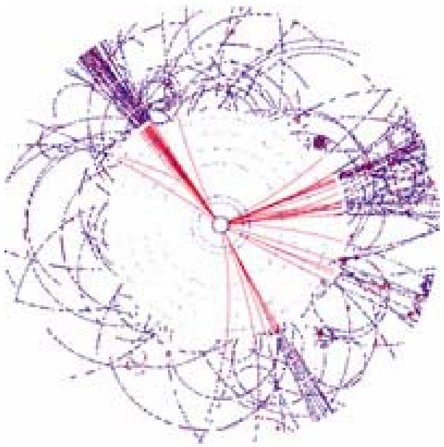
Particle Detectors

A brief introduction with emphasis on high energy physics applications

TRIUMF Summer Institute 2006
July 10-21 2006



- Lecture I
  - measurement of ionization and position
- Lecture II
  - scintillation and photo detection
  - calorimetry
- Lecture III
  - particle identification
  - detector systems

Michel Lefebvre
Physics and Astronomy
University of Victoria

Lecture II

- Scintillation and photo detection
  - Organic scintillators
  - Inorganic scintillators
  - Scintillator readout
  - Photo detectors
- Calorimetry
  - Interactions of electrons and photons in matter
  - Electromagnetic and hadronic showers
  - Electromagnetic and hadronic calorimeters
  - Example: LAr accordion EM calorimetry

Scintillation and photo detection

- Energy deposition by ionizing particles
  - production of scintillation light (luminescence)
- Scintillators are multi purpose detectors
  - trigger counters
  - veto counters
  - time of flight measurement
  - tracking detectors
  - calorimetry
  - others!
- Inorganic and organic scintillators
  - Inorganic: high light output, but slow
  - Organic: fast, but lower light output

Organic scintillators

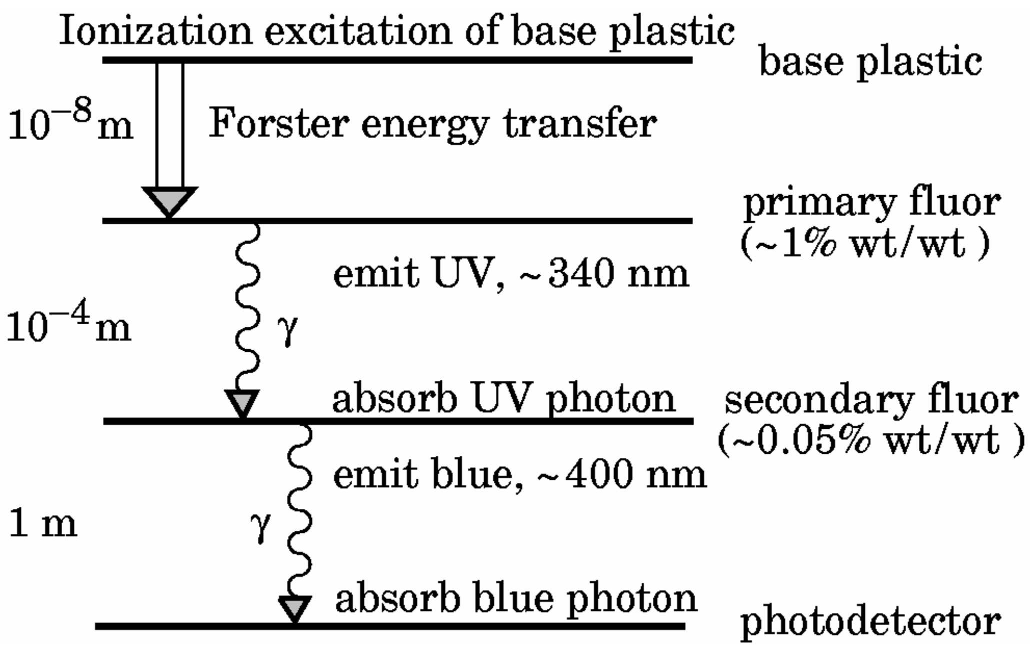
- Plastic scintillators are the most widely used
  - Ionization by charged particles
    - generate optical photons (blue – green)
    - densities: between 1.03 and 1.20 g cm^{-3}
    - typical yield:1 photon per 100 eV of deposited energy
      - MIP in 1cm thick material yields $\approx 2 \times 10^4$ photons
  - Response not linear with ionization density
    - Birks factor

$$\frac{dL}{dx} = L_\circ \frac{\frac{dE}{dx}}{1 + k_B \frac{dE}{dx}}$$

  - Decay times a few ns
    - rise times much faster (allows sub-ns timing)
    - light decay can depend on exciting particle, allowing ID
  - Production to desired shape, low cost
    - also scintillating fibres

Organic scintillators

Scintillation mechanism



Particle Data Group

scintillation, followed by resonant dipole-dipole interaction with fluor; strong coupling increases

fluor shifts wavelength to where the base is more transparent; shortens the decay time of scintillation and increases yield

Cautions: aging and handling, radiation damage, ...

- they have low *Z*, being mainly made of H and C
  - low γ detection efficiency (≈ only Compton effect).
  - but high neutron detection efficiency via (n,p) reactions

Organic scintillators

Table A6.3 Properties of some organic scintillators

scintillator	density (g/cm³)	index of refraction	wavelength of maximum emission (nm)	decay time constant (ns)	scintillation pulse height [1]	H/C ratio [2]
Monocrystals						
naphthalene	1.15	1.58	348	11	11	0.800
anthracene	1.25	1.59	448	30-32	100	0.714
trans-stilbene	1.16	1.58	384	3-8	46	0.857
p-terphenyl	1.23		391	6-12	30	0.778
Plastics [3]						
NE 102 A	1.032	1.58	425	2.5	65	1.105
NE 104	1.032	1.58	405	1.8	68	1.100
NE 110	1.032	1.58	437	3.3	60	1.105
NE 111	1.032	1.58	370	1.7	55	1.096
Plastics [4]						
BC-400	1.032	1.581	423	2.4	65	1.103
BC-404	1.032	1.58	408	1.8	68	1.107
BC-408	1.032	1.58	425	2.1	64	1.104
BC-412	1.032	1.58	434	3.3	60	1.104
BC-414	1.032	1.58	392	1.8	68	1.110
BC-416	1.032	1.58	434	4.0	50	1.110
BC-418	1.032	1.58	391	1.4	67	1.100
BC-420	1.032	1.58	391	1.5	64	1.100
BC-422	1.032	1.58	370	1.6	55	1.102
BC-422Q	1.032	1.58	370	0.7	11	1.102
BC-428	1.032	1.58	480	12.5	50	1.103
BC-430	1.032	1.58	580	16.8	45	1.108
BC-434	1.049	1.58	425	2.2	60	0.995

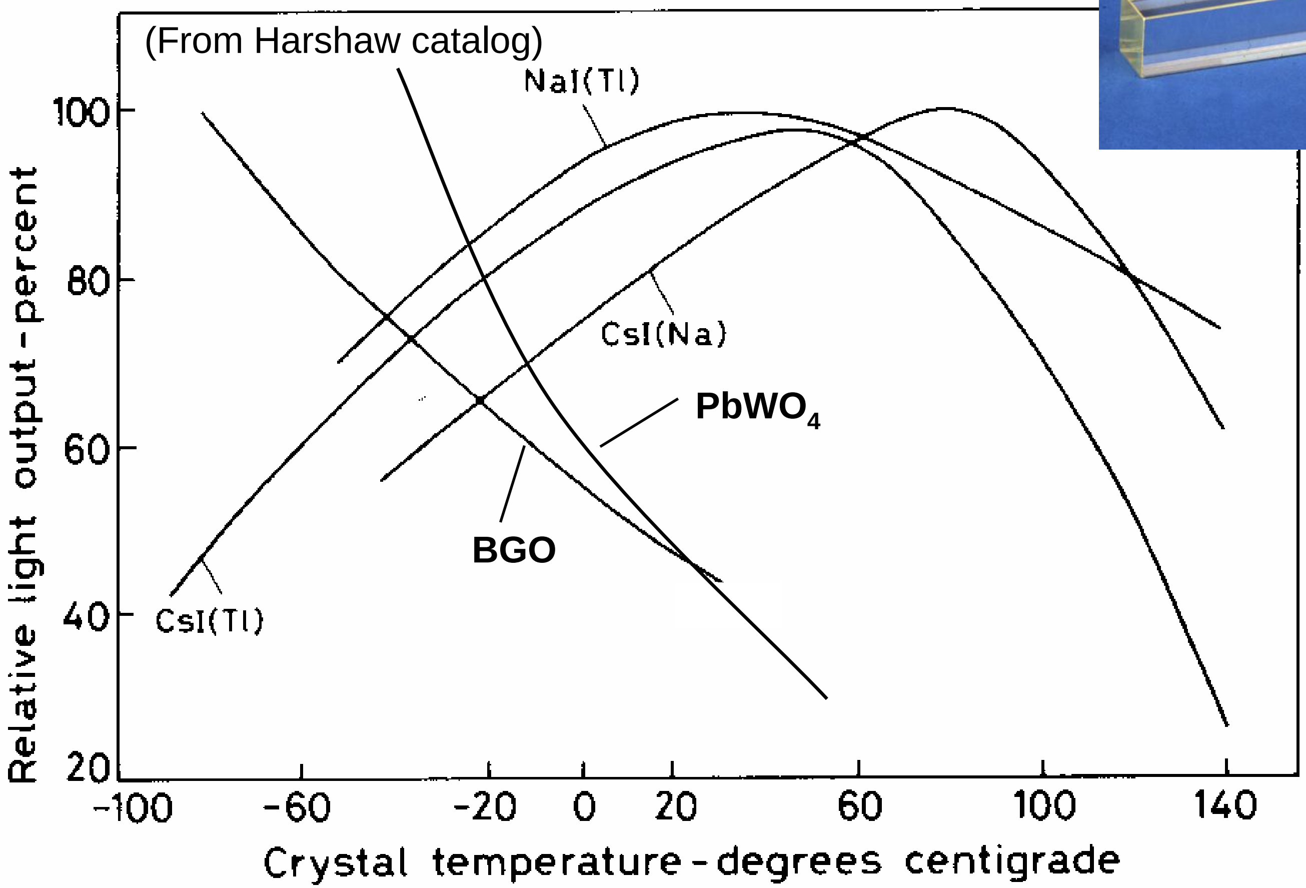
1) relative to anthracene
2) ratio of hydrogen to carbon atoms
3) Nuclear Enterprises Ltd. Sighthill, Edinburgh, U.K.
4) Bicron Corporation, Newbury, Ohio, USA

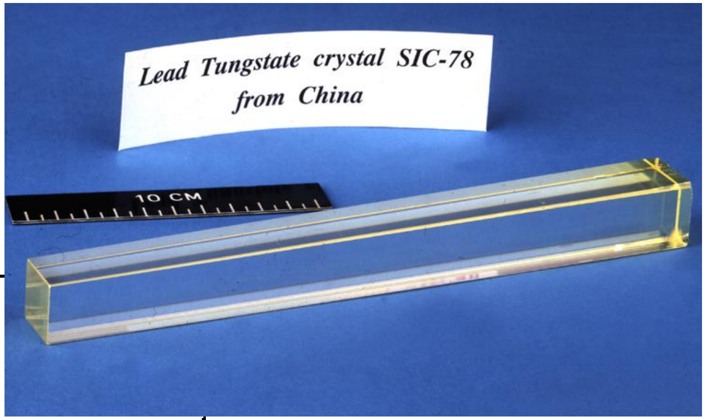
Inorganic scintillators

- Inorganic crystalline scintillators
  - Ionization by charged particles
  - NaI, CsI, BaF_2, $Bi_4Ge_3O_{12}$, $PbWO_4$,...
  - High density and high Z
  - well suited for detection of charged particle and γ
    - densities: between ~4 and ~8 g cm^{-3}
    - high dE/dx
    - high conversion efficiency for electrons and γ
    - often with very high light output
  - often more than two time constants
    - fast recombination from active centers (ns to μs)
    - delayed recombination due to trapping ($\approx$100 ns)

Inorganic scintillators

- light ouput has strong temperature dependence

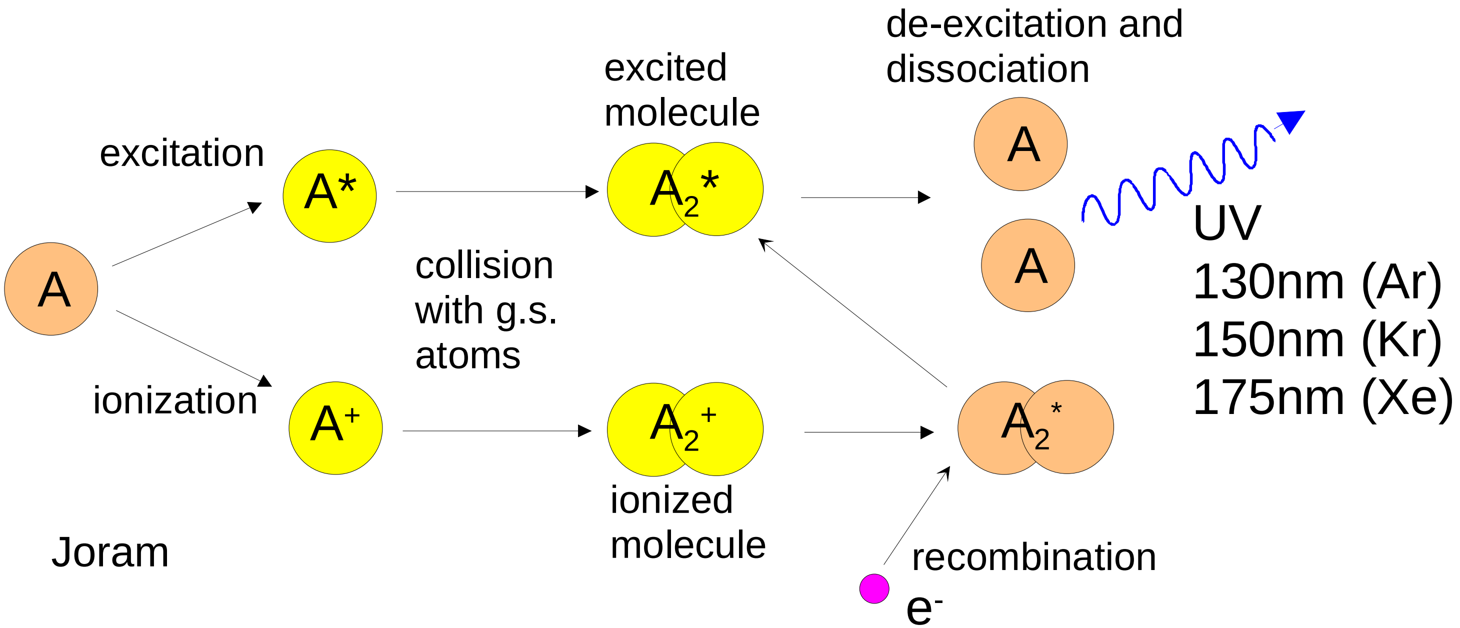




PWO4 final polished cristal for CMS calorimetry

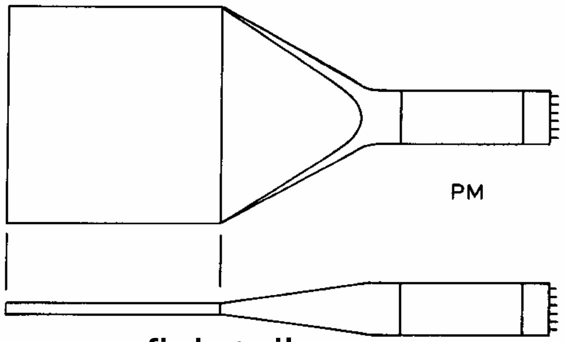
Inorganic scintillators

- Liquid noble gases (LAr, LKr, LXe)
  - also two time constants
    - few ns and 100 to 1000 ns, but same wavelegth

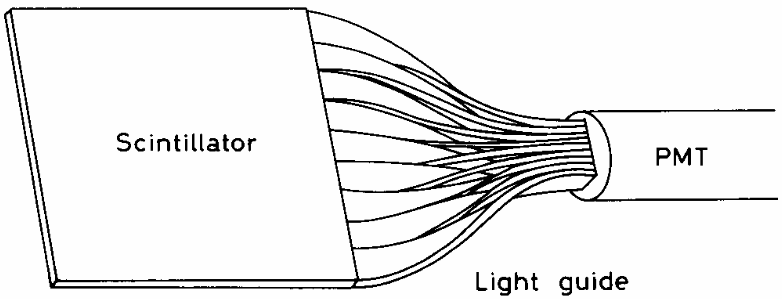


Scintillator readout

- light guides
  - transfer by total internal reflection (and reflector)

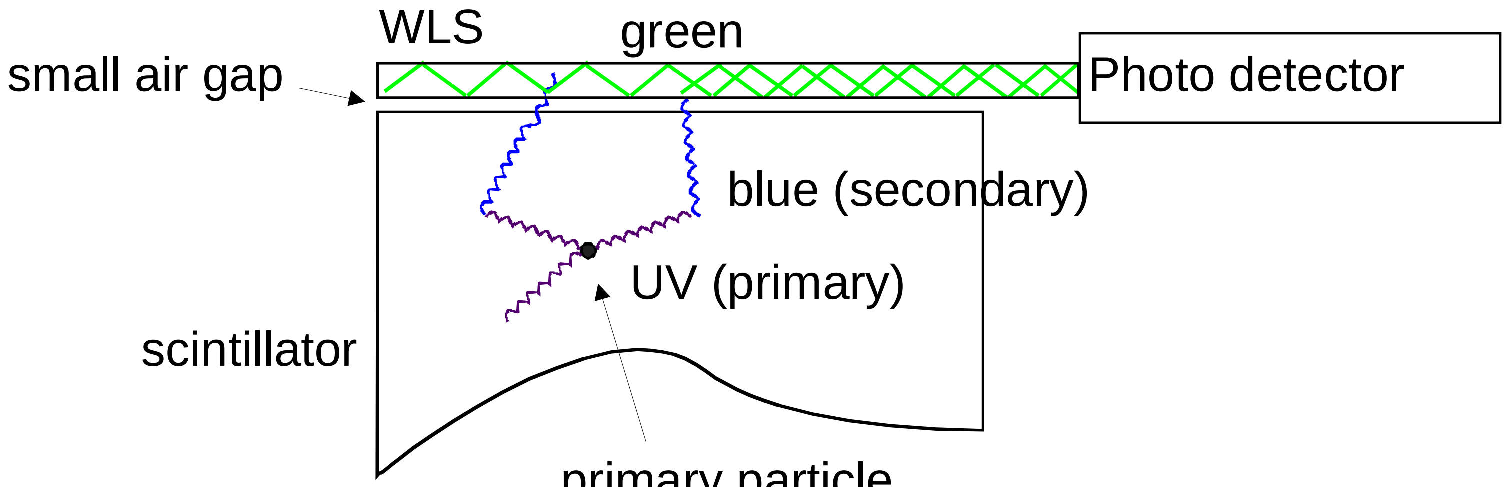


fish tail



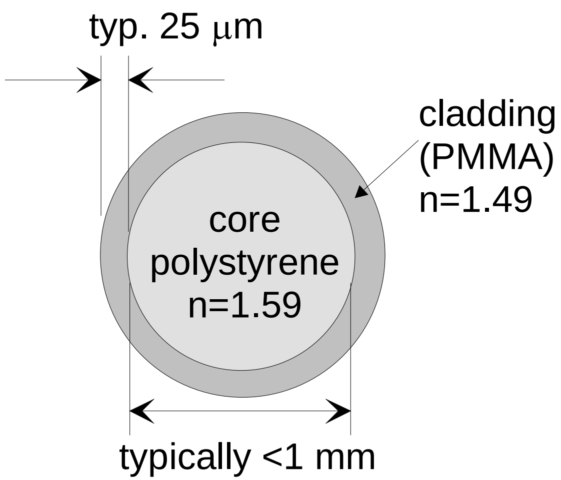
adiabatic

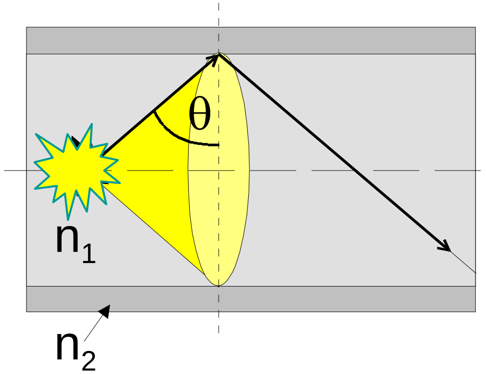
- wavelength shifter (WLS) bars



Scintillator readout

- optical fibres
  - light transport by total internal reflection



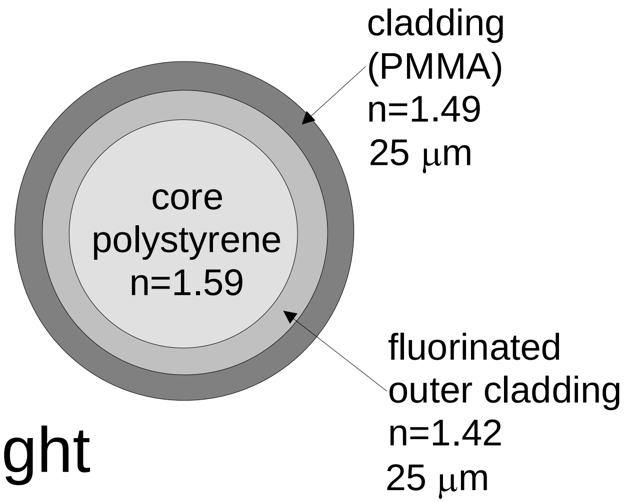


$$\frac{d\Omega}{4\pi} = 3.1\%$$

in one direction

- multi-clad fibres for improved aperture and absorption length

$$\frac{d\Omega}{4\pi} = 5.3\%$$ in one direction

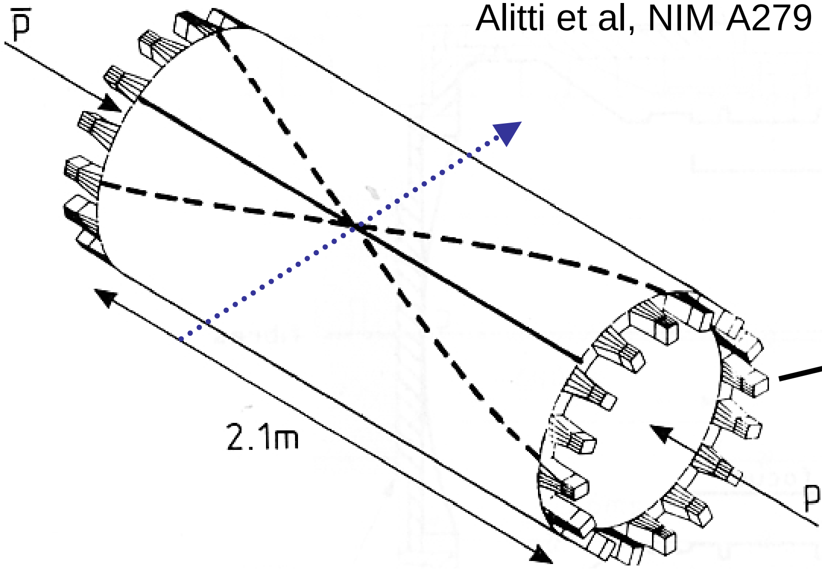


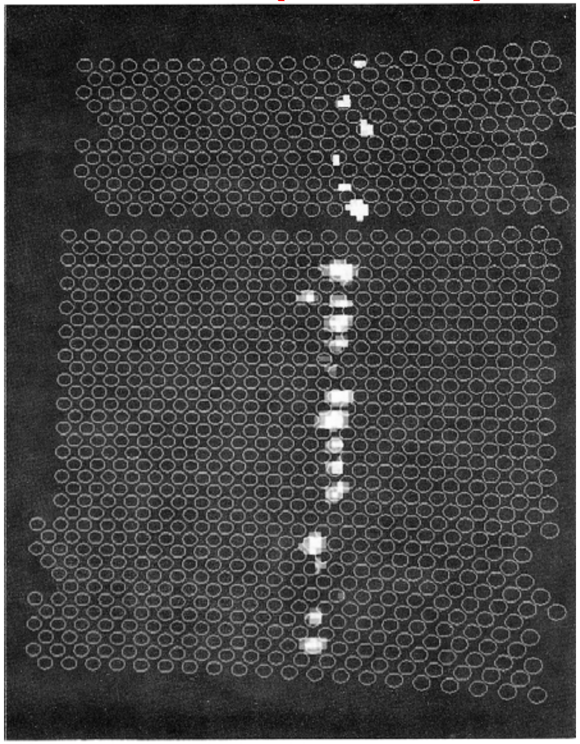
attenuation length > 10 m for visible light

Scintillating fibre tracker

- scintillating plastic fibres
  - many advantages
    - high geometrical flexibility; fine granularity; low mass
    - fast response (ns if fast readout; suitable for triggering)
  - UA2 upgrade scintillating fibre tracker (1987!)

Ansorge et al, NIM A265 (1988) 33-49
Alitti et al, NIM A279 (1989) 364-375

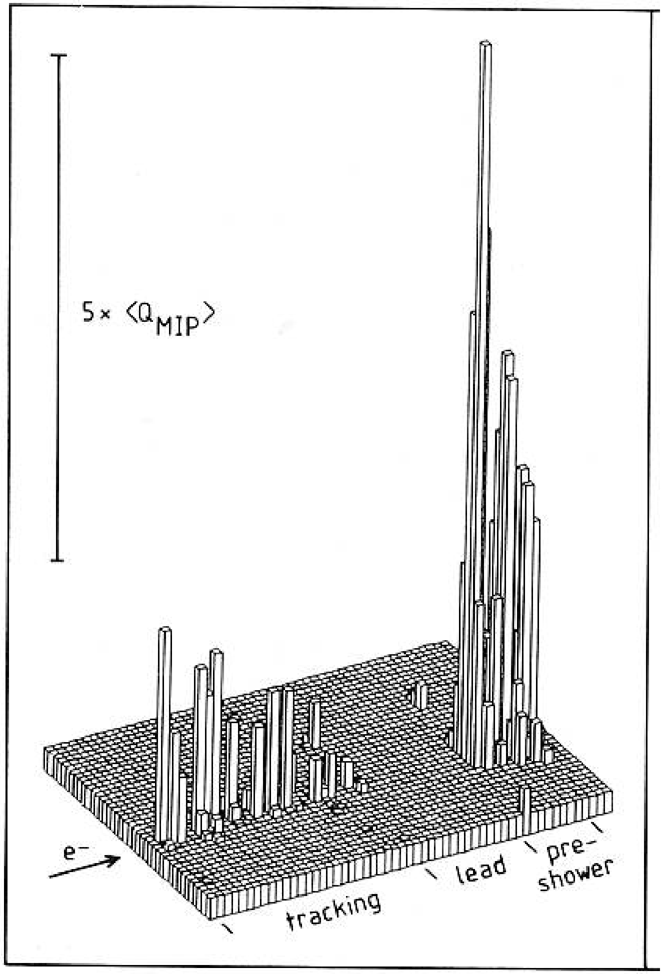




Scintillating fibre tracker

- UA2 upgrade SFD

Ansorge et al, NIM A265 (1988) 33-49
Alitti et al, NIM A279 (1989) 364-375



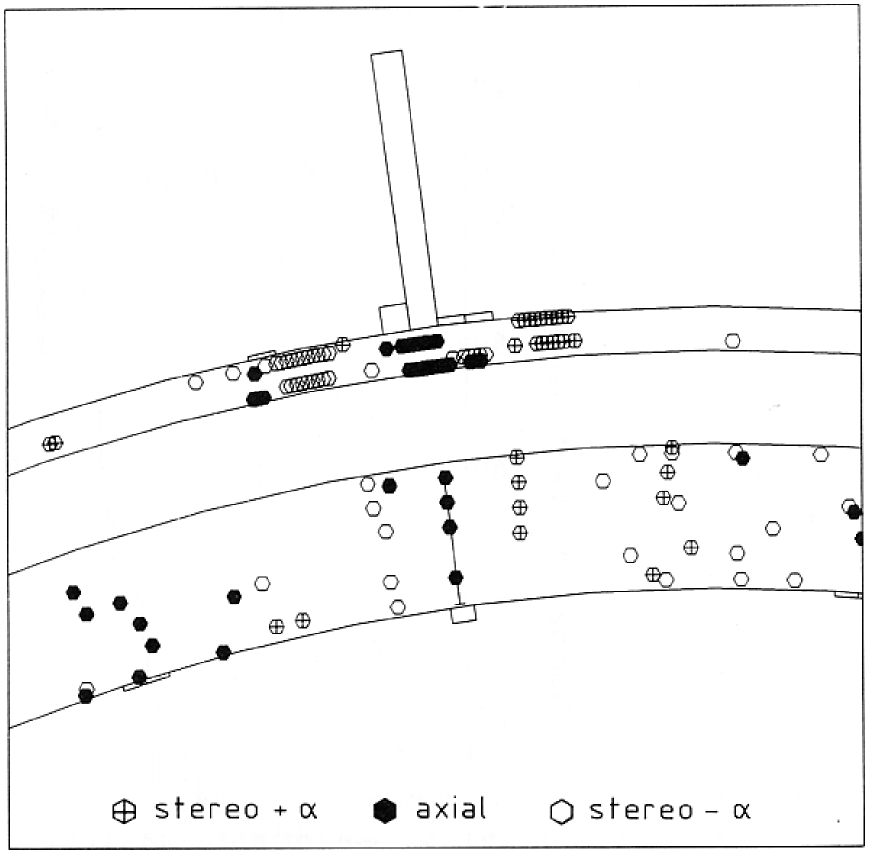


Fig. 13. The detection of an electron in the SFD. The hit fibres are displayed in the $z = 0$ plane with their radius enlarged by a factor 3 for clarity.

Photo detectors

- Convert light into detectable electronics signal
  - use photoelectric effect to convert photons to photoelectrons
  - require high sensitivity
    - quantum efficiency = Q.E. = $N_{p.e}/N_{\gamma}$

      ~15-20% for PMT
      ~70% for Si photo diodes
  - many type of photodetectors
    - gas based devices (RICH)
    - vacuum based
    - solid state
  - thresholds

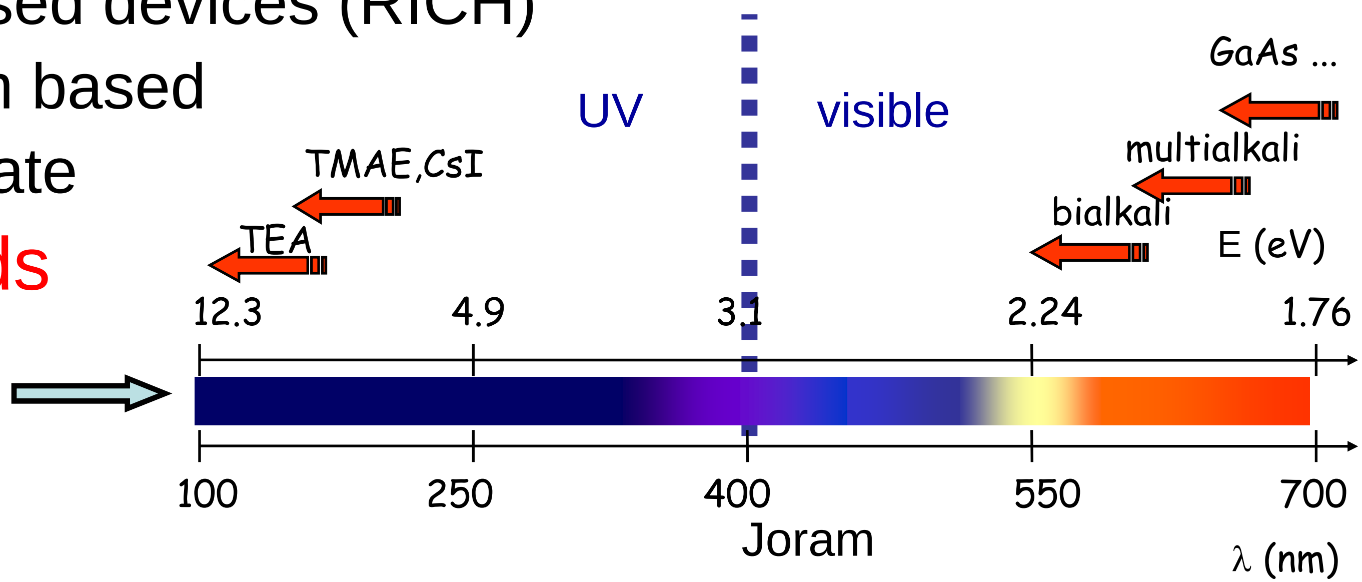
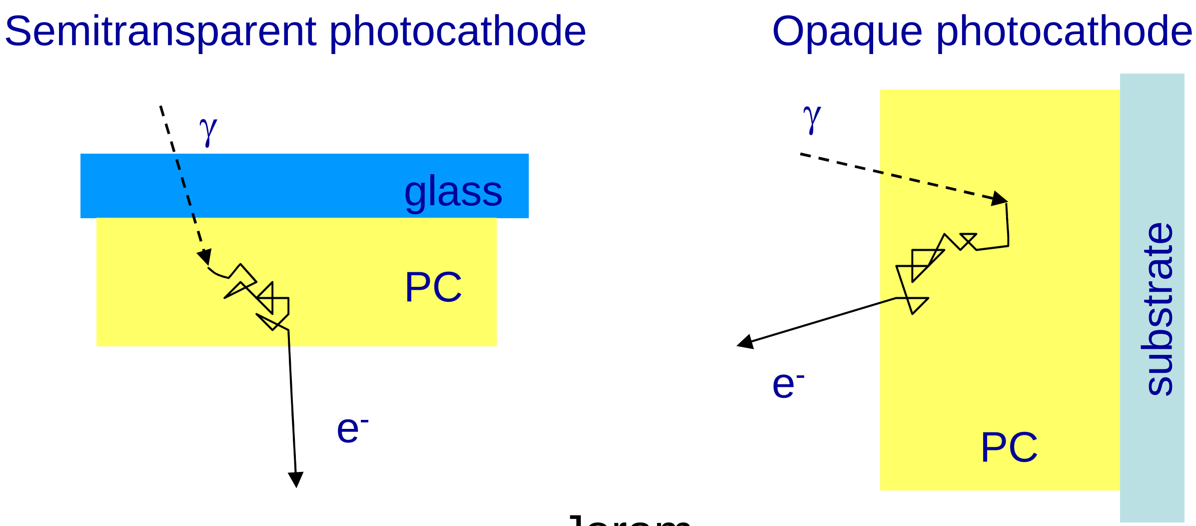


Photo detectors

- Photoelectric effect in photocathodes
  - 3-step process
    - photo inonization of molecule
    - electron propagation through cathode
    - escape of electron back into the vacuum

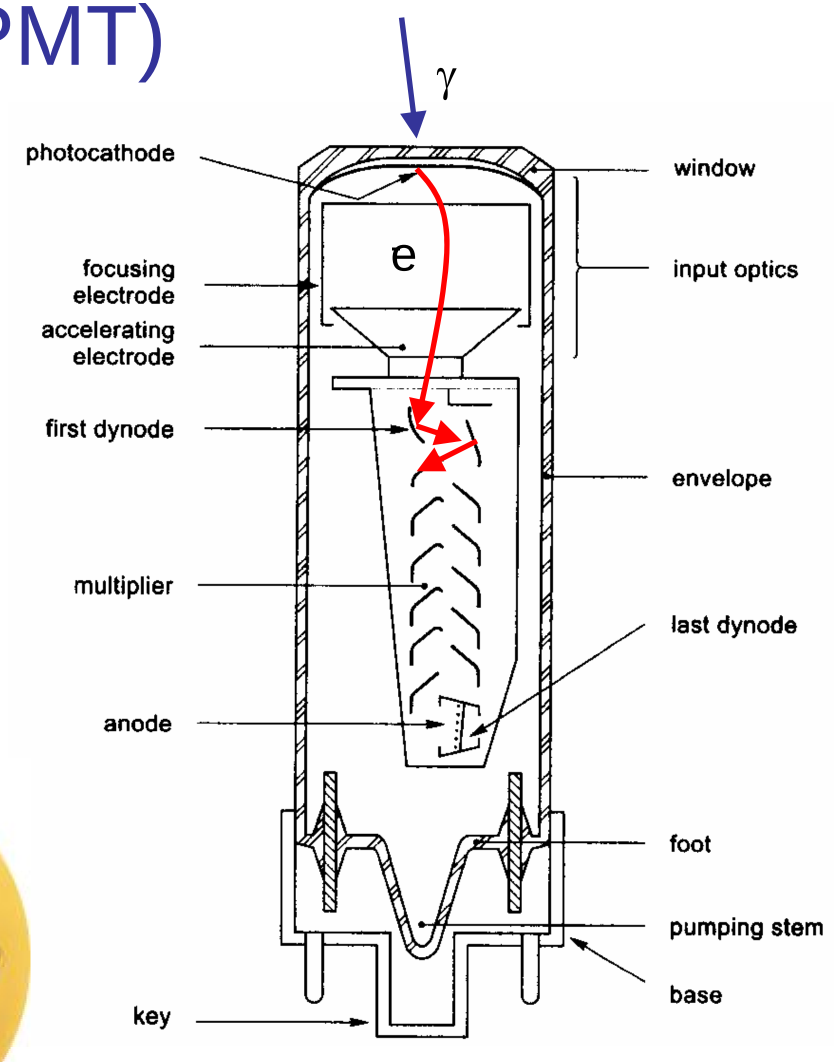


Joram

Vacuum based photo detectors

Photo multiplier tubes (PMT)

- photo emission from photocathode (PC)
- secondary emissions from dynodes
  - dynode gain: g = 3 to 50
  - 10 dynodes with g = 4: total gain $G = 4^{10} \approx 10^6$

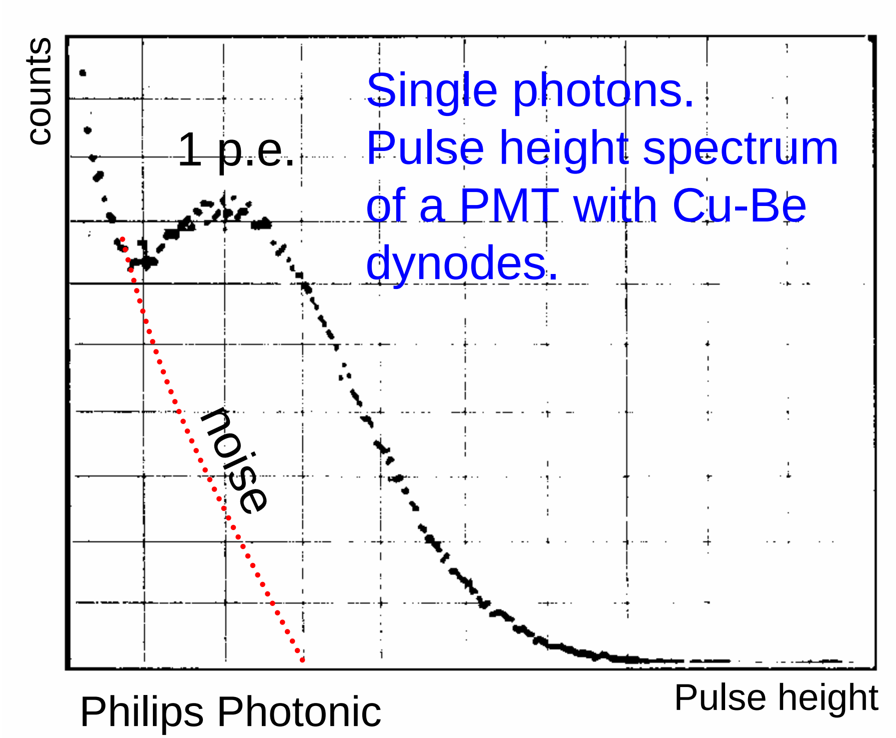


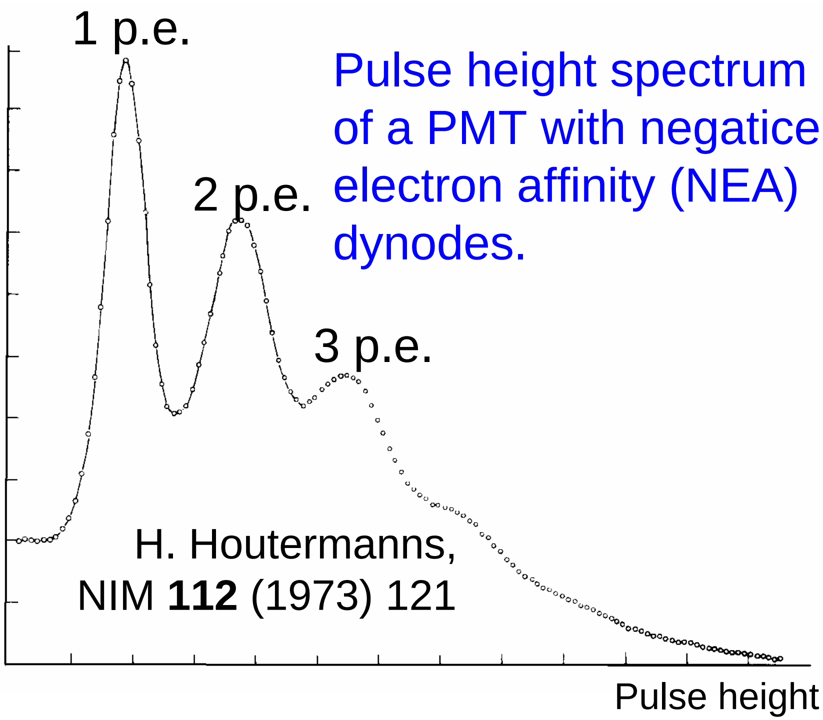
(Philips Photonic)

Vacuum based photo detectors

Energy resolution of PMT

- determined mainly by the fluctuation of the number of secondary electrons emitted from the dynodes

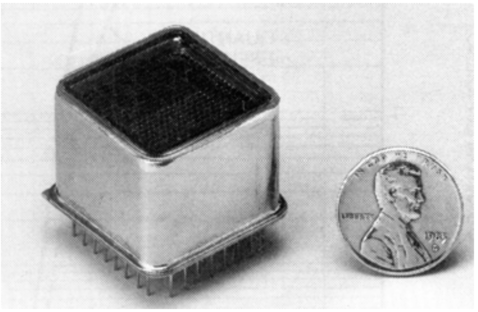




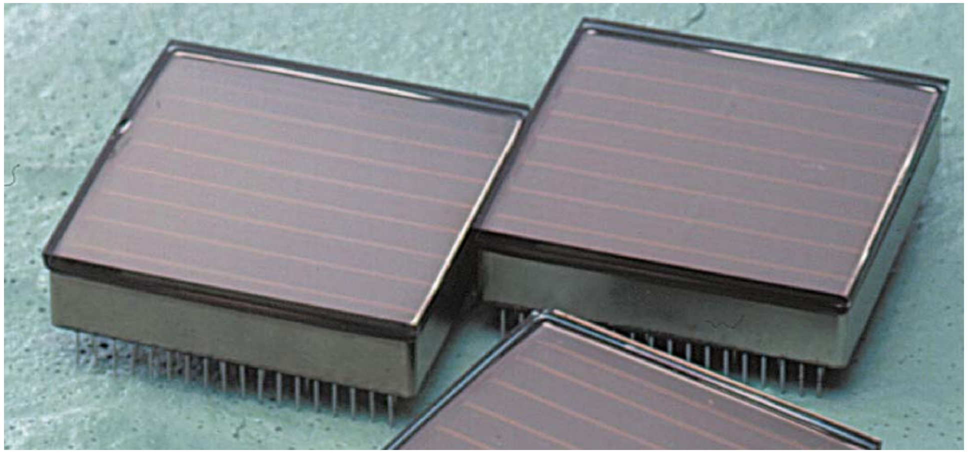
Vacuum based photo detectors

Multi anode PMT

- example: Hamamatsu R5900 series
  - up to 8x8 channels
  - size 28x28 mm^2, active area 41%
  - bialkali PC: Q.E. = 20% at 400 nm
  - gain $G \approx 10^6$

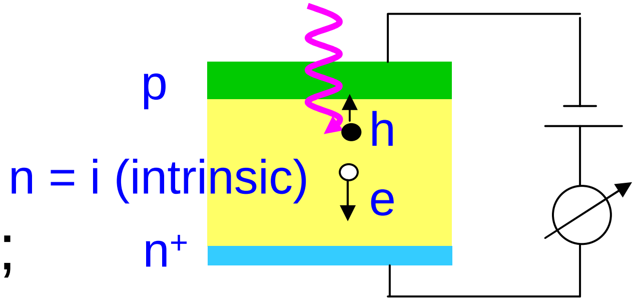


- recent example: Hamamatsu flat panel PMT
  - active area > 90%

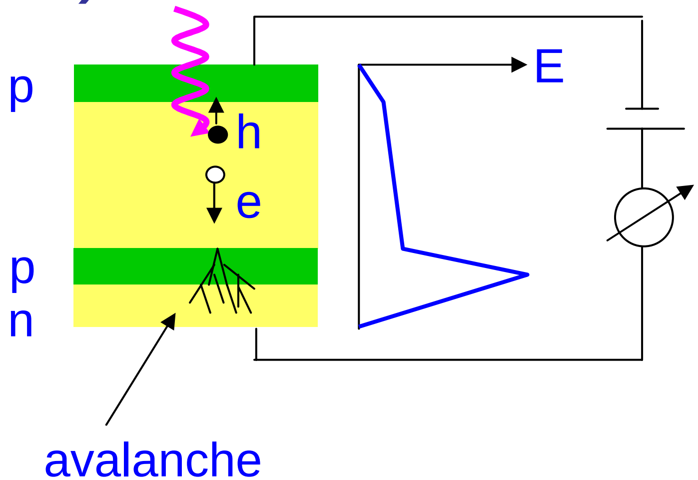


Solid state photo detectors

- **Photo diodes (PD)**
  - high Q.E. but no gain ($G = 1$)
    - p layer must be very thin (< 1 μm); visible light absorbs rapidly in Si
    - Q.E. ≈ 80% at λ = 700 nm
    - good for read out of scintillators



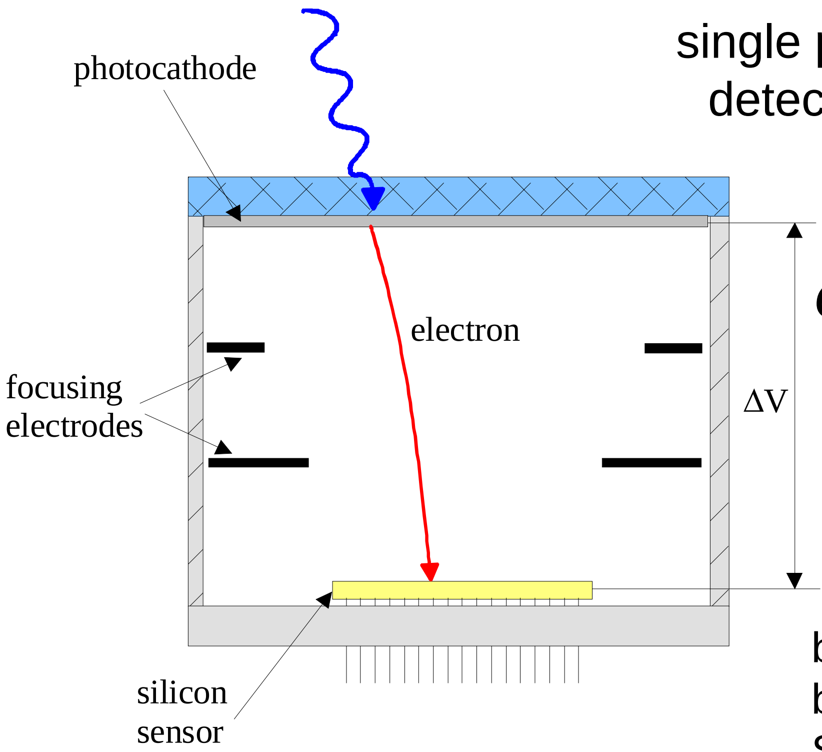
- **Avalanche photo diodes (APD)**
  - avalanche multiplication
    - high reverse bias $\Delta V \approx$ 100 to 200V
    - high internal field leads to avalanche



Hybrid photo detectors

Hybrid photo diodes (HPD)

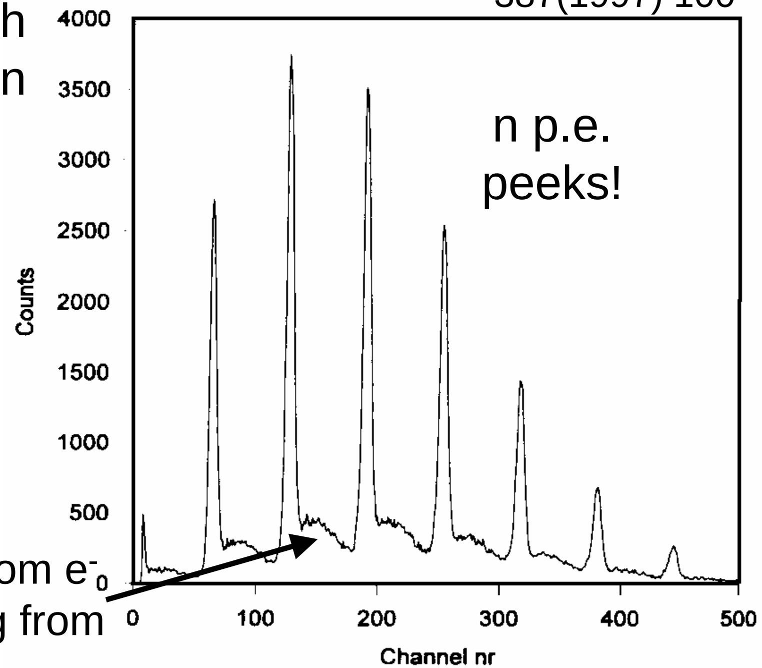
- photocathode (like in PMT)
- photo-electron acceleration
- silicon detector (pixel, strip, pads)



single photoelectron detection with high resolution

$$G = \frac{e\Delta V}{W} = \frac{20\ \text{keV}}{3.6\ \text{eV}} \approx 5\times10^{3}$$

Commercial HPD (DEP PP0270K) with slow electronic (2μs shaping time) C.P. Datema et al. NIM A 387(1997) 100



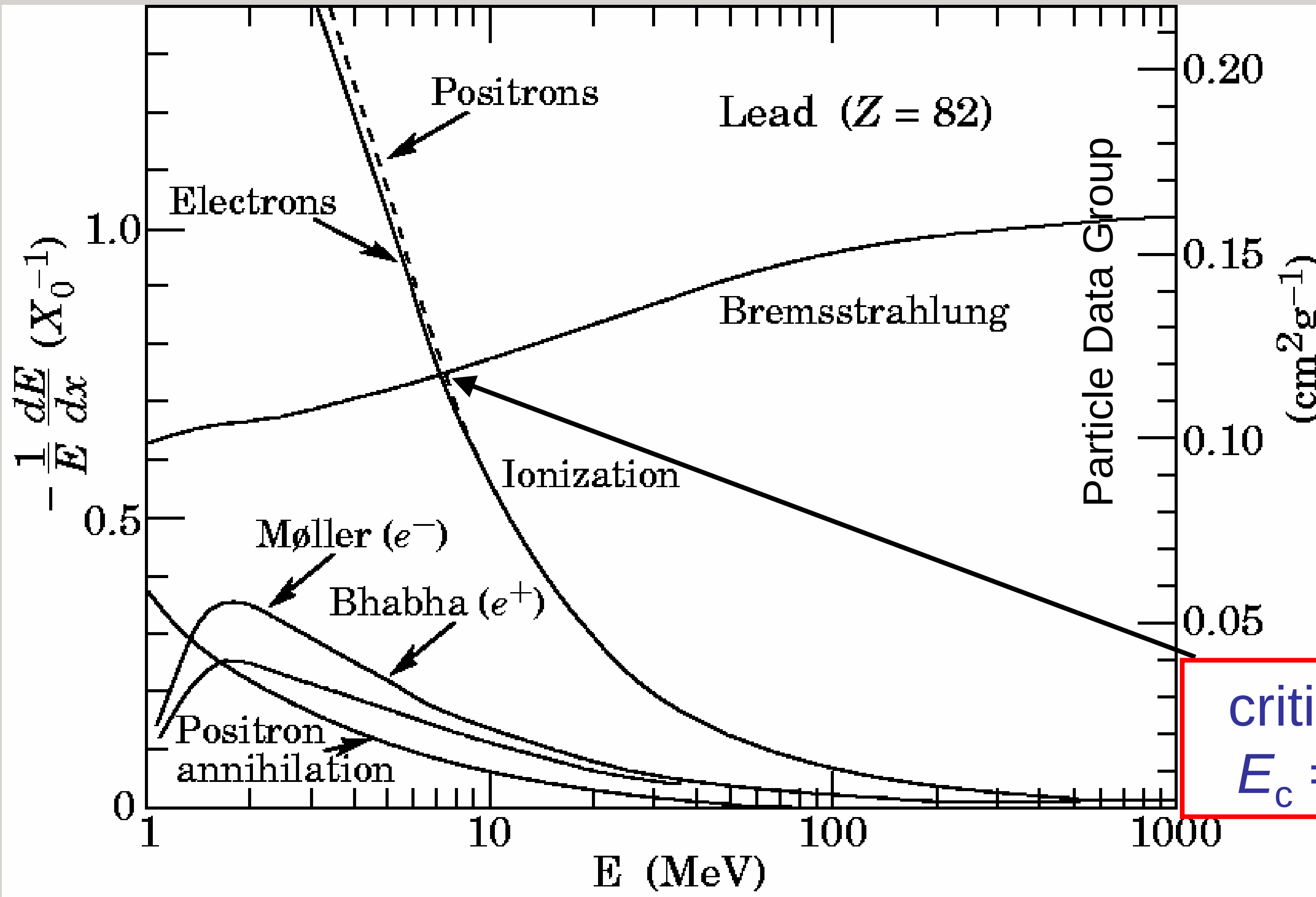
background from e^- backscattering from Si surface

Calorimetry

- Energy measurement by total absorption
  - works for charged and neutral particles
  - spatial reconstruction
  - particle identification capability
- Measured particle is lost (destructive method)
- Basic mechanism
  - electromagnetic or hadronic showers
- Detector response is proportional to E
  - not always true for hadronic showers
- Energy converted into ionization and/or excitation of matter

Interactions of electrons in matter

- Ionization and bremsstrahlung



critical energy
E_c = 6.9 MeV

Interactions of electrons in matter

- bremsstrahlung
  - photon produced in the Coulomb field of the absorber nuclei

$r_e = 2.82 \times 10^{-13}$ cm

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 r_e^2 \frac{m_e^2}{m^2} E \ln \frac{183}{Z^{1/3}} \propto \frac{E}{m^2}$$

    - important for electrons and ultra relativistic muons
  - for electrons

$$-\frac{dE}{dx} = \frac{E}{X_\circ} \longrightarrow E = E_\circ e^{-\frac{x}{X_\circ}}$$

$$X_\circ = \left[4\alpha N_A \frac{Z^2}{A} r_e^2 \ln \frac{183}{Z^{1/3}} \right]^{-1}$$

radiation length
(normally in g/cm^2)
See also table on page II/33

Interactions of electrons in matter

- critical energy
  - bremsstrahlung loss = ionization loss
  - for electrons

$$E_c^{\text{solid and liquid}} \approx \frac{610\ \text{MeV}}{Z+1.24} \qquad E_c^{\text{gas}} \approx \frac{710\ \text{MeV}}{Z+1.24}$$

  - for muons

$$E_c \approx E_c^{\text{e}} \left(\frac{m_\mu}{m_{\text{e}}}\right)^2 = 207^2 E_c^{\text{e}}$$

Interactions of photons in matter

Photo-electric effect

$$\gamma + A = \mathrm{e}^- + A^+$$

energy-momentum conservation requires a third partner close by $\rightarrow$ photo effect releases electrons mainly from the inner most atomic shell (K)

$$\sigma^{\mathrm{K}}_{\text{photo-e}} = 32\pi\sqrt{\frac{2}{3\varepsilon^7}}\alpha^4 Z^5 r_{\mathrm{e}}^2 \xrightarrow{\varepsilon \gg 1} 4\pi r_{\mathrm{e}}^2 \alpha^4 Z^5 \frac{1}{\varepsilon} \qquad \varepsilon \equiv \frac{E_\gamma}{m_{\mathrm{e}} c^2}$$

Compton scattering

$$\gamma + \mathrm{e}^- = \gamma + \mathrm{e}^- \qquad \Delta\lambda = \lambda_C \left(1 - \cos\theta\right)$$

$$\sigma^{\text{atomic}}_{\text{Compton}} = Z\sigma^{\mathrm{e}}_{\text{Compton}} \xrightarrow{\varepsilon \gg 1} \sigma^{\text{atomic}}_{\text{Compton}} \propto \frac{\ln\varepsilon}{\varepsilon}$$

Interactions of photons in matter

Pair production

$$\gamma + A = \mathrm{e}^{+}\mathrm{e}^{-} + A$$

In the Coulomb field of a nucleus or electron.
Only possible if $E_\gamma \geq 2m_\mathrm{e}$ of course.

$$\sigma_{\text{pair}} \xrightarrow{\varepsilon \gg 1} \frac{7}{9}\frac{A}{N_A}\frac{1}{X_\circ} \qquad \lambda_{\text{pair}} \xrightarrow{\varepsilon \gg 1} \frac{9}{7}X_\circ \qquad \varepsilon \equiv \frac{E_\gamma}{m_\mathrm{e}c^2}$$

Mass attenuation coefficient μ

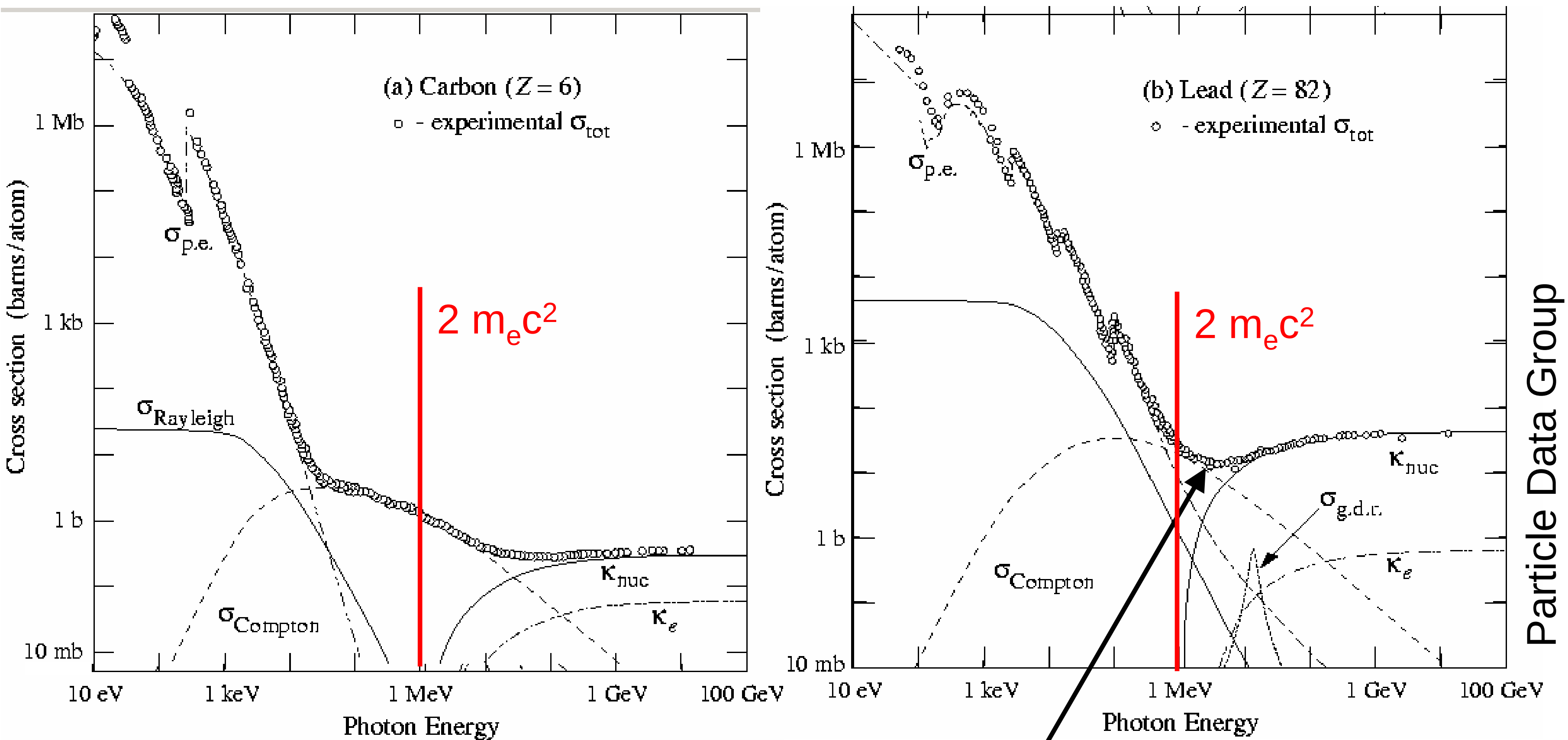
$$I_\gamma = I_\circ e^{-\mu x}$$

normally μ in cm^2/g
and x in g/cm^2

$$\mu = \mu_{\text{photo-e}} + \mu_{\text{Compton}} + \mu_{\text{pair}} + \cdots$$

$$\mu_i = \frac{N_A}{A}\sigma_i$$

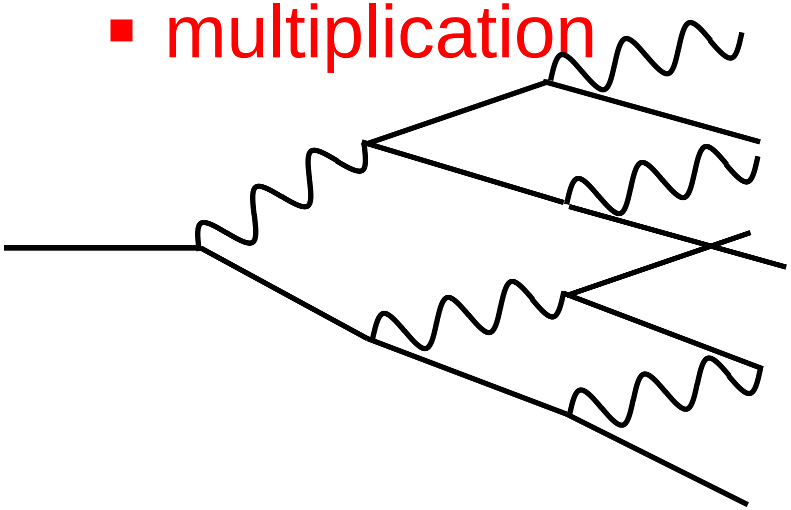
Interactions of photons in matter

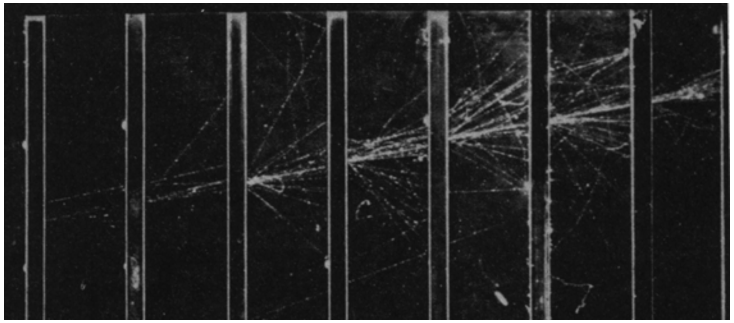


min is 14.2 b/atom

Electromagnetic showers

- Simple model
  - multiplication





electron shower in a cloud chamber with lead absorbers (Joram)

Only consider bremsstrahlung ($e^{\pm}$) and pair production (γ) $\rightarrow$ assume E_γ large.

Multiplication stops when average shower particle energy = critical energy. At this stage the $e^{\pm}$ will mainly lose energy through ionization and the multiplication will stop. This happens before the photons have less than $2m_ec^2$ energy.

Electromagnetic showers

Let k be the number of steps needed for the multiplication to stop.

$$E = E_C 2^k$$

The corresponding maximum number of particles in the shower is then

$$\sum_{n=0}^{k} 2^n = 2^{k+1} - 1 \approx 2 \times 2^k = 2\frac{E}{E_C}$$

Each step takes place over a characteristic length: X_o for $e^{\pm}$ and $9X_o/7$ for γ. Assume X_o for both. Then

$$k = \frac{1}{\ln 2}\ln\frac{E}{E_C} = 1.44\ln\frac{E}{E_C}$$

In practice, ionization energy losses and fluctuations lowers somewhat this number

$$k = \frac{X_{\text{max}}}{X_\circ} = \begin{cases} \ln\dfrac{E}{E_C} - 1.1 & \text{for electrons} \\ \ln\dfrac{E}{E_C} - 0.3 & \text{for photons} \end{cases}$$

Kleinknecht

This is the number of X_o needed to stop shower multiplication. This corresponds to "shower max". Grows like ln*E.*

Electromagnetic showers

Simple model

- attenuation

Complicated mixture of ionization losses, radiation losses and Compton scattering. But the electromagnetic shower attenuation seems to follow the minimum attenuation for photons. The corresponding photon mean free path is

$$\lambda_\gamma = \frac{A}{N_A \rho \sigma_\gamma^{\mathrm{min}}}$$

The attenuation follows exponentially with a mean free path of λ_γ. So to attenuate down to 95%, one needs $3\lambda_\gamma$.

Therefore to contain 95% of a shower energy we need an absorber thickness of

$$k\frac{X_\circ}{\rho} + 3\lambda_\gamma$$

This is actually close to experimental results!

For 100 GeV electrons on lead this gives $20X_o = 11\mathrm{cm}$

Electromagnetic showers

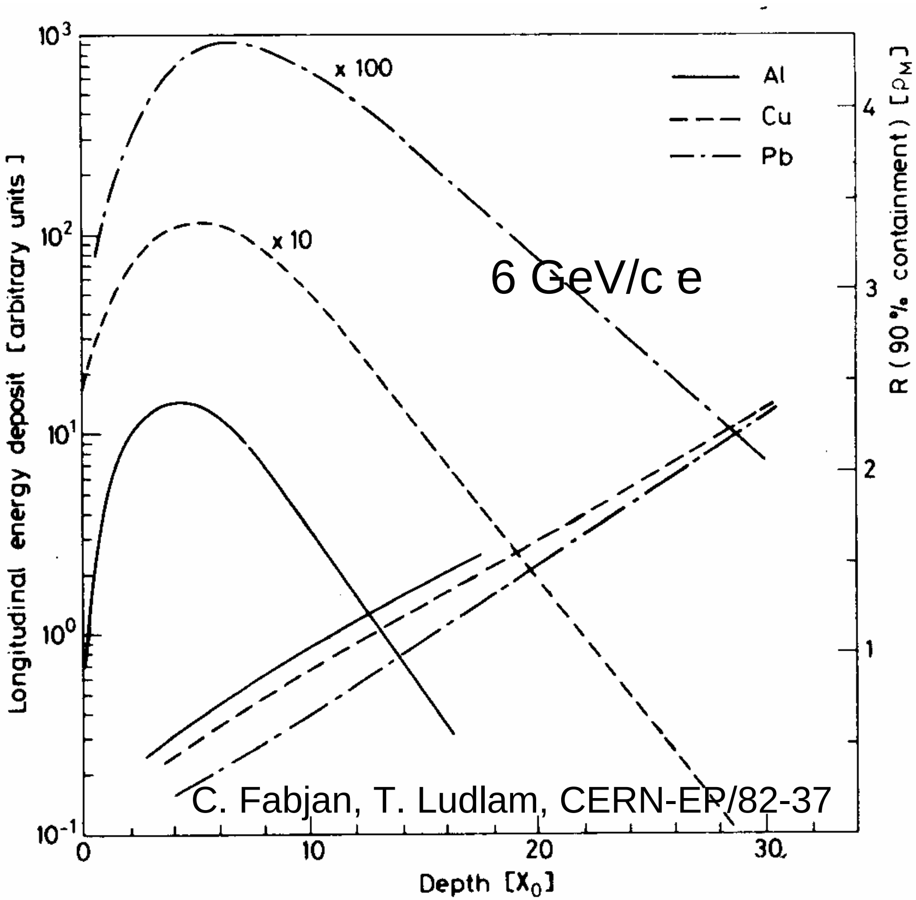
Transverse shower development

- 95% containment in a cylinder of radius $2R_M$
  - Molière radius

$$R_M = \frac{21\ \text{MeV}}{E_C} X_\circ$$

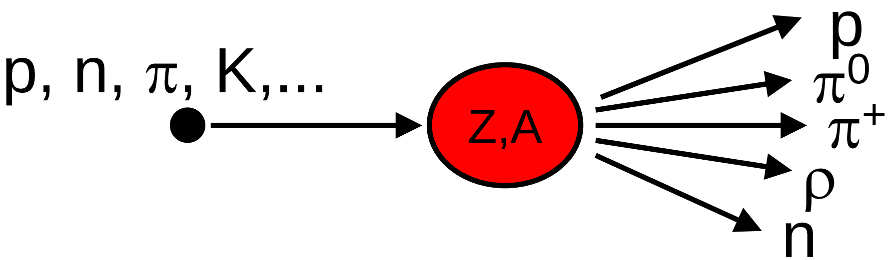
  - For 100 GeV electron in lead this gives

    1.7 cm



Nuclear interactions

- Inelastic nuclear processes
  - determines the interaction of energetic hadrons



$N \propto \ln(E_o)$

transverse momentum about 0.35 GeV/c

  - Excitation and breakup of nucleus
    - nucleus fragments and secondary particles
  - cross section depends ~only on A
    - $\sigma_{\text{inelastic}} \approx \sigma_\circ A^{0.7}$ $\sigma_\circ \approx 35$ mb A in g/mol
  - hadronic absorption length

$$\lambda_a = \frac{A}{N_A \sigma_{\text{inelastic}}}$$

Interaction and hadronic absorption lengths

Material	Z	A	ρ [g/cm^3]	X_0 [g/cm^2]	λ_a [g/cm^2]
Hydrogen (gas)	1	1.01	0.0899 (g/l)	63	50.8
Helium (gas)	2	4.00	0.1786 (g/l)	94	65.1
Beryllium	4	9.01	1.848	65.19	75.2
Carbon	6	12.01	2.265	43	86.3
Nitrogen (gas)	7	14.01	1.25 (g/l)	38	87.8
Oxygen (gas)	8	16.00	1.428 (g/l)	34	91.0
Aluminium	13	26.98	2.7	24	106.4
Silicon	14	28.09	2.33	22	106.0
Iron	26	55.85	7.87	13.9	131.9
Copper	29	63.55	8.96	12.9	134.9
Tungsten	74	183.85	19.3	6.8	185.0
Lead	82	207.19	11.35	6.4	194.0
Uranium	92	238.03	18.95	6.0	199.0

Hadronic shower

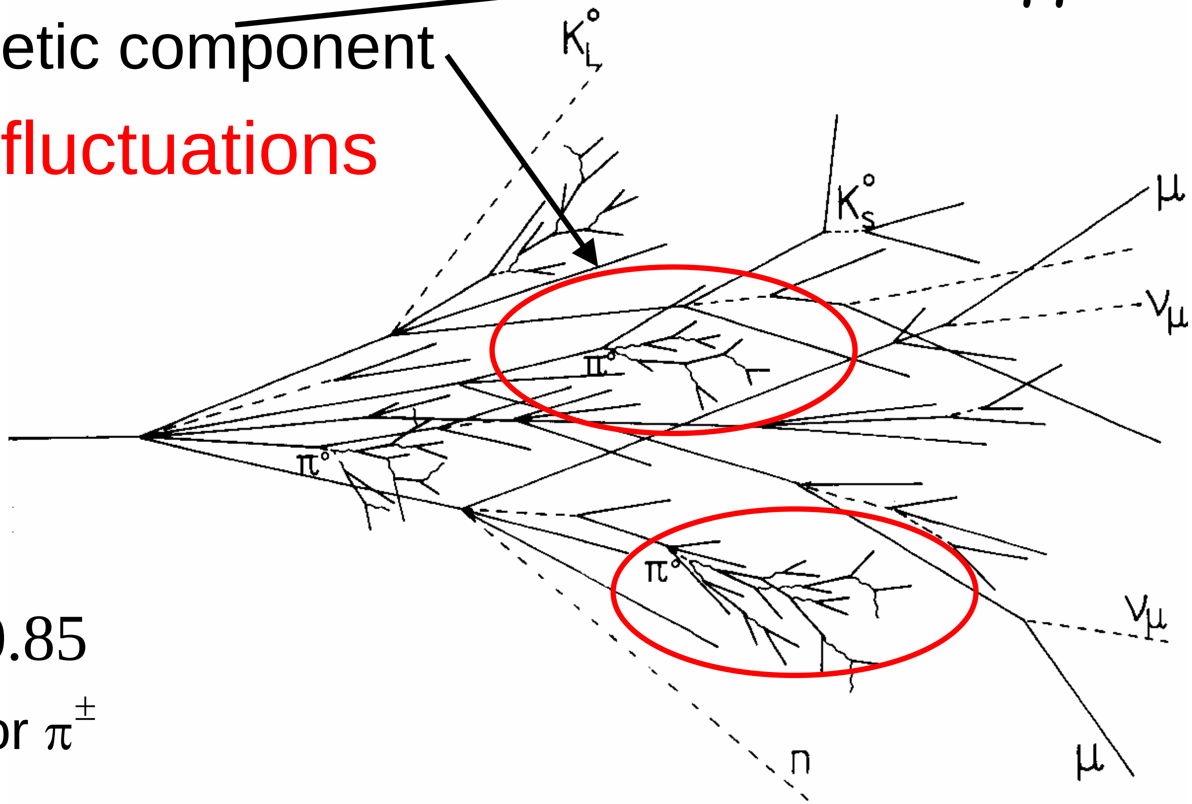
- many processes involved
- more complex (and larger) than EM showers
  - hadronic component
  - electromagnetic component $\pi^0 \to \gamma\gamma$
- large energy fluctuations
  - limited $\sigma(E)$

$$\left(\frac{E}{E_0}\right)^{m-1}$$

$$0.80 \le m \le 0.85$$

$E_0 \approx 1$ GeV for $\pi^{\pm}$

$E_0 \approx 2.6$ GeV for p



Grupen

Calorimeter types

- Homogeneous calorimeters
  - the detector is the absorber
  - good energy resolution
  - limited spatial resolution, especially longitudinal
  - only used for electromagnetic calorimetry
- Sampling calorimeters
  - the detector and absorber are separated
  - only sample part of the shower
    - additional sampling fluctuations affect energy resolution
  - limited energy resolution
  - good spatial resolution

Homogeneous calorimeters

- Two main types
  - Scintillation crystals
  - Glass blocks, through Cherenkov radiation
- Scintillation crystals

Scintillator	Density [g/cm^3]	X_0 [cm]	Light Yield γ/MeV (rel. yield)	τ_1 [ns] λ_1 [nm]	Rad. Dam. [Gy]	Comments
NaI (Tl)	3.67	2.59	4×10^4	230 415	$\geq$10	hydroscopic, fragile
CsI (Tl)	4.51	1.86	5×10^4 (0.49)	1005 565	$\geq$10	Slightly hygroscopic
CSI pure	4.51	1.86	4×10^4 (0.04)	10 310 36 310	10^3	Slightly hygroscopic
BaF_2	4.87	2.03	10^4 (0.13)	0.6 220 620 310	10^5	
BGO	7.13	1.13	8×10^3	300 480	10	
$PbW0_4$	8.28	0.89	$\approx$100	10 $\approx$440 10 $\approx$530	10^4	light yield =f(T)

Joram

Relative light yield: rel. to NaI(Tl) readout with PM (bialkali PC)

  - example: CMS electromagnetic calorimeter uses $PbWO_4$
  - example: L3 used BGO for its EM calorimeter

Homogeneous calorimeters

Cherenkov radiators

Cherenkov radiation

- produced when a charged particle travels in a dielectric (index of refraction *n*) at a velocity greater than the speed of light in that dielectric (*c*/*n*).

Material	Density [g/cm^3]	X_0 [cm]	n	Light yield [p.e./GeV] (rel. p.e.)	λ_{cut} [nm]	Rad. Dam. [Gy]	Comments
SF-5 Lead glass	4.08	2.54	1.67	600 (1.5×10^{-4})	350	10^2	
SF-6 Lead glass	5.20	1.69	1.81	900 (2.3×10^{-4})	350	10^2	
PbF_2	7.66	0.95	1.82	2000 (5×10^{-4})		10^3	Not available in quantity

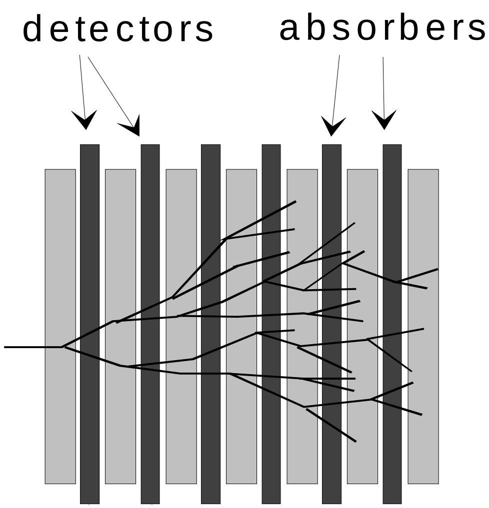
Joram

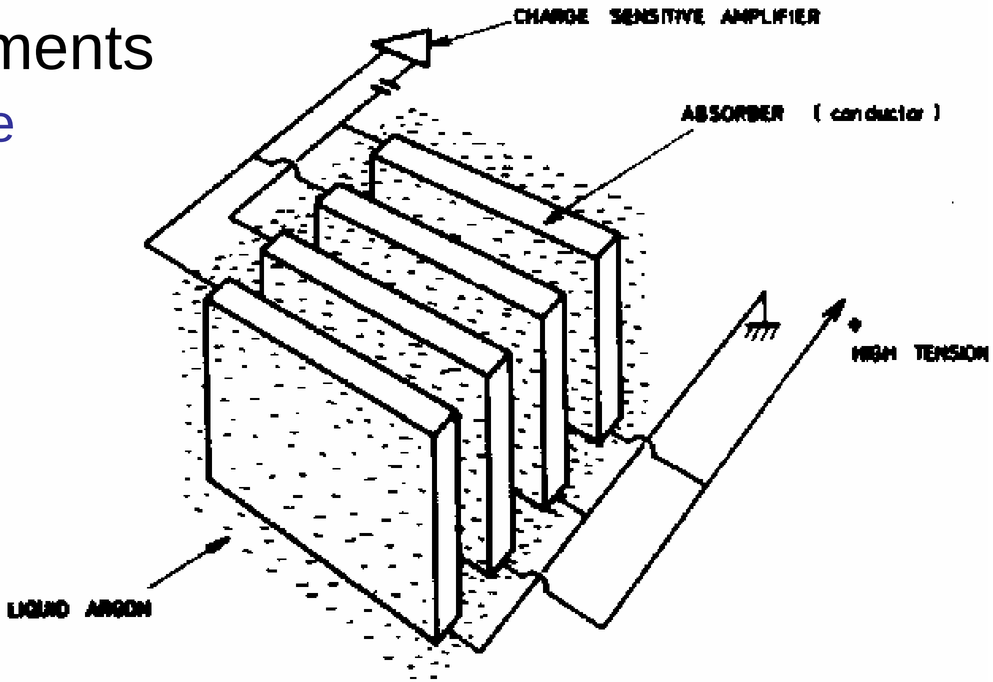
Relative light yield: rel. to NaI(Tl) readout with PM (bialkali PC)

- example: OPAL used lead glass for its barrel and end-cap calorimeters

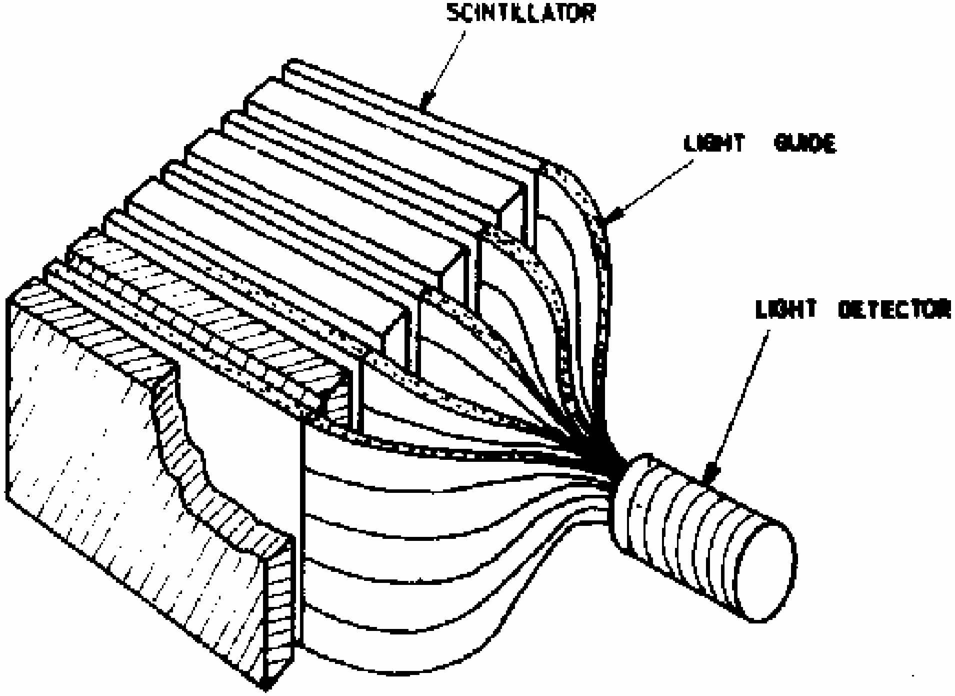
Sampling calorimeters

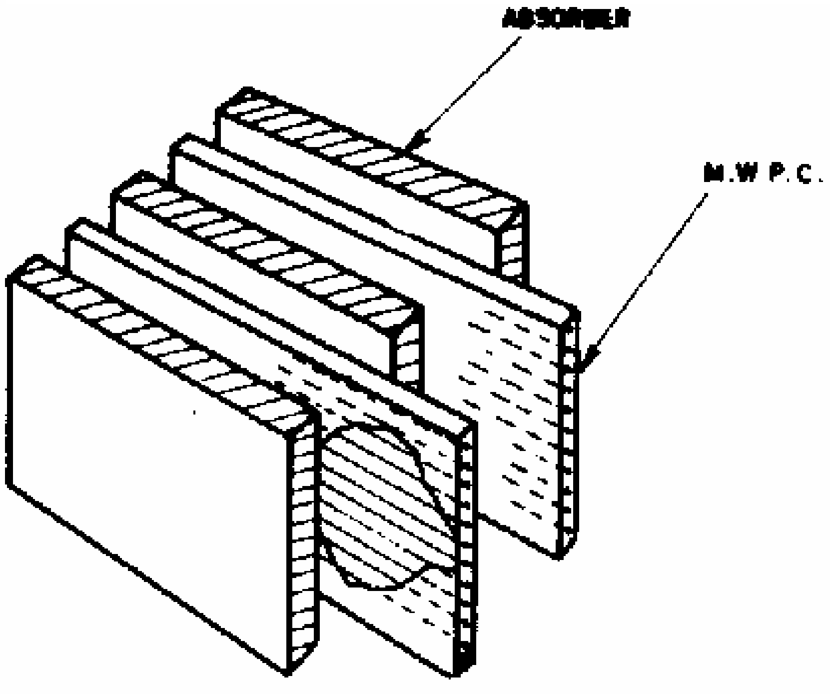
- Sample a fraction of the shower
  - variety of detectors used
    - MWPC
    - warm liquids
      - TMP (tetramethylpentane)
      - TMS (tetramethylsilane)
    - liquid noble gase elements
      - LAr (mainly), LKr, LXe
    - scintillators, fibres
    - silicon detectors





Sampling calorimeters





Electromagnetic calorimeters

- Use EM shower results:
  - number of particle at shower max is prop. to E_o
  - total track length of $e^\pm$ is prop. to E_o
- Linearity
  - if the calorimeter signal is proportional to the $e^\pm$ track length
  - if the EM shower is completely contained in the calorimeter
  - $\rightarrow$ then the calorimeter signal is proportional to E_o

Electromagnetic calorimeters

Intrinsic limit to energy resolution

- total number of track segments $N \propto \frac{E_\circ}{E_C}$
- energy resolution improves with incident energy

$$\frac{\sigma(E)}{E} \propto \frac{\sigma(N)}{N} \propto \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{E_\circ}}$$

- spatial resolution also scales the same way

General parametrization

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

stochastic or sampling term

constant term

comes from inhomogeneity, bad calibration, non-linearity

noise term

including electronic and pileup noise

Hadronic calorimeters

Sampling calorimeters

- EM and hadronic energy depositions are measured with different efficiencies
  - e/h ratio

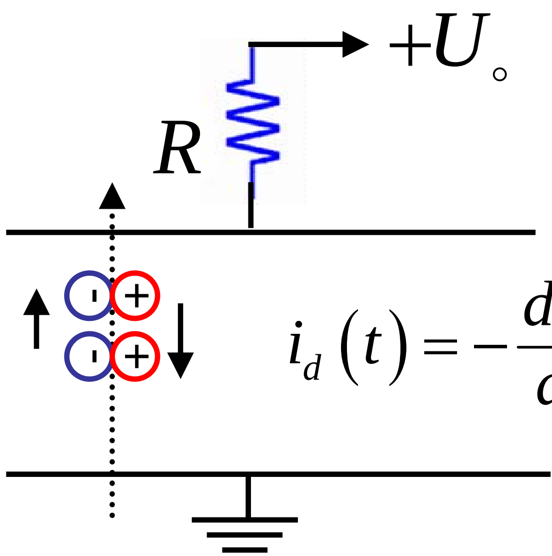
$$\text{"}\pi/\text{e"} = 1 - \left(1 - \text{h/e}\right)\left(\frac{E}{E_0}\right)^{m-1}$$

  - if e/h = 1, the calorimeter is compensating
  - non compensations worsen the energy resolution

Grupen

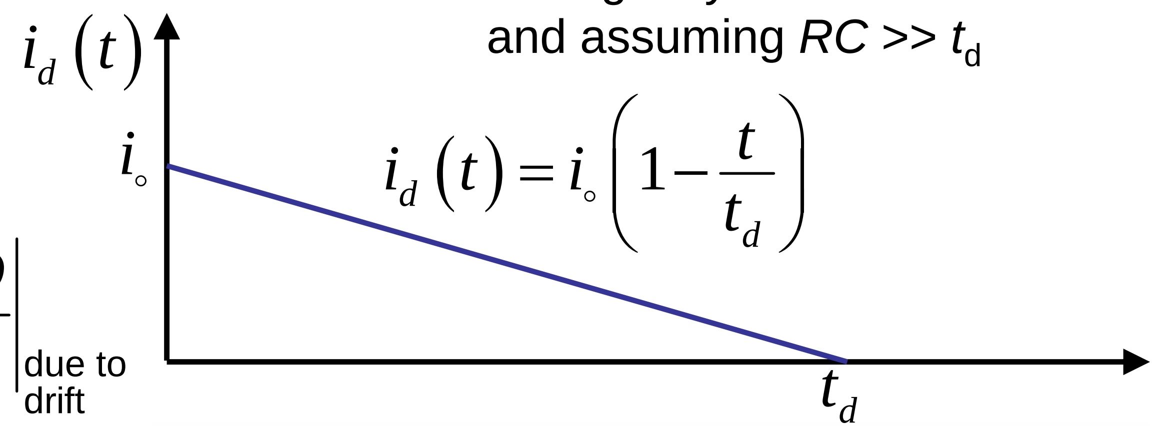
Liquid argon calorimetry

LAr ionization chamber



$$i_d(t) = -\left.\frac{dQ}{dt}\right|_{\text{due to drift}}$$

considering only the electron drift and assuming $RC \gg t_d$



$$i_d(t) = i_\circ\left(1 - \frac{t}{t_d}\right)$$

typical values:

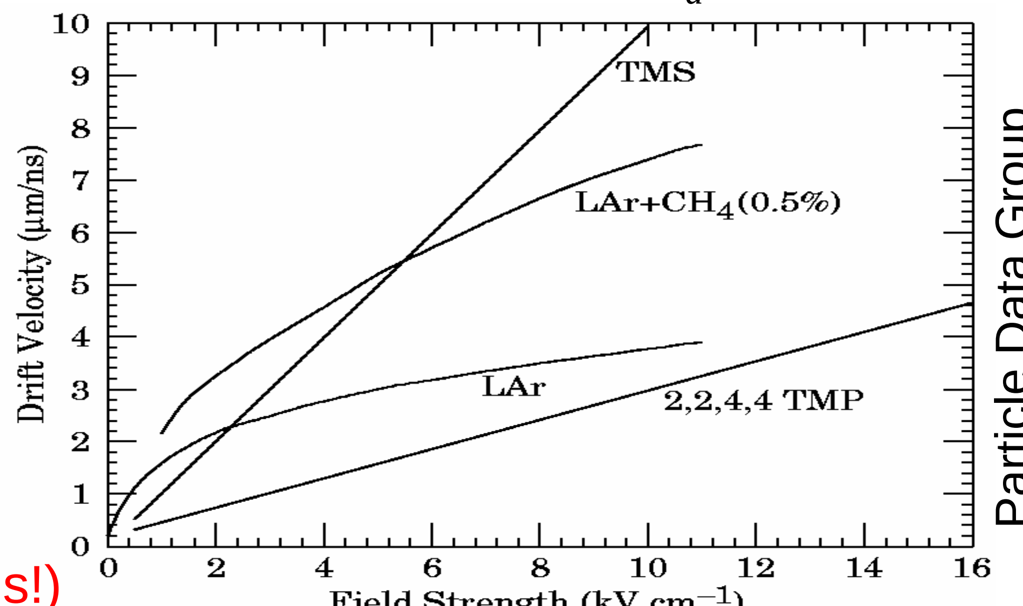
$T = 87$ K, $\rho = 1.40$ g/cm^3

$X_0 = \rho$ 13.9 cm

W = 23.6 eV

$U_0 = 2$ kV over 2 mm gaps

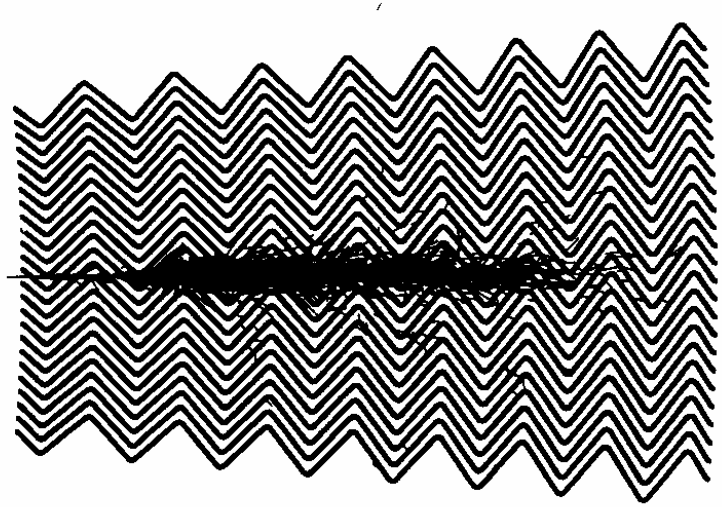
$t_d \approx 450$ ns (compare to LHC 25 ns!)



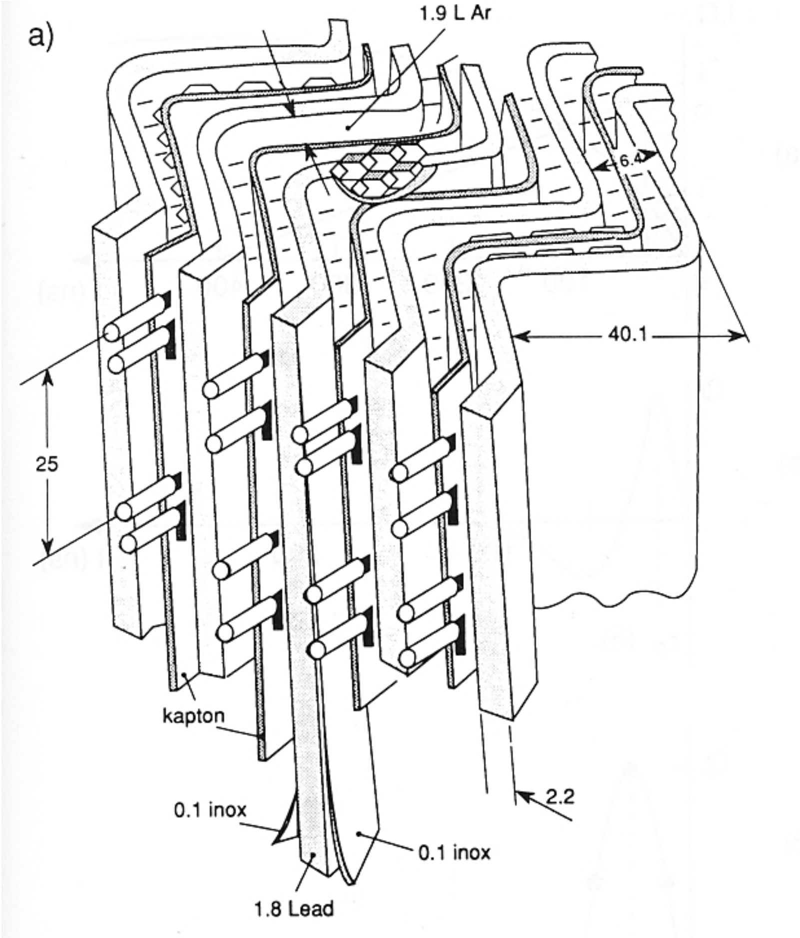
Liquid argon calorimetry

- Accordion design
  - novel hermetic design
  - used for all ATLAS EM calorimetry
    - Lead-steel absorbers
    - multilayer readout boards
    - LAr is radiation hard

RD3 collaboration, NIM A309 (1991) 438-449



M. Lefebvre

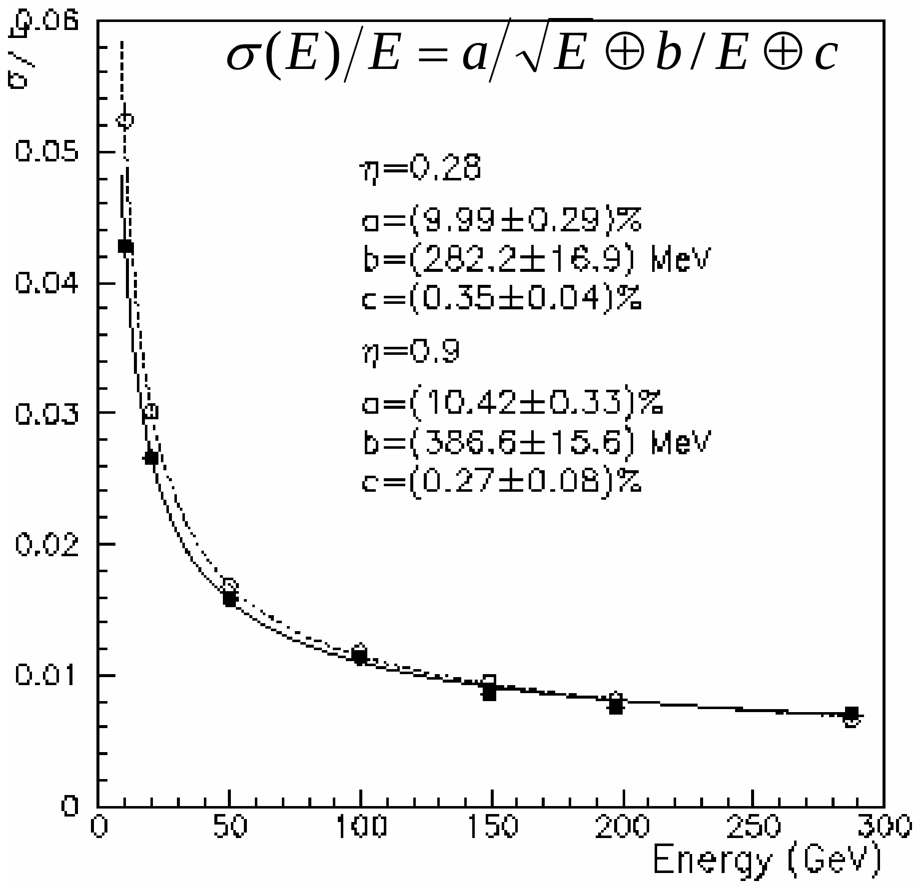


angle change with radius to keep LAr gap constant thickness

Liquid argon calorimetry

Accordion EM calorimeter beam test results

ATLAS TDR



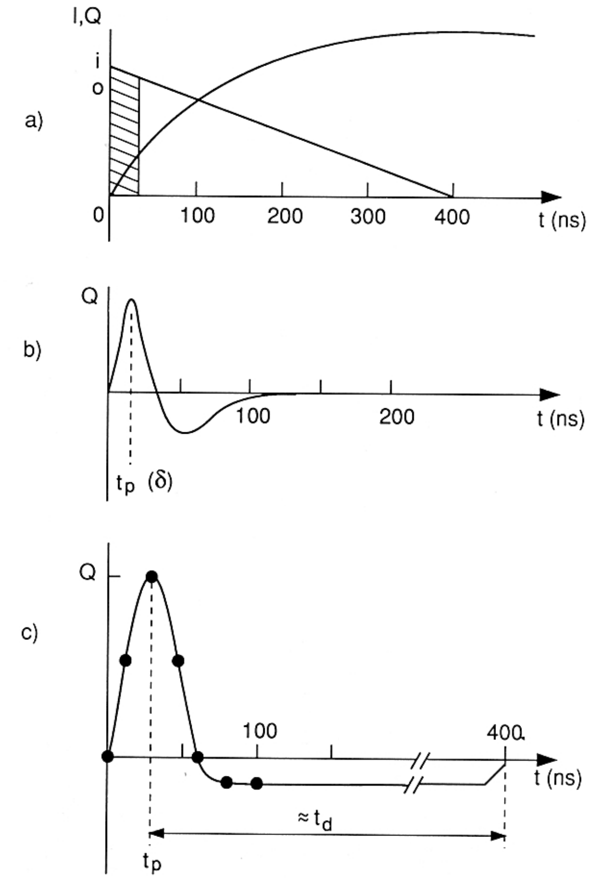


Fig. 1. (a) Drift current and integrated charge vs time for an ion chamber calorimeter. (b) Response of a shaping amplifier to a short current pulse (δ). (c) Response of a shaping amplifier to the current form shown in (a). The dots indicate where the beam crossings (every 15 ns) would appear if $t_p(\delta) = 20$ ns.

RD3 collaboration, NIM A309 (1991) 438-449

Lecture II: Questions

- Question II.1
  - Use the numbers shown on slide II/11 to obtain the solid angle aperture (in one direction) quoted, namely 3.1% and 5.3%.
- Question II.2
  - Using the lectures notes, obtain the result quoted at the bottom of slide II/30, namely that 100 GeV electron EM showers in lead are 95% contained in a depth of $20X_o$ = 11cm.