Particle Detectors

- Particle Detectors & How They Work
  - physics goals & experiment types
  - specialized detectors
    - basic particle-matter interactions
    - tracking, velocity, energy, time
- Designing & Optimizing Detectors
  - how to do mini-studies
    - optimizing performance
    - trade-offs you may have to make
    - mistakes you can avoid!

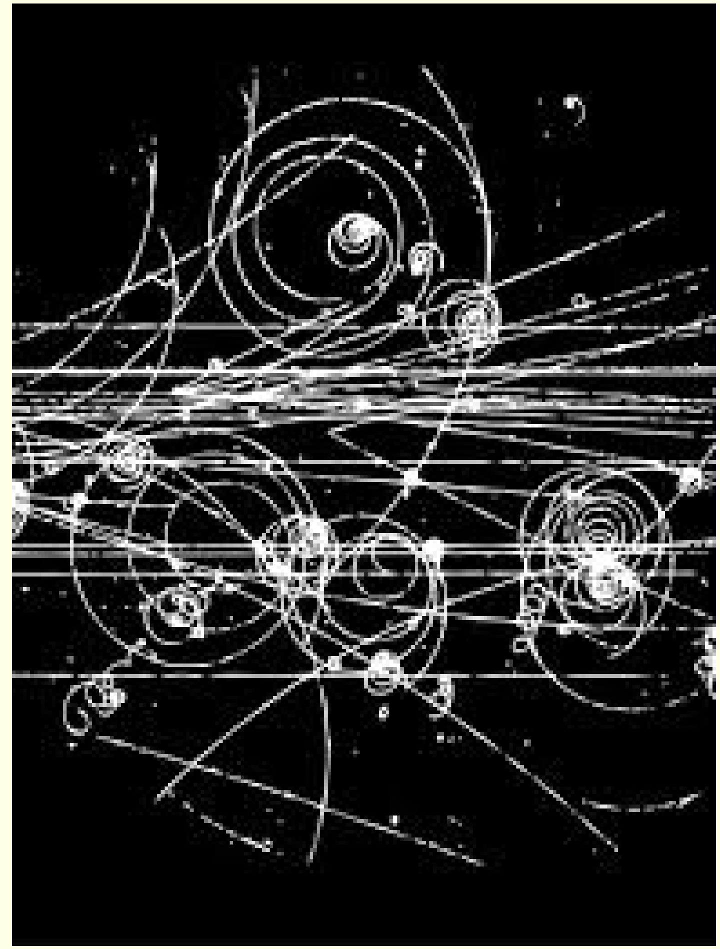
Importance of Detectors

- Technological advances in particle detection instrumentation is one of two factors underlying the considerable progress in nuclear and hadronic physics of the last 50 years; the other being the development and extension of theoretical techniques.
- Fifty years ago, particles were detected in small table-top size devices at rates of a few per second.
- Today, detectors the size of auditoriums are filled with instruments comprising hundreds of thousands of signal channels with overall event rates in the tens of thousands per second.

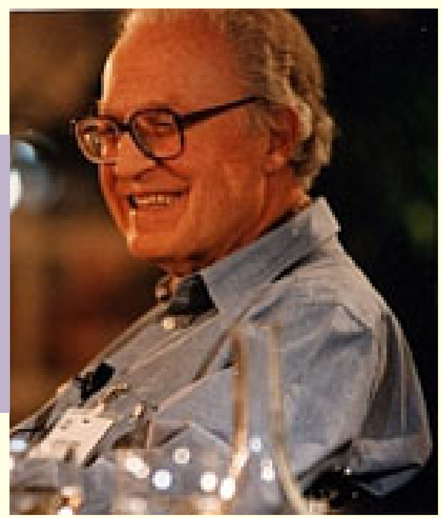
Seeing Tracks using Ionization

Bubble Chamber Photo

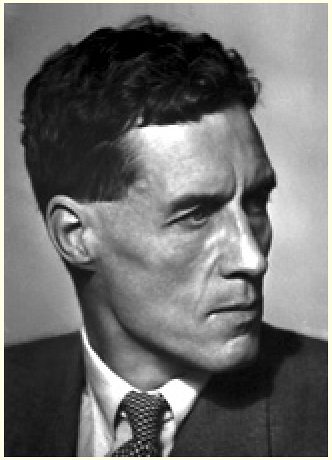
'super-critical' liquid near boiling
- boiling begins along ion trail
- time-consuming to analyze
- low data rate
- excellent imaging quality



Don Glaser:
-inventor of the bubble chamber
1960 Nobel Prize



The predecessors of the bubble chamber



- **Charles Thomson Rees Wilson** in **1927** "for his method of making the paths of electrically charged particles visible by condensation of vapour".

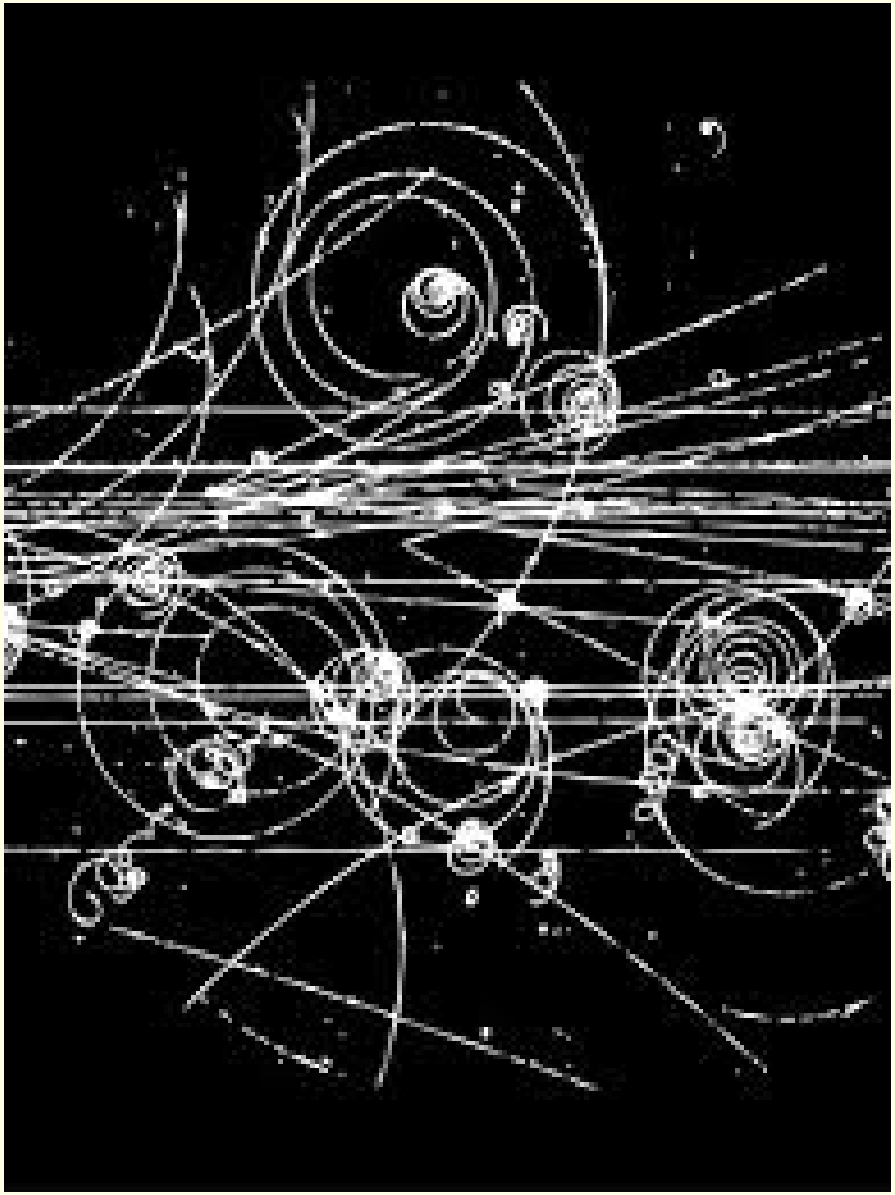
- The Nobel Prize in Physics **1948** was awarded to **Patrick M.S. Blackett** "for his development of the Wilson cloud chamber method, and his discoveries therewith in the fields of nuclear physics and cosmic radiation”.

Bubble Chamber Photograph:

- Measure trajectory (in B-field)
- correlate tracks with vertices (particle decay)
- ionization density & curvature: measure **P**, b
- ‘vee’s à see neutrals
- constrained fitting

Modern detector:

- specialized detectors



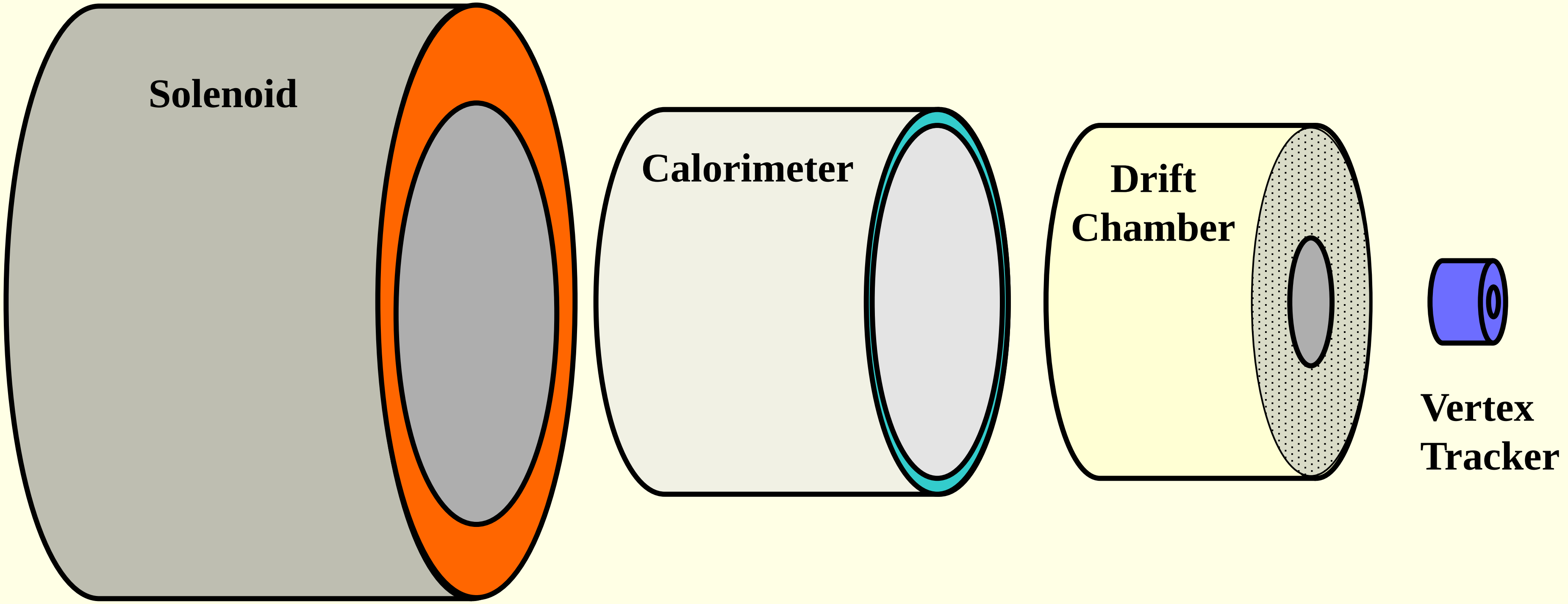
Particle Experiments: Physics Goals

Type	Beam / Target	Physics Goal	Comments
Colliding beams	$e^+ \ e^-$	study quarkonia, hadronization, search	good for specific searches, spectroscopy (when masses are ~known)
	$e^+ \ e^-$ (asymm.)	weak decays	asymm. Lorentz boost à asymm. detector
	$pp, p\overline{p}$	hadronization, search	good for general search (e.g. Higgs)
	AA	QGP, hadronization	very high particle multiplicity
Fixed Target	ep	GPD's, SIDIS, exclusive	polarized beam, target possible; very high luminosity, good for production experiments
	gp	glueballs, hybrid states, spectroscopy	

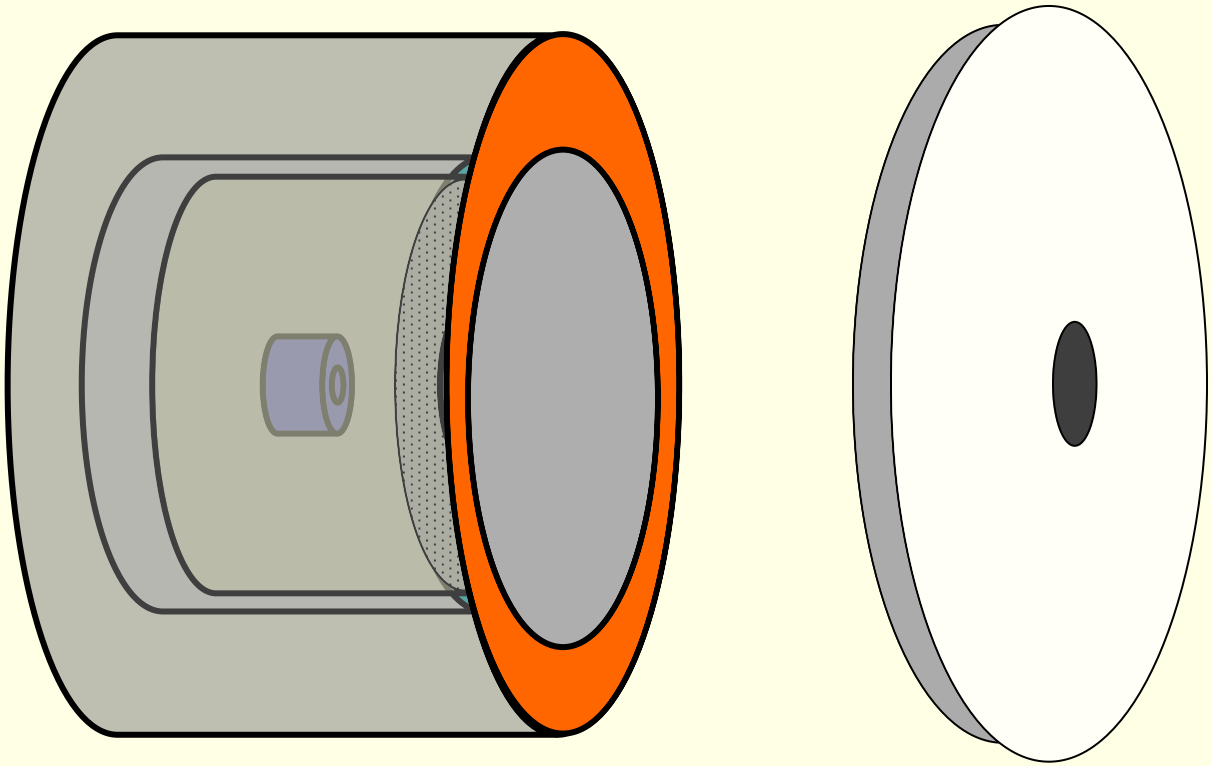
Experiment Set-ups

Type	Projectiles	Detector Type
Colliding beams	e+e-, e+e- (asymm.) PP, PP, AA	Solenoid; perhaps with asymmetric end-caps
Fixed Target	eP, gP, pP, PP	small-aperture, focussing spectrometer
		large-acceptance magnetic spectrometer

Typical Solenoid Detector
- Central Part -

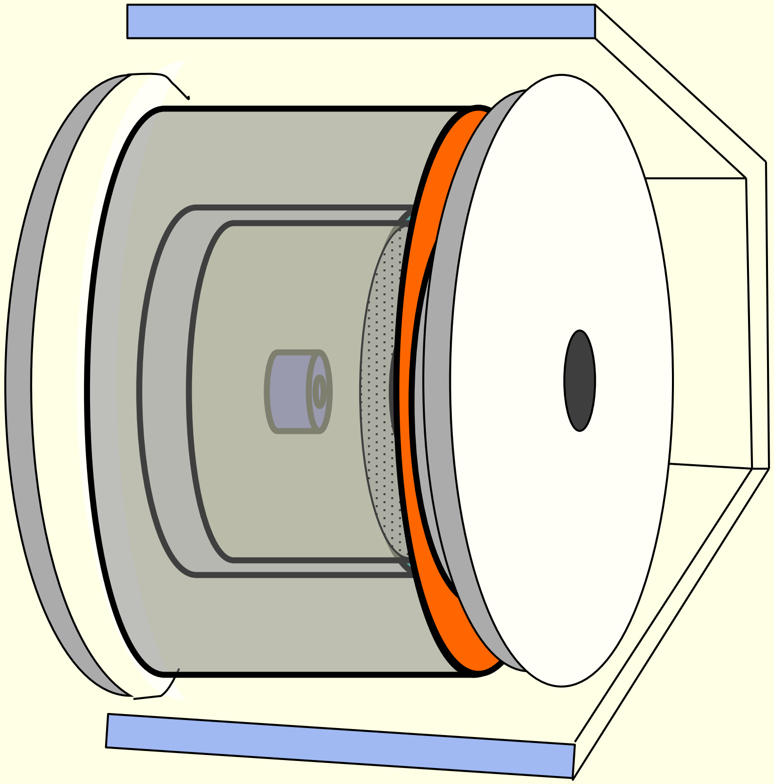


Solenoid Detector
… add an end-cap

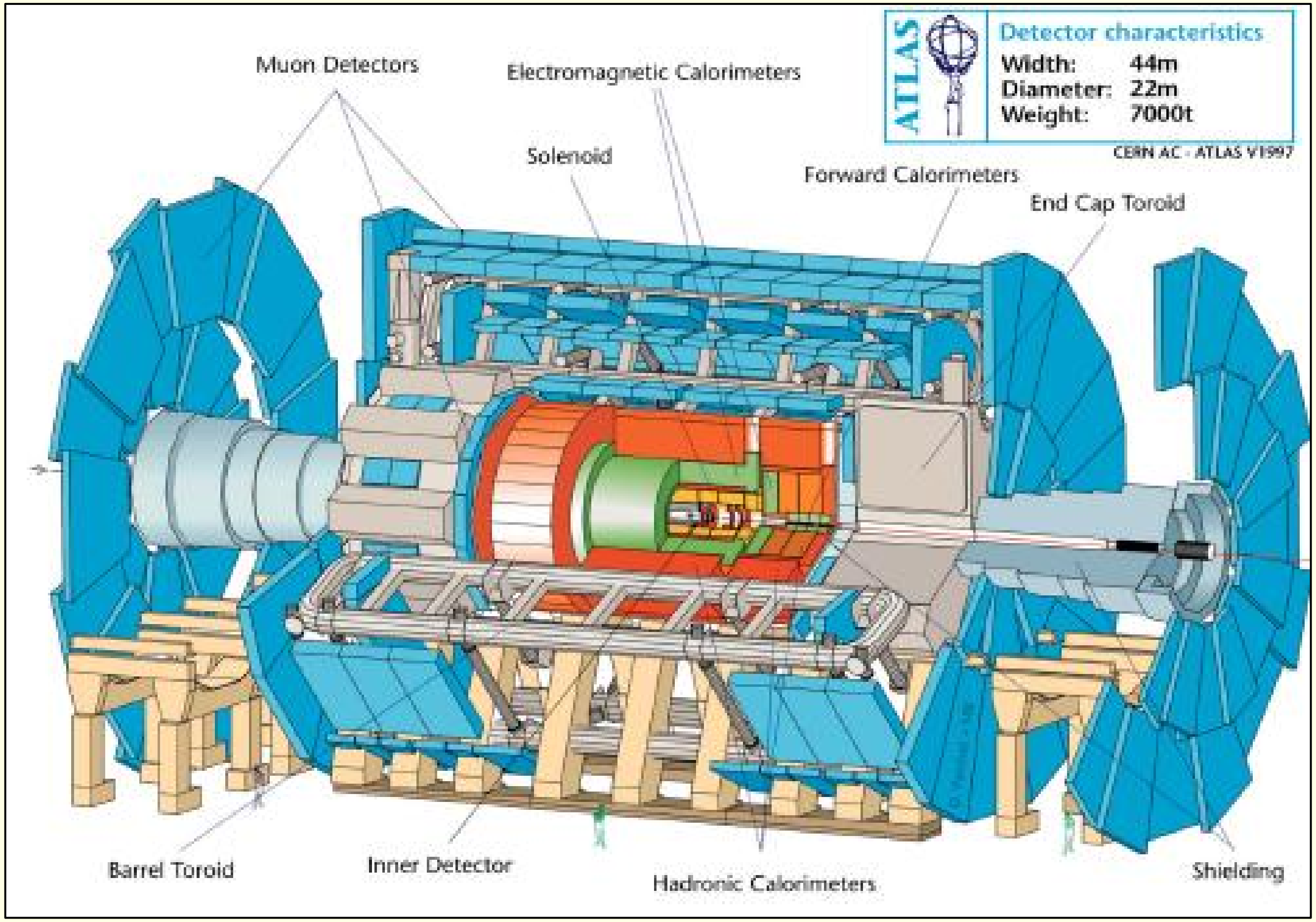


“End-cap” forward-going charged and neutral particles

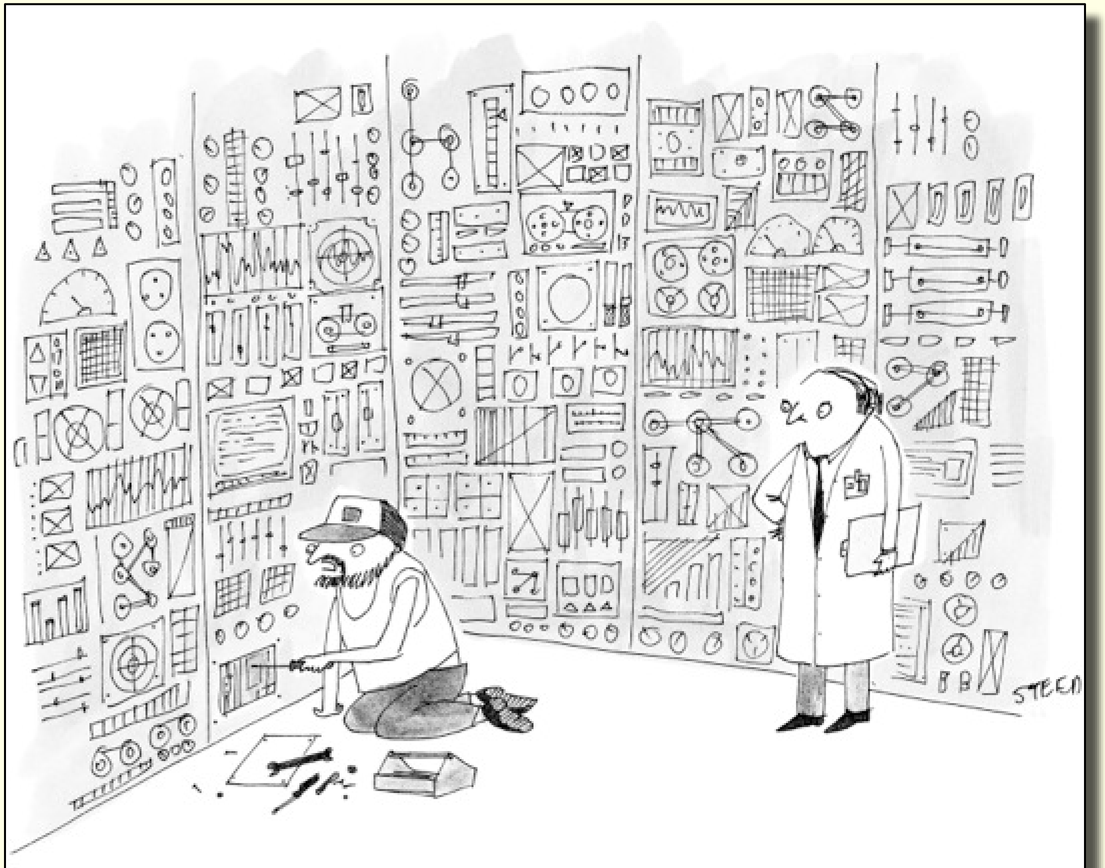
… muon counters on outside



Atlas detector at the LHC

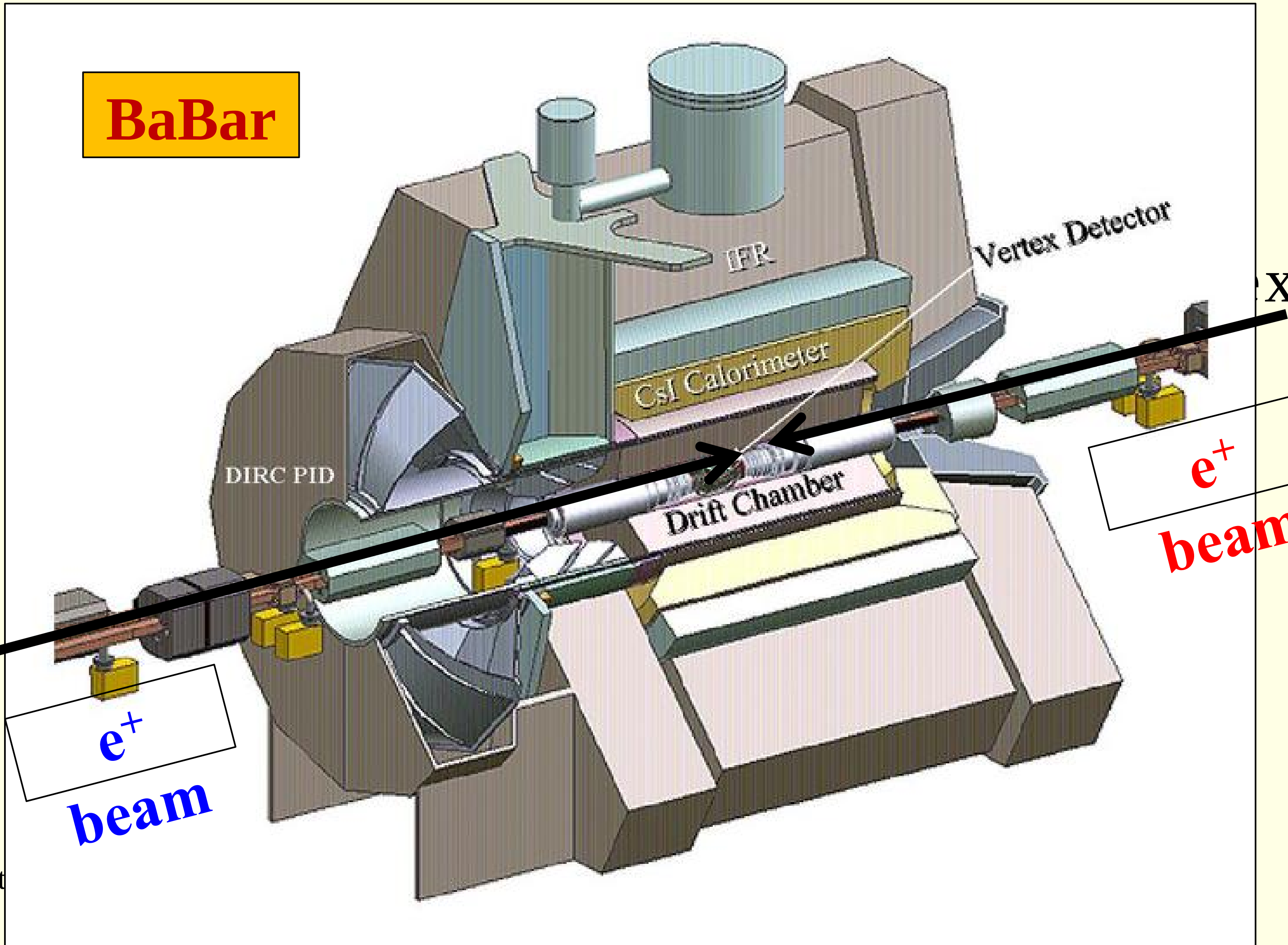


Realities of an Experimentalist's Life



"All right, pal, I'm just saying, that's what I'd do if it was my Large Hadron Collider."

a detector for weak decays



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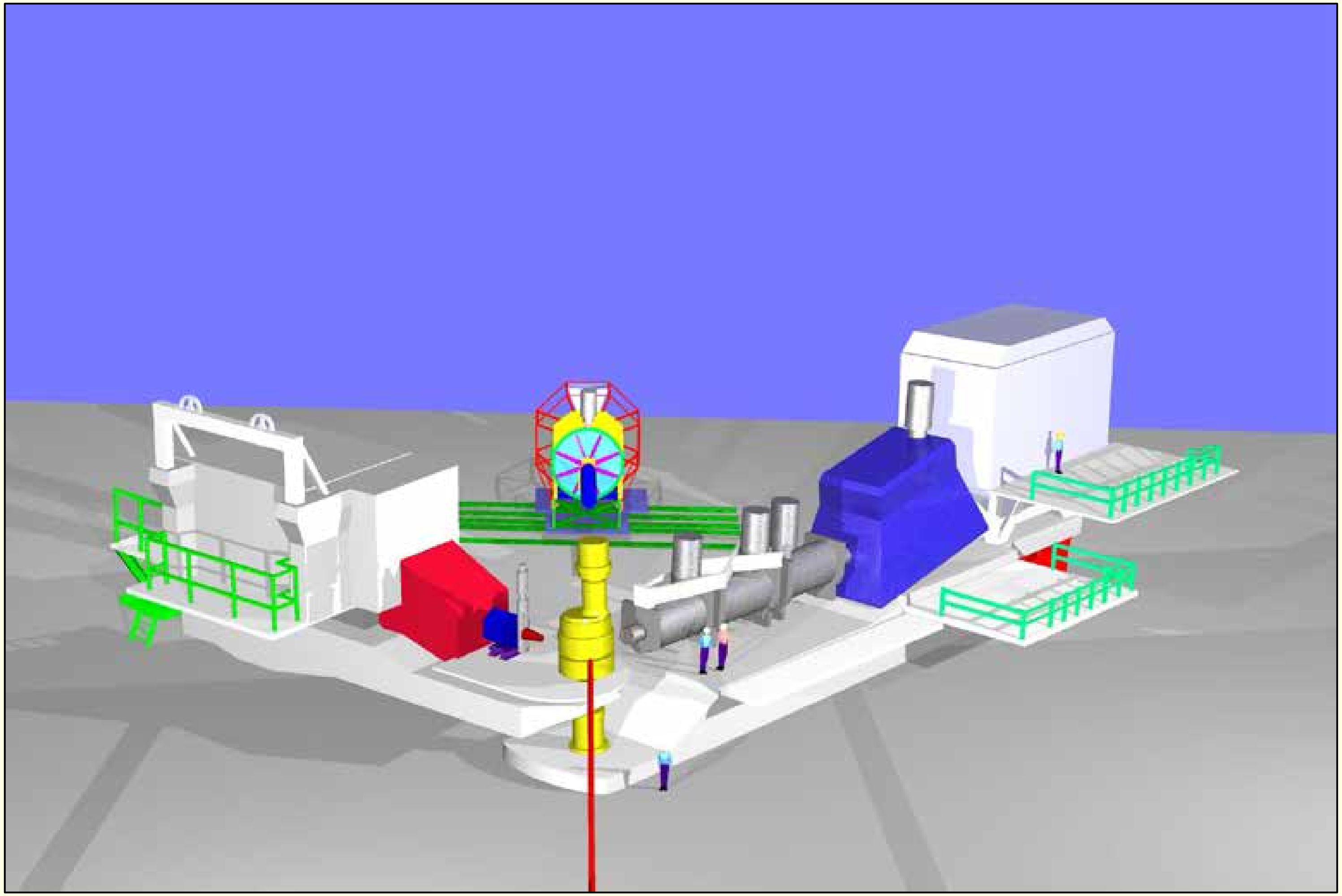
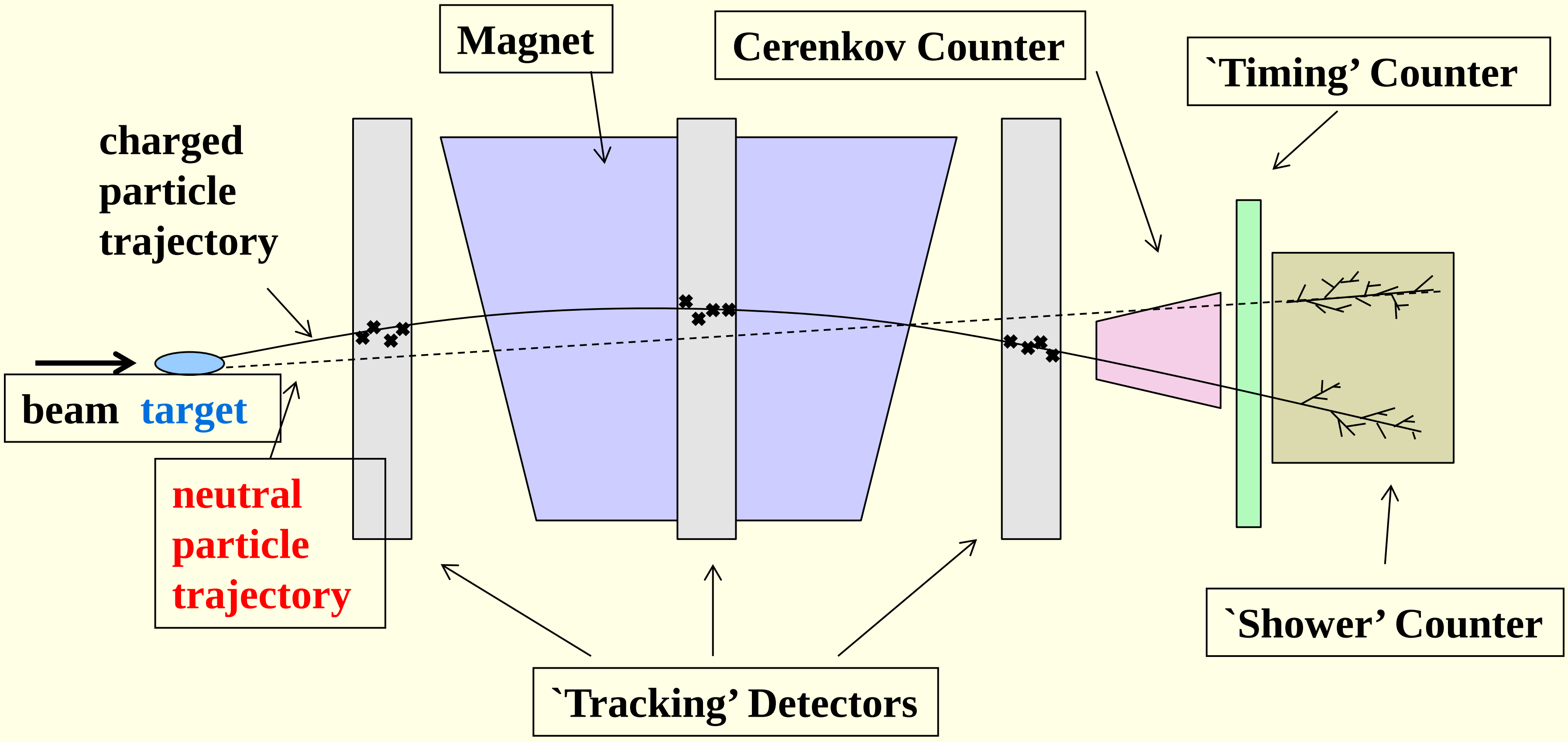
Fixed Target Experiments

- Lower center-of-mass energy than colliding beams
- Typically higher luminosity (high particle density in a target !)
- Good for studying target (e.g. proton) structure
- Good for studying production mechanisms, polarization variables

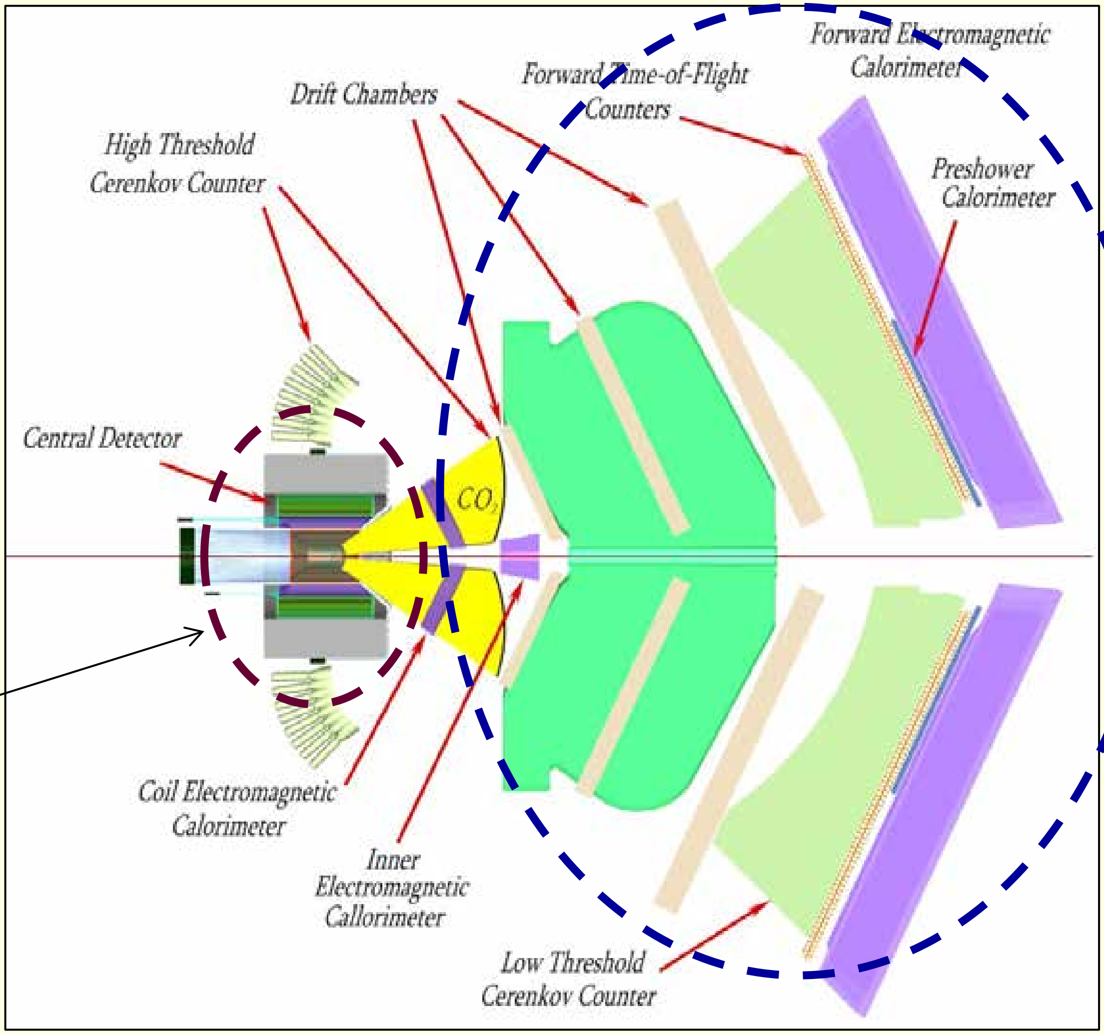
Fixed Target Detectors



A (typical?) fixed-target detector



CLAS12 detector at Jlab



CLAS12 Forward Detector

CLAS12 Central Detector

Specialized Detector Types by Measurement Goal

1. Tracking chambers for charged particles
   – trajectory through magnetic field
   – momentum, angle of charged track
2. Timing counters
   – determine elapsed time-of-flight
   – path length, momentum à b, mass
3. Velocity detectors
   – use 'Cerenkov' light for direct b measurement
4. Energy deposition
   – 'calorimeter' measures energy of neutral particles

Primary Particle Interactions

Useful Formulas

Energy loss = 2 MeV/g/cm
(for minimum ionizing)
~1 interaction / 300 μm in gas
~100 electrons / cm in gas

$N_{photons}$ ~ 2 * 10^4 / cm
transparency very important

Threshold: $V_{particle} / V_{light} > 1$

$\tan\theta_c = \sqrt{\beta^2 n^2 - 1}$

$\frac{d^2N}{dx\,d\lambda} = 2$

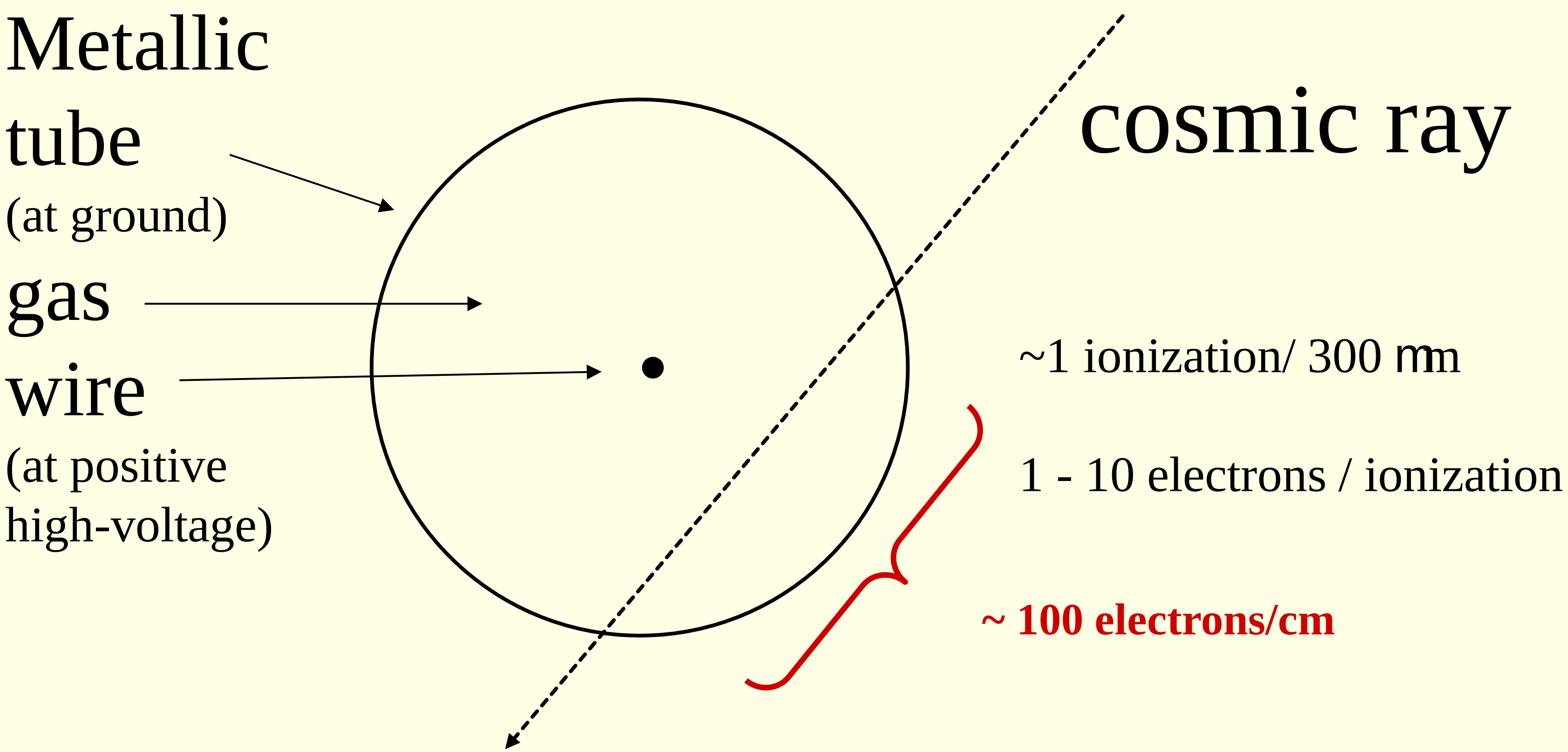
Sub-Detector Fabrication

- Tracking chambers
  - Liquid: Bubble Chambers
  - Gaseous: Wire Chambers, GEM's, Micromegas
  - Solid-state: Silicon
- Timing counters
  - scintillator 'paddles' with PMT readout
- Velocity detectors
  - 'Cerenkov' light: threshold or imaging
- Energy deposition
  - 'shower counters', radiator + scintillator stack

Types of Tracking Chambers

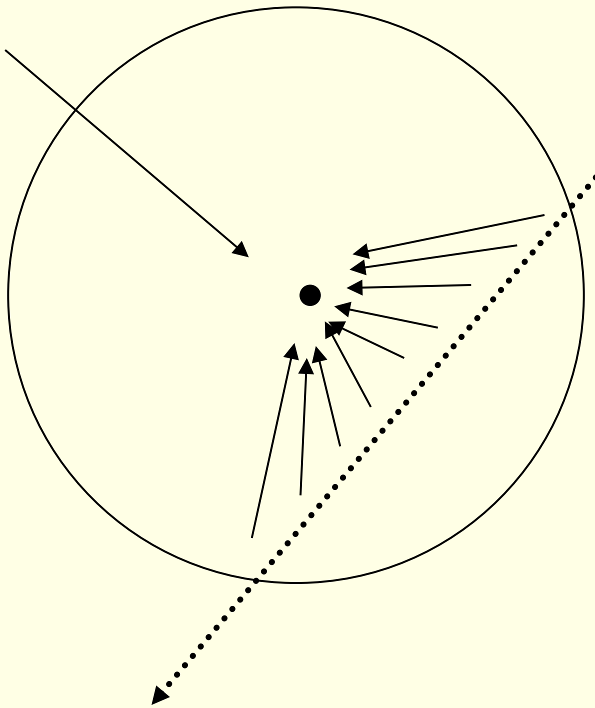
- Wire Chambers (Geiger tubes to drift chambers)
  - gas amplification à signal
  - electron ‘avalanche’ in high-field near small-diameter wire
  - use ‘time of arrival’ to estimate ‘distance of closest approach’
- Micro-pattern gas amplification devices
  - gas amplification à signal
  - lithography techniques à amplification and pick-up features
  - ‘GEM’s and ‘Micromegas’
- Solid-State Detectors
  - etched and micro-fabricated Silicon structure
  - collect primary ions; no intrinsic amplification

‘Geiger’ tube


Metallic
tube
(at ground)
gas
wire
(at positive
high-voltage)
cosmic ray
~1 ionization/ 300 µm
1 - 10 electrons / ionization
~ 100 electrons/cm

“drifting” of the electrons

wire at positive voltage



- electrons drift to the wire
- strike a molecule every 4 μm
- velocity ~ 50 μm/ns (max)

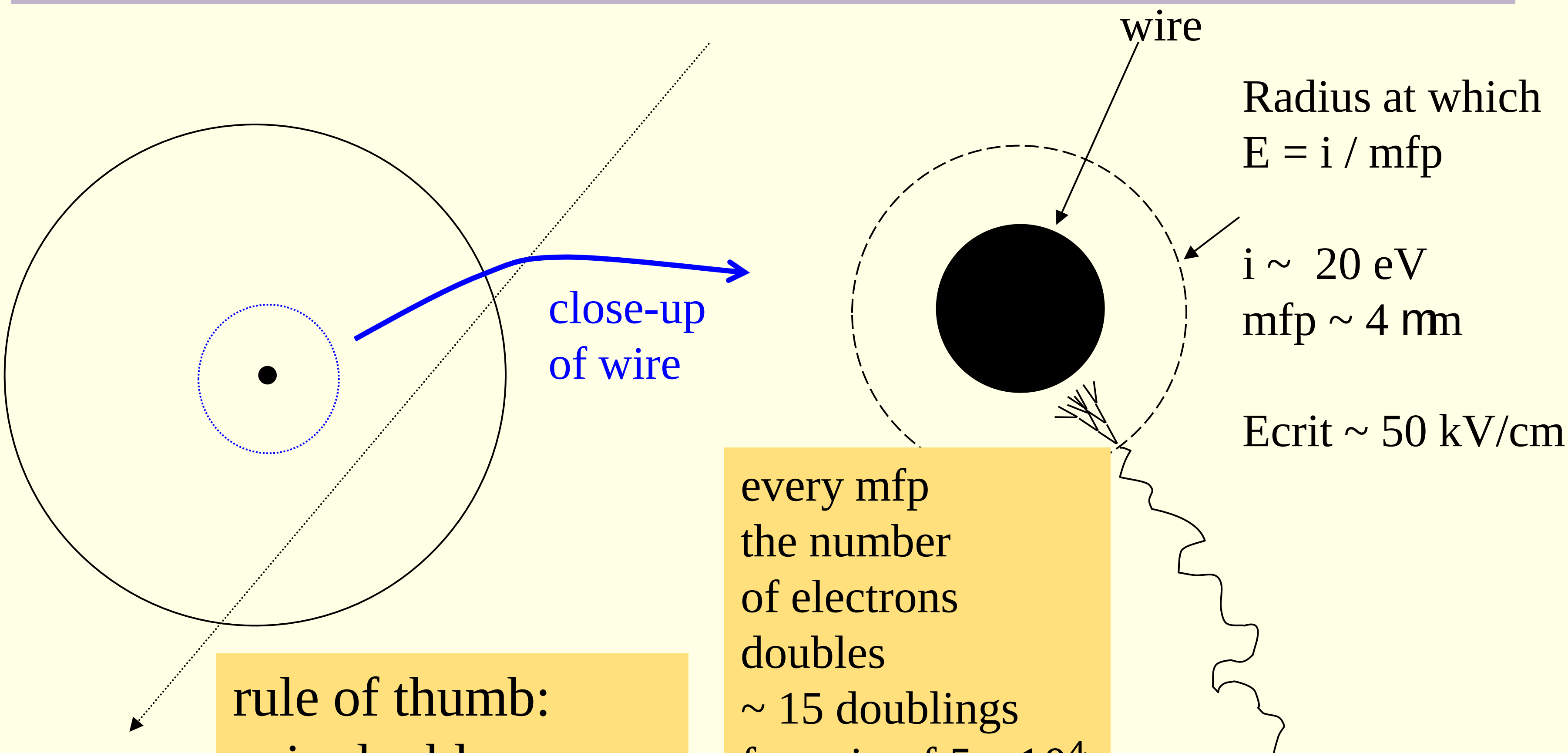
To see this:

$$\frac{1}{2}\left(\frac{m}{c^2}\right)v^2 = \Delta * E, \text{ where}$$

$$\Delta \cong 4\mu m, \quad E \cong 300\,\frac{V}{cm}$$

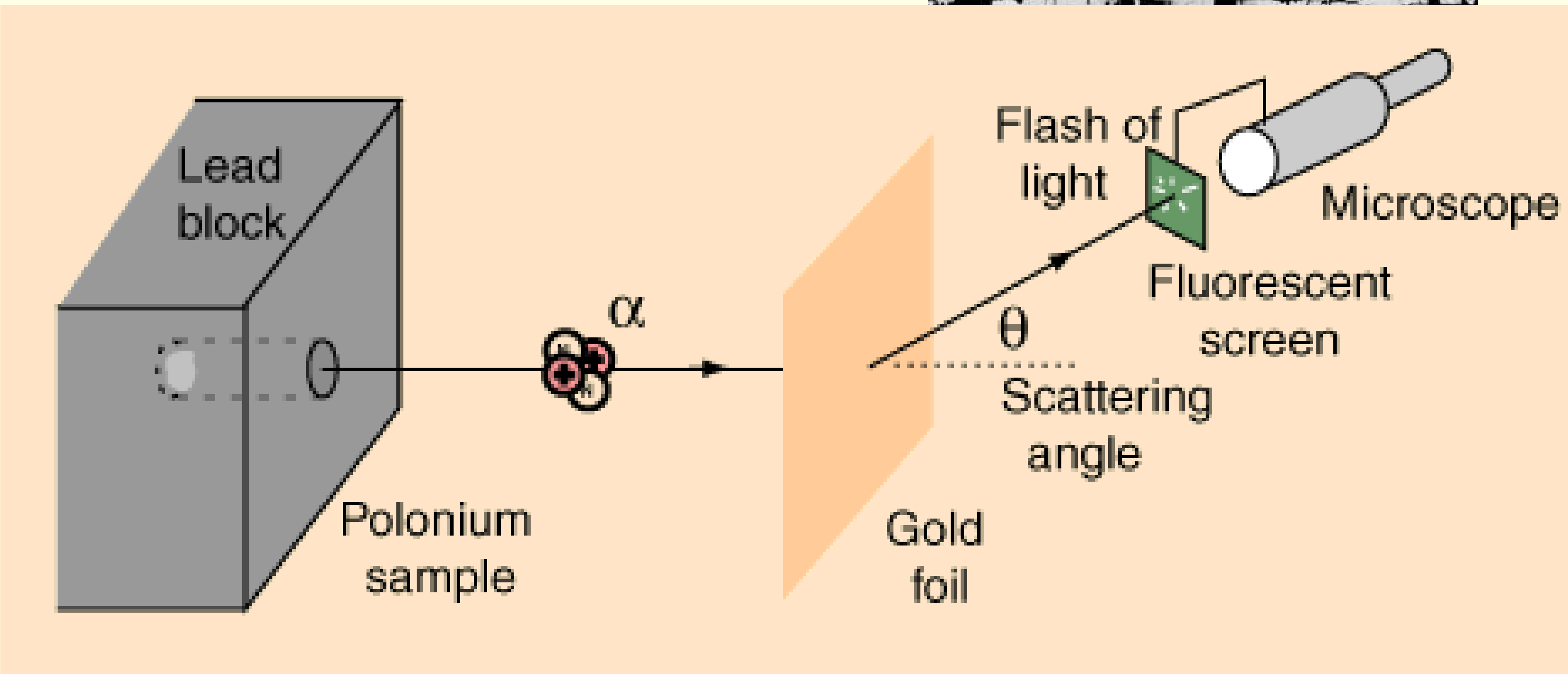
$$v_{max} = \sqrt{\frac{2\Delta * E}{m}} * c = 150\ \mu m/ns$$

the “avalanche”



every mfp
the number
of electrons
doubles
~ 15 doublings
for gain of $5 * 10^4$

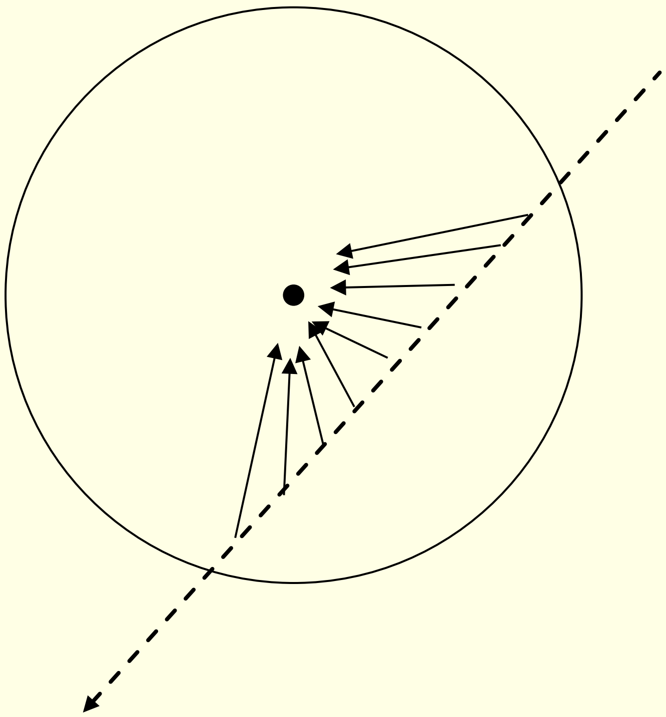
rule of thumb:
gain doubles every
75 or 100 Volts



Ernest Marsden

“drifting” of the electrons

wire at positive voltage



- electrons drift to the wire
- strike a molecule every 4 mm
- velocity ~ 50 mm / ns

- **New Idea** **- increase the accuracy of the tube by measuring the time difference between the wire signal and another prompt signal**

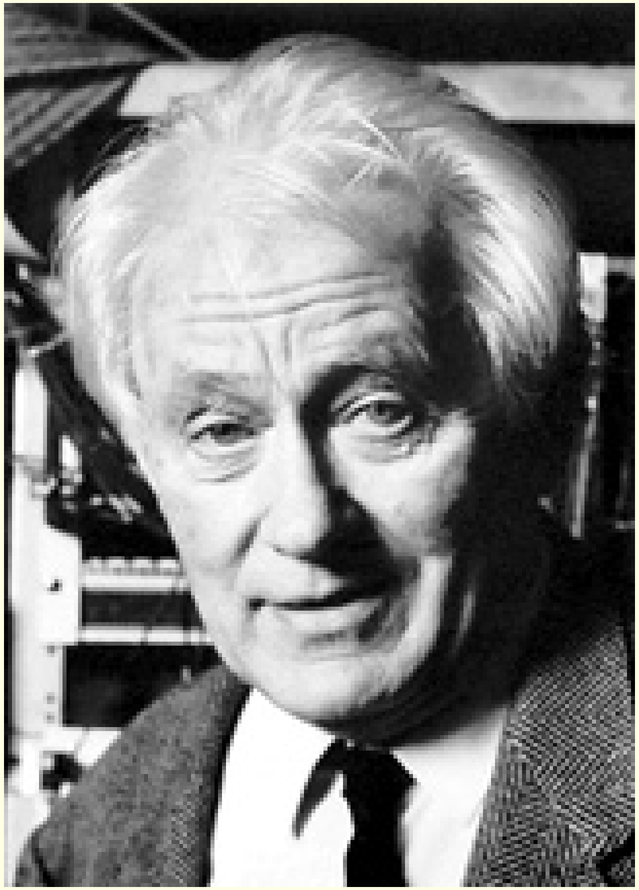
à name ‘drift chamber’

Nobel Prize Winner

Georges Charpak:

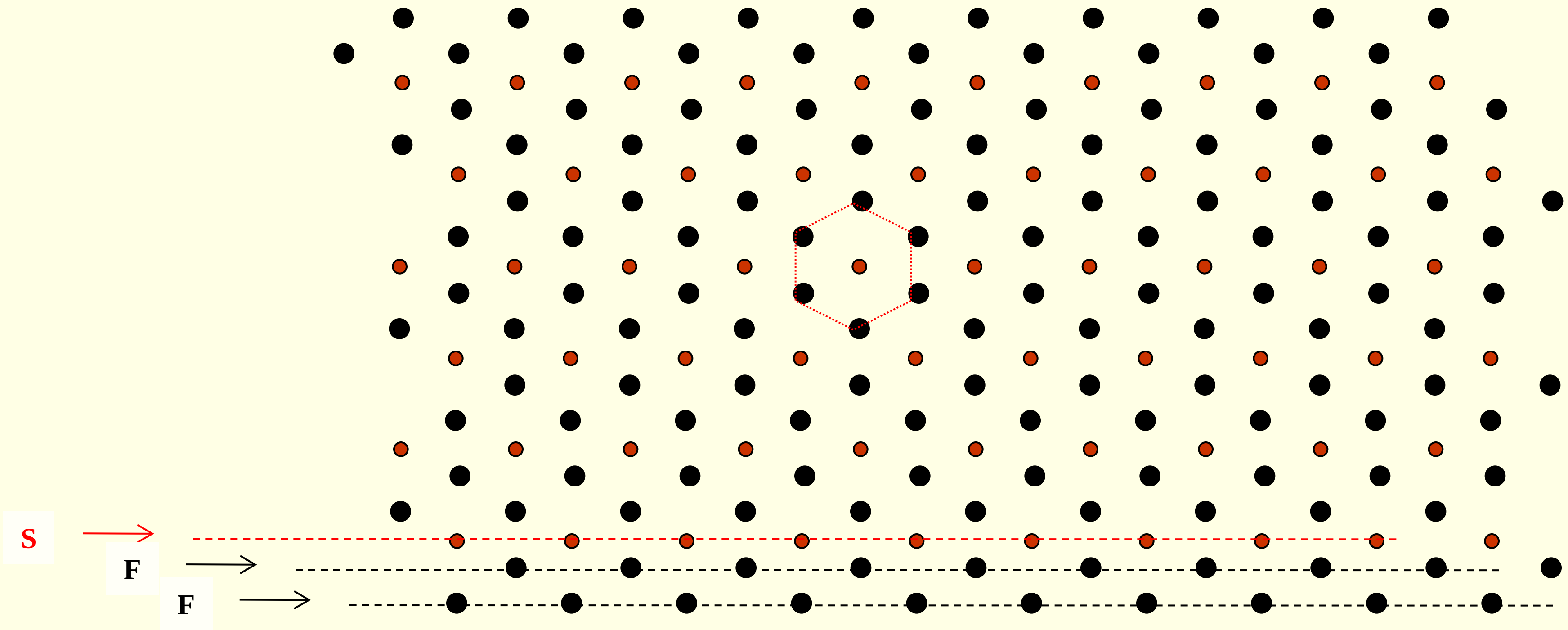
-inventor of the multi-wire proportional chamber
1992 Nobel Prize

-in a key 1968 paper, he also pointed the way to using drift time to improve measurement accuracy

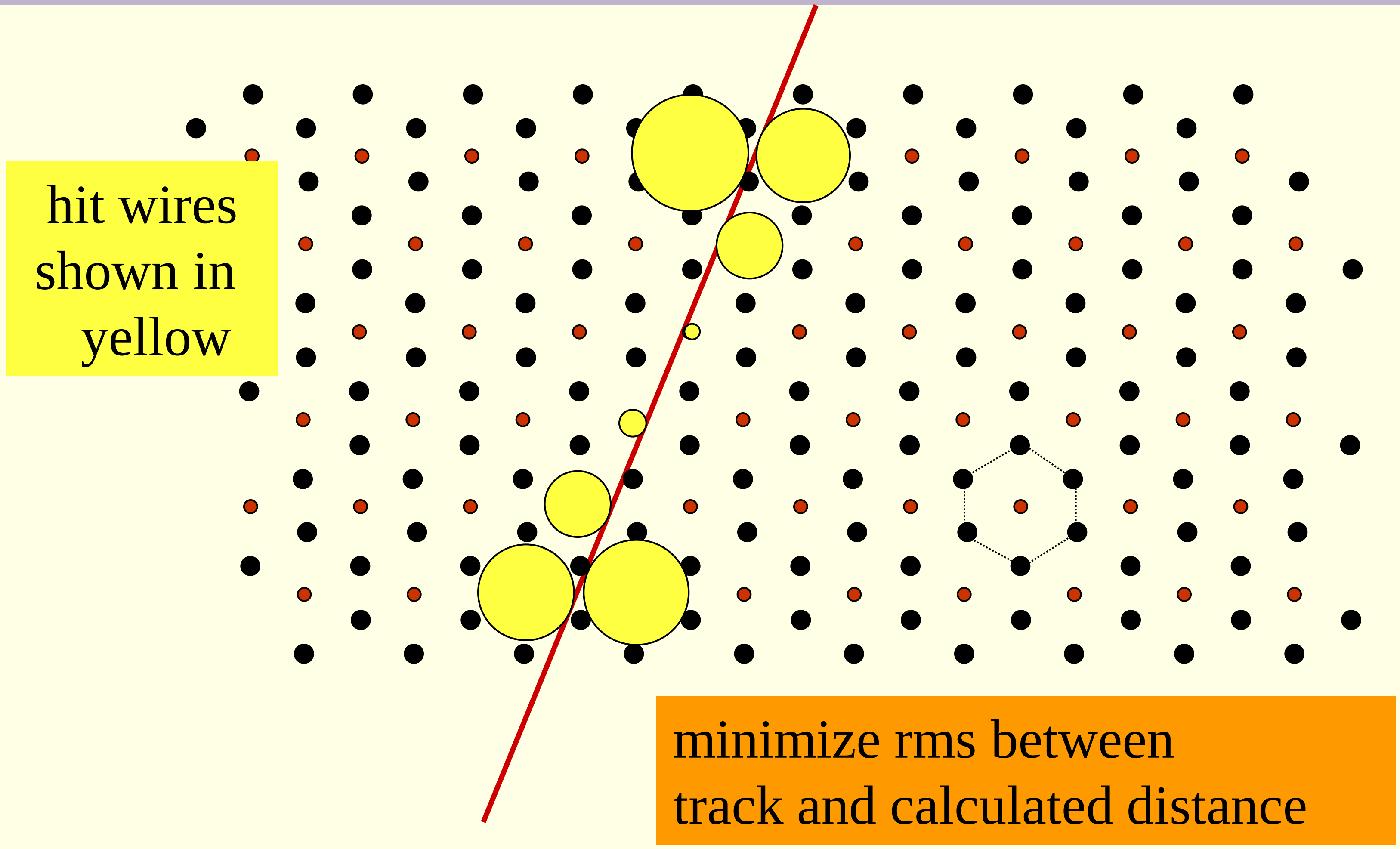


“all-wire” drift chamber

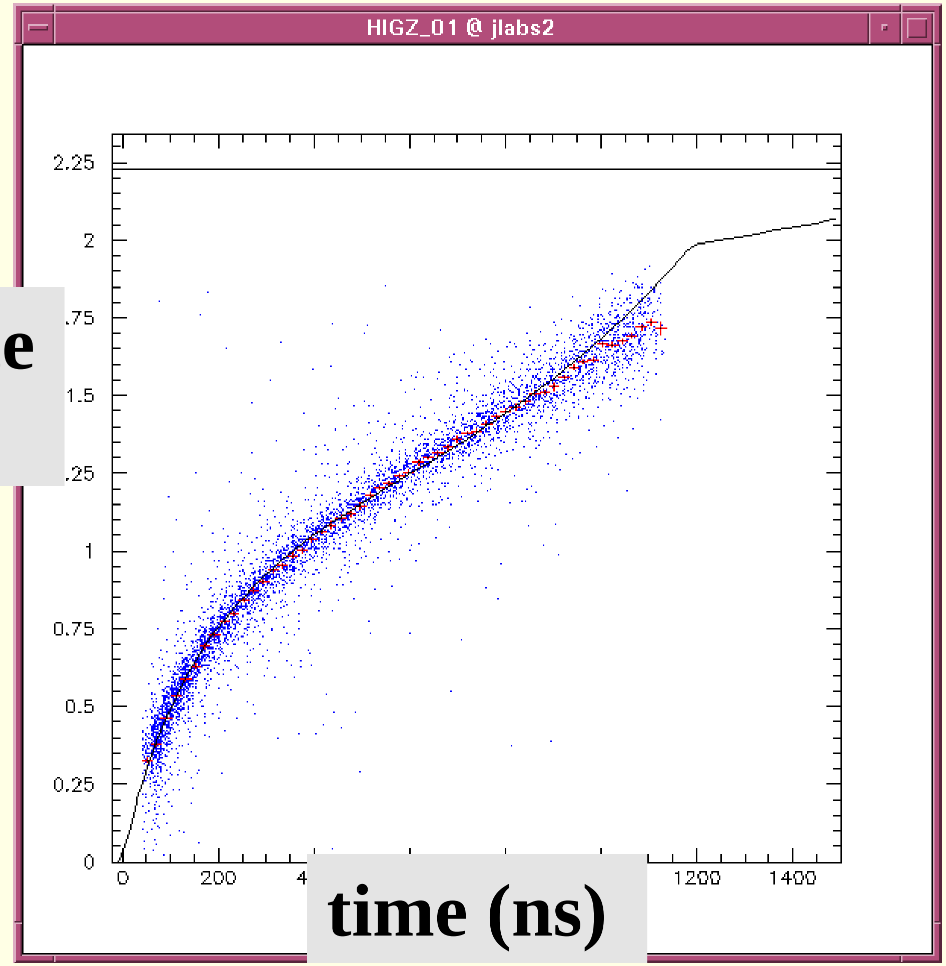
wires in layers
“brick-wall” fashion



how tracking works



drift velocity calibration necessary



CLAS12 DC Design Decisions

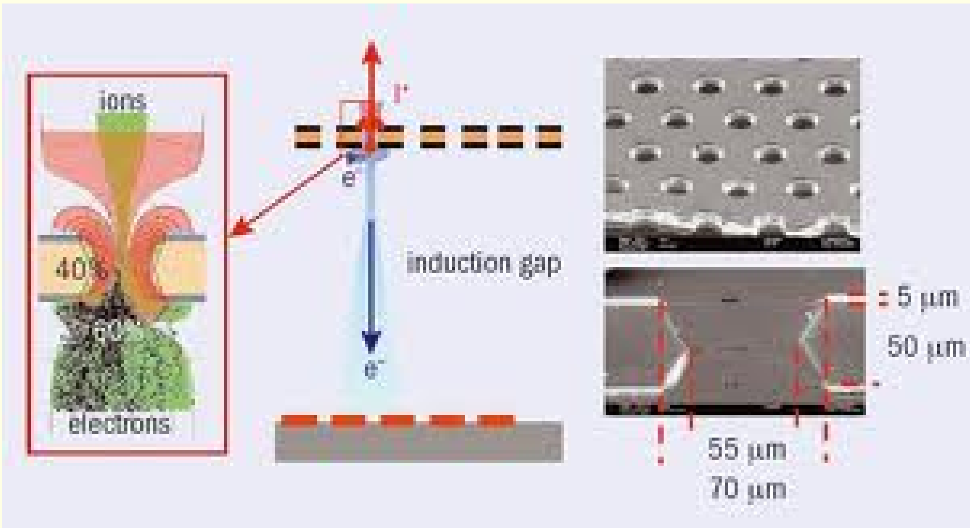
solenoidal shield	necessary for 10^{35}
fwd./bck. separation	fwd. trks.; magnet interactions
high ∫B·dl torus	good dp/p for fwd. tracks
6x6 layers	robust track-finding
+/- 6^{o} stereo	better f resolution; more ambigs.
planar; self-supporting	identical cells, easy to calibrate, survey, repair
112 wires/layer	cell-size; cost
30 mm sense wire 92/08 Ar:CO_2	faster, linear xvst, strong, more reliable stringing
on-chamber amplifiers	long cable runs
re-use hv, lv, ADB, TDC	lots of spares; cost

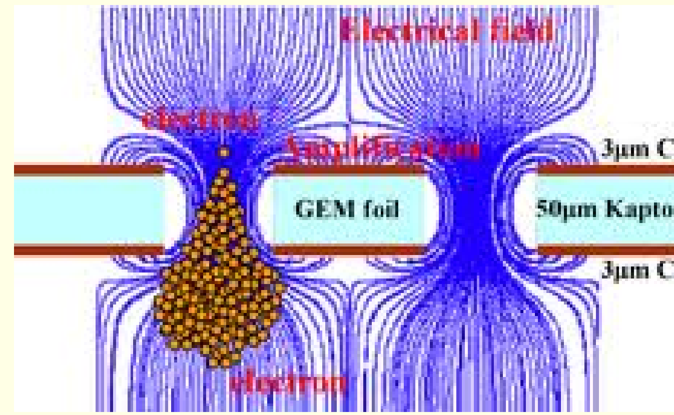
Use Lithography to Replace Wires!

Micro-pattern gas detectors

- No wires to break, accurate patterns, fast ion clearing, anode at ground
- Ideal for TPC's; not as uniform as wires
- Less multiple scattering than Silicon
- Multi-GEM's -> less ion feedback
  - more stable at same gain
- shape of dielectric important
- Micromegas w/ resistive anodes
  -> competitive with GEM's
- Flexible readout schemes !

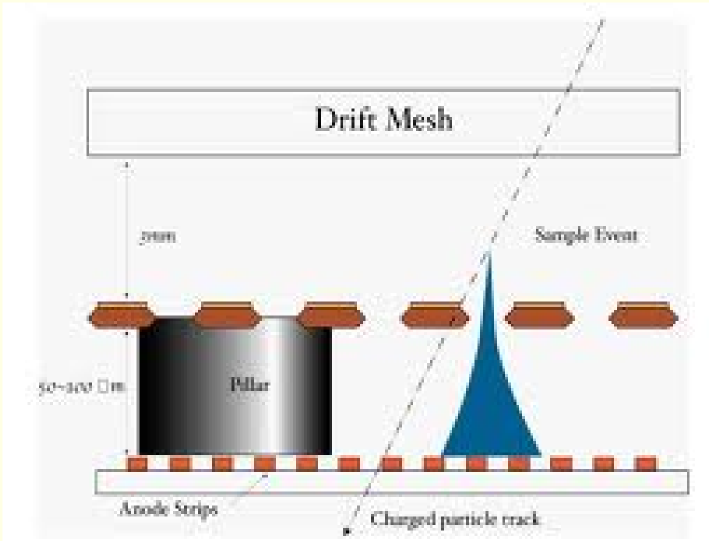
Gas Electron Multiplier Detector

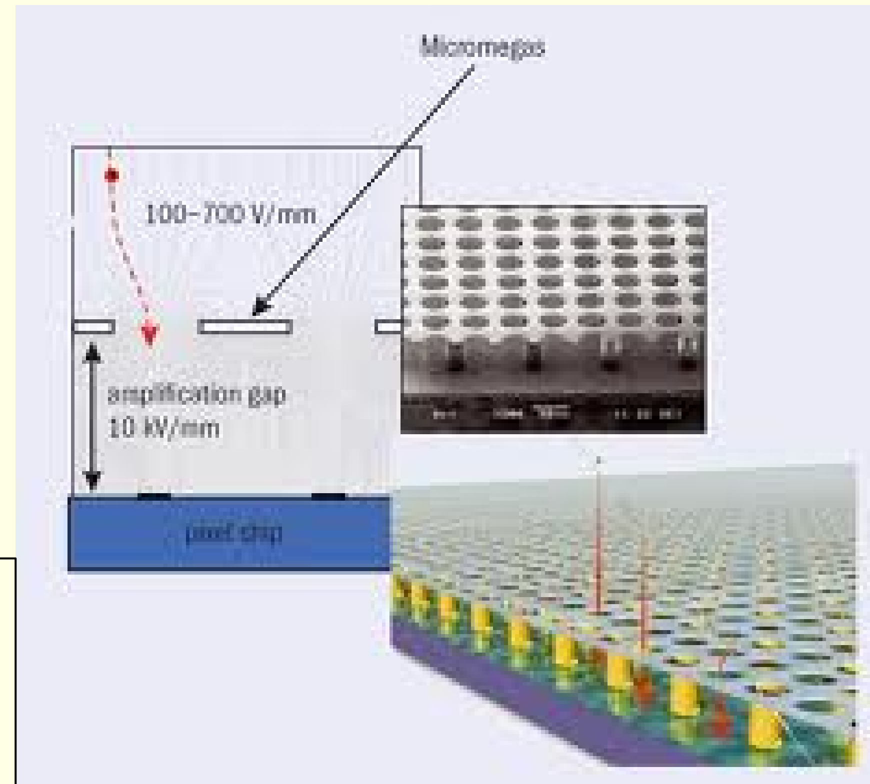




Drift region: low field: few thousand V/cm
High field in hole
- avalanche occurs in hole
- charge current induced on electrodes

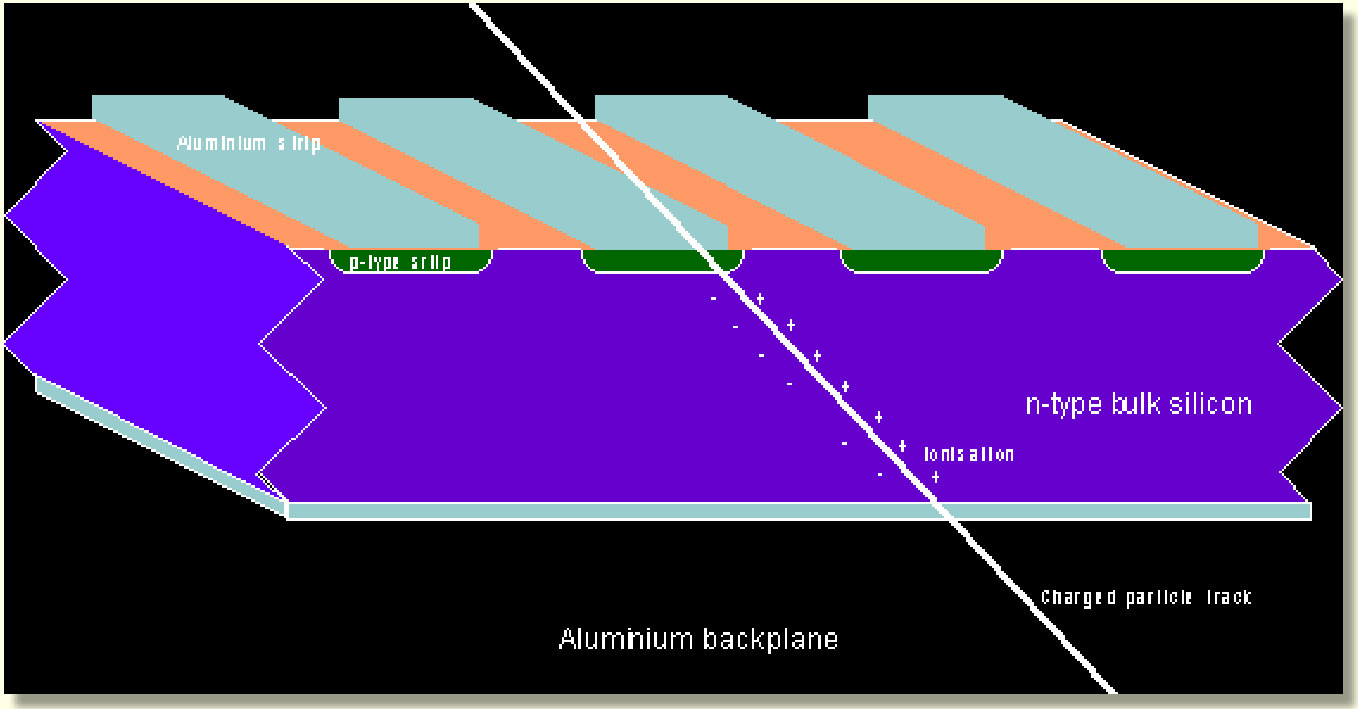
MicroMeshGas Detector





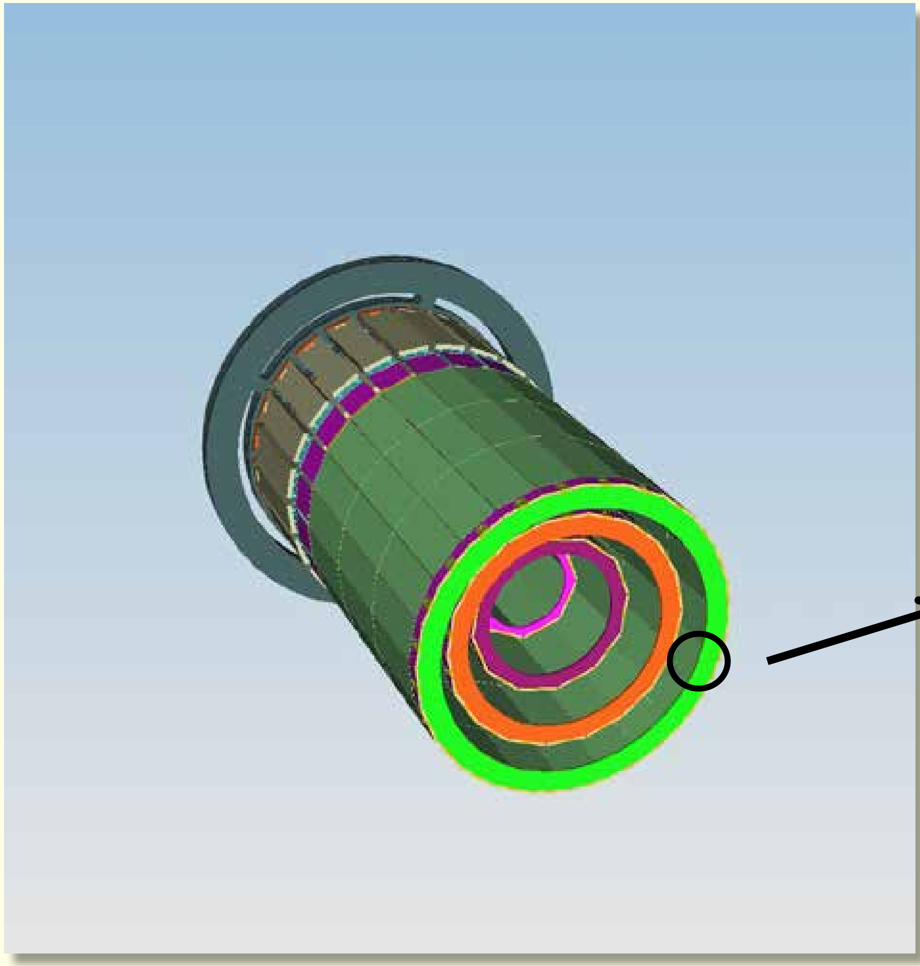
Drift region: low field: few thousand V/cm
High field between mesh and anodes
- avalanche occurs in gap
- charge picked up on electrodes

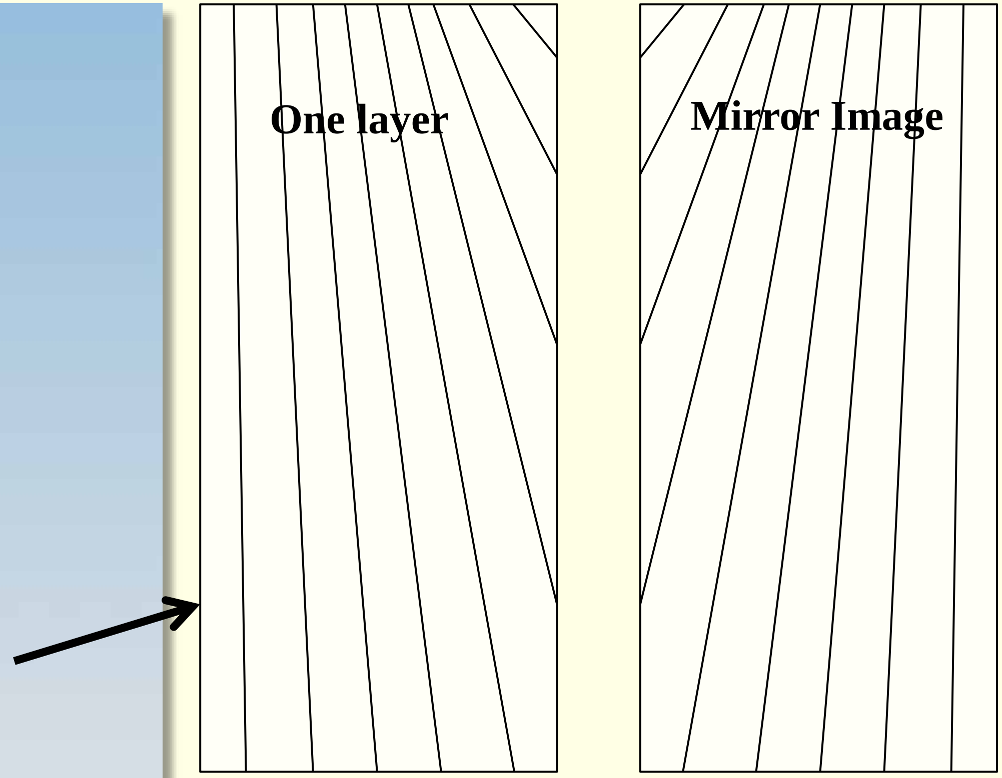
Silicon Strip Detector



- Ions produced in bulk layer
- Drift to pick-up strips
- No intrinsic amplification
- Resolution ~ strip pitch / $\sqrt{12}$

How to measure x,y,z with straight stips (and read out in the back?)





'stereo' layers allow 2-d measurement

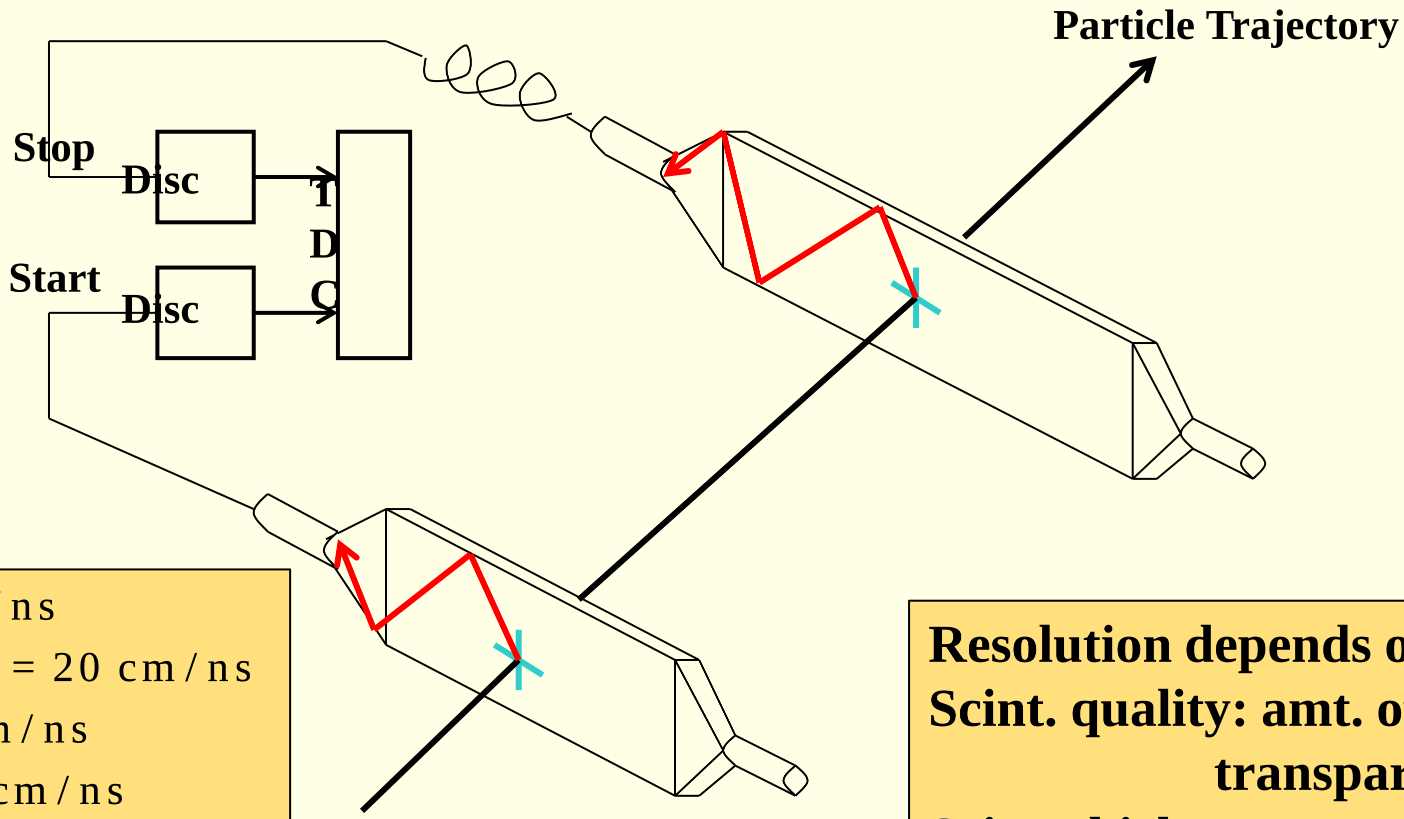
Tracking Detectors: a Comparison

Detector Type	Basic measurement type	Principle of signal generation	Resolution	Remarks
Wire chamber	Proportional Counter	Ion drift in an electric field; gas amplification by 'avalanche'	cell width / $\sqrt{12}$	fast response
	Drift Chamber		100 – 300 mm	inexpensive, detailed calibration
Micro-pattern gas	GEM		~100 mm	complicated system
	MicroMegas		~100 mm	can spark
Solid-state	Silicon, diamond	Ion (or hole) drift; no internal amplification	~20 – 50 mm	expensive; large mult. scattering; low noise critical

Detector Purpose

- Tracking chambers
  - trajectory through magnetic field
  - momentum, angle of charged track
- Timing counters
  - determine elapsed time-of-flight
  - path length, momentum à b, mass
- Velocity detectors
  - use ‘Cerenkov’ light for direct b measurement
- Energy deposition
  - ‘calorimetry’ measure energy of neutral particles

Time of Flight test set-up

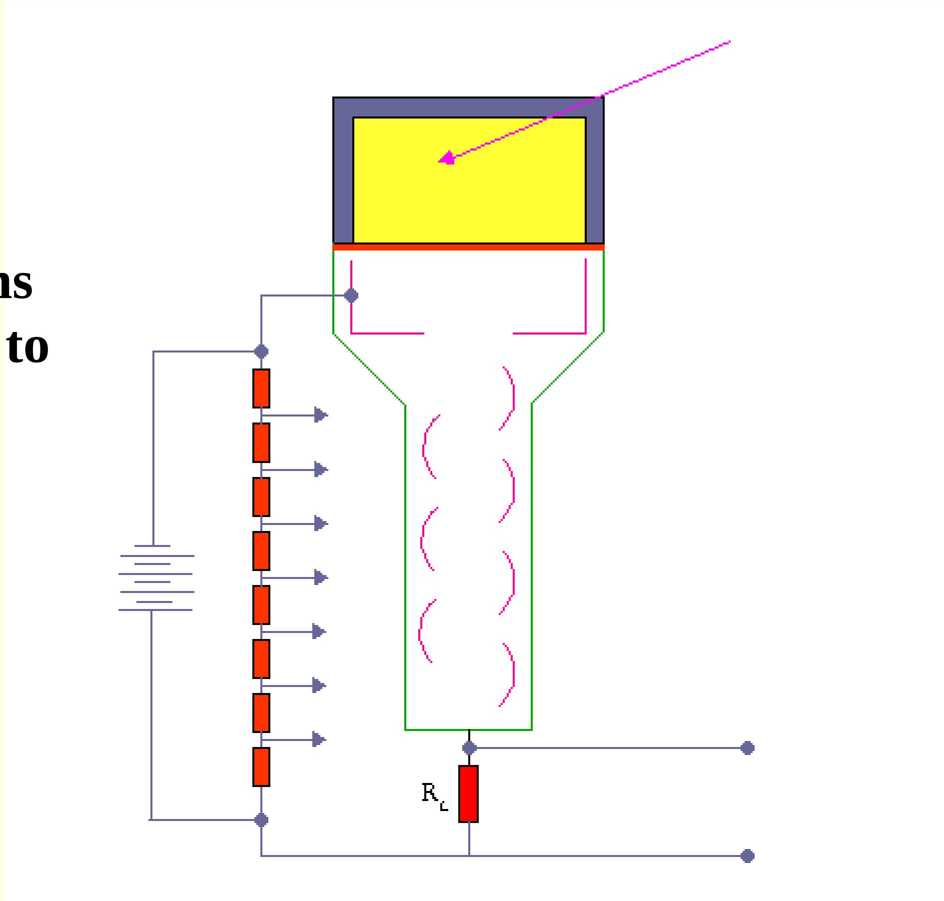


c = 30 cm/ns
v_{scint} = c/n = 20 cm/ns
v_{eff} = 16 cm/ns
v_{pmt} = 0.6 cm/ns
v_{cable} = 20 cm/ns

Resolution depends on:
Scint. quality: amt. of light transparency
Scint. thickness; more light fewer bounces

… how Photo-Multiplier Tubes work

- **photon strikes cathode**
- **releases one or more electrons**
- **electric fields push electrons to first dynode**
- **1 electrons releases 2**
- **go to next dynode**
- **…..**
- $\boldsymbol{gain = 2^n}$



How to Measure Particle Mass?

$$p = m\gamma\beta \quad \rightarrow \quad m = \frac{p}{\gamma\beta}$$

Measure (p) and track length (D)with a tracking chamber

Measure elapsed (time) with a scintillator counter,

$$\beta = {}^{D}/_{time} \;\; ; \;\; \gamma = \sqrt{\frac{1}{1-\beta^2}}$$

$$m = \frac{p}{\gamma\beta}$$

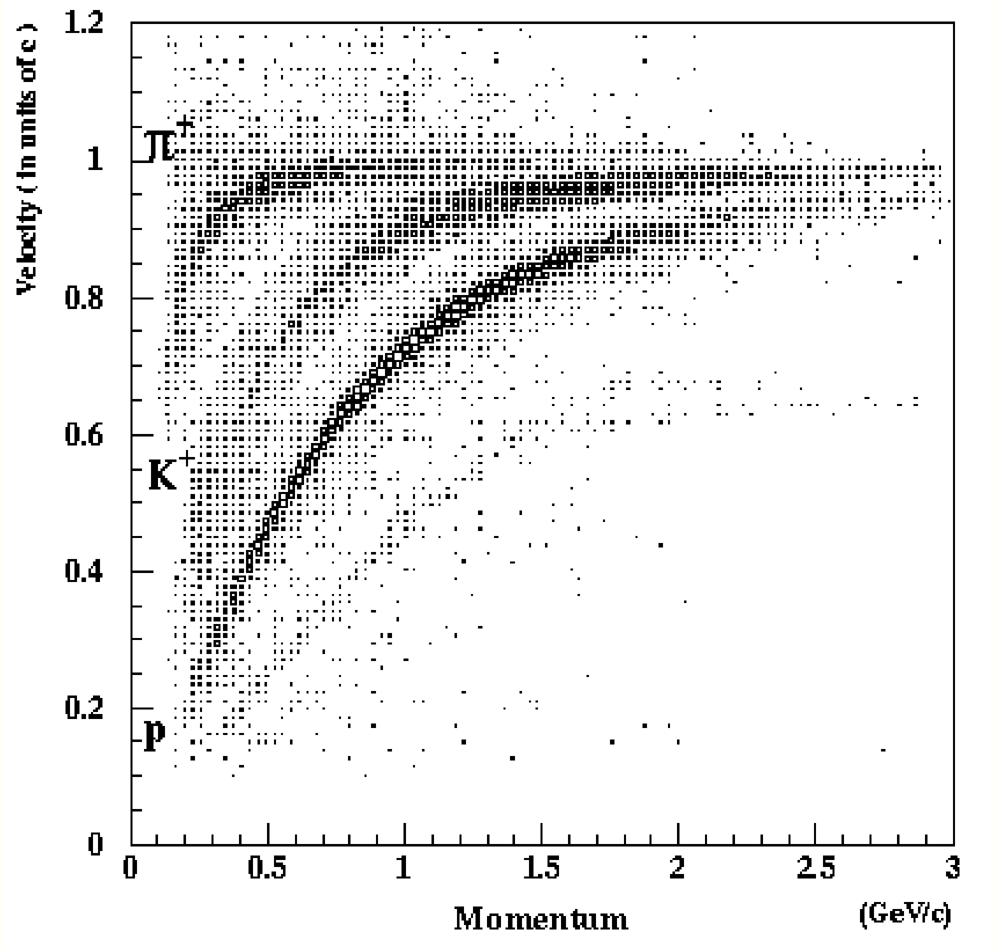
Particle Separation by TOF

Good particle identification

- good time resolution
- long flight-path
- here's an example from the CLAS detector: ~200 ps resolution, ~ 5m path length
- • p/k/P separation to ~2GeV/c

$$p = m\gamma\beta \quad \rightarrow \quad m = \frac{p}{\gamma\beta}$$

$$\left(\frac{\delta m}{m}\right)^2 = \left(\frac{dp}{p}\right)^2 + \gamma^4 \left(\frac{\delta\beta}{\beta}\right)^2$$



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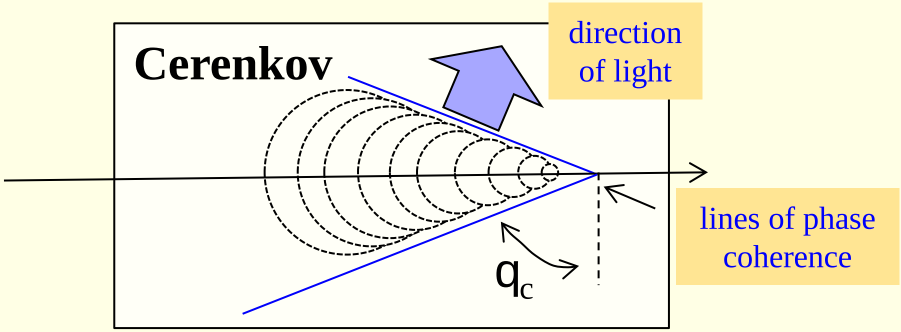
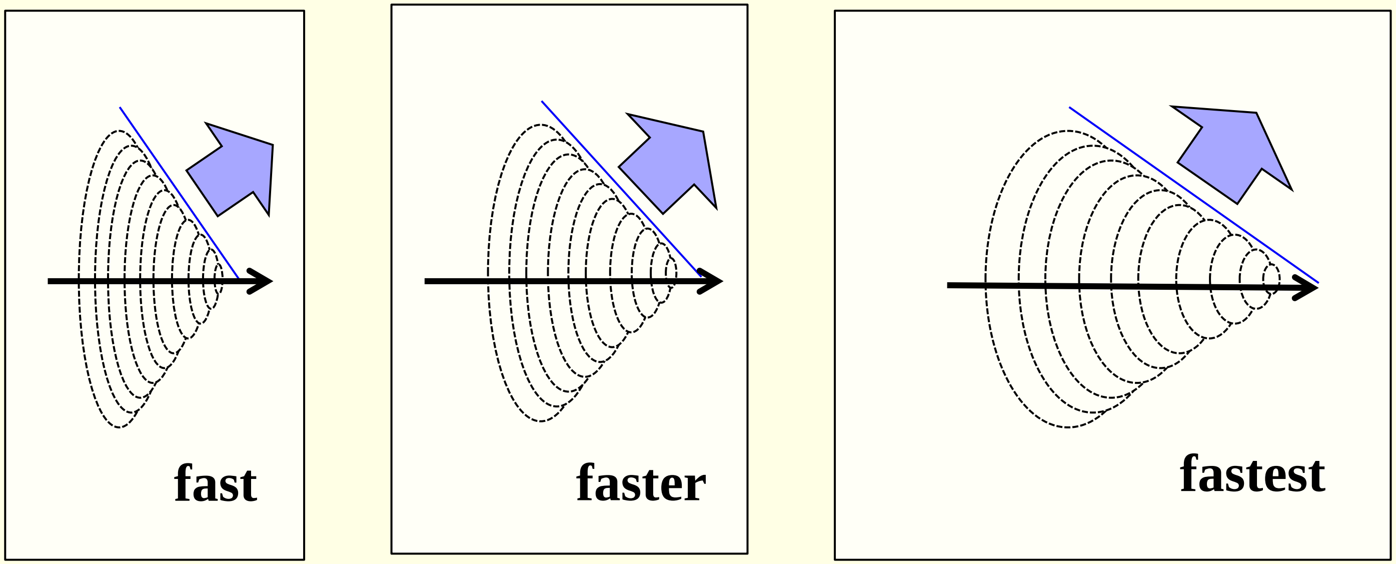
Cerenkov Light Detectors



Pavel Cerenkov
Discoverer of
'Cerenkov' radiation
1958 Nobel Prize

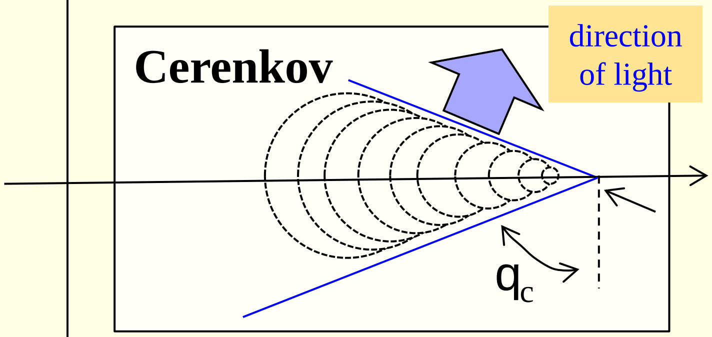
b-dependence: Cerenkov Light

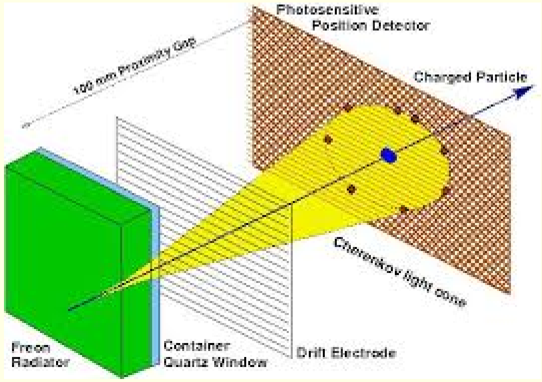


Angle of emission becomes larger
More light emitted; proportional to length of light-front
Measure b-dependence !

Two Kinds of Cerenkov Counters

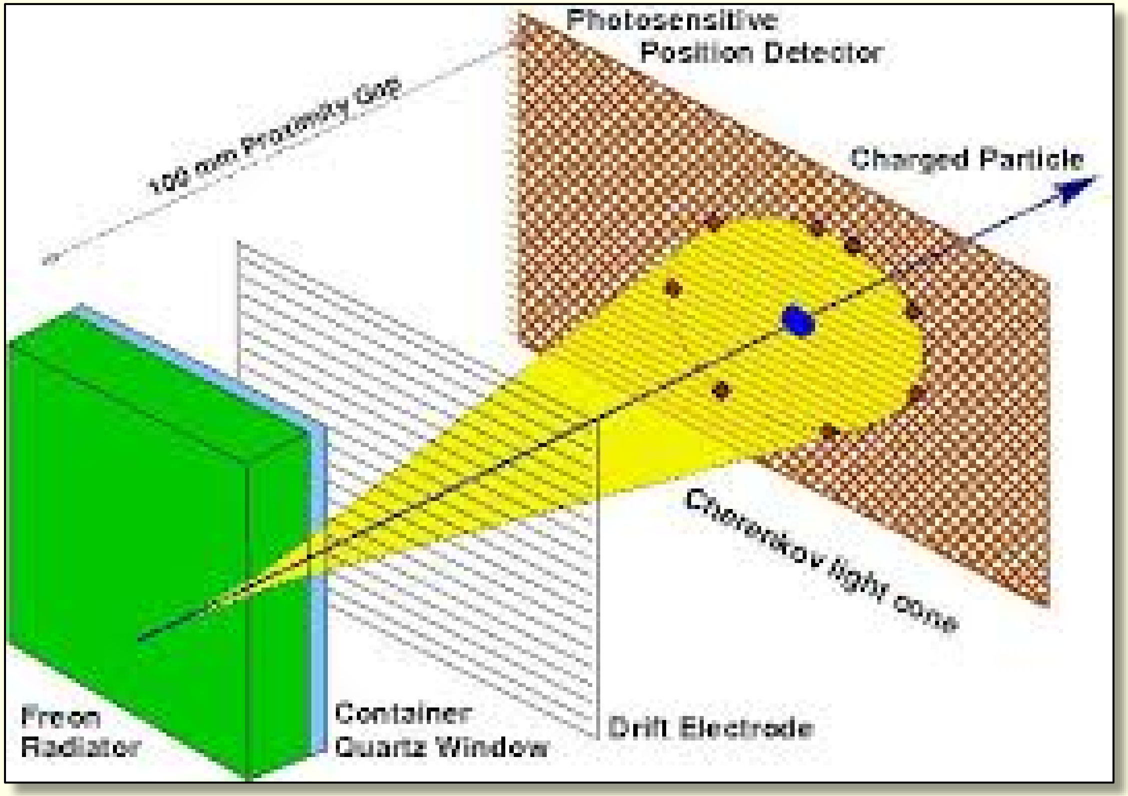
- Threshold counter
  - less massive particle produces light
  - heavier particle above threshold
- “RICH” – Ring Imaging Cherenkov





RICH Detector

Measure circle of photons



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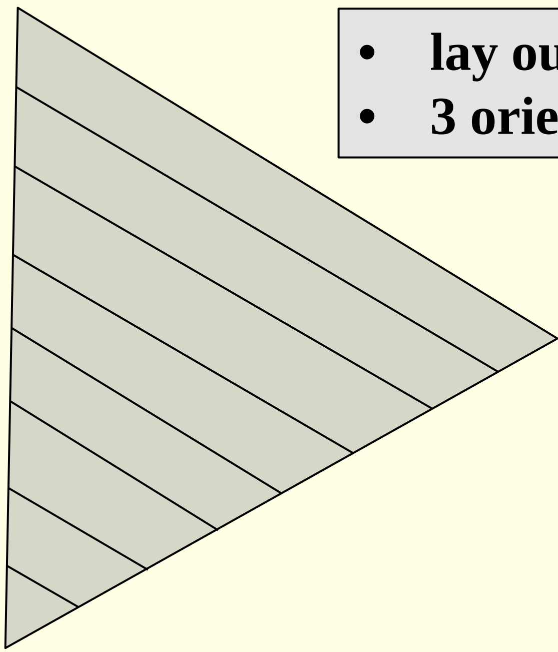
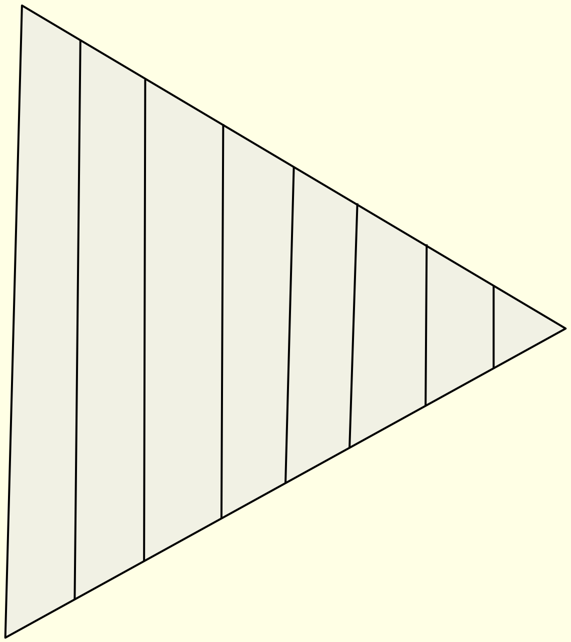
Electromagnetic Calorimeters

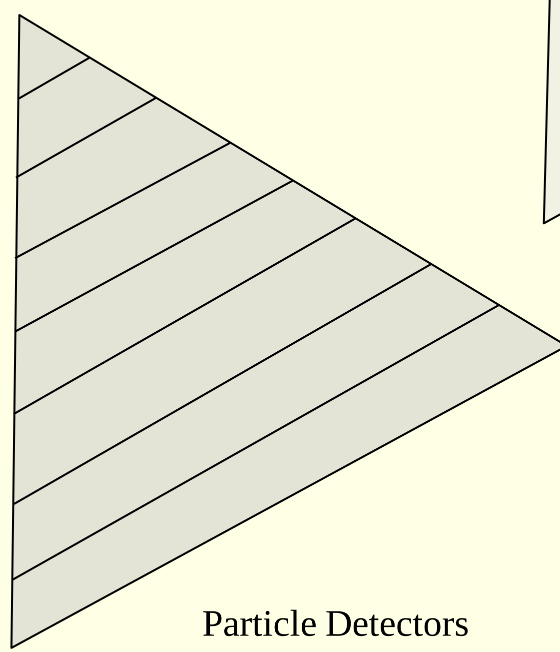
- … also known as `shower counters'
  - entering particles initiate an electromagnetic shower (lead plates)
  - ionization à scintillator or Cerenkov light
  - measure light à energy deposited
- Determine 'cluster' position
- Energy and position of neutral shower

… how to build a shower counter



- **lay out ‘slabs’ of scintillator**
- **3 orientations**

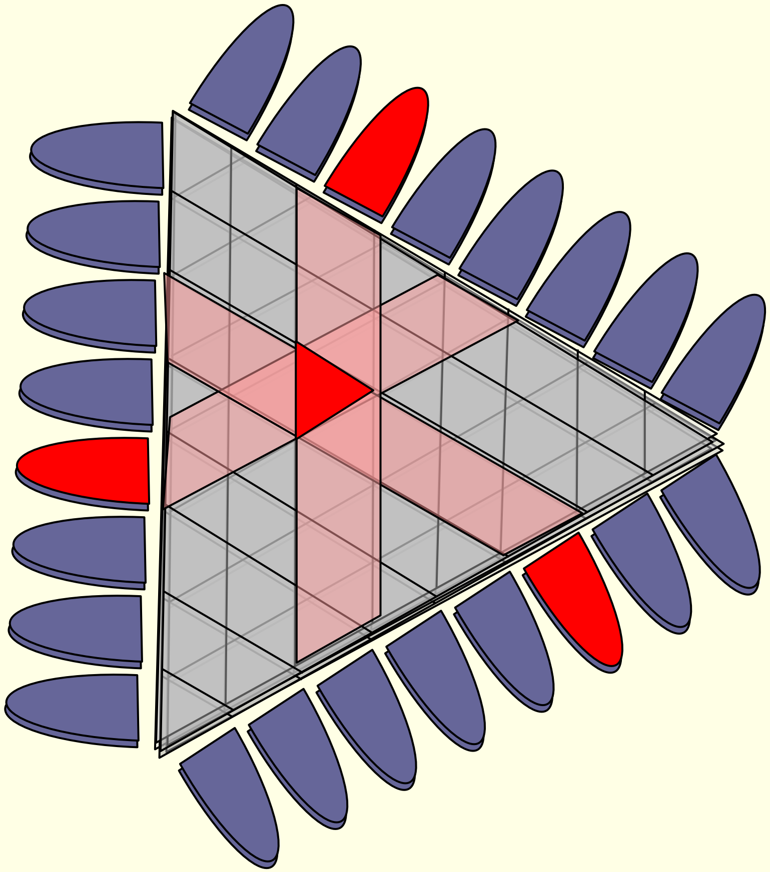




… building a shower counter, cont.

- stack layers of scintillator
- lead sheets interleaved
- add readouts on 3 sides

à cluster position and energy

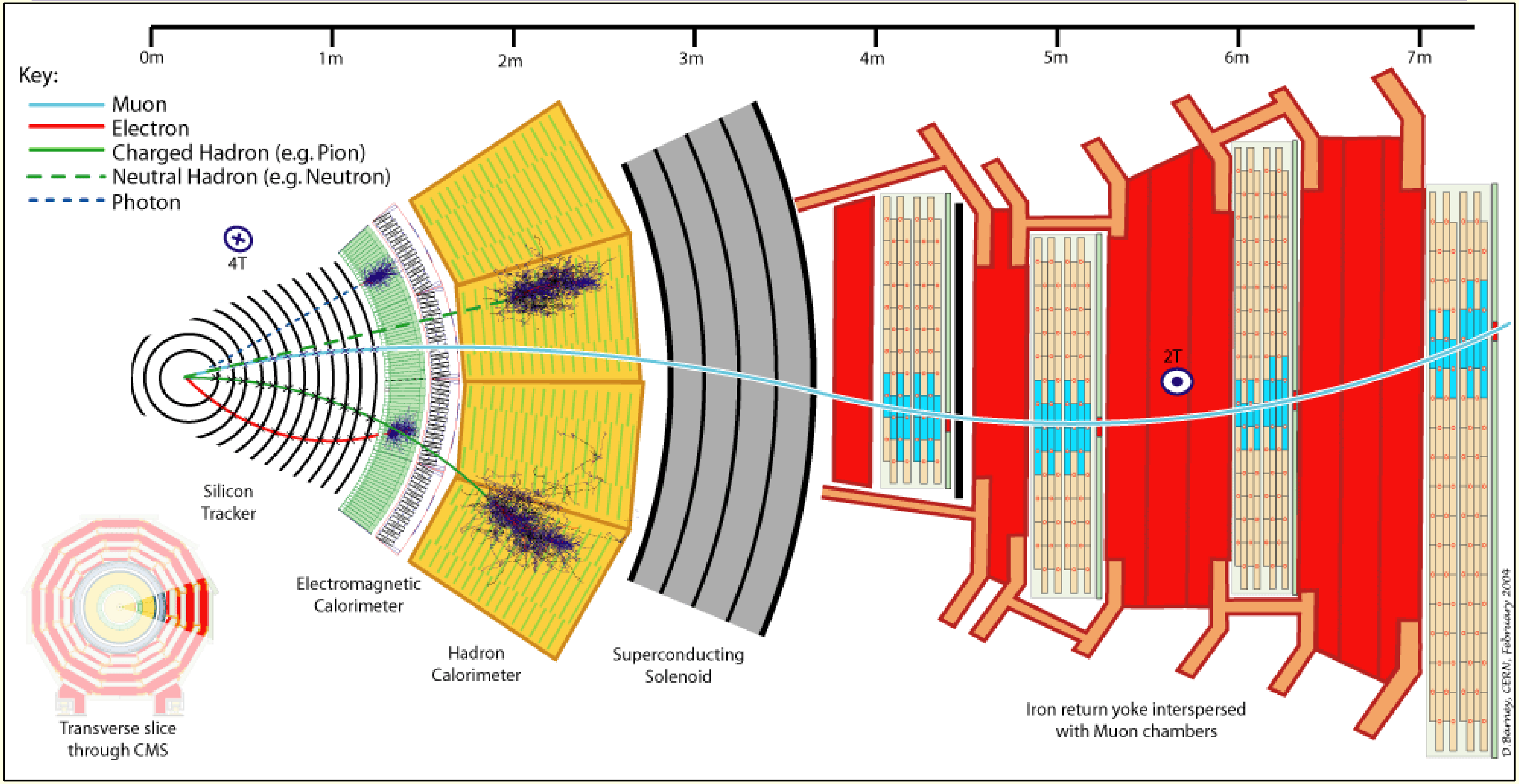


Particle Detectors: a Comparison

Detector Type	Measurement Type	Signal Generation	Remarks
Tracking (gas)	Spatial position	Ionization, gas amplification	Positive ions drift slowly, local "dead time" for wire chamber
Tracking (solid state)	Spatial position	Ionization, charge collection	No internal amplification; good S/N essential
TOF	Flight time	scintillation	More light, less jitter
Cerenkov	Particle velocity	Coherent light emission	Since speed of light is frequency dependent, so is emission angle
Calorimeter	Energy deposition	Shower -> scintillation	"Dead" material can hide fluctuations

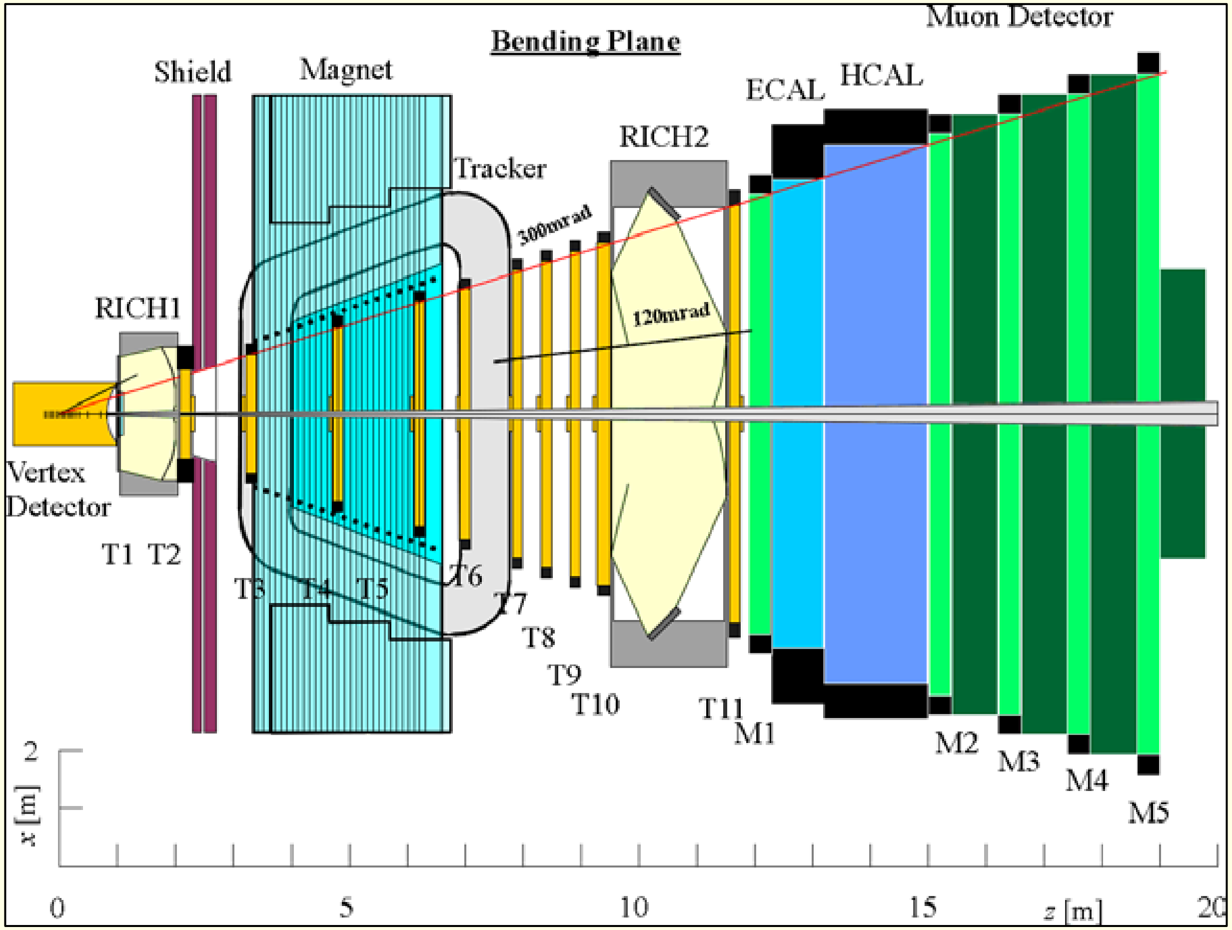
backups

Example: CMS detector

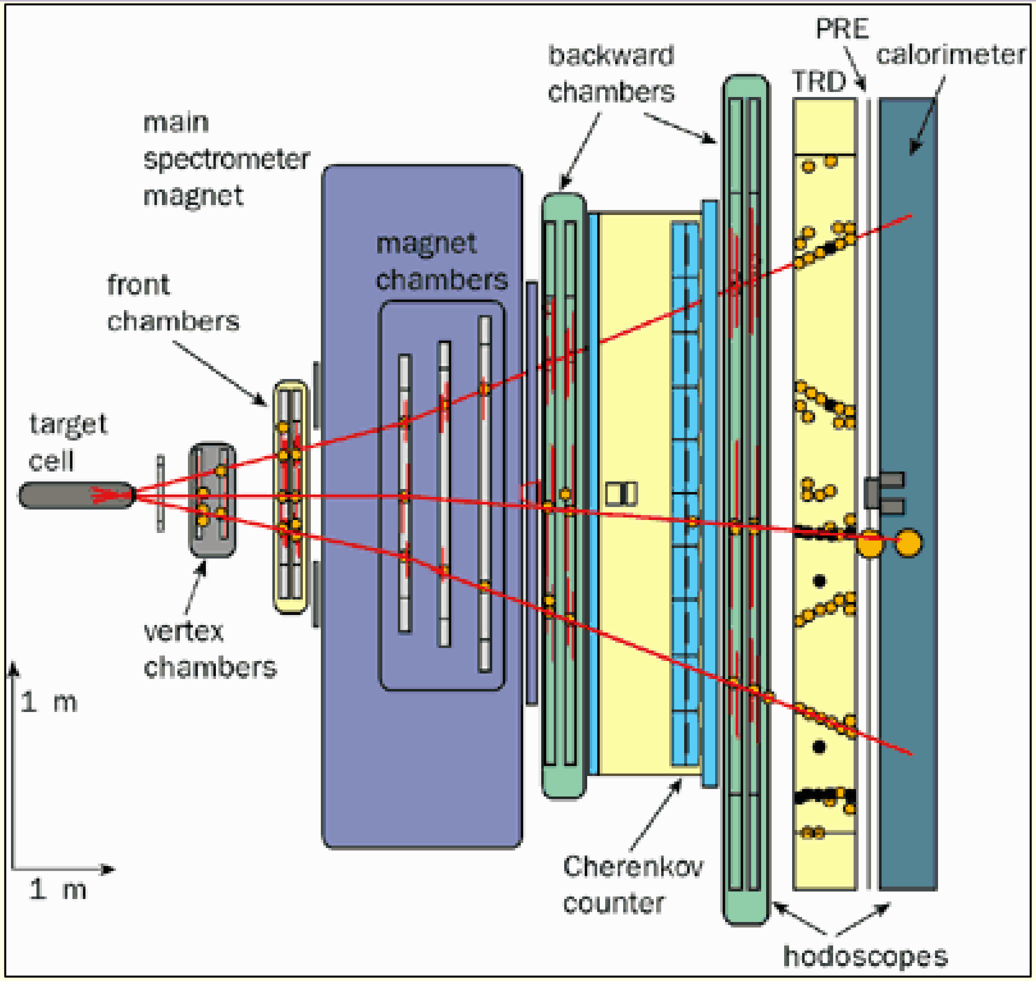


LHCb: beauty physics

asymmetric detector: optimized for detached vertices

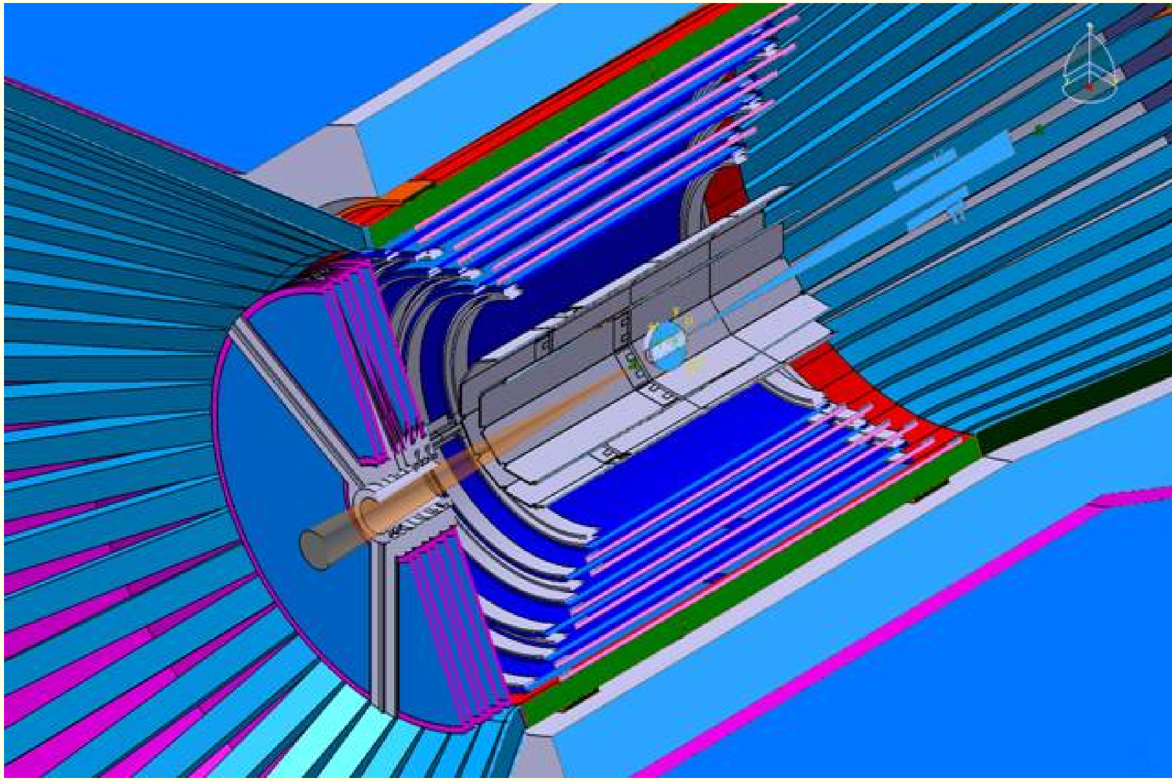


HERMES detector at DESY



CLAS12 Central Detector

- 3 double-layers Silicon
- 3 double-layers MicroMeGas
- 1 layer TOF with double readout
- 3 layers Neutron Detector



examples of tracking, TOF, shower counter

Tracking Detectors: Wire Chambers

What is the purpose?

- to measure particle trajectories to determine the momentum

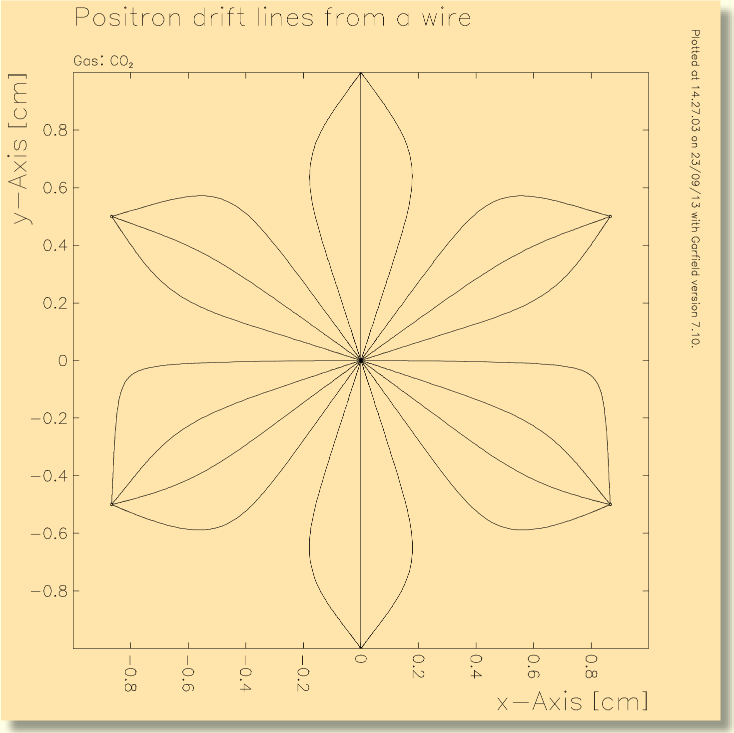
What is measured?

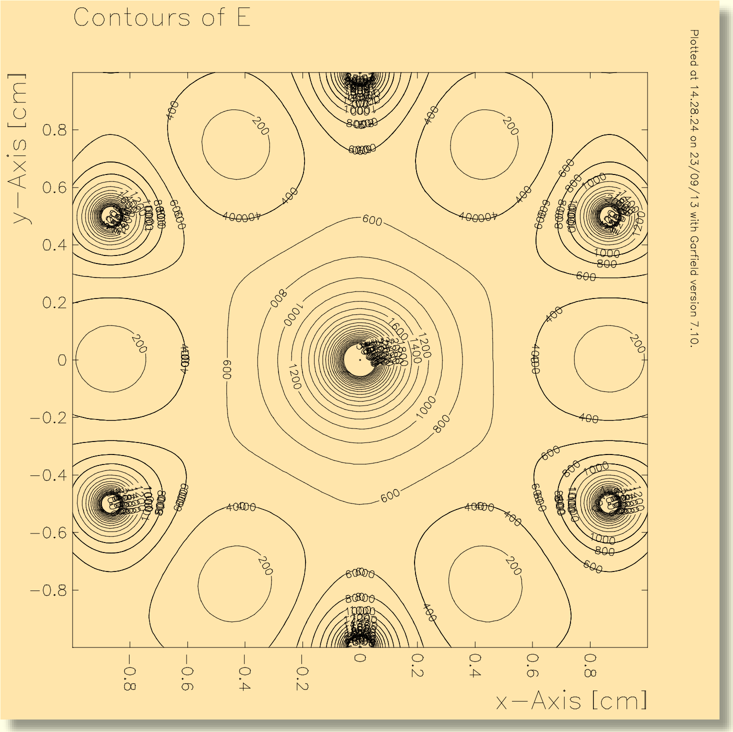
- spatial positions along a trajectory

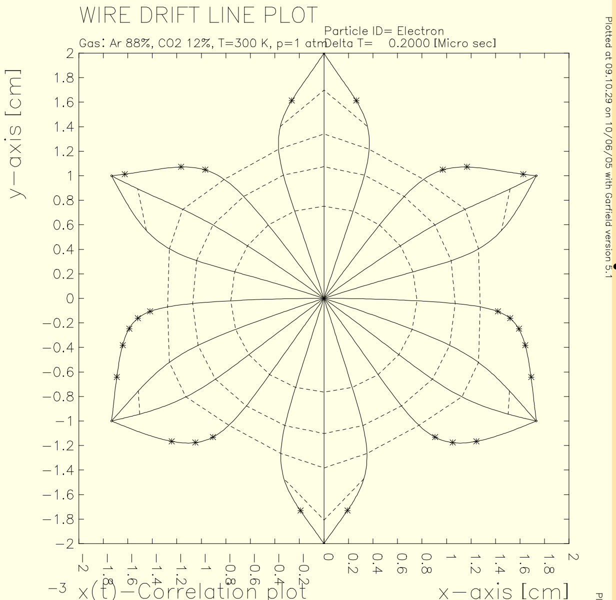
What provides the primary signal?

- ionization of gas molecules

Electric Field Pattern & Strength







Drift Velocity Calculation

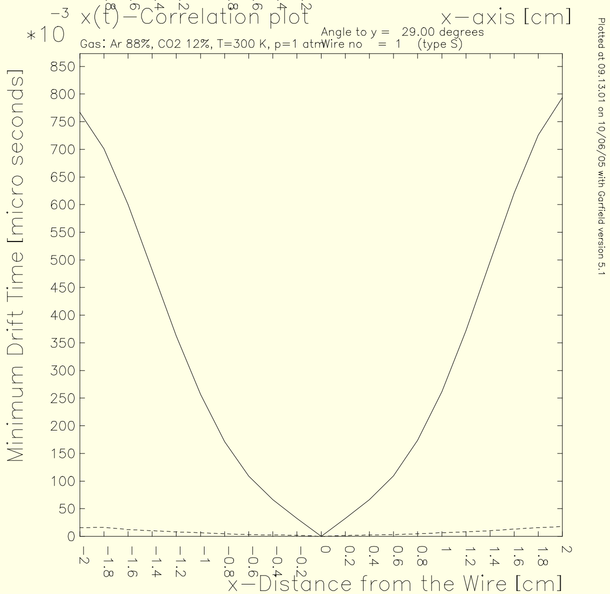
20 mm wire
2325 V
88:12 AR:CO_2

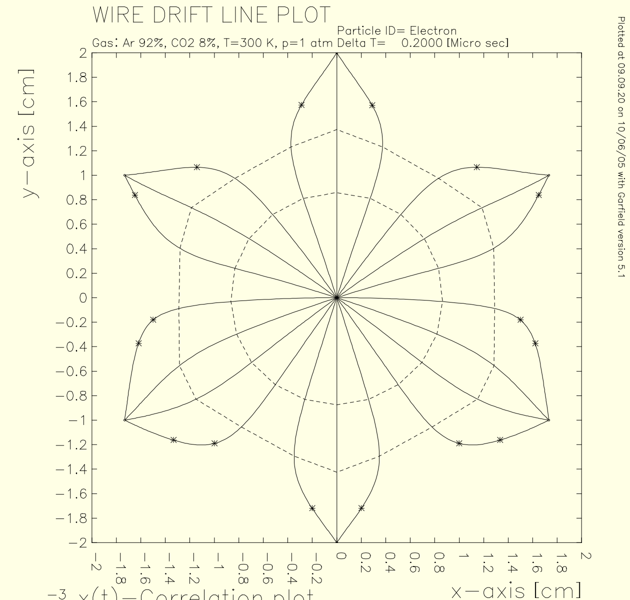
30 mm wire
2550 V
92:08 AR:CO_2

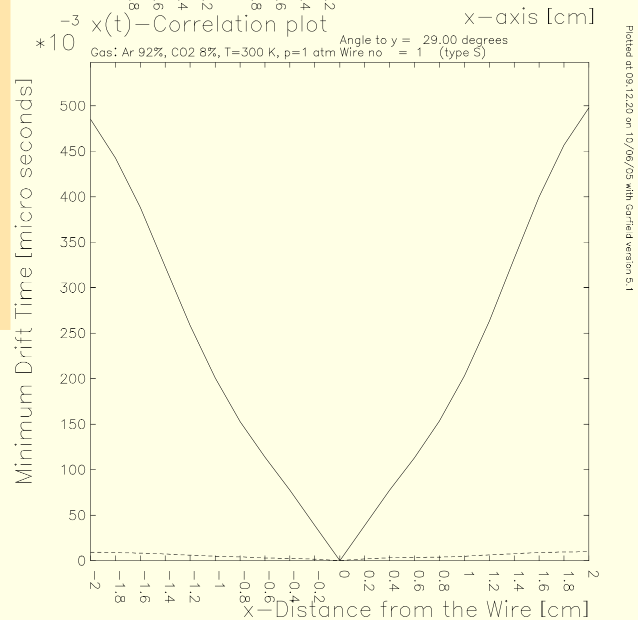
← same gain →

58% faster ⇉

- and more linear !

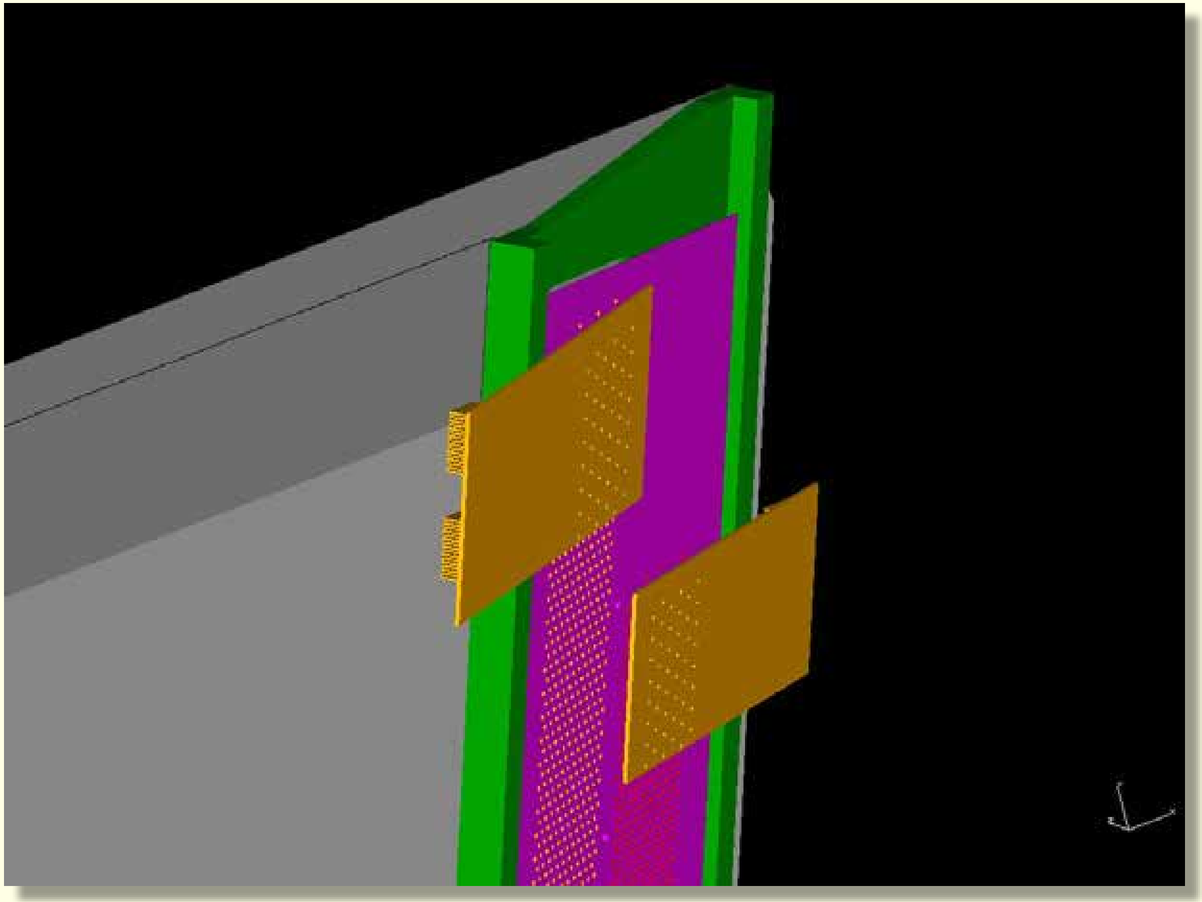




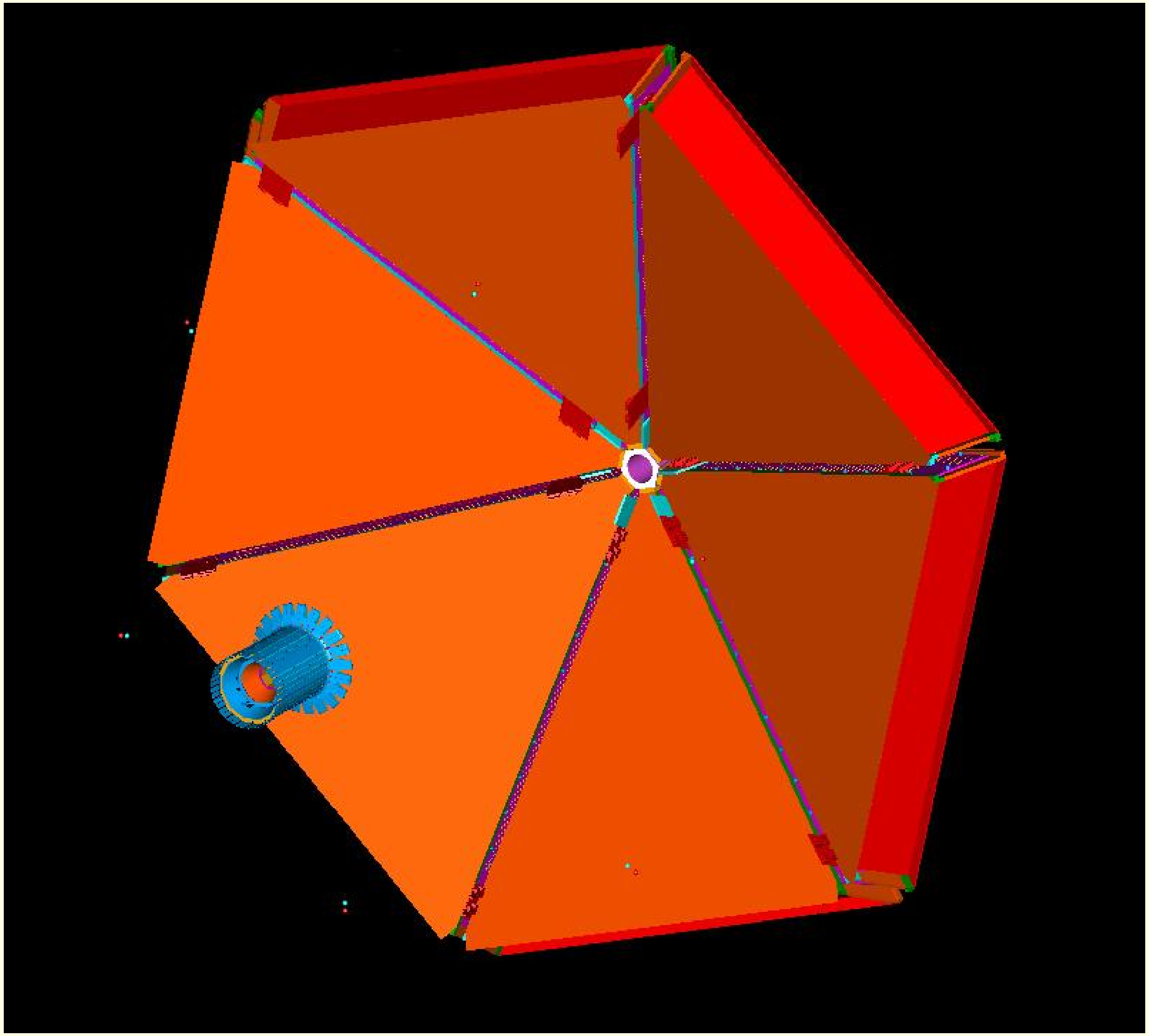


Small 'aspect ratio' for electronics

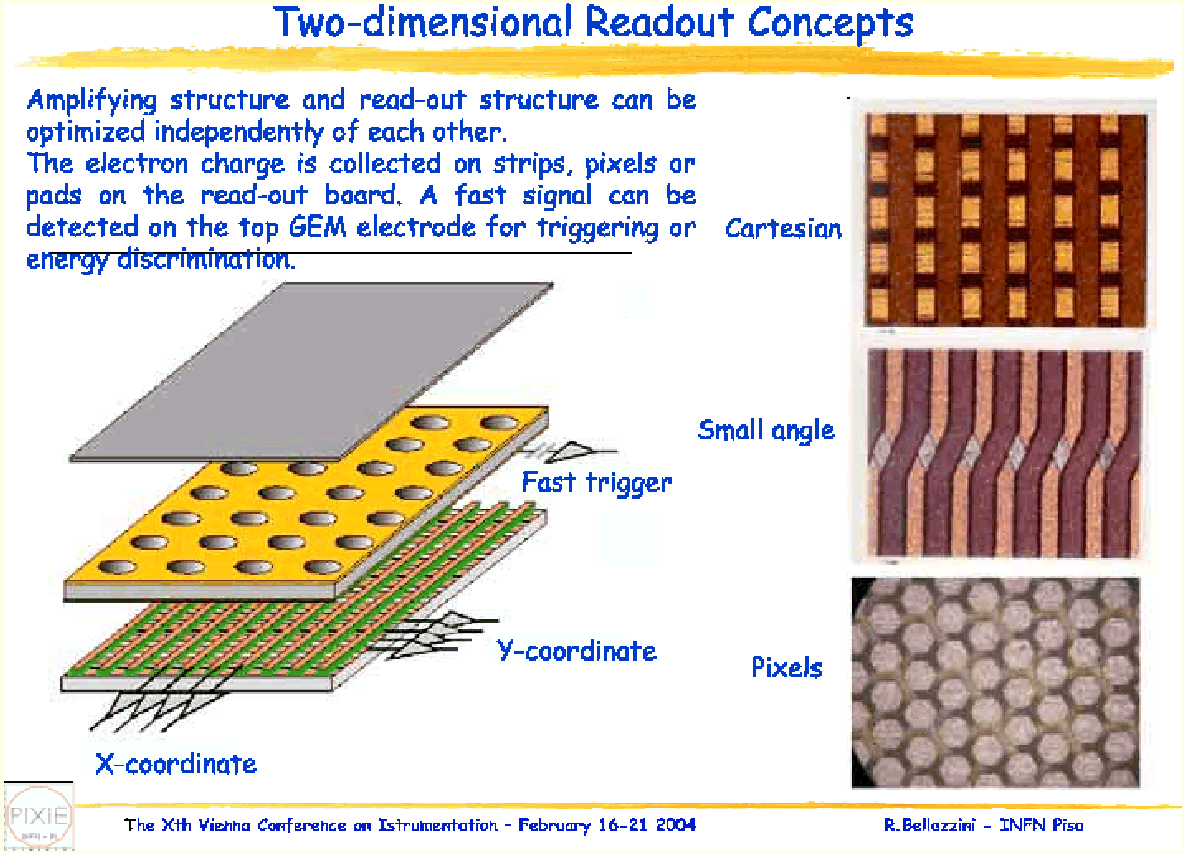
Mechanical issues important: attachments, survey holes, gas lines, cables, electronics boards



Designers have the coolest drawing packages:
here we see a tricky docking maneuver between our vertex tracker and our first collection of drift chambers



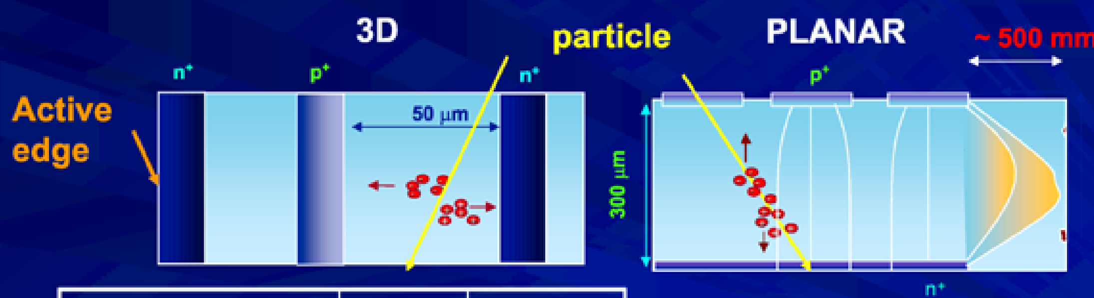
Monolithic pixel detectors



Other Types of Silicon Trackers

3-D sensors

- Combine **VLSI** and **MEMS** (Micro Electro Mechanical Systems) technology.
- **Electrodes** processed inside the bulk instead then implanted on surface.
- **The edge** could become electrode! Dead volume at the Edge < 10 microns!



	3D	Planar
Q collection path	50μm	300 μm
$V_{depletion}$	<10V	70 V
Edge sensitivity	10μm	500 μm
Q Collection time	1-2 ns	10-20 ns

Proposed by Parker, Kenney1995

- NIMA 395 (1997) 328
- IEEE TNS 46 4 (1999) 1224
- IEEE TNS 48 2 (2001) 189
- IEEE TNS 48 6 (2001) 2405
- IEEE TNS 48 5 (2001) 1629
- CERN Courier, Vol 43, Number 1, Jan 2003

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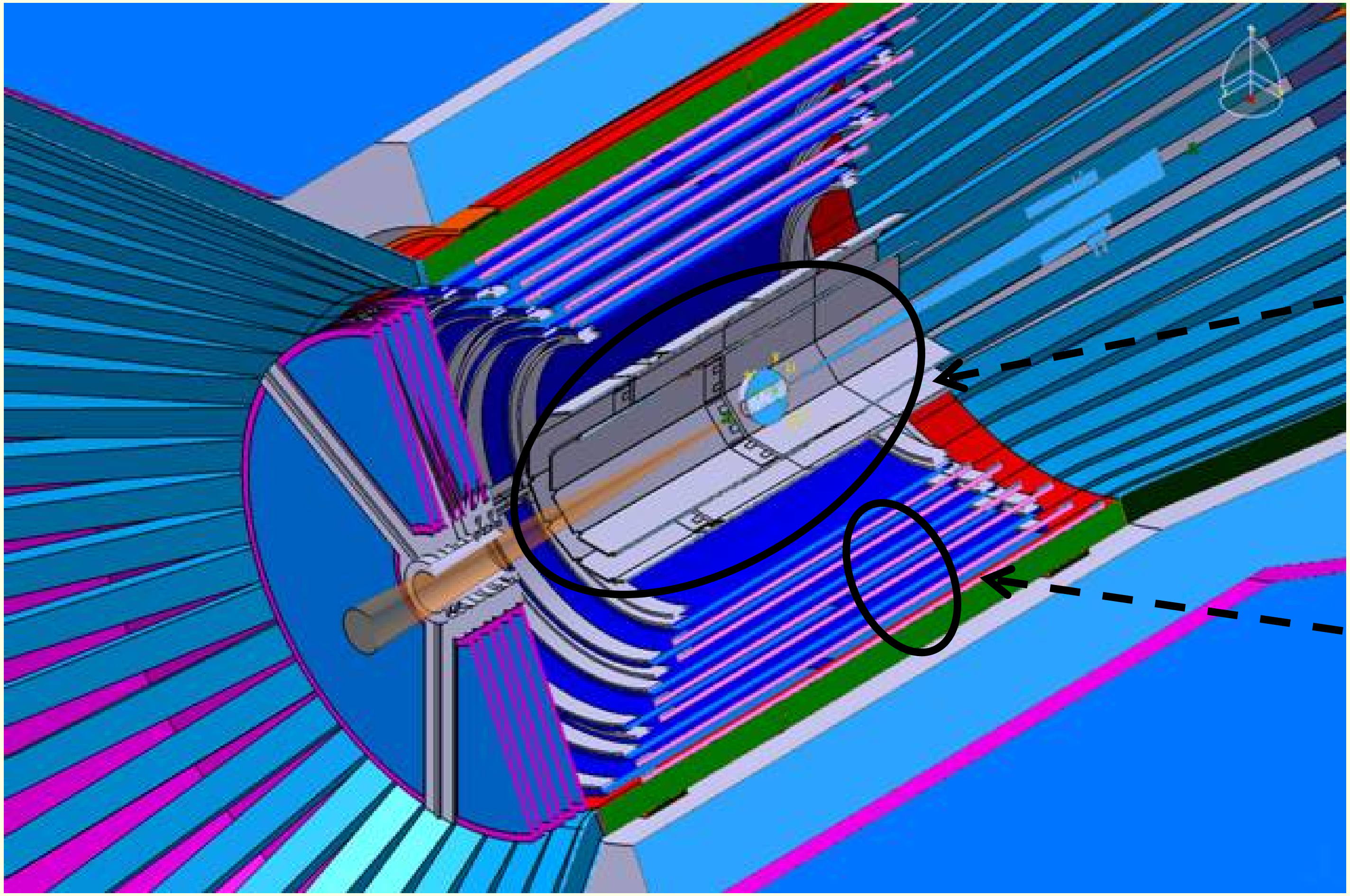
Optimizing Resolution



Silicon close to beam line with small-angle stereo

Micromegas at larger radius with 90^0 stereo readout

Tracking Technology

Advantages / Disadvantages	
Wire Chambers	**Spatial resolution: ~300 microns** **Low mass – low multiple scattering** **Inexpensive for large area coverage** **Sensitive to magnetic fields, hard to calibrate**
Micro-Pattern Gas (GEM, Micromegas)	**Better resolution; ~ 50 – 100 microns** **Low mass – low multiples scattering** **Many output channels → fairly expensive** **Sensitive to magnetic fields**
Silicon Detectors	**Good resolution; ~ 10 – 50 microns** **High multiple scattering – low-momentum** **Expensive for large areal coverage** **Needs careful attention to electronic noise**

Energy deposited in scintillator