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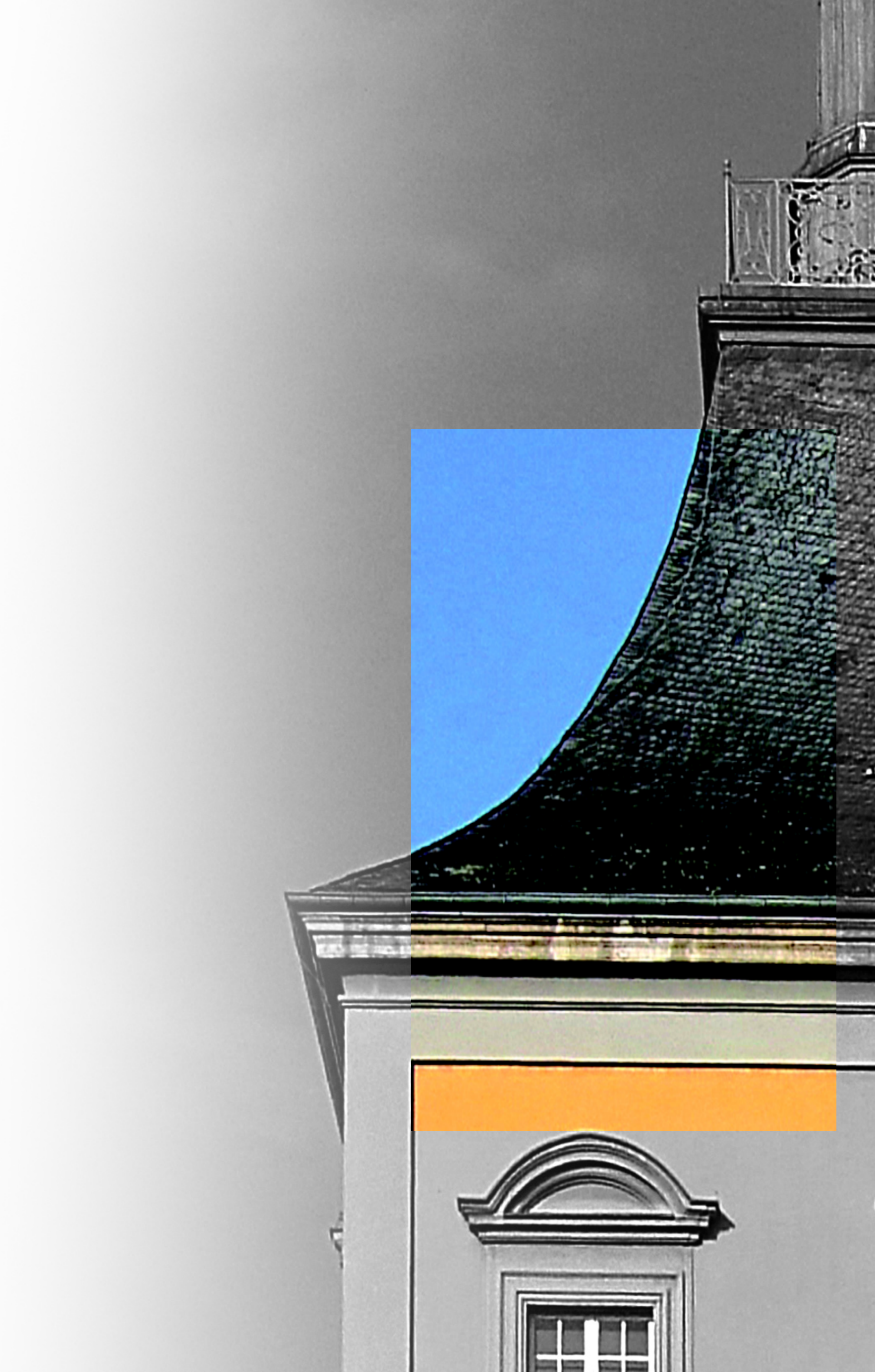
DETECTORS
GENERAL ASPECTS

LECTURE: ESIPAP-2021 SCHOOL

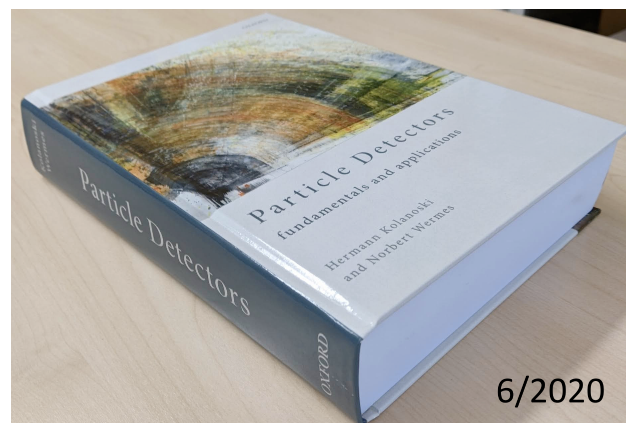
GRENOBLE, FEBRUARY 15, 2021

NORBERT WERMES
UNIVERSITY OF BONN

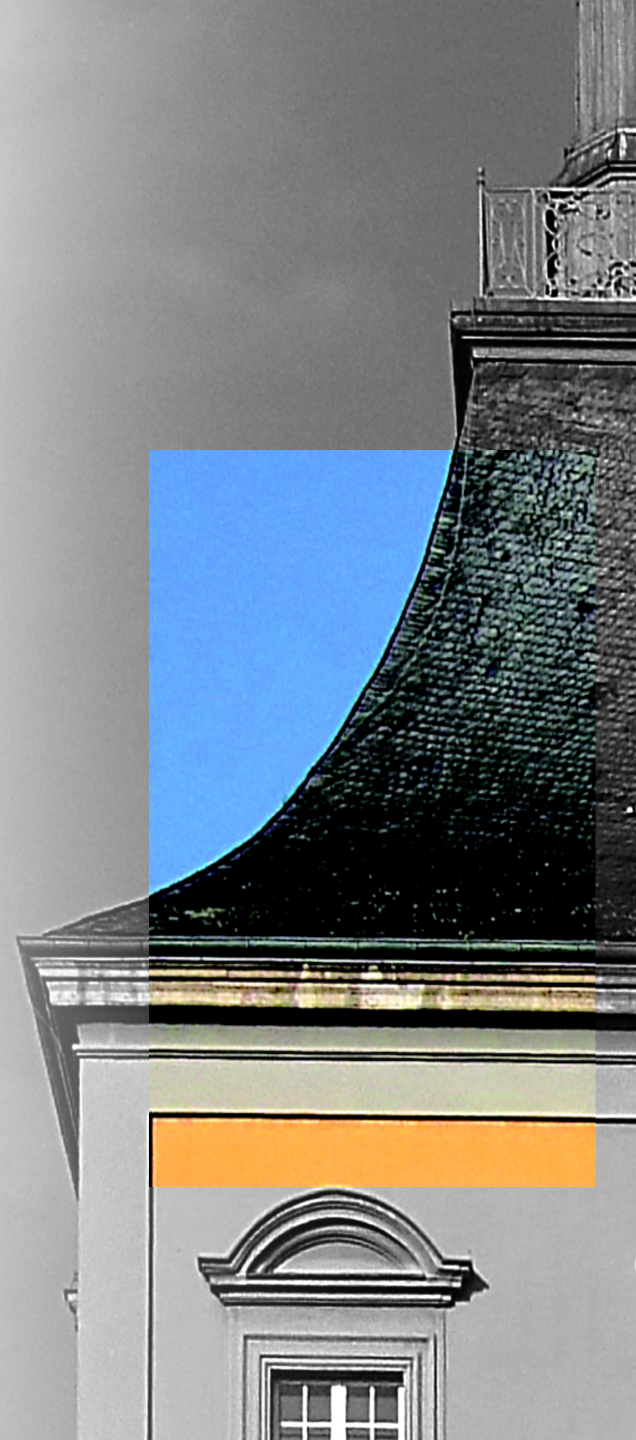


Outline of this "introductory lecture"

- ❑ Detectors – what is their task?
- ❑ The possibilities: some important detector types
- ❑ How well can one measure? – 2 examples
- ❑ The detection process: interaction – signal formation – readout
- ❑ The "signal" … generation and processing
- ❑ … and (finally) the noise … why bother?



The tasks of (particle) detectors



Measure …

… 4 – vectors of particles or “jets ≈ quarks/gluons”

$$p^\mu = (E, p^x, p^y, p^z) = \left(\sqrt{p^2 + m^2}, \vec{p}\right)$$

… measure

energy E

momentum $|\vec{p}|$
direction (θ, ϕ)

mass $\Rightarrow$ particle ID

… are usually measured indirectly by measuring other properties like

- curvature of flight path
- energy lost over a distance
- the particle’s velocity (β or γ)
- the distance to decay
- …

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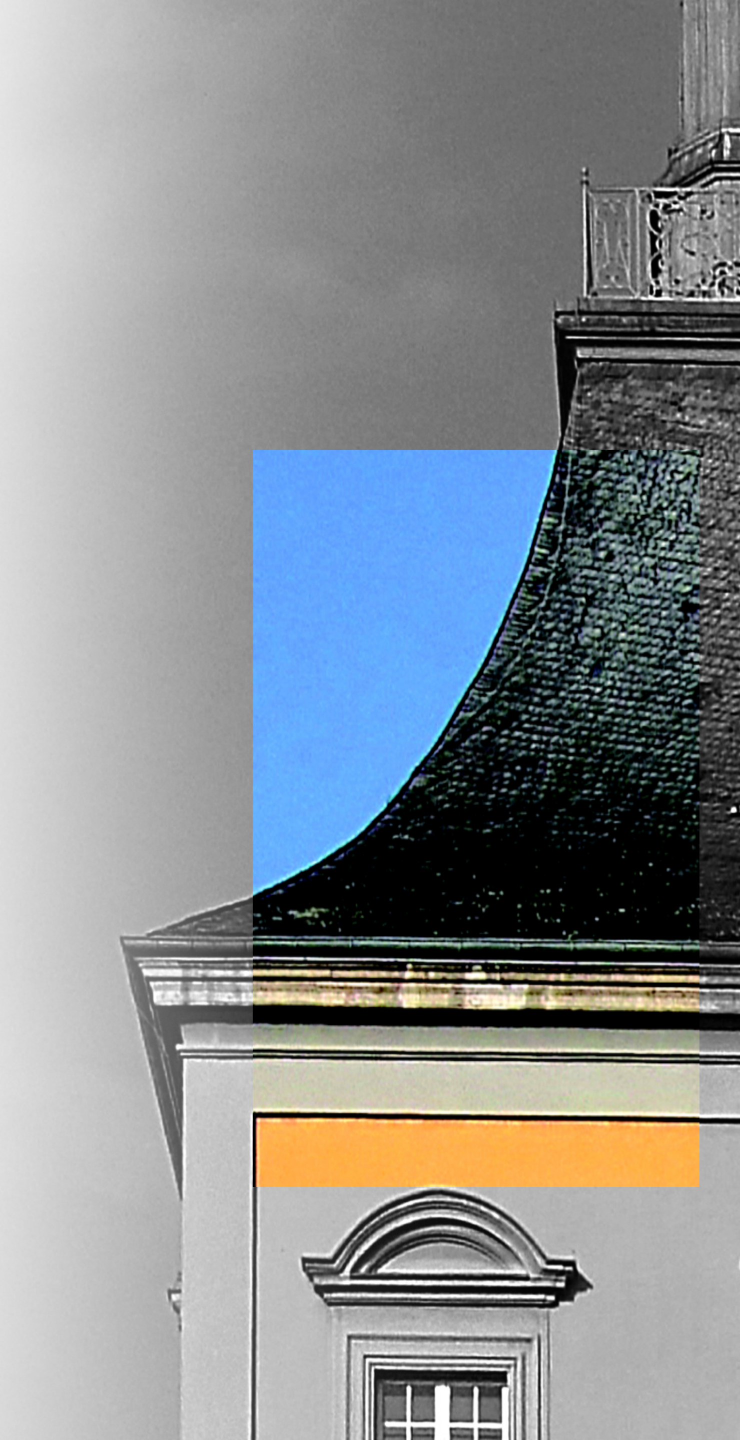
Three examples



Example 1: First observation of $B\bar{B}$ mixing (ARGUS 1987)

$\Upsilon(4s) \rightarrow B^0 \, \overline{B^0}$

($b\bar{b}$-state)

$B^0 \rightarrow D^{*-} \mu^+ \nu$

$\quad \hookrightarrow \pi^- \overline{D^0}$

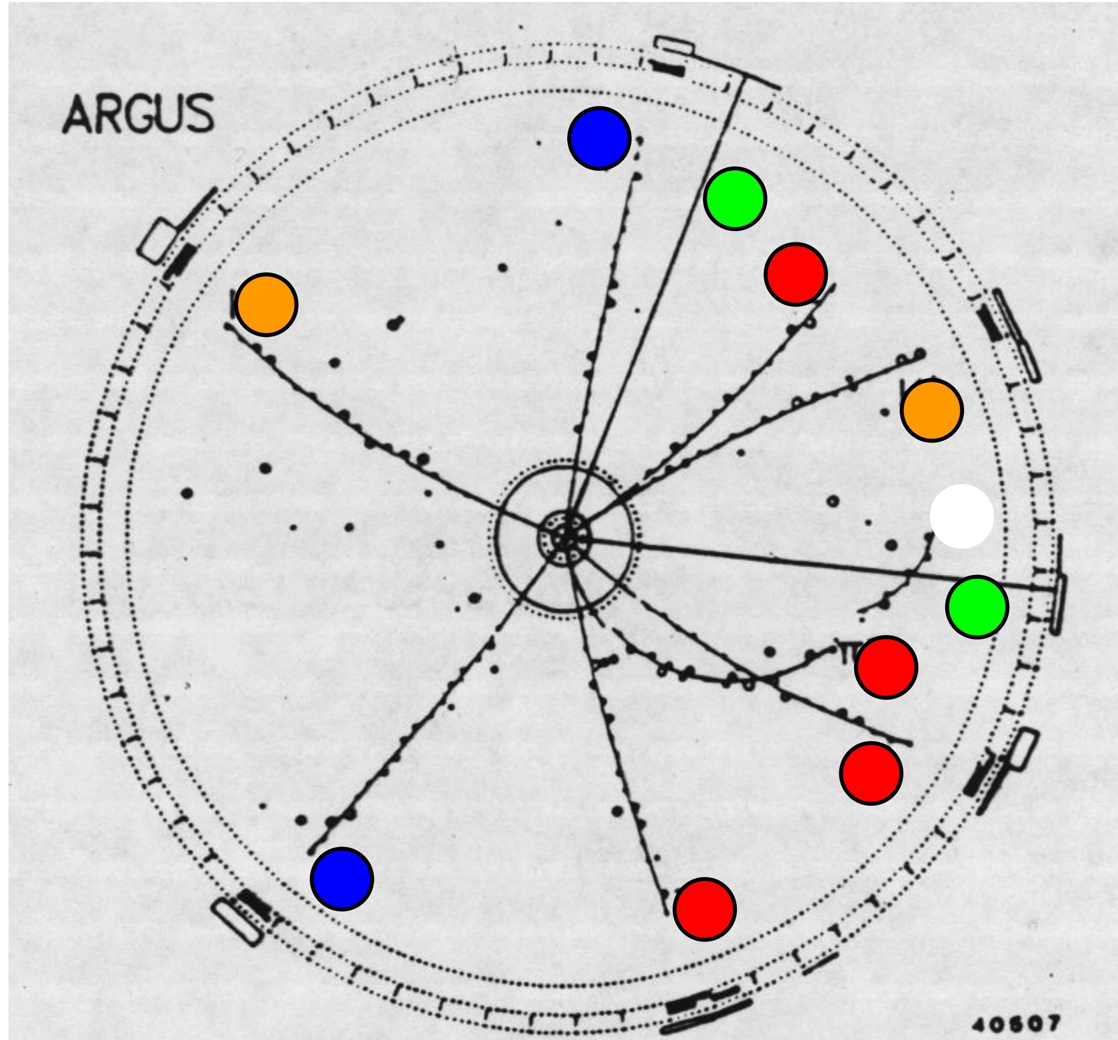
$\quad\quad \hookrightarrow K^+ \pi^-$

$\overline{B^0} \rightarrow B^0 \rightarrow D^{*-} \mu^+ \nu$

mixing !

$\quad \hookrightarrow \pi^0 D^-$

$\quad\quad \pi^0 \rightarrow \gamma\gamma$, $\quad D^- \rightarrow K^+\pi^-\pi^-$



important: momentum resolution & particle ID

see also Lectures by J. Baudot & G. Unal (Course 1)

Example 2: “hadron-blind” – ”electron sharp” experiment

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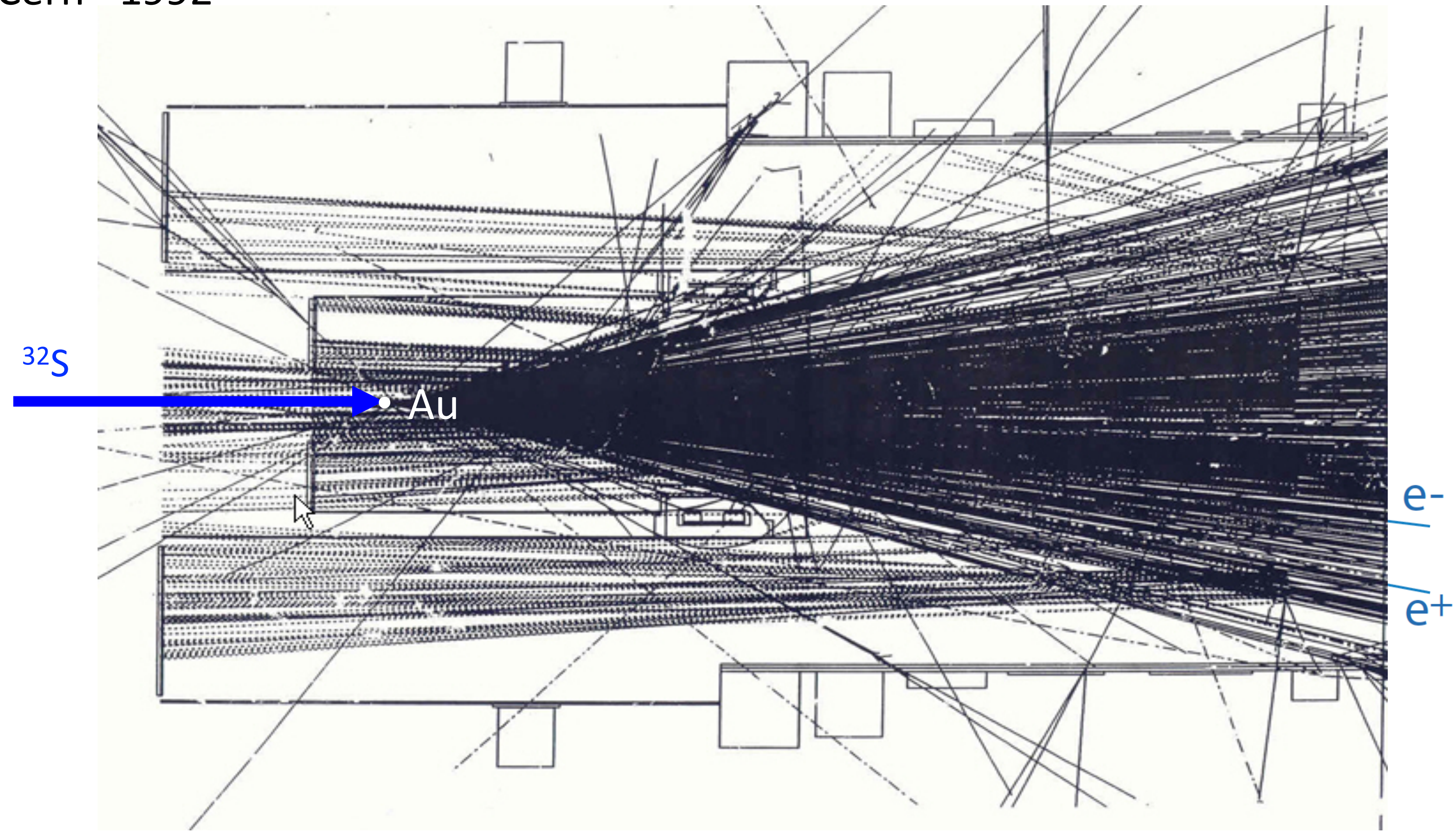
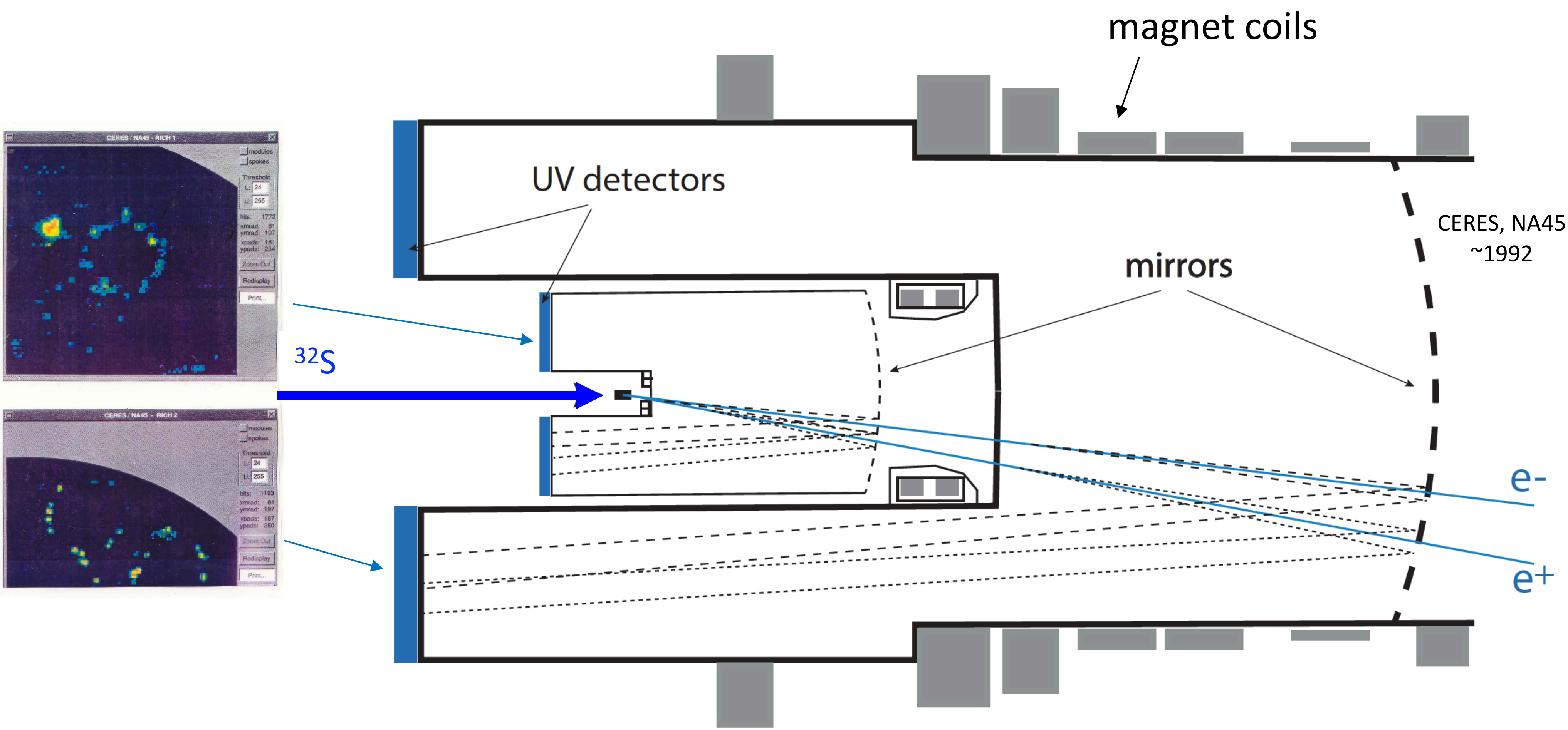
CERES, NA45, Cern ~1992



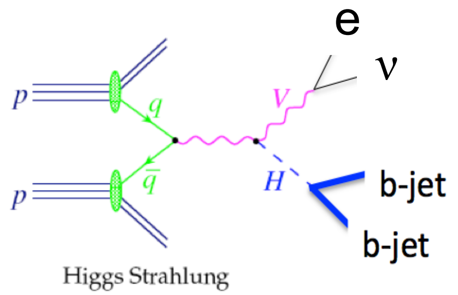
Example 2: "hadron-blind" – "electron sharp" experiment

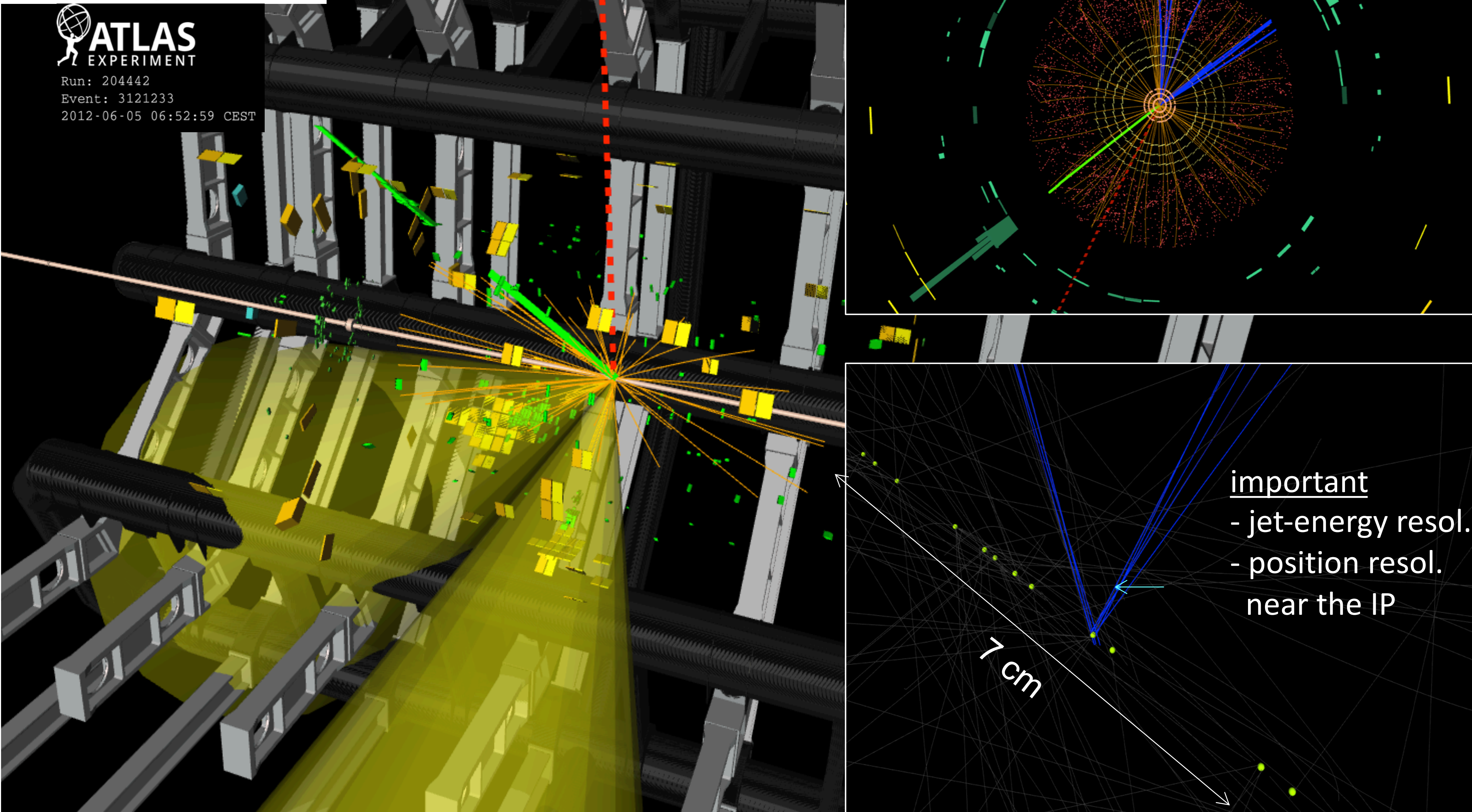


two interlaced gas Cherenkov detectors

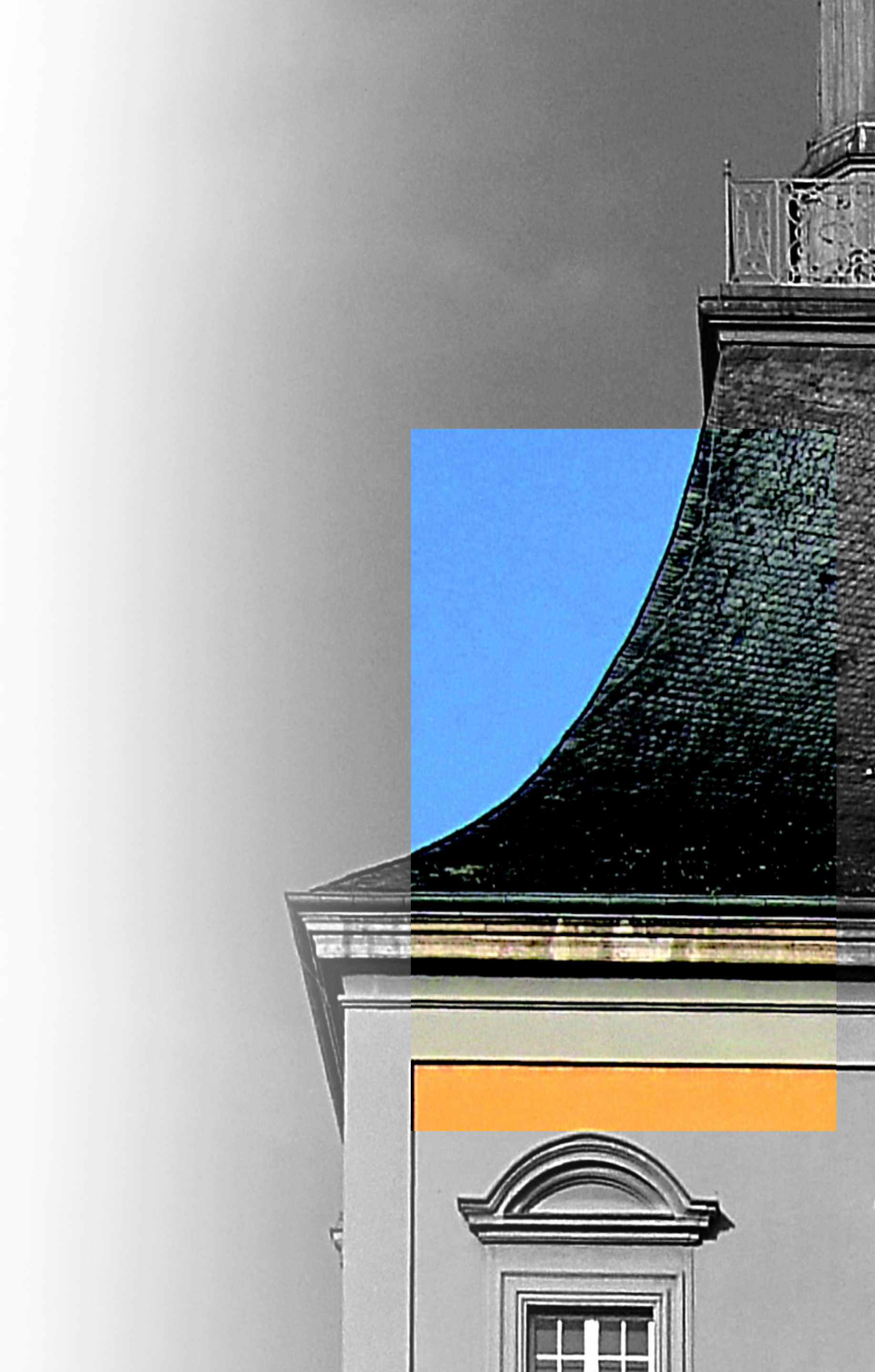
see Lectures by C. Joram on 18.2.21
and by F. Montanet (Course 1)

Example 3: LHC: pp -> WH -> νl + bb





The detection process



Requirement of every detecting measurement

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Interaction of the particle (charged, neutral, γ-ray, photon or visible light)

with MATTER (= detector)

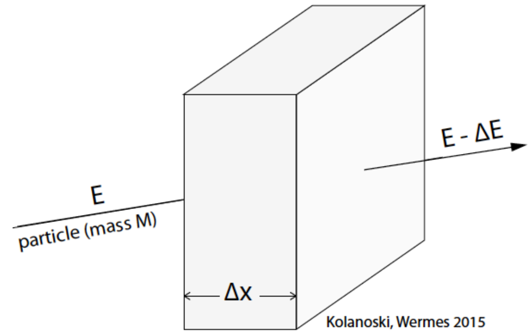
producing …

secondaries (charge release, light, X-rays, kicked-off nucleons/nuclei)

which can become a “signal” .

"Signals" for detectors

"signals" are generated when
particles go through matter in detectors



- Ionisation and excitation of atoms in media by charged particles
- Bremsstrahlung: photon emission off charged particles in the field of a nucleus
- Photon scattering and photon absorption
- Cherenkov and transition radiation
- Nuclear reactions: hadrons (p, n, , , . . .) with nuclear matter
- Weak interactions constituting the only possibility to (directly) detect neutrinos

- Q: Are these 6 different types of detection processes?
- A: Yes and No ... in the final detection process is usually
  of electromagnetic nature or is heat or "quantum" type.

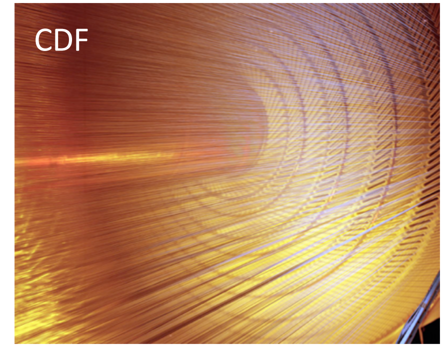
Six important detector types …

Some important detector types - 1

Ionisation detectors

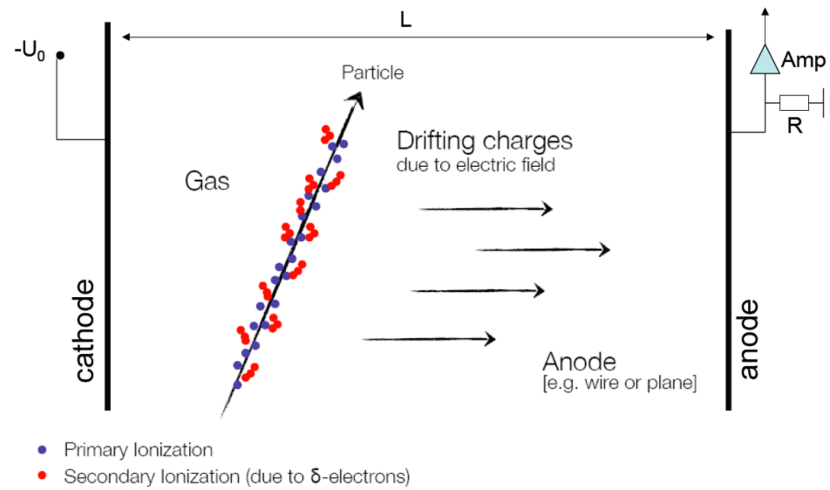
gaseous

MWPC



driftchamber

- ~30 eV per e/ion needed
- 94 e/ion pairs per cm (in Ar)
  => (gas-)amplification needed
- "signal" due to separation and movement of charges in E-field
- Output: current on electrode charge -> V_{out} after amplifier

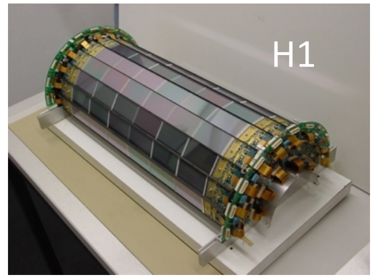


see Lecture by J. Brom on 16.2.21

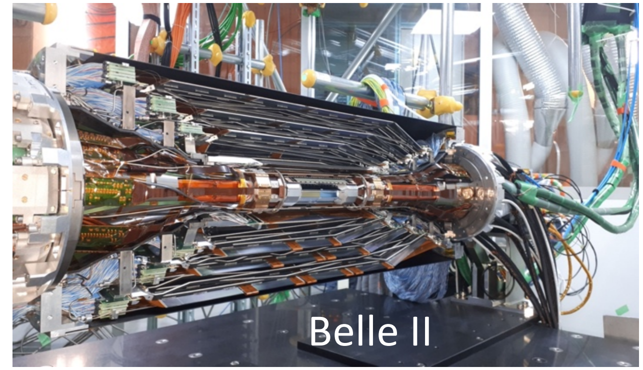
Some important detector types - 2

Ionisation detectors

semiconductor



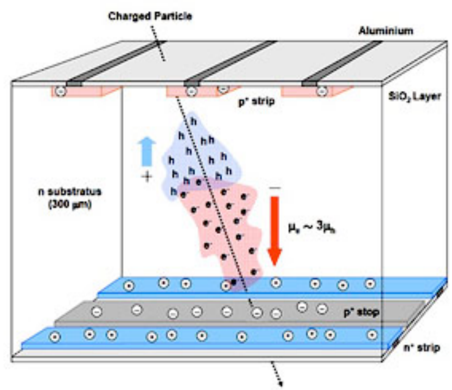
microstrips



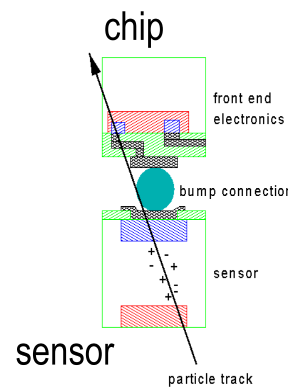
strips & pixels

- ~1-5 eV per e/h pair needed
- ~10^6 e/h pairs (in Si) per cm (20.000/300 μm)
- "signal" due to separation and movement of charges in E-field
- Output: current on electrode charge -> V_{out} after amplifier

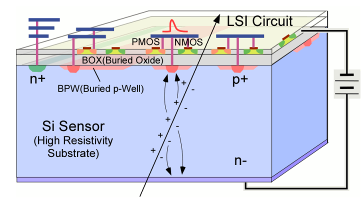
see Lecture by J. Brom on 17.2.21



strips



hybrid



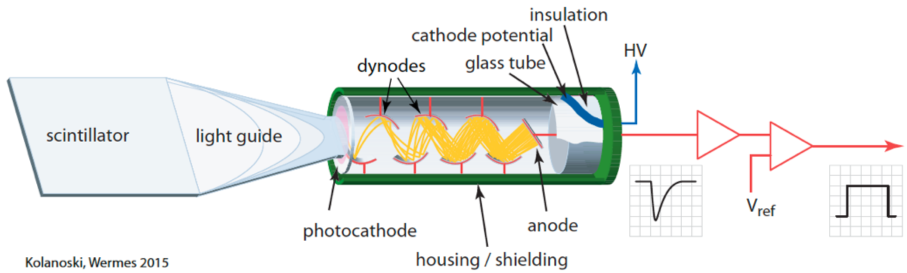
monolithic

pixels

Some important detector types - 3

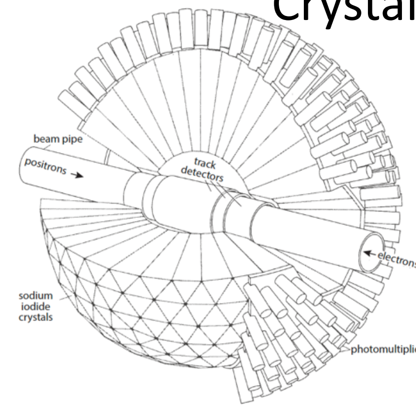
Scintillation detectors

- particles excite molecules
- de-exitation produces light



Plastic scintillator

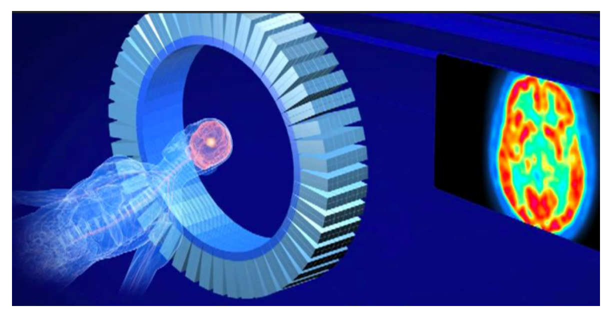
Crystals



- ~10 eV per (light) photon needed
- 10.000 (plastic)/40.000 photons/MeV energy input
- "signal" due to conversion of photons (light) into charged electrons
  - intrinsic amplification => direct detection
  - detection by ionisation (PMT, PD, APD, SiPMs) => electric signals

see Lecture by E. Auffray Hillemanns on 19.2.21

Crystal Ball (NaI(Tl)) detector



PET scanners

For very low energy detection:

=> need detectors with only meV energy input per quantum production

=> e.g. heat (phonon excit.) or quanta (e.g. Cooper pairs break up)

Some important detector types - 4

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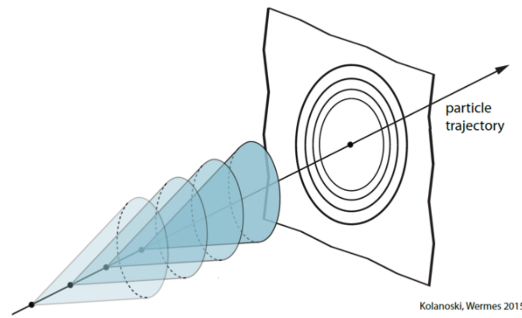
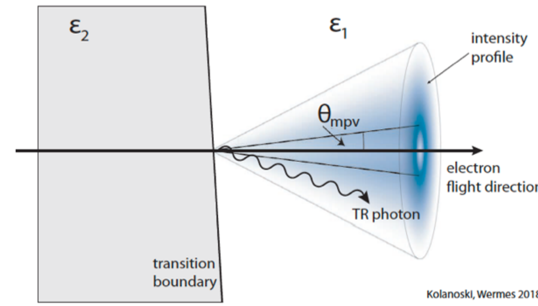
Cherenkov detectors
Transition radiation detectors

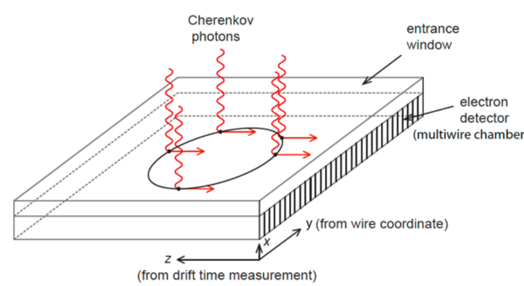


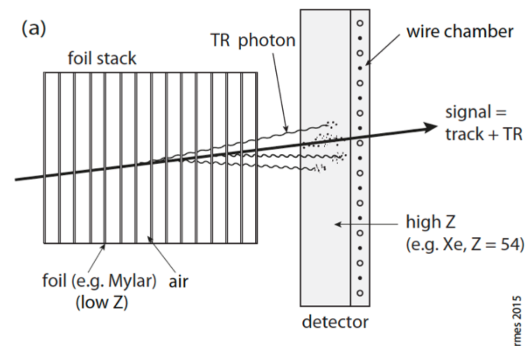
Cherenkov
UV light



Transition Radiation
X-rays

- from very few (o(10)) to "many" photons emitted (UV or X-ray, resp.)
- conversion into electrons (Cherenkov) or direct absorption (TR) -> conversion into e/ion or e/h
- detection by ionisation detector output then as before





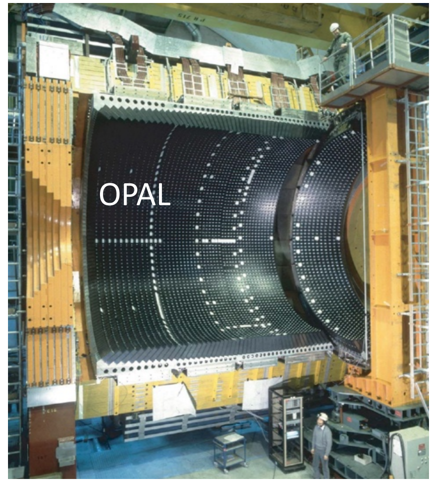
see Lecture by F. Montanet (Course 1) and by C. Joram on 18.2.21

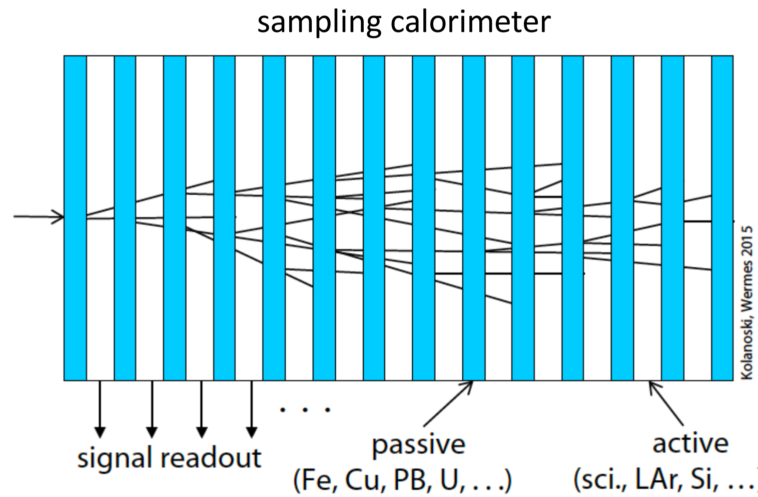
here: final detection is by ionisation

Some important detector types - 5

Calorimeters

crystal calorimeter



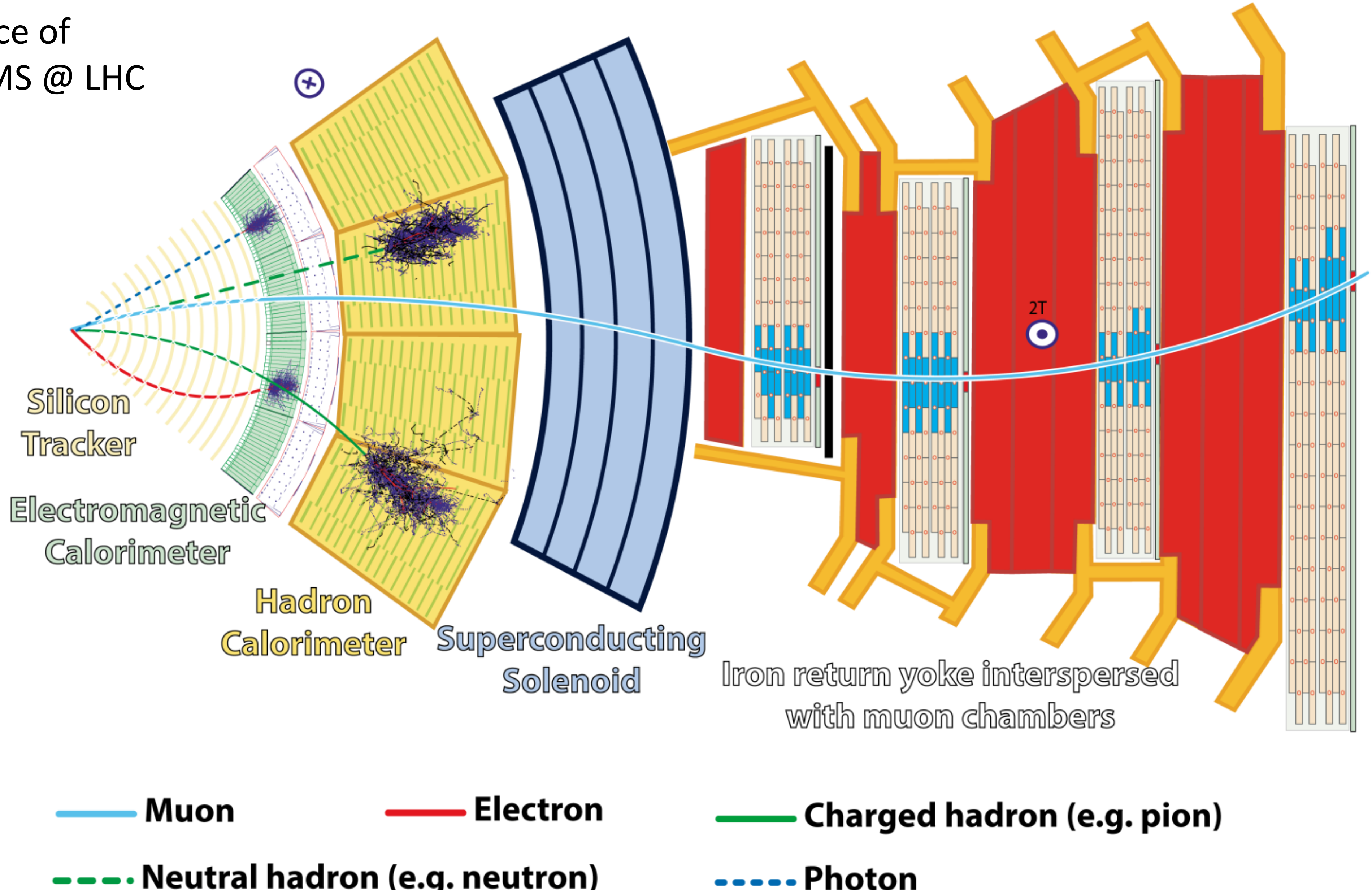


- many e+/e- (ECAL), many charged particles (HCAL)
  neutral particles (n,γ,K^0) converted into charged particles
- "signal" due to
  - (1) in crystal calorimeters: conversion of scintillation light (or Cherenkov radiation) into electrons (PMT) or e/h (PD; APD) -> then further amplification or direct detection
  - (2) in sampling calorimeters: detection by ionisation (liq. Ar, Si pads, drift tubes, …)

output then as before

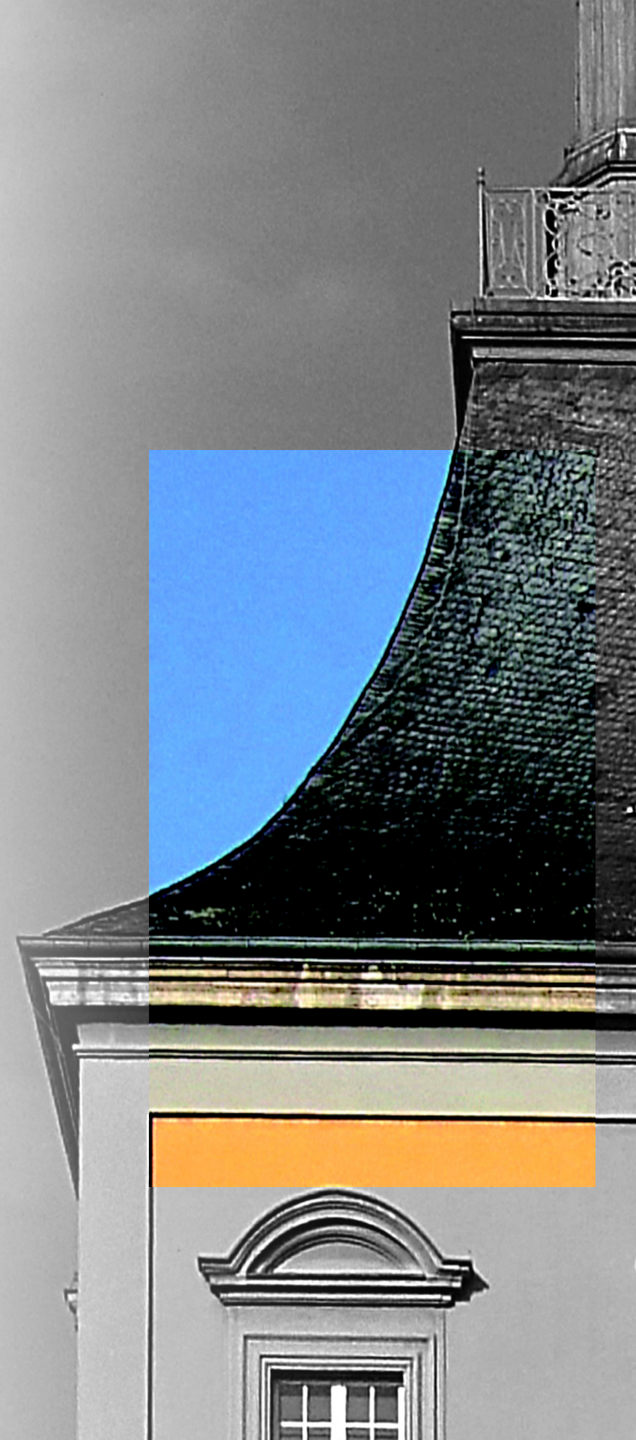
Combining detectors into an “experiment” = “(big) detector"

slice of
CMS @ LHC

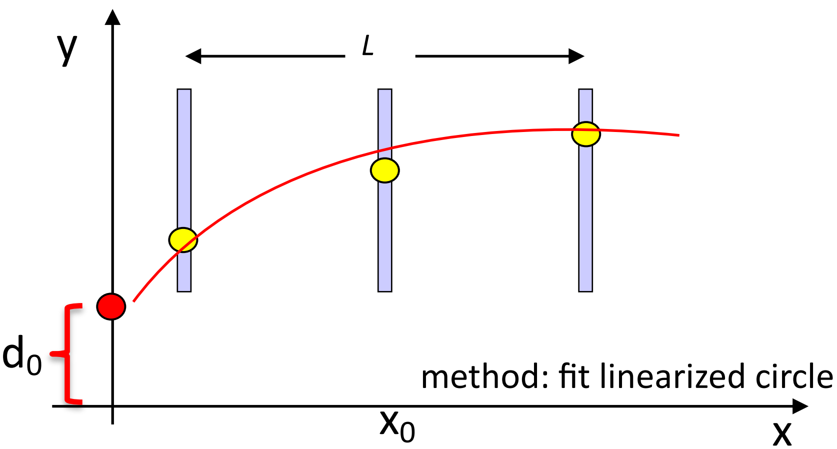


How well can you measure?
What does it depend on?

2 examples …



Example 1: tracking detector



$$\left(\frac{\sigma_{p_T}}{p_T}\right)_{\text{meas}} = \frac{p_T}{0.3|z|}\frac{\sigma_{\text{meas}}}{L^2 B}\sqrt{\frac{720}{N+4}} \otimes \sigma_{MS}$$

$$[p_T] = \text{GeV/c}, \ [L] = \text{m}, \ [B] = \text{T}$$

Gluckstern NIM 24 (1963) 381

$$\sigma_{d_0} = \frac{\sigma_{\text{meas}}}{\sqrt{N}}\sqrt{1 + r^2\frac{12(N-1)}{(N+1)} + r^4\frac{180(N-1)^3}{(N-2)(N+1)(N+2)} + r^2\frac{30N^2}{(N-2)(N+2)}} \otimes \sigma_{MS}$$

r = x_0/L = extrapolation parameter
MS = multiple (Coulomb) scattering

- optimize σ_{meas} until other effects dominate (e.g. MS)
- $1/L^2$: the longer *L* the better
- place first plane as near as possible to the prod. point
- p_T resolution is linearly better with B-field strength … but more confusion if many tracks
- Increasing N improves the resolution, but only as $1/\sqrt{N}$

Technology most often used: Si - detectors

PRO – high resolution σ_{meas} ~ 10 µm

CON – expensive
– small *N*
– small *L*
– high density => large mult. scatt.

see also Lecture by J. Baudot on 27.&28.1.21

PRO – high rate capability

Example 2: Energy measurement

relative
energy resolution (%)

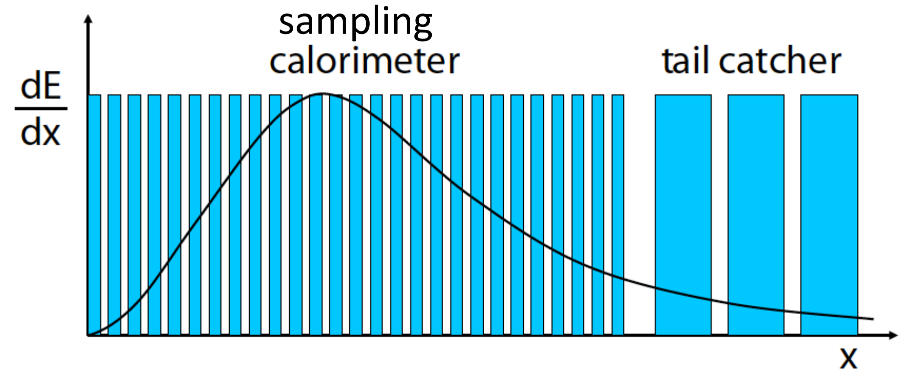
$$\frac{\sigma_E}{E} = \sqrt{\frac{a^2}{E} + \frac{b^2}{E^2} + c^2} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

a: stochastic fluctuations($\propto 1/\sqrt{N} \propto 1/\sqrt{E}$)
of the shower development, particularly strong for sampling calorimeters due to incomplete sampling

b: noise term (independent of E) $\Rightarrow 1/E$ term in relative resolution

c: imperfections (mech. & elec.), losses, calibration errors which rise with E, i.e. const. in σ_E/E

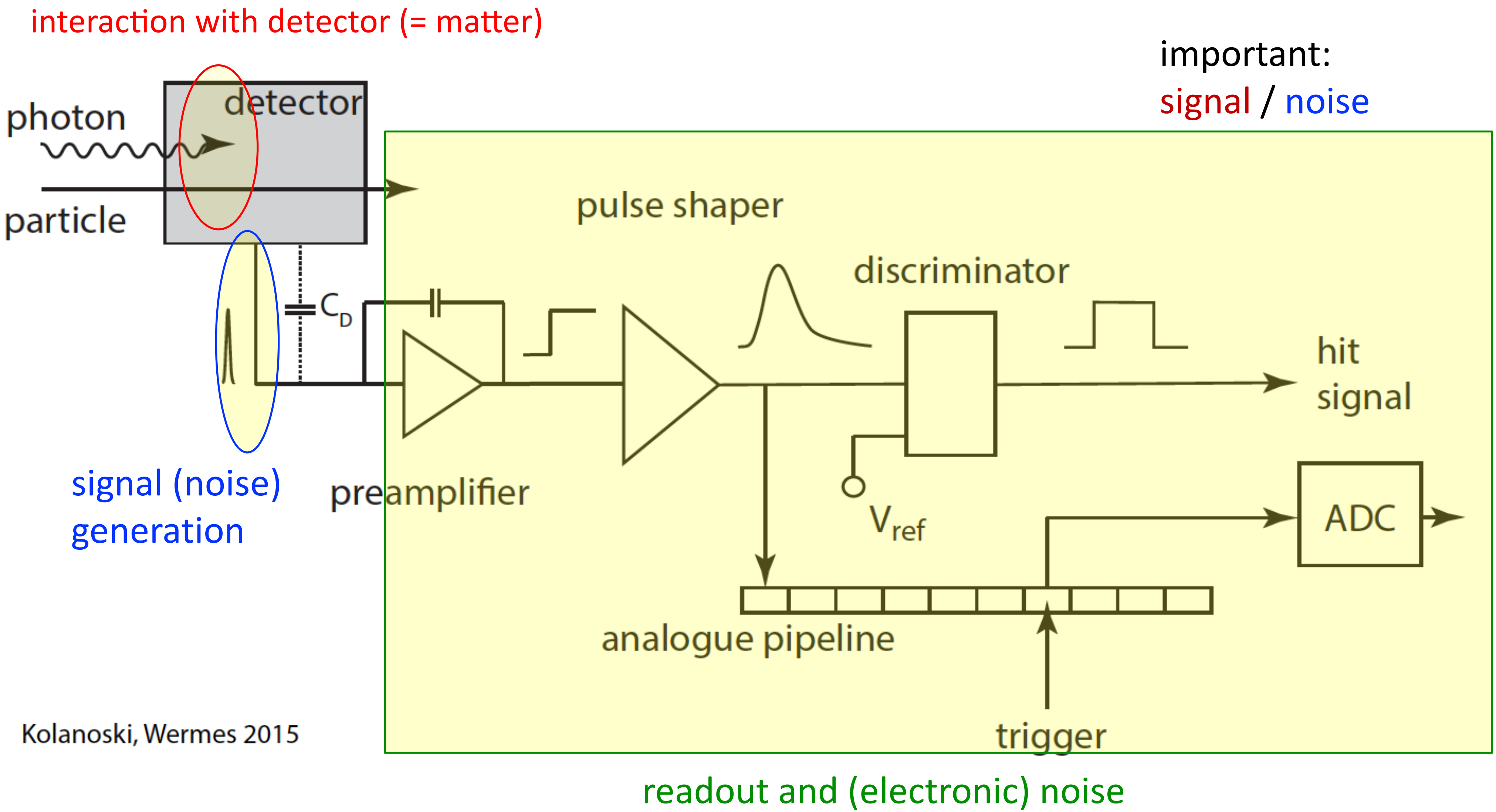
- optimize sampling (active/passive layers)
- minimize losses (-> tail catcher)
- work on (inter)calibration



Kolanoski, Wermes 2015

A detector in “full”

The “detector” is more than just a detector …



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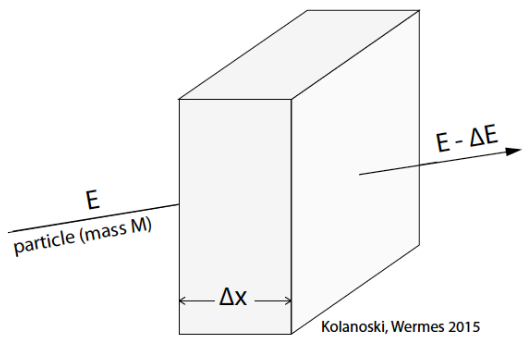
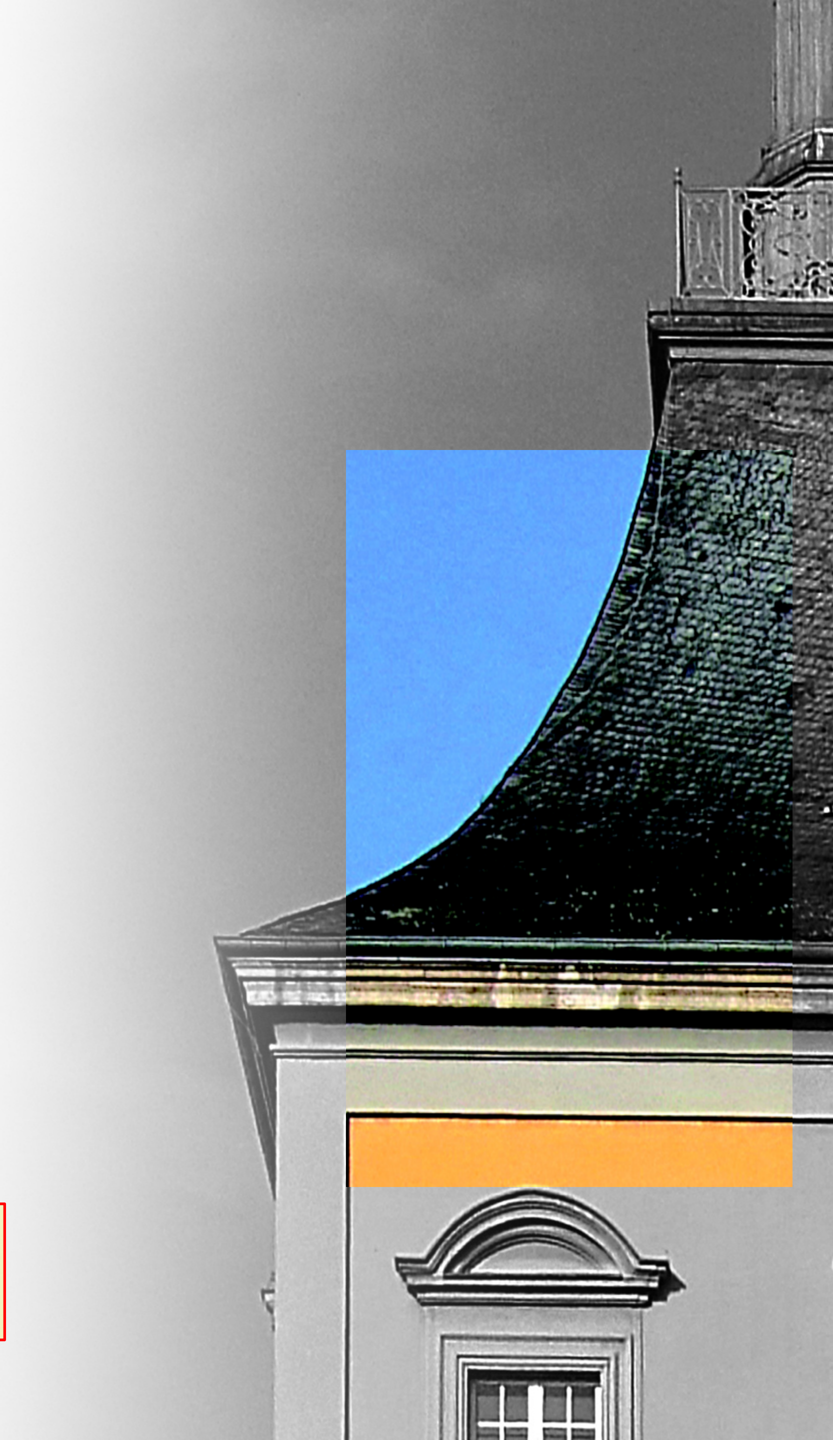
Interacting with matter



already known?



Very important: energy loss of (heavy) particles by ionisation / excitation

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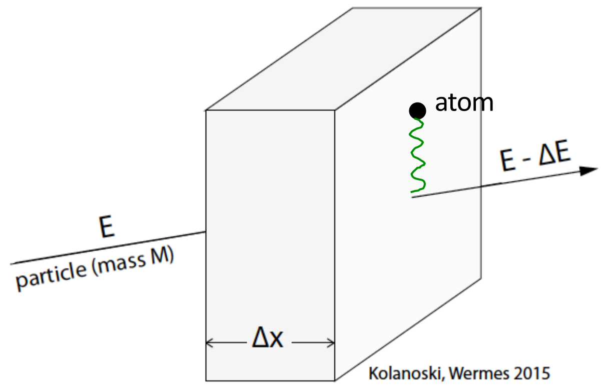
- see: "Interaction of particles with matter", Course 1, 2 Lectures + Tutorial

Bohr, N.: In: Phil. Mag. 25 (1913) – classic calculation
Bethe, H.: Zur Theorie des Durchgangs schneller Korpuskularstrahlen durch Materie. Ann. Phys. 5 (1930), p. 325400
Bloch, F.: Zur Bremsung rasch bewegter Teilchen beim Durchgang durch Materie. In: Ann. Phys. 16 (1933), p. 285

How to think of the problem?

(distant) electromagnetic interaction of the particle with the surrounding atoms leading to energy loss treated by Bohr, Bethe and Bloch



$$\left[\left\langle \frac{\mathrm{dE}}{\mathrm{dx}} \right\rangle\right] = \frac{\mathrm{MeV}}{\mathrm{cm}}$$

or

$$\left[\left\langle \frac{\mathrm{dE}}{\mathrm{d}\tilde{\mathrm{x}}} \right\rangle\right] = \frac{\mathrm{MeV}}{\mathrm{gcm}^{-2}}$$

$$\tilde{x} = \rho x$$

average energy loss

$$-\left\langle \frac{dE}{dx} \right\rangle = n \int_{T_{min}}^{T_{max}} T \, \frac{d\sigma_A}{dT}(M, \beta, T) \, dT$$

≈ Rutherford x-section

range of possible energy transfers to the atom
T_{min} ≙ far away: lowest possible atom excitation => QM
T_{max} ≙ head-on collision => easy

Average energy loss of (heavy) particles by ionisation / excitation

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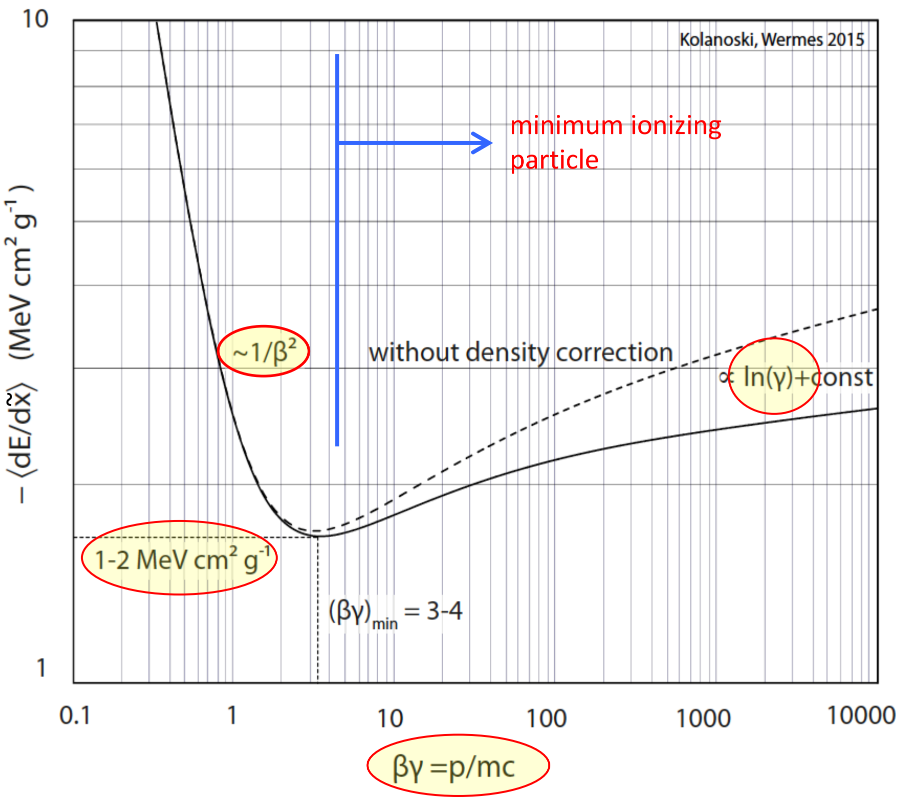
Bethe – Bloch formula

average energy loss of (“heavy”) particles

corrections

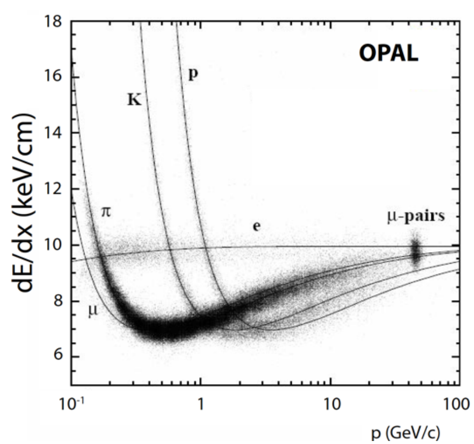
$$-\left\langle \frac{dE}{dx} \right\rangle = K \frac{Z}{A} \rho \frac{z^2}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} - \frac{C(\beta\gamma, I)}{Z} \right]$$



notice

plotted as a function of $\beta\gamma$=p/m => universal curve for all z=1 particles

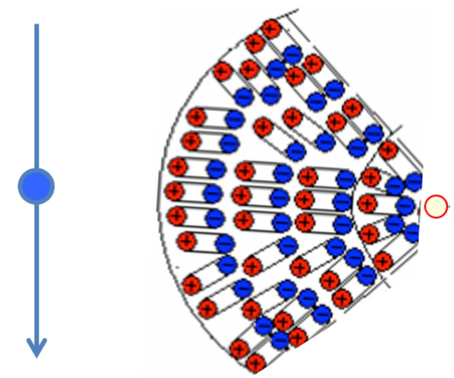
plotted as a function of p
=> different curves depending on m
=> exploit for particle ID



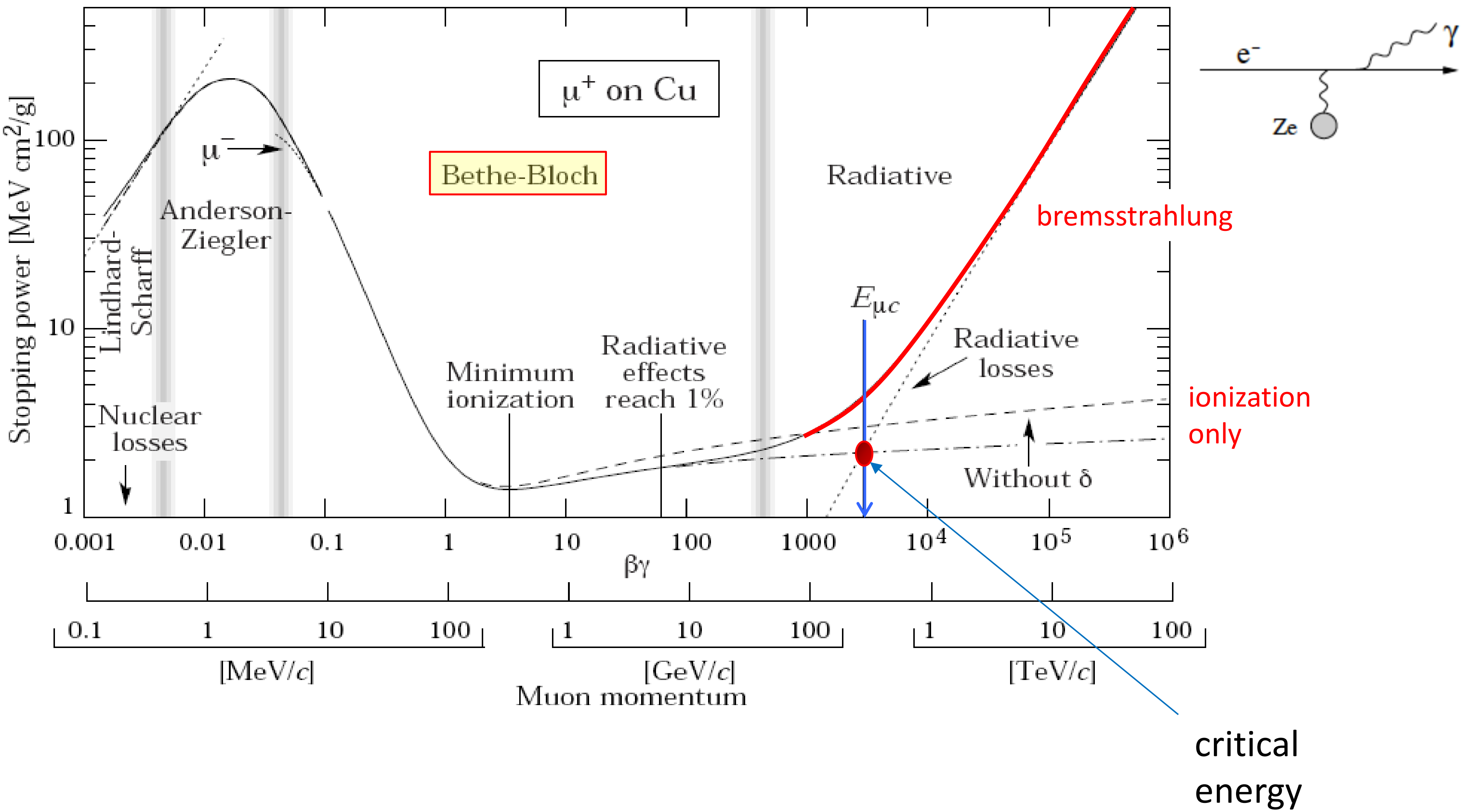
notice

- $1/\beta^2$
- minimum
- rel. rise

  γ rise => $E_\perp$,T_{max}
- density effect



More than BBF: average energy loss...

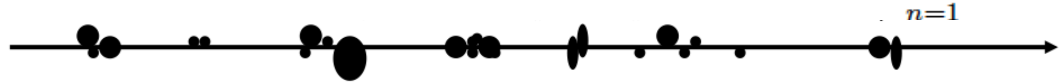


… this was mean energy loss … how about the distribution?

- BBF -> **average** energy loss per path length.
- In fact, however, the energy loss is a **statistical process** involving many small energy transfers which lead to fluctuations

1) Number fluctuations => Poissonianly distributed
2) Fluctuations in the amount of energy δE transferred

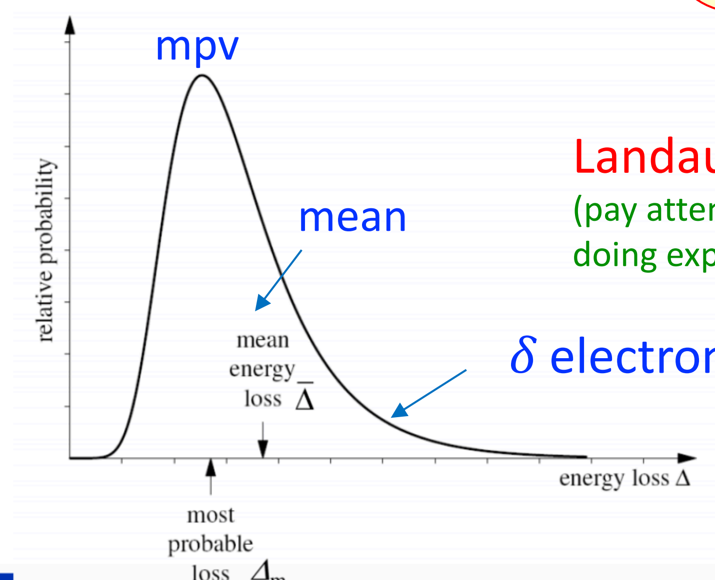
$$\Delta E = \sum_{n=1}^{N} \delta E_n$$



The distribution of δE between E_{min} and E_{max} has a $1/(\delta E)^2$ shape (i.e. $1/T^2$). The most probable energy transfer (the maximum of the distribution) is in fact near E_{min} but sometimes large energies up to $E_{max} \approx E$ are transferred (δ electrons) leading to a long tail of the distribution to high energies.

$$\frac{d\sigma}{dT} = \frac{2\pi\, z^2 \alpha^2 \hbar^2}{\beta^2\, m_e} \frac{1}{T^2}$$

L. Landau. On the energy loss of fast particles by ionization. *J. Phys.U.S.S.R.*, 8:201, 1944.
P.V. Vavilov. Ionization Losses of High-Energy Heavy Particles. *Sov. Phys. JETP*, 5(4):749–751, 1957.

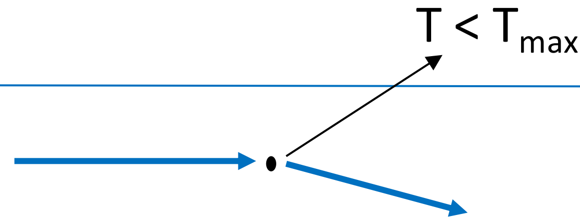


Landau distribution
(pay attention when doing experiments!)

$$f_L(\lambda) = \frac{1}{\pi} \int_0^{\infty} e^{-t\ln t - \lambda t} \sin(\pi t)\, dt\,.$$

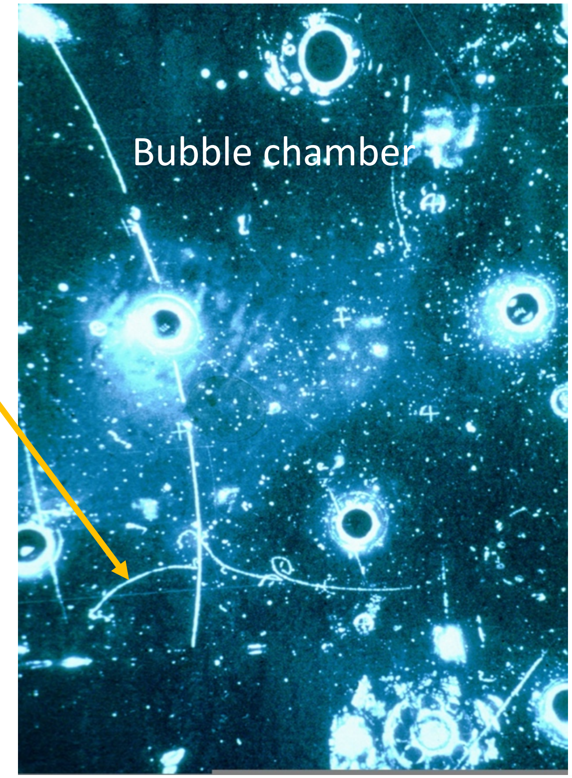
A word on … δ - electrons

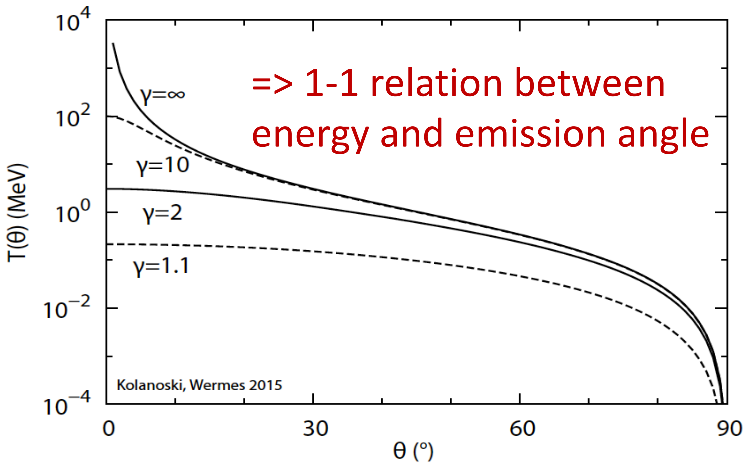
”high-energy knock-on electrons”

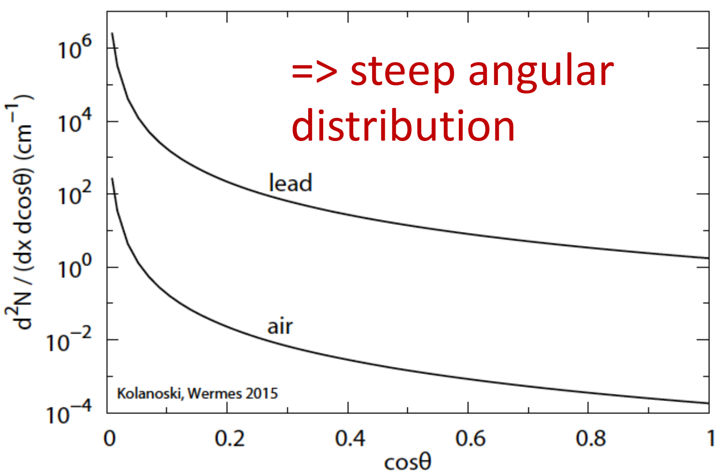


- easy to calculate because (1) 2-body kinematics
  (2) Rutherford scattering

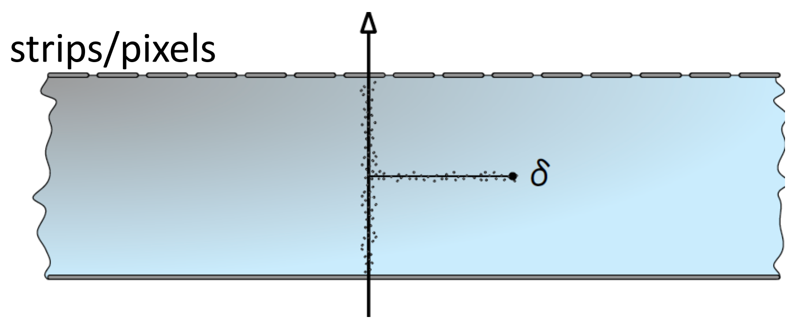
δ







for experimentalists: almost all δ electrons are emitted under 90° !

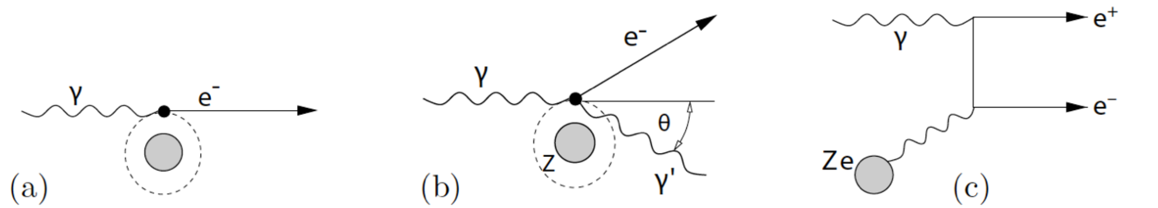


$$\frac{\frac{dN}{dx}(89^\circ)}{\frac{dN}{dx}(1^\circ)} \approx 10^7$$

=> mismeasurements in 1) E-loss and 2) position

What about other particles

- neutrons => kick out a proton from (light) matter & detect proton
- neutrinos => (weakly) interact with n,p producing e, μ (or τ) ... very rare/inefficient
- other like $K^0_{S,L}$ => detect decay particles or measure by hadron calorimetry
- photons => detected via photoeffect, Compton effect or pair creation



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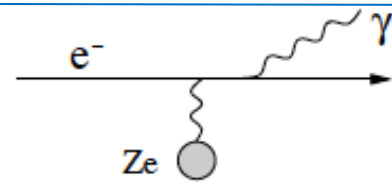
electromagnetic shower

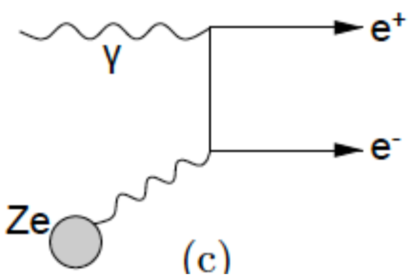
Radiation Length X_0

- X_0 is defined from the Bremsstrahlung E-loss



$$-\frac{dE}{dx} = \frac{1}{X_0}E \Rightarrow \frac{dE}{E} = -\frac{1}{X_0}dx \Rightarrow E(x) = E_0 e^{-x/X_0}$$

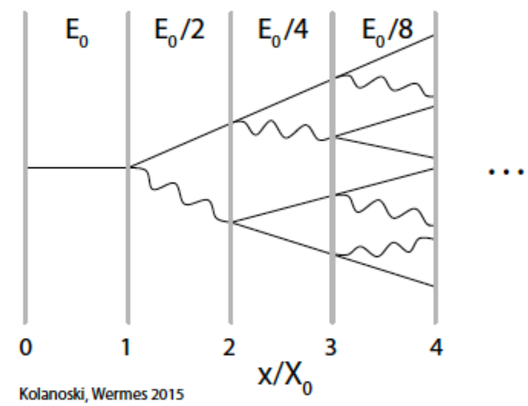
length over which a particle‘s energy is reduced to 1/e due to bremsstrahlung: $E(x)=E_0 \exp(-x/X_0)$



- X_0 is also important for pair creation ... and for elm. showers

length over which pair production takes place with a probability $P = 1 - e^{-7/9} = 54\%$.

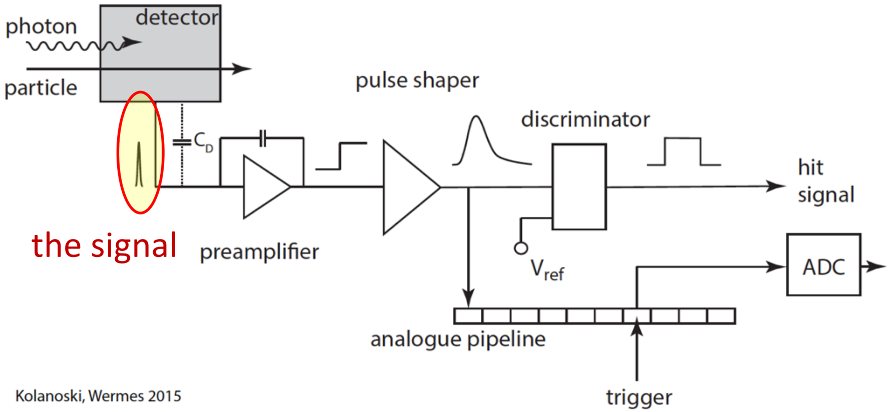
- X0 therefore is a measure of material “thickness”



- remember $$\frac{1}{X_0} \propto \rho \frac{Z^2}{A}$$

skip Q?

What is the detector “signal”?



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Induced charge / current

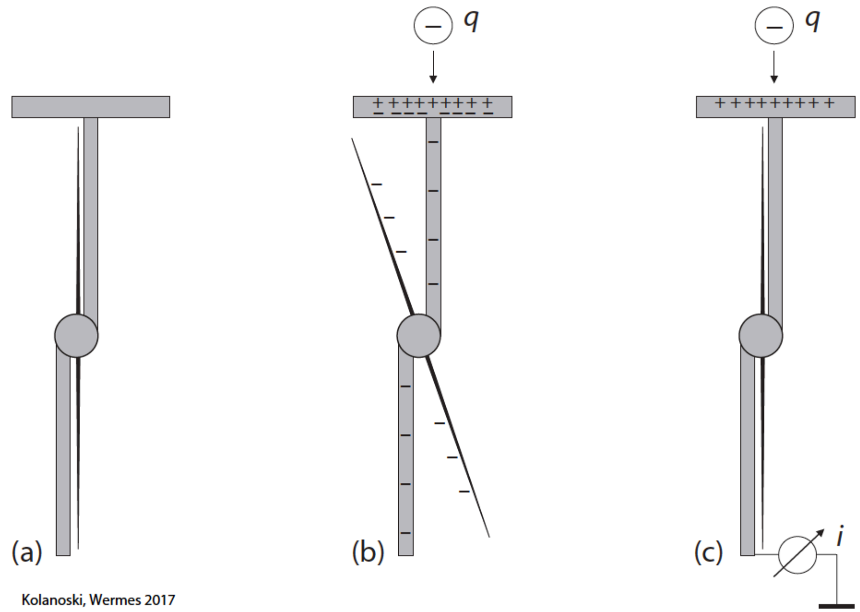


Fig. 5.1 Effect of a charge approaching an electrometer. a) An uncharged electrometer which is insulated against ground. b) A charge q, approaching from infinity, induces a counter-charge on the metal surface of the electrometer which increases as the distance becomes smaller. Within the free-floating electrometer the charge is conserved and hence can only be separated. The charge with sign opposite of that of q (here $q < 0$) accumulates on the metal surface close to q and the same sign charge accumulates on the surfaces further away. This generates a deflection of the electrometer's needle. c) Grounding the electrometer pedestal allows the (negative) charge to drain off so that a current signal can be measured on the path to ground.

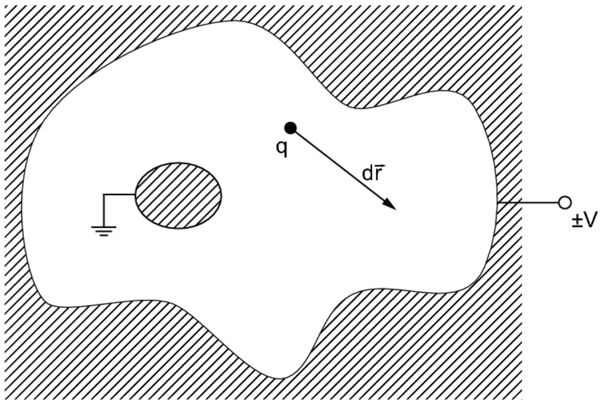
… notice

A detector is a **current source**

It delivers a current pulse
independent of the load

One can convert current into
charge (integral) or voltage (via R or C)

Signal generation in an electrode configuration



How does a moving charge couple to an electrode ?

- respect Gauss' law and find

Shockley- Ramo theorem
(Shockley J Appl.Phys 1938, Ramo 1939)

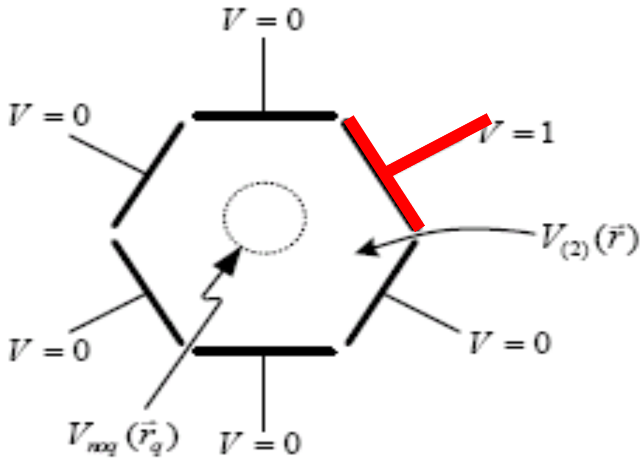
weighting field
determines how charge movement couples to a specific electrode (≠ electric field)

$$i_S = -\frac{dQ}{dt} = q\,\vec{E}_w\,\vec{v}$$

$$dQ = q\vec{\nabla}\Phi_W\,d\vec{r}$$

induction (weighting) potential
determines how charge movement couples to a specific electrode

Shockley - Ramo Theorem, weighting field



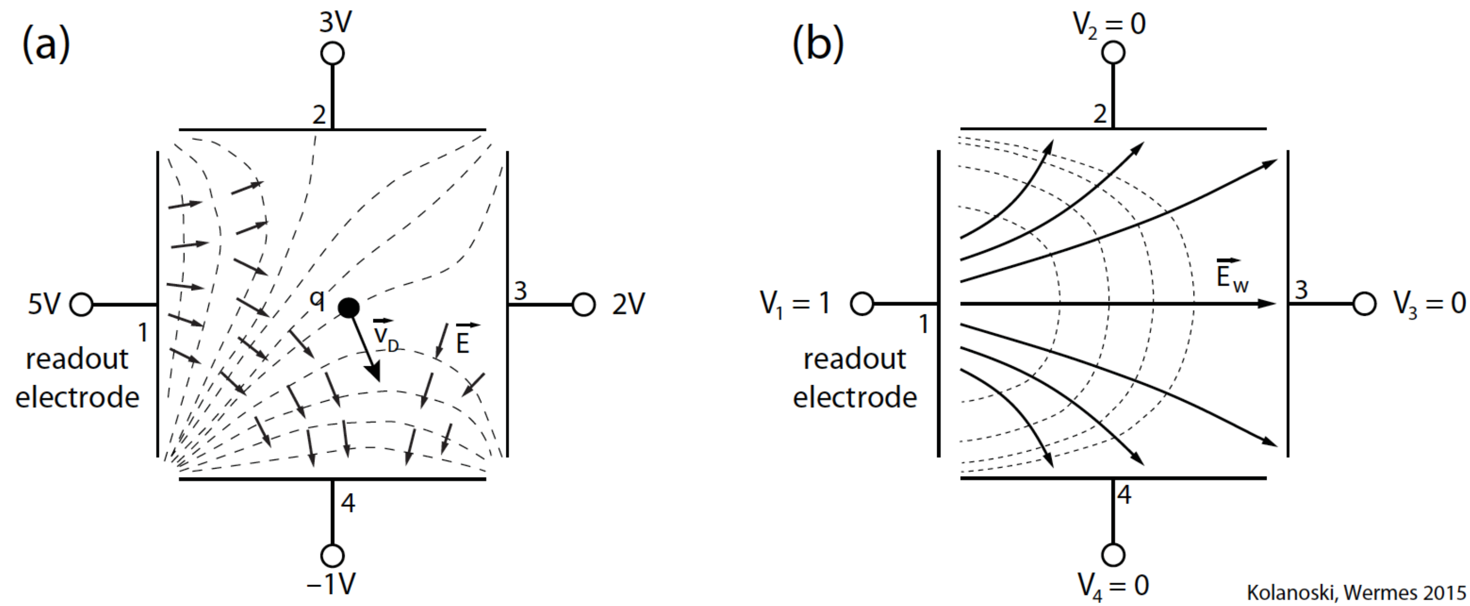
Calculate weighting potential
by setting readout electrode to
V = 1 and all other electrodes to V = 0.

$$dQ_i = -q\vec{\nabla}\Phi_{w,i}d\vec{r}$$

$$i_{S,i} = q\,\vec{E}_{w,i}\,\vec{v}$$

skip example?

Shockley - Ramo Theorem, weighting field



- The weighting field with respect to electrode i is obtained by setting the potential of electrode i to 1 (1V) and all other potentials to 0 (0V)
- It tells us, how the induced charge dQ (current i_S) changes when the charge moves (either by the influence of E_{true} or even by moving it „by hand")

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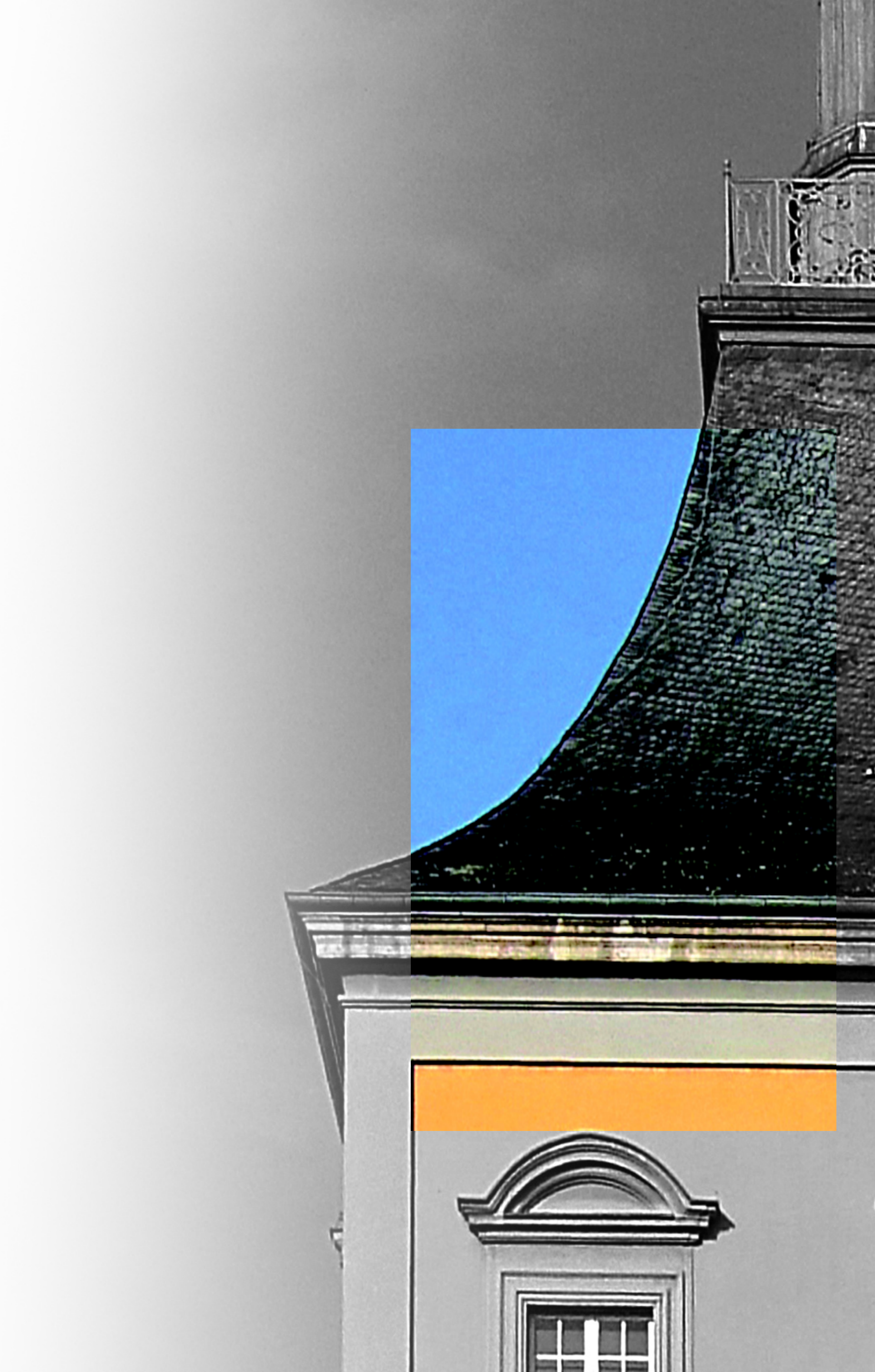
Examples of signals by moving charges



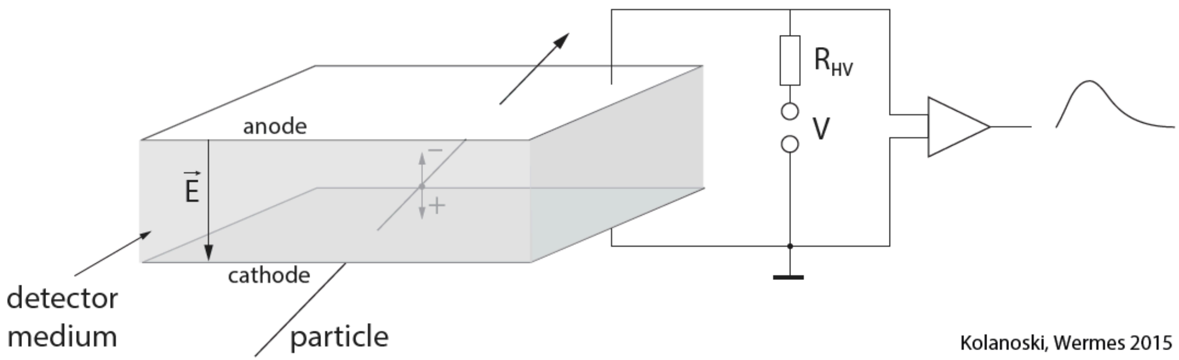
Example 1: Parallel plate gaseous chamber or semiconductor

- Two electrodes only (anode and cathode)
- Output is a charge … or better: an integrated current

$$\vec{E} = -\frac{V_0}{d}\vec{e}_x \,, \qquad C = \frac{\epsilon\epsilon_0 A}{d}$$

- constant E-field
- almost constant velocity (v=μE)
- weighting field simple

$$dQ = -q\frac{\vec{E}}{V_0}d\vec{r} \qquad \vec{E}_w = -\frac{1}{d}\vec{e}_x$$



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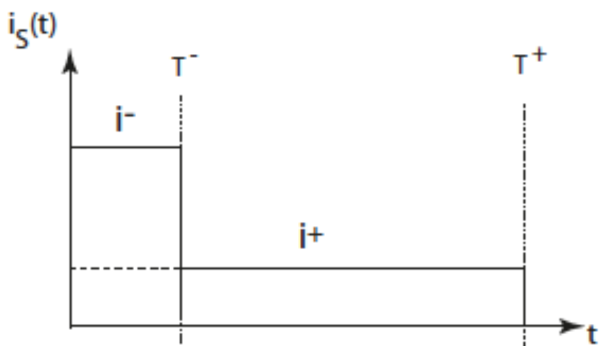
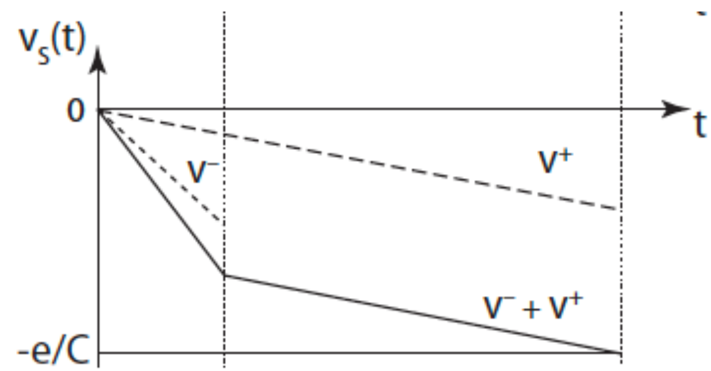


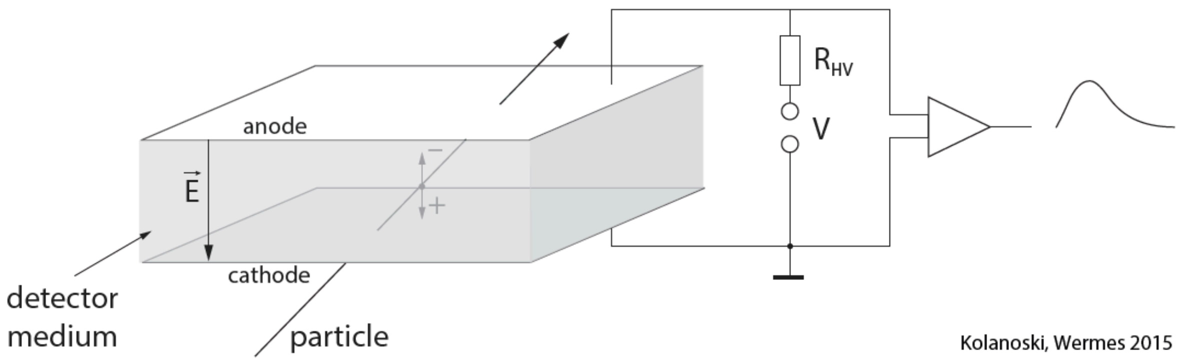
$$i_S^{\pm} = q^{\pm}\vec{E}_w\,\vec{v}^{\pm} = -\frac{q^{\pm}}{d}\,\vec{e}_x\,\vec{v}^{\pm} = \frac{e}{d}v^{\pm}$$

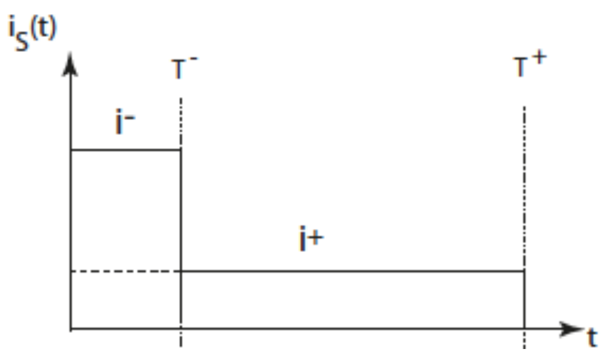


$$Q_S^{tot} = Q_S^- + Q_S^+ = -\frac{e}{d}\left(\int_0^{T^-} v^- dt + \int_0^{T^+} v^+ dt\right)$$
$$= -\frac{e}{d}v^-\left(\frac{d-x_0}{v^-}\right) - \frac{e}{d}v^+\left(\frac{x_0}{v^+}\right) = -e\,.$$

Example 1: Parallel plate gaseous chamber or semiconductor

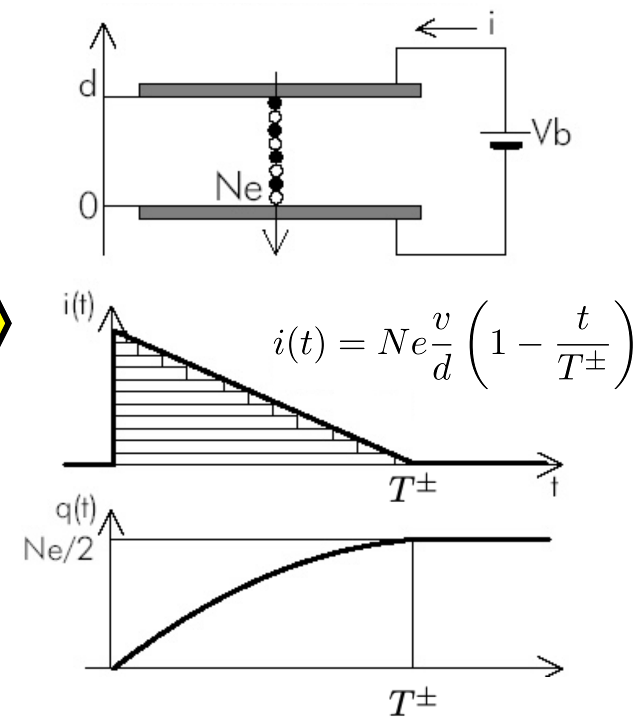
- Two electrodes only (anode and cathode)
- Output is a charge … or better: an integrated current





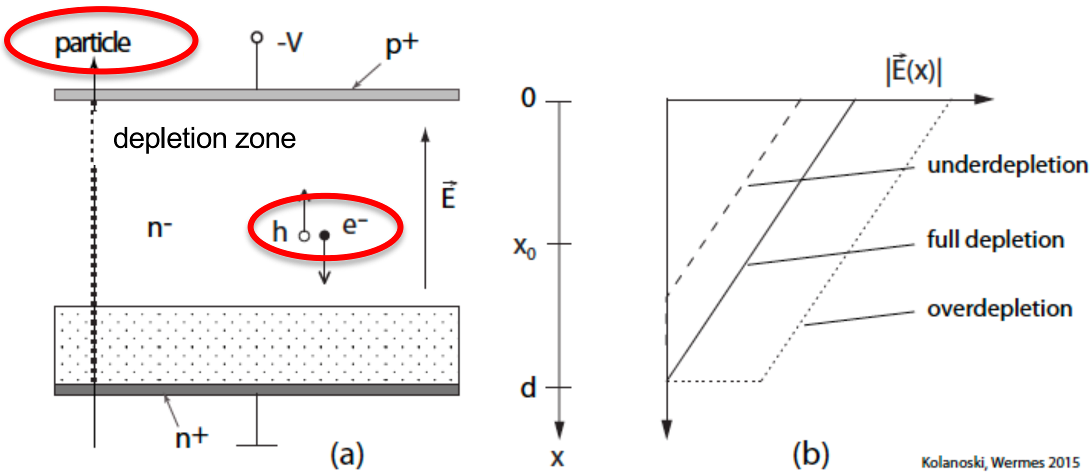
$$i_S^{\pm} = q^{\pm} \vec{E}_w \, \vec{v}^{\pm} = -\frac{q^{\pm}}{d} \, \vec{e}_x \, \vec{v}^{\pm} = \frac{e}{d} v^{\pm}$$

continuous ionisation



$$Q_S^{\pm}(t) = \int_0^t i^{\pm}(t')dt' = Ne\left[\frac{t}{T^{\pm}} - \frac{1}{2}\left(\frac{t}{T^{\pm}}\right)^2\right]$$

Signal in a Silicon detector (= parallel plate w/ space charge)



- E-field not constant
- velocity not constant
- weighting field still the same

$$\vec{E}_w = -\frac{1}{d}\vec{e}_x$$

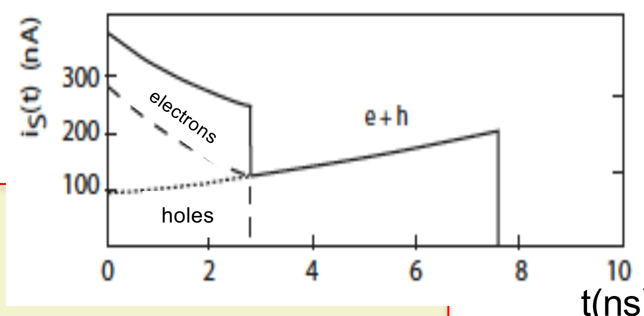
$$\vec{E}(x) = -\left[\frac{2V_{dep}}{d^2}(d-x) + \frac{V - V_{dep}}{d}\right]\vec{e}_x \quad = -\left[\frac{V + V_{dep}}{d} - \frac{2V_{dep}}{d^2}x\right]\vec{e}_x = -(a - bx)\,\vec{e}_x$$

$$v_e = -\mu_e E(x) = +\mu_e\,(a - bx) = \dot{x}_e$$

$$v_h = +\mu_h E(x) = -\mu_h\,(a - bx) = \dot{x}_h$$

$$i_S(t) = i_S^e(t) + i_S^h(t)$$

$$= \frac{e}{d}\left(\frac{a}{b} - x_0\right)\left(\frac{1}{\tau_e}e^{-t/\tau_e}\,\Theta(T^- - t) + \frac{1}{\tau_h}e^{t/\tau_h}\,\Theta(T^+ - t)\right)$$



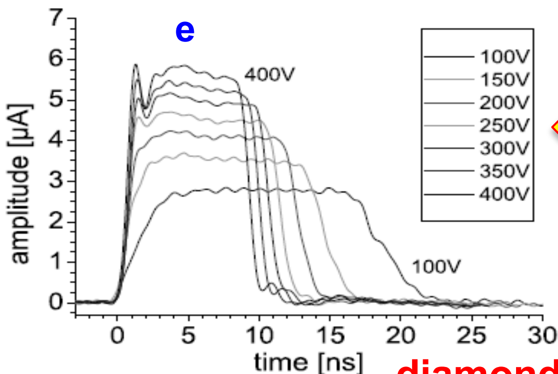
next

difference: exponential velocity function due to E-field

Current pulse measurements: TCT technique

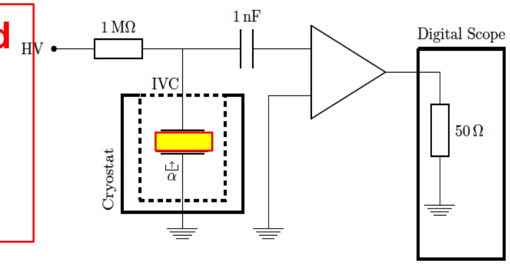
Pop-up Question: Which detector?

transient current

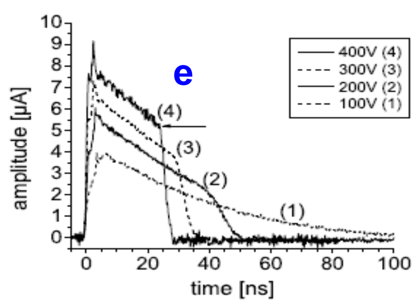


diamond

single crystal **diamond** is like a parallel plate detector filled with a dielectric w/o space charge

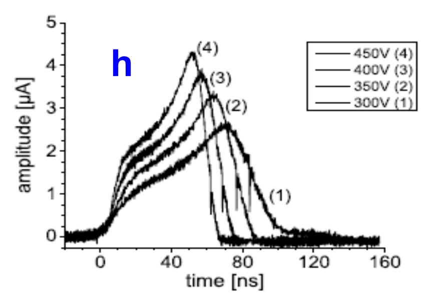


1mm pn – Diode **silicon**
- same weighting field
- different electric field



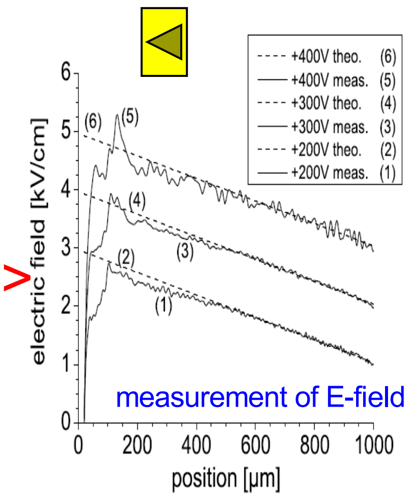
(a) Electron signals from α-particles impinging on the cathode.

Si



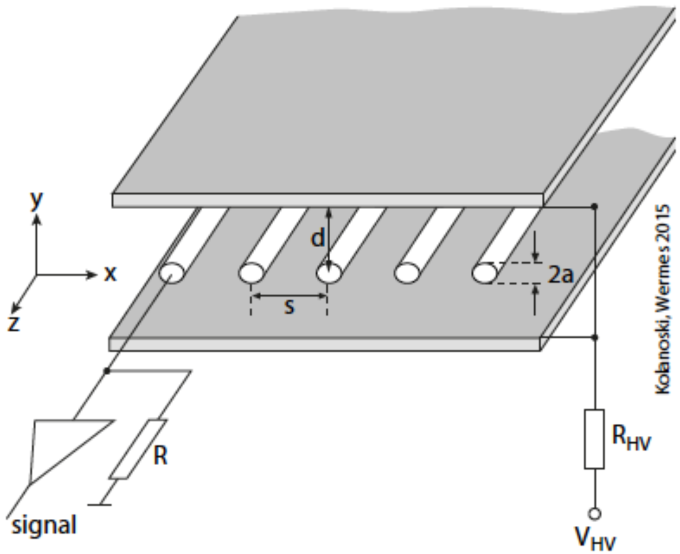
(b) Hole signals from α-particles impinging on the anode.

=>



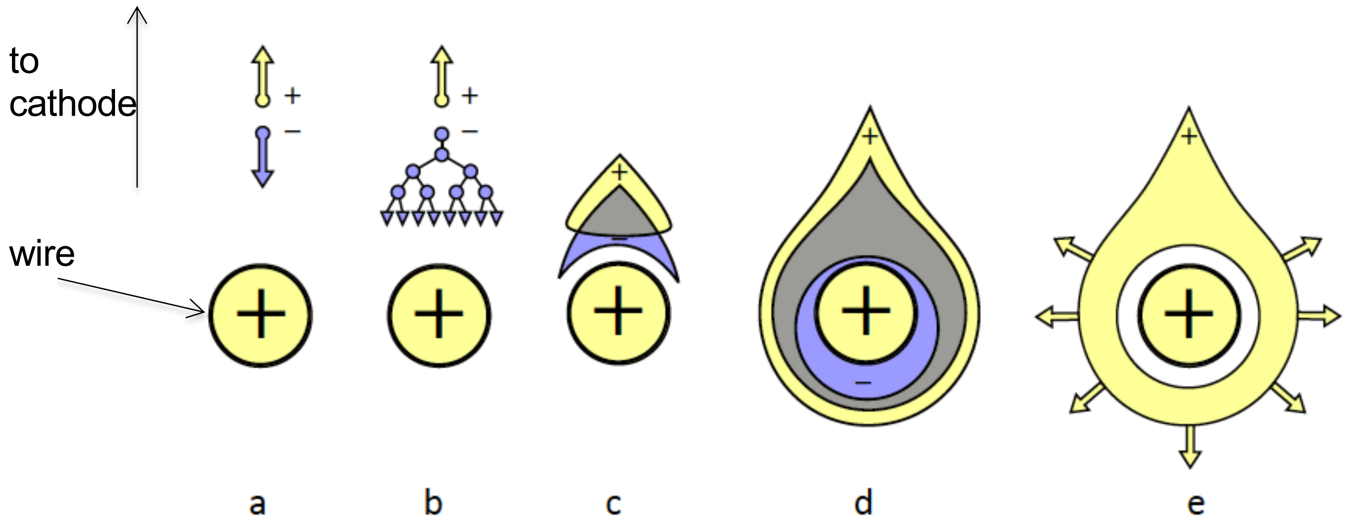
measurement of E-field

WIRE CHAMBER



see Lecture by J. Brom on 16.2.21

Signal development in a wire chamber



big difference:

- ❑ electrode (wire) does not “see” (too small) the charge before gas amplification
- ❑ signal (on wire) shape is governed by the (large) ion cloud moving away from the wire to cathode

Avalanche process:

$$dN = \alpha(E)\, N\, ds$$

$$N(x) = N_0 e^{\alpha x}$$

gas gain

$$\frac{N}{N_0} = G = e^{\alpha x}$$

α = 1st Townsend coefficient

Signal development in a wire chamber like configuration (1)

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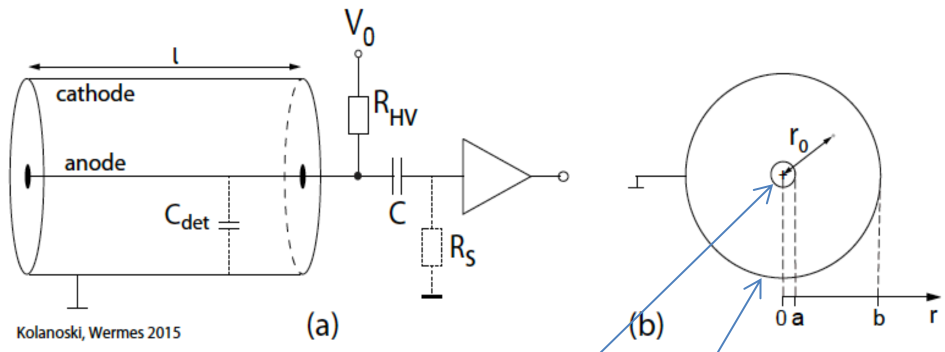
configuration



$$\vec{E}(r) = \frac{1}{r}\frac{V_0}{\ln b/a}\frac{\vec{r}}{r}\,, \qquad \phi(r) = -V_0\frac{\ln r/b}{\ln b/a}\,, \qquad C_l = \frac{2\pi\epsilon_0}{\ln b/a}$$

- We follow our Shockley-Ramo-recipe: find the weighting field E_W or the weighting potential Φ_W by setting

$$\phi_w(a) = 1\,, \quad \phi_w(b) = 0^{(*)}$$

- Since this is also a 2-electrode configuration we know already the shape of $\Phi_W \sim \ln r$ and of $E_W \sim 1/r$ to be the same as for Φ,E electric.

$$\vec{E}_w(r) = \frac{1}{r}\frac{1}{\ln b/a}\frac{\vec{r}}{r}\,, \qquad \phi_w(r) = -\frac{\ln r/b}{\ln b/a}$$

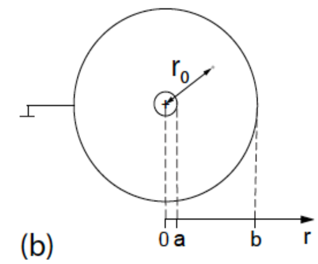
which fulfills (*)

very different weighting field than before ~1/r

Signal development in a wire chamber like configuration (2)

- Now use Shockley-Ramo to get the induced charge: $dQ_S = -q\vec{E}_w d\vec{r}$

- We assume that N e/ion-pairs are produced at r = r_0 (= avalanche production point). Then we get immediately



$$Q_S^- = -(-Ne)\frac{1}{\ln b/a}\int_{r_0}^{a}\frac{1}{r}dr = -Ne\frac{\ln\ r_0/a}{\ln\ b/a}$$

$$Q_S^+ = -(+Ne)\frac{1}{\ln b/a}\int_{r_0}^{b}\frac{1}{r}dr = -Ne\frac{\ln b/r_0}{\ln b/a}$$

(**)

- and the total charge is $Q_S^{tot} = Q_S^- + Q_S^+ = -Ne$ ✓

- However, due to the 1/r dependence of the weighting field the situation is much different from that of a parallel plate detector: the contribution from electrons and ions is not necessarily the same, but depends on r_0 (i.e where the avalanche is created), since only there N becomes large enough that the signal is "felt" by the electrode (wire).

ratio depends on r_0

$$\left(\frac{Q_S^-}{Q_S^+}\right)_{r_0} = \frac{\ln r_0/a}{\ln b/r_0}$$

far away from wire

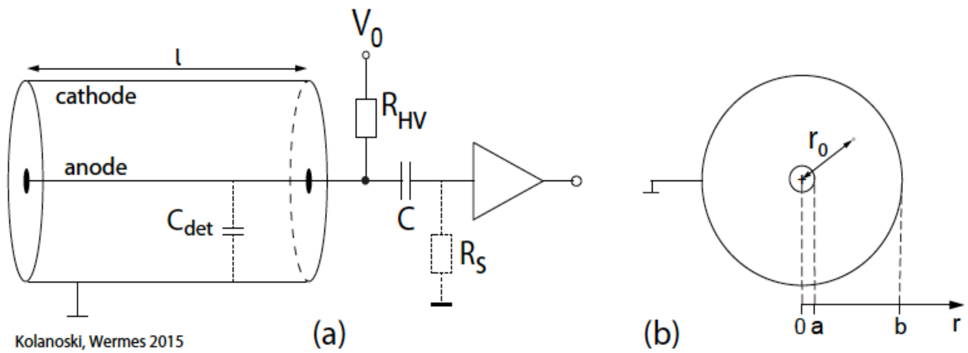
$$\left(\frac{Q_S^-}{Q_S^+}\right)_{r_0=b/2} \approx 9$$

for a typical config (a=10 µm, b=10 mm)

$$\left(\frac{Q_S^-}{Q_S^+}\right)_{r_0=a+\epsilon} \approx 0.01 - 0.02$$

In wire chambers the (integrated) signal is dominated by the ion contribution. Reason: point of signal creation and specific form of the weighting field.

Signal development in a wire configuration (3)



using Ramo and r(t) from the 1/r - E-field, we get …

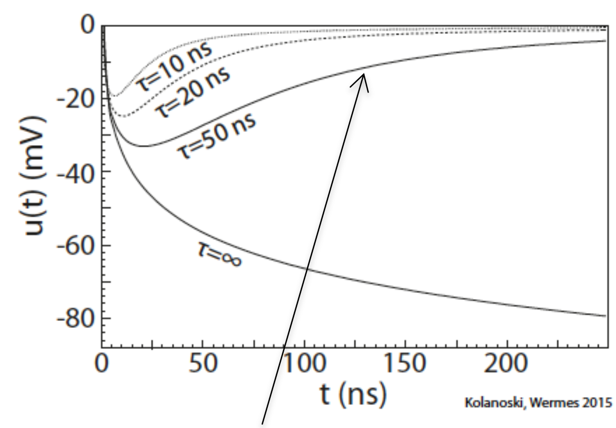
$$i_S^+(t) = \frac{Ne}{2\ln b/a}\,\frac{1}{t+t_0^+}$$

$$t_0^+ = \frac{r_0^2 \ln b/a}{2\mu^+ V_0}$$

char. time

ions only

$$v_s(t) = \frac{Q_S(t)}{C_l\, l} = -\frac{N\,e}{2\pi\epsilon_0\, l}\ln\left(1+\frac{t}{t_0^+}\right)$$



with τ = RC filter

Upshot: Signal formation characteristics in a wire chamber

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- electric field is large close to the wire @ $r \approx r_{wire}$
  => secondary ionisation has a much larger effect on signal
  than primary ionisation
  => avalanche near wire: $q \rightarrow q \times 10^{4\text{-}7}$

- from there (µm's away from wire) the electrons reach the wire fast
  => very small and fast e^- component of Q_{tot}

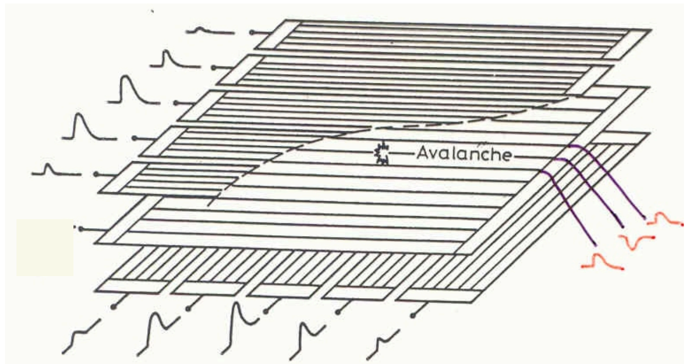
- ions move slowly away from wire => main component of $Q_{tot}(t)$

- signal <u>only</u> relevant after avalanche ionization $\cong$ quasi only $Q^+(t)$

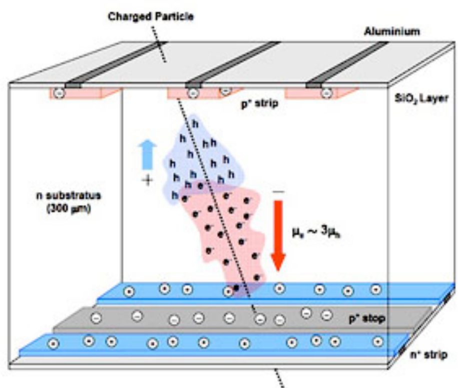
- the term 'charge collection' is more justified in wire chambers than in other ionisation detectors (e.g. parallel plate detectors) since most of the signal is created only very close to the wire

Cathode readout

Signals are <u>induced</u> on BOTH (ALL) electrodes => exploit for second coordinate readout

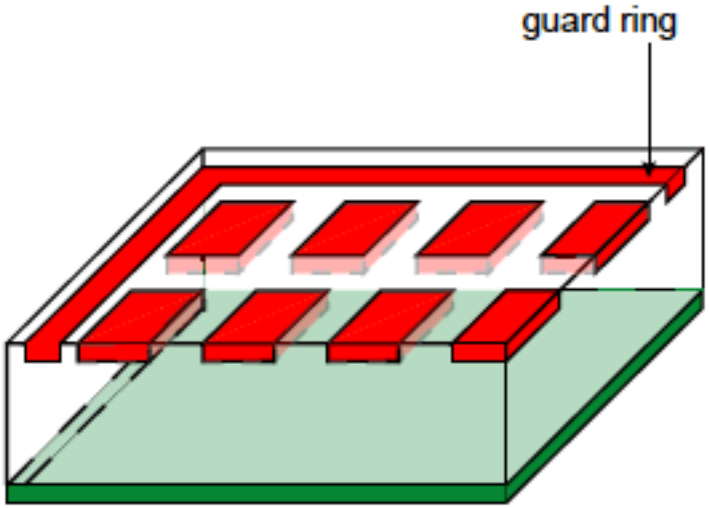


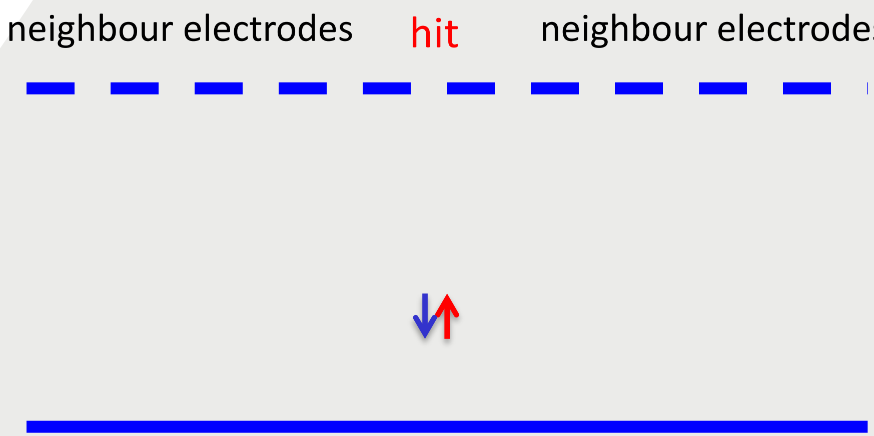
wire chamber
with cathode readout



double sided
silicon strip detector

Structured Electrodes





Signal generation in a segmented detector (1-dim)

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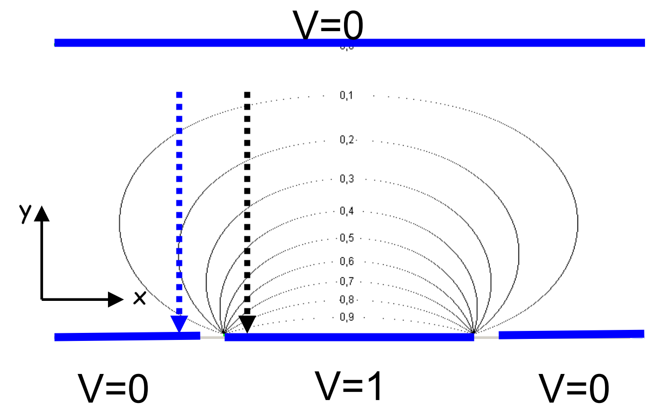
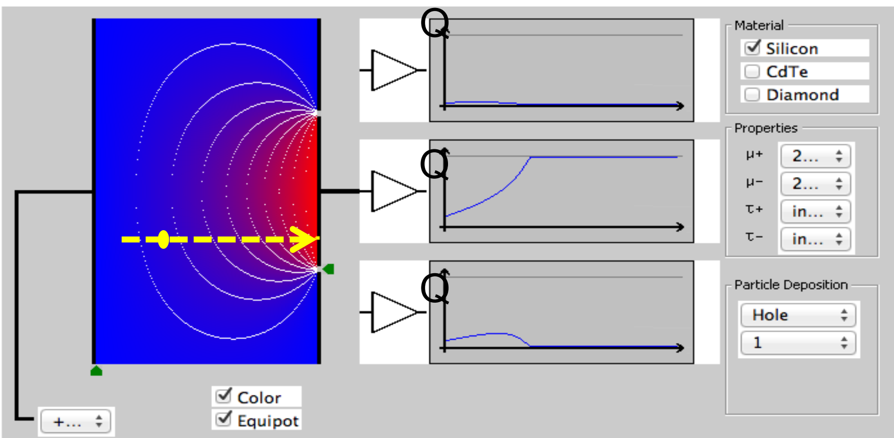
Φ_W for a strip/pixel geometry

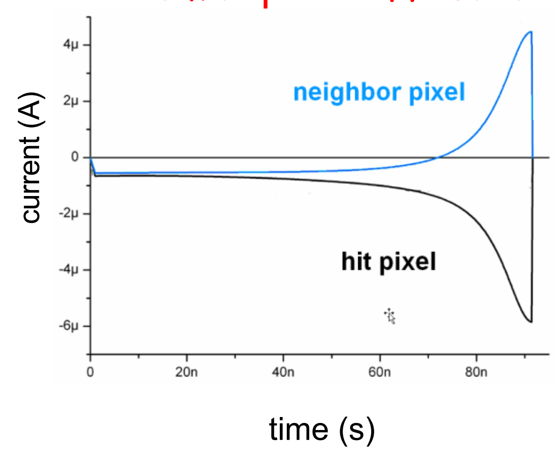
$$\Phi(x,y) = \frac{1}{\pi}\arctan\frac{\sin(\pi y)\cdot\sinh(\pi\frac{a}{2})}{\cosh(\pi x)-\cos(\pi y)\cosh(\pi\frac{a}{2})}$$

(Can be calculated e.g. by "conformal mapping" technique (see e.g. Kolanoski, Wermes, Appendix B) or by using "Schwarz-Christoffel transformations" (e.g. in Morse, Feshbach: Methods of Theoretical Physics, Part I and II., McGraw-Hill)





"small pixel effect" !



skip questions?

Pop-up questions

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- What does the term “charge collection” imply and to what extend is it misleading?
  - integration of the deposited charge at the electrode until arrival of all charges
    is “misleading”: since the signal appears instantly, not only after arrival;
    the term is appropriate for wire chambers with intrinsic charge amplification.
- What does the “weighting field” specify?
  - the coupling of moving charges to the measurement electrode.
- Formulation of the Shockley-Ramo Theorem?
  - current: $i_{S,i} = q\vec{E}_{w,i}\vec{v}$ charge: $dQ = q\vec{\nabla}\Phi_W d\vec{r}$
- What changes regarding signal development when going from a parallel-plate gas-filled detector to a semiconductor detector with space charge?
  - Weighting field remains the same, electric field is no longer constant
- For multi-electrode geometries … how is the signal development for the “hit” electrode compared to neighbouring electrodes?
  - (hit) current returns to zero upon arrival of last charges (unipolar); (neighbour) bipolar

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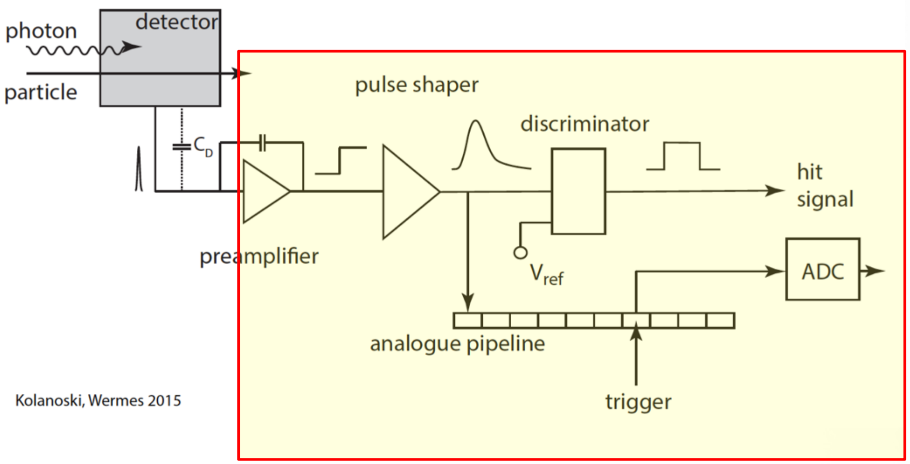
The readout chain



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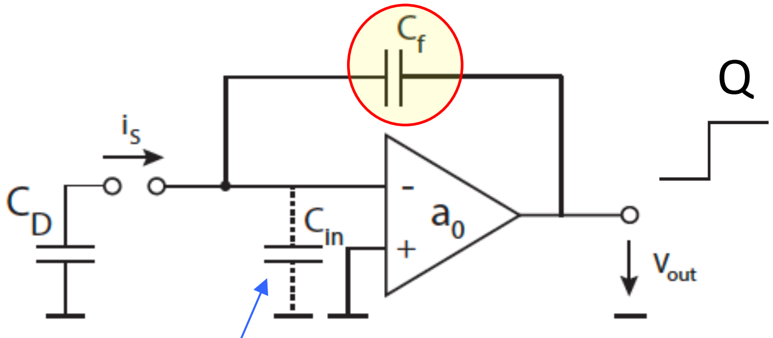
see also Lectures by E. Delages & D. Dzahini
on 16.2. & 17.2. & 18.2.21

Very typical for HEP: Charge Sensitive Amplifier (CSA)



(b) Capacitive feedback.

charge (sensitive) amplifier (CSA)
(= current integrator)

The signal current is integrated via C_f

$$v_{out}(t) = -a_0\, v_{in}(t) = -\frac{1}{C_f}\int_0^t i_S\, dt' = -\frac{Q_S(t)}{C_f}$$

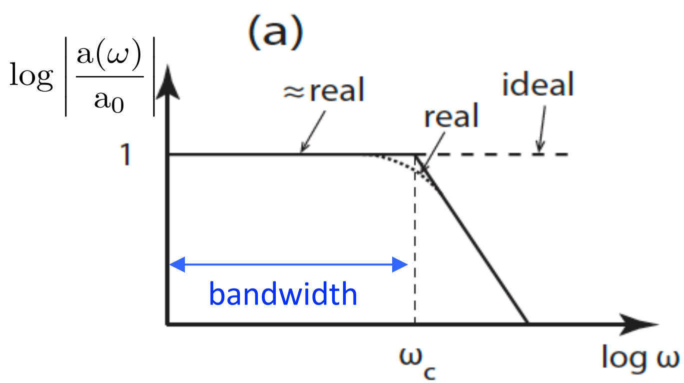
$$C_{in} = C_f\,(a_0 + 1)$$

dynamic input capacitance
(should be very large, else C_D incompletely discharged => unwanted x-talk possible)

$$A_Q = \left|\frac{v_{out}}{Q_S}\right| \approx \frac{1}{C_f}$$

gain

Bode Plot

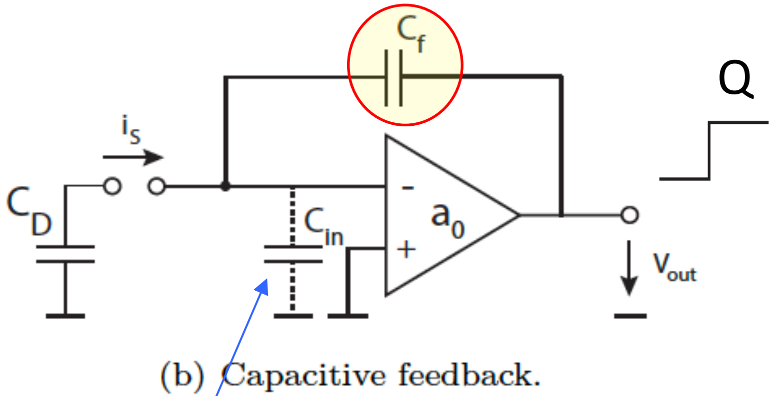


frequency domain

$v(t) = v_0\,(1 - e^{-t/\tau})$

time domain

Very typical for HEP: Charge Sensitive Amplifier (CSA)



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gain

"timing"
(fast R/O)

det. capacitance

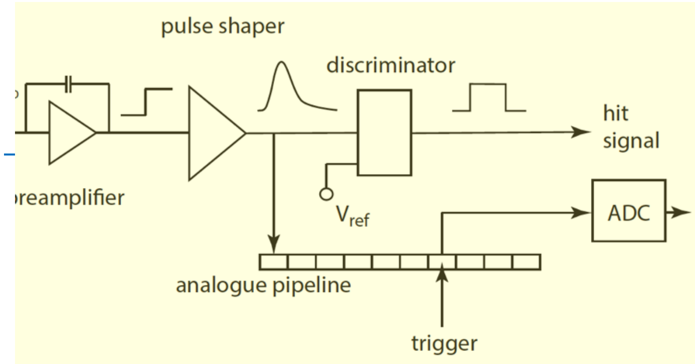
$$\tau_{CSA} = C_D R_{in} = \frac{C_D}{C_f}\frac{C_0}{g_m}$$

"power"

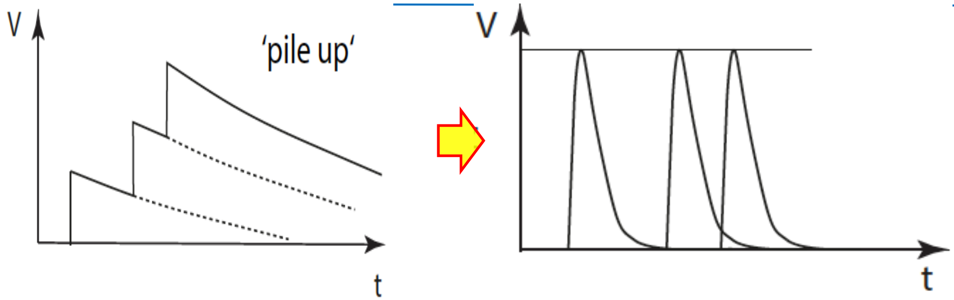
C_0 = cap. of amplifier

Reading out large detector electrodes (large C_D) very fast requires lots of power => much cooling => much material => much particle scattering / showering

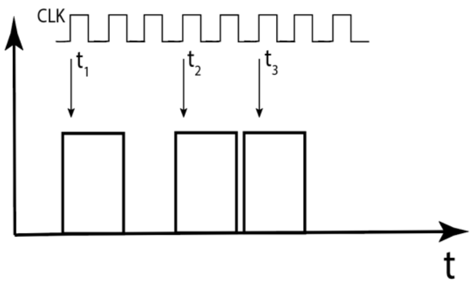
The remaining part of a typical R/O chain



- Pulse shaping
  (= filter)



- Discrimination & (Time stamping)



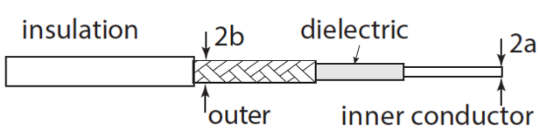
standard pulses (NIM, TTL, CMOS, …)

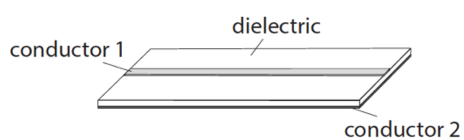
- Storing for trigger coincidence (e.g. buffers, pipelines)
  often the experiment trigger arrives with a significant delay

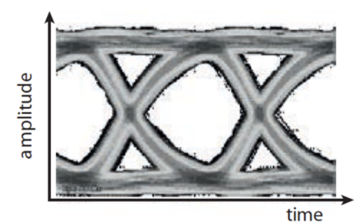
- Digitisation (ADC = analog to digital converter, TDC = time to digital converter, etc.)

011111001111111101101

- Transmission of (digitised) signals to read end processing / storage







eye diagram

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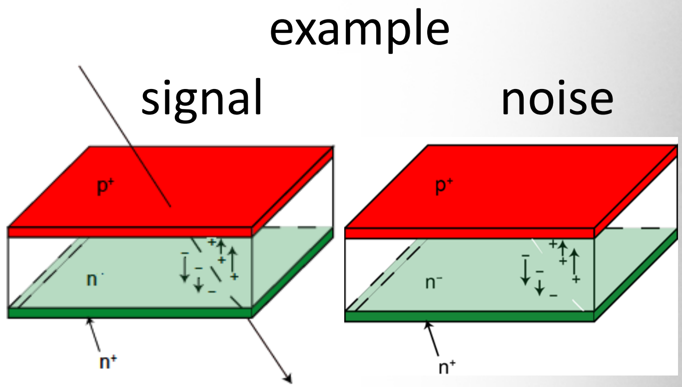
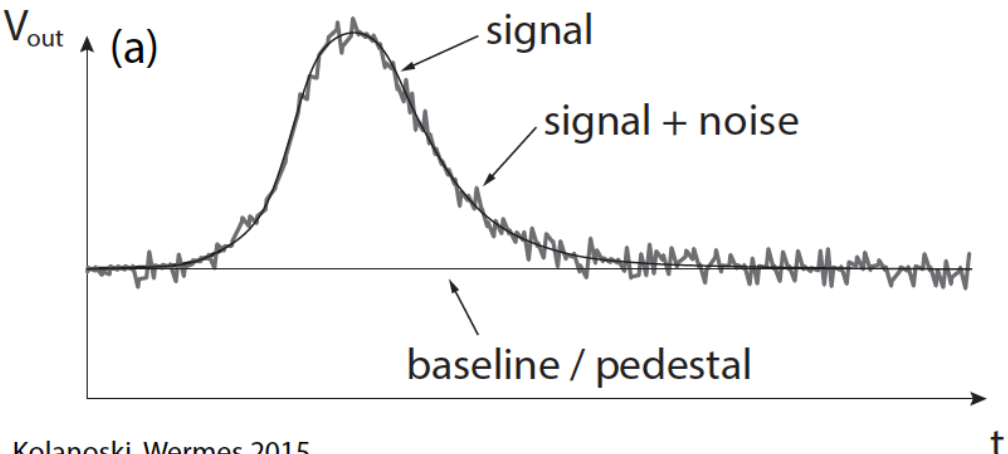
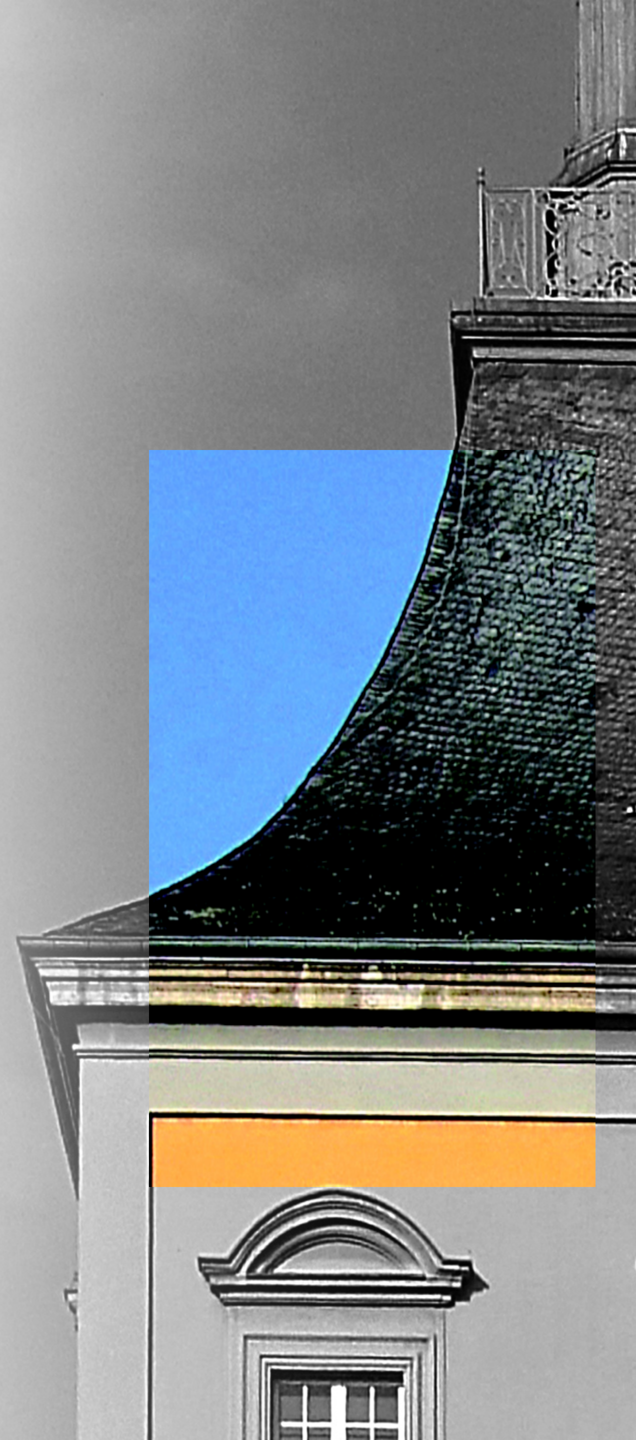
Noise



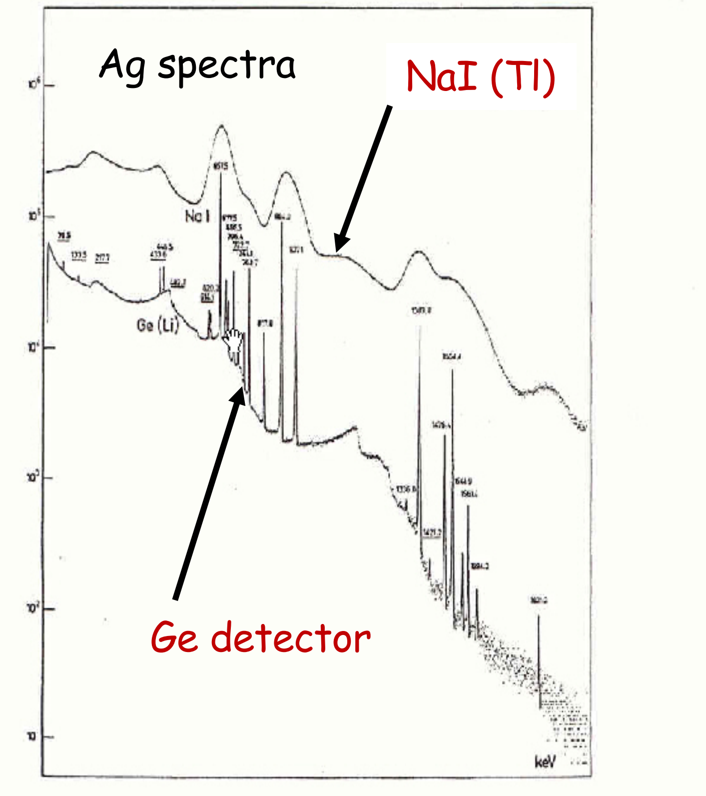


Kolanoski, Wermes 2015



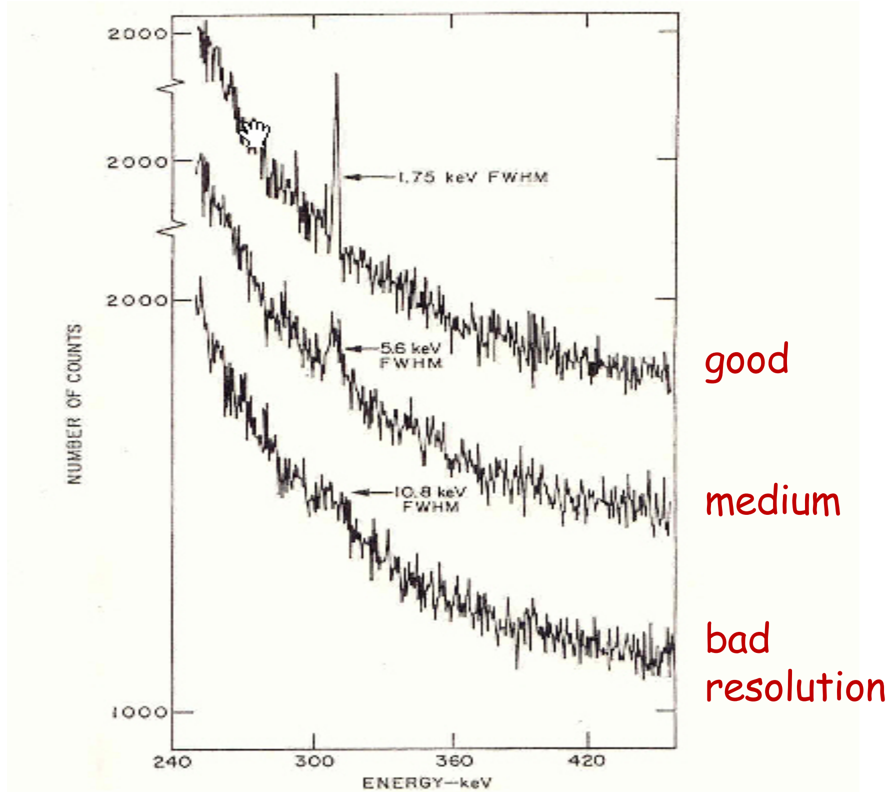
see also Lectures by E. Delages & D. Dzahini
on 16.2. & 17.2. & 18.2.21

Why bother about noise?



(J.Cl. Philippot, IEEE Trans. Nucl. Sci. NS-17/3 (1970) 446)

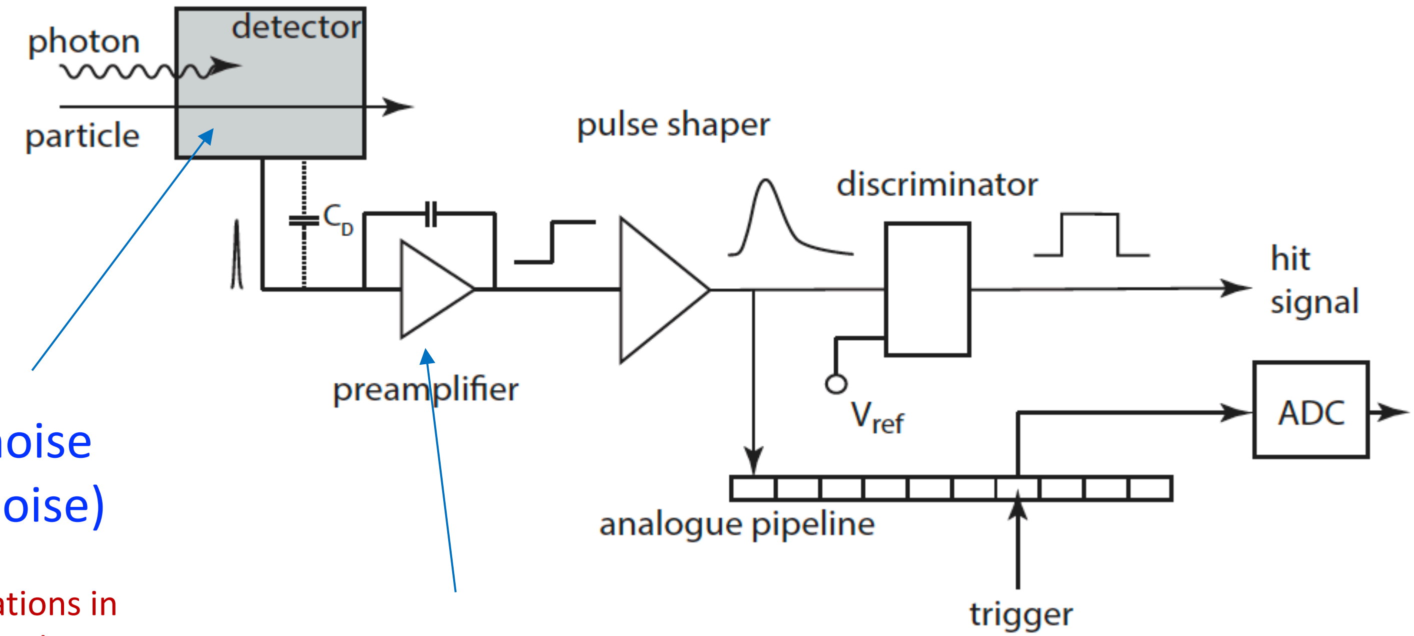
Low noise improves the resolution and the ability to distinguish (signal) structures.



G.A. Armantrout *et al.*, IEEE Trans. Nucl. Sci. NS-19/1 (1972) 107

Low noise improves the signal to back-ground ratio (signal counts are in fewer bins and thus compete with fewer background counts).

Distinguish



signal noise (Fano noise)

- fluctuations in the signal generation process

electronic noise

- fluctuations in the electronic signal processing
- occurs dominantly/exclusively in the first amplification stage

Noise

current noise

shot noise

flicker noise

resistor noise

series noise

white noise

switching noise

popcorn noise

burst noise

just 3 are important

Nyquist Noise

parallel noise

Johnson Noise

kT/C noise

Thermal noise

RTS noise

1/f noise

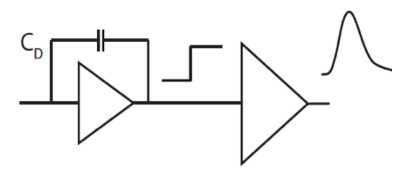
Equivalent Noise Charge (ENC)

since the input is a charge (integrated current) … refer the noise to 1e at the input to express its magnitude

$$\mathrm{ENC} = \frac{\text{noise output voltage (V)}}{\text{output voltage of a signal of } 1\,\mathrm{e}^- \ (\mathrm{V}/\mathrm{e}^-)}$$

$$\mathrm{ENC}^2 = \frac{\langle v_{\mathrm{sh}}^2 \rangle}{v_{\mathrm{sig}}^2}$$

for a "typical" detector readout system: CSA + shaper



$$\frac{\mathrm{ENC}^2}{e^2} = 11\,\frac{I_0}{\mathrm{nA}}\,\frac{\tau}{\mathrm{ns}} + 740\,\frac{1}{WL/(\mu\mathrm{m}^2)}\,\frac{C_D^2}{(100\,\mathrm{fF})^2} + 4000\,\frac{1}{g_m/\mathrm{mS}}\,\frac{C_D^2/(100\,\mathrm{fF})^2}{\tau/\mathrm{ns}}$$

shot — 1/f — thermal

I_0 = leakage current
τ = shaping (filter) time
W = gate width of preamp input transistor
L = gate length of preamp input transiator

C_D = detector capacitance
g_m = transconductance of input transistor (≙ power)

Noise in a pixel/strip/liq.Ar detector (ionisation detector)

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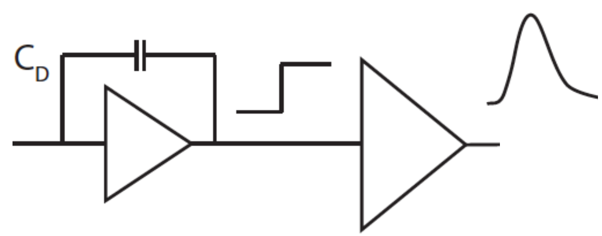
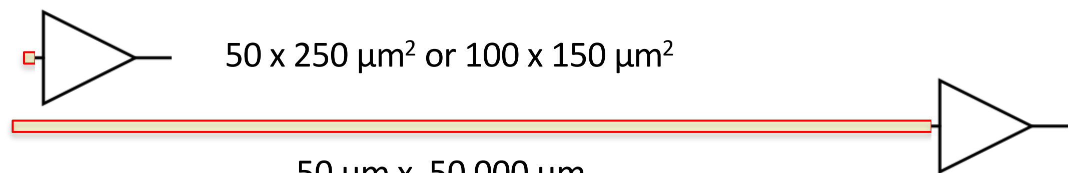
… for systems with CSA preamplifier & shaper



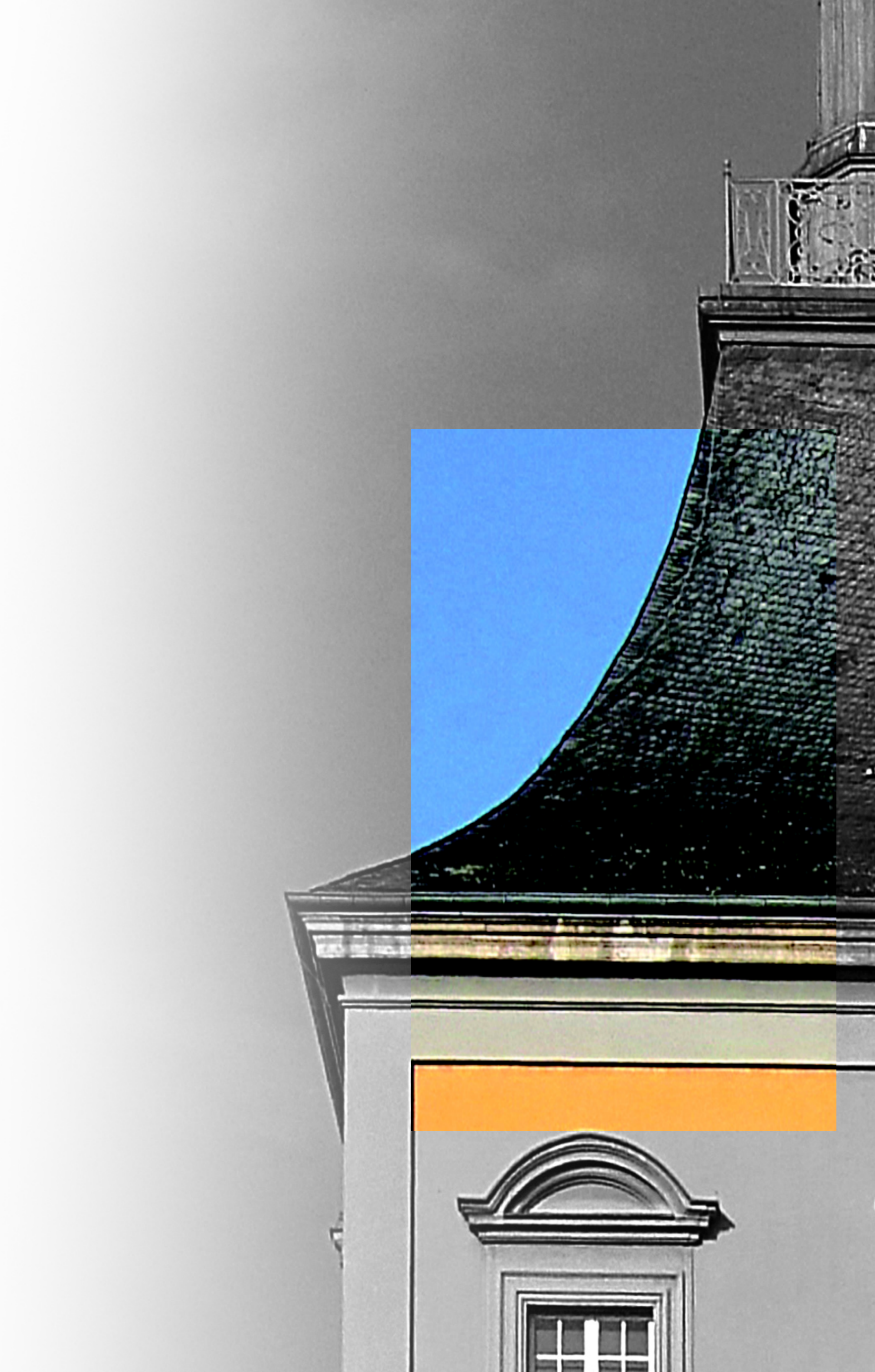
comparing pixels
and strips



	C_D	I_0	τ	W	L	g_m	ENC therm	ENC 1/f	ENC shot	ENC tot
pixel	200 fF	1 nA	50 ns	20 μm	0.5 μm	0.5 mS	25 e⁻	17 e⁻	24 e⁻	**40 e⁻**
strip	20 pF	1 μA	50 ns	2000 μm	0.4 μm	5 mS	800 e⁻	200 e⁻	750 e⁻	**1100 e⁻**
liq. Ar	1.5 nF	2 μA	50 ns	3000 μm	0.25 μm	100 mS	13 500 e⁻	15 000 e⁻	1000 e⁻	**20 200 e⁻**

agrees very well with what is measured

THE END



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Further Reading

Kolanoski, H. and Wermes, N. (new edition)
Particle Detectors – fundamentals and applications
(Oxford University Press 2020)

6/2020