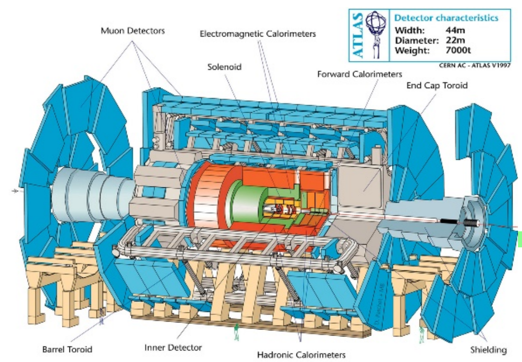
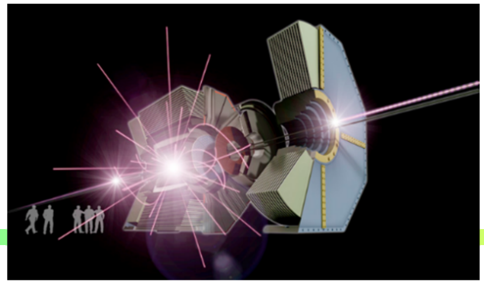
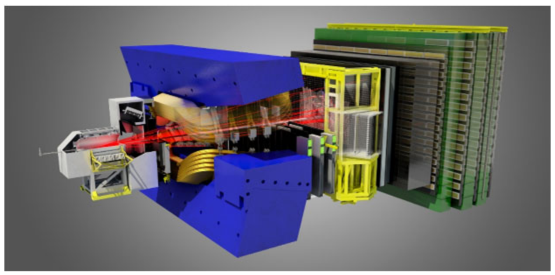
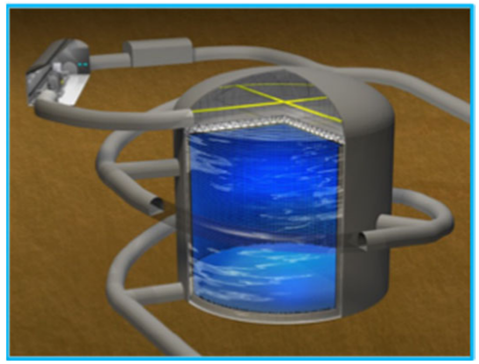








Particle Detectors – part 1

Peter Križan

University of Ljubljana and J. Stefan Institute

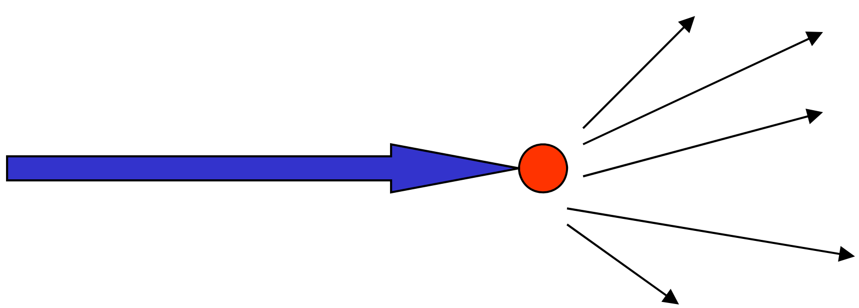
Contents

Particle physics experiments

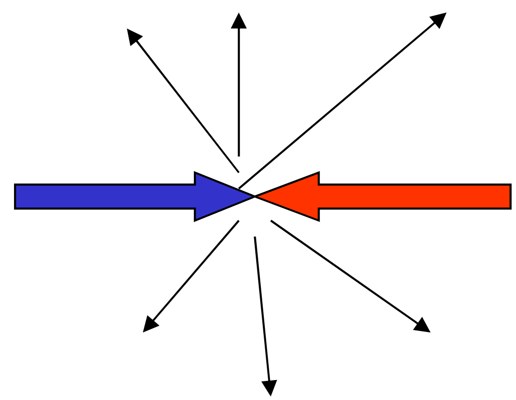
Accelerate elementary particles, let them collide → energy released in the collision is converted into mass of new particles, some of which are unstable

Two ways how to do it:

Fixed target experiments

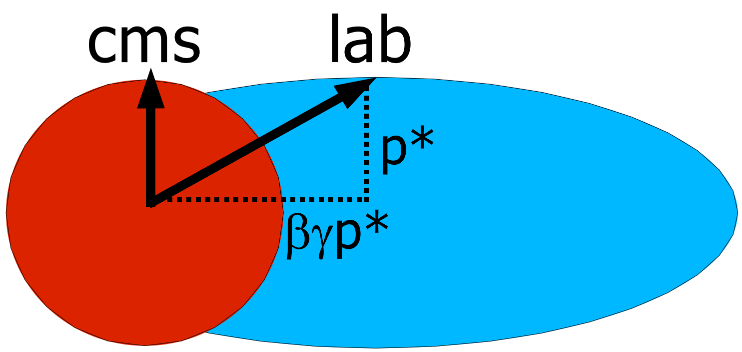


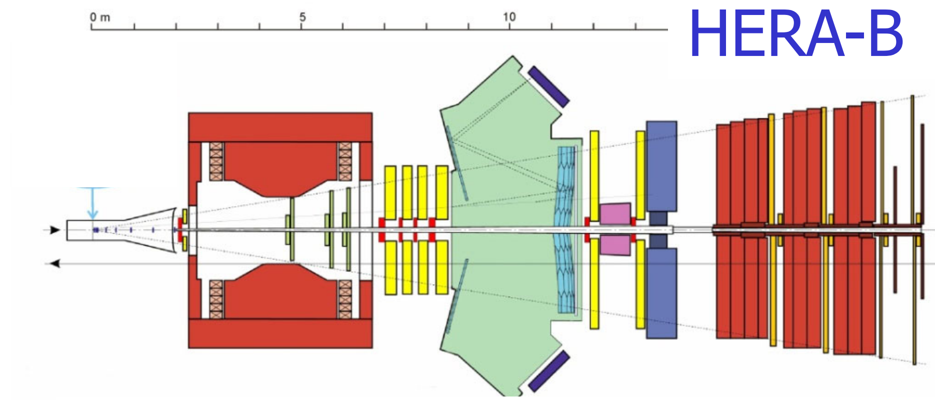
Collider experiments

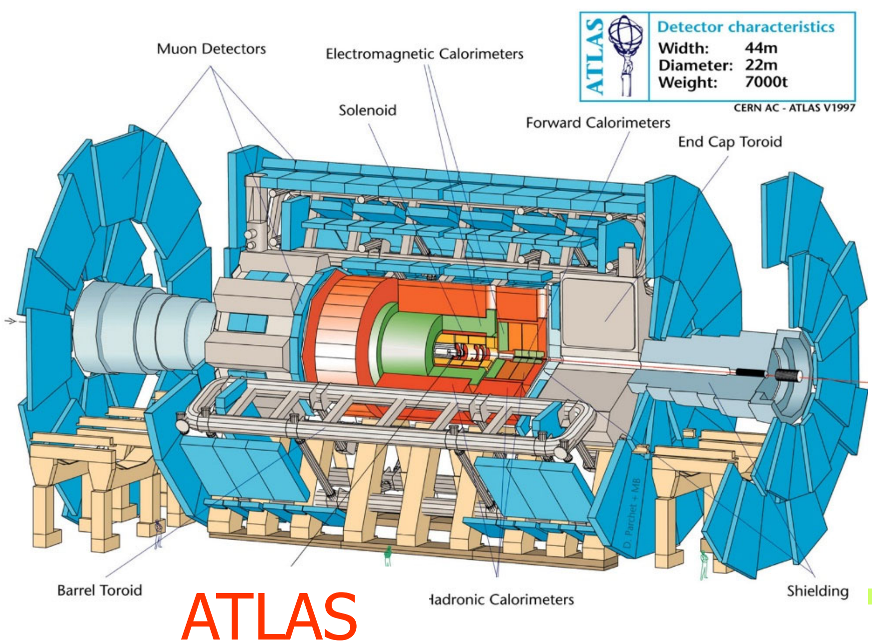


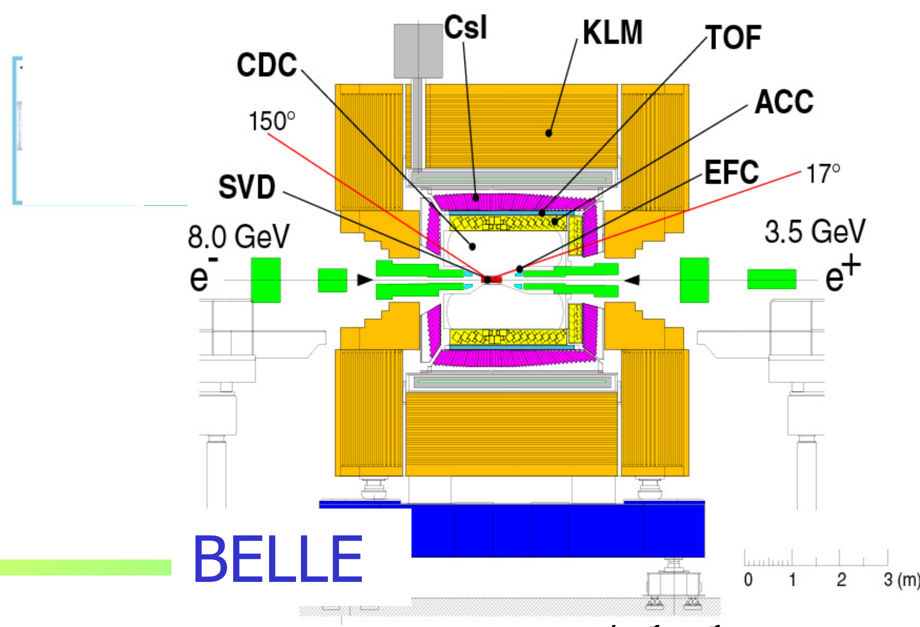
Experimental aparatus

Detector form: symmetric for colliders with symmetric energy beams; extended in the boost direction for an asymmetric collider; very forward oriented in fixed target experiments.

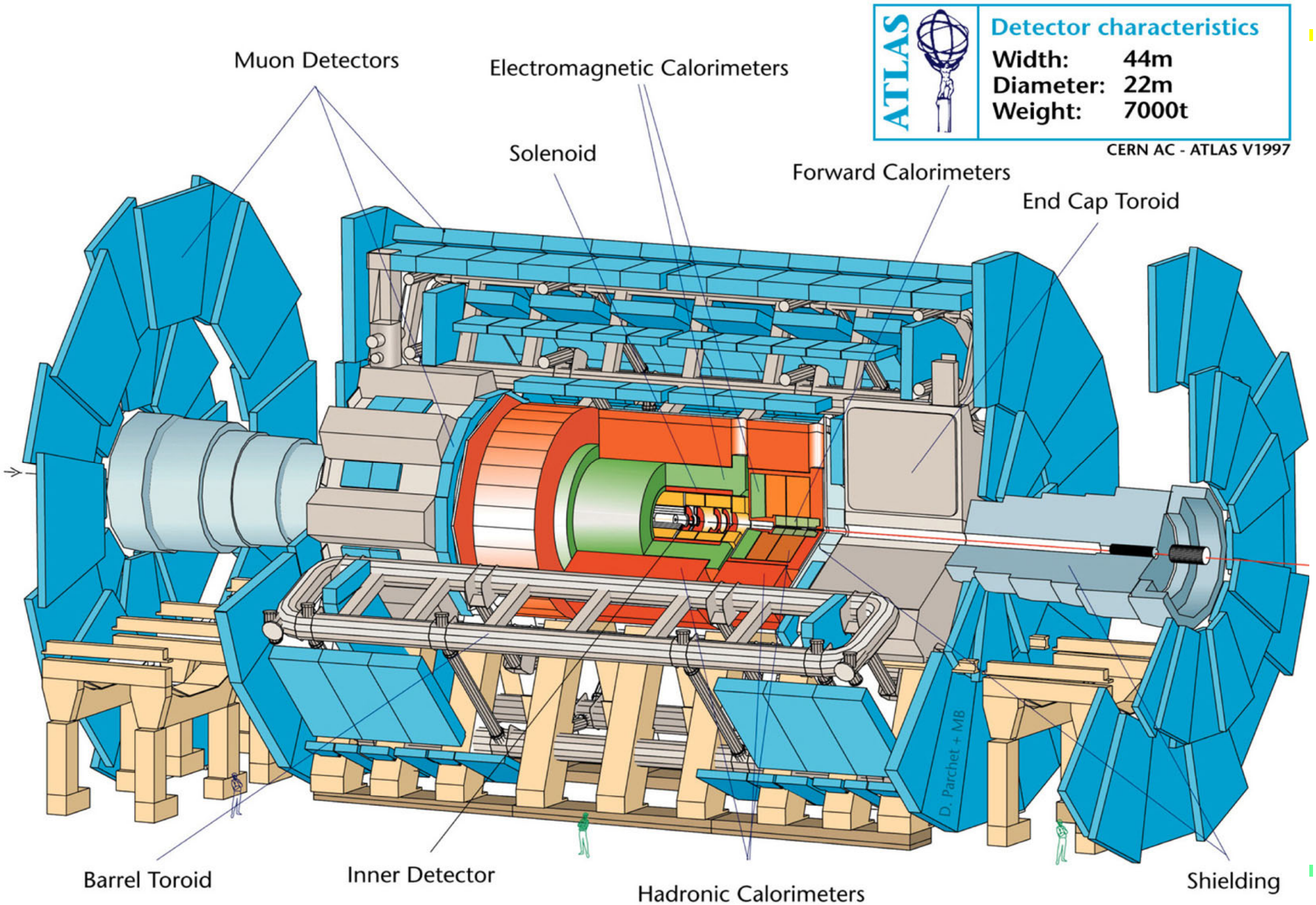




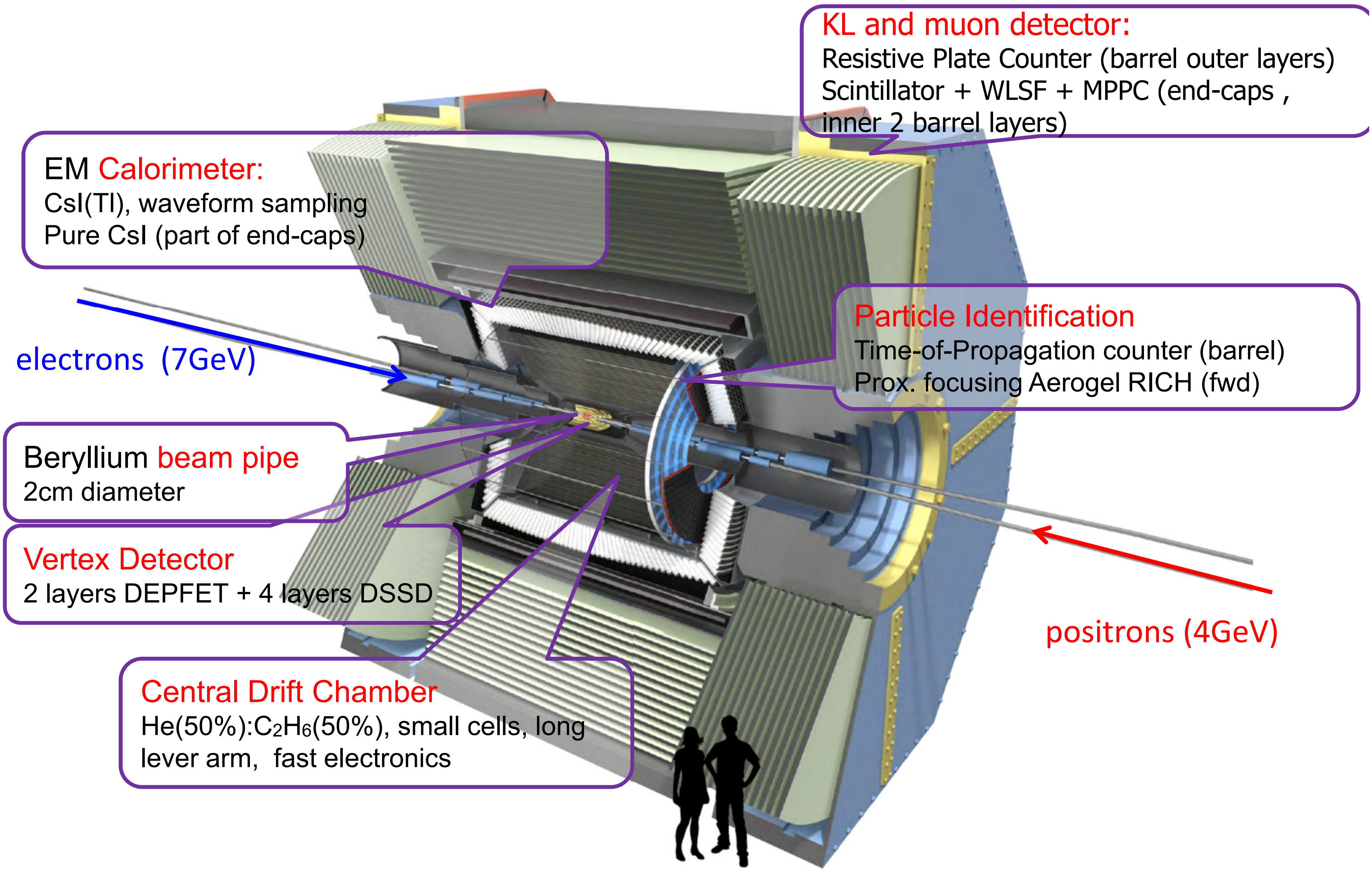




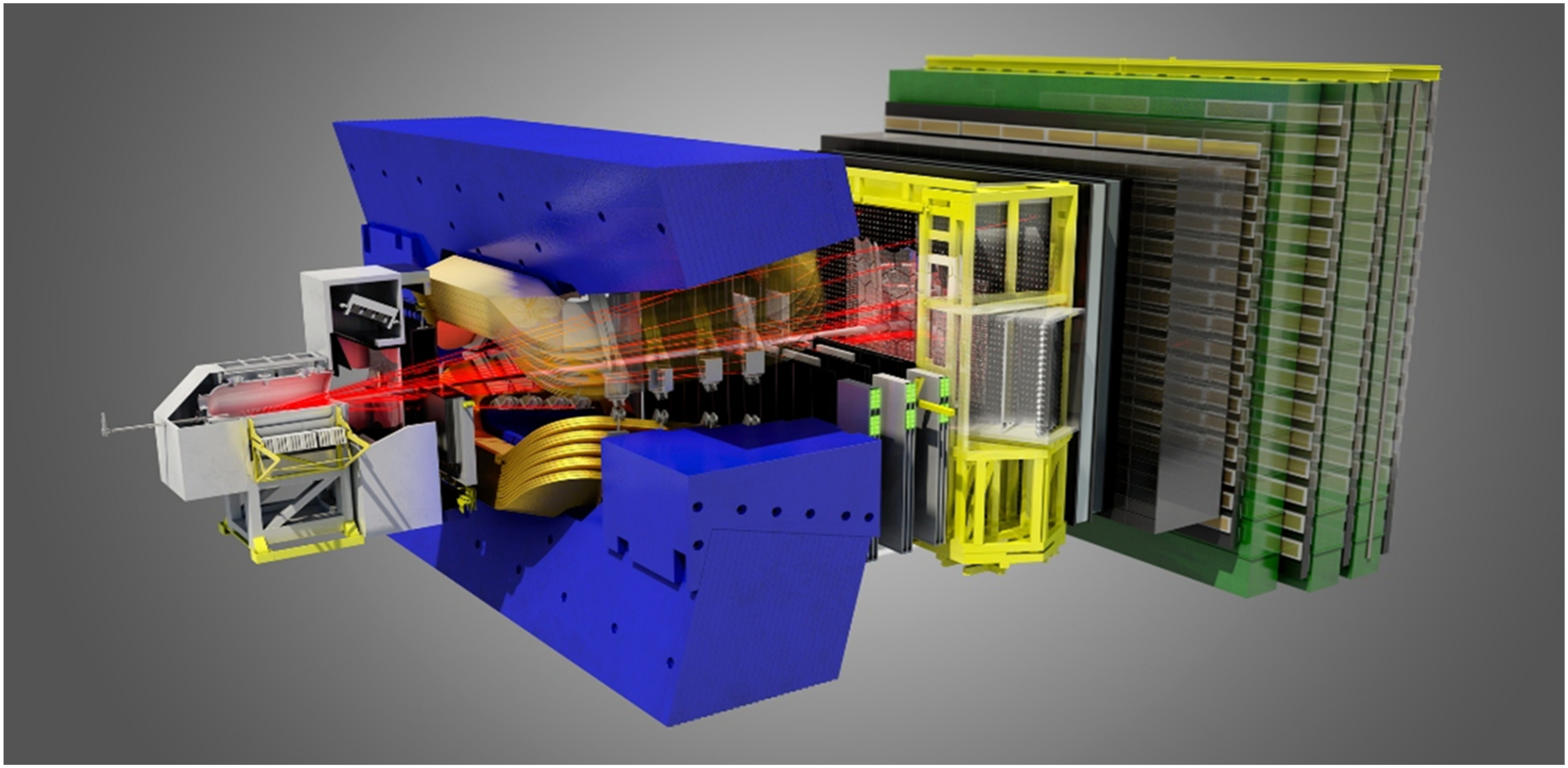
A ‘typical‘ particle physics experiment 1: ATLAS



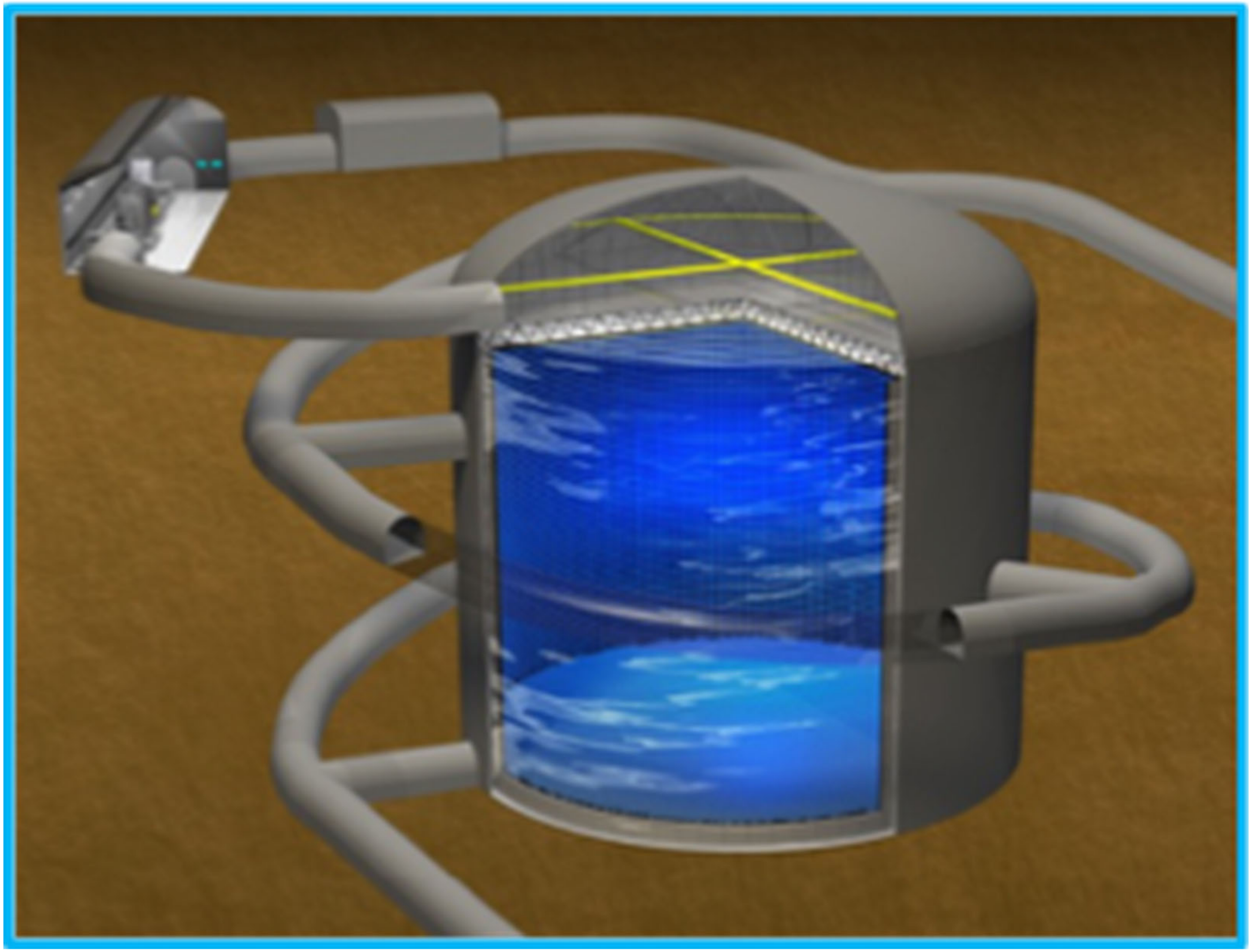
A ‘typical‘ particle physics experiment 2: Belle II



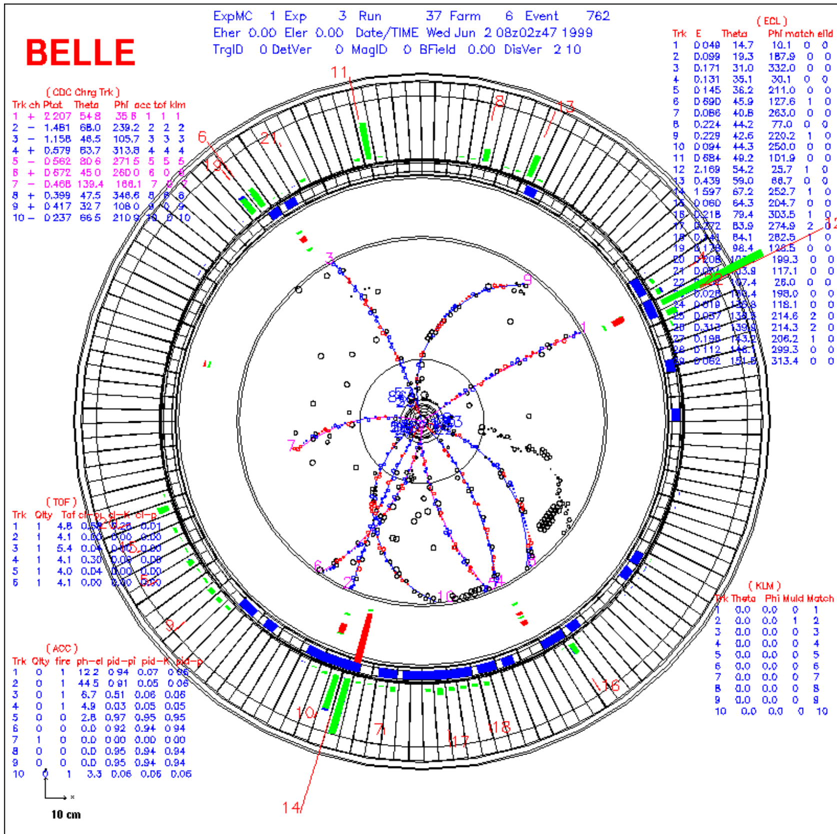
A ‘typical‘ particle physics experiment 3: LHCb

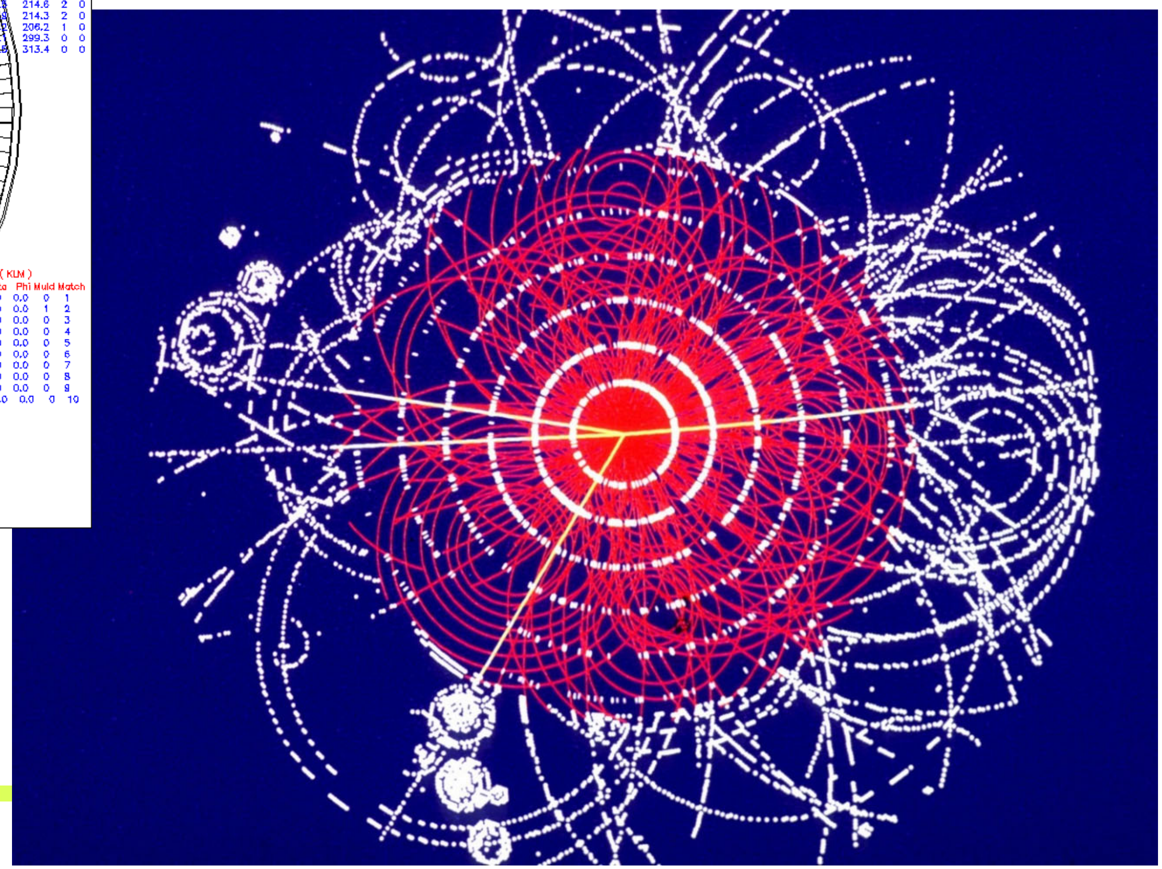


A ‘typical‘ particle physics experiment 4: HyperKamiokande



How to understand what happened in a collision?





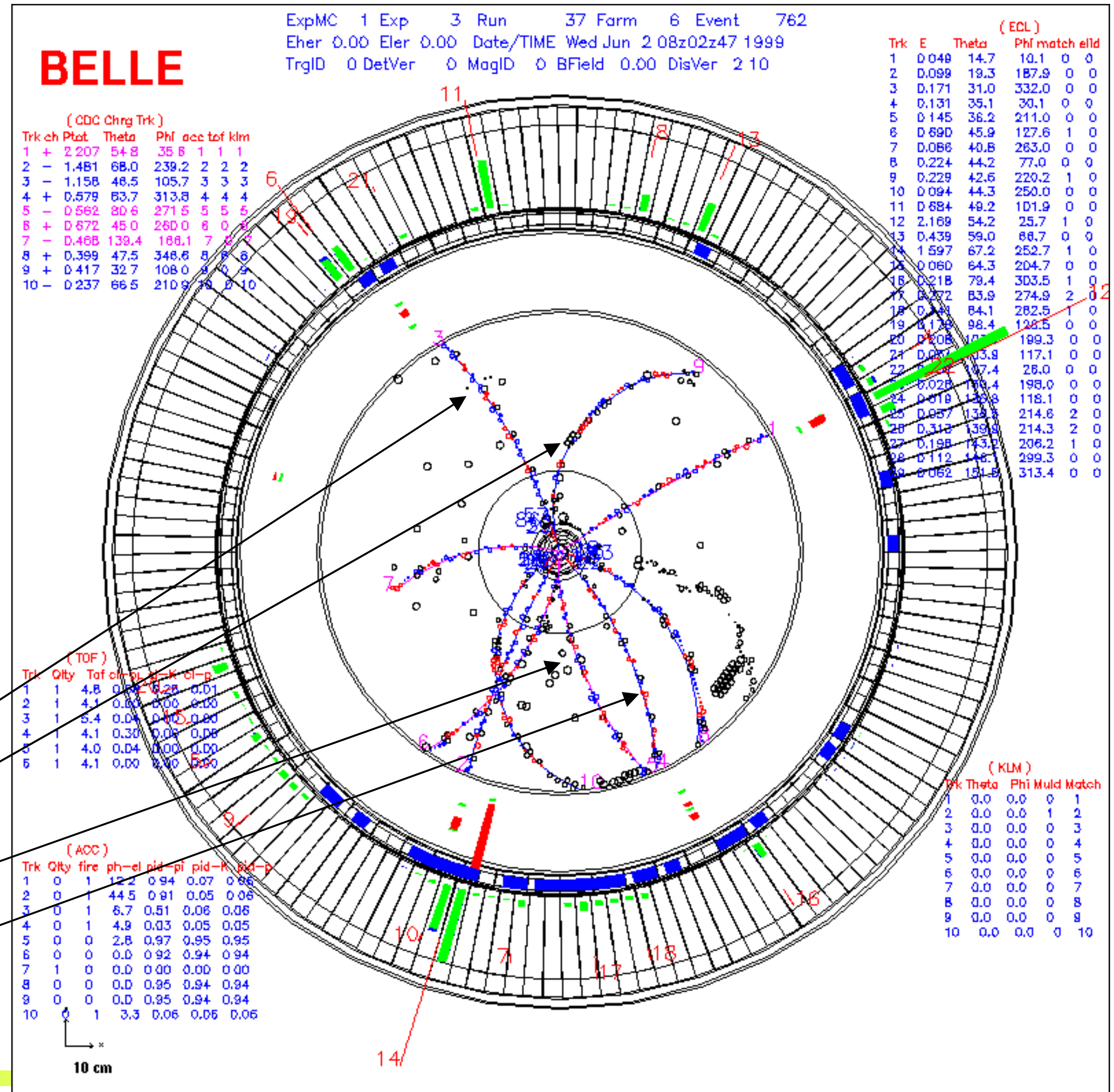
How to understand what happened in a collision?

- Measure the coordinate of the point ('vertex') where the reaction occured, and determine the positions and directions of particles that have been produced
- Measure momenta of stable charged particles by measuring their radius of curvature in a strong magnetic field (~1T)
- Determine the identity of stable charged particles (e, μ, π, K, p)
- Measure the energy of high energy photons γ
- Detect neutral hadrons

- Combine final state particles to form intermediate states that decayed too quickly to be directly detected

How to understand what happened in a collision?

Illustration on an example:



$B^0 \rightarrow K^0_S \, J/\psi$

$K^0_S \rightarrow \pi^- \pi^+$

$J/\psi \rightarrow \mu^- \mu^+$

Search for particles that decayed close to the production point

How do we reconstruct reaction products that decayed to several stable particles (e.g., 1, 2, 3)?

From the measured tracks calculate the invariant mass of the system (i = 1, 2, 3):

$$M = \sqrt{(\sum E_i)^2 - (\sum \vec{p}_i)^2}$$

The candidates for the X→123 decay show up as a peak in the distribution on (mostly combinatorial) background.

The name of the game: have as little background under the peak as possible without loosing the events in the peak (=reduce background and have a small peak width).

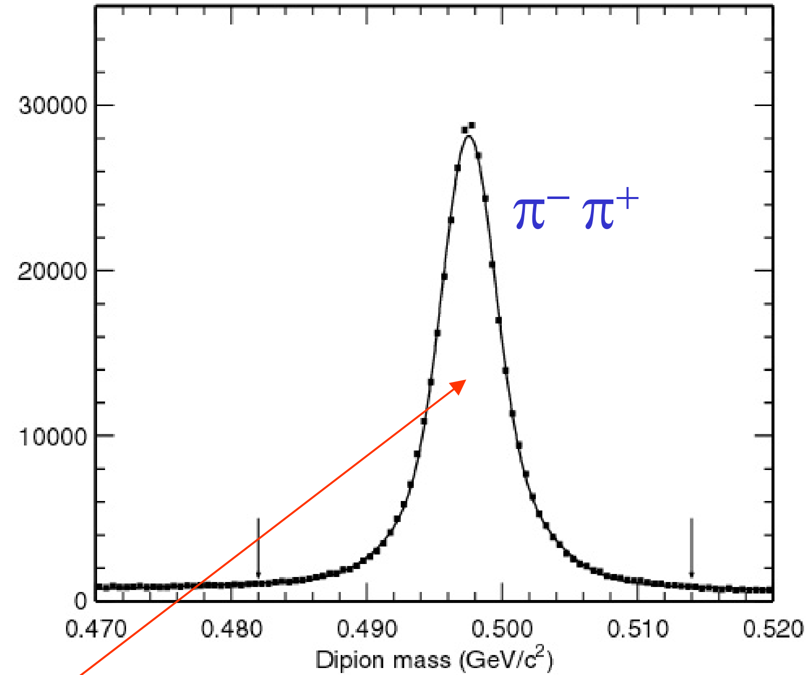
How do we know it was precisely this reaction?

$B^0 \rightarrow K^0_S\ J/\psi$

$K^0_S \rightarrow \pi^- \pi^+$

$J/\psi \rightarrow \mu^- \mu^+$

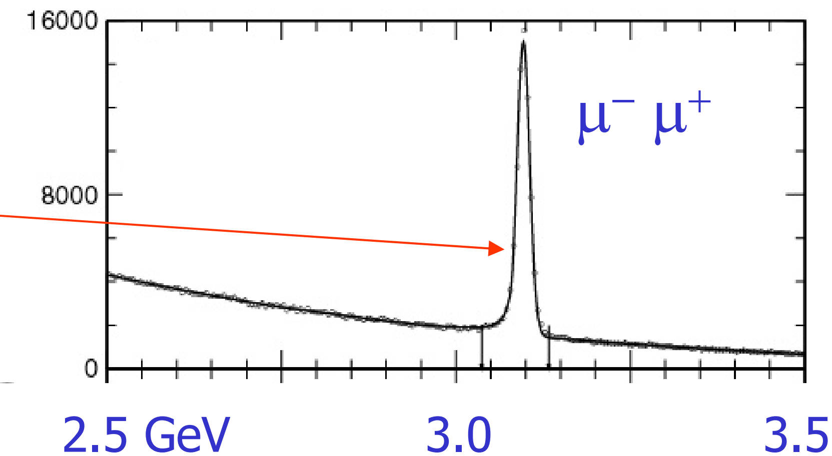
detect



For $\pi^- \pi^+$ in $\mu^- \mu^+$ pairs we calculate the invariant mass:

$$M = \sqrt{(\sum E_i)^2 - (\sum \vec{p}_i)^2}$$

Mc^2 must be for K^0_S close to 0.5 GeV, for J/ψ close to 3.1 GeV.



Rest in the histrogram: random coincidences ('combinatorial background')

Components of an experimental apparatus (‘spectrometer’)

- Tracking and vertexing systems
- Particle identification devices
- Calorimeters (measurement of energy)

How do we detect particles?

Particles are detected through their interaction with the detector medium

- Interaction of charged particles
- Interaction of photons
- Interaction of neutral hadrons (n, K_L)
- Interaction of neutrinos

Interaction of charged particles with matter

Energy loss for heavy ($M>>m_e$) particles with charge z: dominated by elastic scattering with atomic electrons - Bethe-Bloch formula

$$\frac{1}{\rho}\left\langle -\frac{dE}{dx}\right\rangle = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right].$$

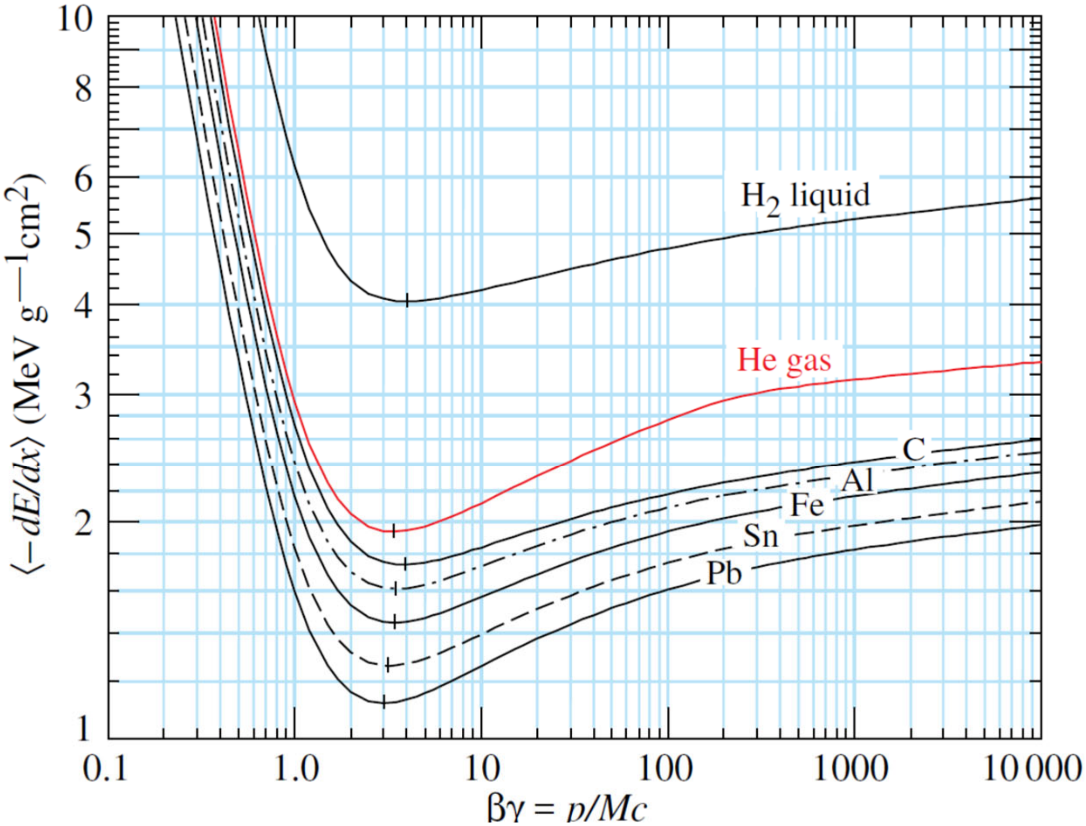
with $K = 4\pi N_A r_e^2 m_e c^2$

$W_{max} = 2m_ec^2\beta^2\gamma^2$
= max energy transfer in a single collision

I: mean excitation energy

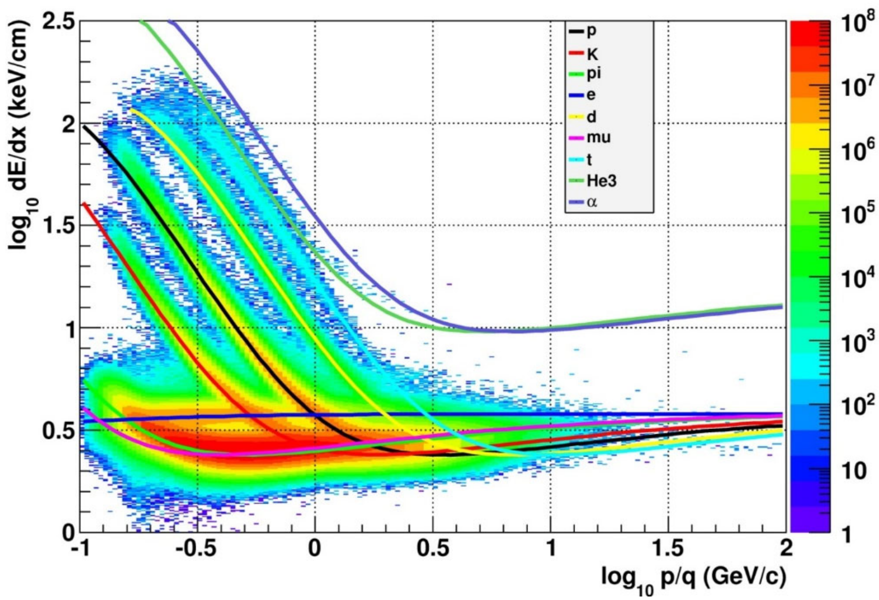
δ: density-effect correction

ρ: density

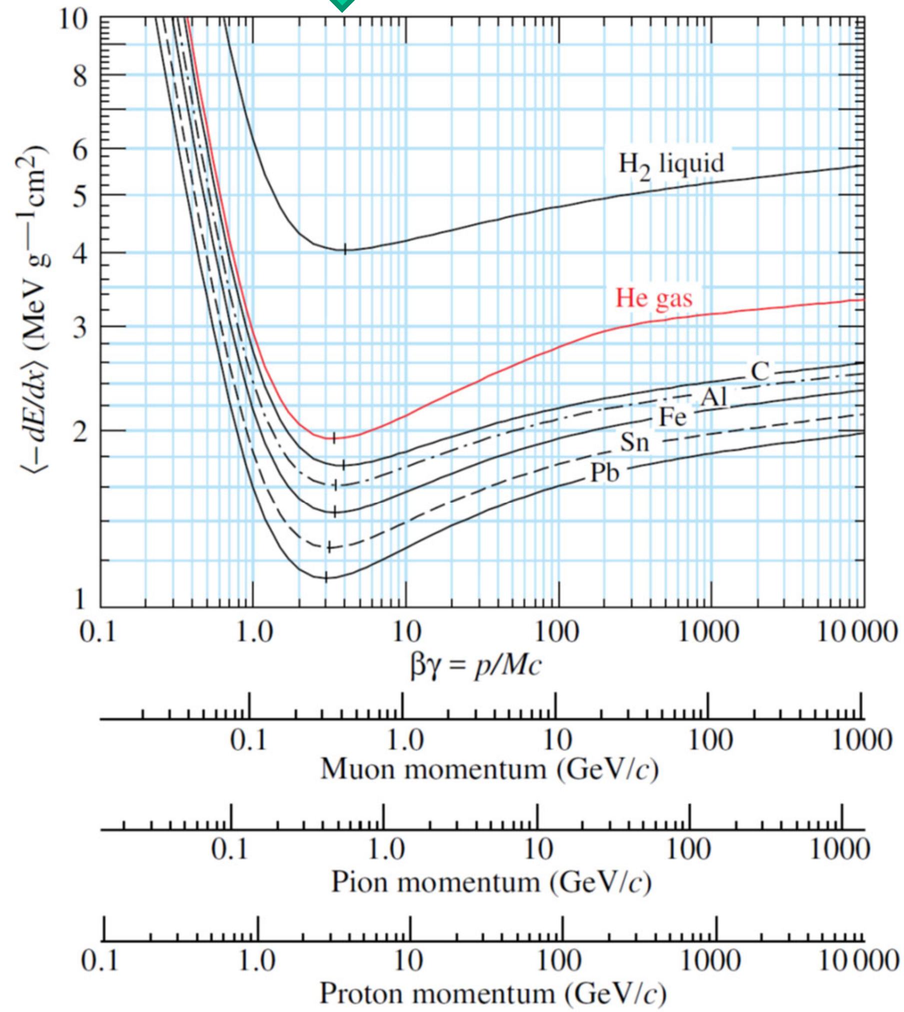


Interaction of charged particles with matter

Energy loss - as a function of momentum



Minimum ionizing particles (MIP)



Interaction of charged particles with matter

Energy loss: electrons

- Incident and target particles have the same mass (e^- and e^+)
- Incident and target particles are identical particles (e^- only)

→ modification to Bethe Bloch formula

For e^- and e^+ with E>10-30MeV the dominating process is Bremstrahlung

- Radiation of a photon from an electron accelerated in the field of an atom

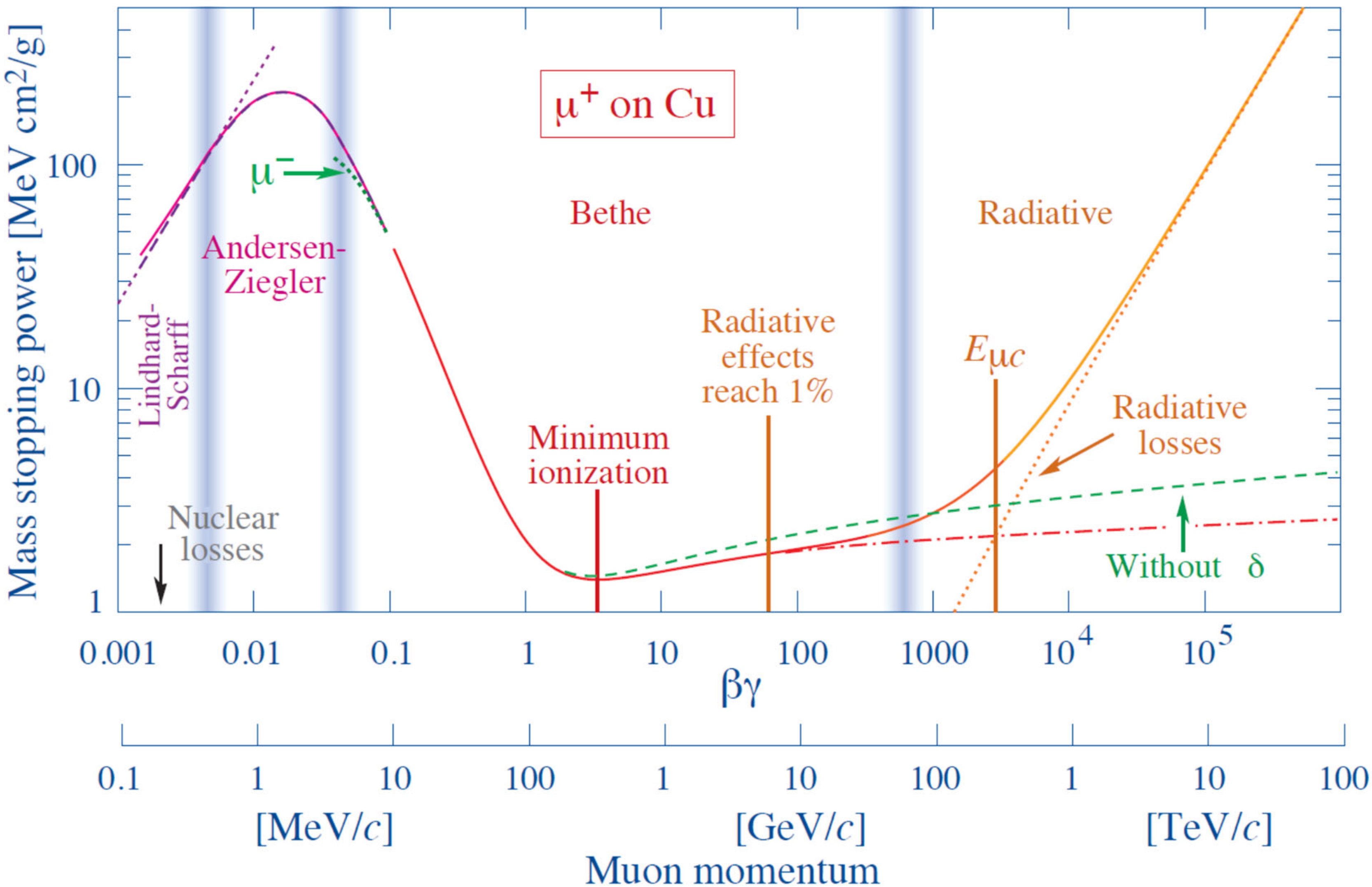
$$-\frac{dE}{dx} = 4\alpha N_A \frac{z^2 Z^2}{A} \left(\frac{1}{4\pi\epsilon_0} \frac{e^2}{mc^2} \right)^2 E \ \ln \frac{183}{Z^{\frac{1}{3}}}$$

- Proportional to E/X_0 , only relevant for electrons (and very energetic muons).
- X_0 is called "radiation length"

$$X_0 = \frac{A}{4\alpha N_A \ Z^2 r_e^2 \ \ln \frac{183}{Z^{\frac{1}{3}}}}$$

Interaction of charged particles with matter

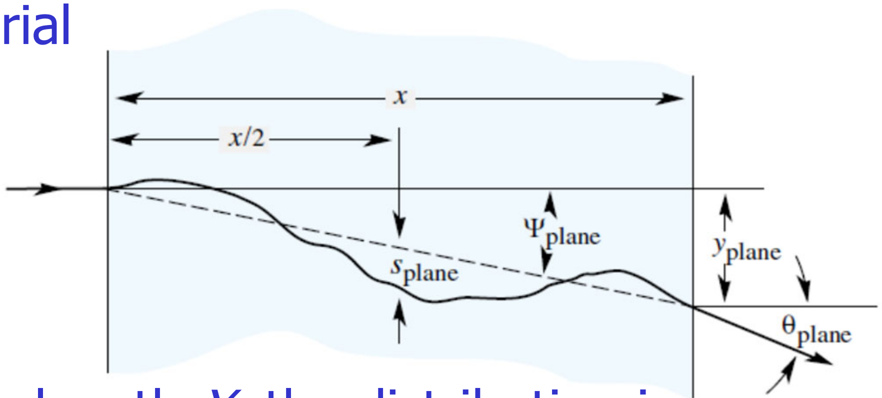
Energy loss: muons



Interaction of charged particles with matter

Multiple scattering

- Many scattering events in the Coulomb field of the nuclei → uncertainty in the direction after traversing the material



- For material of thickness *x* and radiation length X_0 the distribution is approximately

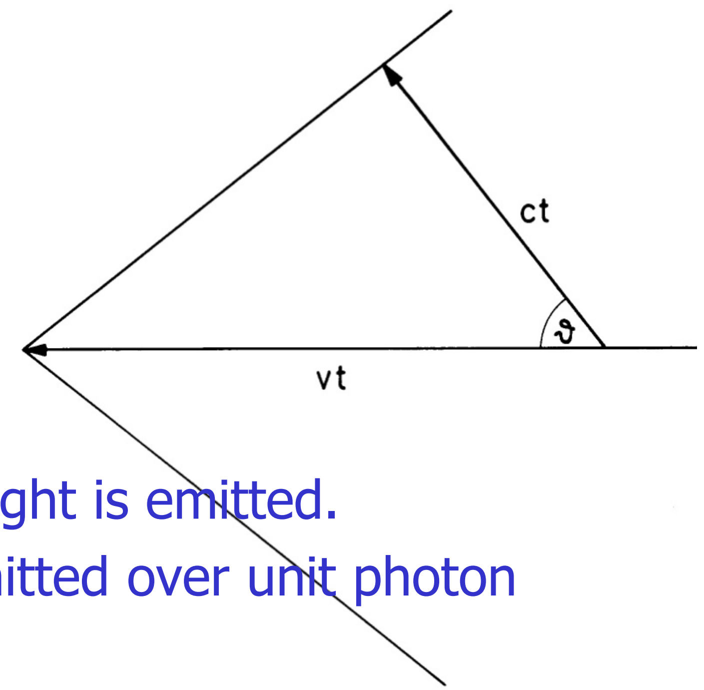
$$\frac{1}{\sqrt{2\pi}\,\theta_0} \exp\left(-\frac{\theta_{\rm plane}^2}{2\theta_0^2}\right) d\theta_{\rm plane},$$

with
$$\theta_0 = \frac{13.6\ {\rm MeV}}{\beta c p}\, z \sqrt{\frac{x}{X_0}}\left[1 + 0.088 \log_{10}\left(\frac{x\, z^2}{X_0 \beta^2}\right)\right]$$

Interaction of charged particles with matter: Cherenkov radiation

A charged track with velocity $v=\beta c$ exceeding the speed of light c/n in a medium with refractive index n emits polarized light at a characteristic (Cherenkov) angle,

$$\cos\theta = c_0/nv = 1/\beta n$$



Two cases:

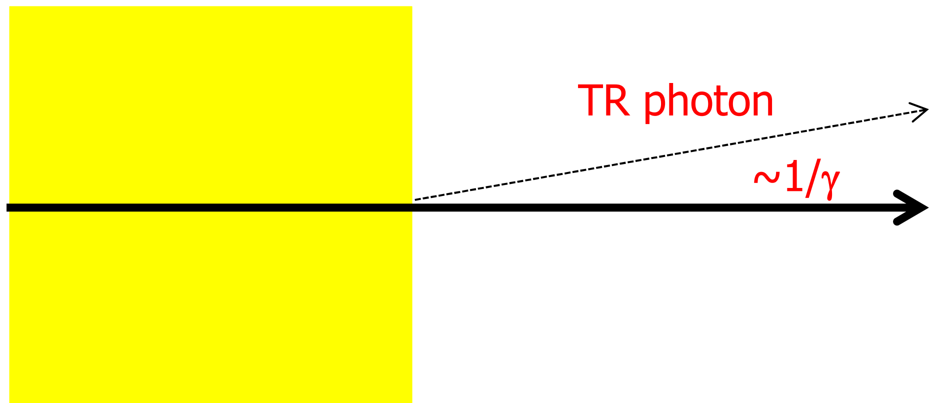
→ $\beta < \beta_t = 1/n$: below threshold no Cherenkov light is emitted.

→ $\beta > \beta_t$: the number of Cherenkov photons emitted over unit photon energy E=hν in a radiator of length ***L***:

$$\frac{dN}{dE} = \frac{\alpha}{\hbar c} L \sin^2\theta = 370(cm)^{-1}(eV)^{-1} L \sin^2\theta$$

Interaction of charged particles with matter: Transition radiation

Electromagnetic radiation emitted by a charged particle at the boundary of two media with different refractive indices



Analogy:

- Accelerated particle emits E.M. radiation
- Transition radiation: particle has a constant velocity, but the phase velocity of the medium changes abruptly at the boundary → radiation

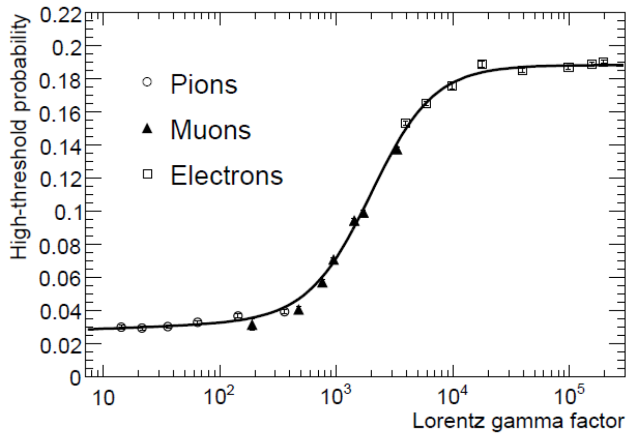
Emission rate depends on γ (Lorentz factor): becomes important at γ~1000

- Electrons at 0.5 GeV, pions above 140 GeV

Emission probability per boundary ~α = 1/137

Emission angle ~$1/\gamma$

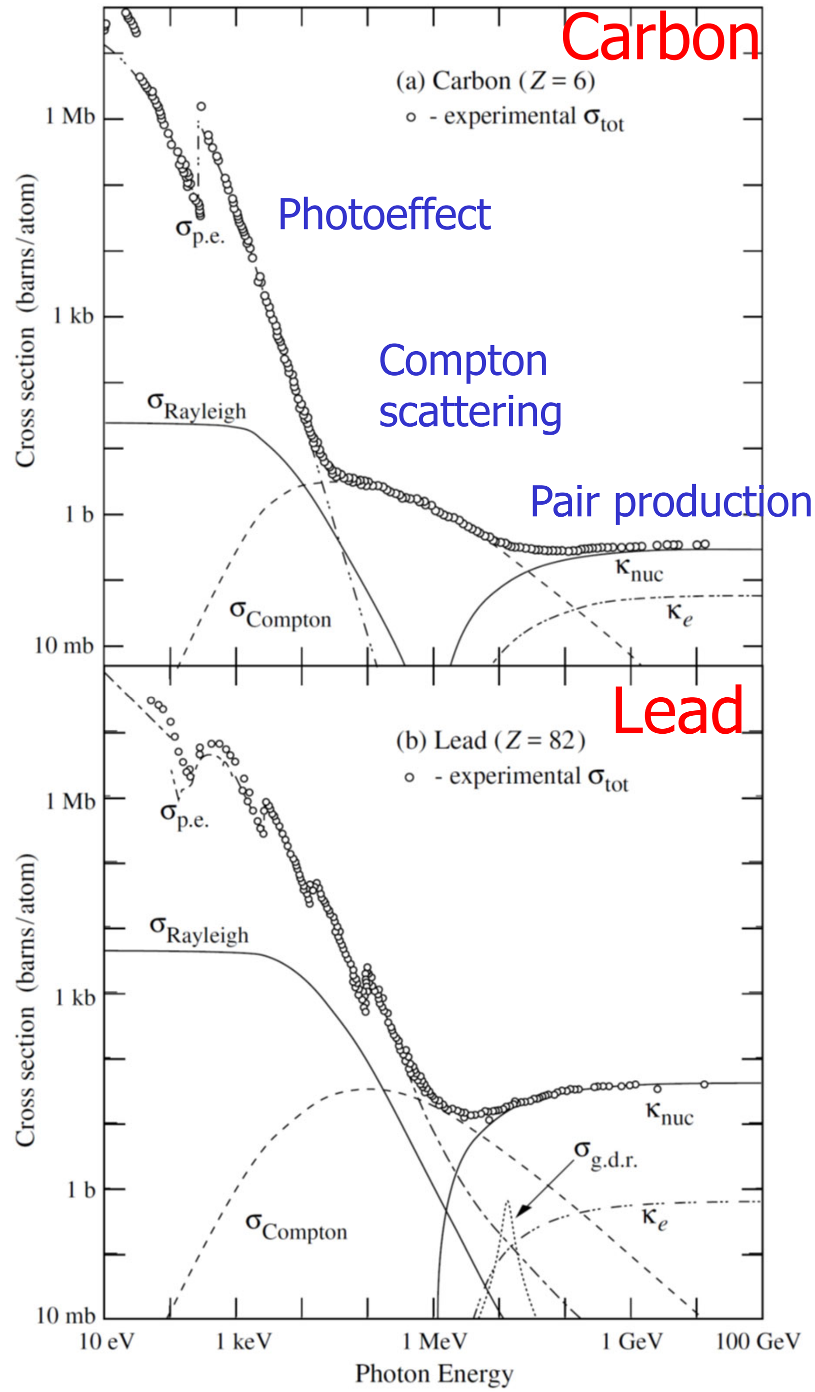
Typical photon energy: ~10 keV → X rays



Interaction of photons with matter

Three processes

- Photoeffect: γ is absorbed in an atom, electron is kicked out
- Compton scattering: γ is elastically scattered off a ~free electron
- Pair production: an e^+ e^- pair is produced in the electric field of the nucleus.



Interaction of neutrinos

Neutrinos only interact weakly.

For detection of neutrinos, make use of the inverse beta decay

$\nu_e + n \rightarrow p + e^-$

$\bar{\nu}_e + p \rightarrow n + e^+$

However: cross section is very small!

$6.4\ 10^{-44}\ cm^2$ at 1MeV

Probability for interaction in 100m of water = $4\ 10^{-16}$

$\nu_\mu + n \rightarrow p + \mu^-$

$\bar{\nu}_\mu + p \rightarrow n + \mu^+$

$\nu_\tau + n \rightarrow p + \tau^-$

$\bar{\nu}_\tau + p \rightarrow n + \tau^+$

Interaction cross section for high energy neutrinos

Neutrinos: $0.67\ 10^{-38}$ E/1GeV cm^2 per nucleon

Antineutrinos: $0.34\ 10^{-38}$ E/1GeV cm^2 per nucleon

At 100 GeV, still 11 orders below the proton-proton cross section

Detector types

- Ionisation detectors
- Semiconductor detectors
- Scintillators
- Photon detectors

Detector types

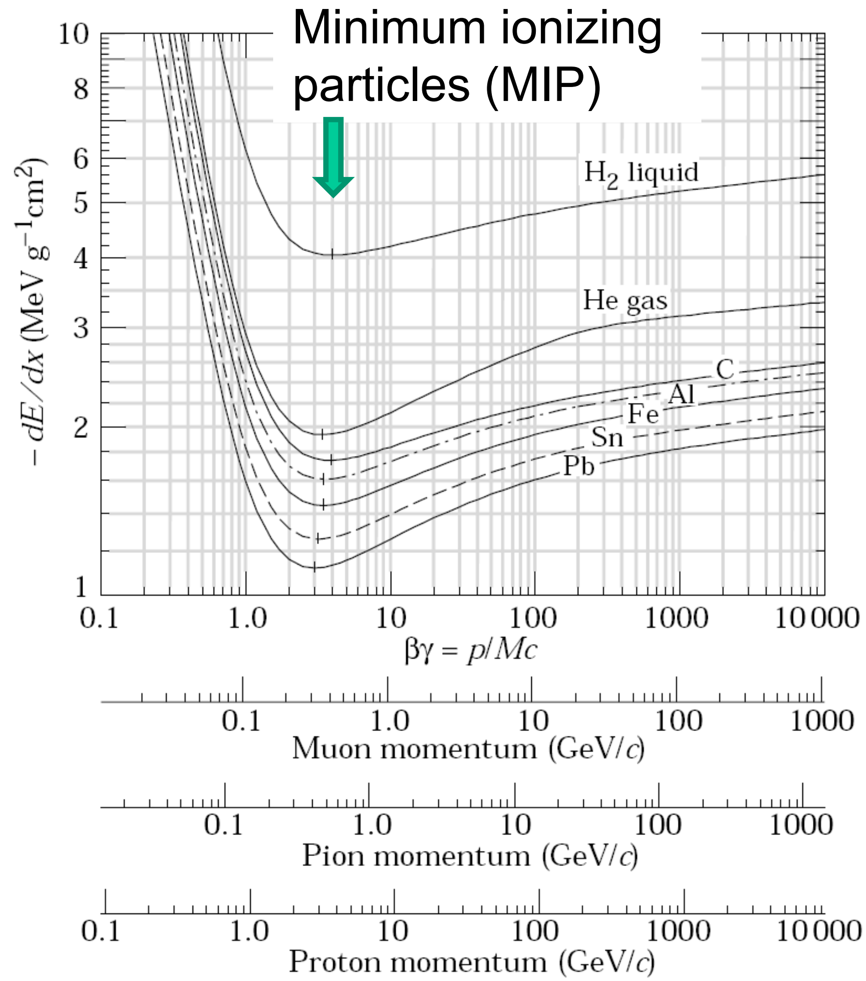
- Ionisation detectors
- Semiconductor detectors
- Scintillators
- Photon detectors

Ionisation in gases

As already discussed, energy loss of charged particles depends on βγ, typically about 2 MeV/cm ρ/(g cm^{-3}).

Liquids, solids: few MeV/cm

Gases: few keV/cm



Primary ionisation: charged particle kicks electrons from atoms.

In addition: excitation of atoms (no free electron), on average need W_i (>ionisation energy) to create e-ion pair.

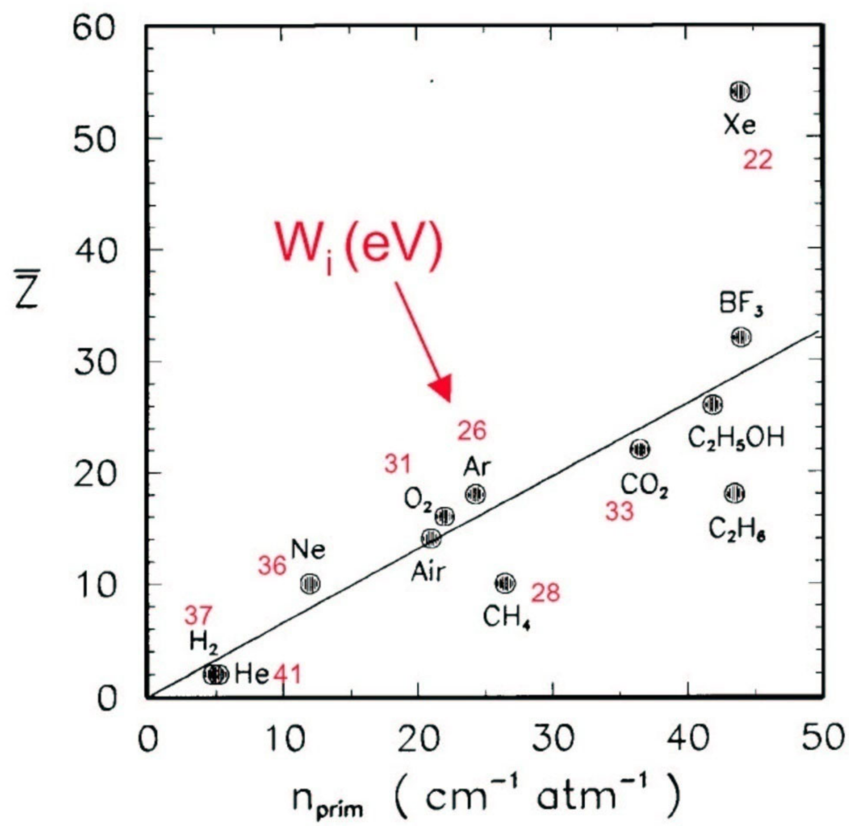
W_i typically 30eV → per cm of gas about 2000eV/30eV=60 e-ion pairs

Ionisation

n_{prim} is typically 20-50 /cm

The primary electron ionizes further: secondary e-ion pairs, typically about 2-3x more.

Finally: 60-120 electrons /cm



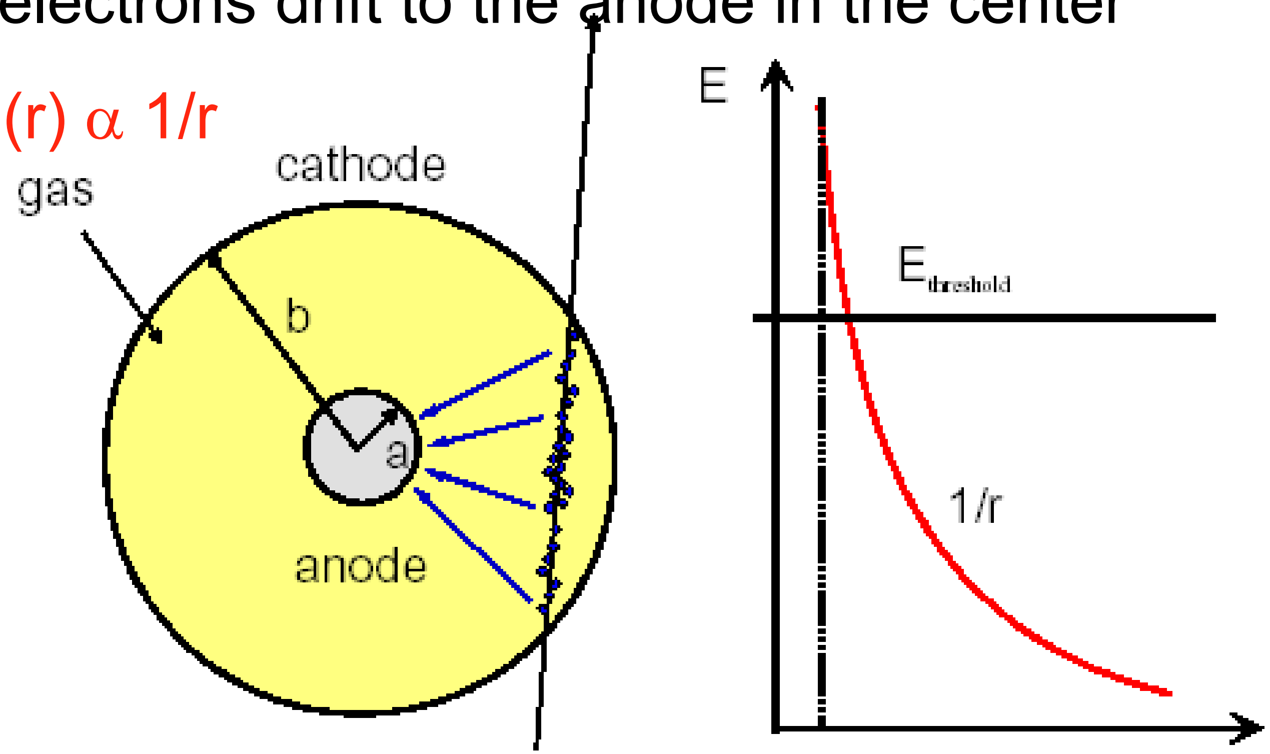
Can this be detected? 120 e-ion pairs make a pulse of $V=ne/C=2mV$ (at typical C=10pF) → NO

→ Need multiplication

Multiplication in gas

Simplest example: cylindrical counter, radial field, electrons drift to the anode in the center

$E = E(r) \propto 1/r$



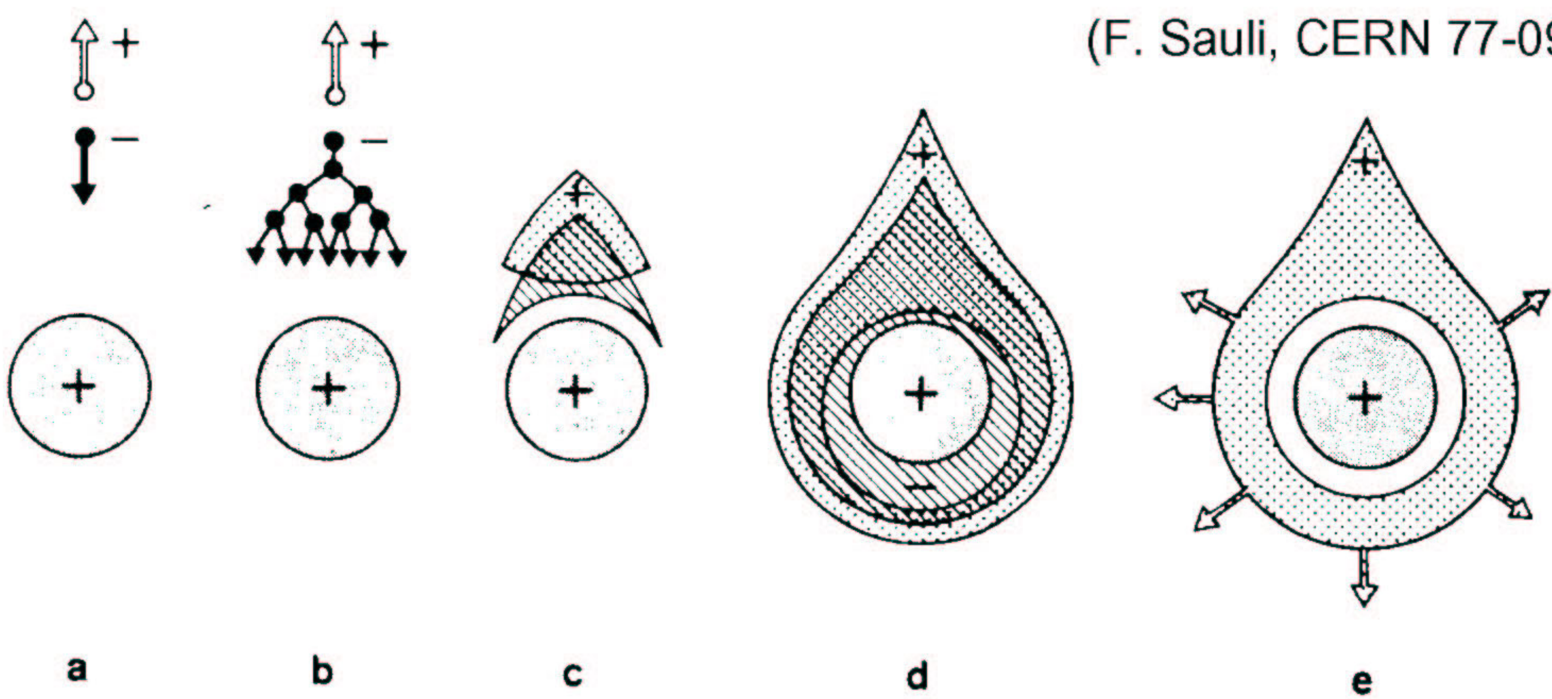
If the energy eEd gained over several mean free paths (d around 10mm) exceeds the ionisation energy → new electron

Electric field needed → E = I/ed = 10V/mm = 10kV/cm

Multiplication in gas

Electron travels (drifts) towards the anode (wire); close to the wire the electric field becomes high enough (several kV/cm), the electron gains sufficient energy between two subsequent collisions with the gas molecules to ionize → start of an avalanche.

(F. Sauli, CERN 77-09)



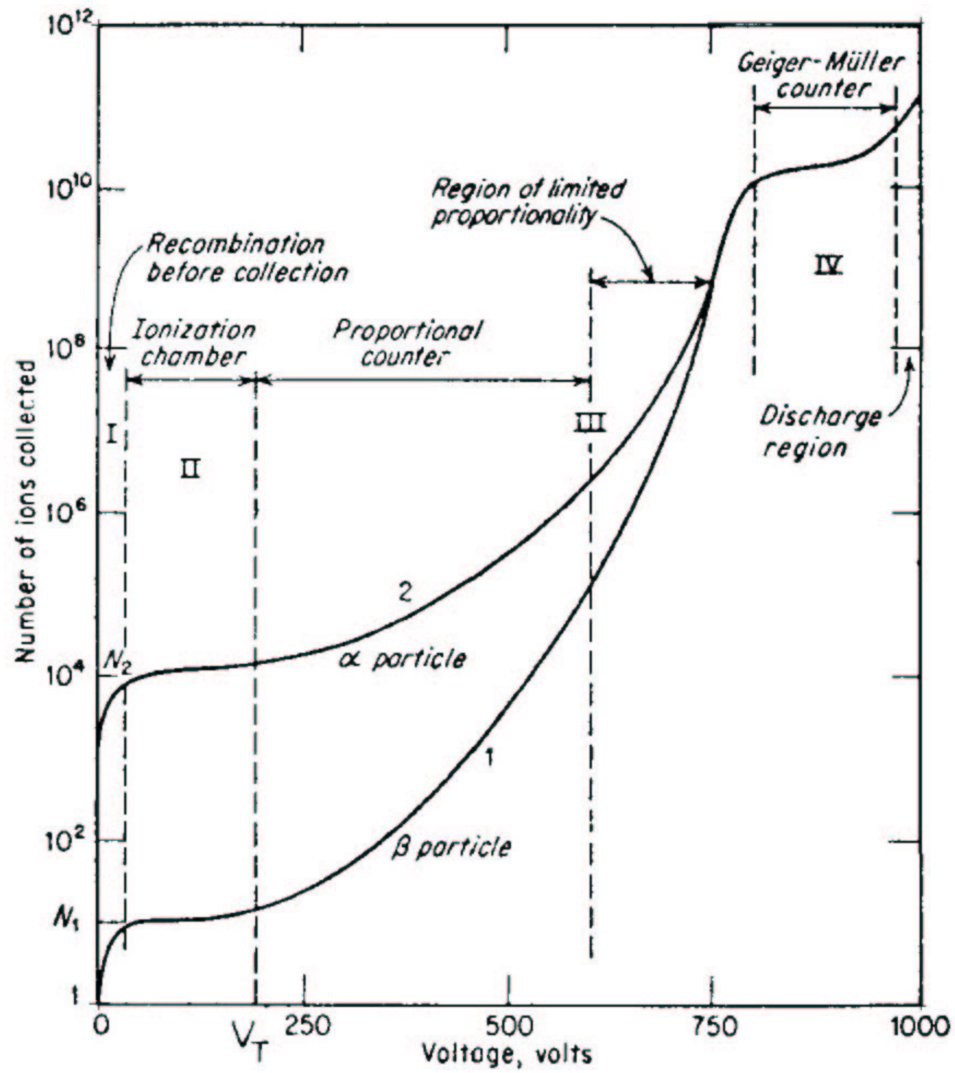
Multiplication in gas: operation modes

•Ionization mode: full charge collection, but no charge multiplication.

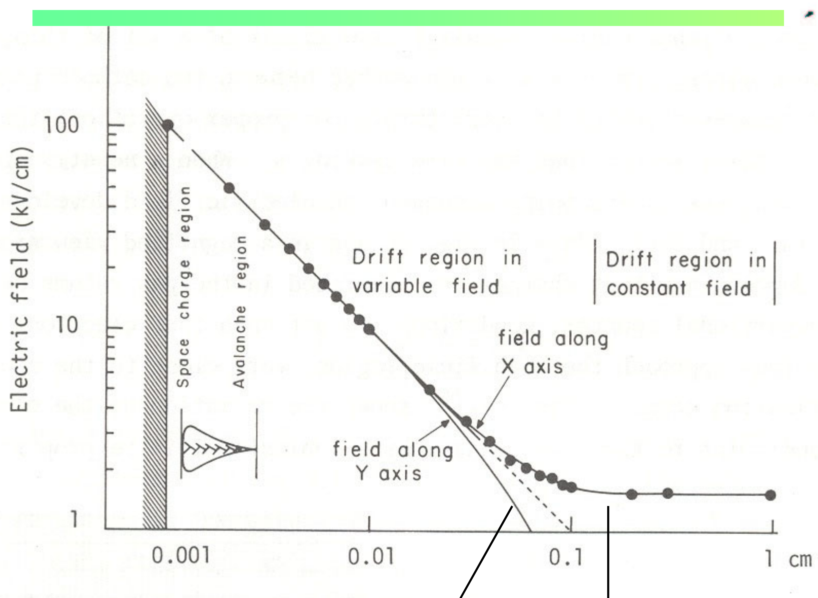
•Proportional mode: above threshold voltage V_T multiplication starts. Detected signal proportional to original ionization → energy measurement

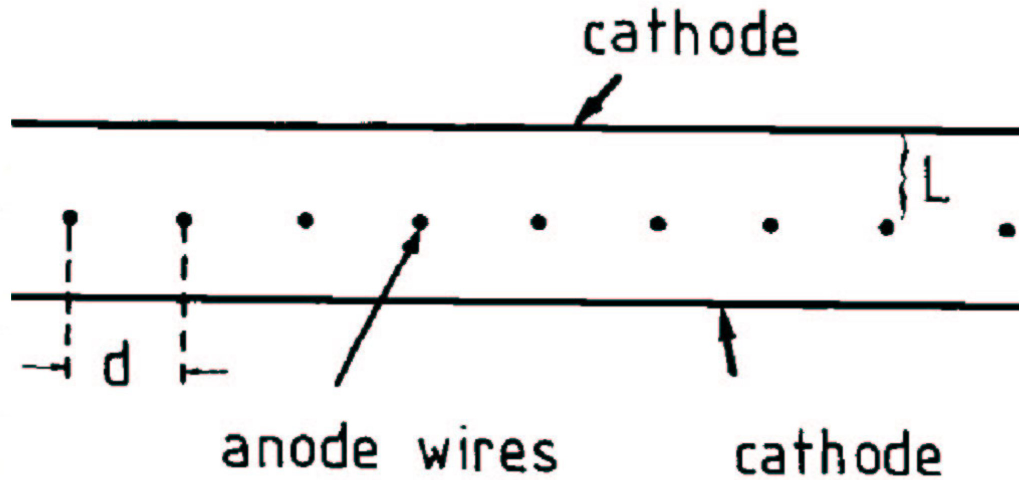
•Limited Proportional → Saturated → Streamer mode: Strong photo-emission. Secondary avalanches, merging with original avalanche. Requires strong quenchers or pulsed HV. High gain (10^{10})

•Geiger mode: Massive photo emission. Full length of anode wire affected. Stop discharge by cutting down HV. Strong quenchers needed as well. Huge signals → simple electronics.



Multiwire proportional chamber (MWPC)

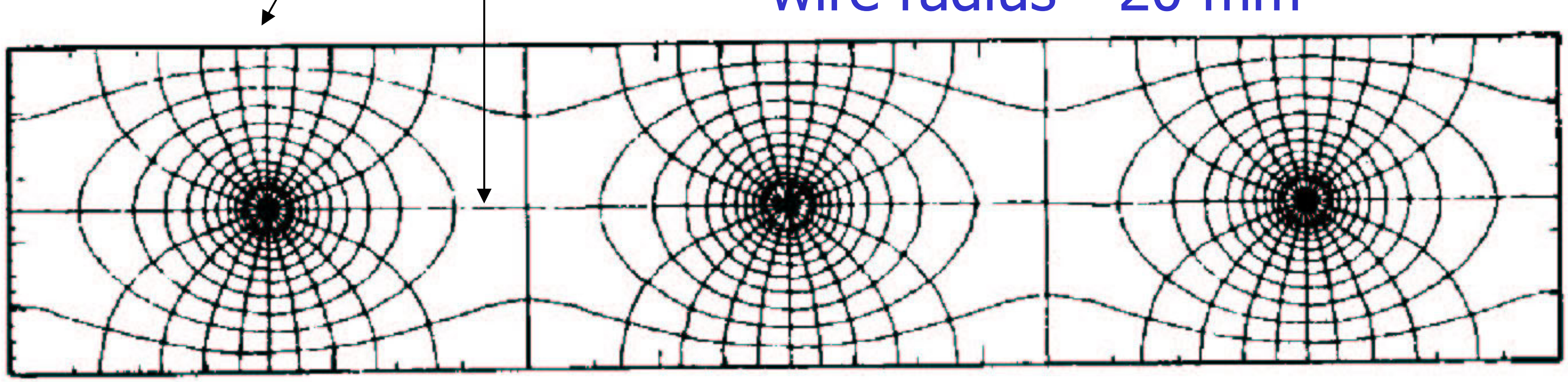




Typical parameters:

L=5mm, d=1-2mm,

wire radius =20 mm



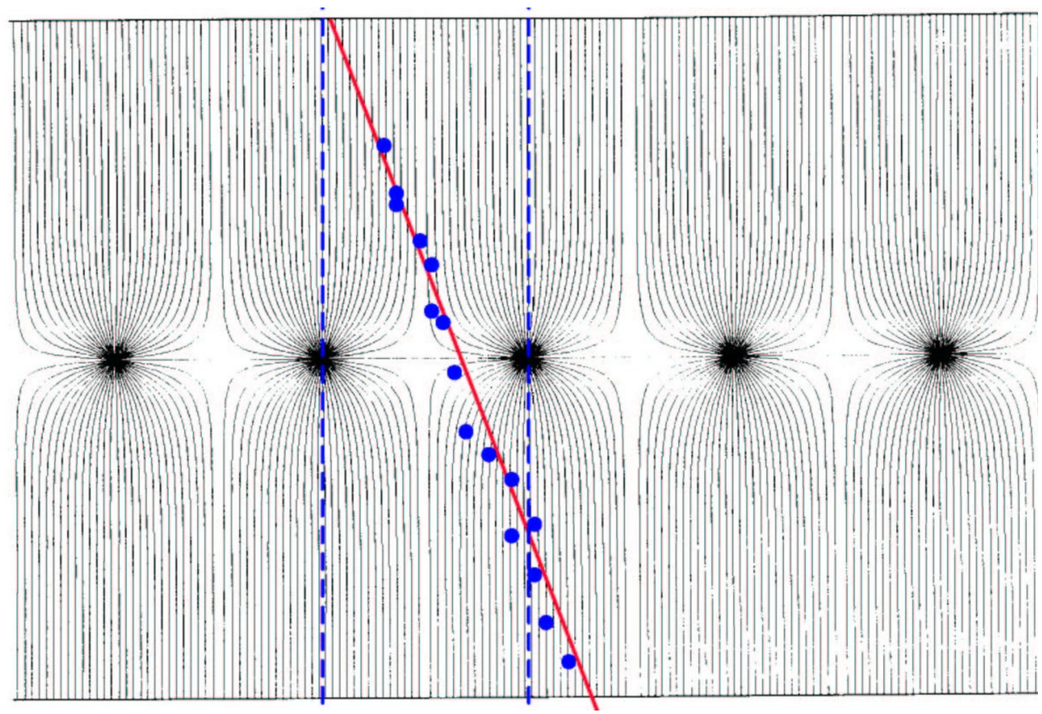
Multiwire proportional chamber (MWPC)

The address of the fired wire gives only 1-dimensional information.

Normally digital readout: spatial resolution limited to

$\sigma = d/\mathrm{sqrt}(12)$

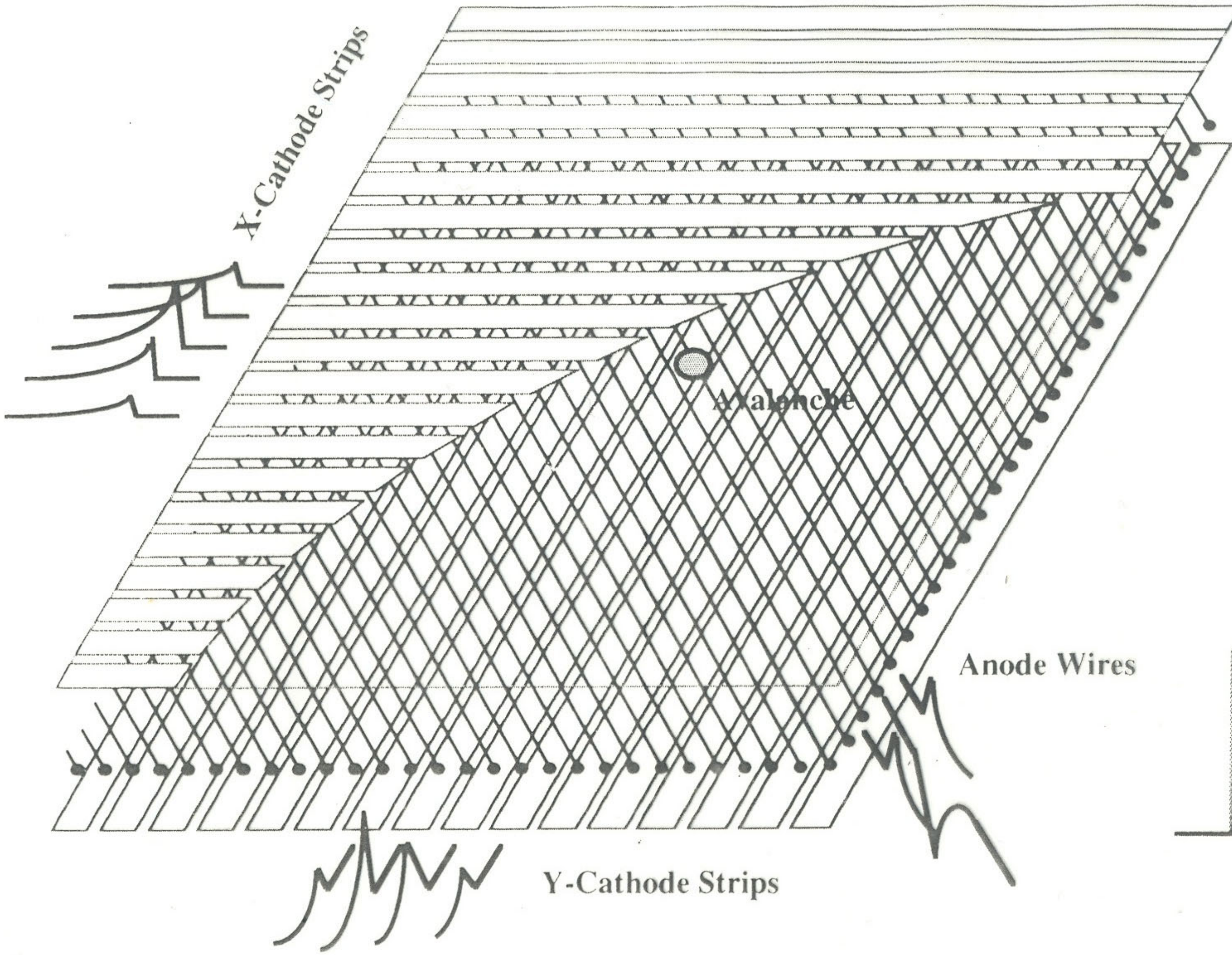
for d=1mm → σ =300 mm

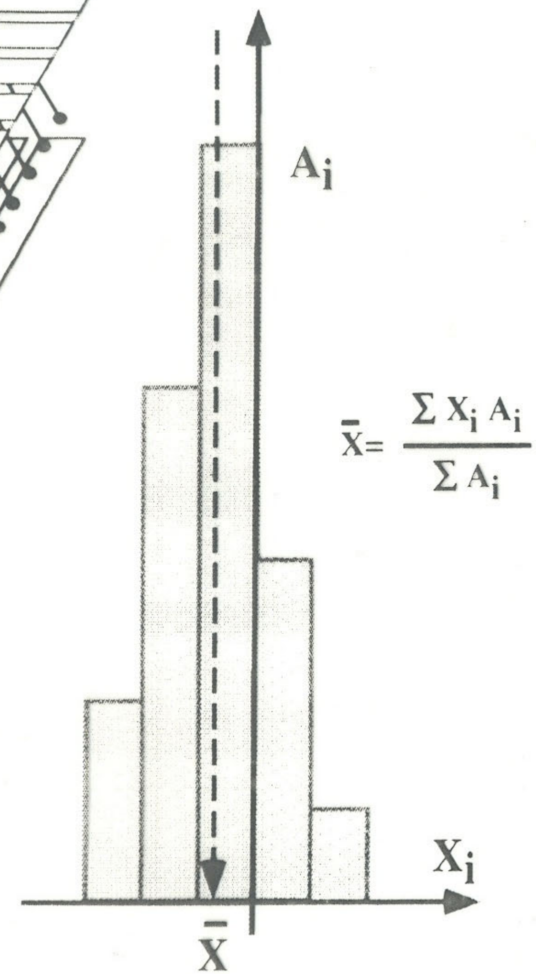


Revolutionized particle physics experiments
→ Nobel prize for G. Charpak

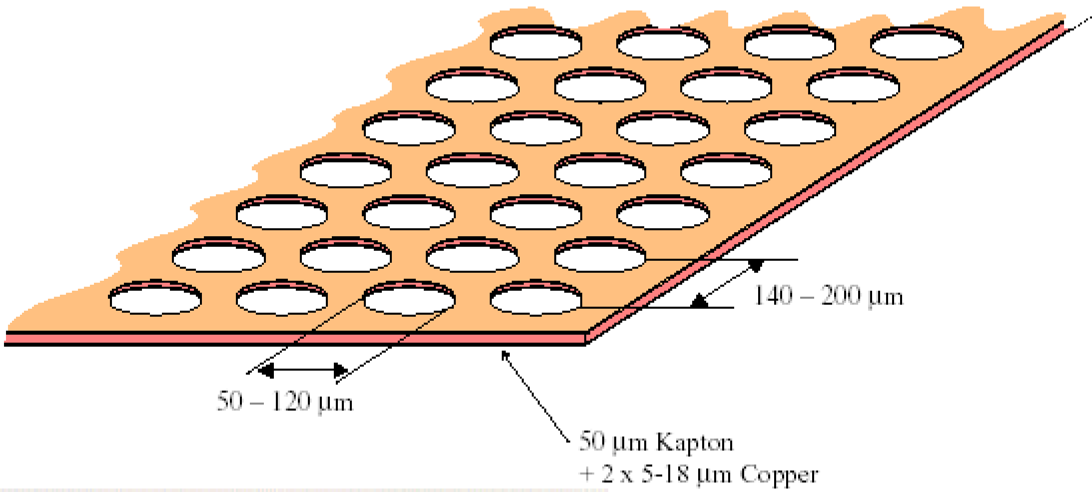
Two dimensional read-out: use cathode strips

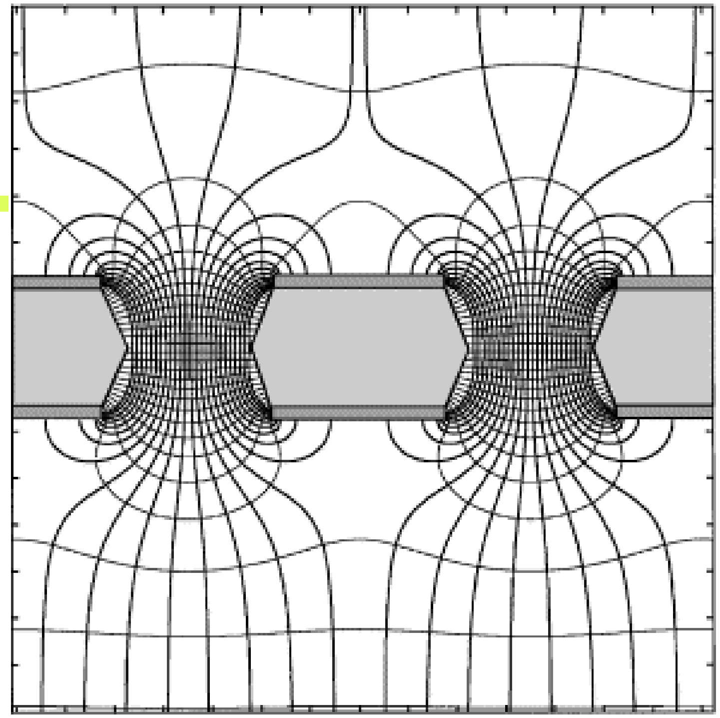
Fabio Sauli-NSS98

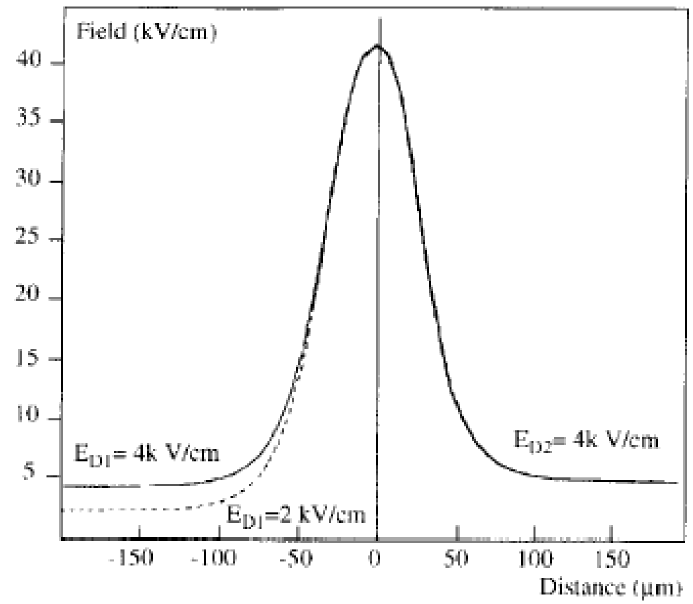




GEM (gas electron multiplier) preamplification





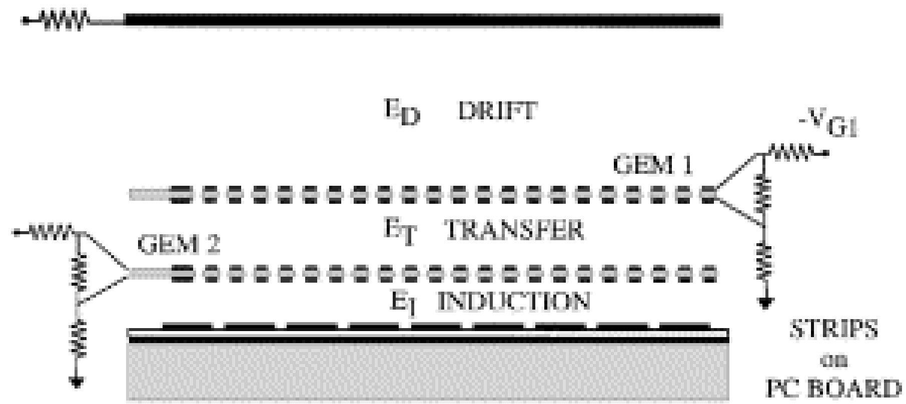


The E field in the holes is non-uniform – large enough to get gas amplification of about 100.

Micro-pattern gas detectors

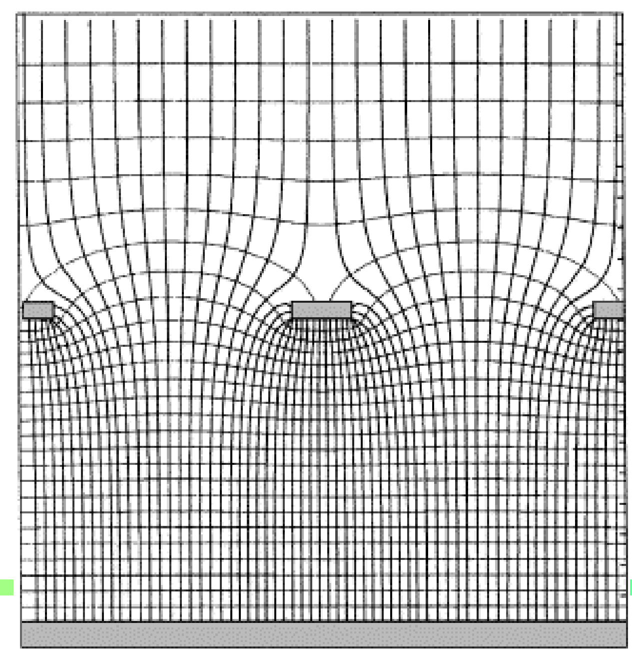
Multiple GEMs + pads

Two amplificatin stages in gas: 2xGEM, cathode with pads for read-out.



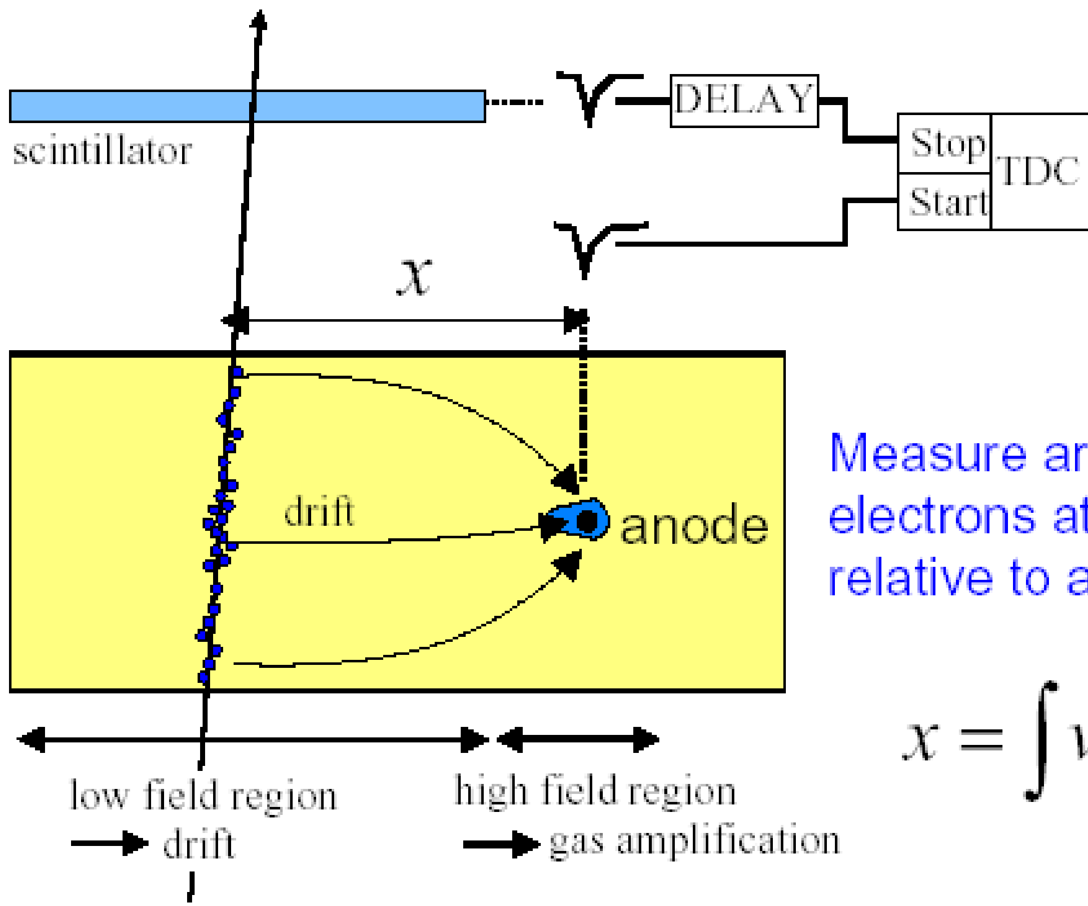
MICROMEGAS

Instead of the GEM foil use a mesh of thin wires. The effect is similar.



Drift chamber

Improve resolution by measuring the drift time of electrons



Measure arrival time of electrons at sense wire relative to a time t_0.

$$x = \int v_D(t)\,dt$$

Drift chamber: resolution

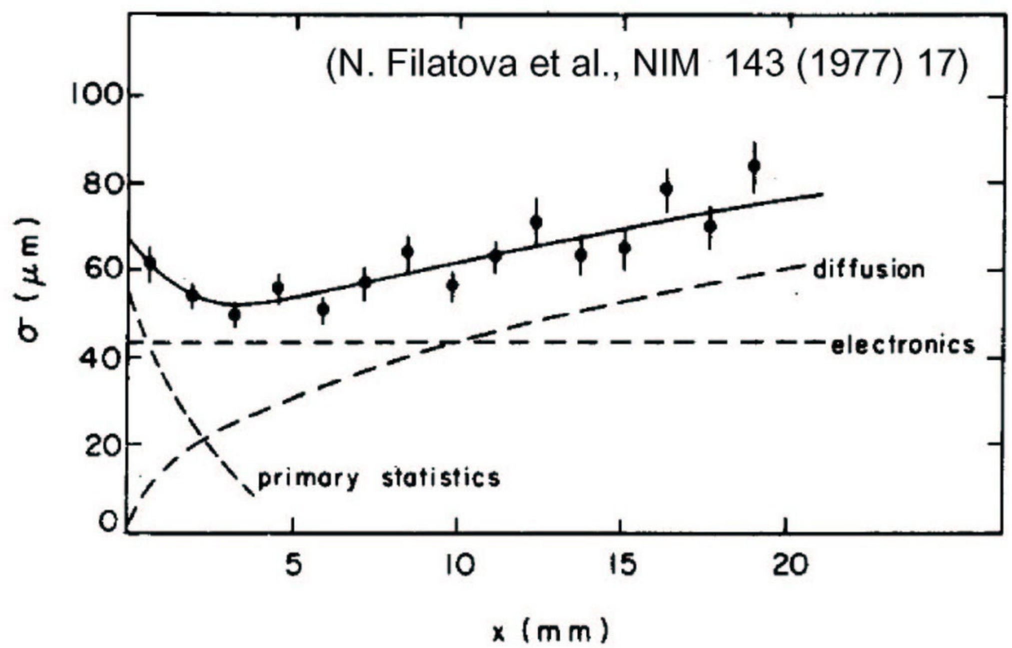
Resolution determined by

- diffusion,
- primary ionisation statistics,
- electronics,
- path fluctuations.

Diffusion: $\sigma_x \propto \sqrt{Dt} \propto \sqrt{x}$

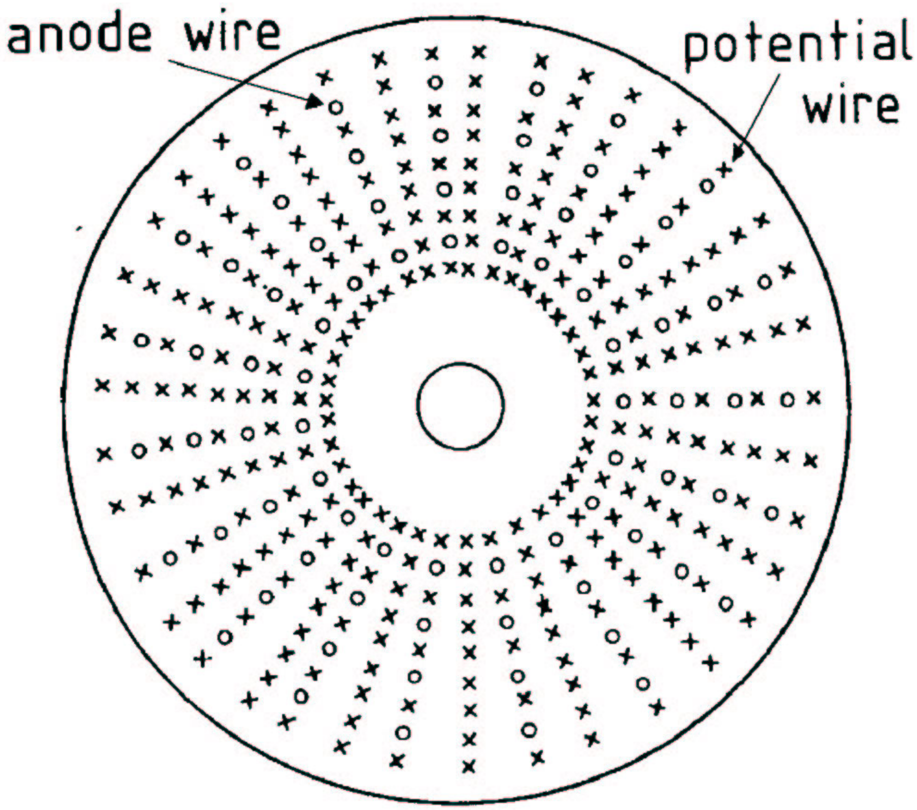
Primary ionisation statistics: if *n* e-ion pairs are produced over distance L, the probability that the first one is produced at x from the wire is $e^{-nx/L}$

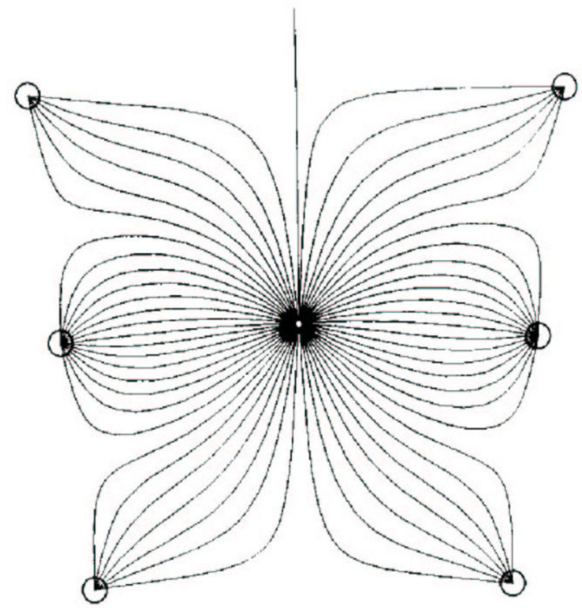
Resolution as a function of drift distance



Drift chamber with small cells

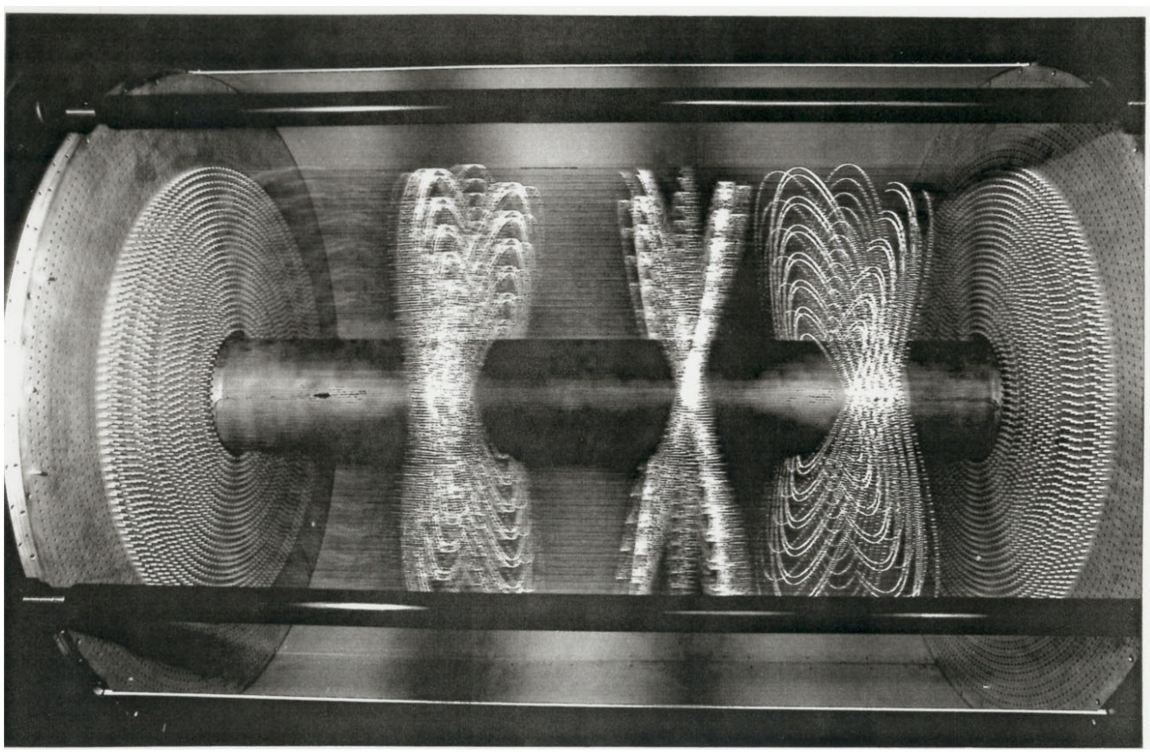
One big gas volume, small cells defined by the anode and field shaping (potential) wires

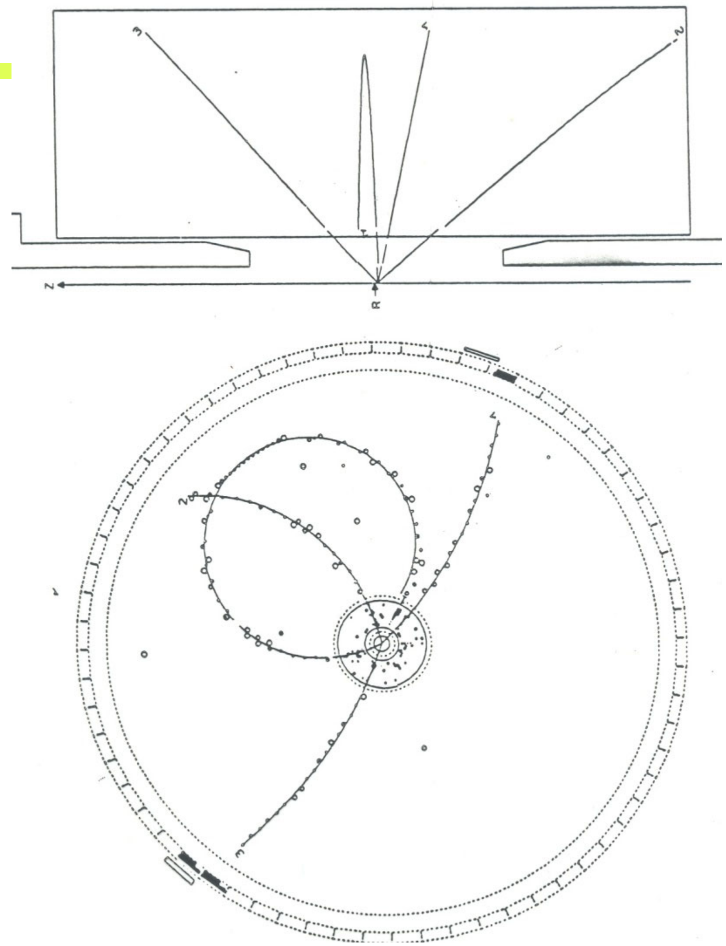




Drift chamber with small cells

Example: ARGUS drift chamber with axial and ‘stereo’ wires (at an angle to give the hit position along the main axis)

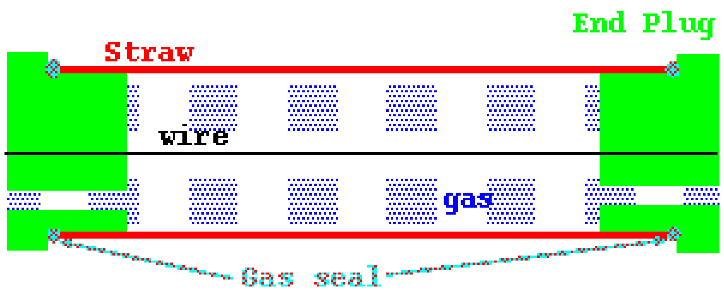




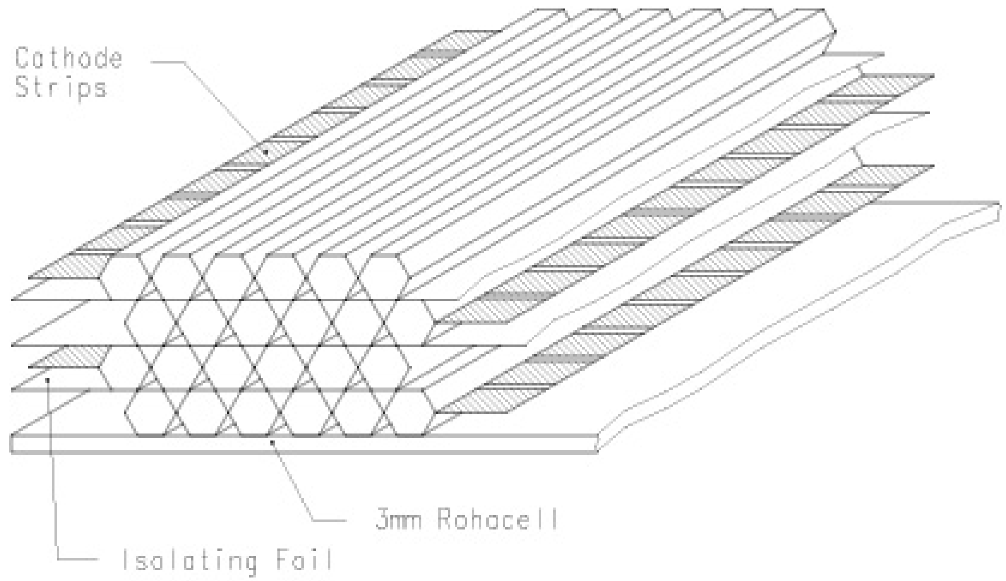
Typical event in two projections

Single cell drift chamber

Simplify manufacturing: put each wire in a tube (straw or hexagonal); useful for large areas.



Cells can be several meters long!



Diffusion and mobility of electrons in magnetic field

E perpendicular to B

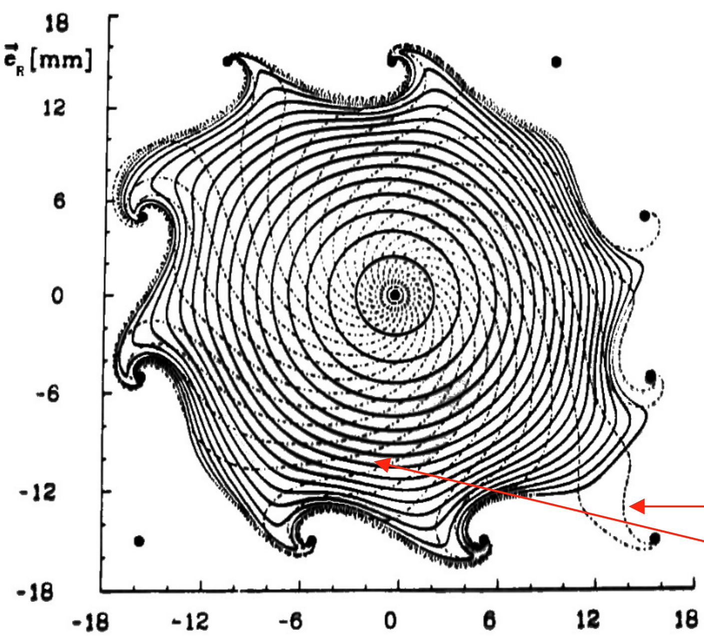
Lorentz force perpendicular to B → net drift at an angle α to E

$tg\alpha = \omega\tau$

α: Lorentz angle

ω: cyclotron frequency, $\omega = eB/m$

τ: mean time between collisions



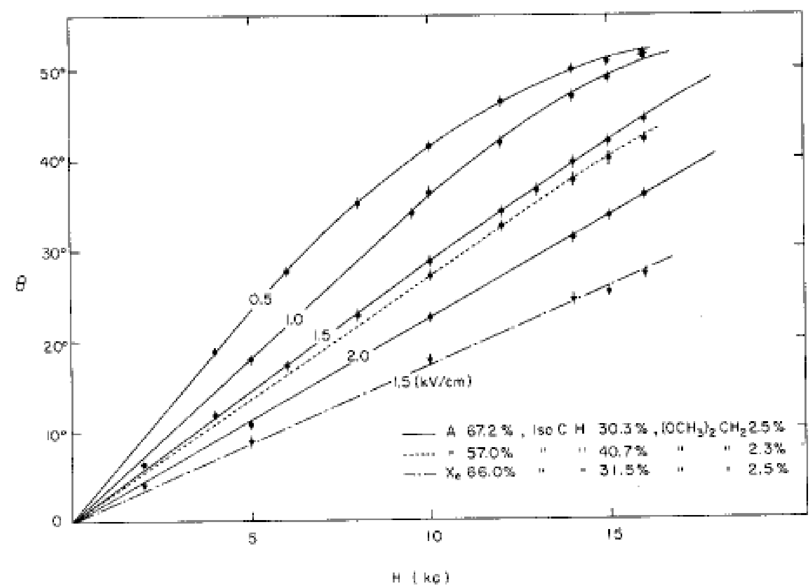


Fig. 38 Measured drift angle (angle between the electric field and the drift directions) as a function of electric and magnetic field strength[9].

Drift lines in a radial E field (dash-dotted)

Isochrones (full lines)

Diffusion and mobility of electrons in magnetic field 2

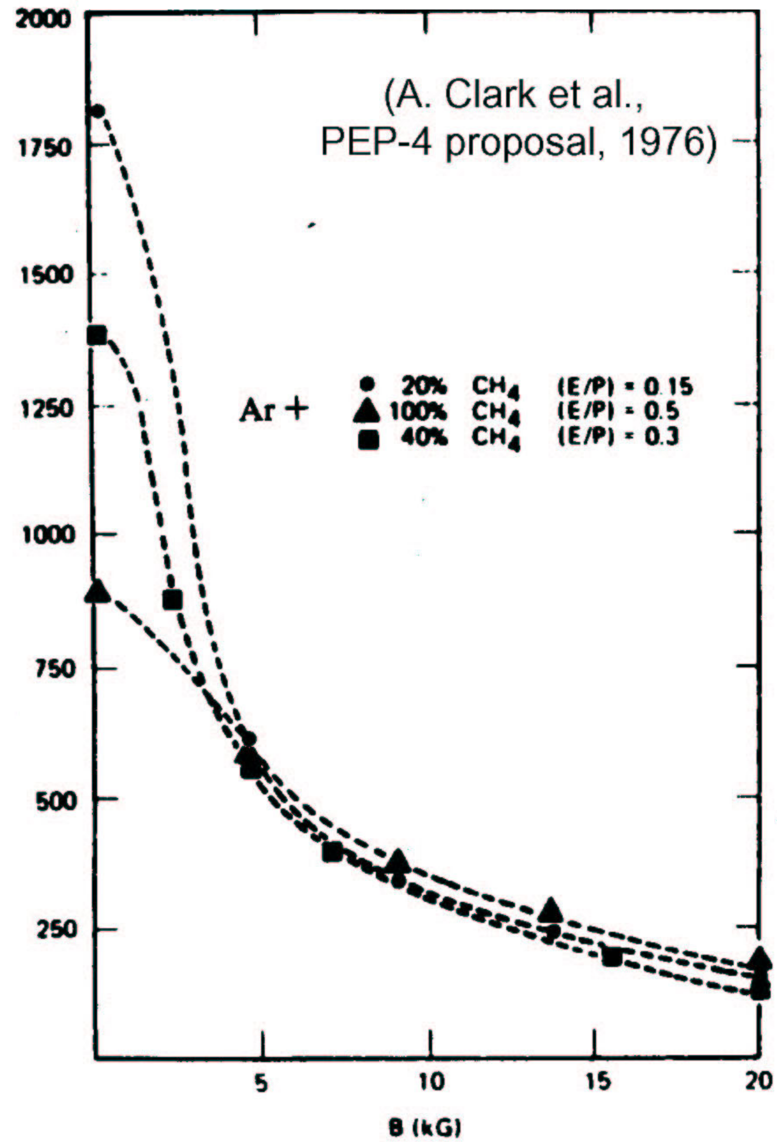
E and B parallel:

drift along E, diffusion in the transverse direction reduced! – departing electrons get curled back:

$$D_T(B) = D_0/(1 + \omega^2\tau^2)$$

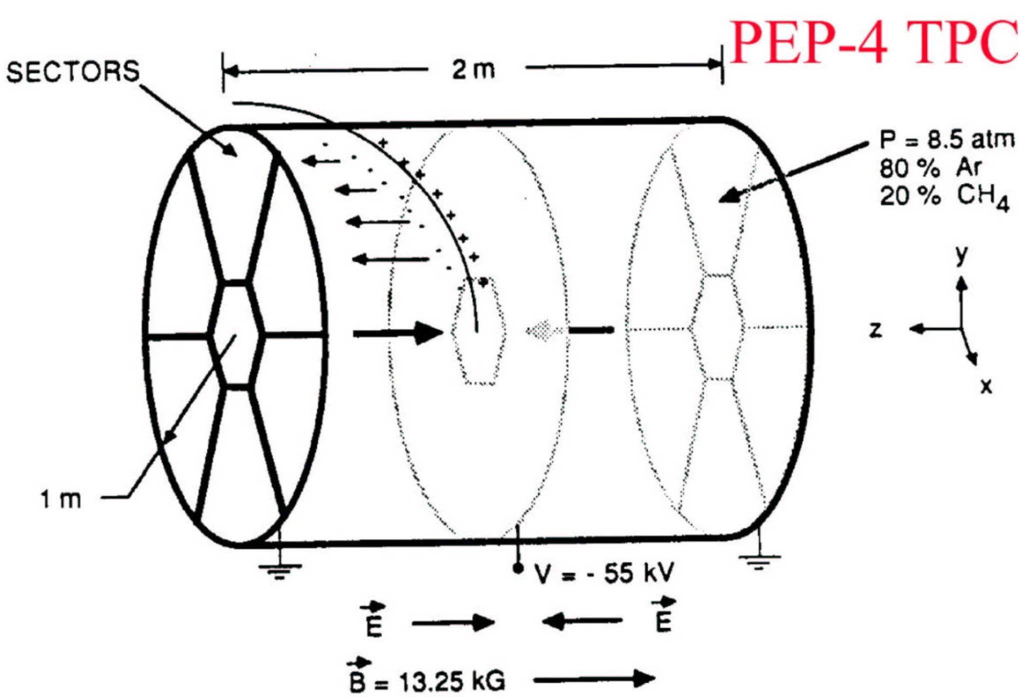
→ Less diffusion in the tranversal direction!

σ (μm) for 15cm drift distance



Drift chamber: TPC – time projection chamber

3-dimensional information: drift over a large distance, 2 dim. read-out at one side



Diffusion: no problem for the tranverse coordinate in spite of the very long drift distance because B parallel to E (drift direction).

Drift chamber: TPC – time projection chamber

z coordinate (along the E, B field): from drift time

2 dim. (x,y) read-out at one side:

- Anode wires and cathode pads
- Anode wires and cathode strips (perpendicular)

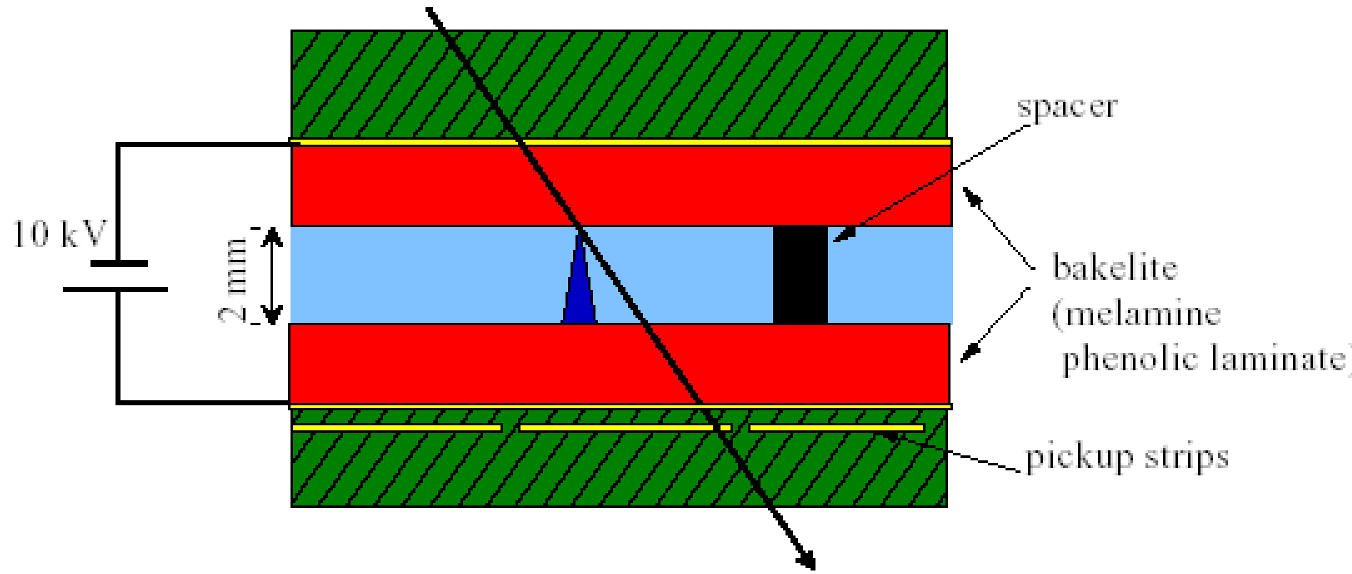
Resolutions for the ALEPH TPC (d=3.6m, L=4.4m):

in x,y: 173 μm, in z: 740 μm.

Potential problems:

- need an excellent drift velocity monitoring (long drift distance)
- high quality gas (long drift distance)
- space charge: ions drifting back to the cathode

Resistive plate chamber (RPC)



- Ionization chamber operated in avalanche or streamer mode
- Gas gap typically 2mm; $C_2F_4H_2$, (C_2F_5H) + few % isobutane
- Resistive electrodes made of bakelite or glass.
- Signal induced on readout electrode

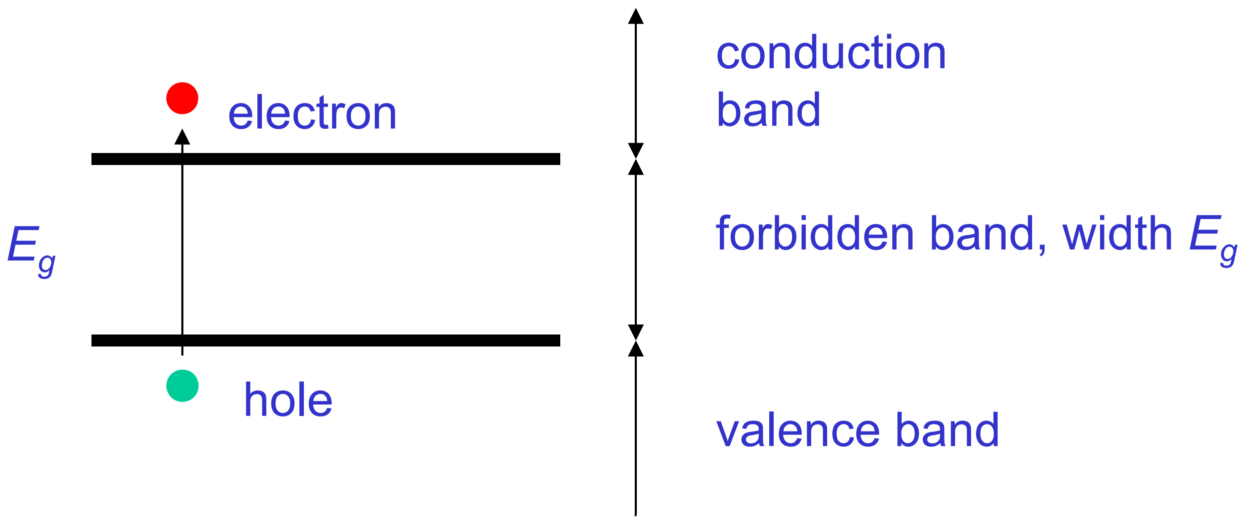
Excellent timing (~1ns), can cover large areas

Detector types

- Ionisation detectors
- Semiconductor detectors
- Scintillators
- Photon detectors

Semiconductor detectors

Semiconductor detector operates just like an ionisation chamber: a particle that we want to detect, produces a free electron–hole pair by exciting an electron from the valence band.



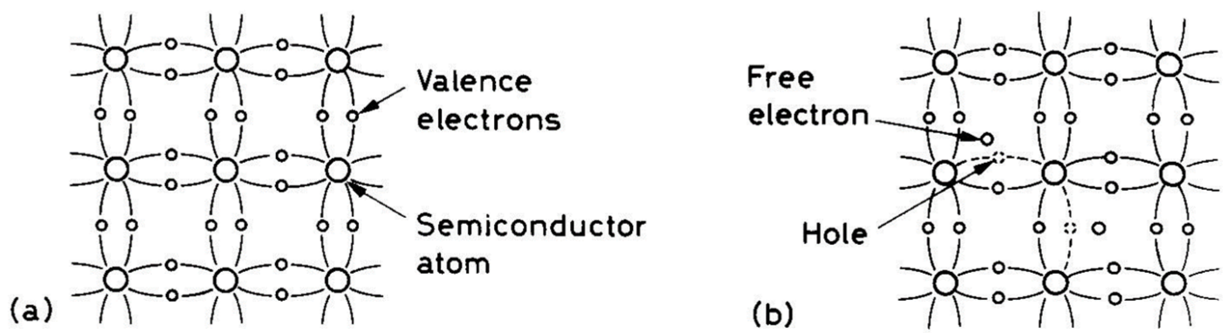


Fig. 10.2. Covalent bonding of silicon: **(a)** at 0 K, all electrons participate in bonding, **(b)** at higher temperatures some bonds are broken by thermal energy leaving a *hole* in the valence band

Properties of semiconductors

	ρ [kg dm^{-3}]	ε	E_g [eV]	μ_e [cm^{2}V^{-1}s^{-1}]	μ_h [cm^{2}V^{-1}s^{-1}]
Si	2.33	11.9	1.12	1500	450
Ge	5.32	16	0.66	3900	1900
C	3.51	5.7	5.47	4500	3800
GaAs	5.32	13.1	1.42	8500	400
SiC	3.1	9.7	3.26	700	
GaN	6.1	9.0	3.49	2000	
CdTe	6.06		1.7	1200	50

Signal vs background

Assume a gamma ray of E=370 keV is absorbed through photo-effect in a Si detector

The number of electron-hole pairs is 370keV / 3.7eV = 10^5

Number of electrons in the conduction band is (at room temperature) $1.4\ 10^{10}$ in cm^3

→ Need a material free of charge carriers

→ Combination of the differently doped Si crystals (p-n junction) with a bias voltage

Properties of semiconductors are modified if we add impurities

- **Donor levels** → neutral, if occupied
  charged +, if not occupied
- **Acceptor levels** → neutral, if not occupied
  chargedi -, if occupied

shallow acceptors – close to the valence band (e.g. three-valent atoms in Si – examples B, Al)

shallow donors – close to the conduction band (e.g. five-valent atoms in Si – examples P, As)

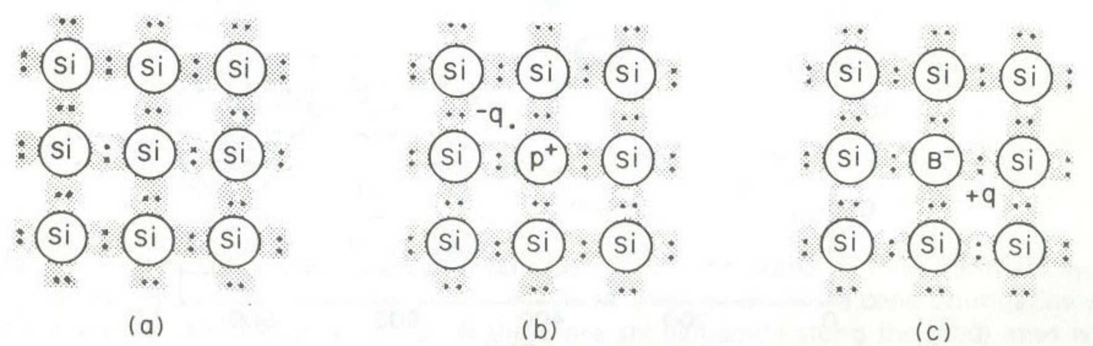
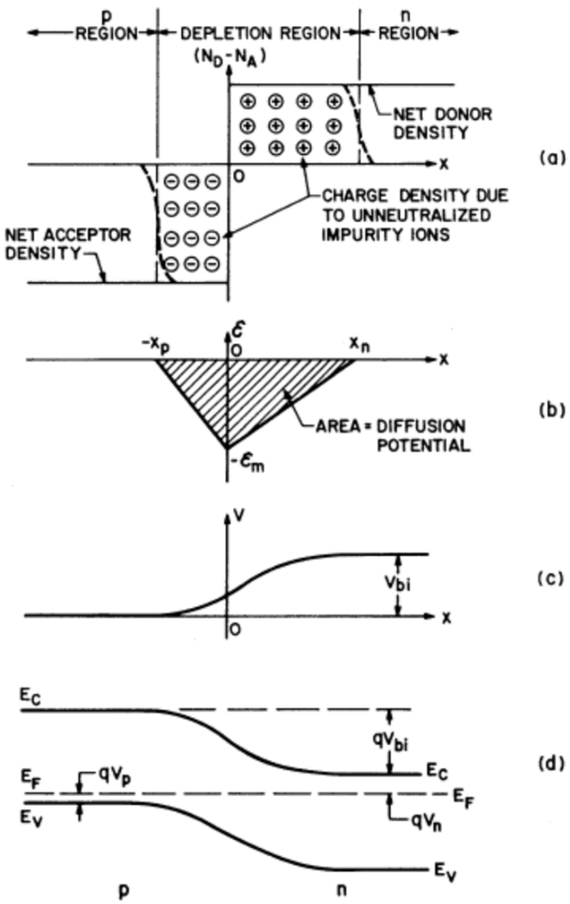


Fig. 9 Three basic bond pictures of a semiconductor. (*a*) Intrinsic Si with negligible impurities. (*b*) *n*-type Si with donor (phosphorus). (*c*) *p*-type Si with acceptor (boron).

p-n structure



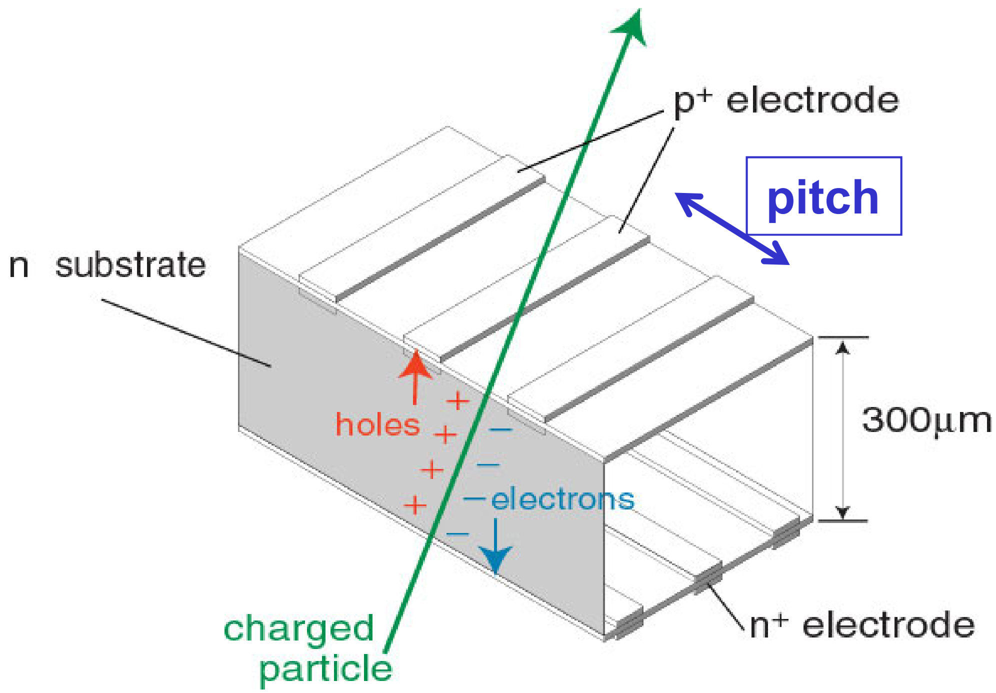
- At the p-n interface we have an inhomogenous concentration of electrons and holes → difussion of electrons in the p direction, and of holes into the n direction

  At the interface we get an electric field

  Potential difference: V_{bi} = built-in voltage difference, order of magnitude 0.6V

The thickness of the depleted region can be increased by applying a bias voltage in the reverse direction (increases as $V_{bias}^{1/2}$) → The depleted region should cover most of the detector volume.
The ionization charge generated in the depletion region can be collected using the electric field in this region.

Silicon strip detectors



Subdivide electrodes into strips, read out each of the strips, record hit yes/no (digital) or charge (analog).

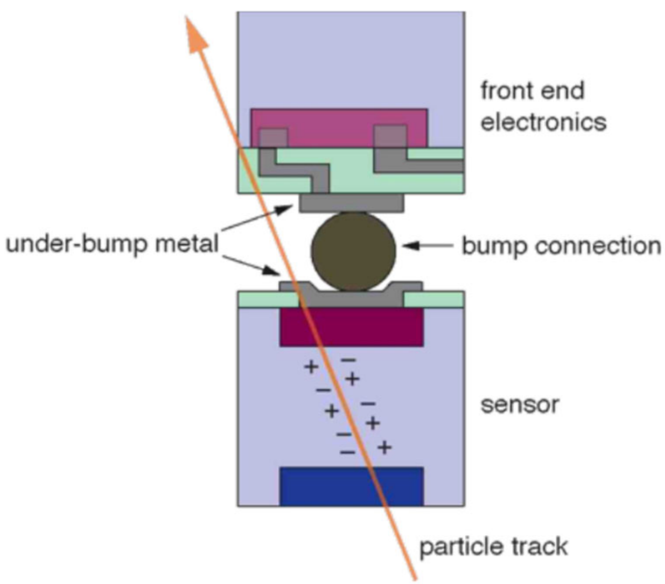
Single sided strip detector: only one of the electrodes is made of strips → one coordinate. Typical pitch 50 µm

Double sided strip detector: strips on both sides (at an angle, e.g. 90 degrees): two coordinates – advantage if multiple scattering in the sensors is a concern (Belle II)

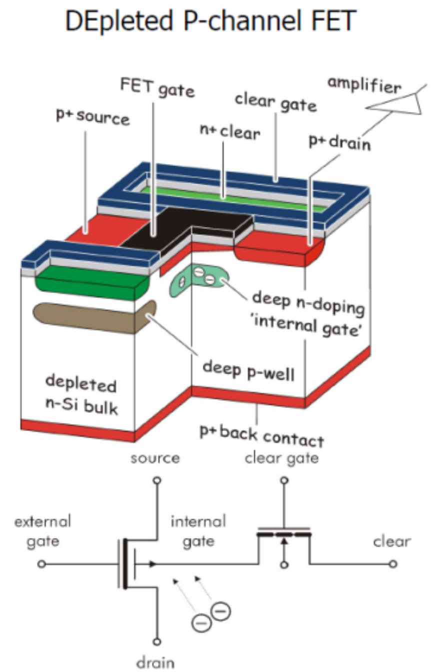
Pixel detectors

Subdivide electrode into pixels strips with individual read-out

- No ambiguity in case multiple tracks hit the same detector module
- Huge number of read-out channels



Read-out chip and the sensor are connected by bump-bonding (using a soft material like indium)



DEPFET sensor (Depleted P-channel FET)

Detector types

- Ionisation detectors
- Semiconductor detectors
- Scintillators
- Photon detectors

Scintillators

Principle: released energy converted into light

- Detection via photosensor – e.g., photomultipliers.

Requirements

- High efficiency for conversion of excitation energy
- Transparency to allow transmission of light
- Spectral range detectable by photosensors
- Short decay time to allow fast response

Material:

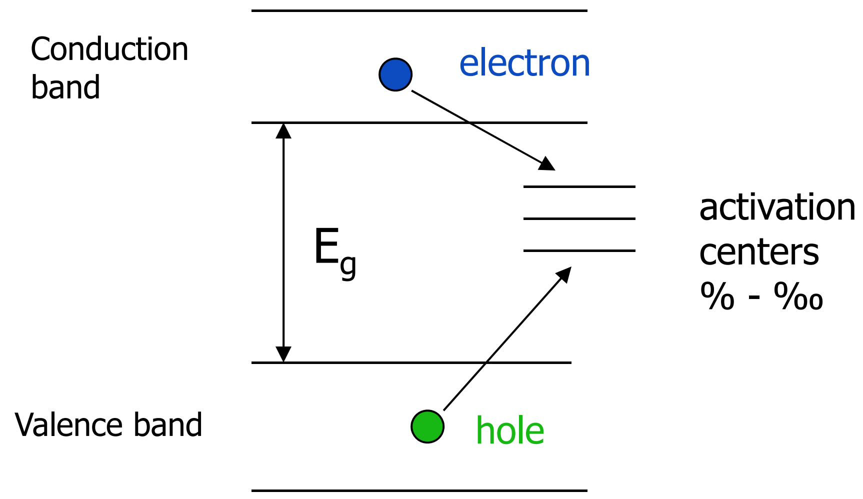
- Solid or liquid. Typically transparent plastic plates
- Doped with molecules that emit light (visible or UV) when excited through ionization energy loss. Can be organic or inorganic or nobel liquid/gas.
- Rest of material must be transparent to that wavelength
- Wavelength shifting technique to avoid re-absorption

Typically 10k photons/MeV deposited

Inorganic scintillators

- e-h neutralize through activation centers, emitting a photon

- $h\nu < E_g$ → the crystal is transparent



examples: NaI(Tl), CsI(Tl), BaF_2 and BGO ($Bi_4Ge_3O_{12}$)

Inorganic scintillators

Scintillator material	Density (g/cm³)	Radiation length	Refractive index	Wavelength at peak	Decay time	Light yield (Y/MeV)
NaI (Tl)	3.67	2.59 cm	1.78	410 nm	230 ns	4.1 $\times 10^4$
CsI (Tl)	4.51	1.86 cm	1.85	550 nm	800–6000 ns	6.6 $\times 10^4$
CsI (Na)	4.51	1.86 cm	1.80	420 nm	630 ns	4.0 $\times 10^4$
$LaBr_3$ (Ce)	5.3	1.88 cm	1.9	358 nm	35 ns	6.1 $\times 10^4$
$Bi_4Si_3O_{12}$ BSO	6.8	1.15 cm	2.06	480 nm	100 ns	0.2 $\times 10^4$
$Bi_4Ge_3O_{12}$ BGO	7.1	1.12 cm	2.15	480 nm	300 ns	0.9 $\times 10^4$
$CdWO_4$	7.9	1.1 cm	2.25	495 nm	5000 ns	2.0 $\times 10^4$
$YAlO_3$ (Ce) YAP	5.5	2.9 cm	1.94	350 nm	30 ns	2.1 $\times 10^4$
$Lu_3Al_5O_7$ (Ce) LuAG	7.4	1.4 cm	1.84	420 nm	40 ns	2.6 $\times 10^4$
Gd_2SiO_5 (Ce) GSO	6.7	1.4 cm	1.87	440 nm	60 ns	0.8 $\times 10^4$
$PbWO_4$	8.3	0.89 cm	1.82	425 nm	25 ns	0.05 $\times 10^4$

Organic scintillators

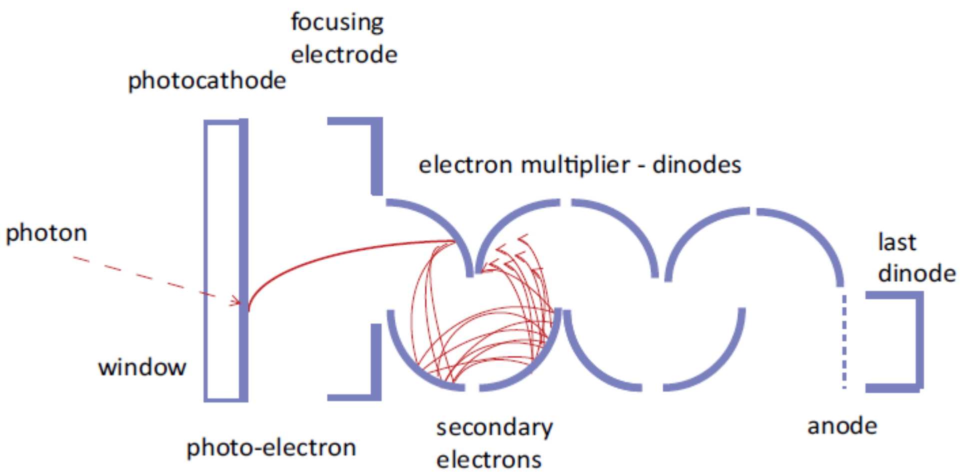
Scintillation light arises from delocalized electrons (π orbitals)

Scintillator material	Density (g/cm³)	Refractive index	Wavelength at peak	Decay time	Light yield (Y/MeV)
Naphtalene	1.15	1.58	348 nm	11 ns	0.4×10^4
Antracene	1.25	1.59	448 nm	30 ns	4×10^4
p-Therphenyl	1.23	1.65	391 nm	6 – 12 ns	1.2×10^4
NE102™	1.03	1.58	425 nm	2.5 ns	2.5×10^4
NE104™	1.03	1.58	405 nm	1.8 ns	2.4×10^4
NE110™	1.03	1.58	437 nm	3.3 ns	2.4×10^4
NE111™	1.03	1.58	370 nm	1.7 ns	2.3×10^4
BC400™	1.03	1.58	423 nm	2.4 ns	2.5×10^4
BC428™	1.03	1.58	480 nm	12.5 ns	2.2×10^4
BC443™	1.05	1.58	425 nm	2.2 ns	2.4×10^4

Detector types

- Ionisation detectors
- Semiconductor detectors
- Scintillators
- Photon detectors

Photon detectors



Transform light into an electric signal

- Photon → photo-electron
- Multiplication of a single photo-electron to a measurable electric signal (seconday emission, Geiger discharge)

Vacuum based

- *Photomultiplier tubes (PMT)*
- *Microchannel plate photomultiplier tubes*

Solid-state photon detectors

Hybrid detectors

- *HPDs and HAPDs*
- *Other hybrid photosensors*

Gaseous photon detectors

Parameters of photo-sensors

Photon detection efficiency (PDE)

- quantum efficiency
- collection efficiency / Geiger discharge probability

Granularity

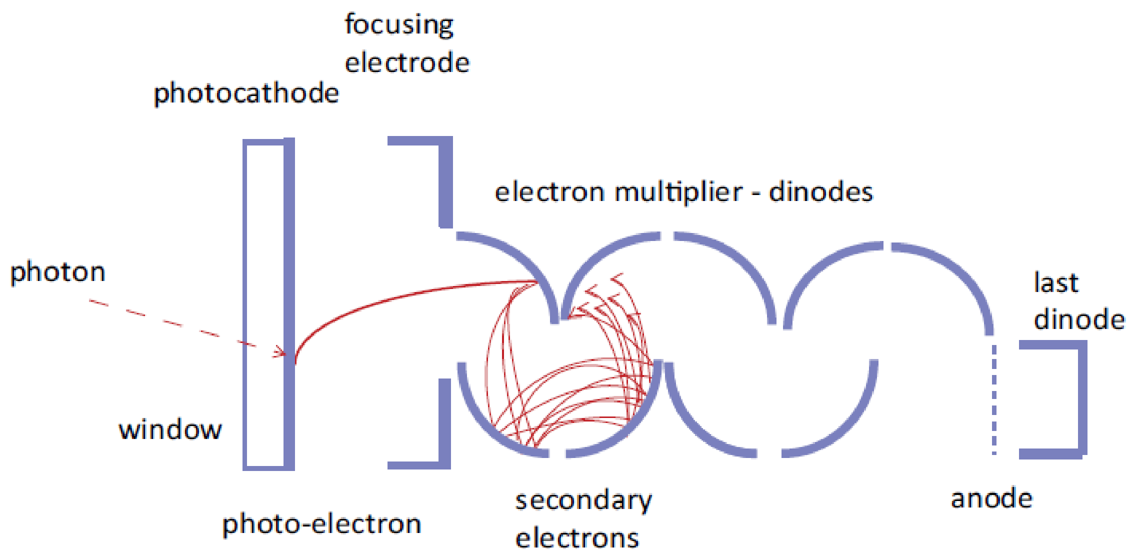
Time resolution (transient time spread – TTS)

Long term stability

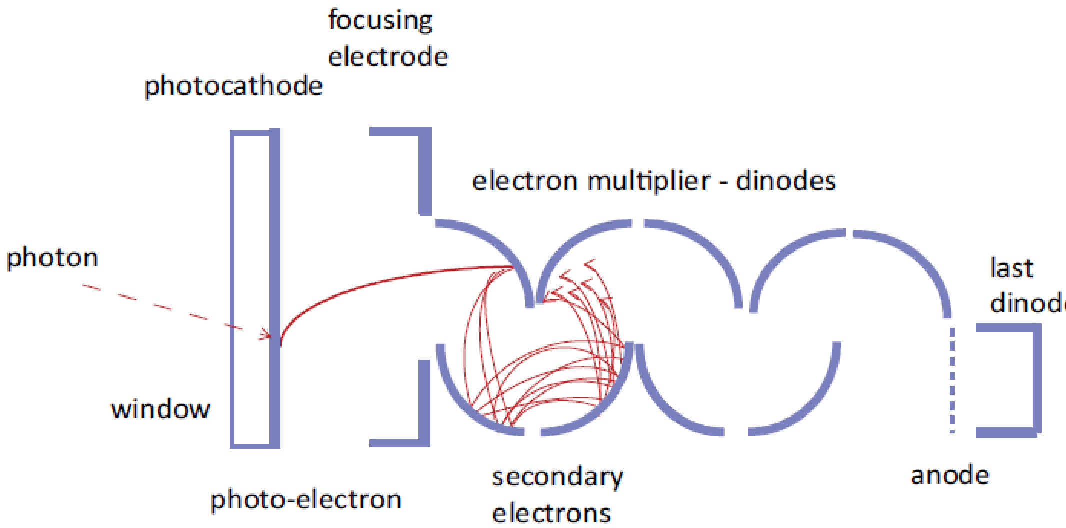
Operation in magnetic field

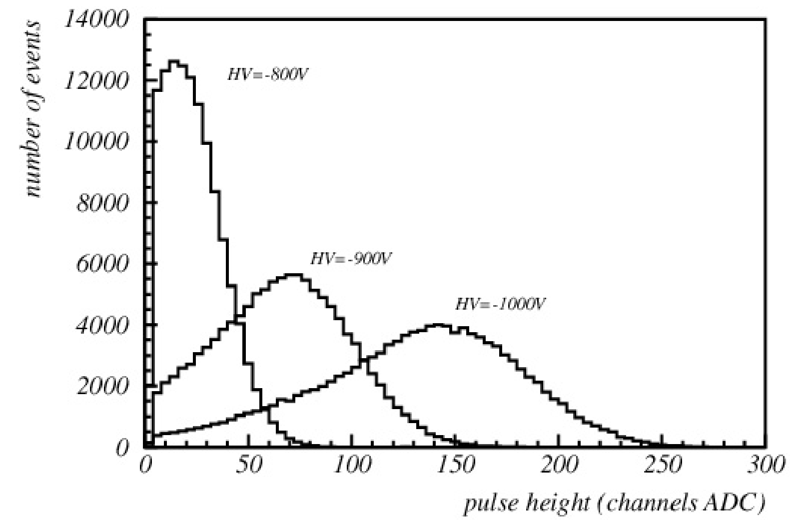
Dark count rate

+ ...

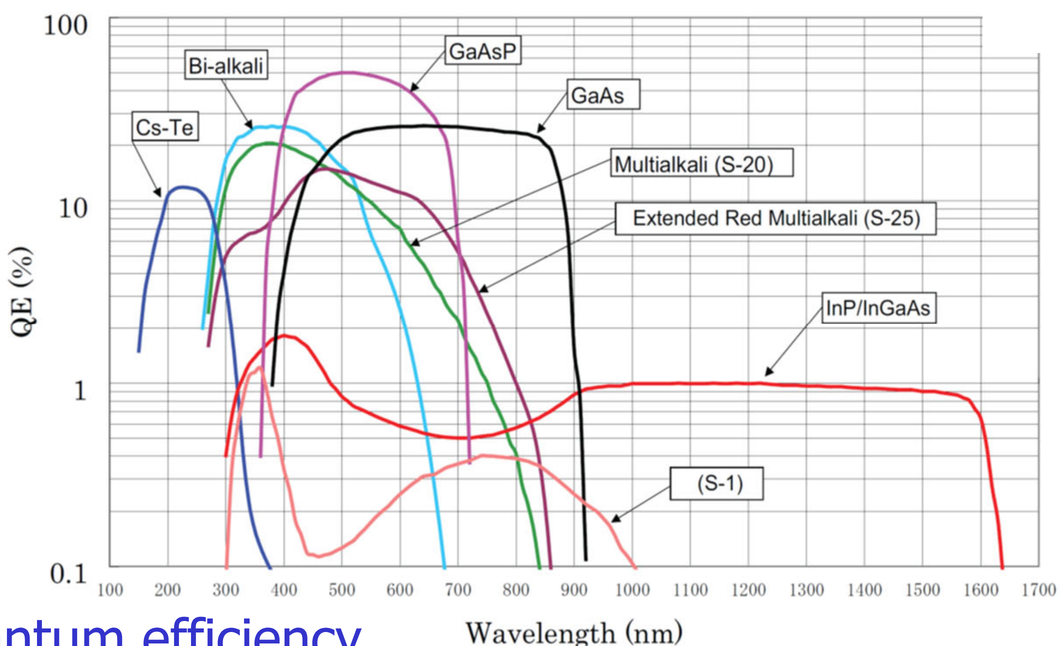


Photomultiplier tube (PMT)





Pulse height distributions for single photoelectrons



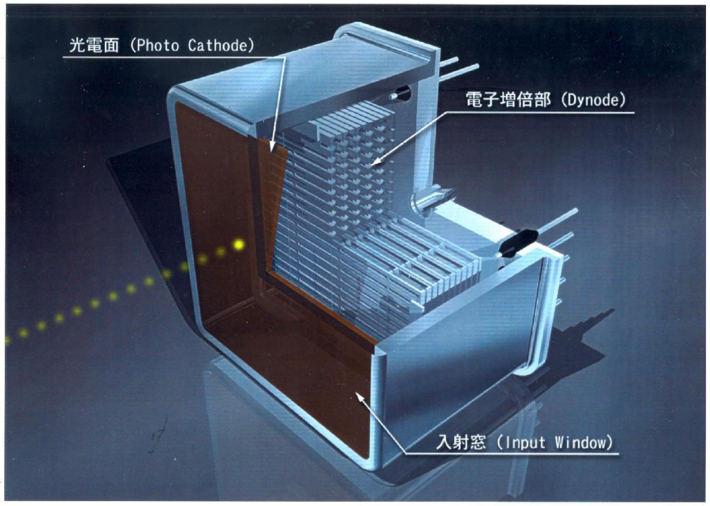
Quantum efficiency

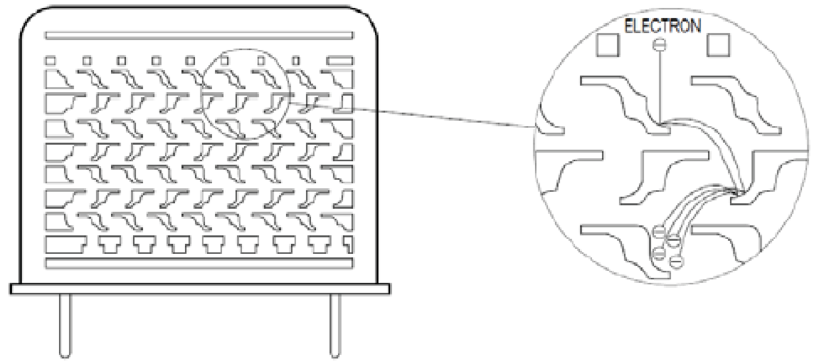
Secondary emission: number of secondary electrons per incoming electron $\delta \approx 3\text{-}5$

Dynode material: usually semiconductors or isolators (same reason as for the photocathode)

Multianode PMTs

Multianode PMTs with metal foil dynodes

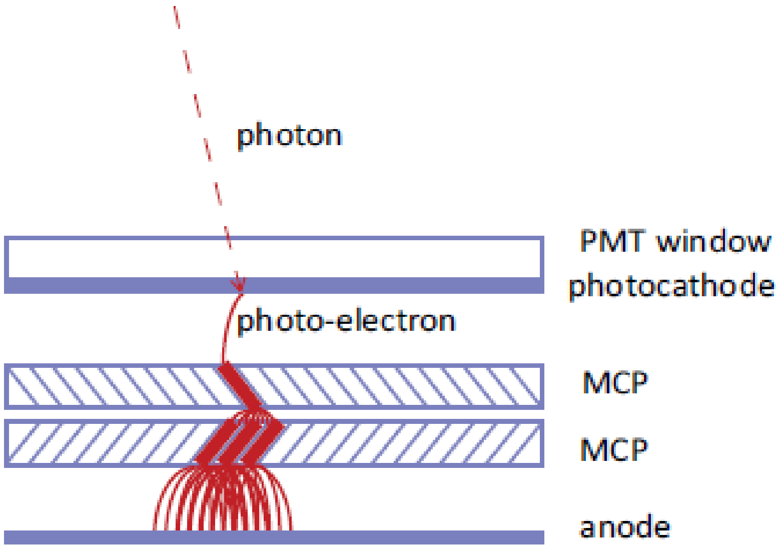


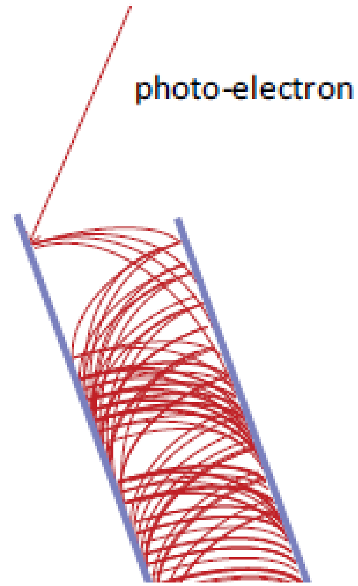


Next generation: flat pannel PMT H8500

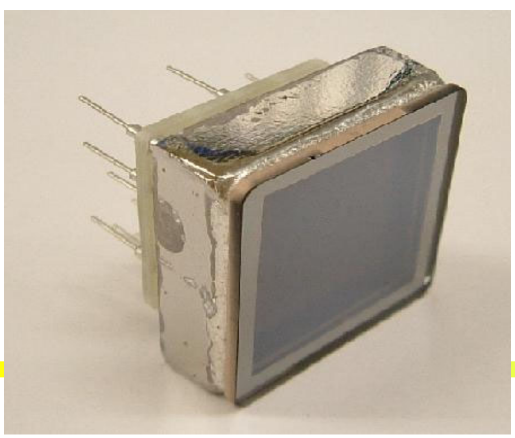
- 52 x 52mm², 89% effective coverage
- 64 channels, pixel size 5.8 x 5.8 mm2
- 12 dynodes, metal foil type
- Bialkali photocathode

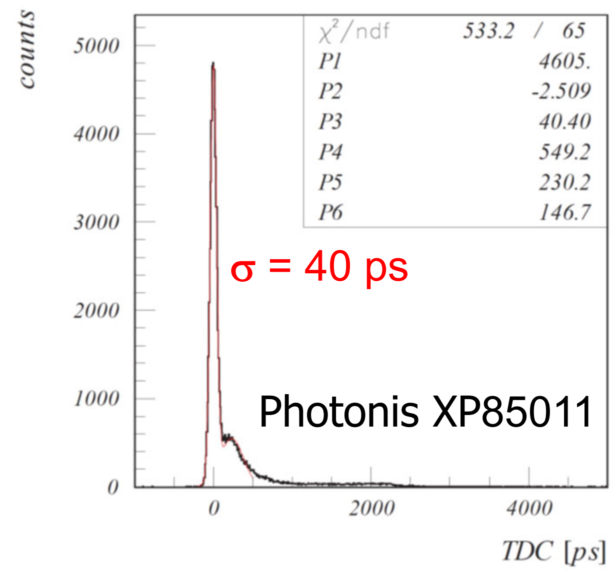
Micro-channel plate PMTs



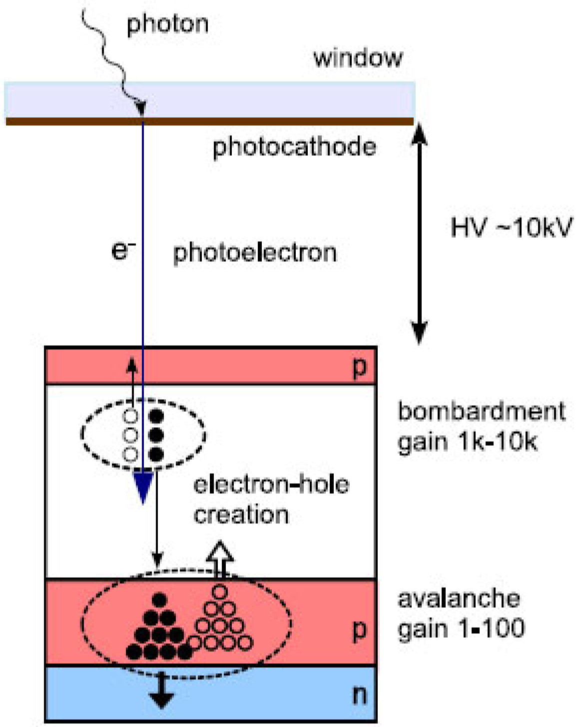


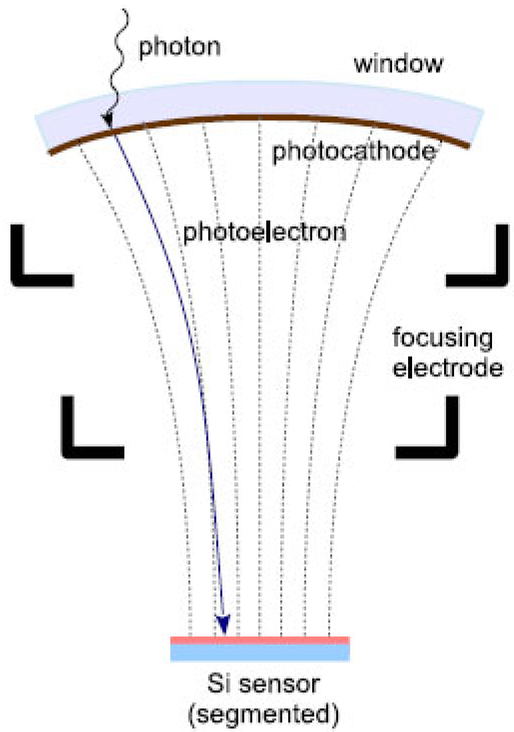
- Fast
- Immune to an axial magnetic field



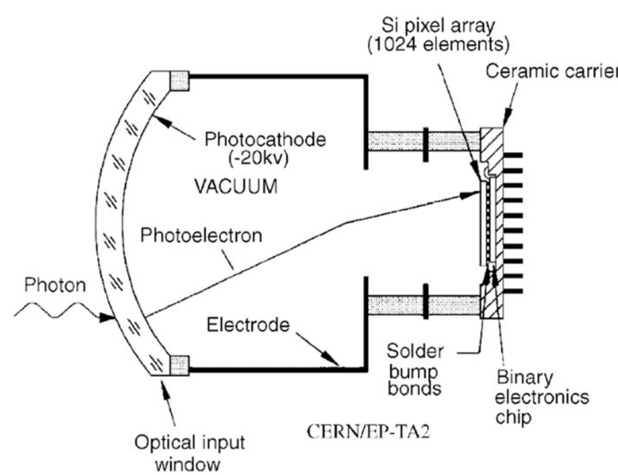


Hybrid photodetectors





LHCb RICH detectors

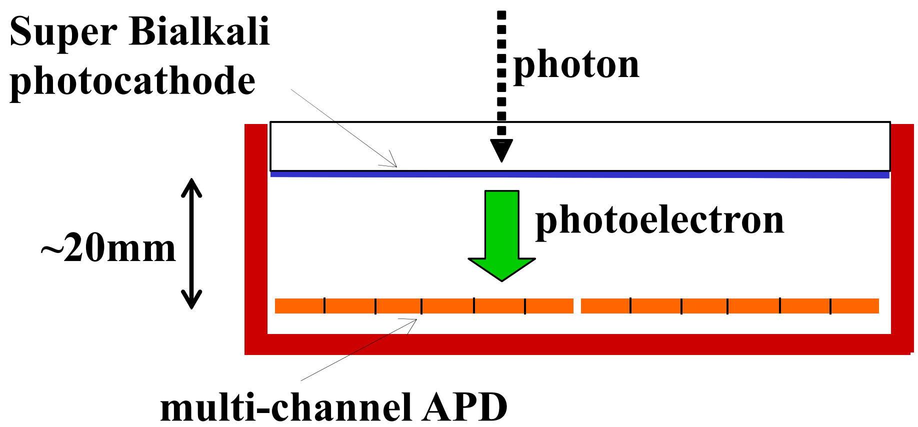


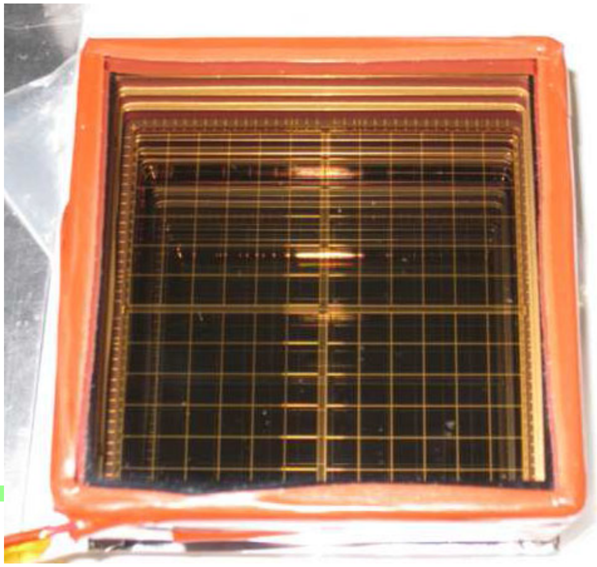
Instead of secondary multiplication: accelerate photoelectrons over a large voltage difference (~10kV), and let them hit a Si sensor.

Proximity focusing HAPD

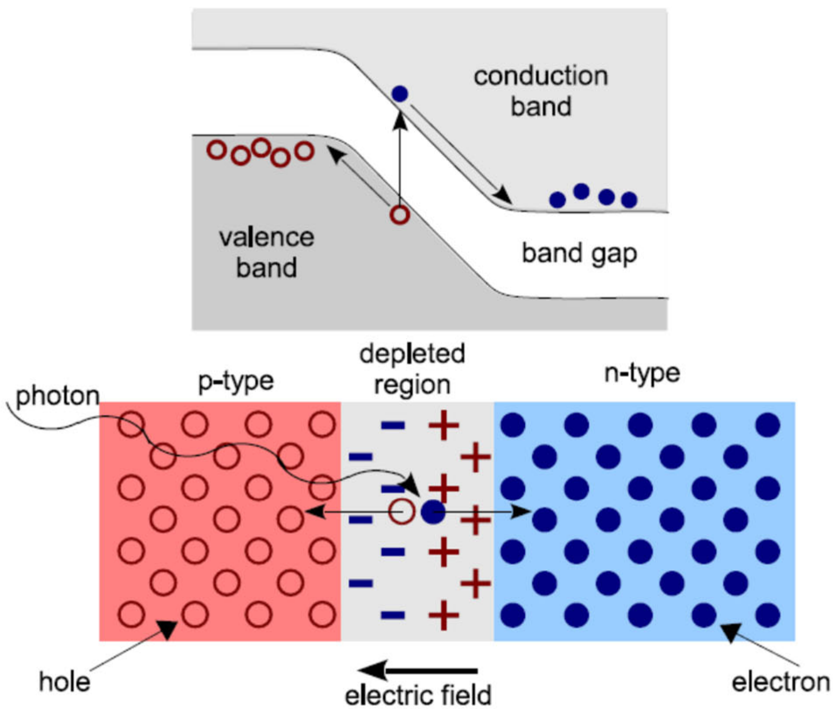
Hybrid avalanche photo-detector developed in cooperation with Hamamatsu Photonics K.K. for the Belle II ARICH detector

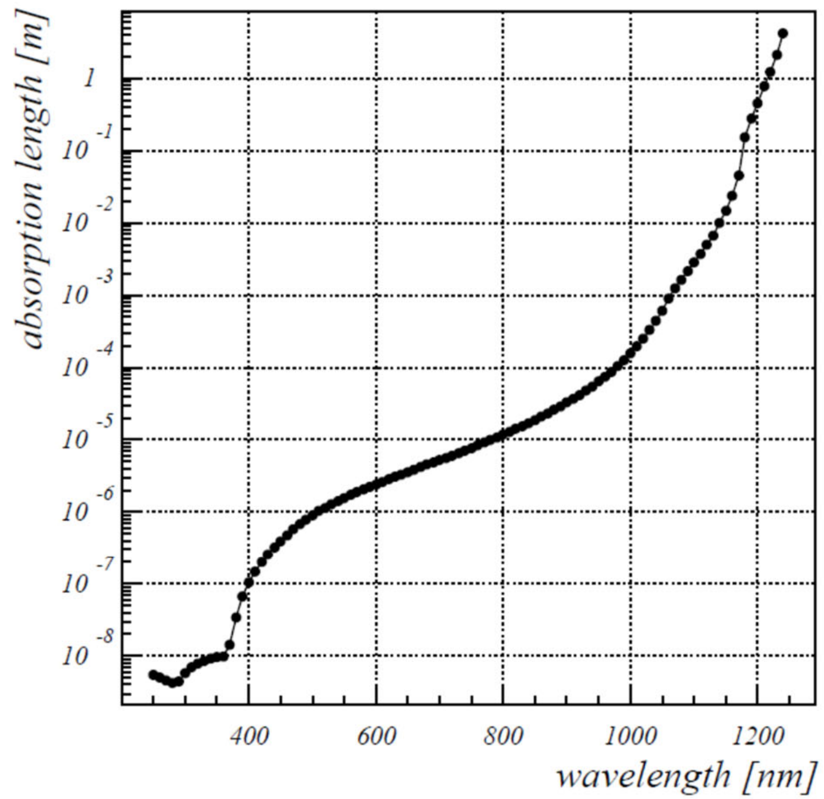
- 12 x12 channels (~ 5 x 5 mm^2)
- size ~ 72 mm x 72 mm
- ~ 65% effective area
- total gain > 4.5x10^4 (two steps: bombardment > 1500, avalanche > 30)
- detector capacitance ~ 80pF/ch.
- super bialkali photocatode, typical peak QE ~ 28% (> 24%)
- works in mag. field (~ perpendicular to the entrance window)





Semiconductor light sensor: photodiode





Everywhere: CCD sensors in cameras and phones - but not useful for single (or few) photons and fast read-out

Semiconductor light sensor: SiPM

Geiger mode avalanche photo-diode G-APD, also known as SiPM – Silicon Photomultiplier

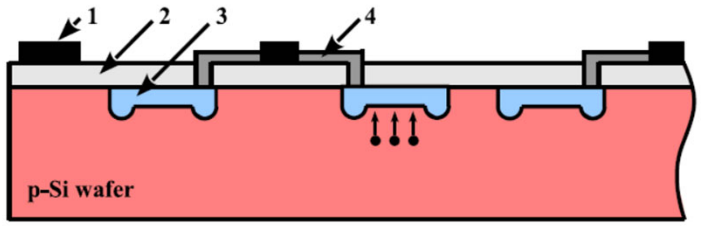
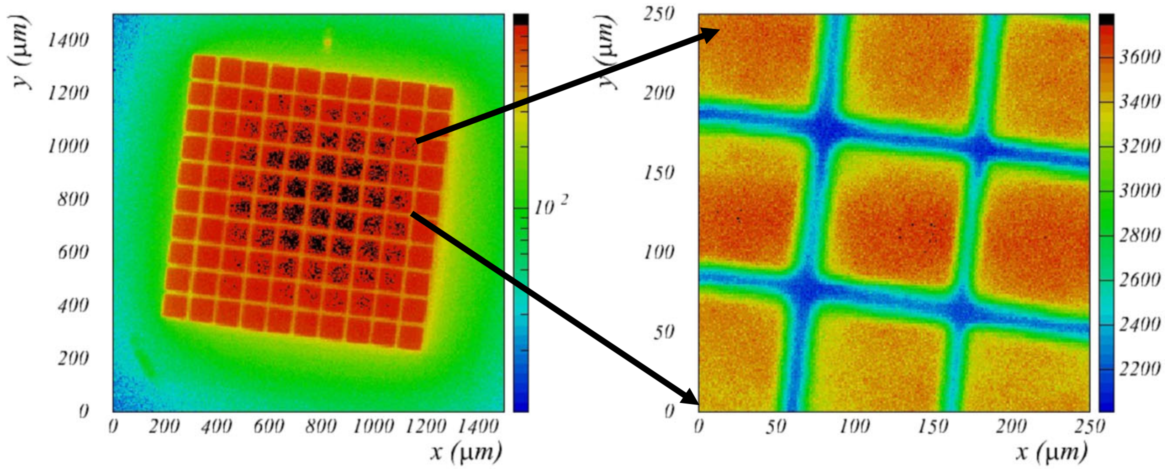


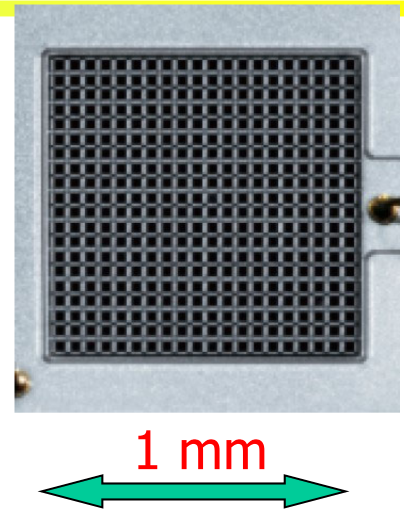
Figure 9: Schematic drawing of a cross-section of a SiPM: metal electrode (1), silicon oxide layer (2), p-n junctions/micro-cell (3) and individual quenching resistor (4) (23).

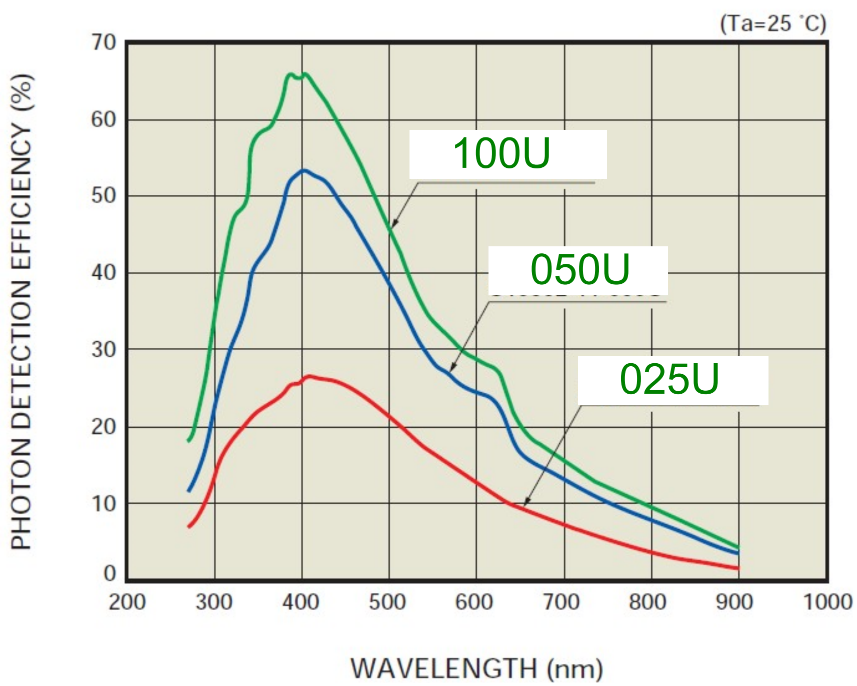
SiPM is an array of APDs operating in Geiger mode. Characteristics:

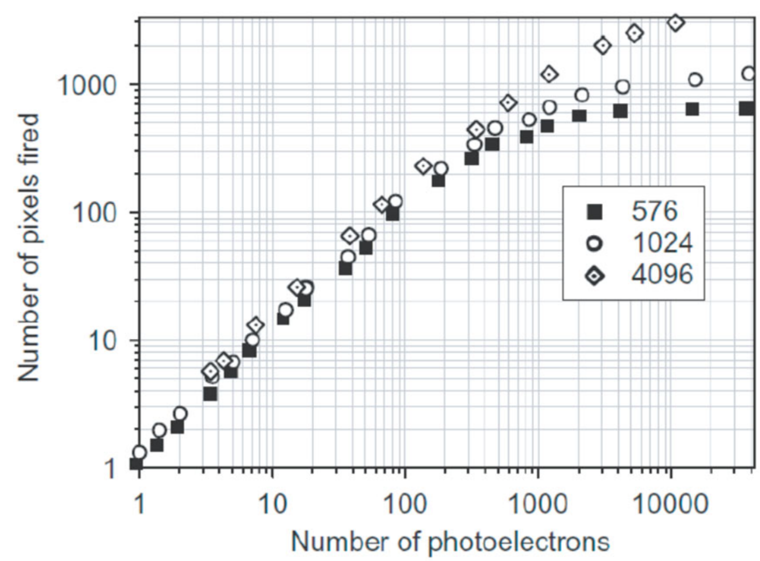
- low operation voltage ~ 10-100 V
- gain ~ 10^6
- peak PDE up to 65%(@400nm)
  $PDE = QE \times \varepsilon_{geiger} \times \varepsilon_{geo}$ (up to 5x PMT!)
- ε_{geo} – dead space between the cells
- time resolution ~ 100 ps
- works in high magnetic field
- dark counts ~ few 100 kHz/mm^2
- radiation damage (p,n)

SiPMs as photon detectors



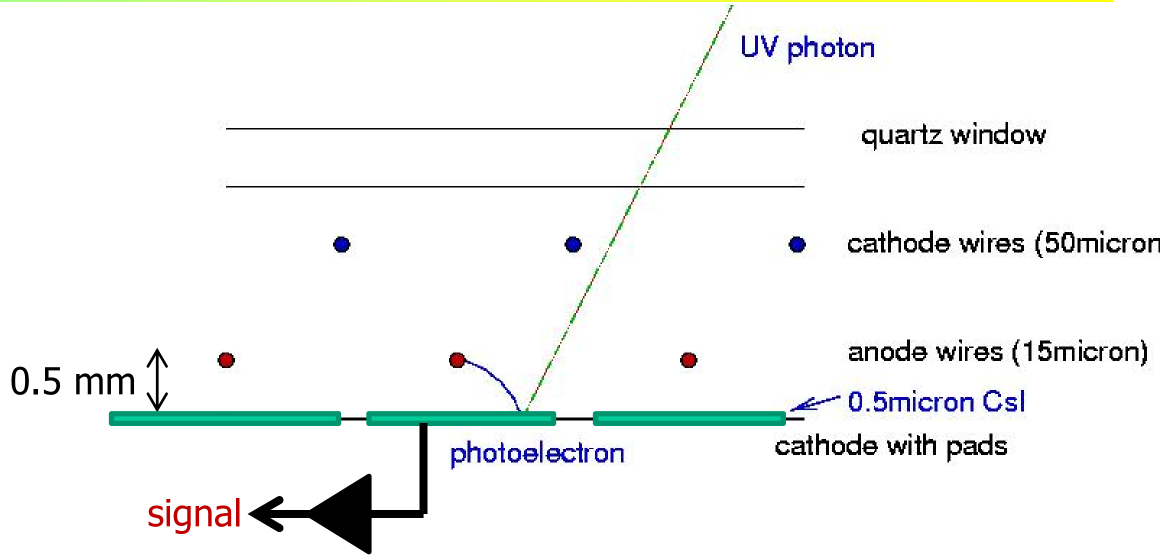






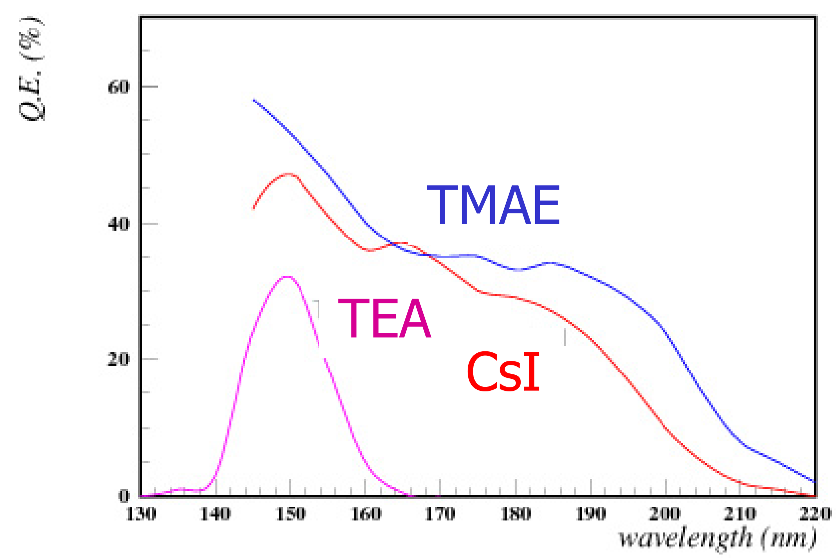
Gas chamber based photosensors

Multiwire chamber with
cathode pad read-out:
→ short drift distances,
fast detector



Photosensitive component:

- in the gas mixture (TEA): CLEOIII RICH
- or a layer on one of the cathodes (CsI on the printed circuit cathode with pads): HADES, COMPASS, ALICE RICH detectors



Works in high magnetic field!

End of Part 1 ☺