The Electron-Ion Collider

A world-wide unique collider to unravel the mysteries of visible matter

Elke-Caroline Aschenauer (BNL)
What is the EIC:
A high luminosity ($10^{33} - 10^{34} \text{ cm}^{-2}\text{s}^{-1}$) polarized electron proton / ion collider with $\sqrt{s_{\text{ep}}} = 28 - 140 \text{ GeV}$

What is special:
EIC is the ONLY world-wide new collider in foreseeable future. Allows to remain at frontier of Accelerator S&T.

factor 100 to 1000 higher luminosity as HERA
both electrons and protons / light nuclei polarized, nuclear beams: d to U
Fixed Target Facilities i.e.:
at minimum > 2 decades increase in kinematic coverage in $x$ and $Q^2$

State of the art general purpose collider detector

Science Program: An EIC can uniquely address three profound questions about nucleons — neutrons and protons — and how they are assembled to form the nuclei of atoms:
Why do we need different probes

Complementarity
QCD has two concepts which lay its foundation:
- factorization
- universality

To test these concepts and separate interaction dependent phenomena from intrinsic nuclear properties, different complementary probes are critical.

**Probes:** high precision data from ep, pp, e+e-

**Factorization**

Example: Measure PDFs at HERA at $\sqrt{s}=0.3$ TeV:

Predict pp and $p\bar{p}$ measurements at $\sqrt{s}=0.2$, 1.96 & 7 TeV

**Universality**

(un)polarized cross section $\sim$

PDF $\otimes$ hard-scattering $\otimes$ Hadronization

hard-scattering: calculable in QCD
PDFs and Hadronization: need to be determined experimentally
Different Processes

Hadron-Hadron:
- probe has complex structure
- no simple access to parton kinematics:
  \[ \eta \rightarrow x; \ p_t^2 \rightarrow Q^2 \rightarrow x-Q^2 \]
- Gluons can be accessed directly
  \[ \rightarrow qg \ & gg \]
  - gluon fragmentation

Ultra-Peripheral Collisions:
- Photon induced process
- no simple access to parton kinematics:
  \[ \eta \rightarrow x; \ M^2 \rightarrow Q^2 \] can only be varied by VM
- access to initial state

Electron-Hadron:
- Point-like probe \( \rightarrow \) resolution
- High precision & access to partonic kinematics through scattered lepton
  \( \rightarrow x_B, Q^2 \)
- initial and final state effects can be cleanly disentangled
  - inclusive measurements of Structure functions
    only sensitive to initial state

E.C. Aschenauer
What is needed to address the EIC Physics

The Golden Process:
Deep Inelastic Scattering (DIS):

- As a probe, electron beams provide unmatched precision of the electromagnetic interaction
- Direct, model independent determination of parton kinematics of physics processes

\[ Q^2 = s \cdot x \cdot y \]

- \( s \): center-of-mass energy squared
- \( Q^2 \): resolution power
- \( x \): the fraction of the nucleon’s momentum carried by the struck quark (0<\(x<1\))
- \( y \): inelasticity

Large kinematic coverage:
- \( \sqrt{s} \): 20 – 140 GeV
- Access to \( x \) and \( Q^2 \) over a wide range
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?
There are many reasons why one wants to have a 3d picture of nucleons and nuclei collective effects are one of them.

Obtaining a full picture is definitely an other one
Simultaneous extraction of PDFs and FF required
\[
\frac{1}{2} \hbar = \left\langle P, \frac{1}{2} \left| J^z_{QCD} \right| \frac{1}{2} P \right\rangle = \frac{1}{2} \int_0^1 dx \Delta \Sigma(x, Q^2) + \int_0^1 dx \Delta G(x, Q^2) + \int_0^1 dx \left( \sum_q L_q^z + L_g^z \right)
\]

Key Observables: Structure function \( g_1(x, Q^2) \) for proton and \( \text{He}^3/\text{D} \rightarrow \Delta \Sigma \) and \( \Delta G \) 
SIDIS double spin asymmetries for \( \pi, K \rightarrow \) flavor separated \( \Delta q \)
Proton structure important for QGP in small systems

Collective phenomena seen in pA collisions, i.e. ATLAS & CMS

Examples of proton density profiles at $x \sim 10^{-3}$

H. Mäntysaari & B. Schenke
arXiv:1607.01711

In a hydro-picture (used in AA) fluctuations in the proton are crucial to understand the seen pA@LHC behaviors

Study coherent and incoherent $J/\Psi$ prod.

EIC can map out the spatial quark and gluon structure of the proton in $x$ and $Q^2$
High precision imaging at EIC at low and high $x$

Golden channels:

**DVCS**

\[ \gamma^* + p \rightarrow \gamma + p \]

\[ e + p \rightarrow e + p + \gamma \]

\[ \int \text{d}t = 10 \text{ fb}^{-1} \]

\[ 10 < Q^2 < 17.8 \text{ GeV}^2 \]

\[ \sqrt{s} = 45 \text{ GeV} \]

\[ 1.6 \times 10^{-2} < x < 2.5 \times 10^{-2} \]

\[ \sqrt{s} = 140 \text{ GeV} \]

\[ 1.6 \times 10^{-3} < x < 2.5 \times 10^{-3} \]

\[ x_B, F(x_B, b_T) \text{ (fm}^{-2}) \]

**J/ψ**

\[ \gamma^* + p \rightarrow J/ψ + p \]

\[ e + p \rightarrow e + p + J/ψ \]

\[ \int \text{d}t = 10 \text{ fb}^{-1} \]

\[ 15.8 < Q^2 + M_{J/ψ}^2 < 25.1 \text{ GeV}^2 \]

\[ 0.0016 < x_B < 0.0025 \]

\[ 0.004 < x_B < 0.0063 \]

\[ 10 < Q^2/\text{GeV}^2 < 17.8 \]

\[ b_T \text{ (fm)} \]

\[ x_E \]

\[ x_F(x_B, b_T) \text{ (fm}^{-2}) \]
Diffractive vector meson production: $e + Au \rightarrow e' + Au' + J/\psi, \varphi, \rho$

Momentum transfer $t = |\mathbf{p}_{Au} - \mathbf{p}_{Au'}|^2$ conjugate to $b_T$

Incoherent events are by themselves interesting
- Different $|t|$ regions of the spectrum sensitive to different sizes
- Energy dependence of incoherent spectra with differential binning in $|t|$ could tell us about growth of nuclei and evolution of fluctuations
- Recent results from Mantysaari, et al. (arXiv:2303.04866) show different regions of spectrum to be sensitive to different kinds of shape deformations e.g Uranium
Does the rise of $g(x,Q^2)$ get tamed?

Important to understand the initial condition for heavy ion collisions

Scattering of electrons off nuclei:

- Probes interact over distances $L \sim (2m_N x)^{-1}$
- For $L > 2R_A \sim A^{1/3}$ probe cannot distinguish between nucleons in front or back of nucleon
- Probe interacts \textit{coherently} with all nucleons

\[ Q_s^2 \sim \frac{\alpha_s xG(x,Q_s^2)}{\pi R_A^2} \]

\text{HERA} : \quad xG \sim \frac{1}{x^{0.3}}

\text{A dependence} : \quad xG_A \sim A

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

Enhancement of $Q_s$ with $A$ \Rightarrow non-linear QCD regime reached at significantly lower $\sqrt{s}$ in nuclei than in proton
Forward rapidities at STAR provide an absolutely unique opportunity to have very high gluon densities → proton – Au collisions combined with an unambiguous observable counting experiment of Di-hadrons (jets) in pp and pA

Non-linear QCD effects:
Disappearance of backward hadron (jet) in pA

- **A dependence**: at low $p_T$ more suppression in pAu than pAl in comparison to the pp
- **x dependence**: at high $p_T$ (large $x$) no suppression in pA
EIC has the unique opportunity to have very high gluon densities → electron – lead collisions combined with an observable counting experiment of Di-hadrons (jets) in ep and eA

Saturation:
Disappearance of backward hadron (jet) in eA

EIC can map the transition from a linear to a non-linear QCD regime → evolution of $Q_s$ with $x$

Coverage of Saturation Region for $Q^2 > 1$ GeV$^2$

- $\sqrt{s}=90$ GeV
- $\sqrt{s}=63$ GeV
- $\sqrt{s}=40$ GeV

#backward jets in eA / ep

$C(\Delta \phi)e^{\text{Au}/\text{ep}}$ vs. $\Delta \phi$ (rad)

$\sqrt{s}=40$ GeV
$\sqrt{s}=63$ GeV
$\sqrt{s}=90$ GeV

increased $\sqrt{s} \rightarrow$ increased suppression
Jets have several properties which will make them important tools for realizing the EIC physics program:

- Well understood theoretically and experimentally
- Excellent proxies for the underlying parton kinematics
- Showers probe QCD from hard interaction to hadronization scale within the same event – can explore dynamics at different time (angular) scales
- Precision tools exist to probe these shower properties - substructure

Global properties and parton structure of hadrons

Multi-dimensional imaging of nucleons, nuclei and mesons

The nucleus: a laboratory for QCD

Understanding hadronization

The importance of jet probes was reflected in the EIC Yellow Report where they touched on nearly every major physics topic (Nucl. Phys. A, Vol 1026, 122447)
The EIC Accelerator
Double Ring Design Based on Existing RHIC Facilities

**Hadron Storage Ring:** 40, 100 - 275 GeV

- RHIC Ring and Injector Complex: p to Pb
- 1A Beam Current
- 10 ns bunch spacing and 1160 bunches
- Light ion beams (p, d, $^3$He) polarized (L,T) > 70%
- Nuclear beams: d to U
- Requires Strong Cooling: new concept → CEC
- One High Luminosity Interaction Region(s):
  - 25 mrad Crossing Angle with Crab Cavities

**Electron Storage Ring:** 5 - 18 GeV

- 9 MW Synchrotron Radiation
- Large Beam Current - 2.5 A
- Polarized electron beam > 70%

**Electron Rapid Cycling Synchrotron**

- Spin Transparent Due to High Periodicity
Accelerator Science and Technology – Ongoing EIC R&D

**ESR Cavity Prototype**

**ESR Vacuum R&D**

**ESR RF 500kW FPC**

**ESR RF HOM Damper**

**2nd IR**

**Electron Injection Fast Kicker**

**Strong Cooling**

**Cooler Electron Source**

**Polarized e⁻ Source**

**ESR Vacuum R&D**

**Hadron Polarimetry**

**HSR Vacuum Upgrade**

**Electron Cooler**

**Electron Storage Ring**

**Electron Ring**

**Taking 100 meters**

**Existing tunnel and experiment halls**

**Crab Cavity Prototype**

**IR Design and Magnet Prototyping**

**IR Vacuum Chamber**

**Proton Injection Fast Kicker**
Brings focusing magnets close to IP ➔ high luminosity
Beam separation without separation dipoles ➔ reduced synchrotron radiation background

But significant loss of luminosity

Solution: Crab crossing

- Head-on collision geometry is restored by rotating the bunches before colliding ("crab crossing")
- Bunch rotation ("crabbing") is accomplished by transversely deflecting RF resonators ("crab cavities")
- Actual collision point moves laterally during bunch interaction

Completely new concept for a collider
Year-long EIC User Group driven EIC Yellow Report activity (December 2019 – February 2021)
  - Science Requirements and Detector Concepts for the EIC

<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
<th>Date</th>
</tr>
</thead>
</table>
| 2020 | **Call for Expressions of Interest (EOI)**  
|      | EOI Responses Submitted                                                                               | November 2020 |
|      | Assessment of EOI Responses                                                                           | On-going &    |
| 2021 | **Call for Collaboration Proposals for Detectors**                                                   | March 2021    |
|      | https://www.bnl.gov/eic/CFC.php                                                                        |               |
|      | BNL/TJNAF Proposal Evaluation Committee                                                                | Spring 2021   |
|      | Collaboration Proposals for Detectors Submitted                                                       | December 2021 |
| 2022 | **Decision on Project Detector – baseline “ECCE”**                                                   | March 2022    |
|      | Process to consolidate ECCE & ATHENA to the EIC Project Detector                                      | Spring 2022   |
|      | ePIC Collaboration* Formed – 160 institutions                                                         | July 2022     |
| 2023 | ePIC Charter ratified & elected Leadership Team                                                       | February 2023 |
|      | Resources Review Board Meeting                                                                         | April 2023    |
|      | ePIC Detector remaining technology choices made                                                        | April 2023    |

*Remains ongoing until formal agreements are in place – it originally led to confirmation that in-kind level assumed for the EIC detector was in range.
World-Wide Interest in EIC Physics

The EIC Users Group: EICUG.ORG

Formed 2016, Current Status
1387 collaborators, 36 countries, 271 institutions (Experimentalists ~860, Theory ~360, Acc. Sci. 160)

➢ EICUG has continuously grown since its formation (400@01/2016), notably after CD-0 and site-selection
➢ Growth will continue as EIC project moves into construction

Location of Institutions

Next EIC-UG Meeting in person July 2023 in Warsaw Poland

Would love to welcome more collaborators from Brazil and Southamerica
Collaboration fully formed

- December 2022: Collaboration Charter ratified
- February 14th 💌 2023: Spokespeople elected
  Spokesperson: John Lajoie (Iowa)
  Deputy – Spokesperson: Silvia Dalla Torre (INFN Trieste)
- Collaboration Council fully formed
  Chair: Ernst Sichtermann (LBNL)
  Vice-Chair: Bernd Surrow (Temple Univ.)

ePIC welcomes new groups and institutions

**Monolithic Active Pixel Silicon Tracker:**
- 1 single technology: 65-nm MAPS
  - O(10 μm) pitch, <20 mW/cm²
  - Developed for ALICE ITS3
- Silicon VERTEX (3 layers)
  - First layer @ R ~ 4 cm
  - Material: 0.05% X/X₀ / layer
- Silicon BARREL (2 layers)
  - Material: 0.55% X/X₀ / layer
- F & B Silicon DISKs
  - (5 in Front and Back)
  - Material: 0.24% X/X₀ / layer

**Multi Pattern Gas Detectors:**
- Cylindrical microMEGAS
  - Additional space point for pattern recognition / redundancy
  - Ongoing geometry optimization
- μRWell planar layer behind hpDIRC
  - Impact point and direction for the ring seeding of hpDIRC
  - Additional space point for pattern recognition / redundancy
  - Not be required if imaging calorimeter is used

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**ePIC Tracking Detectors**

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Backwards HCal
Steel/Sc Sandwich
tail catcher

Barrel HCAL
(re-used from sPHENIX)

High granularity
W/SciFi EMCal

Longitudinally separated
HCAL
Steel/Sc & W/Sc sandwich
with SiPMs embedded in Scintillator

Barrel ECal: Pb/SciFi with
hybrid imaging part

5 imaging layers
preceded by a
time-layer
Uses: ASTROPIX
MAPS

Recent Technology Choice
Review completed 03/14/23
Decision by 04/21/23

Backwards EMCal
PbW04 crystals
with SiPMs as
Photonsensors

world’s first
at ePIC

E.C. Aschenauer
In general, need to separate:

- Electrons from photons $\rightarrow 4\pi$ coverage in tracking
- Electrons from charged hadrons $\rightarrow$ mostly provided by calorimetry & tracking
- Charged pions, kaons and protons from each other on track level $\rightarrow$ Cherenkov detectors
  - Cherenkov detectors, complemented by other technologies at lower momenta
    - Time-of-flight or $dE/dx$

Physics requirements:

<table>
<thead>
<tr>
<th>Rapidity</th>
<th>$\pi/Kp$ and $\pi0/\gamma$</th>
<th>$e/h$</th>
<th>Min $p_T$ (E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3.5 − -1.0</td>
<td>7 GeV/c</td>
<td>18 GeV/c</td>
<td>100 MeV/c</td>
</tr>
<tr>
<td>-1.0 − 1.0</td>
<td>8-10 GeV/c</td>
<td>8 GeV/c</td>
<td>100 MeV/c</td>
</tr>
<tr>
<td>1.0 − 3.5</td>
<td>50 GeV/c</td>
<td>20 GeV/c</td>
<td>100 MeV/c</td>
</tr>
</tbody>
</table>
ePIC Particle Identification Detectors

hpDIRC (High Performance DIRC)
- Quartz bar radiator → Reuse of BaBAR DIRC bars
- light detection with MCP-PMTs
- Fully focused
- π/K 3σ sep. at 6 GeV/c

Backward RICH:
- Aerogel Cherenkov Det.
- e, π, K, p separation
- π/K 3σ sep. at 10 GeV/c
- Photon-sensor: LAPPDs to include TOF

Single volume proximity focusing aerogel RICH with long proximity gap (~30 cm)

AC-LGAD (Low Gain Avalanche Detector)
- 20-35 psec
- Accurate space point for tracking
- forward disk and central barrel
- R&D and PED by International consortium HEP & NP

Recent Technology Choice
Review completed 03/21/23
Decision by 04/21/23

world's first at ePIC

world's first at ePIC

world's first at ePIC

E.C. Aschenauer
- We have 23 different detector technologies in the ePIC detector
- It would be intractable if all have different readout electronics
  → the goal is to minimize the number of different ASICs and use common readout solutions

**Electronics Readout Chain**

<table>
<thead>
<tr>
<th>Detector Group</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAPS</td>
</tr>
<tr>
<td>TOTAL</td>
<td>32 B</td>
</tr>
</tbody>
</table>

**ASIC**

- ITS-3
- EICROC
- FCFD
- HPsOC
- ASROC
- FAST
- Discrete/COTS
- HGROC3
- ALCOR-EIC
- SALSA

- Based on existing ASICs → reduce cost & time
- Much synergy with international efforts
  - Salsa → Brazil
- Triggerless streaming architecture gives much more flexibility to do physics.
- Rates quoted are at output of each stage.
- Integrate AI/ML as close as possible to subdetectors → cognizant Detector.
every cm counts → integration and communication with accelerator team is crucial
Far-forward physics at EIC

**e+p DVCS events with proton tagging.**

- **Diffraction**
- Saturation (coherent/incoherent J/ψ production)
  - **Meson structure:**
    - with neutron tagging \((ep \rightarrow (π) \rightarrow e' n X)\)
    - Lambda decays \((Λ \rightarrow pπ^- \text{ and } Λ \rightarrow nπ^0)\)

**e+d incoherent J/Psi events with proton or neutron tagging**

- **e+He3 with spectator proton tagging.**
  - Tagging of coherent light ions (d, He3, He4) from coherent scattering.

**e+Au events with neutron tagging to veto breakup and photon acceptance.**
Far-Forward Ancillary Detector Integration

Technologies defined
- Silicon: AC-LGAD & MAPS
- Zero Degree Calorimeter:
  - ECAL (PbWO4)
  - HCAL (PbSi + PbScint)

<table>
<thead>
<tr>
<th>Detector</th>
<th>Angular accept. [mrad]</th>
<th>$p_T$ coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZDC @ ~30m</td>
<td>$\theta &lt; 5.5 \ (\eta &gt; 6)$</td>
<td>$p_T &lt; 1.3 \text{ GeV}$</td>
</tr>
<tr>
<td>Roman Pots</td>
<td>$0 * \theta &lt; 5.0 \ (\eta &gt; 6)$</td>
<td>*Low $p_T(t)$ cutoff (beam optics)</td>
</tr>
<tr>
<td>Off-Momentum Detectors</td>
<td>$0. \theta &lt; 5.0 \ (\eta &gt; 6)$</td>
<td>Low-rigidity particles from nuclear breakups</td>
</tr>
<tr>
<td>B0 forward spectrometer</td>
<td>$5.5 \leq \theta &lt; 20.0 ,$</td>
<td>High $p_T(t)$</td>
</tr>
<tr>
<td></td>
<td>$(4.6 \leq \eta &lt; 5.9)$</td>
<td></td>
</tr>
</tbody>
</table>
Vetoing Incoherent Events

Veto.1: ➢ no neutron in ZDC
Veto.2: ➢ Veto1 + no proton in Roman Pots
Veto.3: ➢ Veto2 + no proton in off-momentum detector
Veto.4: ➢ Veto3 + no proton in B0
Veto.5: ➢ Veto4 + no anything in preshower
Veto.6: ➢ Veto5 + no photon \( E > 50 \text{ MeV} \) in ZDC
Veto.7: ➢ Veto6 + no activities \(|\eta| < 4.0 \& p_T > 100 \text{ MeV}/c \& E > 50 \text{ MeV}\)
other than e- and \( J/\psi \) in the main detector

With these requirements, the rejection power is found to be not enough to reach the three minimum positions.

Beam pipe design and material critical to vetoing power
Luminosity Detector and Low Q$^2$ Tagger

Luminosity Detector Concept:
Use Bremsstrahlung $ep \rightarrow e\gamma$ as reference cross section

Goals for Luminosity Measurement:
- Integrated luminosity with precision $\delta L/L < 1\%$
- Measurement of relative luminosity: physics-asymmetry/10 $\rightarrow 10^{-4} - 10^{-5}$

Low Q$^2$-Tagger:
Purpose:
Detection of scatter electron for Q$^2 < 0.1$ GeV$^2$
Critical for calibration of Lumi-detector
Beam divergence and energy spread impact performance

Technology:
Electromagnetic calorimetry with Si-tracking
$\rightarrow$ strong synergy with luminosity detector

Combine pair spectrometer $\rightarrow$ high precision
with zero degree photon calorimeter $\rightarrow$ fast feedback for collider

Technology:
Electromagnetic calorimetry with Si-tracking
The EIC Project
EIC Critical Decision Plan

- CD-0/Site Selection: December 2019 ✓
- CD-1: June 2021 ✓
- CD-3a: January 2024
- CD-2: January 2025
- CD-3: April 2025
- CD-4a early finish: April 2031
- CD-4: April 2032
- CD-4 early finish: April 2032
- CD-4: April 2034

Conclusion of RHIC Operation
- **Inflation Reduction Act funding of $138.24M** is a game changer and mitigates risk of slower than optimum ramp of new funding to the $150M/year needed.
- Possibility of significant package of long lead procurement items (CD-3A) helping to mitigate risks including procurement, supply chain, inflation and schedule.
- RHIC will shut down in June 2025 and significant RHIC Operations funding is redirected to EIC construction.
Why is now the time to built EIC?

“all stars align”:

- theory developments will allow to obtain the answers to the big questions discussed
- detector technologies allow for a collider detector with high resolution, wide acceptance and particle identification

**BUT MOST IMPORTANTLY**

- accelerator technologies allow to built a collider with
  - high luminosity
  - highly polarized electron and light hadron beams
  - a wide range in center of mass energies
  - hadron beams with highest A
  - demanding acceptance requirements can be realized in IR design
Let’s get to work and built the EIC

Please join us

Engineers, Designers, Technicians, Administrators, Experimentalists, Theorists, Accelerator Physicists, ......
### EIC

- Collide different beam species: ep & eA
  - Consequences for beam backgrounds
    - Hadron beam backgrounds, i.e. beam gas events
    - Synchrotron radiation
- Asymmetric beam energies
  - Boosted kinematics
    - High activity at high |\eta|
- Small bunch spacing: \sim 10 \text{ ns}
- Crossing angle: 25\text{ mrad}
- Wide range in center of mass energies
  - Factor 6
- Both beams are polarized \sim 70%
  - Stat uncertainty: \sim 1/(P_1 P_2 (\int \mathcal{L} \, dt)^{1/2})

### LHC / RHIC

- Collide the same beam species: pp, pA, AA
  - Beam backgrounds
    - Hadron beam backgrounds, i.e. beam gas events, high pile up
- Symmetric beam energies
  - Kinematics is not boosted
    - Most activity at midrapidity
- Moderate bunch spacing: 25 \text{ ns}
- No significant crossing angle yet (150 \text{ mrad now})
- LHC limited range in center of mass energies
  - Factor 2
- RHIC wide range in center of mass energies:
  - Factor 26 in AA and 8 in pp
- No beam polarization
  - Stat uncertainty: \sim 1/\left(\int \mathcal{L} \, dt \right)^{1/2}

**Differences impact detector acceptance and possible detector technologies**
Strong synergies with CERN

CERN – EIC R&D Day November 2021  
https://indico.cern.ch/event/1063927/

- **MAPS**: ALICE-3 – ITS-3 development
- **PID**: LHC-b and ALICE-3
- **Photon-sensors**: LAPPDs with LHC-b
- **MPGD**: long-term CERN R&D program RD51
- **DAQ**: strong developments on streaming DAQs for all LHC experiments
- **AI/ML and high-performance distributed computing**
**EIC Project Detector R&D**

**MAPS-Tracker:**
- Development of a full tracking detector solution composed of 65 nm MAPS sensors.
- Modules from stitched sensors, barrel & discs, mechanics, integration & cooling.
- Reduce the services material load → Improved powering and readout system.
- Development of the EIC sensor: design & characterization.

**MPGDs:**
- Development of prototypes of cylindrical MPGDs & planar thin gap MPGDs.

**AC-LGAD:**
- Develop system including sensors, ASIC & services for auxiliary detectors and ToF.

**PID-Detectors:**
- DIRC: focus on Cosmic ray telescope (CRT), validation of BaBar bars reuse option, and completion of cost optimized hpDIRC design.
- mRICH: optimize photonsensors + electronics; testbeam of improved prototype.
- dRICH: Characterize mirror & aerogel; Assessment of dRICH prototype performance with the EIC detection plane.

**ECals:**
- bECAL: Full characterization of full SciGlass block designed for EIC by beam test.
- fECAL: construct 64 channel prototype to optimize light uniformity, light guides, verify performance by test beam.

**HCals:**
- Prototype SC-tile production using machining & injection molding & detailed characterization.
- Sensor board development.
- First prototype of one full segment.

**Photon-Sensors:**
- WBS 6.10.04 & 05 & 06.
  - Assess current state of LAPPD performance. Improve design through iterations to fulfill EIC specifications.
    - Spatial resolution for Cherenkov imaging applications.
    - Timing resolution in a single photon mode.
    - Performance in a strong (inhomogeneous) magnetic field.
    - QE & PDE spectrum optimization.
    - Geometric form factor optimization.

**Electronics & DAQ/Computing**
- Development of readout solutions for calorimeters with SiPMs, ASIC based & ADC based.
  - dRICH with SiPMs based on ALCOR.
  - AC-LGAD readout chain with EICROC & FCFD.
  - MPGD readout based on SALSA-ASIC.

**Hadron Polarimetry:**
- R&D through Accelerator.
  - Validate concepts to veto breakup of He-3.
  - New targets for pC-polarimeters.

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E.C. Aschenauer
What do we know: Mass of the Proton, Pion, Kaon

Visible world: mainly made of light quarks – its mass emerges from quark-gluon interactions.

**Proton**
- Quark structure: uud
- Mass ~ 940 MeV (~1 GeV)
- Most of mass generated by dynamics.
- Gluon rise discovered by HERA e-p

**Pion**
- Quark structure: ud
- Mass ~ 140 MeV
- Exists only if mass is dynamically generated.
- Empty or full of gluons?

**Kaon**
- Quark structure: us
- Mass ~ 490 MeV
- Boundary between emergent- and Higgs-mass mechanisms.
- More or less gluons than in pion?

For the **pion and the kaon** the EIC will allow determination of the quark and gluon contributions to mass with the Sullivan process.

For the **proton** the EIC will allow determination of an important term contributing to the proton mass, the so-called “QCD trace anomaly”
**EIC Science Highlights**

**Proton:**

- EIC Y 10 on 100 GeV (100 fb⁻¹)
- GlueX J/ψ, R. Wang et al. (2020)
- SolID J/ψ Projection

![Proton Mass and Spin](image)

**Nuclei:**

- Non-linear QCD effects → Saturation

![Nuclei Imaging](image)

**3d-Imaging of nuclei**

![3d-Imaging](image)

**EIC Data Highlights**

- √s < 90 GeV

![Data Highlights](image)
• Requirement for fringe field: <10 Gauss at forward and backward side and at RCS location

• Challenges detector design not symmetric

  ➔ critical that forces get balanced

• Consequences on design:
  ➢ backward HCal moved as far back as possible
  ➢ add both sPHENIX flux return doors behind bHCal
  ➢ forward HCal need to have first tungsten/Sc and then Steel/Sc
  ➢ add additional steel around barrel HCal

layered barrel extra flux return
6 layers 50 mm steel 40 mm air

Reach 14 gauss and lower
Large-scale superconducting detector magnets have a limited worldwide vendor supply and carry known technical, cost and schedule risk during the construction phase. → A “known” LLP candidate

Magnet status:
- CD-1 Approval
- 3T Detector solenoid preliminary design report
- Incremental (30%) Design and Safety Review
- DPAP closeout report – led to reduced field (< 3 T)
- Contract for 60% Design Review
- 60% design team formation and kick off meeting
- Mid-Project Progress meeting (@BNL, hybrid meeting)
- Point design adjusted to stretch goal of 2 T (operation at 1.7 T)
- 60% Design and safety Review
- 90% Design contract in place
- Found qualified vendor willing to make conductor

Magnet planning:
- RFI on the street
- 90% Design completion and review
  (90% design completion is 100% - final design - for “Vendor Design-Build” procurement).
- P6: Milestone FDR date

→ Magnet is on track to be ready for procurement at CD-3A date
**What is new/special for a EIC GPD**

**Vertex detector** → Identify primary and secondary vertices,
- Low material budget: 0.05% X/X₀ per layer;
- High spatial resolution: 10 μm pitch CMOS Monolithic Active Pixel Sensor

**Central tracker** → Measure charged track momenta
- MAPS – tracking layers in combination with micro pattern gas detectors
- MPGD: μ-RWell or MicroMegas

**Electron and hadron endcap tracker** → Measure charged track momenta
- MAPS – disks in combination with micro pattern gas detectors

**Particle Identification** → pion, kaon, proton separation on track level
- RICH detectors (modular and dual radiator RICH, DIRC) & Time-of-Flight
- high resolution timing detectors (LAPPS, LGAD) 10 – 30 ps
- novel photon sensors: MCP-PMT / LAPPD

**Electromagnetic calorimeter** → Measure photons (E, angle), identify electrons
- PbWO₄ Crystals (backward), W/SciFi Spacal (forward)
- Barrel: Pb/SciFi-imaging part or new Scintillating glass → cost effective

**Hadron calorimeter** → Measure charged hadrons, neutrons and K⁺⁰
- challenge achieve ~50%/√E + 10% for low E hadrons (<E> ~ 20 GeV)
- Fe/Sc sandwich with longitudinal segmentation

**DAQ & Readout Electronics:** trigger-less / streaming DAQ
- Integrate AI into DAQ → cognizant Detector

**Very forward and backward detectors** → scattered particles under very small angles
- Silicon tracking layers in lepton and hadron beam vacuum
- Zero – degree high resolution electromagnetic and hadronic calorimeter

**Polarimetry**

**Lepton:** integrated transverse and longitudinal Compton polarimeter
**Hadron:** absolute and relative hadron polarimetry in the CNI region
The HERA and KEK experience show that having backgrounds under control is crucial for the EIC detector performance.

There are several background/radiation sources:
- primary collisions
- beam-gas induced
- synchrotron radiation

**Important to note:**
- low multiplicity per event: < 10 tracks
- \( \eta > 2 \): avg. hadron track momenta @ 141 GeV: \(~20\) GeV
- No pileup from collisions 500 kHz @10^{34} cm^{-2}s^{-1} \rightarrow coll. every 200 bunches
- radiation environment much less harsh than LHC \rightarrow \text{factor 100 less}

**Synchrotron Radiation:**
- Origin: quads and bending magnet upstream of IP
- Tails in electron bunches: can produce hard radiation
- Studied using Synrad3D
Since CD-1 we made significant progress in the preliminary design for the 2nd IR with a focus on complementarity

<table>
<thead>
<tr>
<th>Geometry:</th>
<th>1st IR (IP-6)</th>
<th>2nd IR (IP-8)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ring inside to outside</td>
<td>ring outside to inside</td>
</tr>
<tr>
<td></td>
<td>tunnel and assembly hall are larger</td>
<td>tunnel and assembly hall are smaller</td>
</tr>
<tr>
<td></td>
<td>Tunnel: $\mathbb{Q}$ 7m +/- 140m</td>
<td>Tunnel: $\mathbb{Q}$ 6.3m to 60m then 5.3m</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Crossing Angle:</th>
<th>25 mrad</th>
<th>35 mrad</th>
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<tbody>
<tr>
<td></td>
<td>different blind spots</td>
<td>secondary focus</td>
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<tr>
<td></td>
<td>different forward detectors and acceptances</td>
<td></td>
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<td></td>
<td>different acceptance of central detector</td>
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<table>
<thead>
<tr>
<th>Luminosity:</th>
<th>more luminosity at lower $E_{CM}$</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>optimize Doublet focusing FDD vs. FDF</td>
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<tr>
<td></td>
<td>$\rightarrow$ impact of far forward $p_T$ acceptance</td>
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<thead>
<tr>
<th>Experiment:</th>
<th>1.5 Tesla or 3 Tesla</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>different subdetector technologies</td>
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</table>
IR Highlights and Challenges
- High Luminosity → High current (~ 2.5 A)
- High number of bunches (1160, ~10 ns separation)
  - Avoid parasitic collisions at IR
  - Crossing angle
  - Both focusing elements close to IP
- Small $\beta^*$ values (h: 80/7.2 cm, e: 45/5.6 cm)
  - Strong final focus magnets close to IR
  - Aperture: challenging magnet designs
- Polarization
  - Lattice constraints to enable polarized beams
  - Polarized hadrons / electrons
  - Polarmetry (local and global)
  - Spin rotators & Snakes
- Electrons: Frequent on-energy bunch replacements
- Experimental detector
  - Forward detectors
  - Experimental solenoid & compensation

The same highlights and challenges as IP-6
- Different: pre-conceptual design with 35mr crossing angle and secondary focus for science complementary checks.
- Further study needed for the feasibility of the IR magnets → Nb3Sn magnets are being evaluated as an option.

2nd focus enables:
- enhanced low $P_T$ acceptance, DVCS on nuclei, Light ion tagging, Diffraction, improved Gluon imaging by detection of (A-1) nuclei.
What do we want from “Complementary”

- **Cross-checking important results (obvious!)**
  - Many examples of wrong turns in history of nuclear and particle physics.
  - Independent cross checks (detector, community, analysis tools) are essential for timely verifications and corrections.

- **Cross Calibration**
  - Combining data gave well beyond the $\sqrt{2}$ statistical improvement …
  - Different dominating H1, ZEUS systematics…
  - Effectively use H1 electrons with ZEUS hadrons
    - … not all optimal solutions have to be in one detector…

- **Technology Redundancy**
  - … by applying different detector technologies and philosophies to similar physics aims
    - mitigates technology risk vs. unforeseen backgrounds
    - differently optimizes precision and systematics

- **Different primary physics focuses**
  - … EIC has unusually broad physics program
    - (from exclusive single particle production to high multiplicity eA or $\gamma$A with complex nuclear fragmentation)
  - Impossible to optimize for the full program in a single detector.
  - Impact on IR design