The Role of Detectors in Large, Accelerator-based Experiments

and R&D efforts to make them better

D. Mack (Jefferson Lab)

Chair, EIC-related Generic Detector R&D Committee

March 16, 2023

DOE/NIH Workshop

The Purpose of Detectors in Nuclear and Particle Physics, Accelerator-based Experiments

We have

Beam particle + Target particle → A + B + etc

We usually know everything about the beam and target: mass, charge, energy, direction.

A lot can happen in the final state. Nailing down the final state is what detectors do for us, and it's absolutely critical.

<u>Conservation of Momentum and Energy</u>

What is the momentum <u>or</u> energy of particles A, B, etc?

What is the mass of particles A, B, etc?

Then we could, for example, apply energy and momentum conservation rules to reject bkg:

$$\mathbf{E}_{\text{initial}} = \mathbf{E}_{\text{final}} \qquad \text{(1 equation)}$$

$$\textbf{Momentum}_{\text{initial}} = \textbf{Momentum}_{\text{final}} \qquad \text{(3 equations)}$$

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<u>What are the natures of particles A, B, etc?</u>

Is it a strongly interacting particle?

We infer this from the mass since the list of likely suspects is short. For example,

pion vs electron: detecting an electron may mean the interaction was electromagnetic, and a virtual photon was exchanged

pion vs kaon: detecting a kaon means we created strange quarks

Typical Detector Environment/Constraints

Can the candidate detector technology:

- tolerate the magnetic field? (it may range up to O(1) Tesla)
- tolerate the radiation dose expected over the experiment lifetime? (it may range up to O(1) Mrad)
- tolerate elevated levels of helium in the atmosphere? (Bkg is 5 ppm. It can be 10x higher near a pile of leaky SC magnets.)
- introduce only limited material next to the scattering vertex?:
    - To preserve momentum resolution in the face of multiple scattering
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- introduce only limited material next to the scattering vertex?:
  - To preserve momentum resolution in the face of multiple scattering
  - To reduce loss of strongly interacting particles due to nuclear reactions (1% loss per g/cm2)
  - To reduce loss of hard photons due to conversion to e+e-
- achieve sufficiently low noise levels?:
  - for acceptable Signal/Noise, and
  - without overwhelming the data acquisition?
- be procured at reasonable cost?
- be operated without servicing nitemares? (eg, in providing LV, HV, cooling, condensation, heat removal)
- What about availability? (Is there a long lead time and/or supply chain fragility?)

That's a lot of constraints.

Developing technologies subject to fewer constraints is an important goal of generic R&D.

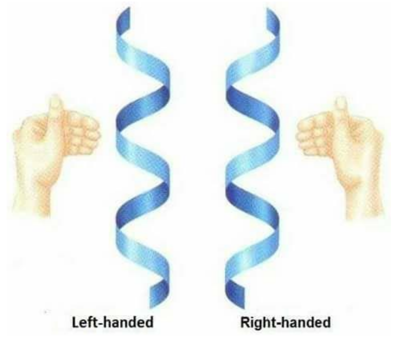
Some constraints are yes/no (eg, whether the detector technology will function in a 1.5T field). Sometimes one can compromise.

Hand-waving Categorization of Detectors

<u>Tracking</u>

For charged particles curving in a magnetic field, thin tracking detectors determine the <u>momentum</u>.

The direction of the curving (which can be a helix in a solenoid) determines whether the <u>charge</u> is + or -.



<u>Calorimetry</u>

For neutral particles like the photon, thick calorimeters determine the <u>energy</u>.

<u>Timing</u>

For charged particles, relatively thin timing detectors can help determine <u>start time</u> and <u>velocity</u>.

<u>Particle Identification (or PID)</u>

For charged particles, thin "PID" detectors are used to infer particle <u>mass</u>.

Two Very Different Detector Environments

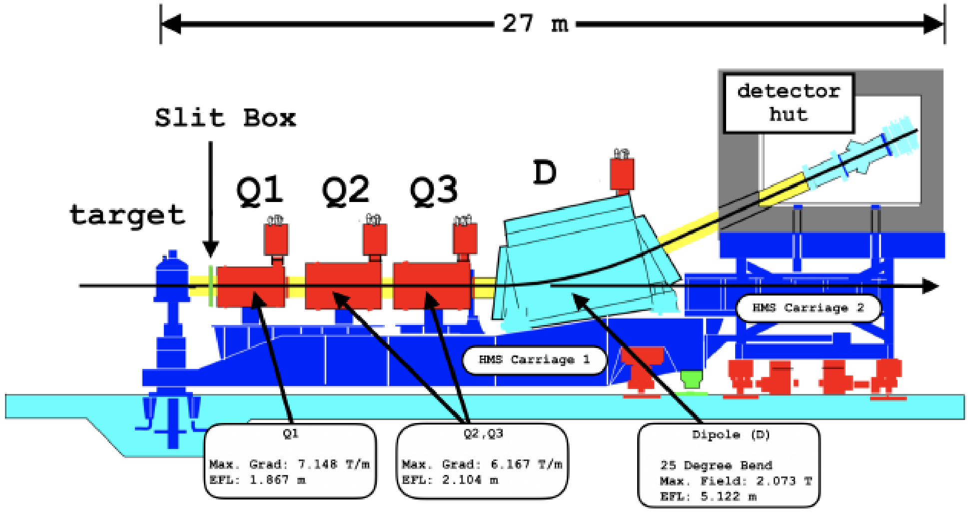


Figure 3.20: High Momentum Spectrometer (HMS) side view.

<u>The High Momentum Spectrometer in Hall C</u>

- Primary electron beam
- Bigger than my house. Quad+Quad+Quad+Dipole (all SC)
- Magnetic field at detectors O(1) Gauss
- Detects 1 particle at a time (Hall C has 2 such spectrometers)
- Detectors shielded from low energy background
- Outside of the detector shield hut, a horrid environment for silicon, polymers, and biology. High prompt radiation as well as some O_3 and NO_2. Significant activation near downstream beamline; keep-out areas are mapped and roped off.
- Hard to completely suppress helium leaking around old and/or rad-damaged O-rings, hence rapid death for quartz window PMTs.

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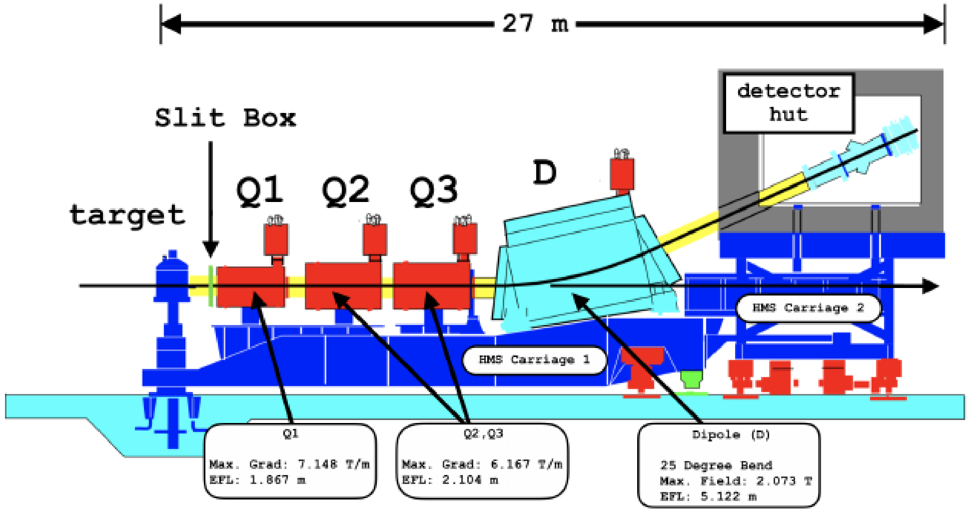

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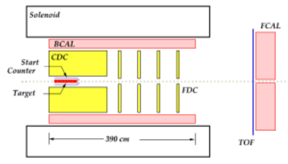

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GlueX Spectrometer in Hall D

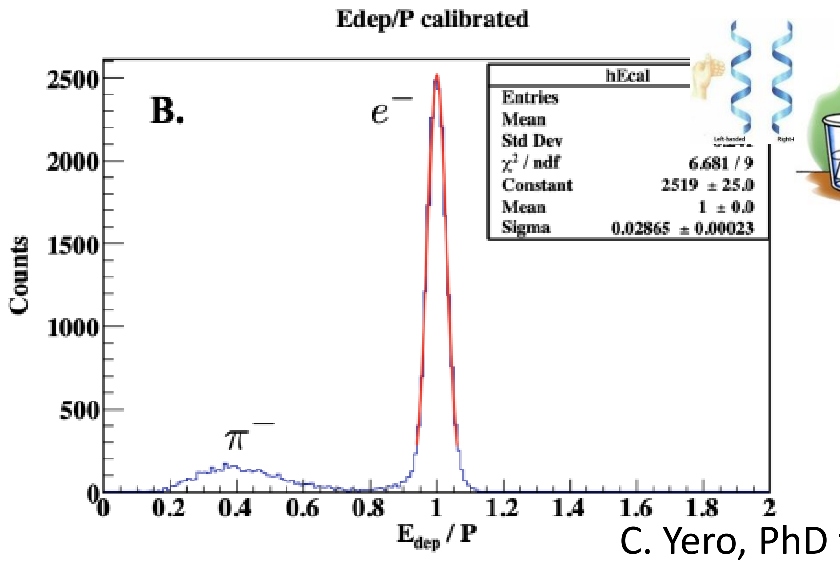
- Secondary beam of photons
- Smaller than my house, bigger than my garage. Solenoid (SC)
- Magnetic field at detectors O(1) Tesla
- Routinely detects 5-8 particles from a single event
- Detectors exposed to low energy background at small angles
- SiPM lifetime is decade-scale, and personnel can enter the hall shortly after beam goes off in a low drama "rapid access" procedure.
- No serious helium leak problem that I'm aware of.

Detector Categories Work Together, and Sometimes Even Hybridize

Example of Tracking+Calorimetry functioning in concert:

Identifying electrons in an orders-of-magnitude larger pi- background is one of the most important and difficult particle ID challenges. Above a momentum of 1 GeV, both these low mass particles have velocity close to c.

Energy is determined by a Hall C calorimeter, while momentum is determined by tracking. When **"E/p"** is normalized to 1 for (usually) contained e- showers, then the (usually) poorly contained pi- showers show up at << 1.



C. Yero, PhD thesis

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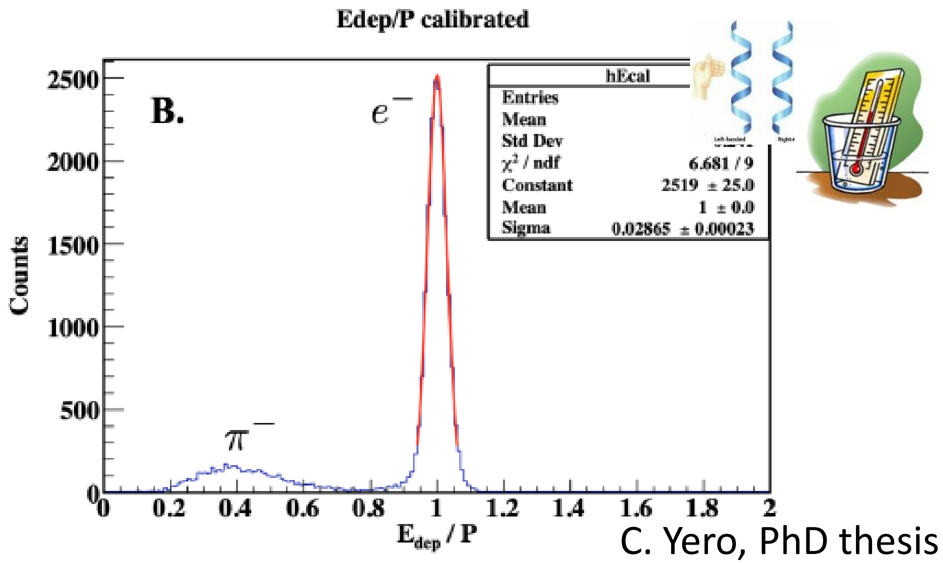

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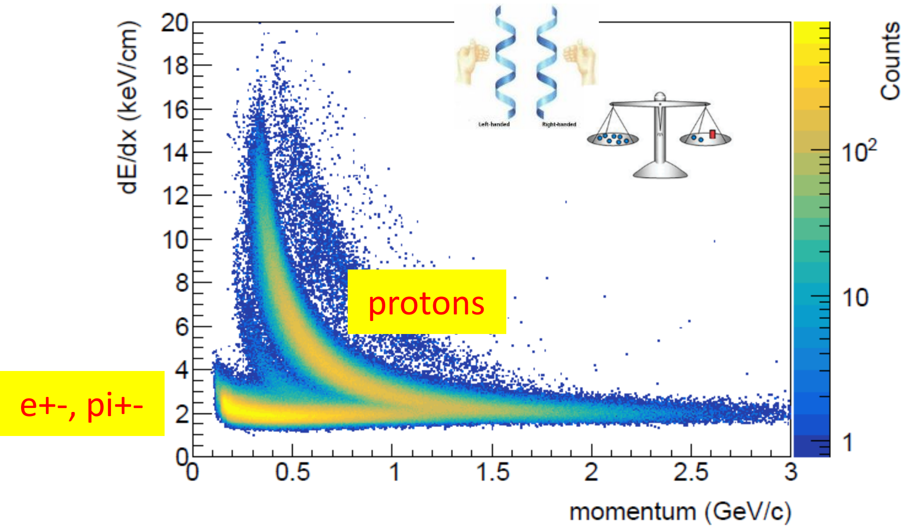
Example of Tracking detector + Particle ID hybridization:

The Central Drift Chamber (CDC) in Hall D helps determine momentum via tracking.

But it also makes many dE/dx measurements of the ionization.

Combining the two pieces of information makes the Central Drift Chamber an important particle ID detector for momenta below 1 GeV/c.



CDC NIM article

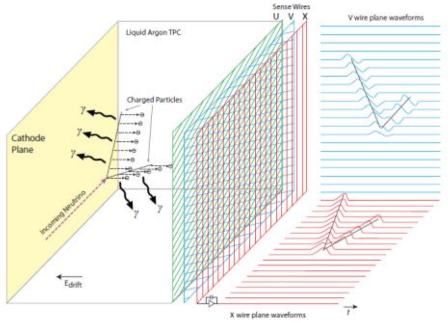
Tracking

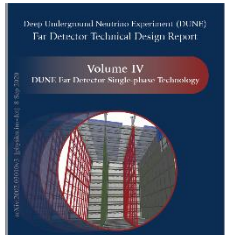
The DUNE Time Projection Chamber Provides Actual Tracks!

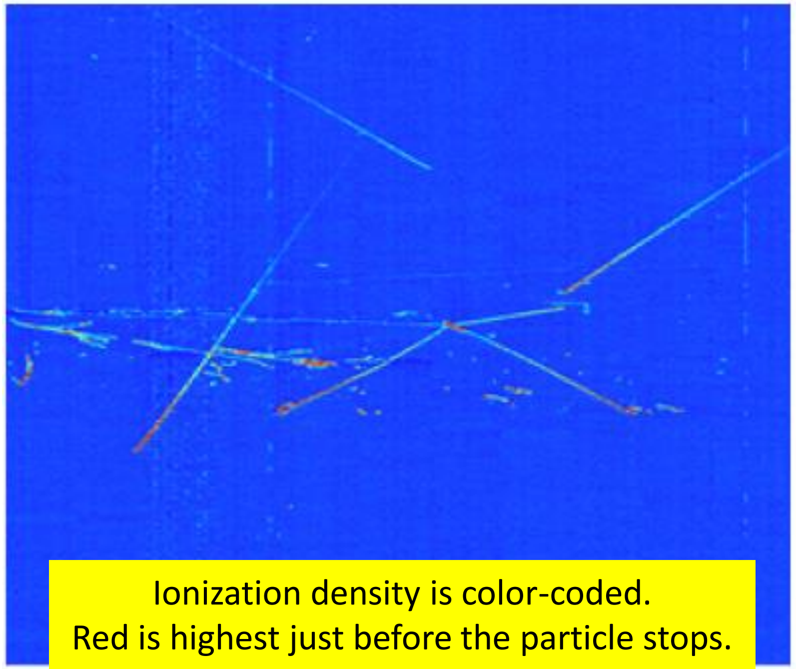
Before I disappoint you with what tracking usually looks like at accelerator-based facilities, admire along with me this plot from a DUNE TPC prototype.

The ionization trail from a charged particle in liquid Argon drifts in an electric field to be collected on U, V, and X sense wires. Knowing the drift velocity, time maps to position. (hence the name: Time Projection Chamber)
There's no magnetic field to measure momentum (the LAr tanks will be 4 stories tall and deep underground) but the track length and ionization intensity help determine particle energy and mass.

1.2 The Single-Phase Liquid Argon Time-Projection Chamber







X plane

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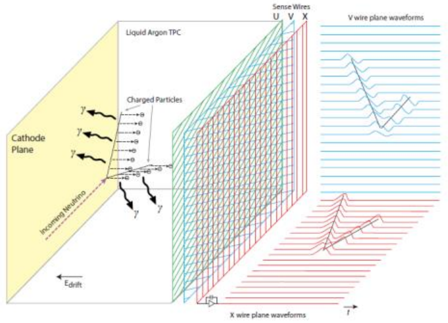
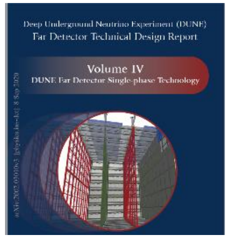
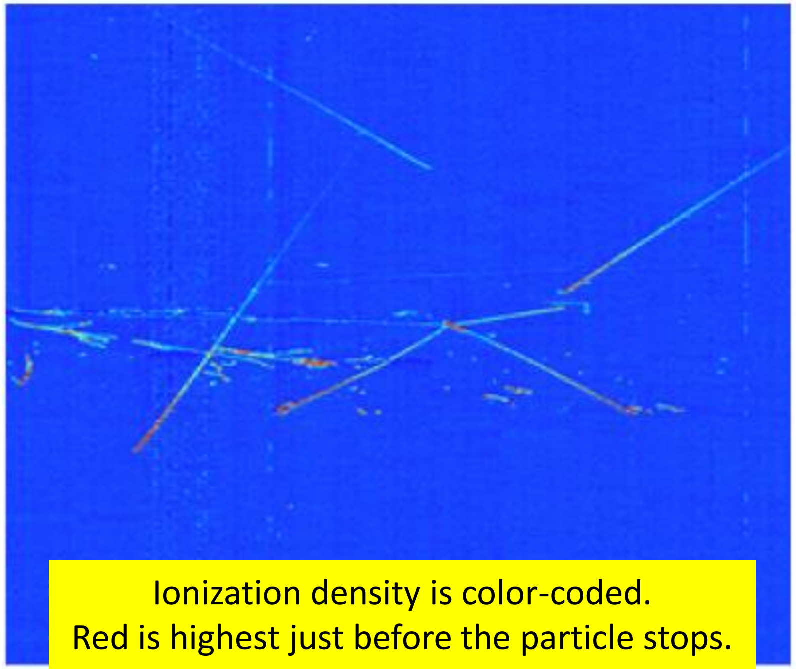


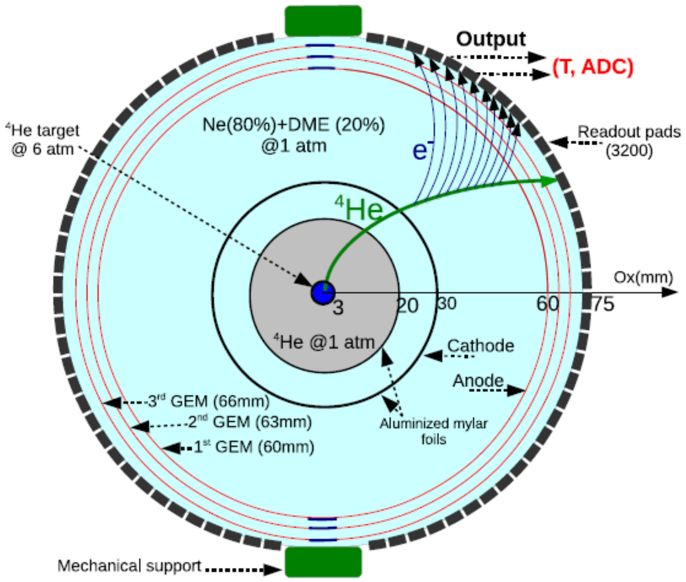




Ionization density is color-coded.
Red is highest just before the particle stops.

X plane

Nuclear Inst. and Methods in Physics Research, A 898 (2018) 90–97



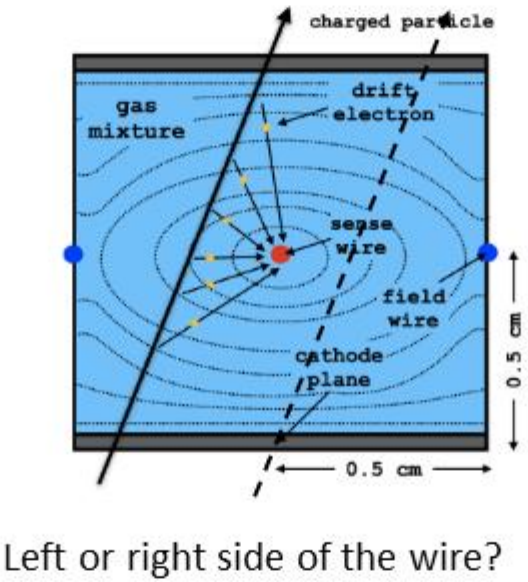
TPCs are arguably too slow for use at very high rates, but they have a niche:
A gas-phase version of TPC has been used in Jlab Hall B in a magnetic field. This allow momentum and dE/dx measurements. One "trick" is crucial to reduce backgrounds from the electron beam: setting the threshold/gain ratio high so that only very heavily ionizing particles of interest are sensed: eg, low energy proton and alpha particles.

Horizontal Drift Chambers

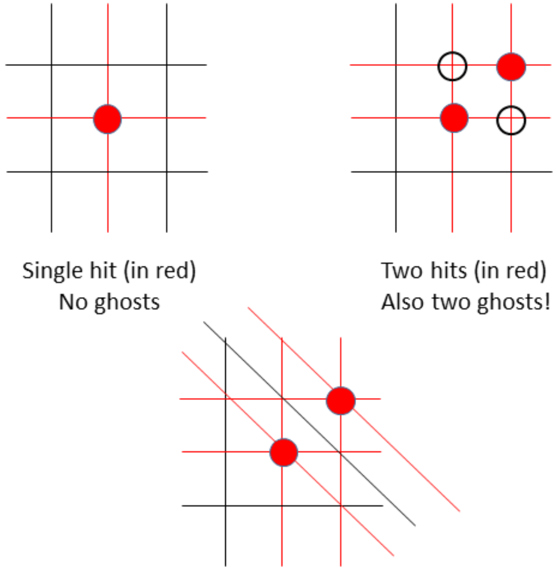
A charged particles ionizes gas, and electrons drift to a sense wire under an electric field of O(1)kV/cm. The small diameter sense wire has a tremendous electric field near its surface, causing an avalanche which multiplies the number of electrons.
Although the sense wires may be separated by O(1)cm, the precise drift time to the wire can yield a diffusion-limited resolution of ~150 microns. A single plane of a drift chamber measures a single position coordinate.

This is not a camera that sees tracks. Hits are detected. We have to fit/infer the track.

To uniquely determine an (X,Y) position in the face of ambiguities, several planes of measurements at different angles are needed.



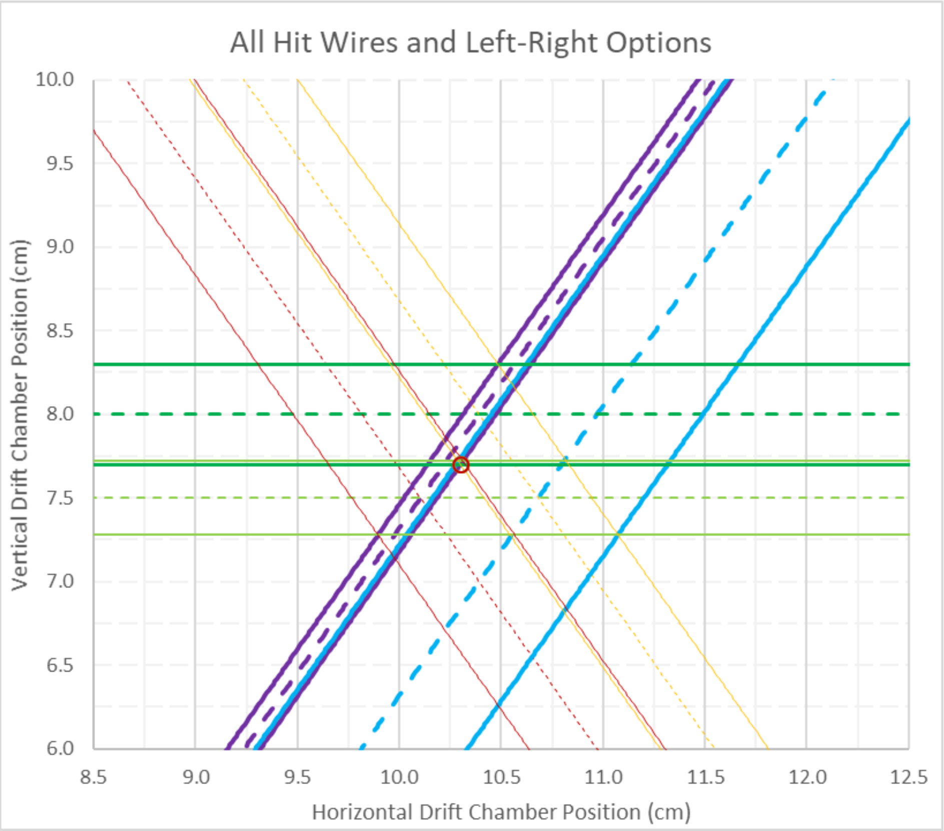
Individual cell in a Hall C DC.
The B field is only O(1) Gauss.



Single hit (in red)
No ghosts

Two hits (in red)
Also two ghosts!

Two hits (in red)
3rd wire plane at 45deg
No ghosts!

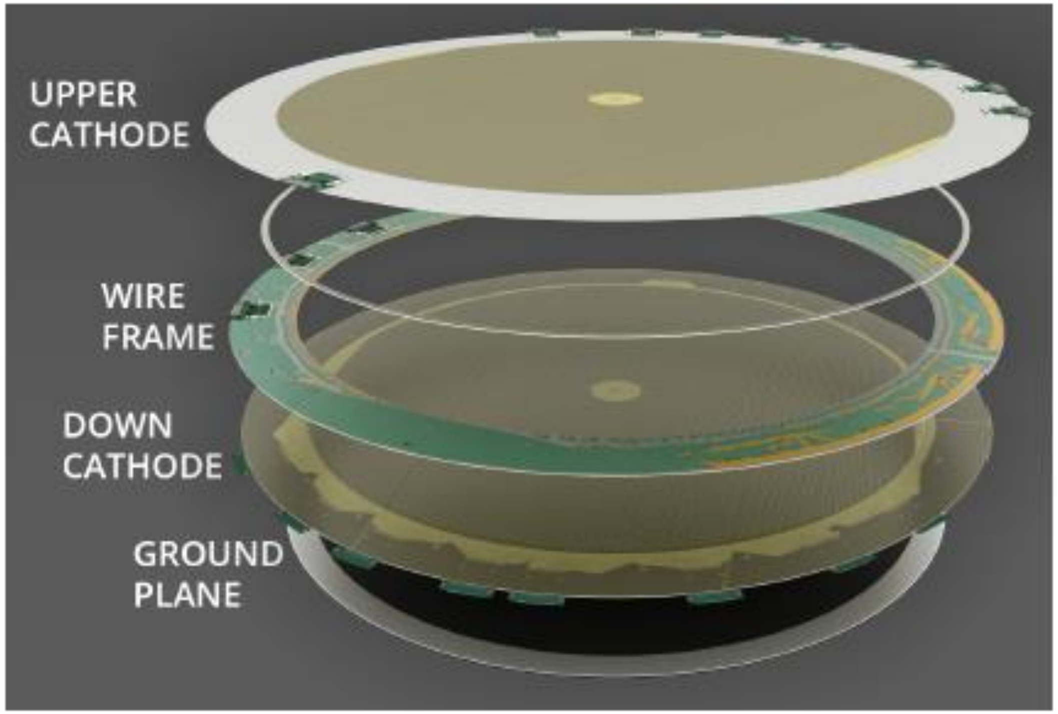


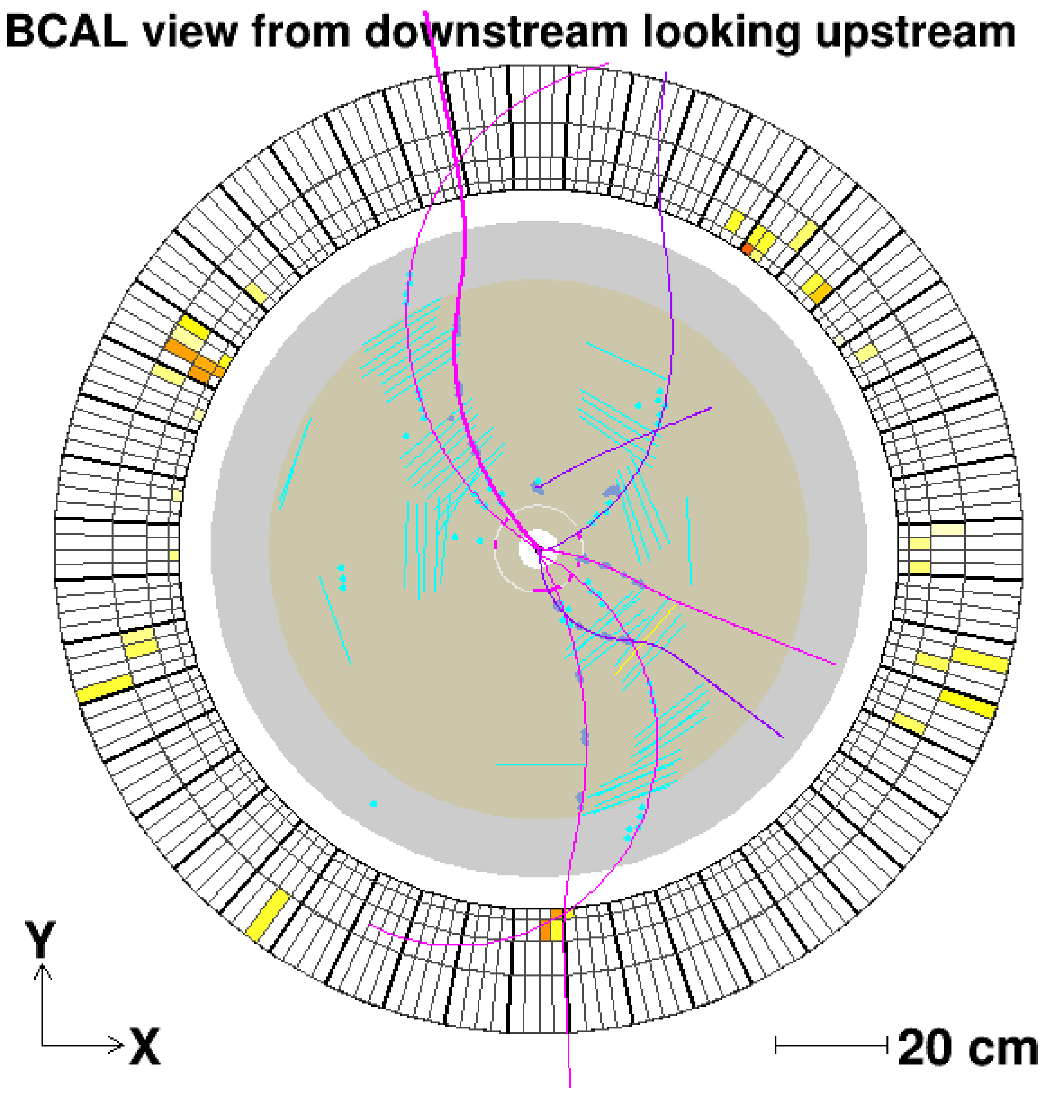
Drift Chambers in High Magnetic Fields

Drift chambers work fine in high magnetic fields, though the electrons drift to the wires in a spiral due to the combination of E and B fields.

The Hall D FDC (below left) has an advanced design to minimize ambiguities at high rates, with each wire plane signal complemented by induced signals in two adjacent cathode planes oriented at +-75 degrees. This yields (X,Y) rather than just X for example. The B field is O(1) Tesla.

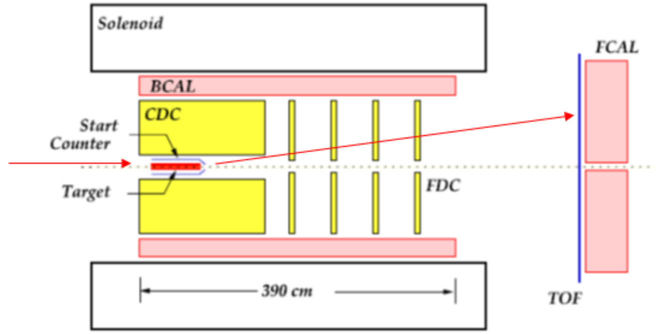
If you look closely at the track reconstruction at right, you can see the dark blue (X,Y) hits in the FDC to which tracks are fitted.





Calorimetry

Barrel Calorimeter (BCAL)

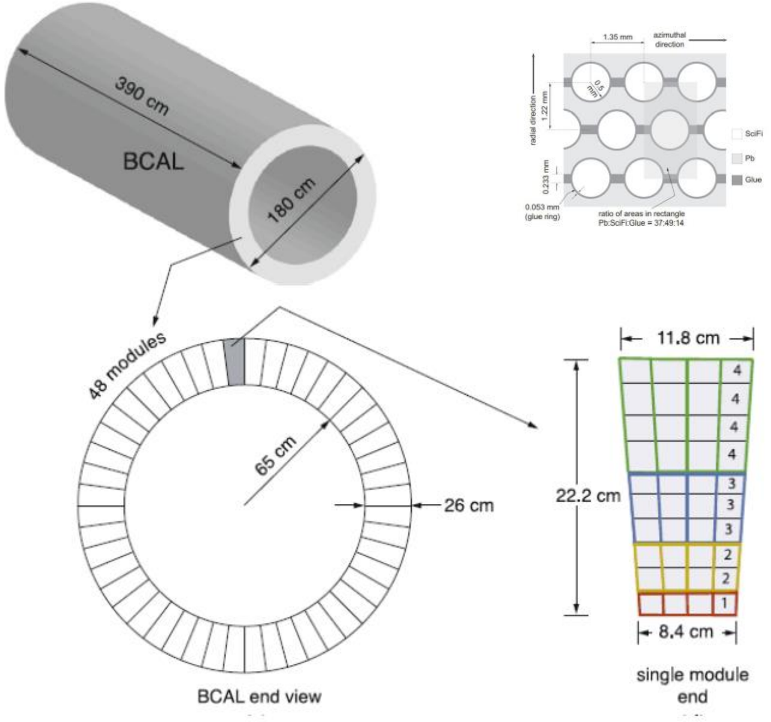


BCAL was needed to affordably cover a large solid angle in Jlab Hall D, while fitting within an existing solenoid with high magnetic field of O(1) Tesla. Given the kinematics, the energy range was 50 MeV to 2.5 GeV.

Sampling calorimeter: Scintillating fibers are place in grooved lead sheets. Energy deposited in lead is not measured. Energy in scint is measured well. Need lots of samples to make up for the “dead lead” though.

SiPMs were used to read out the light at both ends of a “log”, since the radiation dose is modest. (Light levels are high enough that SiPM noise is not an issue, with only modest nonlinearity due to SiPM pixel saturation at 2 GeV.)

Radial resolution is, for all practical purposes, limited by photosensor readout pitch. Longitudinal resolution is determined by the time difference to several cm.



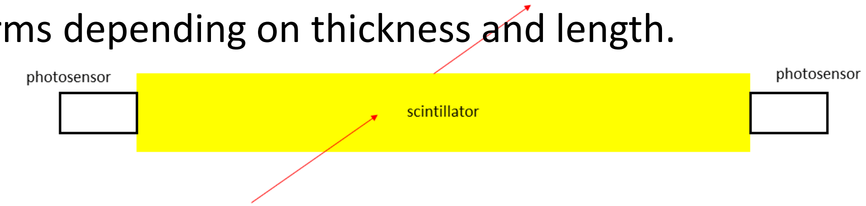
Parameter	Value
Energy resolution	~5%/sqrt(E) + 3.6%
Effective Moliere radius	3.6cm
Effective radiation length	1.5cm
Sampling fraction	10%
Thickness	22cm (15 radiation lengths)

For more information, see NIM A 896 (2018) 24–42

Timing

Scintillating Hodoscope

The workhorse of timing detectors is a scintillator connected to a photosensor. Both are relatively inexpensive.
The use of optically isolated bars reduces the rate per channel, and provides crude position resolution which is useful for bkg rejection.
Timing resolution can vary from 60-300ps rms depending on thickness and length.



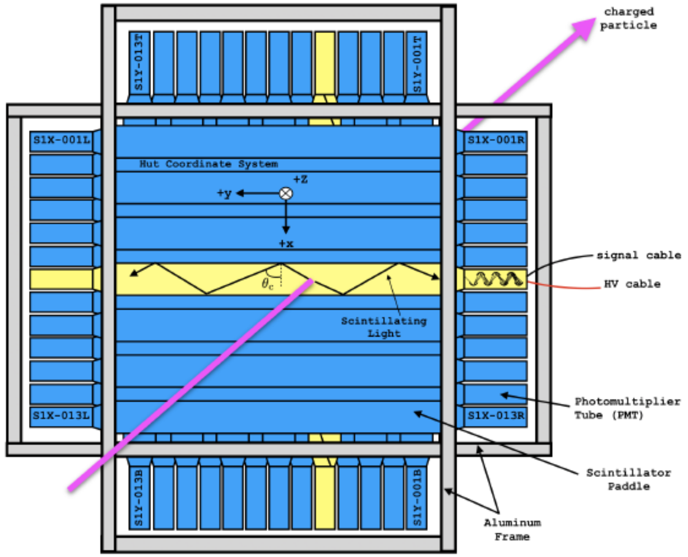
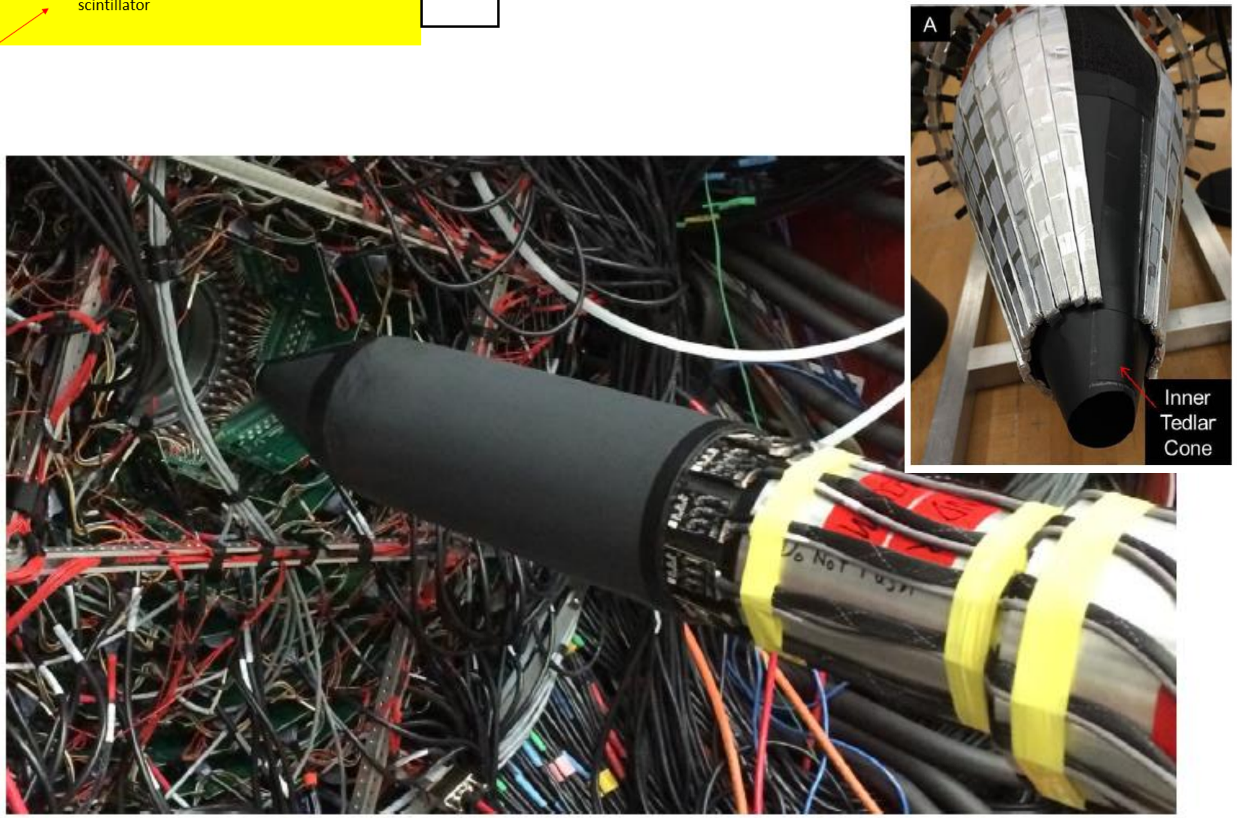


Figure 3.26: Front view of the SHMS S1X (front) and S1Y (back) hodoscope planes.



Hall C hodoscope with PMTs
O(1) Gauss magnetic field
Low rad dose

Hall D Start counter with SiPMs
O(1) Tesla magnetic field
Low rad dose

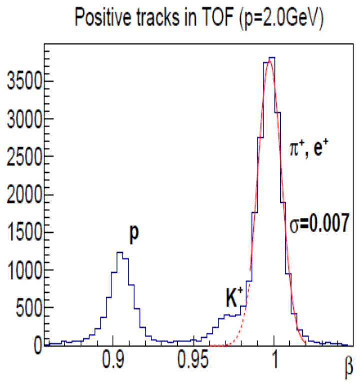
Relativity

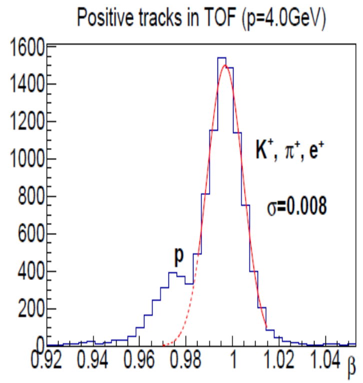
Identifying particles with velocities v/c <<1 is easy using Time-of-flight or dE/dx (ie, ionization).

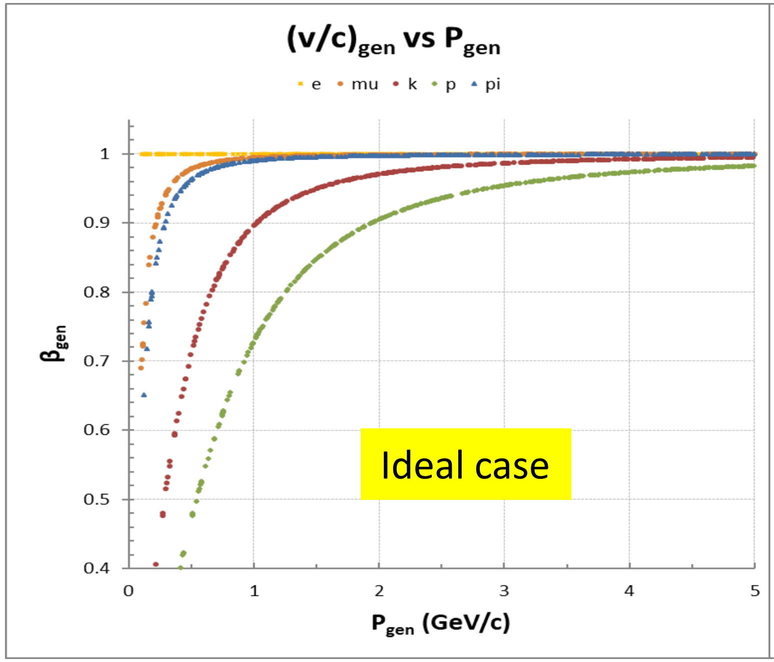
At higher velocities, relativity happens: multiple possible mass choices may be indistinguishably close to the speed of light.

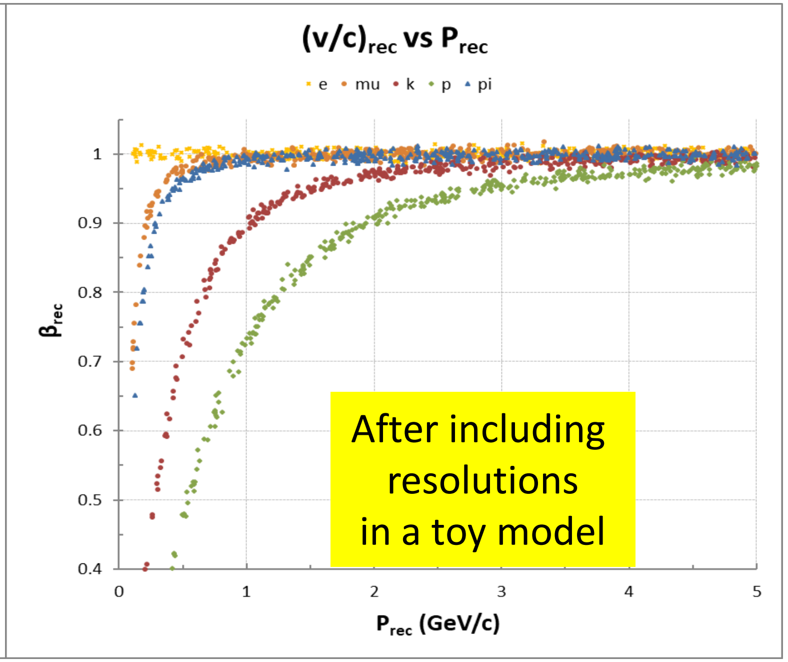
Figures below: Each locus corresponds to a different particle mass.
Figures at right: one can see difficult mass determination becomes above 2 GeV/c, even with scintillators that are 1” thick!!!

The challenges at Jlab have grown as the beam energy increased from 4 GeV to 12 GeV.
The EIC will present new challenges. This motivates detectors with better timing resolution.

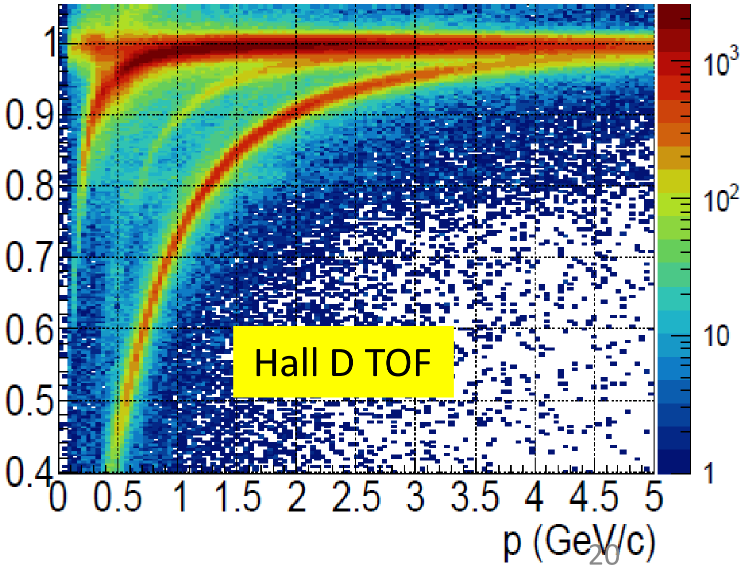








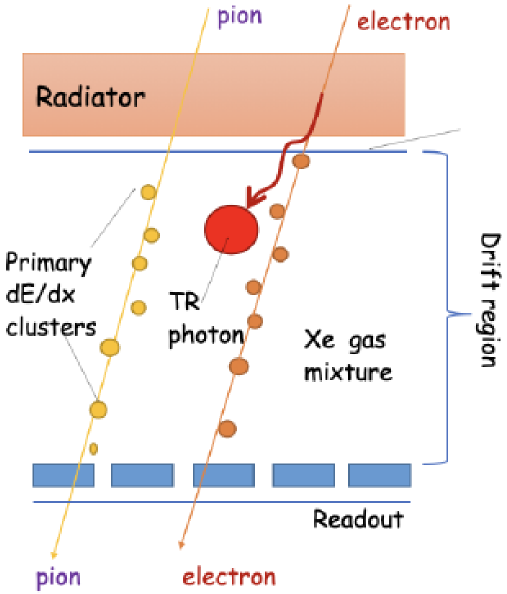
The Hall D TOF detector makes 2 measurements with 100ps resolution over a ~5.5m distance.



Highly relativistic Particle ID

A proposal for Micro Pattern Gaseous Detector-based transition radiation detector/tracker

Y. Furletova (yulia@jlab.org), and J. Velkovska (julia.velkovska@vanderbilt.edu)

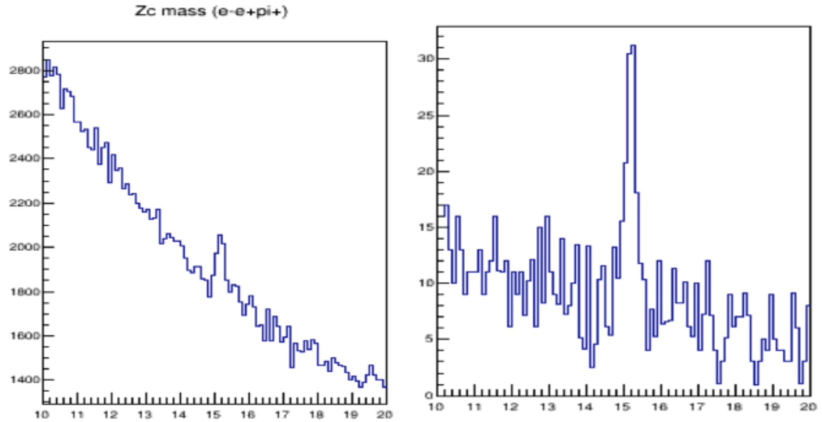


Transition radiation in the x-ray spectrum is emitted when a charged particle sees sudden changes in the index of refraction, such when passing thru a polymer in the form of sheets, foam, or "wool". The intensity is proportional to Energy/mass, so provides some discrimination between a relativistic pi- and an ultra-relativistic e-.

Figure upper right: the x-rays are absorbed in a Xe rich gas mixture, the electrons drift in a an electric field to a structure with gas gain such as a GEM, and the signal is read out.

The PIs' collaboration is testing alternative gas gain structures which are potentially cheaper, simpler to fabricate, and easier to operate than GEMs. They will also continue to optimize the radiator, and try to mitigate cost and supply chain issues with Xe.

Figure lower right: a simulated spectrum for Zc → e+e- at EIC, without and with an additional factor of ~10 rejection of pi+- using a TRD.



For more information including references, see the 2022 proposal #2 at https://www.jlab.org/research/eic_rd_prgm/receivedproposals

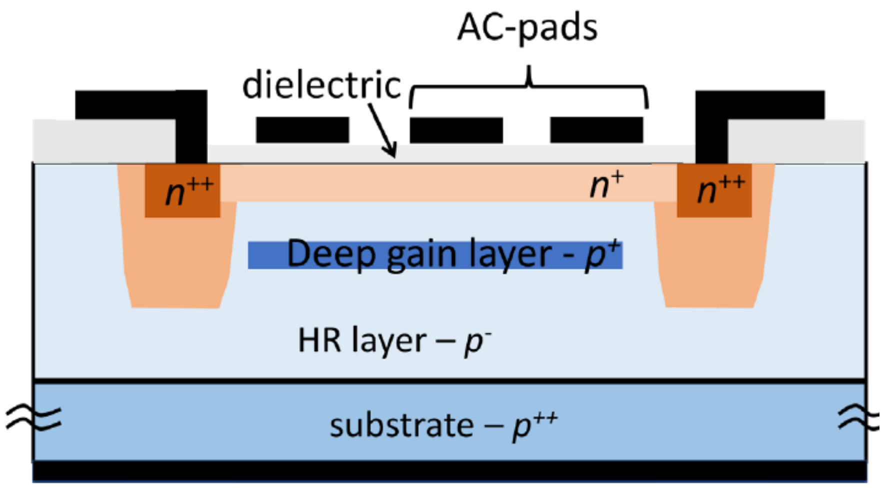
More EIC-related Generic Detector R&D

Simplified LGAD structure with fine pixelation

G. Giacomini (giacomini@bnl.gov), B. Schumm (baschumm@ucsc.edu)

The existing AC-LGAD detector has several highly desired properties:

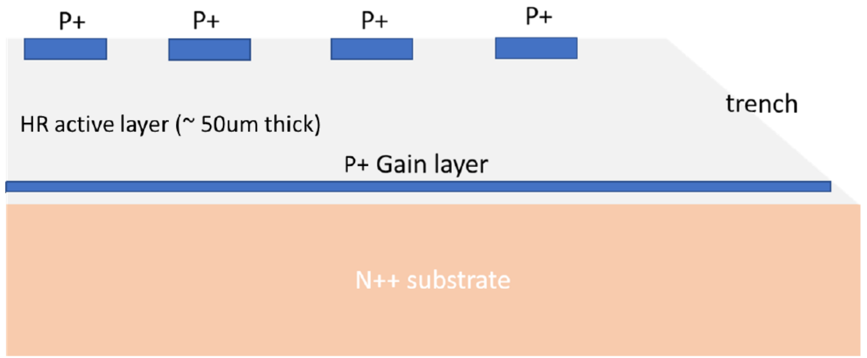
- ~100% fill factor,
- superb timing resolution (30 ps),
- superb position resolution (few microns).



But the AC-LGAD structure and hence fabrication is somewhat complex. (See figure at right.) Also, performance is somewhat compromised by cross-talk (a limitation at high rates) and relatively large capacitance (a limitation when increasing strip sizes to the cm scale).

The PI's intend to fabricate a new device they call, "a novel LGAD structure". It would

- retain the good proper properties of the AC-LGAD,
- reduce cross-talk and capacitance due to its DC-coupled nature,
- be easier to fabricate resulting in higher yields and lower costs.



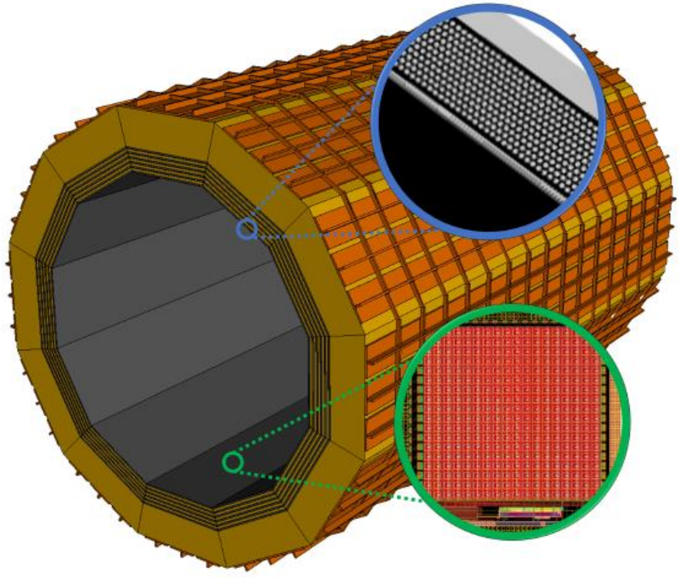
The perfect 4D detector (ie, precise in both position and time) is arguably the Holy Grail. But even if the "novel LGAD structure" is successful and finds important applications, the search for the Holy Grail will probably continue to reduce multiple scattering, power consumption, etc.

For more information including references, see the 2022 proposal #24 at
https://www.jlab.org/research/eic_rd_prgm/receivedproposals

Imaging Calorimetry for the Electron-Ion Collider

Maria Zurek (zurek@anl.gov), Zisis Papandreou (Zisis.Papandreou@uregina.ca)

How could one improve on the lead sci-fi barrel calorimeter concept, introduced on an earlier slide under the name BCAL?



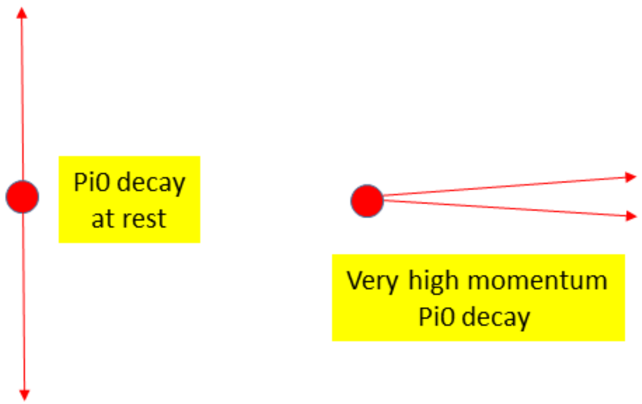
Much better position resolution of shower development :

i. longitudinally, for better discrimination between deeper pi+- showers and shallower e+- showers (generally speaking)
ii. transversely, to better separate the two showers from pi0→gamma + gamma decays (which can otherwise "fuse" in the data analysis and mimic a high energy photon, which is obviously a horrible background in interesting measurements looking for rare events with single, high energy photons)

The PIs' collaboration intends to improve position resolution by:

i. finer pixelization of the photosensors (2x2cm^2), and
ii. sandwiching Astropix silicon tracking between the innermost layers

Simulated pi/e discrimination and pi0 shower separation are excellent. (see backups)

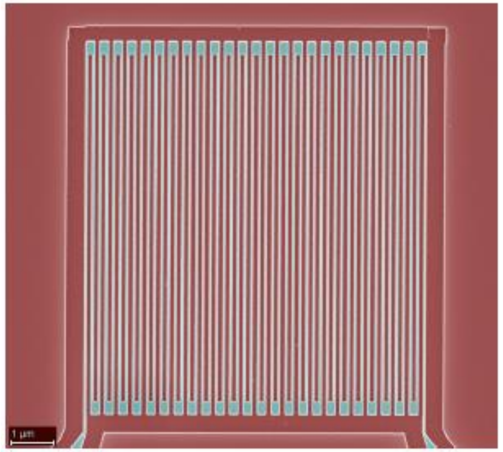


The collaboration has been funded to measure the energy resolution at high beam energy, and compare SiPM and MCP-PMT photosensor readout.

For more information including references, see the 2022 proposal #22 at https://www.jlab.org/research/eic_rd_prgm/receivedproposals

Superconducting Nanowire Detectors for the EIC

Whitney Armstrong (warmstrong@anl.gov)



Potential application of a relatively new technology to particle physics:

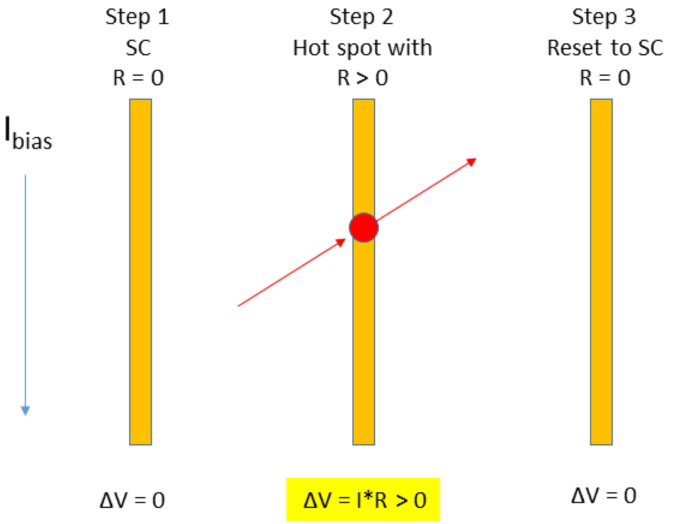
Superconducting nanowire single photon detectors (SNSPDs) have high quantum efficiency, rapid time response, and ability to operate in multi-Tesla magnetic fields.

Stages in detection (see figure at lower right):

- Wire is superconducting with a bias current flowing thru it. $\Delta V = 0$
- Absorption of particle energy induces a local transition to resistive. $\Delta V > 0$
- The hot spot cools and the wire is ready for another hit. $\Delta V = 0$

The PI's collaboration is testing whether this technology can work for the detection of charged particles in a high radiation environment very close to the EIC hadron beamline, closer than perhaps silicon options can tolerate.
(It will also be interesting to see how long the reset times are for charged particles, which will deposit much more energy in a wire than O(1) eV.)

For more information including references, see the 2022 proposal #18 at
https://www.jlab.org/research/eic_rd_prgm/receivedproposals



Summary

I’ve given a quick overview of some detector technologies used in nuclear/particle physics experiments in accelerator-based experiments.

Physics detectors need to determine particle <u>momentum</u>, <u>charge</u>, <u>energy</u>, <u>timing</u>, and <u>mass</u>.

Major detector categories are <u>tracking</u>, <u>calorimetry</u>, <u>timing</u>, and a particularly challenging area I call “<u>highly relativistic particle ID</u>”.

When selecting a detector, our constraints include magnetic fields, radiation dose, sensitivity to elevated helium levels, material (g/cm^2), noise, cost, services, and availability/supply chain. Some of these may be unique to nuclear/particle physics, but I’m sure we share some of these constraints with the NIH community.

(Developing technologies subject to fewer constraints is an important goal of generic R&D.

I gave some examples from each detector category, and how they work together to determine mass and reduce backgrounds.

I explained how detector categories are continuing to hybridize to improve the performance and possibly reduce material, etc.

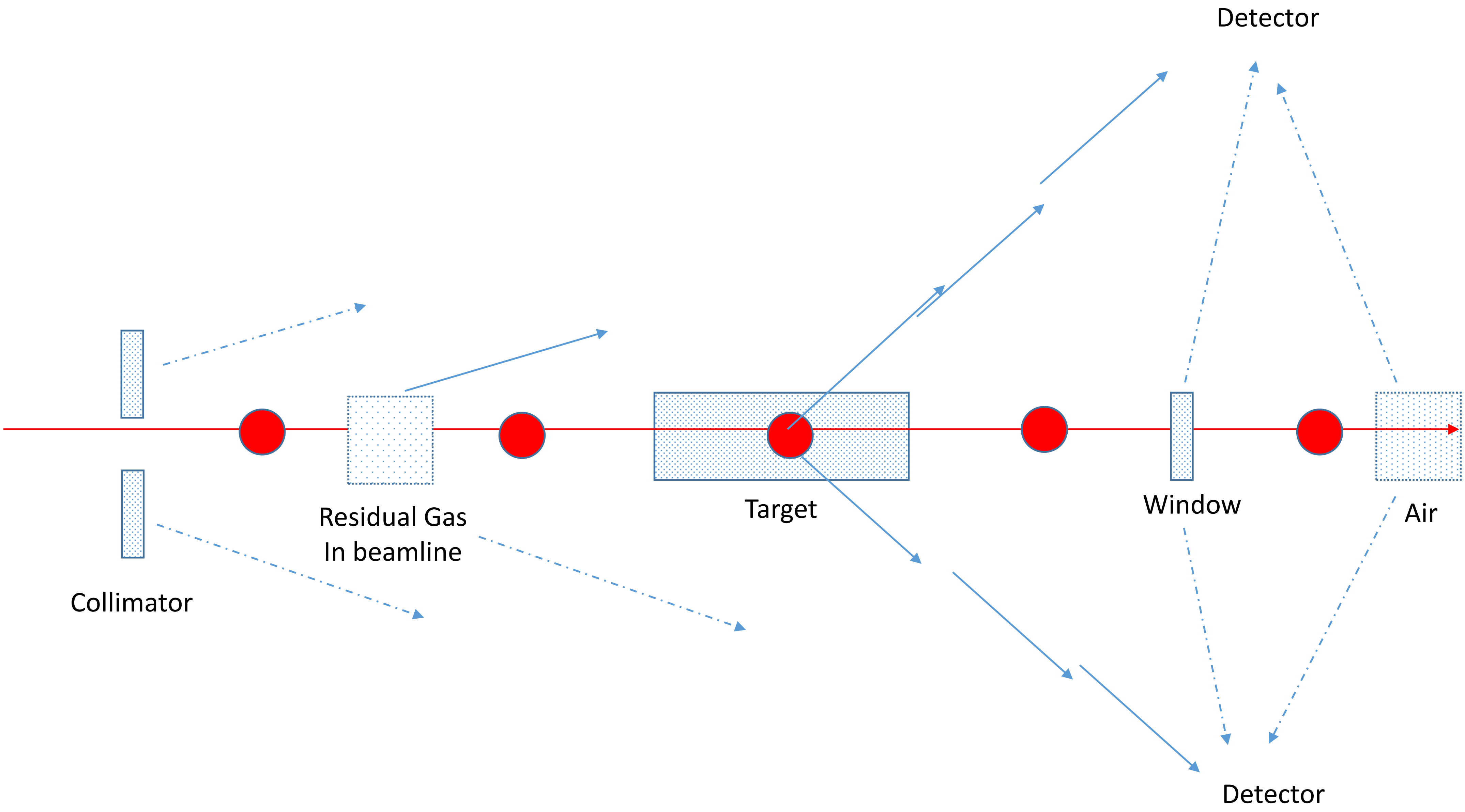
(This is another active area for generic R&D.)

I left you with one example of a new-ish type of detector which is under study.

<u>Acknowledgements</u>

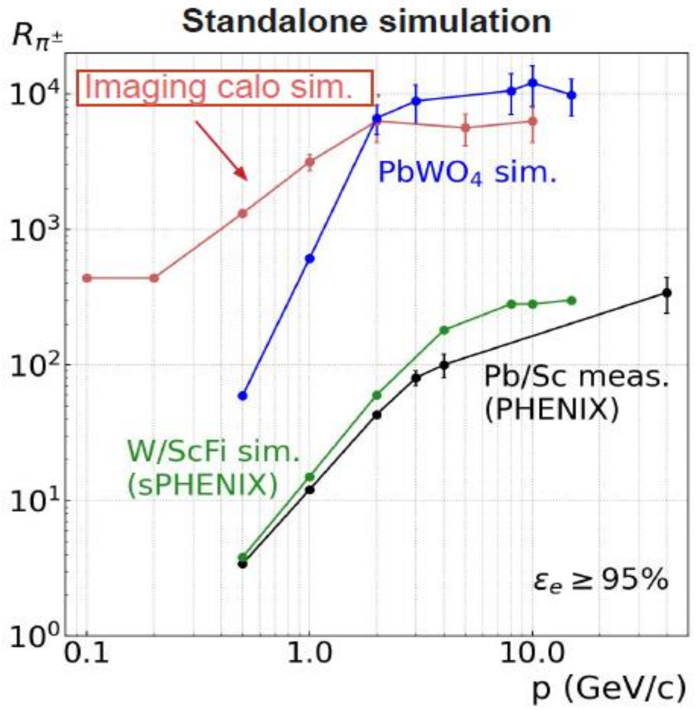
Chats with and/or plots from Simon Taylor, Bennie Zihlmann, Hanjie Liu, Carlos Yero, and the organizers. Also, thanks to the 16 review committee members for the DOE supported EIC-related generic detector R&D program who are teaching me to see more of the whole elephant.

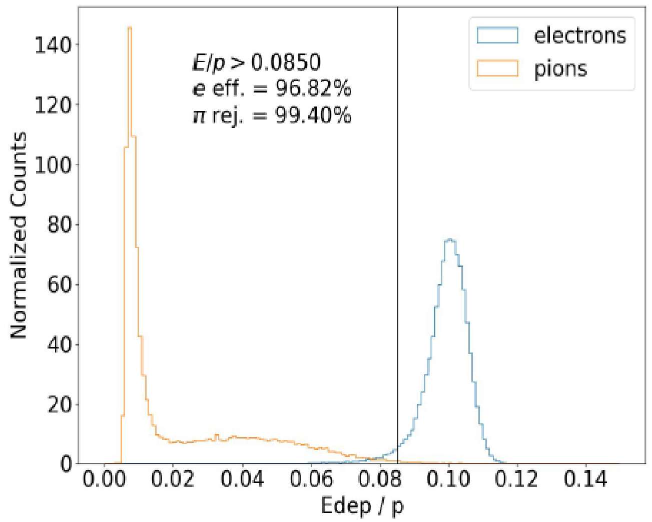
extras


Detector
Residual Gas
In beamline
Target
Window
Air
Collimator
Detector

Imaging Calorimetry for the Electron-Ion Collider

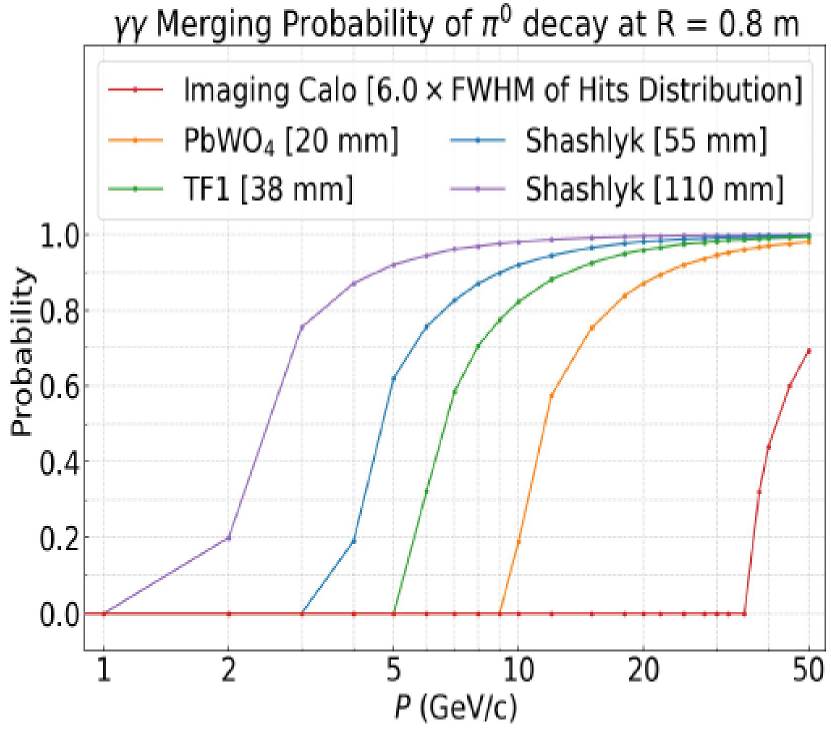
Maria Zurek (zurek@anl.gov), Zisis Papandreou (Zisis.Papandreou@uregina.ca)

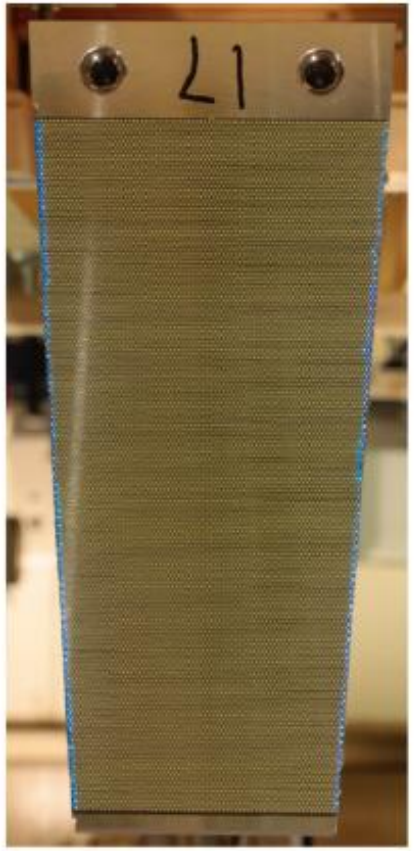


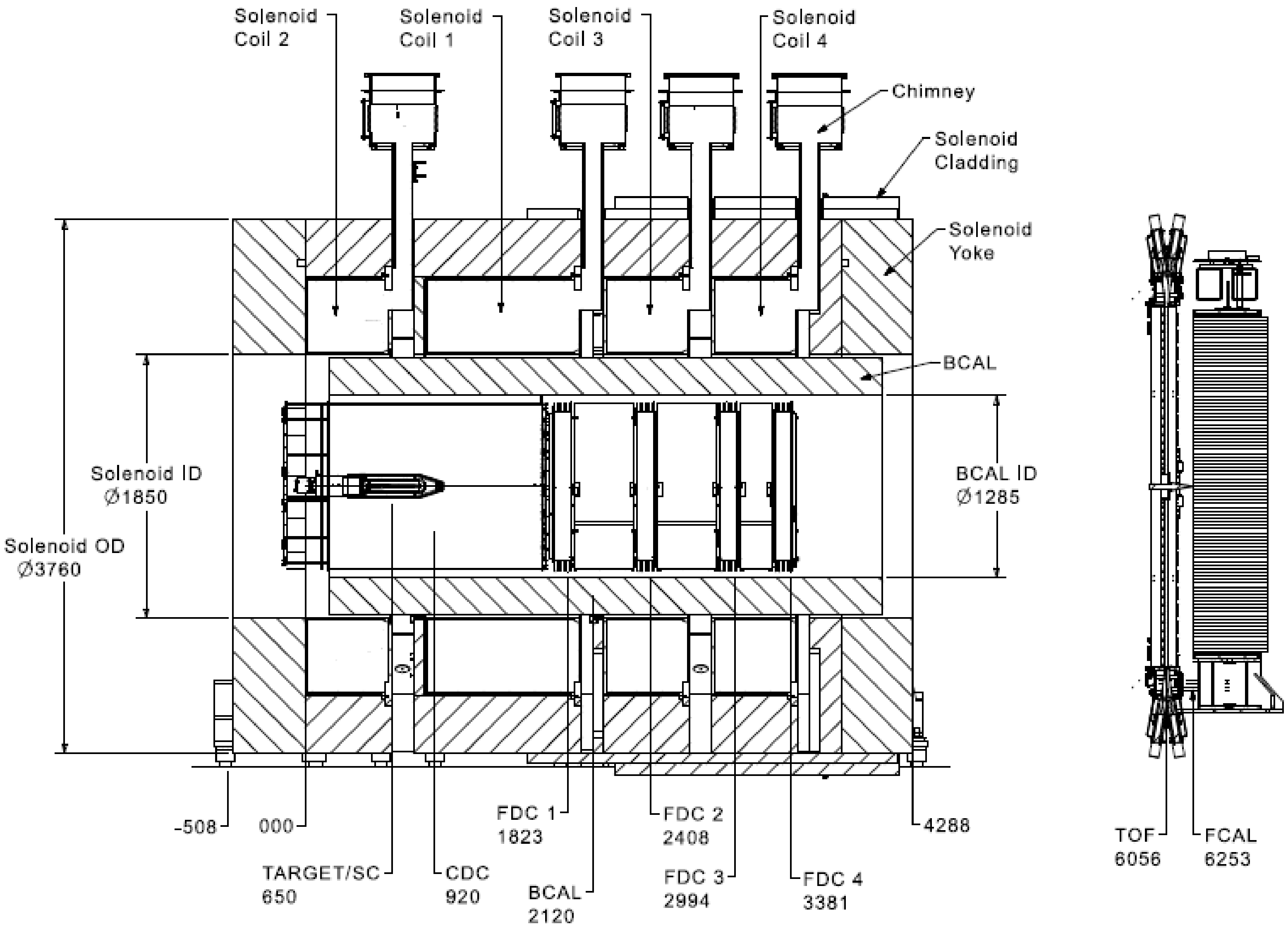


Initial cut on E/p from SciFi/Pb layers for e-π separation

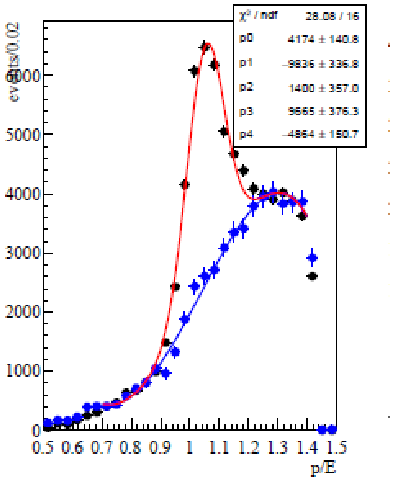
Separation of γ/π^0



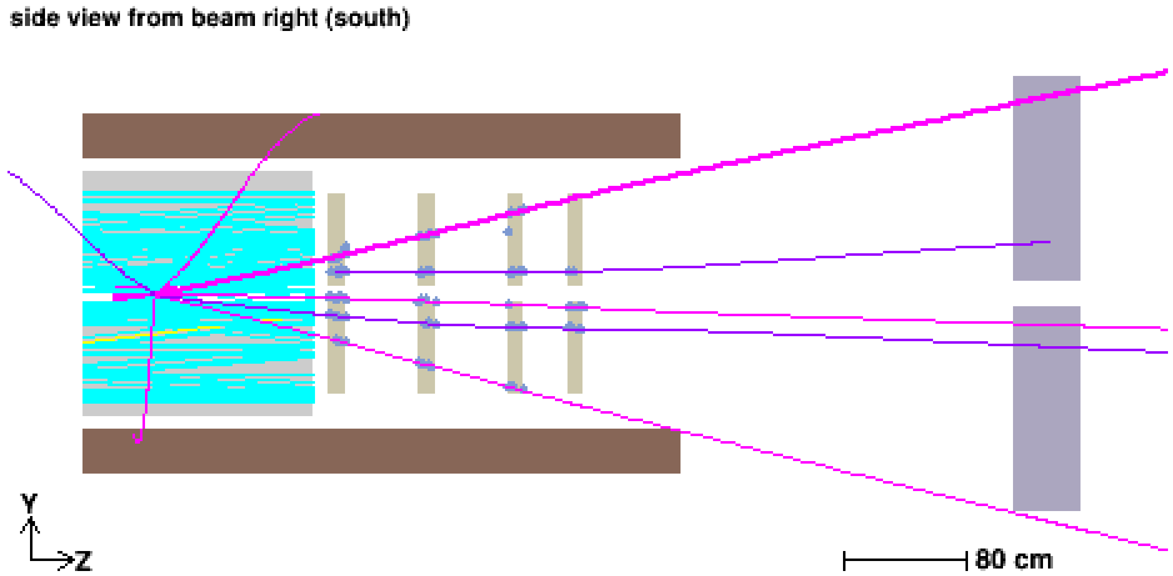




Solenoid Coil 2
Solenoid Coil 1
Solenoid Coil 3
Solenoid Coil 4
Chimney
Solenoid Cladding
Solenoid Yoke
BCAL
Solenoid ID Ø1850
Solenoid OD Ø3760
BCAL ID Ø1285
-508
000
TARGET/SC 650
CDC 920
FDC 1 1823
BCAL 2120
FDC 2 2408
FDC 3 2994
FDC 4 3381
4288
TOF 6056
FCAL 6253



events/0.02
6000
5000
4000
3000
2000
1000
0
0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5
p/E
χ² / ndf 28.08 / 16
p0 4174 ± 140.8
p1 −9836 ± 336.8
p2 1400 ± 357.0
p3 9665 ± 376.3
p4 −4864 ± 150.7



side view from beam right (south)
Y
Z
80 cm

Intro1: the purpose of detectors
Intro2: environment/constraints
Intro3: detector categories
Intro4: a tale of 2 very different spectrometers
Intro5: detector categories working together or hybridizing

Tracking 6: real tracks from TPC
Tracking 7: DC
Tracking 8: FDC

Calor 9: BCAL

Timing10: scintillators
Timing11: relativity

High p PID1:TRD with MPGD readout

More areas of R&D1:LGAD with fine pixels
More areas of R&D2:imaging calorimetry
More areas of R&D3:nanowires
Summary

15 minutes
16 slides