EIC Detectors: An Overview

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Electromagnetic Interactions with Nucleons and Nuclei EINN2017
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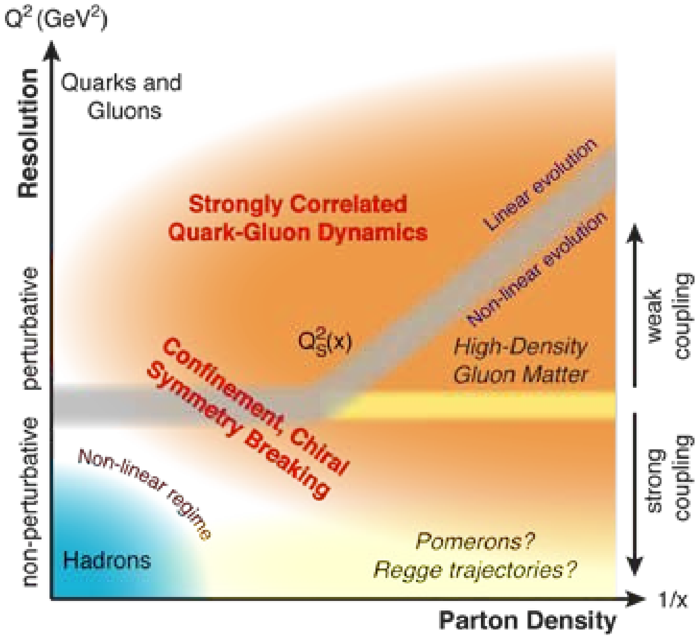
Electron-Ion Collider EIC

Polarized ep, eA collider

$\sqrt{s}$ = 35 – 180 GeV
Luminosity = 10^{34} cm^{-2}s^{-1}

Two possible sites

Brookhaven -> eRHIC
Jefferson lab -> JLEIC



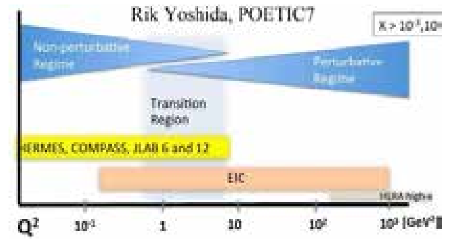
Scientific goals

Study of perturbative & non-perturbative QCD
Tomography (including transverse dimension) of the nucleon, nuclei
Understanding the nucleon spin
Discovery of gluon saturation…

Construction to start in 2025

Community optimistic about prospect of realization

Quantum Chromodynamics QCD



Theory of hadronic interactions (no doubts!)

Has been validated in countless experiments (LEP, HERA, Tevatron, LHC…)
where **perturbative calculations** are possible (high energy -> small coupling)

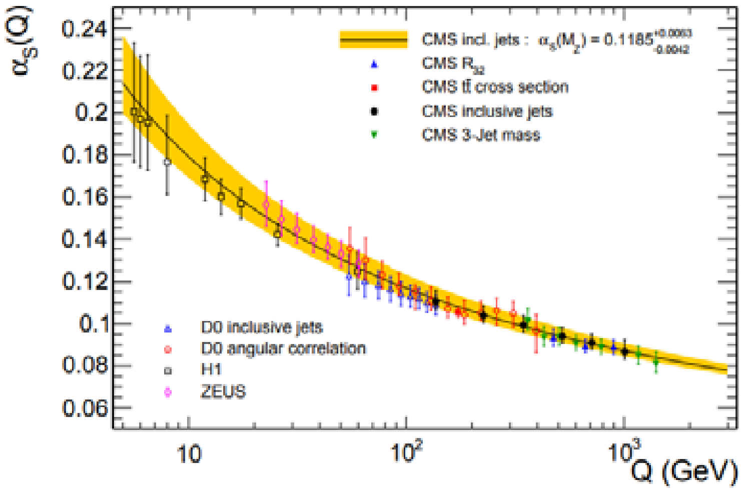
A deeper understanding of QCD requires exploring

The **non-perturbative** regime of the theory

3D tomography of the nucleon and nuclei

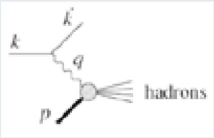
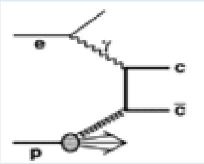
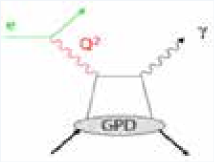
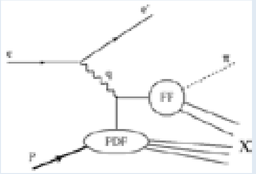
Generalized Parton Distributions (GPDs)
Transverse Momentum Distributions (TMDs)

Contributions to the nucleonic spin
Confinement
Nuclear modifications of the parton density functions
Non-linear evolution (saturation)
….

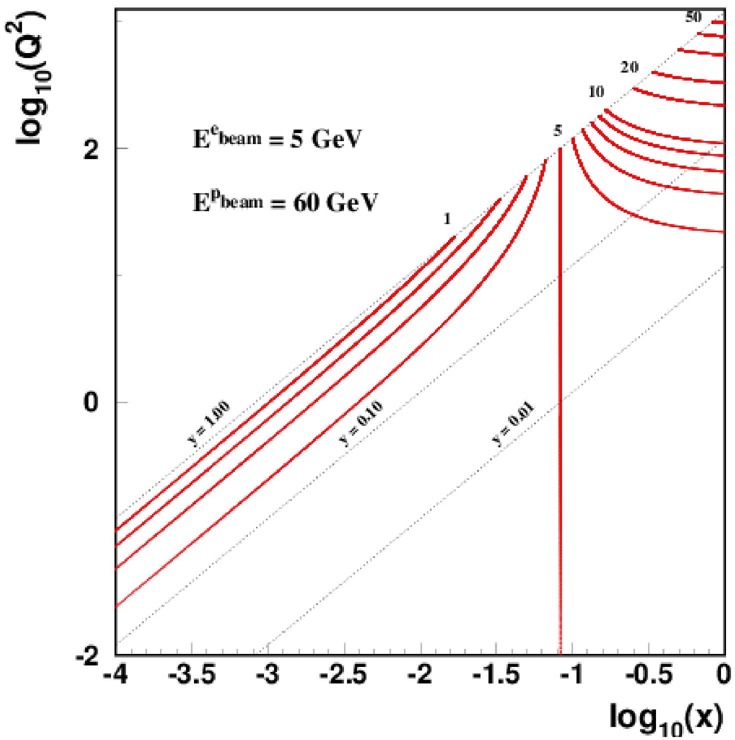


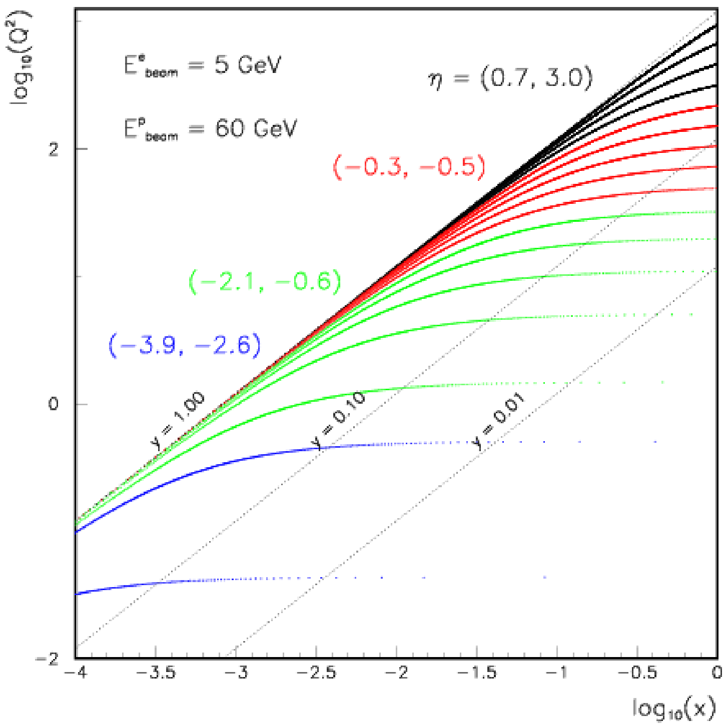
These questions are to be addressed by the EIC

Measurements at the EIC

Physical quantity	Process	Measurement challenges
Structure functions F_2, F_L Nuclear structure functions	Inclusive scattering 	Electron identification, background rejection, luminosity
Spin structure functions	Inclusive scattering	+ polarization
Gluon density 	Charm, dijet production …	Secondary vertex, pion/kaon separation, hadronic jets
Generalized Parton Distributions GPDs	Deeply Virtual Compton Scattering 	Forward proton, e, γ measurements background rejection
Transverse Momentum Distributions TMDs 	Semi-inclusive Deep Inelastic Scattering	Pion/kaon separation
Nuclear PDFs	Scattering on nuclei	Nuclear fragments
Many more		

Scattered electron in Neutral Current DIS





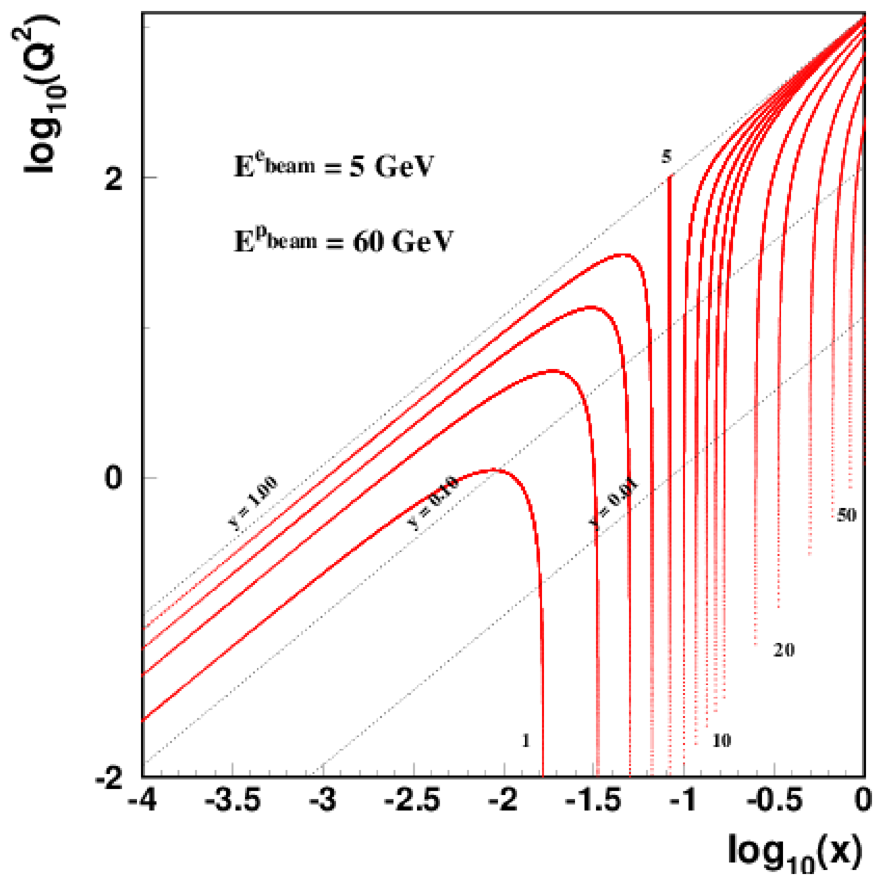
At low y, electron energy is a poor estimator of x

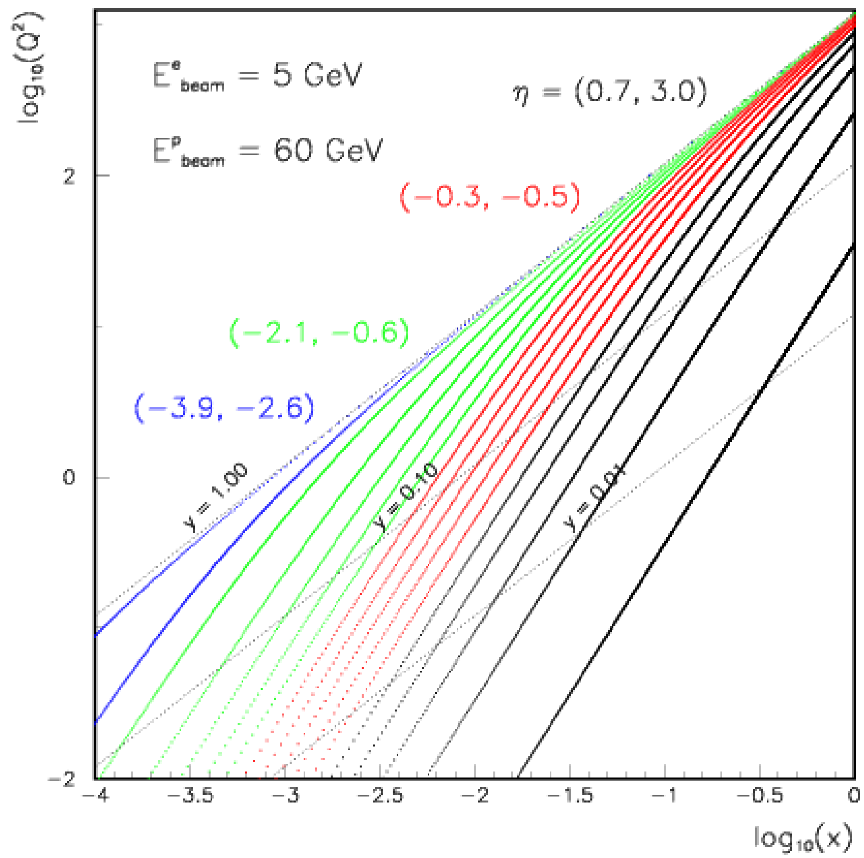
$$\frac{dx}{x} = \frac{1}{y}\frac{dE_e}{E_e}$$

Electron angle good estimator of Q^2

Need large coverage and good electron ID

Scattered quark in NC/CC DIS





At low y, quark energy good estimator of x

$$\frac{dx}{x} = \frac{1}{1-y}\frac{dE_q}{E_q}$$

Good hadron energy resolution essential

Requirements for EIC Detectors

Vertexing
Event vertex, secondary vertices, track impact parameter

Electron identification and measurement
$-4 < \eta < +4$

Hadronic jet measurement
Excellent energy resolution, kinematic reconstruction

Pion/kaon/proton separation
For most of the solid angle PID needed for $p < 7$ GeV/c
In forward direction needed for $p < 50$ GeV/c

Forward proton/ion detection and measurement
Large acceptance for momenta up to almost the beam energy

Forward neutron detection and measurement
Excellent energy and angle measurement

Vertex detector

Central tracker and solenoid

Calorimeter

TOF or Cerenkov

Roman pots

0^0 calorimeter

Polarimeter
Luminosity measurement

The HERA Detectors I

Multi-purpose 4π detector with

Charged particle tracking

Si - μVTX
Central drift chamber

Liquid Argon calorimeter

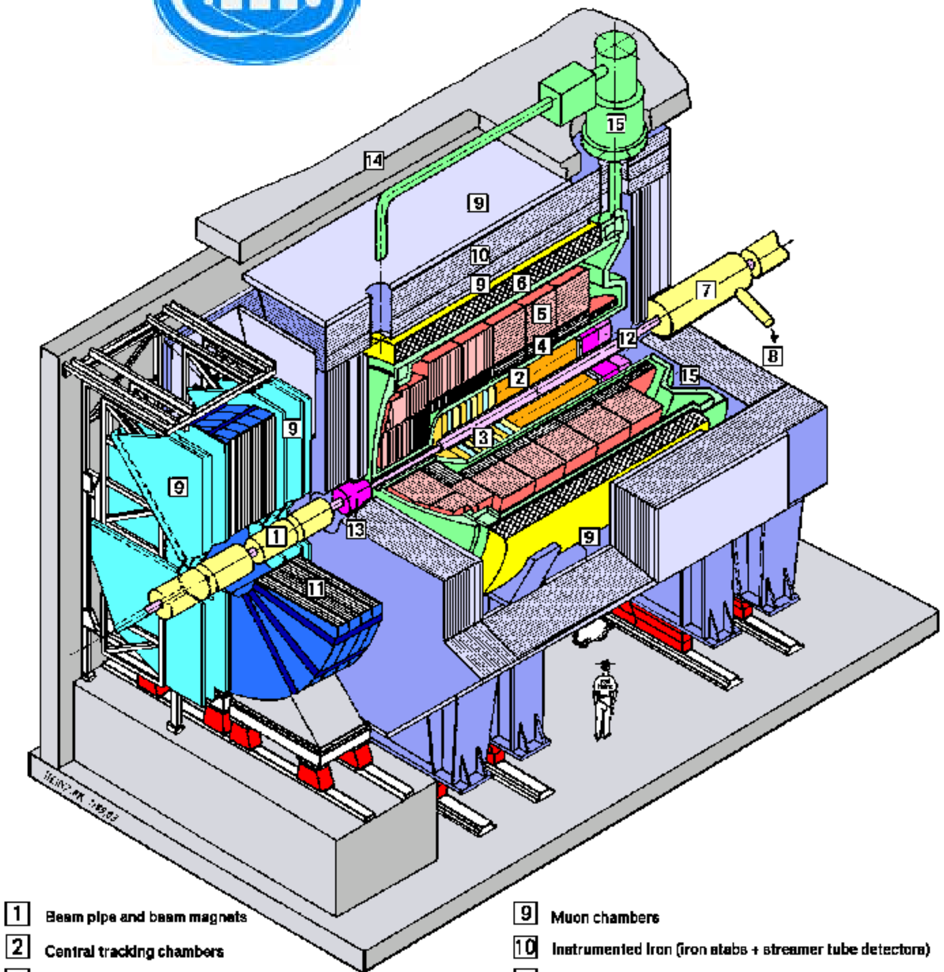
$$\frac{s_{em}}{E} = \frac{12\%}{\sqrt{E(GeV)}}$$

$$\frac{s_{had}}{E} = \frac{50\%}{\sqrt{E(GeV)}}$$

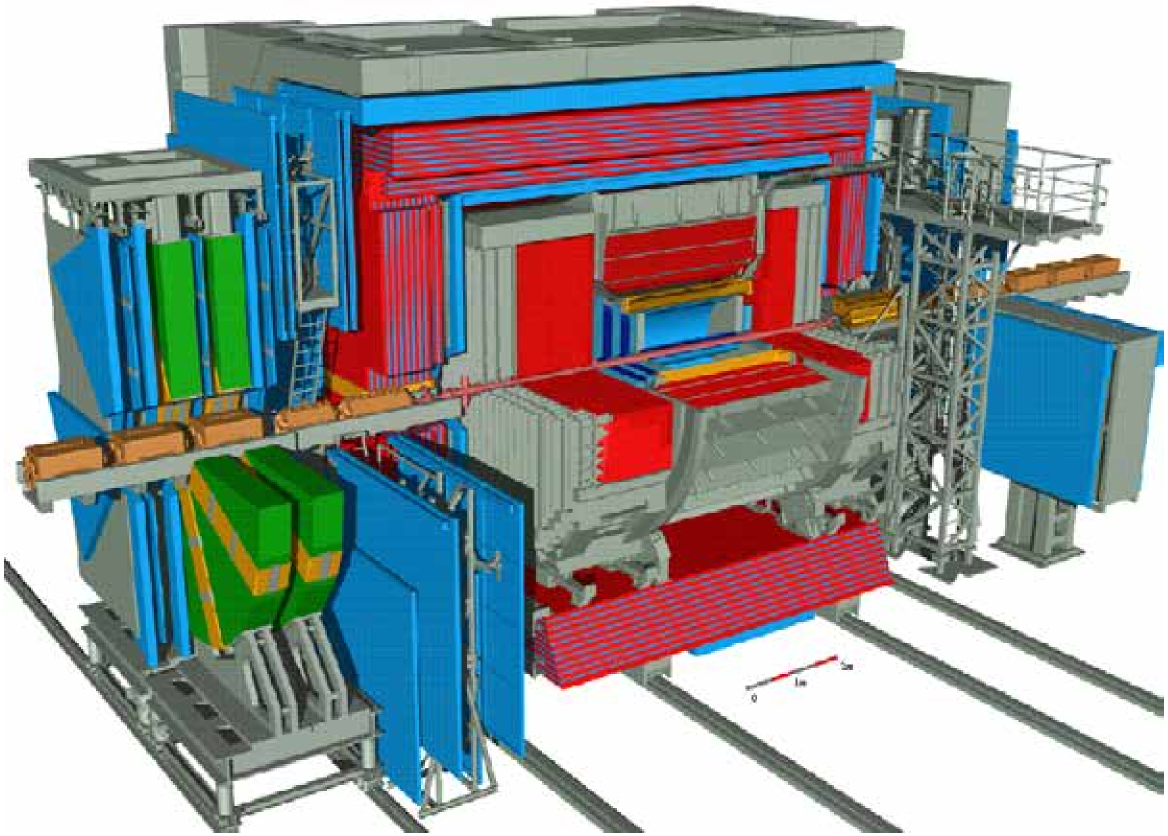
Rear Pb-scintillator plug

$$\frac{s_{em}}{E} = \frac{7.5\%}{\sqrt{E(GeV)}}$$

Muon chambers and more…



The HERA Detectors II



Multi-purpose 4π detector with

Charged particle tracking

Si - μVTX
Central drift chamber

Uranium-Scintillator calorimeter

$$\frac{\sigma_{em}}{E} = \frac{18\%}{\sqrt{E(GeV)}}$$

$$\frac{\sigma_{had}}{E} = \frac{35\%}{\sqrt{E(GeV)}}$$

Muon chambers and more…

Note: both detectors are
- **asymmetric around the interaction point**
- **have no particle ID**
- **limited acceptance in forward direction**

Choices I

General purpose detector (such as ATLAS and CMS at the LHC or H1/ZEUS at HERA)

Advantage of 1 device for all, better background rejection
More challenging to design

This talk

or

Specialized detectors (such as ALICE and LHCb at the LHC)

Potentially better for the measurement of a particular process
Less boundary conditions – easier to design

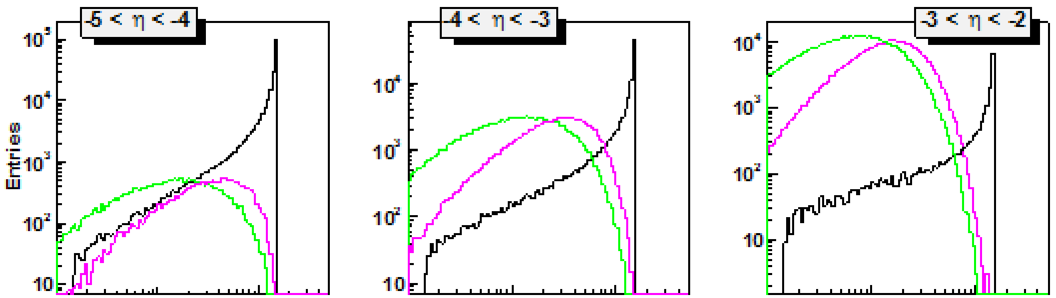
or

Mixture of both

Personally, I would opt for one (1) state-of-the-art detector

Choices II

15 GeV e^- x 250 GeV p: e^-, γ , h^-



From E.C. Aschenauer

Asymmetric versus symmetric detector

Beam energies will be asymmetric, i.e. more energy in the hadron direction

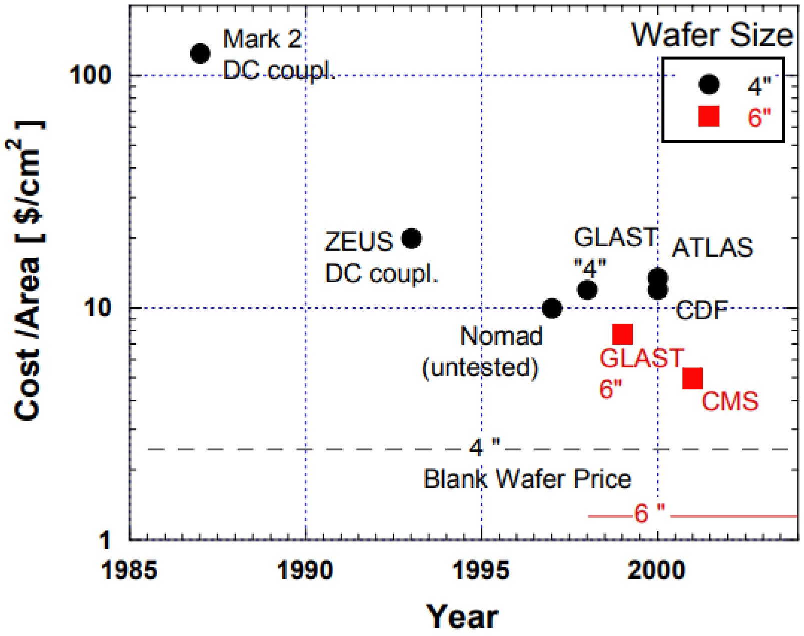
HERA experiments reduced the calorimeter depth in the electron direction (later H1 added a hadron calorimeter behind their backward end-plug calorimeter)

With high luminosity, both scattered electrons and hadrons will go everywhere

An asymmetric detector results in an asymmetric force on the solenoid

No reason to go asymmetric, apart from special very forward detectors

Choices III



From H. Sadrozinski (2001)

Cost

Some detectors are cheap (e.g. RPCs)
Some are more expensive (e.g. Silicon)

However, the cost is not constant with time (e.g. Silicon and CMS)

➡ **In the early stages, cost should not be overemphasized**

An optimal detector means maximum use of luminosity

Popular choices for the Major Subsystems

Vertex detector -> Identify event vertex, secondary vertices, track impact parameters
Silicon pixels, e.g. MAPS

Central tracker -> Measure charged track momenta
~~Drift chamber~~, TPC + outer tracker or Silicon strips

Forward tracker -> Measure charged track momenta
GEMs, Micromegas, or Silicon strips

Particle Identification -> pion, kaon, proton separation
Time-of-Flight or RICH + dE/dx in tracker

Electromagnetic calorimeter -> Measure photons (E, angle), identify electrons
Crystals (backward), Shashlik or Scintillator/Silicon-Tungsten

Hadron calorimeter -> Measure charged hadrons , neutrons and K_L^0
Plastic scintillator or RPC + steel

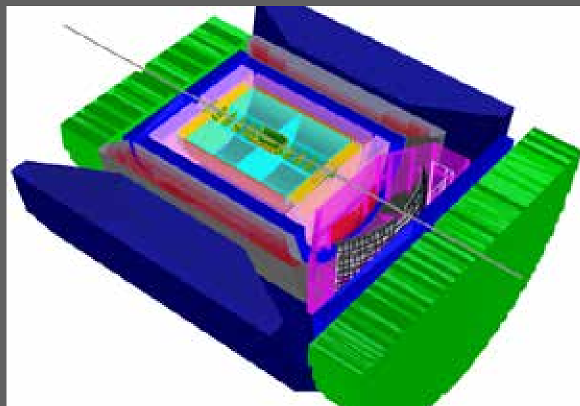
Muon system -> Identify muons as punch-throughs
Plastic scintillator or RPCs + yoke or none

+ Beam pipe, Solenoid, very forward and backward detectors

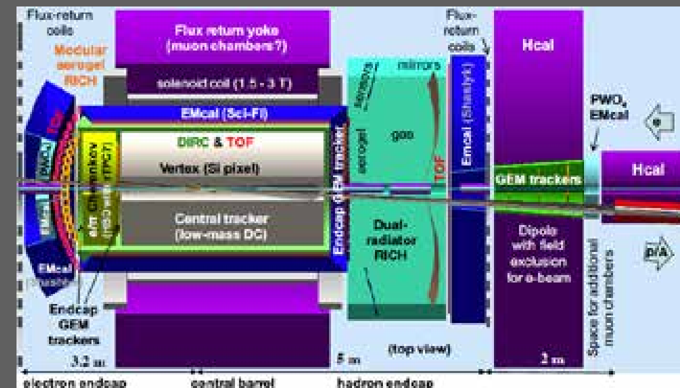
Radius/Distance from IP

4 Detector Concepts for the EIC

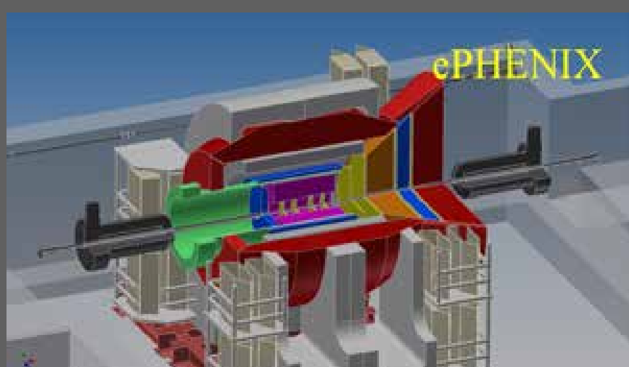
Brookhaven concept: BEAST



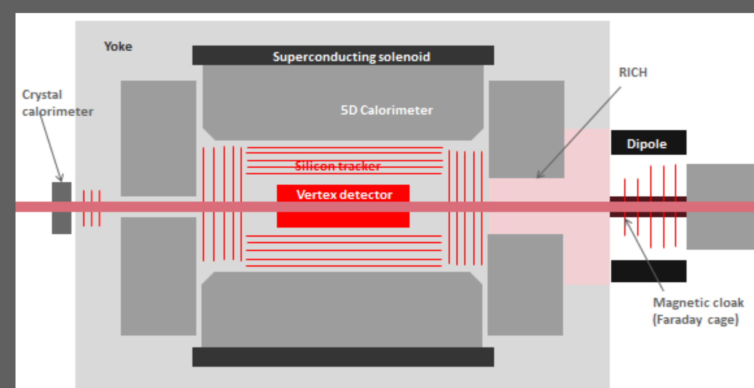
Jefferson lab concept: JLEIC



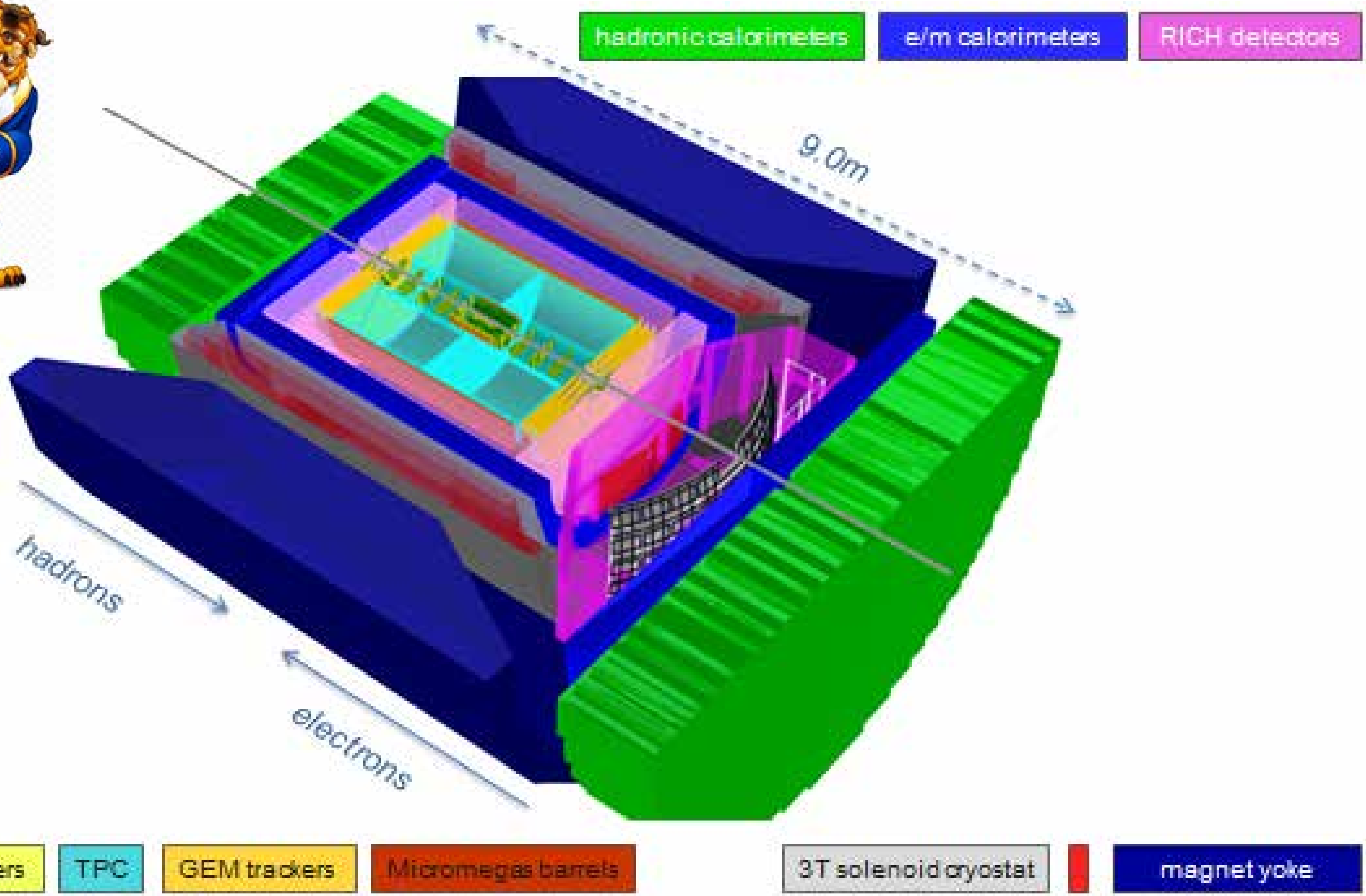
sPhenix -> ePhenix



Argonne concept: SiEIC



BEAST (Brookhaven eA Solenoidal Tracker)



From A. Kiselev

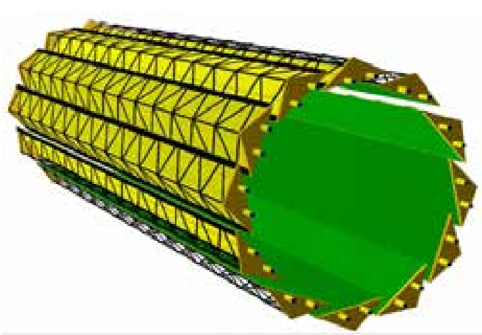
BEAST: Tracker I

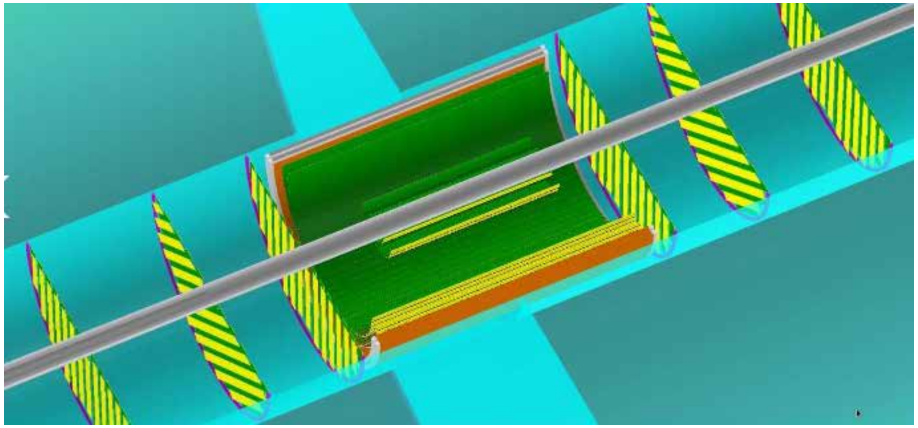
Silicon vertex detector

Inspired by the ALICE ITS (inner tracking system) design (upgrade for LS2 2019-2020)

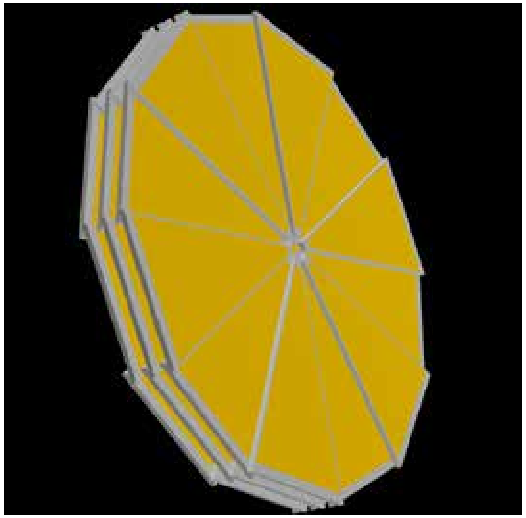
Based on MAPS with 20 x 20 μm^2 pixels
-> Monolithic Active Pixel Sensors
-> Incorporate a matrix of charge collection diodes (pixels)
+ electronics (signal amplification, digitization, and 0 suppression)
-> only hit/no hit information!

Barrel: 4 layers with 0.3% X_0 each
Endcap: 3 disks





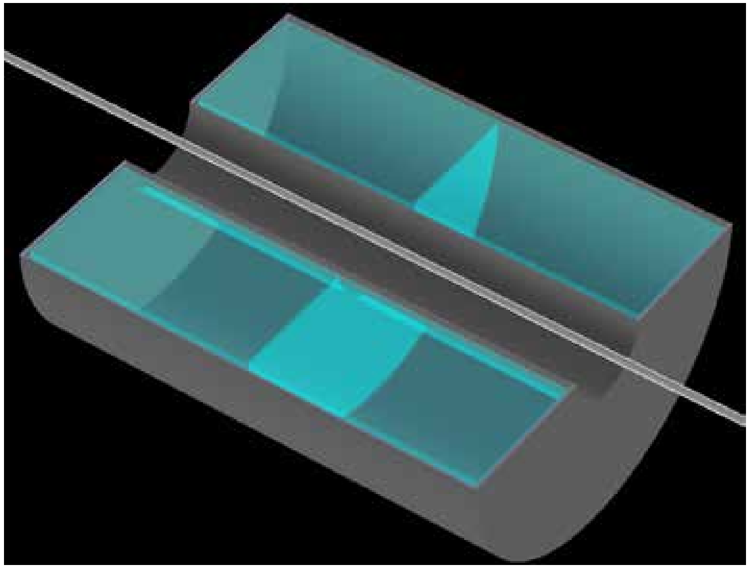
BEAST: Tracker II



Central TPC

2 m long, $R_{inner/outer}$ = 22.5/77.5 cm
Gas mixture: e.g. Argon:Freon:Isobutane = 95:3:2
5 – 6 % X_0 field cage in barrel + 15% X_0 at endcaps
GEM readout: pads 5 mm long, assume 50 μm resolution

+ Micromegas



Inside and outside the TPC
For track seeding
Number of layers to be determined

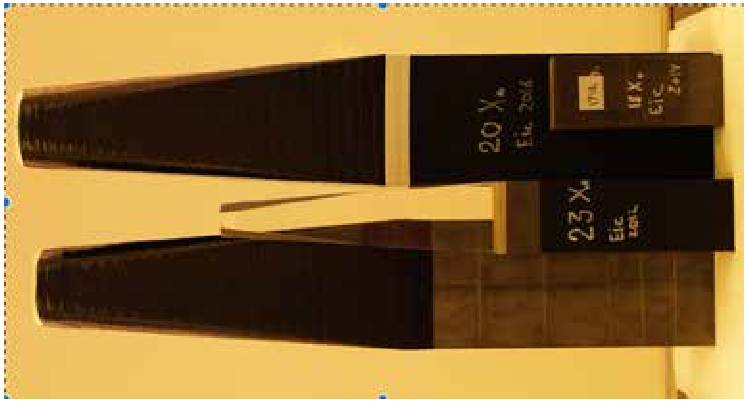
Endcap

GEM: 3 disks

Superconducting Solenoid

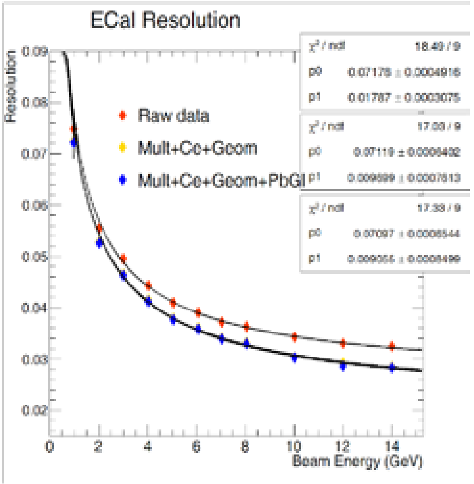
3 Tesla (+- 4%) in TPC region
Outside the electromagnetic calorimeter

BEAST: Calorimetry



Electromagnetic calorimeter

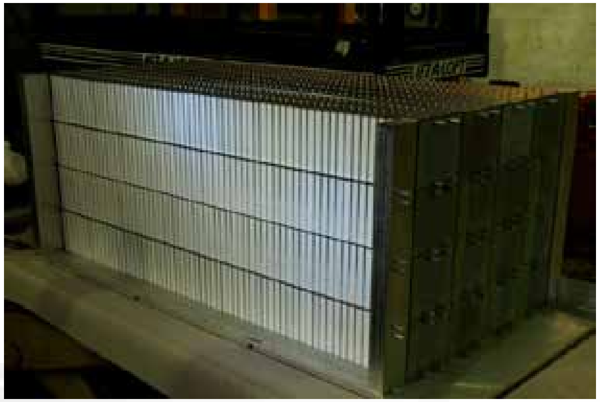
- Very backward pseudo-rapidities (η< -2)
  - $PbWO_4$ crystals with ~2%/√E energy resolution



- Barrel and forward region (-2 < η < 3.5)
  - Tungsten powder + scintillating fiber with 7 – 10%/√E

Hadron calorimeter

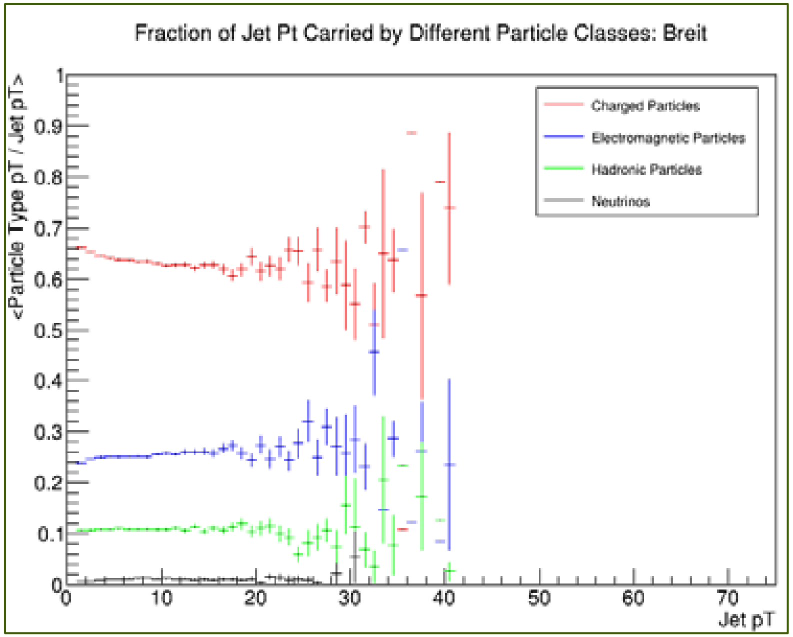
- Only in the forward (measure hadrons) and backward (identify electrons) direction
- Scintillator plate + lead absorber with ~50%/√E
- No hadron calorimeter in the barrel region



Comment to barrel hadron calorimeter

BEAST

Does not feature a barrel hadron calorimeter



Argument

Not needed

Fraction of jet energy carried by neutral hadrons (neutrons and K_L^0) is small ~10%

Charged hadrons measured by tracker

However

The EIC is a precision machine (at the 1% level)

$E_{neutral}$ is small in average, but large fluctuations

Electron ID is needed in the barrel region and is helped by an hadron calorimeter

Kinematic reconstruction needs all hadrons (double angle)

-> In particular for charged current events (no electron)

-> At medium/large x (where the electron method fails)

Background rejection requires hermeticity

BEAST: Particle Identification

Low momenta ($p < 1$ GeV/c)

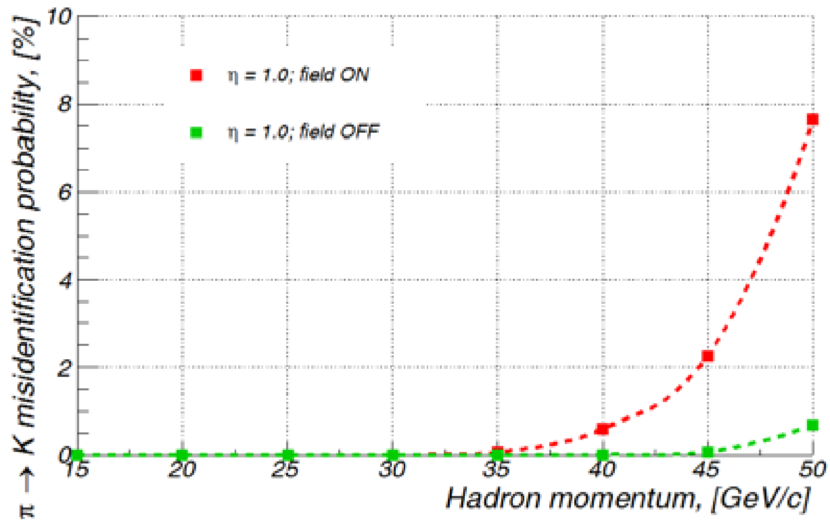
dE/dx in tracker or time-of-flight (with moderate resolution)

Intermediate momenta ($1 < p < 3 – 4$ GeV/c)

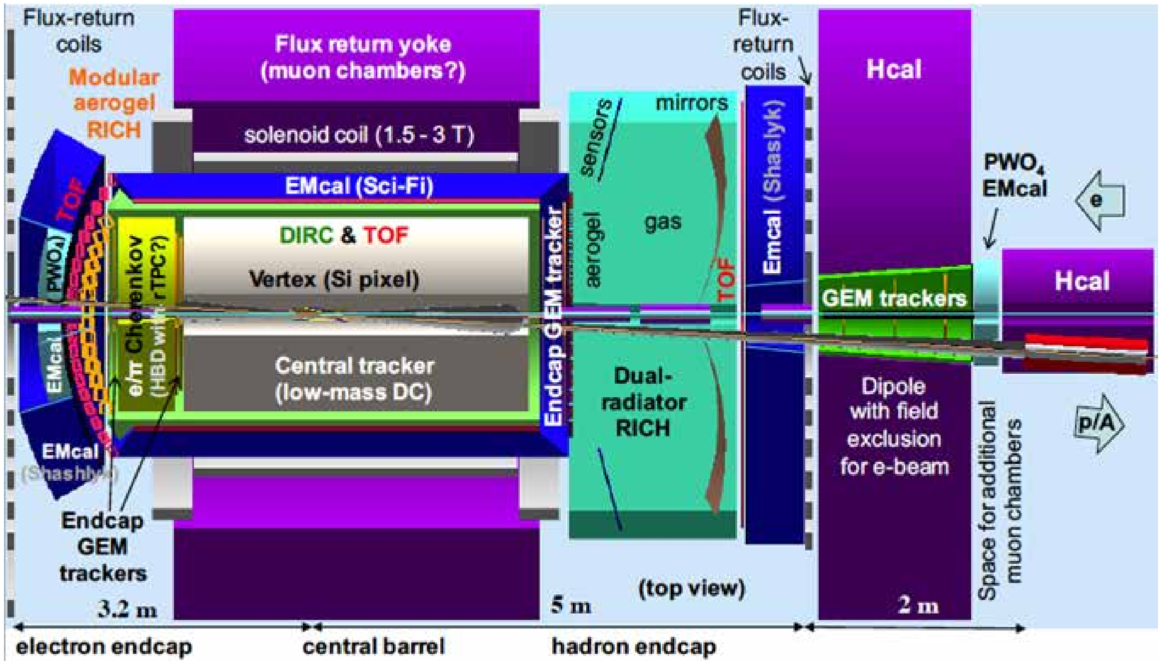
Ring Imaging Cerenkov with Aerogel (n~ 1.05)

High moment ($10 < p < 50$ GeV/c)

Ring Imaging Cerenkov with gas radiator
Requires about 1m depth
(to produce enough light)
Only needed and practical in the
forward direction



The JLEIC Concept



Central detector

Similar concept to BEAST

- Vertex detector
- Central tracker
- Forward tracking
- Cerenkov detectors
- Electromagnetic calorimeters
- Hadron calorimeter in the forward direction

Muon chambers

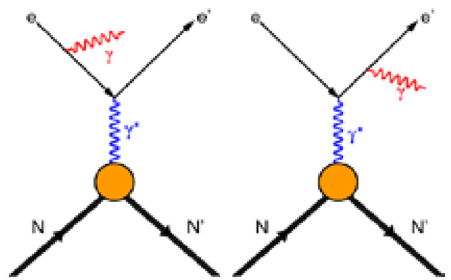
Particular emphasis on

Forward and backward detectors
(other concepts could do this too, but JLEIC put more effort into this)

JLEIC: Electron Direction

0^0 angle photon calorimeter

-> Luminosity via Bethe-Heitler Process

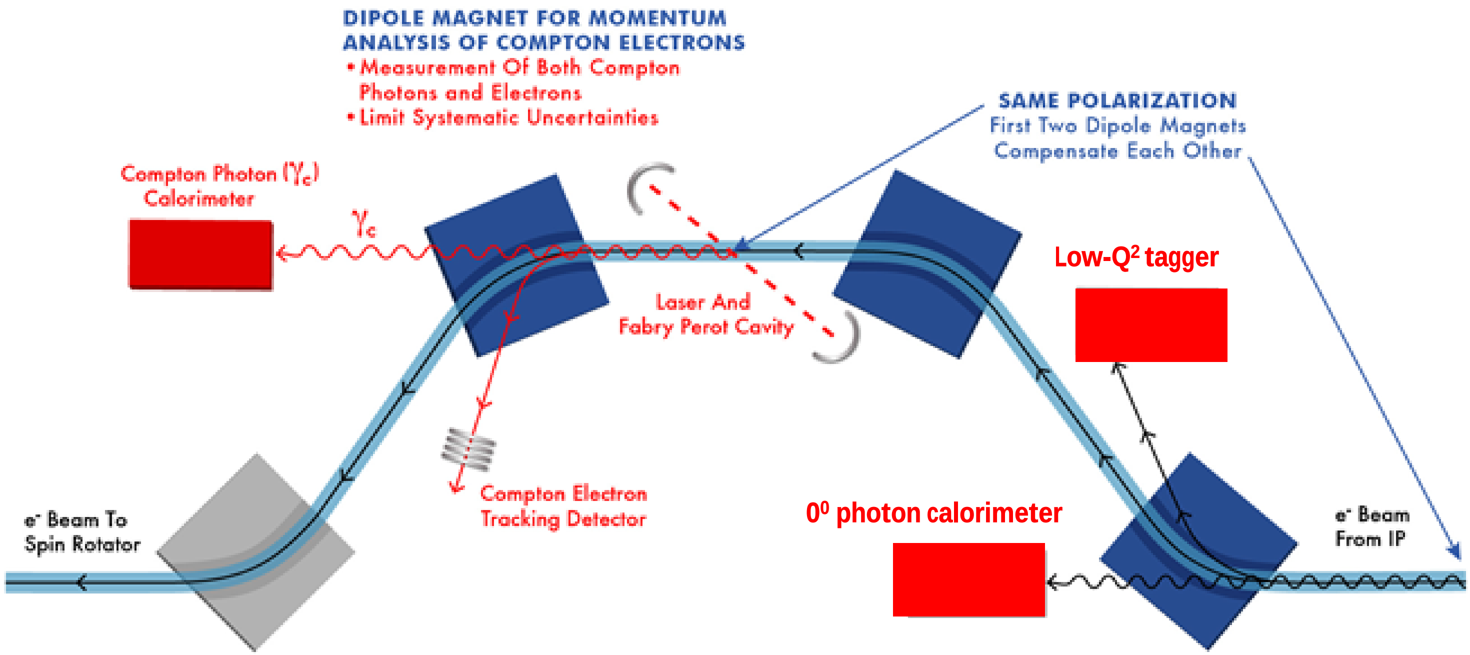


Low-Q^2 tagger

-> Measurement of low-energy electrons

Laser + Compton Photon calorimeter + Electron tracking detector

-> Polarization measurement



JLEIC: Proton/ion Direction

Dipole magnet

Provides analyzing power to forward fragments
Requires magnetic cloak to shield stored electron beam (being developed by Stonybrook)

GEM trackers

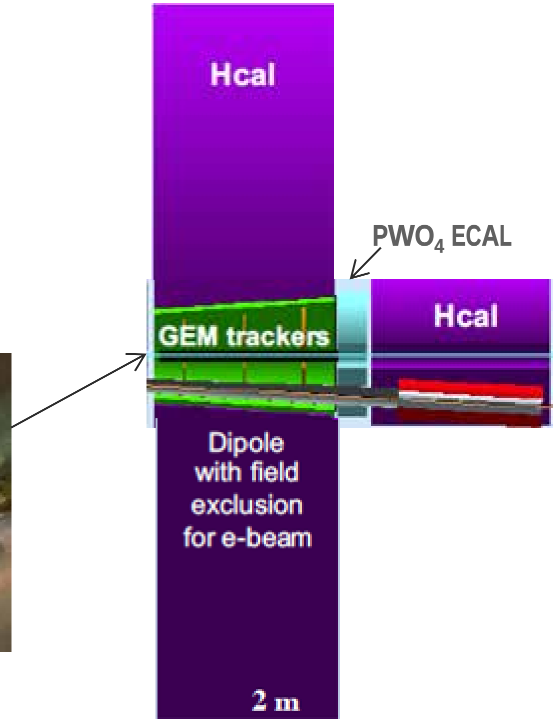
Inside dipole

Roman pots further down the beam line

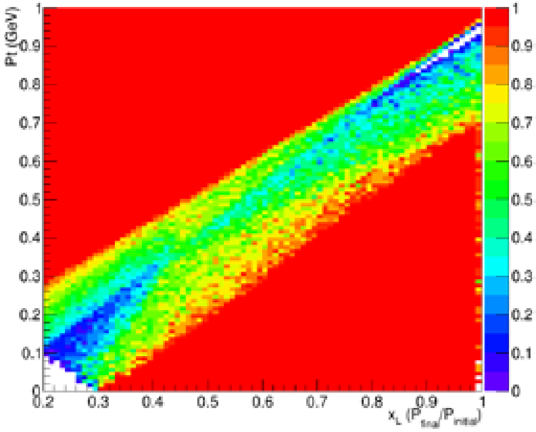
Acceptance close to 100% for diffractive peak ($x_L > 0.98$)

0^0 calorimeter further down

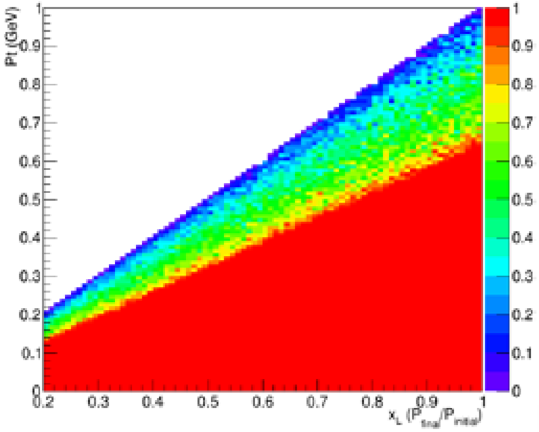
Measure forward neutrons
Large acceptance



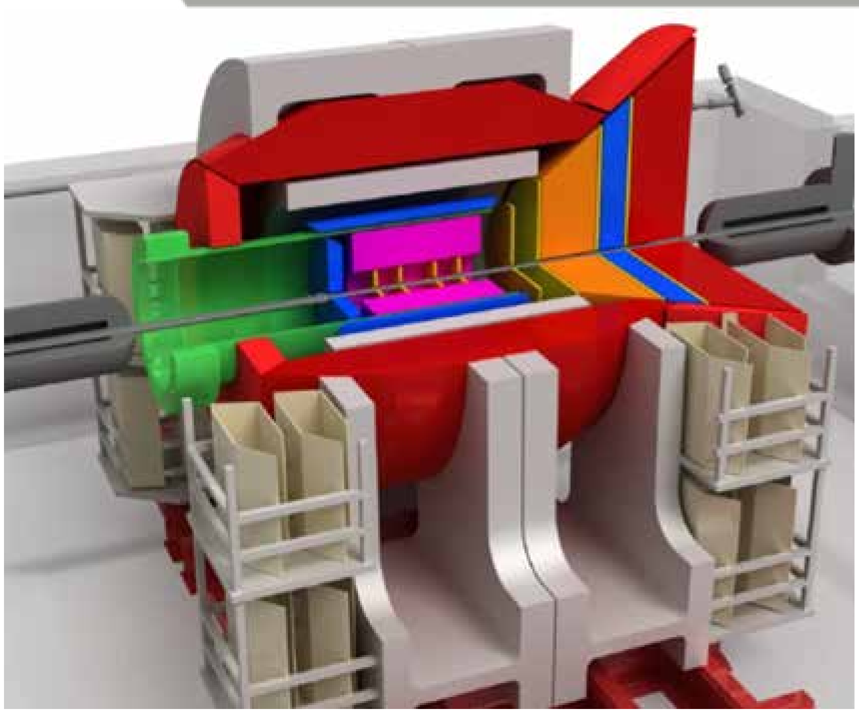
Acceptance of Proton Spectrometer



Acceptance of 0^0 calorimeter



The ePHENIX Concept



Evolution

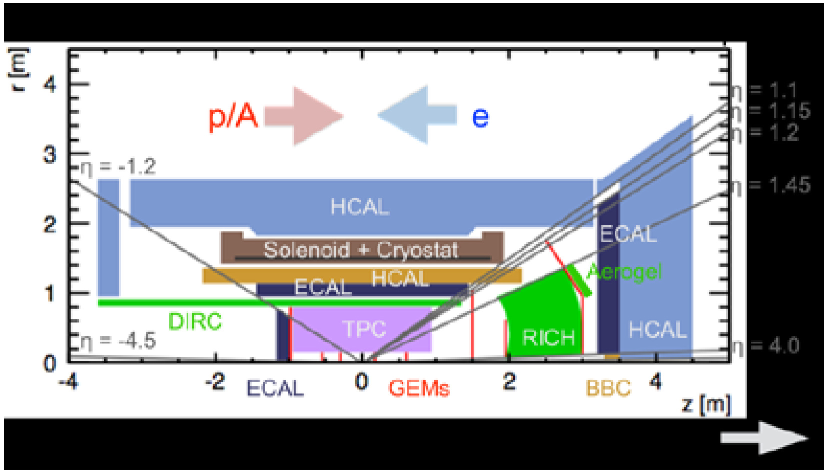
PHENIX -> sPHENIX -> ePHENIX
(CD-4 by 2023)

Superconducting solenoid

Scavenged from Babar: 1.5 T

Central detector

Compact-TPC
RICH + DIRCs
ECAL: Tungsten-fiber shashlik (12%/√E)
Barrel HCAL: Scintillator-steel (100%/√E)



Forward detection

Crystal calorimeters, Roman pots, 0^0 calorimeters

-> **Could be ready on Day 1 of the EIC Physics program**

List of particles

MC Hadron level

DIS event

Particle ID	P_x	P_y	P_z
11 (e^-)	-0.743	-0.636	-4.842
321 (K^+)	0.125	0.798	6.618
-211 (π^-)	0.232	0.008	3.776
-211 (π^-)	0.151	-0.007	4.421
211 (π^+)	0.046	0.410	2.995
111 (π^0)	-0.093	0.048	1.498
2112 (p)	0.115	-0.337	31.029
211 (π^+)	0.258	0.145	6.336
310 (K_S^0)	0.385	-0.408	3.226

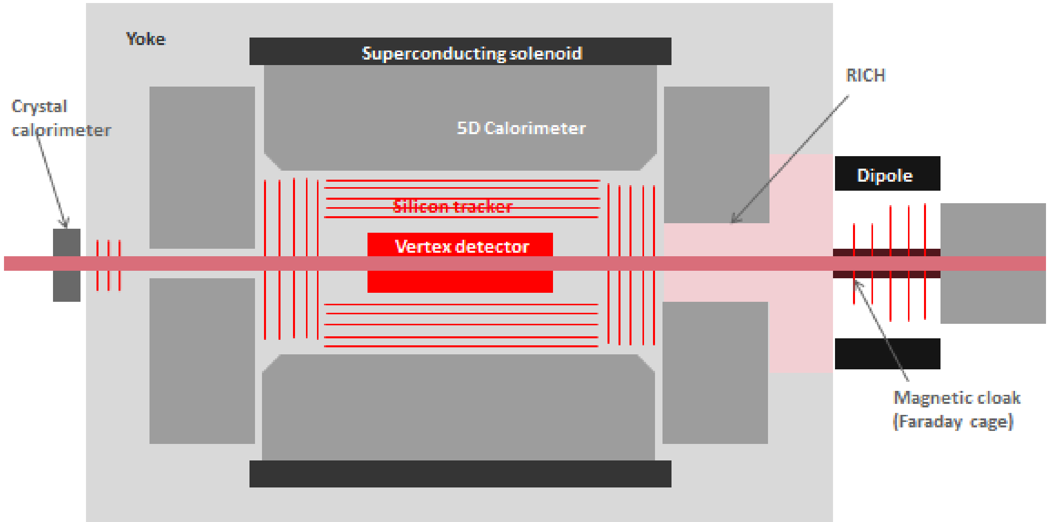
Detector output

Wouldn’t it be nice to have the same information?

Argonne: SiEIC: The 5D Concept

The idea

Measure (E,x,y,z,t) for every hit in tracker + CAL



Silicon pixel vertex + **strip tracker**
Imaging calorimeter
Superconducting solenoid (3T)
Forward gaseous RICH
Forward dipole + cloak or toroid w/out cloak
Forward silicon disks
Forward calorimetry
Backward silicon disks
Backward crystal calorimeter

Particle identification (π – K – proton separation)

Particle momenta < 10 GeV/c for most of the solid angle from tracker + calorimeter
Requires **silicon sensors with time resolution of about 10 ps**

Eliminates

The need for preshower counters, TRDs, TOF or Cerenkov (in front of the calorimeter), muon chambers (in back of calorimeter)

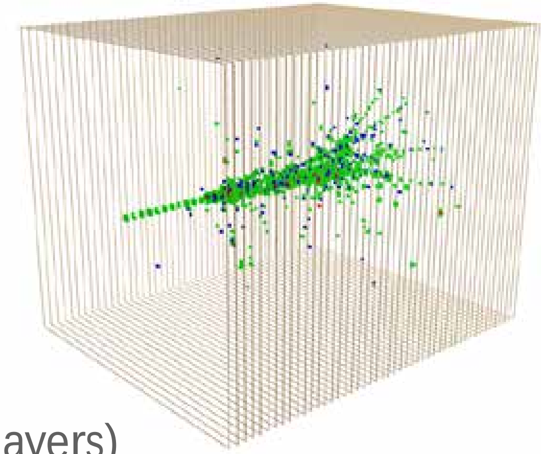
Imaging Calorimetry

Replace

Tower structure with very fine granularity (lateral and longitudinally)
Few 1,000 channels -> few 10,000,000 channels
Option to reduce resolution on single channels to 1 – 2 bits (digital readout)

Technologies developed in past decade

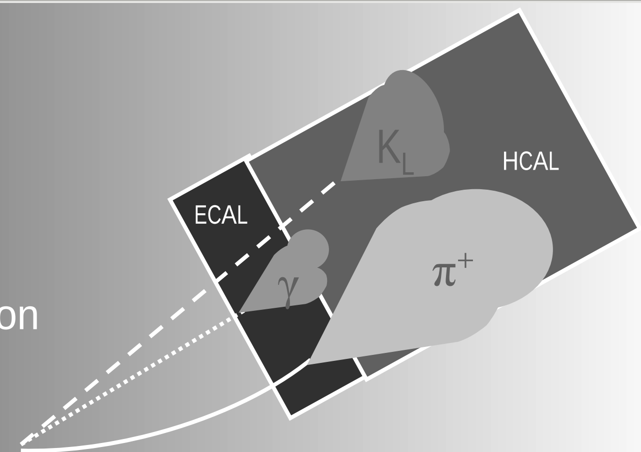
Silicon sensors with 1 x 1 cm^2, 0.25 x 0.25 cm^2 and 0.16 cm^2 pixels
Scintillator strips (4.5 x 0.5 cm^2) or scintillator pads (3 x 3 cm^2)
Resistive Plate chambers with 1 x 1 cm^2 pads
Micromegas and GEMs with 1 x 1 cm^2 pads



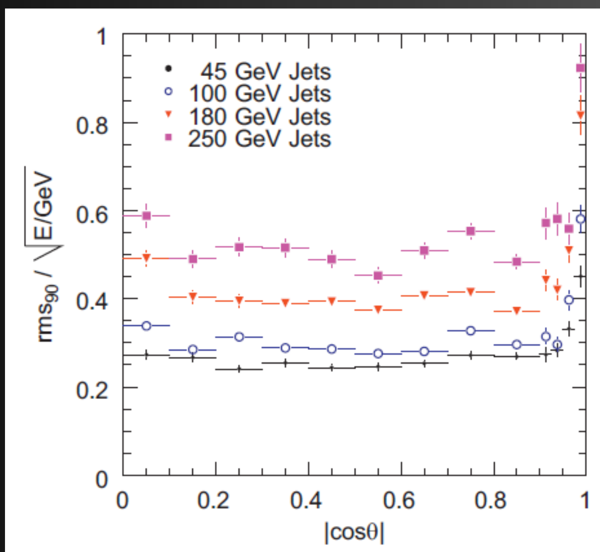
Advantages

Particle ID (electron, muon) almost trivial
Software compensation possible (improvement in resolution)
Longitudinal leakage corrections (using information from last layers)
Monitoring of gain (using track segments)
Identification of underlying events (low p_T background)
Application of Particle Flow Algorithms (PFAs)

Particle Flow Algorithms



Attempt to measure the energy/momentum of each particle in a hadronic jet with the detector subsystem providing the best resolution



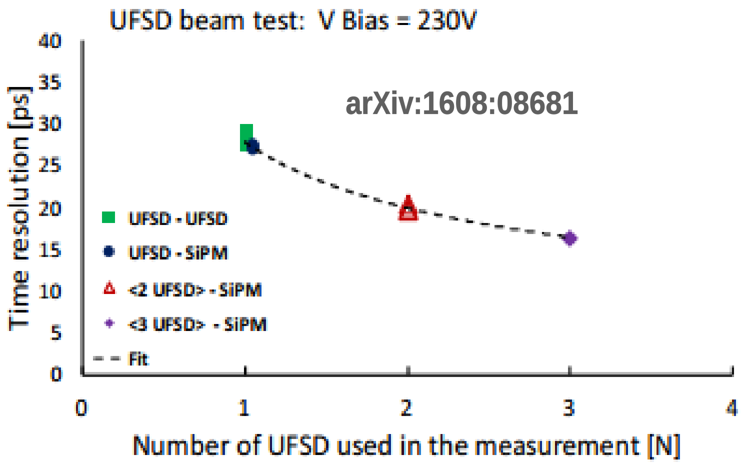
PANDORA PFA based on ILD detector concept

Particles in jets	Fraction of energy	Measured with	Resolution [σ^2]
Charged	65 %	Tracker	Negligible
Photons	25 %	ECAL with 15%/√E	$0.07^2\ E_{jet}$
Neutral Hadrons	10 %	ECAL + HCAL with 50%/√E	$0.16^2\ E_{jet}$
Confusion	If goal is to achieve a resolution of 30%/√E →		**≤ $0.24^2\ E_{jet}$**

18%/√E

Factor ~2 better jet energy resolution than previously achieved
EIC environment: particularly suited for PFAs, due to low particle multiplicity and low momenta

Ultra-fast Silicon Sensors



Needed in

Calorimeter and tracker for Particle ID
(π- K – p separation)
Resolution of 10 ps -> separation up to ~ 7 GeV/c

Current status

Being developed based on the LGAD technology
Best timing resolution about 27 ps

Future

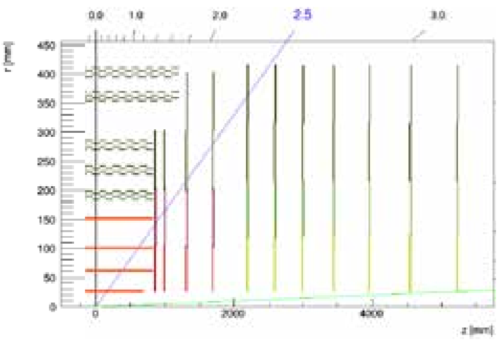
Further improvements ongoing
Interest in developing ultra-fast CMOS sensors (addition of amplification layer)

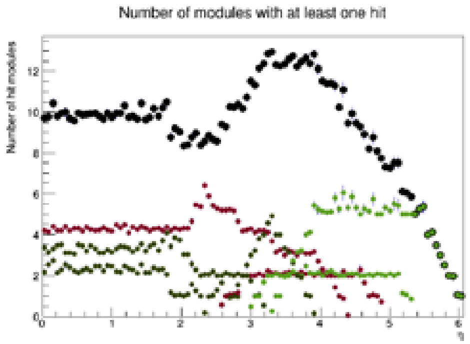
Time distribution system

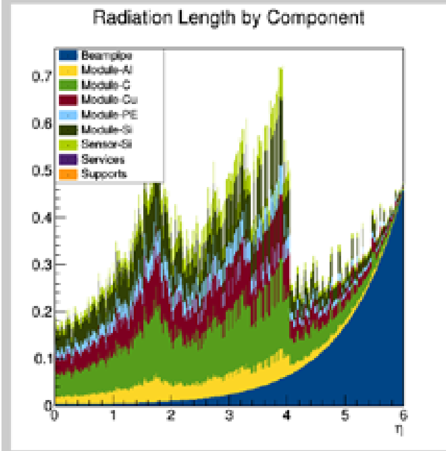
Initiated development and tests at Argonne

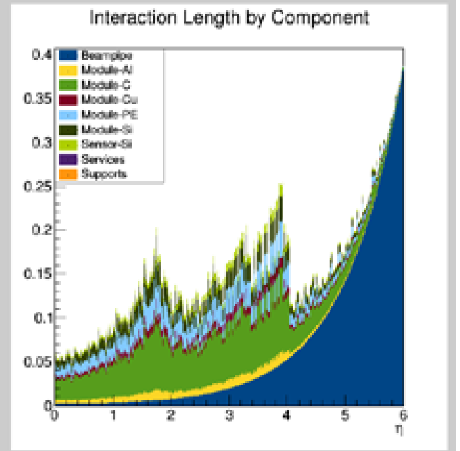
Silicon Tracker: Considering tilted sensors

Non Tilted Sensor Planes



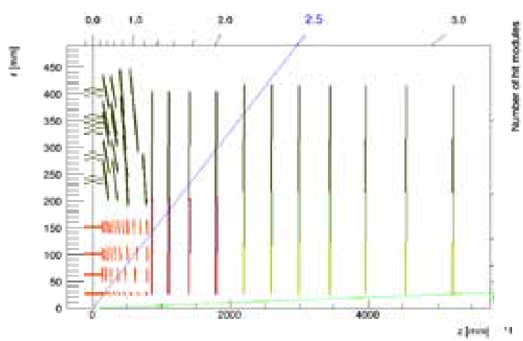


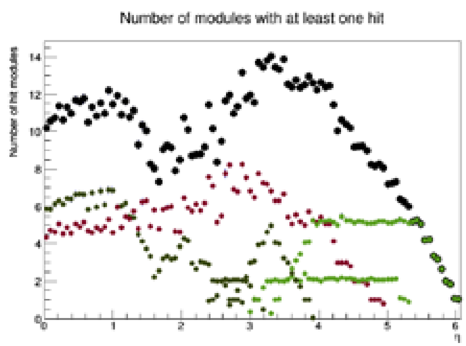


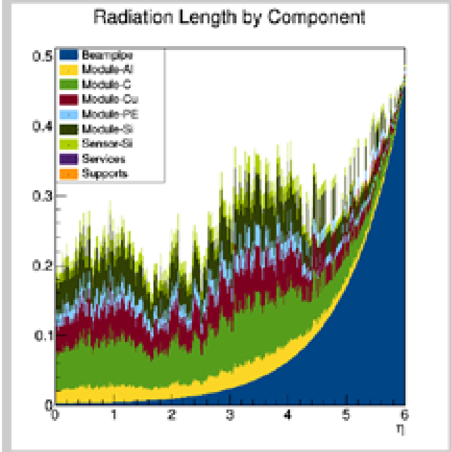


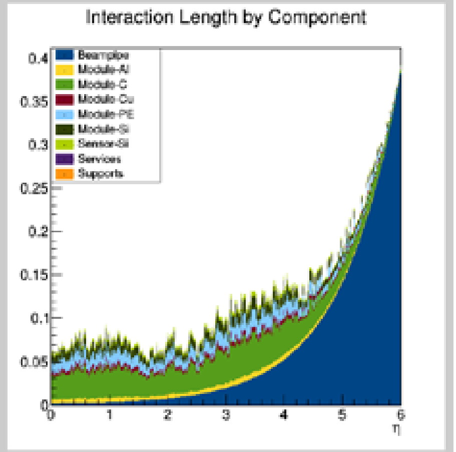
Tilted Sensor Planes

More hits, 25% less material (in X_0)



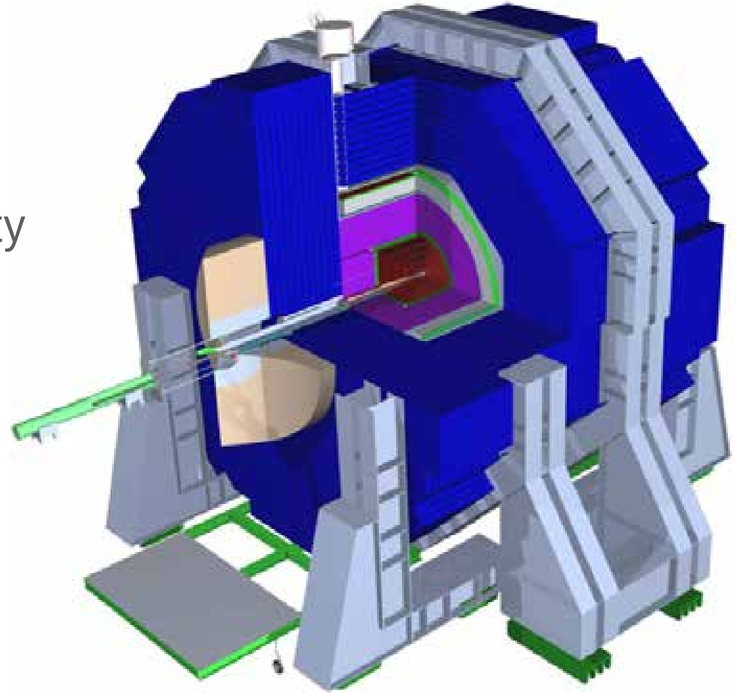






Taken from Peter Kostka and Alessandro Polini (LHeC studies)

SiEIC in Simulation



Starting point

SiD detector concept developed by ILC community

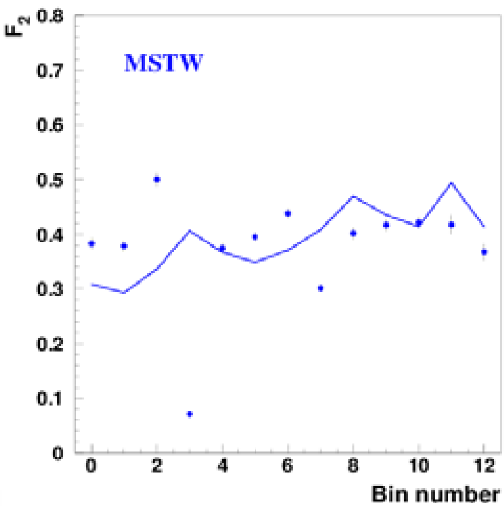
SiEIC

Some initial modifications from SiD

Longer barrel, lower B-field, shallower calorimeters

No performance tuning yet
(detector optimized for $|\eta| < 3.0$)

Simulation



Entire chain available
-> EG, GEANT4, digitization, reconstruction, analysis
Introduced DD4Hep
-> One geometry file for sim., dig., rec., analysis
Ongoing replacement of parts difficult to maintain/develop
-> digitization, tracking -> generic tracking
(full JLEIC det. sim., dig. and rec. to be available soon)

Conclusions

EIC environment/physics poses specific challenges

- Detection of forward proton/neutron/ions
- Measurement of scattered electron at low angles
- Particle identification (pion – kaon – proton) over large solid angle
- Kinematic reconstruction of charged current events (no scattered electron)

Challenges being addressed by various concepts being developed

- BEAST, sPHENIX, JLEIC; SiEIC

Thanks to

Elke Aschenauer, Alexander Kiselev, Pawel-Nadel Turonski, Rik Yoshida

from whom I took material and adopted ideas…