Status of the EIC Project

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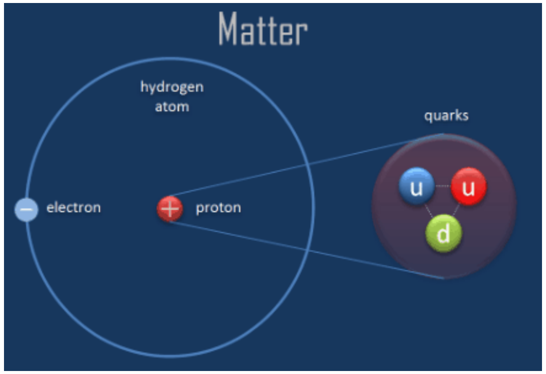
(for ePIC Collaboration)

Outline

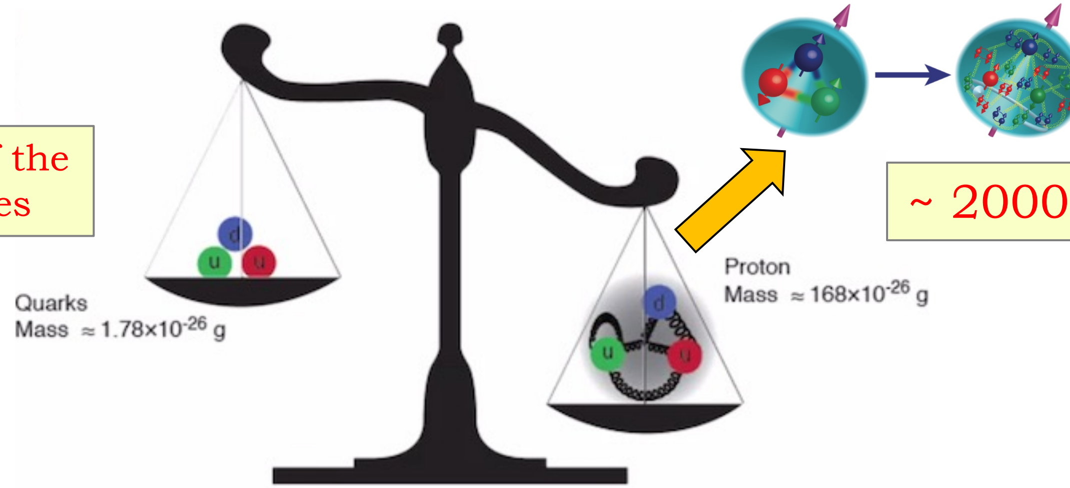
- Introduction
- Electron Ion Collider
- Physics Goals, Methodology, and Detector Requirement
- ePIC Detectors (Proposed)
- Summary

Introduction

Around 1970



One of the issues

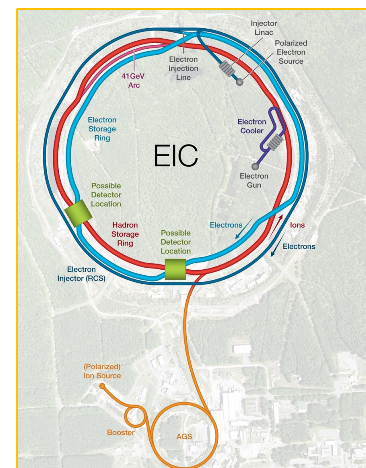


~ 2000

Even after hundred years of discovery of proton, we do not know its internal structure completely!

Need multidimensional imaging of the proton structure

Electron Ion Collider (EIC) @ Brookhaven National Laboratory, USA



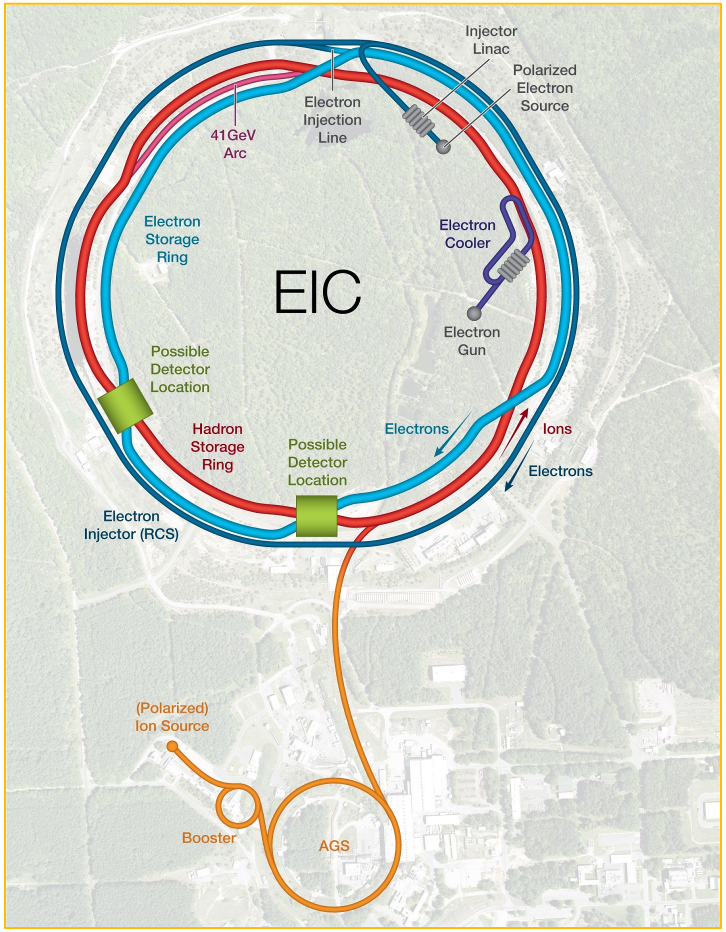
Electron Ion Collider (EIC)

EIC:

- A new, innovative, large-scale particle accelerator facility planned for construction at Brookhaven National Laboratory (BNL), New York, USA.
- Highest priority project appeared in the 2015 & 2023 US Nuclear Physics Long Range Plan.
- Favorably endorsed by a committee established by the National Academy of Sciences (US) in 2018.
- Granted Critical Decision Zero (CD0) [2019] by the US Department of Energy (DOE) – marked as the official project of the US government.

US-NSAC Long Range Plan, 2015
US-NSAC Long Range Plan, 2023

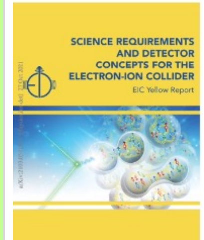
EIC Yellow Report



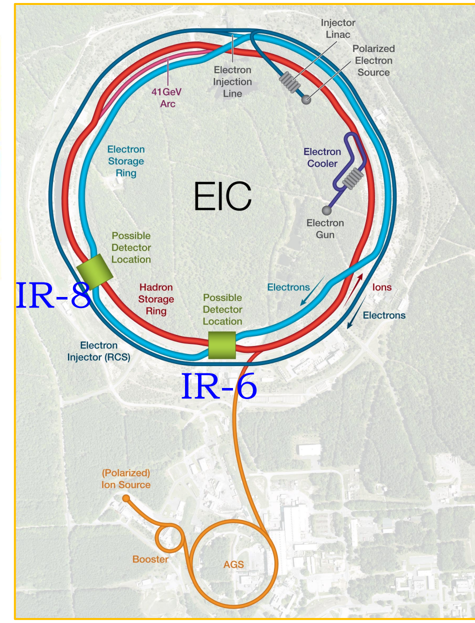
Only new collider in foreseeable future – will remain at frontier of accelerator S&T

EIC Project Design Goals

- High Luminosity: L= $10^{33} - 10^{34} cm^{-2} sec^{-1}$, $10 - 100\ fb^{-1}$/year
- Highly Polarized Beams: 70%
  -- requires high precision polarimetry
- Large Center of Mass Energy Range:
  E_{cm} = 29 – 140 GeV
  -- large detector acceptance
- Large Ion Species Range: proton-Uranium
  -- requires forward detectors integrated in beam lattice
- Good Background Conditions
- Accommodate a Second Interaction Region (IR) -- *IR-8*



EIC Yellow Report



EIC:

- 1^{st} high-luminosity e-p collider
- 1^{st} polarized target collider
- 1^{st} electron-nucleus collider

← Backward | Forward →

p: 41 GeV, 100 to 275 GeV — p/A beam →

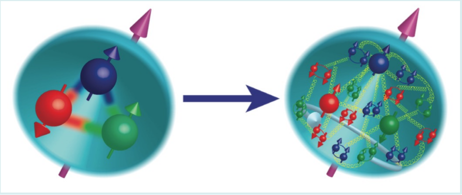
← e beam — e: 5 GeV to 18 GeV

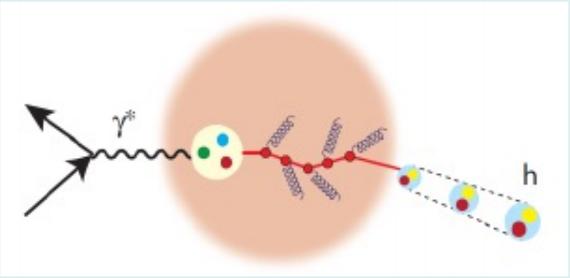
z

EIC Physics Goals

Address following questions

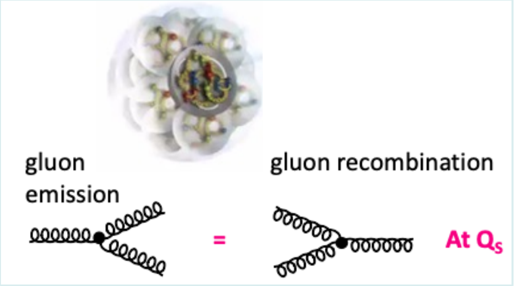
- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
- How do the nucleon properties (mass, spin..) emerge from them and their interactions?





- How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
- How do the confined hadronic states emerge from these quarks and gluons?
- How do the quark-gluon interactions create nuclear binding?

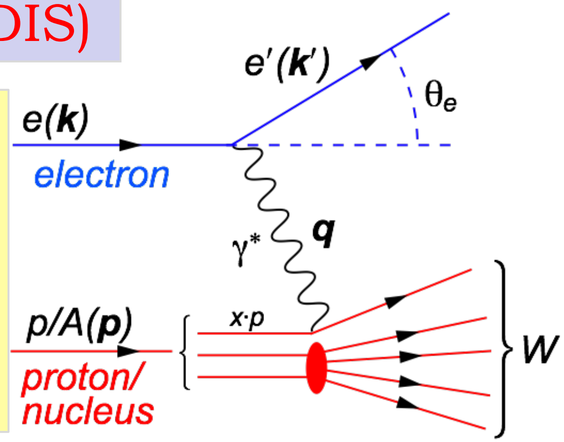
- What happens to the gluon density in nuclei?
- Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?



Methodology

Physics Methodology: 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



Terminology: $q = k - k'$ | $-Q^2 = (k - k')^2$ | $s = (k + p)^2$ | $W = (p + q)^2$

s: Center-of-mass energy squared for DIS system

Q²: Square of the momentum transfer between the electron and proton; inversely proportional to the resolution

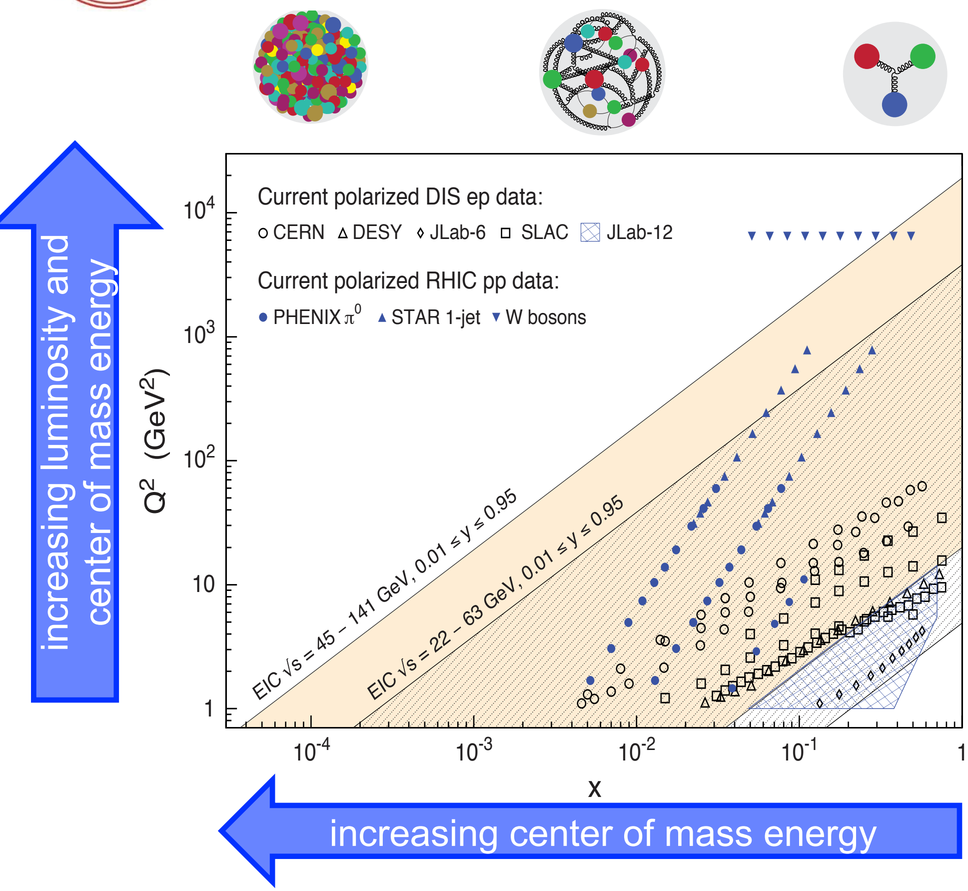
y: inelasticity ($0 \leq y \leq 1$)

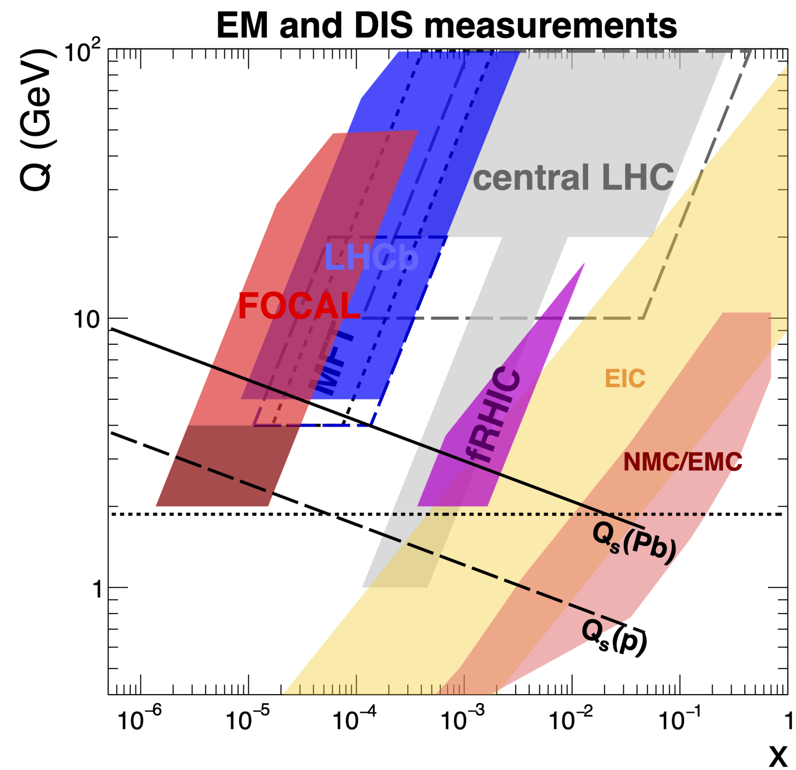
x: the fraction of the nucleon's momentum carried by the struck quark ($0<x<1$)

W: Center-of-mass energy for photon-nucleon system

Variables x, Q^2, s are related through the equation: $Q^2 = s \bullet x \bullet y$

Kinematic Range Comparison





EIC covers large kinematic coverage:
- Access to x and Q^2 over a wide range

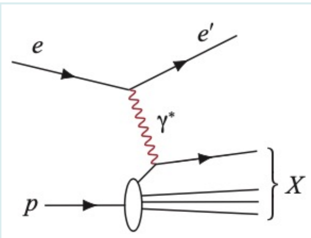
- EIC – Bridge the gap b/w LHC and HERA experiments
- EIC + other experiments give almost full and complementary access to x and Q^2 – *comprehensive data set*

Physics Processes Measured @ EIC

Neutral-current inclusive DIS ⇐ **Inclusive DIS** ⇒ **Charged-current inclusive DIS**

Neutral-current inclusive DIS

$$e + p/\mathrm{A} \longrightarrow e' + \mathrm{X}$$

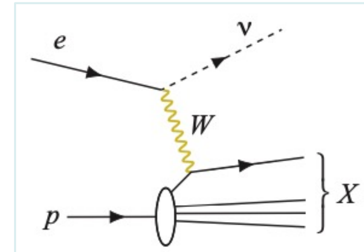


- Essential to detect the scattered electron, e′, with high precision.
- All other final state particles (X) are ignored.
- The scattered electron is crucial for all processes to determine the event kinematics.

Charged-current inclusive DIS

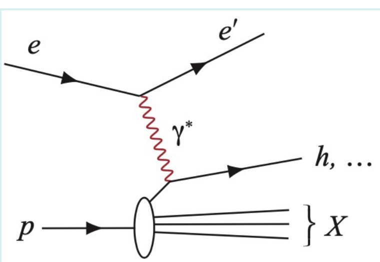
- At high enough Q^2, the electron-quark interaction is mediated by $W^{\pm}$ instead of γ^*.
- Event kinematic cannot be reconstructed from the scattered electron; reconstructed from the final state particles.

$$e + p/\mathrm{A} \longrightarrow \nu + \mathrm{X}$$



Semi-inclusive DIS

$$e + p/\mathrm{A} \longrightarrow e' + h^{\pm,0} + \mathrm{X}$$

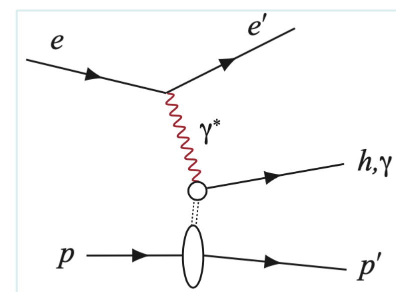


Requires measurement of at least one identified hadron in coincidence with the scattered electron.

Exclusive DIS

$$e + p/\mathrm{A} \longrightarrow e' + p'/A' + \gamma/h^{\pm,0}/VM$$

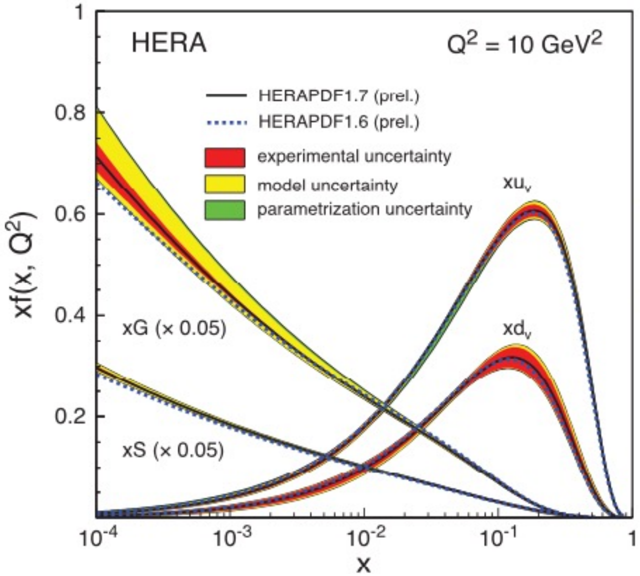
Requires the measurement of all particles in the event with high precision.



Initial state: *Colliding electron (e), proton (p), and nuclei (A).*
Final state: *Scattered electron (e'), neutrino (ν), photon (γ), hadron (h), and hadronic final state (X).*

Gluon Saturation @ EIC

Parton Distribution Functions

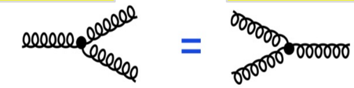


F.D. Aaron, et al., H1 Collaboration, ZEUS Collaboration, JHEP 01 (2010) 109

At high energies, gluon density is high at low-x
-- Cannot continue to rise & must saturate!
-- Saturation of parton density called Color Glass Condensate (CGC)

gluon emission

gluon recombination



No. of hard gluons splitting into softer gluons

No. of soft gluons recombining into harder gluons

Gluon saturation

Possibility at EIC:

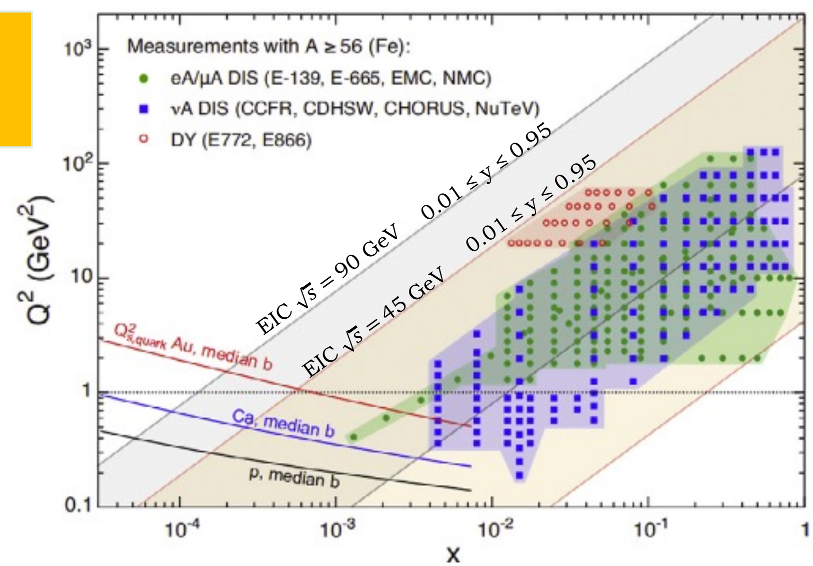
Saturation scale:

$$Q_{\text{sat}}^2 \approx \frac{x g_A(x, Q^2)}{\pi R_A^2} \propto A^{1/3} x^{-\lambda}$$

Large A => Enhance Q_{sat} scale

$$x_{1,2} \approx \frac{2 p_T \exp(\pm y)}{\sqrt{s}}$$

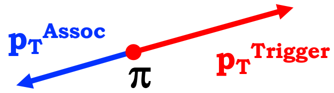
Low-x => forward rapidity



Gluon Saturation effects accessible at EIC!

Gluon Saturation @ EIC

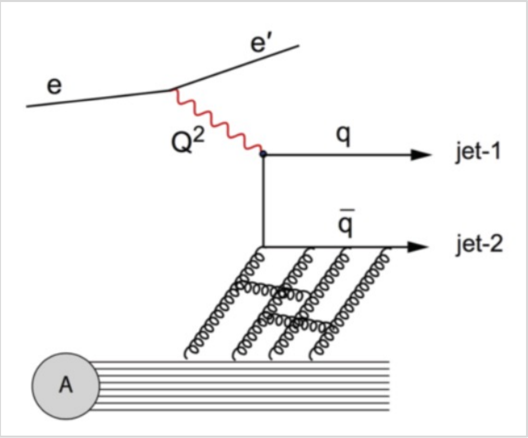
Dihadron Correlations:



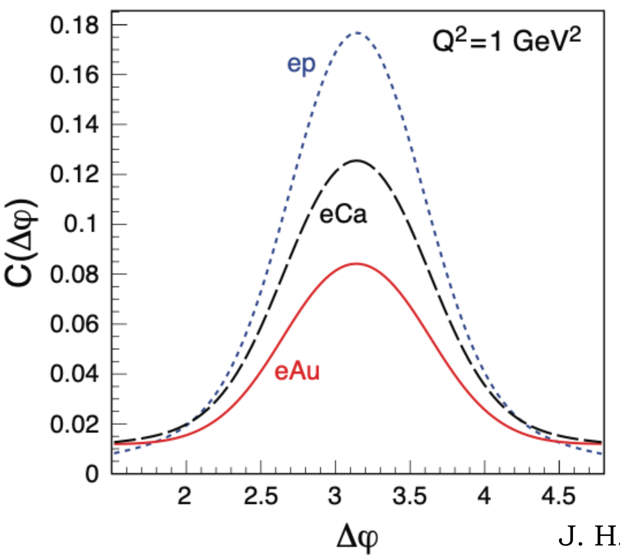
Measure: Azimuthal correlation between two hadrons produced in lepton-nucleus DIS

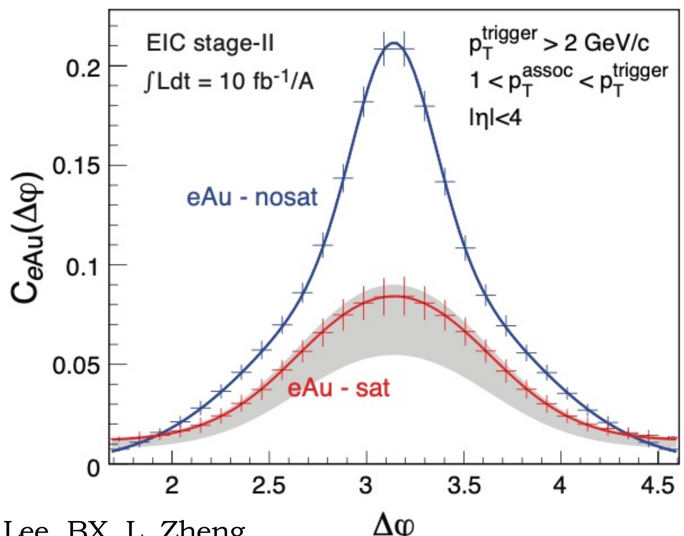
Sensitive to: p_T-dependence of gluon distribution and their correlations

Expectation: Disappearance of back-to-back correlations with increasing A (in dense gluonic matter)



E. Sichtermann, NPA 956, 233 (2016)



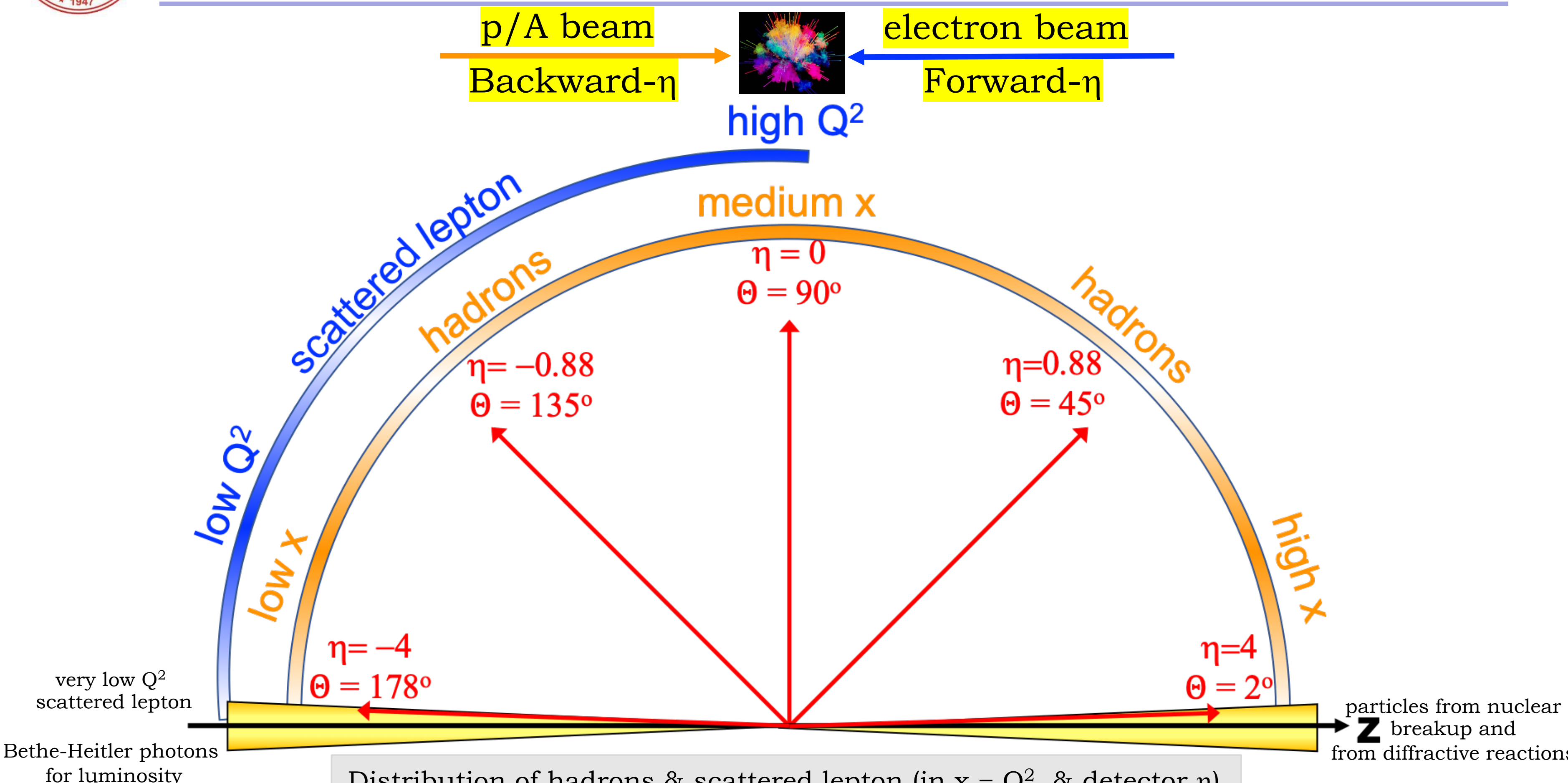


J. H. Lee, BX, L. Zheng

Away side peak is suppressed in dense nuclear matter

Detector Requirement: Tracking detector with full azimuth and wide rapidity coverage

Detector Requirements



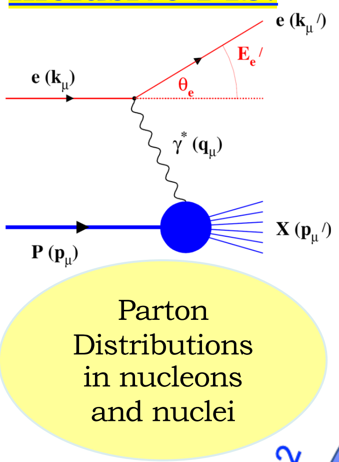
Distribution of hadrons & scattered lepton (in x – Q^2 & detector η)

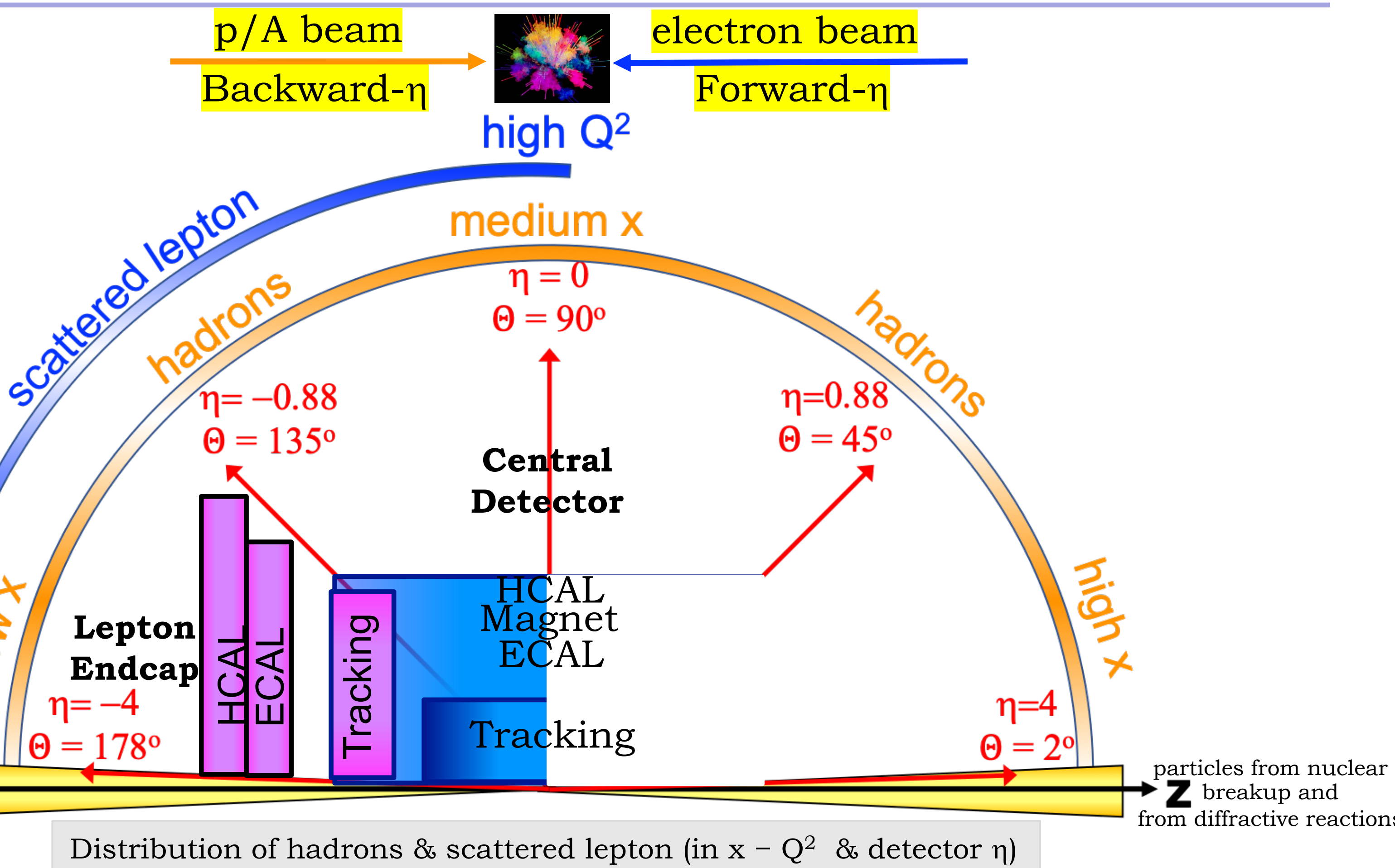
Detector requirement: Access full x – Q^2 plane at different $\sqrt{s}$ and suitable for strong asymmetric beam-energy combinations
-- Reconstruct events over a wide span in polar angle (θ) and η.

Stringent requirements on detector acceptance and the resolution of meas. quantities

Detector Requirements

inclusive DIS:



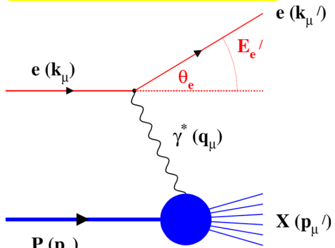


Luminosity Detector

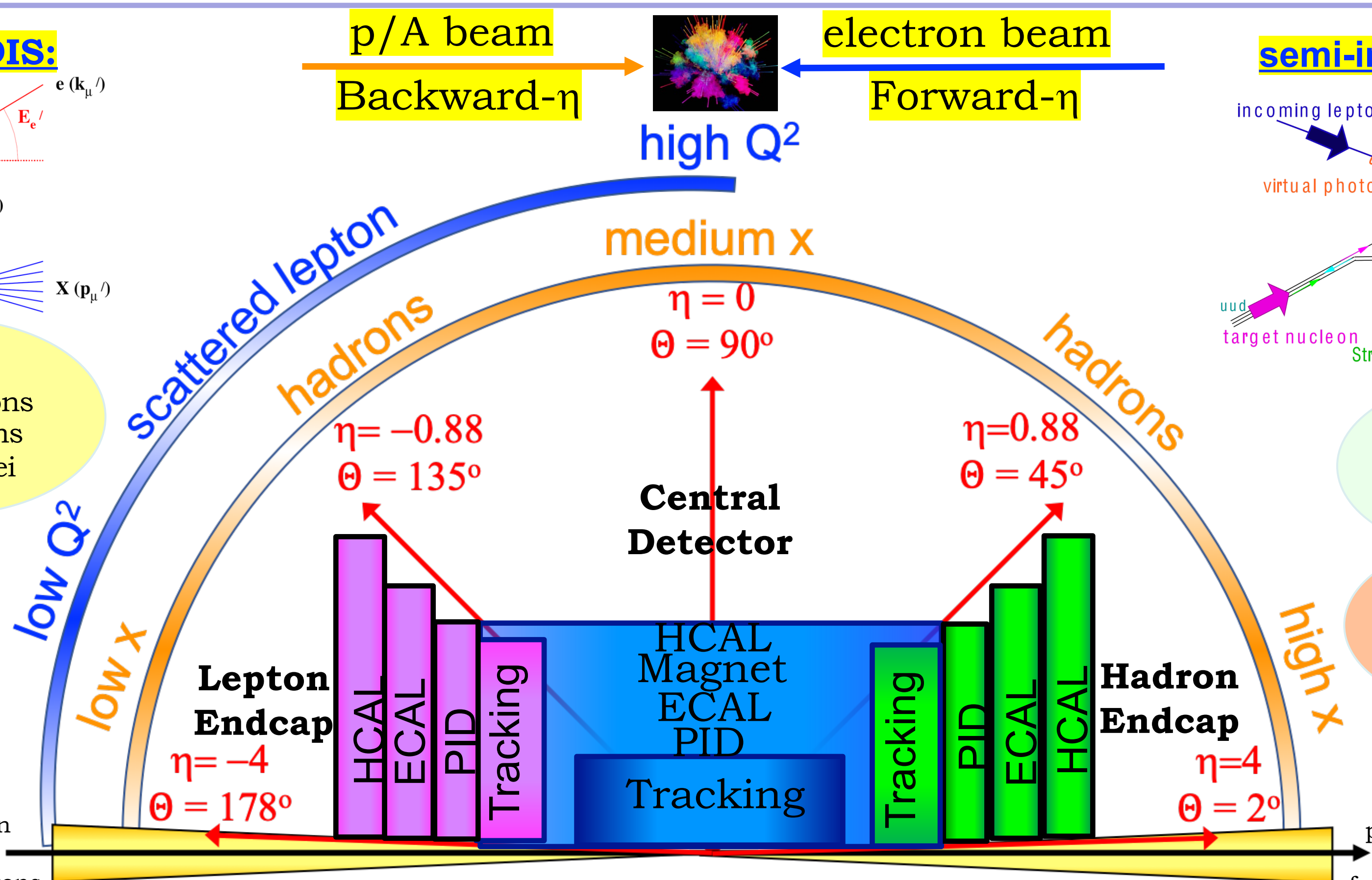
Low Q^2-Tagger

Detector Requirements

inclusive DIS:

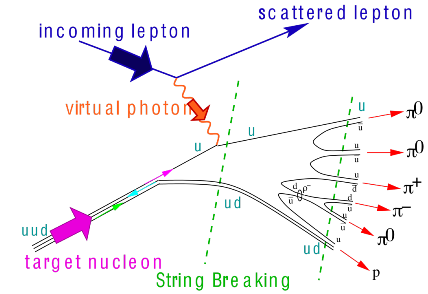


Parton Distributions in nucleons and nuclei



Distribution of hadrons & scattered lepton (in x − Q² & detector η)

semi-inclusive DIS



Spin and Flavor structure of nucleons and nuclei

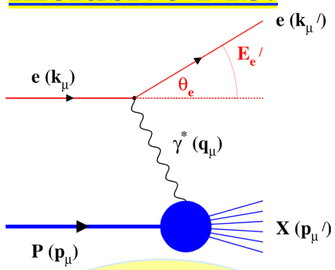
Tomography Transverse Momentum Dist.

Luminosity Detector

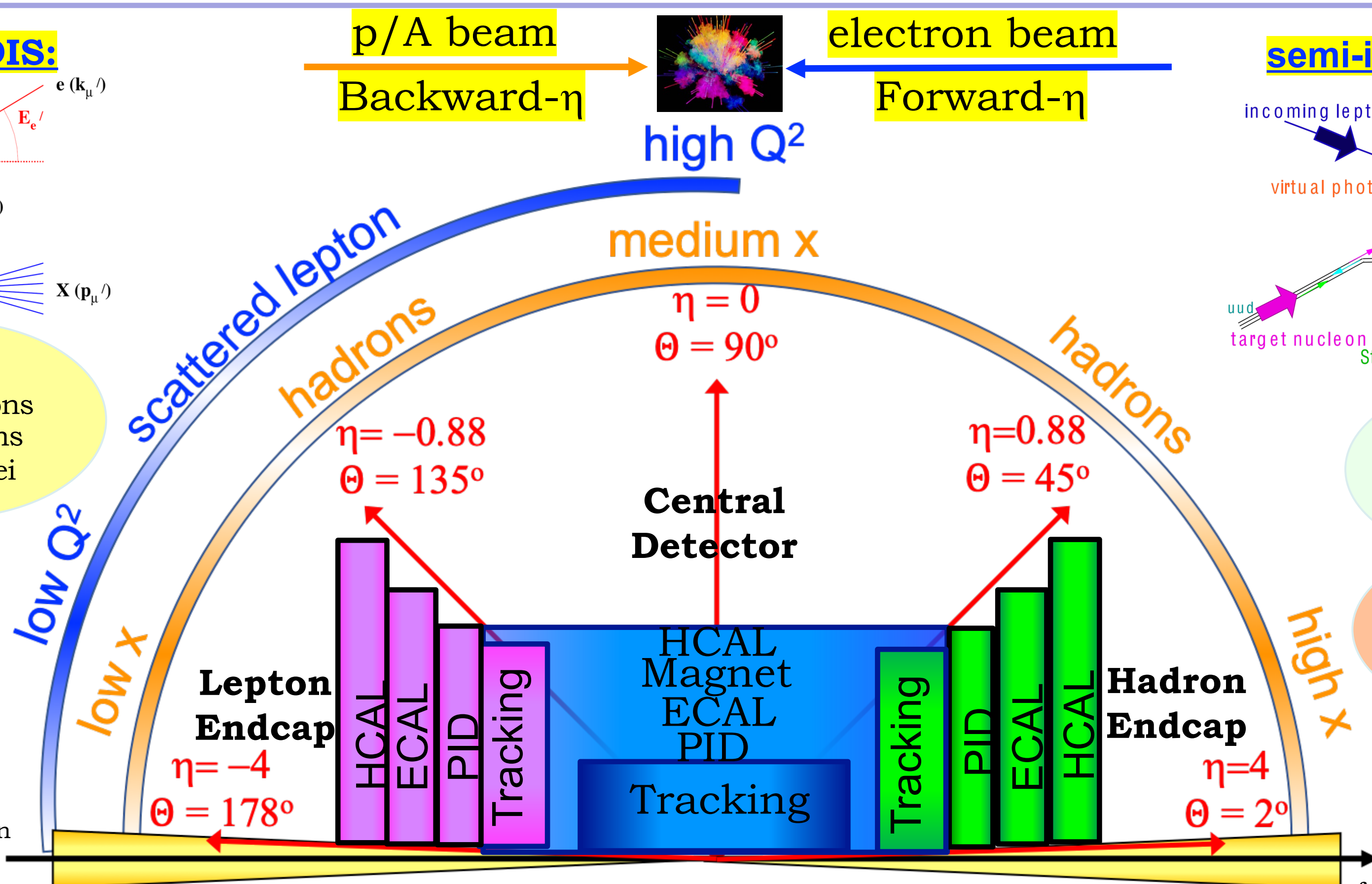
Low Q^2-Tagger

Detector Requirements

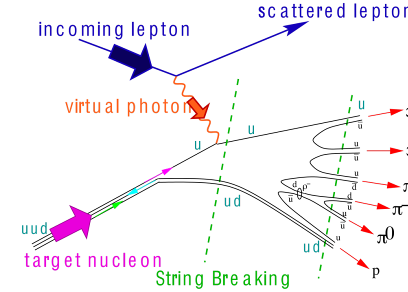
inclusive DIS:



Parton Distributions in nucleons and nuclei



semi-inclusive DIS



Spin and Flavor structure of nucleons and nuclei

Tomography Transverse Momentum Dist.

very low Q² scattered lepton

Bethe-Heitler photons for luminosity

particles from nuclear breakup and from diffractive reactions

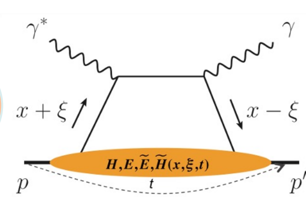
Distribution of hadrons & scattered lepton (in x – Q² & detector η)

Luminosity Detector

Low Q²-Tagger

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging



exclusive DIS

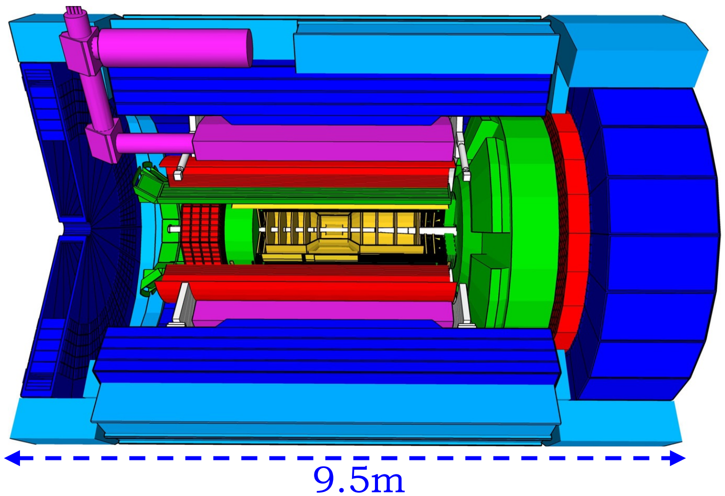
ZDC

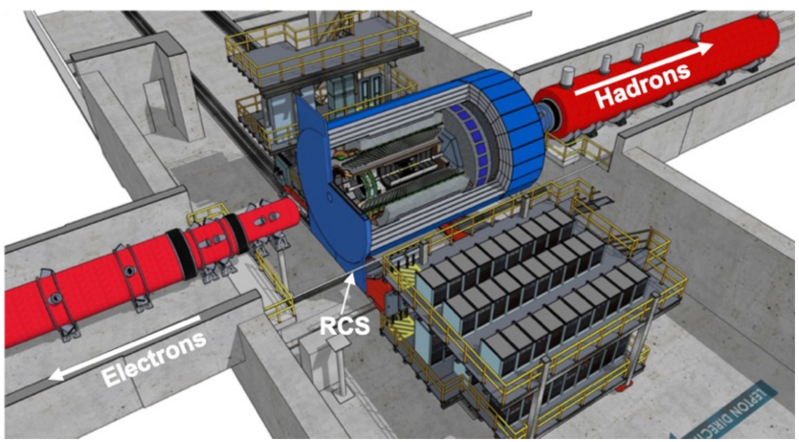
Forward Tracking

The Detector: electron Proton Ion Collider

hadronic calorimeters | solenoid coils | ToF, DIRC, RICH detectors

e/m calorimeters | MPG & MAPS trackers





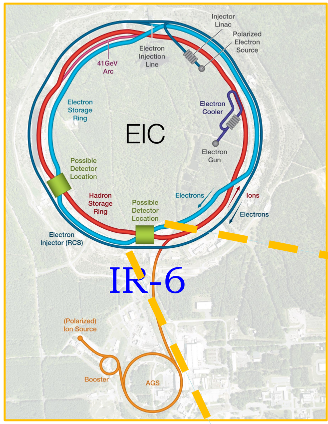
Overall detector requirement

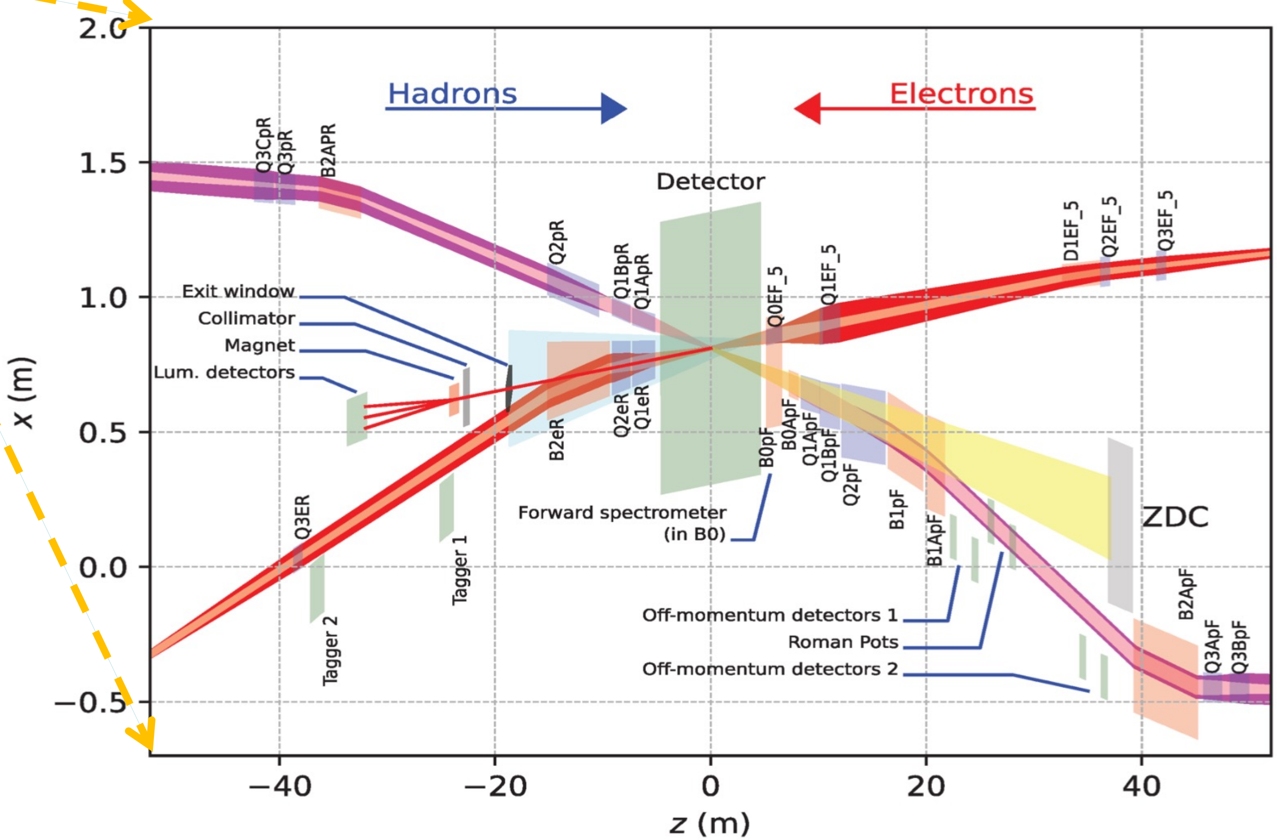
- Large rapidity (-4 < η < 4) coverage; and far beyond especially in far-forward detector regions
  - Large acceptance for diffraction, tagging, neutrons from nuclear breakup: critical for physics program, Many ancillary detector along the beam lines: low-Q^2 tagger, Roman Pots, Zero-Degree Calorimeter, ….
- High precision low mass tracking
  - small (μ-vertex Silicon) and large radius (gaseous-based) tracking
- Electromagnetic and Hadronic Calorimetry
  - equal coverage of tracking and EM-calorimetry
- High performance PID to separate e, π, K, p on track level
  - good e/h separation critical for scattered electron identification
- Maximum scientific flexibility
  - Streaming DAQ → integrating AI/ML

Details about ePIC
https://wiki.bnl.gov/EPIC/index.php?title=Main_Page

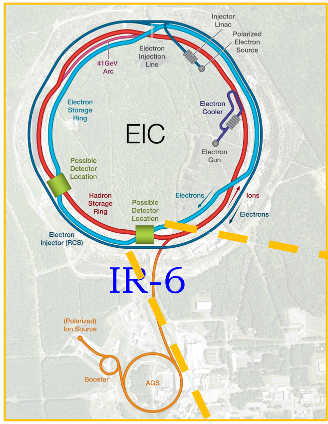
These requirements push the technology limit

The Interaction Region & Detectors

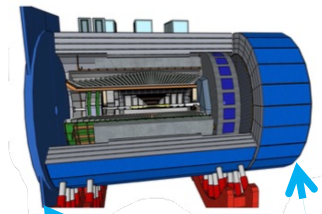


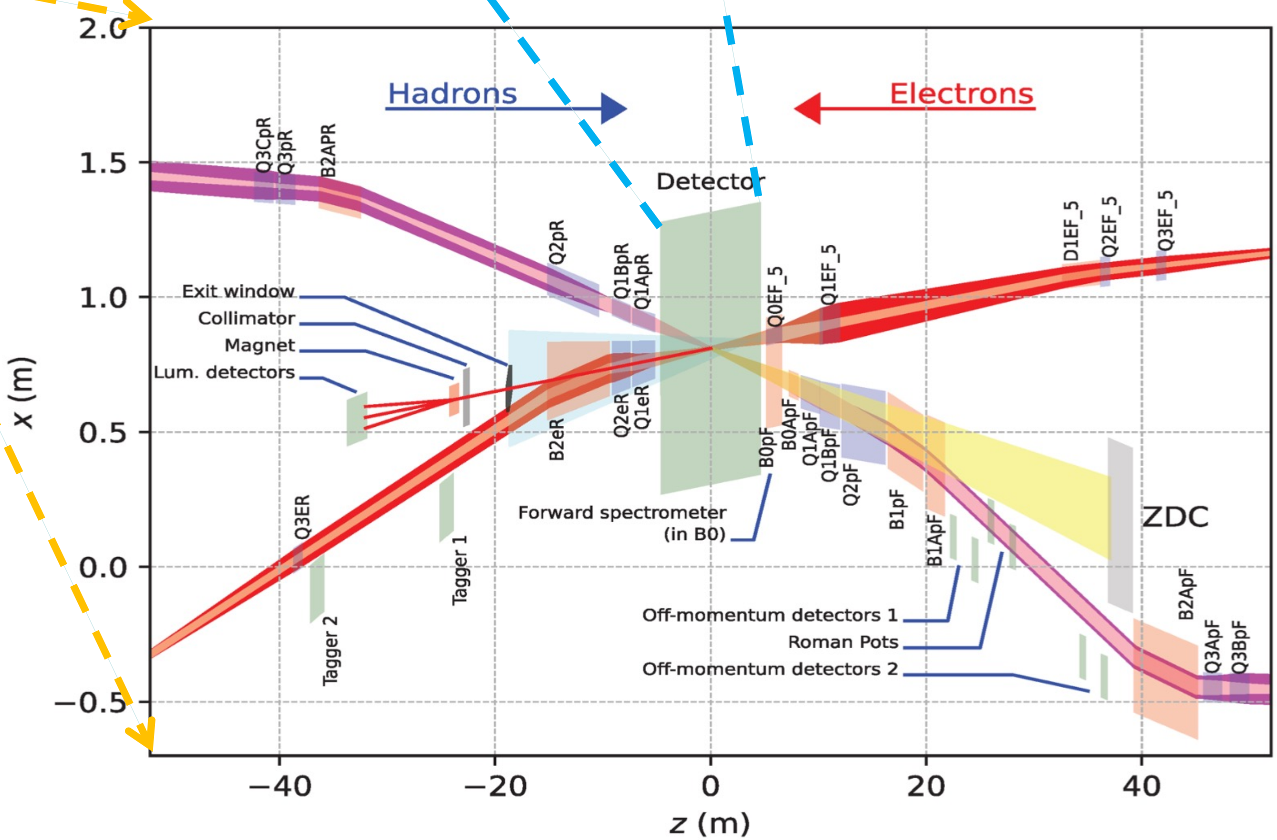


The Interaction Region & Detectors



Central





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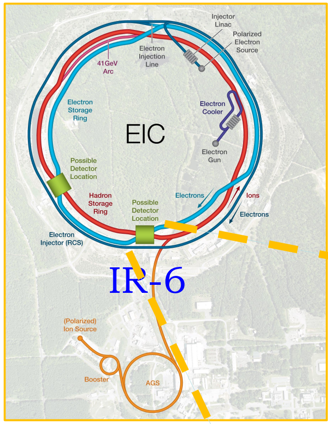

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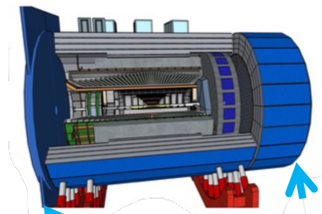
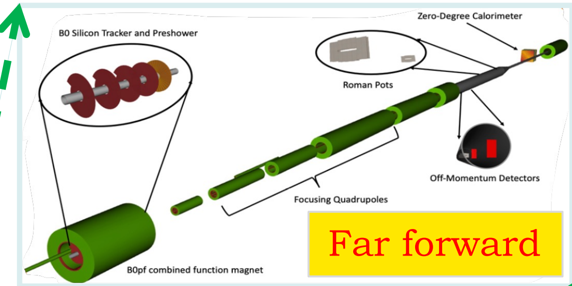
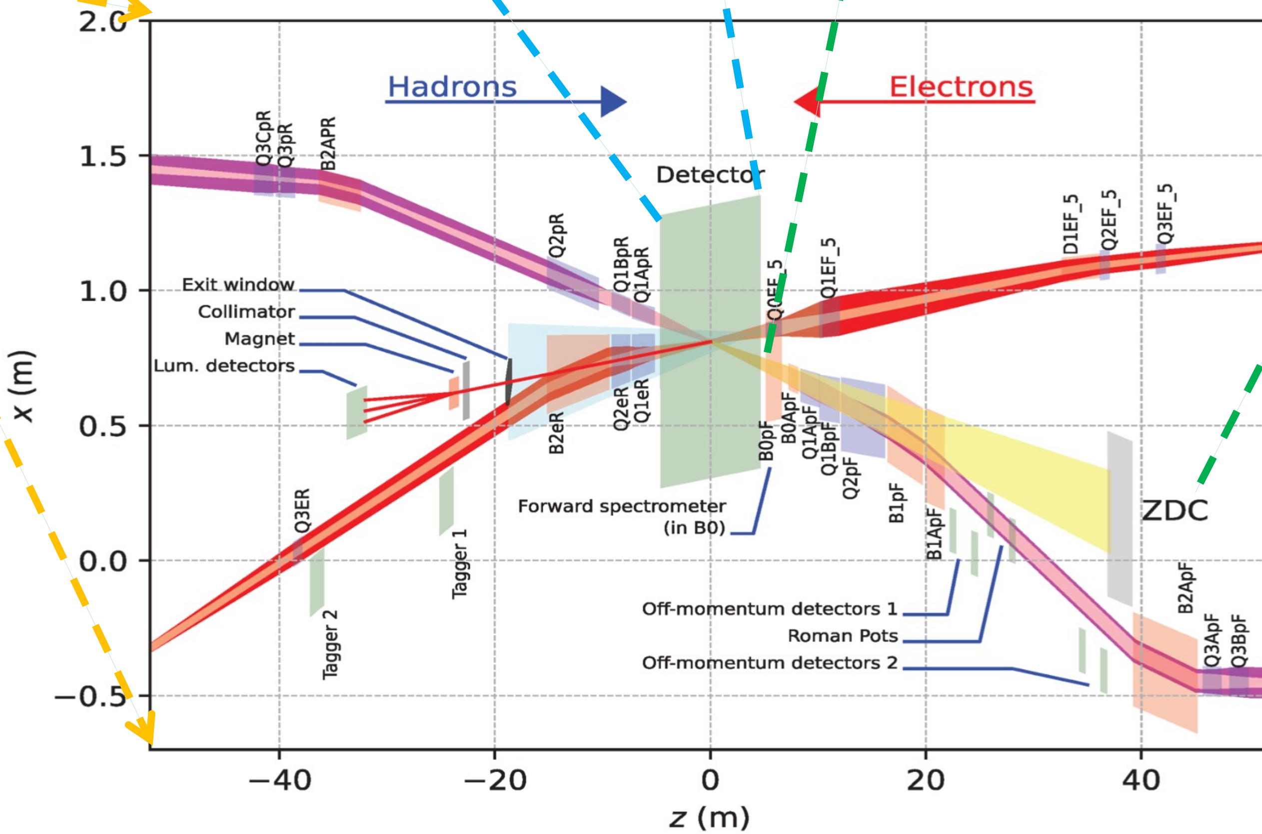
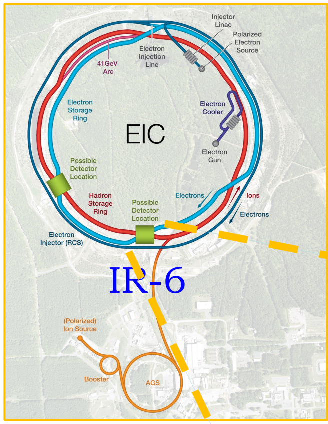




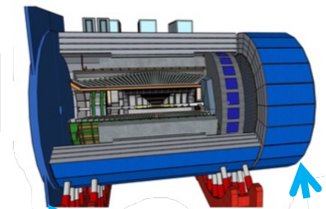
Far forward

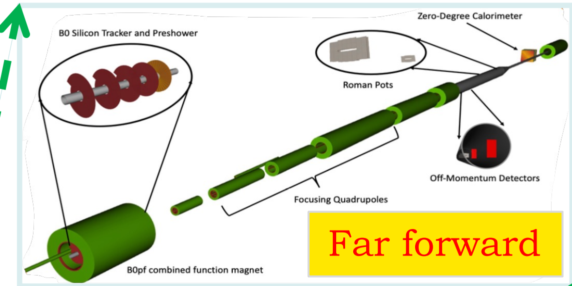


The Interaction Region & Detectors



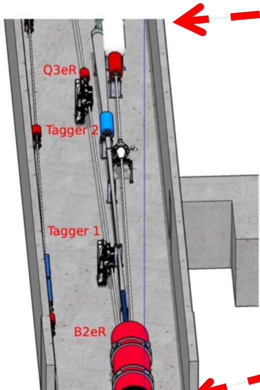
Central

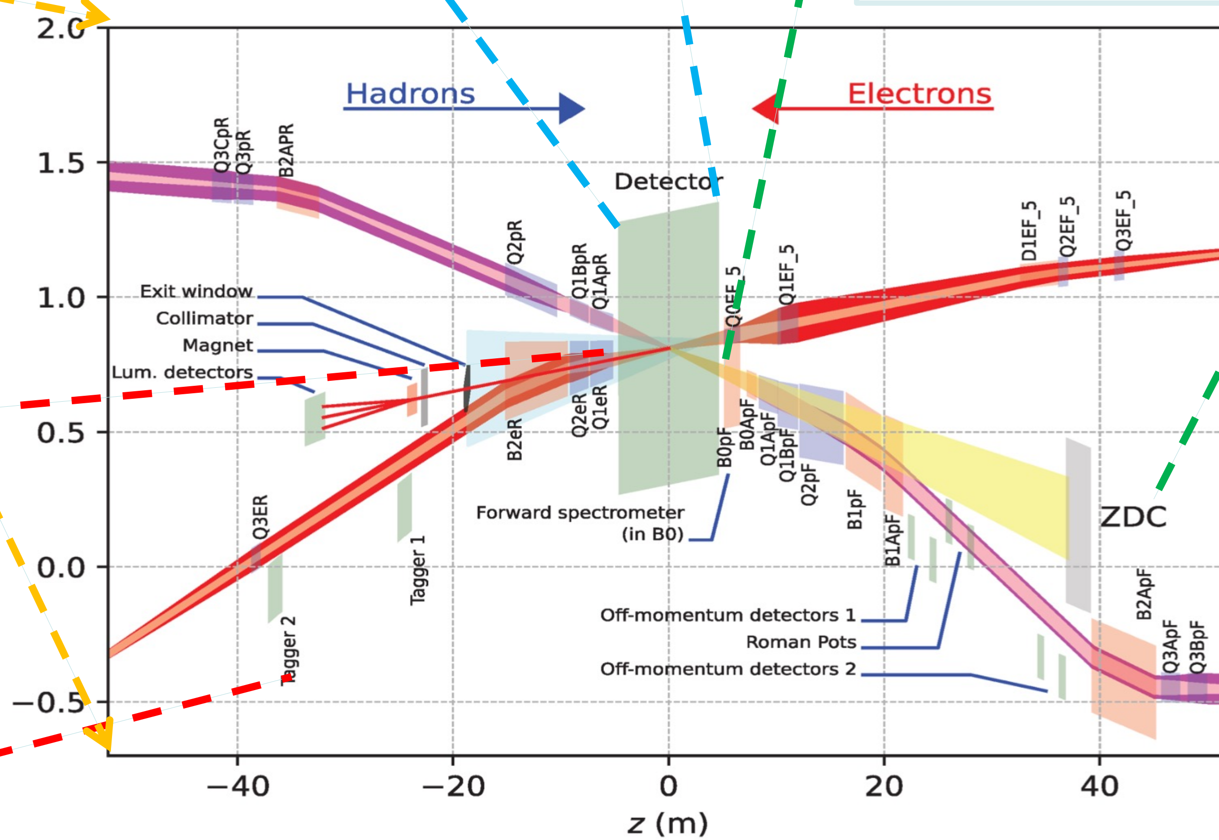




Far forward

Far-Backward



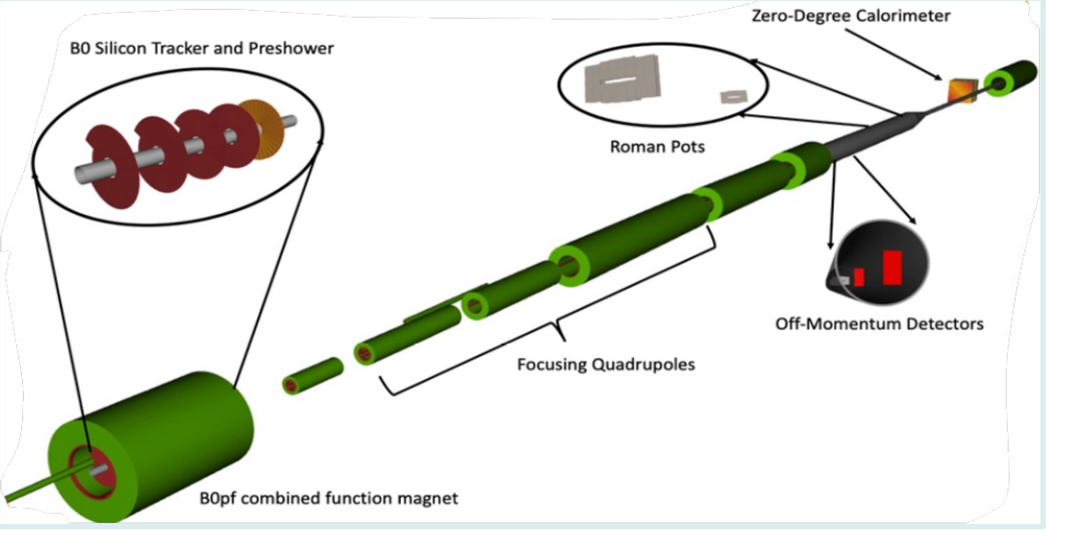


The Far-Forward Detectors

Many physics channels require the tagging of charged and neutral particles scattered at very small angles to the incoming proton/ion beam.

Main detectors: B0, Off-Momentum detectors, Roman Pot detectors, and Zero-Degree calorimeter.

Detector	**Acceptance**	**Particles**
ZDC	$\theta < 5.5$ *mrad* ($\eta > 6$)	Neutrons, photons
Roman pots (2 stations)	$0.0 < \theta < 5.0$ *mrad* ($\eta > 6$)	Scattered protons, light nuclei
Off-Momentum Detectors (2 stations)	$\theta < 5.0$ *mrad* ($\eta > 6$)	Charged particles from decays
B0 Detector	$5.5 < \theta < 20.0$ *mrad* ($4.6 < \eta < 6$)	Charged particles, tagged photons

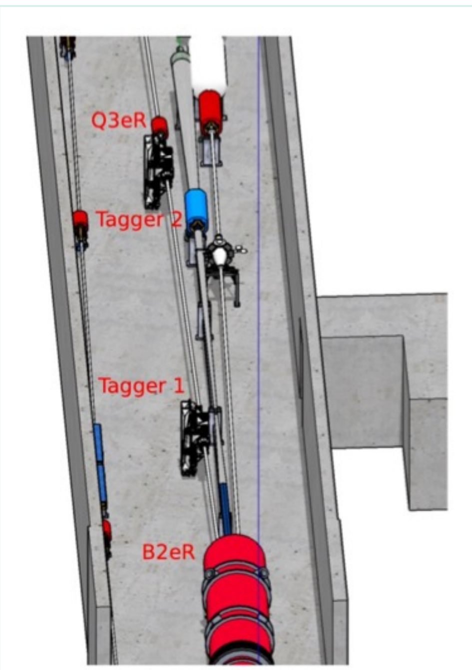


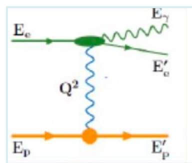
The Far-Backward Detectors

Measurement of the absolute and relative luminosity, as well as tagging of low-Q^2 electrons.

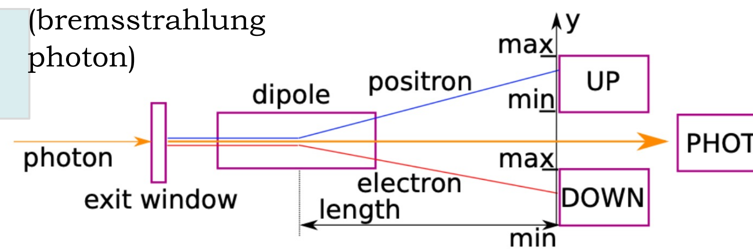
Main detectors: Direct Photon detector, the Pair Spectrometer, and the Low Q^2 taggers.

Luminosity Measurement





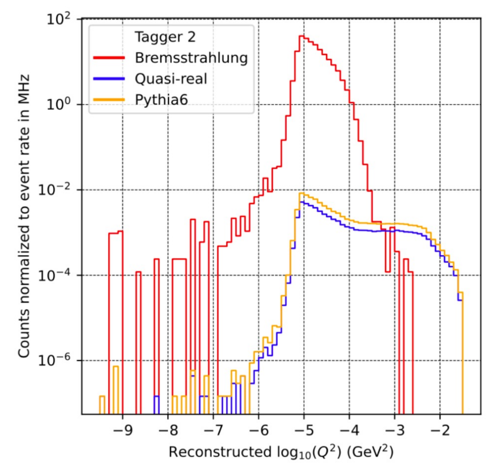
e+p --> e γ p
e+Au --> e γ Au



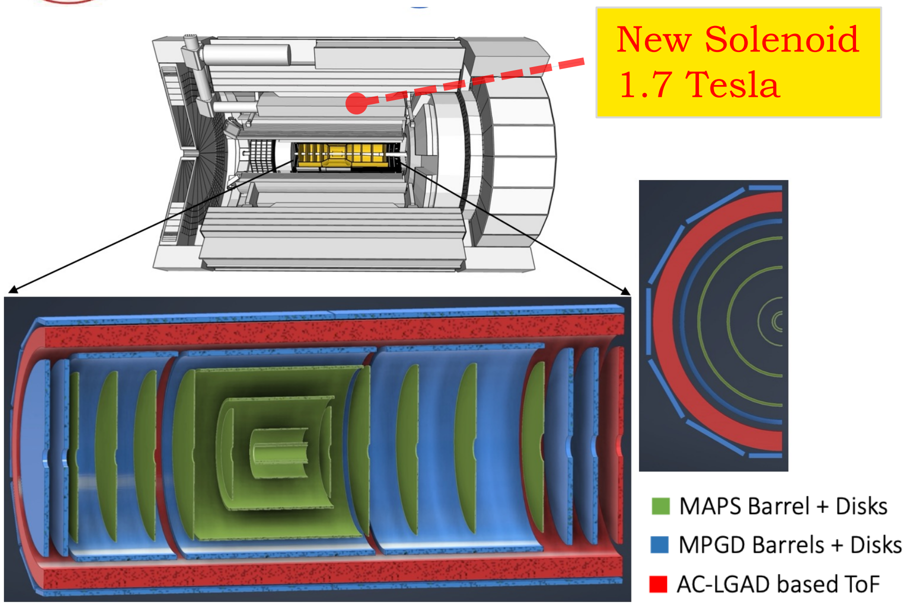
Absolute precision : better than 1%; Relative precision : better than 10^{-4}

Low-Q^2 tagger

Clean photoproduction signal for:
$10^{-3} < Q^2 < 10^{-1}$ (GeV^2)



Central Region: Tracking Detectors



MAPS Tracker:

- Ultra thin bent silicon around beampipe
- Small pixels (20 μm), low power consumption (<20 mW/cm^2) and material budget (0.05% to 0.55% X/X0) per layer
- Based on ALICE ITS-3 development
- Vertex layers optimized for beam pipe bakeout and ITS-3 sensor size
- Barrel layers based on EIC LAS development
- Forward and backwards disks

MPGD Layers:

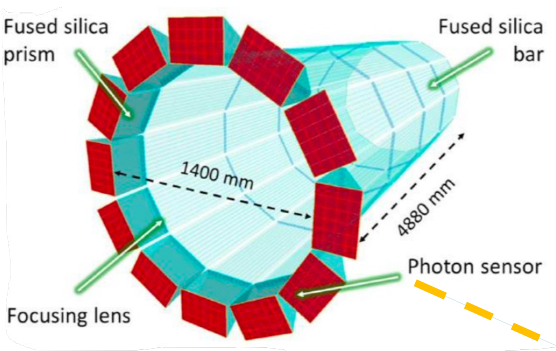
- Provide timing and pattern recognition redundancy
- Cylindrical barrel μMEGAs
- Planar End cap μRWells+single GEM before hpDIRC
- Impact point and direction for ring seeding

AC-LGAD based TOF (BECal):

- Additional space point for pattern recognition / redundancy.

MAPS: Monolithic Active Pixel Sensor
MPGD: Micropattern Gaseous Detector
LGAD: Low Gain Avalanche Detector

Central Region: PID Detectors



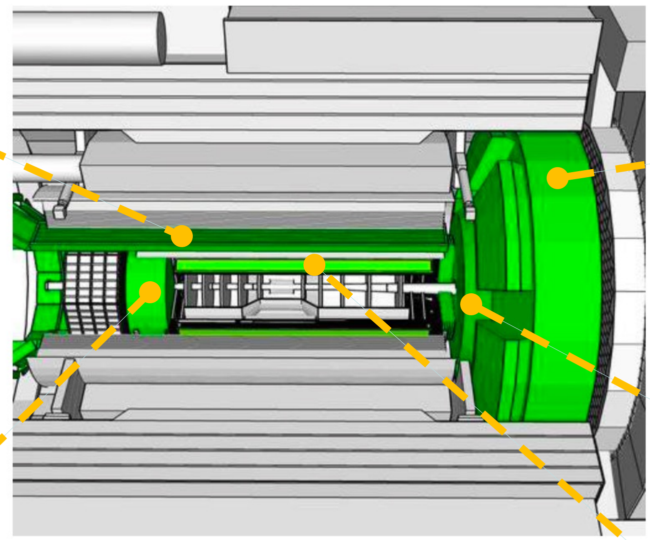
High-Performance DIRC (hpDIRC)

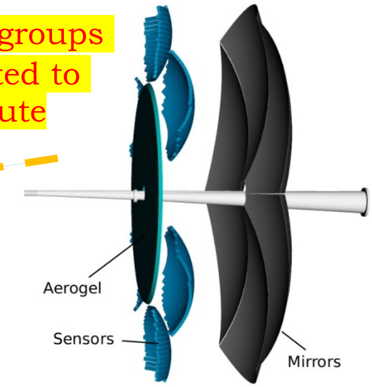
- Quartz bar radiator (reuse BaBAR bars)
- Sensors: HRPPDs
- π/K separation up to 6 GeV/c

Dual-Radiator RICH (dRICH)

- C_2F_6 gas volume and Aerogel
- Sensors: SiPMs tiled on spheres
- π/K separation up to 50 GeV/c

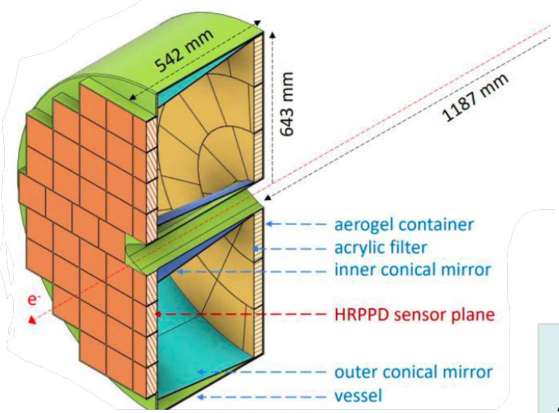
Indian groups interested to contribute





Proximity Focused RICH (pfRICH)

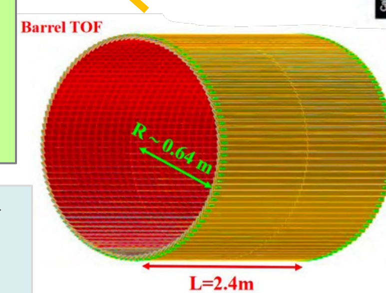
- Long Proximity gap (~40 cm)
- Sensors: HRPPDs (also provides timing)
- π/K separation up to 10 GeV/c
- e/π separation up to 2.5 GeV/c

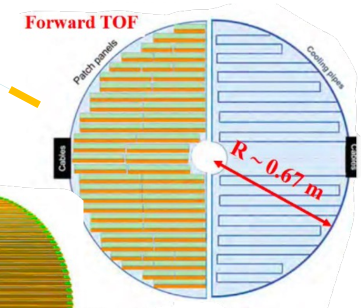


AC-LGAD based TOF:

- t ~30 ps
- Accurate space point for tracking
- Forward disk and central barrel

DIRC: Detection of Internally Reflected Cherenkov
RICH: Ring Imaging Cherenkov Detector
TOF: Time Of Flight

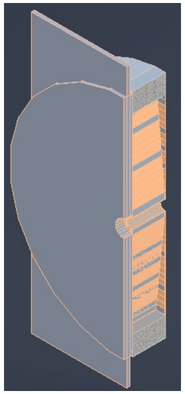




Indian groups interested to contribute

Central Region: Calorimetry

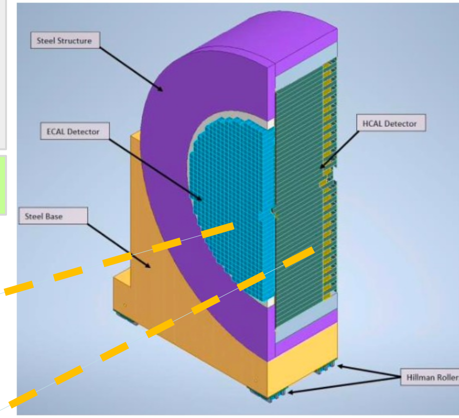
Electron Endcap HCal
Steel/Sc sandwich



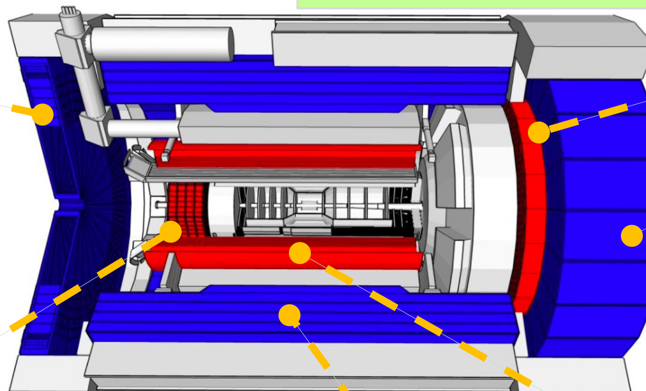
Electron going direction

Hadron Endcap EMCal
High granularity W-powder/SciFi
Hadron Endcap HCal
Longitudinally segmented Steel/Sc

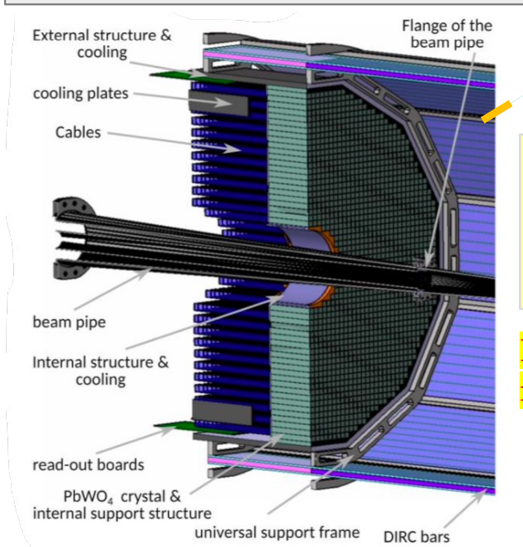
Indian groups interested to contribute



Hadron going direction



Electron Endcap EMCal
- Lead tungstate ($PbWO_4$) crystals



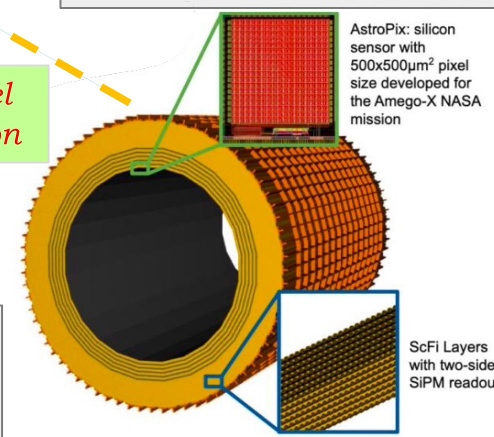
All Calorimeters are readout using SiPM

Indian groups interested in R&D of SiPM

Barrel Region

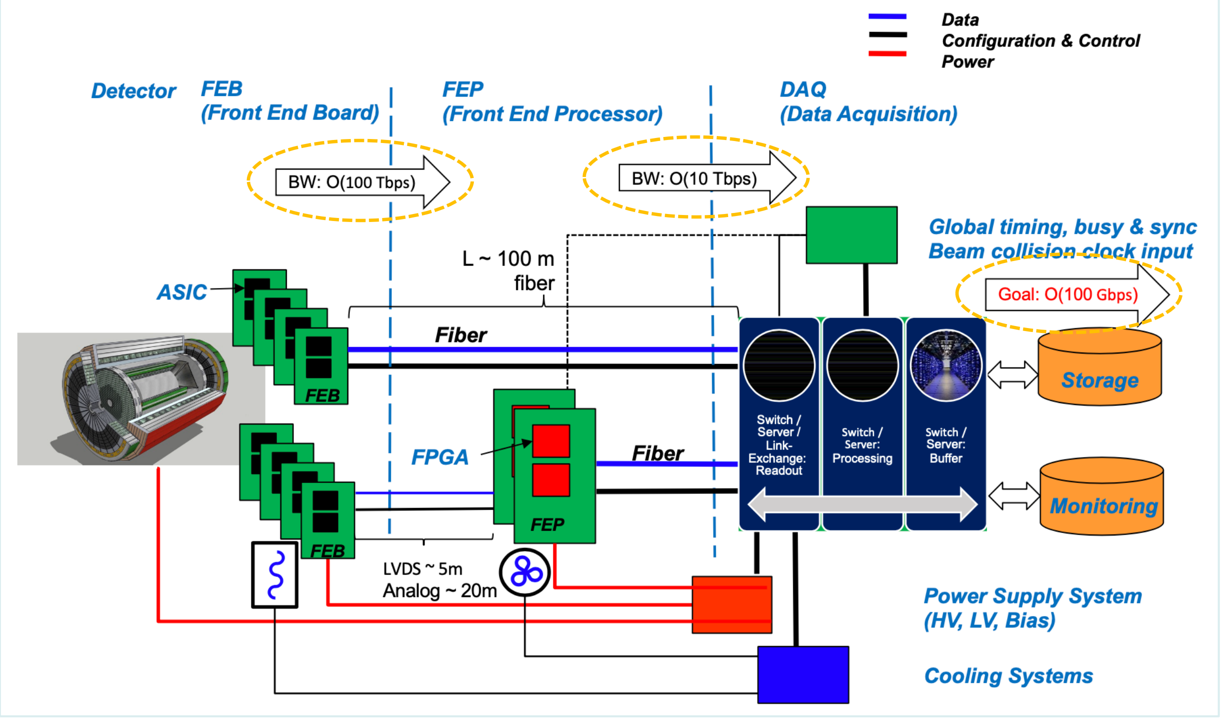
Barrel Hcal:
sPHENIX re-use (with increased granularity)

Barrel Imaging EMCal
Pb/SciFi with a hybrid imaging part (AstroPix Si Sensors)



ePIC Streaming DAQ

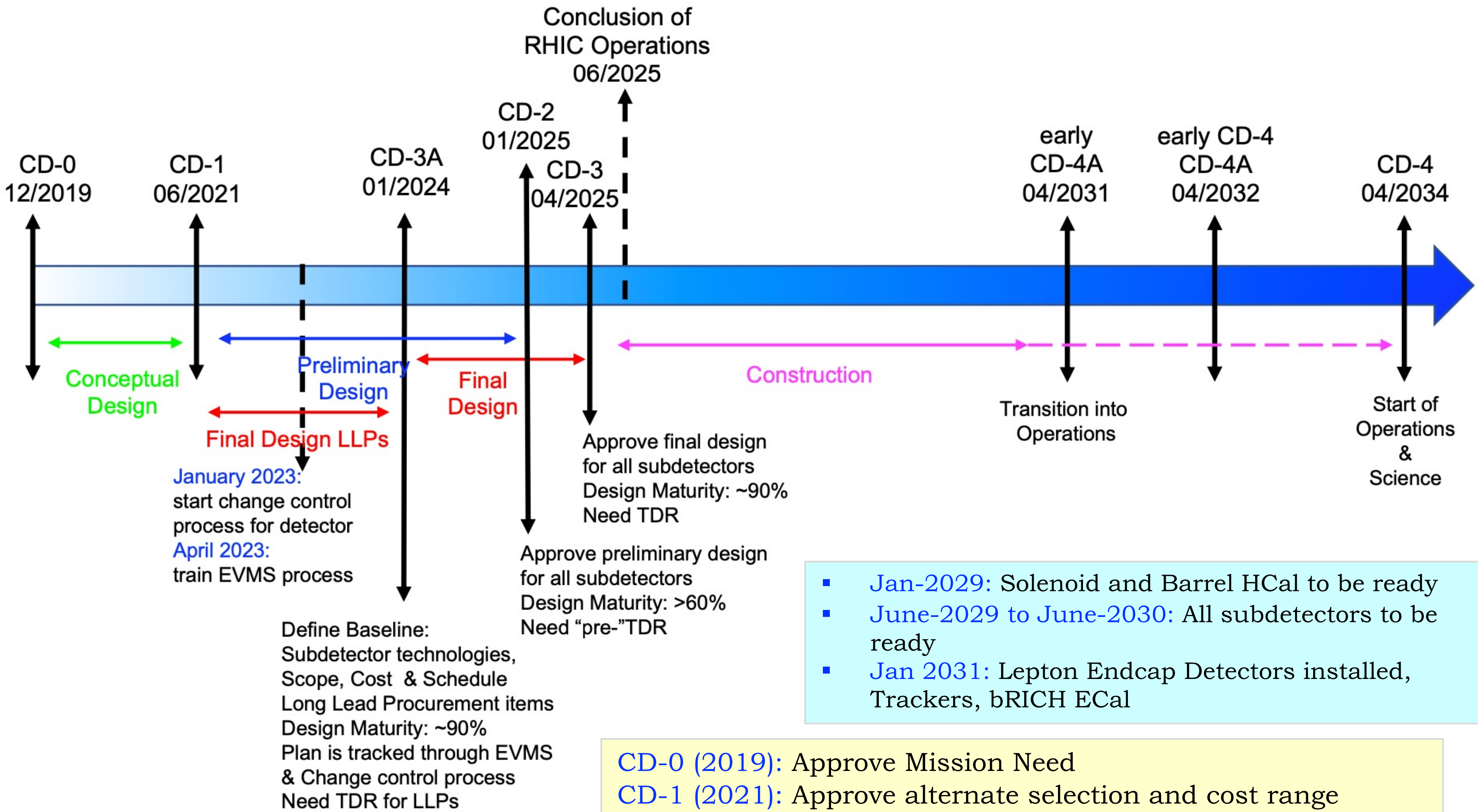
- Triggerless streaming architecture gives much more flexibility to do physics
- Integrate AI/ML as close as possible to subdetectors → cognizant Detector



- No external trigger
- All collision data digitized but aggressively zero suppressed at FEB
- Low / zero deadtime
- Event selection can be based upon full data from all detectors (in real time, or later)
- Collision data flow is independent and unidirectional-> no global latency requirements
- Avoiding hardware trigger avoids complex custom hardware and firmware
- Data volume is reduced as much as possible at each stage

Indian groups interested to contribute

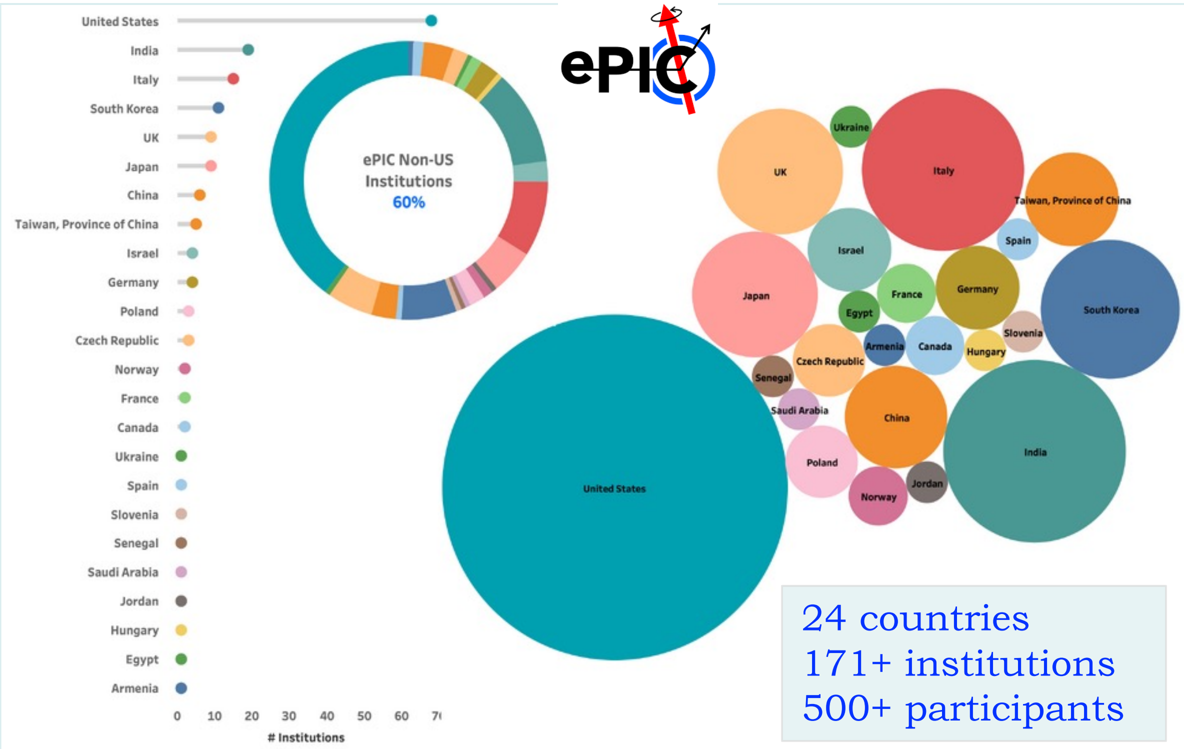
EIC Project Schedule



- Jan-2029: Solenoid and Barrel HCal to be ready
- June-2029 to June-2030: All subdetectors to be ready
- Jan 2031: Lepton Endcap Detectors installed, Trackers, bRICH ECal

CD-0 (2019): Approve Mission Need
CD-1 (2021): Approve alternate selection and cost range
CD-2 (2025): Approve performance baseline
CD-3 (2025): Approve start of construction or execution
CD-4 (2034): Approve start of operations & project completion

The ePIC Collaboration



EIC (ePIC) - India

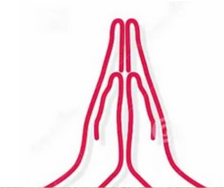
You are welcome to join this exciting Science endeavor!

ePIC-wiki: https://wiki.bnl.gov/EPIC
EICUG: https://www.eicug.org/
EIC-India: eic_india@googlegroups.com

Summary

Electron Ion Collider (ePIC)

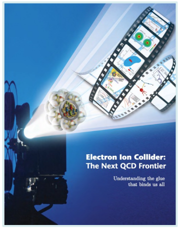
- EIC is a QCD laboratory for discovery science
- ePIC is a new Collaboration formed in 2022 – extraordinary progress since one year
- Consolidation and Optimization of detector layout – almost mature & use innovative technologies
- Progress being made towards key milestone: Technical Design Report for CD3 approval



Acknowledgement:
ePIC Collaboration

Back-up

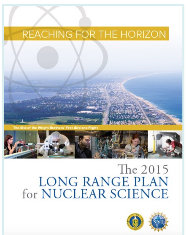
Timeline & Steps Towards 1st Detector



2012-14: EIC White Paper

2015: NSAC Long-Range Plan

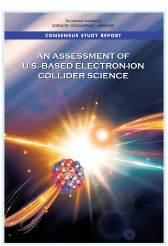
NSAC: Nuclear Science Advisory Committee

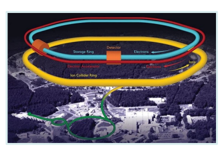


2016: EICUG Formation

2018: NAS Study & Report

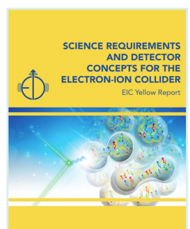
NAS: National Academy of Sciences



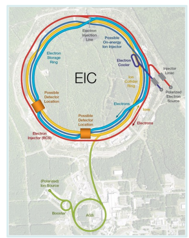


2019-20: CD-0/Site Selection

2021: Yellow Report

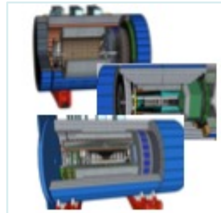


2021: CDR & CD-1



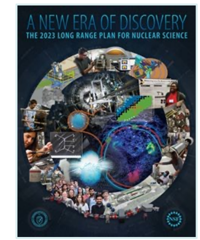
2022: DPAP Review (ATHENA, CORE, ECCE)

DPAP: Detector Proposal Advisory Panel



2022: ECCE as 1st detector; ePIC Collaboration

2023: NSAC Long-Range Plan



electron Proton Ion Collider (ePIC) collaboration progressing well:

- *1st ePIC Collaboration meeting: July 26-29, 2022*
- *ePIC charter approval: Dec. 2022*

Concrete efforts on Indian participation started in 2020

Beam Energies, Parameters

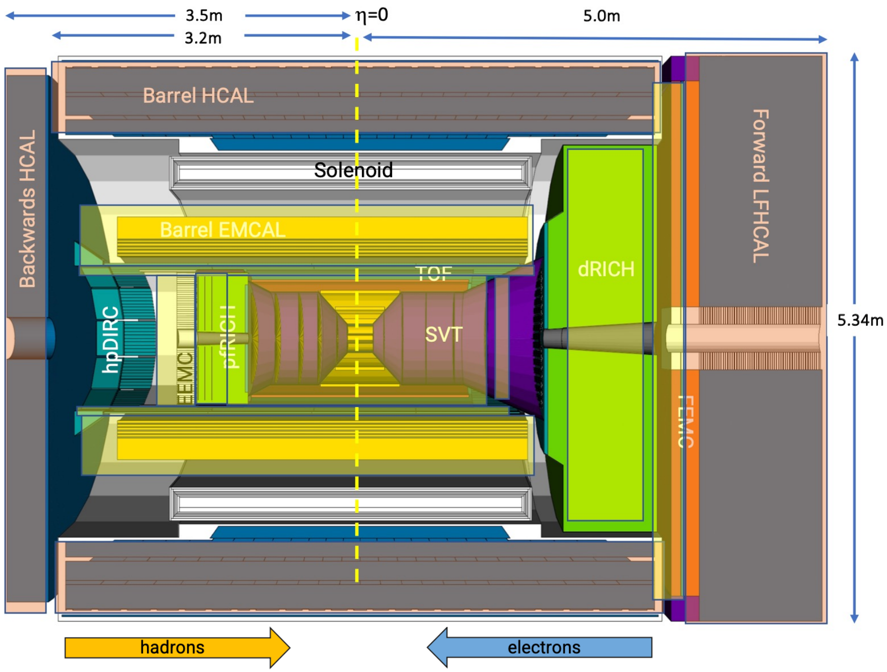
Species	p	e	p	e	p	e	p	e	p	e
Beam energy [GeV]	275	18	275	10	100	10	100	5	41	5
$\sqrt{s}$ [GeV]	140.7		104.9		63.2		44.7		28.6	
No. of bunches	290		1160		1160		1160		1160	
	High divergence configuration									
RMS $\Delta\theta$, h/v [μrad]	150/150	202/187	119/119	211/152	220/220	145/105	206/206	160/160	220/380	101/129
RMS $\Delta p/p$ [10^{-4}]	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8	10.3	6.8
Luminosity [10^{33}cm^{-2}s^{-1}]	1.54		10.00		4.48		3.68		0.44	
	High acceptance configuration									
RMS $\Delta\theta$, h/v [μrad]	65/65	89/82	65/65	116/84	180/180	118/86	180/180	140/140	220/380	101/129
RMS $\Delta p/p$ [10^{-4}]	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8	10.3	6.8
Luminosity [10^{33}cm^{-2}s^{-1}]	0.32		3.14		3.14		2.92		0.44	

Table 10.1: Beam parameters for e+p collisions for the available center-of-mass energies $\sqrt{s}$ with strong hadron cooling. Luminosities and beam effects depend on the configuration. Values for high divergence and high acceptance configurations are shown.

Species	Au	e	Au	e	Au	e	Au	e
Beam energy [GeV]	110	18	110	10	110	5	41	5
$\sqrt{s}$ [GeV]	89.0		66.3		46.9		28.6	
No. of bunches	290		1160		1160		1160	
	Strong hadron cooling							
RMS $\Delta\theta$, h/v [μrad]	218/379	101/37	216/274	102/92	215/275	102/185	275/377	81/136
RMS $\Delta p/p$ [10^{-4}]	6.2	10.9	6.2	5.8	6.2	6.8	10	6.8
Luminosity [10^{33}cm^{-2}s^{-1}]	0.59		4.76		4.77		1.67	
	Stochastic cooling							
RMS $\Delta\theta$, h/v [μrad]	77/380	109/38	136/376	161/116	108/380	127/144	174/302	77/77
RMS $\Delta p/p$ [10^{-4}]	10	10.9	10	5.8	10	6.8	13	6.8
Luminosity [10^{33}cm^{-2}s^{-1}]	0.14		2.06		1.27		0.31	

Table 10.2: Beam parameters for e+Au collisions for the available center-of-mass energies $\sqrt{s}$. Luminosities and beam effects depend on the cooling technique. Values for strong hadronic and stochastic cooling are shown.

The Central Region



Tracking:

- New 1.7T solenoid
- Si MAPS Tracker
- MPGDs (μRWELL/μMegas)

PID:

- High Performance DIRC (hpDIRC)
- Proximity Focused RICH (pfRICH)
- Dual-Radiator RICH (dRICH)
- AC-LGAD (~30ps TOF)

Calorimetry:

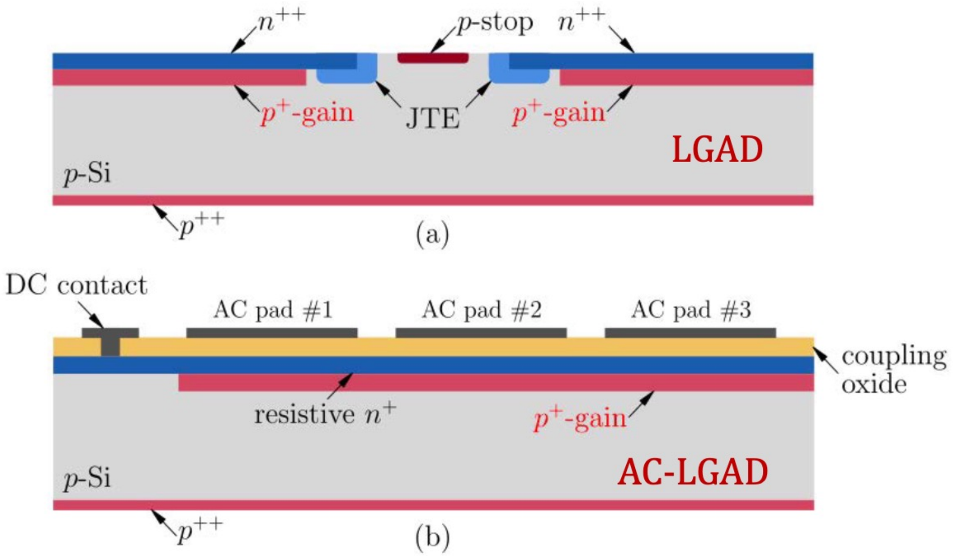
- Imaging Barrel EMCal
- $PbWO_4$ EMCal in backward direction
- Finely segmented EMCal + HCal in forward direction
- Outer HCal (sPHENIX re-use)
- Backwards HCal (tail-catcher)

MAPS: Monolithic Active Pixel Sensor
MPGD: Micropattern Gaseous Detector
LGAD: Low Gain Avalanche Detector

AC-LGAD

LGAD: Low Gain Avalanche Detector

Novel silicon technology -- allowed timing resolution of few tens of picoseconds for number of particle tracks emerging from the interaction regions in high energy physics experiments



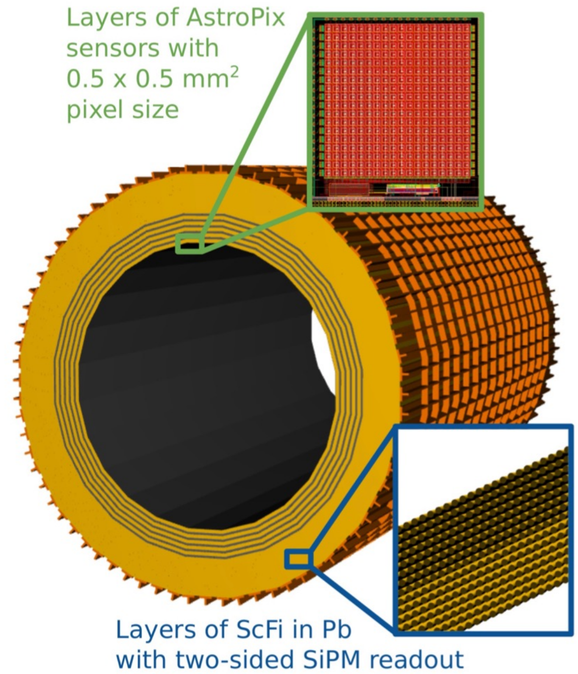
Due to the presence of Junction Termination Edges (JTE) and the gap between LGAD cells, 100% fill factor can not be achieved in LGAD.

AC-LGAD: replacement of the segmented n++ layer by a less doped but continuous n+ layer. Electrical signals in the n+ layer are AC-coupled to neighboring metal electrodes that are separated from the n+ layer by a thin insulator layer.

AC-LGAD not only provides a timing resolution of a few tens of picoseconds, but also 100% fill factor and a spatial resolution that are orders of magnitude smaller than the cell size. Therefore, it is a good candidate for 4D detectors at future high energy experiments.

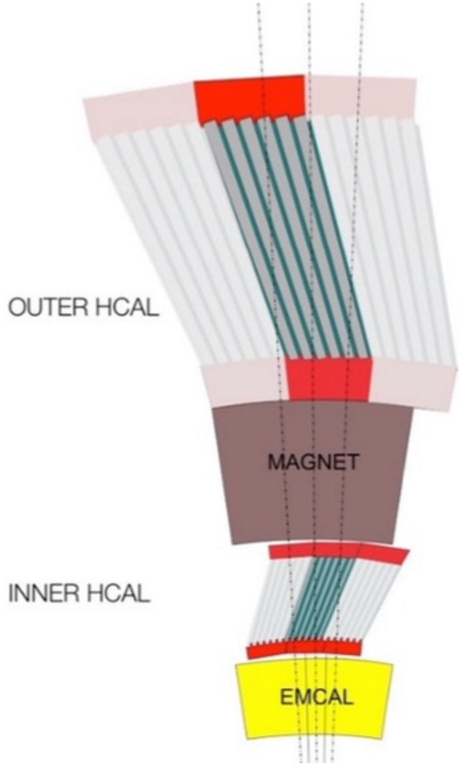
Barrel EM Calorimetry

- **Hybrid concept**
  - Imaging calorimetry based on monolithic silicon sensors AstroPix (NASA's AMEGO-X mission) - 500 µm x 500 µm pixels Nuclear Inst. and Methods in Physics Research, A 1019 (2021) 165795
  - Scintillating fibers in Pb (Similar to GlueX Barrel ECal, 2-side readout w/ SiPMs) Nuclear Inst. and Methods in Physics Research, A 896 (2018) 24-42
- 6 layers of imaging Si sensors interleaved with 5 Pb/ScFi layers and followed by a large chunk of Pb/ScFi section (can be extended to inner HCAL)
- Total radiation thickness for EMCAL of ~20 X_0
- Detector coverage: $-1.7 < \eta < 1.3$ which overlaps with "electron-going" side endcap



Energy resolution - SciFi/Pb Layers: $5.3\% / \sqrt{E} \oplus 1.0\%$
Position resolution - Imaging Layers (+ 2-side SciFi readout): with 1st layer hit information ~ pixel size

Barrel Hadronic Calorimetry



Reuse of sPHENIX outer (outside of the Solenoid) HCal ≈ 3.5λ_I

- Steel and scintillating tiles with wavelength shifting fiber
- $\Delta\eta \times \Delta\phi \approx 0.1 \times 0.1$
  (1,536 readout channels, SiPMs)