Particle Detectors

Tools of High Energy and Nuclear Physics

Detection of Individual Elementary Particles

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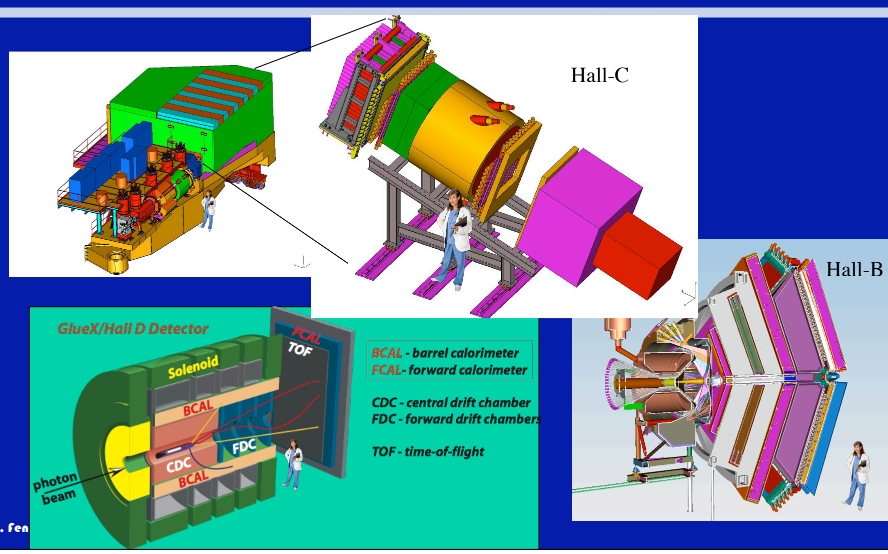
Jefferson Lab
June 14, 2012

12 GeV Detector Systems



Outline of Talk

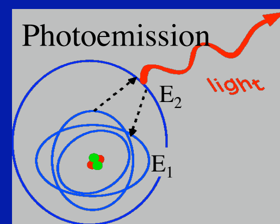
- Interactions of Particles with Matter
  - *Atomic / Molecular Excitation*
  - *Ionization*
  - *Collective Effects*
  - *Radiation Damage to Detectors*
  - *Detectors' Effects on the Particle*
- Using the Interactions: Particle Detectors
  - *Detectors that sense Charge*
    - Aside: Avalanche Multiplication
    - *Ionization Chambers*
    - Aside: Tracking
  - *Detectors that sense Light*
    - *A basic Cerenkov Counter*
    - *Scintillators & arrays*
    - *Some Photo-sensors*
  - *Detectors sensitive to the Amount of light or charge - Calorimeters*
- *A Little Deeper…*
  - *Using second order effects*
  - *Particle Identification*
- Systems of Detectors
  - *Halls A,B,C,D Base Equipment*

Just to get started…

- **p = momentum**
- **m = mass**
- **E = energy**
- **c = speed of light in vacuum**
- **v = particle speed**
- **$\beta = v/c = p/E$**
- **$\gamma = (1-\beta^2)^{-1/2} = E/m$**
- **n = index of refraction**

Interactions of Particles with Matter - Photoemission

- **Excitation** (followed by de-excitation)
  - Atomic Electron
  - Promoted to higher energy state (E_2)
    - Energy comes from the particle
  - Electron falls back to ground state (E_1)
    - Released energy is carried by a photon



$$E_{photon} = E_2 - E_1$$

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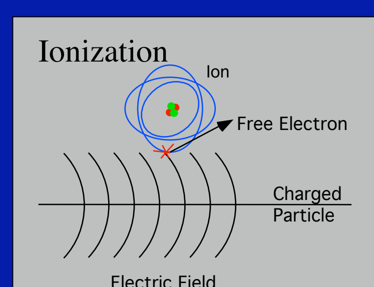
Interactions of Particles with Matter - Ionization

- **Ionization**
  - Atomic electron is knocked free from the atom.
  - The remaining atom now has a net charge as well (it is an ion).
  - The atom may also be left in an excited state and emit a photon as it returns to its ground state.
  - If you are a Solid State Physicist, the ionized atom is a “hole”.



Free Electron
Ion (possibly in excited state)
Photon (sometimes)
Energy: conserved

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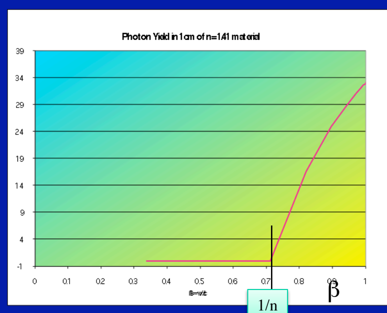
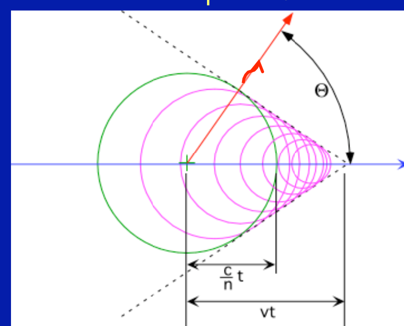
Interactions of Particles with Matter - Collective Effects

The electric field of a particle may have a long-range interaction with material as it passes through a continuous medium.



Cerenkov Effect:

Turns ON when particle speed is greater than light speed in the medium: $v = \beta c > c/n$



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Interactions of Particles with Matter - Collective Effects

Transition Radiation:

The sudden change in electric field as an *ultrarelativistic* charged particle passes from one medium to another results in ~keV photons (x-rays).

Ultrarelativistic: $\gamma >\sim 1000$

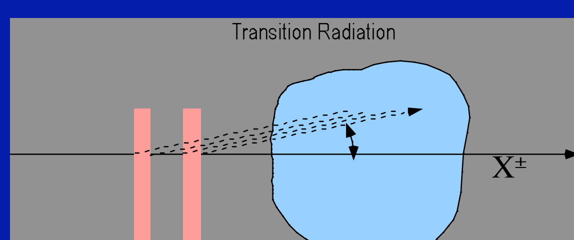
$\gamma \equiv (1- \beta^2)^{-1/2} = E/m$

Light is emitted at the angle

$\Theta \sim 1/\gamma$

(1 milliradian or less)

6 GeV/c			
	electron	pion	proton
mass	0.000511	0.139	0.939
beta	0.999999996	0.999731761	0.987974331
gamma	11741.7	43.2	6.5



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Interactions of Particles with Matter - Radiation Damage

- Particles can have lasting effects on the detector materials.
  - Nuclear Collision
    - Particle undergoes interaction directly with atomic nucleus.
    - May transmute the element (*radiation damage*).
    - May generate *secondary particles* which themselves are detectable (*neutron detector*).
  - Lattice Dislocation
    - Crystalline structure of a material may be disrupted (*diode leakage current increases*).
  - Chemical Change
    - Photographic Film (*photos fogged at airports*) or Emulsion (*visible particle tracks*).

While these effects can be exploited for particle detection, they may also cause permanent damage to detector components resulting in a detector which stops working.

This is sometimes referred to as "aging".

Interactions of Particles with Matter - Effect on the Particle

- For a particle to be detected it must interact with our apparatus.
- ACTION = REACTION
- The properties of the particle may be different after we have detected it.
  - Lower Energy
  - Different Momentum (direction)
  - Completely Stopped

In fact, one method of determining a particle's energy is simply to measure how far it goes through a material before stopping.

Interactions of Particles with Matter - Effect on the Particle

- Detector: Pavement.
- Signal: skid marks.
- Effect on car: reduced energy; changed momentum.

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Interactions of Particles with Matter -

- **Summary:** When charged particles pass through matter they usually produce either free electric charges (ionization) or light (photoemission).
- **Ahead:** Most "particle" detectors actually detect the light or the charge that a particle leaves behind.
- **Next:** In all cases we finally need an electronic signal which is big enough to use in a Data Acquisition System.

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Particle Detectors…
aside: Avalanche Multiplication

We need devices that are sensitive to only a <u>few</u> electron charges:

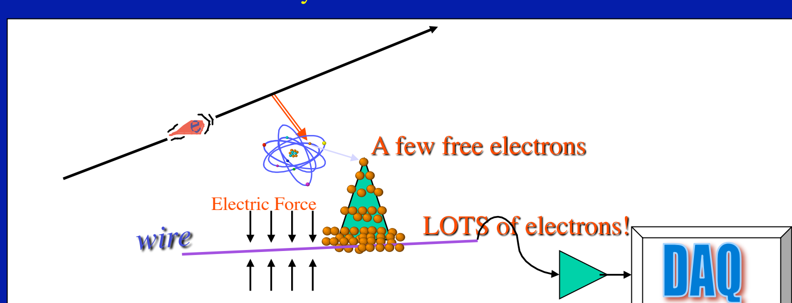
We need to *amplify* this charge.

Typical electronic circuits are sensitive to $\sim 1\mu A = 6.2 \times 10^{12}\ e^-/s$ >> "a few"

By giving the electrons a *push*, we can make them move fast enough so that they *ionize* other atoms when they collide. *Push* those *new* electrons and each one ionizes *more* atoms, releasing *more* electrons. After this has happened several times we have a sizeable free charge that can be sensed by an electronic circuit.

Particle Detectors…
aside: Avalanche Multiplication in a GAS

- Avalanche Gain
  - Electric Field accelerates electrons, giving them enough energy to cause another ionization. Then those electrons do it again...
  - In the end we have enough electrons to provide a large electric current… detectable by sensitive electronics.



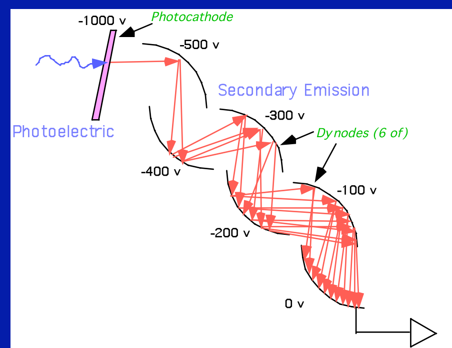
Particle Detectors…
aside: Avalanche Multiplication on a Metal Surface

Photoelectric Effect

- A photon usually liberates a single electron: a ***photoelectron***.

Secondary Emission

- Energetic electrons striking some surfaces can liberate MORE electrons. Those, in turn, can be accelerated onto another surface … and so on.



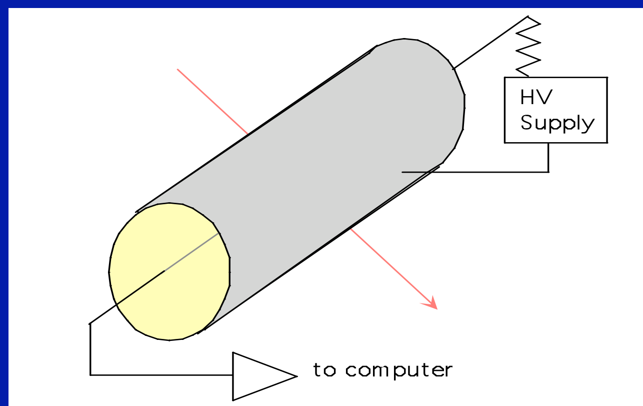
Photomultiplier Tube (PMT)

Particle Detectors…
Gas Filled Wire Chamber

Let's use Ionization and Avalanche Multiplication to build a detector…

- Make a Box.
- Fill it with some gas: noble gases are more likely to ionize than others. Use Argon.
- Insert conducting surfaces to make an intense electric field: The field at the surface of a small wire gets extremely high, so use tiny wires.
- Attach electronics and apply high voltage.
- We're done!!

Particle Detectors…
A Single-wire Gas Chamber



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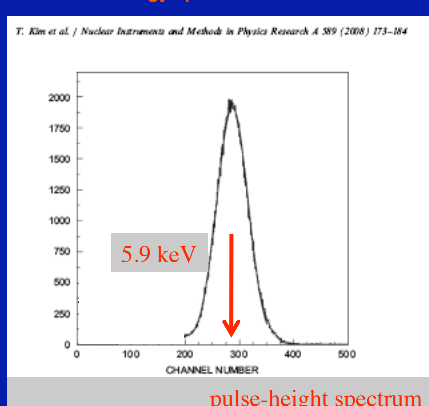
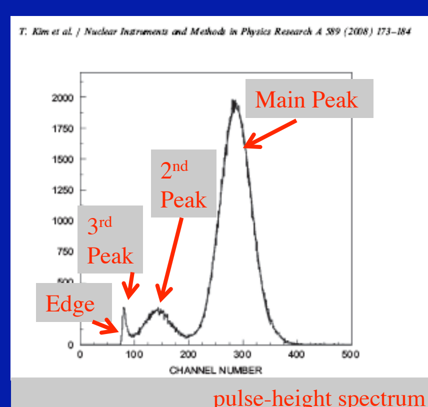
Gas Chamber puzzles

Testing the gas chamber using monochromatic photons.

Using an ^{55}Fe X-Ray Source (5.9 keV) Argon- gas wire chamber you might expect to see the energy spectrum shown below.



Instead, you are likely to see this spectrum. Why???



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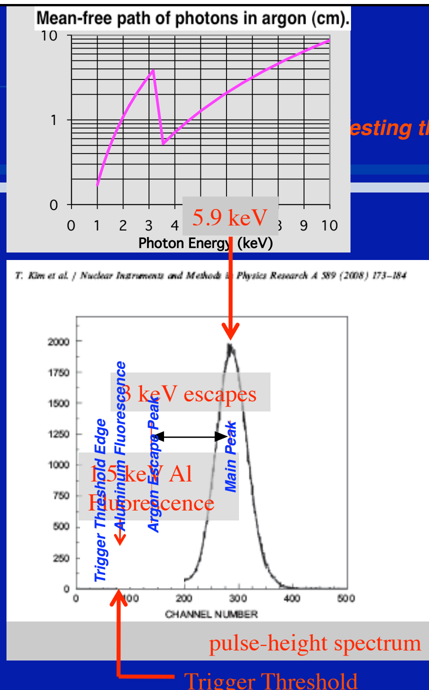


Gas Chamber puzzles

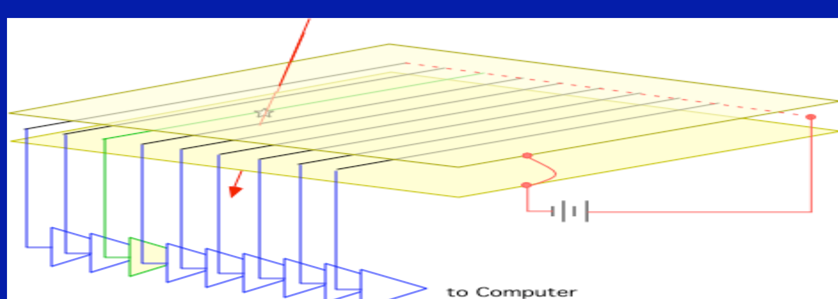
Testing the gas chamber using monochromatic photons.

^{55}Fe X-Ray Source (5.9 keV)
Argon gas wire chamber.

- **Some x-rays leave all their energy as ionization**
- **Because we are using Argon, there is a relatively good chance that ~3keV photons will escape, leaving behind 5.9-3=2.9 keV.**
- **If the gas box has Aluminum walls, they will "glow" at 1.5 keV when struck. Those 1.5 keV photons will ionize the gas and show up as another energy peak in the data.**
- **If the DAQ records only those signals above some threshold, this will appear as an edge.**

Particle Detectors…
Multi-Wire Gas Chamber

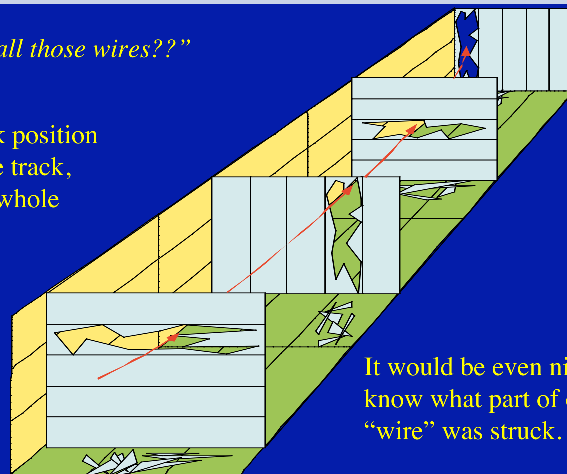
- Multiwire Chamber:
  - WHICH WIRE WAS NEAREST TO THE TRACK?



Particle Detectors…
aside: tracking

"Why does he want all those wires??"

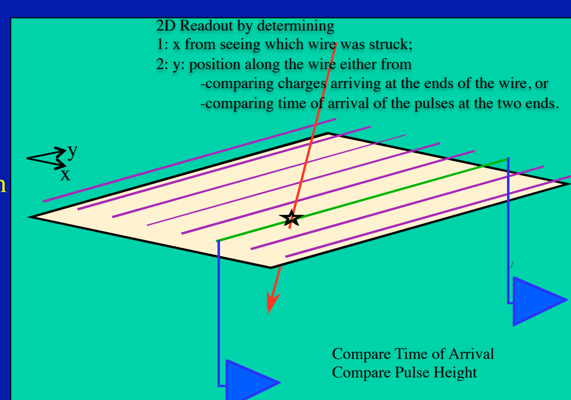
If we make several measurements of track position along the length of the track, we can figure out the whole trajectory.



It would be even nicer to know what part of each "wire" was struck…

Particle Detectors…
…better position information.

- Readout Options for Improved Resolution
  - And for flexible design
    - Charge Division
    - Time Division
    - Charge Interpolation
  - Wire Position gives "x"
  - Measurement along length of wire gives "y".

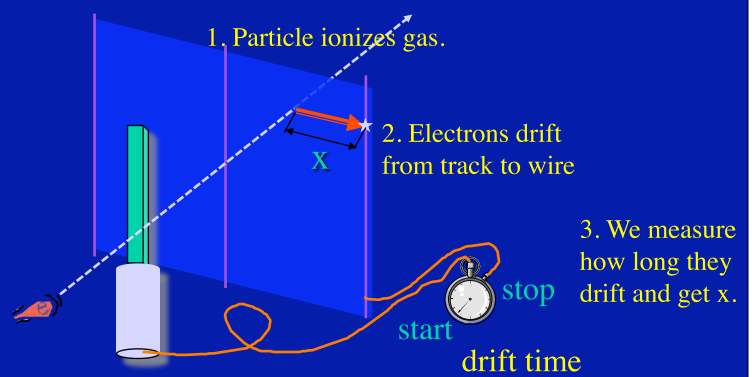


It would be nicer still if we knew the distance between the particle and the struck wire…

Particle Detectors…
…higher resolution tracking.

Drift Chambers…

HOW <u>FAR</u> TO THE NEAREST WIRE?



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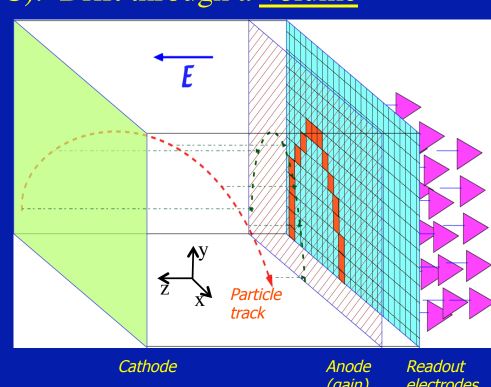
Particle Detectors: TPC…
…3D position information.

Time Projection Chamber (TPC): Drift through a <u>Volume</u>

- Just a box of gas with
  - Electric Field and
  - Readout Electrodes
- Readout elements only on one surface.
- Ionization Electrons drift to Surface for
  - Amplification
  - Charge Collection
- Readout Electrode Position gives (x,y)
- Time of Arrival gives (z).



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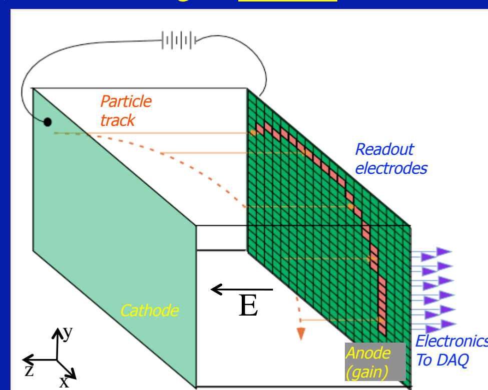

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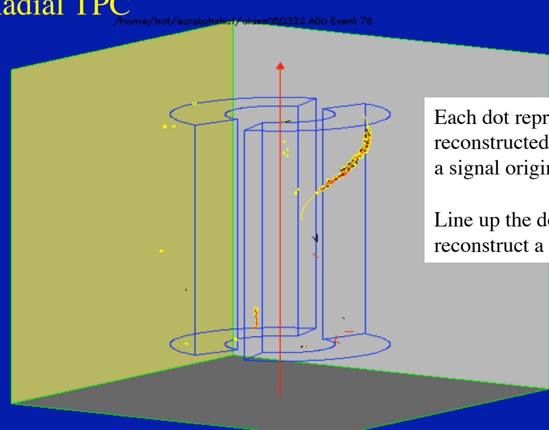
Particle Detectors: TPC…
…3D position information.

"BoNuS" Radial TPC



Each dot represents the reconstructed (x,y,z) at which a signal originated.

Line up the dots to reconstruct a track.

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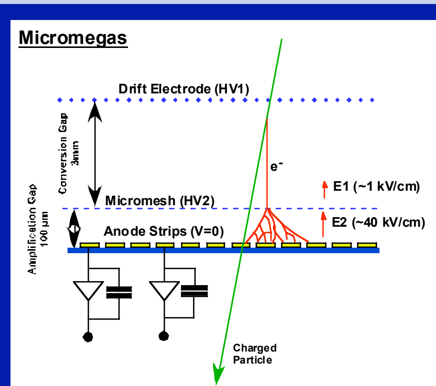
Other ways to get Avalanche Gain: *Micromegas*

- Gas *Ionization* and *Avalanche Multiplication* again, but…
  - … a different way to get an intense electric field,
  - … no tiny wires,
  - … a monolithic structure.

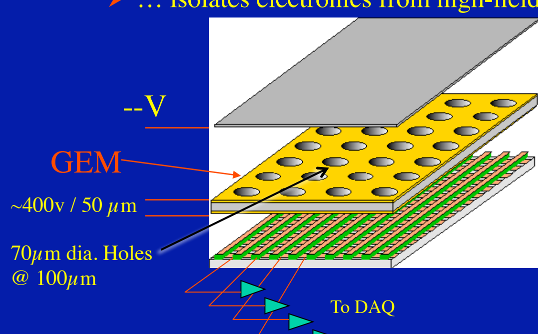


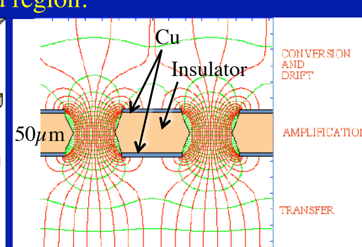
Y. Giomataris, Ph. Rebourgeard, J.P. Robert, and G. Charpak, NIM A376 (1996) 29

Micro (small)
Mesh
Gas (sensitive medium)

Other ways to get Avalanche Gain: *GEM*

- **G**as **E**lectron **M**ultipliers
  - … yet another way to get an intense electric field,
  - … isolates electronics from high-field region.

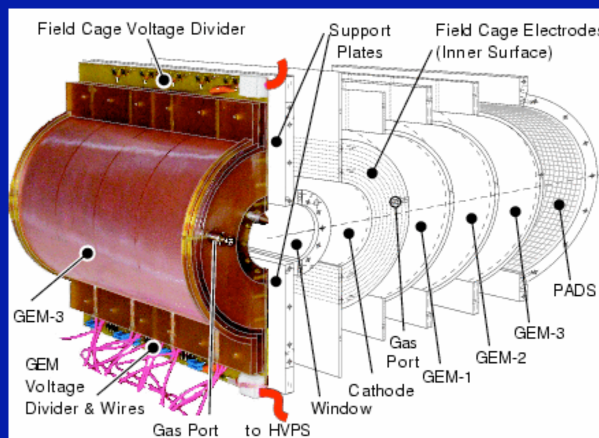




http://gdd.web.cern.ch/GDD/

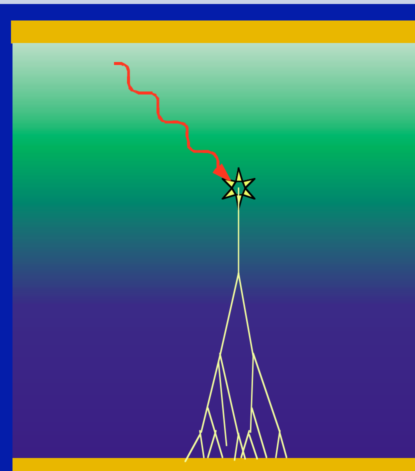
Using a GEM… the *BoNuS* Radial TPC

- GEMs used in the BoNuS Detector were curved.



Other ways to get Avalanche Gain: *in Silicon*

- Ionization in a silicon lattice produces electron/hole pairs.
- If they are accelerated in a high E-field, they avalanche.



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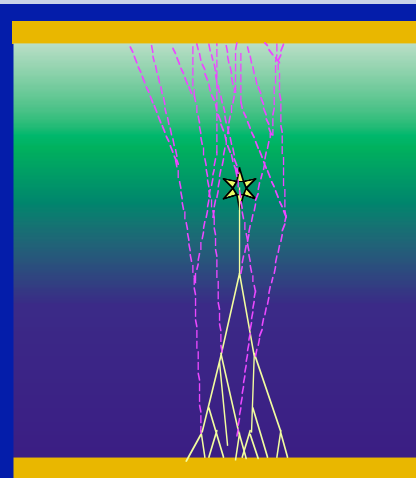
- Each time an electron is produced, a hole is also produced.



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Other ways to get Avalanche Gain: *in Silicon*

- Ionization in a silicon lattice produces electron/hole pairs.
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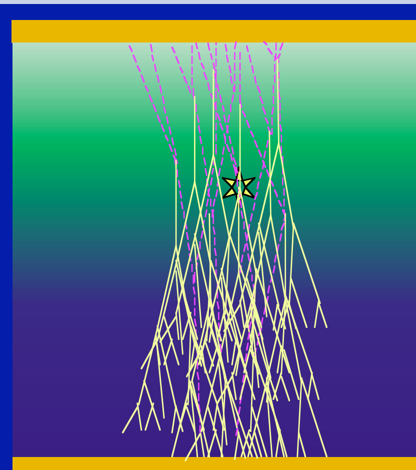
- Generally, BOTH electrons and holes start avalanches. The challenge is STOPPING them.



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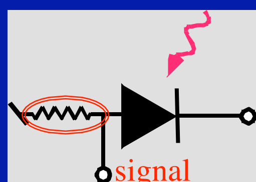

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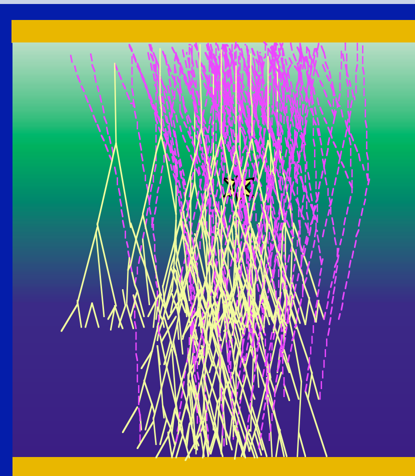
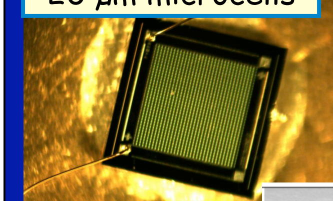


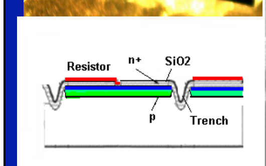
Avalanche Photo-Diode (APD)

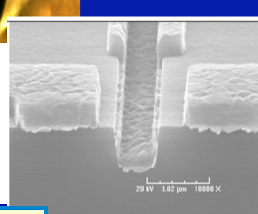
Silicon Photomultiplier (SiPM)

20 μm microcells

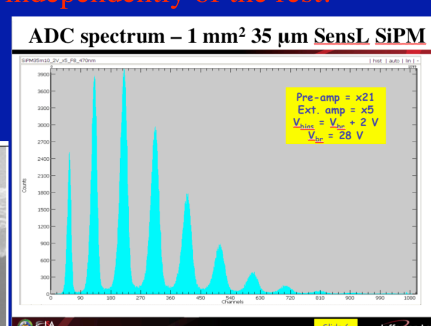


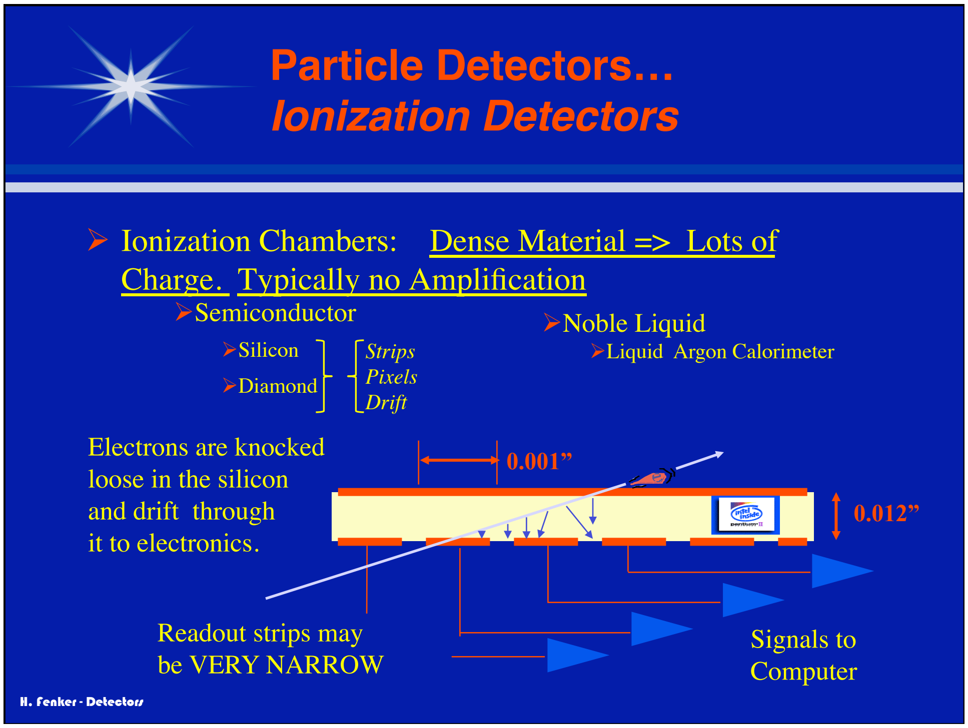
Array of many tiny APD's. Each one operates ~independently of the rest.





Trench to block photon crosstalk




Particle Detectors…
Ionization Detectors
Ionization Chambers: Dense Material => Lots of Charge. Typically no Amplification
Semiconductor
Silicon
Diamond
Strips
Pixels
Drift
Noble Liquid
Liquid Argon Calorimeter
Electrons are knocked loose in the silicon and drift through it to electronics.
0.001”
0.012”
Readout strips may be VERY NARROW
Signals to Computer
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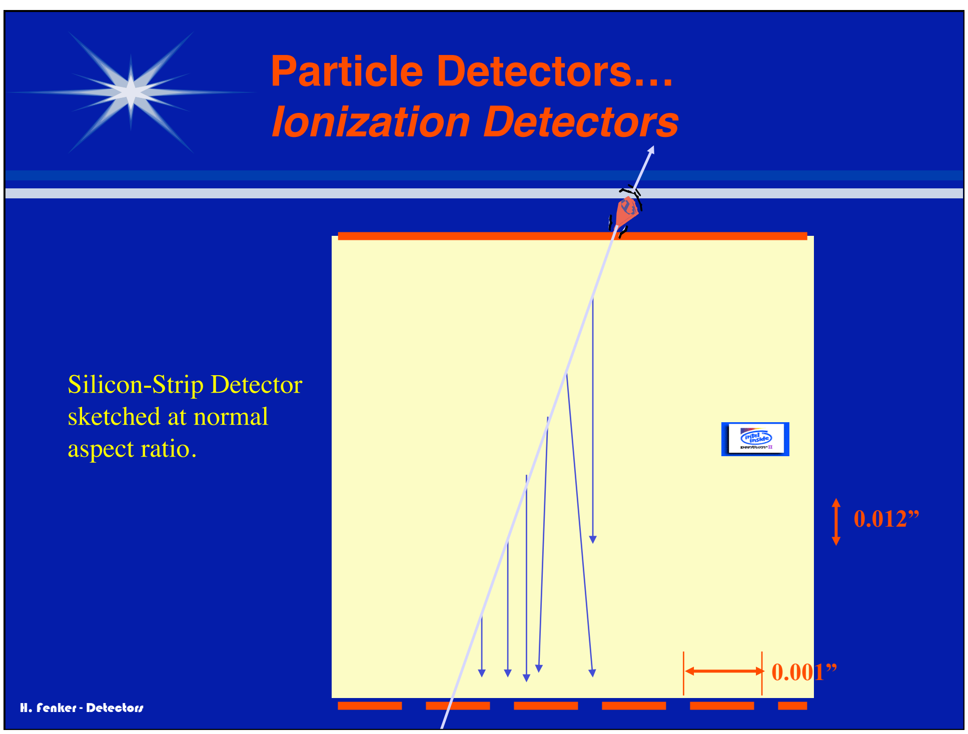
Particle Detectors…
Ionization Detectors
Silicon-Strip Detector sketched at normal aspect ratio.
0.012”
0.001”
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Particle Detectors…
Using the Light

Enough of Ionization!

What about Detectors that use the produced light?

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Particle Detectors…
Using the Light

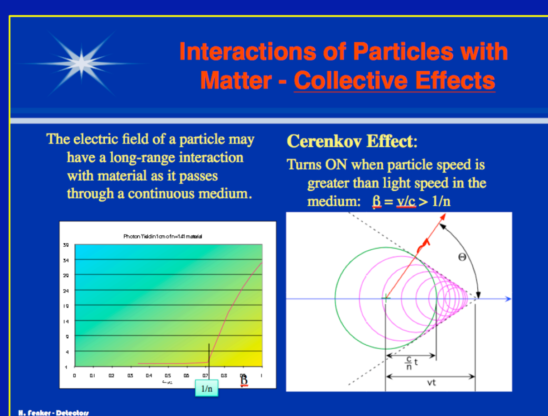
Let's build a Cerenkov Counter.

•Get a light-tight box.

•Fill it with something transparent that has the index of refraction you need…

…and some optical system to collect any light…

…then look for Cerenkov Light.



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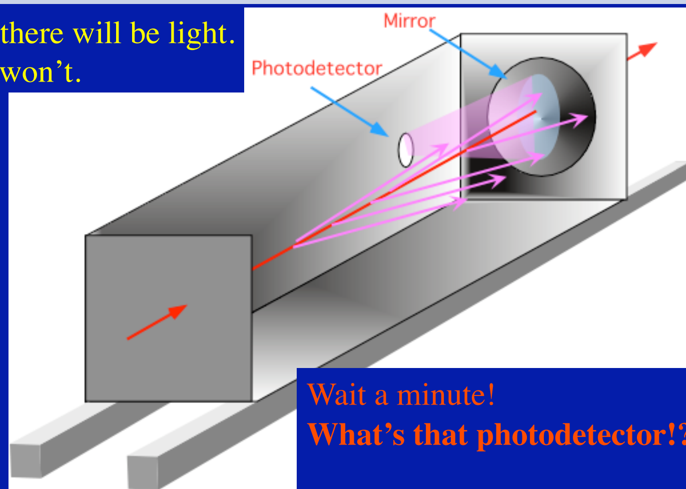
Particle Detectors…
Cerenkov Counter

If v/c > 1/n, there will be light.
If not, there won't.



Wait a minute!
What's that photodetector!?

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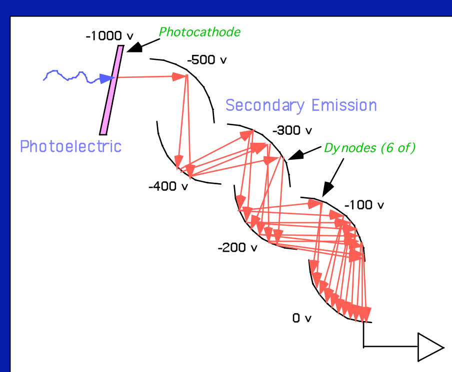
Particle Detectors…
aside: *Photomultiplier Tube*

We saw the **Photo-electron Multiplier Tube (PMT)** earlier.

They are commercially produced and very sensitive.

- One photon --> up to 10^8 electrons!
- Fast! …down to ~ few x 10^{-9} seconds.



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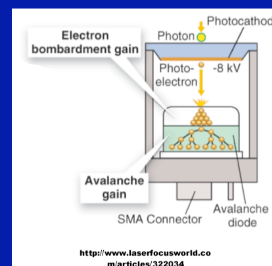
Particle Detectors…
aside: *Other Photodetectors*

- Photocathode + Secondary Emission Multiplication
  - Multichannel PhotoMultiplier Tubes (MCPMT)
  - Microchannel Plates (MCP)
- Solid-State (Silicon) Devices
  - Photodiodes (no gain)
  - Avalanche Photo-Diodes (APD)
  - Solid-State Photomultiplier (SSPM or SiPM)
  - Visible Light Photon Counter (VLPC)
- Hybrids: Photocathode + Electron Acceleration + Silicon

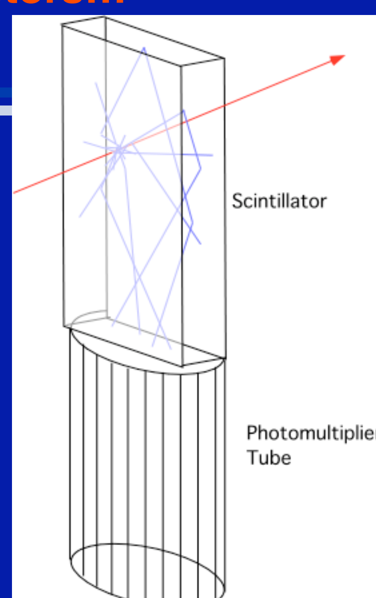


Particle Detectors…
Scintillators

Materials that are good at emitting light when traversed by energetic particles are called **SCINTILLATORS**.

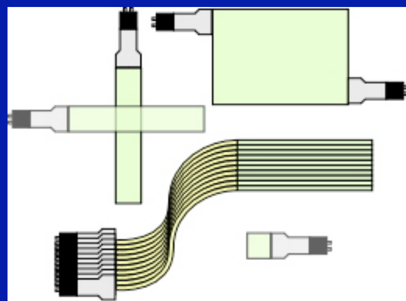
Many materials radiate light, but most also absorb that light so that it never gets out.

Scintillation Counters are probably the most widely used detectors in Nuclear and High Energy Physics.



Particle Detectors… Scintillator uses

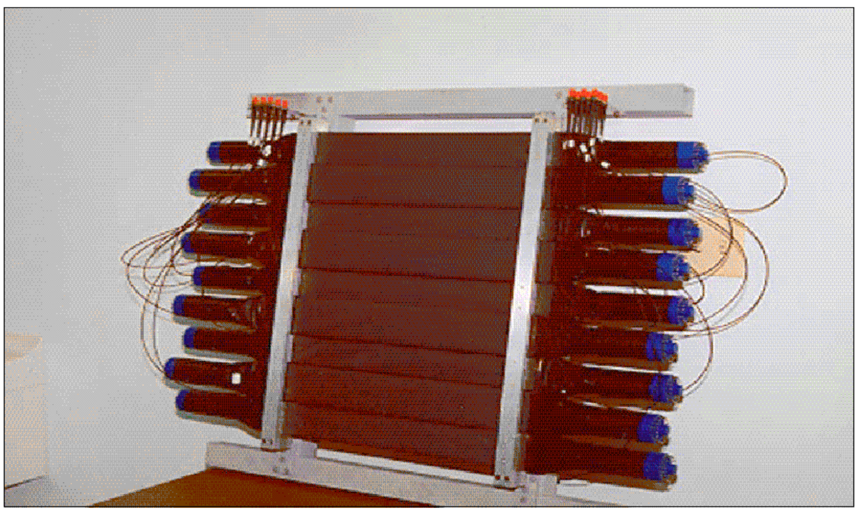
- **Scintillation Counter Uses**
  - Timing and Triggering
    - Paddles or Sheets
  - Tracking
    - Paddles or Strips
    - Fibers
  - Calorimetry & Particle ID



- Each one consists of a piece of scintillating material optically coupled to a light-sensitive transducer.

H. Fenker - Detectors

Particle Detectors… Scintillator Hodoscope



The short orbit spectrometer hodoscope

H. Fen

Particle Detectors… Scintillation Calorimeter

- Scintillation Counter Uses
  - Energy Measurement - stop the particle
    - Large Blocks or
    - Large Volumes of Liquid

If we **STOP** the particle in a scintillator, then the **AMOUNT** of light detected provides a measure of the total **ENERGY** that the particle had. This detector is a **CALORIMETER**.

{*Lead Glass is often used as a calorimeter – its light is created by the Cerenkov Effect, not scintillation.*}

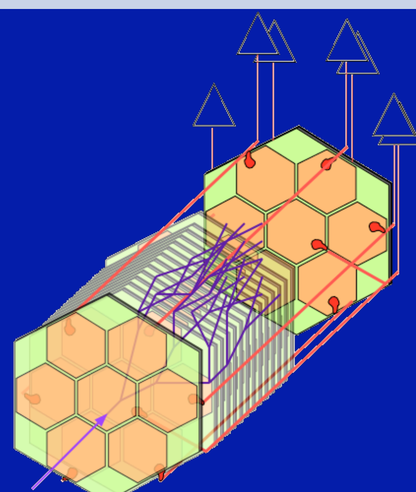
H. Fenker - Detectors

Particle Detectors… Charge-Collection Calorimeter

- Materials other than scintillators can serve as calorimeters.

  Example: Liquid Argon

  In a **Liquid Argon Calorimeter** we collect the electron/ion charge that is released by the stopping particle.



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Particle Detectors…

- That's it! Those are (most of) the Detector Tools!
  - Wire Chambers (gas ionization chambers)
    - Single Wire
    - Multi-Wire
    - Drift, TPC, etc.
  - Solid State Detectors
  - Cerenkov Counters
  - Scintillators
  - Calorimeters

Particle Detectors… … more subtle details.

- What about measuring energy when the particle doesn't completely stop?
- If we have a "thin" detector, the amount of energy lost by a particle as it passes all the way through is related to its speed...

Particle Detectors: Energy Loss

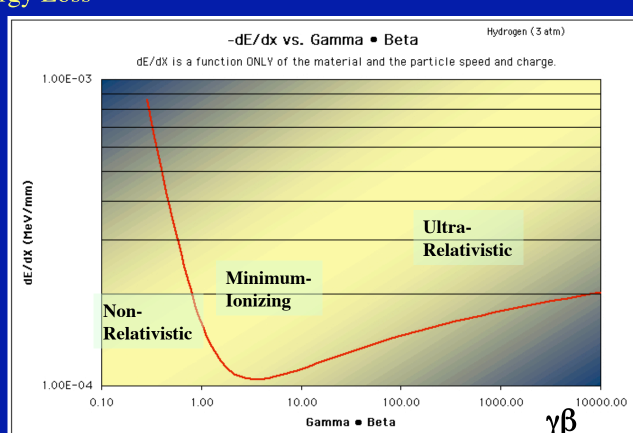
- Energy Loss
  - Heavy Charged Particles lose energy primarily through ionization and atomic excitation as they pass through matter.
    - Described by the **Bethe-Bloch** formula:

$$-\frac{dE}{dX} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

    - where β, γ, relate to particle speed, **z** is the particle's charge..
    - The other factors describe the medium (Z/A, I), or are physical constants.

Particle Detectors: Energy Loss

- Energy Loss



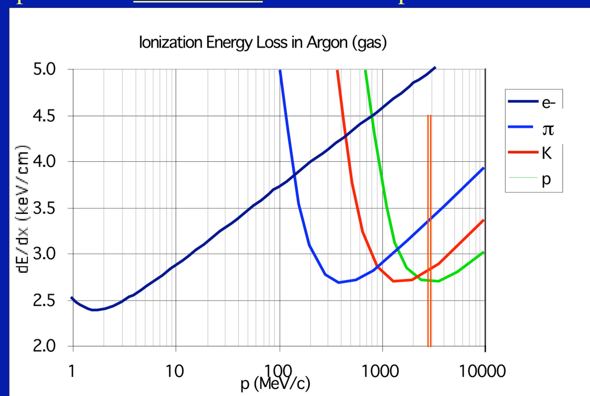
Particle Detectors: Energy Loss

Energy Loss-

- Here is the same curve plotted vs. momentum for different particles.

If we know we are looking at a pion, we can get some measure of its momentum by seeing how much energy it loses in a "thin" detector.

OR: we might determine whether a particle is a pion, electron, kaon, or proton if we know the momentum already.

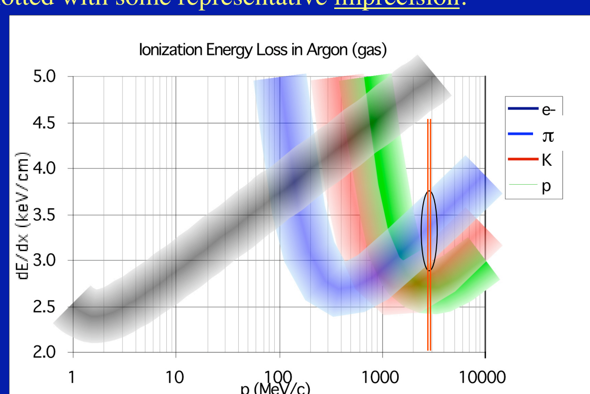


Particle Detectors: Energy Loss

- Energy Loss-

Here is the same curve plotted with some representative imprecision.

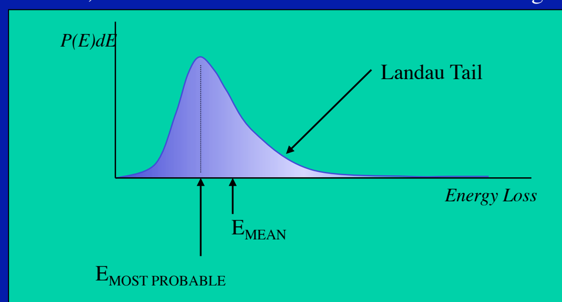
Measurements of energy loss are limited both by detector resolution and by the fundamental statistical nature of the energy loss process…



Particle Detectors: Energy Loss

- … as energy loss may be skewed towards higher values by low-probability hard-scatters, leading to the *Landau Tail*.
  - Thus $E_{MEAN} > E_{MOST\ PROBABLE}$

Two similar particles, with exactly the same momentum, passing through the same detector material, are almost certain to leave behind different signals.



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Particle Detectors: Energy Loss

- Energy Loss- …some actual data

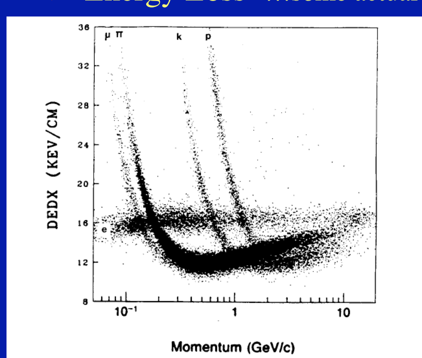
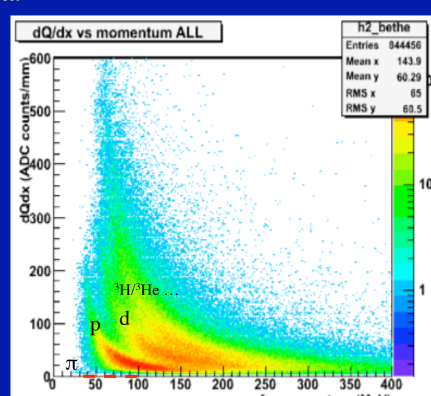


Fig. 13 Average differential energy loss measured as a function of momentum for fast charged particles in the Berkeley TPC. Particles of different mass can be very well identified in the low-momentum zone, and with less resolution in the relativistic rise region.

F. Sauli, CERN-EP/89-74 (1989)



JLab BoNuS Detector -- 2005

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Particle Detectors: Energy Loss

- Of course, if the detector works by measuring lost energy, the energy of the particle has been reduced as a result of passing through the detector.

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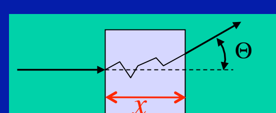
Particle Detectors: Multiple Coulomb Scattering

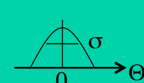
Detectors scatter particles even without energy loss…

- MCS theory is a statistical description of the scattering angle arising from many small interactions with atomic electrons.
- MCS alters the direction of the particle.
- Most important at low energy.



$$\langle \Theta \rangle = 0$$

$$\sigma_\Theta = \frac{13.6\, MeV}{\beta c p} z \sqrt{x / X_0}\left[1 + 0.038 \ln(x / X_0)\right]$$



β is particle speed, z is its charge, X_0 is the material's Radiation Length.

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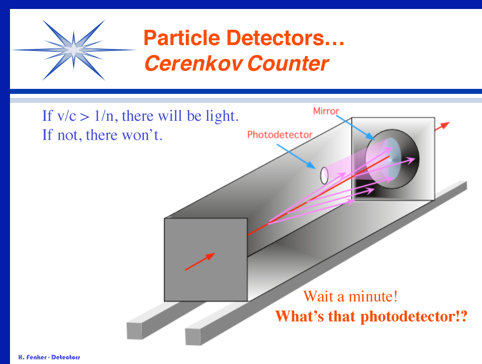
Particle Detectors: Particle Identification

We saw a Cerenkov Counter that signaled when a particle was *fast*.

Since the speed is a function of both mass and momentum, if we know the momentum can we use a Cerenkov counter to determine the mass?



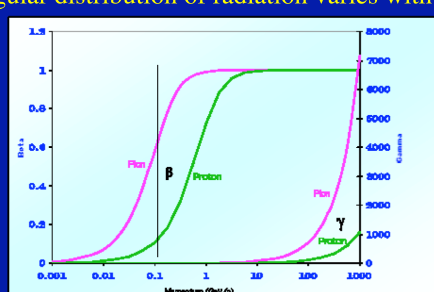
Particle Detectors: Particle Identification

YES! Cerenkov and Transition Radiation Detectors are Used primarily for Particle Identification

- At fixed momentum, Heavy particles radiate less than Low-mass particles.
- Further: angular distribution of radiation varies with particle speed.

Cerenkov Counters – sensitive to β

$\beta = v/c$
$= p/E$



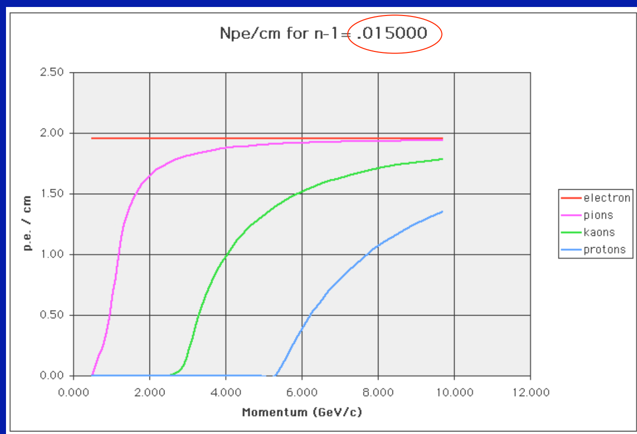
Momentum (GeV/c)

TRD Counters – sensitive to γ

$\gamma = (1 - \beta^2)^{-1/2}$
$= E/m$

Particle Detectors: Particle Identification

Threshold Cerenkov Counter. # Photons vs. Momentum.



Some representative Indices of Refraction

n-1 ~

0.4 lucite

0.02 aerogel

0.0001 – 0.005 gases

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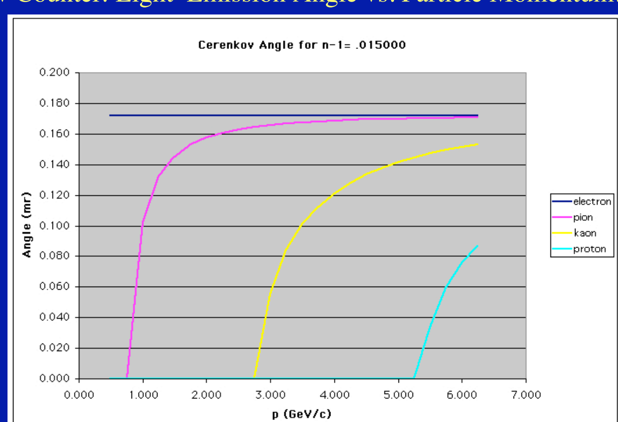
Particle Detectors: Particle Identification

Cerenkov Counter: Light Emission Angle vs. Particle Momentum.



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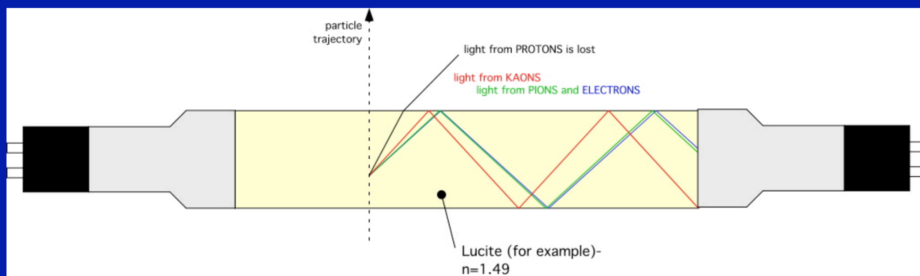
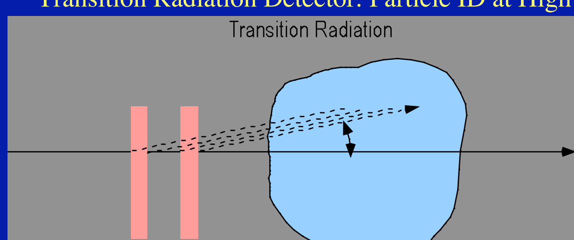
Particle Detectors: Particle Identification

Lucite Cerenkov Counter: use Critical Angle for Total Internal Reflection to differentiate Cerenkov Angles.



Particle Detectors: Particle Identification

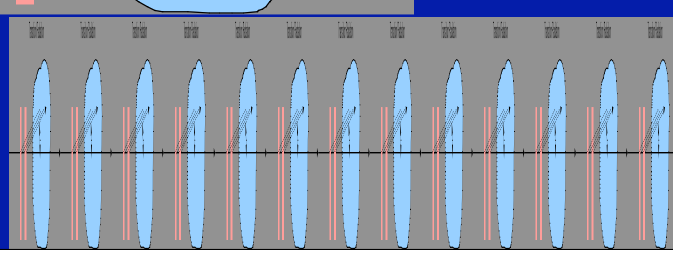
Transition Radiation Detector: Particle ID at High Momentum.



Each *transition* makes only ~0.01 photons…

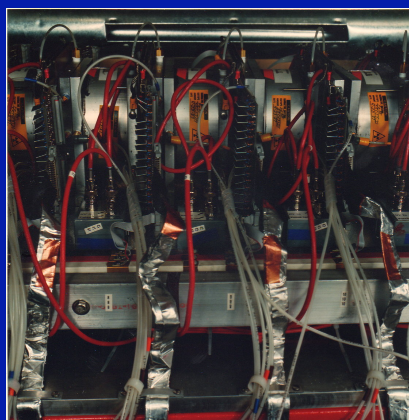
Need many transitions

Need many detectors



Particle Detectors: Particle Identification

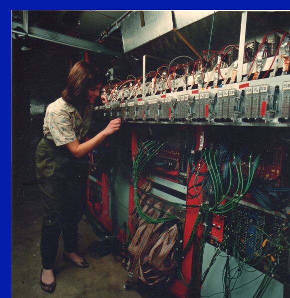
Transition Radiation Detector: Particle ID at High Momentum.



Each *transition* makes only ~0.01 photons…

Need many transitions

Need many detectors



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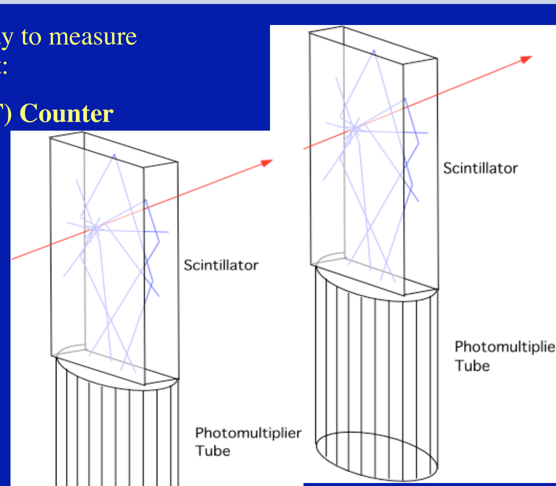
Particle Detectors: Particle Identification

The most straightforward way to measure particle speed is to *time* it:

A Time-of-Flight (TOF) Counter

Knowing the separation of the scintillators and measuring the difference in arrival time of the signals gives us the particle speed.



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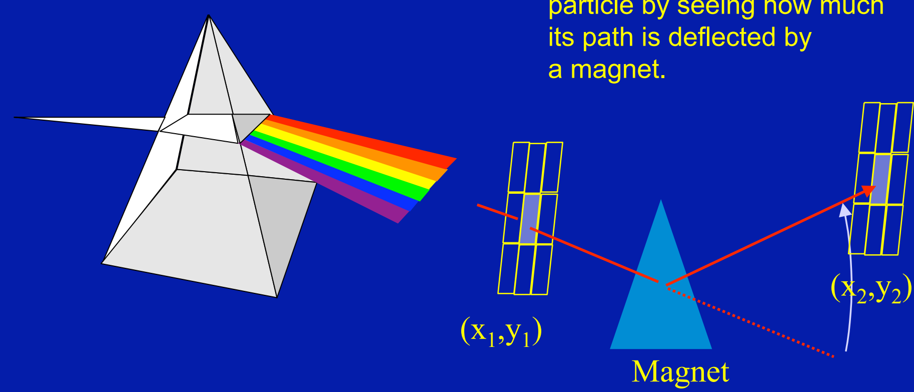
Particle Detectors: aside: magnetic spectrometer

Just as light of different colors is bent differently by a prism...

Nature lets us measure the Momentum of a charged particle by seeing how much its path is deflected by a magnet.



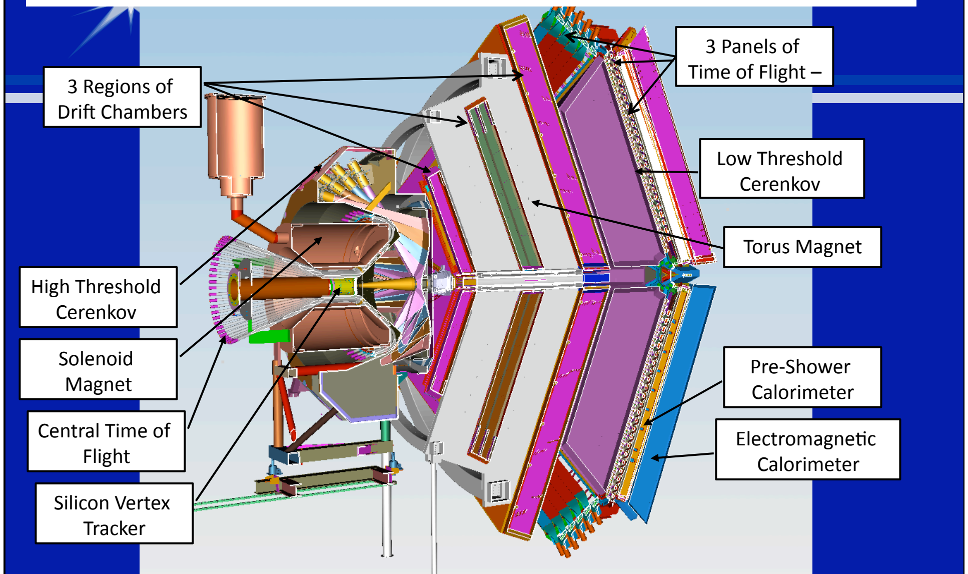
Putting it all Together: A Detector System

The Base Equipment in all of the Experimental Halls is composed of optimized arrangements of the same fundamental detector technologies…

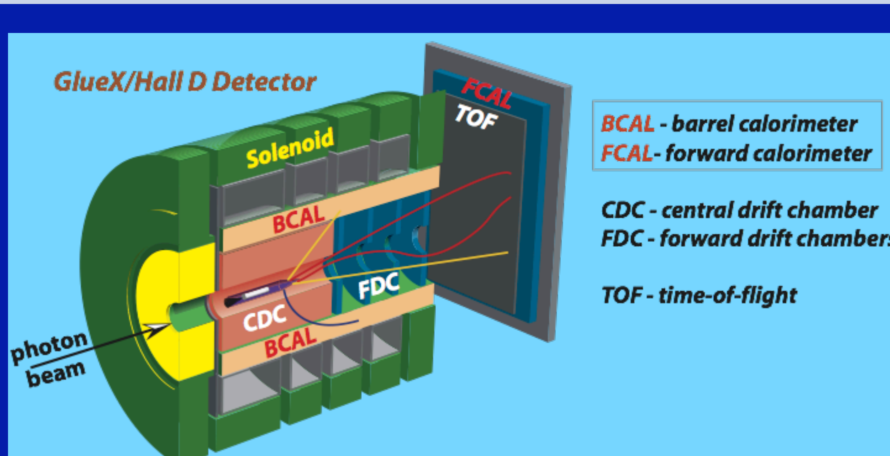
<u>Hall-A: HRS_L / HRS_R</u>
<u>Hall-B: CLAS</u>
<u>Hall-C: HMS, SOS</u>
<u>Hall-D: GlueX Spectrometer</u>

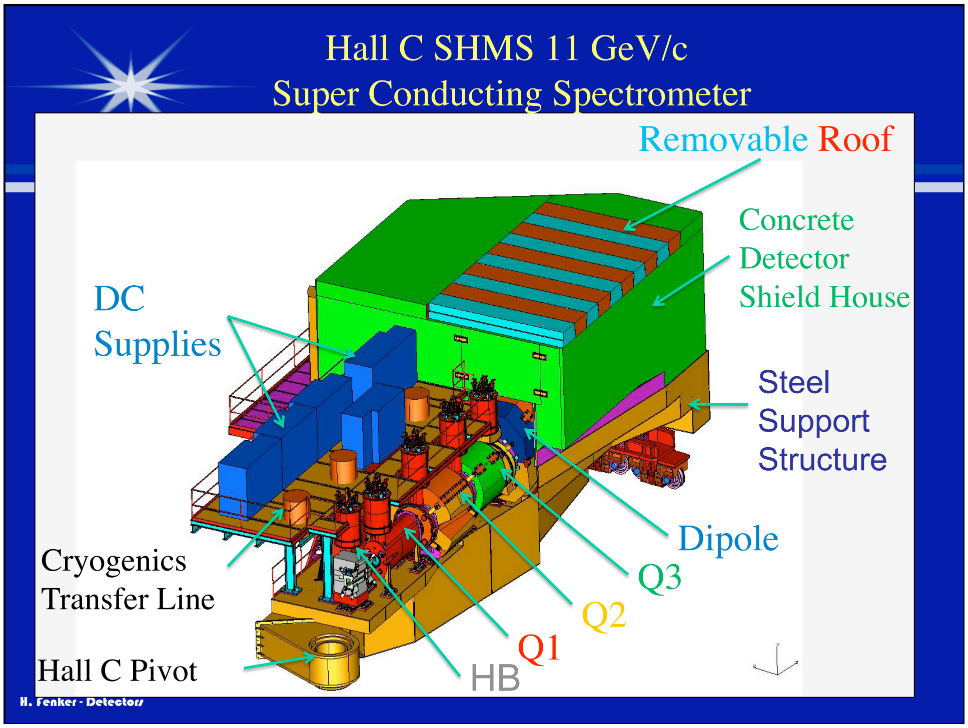
- **Scintillators** for Triggering and Timing
- **Magnetic Field** for Momentum Measurement
- Drift Chambers for **Tracking**
- Particle Identification by
  - Gas/Liquid/Lucite/Aerogel **Cerenkov Counters**
  - **Time-of-Flight**
- Lead-Glass or Scintillator **Calorimetry**

CLAS12 Detectors



GlueX/Hall D Detector




Hall C SHMS 11 GeV/c
Super Conducting Spectrometer
Removable Roof
Concrete
Detector
Shield House
DC
Supplies
Steel
Support
Structure
Dipole
Q3
Q2
Q1
HB
Cryogenics
Transfer Line
Hall C Pivot
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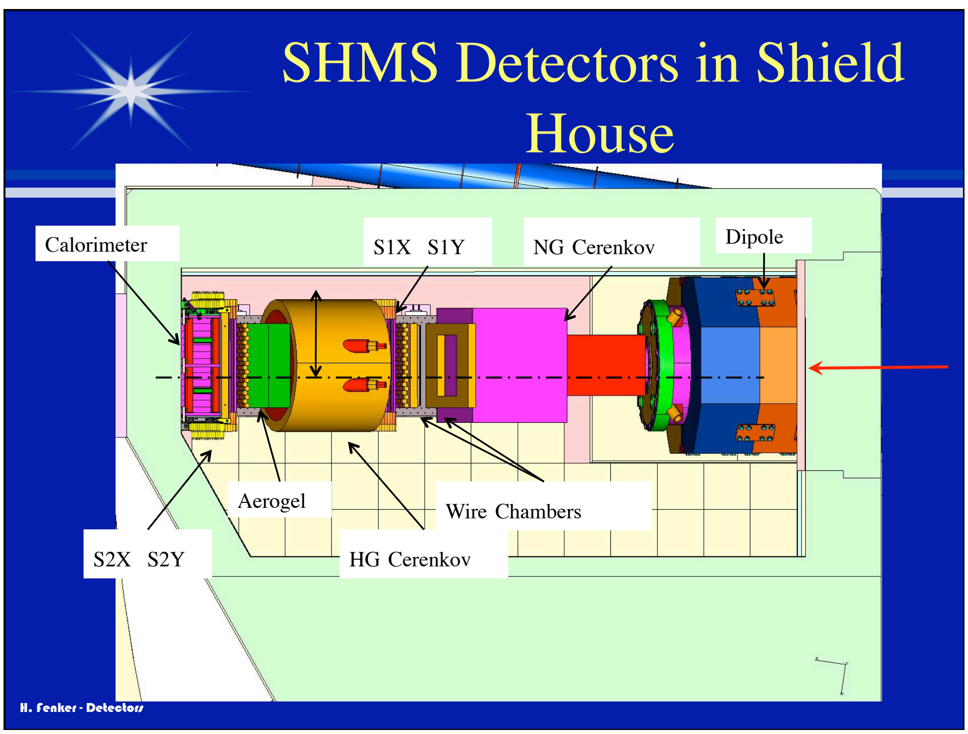
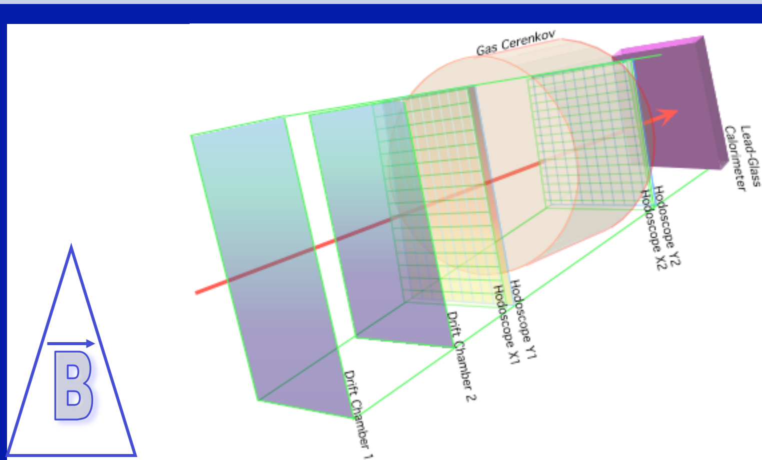

SHMS Detectors in Shield House
Calorimeter
S1X S1Y
NG Cerenkov
Dipole
Aerogel
Wire Chambers
S2X S2Y
HG Cerenkov
H. Fenker - Detectors

Putting it all Together: A Detector System



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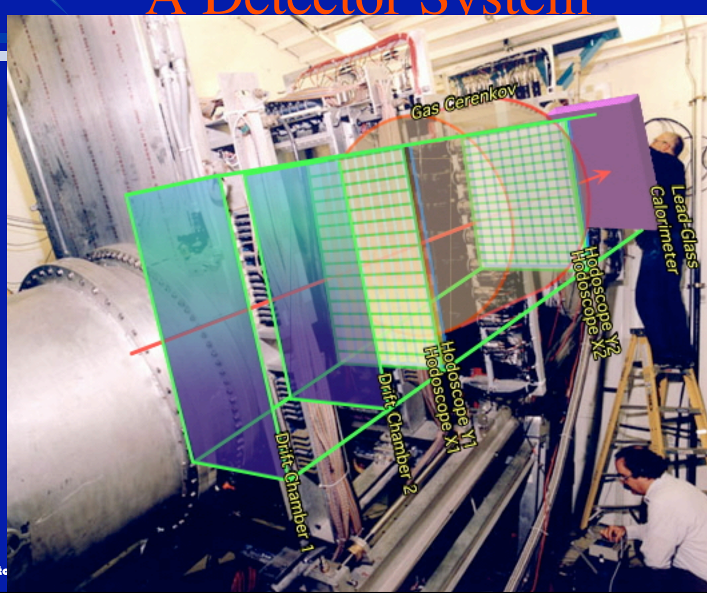
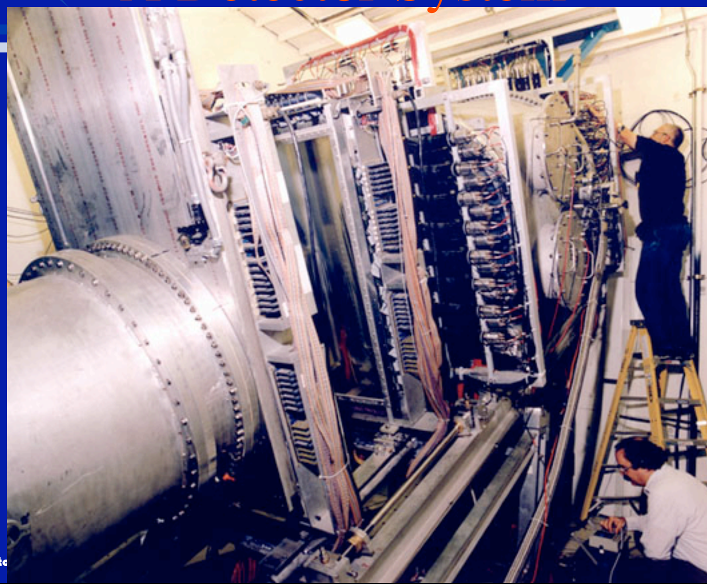
Putting it all Together: A Detector System



H. Fenker - Detecto

Putting it all Together: A Detector System



H. Fenker - Detecto

Particle Detectors- Summary

- Detect Particles by Letting them Interact with Matter within the Detectors.
- Choose appropriate detector components, with awareness of the effects the detectors have on the particles.
- Design a System of Detectors to provide the measurements we need.

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Particle Detectors- Suggested Reading

- The Particle Detector BriefBook: physics.web.cern.ch/Physics/ParticleDetector/BriefBook
- <u>Particle Detectors</u> by Claus Grupen, Cambridge University Press (Jlab Library)
- <u>Techniques for Nuclear and Particle Physics Experiments</u> by W.R. Leo, Springer-Verlag 1994 (JLab Library)
- RCA or Phillips or Hamamatsu Handbook for Photomultiplier Tubes
- Slides from This Lecture:

http://userweb.jlab.org/~hcf/detectors