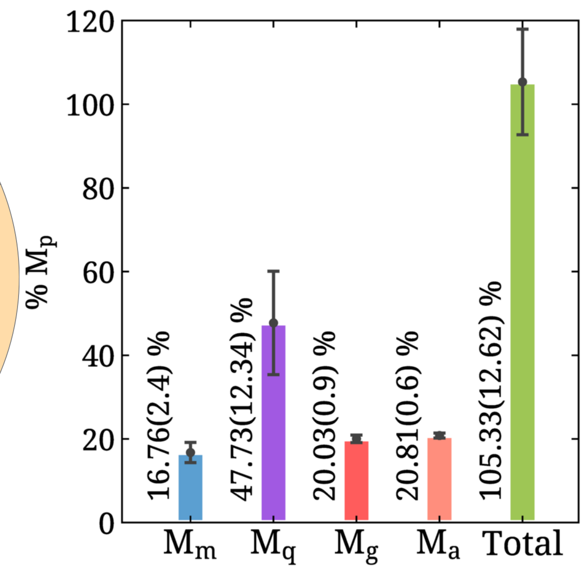
$H_a =$ Trace anomaly $\int d^3x\, \frac{9\alpha_s}{16\pi}(\mathbf{E}^2 - \mathbf{B}^2)$

Sets the scale for the Hadron mass!

X. Ji PRL 74 1071 (1995)



Phenomenology



Lattice QCD simulation

Sets the scale for the hadron mass!

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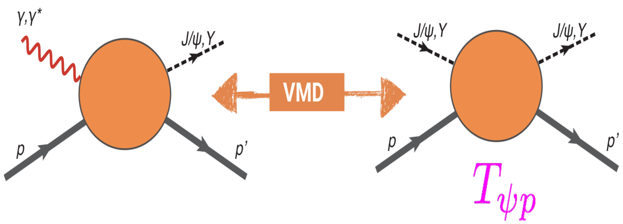
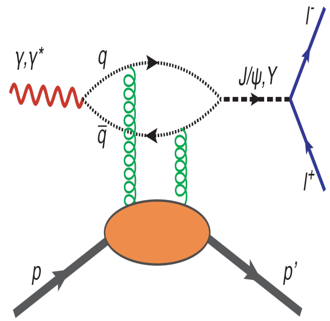
Proton Mass and Quantum Anomalous Energy

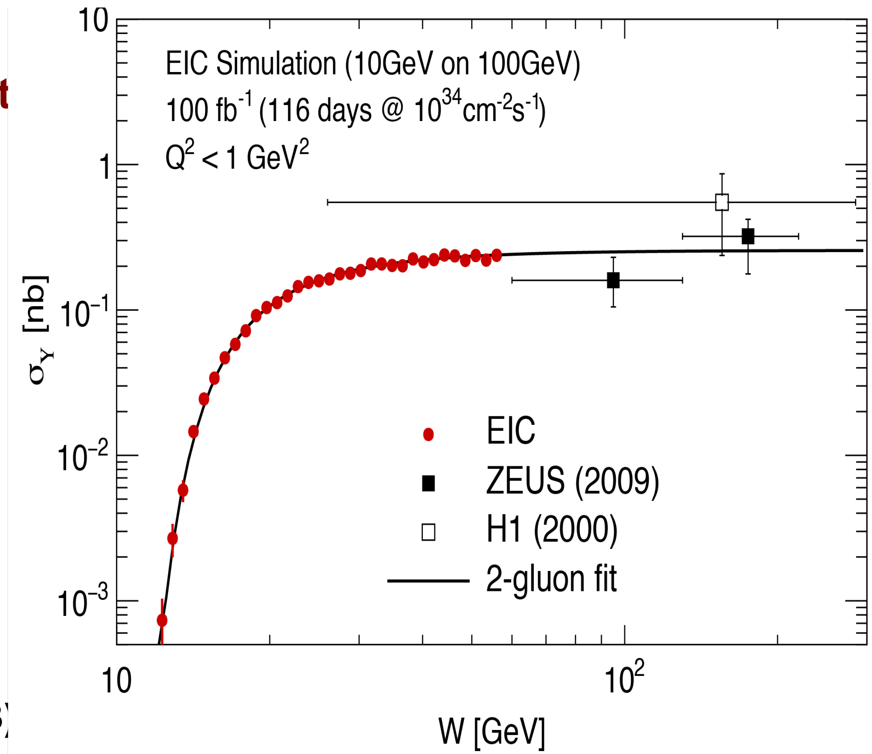
- **Measuring quantum anomalous energy contribution in experiments is an important goal in the future accessed through heavy quarkonium threshold (J/psi & Upsilon) production**





Heavy quark – dominated by two gluons

- **VMD relates photoproduction cross section t scattering amplitude**
  - **Imaginary part** is related to the total cross section through optical theorem
  - **Real part contains the conformal (trace) anomaly;** Dominates the near threshold region and constrained through dispersion relation

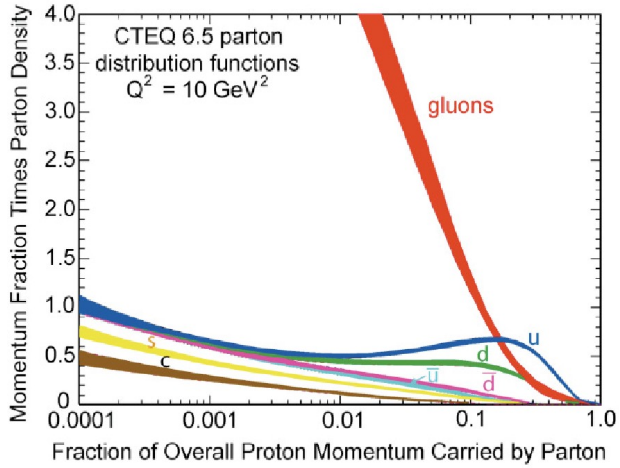


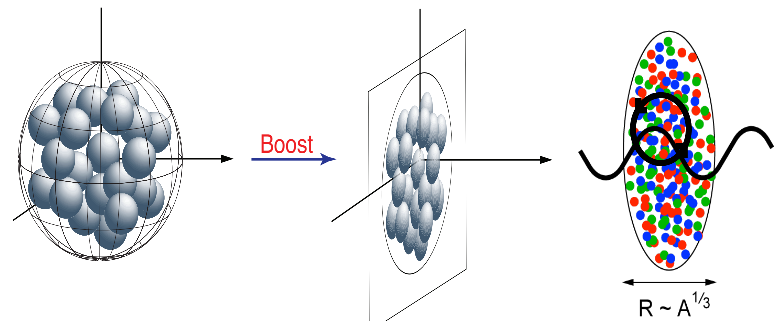
D. Kharzeev, Proc. Int. Sch. Phys. Fermi 130, 105 (1996); R. Wang et al, Eur. Phys. J.C 80 (2020) 6, 507; Gryniuk, Joosten, Meziani, and Vanderhaeghen, PRD 102, 014016 (2020)

B. Duran et al., Nature 615, 813 (2023)

Y. Hatta et al., PRD 98 no. 7, 074003 (2018); Y. Hatta et al., 1906.00894 (2019)

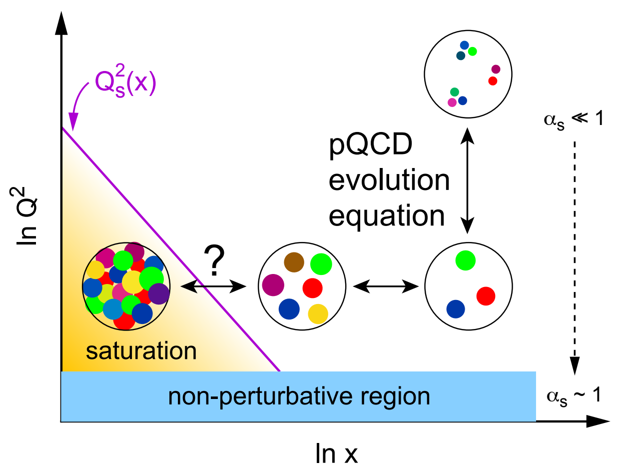
Low x physics with nuclei





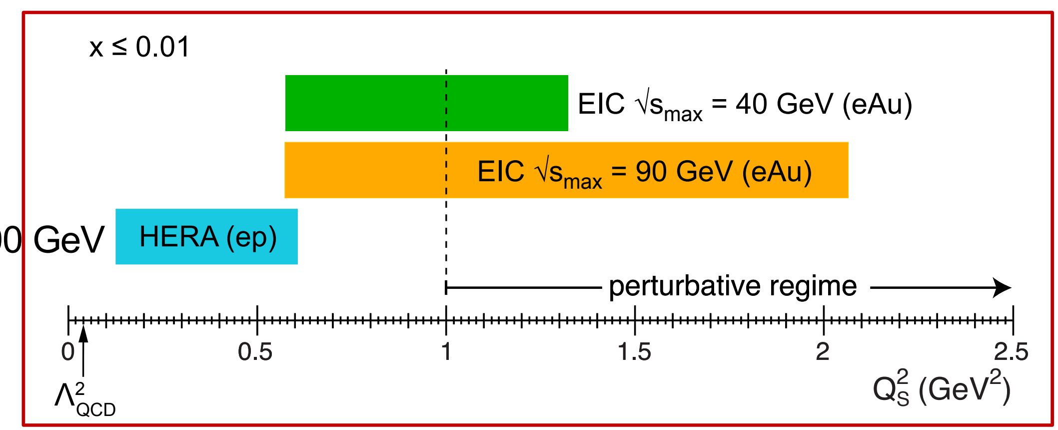
$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

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



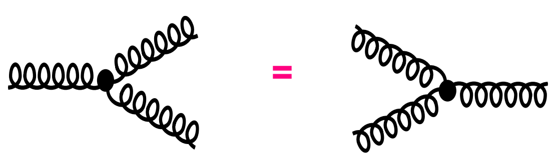
Accessible range of saturation scale $Q_s{}^2$ at the EIC with e+A collisions. arXiv:1708.01527

300 GeV



gluon emission

gluon recombination



At Q_S

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

BNL/TJNAF Special Partnership

BNL/JLab partnership established in early 2020

Integrated management and scope

Serve together as hosts for the EIC experimental program

EIC Detector Proposal Advisory Panel

A scientific-technical committee of renowned and independent experts to evaluate the proposals. Jointly appointed by BNL and JLab.

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 proto-collaborations submitted proposal: ATHENA, CORE and ECCE;
The panel recommended ECCE as the reference design for the EIC project detector

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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.”

ePIC collaboration formed in July 2022 & spokesperson (John Lajoie) and deputy spokesperson (Silvia Dalla Torre) elected Feb 2023

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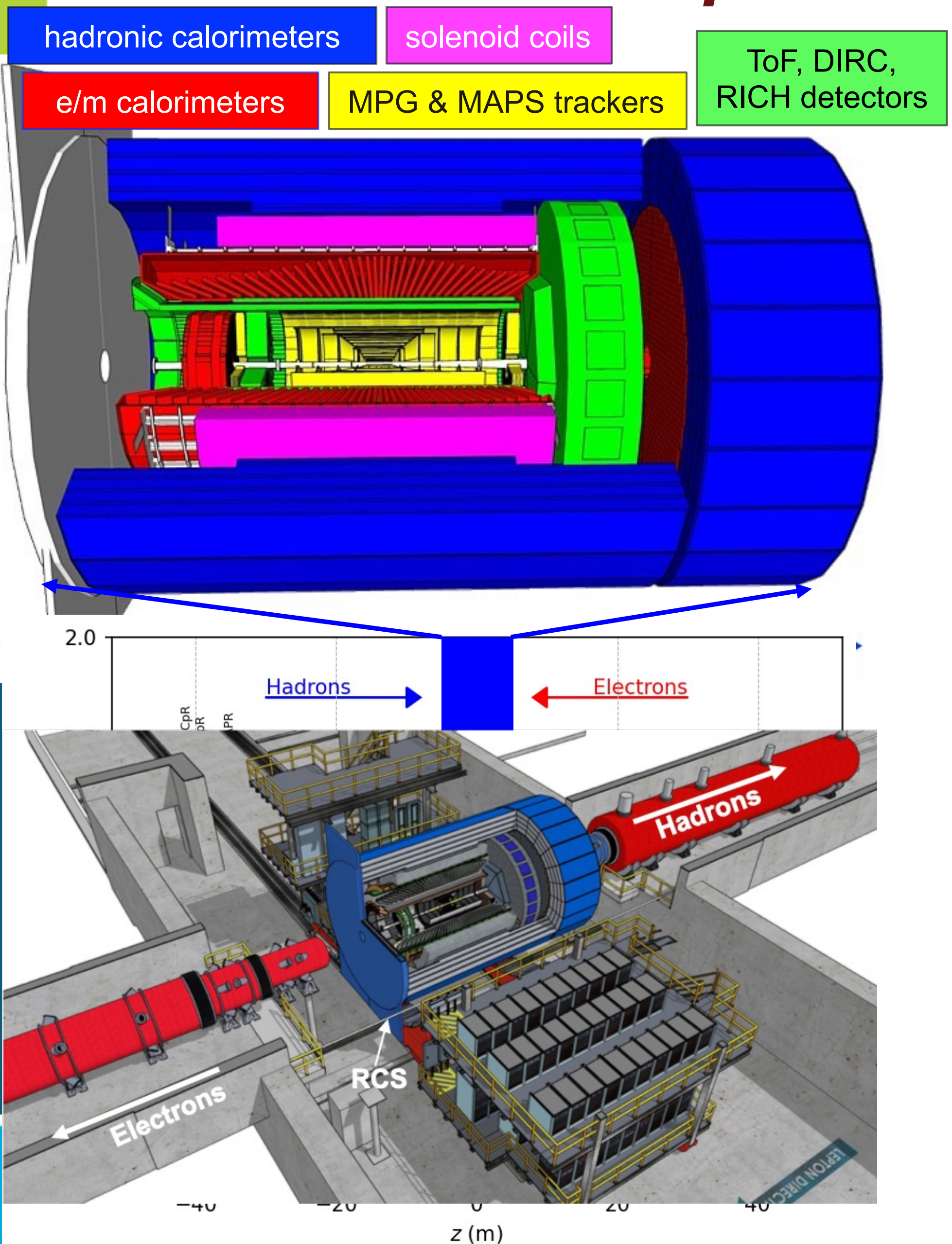
EIC General Purpose Detector: ePIC



Overall detector requirements:

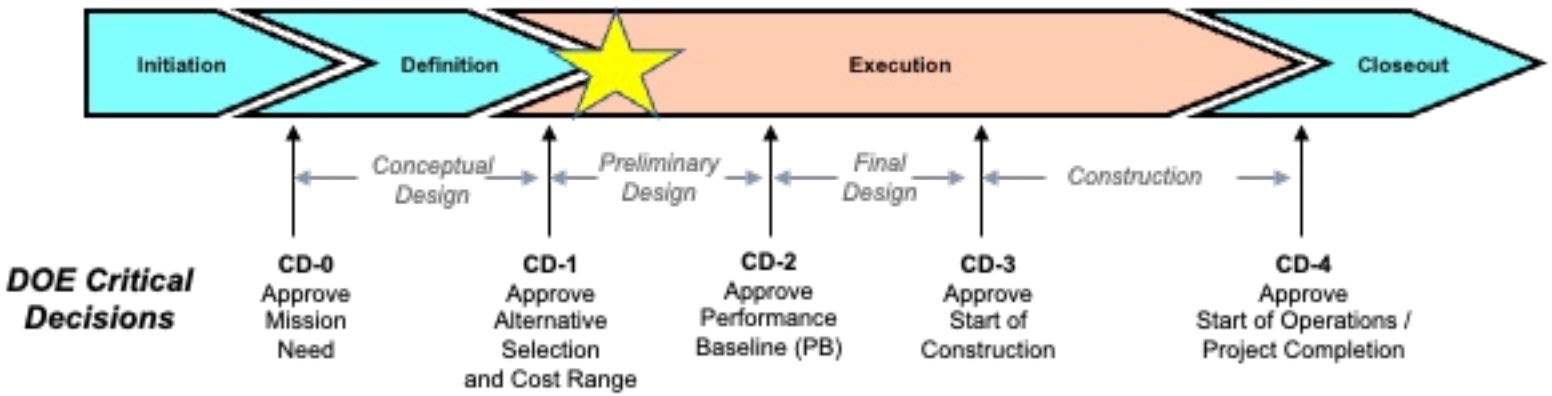
- Large rapidity (-4 < h < 4) coverage; and far beyond in especially far-forward detector regions
- large acceptance 1.7 T(up-to 2 T) Solenoid
- High precision low mass tracking
  - small (m-vertex) and large radius (gaseous-based) tracking
- Electromagnetic and Hadronic Calorimetry
  - equal coverage of tracking and EM-calorimetry
- High performance PID to separate p, K, p on track level
  - also need good e/h separation for scattered electron
- Large acceptance for diffraction, tagging, neutrons from nuclear breakup: critical for physics program
  - Many ancillary detector integrated in the beam line: low-Q^2 tagger, Roman Pots, Zero-Degree Calorimeter, ….
- High control of systematics
  - luminosity monitor, electron & hadron Polarimetry

→ Integration into wider IR (+/- 40 m) critical

Co-Chairs: Diego Bettoni (INFN) and Haiyan Gao (BNL)

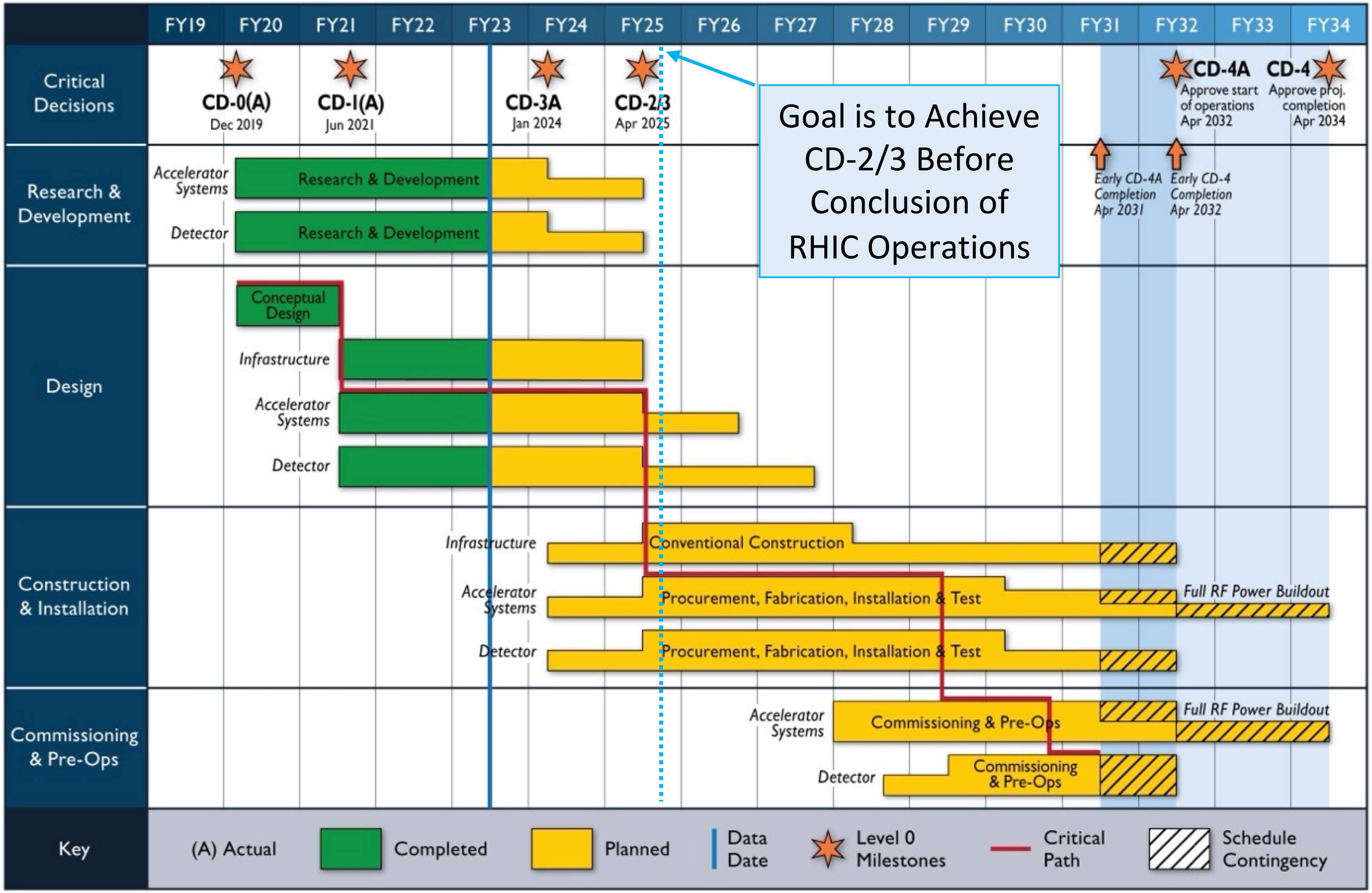
DOE Project Plan

Jim Yeck



Milestone/Event	Date
CD-0, Mission Need Approved	December 2019
DOE Site Selection Announced	January 2020
BNL - TJNAF Partnership Agreement Established	May 2020
CD-1, Alternative Selection and Cost Range Approved	June 2021
CD-3A, Long Lead Procurement Approval	**January 2024**
CD-2/3, Performance Baseline/Construction Start Approval	**April 2025**
Planned Date for RHIC Shut Down	**June 2025**

EIC Schedule



Goal is to Achieve CD-2/3 Before Conclusion of RHIC Operations

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Jim Yeck

Cost Estimate Status (DOE)

CD-1 Approved Cost Range 1.7-2.8B

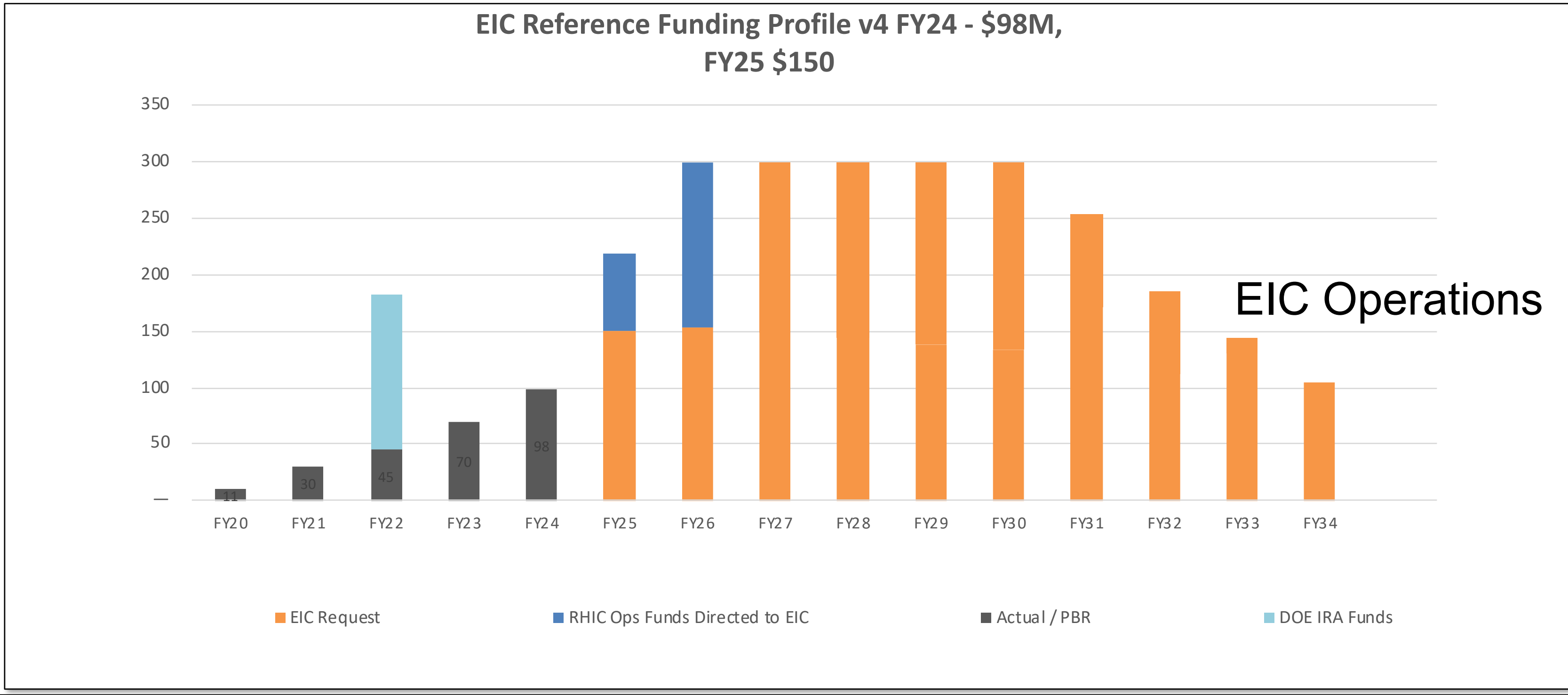
DOE total project cost estimate and overall project schedule provide the basis for the DOE funding profile.

$150M IKC assumptions: $50M accelerator $100M detector (1/3)

10% on LOE activities 35% on balance

WBS	DOE+IRA working schedule Jan-2023	
6.01 - Project Management	$	184,214,124
6.02 - Accelerator Dev. & R&D	$	74,971,335
6.03 - Injector System	$	187,982,740
6.04 - Electron Storage Ring	$	180,590,034
6.05 - Hadron Ring	$	108,733,042
6.06 - Interaction Region & Detector Interface	$	167,463,407
6.07 - Accelerator Systems Support	$	218,809,284
6.08 - RF Systems	$	366,647,360
6.09 - Cryogenics	$	144,964,733
6.10 - Detector	$	225,873,364
6.11 - Infrastructure	$	251,542,932
6.12 - Pre-Operations	$	51,119,308
P6 Total (incl. escalation & overhead)	**$**	**2,162,911,663**
Approved Scope_Cost Changes to be Implemented in P6	$	82,748,000
Less Excess Escalation for activies beyond CD-4 dates (estimated)	$	(58,003,992)
Less In Kind Contributions balance (not coded in P6)	$	(86,977,421)
Less Actual Costs (AC) thru Nov. 22	$	(69,781,005)
Total work to go	**$**	**2,030,897,245**
Contingency	$	627,598,742
Total w Contingency	**$**	**2,658,495,987**
Actual Costs (AC) thru Nov-2022	$	69,781,005
Estimated Total Project Cost	**$**	**2,728,276,992**

Current DOE Funding Plan

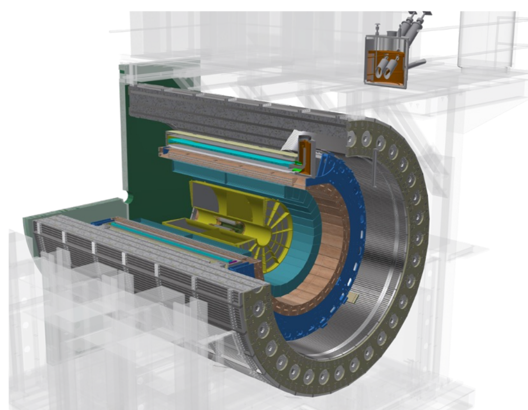


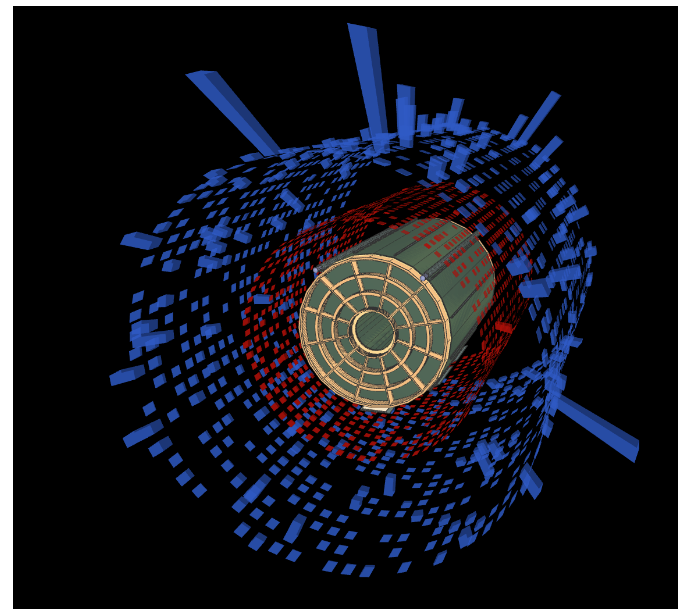
- DOE Inflation Reduction Act funding of $138M allocated in September 2022. Actual FY2023 funding is $70M. DOE request for FY2024 is $98M.
- RHIC shut down planned for June 2025. Significant RHIC Operations funding will be redirected to EIC construction starting in FY2025 and reaching ~$150M/year in FY2026.
- Current funding supports DOE CD-3A, Long Lead Procurement Approval, in January 2024. Long lead procurement items mitigate risks: technical, supply chain, inflation, schedule etc.

Complete RHIC Science Mission in 2015 NSAC LRP and onto the EIC Construction

"There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX.** (2) Map the phase diagram of QCD with experiments planned at RHIC." (completed data taking in 2021)

- sPHENIX will use energetic probes (jets, heavy quarks) to study quark-gluon plasma with unprecedented precision
  - How the structureless "perfect" fluid emerges from the underlying interactions of quarks and gluons at high temperature
- sPHENIX magnet and its hadron calorimeter could be part of the EIC project detector





RHIC data taking scheduled for 2023–2025
sPHENIX upgrade and STAR with forward upgrade will fully utilize the enhanced (~50 times Au+Au design) luminosity of RHIC

Thank you for your time and attention!

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