Particle Detectors

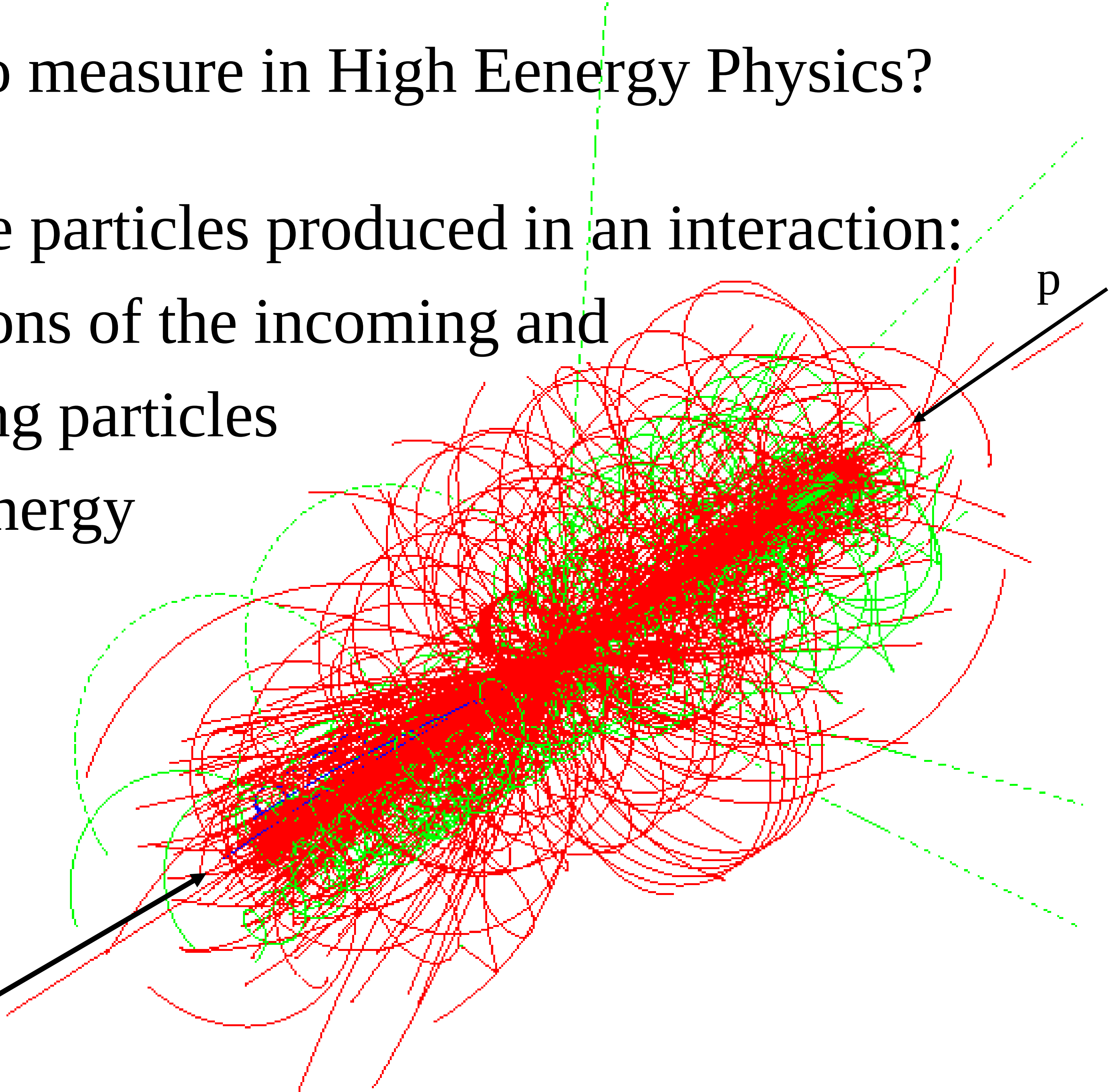
Razmik Mirzoyan

Max-Planck-Institute for Physics, Munich, Germany
National Academy of Sciences of Republic Armenia

What to measure in High Eenergy Physics?

For all the particles produced in an interaction:

- Directions of the incoming and outgoing particles
- Their energy
- Charge
- Type
- Timing



How to measure a radiation

- To measure radiation one needs to find out
  - **Type of radiation**
  - **Its losses in an assumed detector (will we get a signal, is it above the existing noise?)**
  - **Energy** : How much, in which form ?
  - **Interaction type and the** profile in time
  - **Position** : Interaction point, depth
- The ability of a particular instrument to measure the incident radiation can be measured by its
- **Efficiency** : of the detector we choose

Different types of radiation detectors

- Radiation detectors can be made on the basis of different materials
  - **Gas** : Gas filled detectors such as ionisation chambers, proportional counters and Geiger Muller (GM) tubes utilise a gas as the detection medium.
  - The above also includes the air in the atmosphere.
  - **Scintillation detectors** : Utilise either a liquid or solid state scintillator as the detection medium.
  - **Semiconductor detectors** : An elemental or compound semiconductor crystal is used as the detection medium.
- Every type has its own advantages
- A composite approach can often provide much more information about a radiation source.

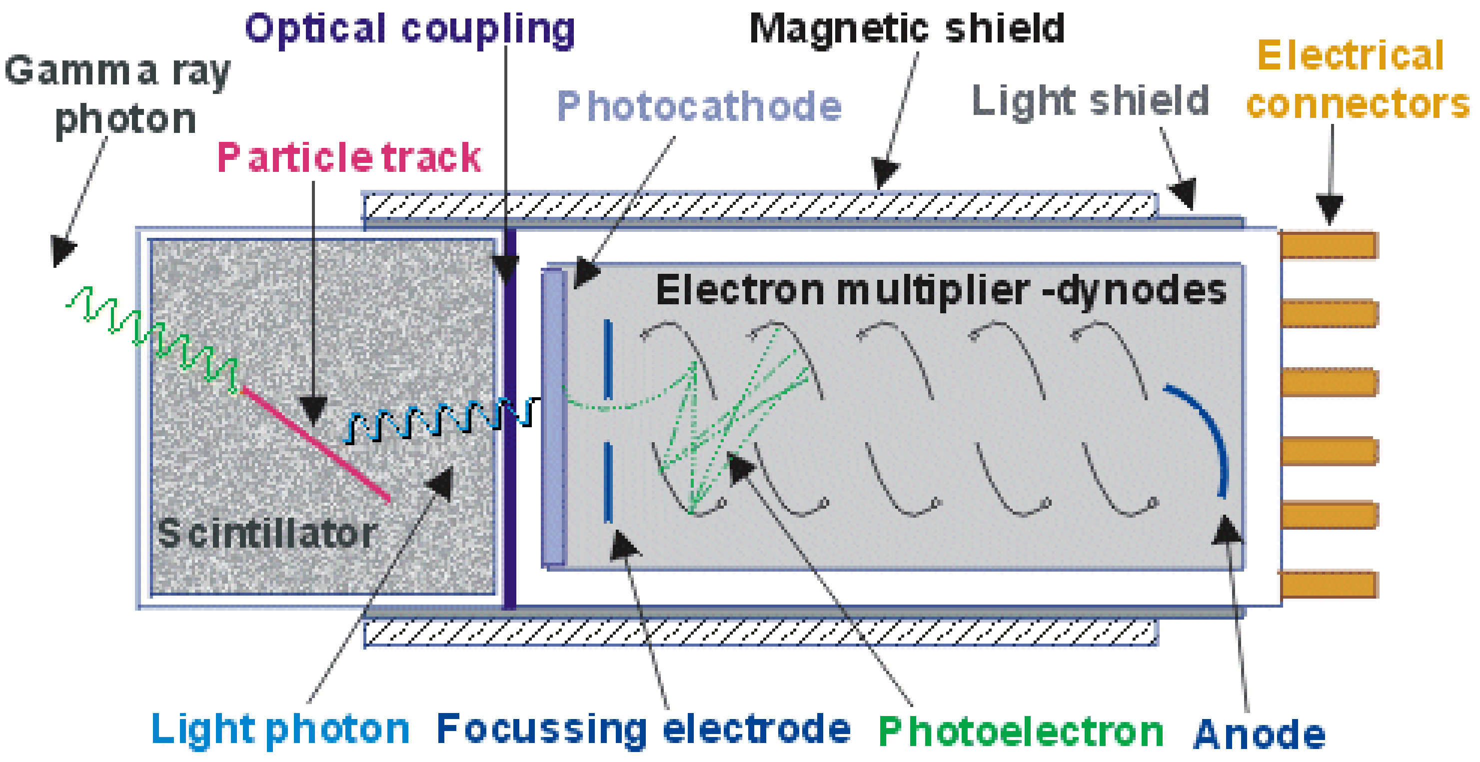
Gas detectors

- Gas detectors in general offer the following:
  - Poor energy resolution
  - Time resolution
  - Excellent position resolution (MWPC)
  - Low Efficiency:
    - Large volume possible
    - Low density/Z – very low stopping power

Solid state detectors

- The use of a solid state detection medium is used in many radiation detection applications.
- For the measurement of high-energy electrons or gamma-rays detector dimensions can be kept much smaller than equivalent gas filled detectors because solid densities are some 1000 times greater than that for a gas.
- **Scintillation detectors** offer:
    - Average energy resolution.
    - Good/very good time resolution (sub ns)
    - Reasonable position resolution (~mm)
    - High efficiency

Scintillation detectors



The energy required to produce one information carrier is of the order of 100eV, the number of carriers created in a typical interaction is usually no more than a few thousand → statistical fluctuations → poor energy resolution.

A dream detector

Should respond to all types of particles, providing:

- particle identification
- measurement of energy/momentum
- measurement of trajectory (direction/origin)
- cover the full 4π solid angle
- time response

in addition:

- provide short dead-time (allow for high rate)
- wide dynamic range
- high radiation hardness
- long-time operation

As a rule, a real detector is a compromise

Ideal domestic animal -
Eierliegende Wollmilchsau

Different particle detection techniques

Particle can interact with matter by producing:

- Ionisation of atoms
- Bremsstrahlung and photon conversions
- Inelastic nuclear interactions
- Cherenkov or transition radiation
- Emission of scintillation or fluorescence light

How can we “visualise” these processes?

- By taking snapshots
- By collection of induced by ionisation charge
- By detecting of photons

Detection technique: Photography

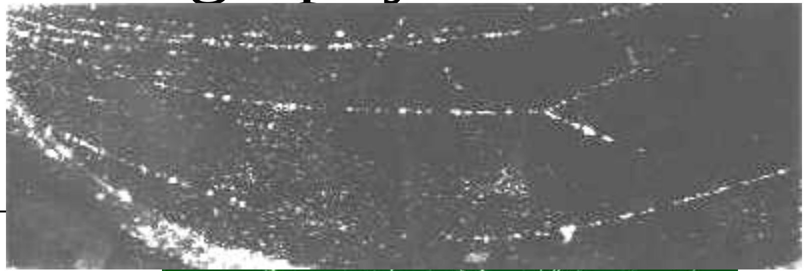
Charged particles ionise atoms along their trajectory.

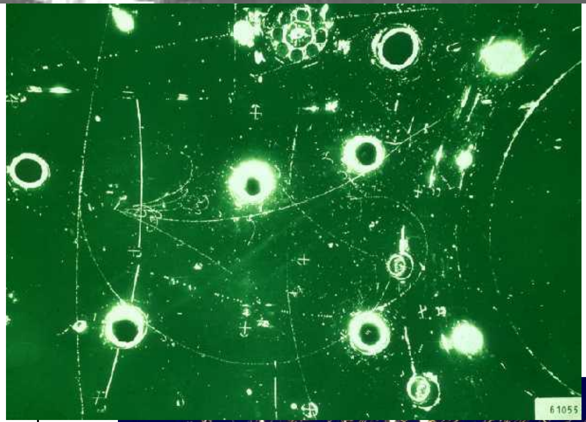
(I) Ions act as seeds for:

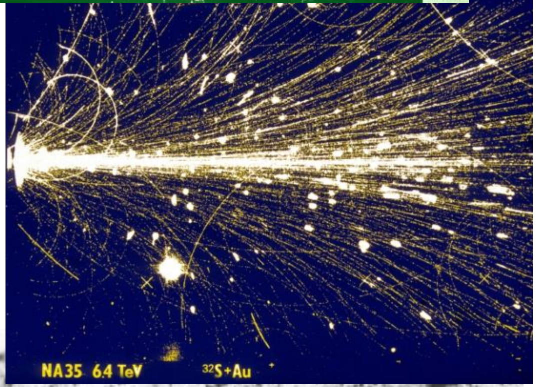
- condensation in super saturated gas (Wilson chamber)

- bubble-formation in super-heated liquid

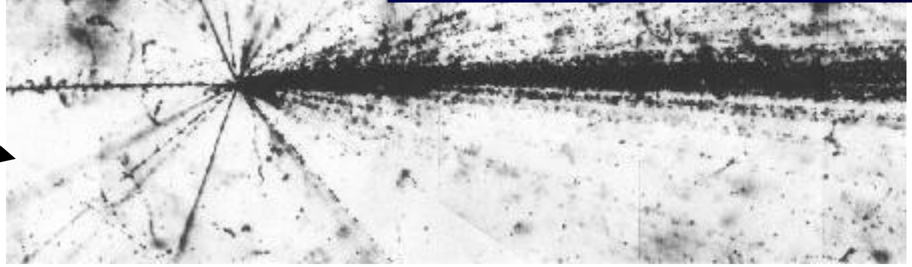
- electrical discharge or plasma formation







(II) Ionisation can also be made visible chemically in emulsion targets



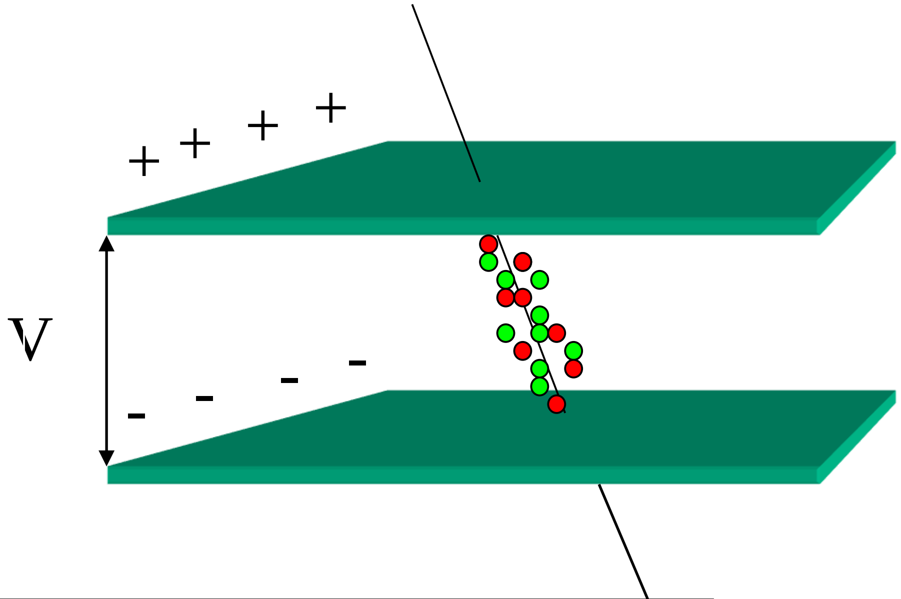
Detection technique: Collect electrical charge

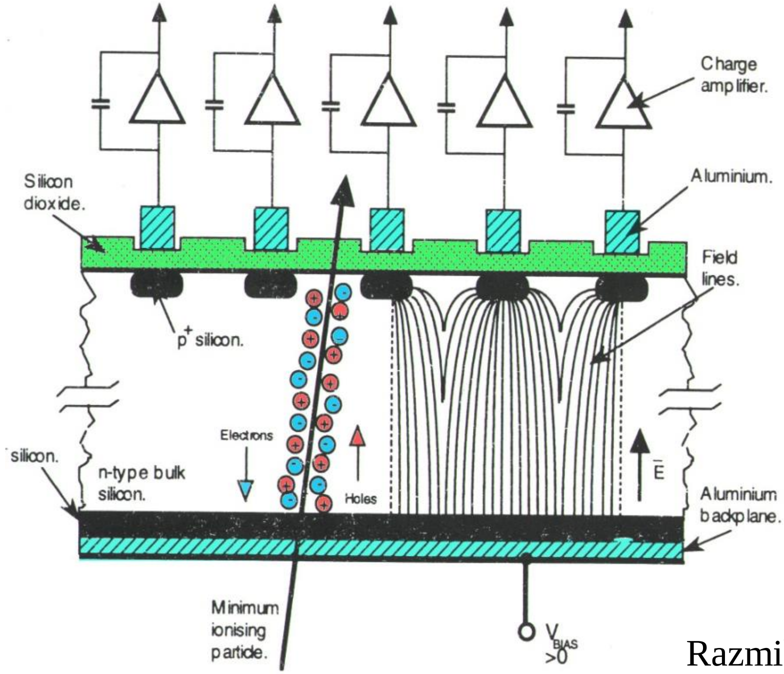
Particle causes ionisation in a material.

Charge is separated/collected by an electric field.

Requirement on material:

- no/few free charge carriers (non-conducting)
- mechanism for transport of charge





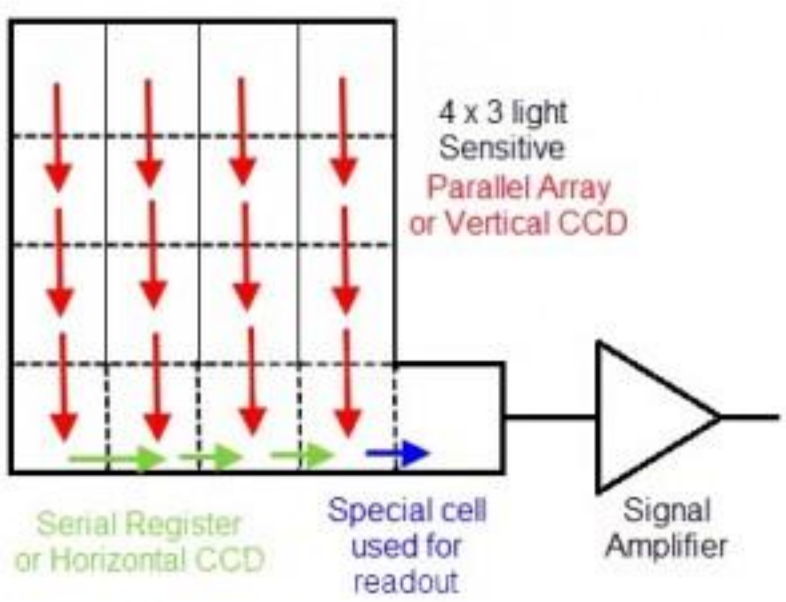
<u>Proportional chambers, Drift chambers, ..</u>

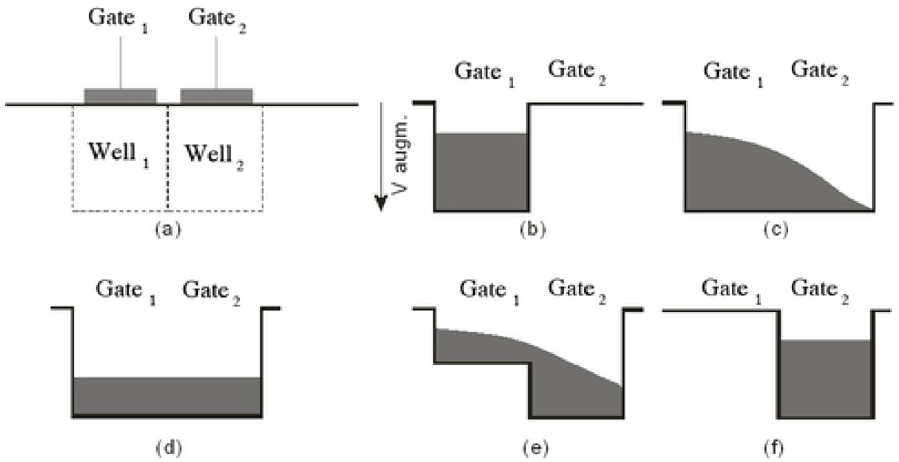
Insulating gas/liquid between anode and cathode (transport through drift). Sometimes also low conductivity solids.

<u>Silicon strip detectors, CCDs, ..</u>

Using a semi-conducting material: Mostly in the form of a reverse-biased pn-junction diode.

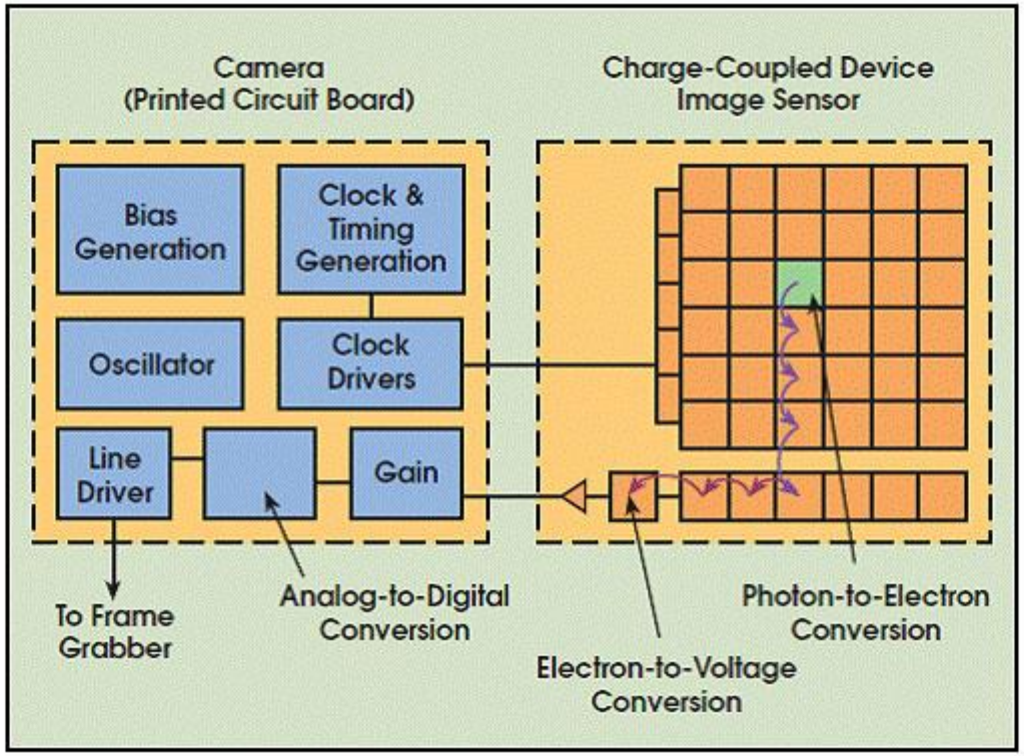
How Functions a Charge Coupled Device (CCD)



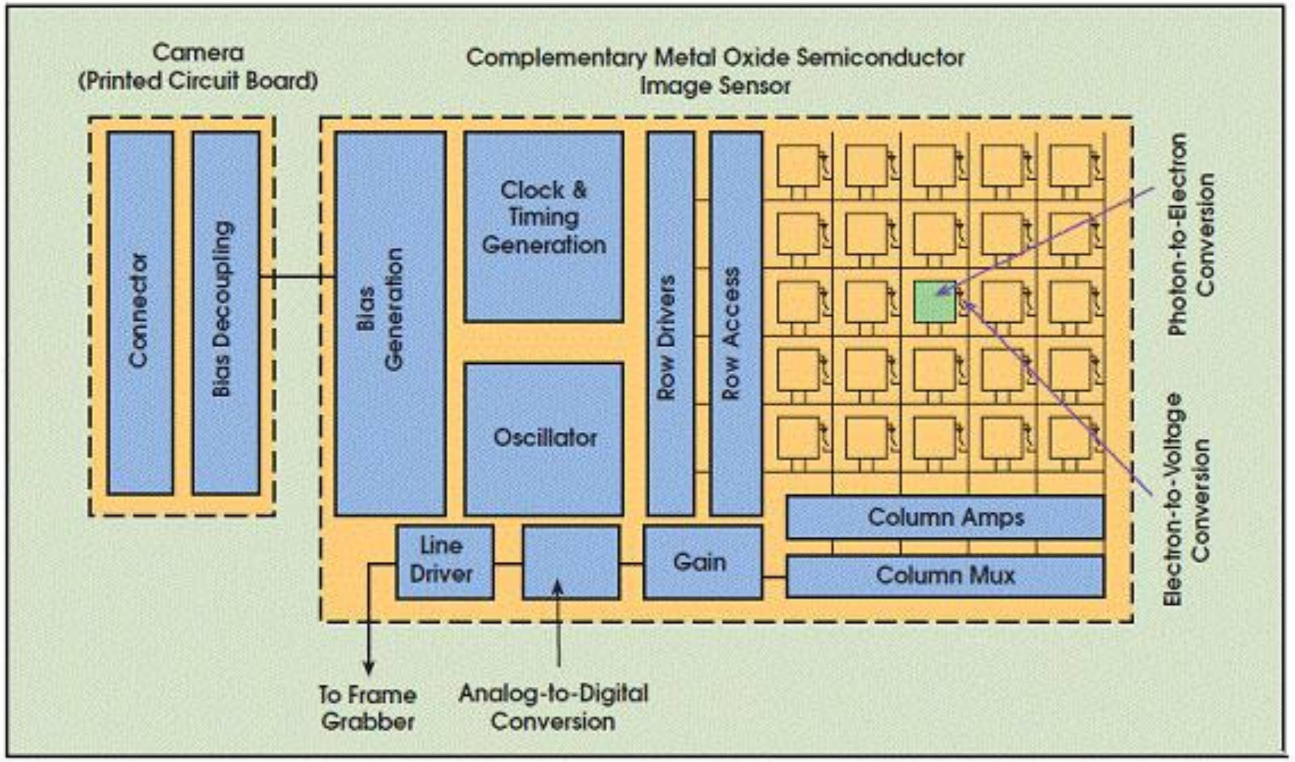


CCD versus CMOS sensor (these are what you have in your pocket, in your mobile phone)

CCD



CMOS



Detection technique: Photo-detection

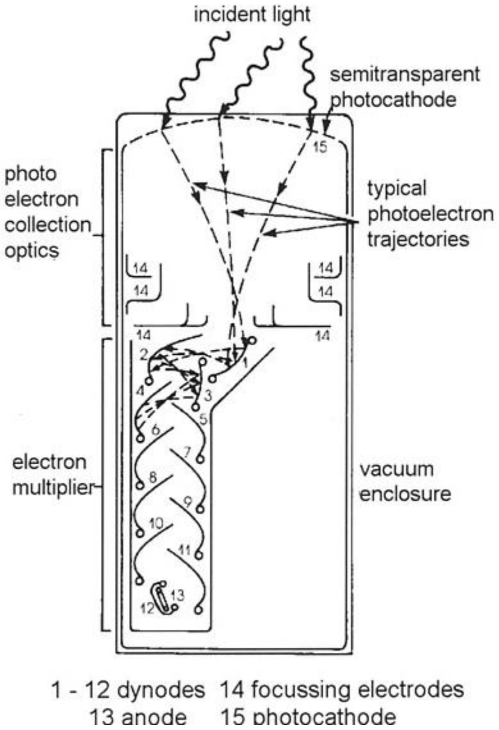
Charged particles can produce photons via scintillation, Cherenkov or transition-radiation effects. One can detect these by using:

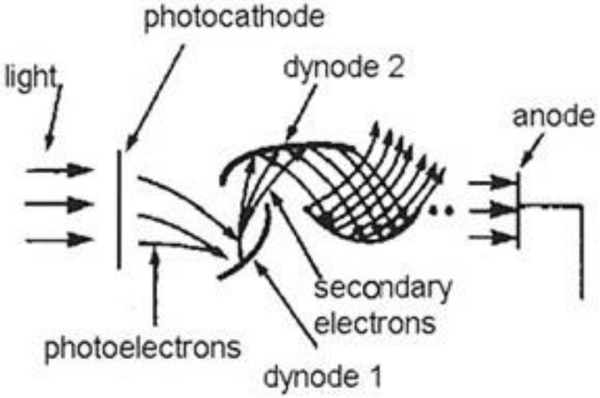
Photo-Multiplier Tube (PMT):

Electrons from photo-electric effect

“Electron multiplier” provides charge cascade

Very sensitive vacuum device

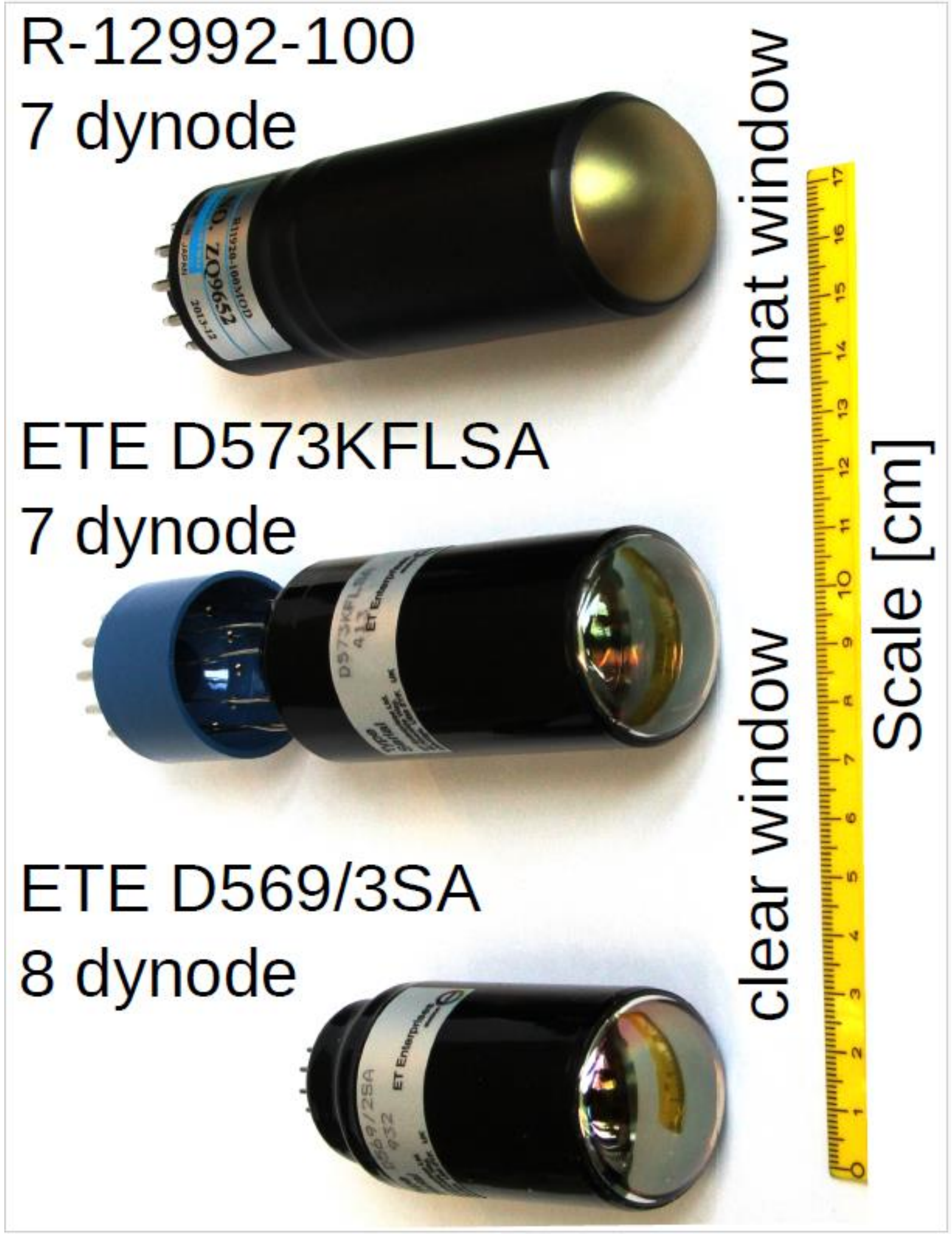




Hamamatsu

Semi-conductor devices:

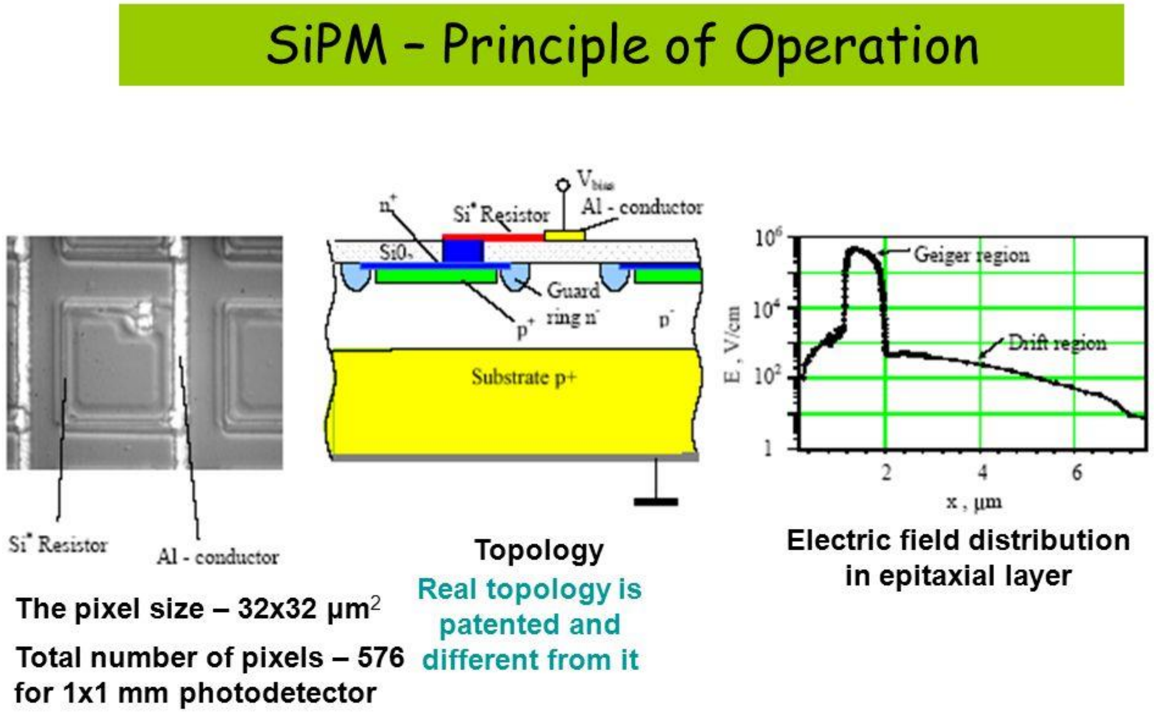
Photo-diodes or CCD’s



- Classical bialkali PMTs developed by us together with Electron Tubes (Great Britain) and Hamamatsu (Japan)

- The PMT on the top is currently worldwide the best

Silicon Photo Multiplier (SiPM)



SiPM – Principle of Operation

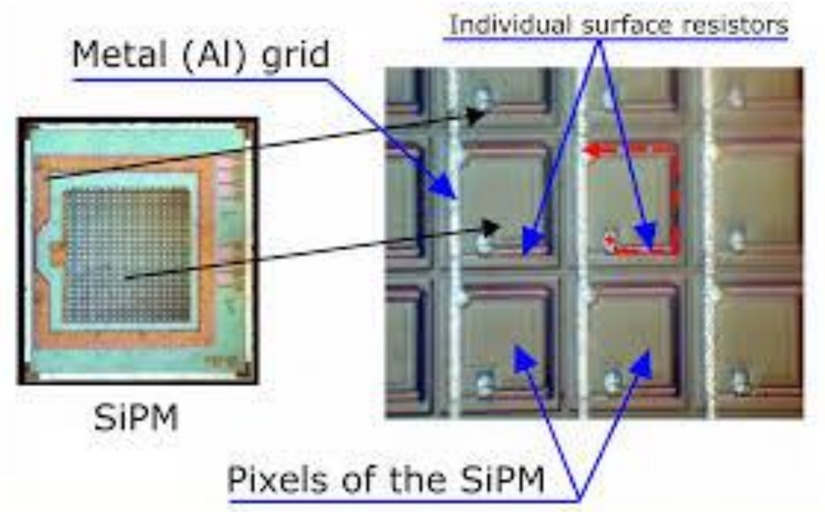
Topology

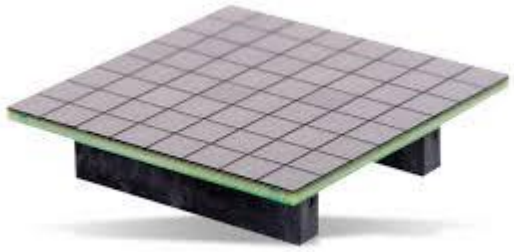
Real topology is patented and different from it

Electric field distribution in epitaxial layer

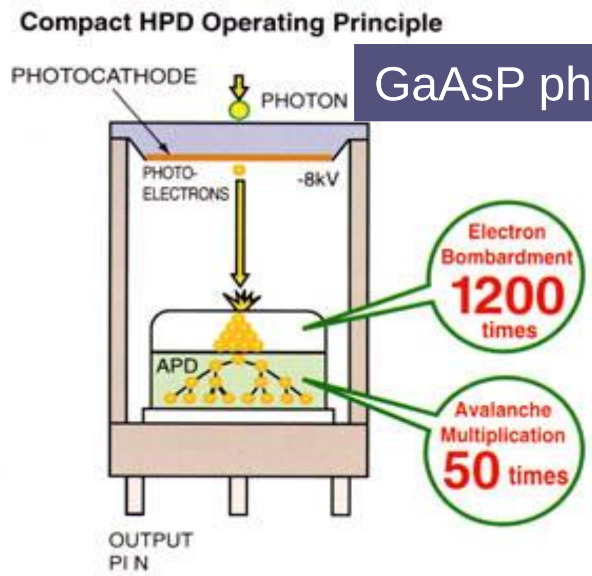
The pixel size – 32x32 μm^2

Total number of pixels – 576 for 1x1 mm photodetector

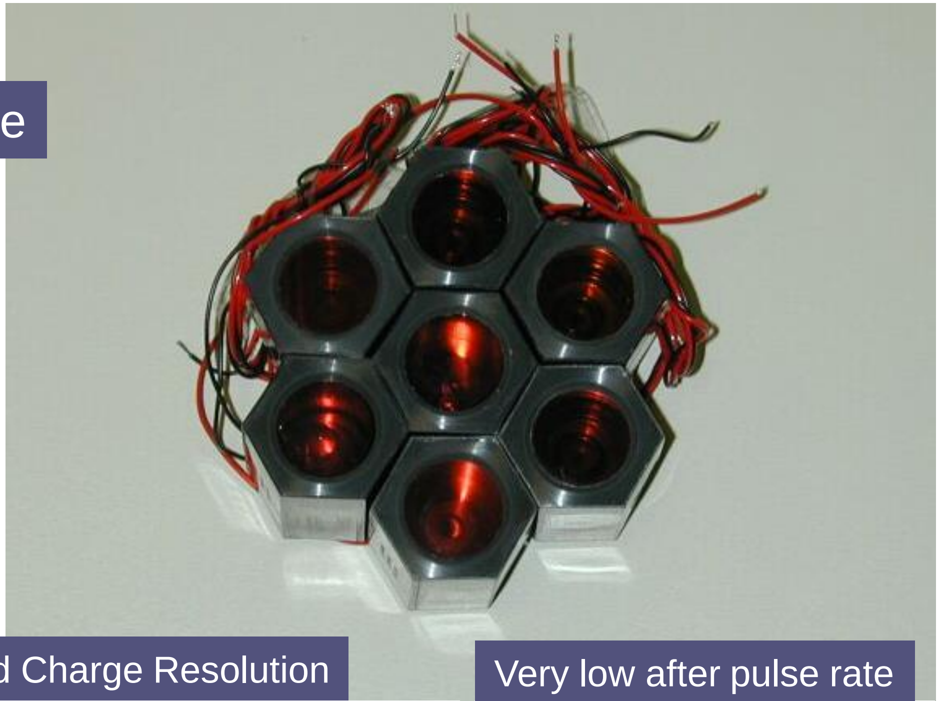




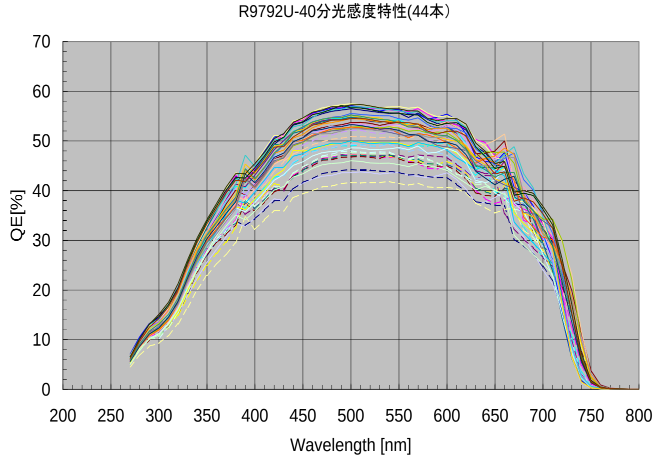
Vacuum detector HPD R9792U-40 developed for MAGIC
18mm GaAsP HPD by us with Hamamatsu



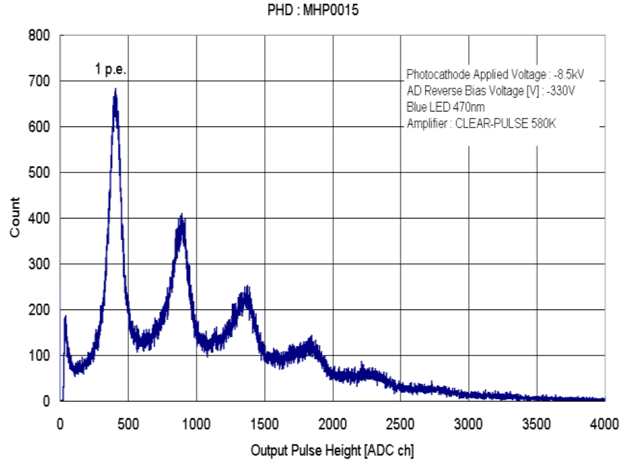
GaAsP photocathode



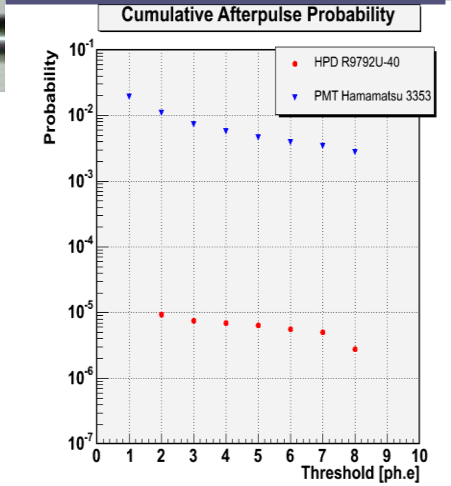
High Q.E.



Good Charge Resolution



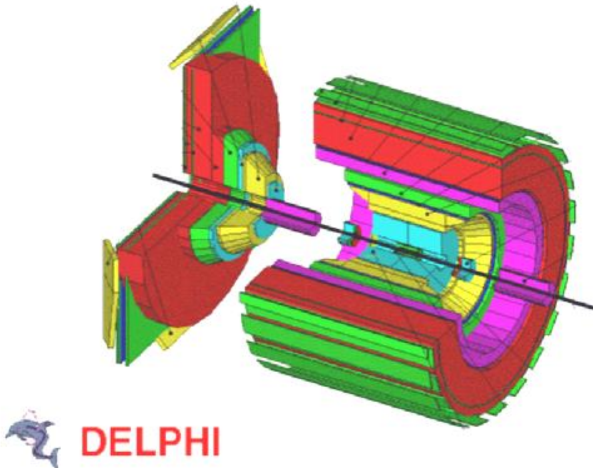
Very low after pulse rate

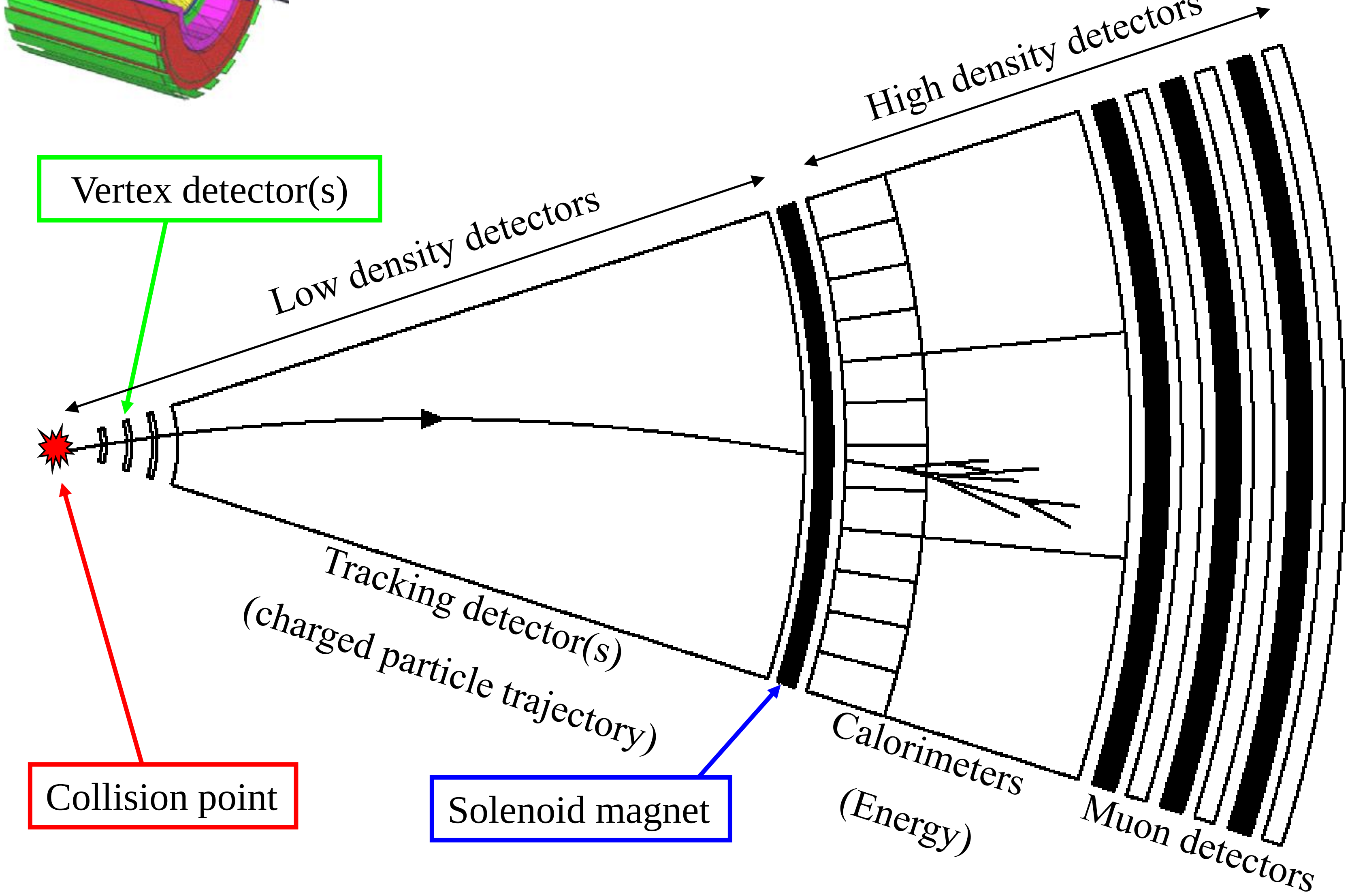


Global detector layout:

- barrel-shape surrounding beam-pipe
- 2 cone- or wheel-shaped end-caps

Nearly 4π coverage and good accessibility!





Low density detectors

High density detectors

Vertex detector(s)

Tracking detector(s)

(charged particle trajectory)

Calorimeters

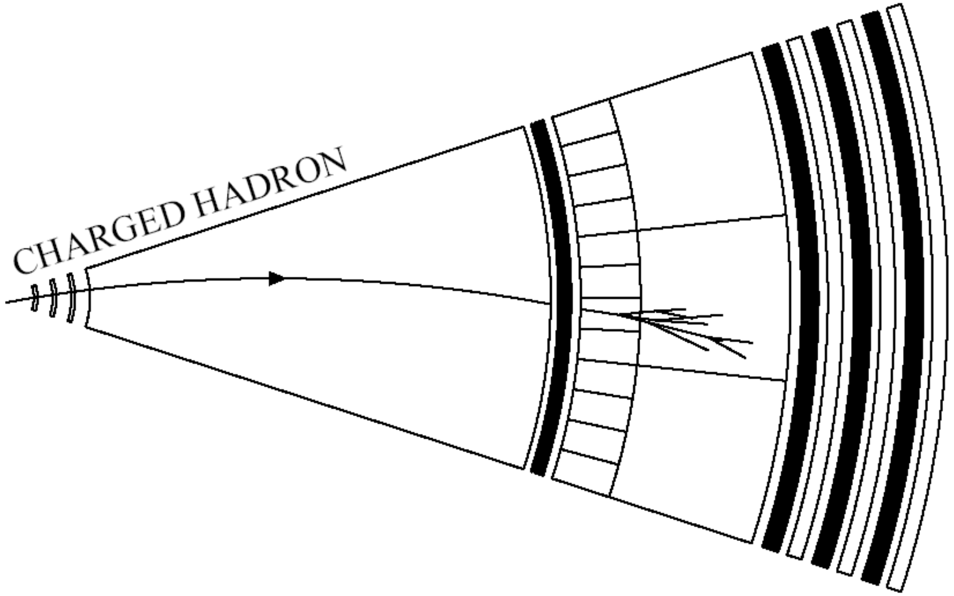
(Energy)

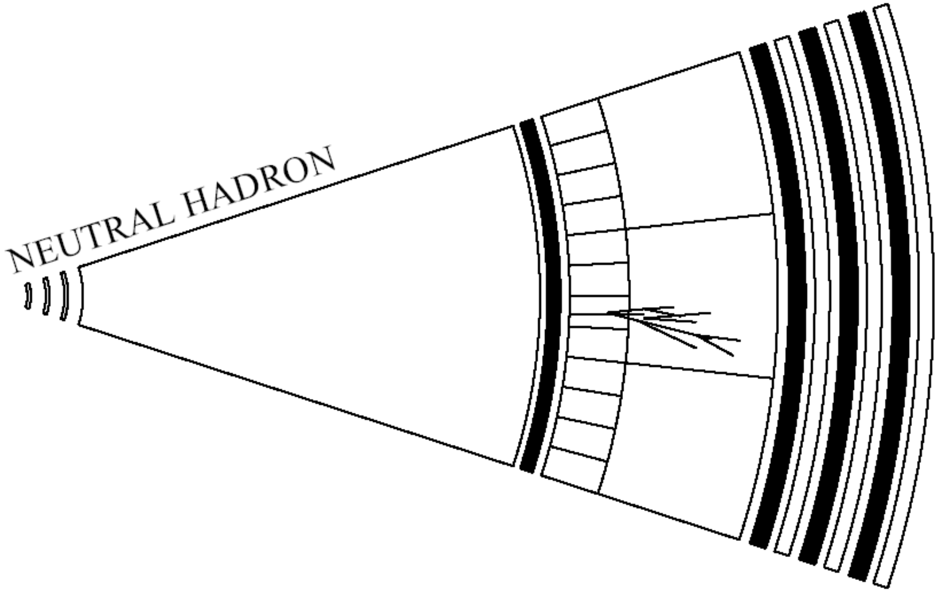
Muon detectors

Collision point

Solenoid magnet

Particle signatures (first glance)





Charged hadrons:

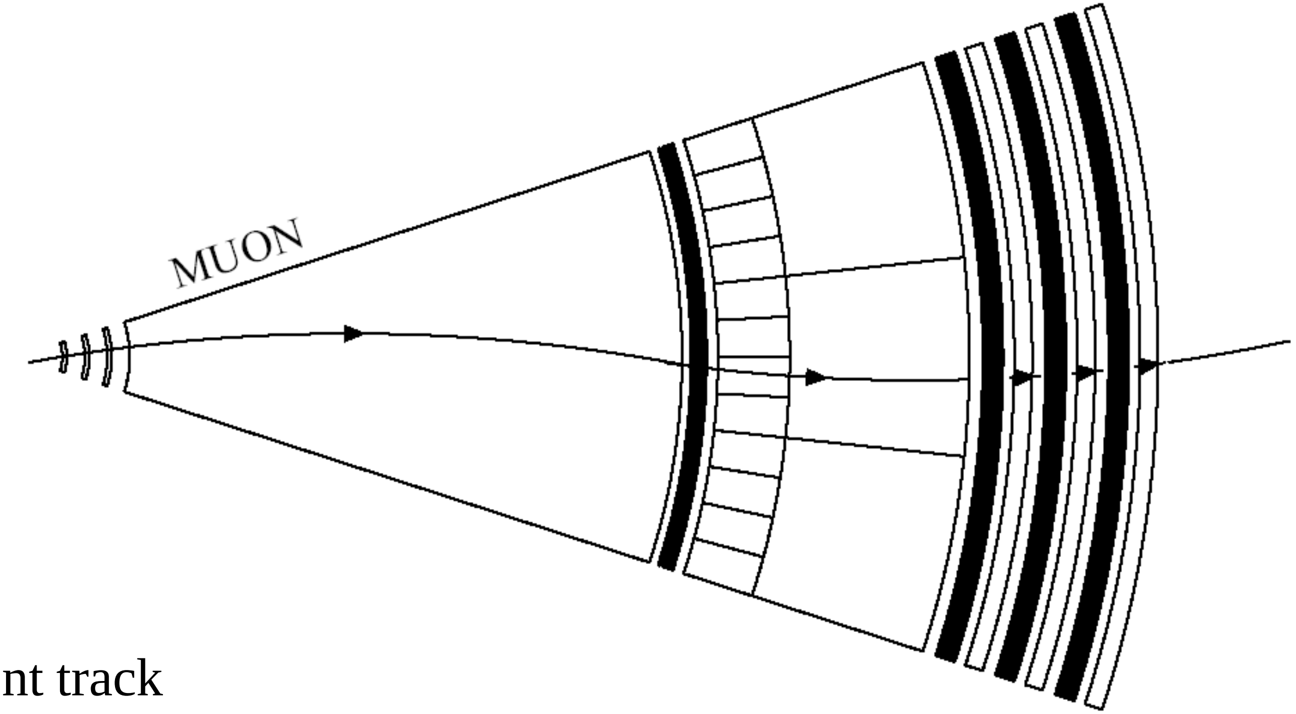
- leave a bent track
- stopped deep in calorimeter

Neutral hadrons:

- leave no track
- stopped deep in calorimeter

Second (+) layers of calorimeter: “*Hadron calorimeter*”

Particle signatures (at first glance)

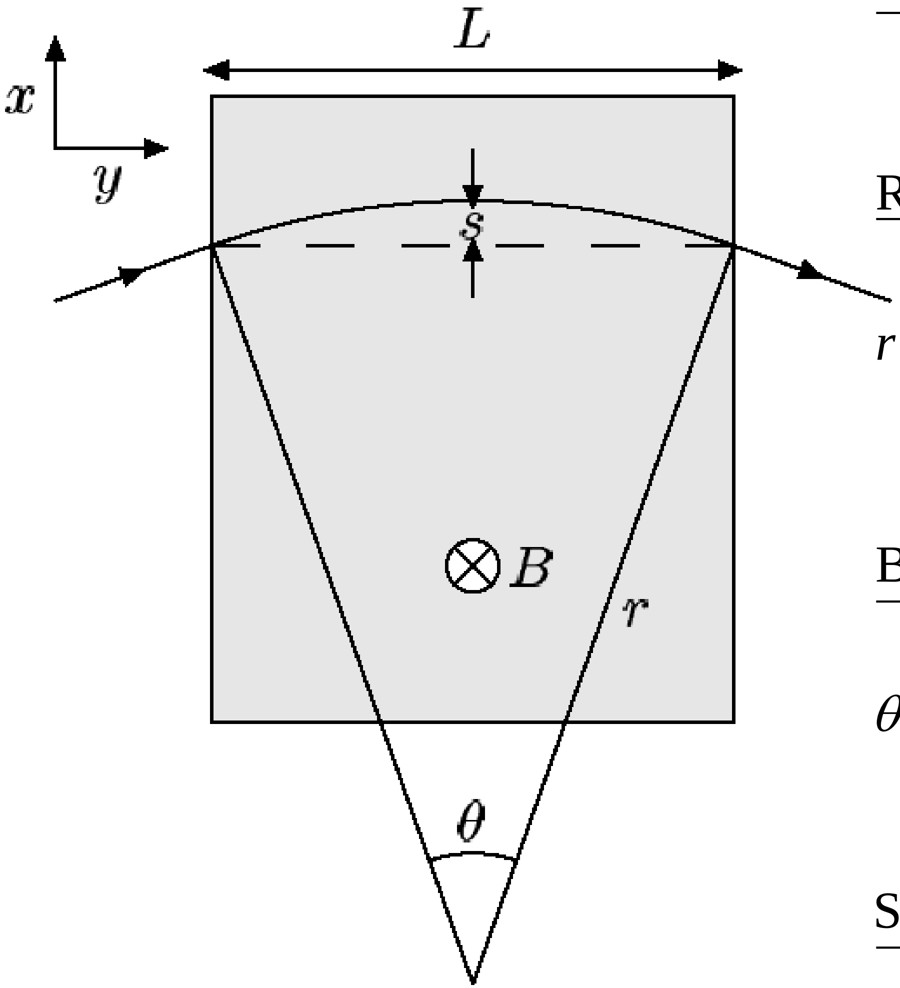


Muons:

- leave a bent track
- not stopped in calorimeter
- track in muon detectors

(Calorimeter, tracking and muon-detector information)

Charged particle in a magnetic field



Magnetic force: $\vec{F} = q(\vec{v} \times \vec{B})$ or $|F| = qv_\perp B$

Centrifugal force: $|F| = \frac{mv_\perp^2}{r}$

Radius: $r = \frac{mv_\perp}{qB} = \frac{P_\perp}{qB}$,

$r = \frac{P_\perp}{0.3B}$ ($P_\perp$ in GeV/c and B in Tesla)

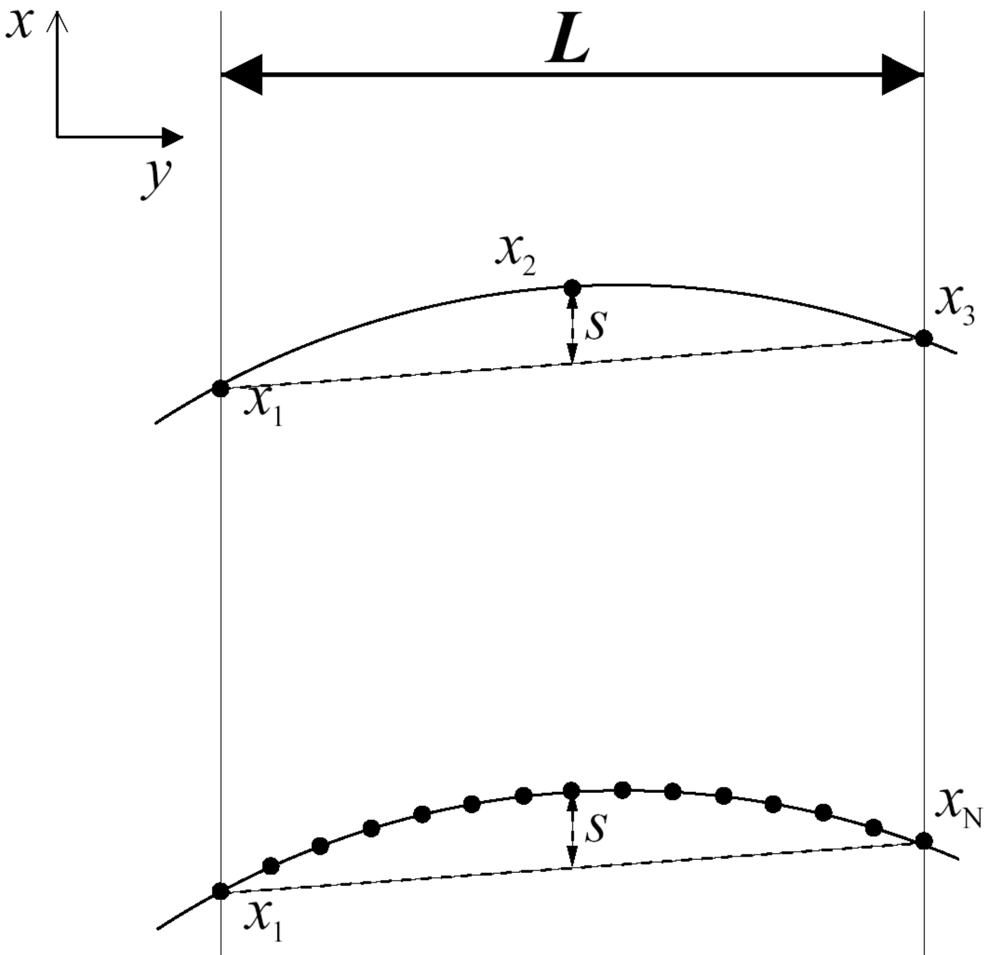
Bending angle: $\frac{\theta}{2} \approx \sin\frac{\theta}{2} = \left(\frac{\mathrm{L}/2}{r}\right) \Rightarrow$

$\theta \approx \frac{0.3BL}{P_\perp}$

Sagitta :

$$s = r - r\cos\frac{\theta}{2} = r\left(1 - \cos\frac{\theta}{2}\right) \approx r\frac{\theta^2}{8} \approx \frac{0.3}{8}\frac{BL^2}{P_\perp}$$

Measurement of the sagitta



For 3 measured points:

x_1, x_2, x_3 at $y = 0,\ L/2,\ L$

$$s = x_2 - \frac{x_1 + x_3}{2}$$

$$\sigma(s) = \sqrt{\frac{3}{2}}\sigma(x)$$

$$\frac{\sigma(P_\perp)}{P_\perp} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x) 8 P_\perp}{0.3 B L^2}$$

For N equidistant measurements:

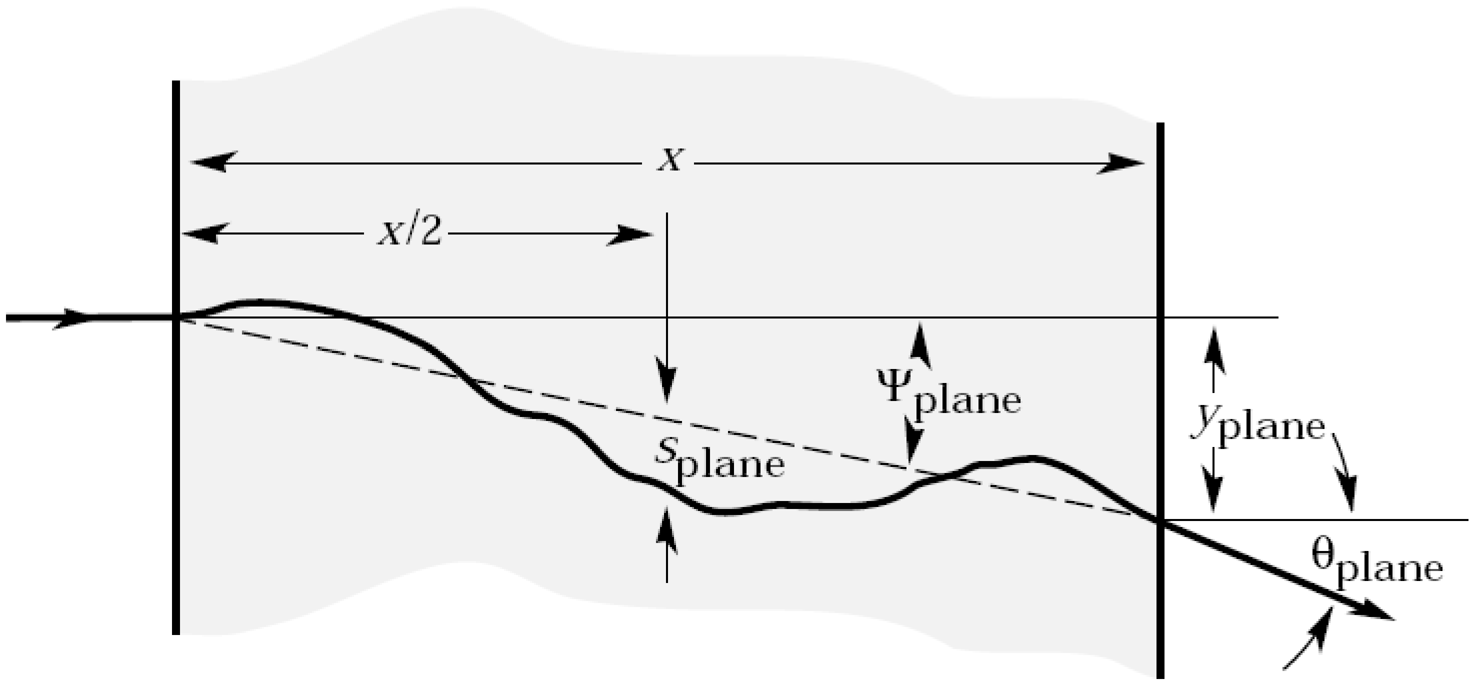
$$\frac{\sigma(P_\perp)}{P_\perp} = \frac{\sigma(x) P_\perp}{0.3 B L^2}\sqrt{\frac{720}{N+4}}$$

(R.L. Gluckstern, NIM 24 (1963) 381)

Thus for precise measurement momentum we need: high B field, large volume tracking detector, many measurements along the trajectory. But …

Multiple Scattering

- Particle



MS Theory

- Average scattering angle is roughly Gaussian for small deflection angles

$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x}{X_0} \right) \right]$$

- With

$$X_0 \equiv \text{ radiation length}$$

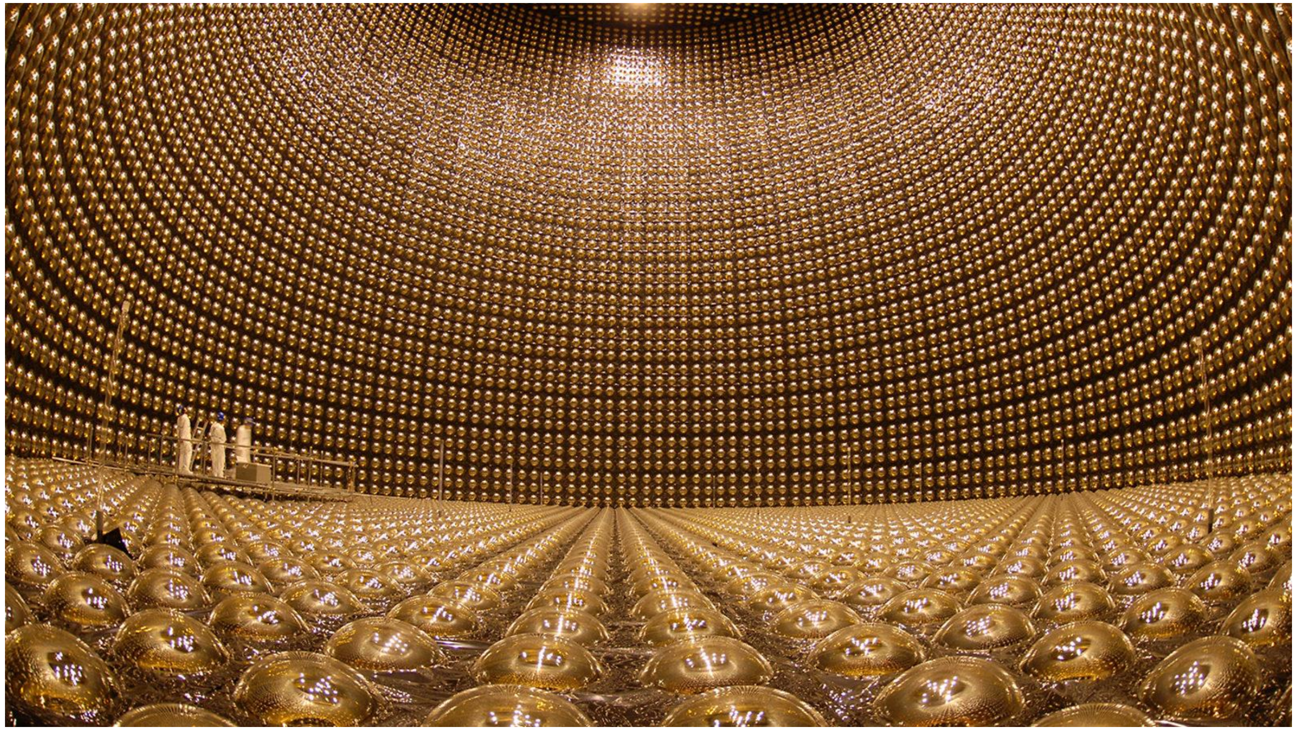
- Angular distributions are given by

$$\frac{dN}{d\Omega} \propto \frac{1}{2\pi\theta_0^2} \exp\left(-\frac{\theta_{space}^2}{2\theta_0^2} \right)$$

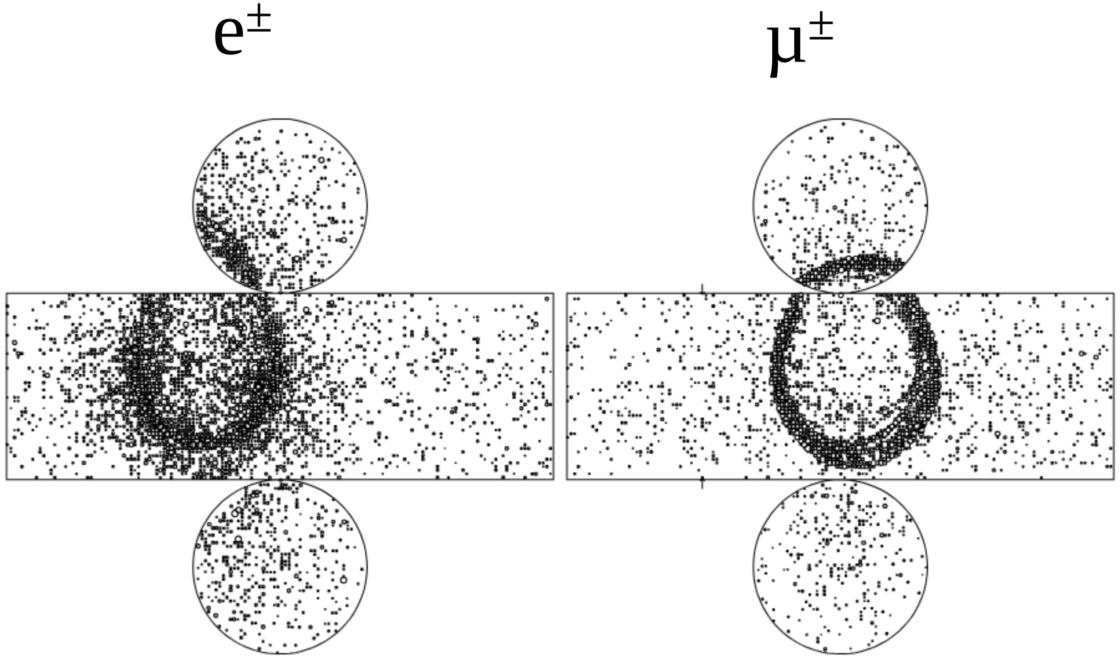
$$\frac{dN}{d\theta_{plane}} \propto \frac{1}{\sqrt{2\pi}\theta_0} \exp\left(-\frac{\theta_{plane}^2}{2\theta_0^2} \right)$$

Electron and muon images in Superkamiokande detector demonstrate the effect of multiple scattering

Kajita, 2004

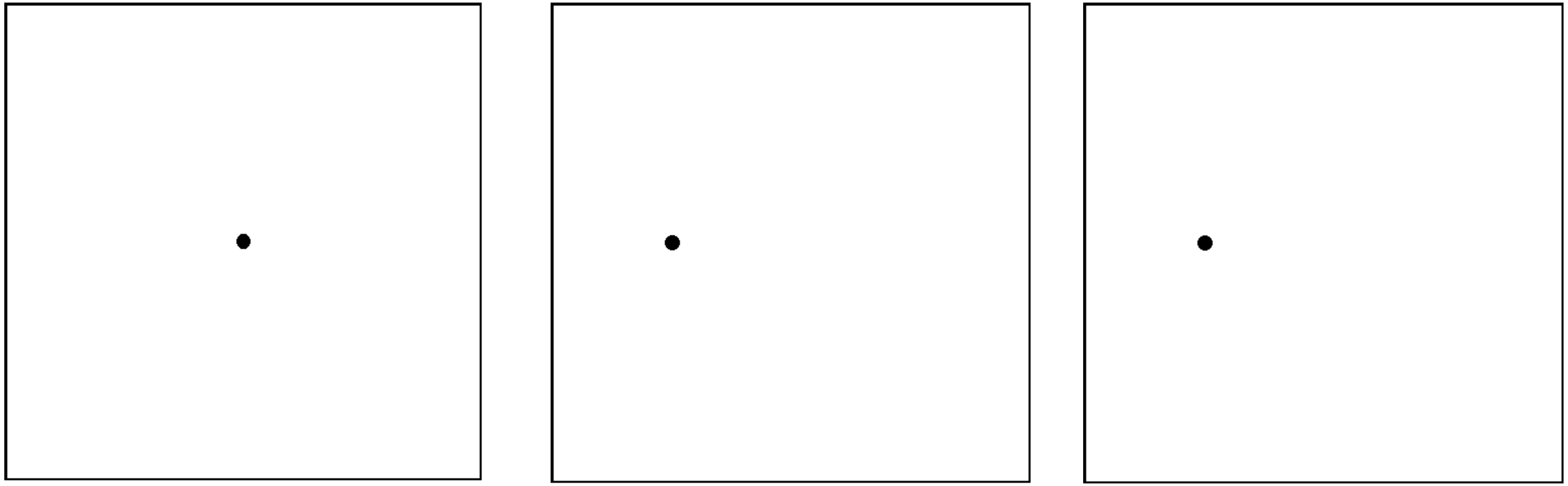


The Superkamiokande detector in Japan
uses 11200 PMTs of 0.5m size



Cherenkov Radiation

- Charge motion in a transparent dielectric medium



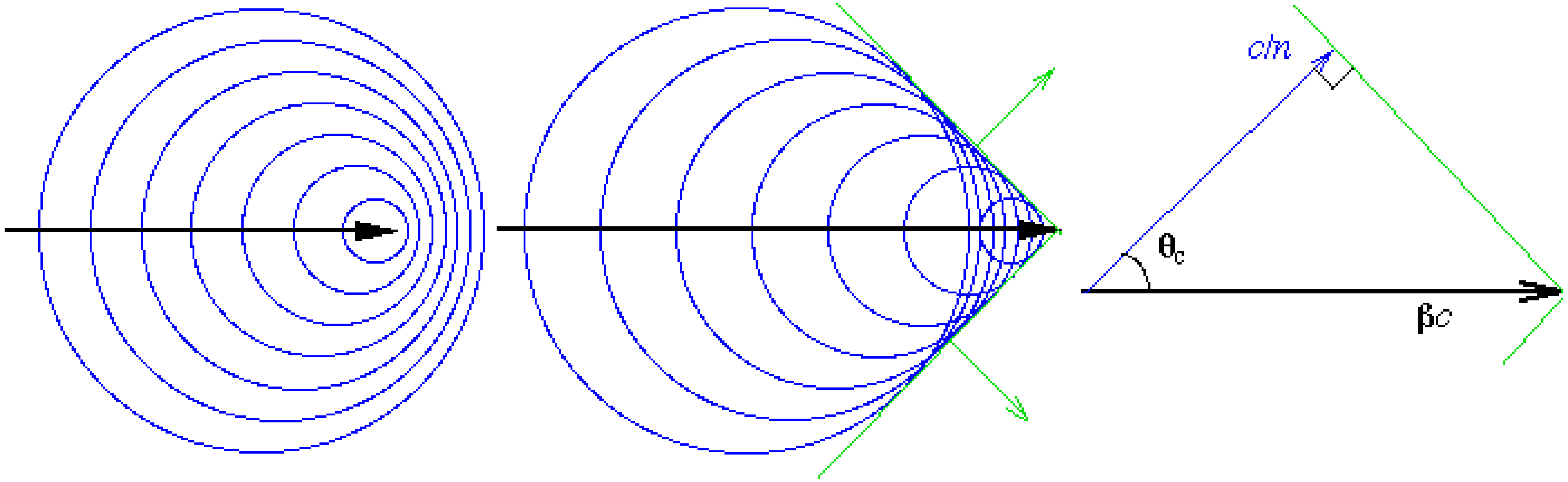
at rest

Slow < c

Fast > c

Cherenkov Radiation (2)

- Wave front comes out at certain angle

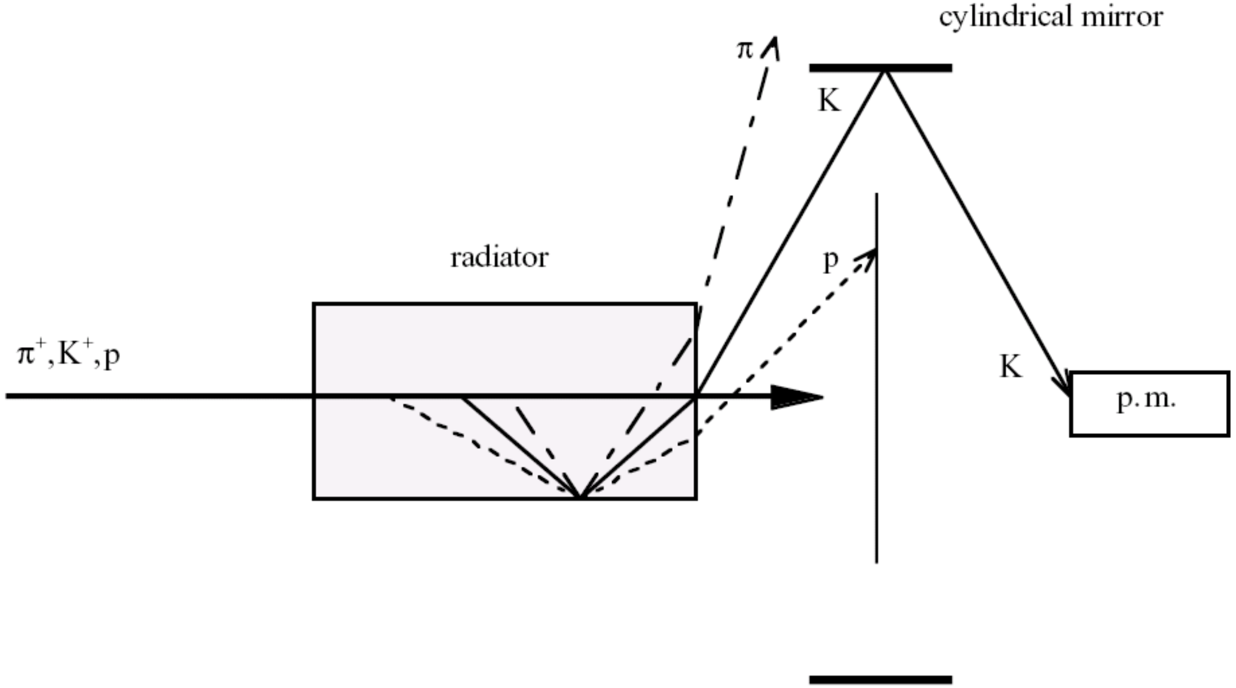


$$\boxed{\cos\theta_c = \frac{1}{\beta n}}$$

Different Types of Cherenkov Detectors

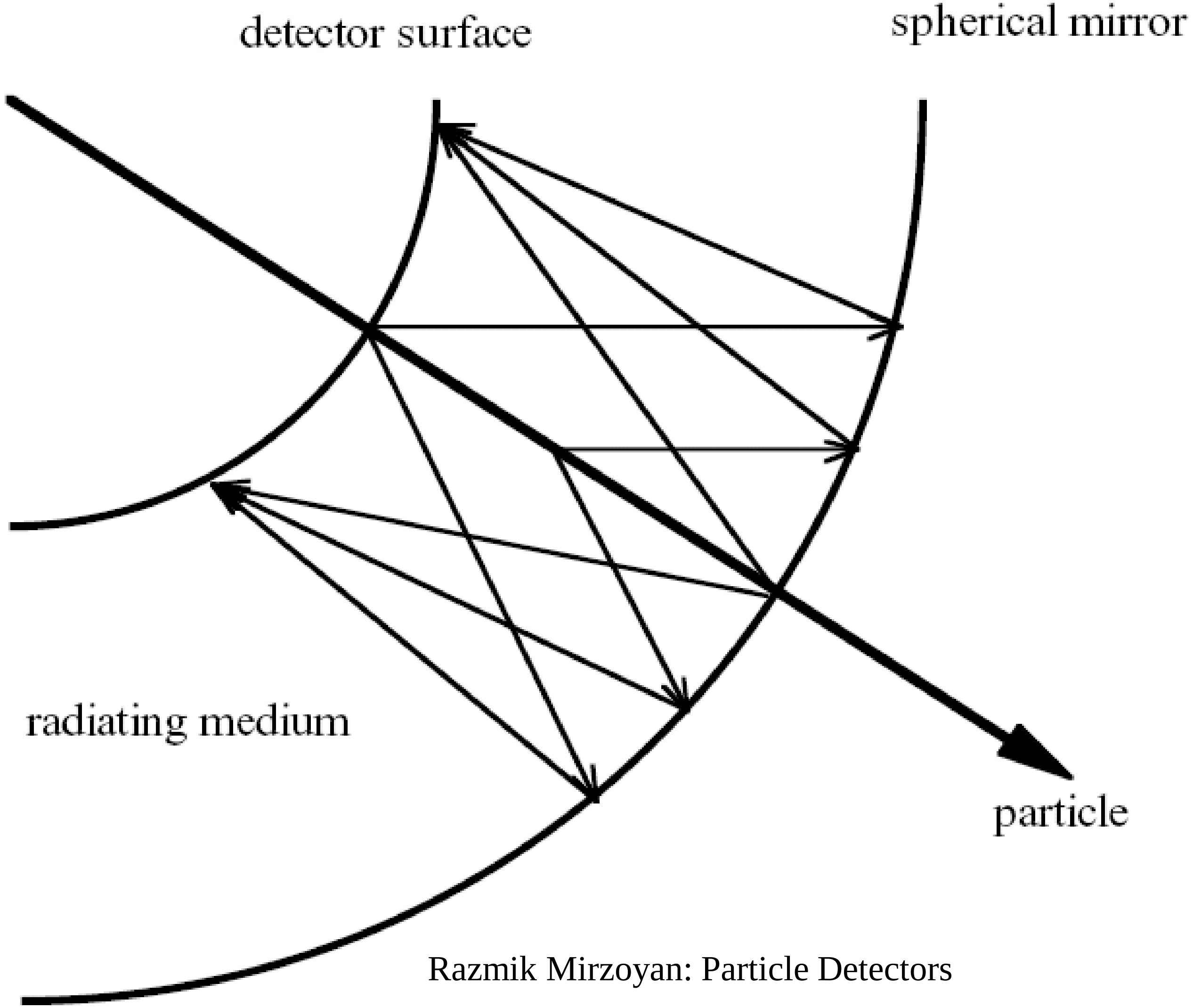
- Threshold Detectors
  - Yes/No on whether the speed is $\beta>1/n$
- Differential Detectors
  - $\beta_{max} > \beta > \beta_{min}$
- Ring-Imaging Detectors
  - Measure β

Differential Detectors



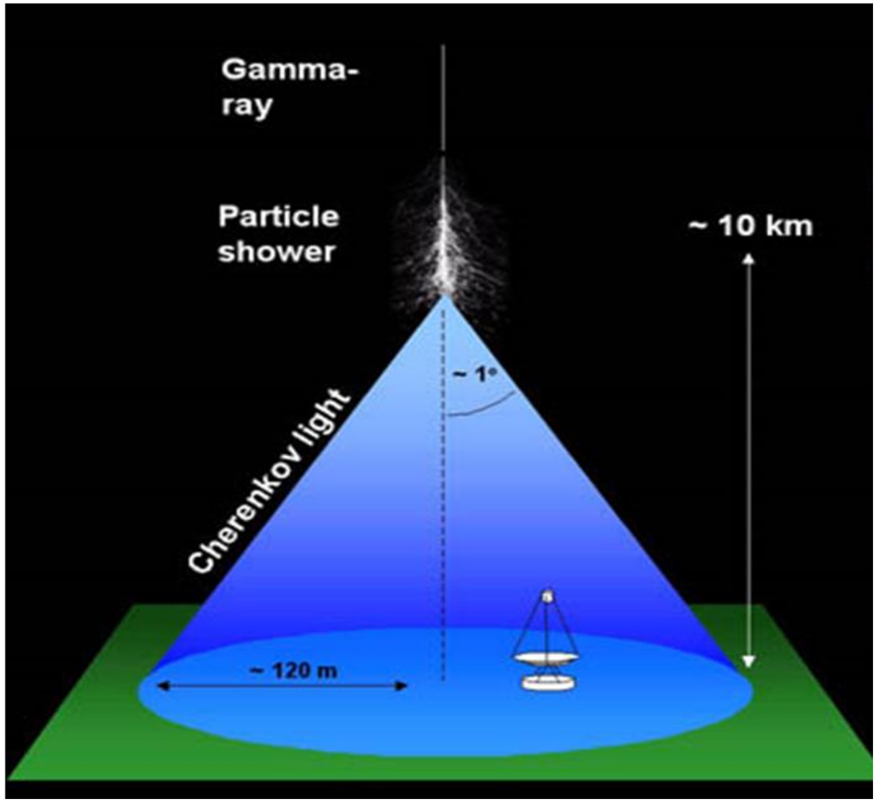
- Will reflect light onto PMT for certain angles only ⬄ β Selecton

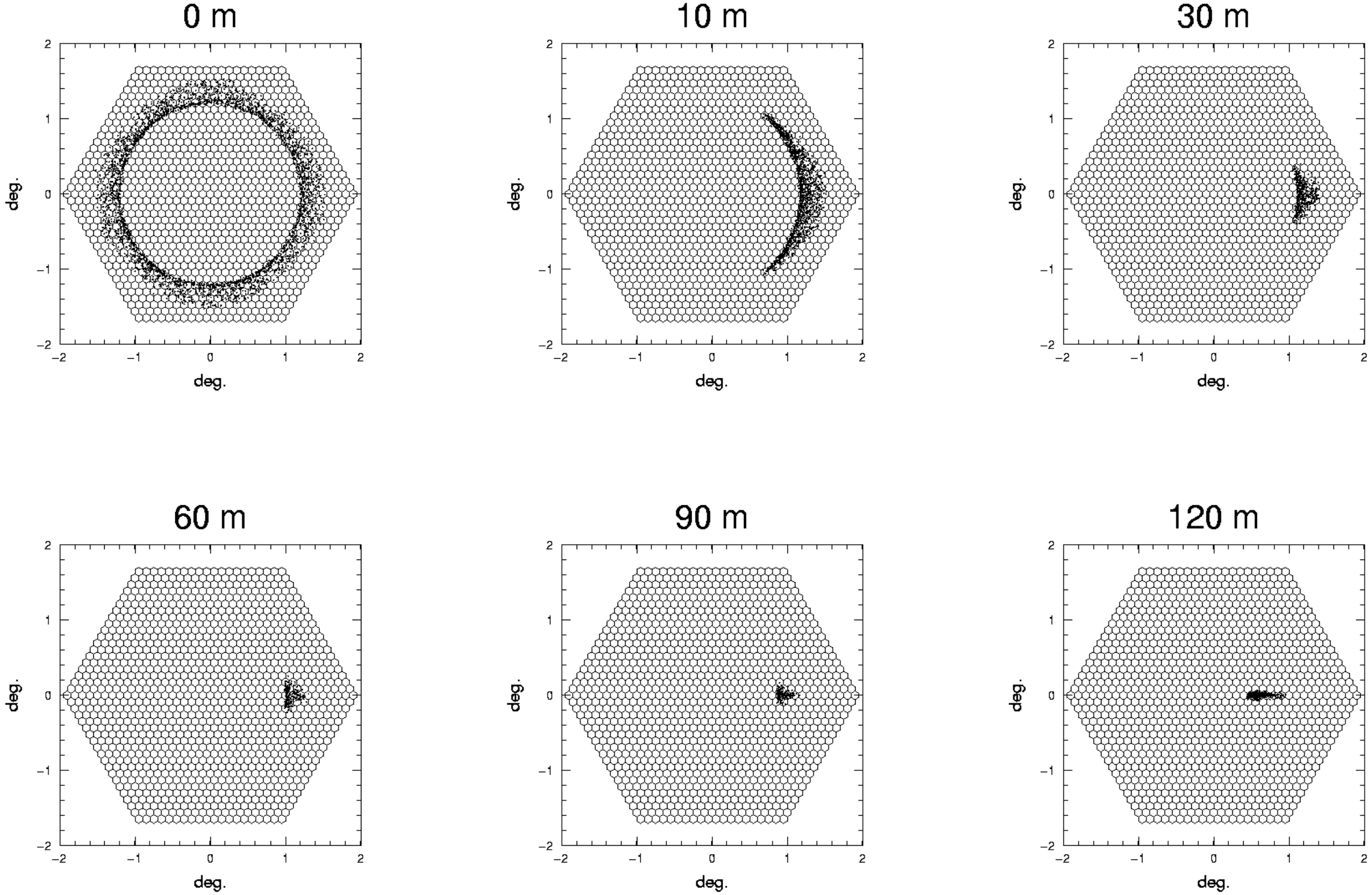
Ring Imaging Detectors (1)



Shape of muon images versus the impact parameter in an Imaging Atmospheric Cherenkov Telescope

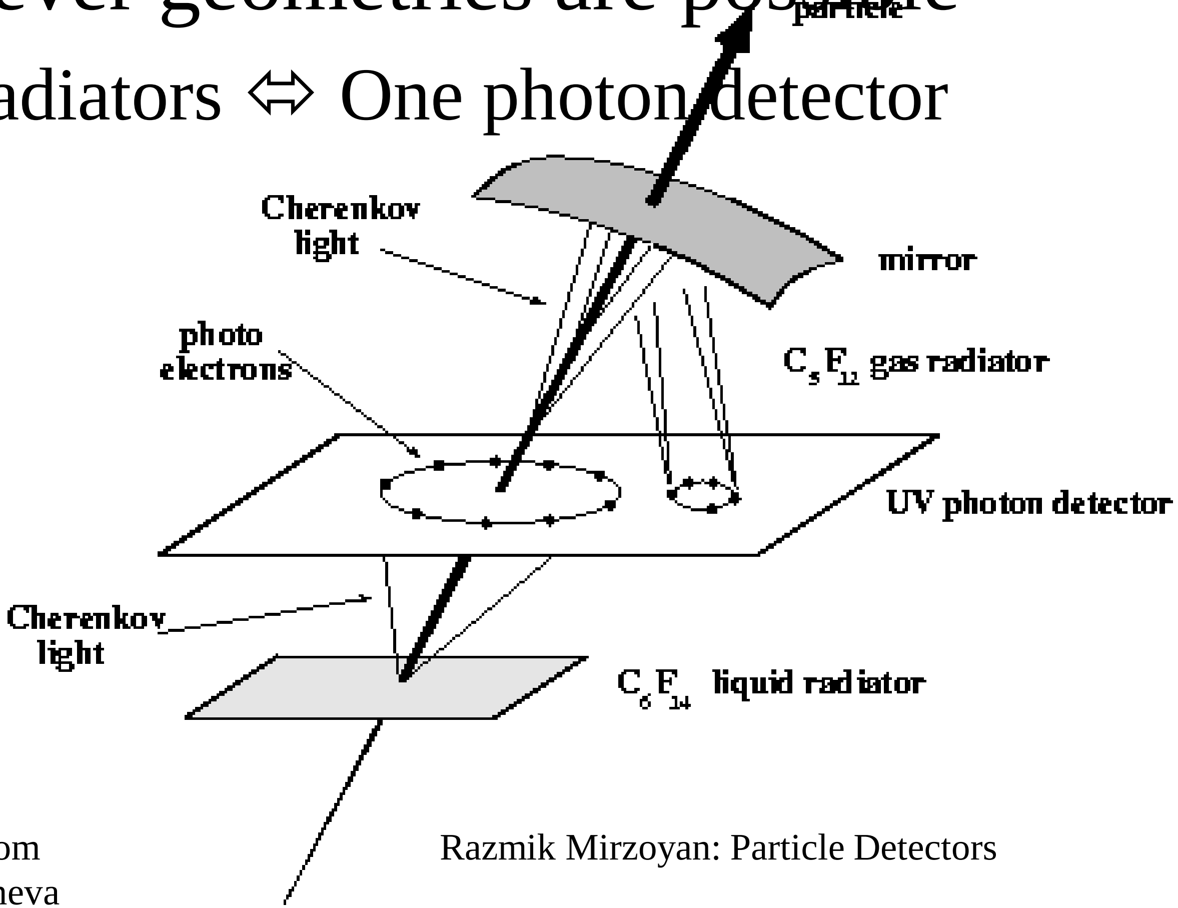
Imagine a downward going muon





Ring Imaging Detectors (3)

- More clever geometries are possible
  - Two radiators ⬄ One photon detector



Transition Radiation (3)

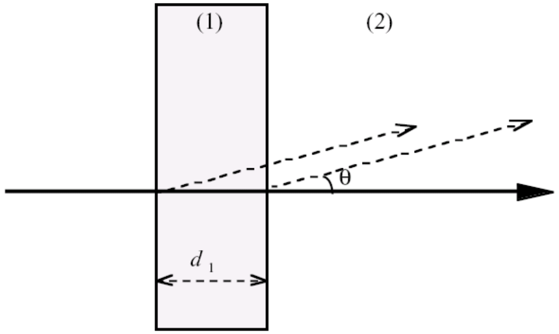
- Consider relativistic particle traversing a boundary from material (1) to material (2)

$$\frac{\mathrm{d}^2 N}{\mathrm{d}\omega\,\mathrm{d}\Omega} = \frac{z^2\alpha}{\pi^2\omega}\phi^2 \times \left(\frac{1}{\omega_p^2/\omega^2 + \phi^2 + 1/\gamma^2} - \frac{1}{\phi^2 + 1/\gamma^2} \right)^2$$

$$\omega_p = \text{plasma frequency}$$

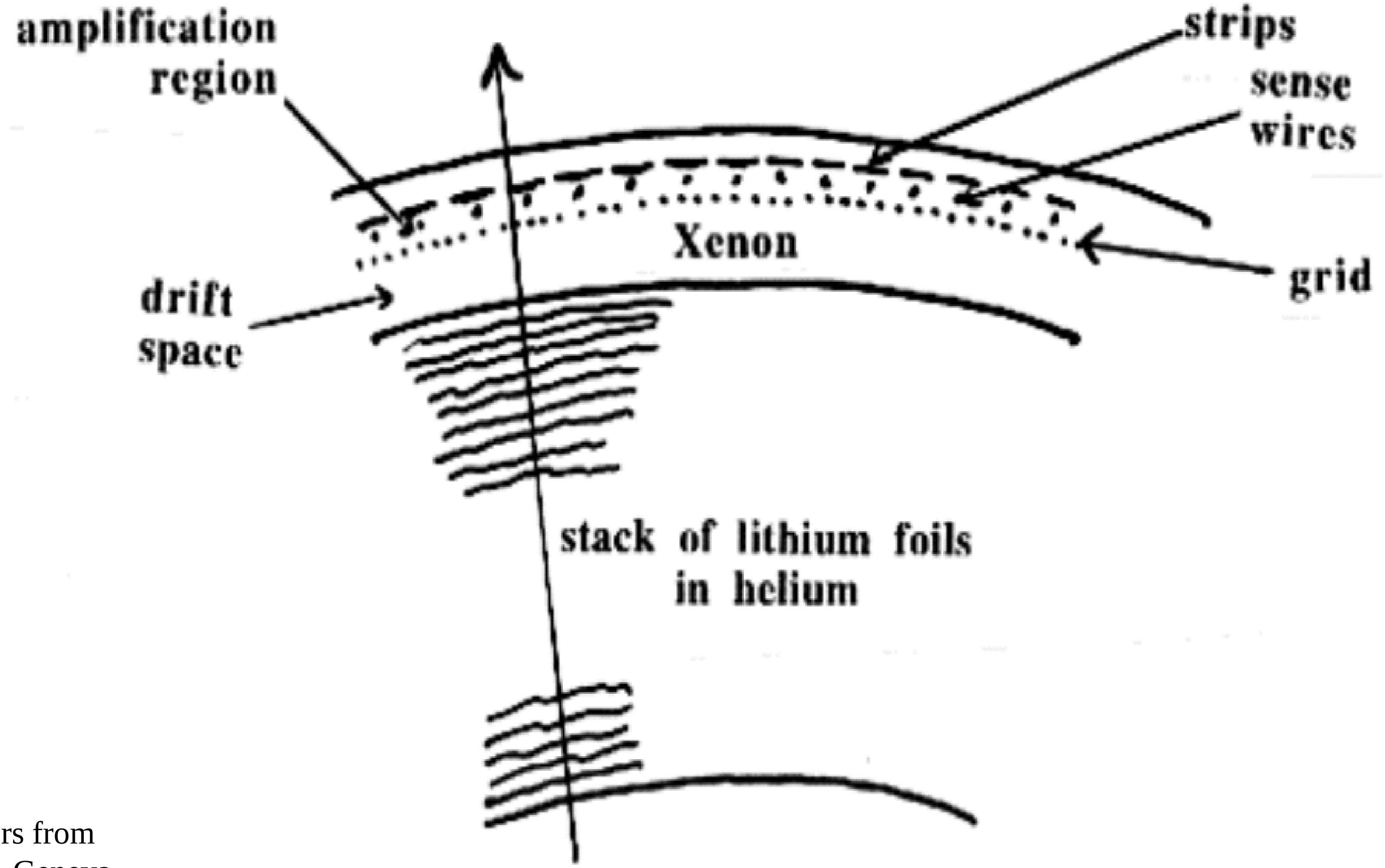
- Total energy radiated

$$\boxed{E_{\mathrm{TR}} = \frac{2}{3}\alpha\,\hbar\omega_{\mathrm{p1}}\,\gamma}$$



- Can be used to measure γ

Transition Radiation Detector



Acknowledgements

- The author thanks for the sources:
  - Phys389 - Semiconductor Applications L11
  - 36. Particle Detectors for Non-Accelerator Physics
  - Particle Detection Techniques in HEP, Post-graduate lecture series, Joost Vossebeld
  - Interaction of Particles with Matter, Alfons Weber, CCLRC & University of Oxford Graduate Lecture 2004
  - New Journal of Physics 6 (20024) 194