Detector technologies

CERN-Fermilab Hadron Collider Physics Summer School

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Overview

- **Introduction** → role of particle detectors
  - evolution of detectors
  - challenges and figures of merit
- **Interactions of particles and matter** → basis for particle detection
  - electromagnetic
  - strong
  - weak
- **Detector technologies** → information from interactions
  - gaseous and semiconductor trackers
  - timing detectors
  - photon detectors
  - calorimeters
  - neutral particle detectors
- **Applications in experiments** → combination of techniques
  - examples and performance

Goals

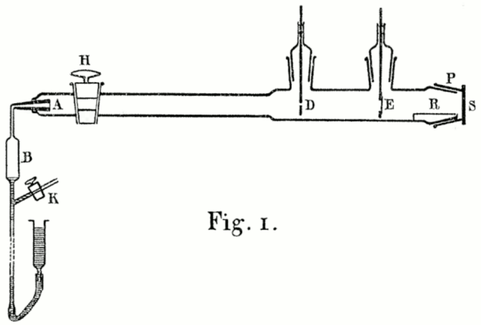
- **concepts and connections**
  instead of rigorous derivations
- **trends and scalings**
  with examples of detectors
- **references and pointers**
  for more in-depth material

Historic examples

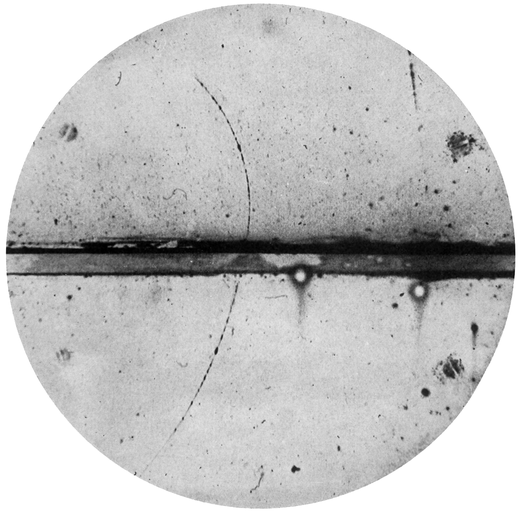
- **Scintillating screens**
  → counting experiments

- **Emulsions** and **cloud/bubble chambers**
  → imaging experiments

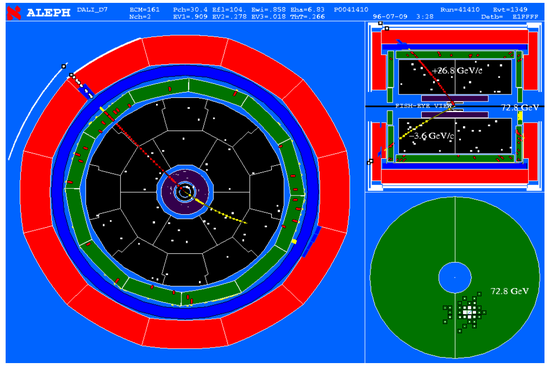
- **Modern experiments**
  → electronic readout and
  full reconstruction of trajectories



Rutherford experiment (1909)



Discovery of positron
in cloud chamber (1932)



ALEPH @ LEP (1982 - 2000)

Particle detectors

- **Particle detectors drive understanding of matter and interactions**
  - through direct discoveries, e.g. positron
  - through detection of decay products and reconstruction of interactions

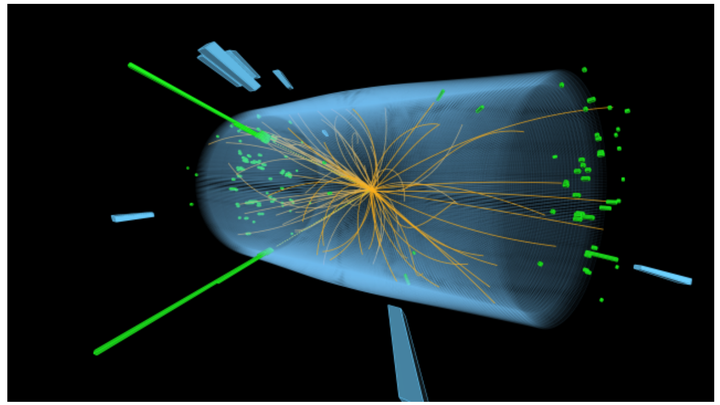
- **Modern experiments typically rely on a combination of detectors**
  to measure properties of particles (at accelerator facilities, from cosmic rays, …)
  - presence and rates
  - momentum, energy, direction
  - mass (→ species)
  - production vertices (→ reactions)
  - …

As fundamental a tool as ever
for progress in particle physics

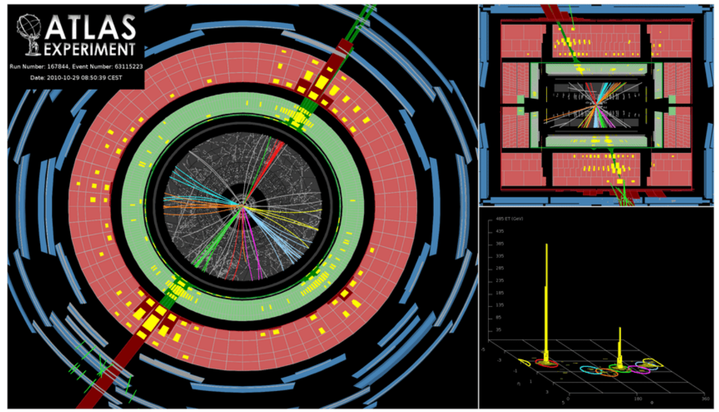
LHC experiments

used as examples

- **Challenging environment from LHC collisions**
  - high interaction rates
  - large multiplicities
  - complex observables
  - large backgrounds
- **Stringent requirements** on
  - rate capability
  - detection efficiency
  - momentum/energy resolution
  - particle identification



CMS



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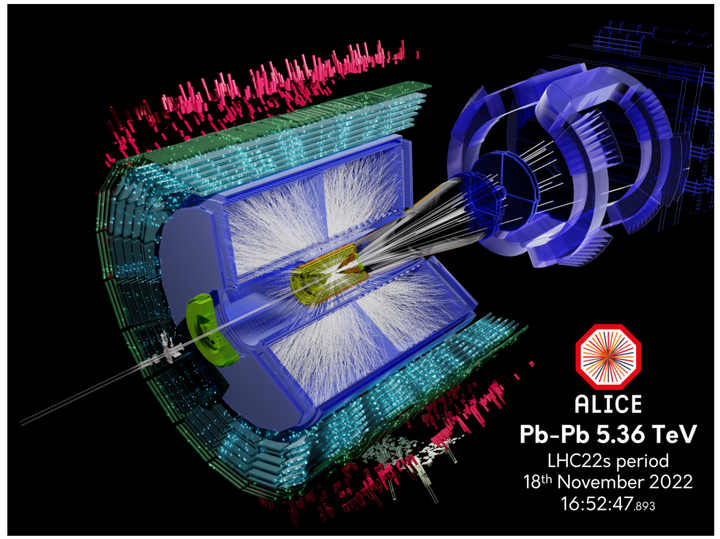
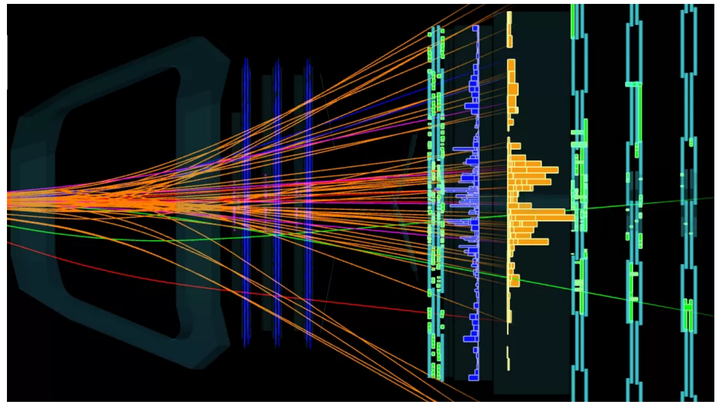


ALICE



LHCb

Figures of merit

- **Momentum resolution**
  - curvature in magnetic field
    → measurement of points along the trajectory of particles
- **Pointing resolution**
  - propagation of tracks to determine production vertices
- **Energy resolution**
  - complete absorption in detector material
    → measurement of response proportional to deposited energy
- **Mass resolution** (particle identification)
  - velocity, mass-dependent radiation
- **Rate capability**
  - large occupancies
  - radiation tolerance

Relevance of various aspects depends on physics goals

→ different optimisations

Interactions as basis of detection

- **Electromagnetic interaction → charged particles, photons**
  - ionisation and excitation (exploited in many different ways)
  - electromagnetic showers
  - scintillation
  - Cherenkov radiation
  - transition radiation

- **Strong interaction → hadrons**
  - hadronic showers

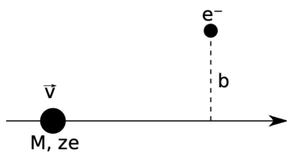
- **Weak interaction → neutrinos**

Detectors rely on interactions of particles with (detector) material

Tracks of charged particles

Charged particles in matter

- Consider a **charged particle X traversing matter**
  - cross section dominated by inelastic collisions with electrons



- **Classical derivation** of interaction (following Bohr, 1913)
  - Coulomb force $F = \frac{ze^2}{r^2}$ leads to

    momentum transfer $\Delta p_\perp = \int \mathrm{d}t\, F = \frac{2ze^2}{bv}$ and, thus,

    energy transfer $\Delta E = \frac{\Delta p^2}{2m_\mathrm{e}}$ to electron
  - Considering all material

    $$\mathrm{d}E(b) = -\, n\, 2\pi\, b\, \mathrm{d}b\, \mathrm{d}x\, \frac{4z^2e^4}{b^2v^2}\frac{1}{2m_\mathrm{e}} = -\frac{4\pi\, nz^2e^4}{m_\mathrm{e}v^2}\frac{\mathrm{d}b}{b}\mathrm{d}x \rightarrow \text{divergent in } b$$

Energy loss of charged particles

- Average energy loss from **integration over relevant range of *b*** (avoiding divergence)
  - b_{min}: localisation limited by uncertainty: $\frac{h}{p} = \frac{h}{\gamma m_{\text{e}} v}$
  - b_{max}: interaction time limited by revolution period of electrons: $t_{\text{int}} < T_{\text{e}}$
- Integration yields

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{4\pi z^2 e^4}{m_{\text{e}} c^2 \beta^2} n \ln \frac{m_{\text{e}} c^2 \beta^2 \gamma^2}{\hbar \langle v \rangle} \text{ with } n = \frac{N_{\text{A}} \rho Z}{A}$$

$\beta = p/E, \gamma = E/m \Rightarrow \beta\gamma = p/m$

Bethe-Bloch equation

- Calculation **considering quantum mechanics** by Bethe and Bloch leads to

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = Kz^2\frac{Z}{A}\rho\frac{1}{\beta^2}\left[\frac{1}{2}\log\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

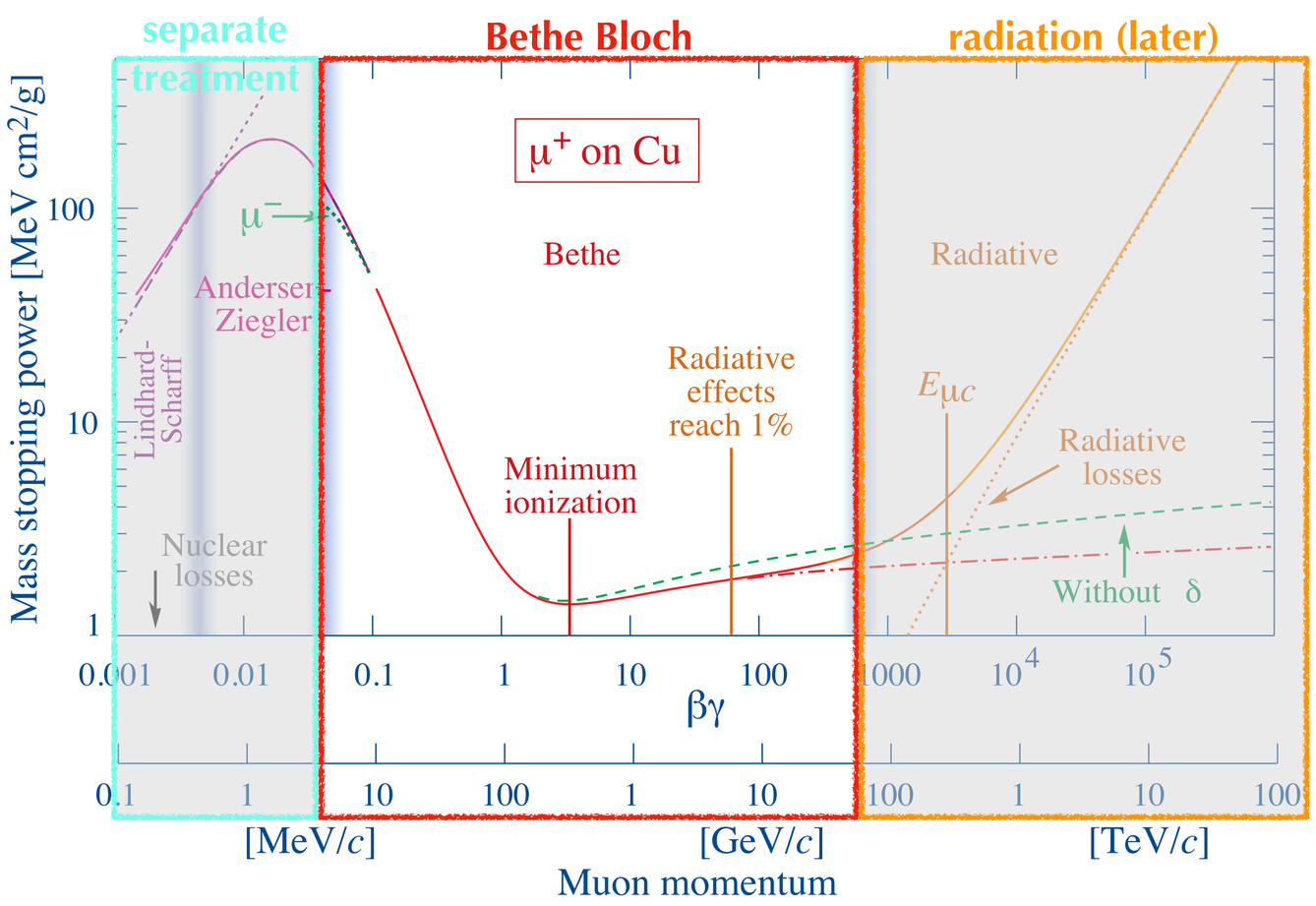
  - T_{max}: max. energy transfer (in single collision)
  - I: ionisation potential (~(10 ± 1) Z eV for elements beyond O)
  - δ/2: density correction (Lorentz contraction + polarisability of material)

- **Modifications for electrons and positrons**
  - indistinguishable particles → W/2
  - annihilation for positrons
  - low mass → deflection more important → longer path length
  - low mass → radiation (bremsstrahlung) important (discussed later)

[H. Bethe, Ann. d. Physik 5 (1930) 325; F. Bloch, Ann. d. Physik 16 (1933) 285]

Specific energy loss

- **General behaviour of Bethe-Bloch equation**
  - **steep rise** towards low energies: $\propto \beta^{-5/3}$ up to $\beta\gamma \approx 1$
  - **broad minimum** of $1 - 2\,\frac{\mathrm{MeV}}{\mathrm{g\,cm^{-2}}}$ around $\beta\gamma \approx 3.5$
  - **logarithmic rise** towards large energies (Fermi plateau)



NB: Average energy loss
(distribution discussed later)

[R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)]

Ionisation from energy loss

- Energy loss of charged particles leads to **ionisation and excitation**
  - primary ionisation n_p
  - secondary ionisation $n_s = (1 - 5)\ n_p$
  - de-excitation

- **Effective ionisation potential *W*** to link ionisation and energy loss

$$\langle n_t \rangle = \frac{L \langle \mathrm{d}E/\mathrm{d}x \rangle}{W}$$

material	I_0 (eV)	W (eV)
He	25	41
Ne	22	36
Ar	16	26
Xe	12	22
Si	1.1	3.6
Ge	0.67	2.85

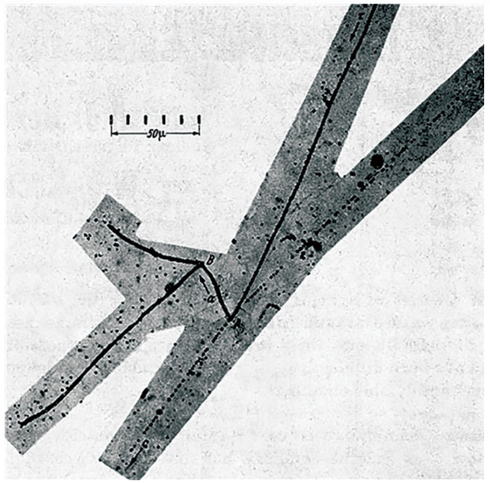
Ionisation properties for a selection of detection material

W is a few 10 eV for gases, few eV for semiconductors
NB: factor 10^3 in density

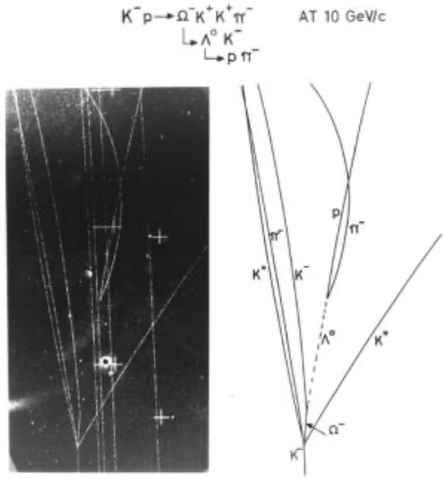
Detection of ionisation

- Many methods exploit ionisation to make tracks of charged particle visible, e.g.
  - **Photographic emulsions**
    - ionisation leads to exposure
  - **Cloud chambers**
    - ions as seeds for condensation
  - **Bubble chambers**
    - ions as seeds for evaporation
- Embedding in magnetic field allows **extraction of momentum** from curvature of the track

specific energy loss
→ ionisation
→ width of trace



Particle tracks in emulsion

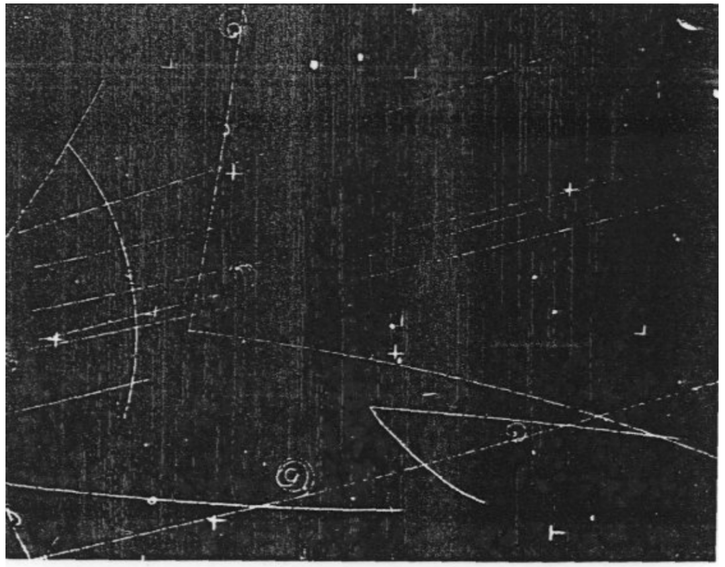


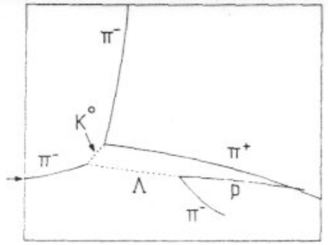
Particle tracks in cloud chamber

Delta electrons

- Curling traces emerging from main particle tracks
  - large energy transfers to electrons allowed for massive highly relativistic particles
  - individual electrons with significant energy are called delta electrons

- Large range
  → not part of total ionisation
  → often lost for ionisation measurement



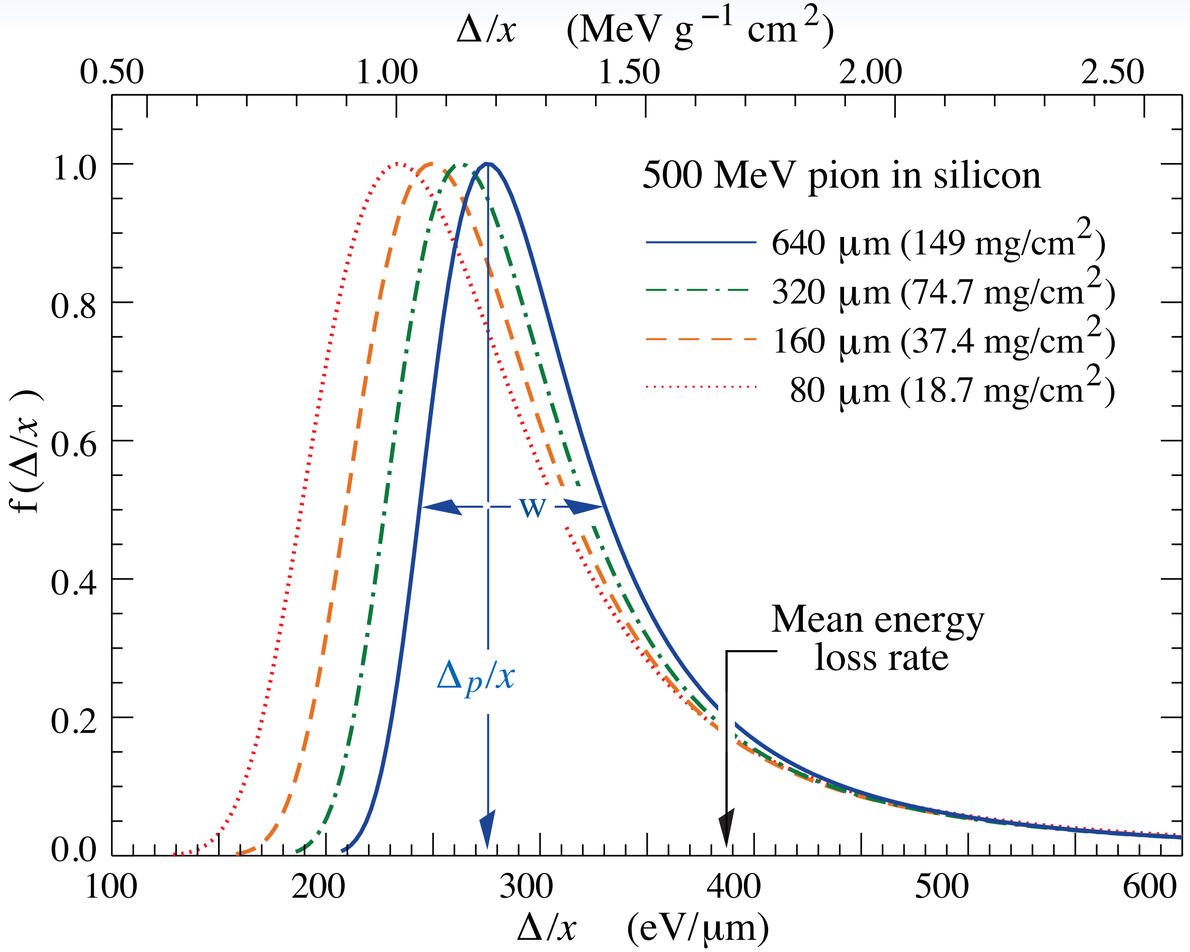


Energy loss distribution

- **Statistical distribution with long tail**
  - Landau distribution for thin absorber
  - Vavilov:
    correction for thicker absorbers
  - Approximation

$$D\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\underbrace{\frac{\frac{\mathrm{d}E}{\mathrm{d}x} - \frac{\mathrm{d}E}{\mathrm{d}x}_{\mathrm{mp}}}{\xi}}_{\lambda} + e^{-\lambda}\right)\right)$$

  - more precise:
    Allison & Cobb (using measurements and numerical solution) Ann. Rev. Nuclear Sci. 30 (1980) 253



Important for dE/dx measurements (estimated from finite number of samples)

Electrons and ions in material

- **Significant life time → movement of charges possible, loss through**
  - recombination
    → generally not important
  - electron attachment ($e + M \rightarrow M^-$)
    → important in presence of electronegative gases (O_2, SF_6, …) or impurities

- **Random motion of electrons and ions**
  with mean free path $\lambda = \dfrac{1}{n\sigma}$

- **Drift:** random motion with acceleration in electric/magnetic fields

Charge transport in gases

- **Electron mobility μ_e in gases**
  - superposition of random motion and acceleration in electric field → drift
  - averaging of Langevin equation leads to

$$m\langle\frac{\mathrm{d}\vec{v}}{\mathrm{d}t}\rangle = e\left(\vec{E} + \langle\vec{v}\rangle \times \vec{B}\right) - \frac{m}{\tau}\vec{v}_\mathrm{D}$$

  - **hot gas** ($T_e \gg kT$) → constant v_D
  - **cold gas** ($T_e \approx kT$) → $v_D \propto E$

Typical values

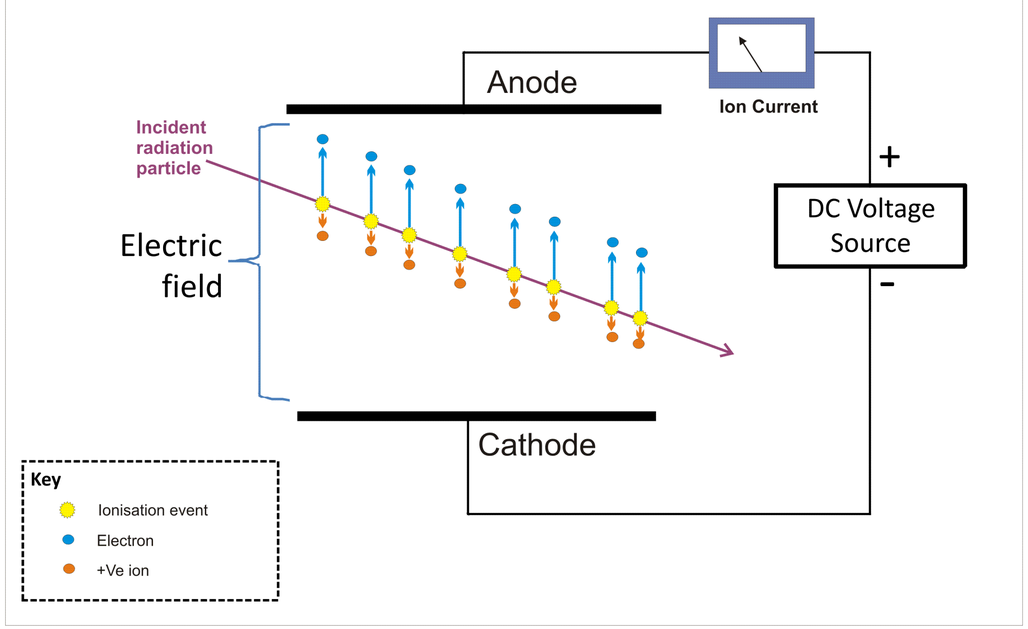
- cm/μs for electrons in gases
- cm/ms for ions in gases ($\cdot 10^{-3}$!)
- cm/μs for e/h in semi-conductors

- **Ion mobility**
  - several orders of magnitude slower than electrons

- **Electron/hole mobility in semi-conductors analogue**
  - similar drift velocities for electrons and holes (within factor ~2)

Ionisation chamber

- Idea: **collect charge in electric field**, e.g.
  - between two plates
  - between cylinder and central wire
- **Moving charges induce current**
  - fast signal from fast drift of electrons
  - slow signal from slow drift of ions
  - position-independent response
    → Frisch grid
- **Limitations**
  - small signal from charges
  - no position information

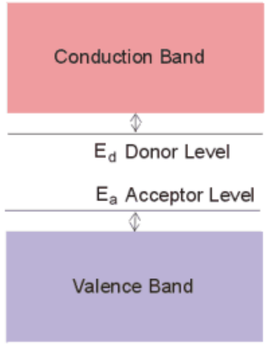


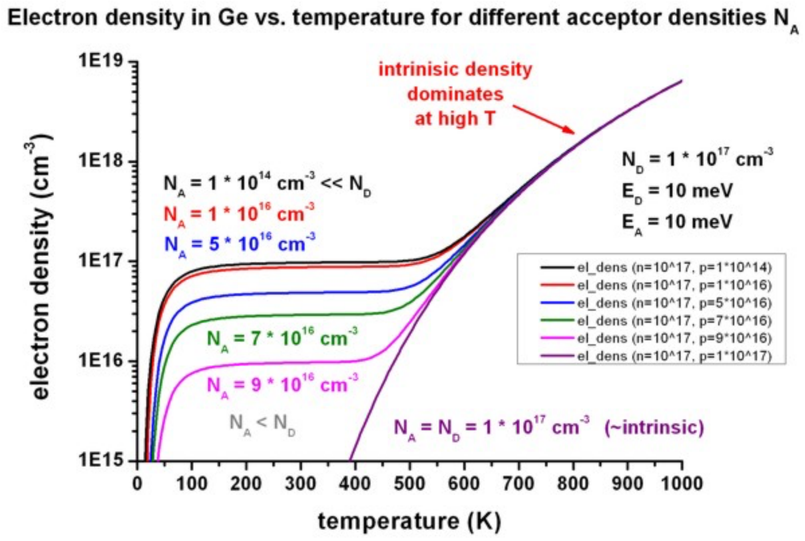
NB: small currents in the pA range

Charge carriers in semi-conductors

- Electrons and holes as **charge carriers**
  - **intrinsic semiconductors**:
    thermal excitation across band gap
  - **extrinsic semiconductors (doping)**:
    excitation from/to donor/acceptor levels
    → saturation

- **Drift of charge carriers** similar to gases $\mathcal{O}$(cm/μs), slower for holes $v_h \approx 0.3 - 0.5 v_e$





pn junction

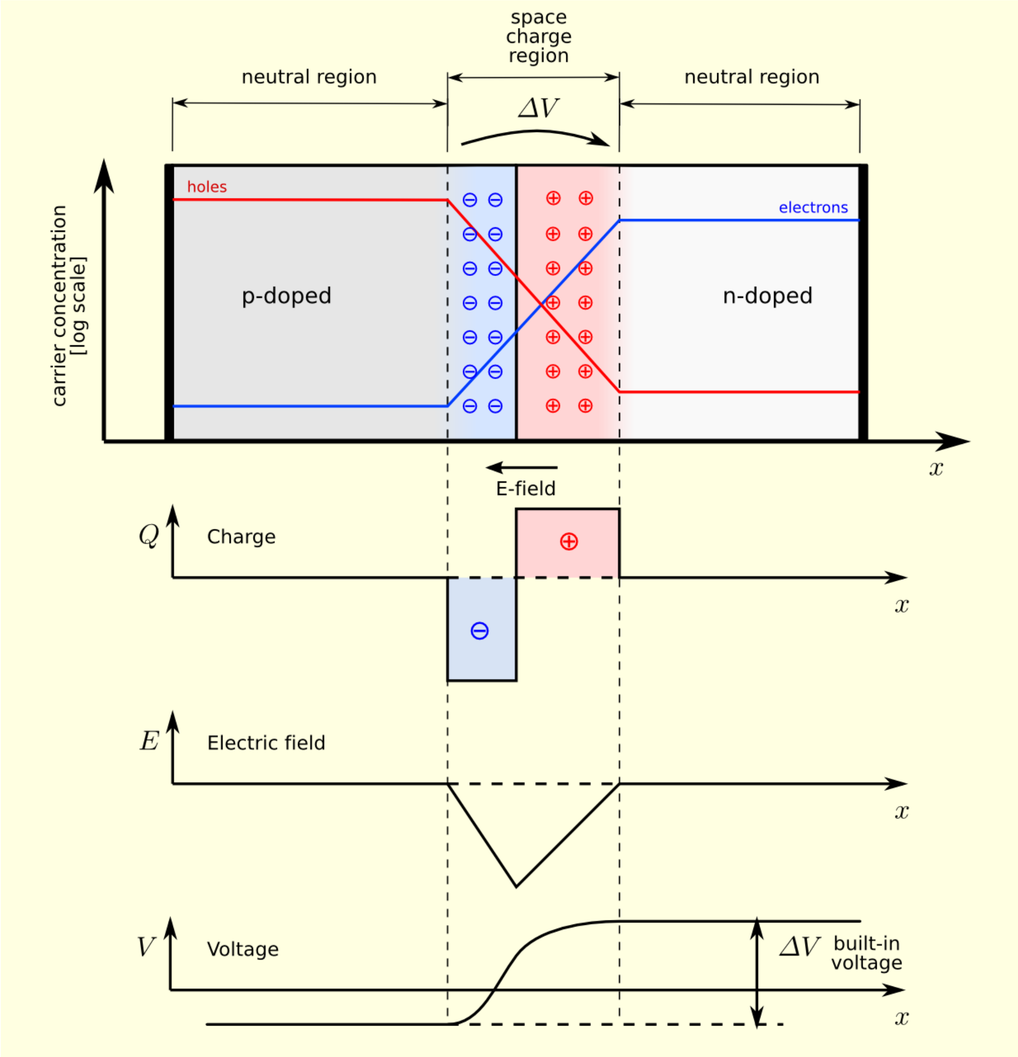
- Contact between p- and n-doped regions
  → **depletion zone**
  - depletion of charge carriers
  - net charge
  - electric field

- **Schottky model**
  - sharp edges of regions
  - thickness of depletion zone

$$d_n = \sqrt{\frac{2\epsilon\epsilon_0 V_D}{e}\frac{N_A/N_D}{N_A+N_D}}$$

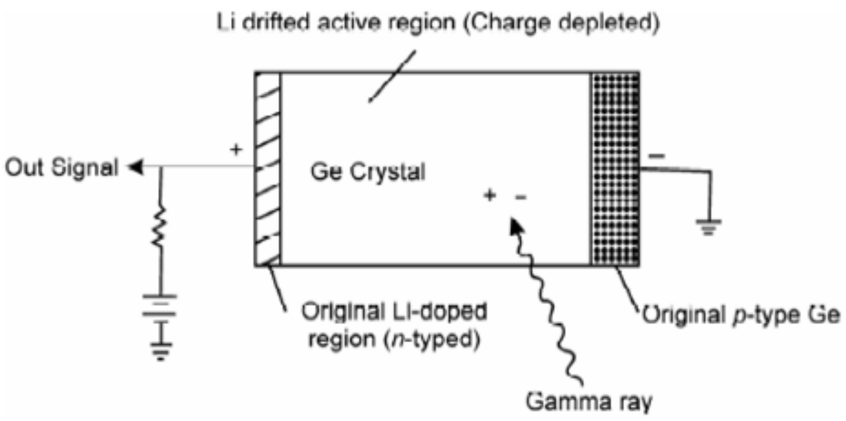
$$d_p = \sqrt{\frac{2\epsilon\epsilon_0 V_D}{e}\frac{N_D/N_A}{N_A+N_D}}$$

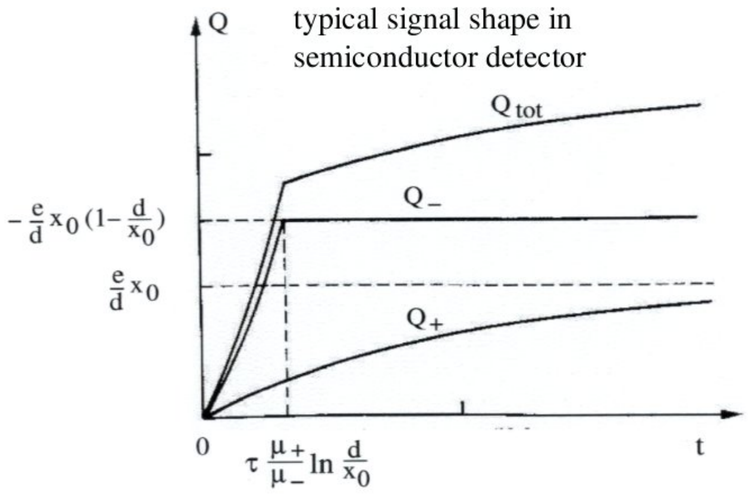
  - large depletion zone achievable
    with highly asymmetric doping and/or bias voltage



Semiconductor sensor

- Ionisation leads to creation of **electrons and holes** (also phonon excitation) in depletion region (used as active volume)
  - electric field leads to drift
    (with similar drift velocities for electrons and holes)

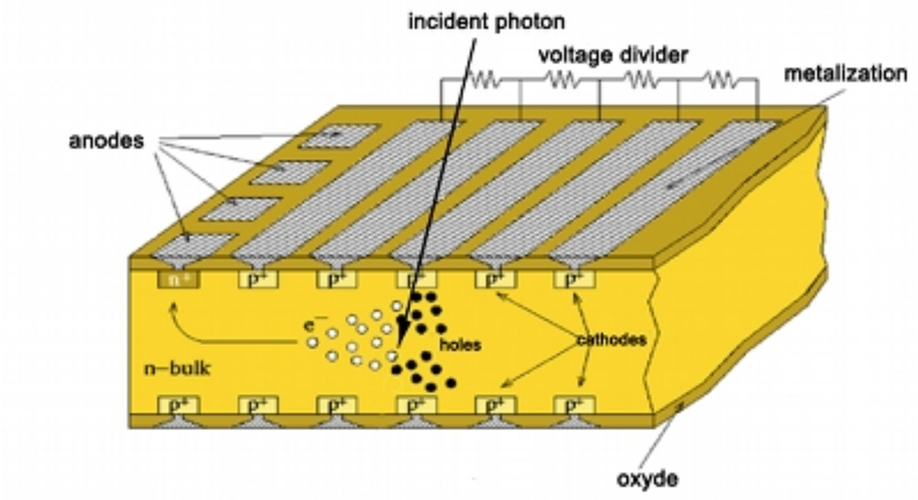




semiconductor analogue of ionisation chamber

Silicon drift sensors

- **Electrodes on surface of sensor**
  - parabolic potential
    → charge collection in central plane
  - longitudinal potential
    → drift to collection electrode
  - readout of charge incl. drift time
    → position information (2D)

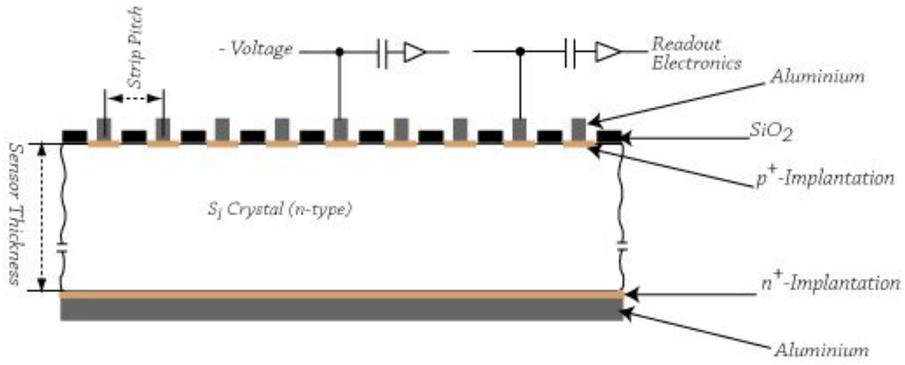


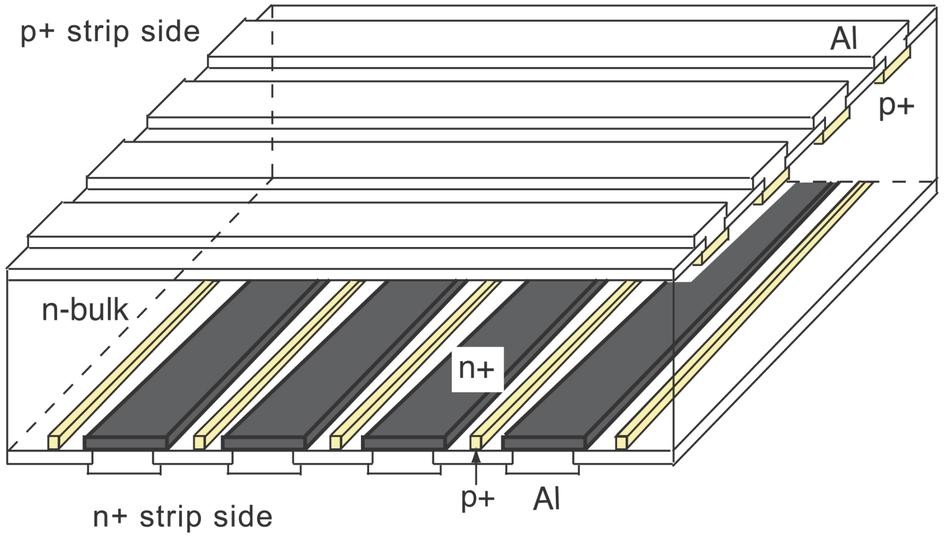
Examples

- Inner trackers at LHC

Silicon strip sensors

- **Strips as collection electrodes**
  → position information
  - microstrips, typical pitch $\mathcal{O}(10\ \mu m)$
  - for 2d information:
    combination of two sensor layers or
    perpendicular strips on both surfaces



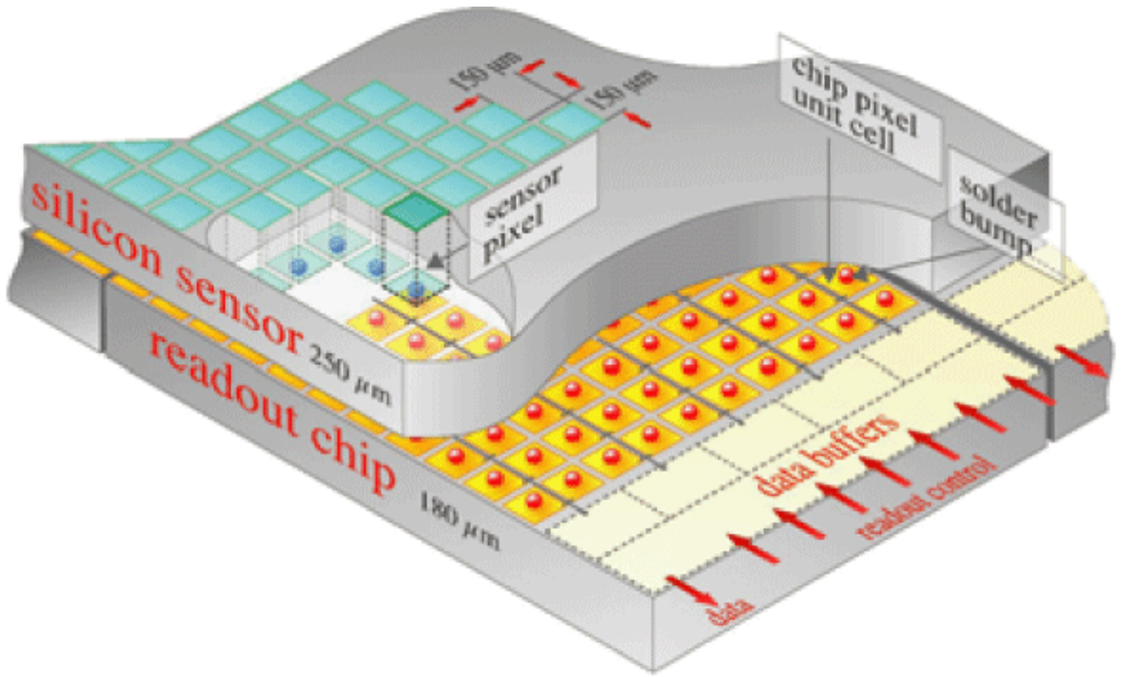


Examples

- Inner trackers @ LHC

Silicon pixel sensors

- Small pads as collection electrodes
  → 2d position information
  - good position resolution
  - large number of readout channels



Examples

- Inner trackers @ LHC

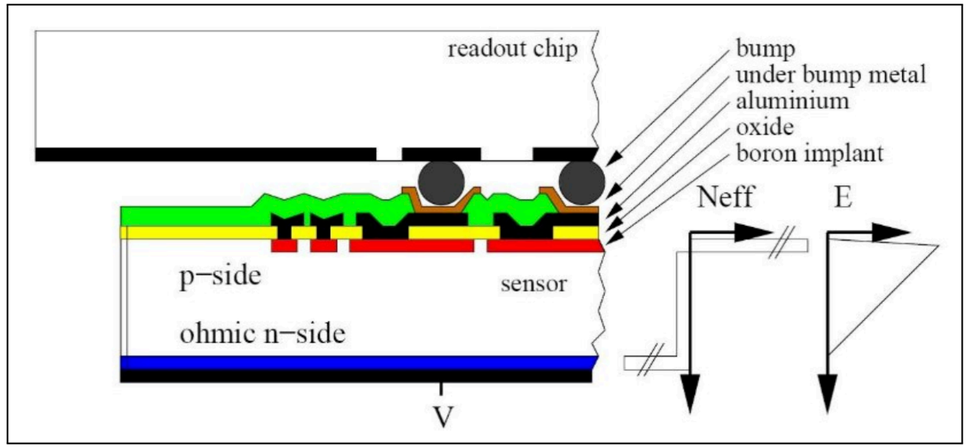
Hybrid vs monolithic

- **Hybrid sensors**
  → separate chips for sensor and readout
  - can be produced in different processes
  - requires bonding
    e.g. bump bonding, wafer to wafer

Examples

- ATLAS Itk
- CMS tracker

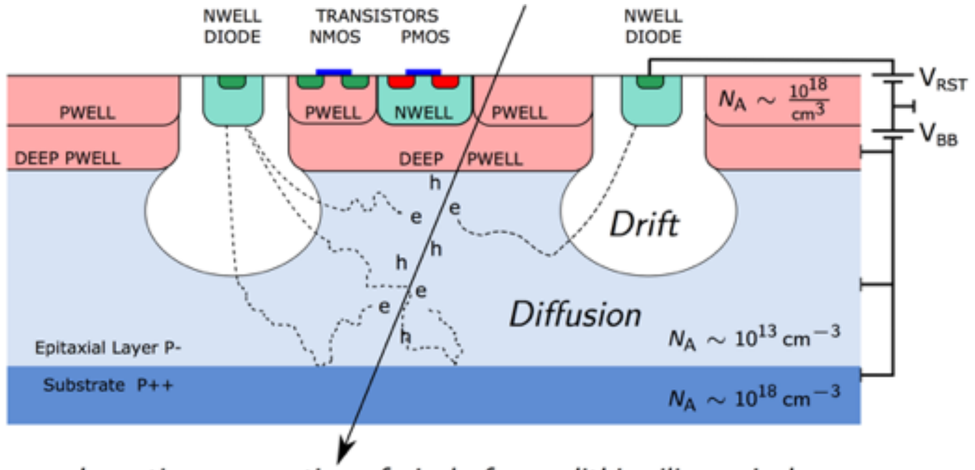
Bump bonding



- **Monolithic sensors**
  → readout circuitry integrated with sensor
  - produced in a single process,
    e.g. CMOS imaging
  - avoids cost and complexity
    of multiple chips and interconnects

Examples

- STAR @ RHIC
- ALICE ITS @ LHC



schematic cross section of pixel of monolithic silicon pixel sensor

Charge amplification

Charge amplification

- **Charge from ionisation limited**,
  in particular for gas detectors (lower ionisation yields!)
  - poor signal-to-noise ratio

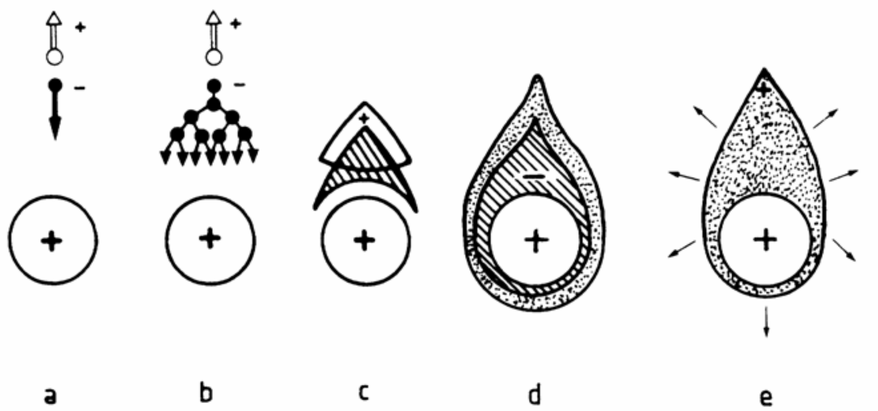
- **Amplification of primary signal**
  - in electronics → front-end (not discussed here)
  - **Amplification of ionisation charge** in sensors
    by feeding energy for additional ionisation
    - high electric field around thin wires (gaseous detectors)
    - high electric field in amplification layer (semiconductor detectors)

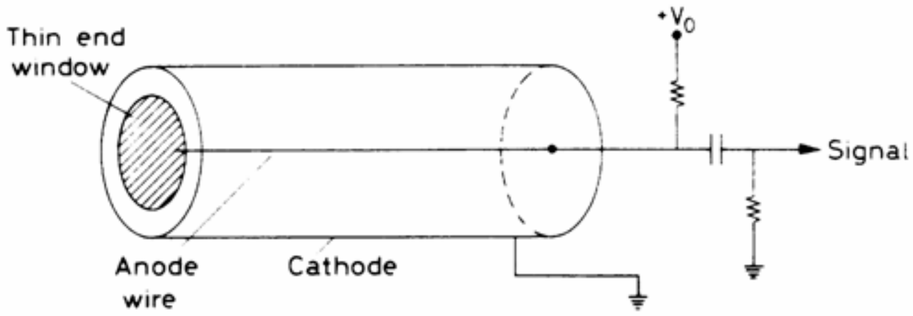
Gas amplification

- High electric field around thin metal wire $\propto 1/r$, typical radii: 10 - 50 μm
  - avalanche formation within few wire radii
- **Gain from avalanche in gas**

$$N(x) = N_0 \cdot \exp(\alpha x) \text{ and } G = \exp\left(\int_{r_1}^{r_2} \mathrm{d}x\, \alpha(x)\right)$$

  - exponential growth with first Townsend coefficient α
  - breakdown for alpha x ≥ 20 (Raether limit)
  - excitation of gas → UV photons → additional avalanches
  - quencher (e.g. CO_2) to absorb UV photons → stable operation with higher gain

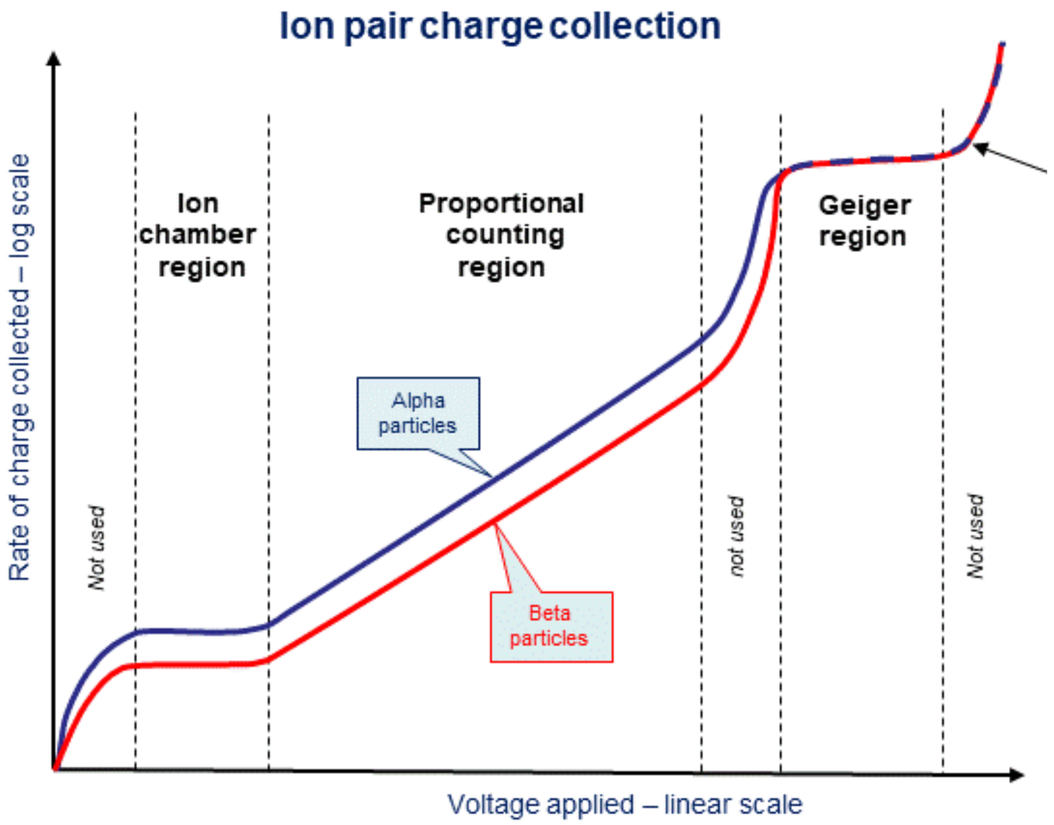




Needs careful control of operating conditions
(pressure, high voltage, temperature)

Operational regimes

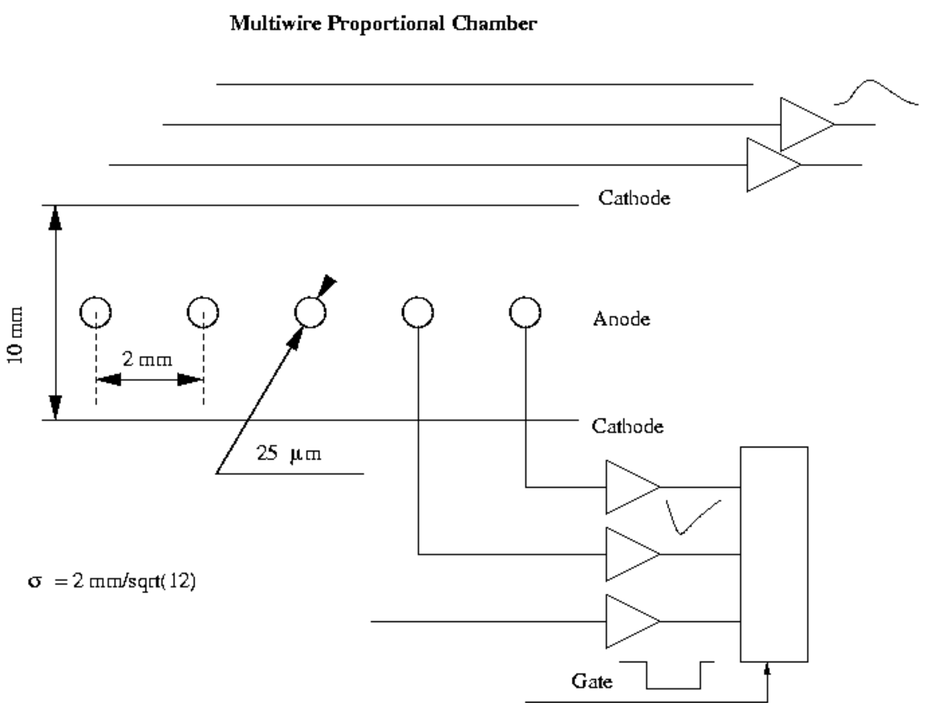
- **Ionisation chamber**
  - collect all charge from ionisation, no gas gain
- **Proportional counter**
  - gain from avalanches
    - proportional to initial ionisation
    - exponential dependence on voltage
- **Geiger counter**
  - gain from avalanches
    - independent of initial ionisation (saturation)



in proportional region:
gain depends exponentially on voltage

Multi-Wire Proportional Chamber

- Combination of
  - primary ionisation in gas
  - drift towards anode wires
  - gas amplification around anode wires
    → larger signal
  - segmented cathode plane for induced charge
    → more precise position information



- **Operation in proportional regime**
  → provides information on
  - position
  - energy loss (dE/dx)

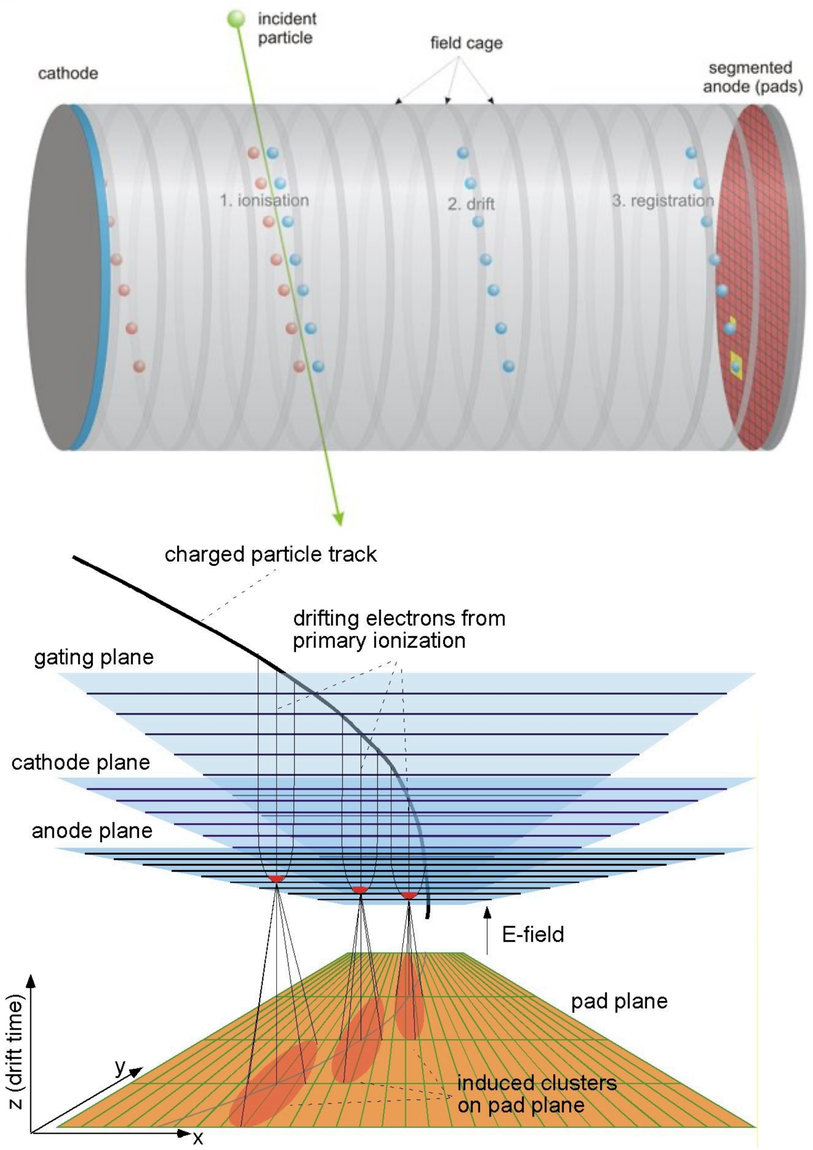
Instrumentation of large areas
(2d position and energy loss)

Time Projection Chamber

- **combination of different techniques**
  - primary ionisation in gas
  - charge collection through drift in electric field
  - read-out at the end of drift volume, e.g. MWPC, GEM
- very powerful detector with some limitations
  - rate limited by ions entering drift region → distortions

Examples

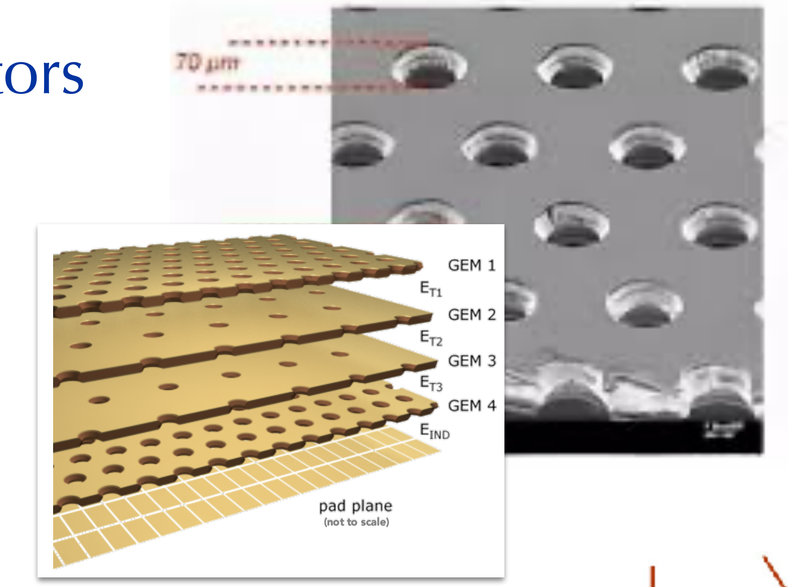
- ALICE TPC

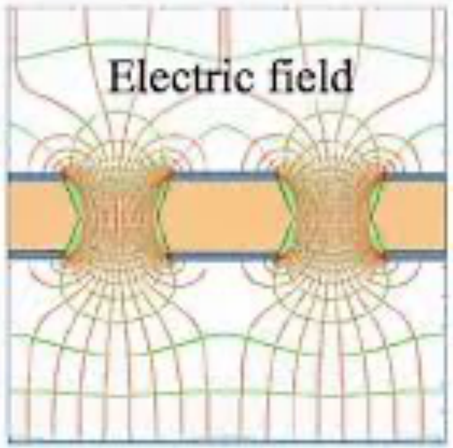


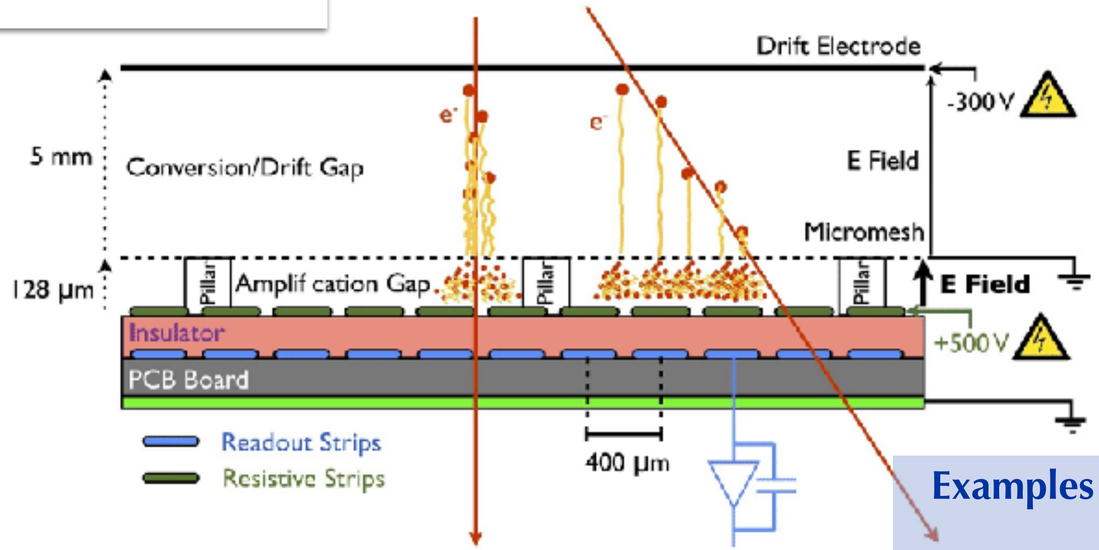
Readout chamber of ALICE TPC

Micro pattern gas detectors (MPGD)

- Reduce structure size in gaseous detectors to cope with high particle flux, e.g.
  - **Gas electron multiplier (GEM)**
    - thin Kapton foil, $\mathcal{O}(50\ \mu m)$
    - copper coating
    - etched holes, $\mathcal{O}(50\ \mu m)$
  - **MICRO-MEsh Gasesous Structure (Micromegas)**
    - drift and amplification regions separated by thin mesh
    - strong field above micro strips





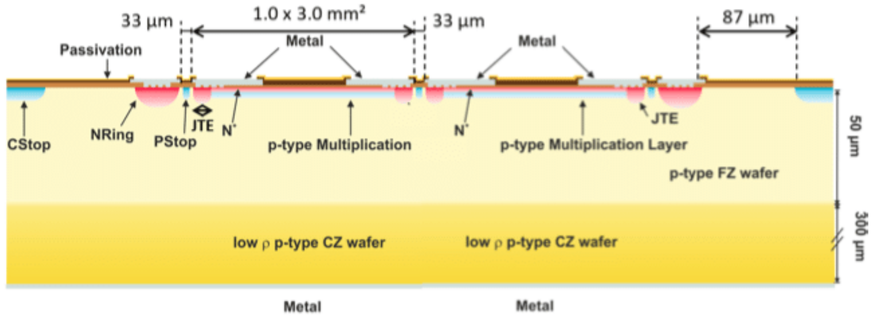


Examples

- ALICE TPC

Charge amplification in semiconductors

- **Amplification also possible in semiconductors**
  - addition of doped layer
    → strong electric field
    → amplification



- **Advantages**
  - larger signal
  - faster charge collection

Examples

- ATLAS/CMS timing

- **Applications**
  - Avalanche Photo Diode (APD, gain 100-1000) → photon detection
  - Single Photon Avalanche Diode (SPAD, breakdown) → single photon detection
  - Low-Gain Avalanche Diode (LGAD, gain 10-100) → timing detectors

Particle identification

Particle identification

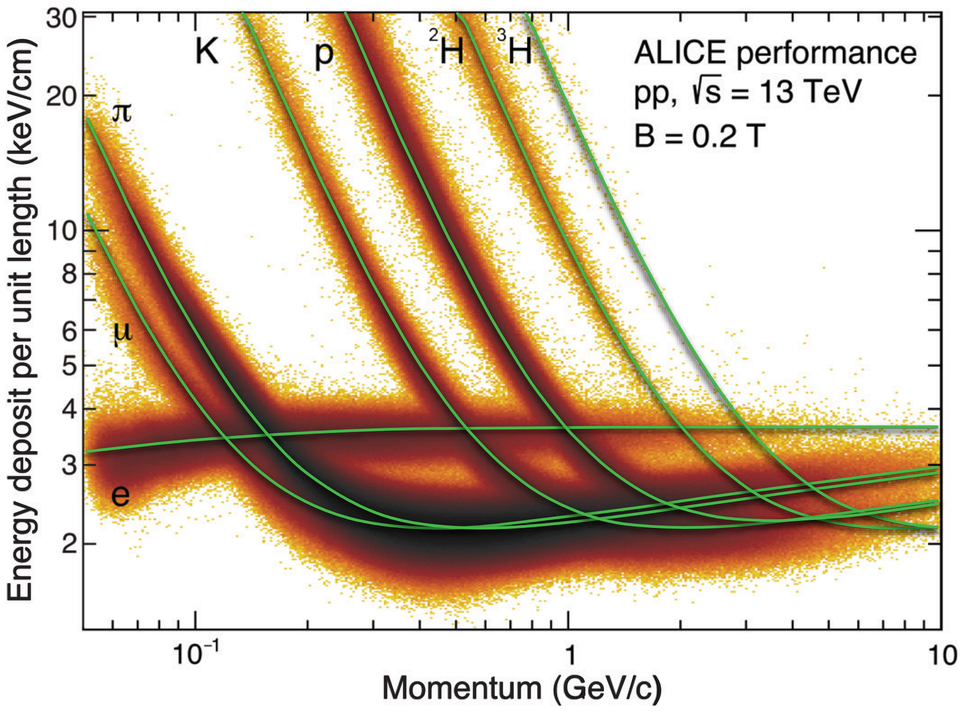
- Idea: extract mass from combination of momentum and
  - **specific energy loss** dE/dx
  - **time of flight** separation $\propto L / \sigma_{\mathrm{tof}}$
    ➟ large path length with fast time resolution
  - **Cherenkov** radiation with angle $\cos\vartheta = 1 / n\beta$
    ➟ refractive index to optimise coverage
    ➟ angular resolution
  - transition Radiation
  - **electromagnetic shower** (electrons)
  - **hadron absorption** (muons)

Combination of techniques
to achieve PID goals

Specific energy loss

- **Specific energy loss (Bethe Bloch)** function of $\beta\gamma = p/m$
  - for given momentum → function of mass
  - ambiguities at line crossings
- Requires **combined measurement** of
  - momentum → tracker
  - dE/dx → deposited charge

ALICE TPC



Time of flight

- Velocity of particle (at given momentum) depends on mass
  → different time of flight for different mass hypotheses:

$$\Delta t = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right) \approx \frac{Lc}{2p^2}(m_1^2 - m_2^2)$$

  - separation requires

- Requires **fast detectors** with time resolutions on the order of **50 ps**
  - Scintillators + PMT
  - MRPCs
  - LGADs (already discussed in context of charge amplification)
  - Cherenkov counters

Scintillators

- **Production of (visible) light** from energy deposited by charged particles (via excitation and ionisation/recombination)

- **Inorganic crystals** (solid)
  - based on crystals with activator doping (high density)
  - typical photon yield ~40 photons / 100 eV of energy deposit (NaI)
  - decay times in the order of μs
  - complicated crystal growth → expensive

- **Organic scintillators** (solid and liquid)
  - based on aromatic matrix, e.g. benzene
  - typical wavelengths 370 - 750 nm, typically peaking around 425 nm
  - typical photon yield ~1 photon / 100 eV of energy deposit
  - decay times in the order of ns
  - easy to produce → cheap

- **Polymers**
  - based on plastics
  - Easy to manufacture (incl. extrusion)

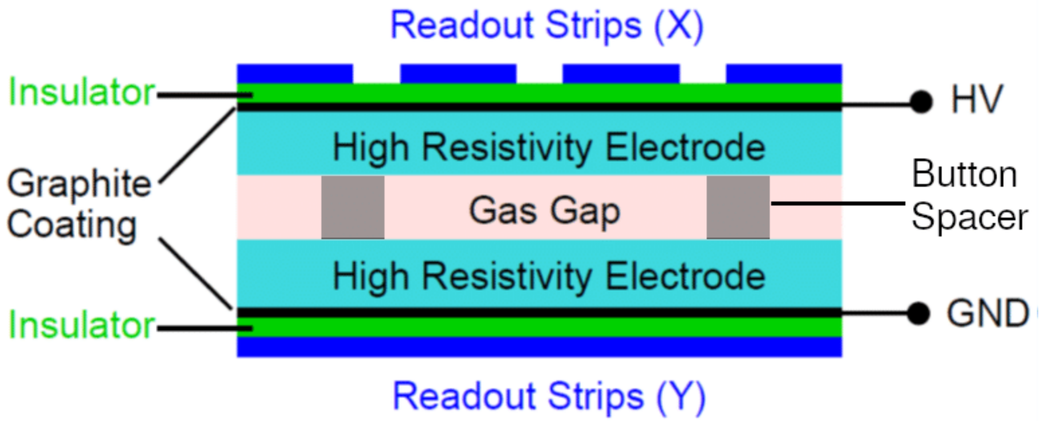
Resistive Plate Chambers

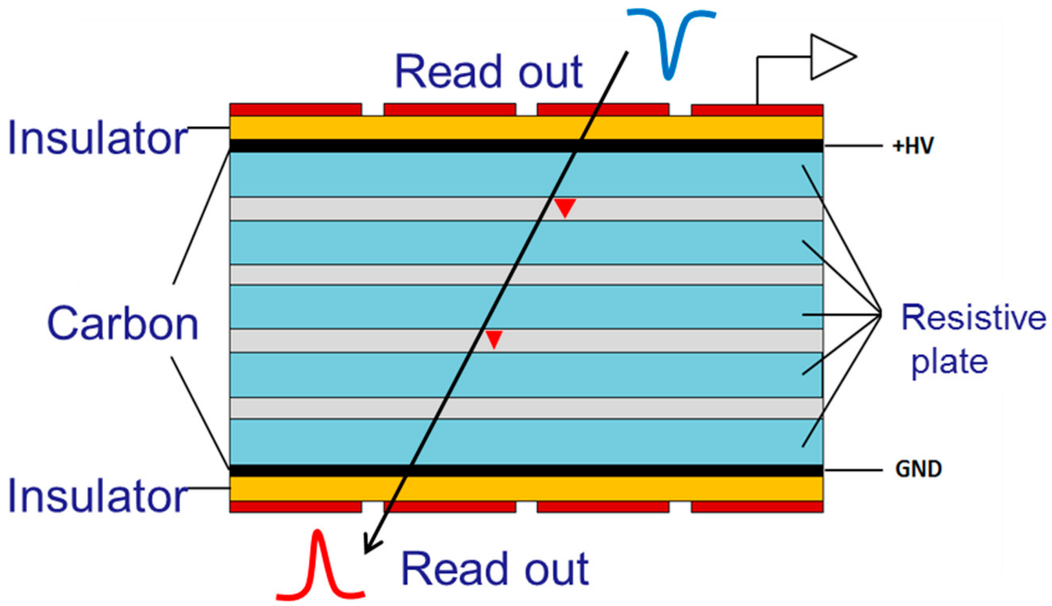
- Resistive Plate Chamber (RPC) with
  - high-resistivity electrodes
  - high fields
    → immediate formation of avalanche
  - quenching in high-resistivity electrode (suppression of continuous discharge)

- Multi-gap Resistive Plate Chamber (MRPC):
  Extension to multi-gap device
  with floating inner plates

Examples

- ALICE TOF

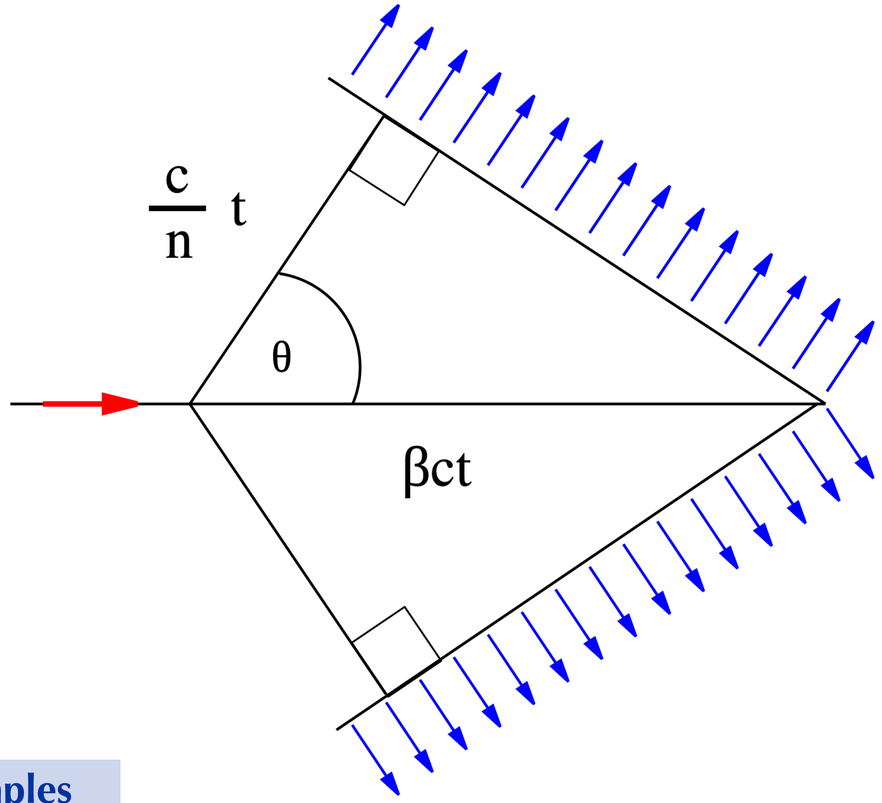




Cherenkov radiation

- Cherenkov effect
  → **emission of light by particles above speed of light**
  - emission under characteristic angle
  - spectrum

- **Applications**
  - timing
  - threshold
  - RICH
  - DIRC



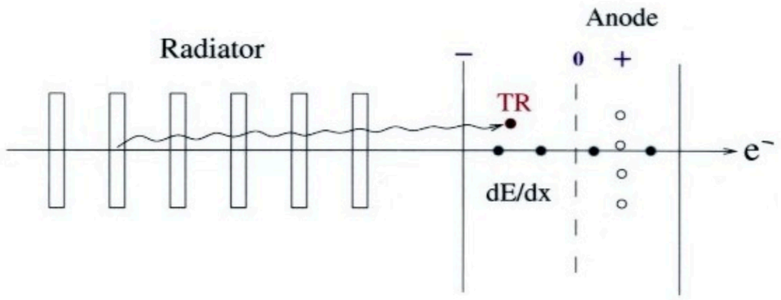
Examples

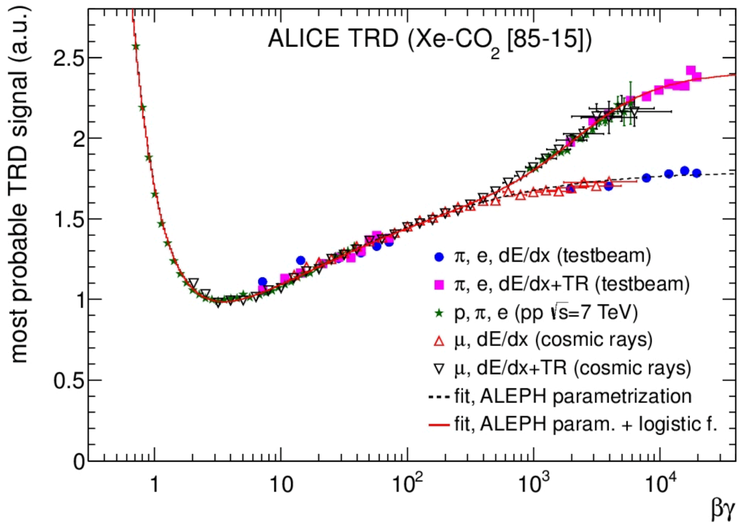
- LHCb RICH

Transition Radiation

- **Generation of real photons**
  when highly-relativistic charged particle traverses boundary between two dielectrics
  - onset for $\gamma \approx 1000$
  - photons typically in UV range

- **At accelerator energies only relevant for electrons**
  → electron identification
  - demonstration with highly energetic muons from cosmic rays





Examples

- ATLAS TRT
- ALICE TRD

Electromagnetic showers
→ interactions of
electrons and photons

Bremsstrahlung

- **Accelerated charge** radiates bremsstrahlung (mostly relevant for electrons)
  - interaction with field of nucleus
    $$\sigma_{\text{brems}} \propto \frac{Z^2\alpha^3}{(m_e c^2)^2}$$
  - energy spectrum approximately
    $$\frac{\mathrm{d}\sigma}{\mathrm{d}k} \approx \frac{A}{X_0 N_A}\frac{1}{k}\left(\frac{4}{3} - \frac{4}{3}y + y^2\right) \text{ with } y = k/E$$

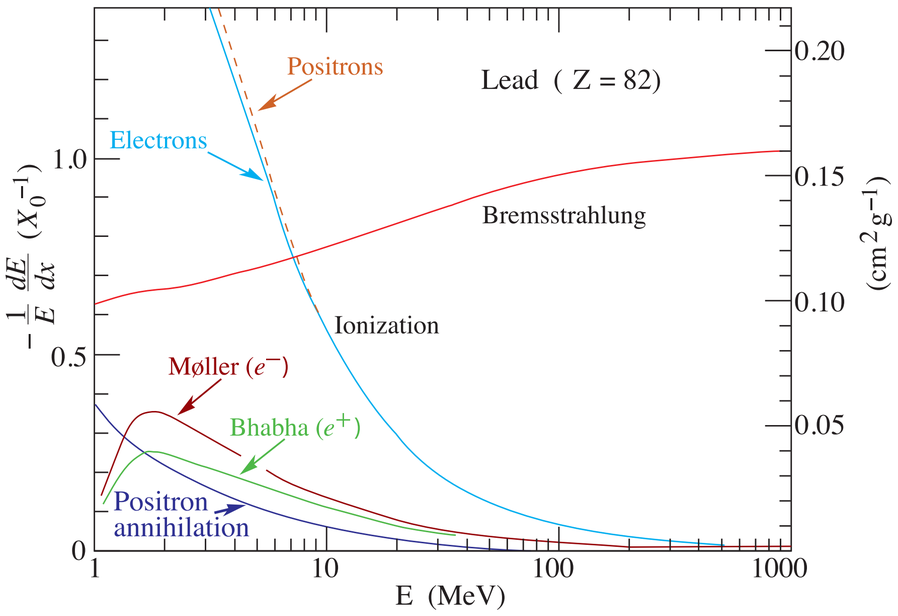
- **Radiation length X_0** to characterise energy loss
  $E(x) = E_0 \exp(-x/X_0)$

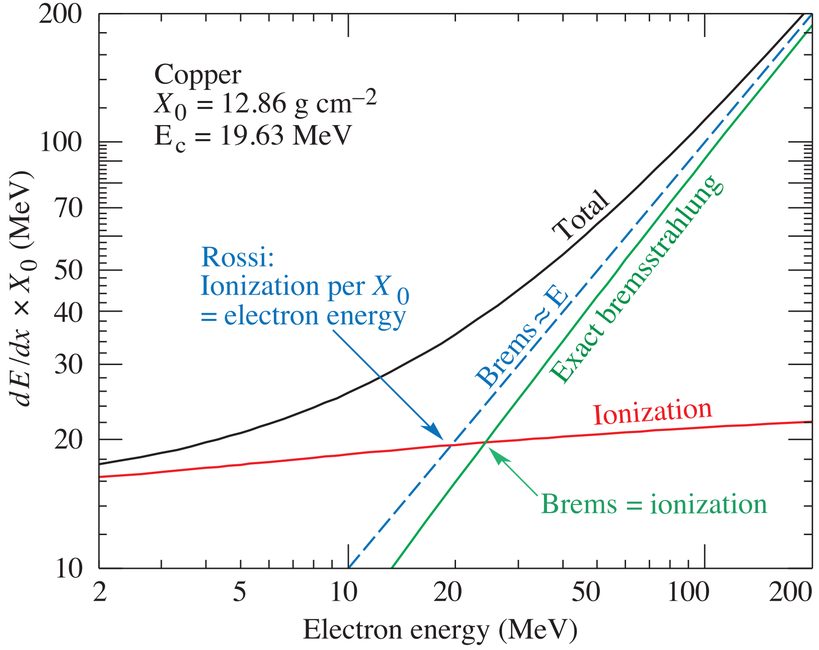
Energy loss of e±

- Contributions from
  - ionisation (Bethe Bloch)
  - bremsstrahlung (∝ -E/X_0)

- At **critical energy** transition from dominance of ionisation and bremsstrahlung

$$E_c \approx \frac{580}{Z} \text{ MeV (for electrons and Z > 13)}$$





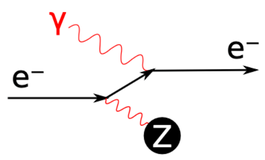
Interactions of photons

- **Absorption** (elimination of photon) instead of energy loss
  → Lambert-Beer law for attenuation (exponential)

- **Mechanisms** (increasingly important with increasing energy)
  - photo effect
  - Compton scattering (incoherent)
  - pair production (in nuclear field)

- **Neglected effects**
  - Rayleigh scattering (coherent)
  - photo-nuclear absorption
  - pair production (in electron field)

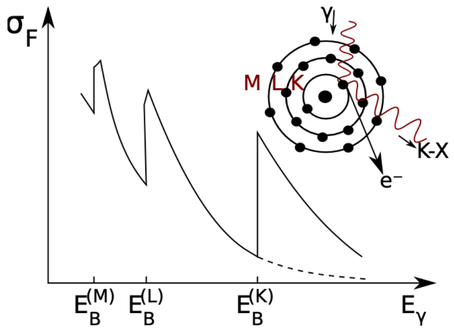
Photo effect



- **ionisation of atom** γ + X → X + e-
  - cross section with strong Z dependence

$$\sigma_{\mathrm{ph}} = \alpha \pi a_b Z^5 \left(\frac{I_0}{E_\gamma} \right)^{\frac{7}{2}} \quad \text{with } I_0 = 13.6\,\mathrm{eV}, a_b = 0.53 \cdot 10^{-10}\,\mathrm{m}$$

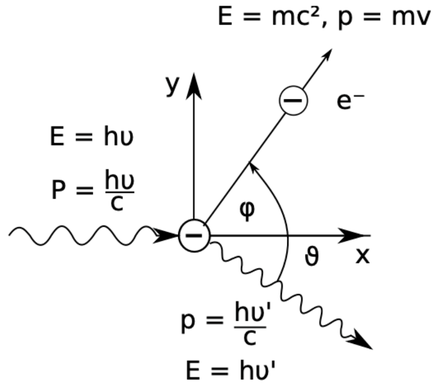
  - **characteristic edges** from shell structure

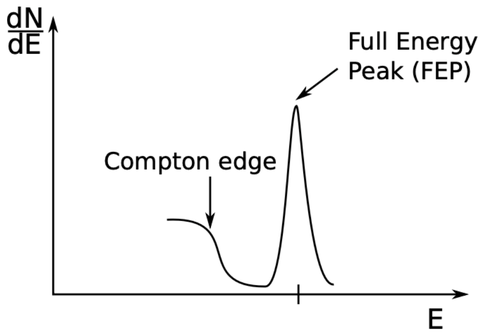


- subsequently, de-excitation with emission of
  - **X-ray photon**
  - **Auger electron**

Compton scattering

- **Scattering of photon off quasi-free electron**
  - extension of Thomson scattering
    $$\sigma_{\mathrm{Th}} = \frac{8\pi}{3} r_e^2$$
    to higher energies (Klein-Nishina)
  - kinematics limits energy transfer
    → Compton edge
  - strongly forward peaked for high energy photons





Pair production (Bethe Heitler)

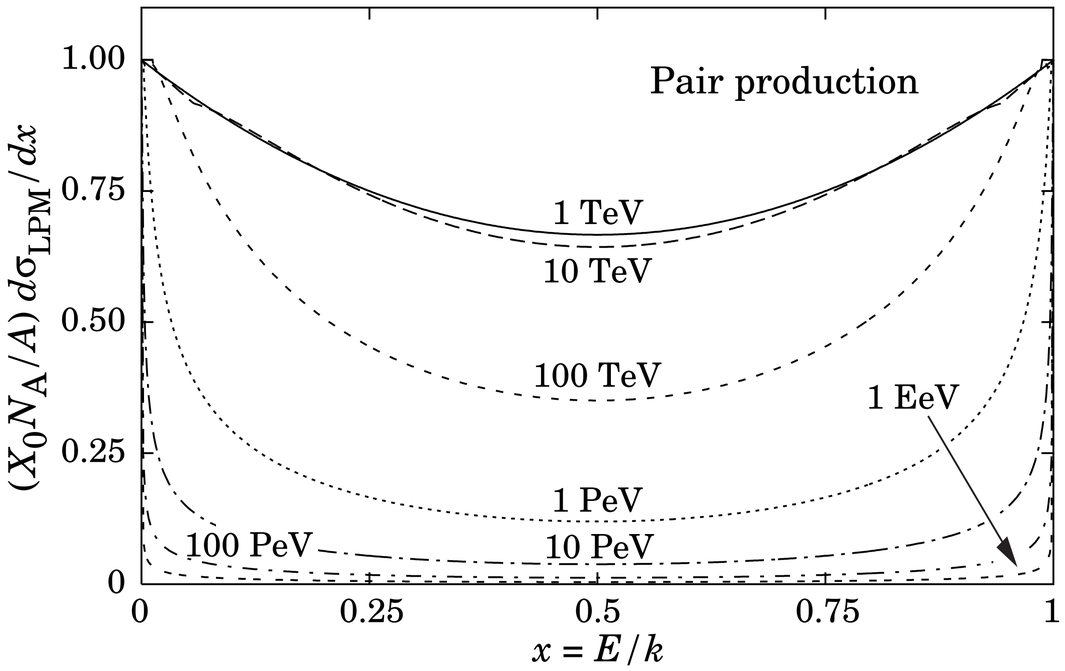
- **Production of e^+e^- pair** from photon
  - requires scattering centre (nucleus) for recoil
  - cross section described by

$$\sigma_{\text{pair}} = 4Z^2\alpha r_e^2\left(\frac{7}{9}\log\frac{183}{Z^{1/3}} - \frac{1}{54}\right)$$

$$\approx \frac{7}{9}\underbrace{4\alpha r_e^2 Z^2 \log\frac{183}{Z^{1/3}}}_{=(A/N_A)X_0}$$

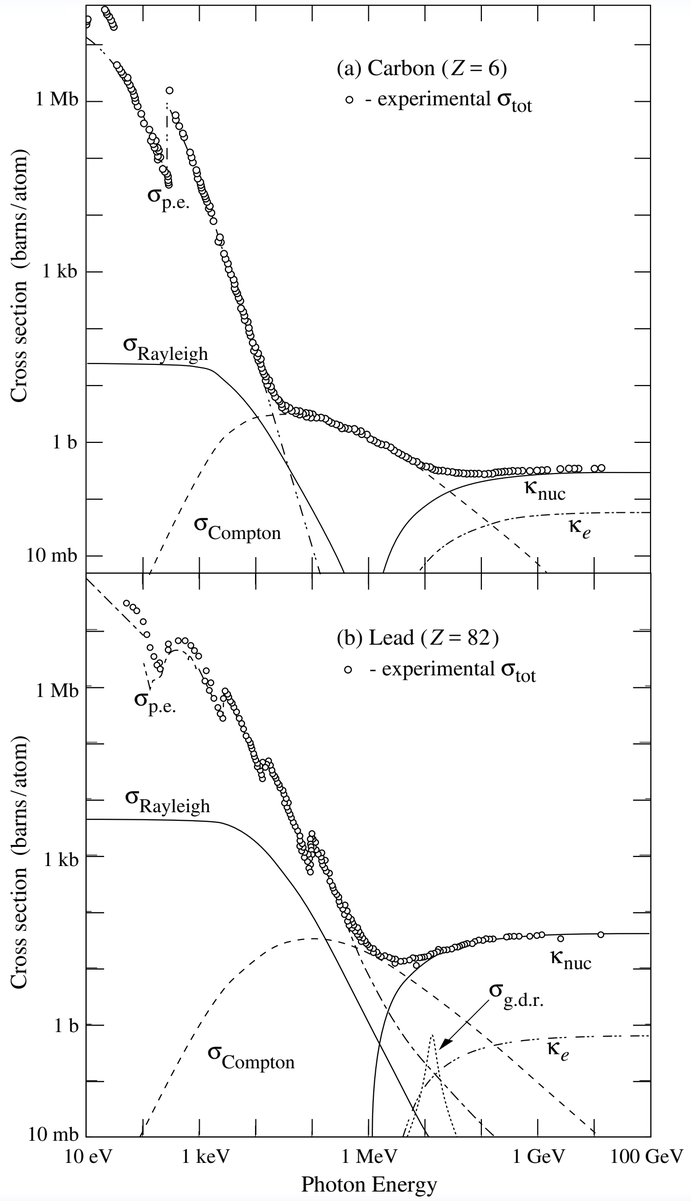
with radiation length X_0

  - asymmetric energy sharing favoured



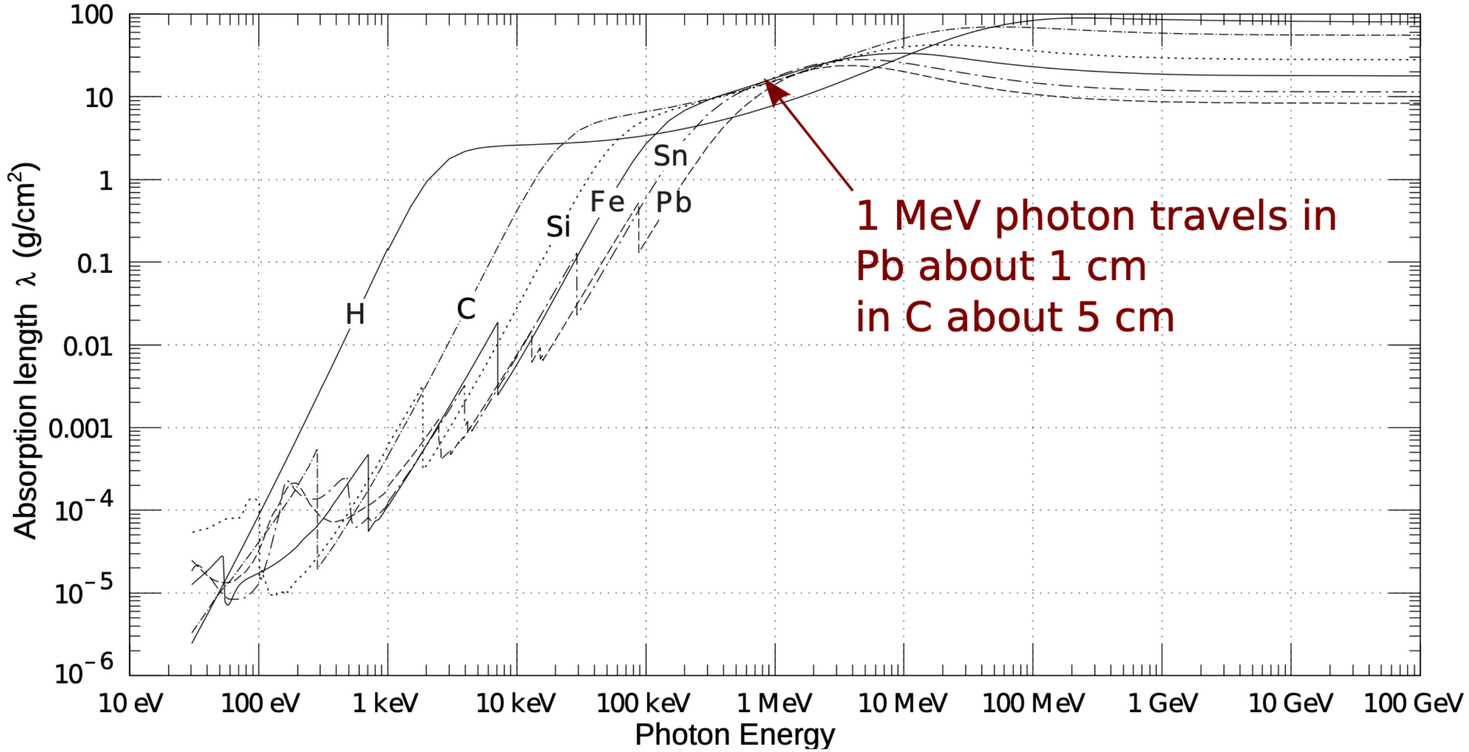
Photon interactions

- **Different effects** dominate depending on energy (in order of increasing relevance with higher energy)
  - photo effect
  - Compton scattering (incoherent)
  - pair production (in nuclear field)
- **Sub-dominant effects**
  - Rayleigh scattering (coherent)
  - photo-nuclear absorption
  - pair production (in electron field)



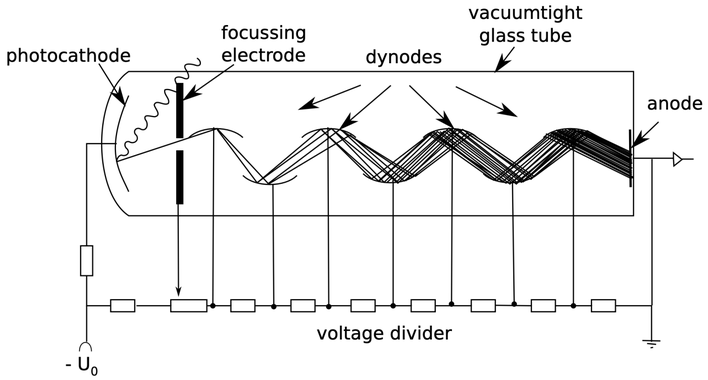
Photon mass attenuation length

- Photon absorption described by absorption length λ (independent of density)
  - multiply by density to obtain absolute length $L = \lambda \cdot \rho$

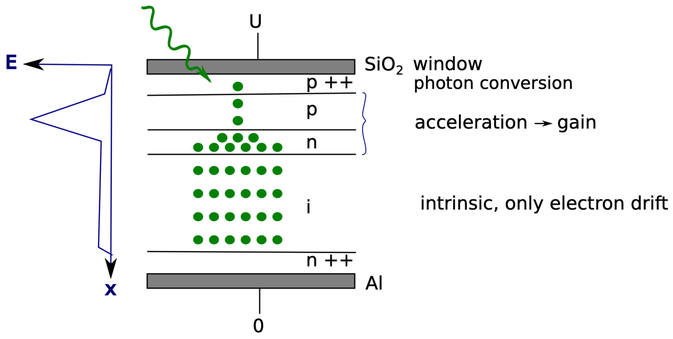


Photon detectors

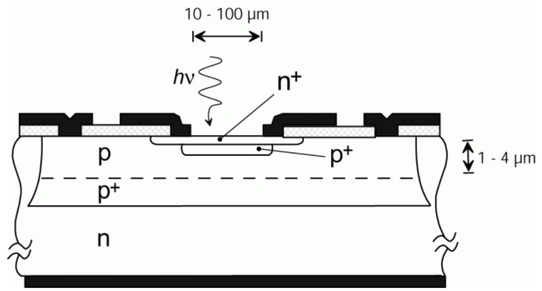
- **PhotoMultiplier Tube (PMT)**
  - amplify electrons from photo effect
  - classic detector, still actively used
  - difficult to operate in B field



- **Avalanche Photo Diode (APD)**
  - amplify charge carriers in amplification layer

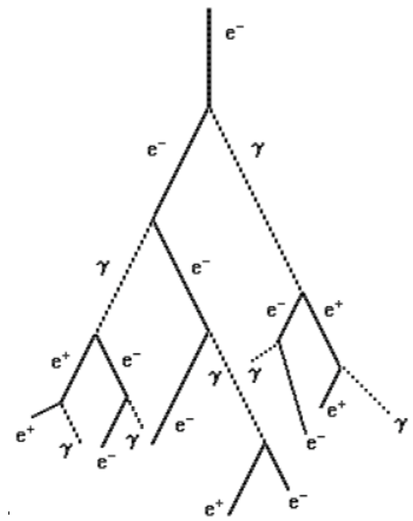


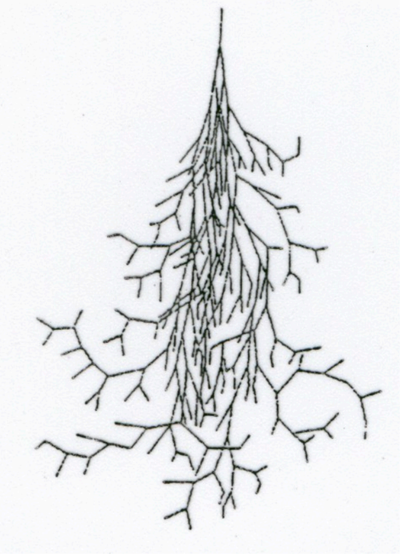
- **Single Photon Avalanche Diode (SPAD)**
  - strong gain (break-down, quenching)
    → sensitive to single photons
  - Silicon Photo Multiplier (SiPM)
    → array of SPADs



Electromagnetic showers

- Cascade of
  - bremsstrahlung $e^{\pm}$ (+ X)→ $e^{\pm}$ (+X) + γ
  - pair production (γ → e^{+} + e^{-})
- Shower modelling
  - $E < E_c$: only ionisation
  - $E > E_c$: only radiation





Longitudinal shower evolution

- **Number of particles** in units of radiation lengths ($t := x/X_0$)

$$N(t) = 2^t,\ E(t) = \frac{E_0}{2^t} \Rightarrow t = \ln\frac{E_0}{E}/\ln 2$$

$$N(E_0, E_1) = 2^{t_1} = 2^{\ln\frac{E_0}{E}/\ln 2} \approx \frac{E_0}{E_1}$$

- **Shower maximum**

$$t_{\text{max}} \approx \ln\frac{E_0}{E_c} \text{ and } N(E_0, E_c) \approx E_0/E_c \propto E_0$$

- **Integrated track length** proportional to energy

$$T = X_0 \sum_{\mu=1}^{t_max} 2^\mu + t_0 \cdot N_max = (4 + t_0)\frac{E_0}{E_c}X_0 \propto E_0$$

Transverse shower evolution

- **Transverse shower development**
  dominated by multiple scattering of electrons (Molière theory)

$$\langle \vartheta^2 \rangle = \left(\frac{21.2\,\mathrm{MeV}^2}{\beta p c} \right) t$$

- **Molière radius**

$$R_\mathrm{M} = \vartheta_\mathrm{rms}\,|_{x=X_0} \approx \frac{21\,\mathrm{MeV}}{E_c} X_0$$

Material properties

material	Z	E_c (MeV)	X_0 (cm)	R_M (cm)
Ar (liq)	18	35	13.9	9.5
Fe	26	21	1.76	1.77
BGO		10	1.12	2.33
Pb	82	7.4	0.56	1.60
U	92	6.8	0.32	1.00

Critical energy $E_c \propto \frac{1}{Z}$

Radiation length $X_0 \propto \frac{180A}{Z^2}(\mathrm{g\ cm^{-2}})$

Molière radius $R_M \approx \frac{19.2\,\mathrm{MeV}}{E_c} X_0 \propto \frac{1}{Z}$

Calorimeters

- Exploit electromagnetic shower to measure energy
  - **homogeneous calorimeter**
    shower material also detection material
  - **sampling calorimeter**
    separate materials for shower and detection

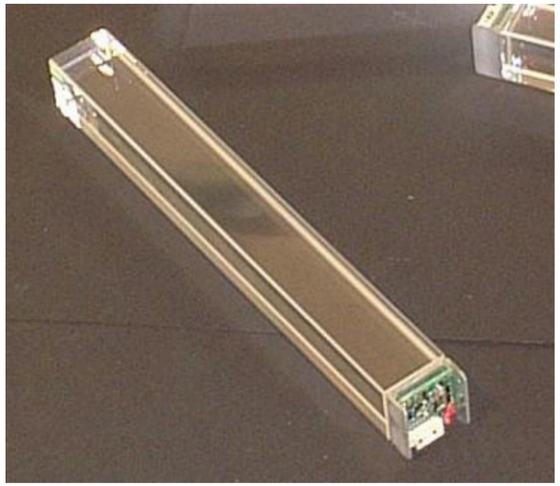
- Performance characterised by **energy resolution** given by
  $$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$
  with contributions from shower fluctuations (A), electronic noise (B), leakage (C)

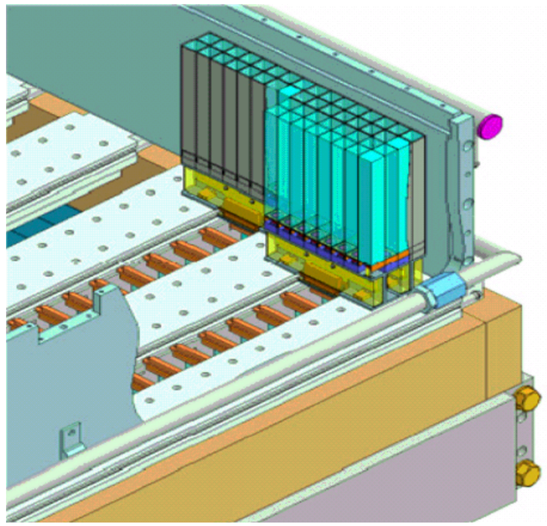
- **Performance improves with energy**
  - cf. momentum resolution from tracking deteriorating with p

Homogeneous calorimeter

- Requires a material serving as absorber and detector
  → **scintillating crystals**, e.g. $PbWO_4$

- **Properties**
  - dense material → compact detector
  - fast detector response
  - full sampling of shower → good energy resolution
  - low light yield, better at low temperatures → cooling
  - crystals are complex to grow → expensive





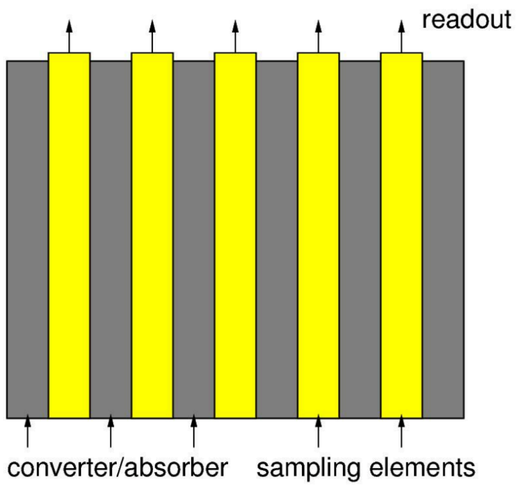
Examples

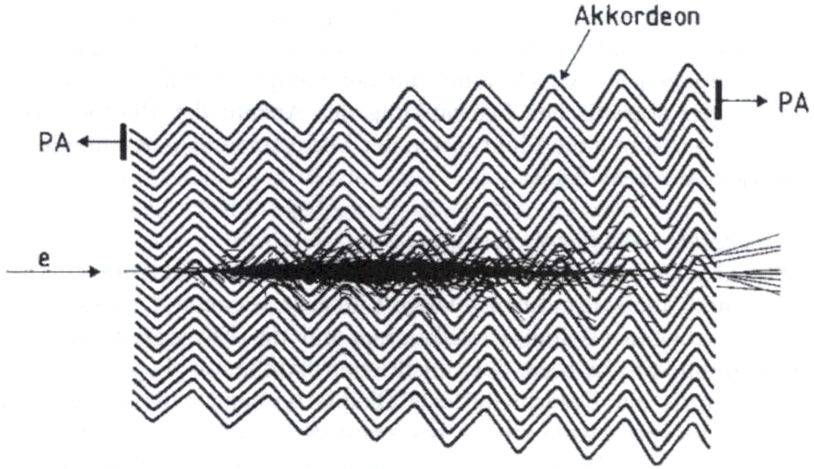
- ALICE PHOS
- CMS crystal calo

Sampling calorimeter

- Combination of
  - dense converter material,
    e.g. Pb, W, U, Fe
  - convenient detection material,
    e.g. plastic scintillators, liquid argon, …

- **Properties**
  - materials readily available
    → cost effective and scalable
  - sampling fluctuations
    → reduced energy resolution





ATLAS LAr calorimeter:
liquid Argon used for operation as ionisation chambers

Examples

- ATLAS LAr calo
- ALICE ECal
  (Pb + scintillator)

Hadronic interactions
→ hadronic showers

Hadronic interactions

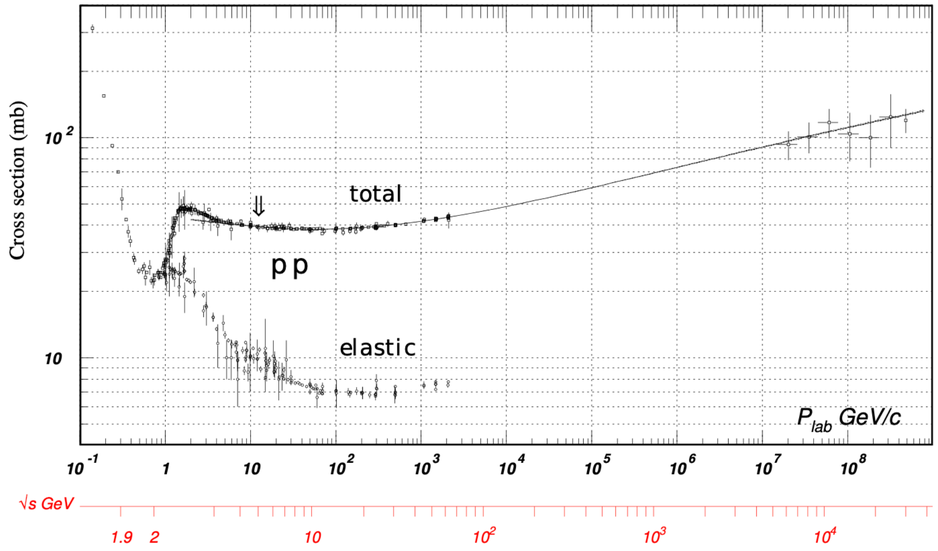
- **Interaction of hadron with nucleon or nucleus** (E > 1 GeV)
  - elastic (about 10 mb)
  - inelastic p + N → X (dominant)

    $\sigma_{\text{tot}}(\text{pA}) \approx \sigma_{\text{tot}}(\text{pp}) \cdot A^{\frac{2}{3}}$

- **Hadronic interaction length**

$$\lambda = \frac{A}{N_{\text{A}}\,\rho\,\sigma_{\text{inel}}} \propto 35 \cdot A^{\frac{1}{3}} (\text{g cm}^{-2})$$

for $Z \geq 15$ and $\sqrt{s} \approx 1 - 100\,\text{GeV}$



material	λ (cm)	X_0 (cm)
C	38.8	19.3
Ar (liq)	85.7	14.0
Fe	16.8	1.76
U	11.0	0.32
scintillator	79.5	42.4

hadronic interaction length much larger than elm. radiation length

Hadronic shower

- **Hadronic shower emerges from sequential inelastic scatterings**
  - inelastic scatterings, e.g. $p + N \rightarrow \pi^+ + \pi^- + \pi^0 + \ldots + N^*$
  - further scatterings of secondary particles
    down to pion production threshold, NB: much higher than E_c
  - sequential decays of produced particles
  - average number of secondary particles proportional to log E
  - about half the energy in production of secondaries (on average)

- Part of energy remains invisible (strong fluctuations)

Hadronic calorimeters

- Much **more complex** than electromagnetic calorimeters
  - hadronic and electromagnetic components
  - fluctuating fraction of invisible energy
  - longer detectors needed
- Sampling calorimeter combining
  - passive absorber (Fe, Pb, U)
  - sampling elements (scintillators, …)

Examples

- CMS HCal

Additional methods

very brief overview

Muon detection

- **Unique signature**
  - electromagnetic interaction
  - no electromagnetic shower (because of mass)
  - no hadronic shower
- **Identification from**
  - behaviour in thick thick calorimeter
  - detection behind thick (hadron) absorber

Examples

- muon chambers

Unstable particles

- **Unstable particles incl. neutral ones, e.g. K^0, Λ, Ξ, Ω, …**
  can often be detected through their decay products
  - identification of decay daughters
  - reconstruction of decay vertices
  - reconstruction of invariant mass

Neutral particles

- No electromagnetic interaction
  → exploit effects **converting energy from neutral particles to charged particles**
  - neutrons → hadronic shower
  - neutrinos → detection of products from weak interactions
  - dark matter → open search

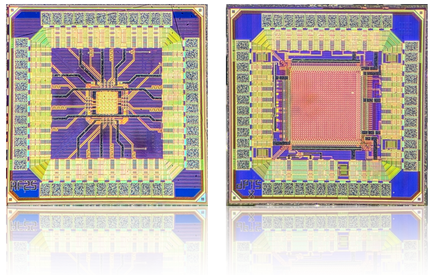
Detector R&D

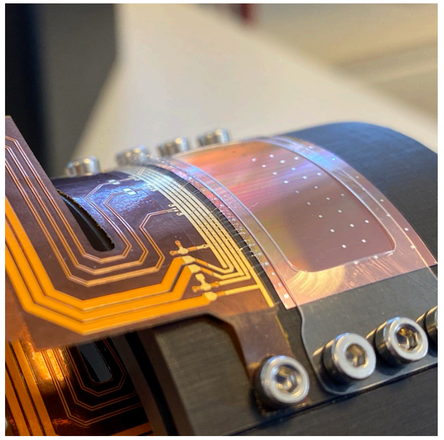
some examples

Silicon pixel sensors

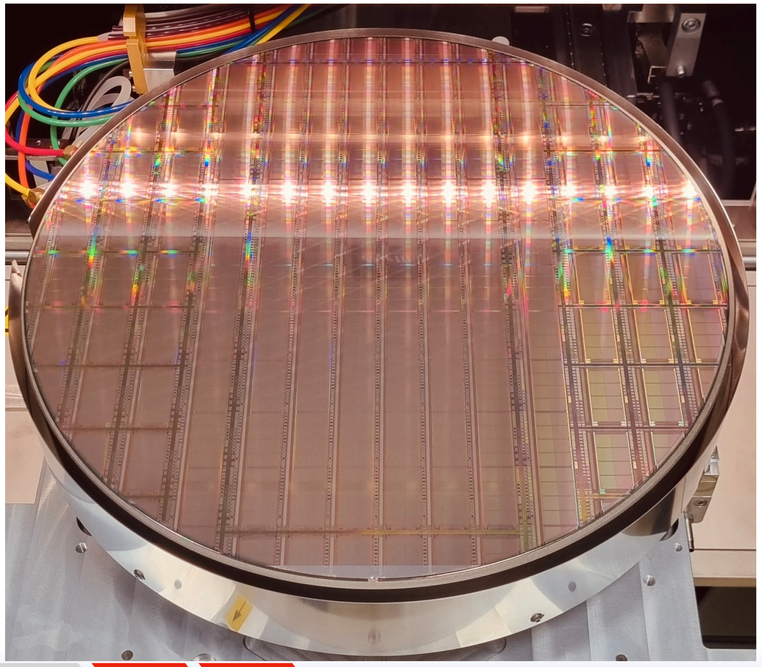
- **Established TPSCo 65 nm process for pixel sensors** (extensive R&D run with 55 different prototypes)
  - excellent performance, also after irradiation

APTS DPTS





- **Established bending of silicon sensors**
  - performance of ALPIDEs not affected at radii down to 1.8 cm
  - prototypes with wafer-scale silicon



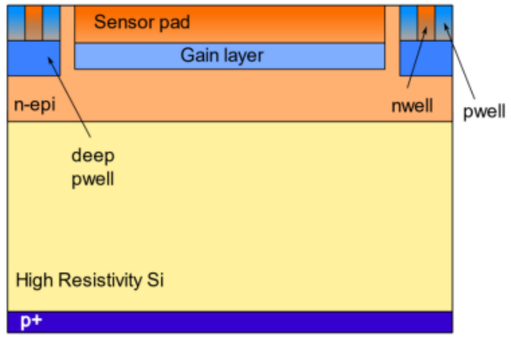
- **Developing wafer-scale sensors**
  - stitching of repeated sensor unit
  - first wafers from engineering run received

Excellent progress with ITS3 R&D
paving the way for ALICE 3

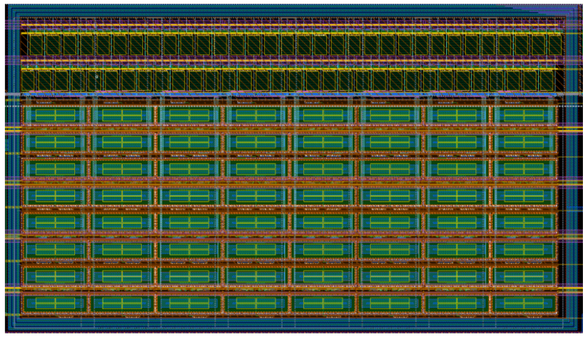
Silicon timing sensors

- **Monolithic timing sensor**
  - test gain layer
    in L-foundry process

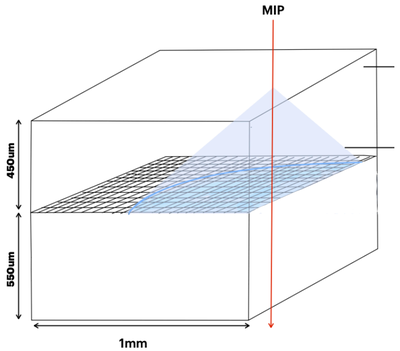
- Beam test of **SiPMs**
  for charged particle detection
  - Cherenkov radiation,
    here in protection layer
  - multiple hits
    → improve time resolution



Demonstrator submitted to L-foundry

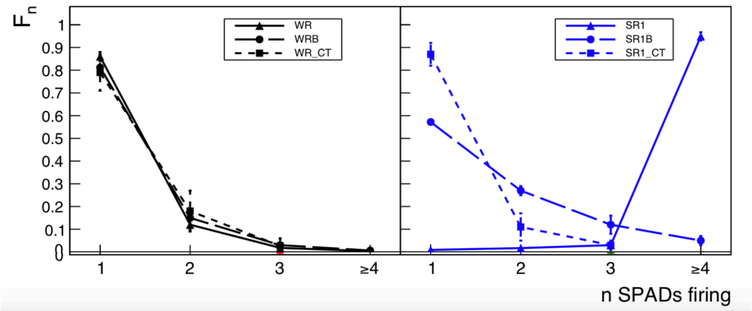


Delivered in January 2023



Cluster size distribution

No protection layer | With protection layer



With protection layer, front-side beam shows large clusters

Further R&D topics

- **European Strategy and CERN committed to reducing the consumption** of greenhouse gases in gaseous detectors, e.g. SF_6, $C_2H_2F_4$, CF_4
  - consolidation of gas systems and minimisation of losses
  - R&D towards alternative gases ongoing

- **Advances in 3d printing** allow production of detector components, e.g. for
  - precise production of metal **absorber for electromagnetic calorimeters**, incl. holes for wave-length shifting fibres
  - production of **scintillators** in (almost) arbitrary shapes

Experiments

ATLAS phase II upgrades

LAr calorimeter

- **Segmented super-cells:** shower-shape discrimination at trigger level

Trigger and DAQ

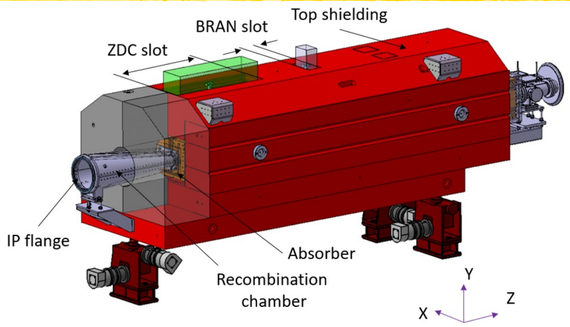
- L1 and HLT improvements
- Further upgrades

Electronics upgrades

Luminosity detectors

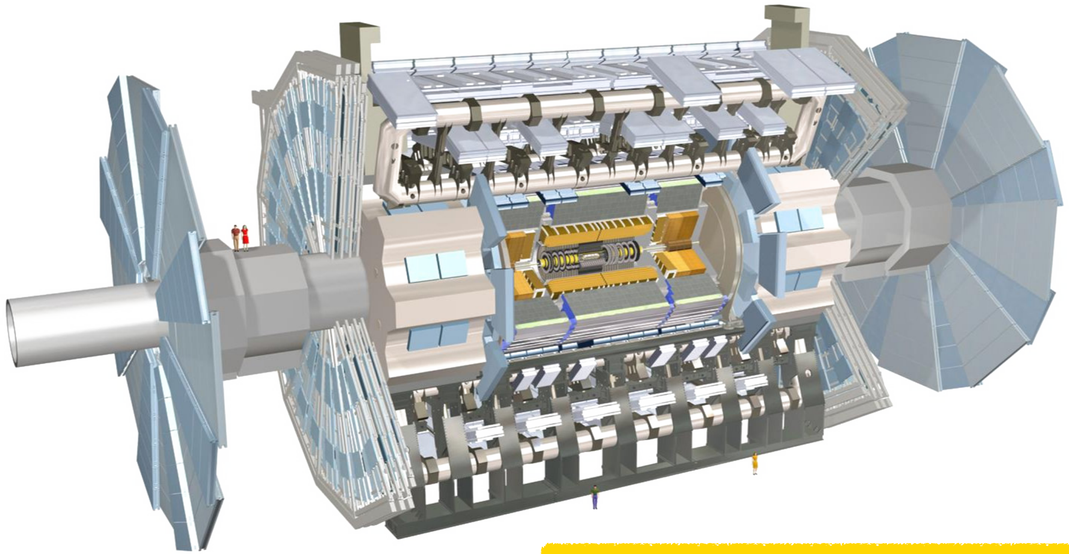
HL-ZDC

- JZCaP (jointly with CMS)
- adapt to new optics
- increase radiation hardness
- Reaction plane detector



High-granularity timing detector

- Based on LGADs
- PID with $\sigma_{TOF} \approx 35$ ps
- Baseline trigger for HI



New Inner Tracker (ITk)

- hybrid silicon pixel and strip sensors
- coverage up to $|\eta| < 4$

Endcap calorimeters

- higher granularity

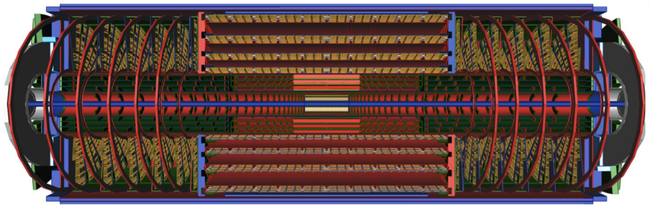
Muon system

- **New Small Wheels** installed → sTGC + MicroMegas
- **New muon chambers**

➟ **Extend tracker acceptance to $|\eta| < 4$**

➟ **Time-of-flight PID $2.5 < |\eta| < 4$**

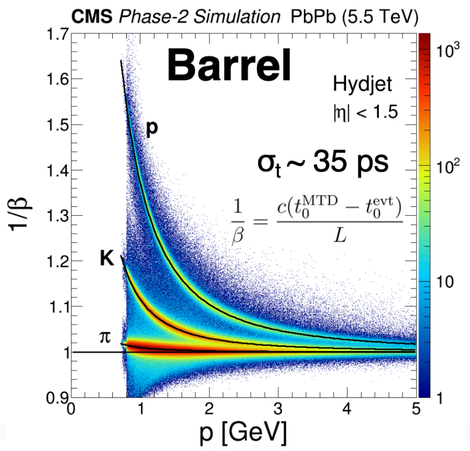
➟ **Endcap calorimeters with higher granularity**



CMS phase II upgrades

MIP timing detector

- barrel: LYSO + SiPMs
- endcaps: LGADs
- $\sigma_{TOF} \approx 30$ ps



Tracker

- inner: hybrid silicon pixels
- outer: hybrid silicon pixels + strips

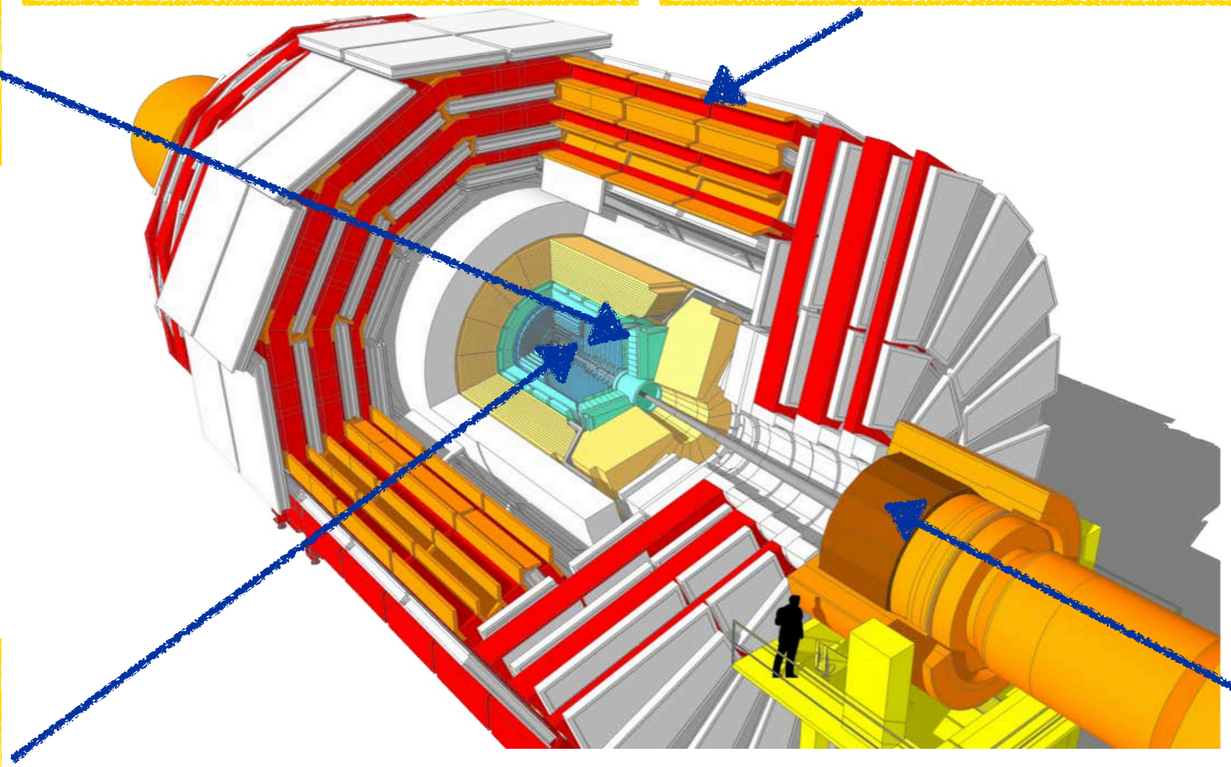
HCal

- HPD → SiPMs

L1 trigger, HLT, DAQ

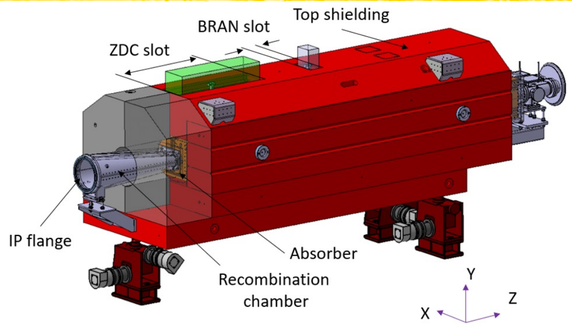
Luminosity detectors

New readout for muon system



HL-ZDC

- JZCaP (jointly with CMS)
- adapt to new optics
- increase radiation hardness
- Reaction plane detector



Endcap calorimeter

- **High-granular ECal + HCal → 4d showers ($\sigma_t \approx 20$ ps)**

- **Charged particle tracking up to |η| < 4, muons up to |η| < 3**
- **Time-of-flight PID up to |η| < 3**
- **High-precision vertexing**
- **Wide coverage calorimetry**

Forward muon system

- All GEM chambers
- new frontend electronics for CSC endcaps

[CERN-LHCC-2021-012]

LHCC review of Framework TDR completed in March 2022

LHCb Upgrade II

RICH

- RICH1 and RICH2
- precision timing

TORCH

- Time-of-flight wall
- precision timing

Run 5 infrastructure

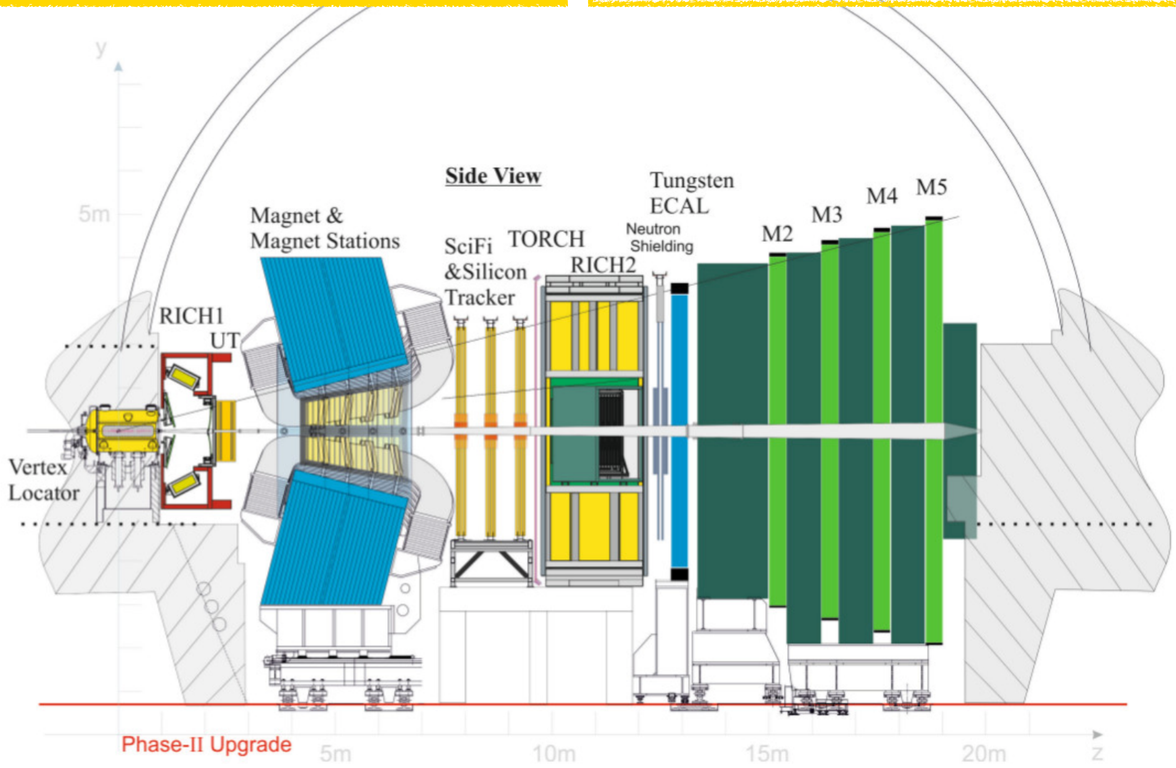
- engineering, mechanical support, shielding

Muon stations

- M2 - M5
- additional shielding (instead of HCal)

Vertex Locator

- new VELO
- precision timing



Tracking

- new Upstream Tracker (timing)
- Mighty Tracker (SciFi + silicon)
- Magnet stations (possibly)
  → p_T below 5 GeV/c

Fixed target

- possible extension with polarised gas target, solid target

Calorimeters

- SPACAL or Shashlik
- precision timing

➟ **No centrality limitation for AA**

➟ **Excellent vertexing capabilities**

[CERN-LHCC-2022-009]

LHCC review of Letter of Intent completed March 2022

ALICE 3 upgrade

Vertex detector

- Retractable detector $R_{in} \approx 5$ mm
- Wafer-scale monolithic CMOS sensors

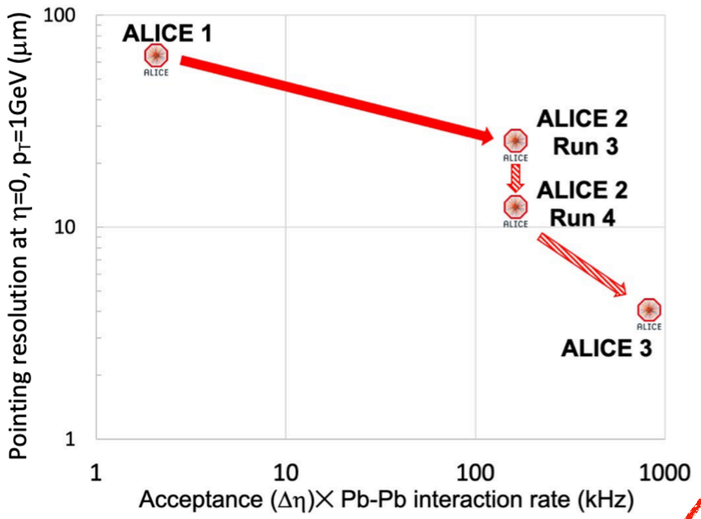
Tracker

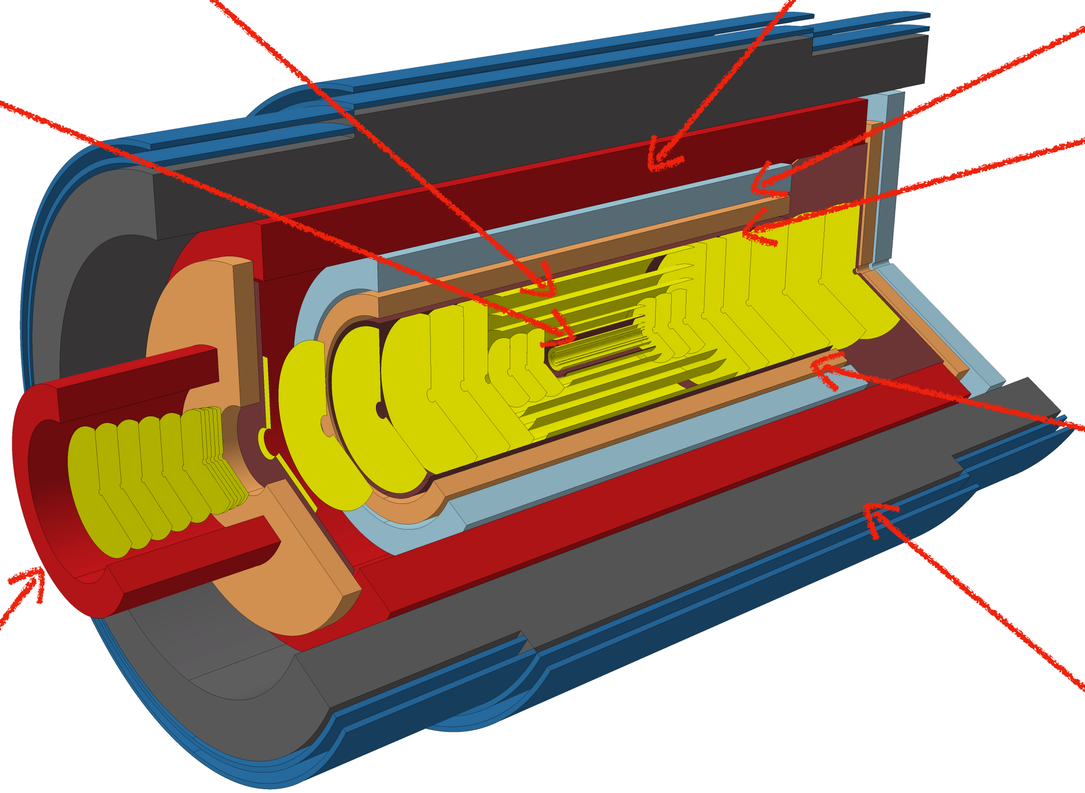
- Monolithic CMOS sensors

Superconducting magnet system

Elm. calorimeter

- PbWO4 in central region
- Pb/Sci for large acceptance





Time-of-flight detector

- monolithic CMOS sensors with gain layer

Ring-imaging Cherenkov detector

- Aerogel radiator
- SiPM read-out

Muon ID

- Iron absorber
- Scintillating bars, WLS, SiPM

Forward Conversion Tracker

- Tracking disks (MAPS)

➡ **Tracking and PID over large acceptance**

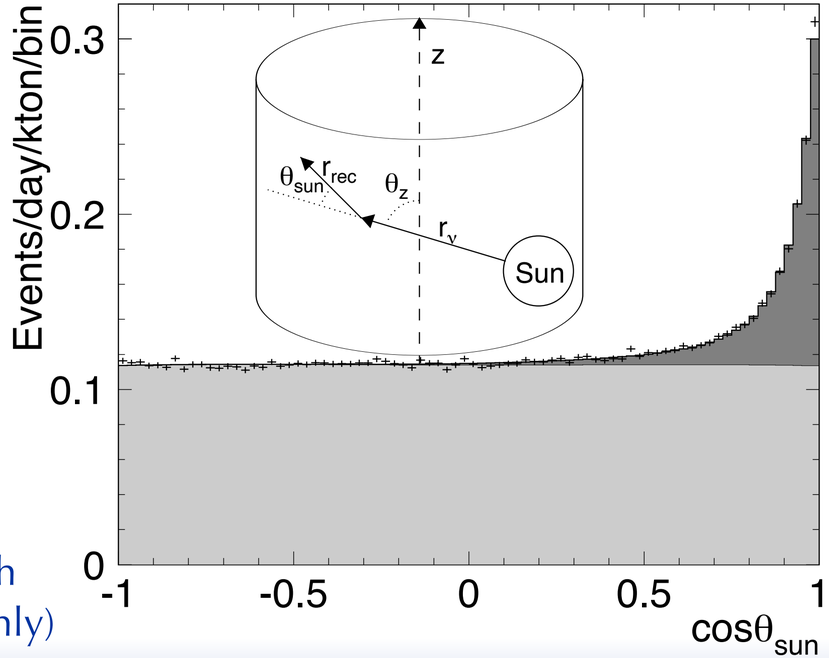
➡ **Excellent vertexing**

➡ **Continuous readout**

(Super-)Kamiokande

Kamioka Nucleon Decay Experiment

- **Physics goals**
  - proton decay
  - solar neutrinos (ne O(MeV))
  - neutrinos from super-novae
- **Detector concept**
  - 50 million litre water tank,
    1.6 km under ground
  - neutrino detection through Cherenkov radiation
    e and μ (bkg) distinguishable through ring sharpness

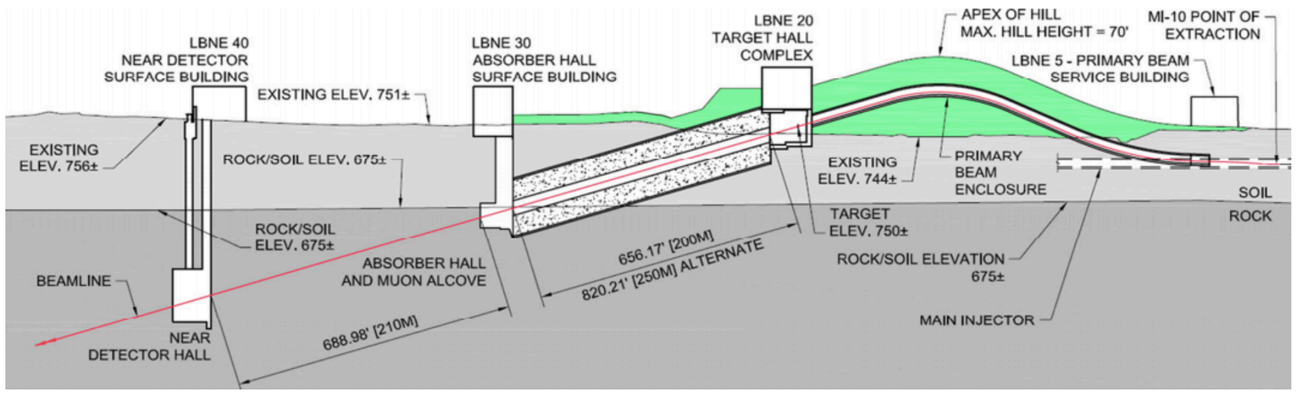


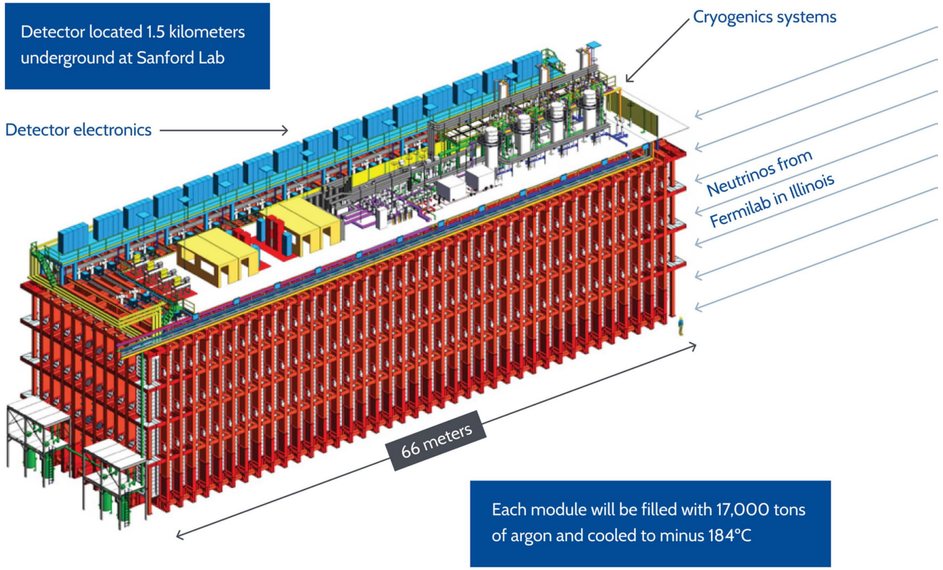
$\nu + e \rightarrow \nu + e$ (elastic scattering) with contributions from NC and CC (ν_e only)

DUNE

Deep Underground Neutrino Experiment

- **Physics goals**
  - neutrino oscillations
  - determination of mass hierarchy
  - super-novae
  - proton decay
- **Detector concept**
  - LArTPC (70 kt in 4 modules) incl. photon detection system
  - R&D: wavelength shifting through Xe doping





Summary

- Particle detectors remain at the core of fundamental research
- Many interesting developments in R&D programmes
- Applications in major upgrade programmes and new experiments

Thank you for your attention!

References & further reading

- **PDG reviews**
  concise treatments of particle interaction in matter and particle detectors

- **Leo: Techniques for Nuclear and Particle Physics Experiments**
  a bit dated but a good reference

- **Kolanoski, Wermes: Particle Detectors**
  recent overview of particle detector

- **Riegler: CERN summer student lectures on Particle Detectors**
  more detailed lectures

- **Stachel: Lectures on Particle detectors**
  university course