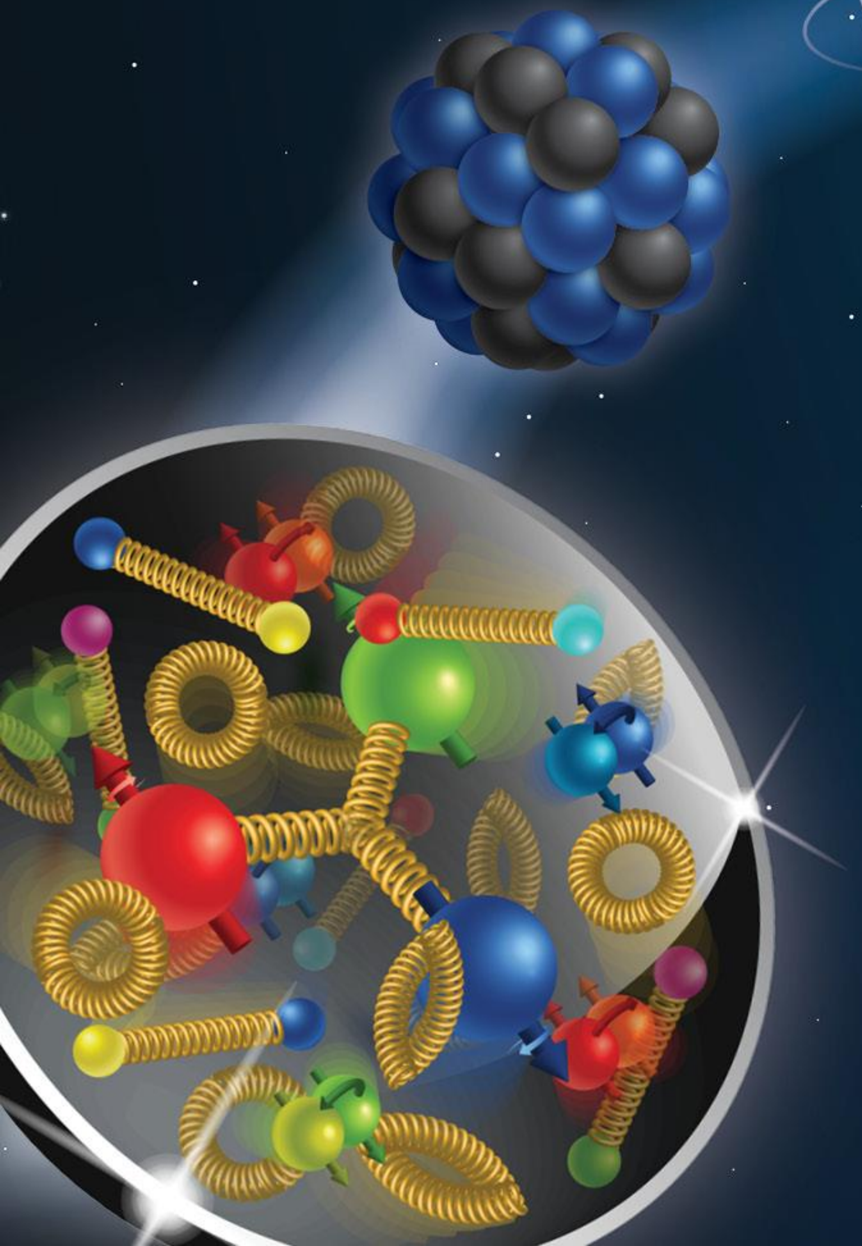
What is the EIC?

An Introduction



Elke-Caroline Aschenauer (BNL)

BROOKHAVEN NATIONAL LABORATORY · Jefferson Lab · U.S. DEPARTMENT OF ENERGY | Office of Science

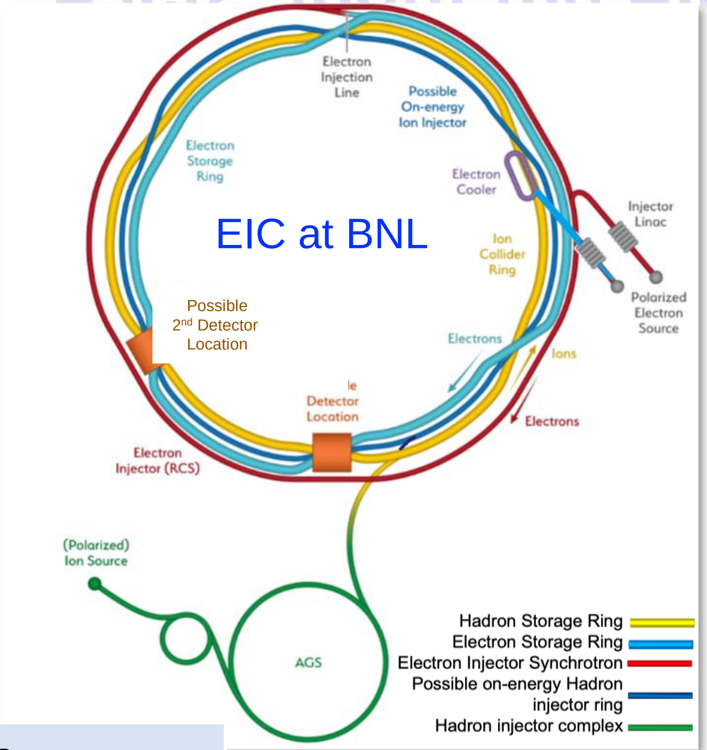
Facts about the EIC

What is the EIC:

A high luminosity ($10^{33} – 10^{34}$ $cm^{-2}s^{-1}$) polarized electron proton / ion collider with $\sqrt{s_{ep}}$ = 28 – 140 GeV

What is new/different:

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



Double Ring Design Based on Existing RHIC Facilities	
Hadron Storage Ring: 40 - 275 GeV	**Electron Storage Ring: 5 - 18 GeV**
RHIC Ring and Injector Complex: p to Pb	1160 bunces, Large Beam Current - 2.5 A
1160 bunces @ 1A Beam Current	9 MW Synchrotron Radiation
9 ns bunch spacing	
Light ion beams (p, d, ^{3}He) polarized (L,T)	Polarized electron beams
Nuclear beams: d to U	**Electron Rapid Cycling Synchrotron**
Requires Strong Cooling: new concept →CEC	Spin Transparent Due to High Periodicity
High Luminosity Interaction Region(s)	
25 mrad Crossing Angle with Crab Cavities	

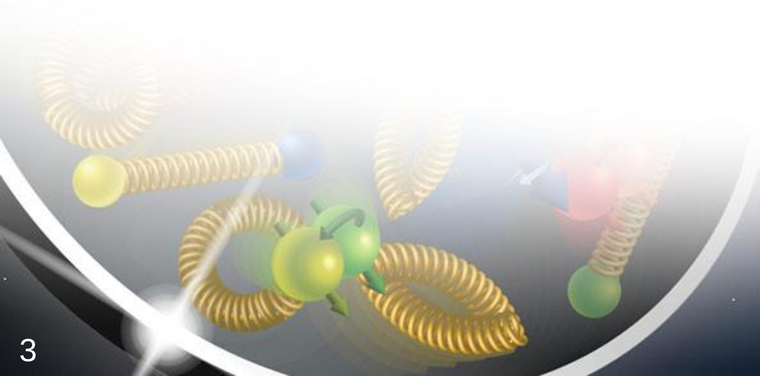
https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf

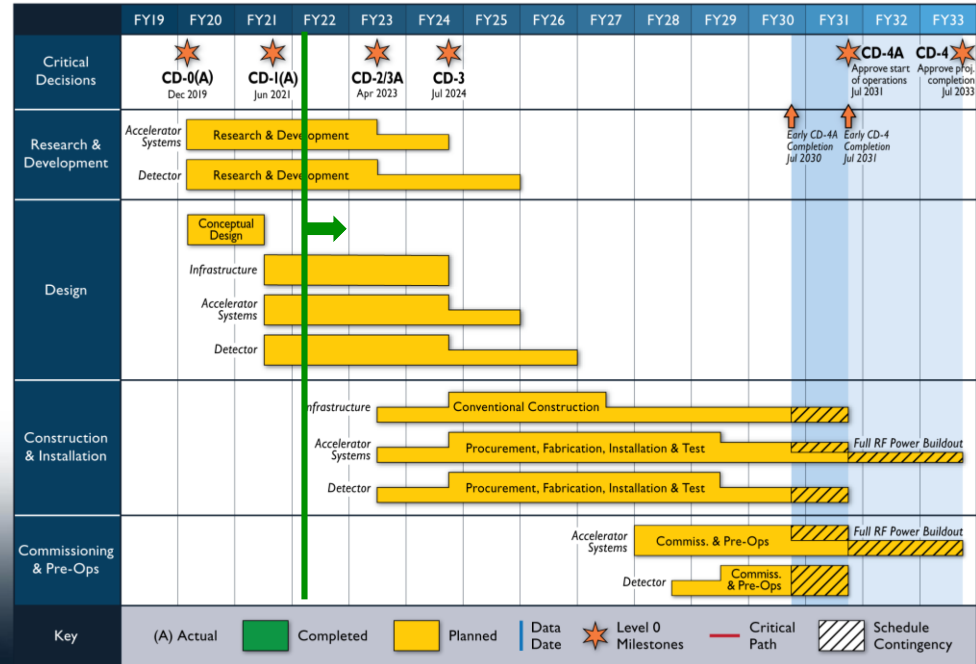
EIC Project Status

January 2020: CD-0 & site selection → BNL

June 28th 2021: EIC received CD-1

Accelerator Technical Reviews	Spring -- Autumn 2021	
Start Preliminary Design	April 2021	
Detector Proposals Submitted	December 2021	
Selection of Project Detector	March 2022	
Start Earned Value Tracking	Summer 2022	
Clarify In-kind Deliverables - Agreements	Summer/Fall 2022	
Goal for CD-2 Approval	April 2023	Baselining the project
Goal for CD-3 Approval	July 2024	Start of Construction
Goal for CD-4 Early Project Completion	**July 2031**	Early Start of Operation





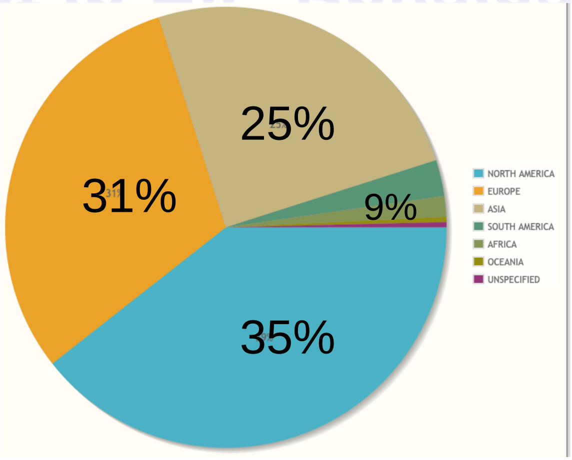
Worldwide Interest in EIC Physics

The EIC Users Group: EICUG.ORG

Formed 2016

November 2021: 1298 collaborators 36 countries, 264 institutions (Exp. 799, Theorists 324, Acc. Sci. 161),

- Size of EICUG has continuously grown since its formation, especially after the award of CD0 / site-selection.
- Expect growth to continue through the phases of the EIC project.



Map of institution's locations

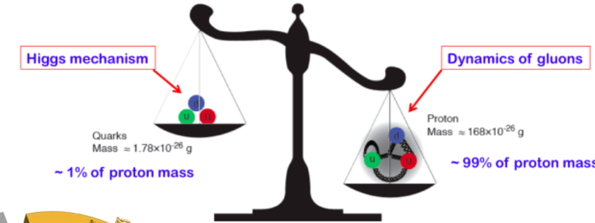
Experimental Program Activities:

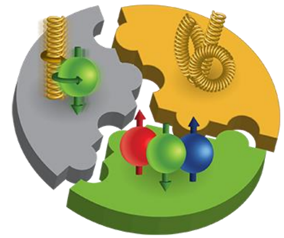
- BNL and TJNAF Jointly Leading Process to Select Project Detector
- 2020:
  - Call for Expressions of Interest (EOI) https://www.bnl.gov/eic/EOI.php
- 2021:
  March 2021:
  - Call for Collaboration Proposals for Detectors https://www.bnl.gov/eic/CFC.php
    Deadline: 1st of December
  - Decision on Project Detector March 2022
- Formation of 3 proto-collaborations started right after call was issued
  - ATHENA (https://sites.temple.edu/eicatip6/)
  - CORE (https://eic.jlab.org/core/)
  - ECCE (https://www.ecce-eic.org)

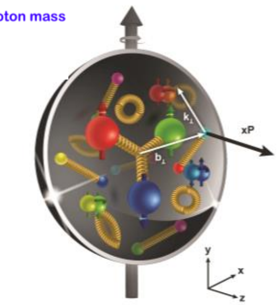
The EIC Physics

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?







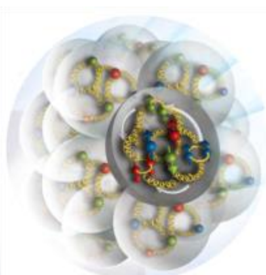
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

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

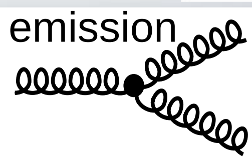
How do the quark-gluon interactions create nuclear binding?

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?

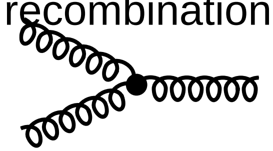


gluon emission



$\stackrel{?}{=}$

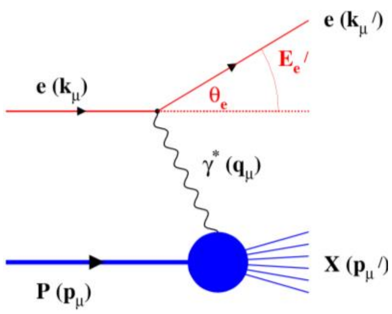
gluon recombination

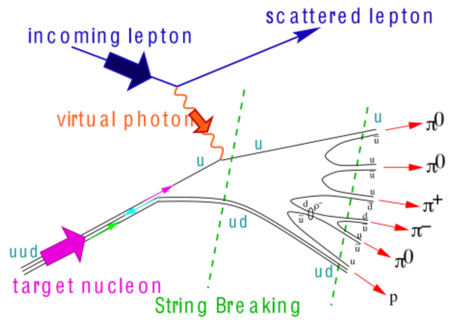


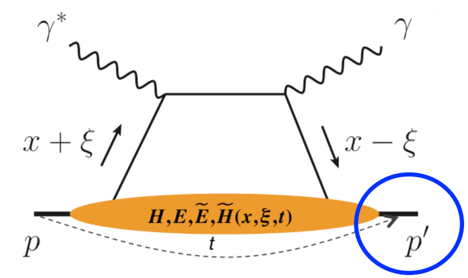
What is needed experimentally?

experimental measurements categories to address EIC physics:

Parton Distributions in nucleons and nuclei | **QCD at Extreme Parton Densities - Saturation** | **Spin and Flavor structure of nucleons and nuclei** | **Tomography Transverse Momentum Dist.** | **QCD at Extreme Parton Densities - Saturation** | **Tomography Spatial Imaging**







inclusive DIS

- measure scattered lepton

→ event kinematics
  - → e-ID: e/h separation
  - → reach to lowest x, Q^2 impacts Interaction Region design

semi-inclusive DIS

- measure scattered lepton and hadrons in coincidence
- multi-dimensional binning: x, Q^2, z, p_T, Θ
  - → particle identification over entire kinematic region is critical
  - → Jets: excellent E_T, jet-energy scale

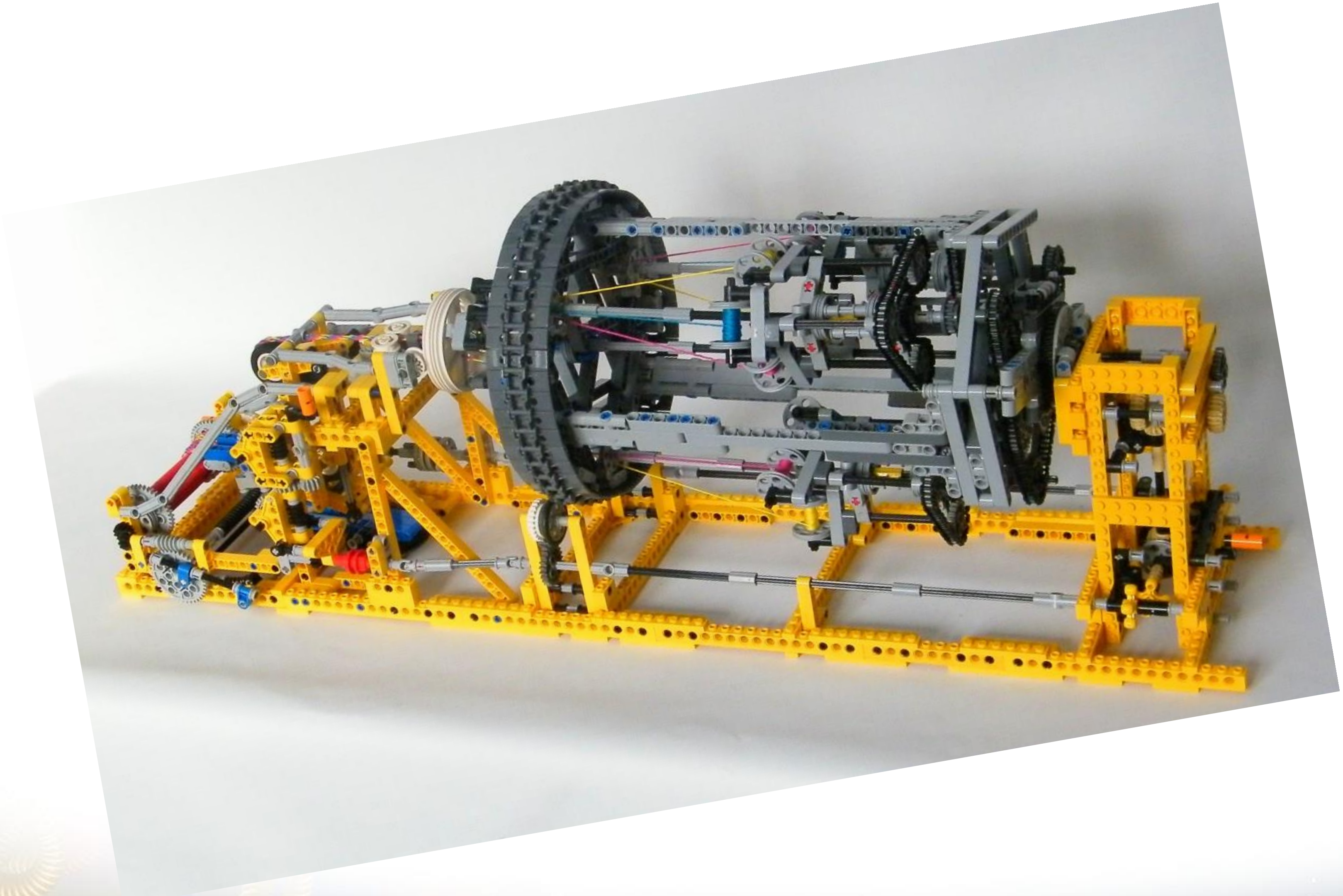
exclusive processes

- measure all particles in event
- multi-dimensional binning: x, Q^2, t, Θ
- proton p_t: 0.2 - 1.3 GeV
  - → cannot be detected in main detector
  - → strong impact on Interaction Region design

$\int Ldt$: 1 fb^{-1} | 10 fb^{-1} | 10 - 100 fb^{-1}

machine & detector requirements

EIC Detector Concept



The EIC: A Unique Collider

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: >= 9ns

crossing angle: 25mrad

wide range in center of mass energies
→ factor 6

both beams are polarized
→ stat uncertainty: $\sim 1/(P_1 P_2 (\int L\, dt)^{1/2})$

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 ns

no significant crossing angle yet (150 μrad 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: $\sim 1/(\int L\, dt)^{1/2}$

Differences impact detector acceptance and possible detector technologies

Important to note:

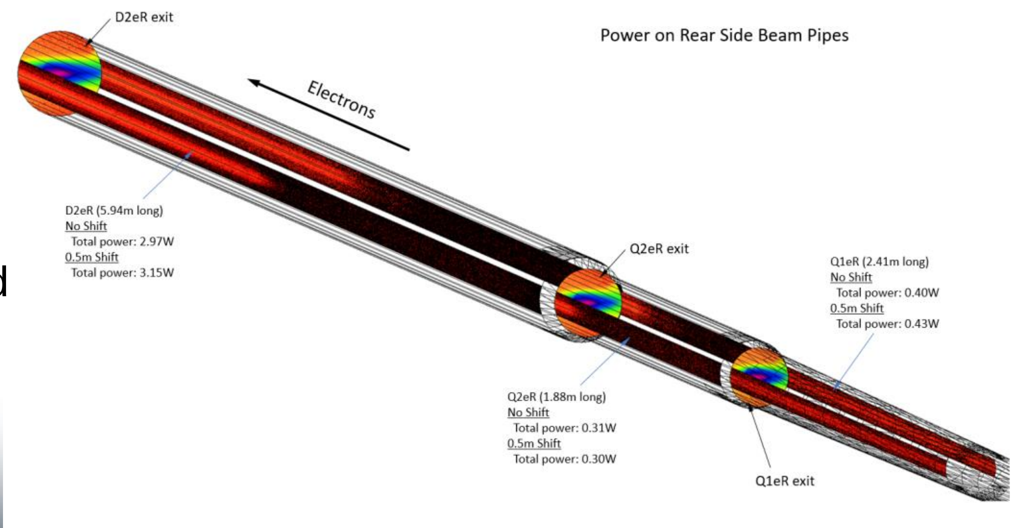
- low multiplicity per event: < 10 tracks
- $\eta > 2$: avg. hadron track momenta @ 141 GeV: ~20 GeV
- No pileup from collisions 500 kHz @10^{34} $cm^{-2}s^{-1}$ → coll. every 200 bunches
- radiation environment much less harsh than LHC → factor 100 less

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

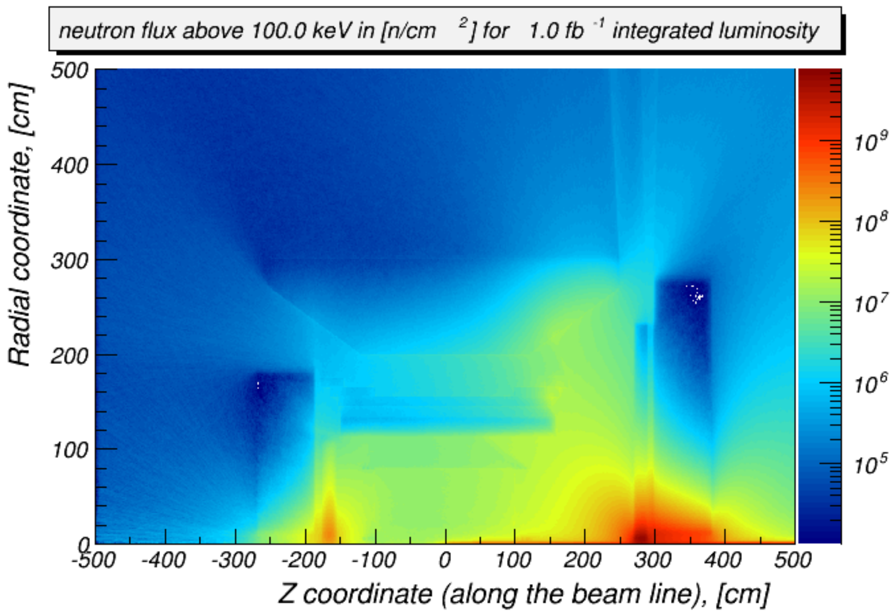
Synchrotron Radiation:

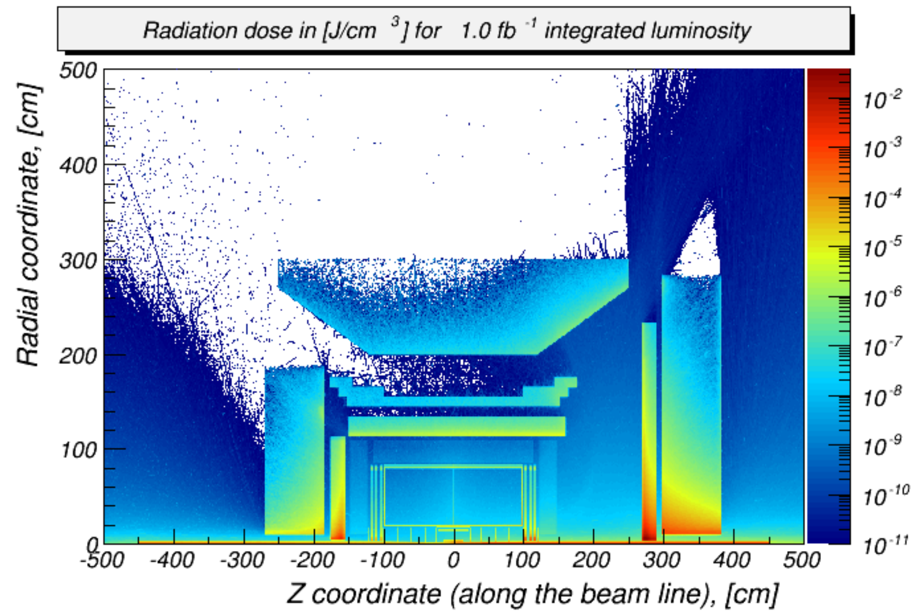
- Origin: quads and bending magnet upstream of IP
- Tails in electron bunches: can produce hard radiation
- Studied using Synrad3D



Background/Radiation

- Primary collisions contribute a substantial fraction of the ionizing radiation and low energy neutron fluence in the experimental hall



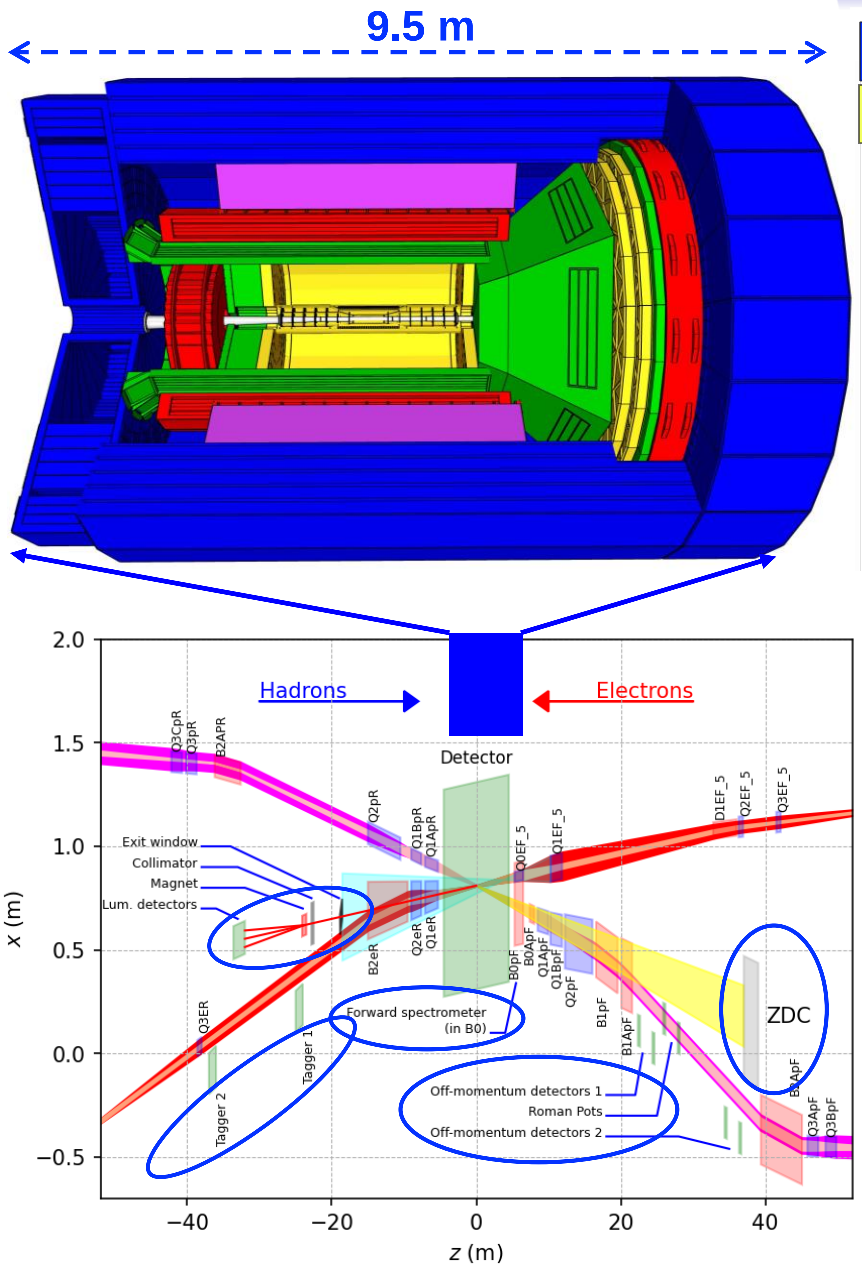


→ forward EmCal: up to ~$5*10^9$ n/cm^2 per fb^{-1} (*inside the towers*); perhaps ~5 less at the SiPM location

→ backward EmCal: ~250 rad/year (at "nominal" luminosity ~10^{33} cm^{-2} s^{-1})

- Beam-gas interactions are one of the main sources of neutrons that thermalize within the detector hall and cause the damage.
- The current FLUKA simulations show that the EIC detector will obtain annual dose of $6*10^{10}$ n/cm^2 (1 MeV equivalent)
  → Impact on SiPMs and Silicon Vertex Tracker → suggested tolerance of 10^{14} n/cm^2

EIC General Purpose Detector



hadronic calorimeters | solenoid coils | e/m calorimeters

MAPS tracker | MPG trackers | ToF, DIRC, RICH detectors

Overall detector requirements:

- 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
    → Integration into IR from the beginning critical
    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
- High control of systematics
  - luminosity monitor, electron & hadron Polarimetry

EICUG: Yellow Report (YR) Initiative

The EIC Users Group: EICUG.ORG
Report: https://arxiv.org/abs/2103.05419

Detector requirements and design driven by EIC Physics program and defined by EIC Community

Physics Topics → Processes → Detector Requirements

Physics Working Group:

Inclusive Reactions
Semi-Inclusive Reactions
Jets, Heavy Quarks
Exclusive Reactions
Diffractive Reactions & Tagging

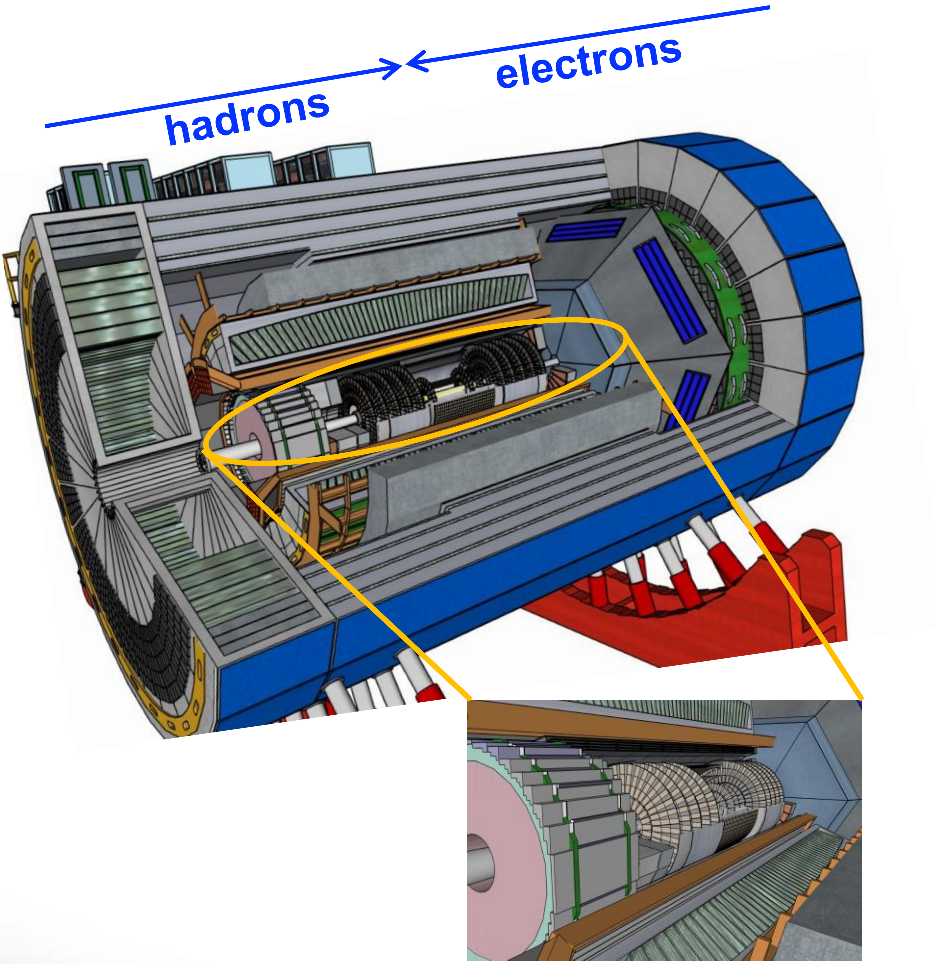
↔

Detector Working Group:

Tracking + Vertexing
Particle ID
Calorimetry
DAQ/Electronics
Polarimetry/Ancillary Detectors
Central Detector: Integration & Magnet
Far- Forward Detector & IR Integration

Provides critical input for detector proposals

EIC General Purpose Detector



YR: EIC general purpose Detector around a new 3T Solenoid

Hermetic coverage:

$2^o < \Theta < 178^o$ ($-4<\eta<4$) with full Φ coverage

→ as close as possible to 4π

Most likely detector technologies further refined by current detector proposal process

https://www.bnl.gov/eic/CFC.php

system	system components	reference detectors
tracking	vertex	MAPS, 20 um pitch
	barrel	TPC
	forward & backward	MAPS, 20 um pitch & sTGCs[c]
	very far forward & far backward	MAPS, 20 um pitch & AC-LGAD[d]
ECal	barrel	W powder/ScFi or Pb/Sc Shashlyk
	forward	W powder/ScFi
	backward, inner	$PbWO_4$
	backward, outer	SciGlass
	very far forward	Si/W
h-PID	barrel	High performance DIRC & dE/dx (TPC)
	forward, high p	double radiator RICH (fluorocarbon gas, aerogel)
	forward, medium p	
	forward, low p	TOF
	backward	modular RICH (aerogel)
e/h separation at low p	barrel	hpDIRC & dE/dx (TPC)
	forward	TOF & areogel
	backward	modular RICH
HCal	barrel	Fe/Sc
	forward	Fe/Sc
	backward	Fe/Sc
	very far forward	quartz fibers/ scintillators

Technologies based on Generic EIC Detector R&D developed by EIC-UG members

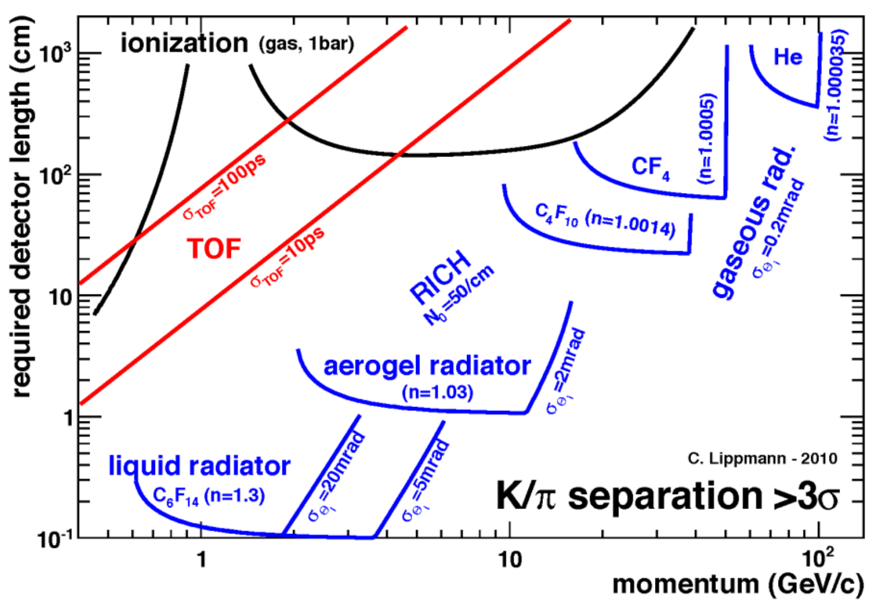
https://wiki.bnl.gov/conferences/index.php/EIC_R%25D

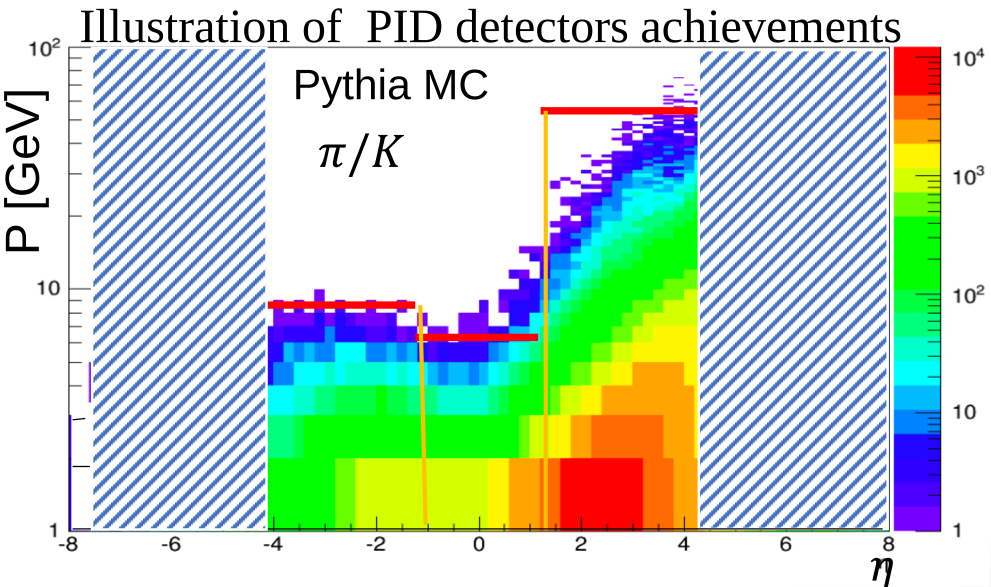
Needs are more demanding than your normal collider detector

needs absolute particle numbers at high purity and low contamination

→ need to separate:

- Electrons from photons → 4π coverage in tracking
- Electrons from charged hadrons → mostly provided by E/p → calorimetry & tracking
- Charged pions, kaons and protons from each other → Cherenkov detectors
  - Cherenkov detectors, complemented by other technologies at lower momenta → ToF





Need more than one technology to cover the entire momentum ranges at different rapidities

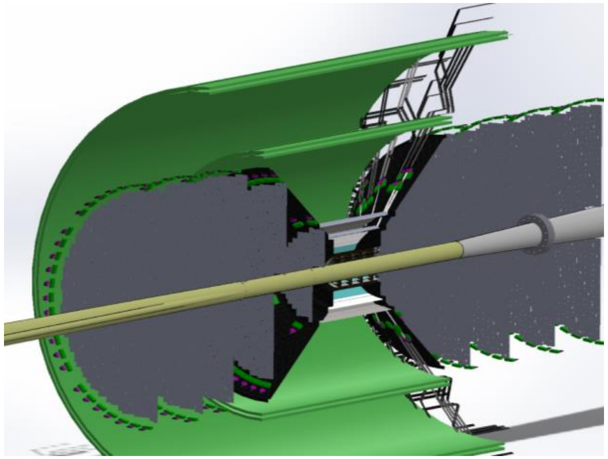
Challenges:

- photon sensors in high magnetic field
  → SiPMs impact on streaming DAQ
- high performance aerogel radiator

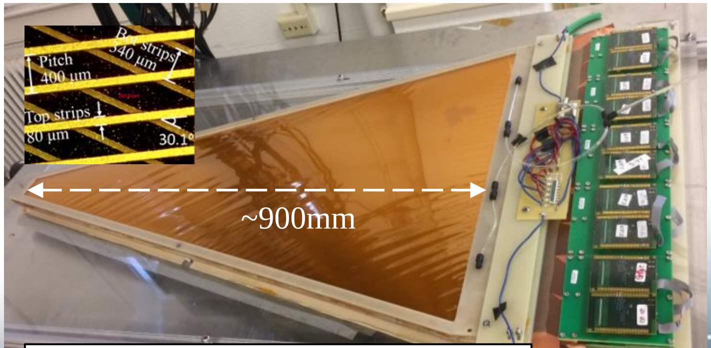
Areas of Possible Synergy: Detector

Tracking:

- Silicon – MAPS
  - already ongoing R&D collaboration with CERN/ALICE ITS development
    - low mass EIC ITS-3 based forward disks new development
  - existing ALPIDE alternative
  - EIC European Groups from UK and Italy



- AC-LGAD
  - EIC triggered the formation of consortium between HEP and NP groups
    - Goal: push technology and readout development for many applications (tracking, ToF, …)
  - EIC European Groups from France
- MPGDs – GEMs
  - GEM foils typically come from CERN for QA
  - clear synergy with CERN RD-51 and ALICE new TPC GEM readout and COMPASS
  - EIC European Groups from Italy



EIC R&D: large 2D GEM module

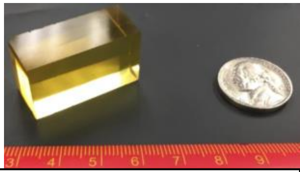
Areas of Possible Synergy: Detector

Photon-Sensors:

- SiPMs:
  - many common generic R&D interest from HEP and NP
    - low noise, improved radiation hardness, large area
  - European Groups from Italy

- LAPPD Photon-Sensors
  - many common generic R&D interest from HEP and NP → CERN LHC-b
    - pixilation, decreased B-field sensitivity, reduced cost
  - EIC European Groups from Italy
  - ARGONNE - LDRDs and US SBIR program to support the R&D

Example: SCI glass

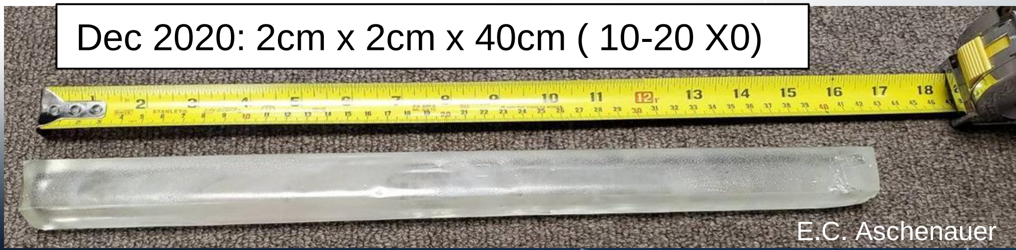


2019: 2cm x 2cm x 4cm

Feb 2020: 2cm x 2cm x 20cm (7 X0)

Calorimetry:

- Glass-based calorimetry:
  - many common generic R&D interest from HEP and NP for compact high resolution, low-cost electromagnetic and hadronic calorimetry
  - US SBIR program to support the R&D

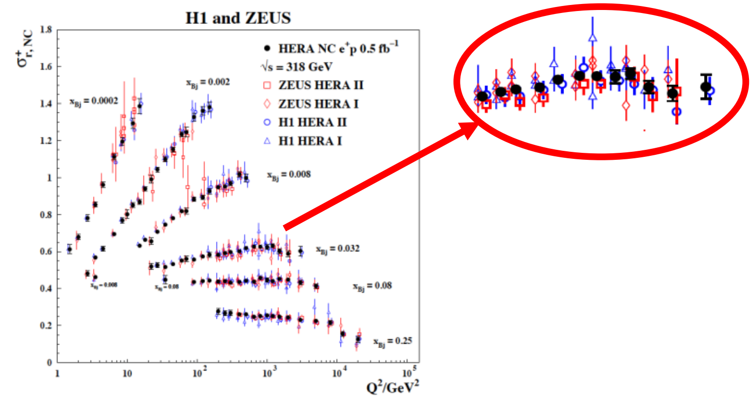


Dec 2020: 2cm x 2cm x 40cm (10-20 X0)

2nd Detector: Complementary is Key

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

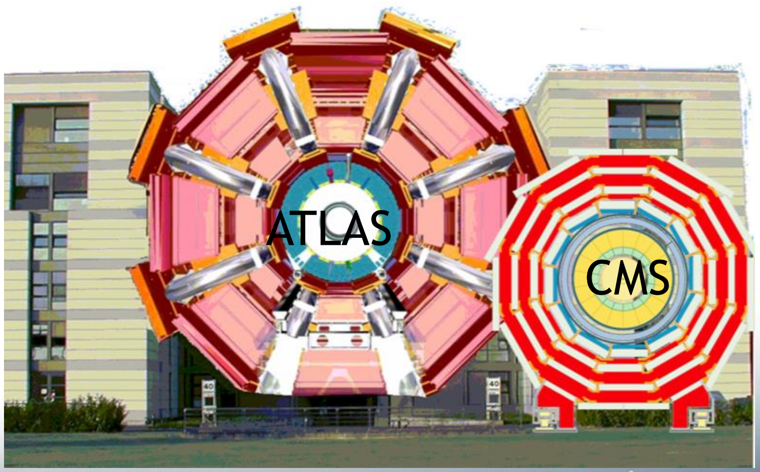


- **Cross Calibration**
  - Combining data gave well beyond the √2 statistical improvement …
  - Different dominating H1, ZEUS systematics…
  - Effectively use H1 electrons with ZEUS hadrons

    … 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**

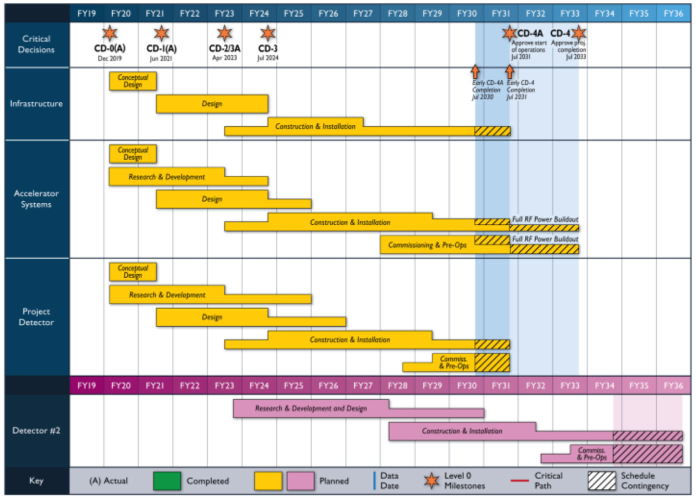
  ... EIC has unusually broad physics program (from exclusive single particle production to high multiplicity eA or γA with complex nuclear fragmentation)

  → Impossible to optimize for the full program in a single detector.

  → Impact on IR design

Enhance 2nd IR complementarity: Nb_3Sn-Magnets

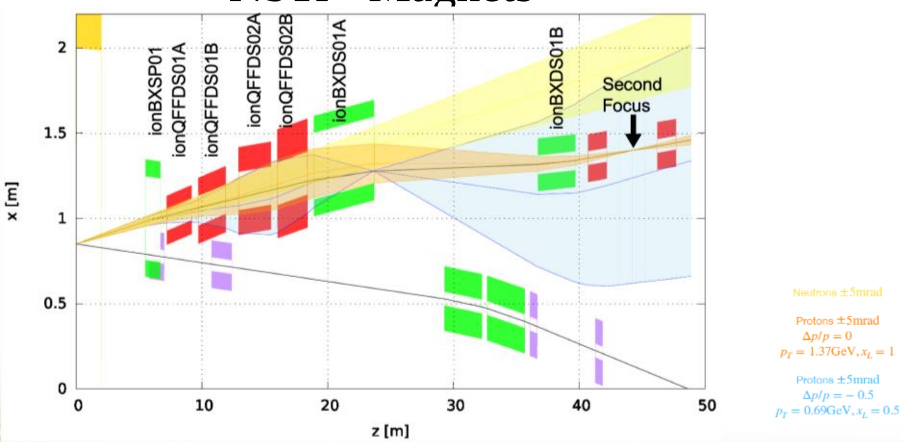
2nd IR: 35 mrad crossing angle & secondary focus
Investigate Nb_3Sn magnets:
allow higher gradients → shorter L* → higher luminosity → compact IR
→ easier matching to existing RHIC arcs
→ technology challenge
  - → Crosstalk: Greater crossing angle but shorter quadrupoles and stronger fields. NbTi version has 4 magnets at nearly full strength.

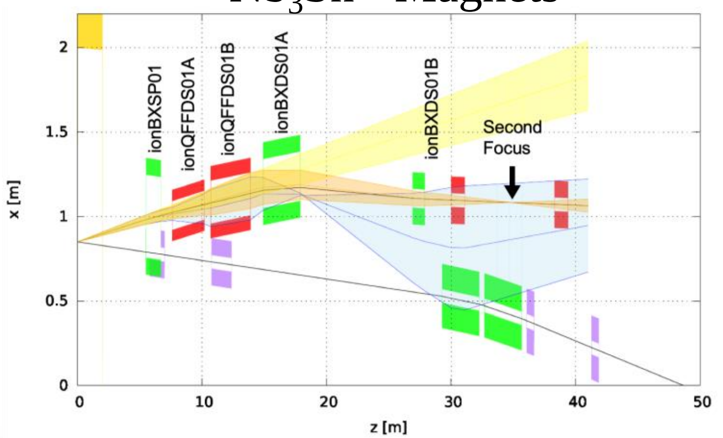


Present 2nd IR pre-conceptual design
NbTi - Magnets

→

2nd IR pre-conceptual design – v1
Nb_3Sn - Magnets





- Split ionQFFDS01A in 2 → Three magnets working as a doublet with the third powered off at low energy operation.
- Can reach smaller β* with same β_{max} at low energies due to shorter focal length.
- Allows to tailor the apertures for acceptance better.

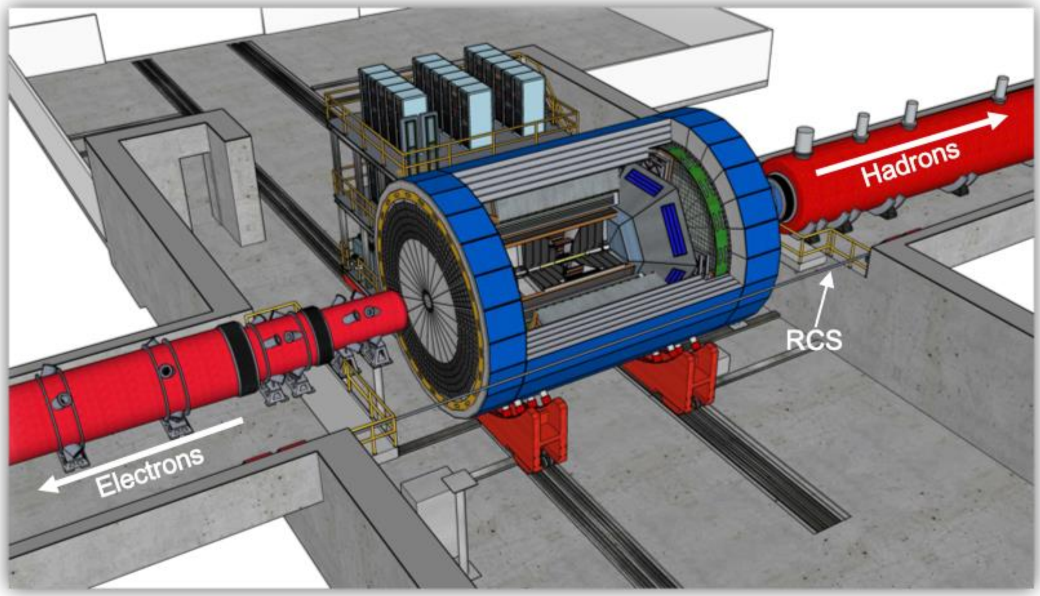
Summary

- Synergies with Accelerator R&D not covered

- Many synergies between EIC Detector R&D and CERN EP RD program
  - Si based tracking
  - Calorimetry
  - MPGDs
  - PID
  - Electronics
  - Computing & Software

discussed in detail in next talks

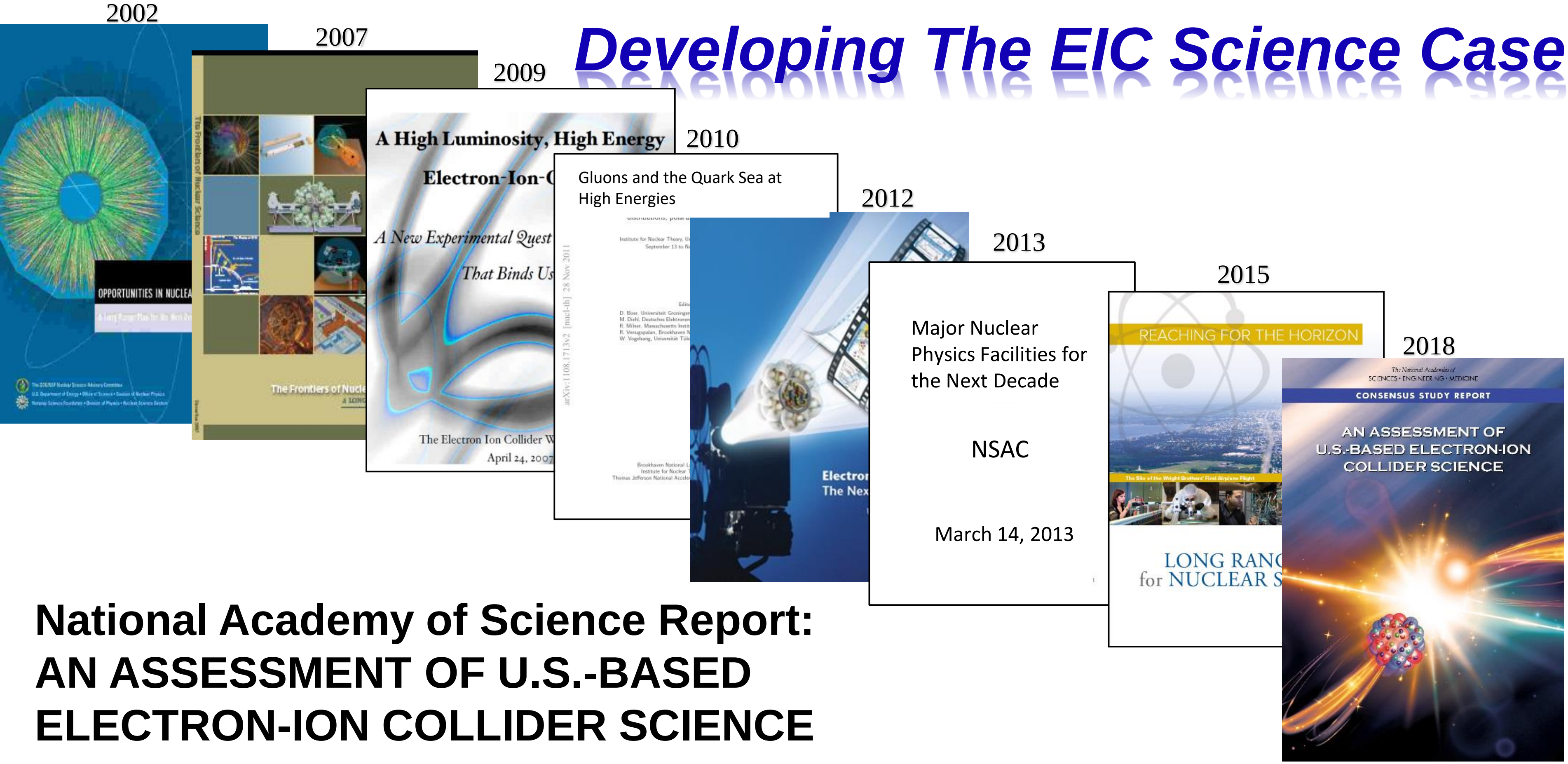
- New magnet technologies, i.e. Nb_3Sn could enhance 2nd IR performance and complementarity



Synergies with LHC science program
- high precision proton & nuclear PDFs
- 3d (momentum and spatial) nucleon and nuclei structure
  → precision determination of initial conditions of QGP studies
- QCD non-linear effects


BACK UP

Developing The EIC Science Case

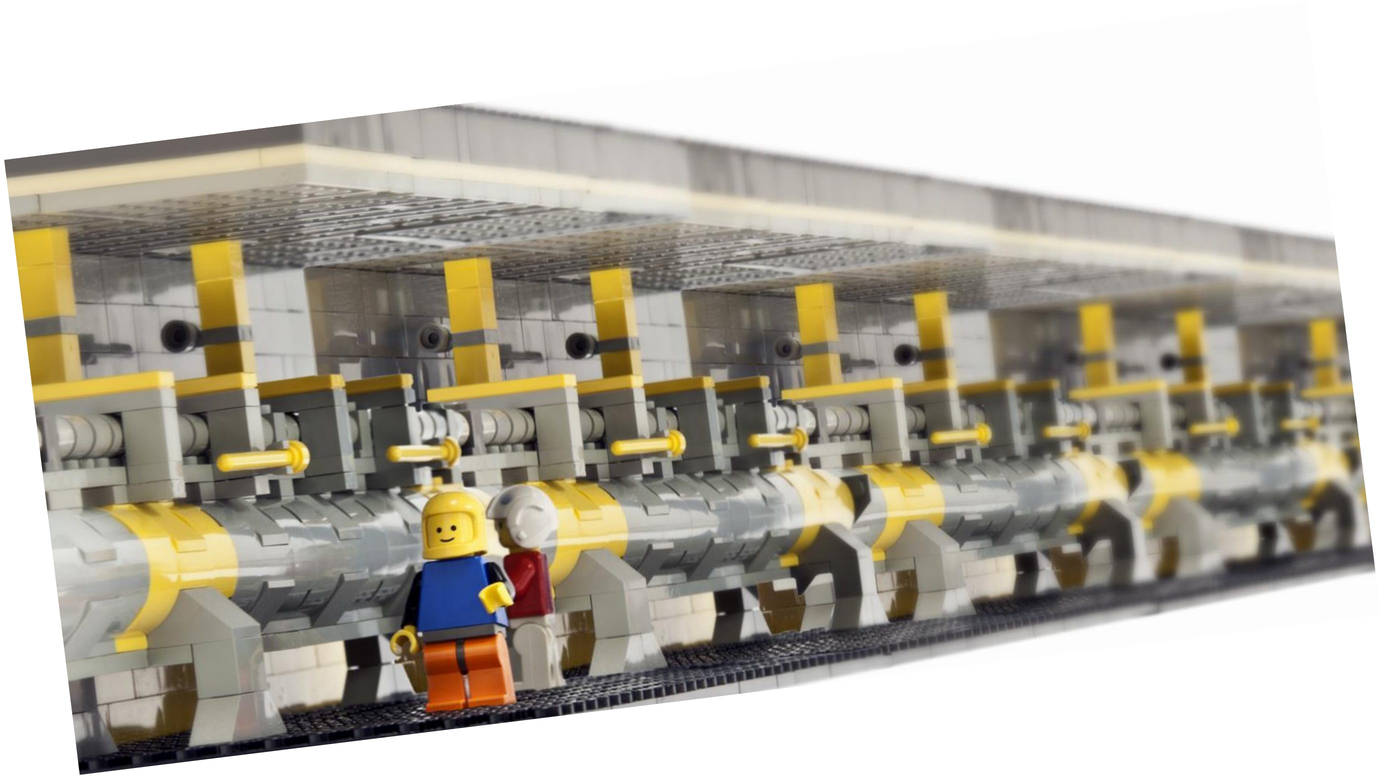


National Academy of Science Report:
AN ASSESSMENT OF U.S.-BASED ELECTRON-ION COLLIDER SCIENCE

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

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

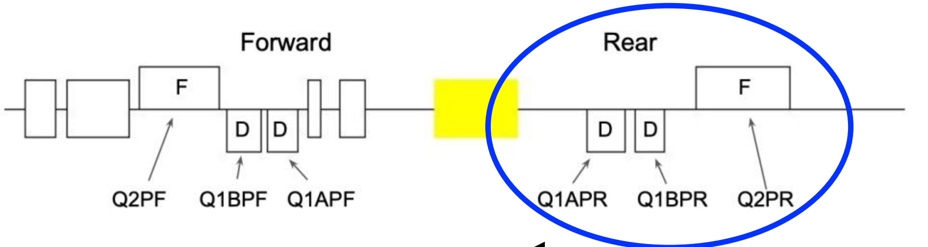
The EIC Accelerator

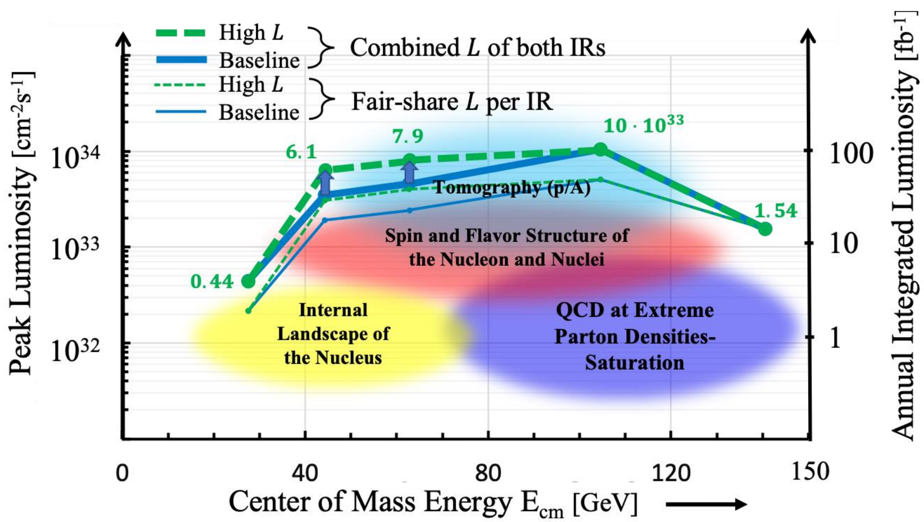


Progress: Luminosity at lower E_{cm}

- Simplest way change focusing scheme of final focusing quads
  - Advantage independent of Interaction Region → can be done both at IP-6 and/or IP-8

change polarity of quads DDF to FDF
→ needs to be done only on the rear side (incom hadron beam) hadron quads
→ change polarity of quads at low E_{CM}

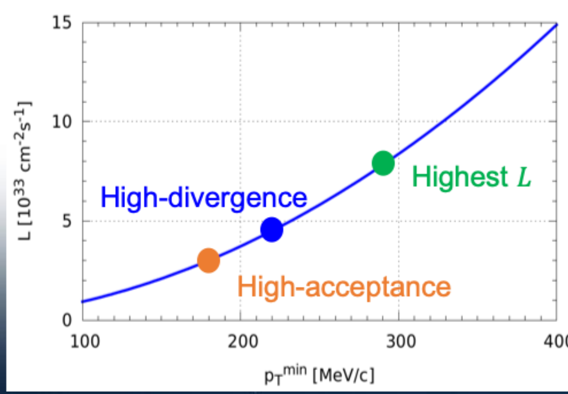




But nothing is for free, there is a direct impact on the low p_T acceptance for forward scattered particles ~β (at RP) x beam divergency σ'^*

Luminosity increases if β* ↓ & σ'^*↑

Highest luminosity → smallest low p_T acceptance at far forward



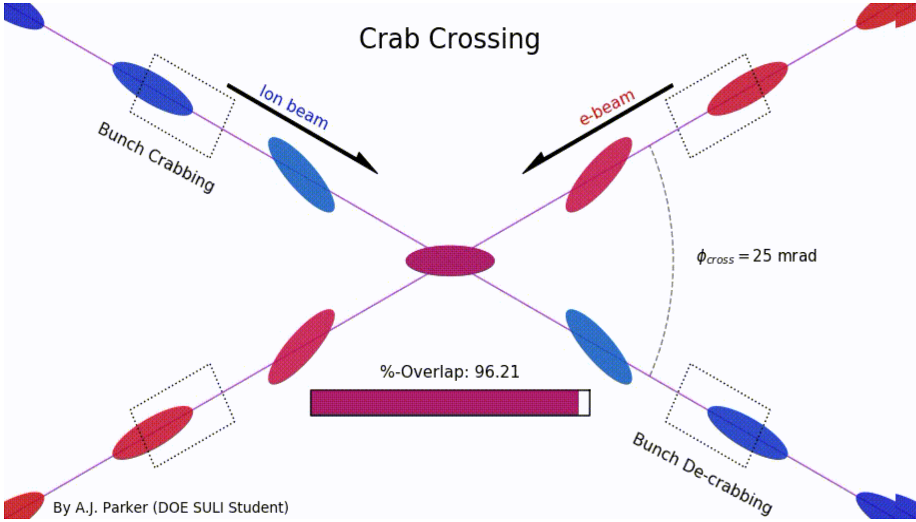
Why a Crossing Angle

- ❑ Brings focusing magnets close to IP
  → high luminosity
- ❑ Beam separation without separation dipoles
  → reduced synchrotron radiation

But significant loss of luminosity

Solution: Crab crossing

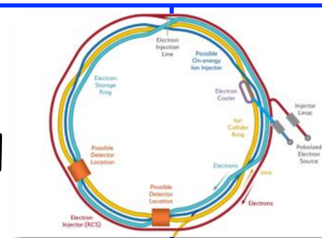
- ❑ Head-on collision geometry is restored by rotating the bunches before colliding ("crab crossing")
- ❑ Bunch rotation ("crabbing") is accomplished by transversely deflecting RF resonators ("crab cavities")
- ❑ Actual collision point moves laterally during bunch interaction
- ❑ Challenges
  - Bunch rotation (crabbing) is not linear due to finite wavelength of RF resonators (crab cavities)
  - Severe beam dynamics effects
  - Physical size of crab cavities



Significant impact on main and forward detector acceptance

Complementarity for 1st-IR & 2nd-IR

Since CD-1 we made significant progress in the preliminary design for the 2nd IR with a focus on complementarity



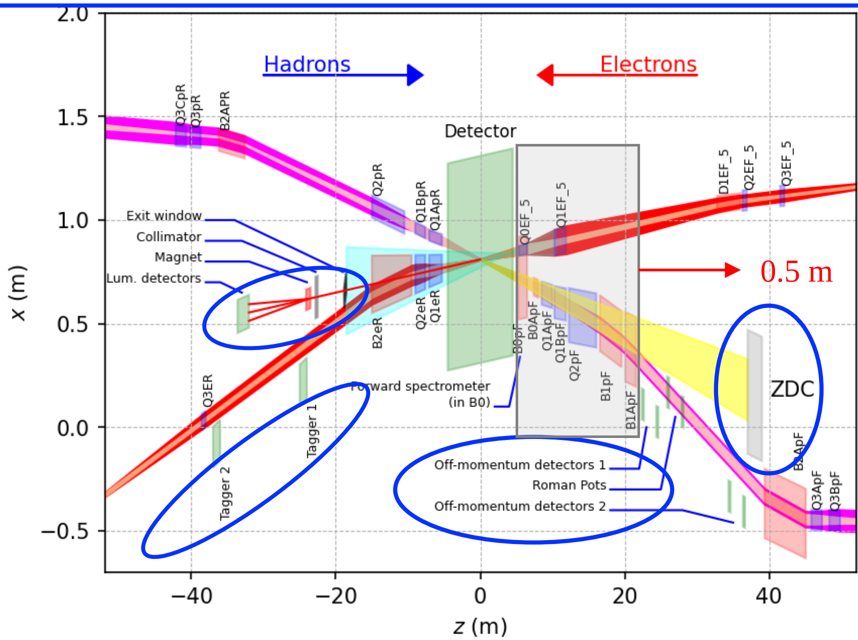
<table>
<tr><th></th><th>1st IR (IP-6)</th><th>2nd IR (IP-8)</th></tr>
<tr><td>Geometry:</td><td>ring inside to outside

tunnel and assembly hall are larger
Tunnel: ⦰ 7m +/- 140m</td><td>ring outside to inside

tunnel and assembly hall are smaller
Tunnel: ⦰ 6.3m to 60m then 5.3m</td></tr>
<tr><td>Crossing Angle:</td><td>25 mrad</td><td>35 mrad
secondary focus</td></tr>
<tr><td></td><td colspan="2">different blind spots
different forward detectors and acceptances
different acceptance of central detector</td></tr>
<tr><td>Luminosity:</td><td colspan="2">more luminosity at lower E_{CM}
optimize Doublet focusing FDD vs. FDF
→ impact of far forward p_T acceptance</td></tr>
<tr><td>Experiment:</td><td colspan="2">1.5 Tesla or 3 Tesla
different subdetector technologies</td></tr>
</table>

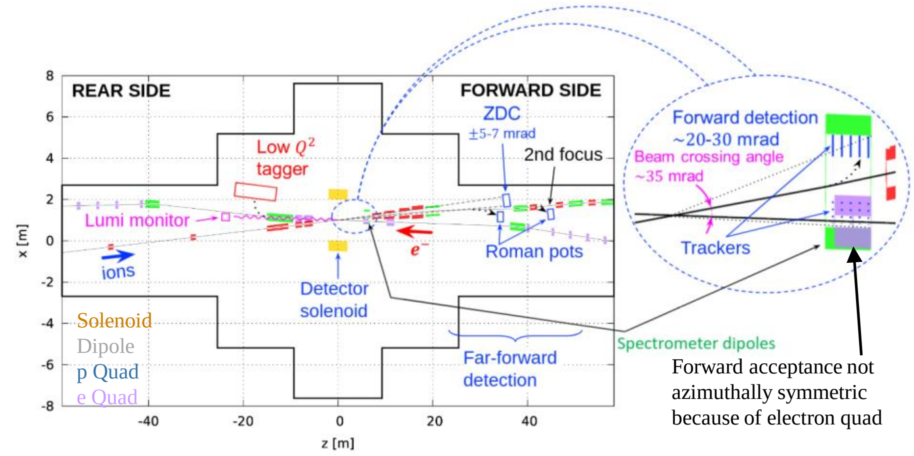
Progress – Interaction Region

1st IR (IP-6)



- Initiated with accelerator colleagues change request to shift forward IR magnets by 0.5 m to provide more space to detector → -4.5 m to +5m
  - approved and now new baseline

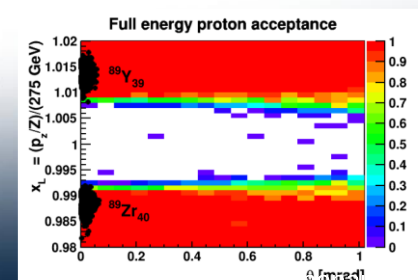
2nd IR (IP-8)



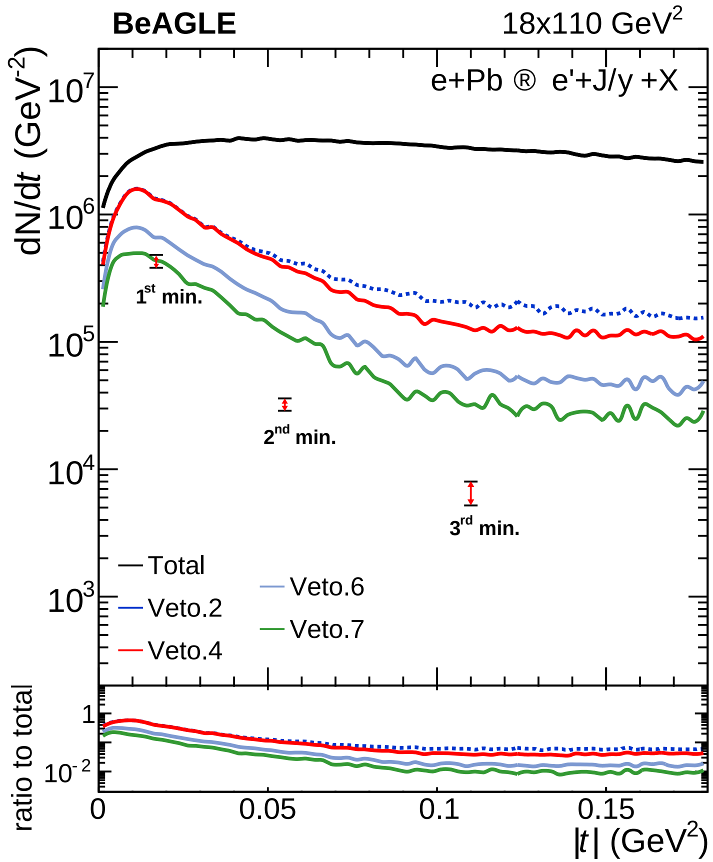
- IR-8: **pre-conceptual** design with 35 mr crossing angle and secondary focus passed on to proto-collaborations for science complementary checks.

2nd focus enables:

enhanced low P_T acceptance, DVCS on nuclei, Light ion tagging, Diffraction, improved Gluon imaging by detection of (A-1) nuclei



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

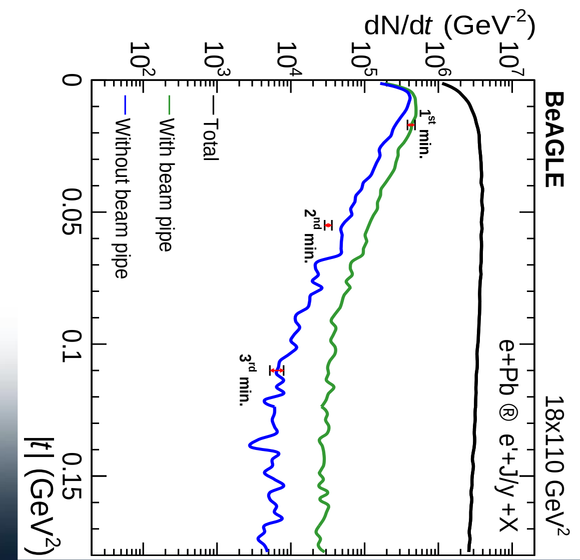
Veto.5:
- Veto4 + no anything in preshower

Veto.6:
- Veto5 + no photon ***E>50MeV*** in ZDC

Veto.7:
- Veto6 + no activities
  $(|\eta| < 4.0 \;\&\; p_T > 100\,\mathrm{MeV/c} \;\&\; E > 50\,\mathrm{MeV})$
  other than e- and J/ψ in the main detector

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

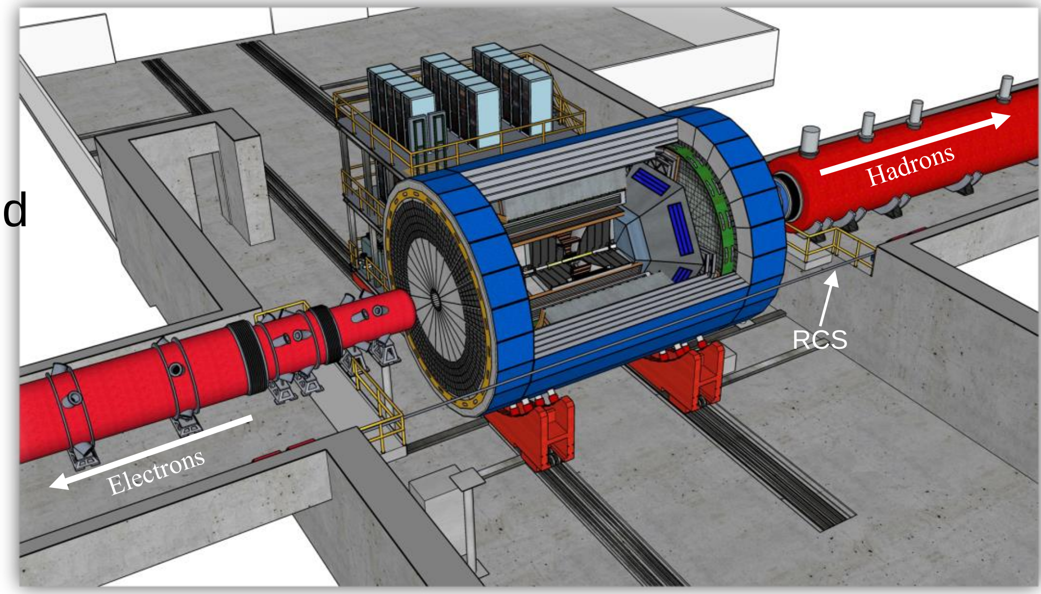
Beam pipe design and material critical to vetoing power



Progress: IR-Integration and Interfaces

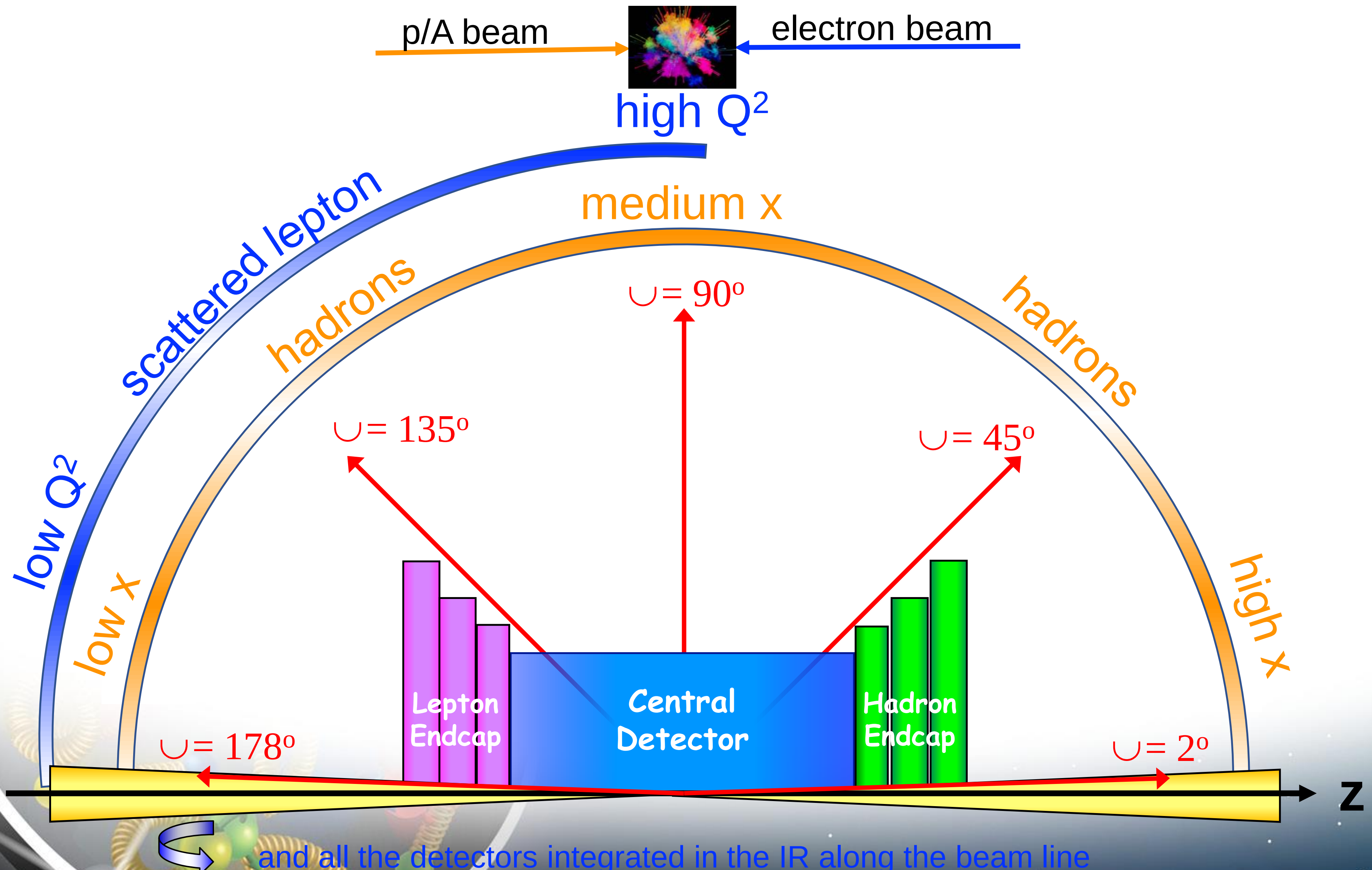
Space Constrains:

- -4.5 m – IP – +5m not negotiable
- 50 cm space to 1st IR-magnet occupied by vacuum pumps, valves, …..
- IP moved 81 cm towards ring inside compared to RHIC; y: 432 cm above floor
- no installation possible in collider hall

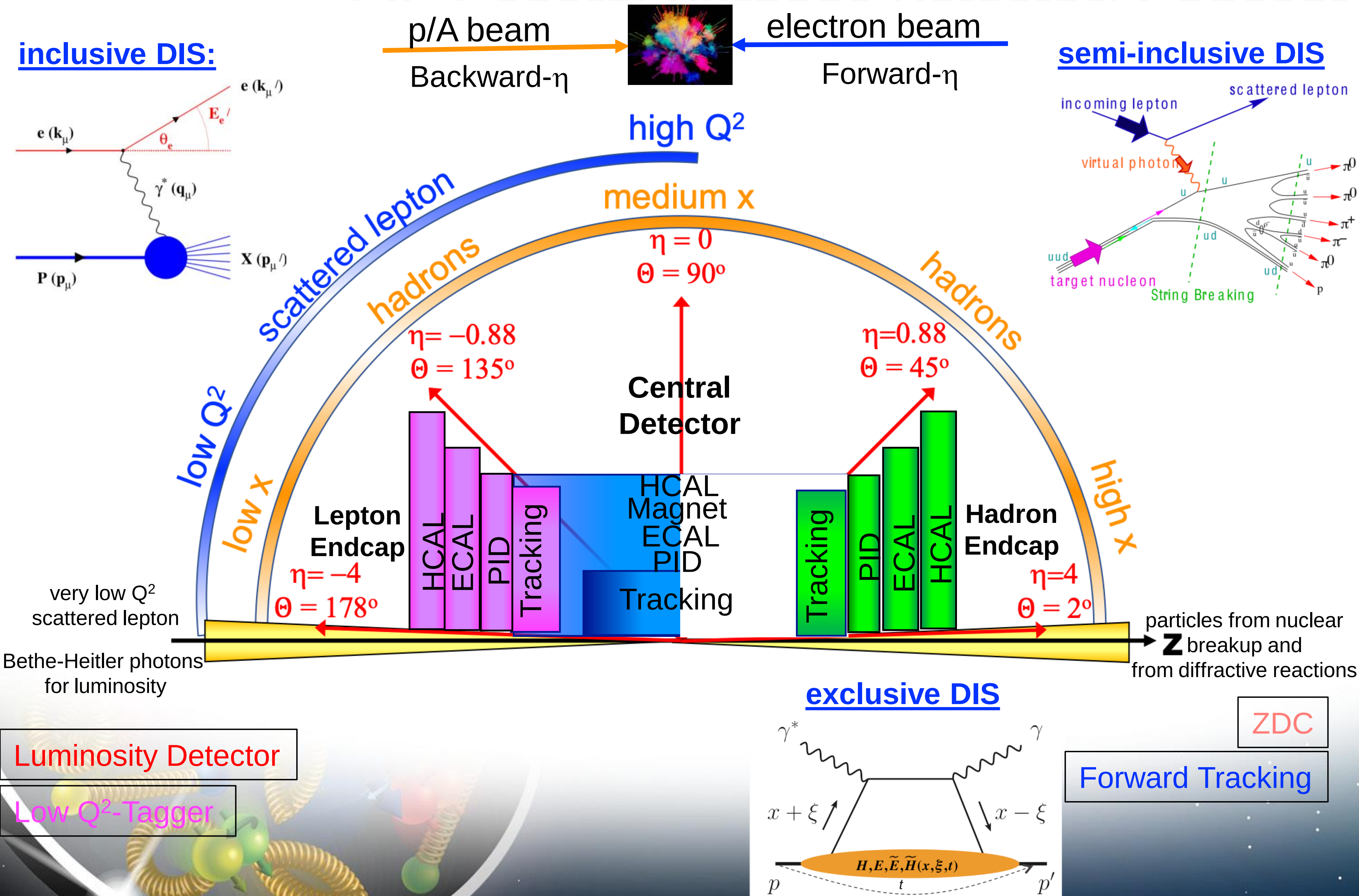


- 9.5 long detector does not fit through the door
  - Door-Size: 823 cm x 823 cm
  - endcap hadron calorimeters need to stay in collider hall, if detector rolls in assembly hall
- RCS to IP: radial distance 335.2 cm at a height of 372 cm from floor
  - Maximum outer radius ~ 3.2 m
- Fringe field requirements for solenoid
  - the fringe field at both endcaps impacting the IR magnets: < 5 gauss
  - and the fringe field radial along z to impact the RCS: < 0.007 Tm

EIC General Purpose Detector: Concept



EIC General Purpose Detector: Concept



What is new/special for a EIC GPD

Vertex detector → Identify primary and secondary vertices,
Low material budget: 0.05% X/X_0 per layer;
High spatial resolution: 10 μm pitch CMOS Monolithic Active Pixel Sensor (MAPS)
→ synergy with Alice ITS3

Central tracker → Measure charged track momenta
MAPS – tracking layers in combination with micro pattern gas detectors

Forward tracker → Measure charged track momenta
MAPS – disks in combination with micro pattern gas detectors

Particle Identification → pion, kaon, proton separation
RICH detectors & 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
Crystals (backward), Shashlik or Scintillator/Silicon-Tungsten
new material development: Scintillating glass → very cost effective

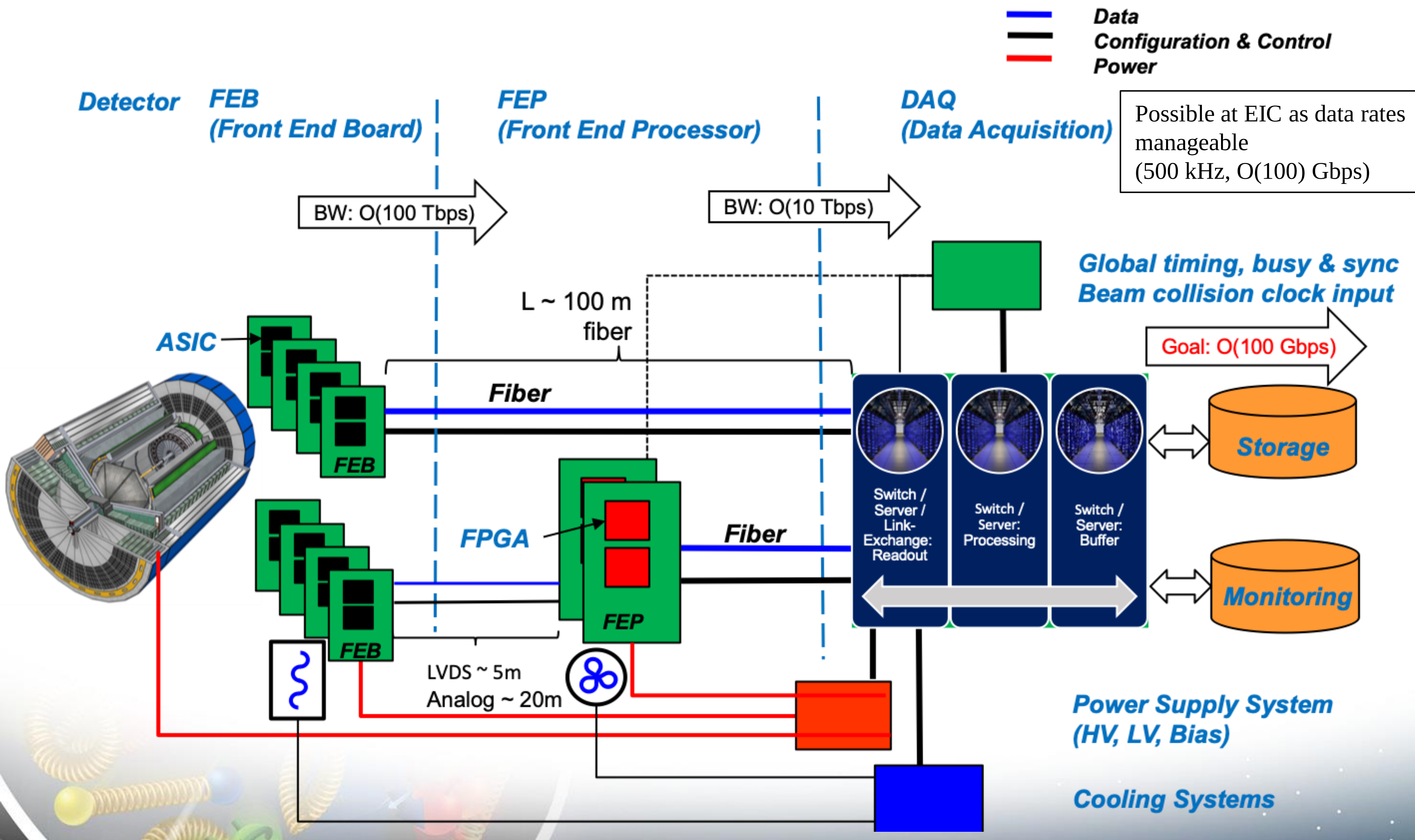
Hadron calorimeter → Measure charged hadrons, neutrons and K_L^0
challenge achieve ~50%/√E + 10% for low E hadrons (<E> ~ 20 GeV)

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

+ Beam pipe and very forward and backward detectors

Radius/Distance from IP

Streaming Readout Architecture



Possible at EIC as data rates manageable
(500 kHz, O(100) Gbps)

EIC Readout Partitioning

- **FEB – Front-End Boards**
  - Custom designed for each detector and populated with ASICs.
  - ASICs designed to process analog signals and digitization tailored to each type of detector technology.
  - Data transport via optical fibers to minimize cabling.

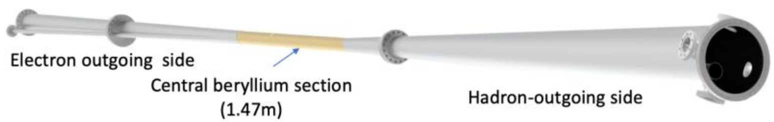
- **FEP – Front-End Processors**
  - Custom designed to process and aggregate data streams from multiple FEBs.
  - FPGAs are dominant components on these PCBs.
  - Algorithms reduce data flow (e.g., zero suppression)
  - Data transport via optical fibers to minimize cabling.

- **Global Timing**
  - High speed and precision combines custom designed and COTS componentry.
  - Provides synchronization of and clock distribution to the readout elements.
  - Jitter better than 1 ps.

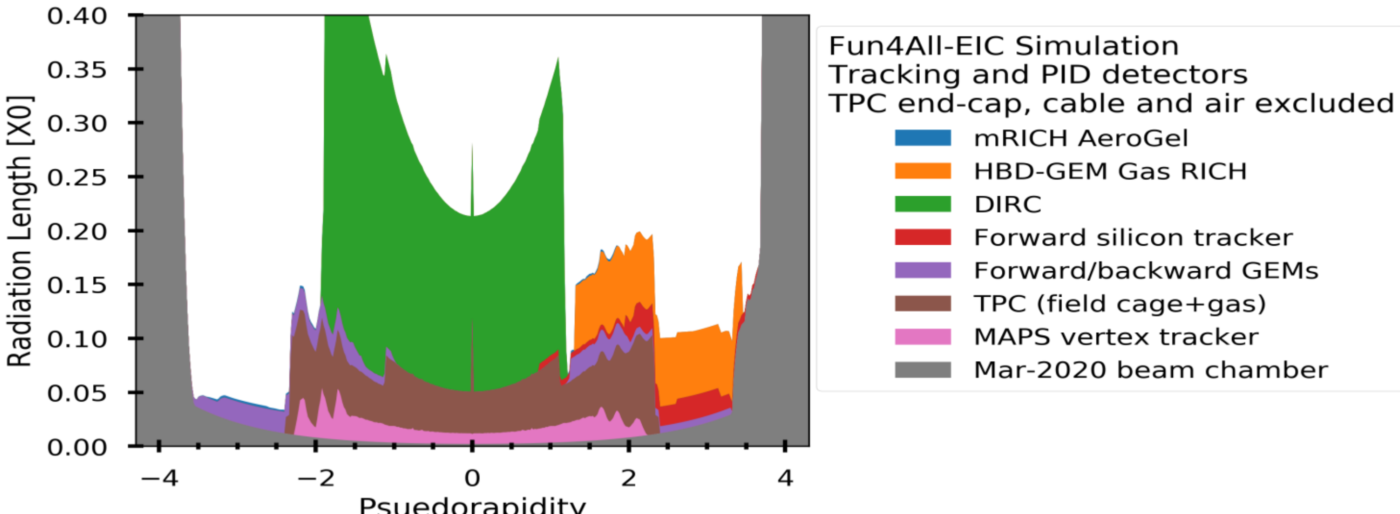
- **Network Switches/Servers/Computing**
  - High performance COTS infrastructure.
  - Enables further reduction of data flow prior to storage via sophisticated algorithms, e.g., ML and AI.

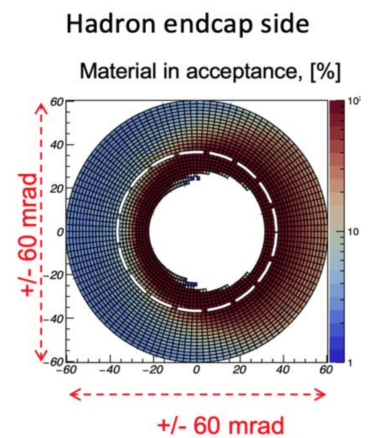
Tracking/Material Budget

- Vertex + central + forward / backward tracker layout (moderate momentum resolution, vertex resolution ~20 μm)
- At most 3T central solenoid field (maximize B*dl integral at high |η|)
- Low material budget
  - Minimize bremsstrahlung and conversions for primary particles
  - Improve tracking performance at large |η| by minimizing multiple Coulomb scattering
  - Minimize the dead material in front of the high resolution e/m calorimeters



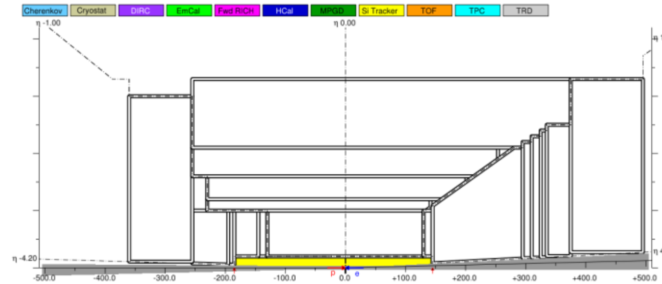
- ❑ Central area of beampipe (around IP): ~1.5m of beryllium to minimize multiple scattering for low Pt particles
- ❑ Low-mass exit window for far-forward particles
- ❑ Few % radiation length material thickness for the required angular range (low angle)

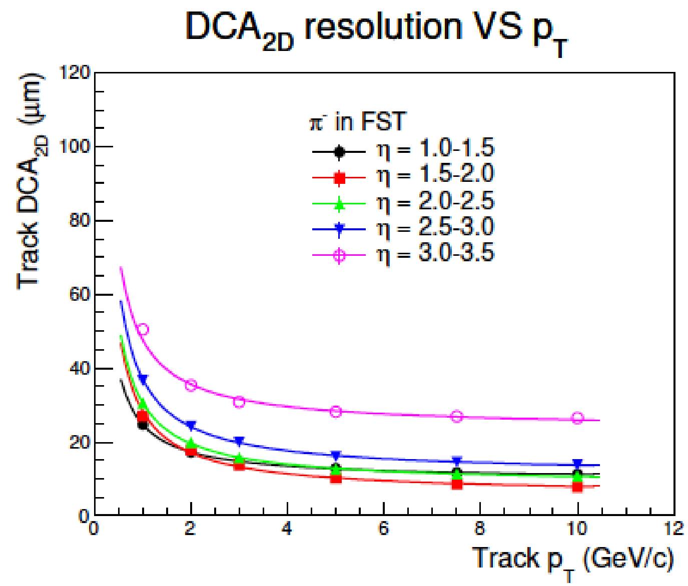


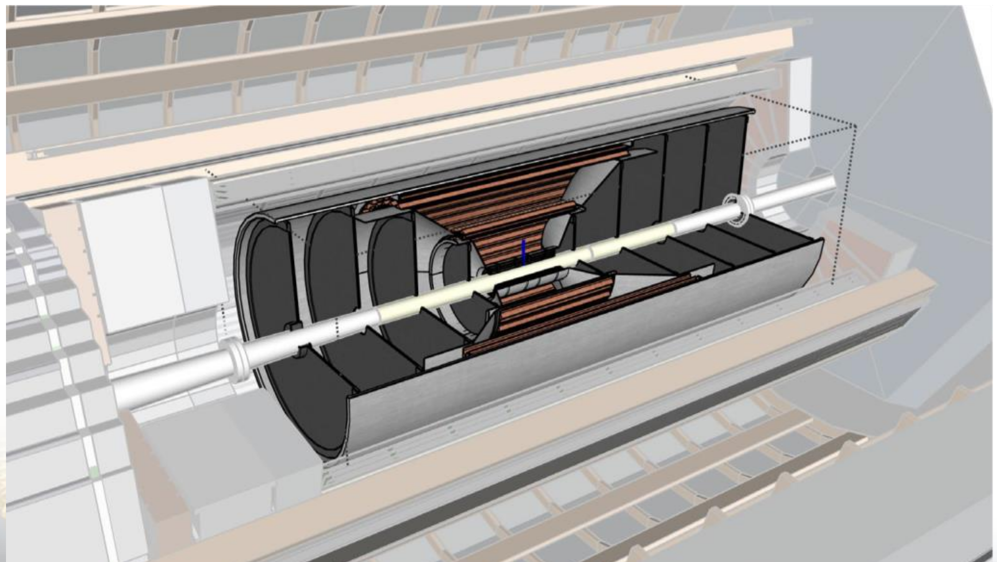


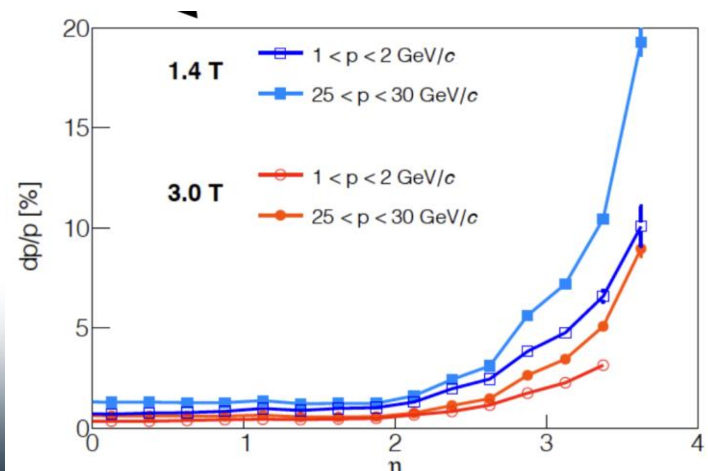
MAPS μVertex

- For primary and secondary vertex reconstruction
- Low material budget: 0.05% X/X_0 per layer
- High spatial resolution: 10 μm pitch MAPS
  → ref. Alice ITS3
- Compromise:
  20 μm (or smaller) pixels and ~0.3% X/X_0 per layer
- Configuration: Barrel+ Disks for endcaps



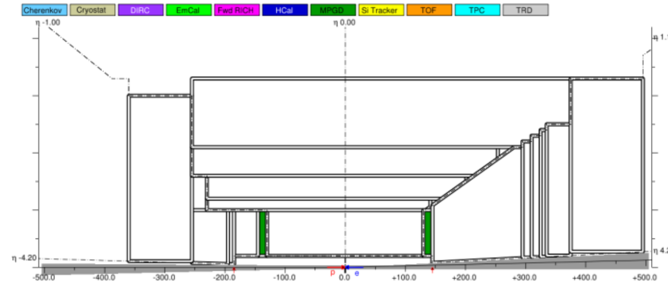


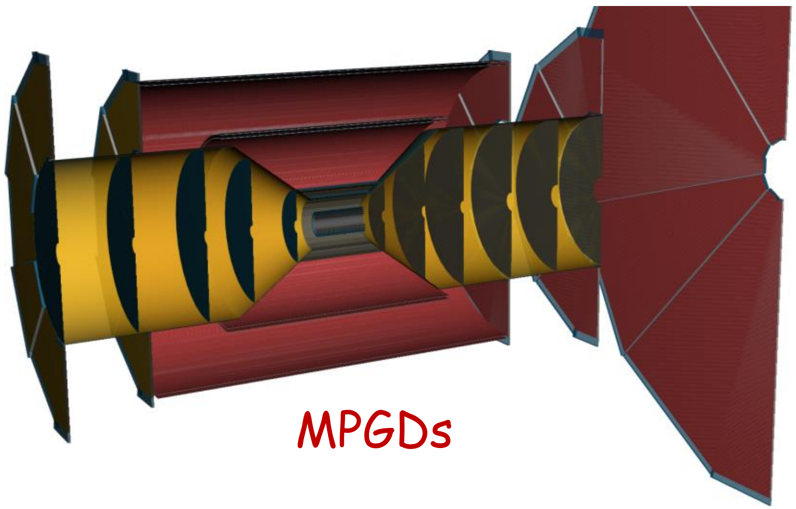


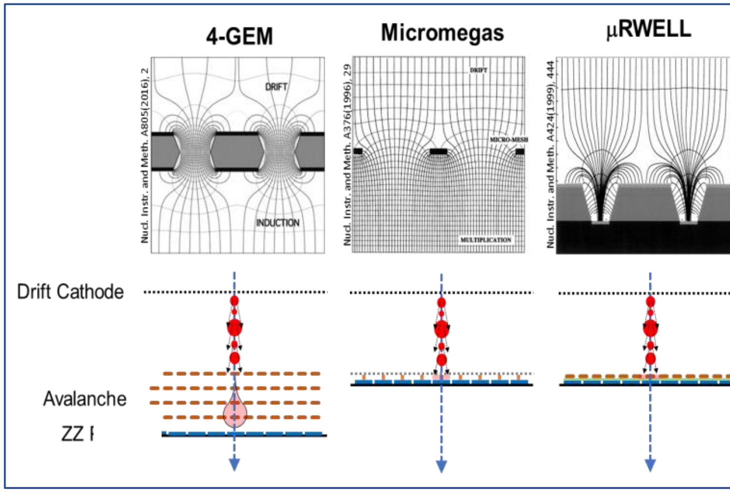


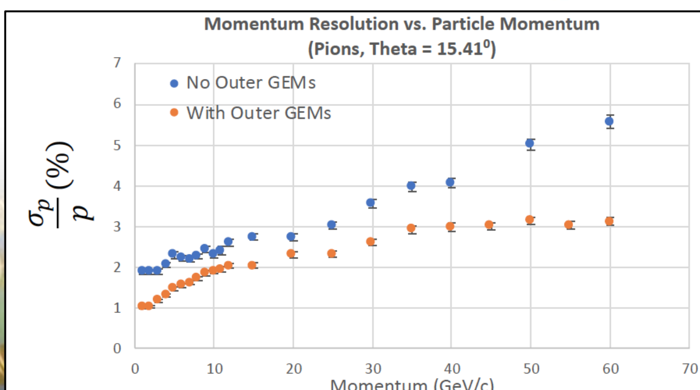
Micro Pattern Gas Detectors

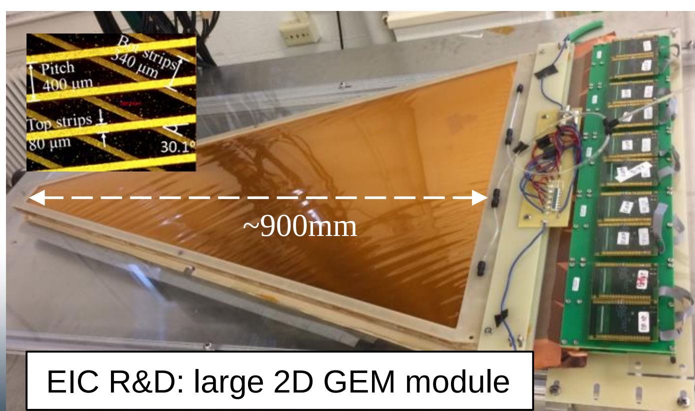
- To improve momentum resolution at large rapidities.
- Spatial resolution well below 100 μm
- Large-area detectors possible
- Cost efficient compared to silicon





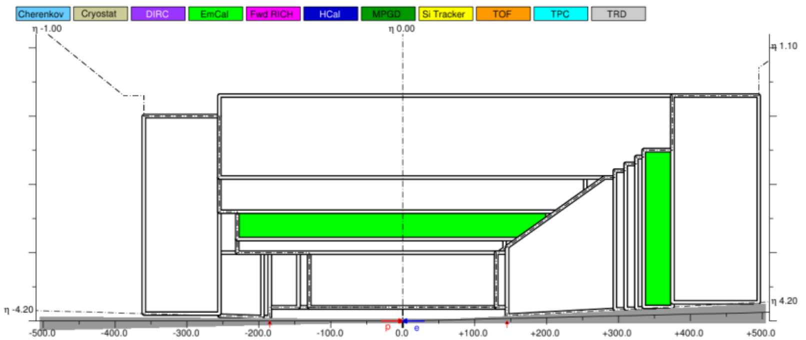




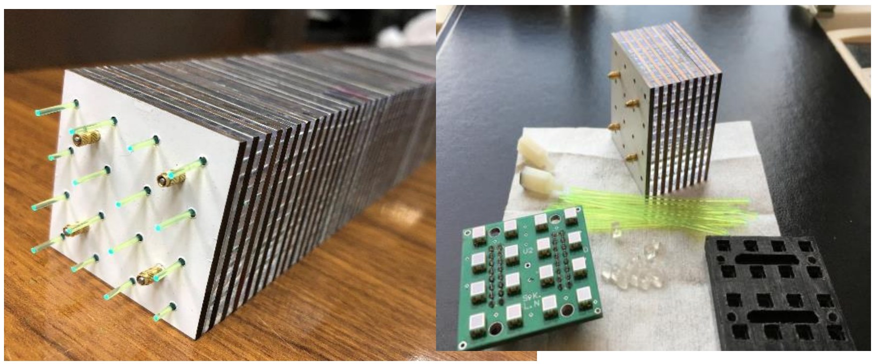


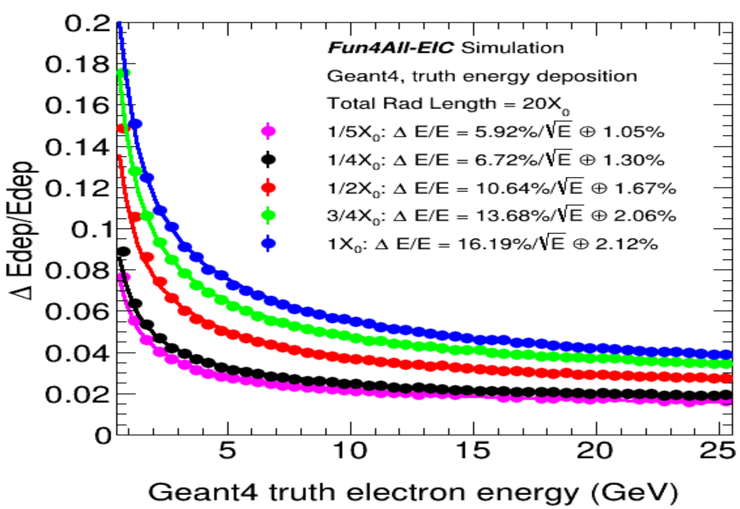
Sampling EmCal

- Well established technology
  - HERA-B, ALICE, PHENIX, PANDA, …
- Medium energy resolution ~7..13%/√E
- Compact (X_0 ~7mm or less), cost efficient

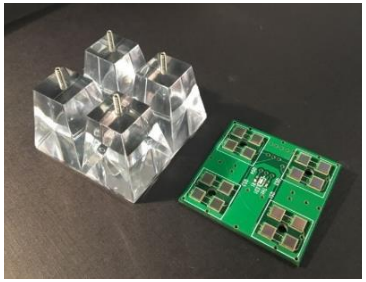


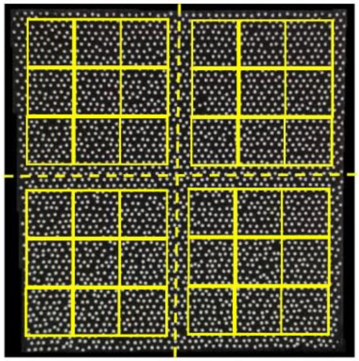
Pb/Sc shashlyk





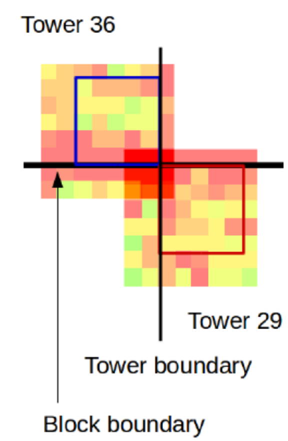
W/SciFi spacal

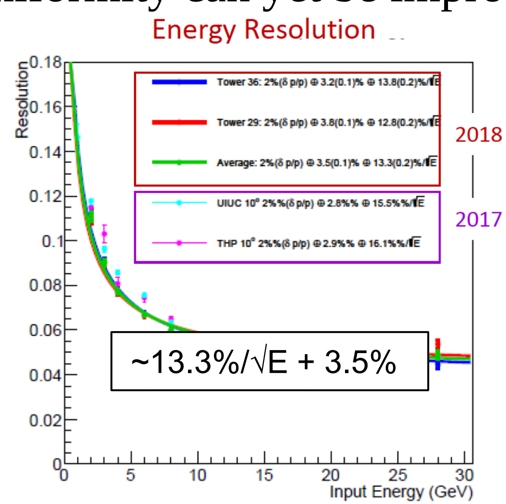




Scintillating Fibers embedded in a W/epoxy mix

Light collection uniformity can yet be improved

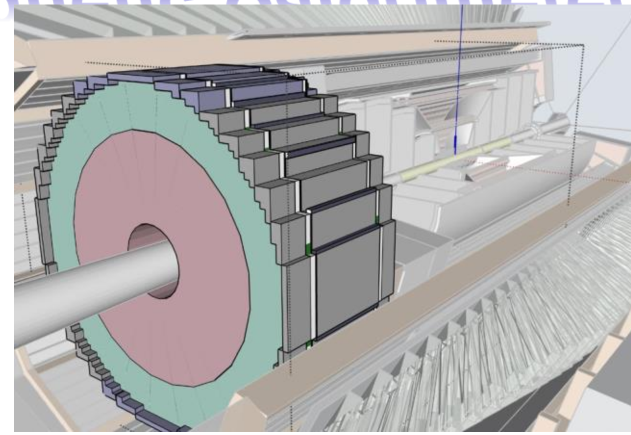




Electro-Magnetic Calorimeter

Applications:

- Scattered electron kinematics measurement at large |η| in the e-endcap
- Photon detection and energy measurement
- e/h separation (via E/p & cluster topology)
- π^0/γ separation



Anticipated stochastic term in energy resolution & π suppression

η	[-4 .. -2]	[-2 .. -1]	[-1 .. 1]	[1 .. 4]
σ_E/E	~2%/√E	~(4-8)%/√E	~(12-14)%/√E	~(4*-12)%/√E
π suppression	Up to $1{:}10^{-4}$	Up to $1{:}10^{-3}$-10^{-2}	Up to $1{:}10^{-2}$	3σ e/π

Other considerations:

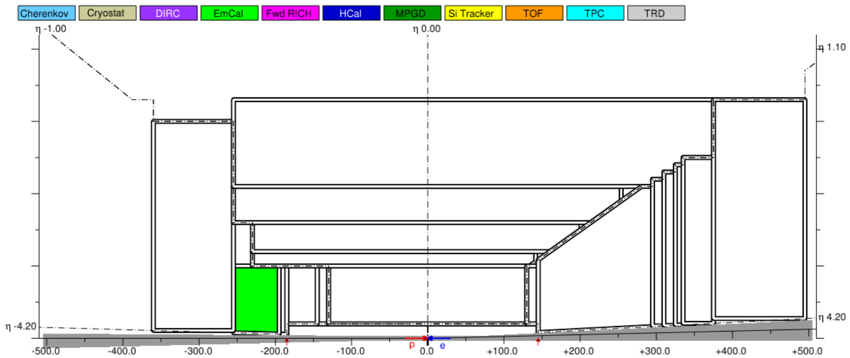
- Fast timing
- Compactness (small X_0 and R_M)
- Tower granularity
- Readout immune to the magnetic field

EIC Yellow Report

#	Type	samp-ling, mm	f_{samp}	X_0 mm	R_M mm	λ_I mm	cell mm^2	$\frac{X}{X_0}$	ΔZ cm	σ_E/E, % α	β
1	W/ScFi**	⌀0.47 ScFi W powd.	2%	7.0	19	200	25^2	20	30	2.5	13
2	$PbWO_4$***	-	-	8.9	19.6	203	20^2	22.5	35	1.0	2.5
3	Shashlyk***	0.75 W/Cu[a] 1.5 Sc	16%	12.4	26	250	25^2	20	40	1.6	8.3
4	W/ScFi** with PMT	0.59^2 ScFi W powd.|	12%	13	28	280	25^2	20	43	1.7	7.1
5	Shashlyk***	0.8 Pb 1.55 Sc	20%	16.4	35	520	40^2	20	48	1.5	6
6	TF1 Pb glass***	-	-	28	37	380	40^2	20	71	1.0	5-6
7	Sc. glass*[b]	-	-	26	35	400	40^2	20	67	1.0	3-4

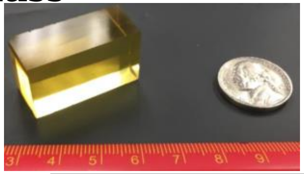
Crystals

- High resolution EmCal in the electron-endcap for the scattering electron measurements
- PWO where space is tight, and the highest possible energy resolution is required
- Scintillating glass (*EIC R&D*) otherwise
  - More cost efficient, easier manufacturing
  - Potentially better optical properties



Example: SC1 glass

2018: 1cm x 1cm x 1cm

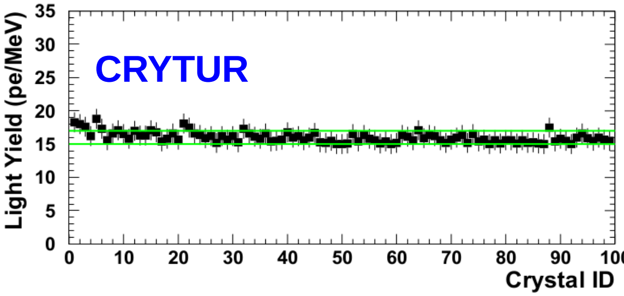


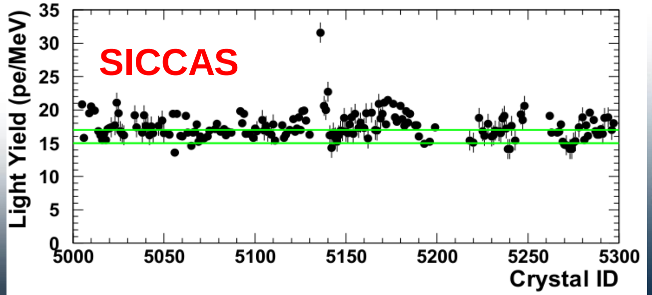
2019: 2cm x 2cm x 4cm

Feb 2020: 2cm x 2cm x 20cm (7 X0)

Dec 2020: 2cm x 2cm x 40cm (10-20 X0)

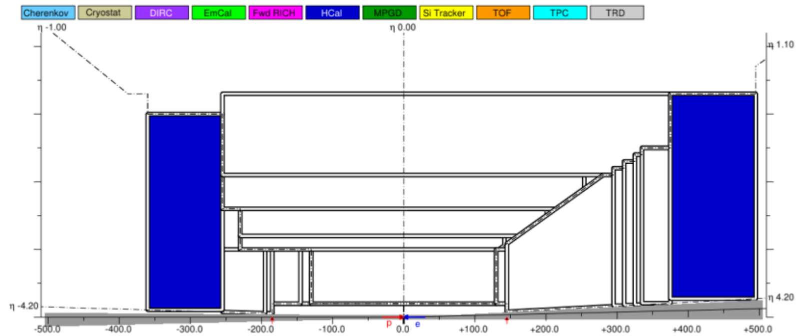
PWO: vendor characterization

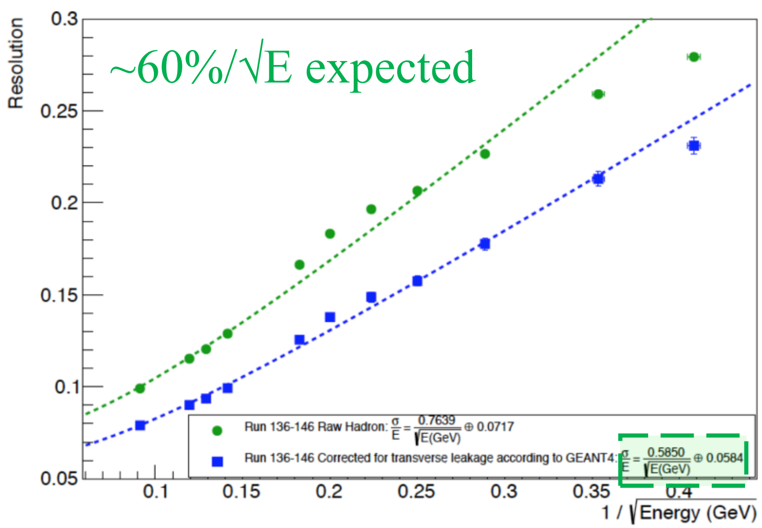


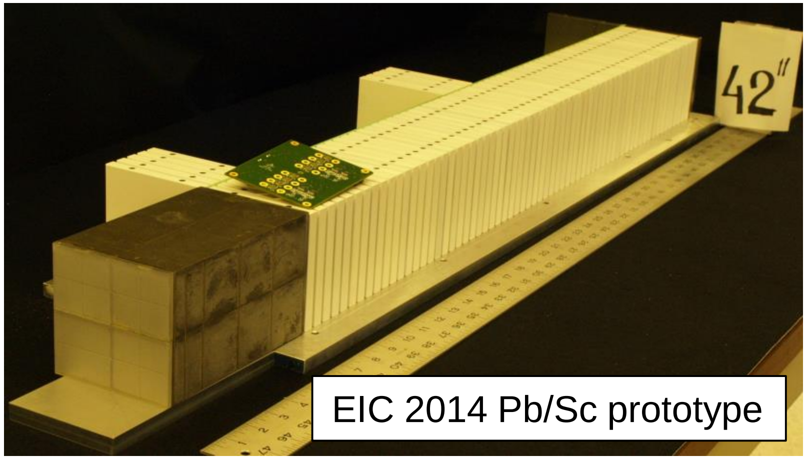


Fe/Sc sandwich

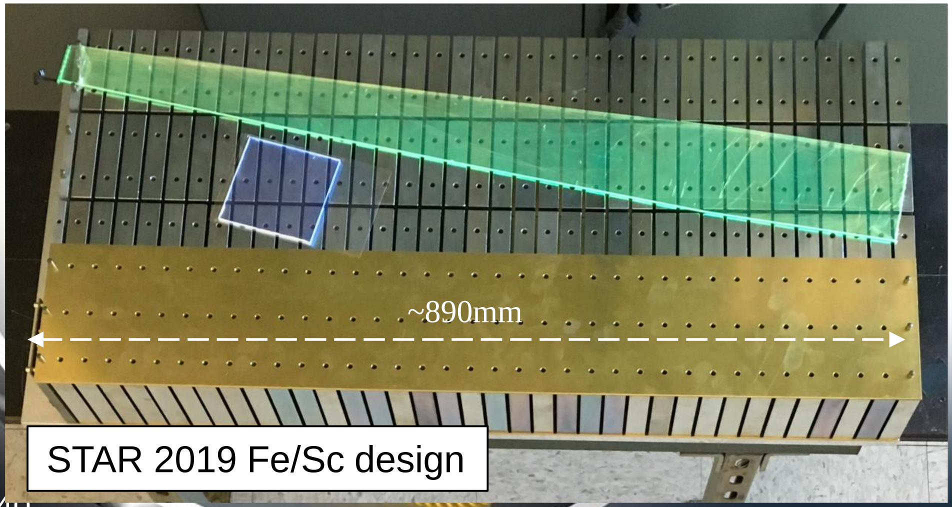
- HCAL in endcap
- Compact LEGO-style design
  - Can be used with a mixed Fe/Pb absorber



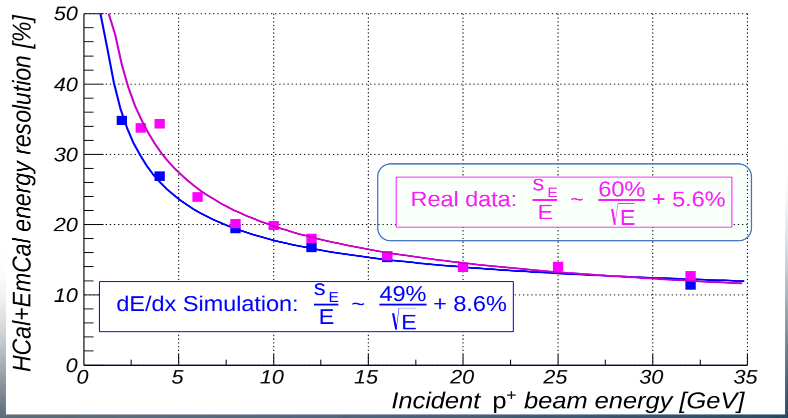




EIC 2014 Pb/Sc prototype

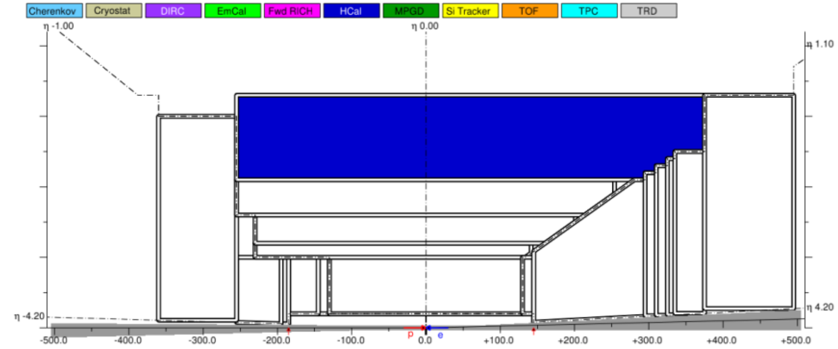


STAR 2019 Fe/Sc design

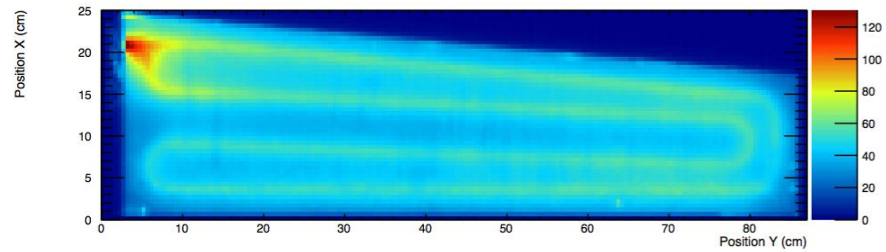


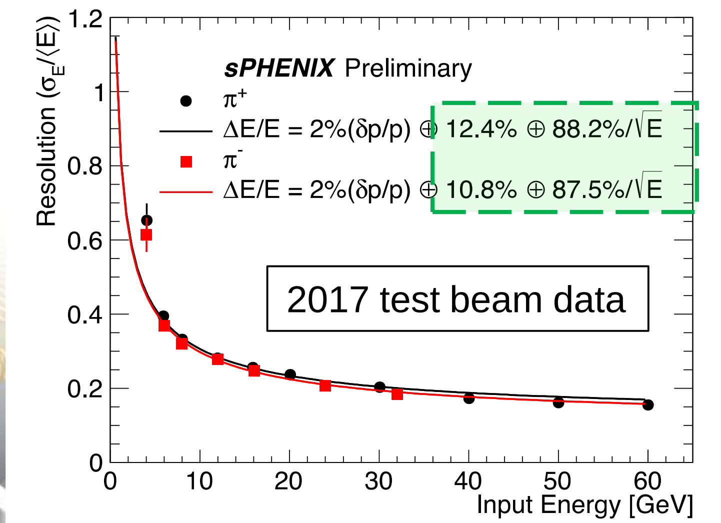
Fe/Sc (barrel)

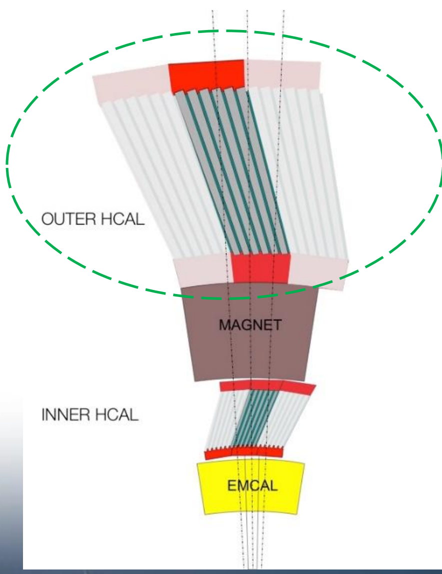
- Similar as used in sPHENIX
  - Solid 32-sector steel frame, but only ~3.5 λ_I
  - Moderate energy resolution



Scintillator plate with embedded WLS fiber





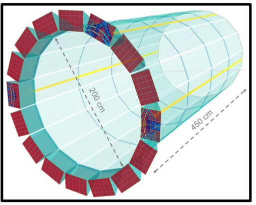


EIC PID
needs
are more demanding
then your
normal
collider detector

EIC
needs absolute
particle numbers at
high purity and low
contamination

Hadron PID

Barrel

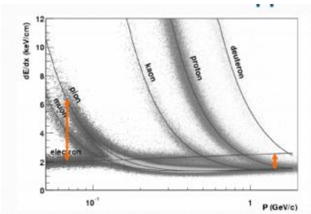


REFERENCE

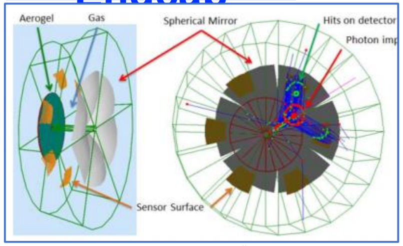
hpDIRC (High Performance DIRC)

- Quartz bar radiator, light detection with MCP-PMTs
- Fully focused
- p/K 3s sep. at 6 GeV/c
- Reuse of BABAR DIRC as alternative
- Integration into a 4π detector can be challenging

dE/dx from gaseous tracker, i.e. TPC complementary
STAR: ~ similar resolution expected



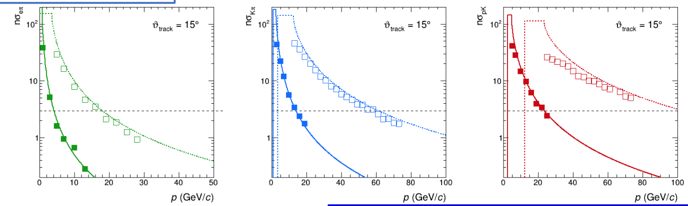
Forward Endcap



REFERENCE

dRICH (dual RICH)

- Aerogel and C-F gas radiators
- Full momentum range
- Sensor: Si PMs(TBC)
- p/K 3σ sep. at 50 GeV/c

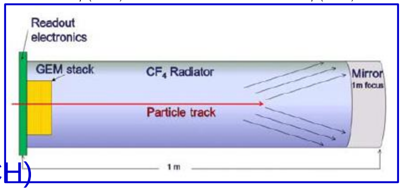


windowless RICH

- Gaseous sensors (MPGDs)
- CF_4 as radiator and sensor gas

Low p complements required:

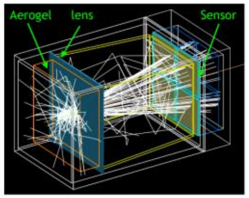
- TOF ~ 2.5m lever arm / Aerogel (mRICH)



HP-RICH (high pressure RICH)

- Eco-friendly alternative for dRICH/windowless RICH
- Ar @ 3. 5 bar ↔ C_4F_{10} @ 1 bar
- Ar @ 2 bar ↔ CF_4 @ 1 bar

Backward Endcap



Geant4 Simulation

With realistic material optical properties

REFERENCE

mRICH (Modular RICH)

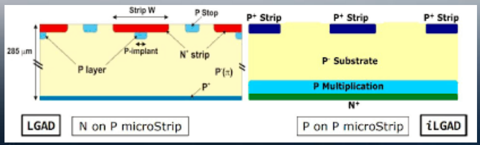
- Aerogel Cherenkov Det.
- Focused by Fresnel lens
- e, pi, K, p
- Sensor: SiPMs/ LAPPDs
- Adaptable to includeTOF
- π/K 3σ sep. at 10 GeV/c

Everywhere

TOF with short lever arm

LGAD (Low Gain Avalanche Detector)

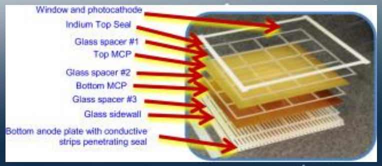
- Silicon Avalanche
- 20-35 psec
- Accurate space point for tracking
- Relevant also to central barrel
- R&D and PED by International consortium HEP & NP



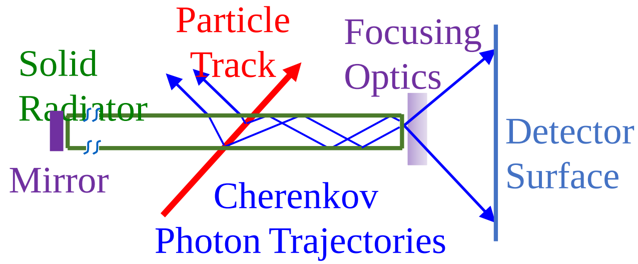
LAPPD (Large Area psec Photon Detector)

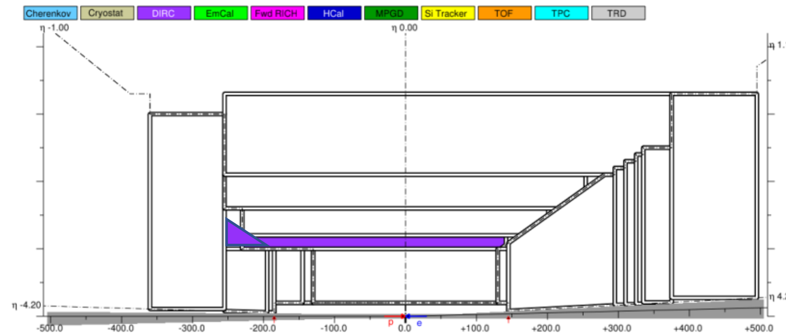
- MCP, Cherenkov in window
- 5-10 psec

→ supported by DOE SBIR program

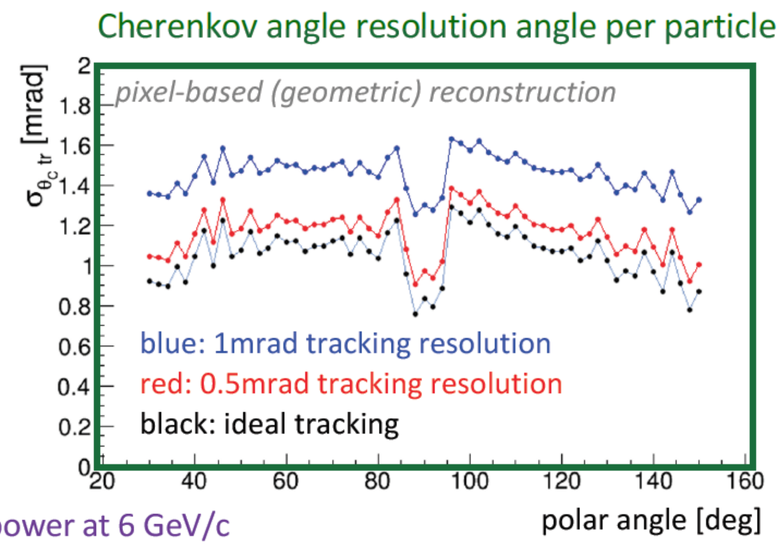


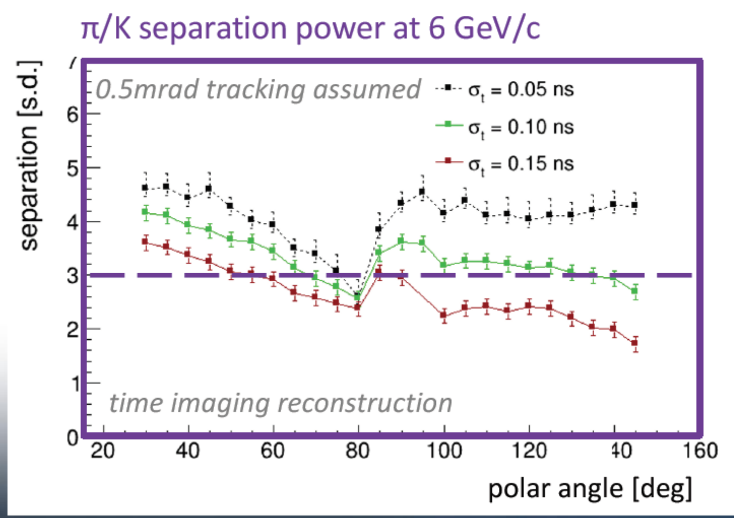
DIRC

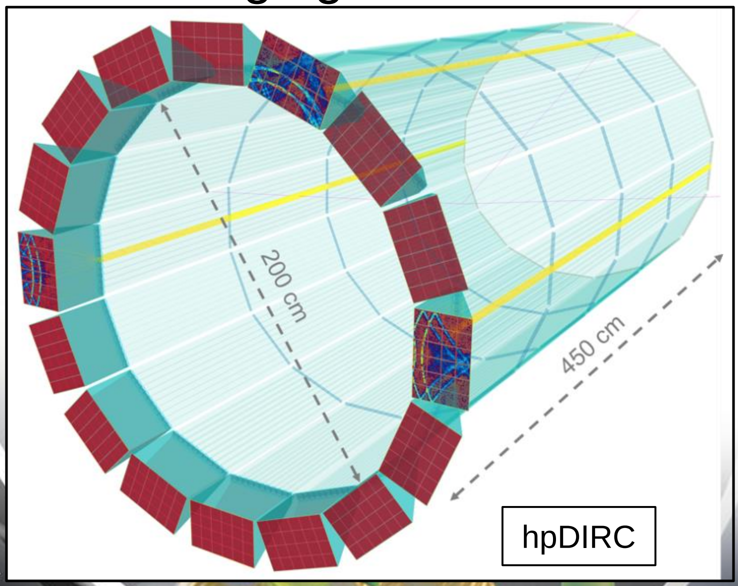




- Radially compact (~ 5cm)
- high-performance DIRC with better optics and <100 ps timing (π/K up to ~6 GeV/c)
- Re-use BaBar quartz bars ?
- Integration into a 4π detector can be challenging

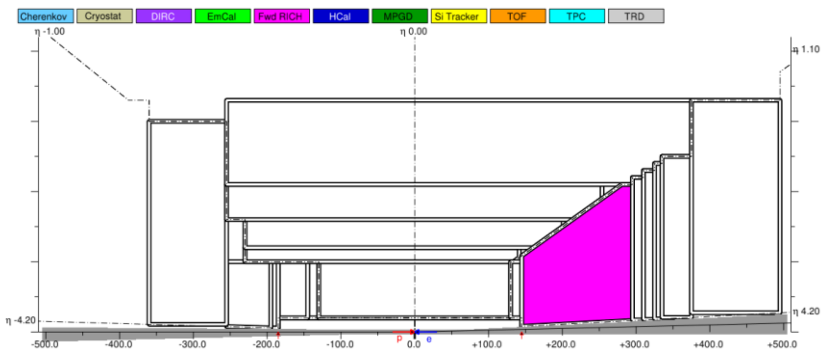


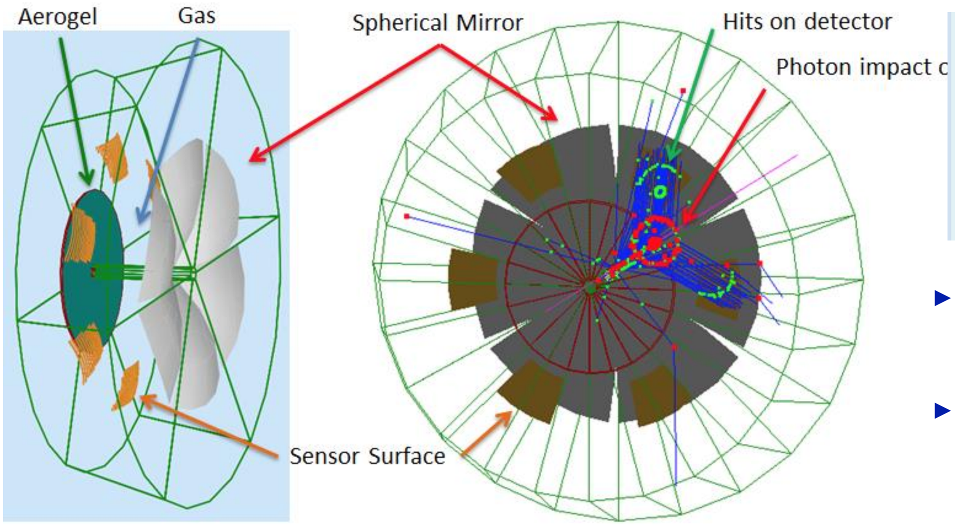




Dual radiator RICH

- Hadron PID in the forward/hadron end-cap
- Use a combination of aerogel and C_mF_n with indices of refraction matching EIC momentum range in the forward endcap
- Similar to LHC-b, HERMES, JLAB/Hall-B, …





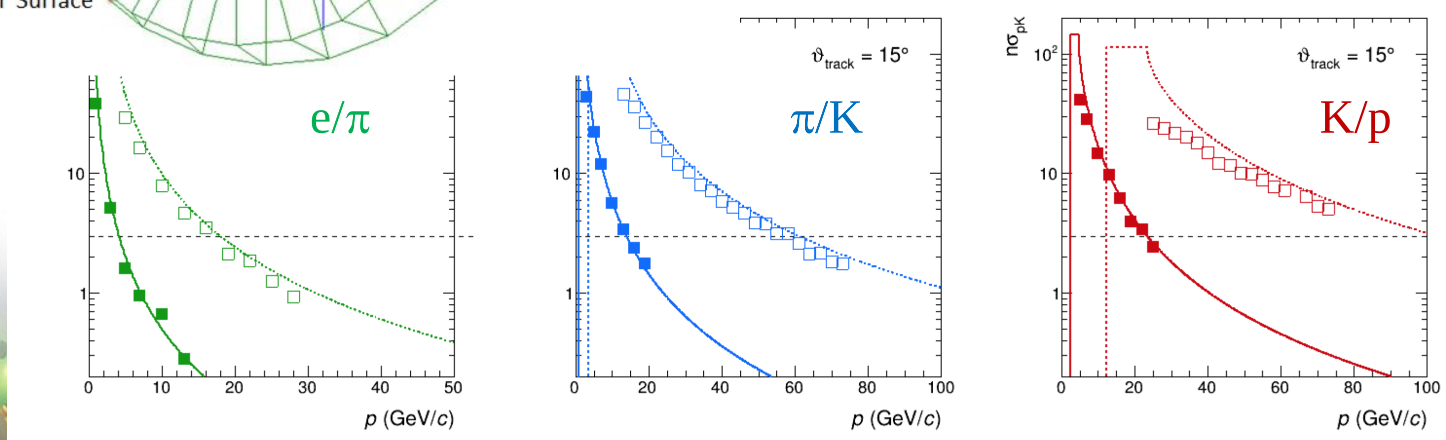
Radiators: Aerogel (n_{AERO}~1.02) + Gas (n_{C2F6} ~ 1.0008)

Detector: 0.5 m²/sector , 3x3 mm² pixel

Single-photon detection in ~1T magnetic field

Outside acceptance, reduced constraints

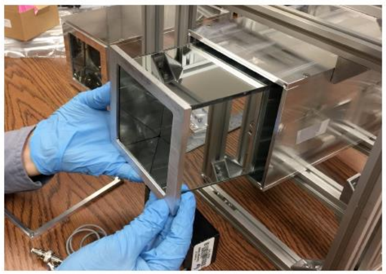
- Continuous **>3σ π/K separation up to 60 GeV/c** and K/p separation to higher momenta
- >3σ e/π separation up to ~15 GeV/c



Modular-RICH (mRICH)

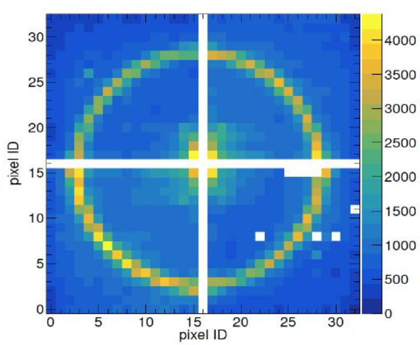
- *For hadron PID in the electron end-cap*
- *Compact* version of a conventional aerogel-based proximity focusing RICH

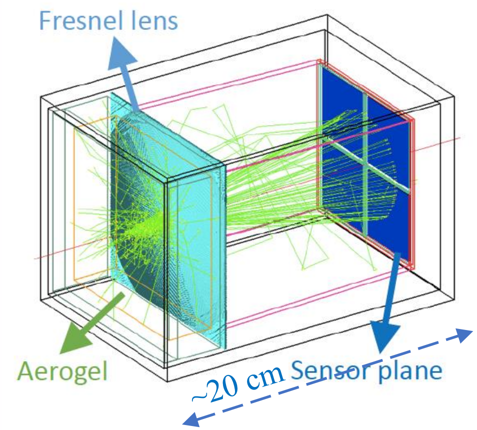
New features: a) separation of optical and electronic components; b) longer focal length (6"); c) 3mm x 3mm photosensors.



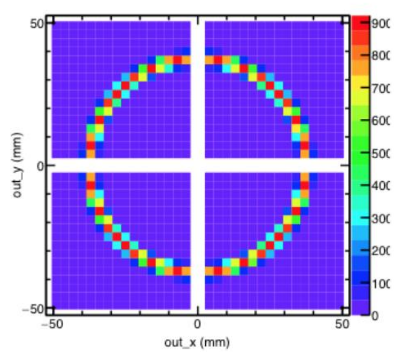
2nd mRICH prototype was tested at Fermilab Test Beam Facility in June/July 2018

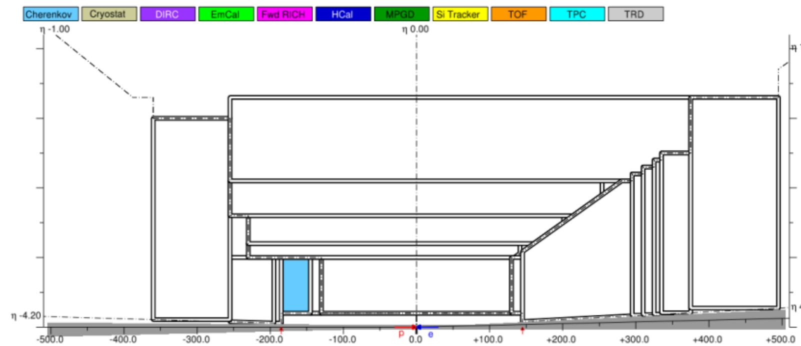
Beam Test at Fermilab

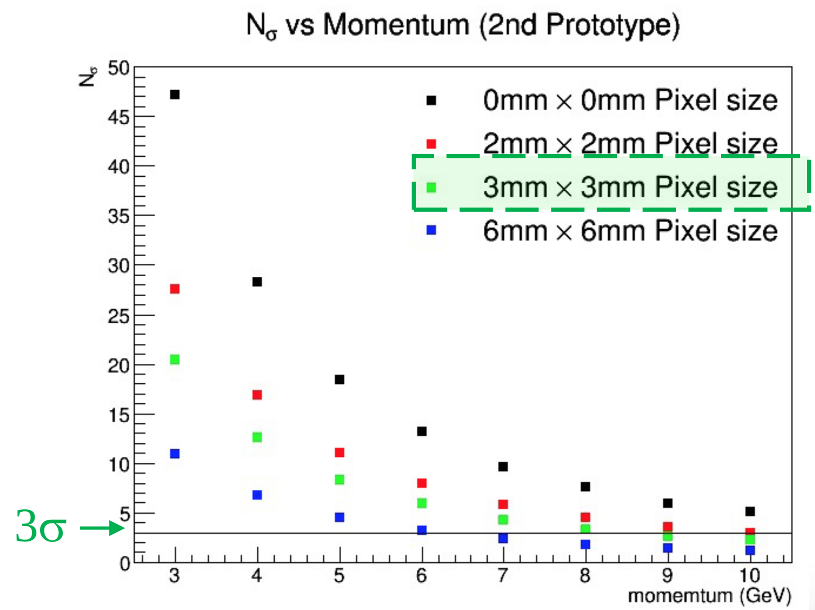




GEANT4 Simulation



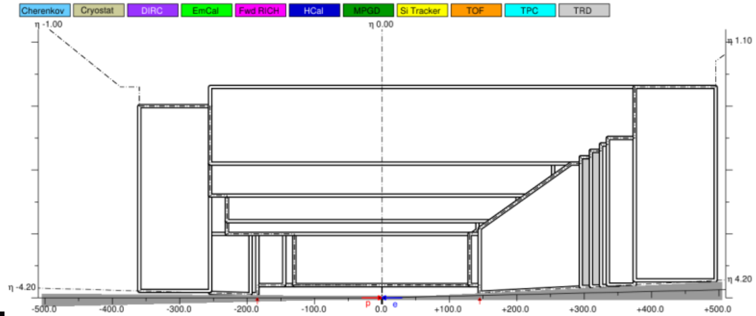




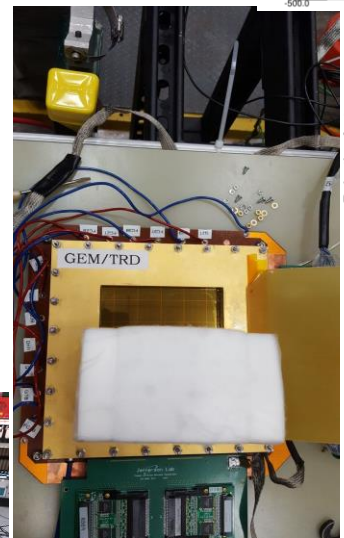
Expect π/K 3σ separation up to 8-10 GeV/c

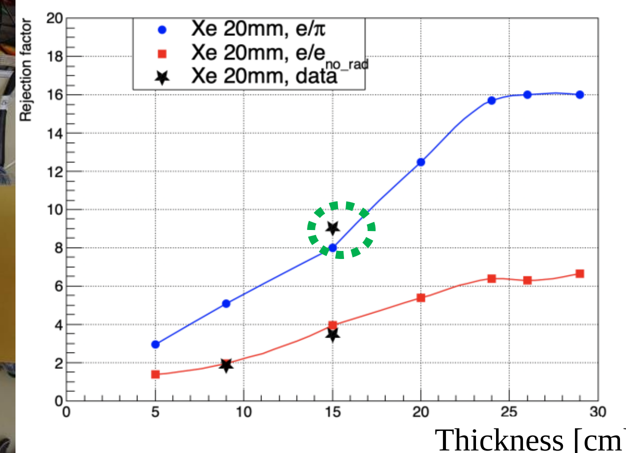
- Was also tested with SiPM readout
- LAPPD readout – spring 2021

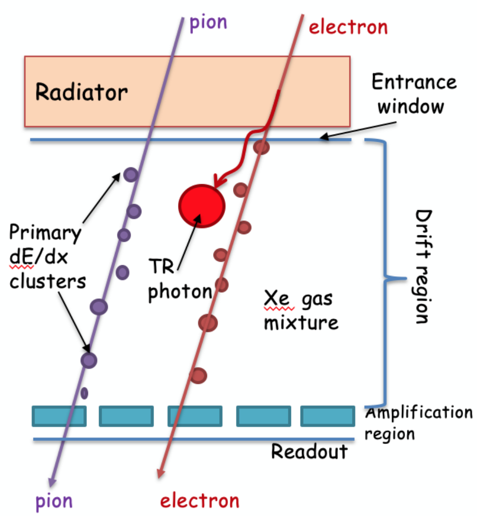
Additional e^- ID

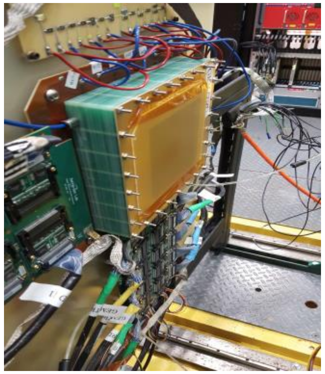


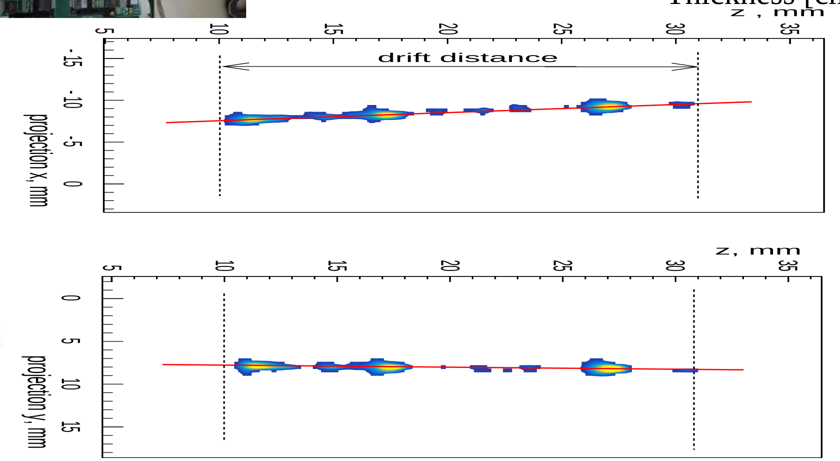
- To improve e-identification for leptonic/semi-leptonic decays.
- In addition to Calorimeters and Cherenkov detectors in the hadron-endcap considering TRD.
- GEM -TRD/Tracker :
  - e/π rejection factor ~10 for momenta between 2-100 GeV/c from a single ~15cm thick module.







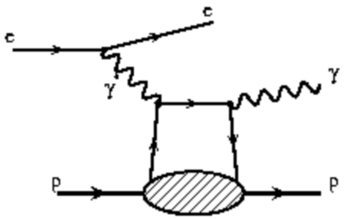




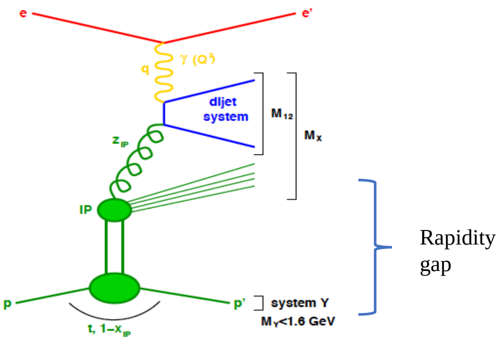
- Very precise Tracking segment behind dRICH:

Far-forward physics at EIC

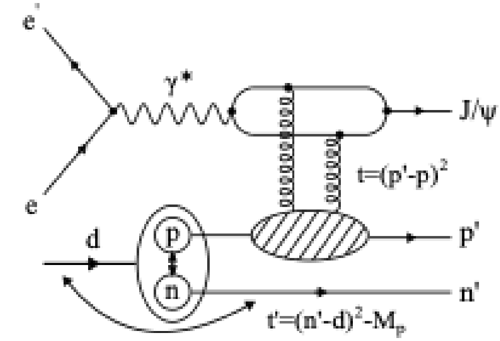
e+p DVCS events with proton tagging.



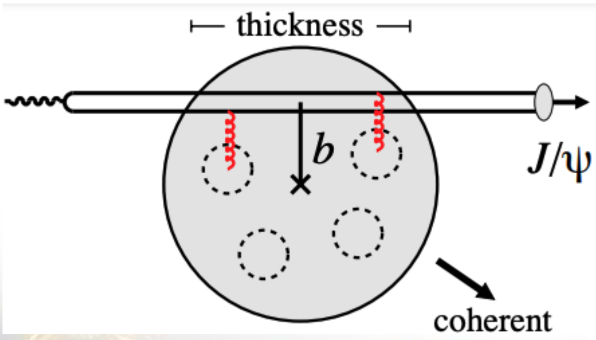
Diffraction



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

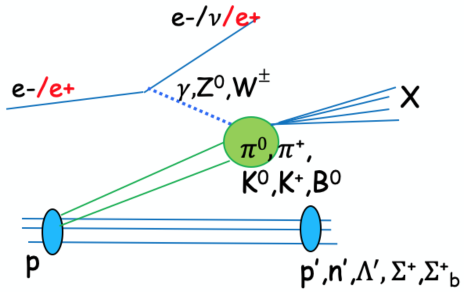


Saturation (coherent/incoherent J/ψ production)



Meson structure:

- with neutron tagging (ep→ (π) →e' n X)
- Lambda decays ($\Lambda \rightarrow p\pi^-$ and $\Lambda \rightarrow n\pi^0$)



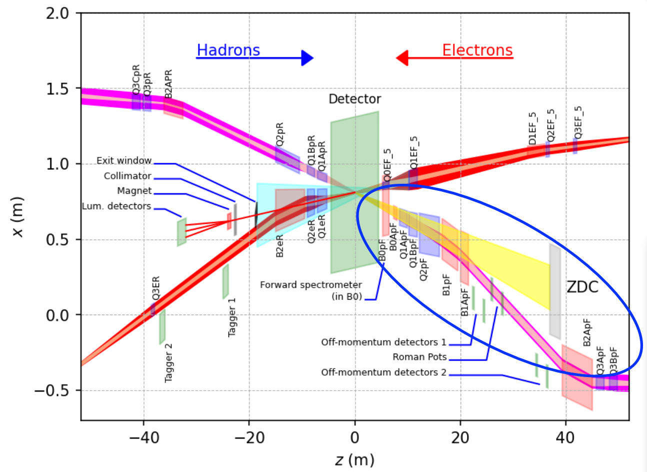
e+He3 with spectator proton tagging.

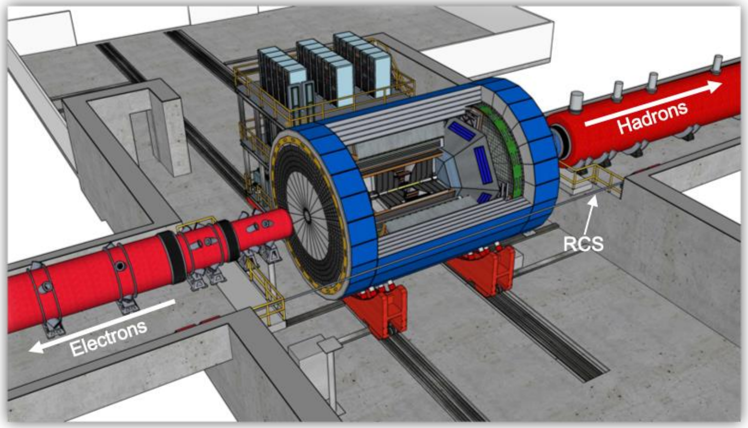
Tagging of coherent light ions (d, He3, He4) from coherent scattering.

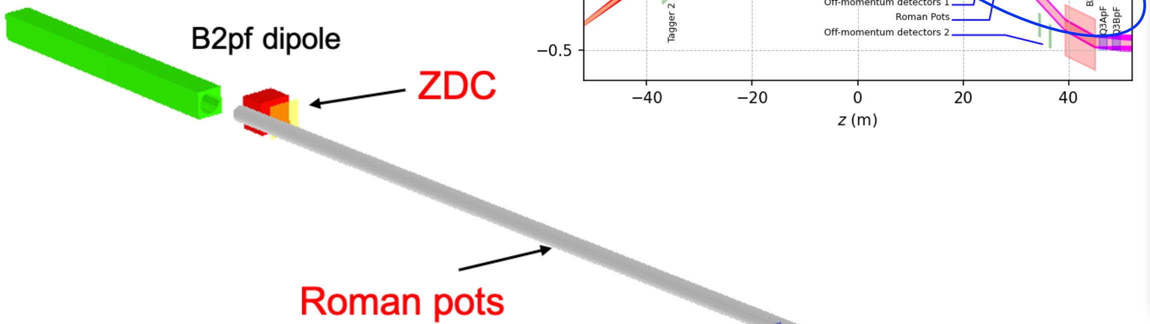
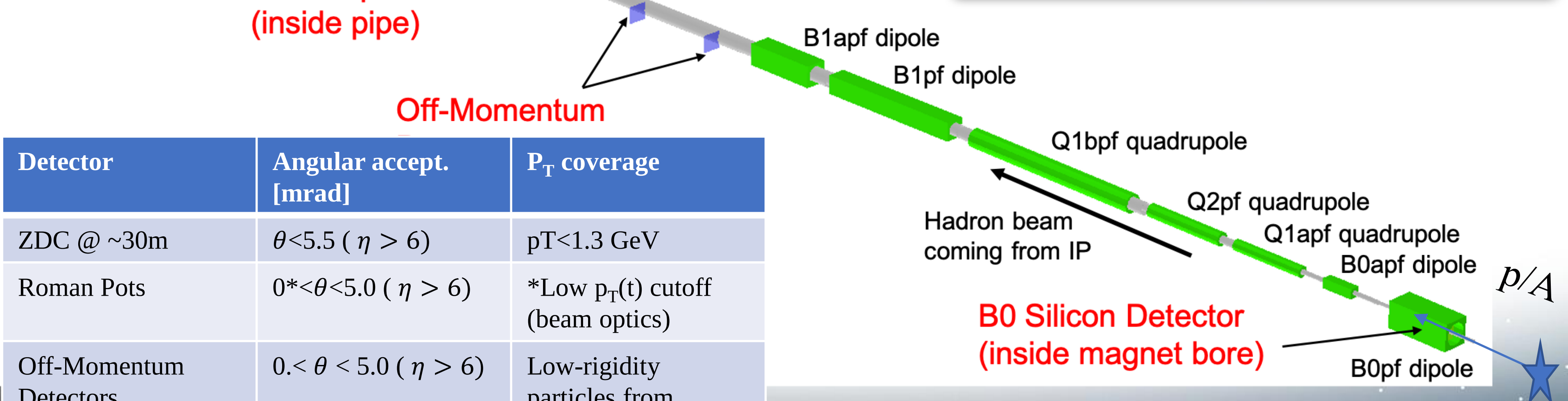
e+Au events with neutron tagging to veto breakup and photon acceptance.

….

Far forward (hadron going) region





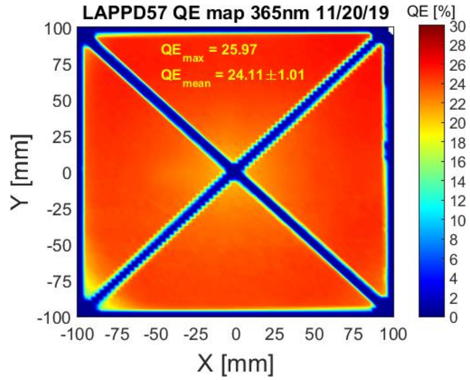
Detector	Angular accept. [mrad]	P_T coverage
ZDC @ ~30m	θ<5.5 ($\eta > 6$)	pT<1.3 GeV
Roman Pots	0*<θ<5.0 ($\eta > 6$)	*Low p_T(t) cutoff (beam optics)
Off-Momentum Detectors	0.< θ < 5.0 ($\eta > 6$)	Low-rigidity particles from nuclear breakups
B0 forward spectrometer	5.5 < θ < 20.0 (4.6< η < 5.9)	High p_T(t)

$$x_L = \frac{p_{z,nucleon}}{p_{z,beam}}$$

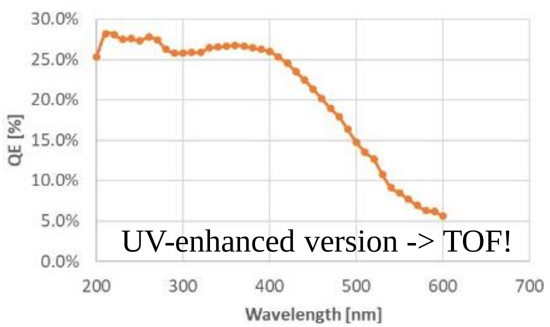
E.C. Aschenauer

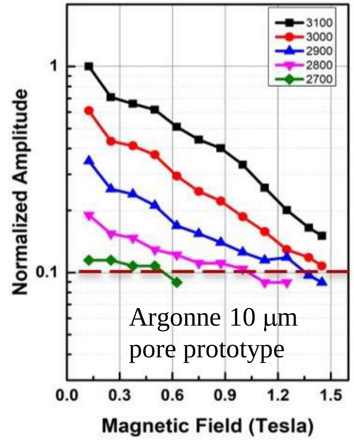
High resolution timing technologies

- *MCP-PMT / LAPPD*



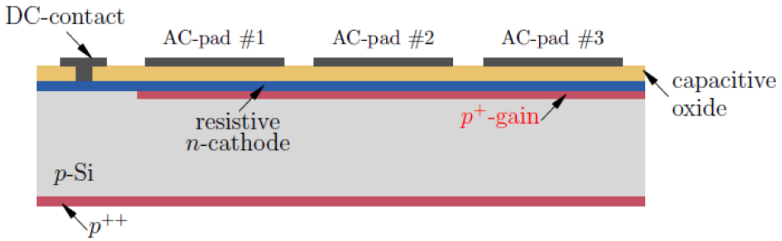
- QE routinely >20%
- >90% gain uniformity
- Single photon TTS <50 ps
- Performance in high B field is still of a concern

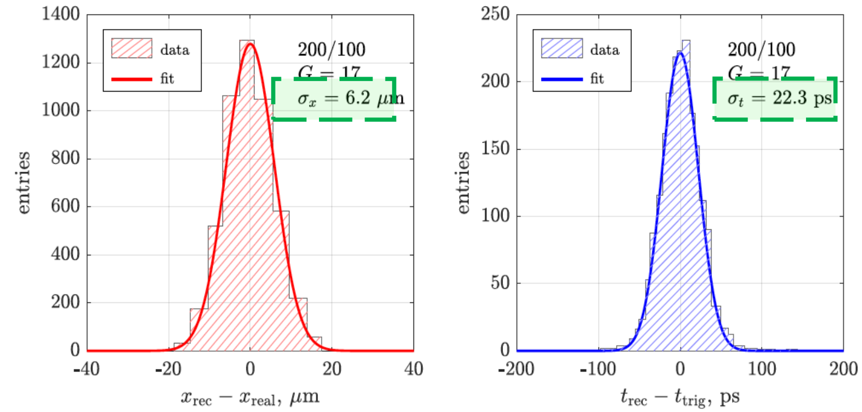




Expecting affordable detectors with <10ps timing on the EIC CD-2 time scale

- *(AC)-LGAD*

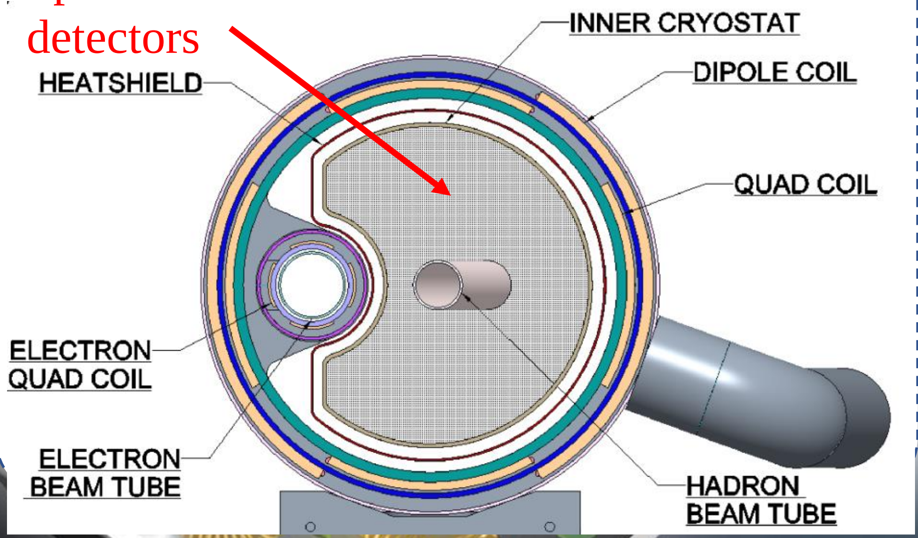




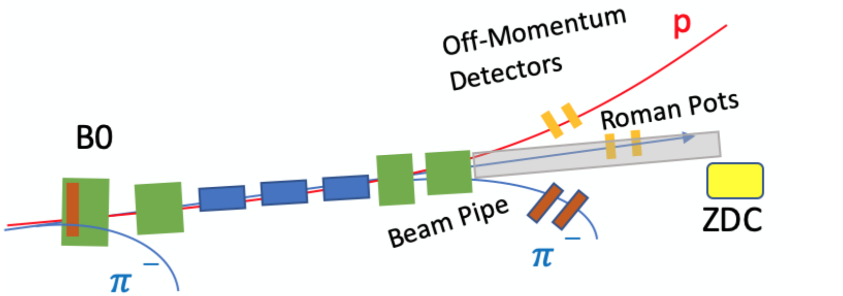
- Detectors can provide <20ps / layer
- AC-coupled variety gives 100% fill factor and potentially a high spatial resolution (dozens of microns) with >1mm large pixels

B0-spectrometer (5.5 < θ < 20.0 mrad)

- Warm space for detector package insert located inside a vacuum vessel to isolate from insulating vacuum.
- Higher granularity detectors needed in this area (**MAPS**) with layers of fast-timing detectors (**LGADs**)
- Shape and coverage of B0 tracker needs to be further evaluated

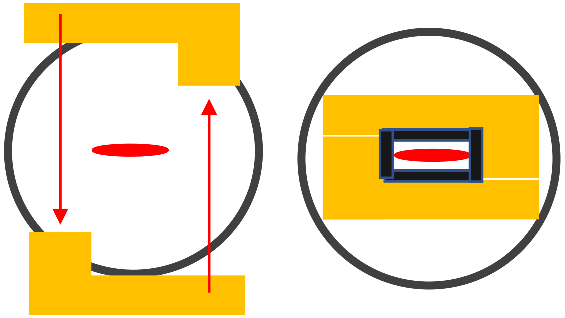


Roman-Pots and Off-momentum detectors 0.0* (10σ cut) < θ < 5.0 mrad



- Low Pt particles Pt < 1.3 GeV
- RPs: movable, integrated into the vacuum system
- Fast Timing and moderate granularity ($500x500\mu m^2$)
- **AC-LGADs**

$$\sigma(z) = \sqrt{\varepsilon \cdot \beta(z)}$$



IR Requirements from Physics

	Hadron	Lepton
Machine element free region	High Luminosity → beam elements need to be close to IP EIC: +/- 4.5 m for main detector beam elements < 1.5^o in main detector volume	
Beam pipe	Low mass material i.e. Beryllium	
Integration of Detectors	Local Polarimeter	Low Q^2-tagger Acceptance: $Q^2 < \sim 0.1$ GeV
Zero Degree Calorimeter	60cm x 60cm x 2m @ ~30 m	
scattered proton/neutron acc. all energies for ep	Proton: 0.18 GeV < p_t < 1.3 GeV $0.5 < x_L < 1$ ($x_L = E'_p/E_{Beam}$) Neutron: p_t < 1.3 GeV	
scattered proton/neutron acc. all energies for eA	Proton and Neutron: Θ < 6 mrad ($\sqrt{s}$=50 GeV) Θ < 4 mrad ($\sqrt{s}$=100 GeV)	
Luminosity	Relative Luminosity: $R = L^{++/--}/L^{+-/-+} < 10^{-4}$ → Flexible spin patters for both beams 1: +-+--+-++-+- 2: -+-++-+--+-+ 3: ++--++--++-- 4: --++--++--++	
		γ acceptance: +/- 1 mrad → $\delta L/L < 1\%$

most demanding

Subdetector Technology Choices

system	system components	reference detectors	detectors, alternative options considered by the community		
tracking	vertex	MAPS, 20 um pitch	MAPS, 10 um pitch		
	barrel	TPC	TPC[a]	MAPS, 20 um pitch	MICROMEGAS[b]
	forward & backward	MAPS, 20 um pitch & sTGCs[c]	GEMs	GEMs with Cr electrodes	
	very far forward & far backward	MAPS, 20 um pitch & AC-LGAD[d]	TimePix (very far backward)		
ECal	barrel	W powder/ScFi or Pb/Sc Shashlyk	SciGlass	W/Sc Shashlyk	
	forward	W powder/ScFi	SciGlass	PbGl	Pb/Sc Shashlyk or W/Sc Shashlyk
	backward, inner	$PbWO_4$	SciGlass		
	backward, outer	SciGlass	$PbWO_4$	PbGl	W powder/ScFi or W/Sc Shashlyk[e]
	very far forward	Si/W	W powder/ScFi	crystals[f]	SciGlass
h-PID	barrel	High performance DIRC & dE/dx (TPC)	reuse of BABAR DIRC bars	fine resolution TOF	
	forward, high p	double radiator RICH (fluorocarbon gas, aerogel)	fluorocarbon gaseous RICH	high pressure Ar RICH	
	forward, medium p		aerogel		
	forward, low p	TOF	dE/dx		
	backward	modular RICH (aerogel)	proximity focusing aerogel		
e/h separation at low p	barrel	hpDIRC & dE/dx (TPC)	very fine resolution TOF		
	forward	TOF & areogel			
	backward	modular RICH	adding TRD	Hadron Blind Detector	
HCal	barrel	Fe/Sc	RPC/DHCAL	Pb/Sc	
	forward	Fe/Sc	RPC/DHCAL	Pb/Sc	
	backward	Fe/Sc	RPC/DHCAL	Pb/Sc	
	very far forward	quartz fibers/ scintillators			

[a] TPC surrounded by a micro-RWELL tracker
[b] set of coaxial cylindrical MICROMEGAS
[c] Small-Strip Thin Gas Chamber (sTGC)
[d] MAPS for B0 and off-momentum poarticles, LGAD for Roman Pots
[e] also Pb/Sc Shashlyk
[f] alternative options: $PbWO_4$, LYSO, GSO, LSO

Alternatives to primary technologies for the different subdetectors fulfilling the requirements

→ risk reduction