

Electron-Ion Collider:

- Generic Detector R&D Program
- Benefits of Two Detectors



based on drawing by Enki Bilal

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*2022 NSAC Long-Range Plan Town
Hall Meeting on Hot and Cold QCD
MIT, September 23, 2022*

Thanks to Dave Mack for help
in preparing the generic R&D part

Detector R&D in Nuclear Physics

- NP has no general detector R&D subprogram
 - ▶ compare to HEP that fosters research on the physics of particle detection as part of their Advanced Technology R&D subprogram
- NP detector R&D was and is centered around **specific projects**
 - ▶ Implies that R&D funding is tied to timeline of project
 - ▶ Example RHIC:

R&D Effort	FY 90 \$	FY 91 \$	FY 92 \$	FY 93 \$	FY 94 \$	FY 95 Plan	Total
Total Generic	1,121,437	1,620,751	215,000	20,000	50,000		3,027,188
Total STAR			1,125,000	1,267,000	1,467,365	1,100,000	4,959,365
Total PHENIX			1,200,523	1,463,984	1,147,300	1,000,000	4,811,807
Total PHOBOS				288,000	340,000	200,000	828,000
Total Allocations	1,121,437	1,620,751	2,540,523	3,038,984	3,004,665	2,300,000	13,626,360
Administration & BNL Support	228,563	331,249	269,477	376,016	450,335	296,000	1,951,640
R&D Total	1,350,000	1,952,000	2,810,000	3,415,000	3,455,000	2,596,000	15,578,000

Source:
T. Ludlam, RHIC Detector R&D:
A History and Summary (1994)

- We knew quite early that an EIC detector is **too complex to wait with R&D** until EIC matures and becomes a DOE project
 - ▶ Recognized in 2007 LRP: We recommend the allocation of resources to develop [...] detector technology necessary to lay the foundation for a polarized Electron-Ion Collider.

World-Wide R&D Efforts with Potential Impact on EIC

- CERN R&D program with partial match with EIC needs (e.g. RD51 Micro-Pattern Gas Detectors Technologies)
 - ▶ prominent and strong R&D program in the past, now restructured
- LHC Experiments R&D for phase-I upgrades, especially ALICE (TPC, ITS, SAMPA) and LHCb (RICH, triggerless DAQ).
 - ▶ LHC related R&D not very strong on PID and forward/backward instrumentation
 - ▶ much emphasis on radiation hardness
- R&D at Belle-II and Panda (crystals, DIRC, ...)
- ILC related R&D (TPC w/ MMG)
 - ▶ Rate and precision requirements compatible
 - ▶ Less emphasis on forward/backward instrumentation
- Laboratory Directed Research & Development Programs (LDRDs) at National Labs in the US (ANL, BNL, JLAB, LANL, LBNL, ORNL)
 - ▶ kicked in after ~2015

Generic EIC Detector R&D Program (2011-2021)

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

- Goals of Effort
 - ▶ Enable successful design and timely implementation of an EIC experimental program
 - ▶ Quantify the key physics measurements that drive instrumentation requirements
 - ▶ Develop instrumentation solutions that meet realistic cost expectations
- Stimulate the formation of user collaborations to design and build experiments

*motivates software/
simulation projects*

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this was absolute key - at least as important as R&D itself

*motivates software/
simulation projects*



First Generic EIC Detector R&D Program

- Started in 2011 by BNL in association with JLab and the DOE Office of NP
- Funded by DOE through RHIC operations funds
- Program explicitly open to international participation
- Standing EIC Detector Advisory Committee consisting of internationally recognized experts in detector technology
- Typical 10-11 projects supported per year
- Over 281 participants from 77 institutions (37 non-US)
- Many of the subsystems in EPIC were developed and matured in the program
- Many PIs and participants of this program now active in EPIC detector working groups
- With start of project R&D, the first generic program ended (2021)



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

Generic R&D Projects 2014-2021

Project	Topic
eRD1	EIC Calorimeter Development
eRD2	A Compact Magnetic Field Cloaking Device
eRD3	Design and assembly of fast and lightweight forward tracking prototype systems
eRD6	Tracking and PID detector R&D towards an EIC detector
eRD10	(Sub) 10 Picosecond Timing Detectors at the EIC
eRD11	RICH detector for the EIC's forward region particle identification - Simulations
eRD12	Polarimeter, Luminosity Monitor and Low Q2-Tagger for Electron Beam
eRD14	An integrated program for particle identification (PID)
eRD15	R&D for a Compton Electron Detector
eRD16	Forward/Backward Tracking at EIC using MAPS Detectors
eRD17	BeAGLE: A Tool to Refine Detector Requirements for eA Collisions in the Nuclear Shadowing/Saturation Regime

eRD18	Precision Central Silicon Tracking & Vertexing
eRD19	Detailed Simulations of Machine Background Sources and the Impact to Detector Operations
eRD20	Developing Simulation and Analysis Tools for the EIC
eRD21	EIC Background Studies and the Impact on the IR and Detector design
eRD22	GEM based Transition Radiation Tracker R&D
eRD23	Streaming Readout for EIC Detectors
eRD24	Silicon Detectors with high Position and Timing Resolution as Roman Pots at EIC
eRD25	Si-Tracking
eRD26	Pulsed Laser System for Compton Polarimetry
eRD27	High Resolution ZDC
eRD28	Superconducting Nanowire Detectors
eRD29	Precision Timing Silicon Detectors for combined PID and Tracking System

Tracking

PID

Calorimetry

Software/Simulations

Other

The Need for Continuing Generic R&D

- EIC Specific
 - ▶ EIC project R&D only supports R&D to reduce risk and optimize technologies used in project detector (EPIC)
 - ▶ Need to continue developing technologies that are not ready for day-1 (CD-4a timeline) but that would offer superior technologies down the road
 - ▶ Support some higher risk items that, if successful, could be ready for day-1
 - ▶ R&D for complementary technologies that could be used in a 2nd EIC detector
 - ▶ Develop technology for future upgrades keeping the EIC on cutting-edge in the future and built on past investments
- Broader Impact
 - ▶ develop more environmental-friendly technologies (e.g. fluorocarbon)
 - ▶ brings benefit for other programs in NP, HEP, and medical application (e.g. PET w/ ToF)

The NEW Generic EIC Detector R&D Program

We were heard: Generic program reconstituted starting this year

- funded by DOE
- coordinated by JLab (Dave Mack)
- https://www.jlab.org/research/eic_rd_prgm
- total of **27** proposals were received on July 25, 2022

The large amount of good proposals on vital technologies shows clearly the need for generic R&D within the community

CSGlass for hadron calorimetry at the EIC
A proposal for MPGD-based transition radiation detector/tracker
Precise Timing with a Micro Pattern Gaseous Detector
BeAGLE, a tool to refine IR and detector requirements for the EIC
Continued Development and Evaluation of a Low-Power High-Density High Timing Precision Readout ASIC for AC-LGADs (HPSoC)
A new radiation tolerant low power Phase-Locked Loop IP block in a 65 nm technology for precision clocking in the EIC frontend electronics
Refined Methods for Transfer Matrix Reconstruction Using Beamline Silicon Detectors for Exclusive Processes at the EIC
TOMATO (end-TO-end siMulation fAst deTectOrs): An end-to-end simulation framework for fast detectors at the EIC
Z-Tagging Mini DIRC
Implementation of a gain layer in Monolithic Active Pixel Sensor (MAPS) for high resolution timing application
Development of a Generic, Low-power and Multi-channel Frontend Readout ASIC for Precision Timing Measurements at EIC
Development of a Novel Readout Concept for an EIC DIRC
Simulations of the physics impact of a solenoid-based compensation scheme for the field of the main detector solenoid in IR8
Tracking and PID with a GridPIX Detector
Particle identification and tracking in real time using Machine Learning on FPGA
Development of High Precision and Eco-friendly MRPC TOF Detector for EIC
Machine Learning for Detection of Low-Energy Photons in the EIC ZDC
Superconducting Nanowire Detectors for the EIC
EIC KLM R&D Proposal
High Quantum Efficiency III-nitrides photocathodes and hybrid photon detectors for EIC
Exclusive and Semi-inclusive reactions in the muonic channel, and development of muon detectors in the far forward region
Injection Molding of Large Plastic Scintillator Tiles at Optical Quality
Development of Thin Gap MPGDs for EIC Trackers
Simplified LGAD structure with fine pixelation
Imaging Calorimetry for the Electron-Ion Collider
Silicon Tracking and Vertexing Consortium
Combined design of a projective tracker and PID system for the EIC Detector-1 with the assistance of Artificial Intelligence

Suggested Input for LRP

- The next Long Range Plan should
 - ▶ detail the need for continuing generic detector R&D
 - ▶ encourage DOE to continue their support and funding
- Relevant question: should one push for NP-wide R&D program?
 - ▶ gain broader support
 - ▶ allow for cross-fertilization between NP communities on advanced technologies
 - ▶ possible overlap with HEP program (synergy)?
- Supporting text needs to be part of the EIC White Paper and the topic needs to be promoted in the LRP resolution meeting

- For the EIC, this effort is connected to the long term future of the program addressing future detector upgrades and technology choices of a potential 2nd EIC detector

Opportunities With a Second EIC Detector

Only one detector is in scope of EIC project

The EIC community is *strongly* in favor of a second detector

- Dedicated chapter in Yellow Report: “Two Complementary Detectors”
- New flyer to outline the benefits of a second detector
- EIC User Group formed a Detector-II Working Group



THE ELECTRON-ION COLLIDER

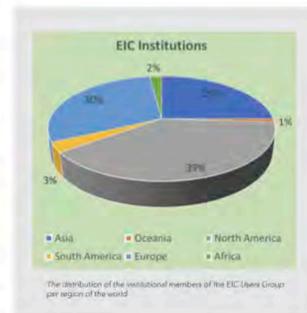
The Benefits of Two Detectors

The Electron-Ion Collider (EIC) is a transformational and unique accelerator that will enable studies of nuclear matter with unprecedented precision. The EIC is required to address fundamental open questions in physics, such as the origin of mass and spin of protons and neutrons, the details of the “glue” that binds them, and the nature of very dense gluon systems in nuclei. This ambitious collider

could not deliver physics results without powerful “cameras” capable of taking the most detailed snapshots of the collisions produced at the EIC. Novel particle detectors must be designed and constructed to capitalize on the investment made on the accelerator side, so that the deepest secrets of the building blocks of matter in our visible universe may be unlocked.

The EIC Project was launched by the U.S. Department of Energy (DOE) in January 2020 and is on track to begin operation in the early 2030s. Located in the U.S., the EIC will be a premier international facility, the success of which hinges on both U.S. and international engagement in advancing accelerator science and fundamental research. The DOE has committed to funding the construction of the collider and a state-of-the-art multipurpose detector at one of two possible interaction points. Historically, projects of similar scientific impact and scope were designed to include two or more complementary detectors. Multiple detectors expand scientific opportunities, draw a more vivid and complete picture of the science, and mitigate the inherent risks that come with exploring uncharted territory by providing independent confirmation of discovery measurements. The physics community behind the EIC project has emphasized the need for at least two detectors for many years. Several community reports, such as the 2007 and 2015 U.S. Long Range Plan reports for Nuclear Science, reference “as many as four interaction points” or the need for colliders “at two interaction points.” This is echoed in the 2018 National Academies of Sciences, Engineering, and Medicine report on an Assessment of U.S.-Based Electron-Ion Collider Science.

The need for and ultimate success of a multi-detector standard have both been demonstrated historically over many decades across multiple subfields of physics. Some 40 years ago, the strong force carrier, the gluon, was discovered by the TASSO, JADE, Mark J, and PLUTO collaborations at the Deutsches Elektronen-Synchrotron (DESY, Germany). Nearly two decades later, the H1 and ZEUS collaborations, also at DESY (Germany), both demonstrated that deep inside a proton, its structure is overwhelmingly dominated by gluons. At the turn of this century, the CLAS collaboration at Thomas Jefferson National Accelerator Facility (Jefferson Lab, USA) and the HERMES collaboration at DESY (Germany) independently performed the first measurements that opened the way to the spatial imaging of quarks inside the proton. Meanwhile, at the European Organization for Nuclear Research (CERN, France and Switzerland) the NA-35 experiment was detecting the first hints of the Quark-Gluon Plasma (QGP), a new state of matter composed of deconfined quarks and gluons that was ultimately observed simultaneously by the BRAHMS, PHOBOS, PHENIX, and STAR collaborations at Brookhaven National Laboratory (BNL, USA). More recently, the discovery of the Higgs boson, the



final piece of the Standard Model of particle physics, was independently confirmed by the ATLAS and CMS collaborations at CERN (France and Switzerland), and the first observation of gravitational waves was made concurrently at the Hanford and Livingston detectors by the Laser Interferometer Gravitational-Wave Observatory (LIGO in USA) collaboration and soon after by the Virgo detector at the European Gravitational Observatory (EGO, Italy and France). In each case, the capability of near-simultaneous discovery by multiple detectors was essential for establishing the validity of the newly emerging paradigm.

The multiple detector efforts discussed above were made possible by engaging resources on a national and international level. The EIC project is well positioned to follow this model and is already attracting interest and expertise from around the world. The international community began self-organizing in late 2015 by forming the EIC Users Group (EICUG), which rapidly grew to over 1,300 physicists at more than 250 institutions in 35 countries world-wide. Now is the time for international collaborators to seize the opportunity for leadership in the many scientific and technical challenges presented by the design and construction of a second interaction region and detector.

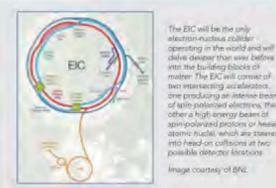
THE ELECTRON-ION COLLIDER'S GOLDEN OPPORTUNITY FOR TWO DETECTORS

Taking Advantage of the RHIC/EIC Collider Layout

The scientific mission of the Electron-Ion Collider includes a diverse set of open physics questions about the nature of matter in our universe. Answering these questions requires state-of-the-art experimental apparatus that would, ideally, detect all particles produced in electron-ion collisions.

This presents unique challenges to the design of an EIC detector and its integration in the collider, with two different beam species moving in opposite directions. The device must cover a large area, extending from the central region, where the remnants from the most energetic collisions are scattered, to the regions very close to the incoming beamlines. The EIC will repurpose the existing layout of the Relativistic Heavy Ion Collider, which currently weaves the beams from varying ring-inside and ring-outside locations at the two possible interaction points. This geometric constraint provides an opportunity to optimize the complementarity of the two detector systems, so that the necessary gaps in coverage occur in different regions, allowing one detector to see particles where the other is blind.

It is also possible to tune the beam optics for each detector to emphasize different physics processes, satisfying what would otherwise be mutually exclusive demands. The flexibility will allow, for example, the EIC to access rare scattering processes, which are critical for imaging the deep internal structure of nucleons and nuclei. The EIC's

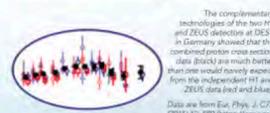


The EIC will be the only electron-ion collider operating in the world and will deliver deeper insights into the building blocks of matter. The EIC will consist of two intersecting accelerators, one producing an intense beam of fully polarized electrons, the other a high-energy beam of spin-polarized protons or heavier atomic nuclei, which are directed into head-on collisions at two possible interaction points. Image courtesy of BNL.

science reach will be significantly enhanced by leveraging the variations of the beamline optics and interaction region design for the two detectors. Further, the separate scientific focus opportunities provided by two customized detectors naturally leads to two independent yet complementary collaborations.

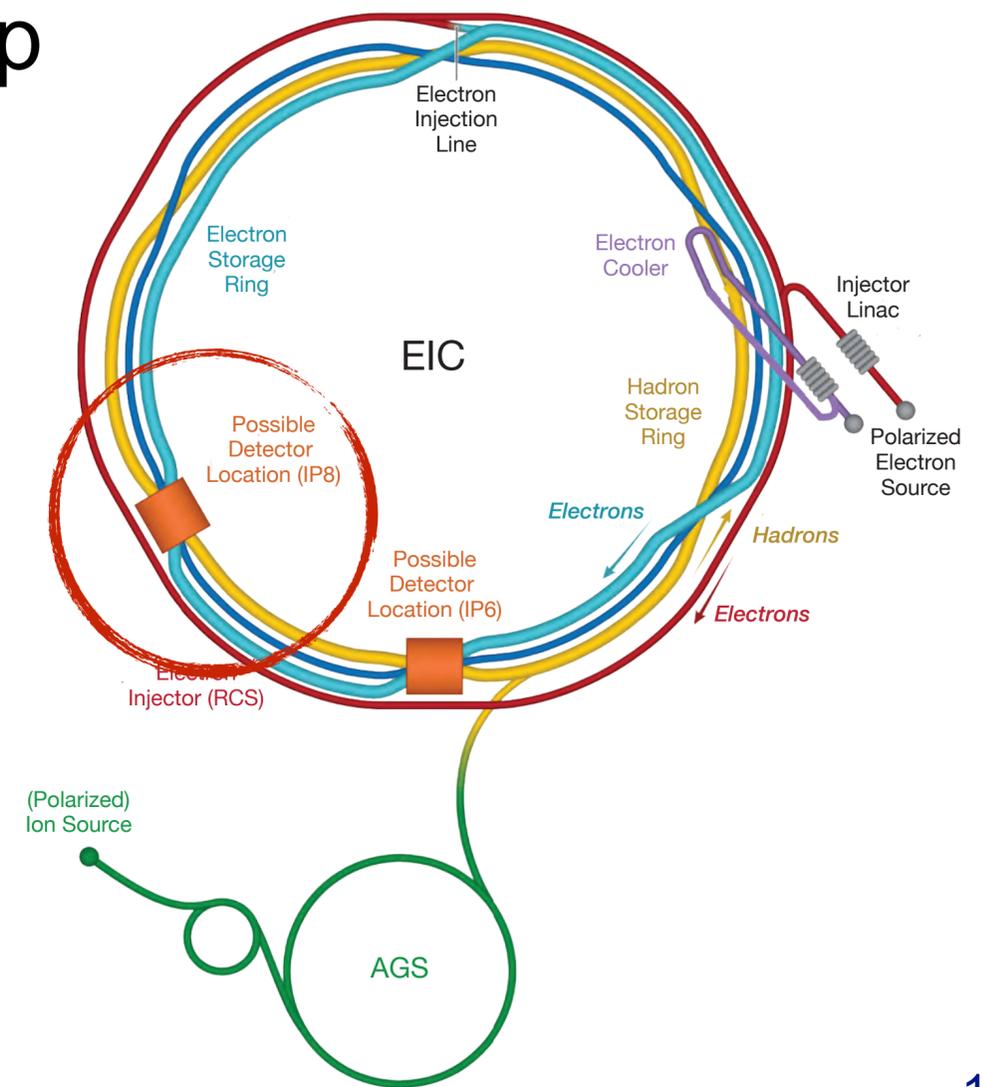
Detector Redundancy and Complementarity

The detector demands an onion-like structure, composed of multiple layers of detector technologies that can be used to determine the type of particles produced and reconstruct their momenta and energy. As detector design for the world's only Electron-Ion Collider facility continues, it is only natural that each subsystem will explore multiple performance optimization routes and push for the most advanced, state-of-the-art technologies that will satisfy the required functionality. Varying design decisions and technology choices between two complementary detector concepts will ensure the necessary redundancy. Alternative technology choices will also allow each experiment to optimize for different types of measurements



while still preserving the ability to perform independent cross-checks. Possible optimization areas include consideration of different magnetic field strengths and associated trade-offs between detector coverage, particle identification capabilities and tracking performance at high particle momenta. These design choices impact the precision with which different physics can be accessed.

The complementarity of multiple detectors enhances the science scope and ultimately leads to higher scientific impact. A prime example is the final dataset from HERA (the Hadron-Electron Ring Accelerator at DESY), which was



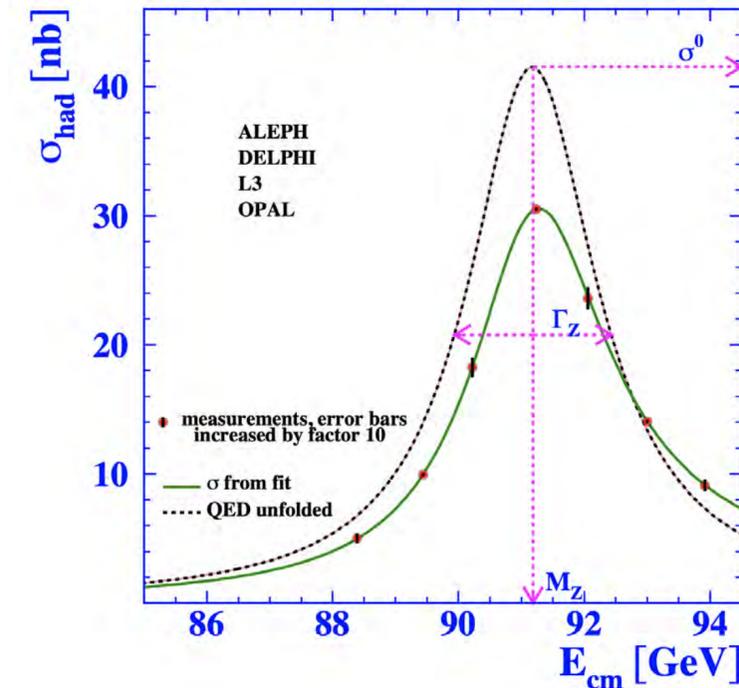
get flyer at eicug.org web site

Arguments for a Second EIC Detector

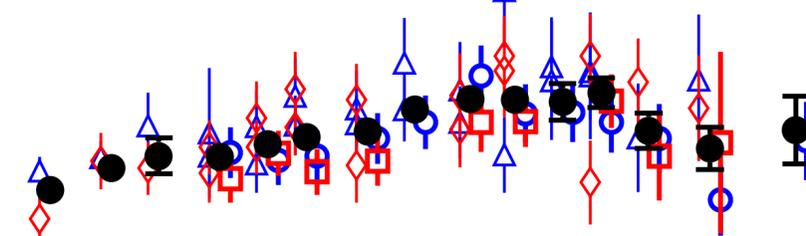
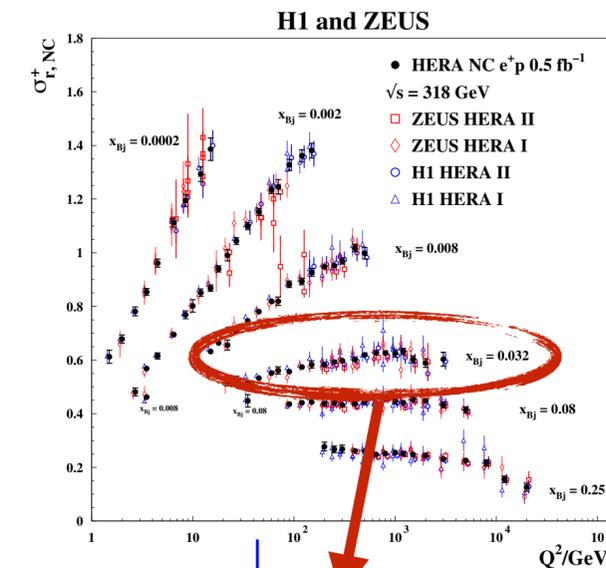
- EIC has unusual broad physics program
 - ▶ runs gamut from detailed investigation of hadronic structure to explorations of new regimes of strongly interacting matter.
 - ▶ EPIC covers full NAS program but impossible to *optimize* the full program in a single detector
 - ▶ Examples of Opportunities and Complementarity:
 - ⦿ secondary focus in IP8 (improve diffractive physics, tagging)
 - greatly enhances the low- p_T and low- x (large- x_L) acceptance of recoiling target system in exclusive reactions on the proton and in coherent scattering by nuclei
 - provides an unprecedented detection of nuclear fragments with magnetic rigidities close to that of the beam, including heavy ions that have lost only one nucleon (A-1 tagging).
 - ⦿ alternative subdetector technologies
 - ⦿ enhanced p_T and/or PID acceptance in areas of phase space
 - ⦿ more emphasize on μ detection
 - ⦿ different B field
 - ⦿ ...

Arguments for a Second EIC Detector (cont.)

- Cross-checking
 - ▶ Many examples of wrong turns in history
 - ▶ Analysis mistakes, instrumental malfunctions, or inevitable statistical fluctuations
- Cross-calibration
 - ▶ A good example is offered by LEP (ALEPH, DELPHI, L3, OPAL) HERA (H1, ZEUS)
 - Improvements well beyond \sqrt{N} statistical improvements
 - Make use of different dominating systematics (not all optimal solutions have to be in one detector)
- Technology redundancy and mitigating of overall risk
 - ▶ by applying different technologies and philosophies to similar physics aims
 - ▶ mitigate risk of reduced performance or failure of detector sub-component
 - ▶ mitigate risks of unforeseen backgrounds
 - ▶ differently optimize precision and systematics



hep-ex/0101027: “The technical precision of the adopted combination procedure is around 5 % of the combined errors.”



$$x_{Bj} = 0.032$$

A Second EIC Detector and R&D

Requires efforts and support to

- study and document a *broadened physics* program
- provide a realistic detector concept that is *complementary* to the current project detector in terms of physics reach, precision, and systematics

A potential 2nd detector is optimally realized with a 3-5 year delay to the first detector opening new opportunities:

- new technologies that are not mature enough or too risky for the 1st detector can be considered to provide full complementarity
- this needs a well-thought-out R&D program that will be guided and inspired by efforts on Detector-II (also EPIC upgrades)
- making full use of the reinstated generic EIC detector program (next slides)

Suggested Recommendation for LRP

(on behalf of the EICUG LRP Task Force)

Initiative: We recommend targeted efforts to enable the timely realization of a second, complementary detector at the Electron-Ion Collider

The EIC is a transformative accelerator that will enable studies of nuclear matter with unprecedented precision. The EIC encapsulates a broad physics program with experimental signatures ranging from exclusive production of single particles in ep scattering to very high multiplicity final states in eA collisions. High statistical precision matched with a similar or better level of systematic precision is vital for the EIC and this can only be achieved with carefully optimized instrumentation. A natural and efficient way to reduce systematic errors is to equip the EIC with two complementary detectors. Two detectors will expand the scientific opportunities, draw a more complete picture of the science, and mitigate the inherent risks that come with exploring uncharted territory by providing independent confirmation of discovery measurements. The second detector effort will rely heavily on the use of generic detector R&D funds and accelerator design effort to integrate the detector into the interaction region. The design and construction of such a complementary detector and interaction region are interwoven and must be synchronized with the current EIC project and developed in the context of a broad and engaged international EIC community.

Backup Slides



Project R&D

Project R&D (> 2022)

- aims at achieving the maturity required to carry out final design and construction of EPIC
- support only projects that perform R&D on technologies used in EPIC
- Guided by Detector Advisory Committee (DAC)
- https://wiki.bnl.gov/conferences/index.php?title=General_Info

Tracking PID Calorimetry Sensors Electronics

FY22/FY23

Project	Topic
eRD101	mRICH / aerogel RICH
eRD102	dRICH
eRD103	hpDIRC
eRD104	Service reduction
eRD105	SciGlass
eRD106	Forward EMCAL
eRD107	Forward HCAL
eRD108	Cylindrical & Planar MPGD
eRD109	ASICs/Electronics
eRD110	Photosensors
eRD111	Si-Tracker (no sensors)
eRD102	ToF with AC-LGAD
eRD103	ITS3/MAPS