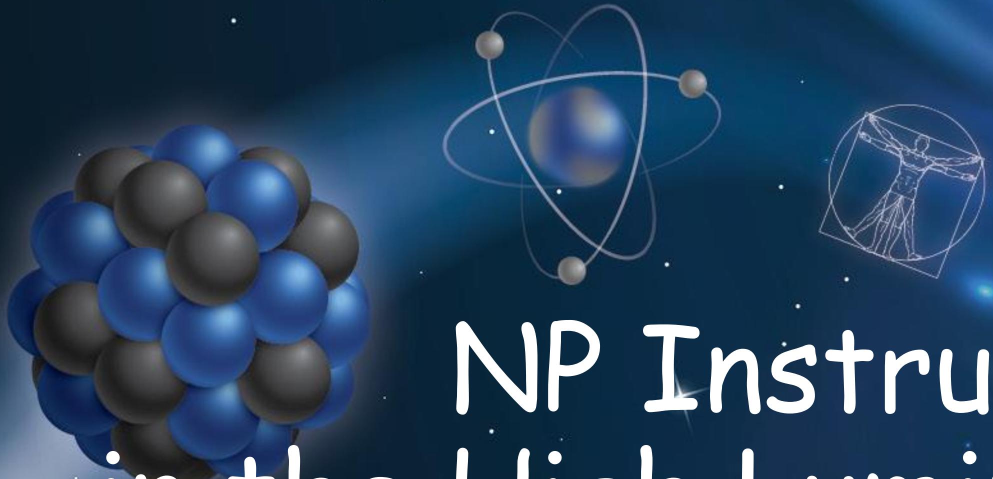
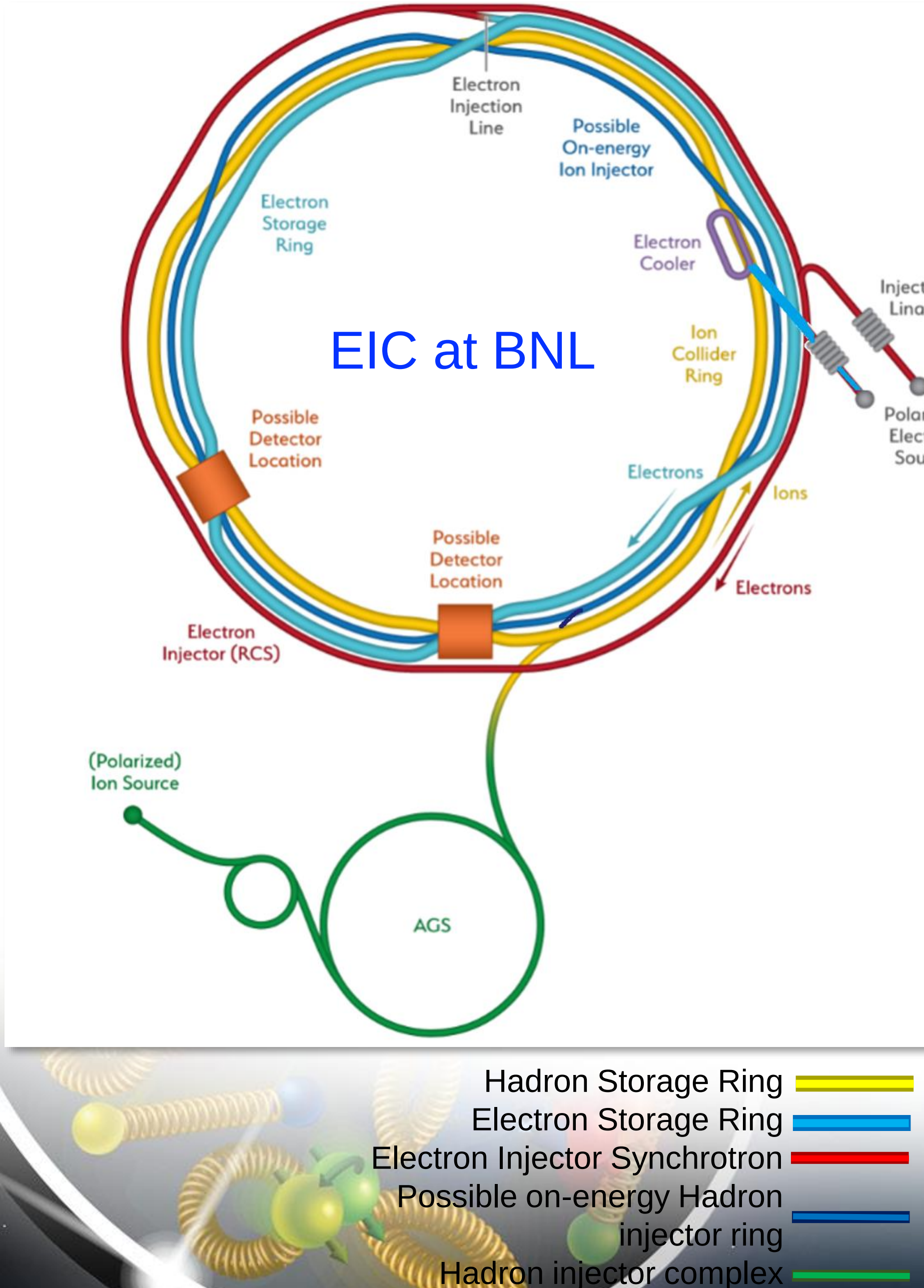


NP Instrumentation in the High Luminosity Era

Elke-Caroline Aschenauer (BNL)
Co-Associate Director for the
EIC Experimental Program

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

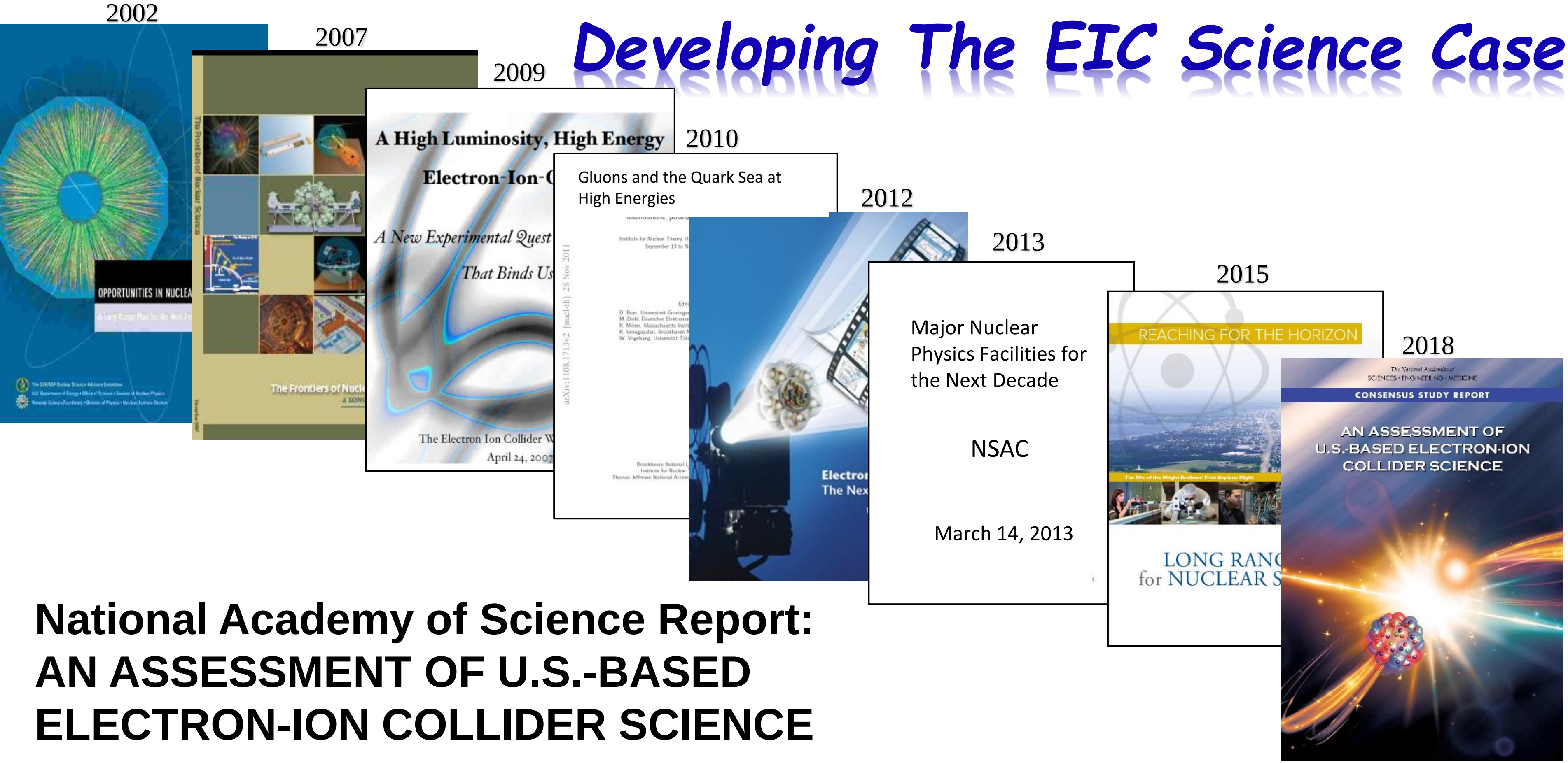
What is new/different:

Hera: factor 100 to 1000 higher luminosity 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

- ☐ Add electron beam 5 GeV to 18 GeV to RHIC hadron beams
- ☐ 25 mrad crossing angle
- ☐ both electrons and light ions (p,d,He-3) polarized
- ☐ 9 ns bunch spacing
- ☐ 2 interaction regions

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:

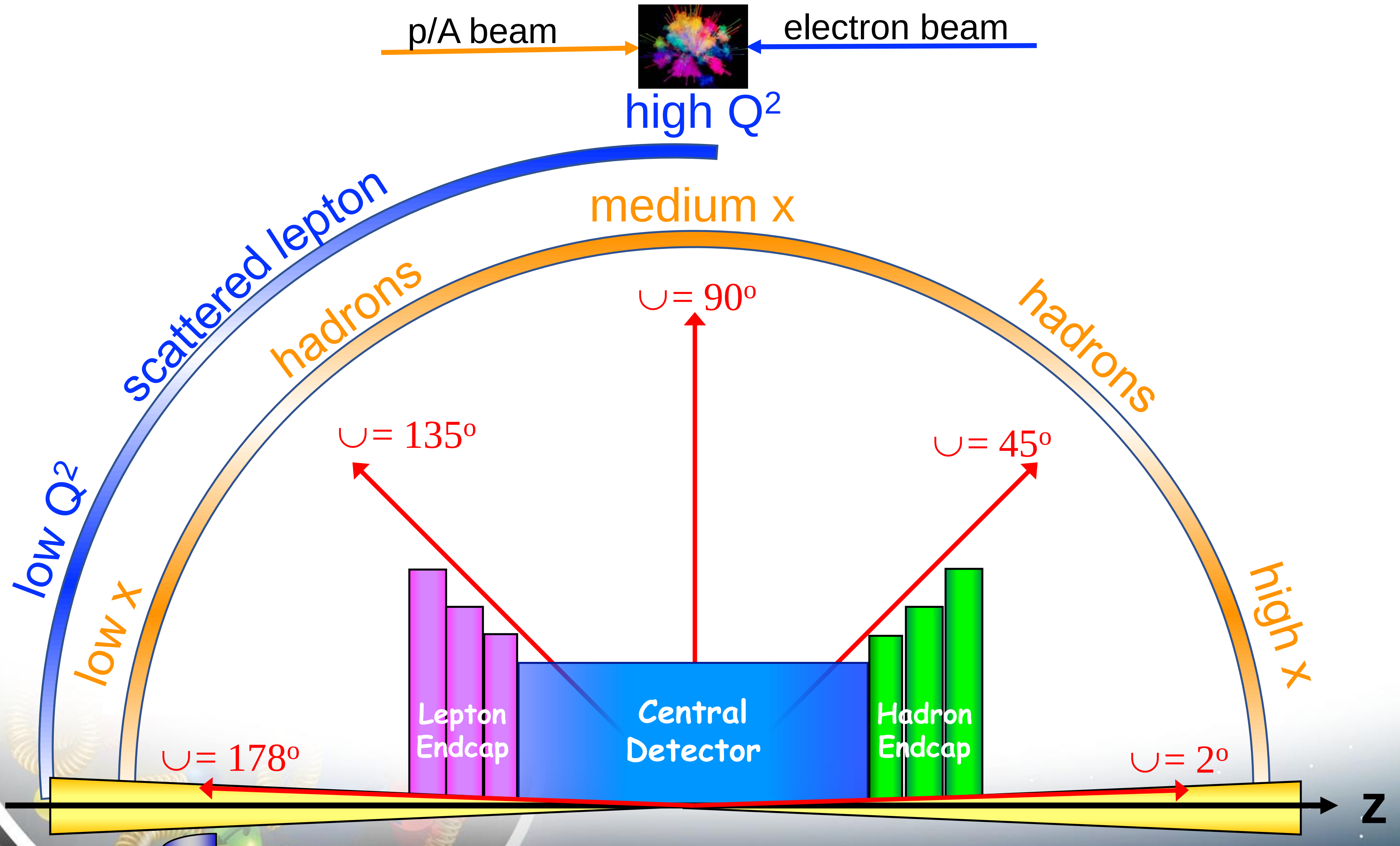
- **How does the mass of the nucleon arise?**
- **How does the spin of the nucleon arise?**
- **What are the emergent properties of dense systems of gluons?”**

The EIC: A Unique Collider

EIC	LHC /RHIC
collide different beam species: ep & eA → consequences for beam backgrounds → hadron beam backgrounds, i.e. beam gas events → synchrotron radiation	collide the same beam species: pp, pA, AA → beam backgrounds → hadron beam backgrounds, i.e. beam gas events, high pile up
asymmetric beam energies → boosted kinematics → high activity at high $\|\eta\|$	symmetric beam energies → kinematics is not boosted → most activity at midrapidity
Small bunch spacing: >= 9ns	moderate bunch spacing: 25 ns
crossing angle: 25mrad	no crossing angle yet
wide range in center of mass energies → factor 6	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
both beams are polarized → stat uncertainty: $\sim 1/(P_1 P_2 (\int L\,dt)^{1/2})$	no beam polarization → stat uncertainty: $\sim 1/(\int L\,dt)^{1/2}$

Differences impact detector acceptance and possible detector technologies

EIC General Purpose Detector: Concept



and all the detectors integrated in the IR along the beam line

Background/Radiation

The HERA and KEK experience show that having backgrounds under control is crucial for the EIC detector performance

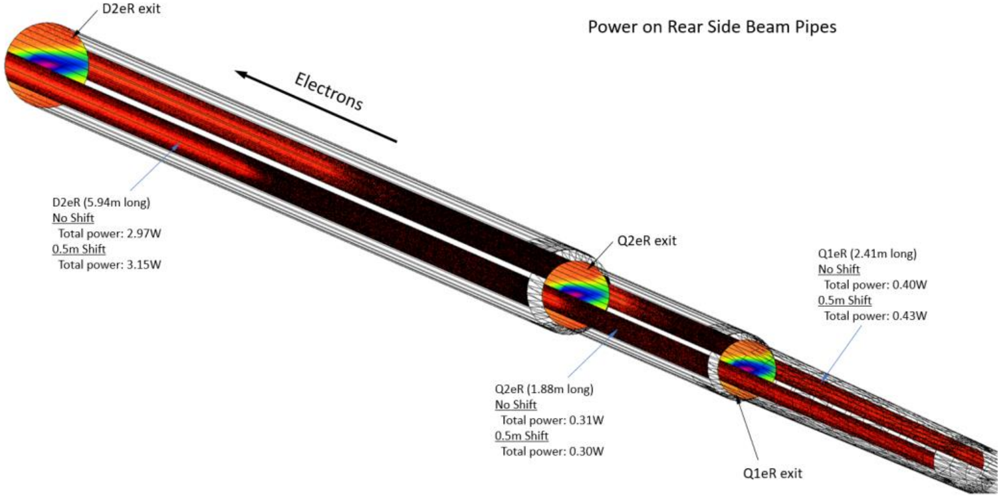
- There are several background/radiation sources :
  - primary collisions
  - beam-gas induced
  - synchrotron radiation

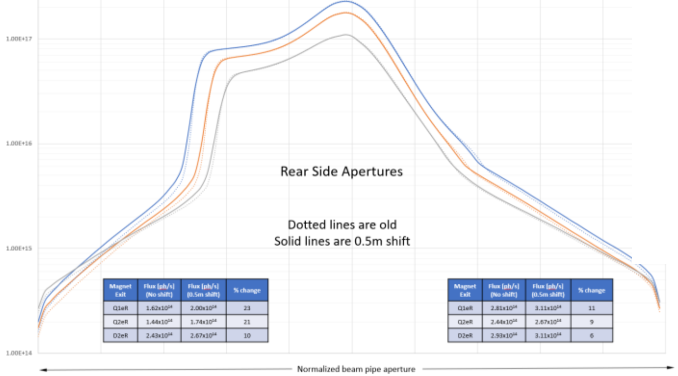
Important to note:

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

Synchrotron Radiation:

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



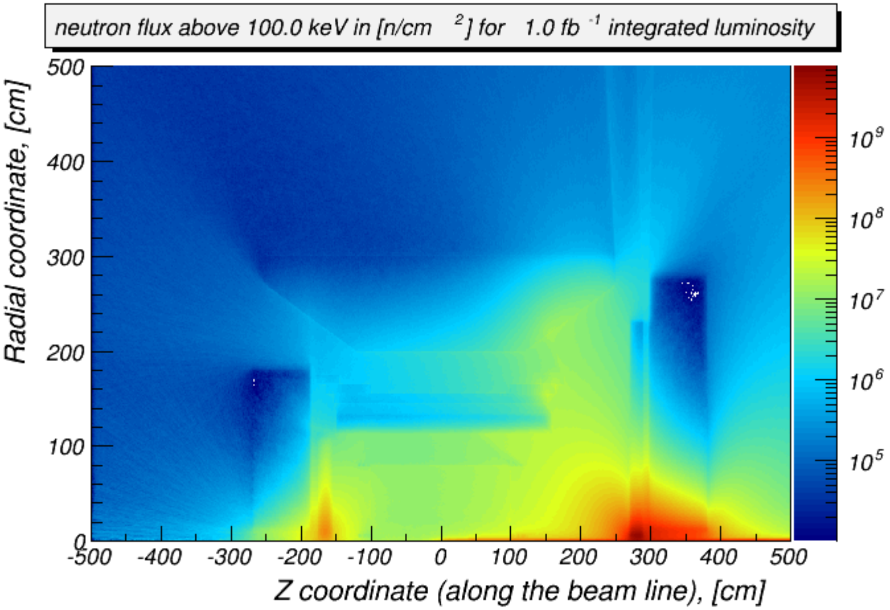


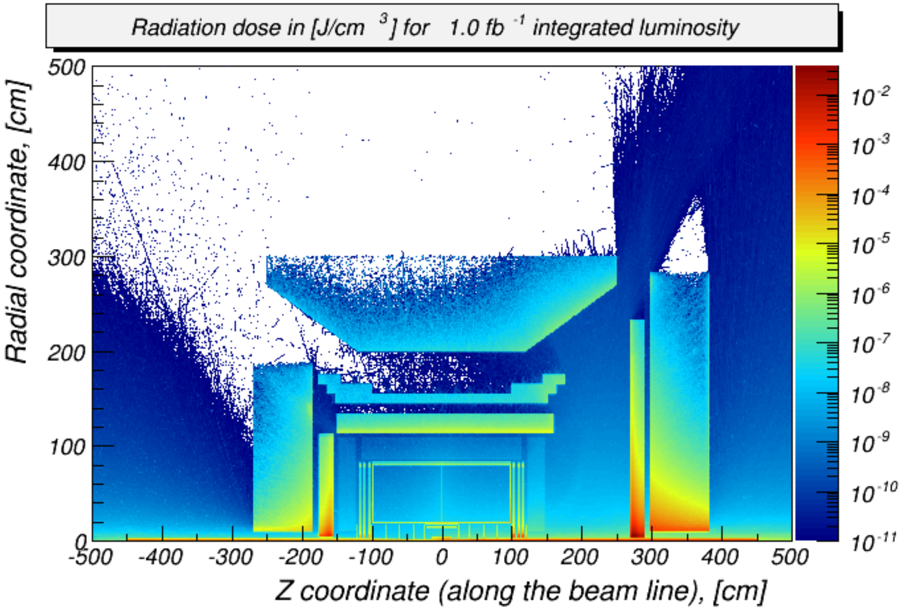
Magnet Exit	Flux (ph/s) (No shift)	Flux (ph/s) (0.5m shift)	% change
Q1eR	1.62×10^{14}	2.00×10^{14}	23
Q2eR	1.44×10^{14}	1.74×10^{14}	21
D2eR	2.43×10^{14}	2.67×10^{14}	10

Magnet Exit	Flux (ph/s) (No shift)	Flux (ph/s) (0.5m shift)	% change
Q1eR	2.81×10^{14}	3.11×10^{14}	11
Q2eR	2.44×10^{14}	2.67×10^{14}	9
D2eR	2.93×10^{14}	3.11×10^{14}	6

Background/Radiation

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



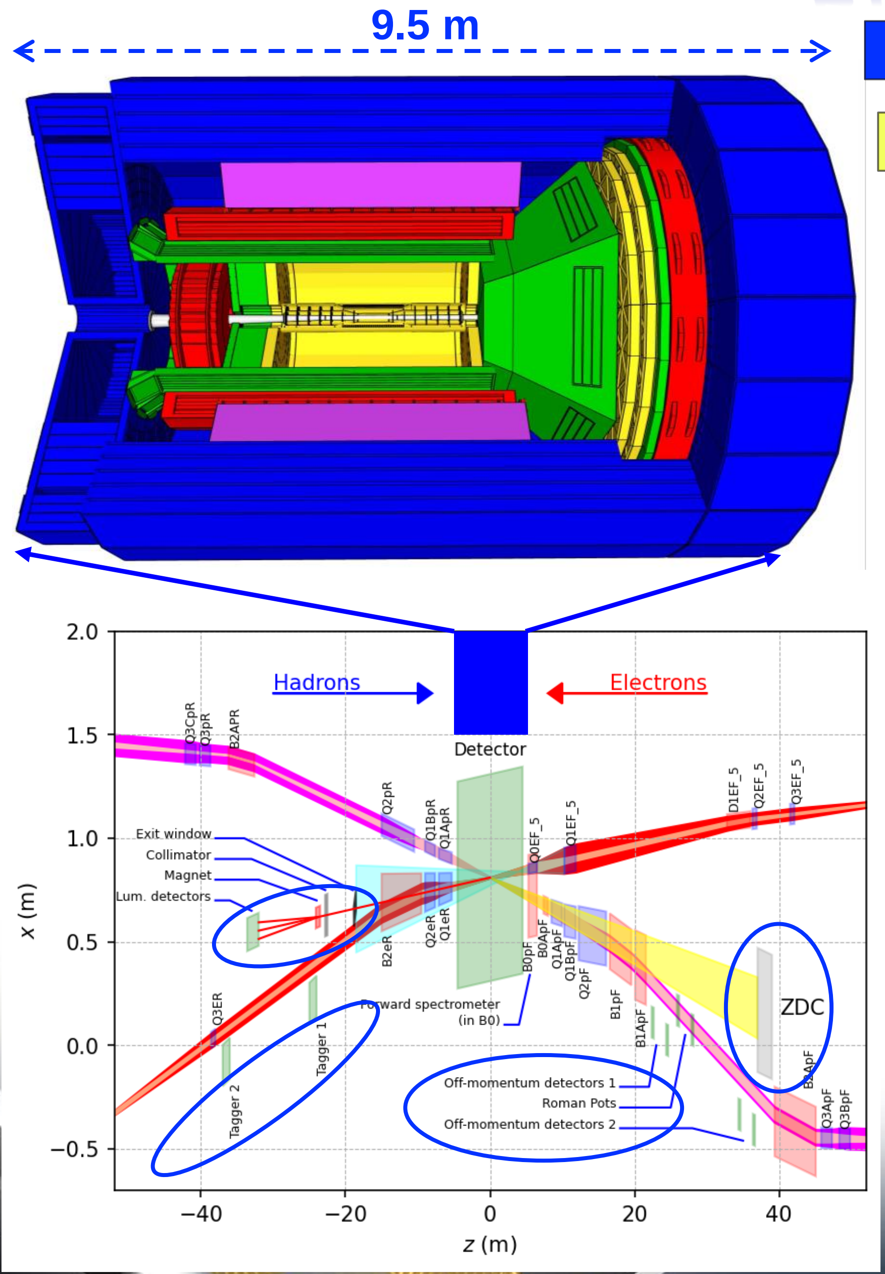


→forward EmCal: up to ~5*10^9 n/cm^2 per fb^{-1} (*inside the towers*); perhaps ~5 less at the SiPM location

→ 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) in the 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 ($-4 < \eta < 4$) coverage; and far beyond in especially far-forward detector regions
- ☐ High precision low mass tracking
  - ○ small (μ-vertex) and large radius (gaseous-based) tracking
- ☐ Electromagnetic and Hadronic Calorimetry
  - ○ equal coverage of tracking and EM-calorimetry
- ☐ High performance PID to separate π, K, p on track level
  - ○ also need good e/h separation for scattered electron
- ☐ Large acceptance for diffraction, tagging, neutrons from nuclear breakup: critical for physics program
  - ○ Many ancillary detector integrated in the beam line: low-Q^2 tagger, Roman Pots, Zero-Degree Calorimeter, ….

  → Integration into IR critical
- ☐ 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

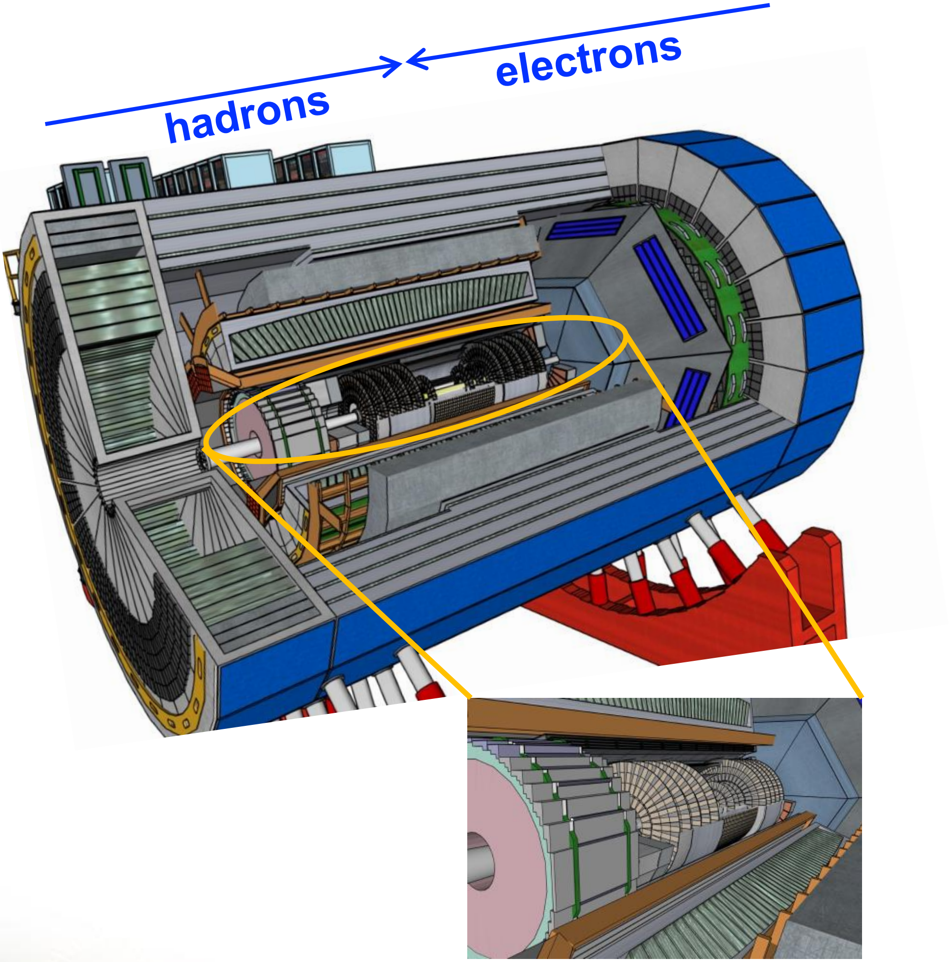
↔

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



EIC general purpose Detector around a new 3T Solenoid

Hermetic coverage:

$2^o < \Theta < 178^o$ ($-4<\eta<4$) with 2π in Φ

→ 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

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

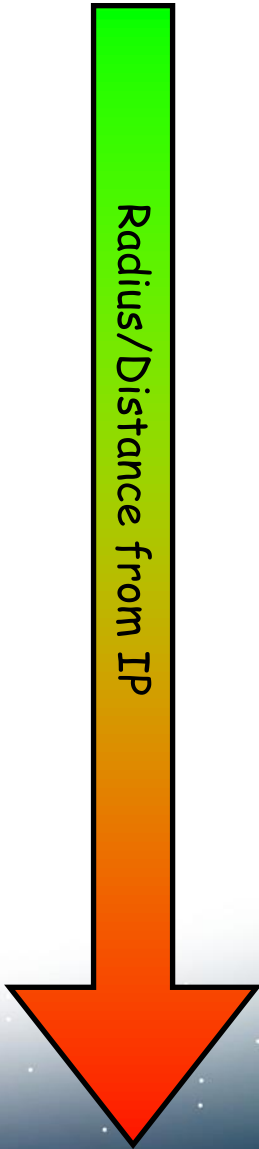
Particle Identification → pion, kaon, proton separation
RICH detectors & Time-of-Flight
high resolution timing detectors (, LAPPS, LGAD) 10 – 30 ps
novel photon sensors: MCP-PMT / LAPPD

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%/$\sqrt{E}$ + 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



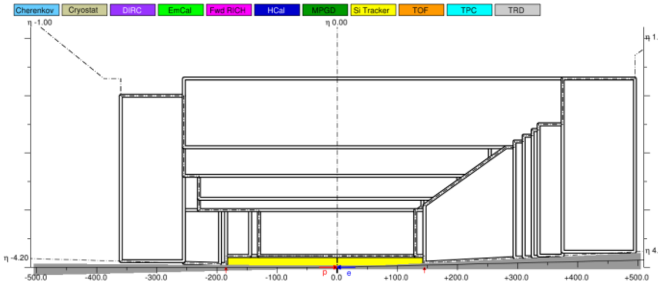
MAPS μVertex

- For primary and secondary vertex reconstruction
- Low material budget: 0.05% X/X_0 per layer

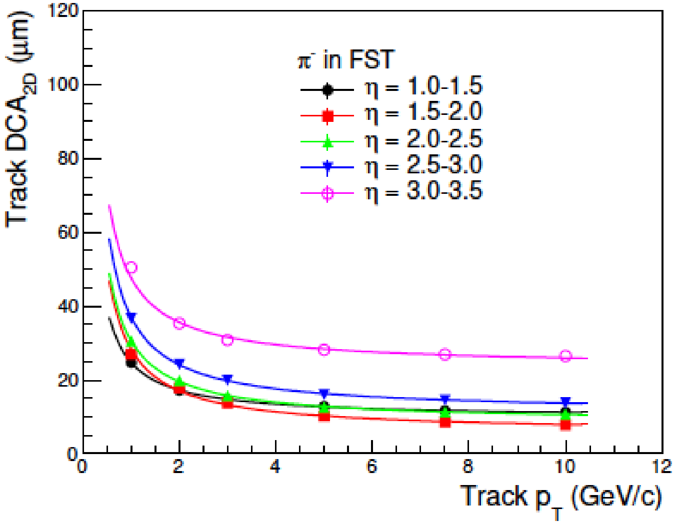
  High spatial resolution: 10 μm pitch MAPS

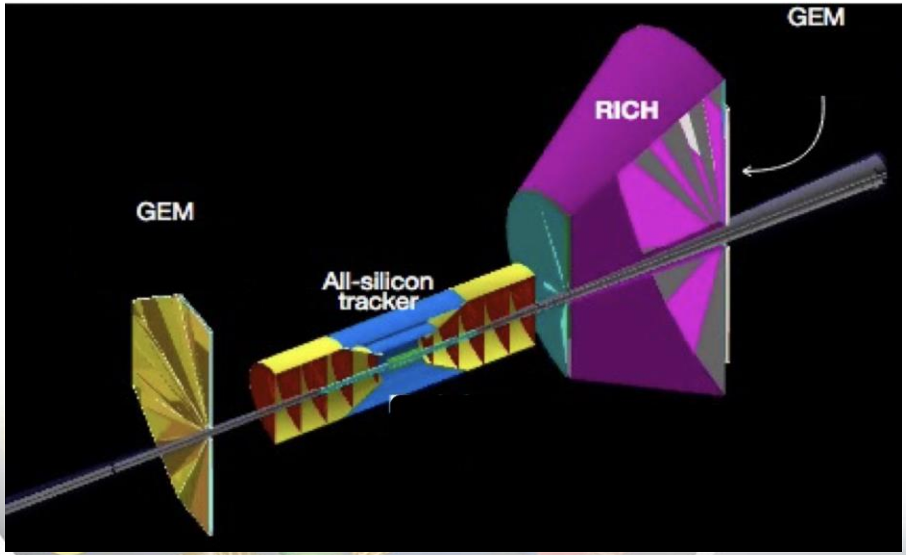
  → ref. Alice ITS3
- Compromise:

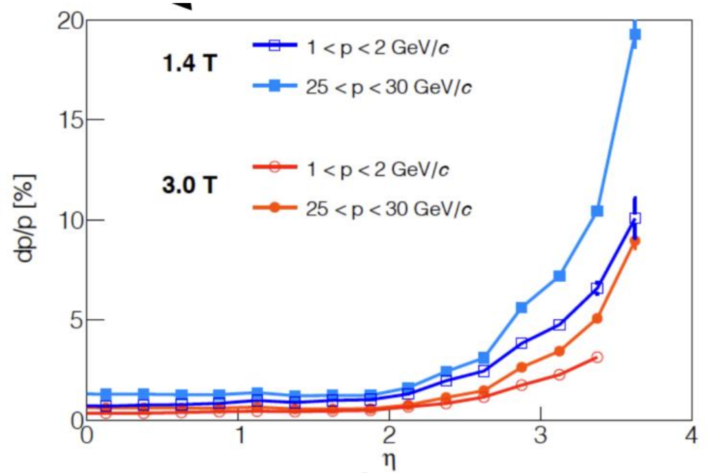
  20 μm (or smaller) pixels and ~0.3% X/X_0 per layer
- Barrel+ Disks for endcaps



DCA$_{2D}$ resolution VS p_T

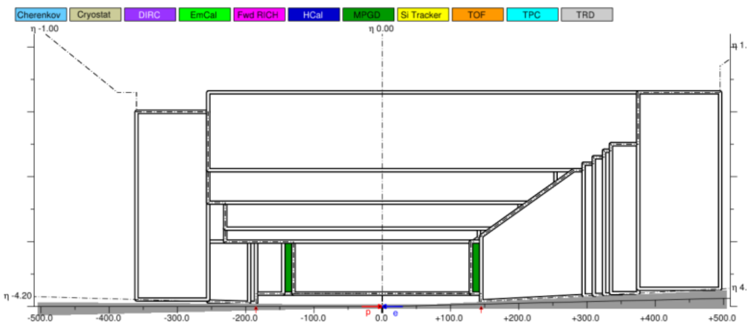


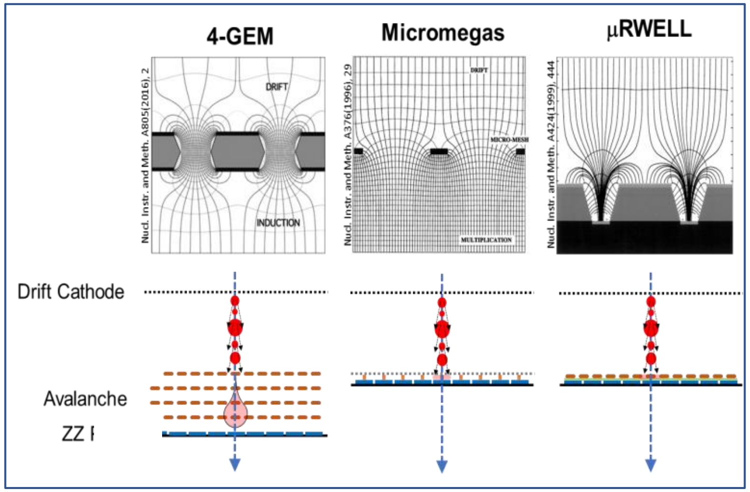


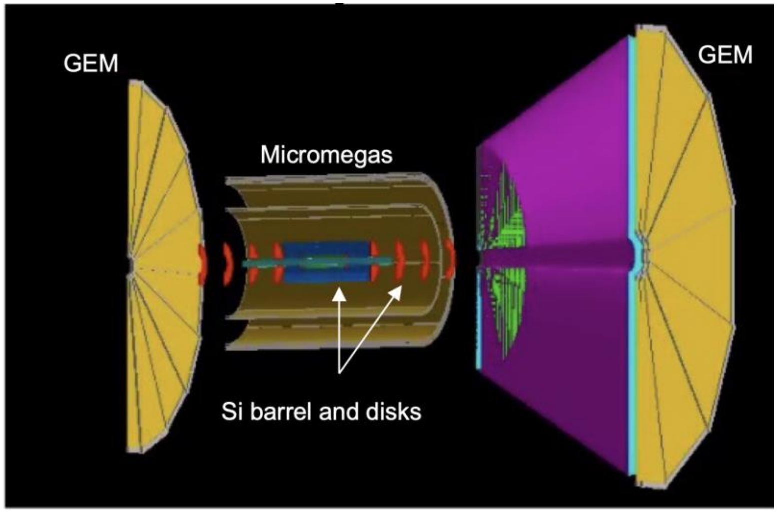


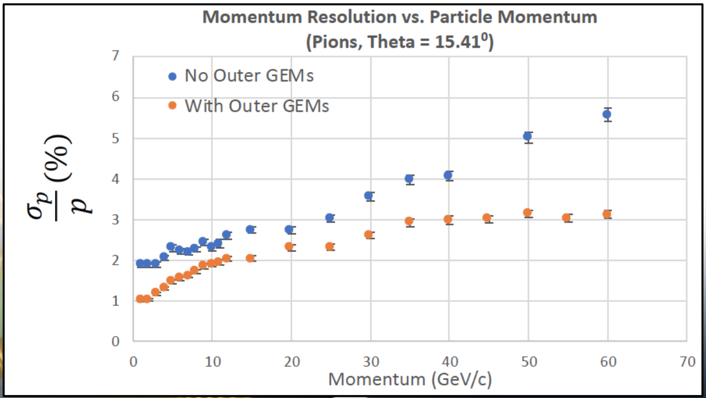
Endcaps: MPGDs

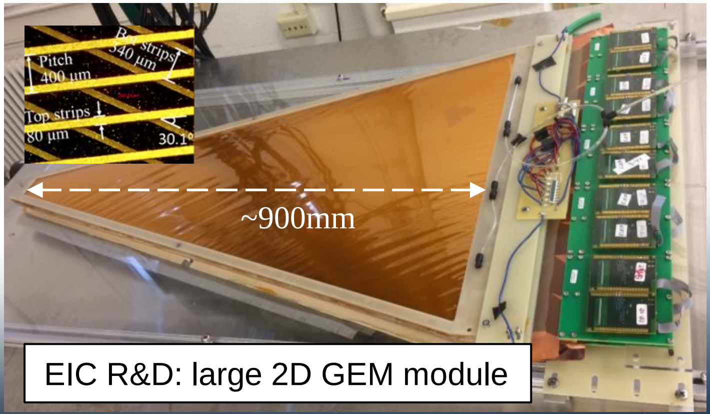
- To improve momentum resolution at large rapidities.
- Spatial resolution well below 100 μm
- Large-area detectors possible
- Cost efficient compared to silicon











EIC R&D: large 2D GEM module

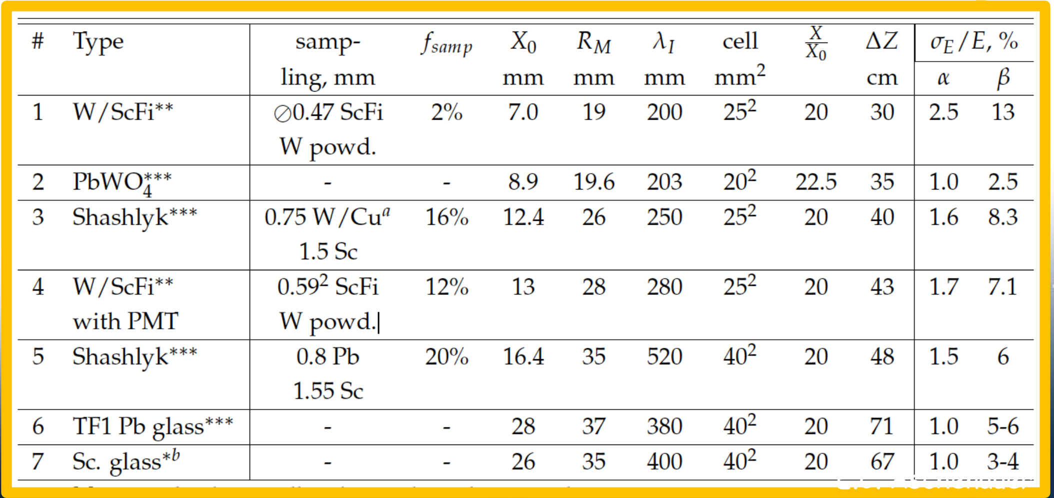
Electro-Magnetic Calorimeter

- 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 → may also consider a highly segmented preshower combined with ToF and tracking → three in one
- Anticipated stochastic term in energy resolution & available space

η	[-4 .. -2]	[-2 .. -1]	[-1 .. 1]	[1 .. 4]
σ_E/E	~2%/√E	~7%/√E	~10-12%/√E	~10-12%/√E
space	~50 cm	~50 cm	~30 cm	~40 cm

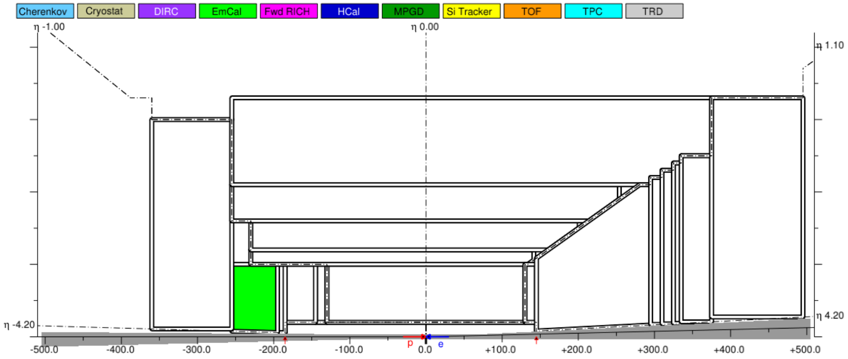
- Other considerations
  - Fast timing
  - Compactness (small X_0 and R_M)
  - Tower granularity
  - Readout immune to the magnetic field

EIC Yellow Report



#	Type	sampling, 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

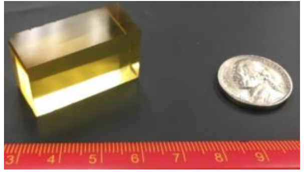
Crystals



- 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

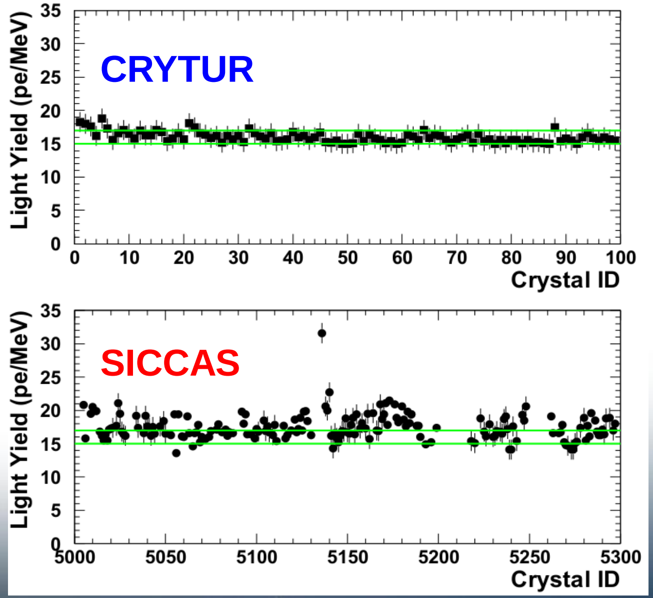


2019: 2cm x 2cm x 4cm

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

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

PWO: vendor characterization



EIC PID

needs
are more demanding
then your
normal
collider detector

EIC

needs absolute
particle numbers at
high purity and low
contamination

Particle ID

- In general, need to separate:
  - Electrons from photons → 4π coverage in tracking
  - Electrons from charged hadrons → mostly provided by calorimetry
  - Charged pions, kaons and protons from each other → Cherenkov detectors
    - Cherenkov detectors, complemented by other technologies at lower momenta

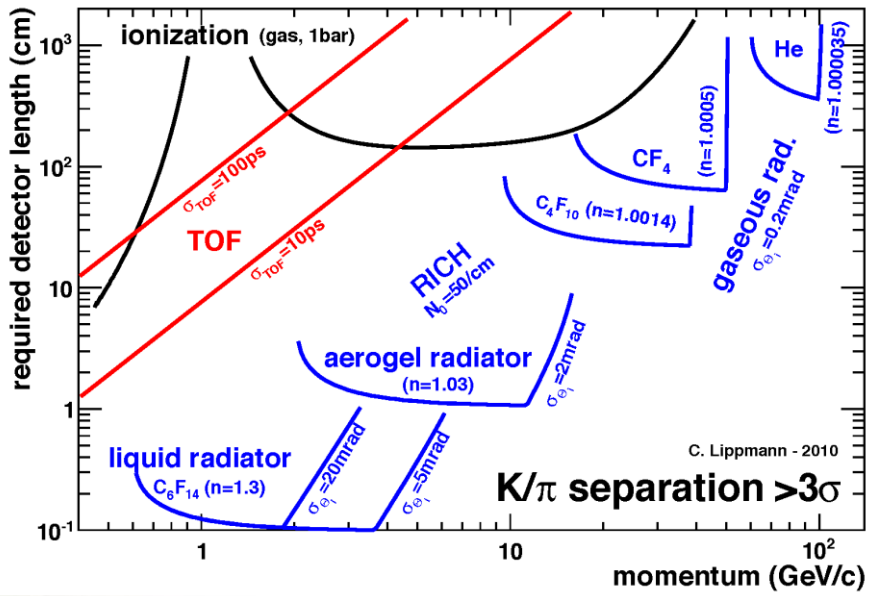
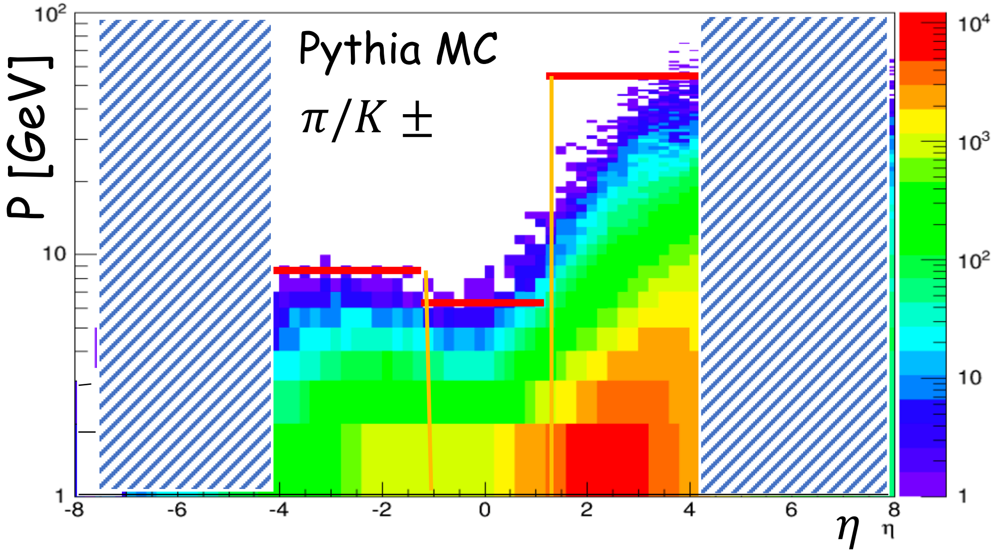


Illustration of PID detectors achievements:

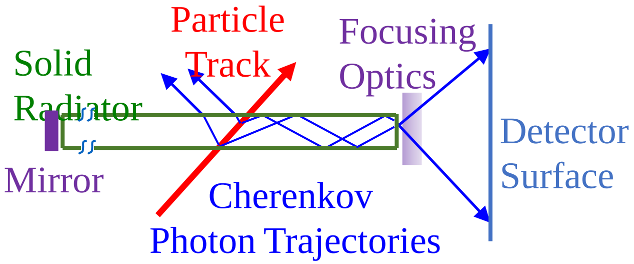


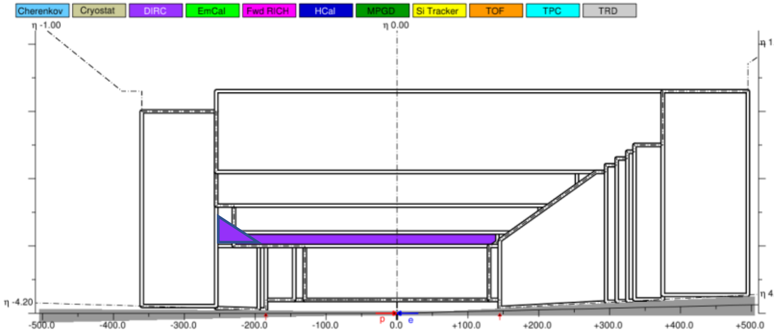
Need more than one technology to cover the entire momentum ranges at different rapidities

Physics requirements:

Rapidity	π/K/p and π0/γ	e/h	Min pT (E)
-3.5 – -1.0	7 GeV/c	18 GeV/c	100 MeV/c
-1.0 – 1.0	8-10 GeV/c	8 GeV/c	100 MeV/c
1.0 – 3.5	50 GeV/c	20 GeV/c	100 MeV/c

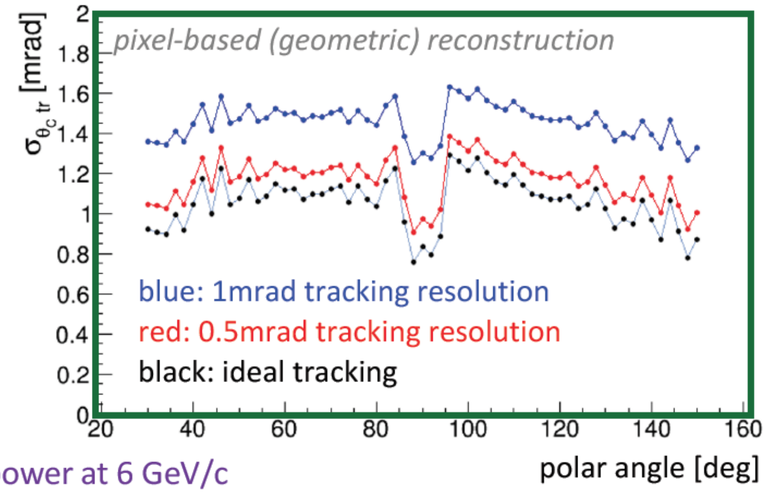
DIRC

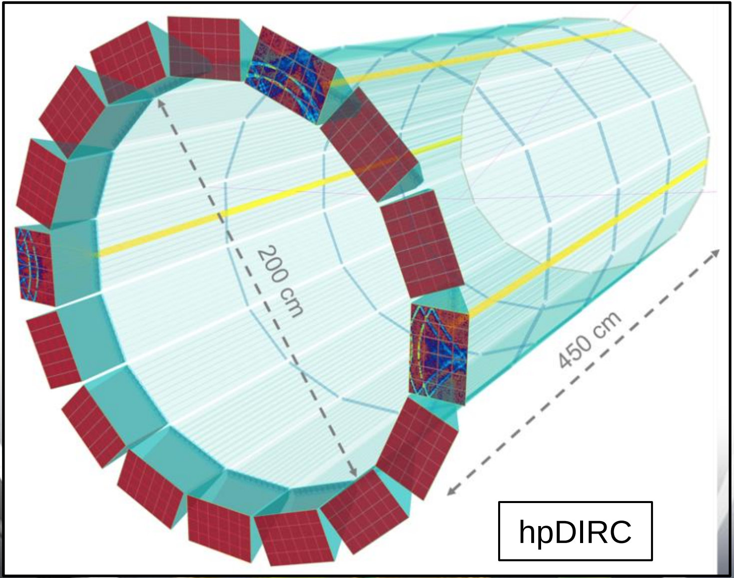




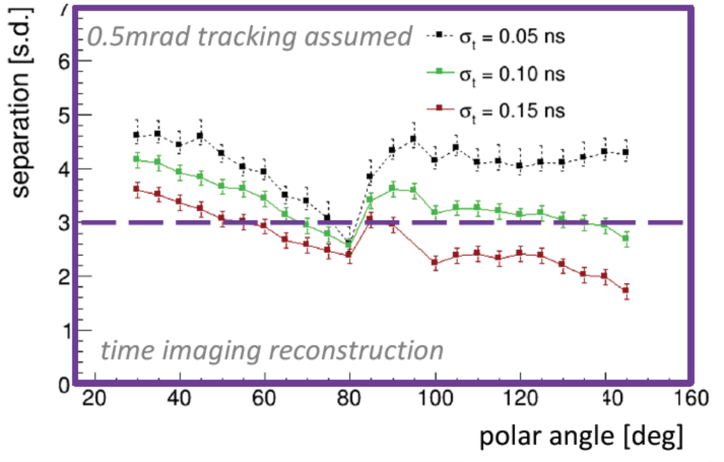
- Radially compact (~ 5cm)
- high-performance DIRC with better optics and <100 ps timing (π/K up to ~6 GeV/c)
- Re-use BaBar quartz bars ?
- Integration into a 4π detector can be challenging

Cherenkov angle resolution angle per particle

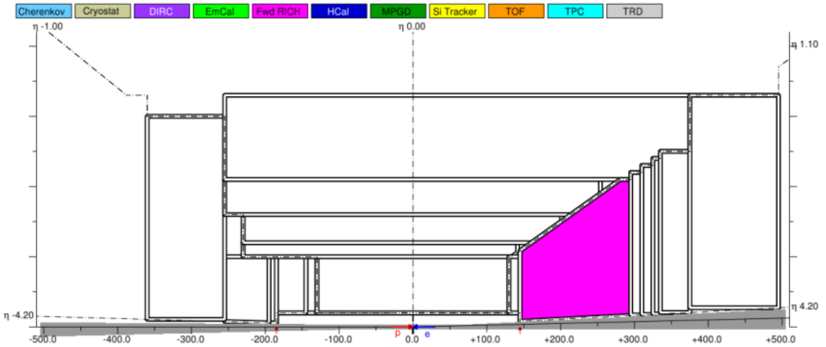




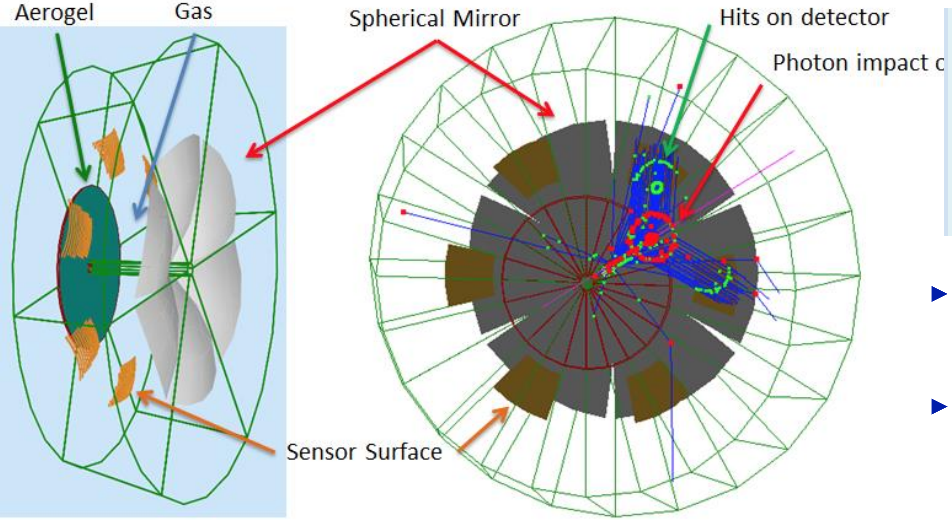
π/K separation power at 6 GeV/c



Dual radiator RICH

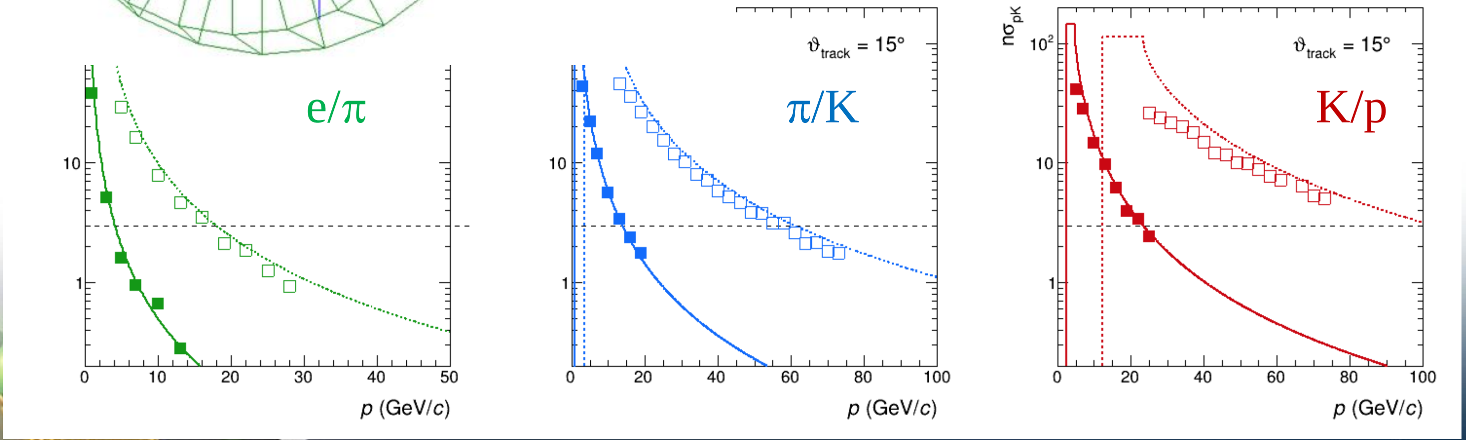


- Hadron PID in the forward/hadron end-cap
- Use a combination of aerogel and C_mF_n with indices of refraction matching EIC momentum range in the forward endcap
- Similar to LHC-b, HERMES, JLAB/Hall-B, …



Radiators:	Aerogel (n_{AERO}~1.02) + Gas (n_{C2F6} ~ 1.0008)
Detector:	0.5 m^2/sector , 3x3 mm^2 pixel
	Single-photon detection in ~1T magnetic field
	Outside acceptance, reduced constraints

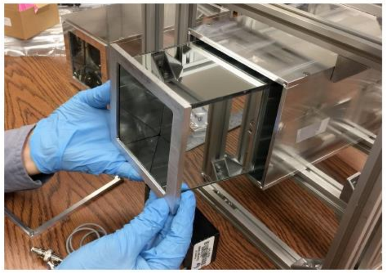
- Continuous **>3σ π/K separation up to 60 GeV/c** and K/p separation to higher momenta
- >3σ e/π separation up to ~15 GeV/c



Modular-RICH (mRICH)

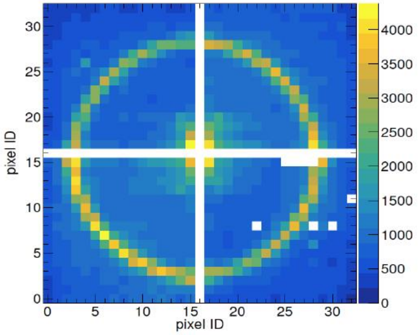
- *For hadron PID in the electron end-cap*
- *Compact* version of a conventional aerogel-based proximity focusing RICH

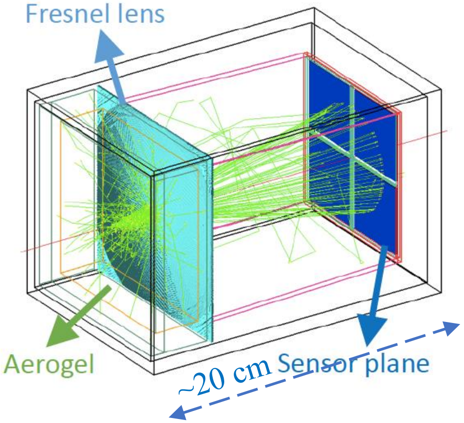
New features: a) separation of optical and electronic components; b) longer focal length (6”); c) 3mm x 3mm photosensors.



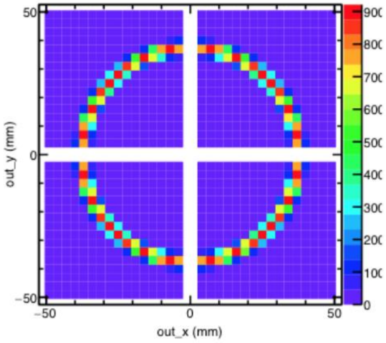
2nd mRICH prototype was tested at Fermilab Test Beam Facility in June/July 2018

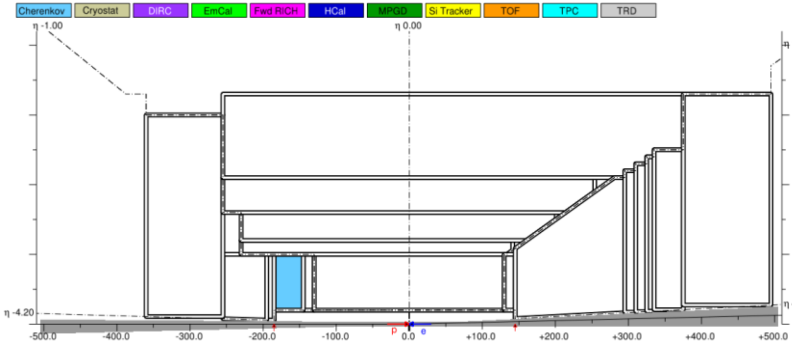
Beam Test at Fermilab

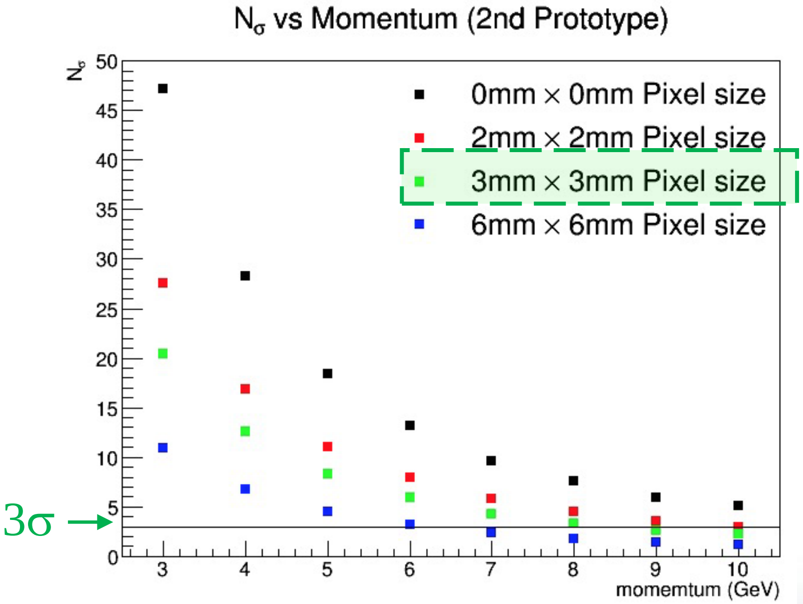




GEANT4 Simulation





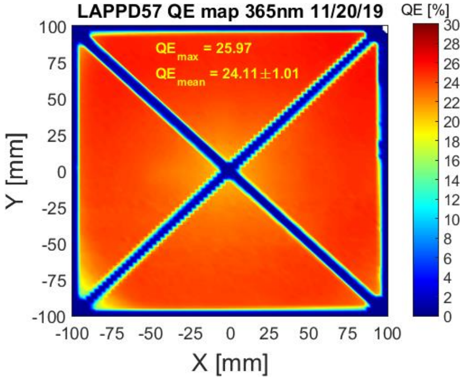

N_σ vs Momentum (2nd Prototype)

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

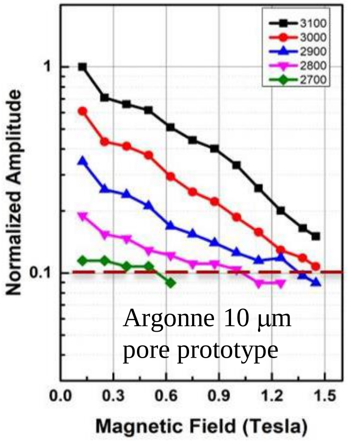
- Was also tested with SiPM readout
- LAPPD readout – spring 2021

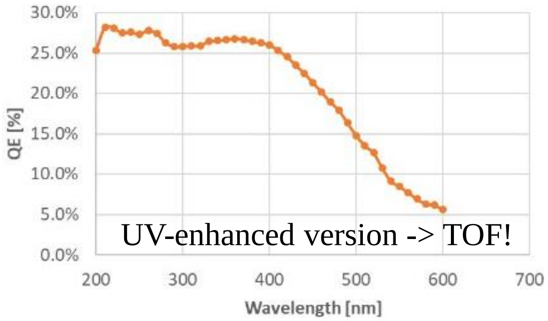
High resolution timing technologies

MCP-PMT / LAPPD



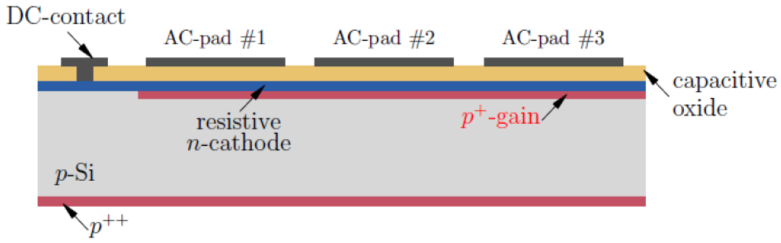
- QE routinely >20%
- >90% gain uniformity
- Single photon TTS <50 ps
- Performance in high B field is still of a concern

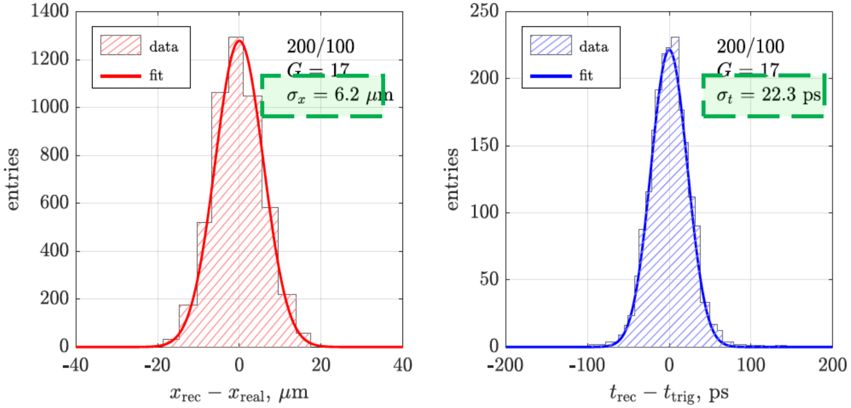




Expecting affordable detectors with <10ps timing on the EIC CD-2 time scale

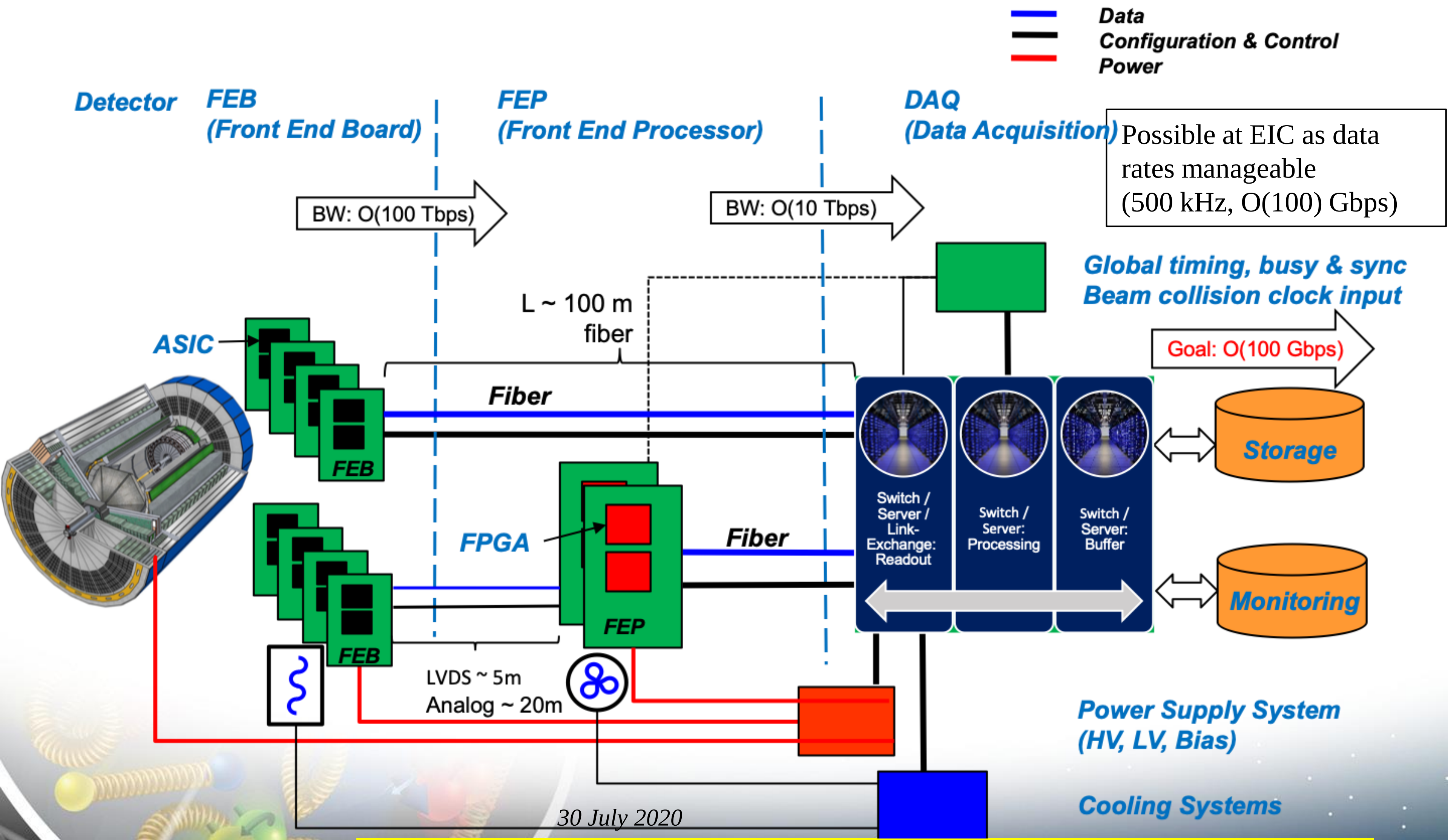
(AC)-LGAD





- 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

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.

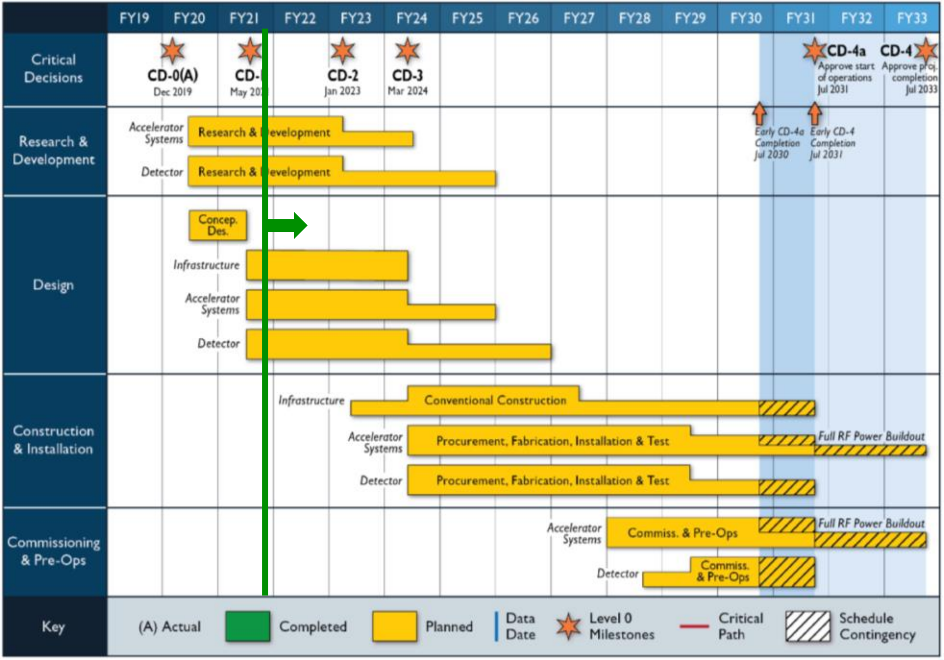
- **Network Switches/Servers/Computing**
  - High performance COTS infrastructure.
  - Enables further reduction of data flow prior to storage via sophisticated algorithms, e.g., ML and AI.

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	January 2023
Goal for CD-3 Approval	March 2024
Goal for CD-4 Early Project Completion	**July 2031**



Take Away Message

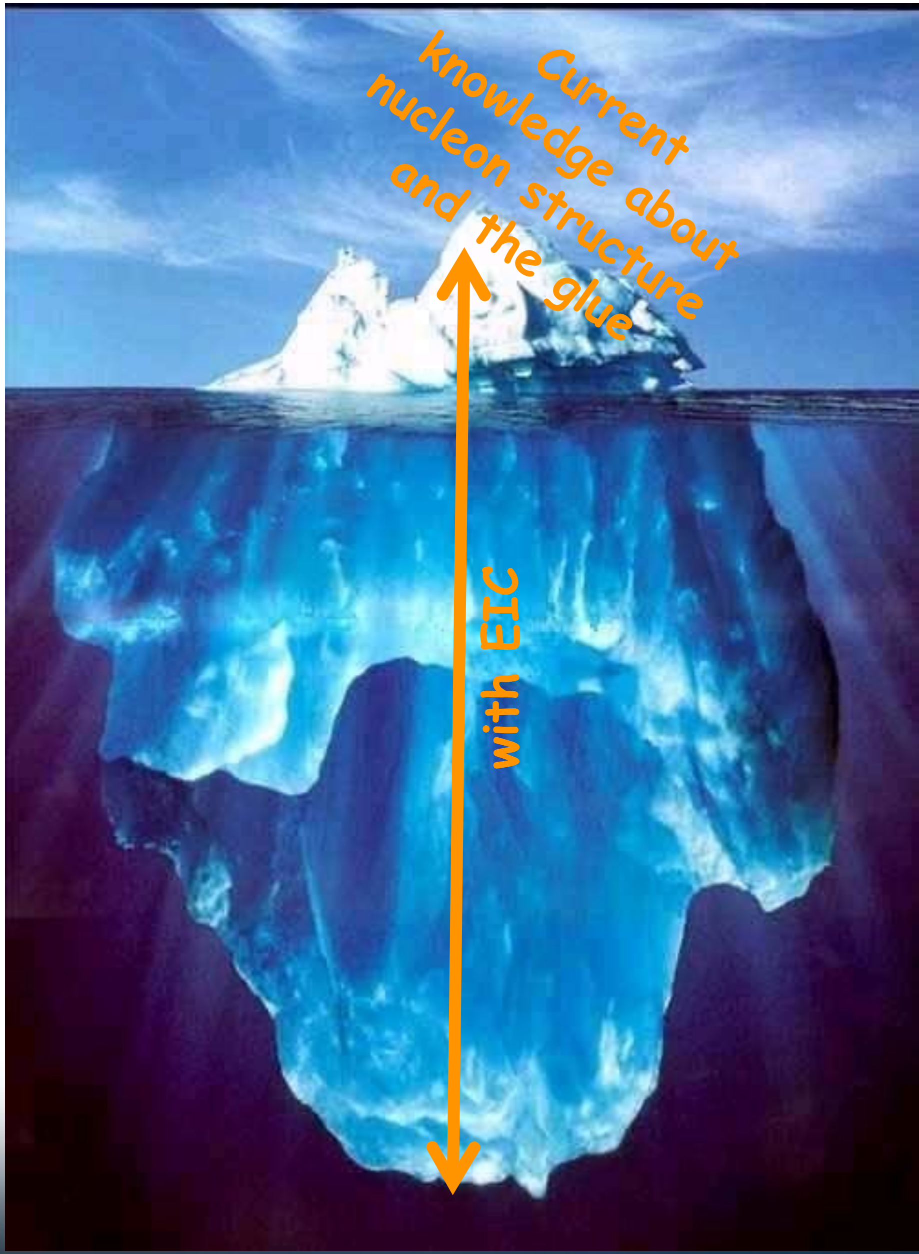
Why EIC now?

“all stars align”:

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

BUT MOST IMPORTANTLY

- ☐ accelerator technologies allow to built a collider with
  - ➢ high luminosity
  - ➢ highly polarized electron and light hadron beams
  - ➢ a wide range in center of mass energies
  - ➢ hadron beams with highest A
  - ➢ demanding acceptance requirements can be realized in IR design



Let’s get to work and built the EIC

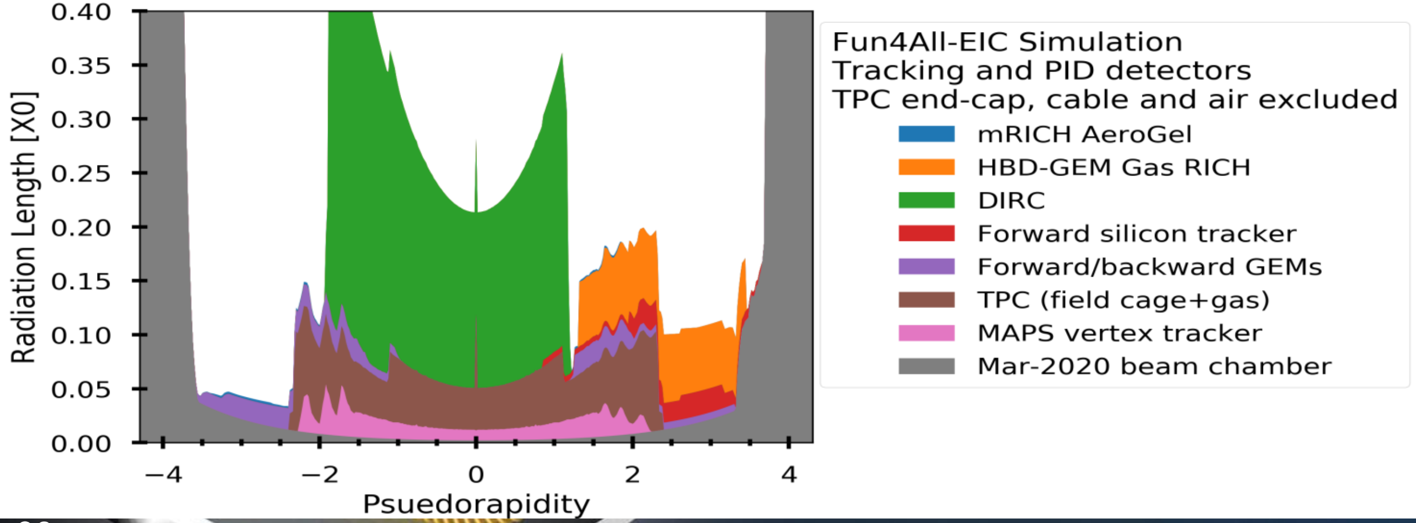
Please join us

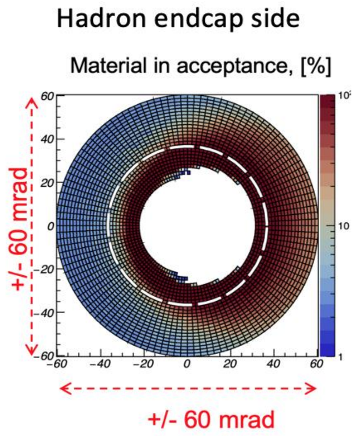
BACK UP

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

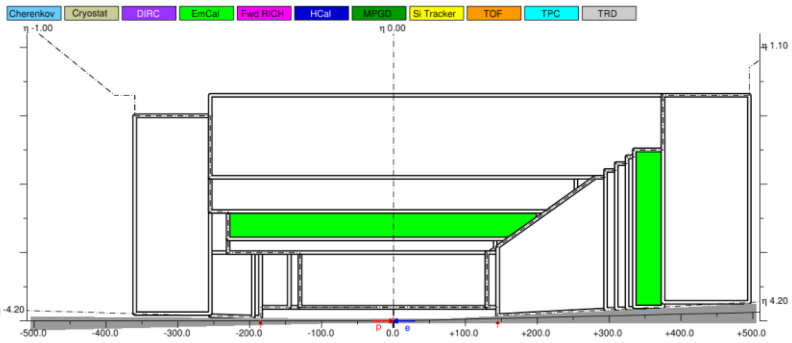
- ☐ Central area of beampipe (around IP): ~1.5m of beryllium to minimize multiple scattering for low Pt particles
- ☐ Low-mass exit window for far-forward particles
- ☐ Few % radiation length material thickness for the required angular range (low angle)



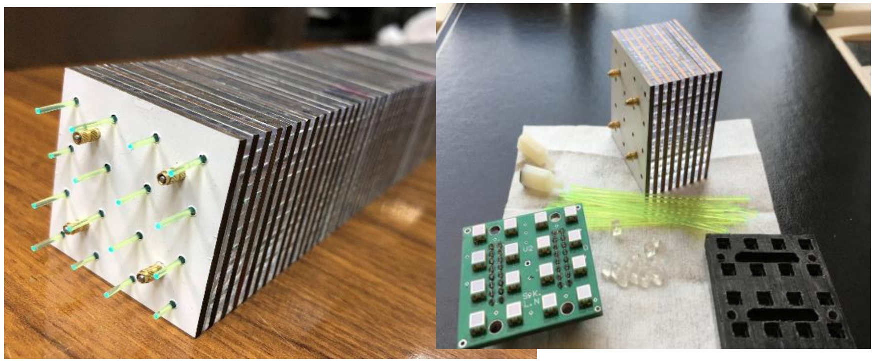


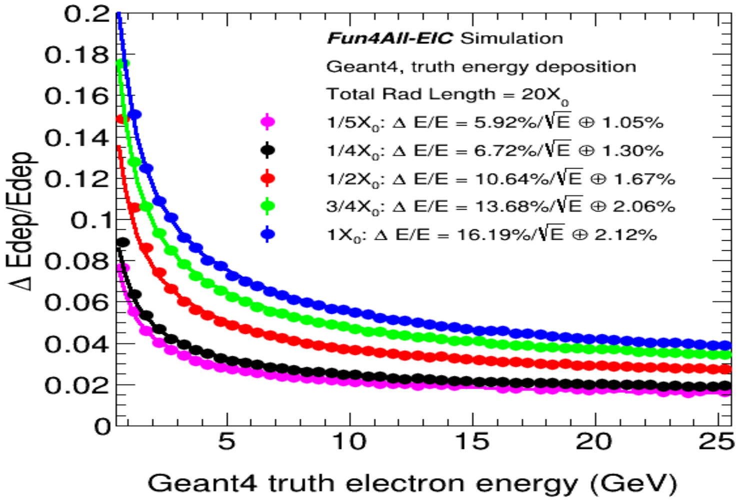
Sampling EmCal

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

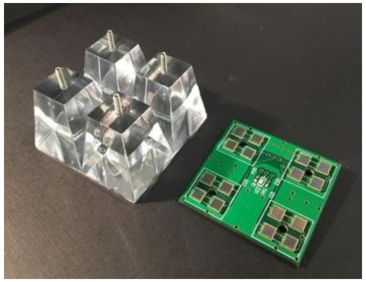


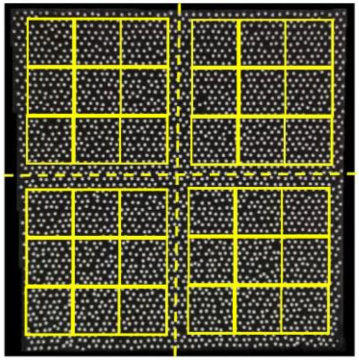
Pb/Sc shashlyk





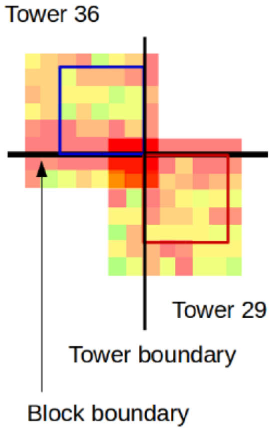
W/SciFi spacal



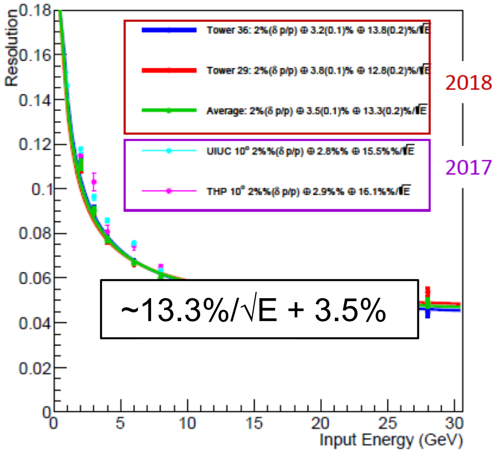


Scintillating Fibers embedded in a W/epoxy mix

Light collection uniformity can yet be improved



Energy Resolution



~13.3%/√E + 3.5%

Hadronic Calorimeter

- Main purpose: jet energy measurement
  - Particle Flow Algorithm usage anticipated (where HCal role is identification and energy measurements of the neutral hadrons, namely neutrons and K_L)

- In general the "conventional" hadronic calorimetry is considered per default

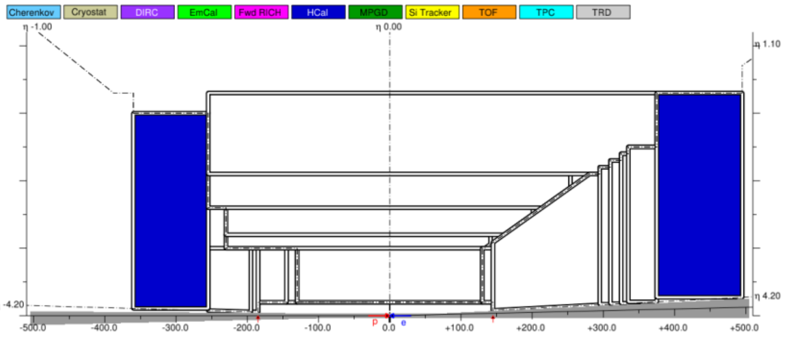
- Anticipated stochastic term in energy resolution & depth

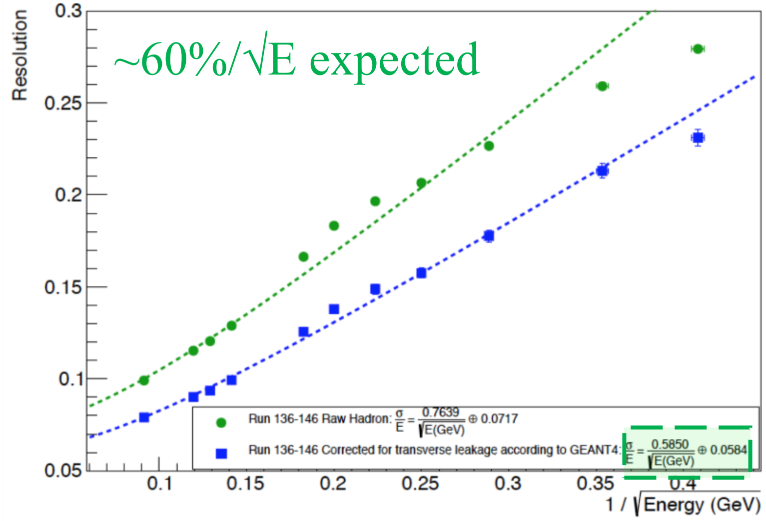
η	[-4 .. -1]	[-1 .. 1]	[1 .. 4]
σ_E/E	$\sim 50\%/\sqrt{E} + 10\%$	$\sim 100\%/\sqrt{E} + 10\%$	$\sim 50\%/\sqrt{E} + 10\%$
depth	$\sim 5\ \lambda_I$	$\sim 5\ \lambda_I$	$\sim 6\text{-}7\ \lambda_I$

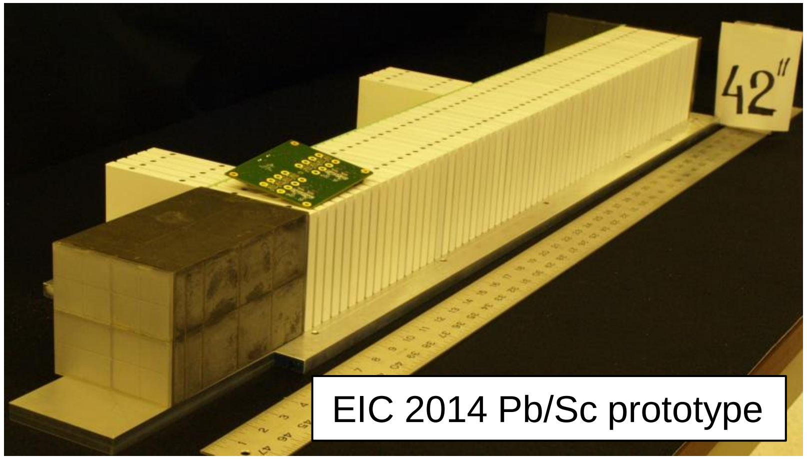
- Other considerations
  - Space!
  - Interplay with EmCal in a "binary" EmCal+HCal configuration
  - Tower granularity (~10 x 10 cm^2 suffices)
  - Readout immune to the magnetic field

Fe/Sc sandwich

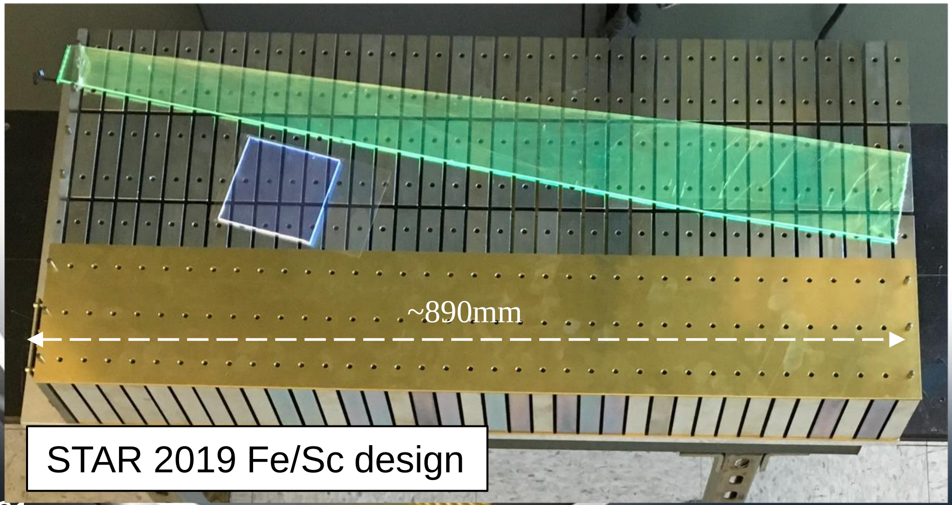
- HCAL in endcap
- Compact LEGO-style design
  - Can be used with a mixed Fe/Pb absorber



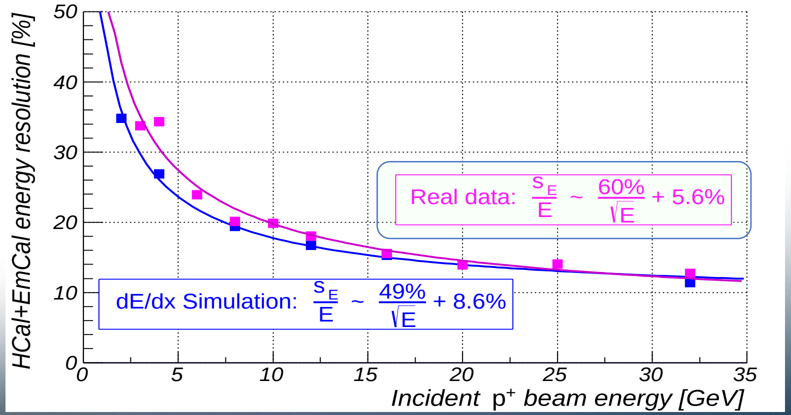




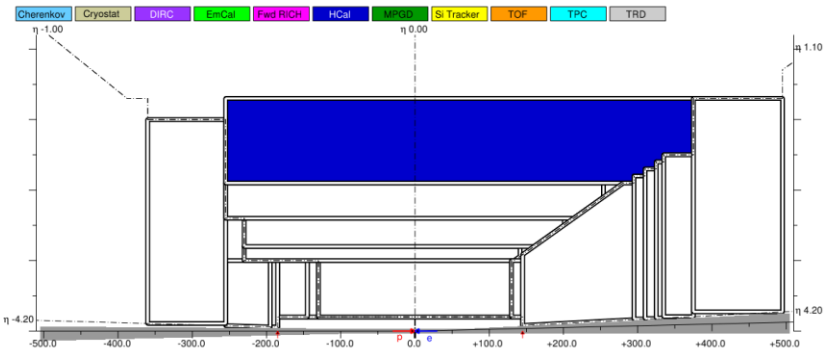
EIC 2014 Pb/Sc prototype



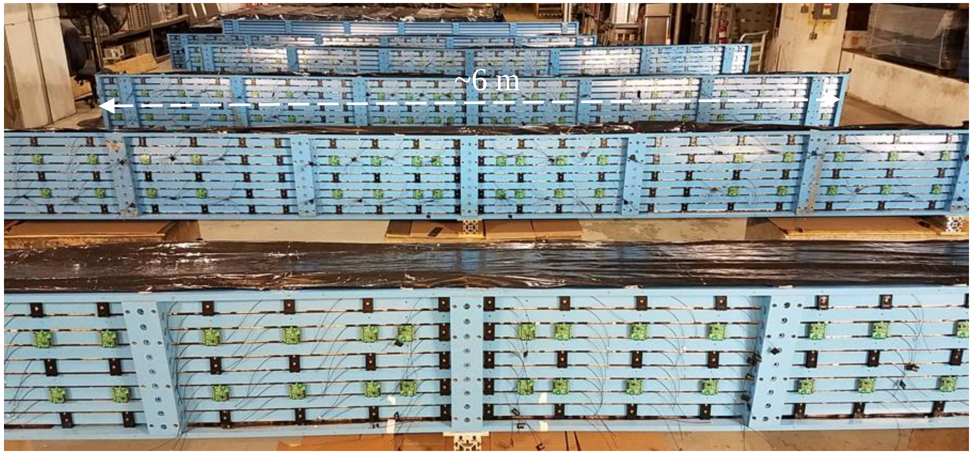
STAR 2019 Fe/Sc design



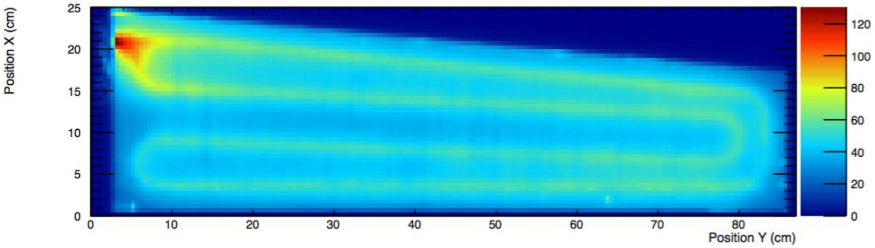
Fe/Sc (barrel)

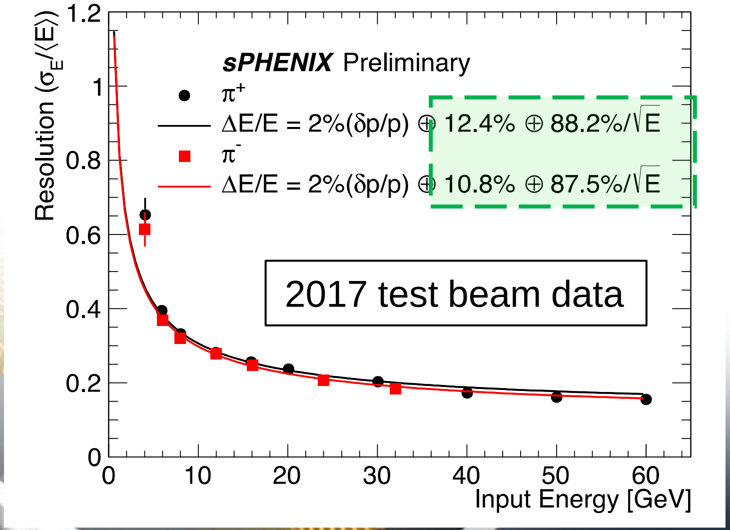


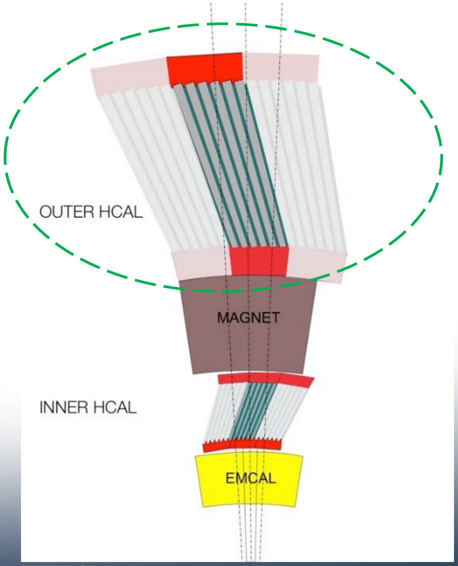
- Similar as used in sPHENIX
  - Solid 32-sector steel frame, but only ~3.5 λ_I
  - Moderate energy resolution



Scintillator plate with embedded WLS fiber

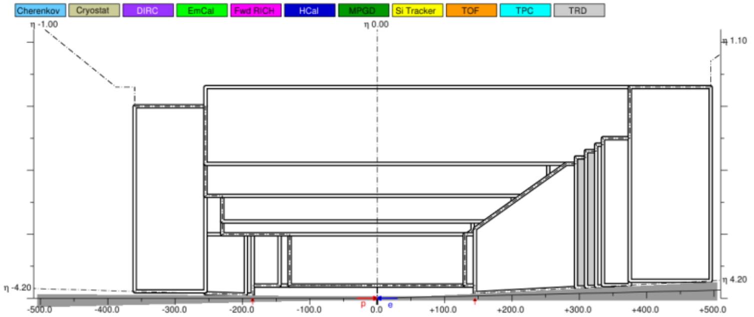


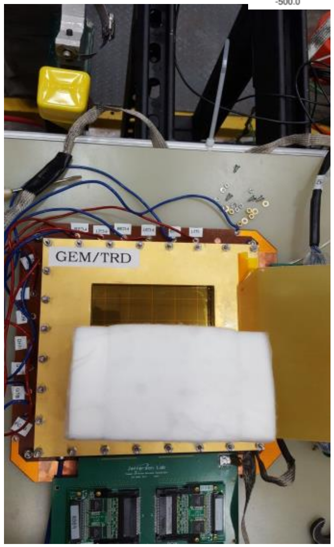


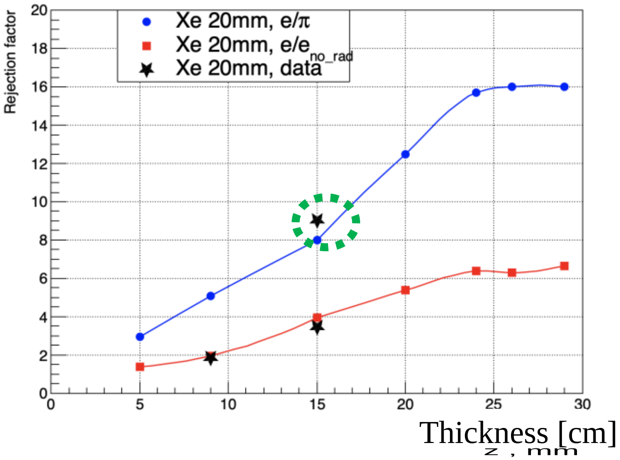


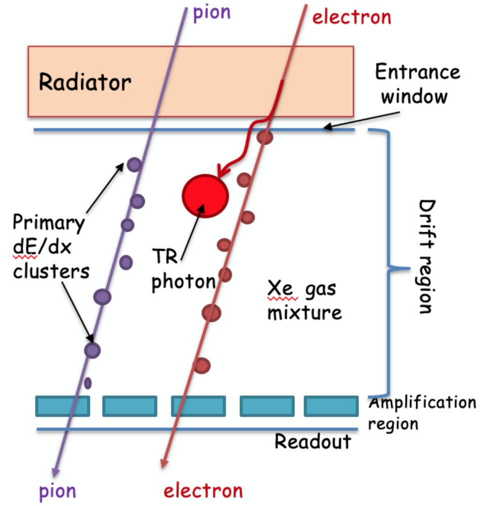
Additional e⁻ ID

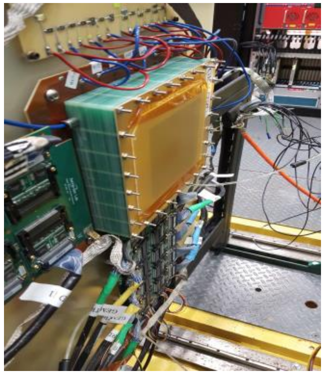
- To improve e-identification for leptonic/semi-leptonic decays.
- In addition to Calorimeters and Cherenkov detectors in the hadron-endcap considering TRD.
- GEM -TRD/Tracker :
  - e/π rejection factor ~10 for momenta between 2-100 GeV/c from a single ~15cm thick module.

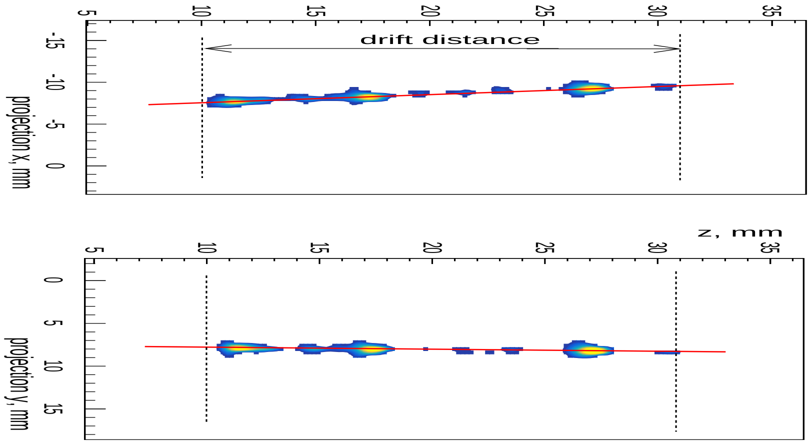






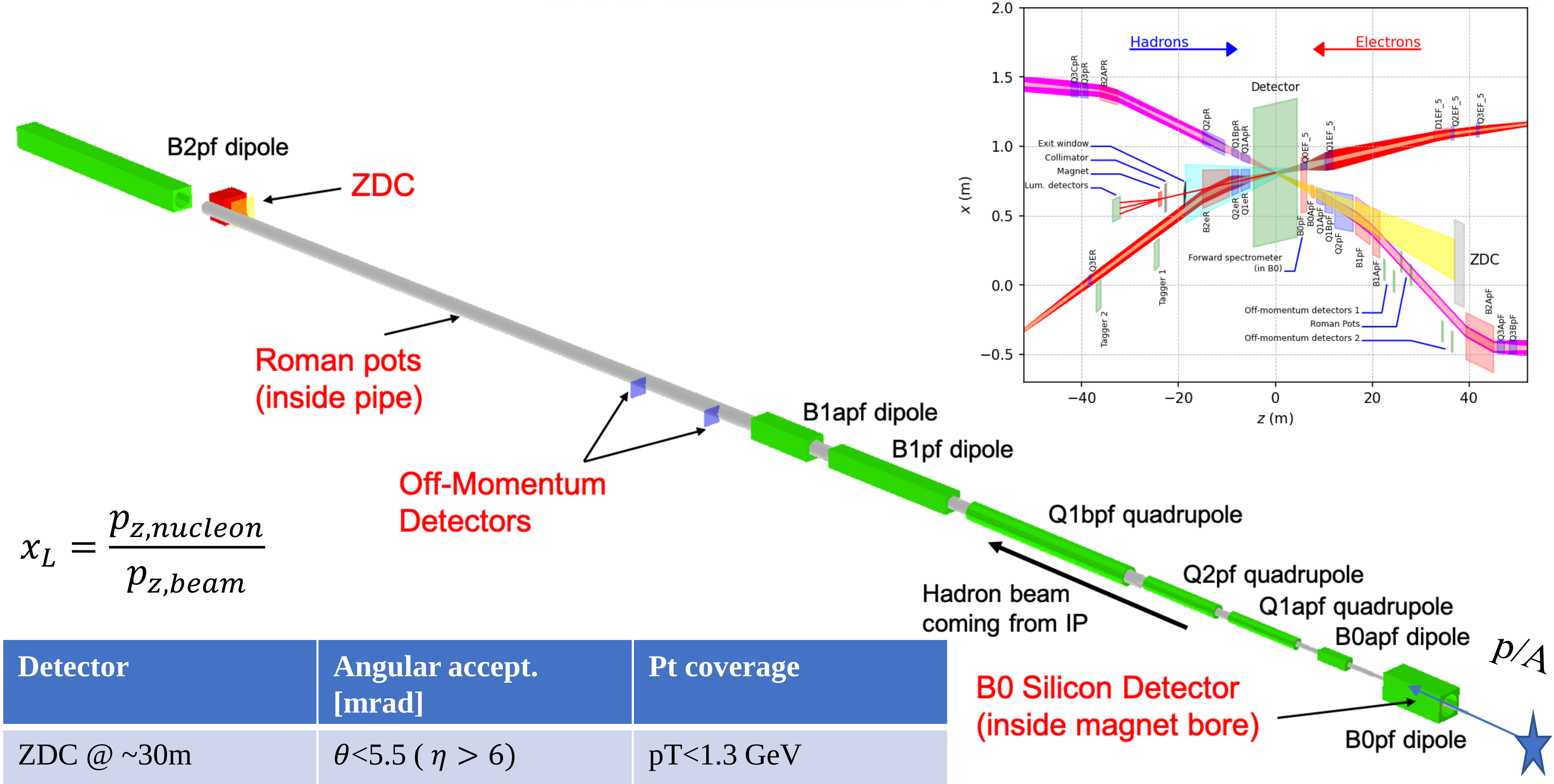






- Very precise Tracking segment behind dRICH:

Far forward (hadron going) region



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

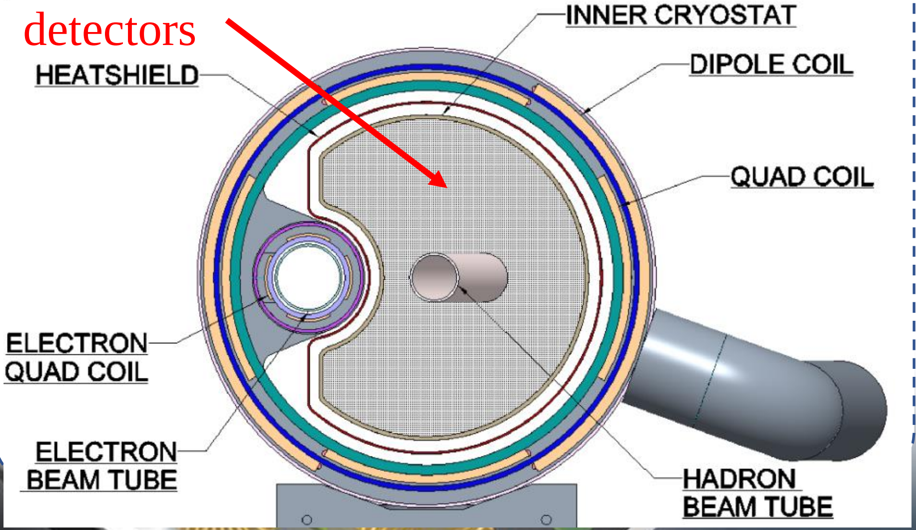
Detector	Angular accept. [mrad]	Pt coverage
ZDC @ ~30m	θ<5.5 ($\eta > 6$)	pT<1.3 GeV
Roman Pots	0*<θ<5.0 ($\eta > 6$)	*Low pT(t) cutoff (beam optics)
Off-Momentum Detectors	0.0< $\theta < 5.0$ ($\eta > 6$)	Low-rigidity particles from nuclear breakups
B0 forward spectrometer	$5.5 < \theta < 20.0$ (4.6< $\eta < 5.9$)	High pT(t)

Far-forward detectors

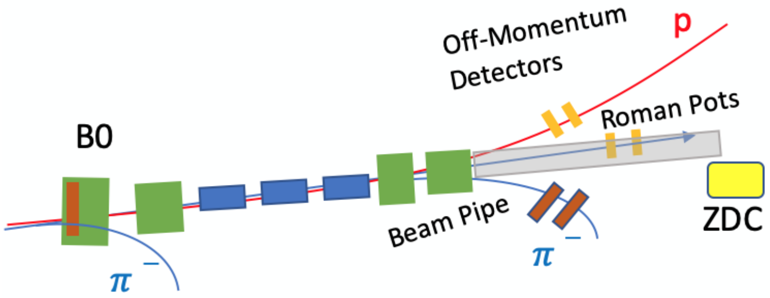
B0-spectrometer (5.5 < $\boldsymbol{\theta}$ < 20.0 mrad)

- 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

Space for detectors

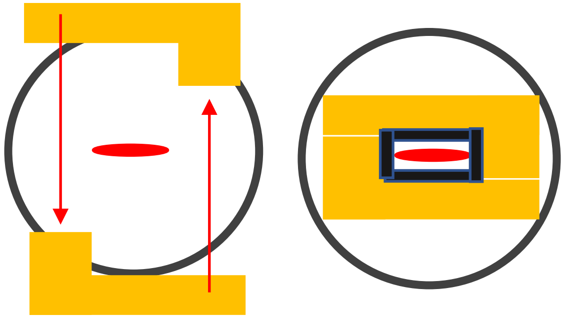


Roman-Pots and Off-momentum detectors 0.0* (10σ cut) < $\boldsymbol{\theta}$ < 5.0 mrad



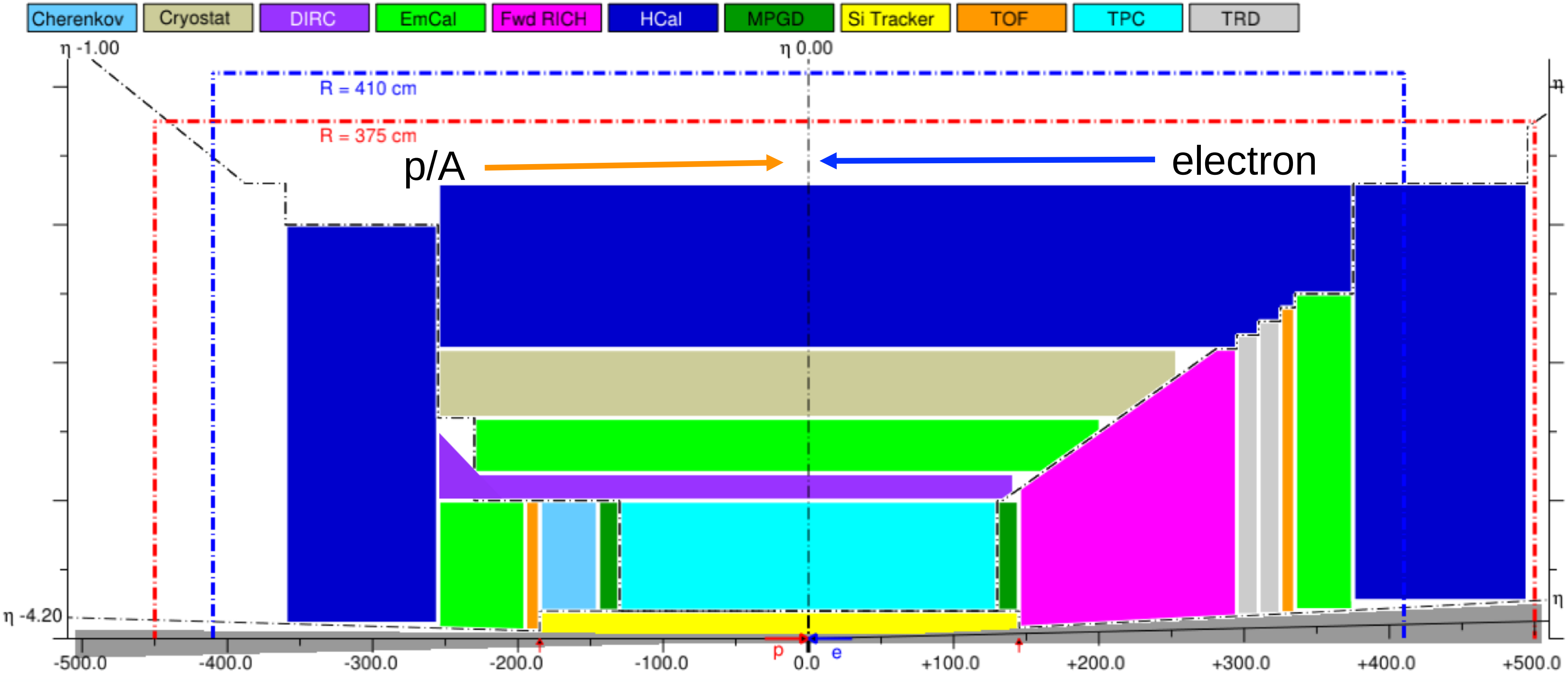
- Low Pt particles Pt < 1.3 GeV
- RPs: movable, integrated into the vacuum system
- Fast Timing and moderate granularity (500x500μm^2)
- **AC-LGADs**

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



EIC General Purpose Detector

EIC general purpose Detector around a new 3T Solenoid with hermetic coverage



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

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° 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: $0.18\ \text{GeV} < p_t < 1.3\ \text{GeV}$ $0.5 < x_L < 1$ ($x_L = E'_p/E_{Beam}$) Neutron: $p_t < 1.3$ GeV	
scattered proton/neutron acc. all energies for eA	Proton and Neutron: $\Theta < 6$ mrad ($\sqrt{s}$=50 GeV) $\Theta < 4$ 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

What is needed experimentally?

experimental measurements categories to address EIC physics:

Parton Distributions in nucleons and nuclei

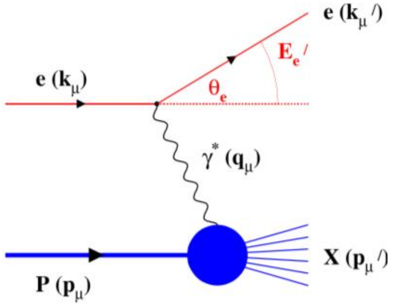
QCD at Extreme Parton Densities - Saturation

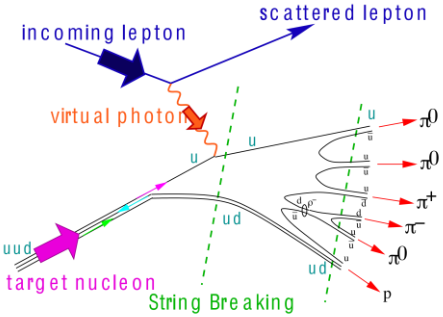
Spin and Flavor structure of nucleons and nuclei

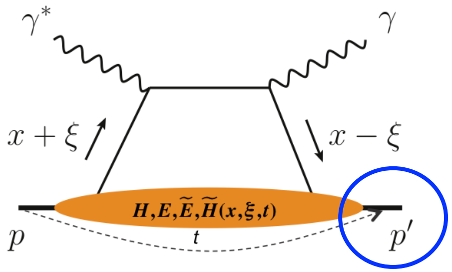
Tomography Transverse Momentum Dist.

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging







inclusive DIS

- measure scattered lepton
- multi-dimensional binning: x, Q^2

→ 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 region is critical

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

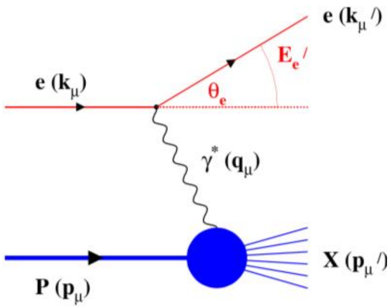
→ strong impact on Interaction Region design

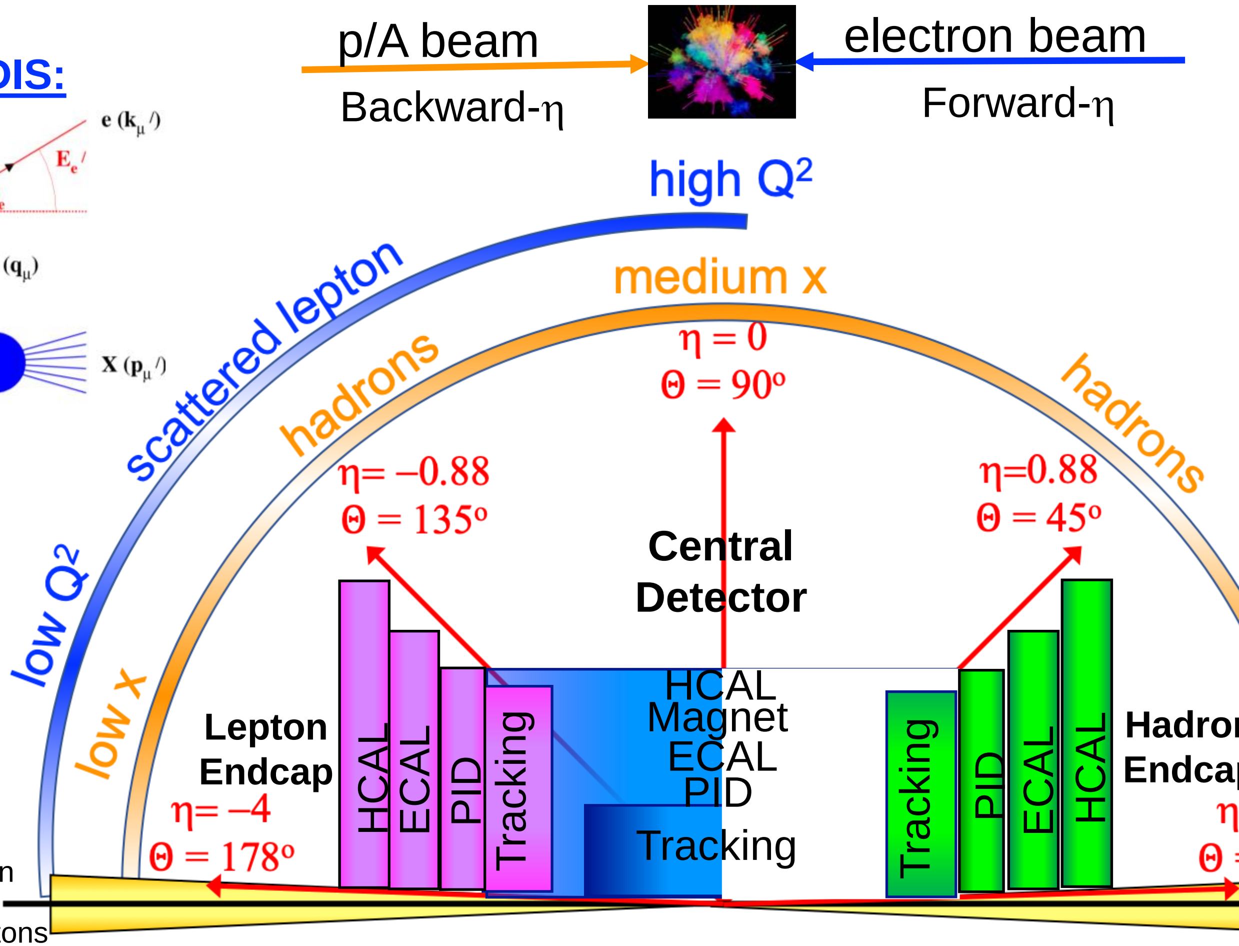
$\int$Ldt: 1 fb^{-1} 10 fb^{-1} 10 - 100 fb^{-1}

machine & detector requirements

EIC General Purpose Detector: Concept

inclusive DIS:





p/A beam

Backward-η

electron beam

Forward-η

high Q^2

scattered lepton

medium x

hadrons

$\eta = 0$
$\Theta = 90^o$

hadrons

$\eta = -0.88$
$\Theta = 135^o$

$\eta = 0.88$
$\Theta = 45^o$

Central Detector

low Q^2

low x

high x

Lepton Endcap

$\eta = -4$
$\Theta = 178^o$

HCAL
ECAL
PID
Tracking

HCAL
Magnet
ECAL
PID
Tracking

Tracking
PID
ECAL
HCAL

Hadron Endcap

$\eta = 4$
$\Theta = 2^o$

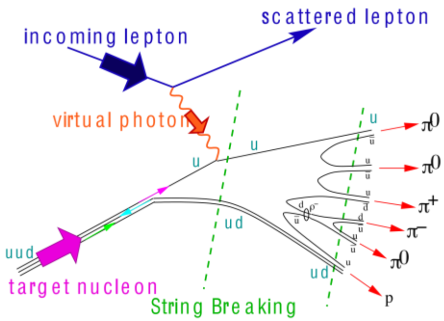
very low Q^2 scattered lepton

Bethe-Heitler photons for luminosity

particles from nuclear breakup and from diffractive reactions

Z

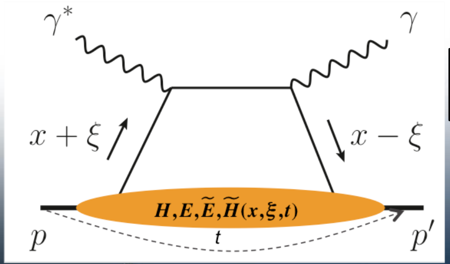
semi-inclusive DIS



Luminosity Detector

Low Q^2-Tagger

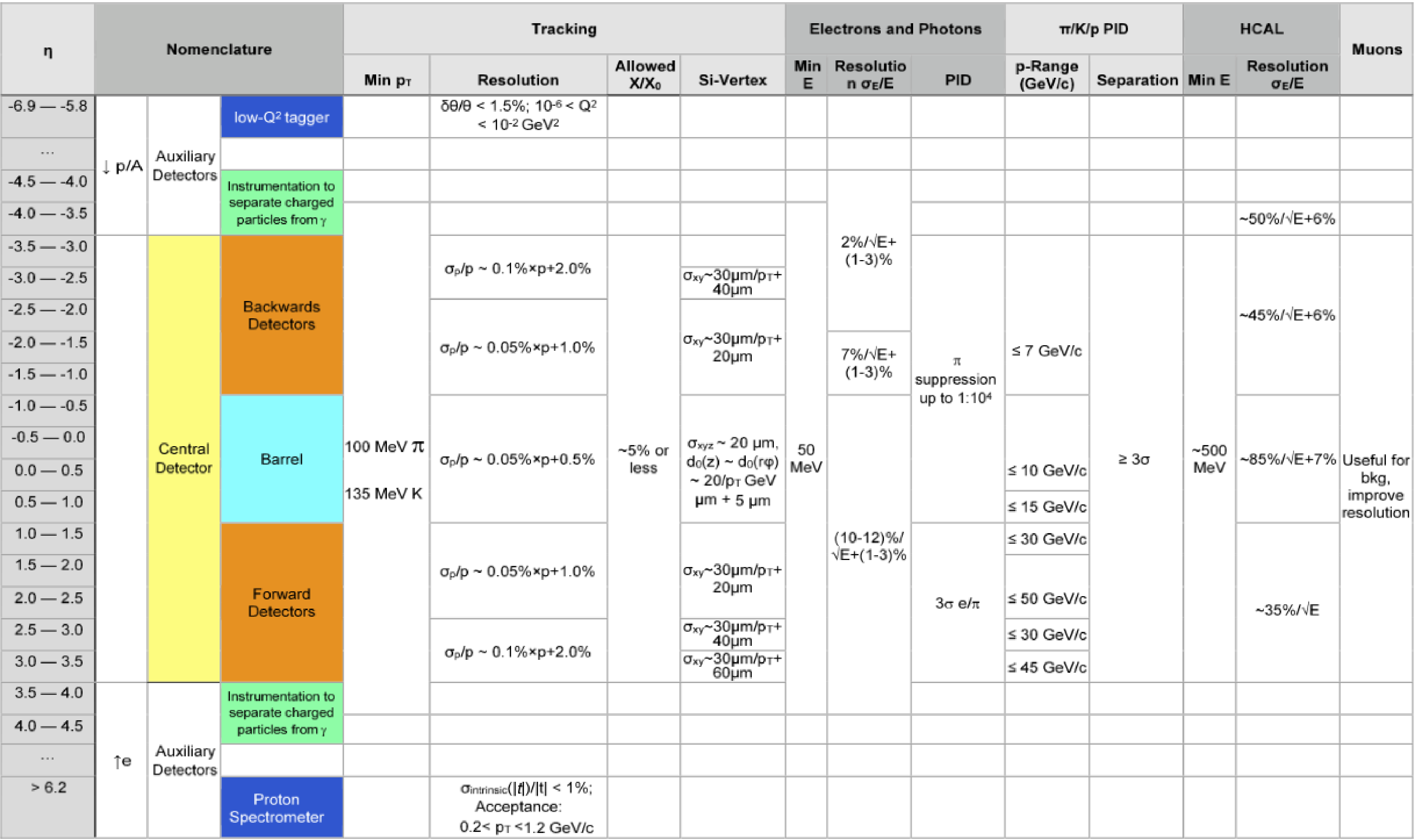
exclusive DIS



ZDC

Forward Tracking

YR: Detector Requirements

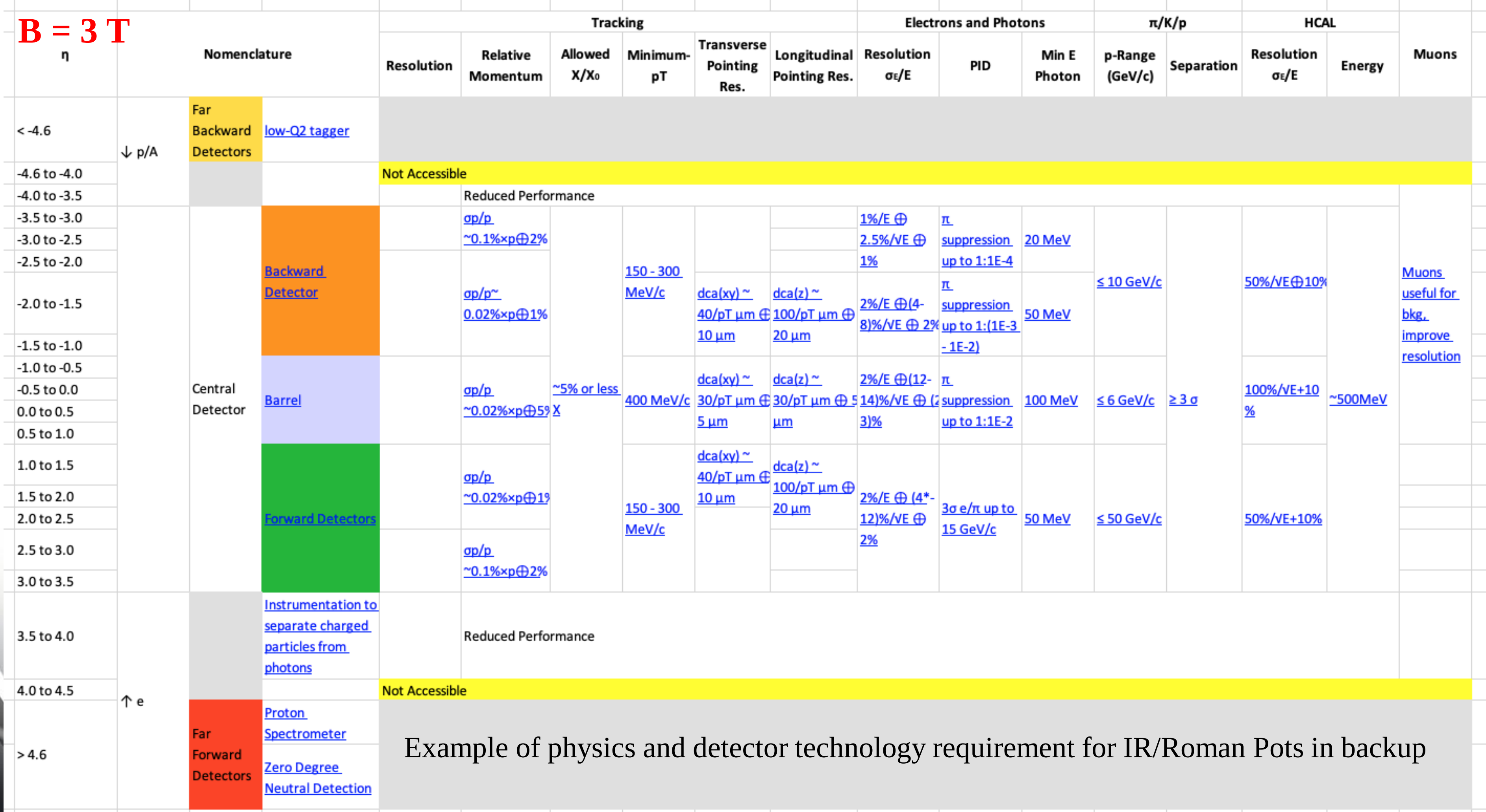


η	Nomenclature			Tracking				Electrons and Photons			π/K/p PID		HCAL		Muons
				Min p_T	Resolution	Allowed X/X_0	Si-Vertex	Min E	Resolution σ_E/E	PID	p-Range (GeV/c)	Separation	Min E	Resolution σ_E/E	
-6.9 — -5.8	↓ p/A	Auxiliary Detectors	low-Q^2 tagger		$\delta\theta/\theta < 1.5\%$; $10^{-6} < Q^2 < 10^{-2}$ GeV^2										
…															
-4.5 — -4.0			Instrumentation to separate charged particles from γ						$2\%/\sqrt{E} + (1\text{-}3)\%$						
-4.0 — -3.5				100 MeV π 135 MeV K				50 MeV						$\sim 50\%/\sqrt{E} + 6\%$	
-3.5 — -3.0		Central Detector	Backwards Detectors		$\sigma_p/p \sim 0.1\% \times p + 2.0\%$	~5% or less				π suppression up to 1:10^4	≤ 7 GeV/c	≥ 3σ	~500 MeV	$\sim 45\%/\sqrt{E} + 6\%$	Useful for bkg, improve resolution
-3.0 — -2.5							$\sigma_{xy} \sim 30\mu m/p_T + 40\mu m$								
-2.5 — -2.0					$\sigma_p/p \sim 0.05\% \times p + 1.0\%$		$\sigma_{xy} \sim 30\mu m/p_T + 20\mu m$								
-2.0 — -1.5									$7\%/\sqrt{E} + (1\text{-}3)\%$						
-1.5 — -1.0															
-1.0 — -0.5			Barrel		$\sigma_p/p \sim 0.05\% \times p + 0.5\%$		$\sigma_{xyz} \sim 20$ μm, $d_0(z) \sim d_0(r\varphi) \sim 20/p_T$ GeV μm + 5 μm		$(10\text{-}12)\%/\sqrt{E} + (1\text{-}3)\%$		≤ 10 GeV/c			$\sim 85\%/\sqrt{E} + 7\%$	
-0.5 — 0.0															
0.0 — 0.5															
0.5 — 1.0											≤ 15 GeV/c				
1.0 — 1.5			Forward Detectors		$\sigma_p/p \sim 0.05\% \times p + 1.0\%$		$\sigma_{xy} \sim 30\mu m/p_T + 20\mu m$			3σ e/π	≤ 30 GeV/c			$\sim 35\%/\sqrt{E}$	
1.5 — 2.0											≤ 50 GeV/c				
2.0 — 2.5															
2.5 — 3.0					$\sigma_p/p \sim 0.1\% \times p + 2.0\%$		$\sigma_{xy} \sim 30\mu m/p_T + 40\mu m$				≤ 30 GeV/c				
3.0 — 3.5							$\sigma_{xy} \sim 30\mu m/p_T + 60\mu m$				≤ 45 GeV/c				
3.5 — 4.0	↑e	Auxiliary Detectors	Instrumentation to separate charged particles from γ												
4.0 — 4.5															
…															
> 6.2			Proton Spectrometer		$\sigma_{intrinsic}(\|t\|)/\|t\| < 1\%$; Acceptance: $0.2 < p_T < 1.2$ GeV/c										

Requirements

EIC-UG Yellow Report results:

- Detailed subdetector simulations and technology performance evaluations tabulated
  - Interactive version: https://physdiv.jlab.org/DetectorMatrix
- performance difference for different magnetic fields (1.4 T vs. 3 T) were evaluated



B = 3 T η	Nomenclature			Tracking						Electrons and Photons			π/K/p		HCAL		Muons
				Resolution	Relative Momentum	Allowed X/X_0	Minimum-pT	Transverse Pointing Res.	Longitudinal Pointing Res.	Resolution σ_E/E	PID	Min E Photon	p-Range (GeV/c)	Separation	Resolution σ_E/E	Energy	
< -4.6	↓ p/A	Far Backward Detectors	low-Q2 tagger														
-4.6 to -4.0				Not Accessible													
-4.0 to -3.5					Reduced Performance												Muons useful for bkg, improve resolution
-3.5 to -3.0		Central Detector	Backward Detector		$\sigma p/p$ ~0.1%×p⊕2%	~5% or less X	150 - 300 MeV/c			1%/E ⊕ 2.5%/√E ⊕ 1%	π suppression up to 1:1E-4	20 MeV	≤ 10 GeV/c	≥ 3 σ	50%/√E⊕10%	~500MeV	
-3.0 to -2.5																	
-2.5 to -2.0					$\sigma p/p$~ 0.02%×p⊕1%												
-2.0 to -1.5								dca(xy) ~ 40/pT µm ⊕ 10 µm	dca(z) ~ 100/pT µm ⊕ 20 µm	2%/E ⊕(4-8)%/√E ⊕ 2%	π suppression up to 1:(1E-3 - 1E-2)	50 MeV					
-1.5 to -1.0																	
-1.0 to -0.5			Barrel		$\sigma p/p$ ~0.02%×p⊕5%		400 MeV/c	dca(xy) ~ 30/pT µm ⊕ 5 µm	dca(z) ~ 30/pT µm ⊕ 5 µm	2%/E ⊕(12-14)%/√E ⊕ (2-3)%	π suppression up to 1:1E-2	100 MeV	≤ 6 GeV/c		100%/√E+10 %		
-0.5 to 0.0																	
0.0 to 0.5																	
0.5 to 1.0																	
1.0 to 1.5			Forward Detectors		$\sigma p/p$ ~0.02%×p⊕1%		150 - 300 MeV/c	dca(xy) ~ 40/pT µm ⊕ 10 µm	dca(z) ~ 100/pT µm ⊕ 20 µm	2%/E ⊕ (4*-12)%/√E ⊕ 2%	3σ e/π up to 15 GeV/c	50 MeV	≤ 50 GeV/c		50%/√E+10%		
1.5 to 2.0																	
2.0 to 2.5																	
2.5 to 3.0					$\sigma p/p$ ~0.1%×p⊕2%												
3.0 to 3.5																	
3.5 to 4.0	↑ e		Instrumentation to separate charged particles from photons		Reduced Performance												
4.0 to 4.5				Not Accessible													
> 4.6		Far Forward Detectors	Proton Spectrometer Zero Degree Neutral Detection														

Example of physics and detector technology requirement for IR/Roman Pots in backup

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