Experimental techniques in high-energy nuclear and particle physics

"Dottorato di Ricerca in Ingegneria dell'Informazione"

LECTURE 4.

Interaction by particles in matter creates detector signal

Calorimetry

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Why do we need accelerators?

Accelerate and collide particles to high energies.

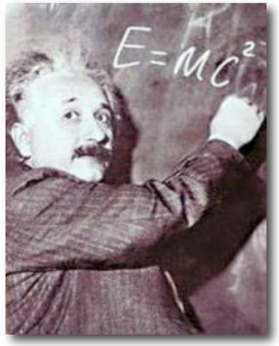
The higher energies allow us

i) To look deeper into matter ($E \propto 1/size$)
$\lambda = h/p$ ("powerful microscopes")

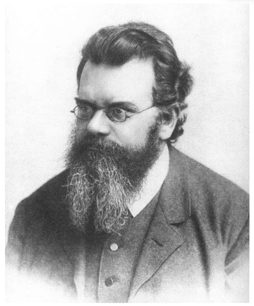
ii) To produce and study properties of new heavier particles ($E = mc^2$)

iii) To probe conditions of matter in the early universe ($E \approx kT$) $\Rightarrow$ Revisit the earlier moments of our "baby" universe ("powerful telescopes"), "looking back in time" to observe phenomena and particles normally no longer visible or existing in our time.

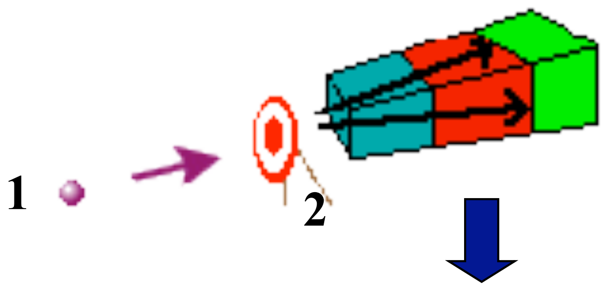
De Broglie



Einstein

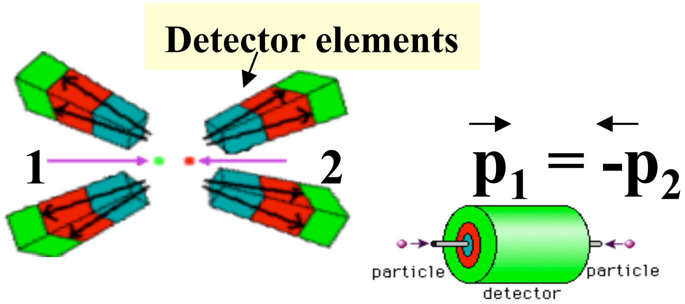


Boltzmann



$$\vec{p}_2 = 0$$

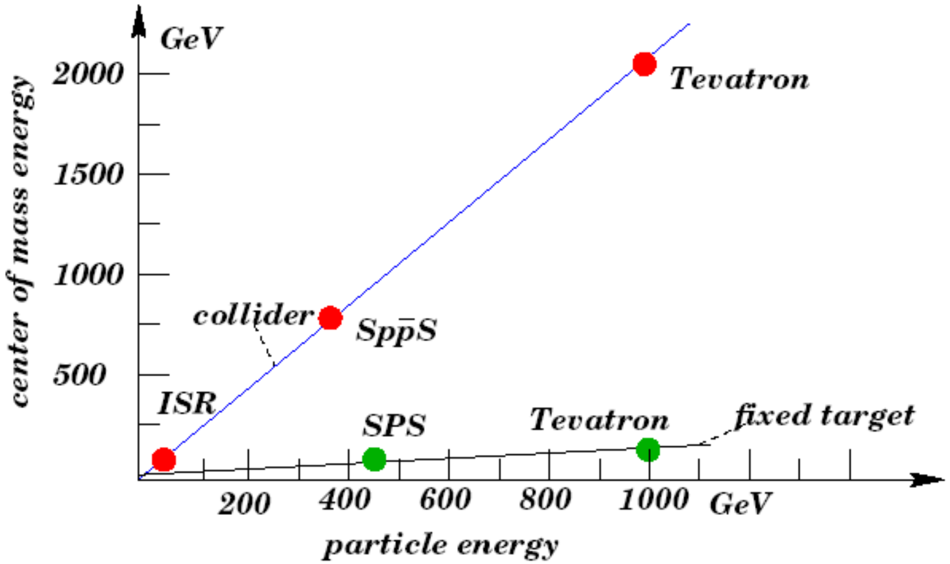
$$E_{CM} = \sqrt{2E_{beam}m_{target}}$$



$$\vec{p}_1 = -\overleftarrow{p}_2$$

$$E_{CM} = 2E_{beam}$$

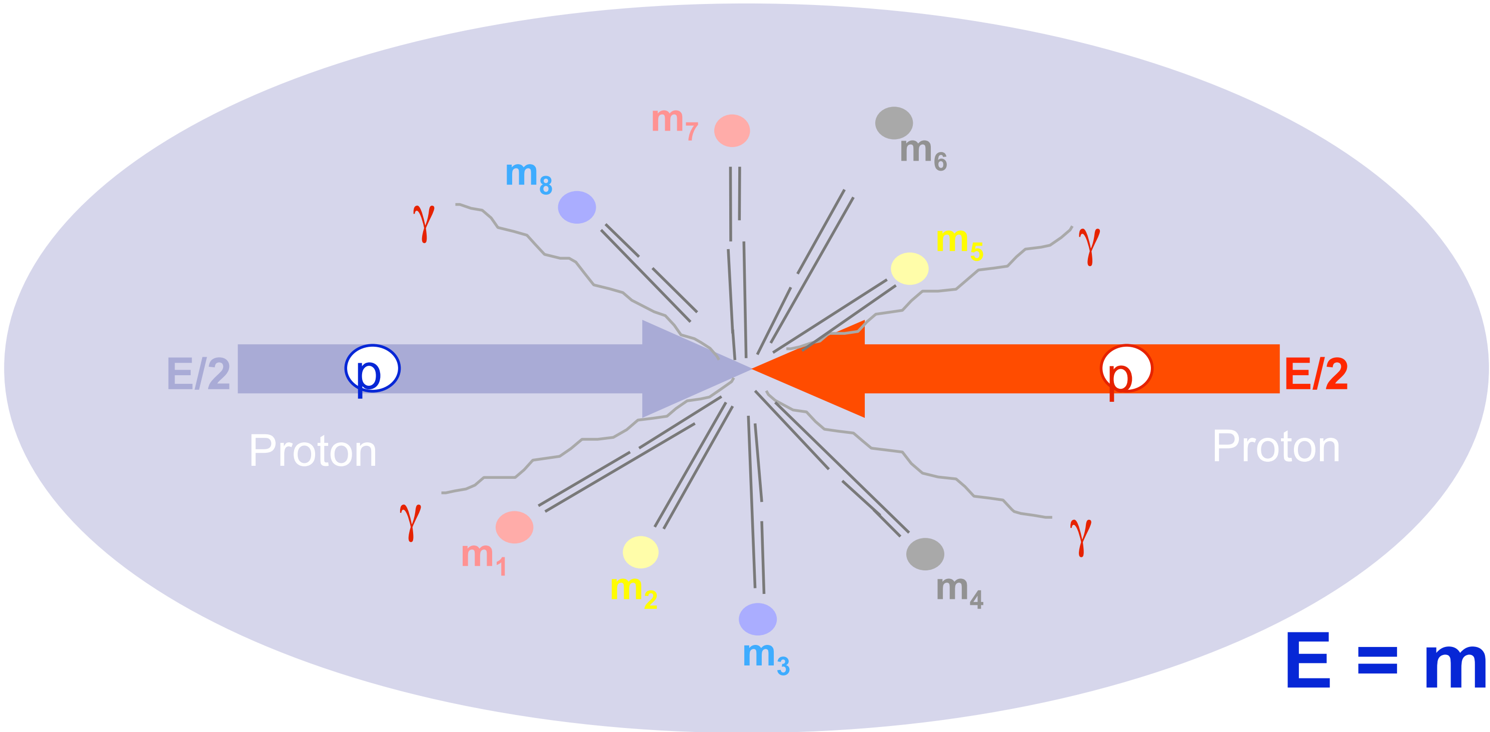
if $E_{beam1} = E_{beam2}$



1960 ↗ : *e^+ / e^- collider*

1970 ↗ : *p^+ / p^- collider*

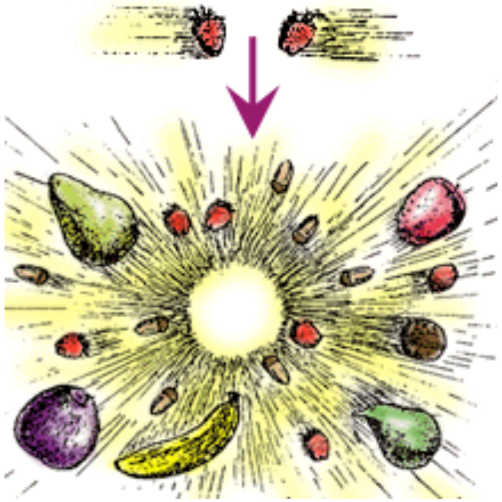
Particle accelerators

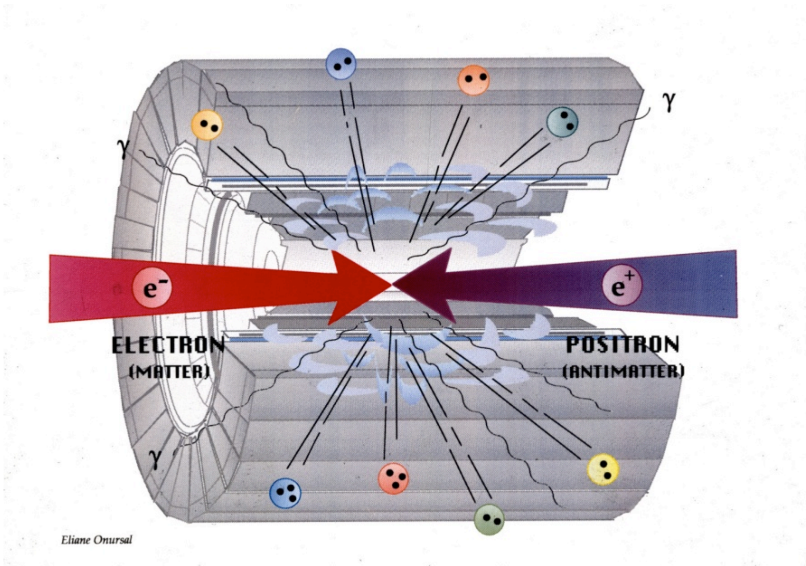


$E = mc^2$

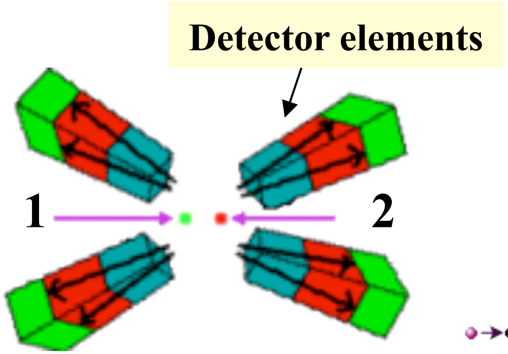
In an high energy collision many particles can be produced both of matter and antimatter

Collide

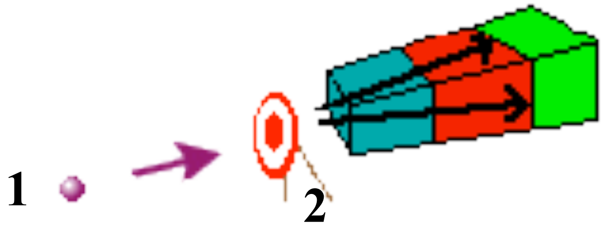



γ
γ
γ
e⁻
ELECTRON
(MATTER)
e⁺
POSITRON
(ANTIMATTER)
Eliane Onursal

Collide



$\vec{p}_1 = -\overleftarrow{p}_2$



$\vec{p}_2 = 0$

Goal : measure as many as possible of the resulting particles from the interaction.

$\Rightarrow$ put detector “around” the interaction point

Particles (stable or with long livetime) to be detected

- **Charged particles**
  - e^-, e^+, p (protons), $\pi^\pm$, $K^\pm$ (mesons), $\mu^\pm$ (muons)
- **Neutral particles**
  - γ (photons), n (neutrons), K^0 (mesons),
  - ν (neutrinos, very difficult)

- Different particle types interact differently with matter and these interactions can be used to detect and identify the various types of particle
  - need different types of detectors to measure different types of particles

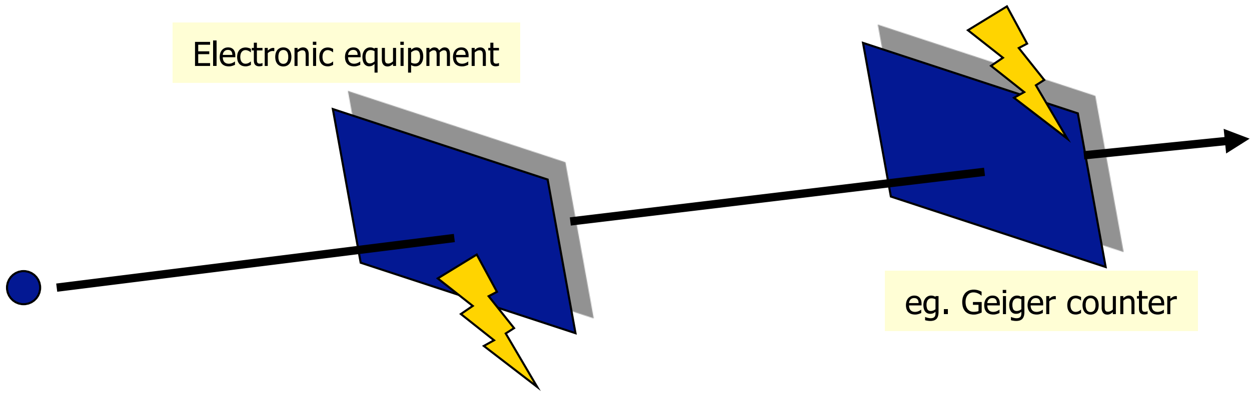
What to measure, why?

- If we have an *"ideal" detector*, we can **reconstruct** the interaction, ie. obtain all possible information on it. This is then compared to *theoretical predictions* and ultimately leads to a better understanding of the interaction/properties of particles

- "*Ideal detector"* measures
  - all produced particles
  - their energy, momentum
  - type (mass, charge, life time, spin, decays)

Measured quantities

- The creation/passage of a particle (--> type)



- Its four-momentum

$$\vec{p} = \begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix}$$

$$\begin{pmatrix} \text{Energy} \\ \text{momentum in x-dir} \\ \text{momentum in y-dir} \\ \text{momentum in z-dir} \end{pmatrix} = \begin{pmatrix} E \\ \vec{p} \end{pmatrix}$$

- Its velocity $\beta = v/c$

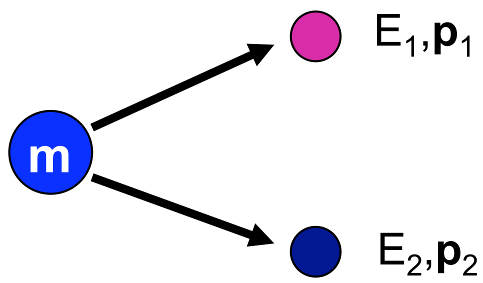
Derived properties

- Mass
  - in principle, if E and **p** measured: $E^2 = \mathbf{m}^2 c^4 + \mathbf{p}^2 c^2$

  - if v and **p** measured: $\mathbf{p} = \mathbf{m}\ v / \sqrt{(1 - \beta^2)}$

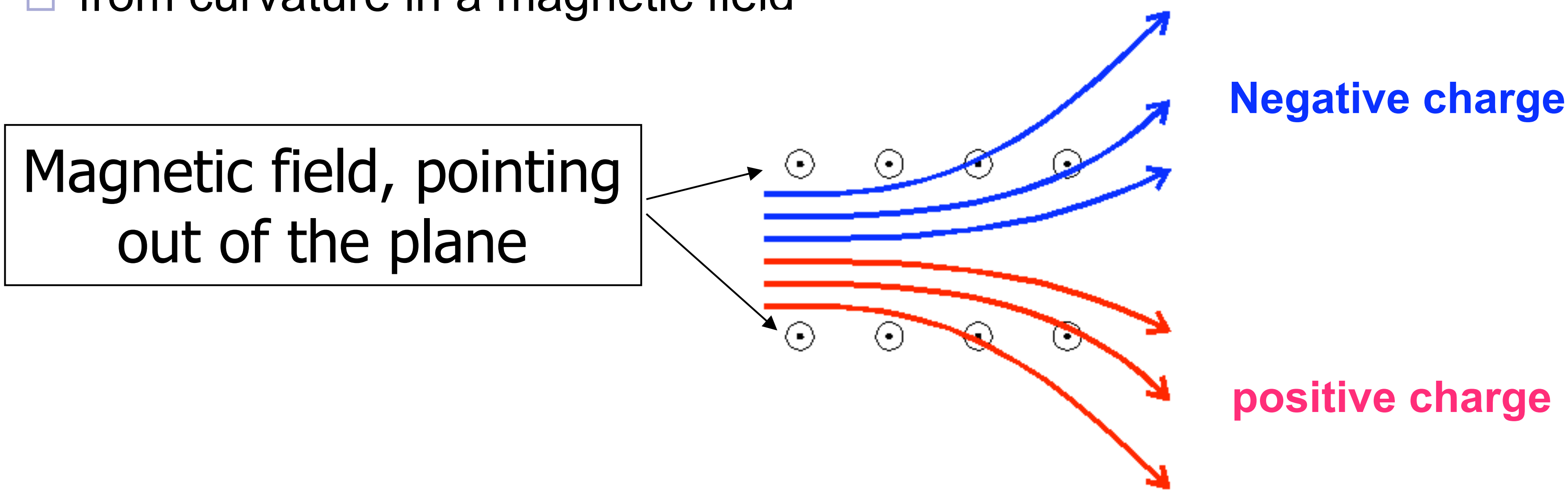
  - from E and **p** of decay products:

    $\mathbf{m}^2 c^4 = (E_1+E_2)^2 - (c\mathbf{p}_1 + c\mathbf{p}_2)^2$

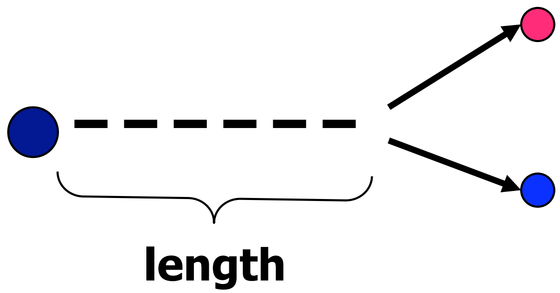


Further measurable properties...

- The charge (at least the sign...)
  - from curvature in a magnetic field



- The lifetime τ
  - from flight path before decay



Interactions of Charged Particles with Matter

The fact that particles interact with matter allows us to measure their properties, and reconstruct high energy interactions.

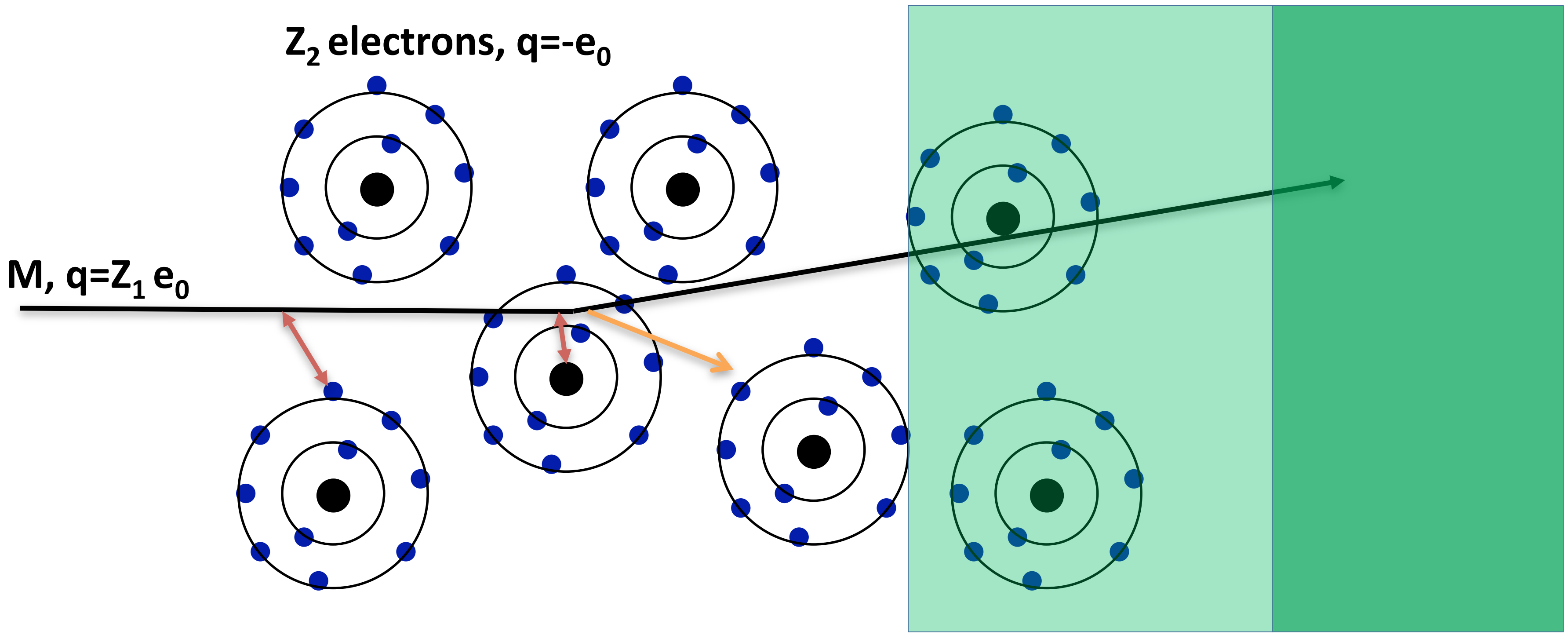
Dominant interaction is due to the electromagnetic force, or coulomb interactions.

Ionization and excitation of atomic electrons in matter are the most common processes.

Radiation can become important, particularly for electrons.

The nuclear interactions play significant role for hadrons in calorimetry measurements

Electromagnetic Interaction of Particles with Matter



Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

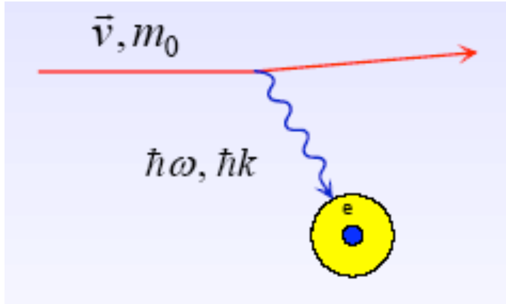
Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted.

In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called Transition radiation.

Principles of measurement
(ionization and exitation)

measureable signals occur via the interaction of charged particles with the detector material.

Dominant interaction is due to the coulomb interactions with the atomic *electrons* of the detector.

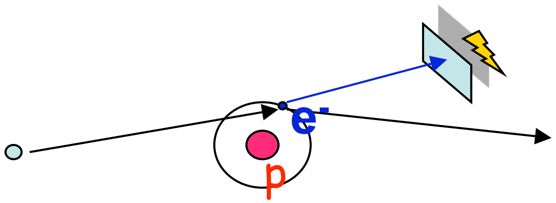


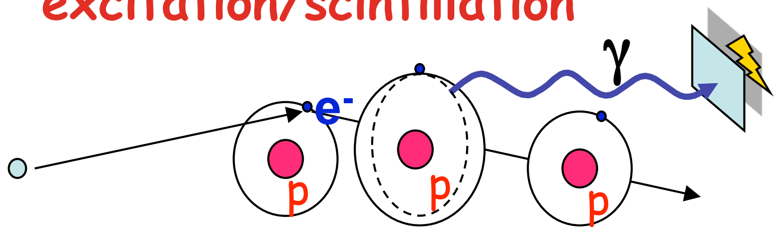
Depending on the $\hbar\omega$ value we may have:

- ionization

or

- excitation/scintillation





Ionization and excitation of atomic electrons in matter are the most common processes and allow to build precise tracking detectors .

Ionization: the Bethe-Bloch formula

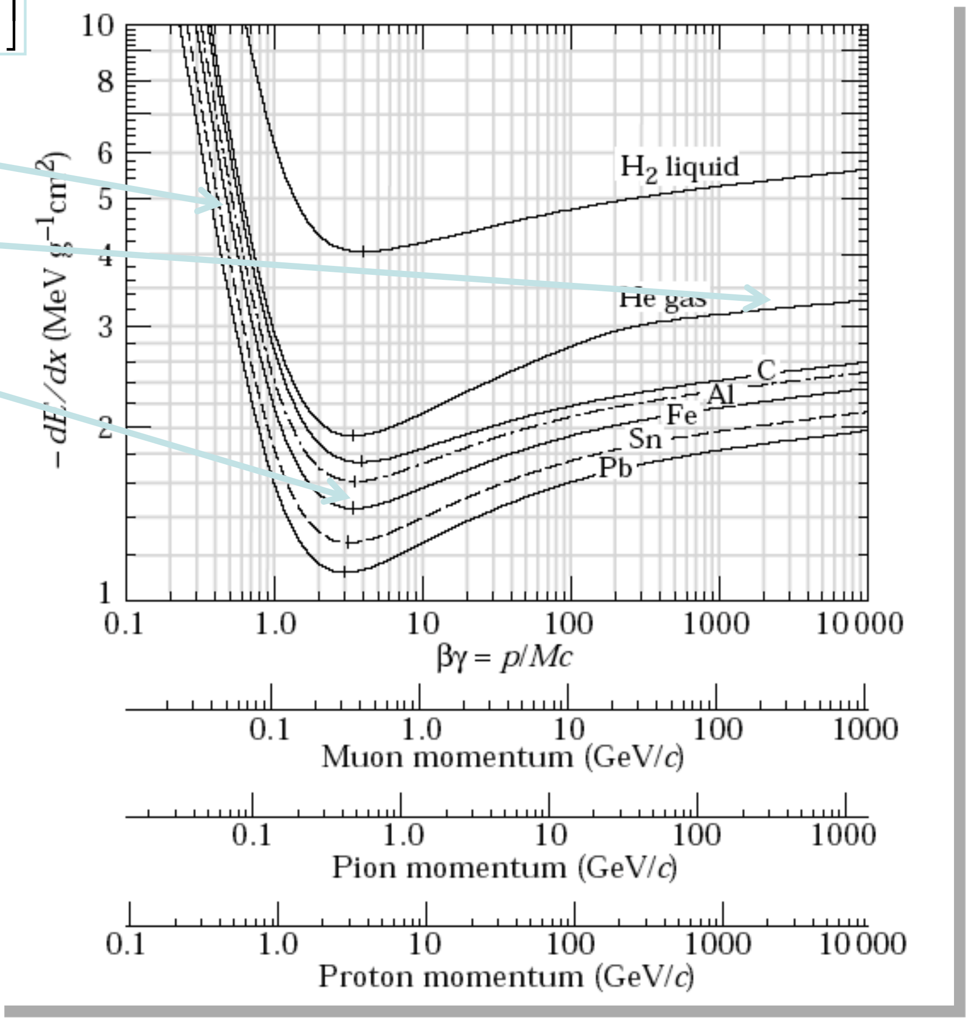
$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2}{I^2}T^{max} - \beta^2 - \frac{\delta}{2}\right]$$

$$T_{max} \approx 2m_e c^2\beta^2\gamma^2$$

$$-\frac{dE}{dx} \approx Kq^2\frac{Z}{A\beta^2}\left[\ln\frac{2m_e c^2\beta^2\gamma^2}{I^2} - \beta^2\right]$$

Charaterized by:

- a fall off at low energy $\sim 1/\beta^2$
- a relativistic rise $\sim \ln \beta\gamma$
- a minimum at $\beta\gamma \approx 3$
- depends only on $\beta\gamma$ not on m



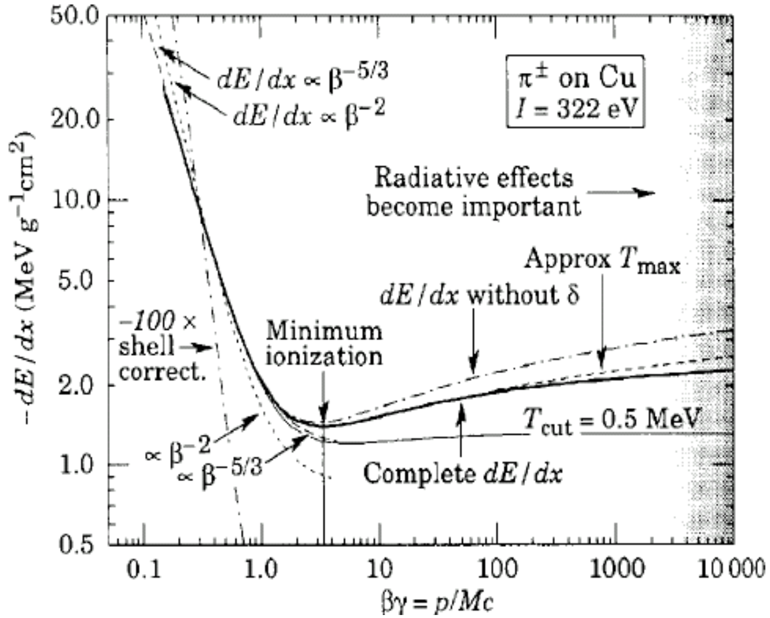
High energy charged particles lose energy slowly in material due to ionization leaving tracks as they pass (For $Z \approx 0.5A$ at $\beta\gamma \approx 3$
$1/\rho \; dE/dx \approx 1.4$ MeV cm^2/g)

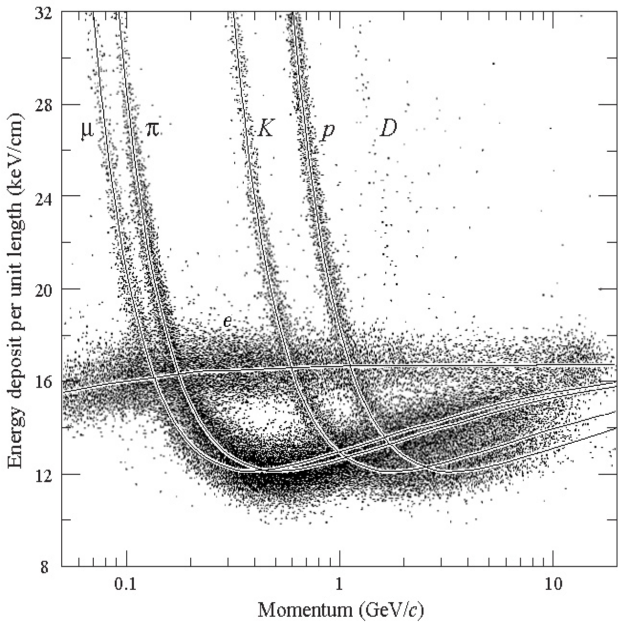
➔ many kinds of tracking detectors can be done !

Particle Identification by Energy Loss

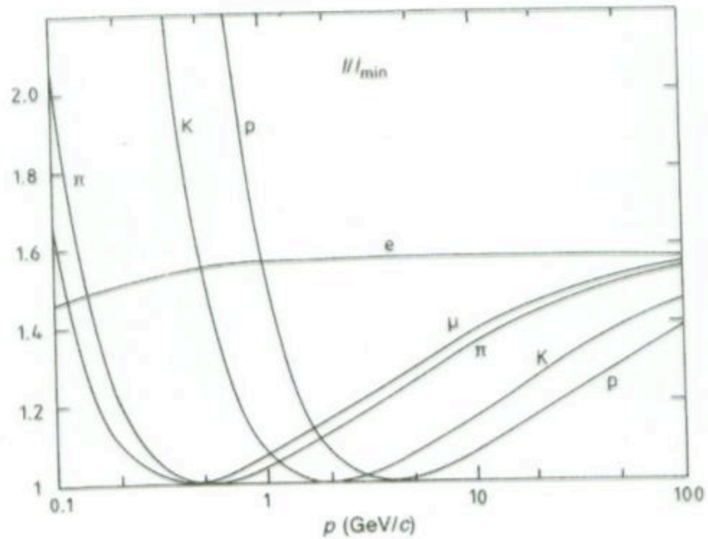
Energy loss depends on the $\beta\gamma$ of the particle and is ≈ independent from the mass of the particle. As a function of particle momentum $p = Mc\beta\gamma$ the energy loss depends on the mass of the particle.

By measuring the energy loss and the momentum of the particle, the mass of the particle can be measured: → Particle Identification !





TPC in magnetic field



$$\frac{1}{\rho}\frac{dE}{dx} = -4\pi r_e^2 m_e c^2 Z_1^2 \frac{p^2 + M^2c^2}{p^2} N_A \frac{Z}{A}\left[\ln\frac{2m_e c^2 F}{I}\frac{p^2}{M^2c^2} - \frac{p^2}{p^2 + M^2c^2}\right]$$

Ionization: the Bethe-Bloch formula

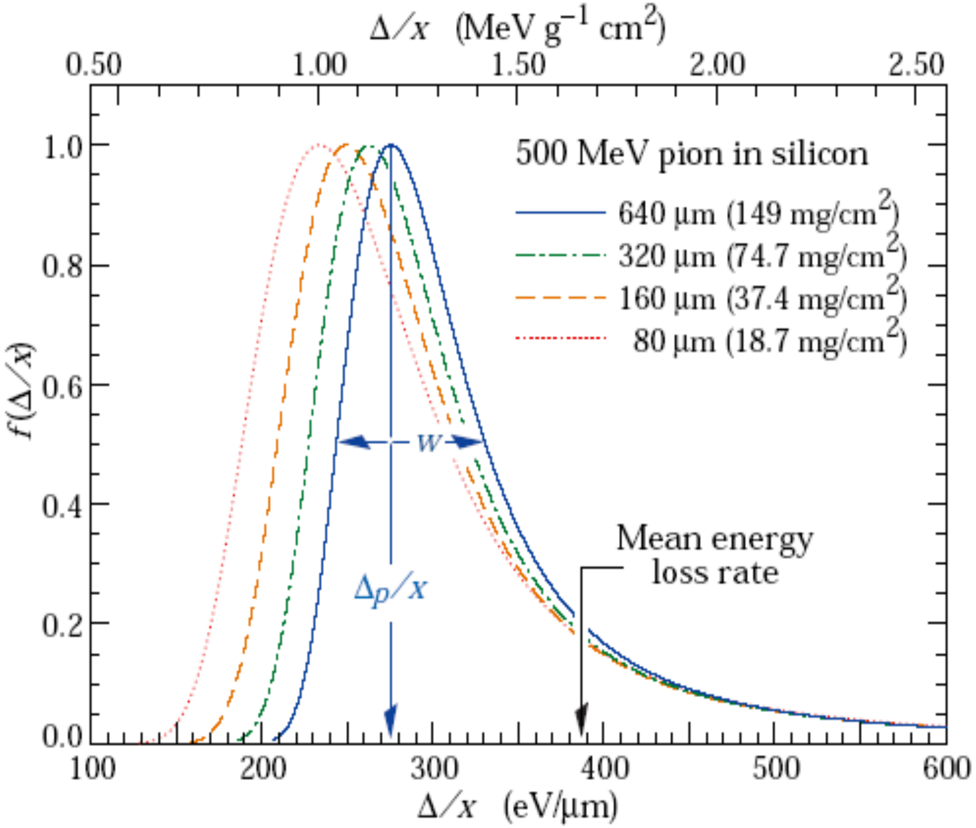
- Bethe-Block formula only gives the average energy loss, and do not take into account fluctuations from event to event.
- Large high energy tail – δ rays

δ -rays : electrons that have sufficient energy to ionize further atoms through subsequent interactions on their own.

Landau distribution:

f (Δ/X): Probability for energy loss Δ in a thickness X of matter.

Very asymmetric distribution: average and most probable energy loss must be distinguished !



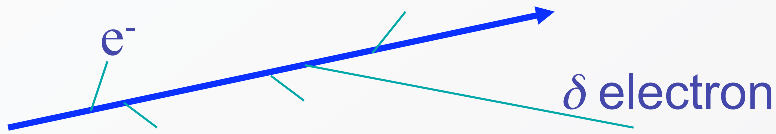
Interaction of charged particles

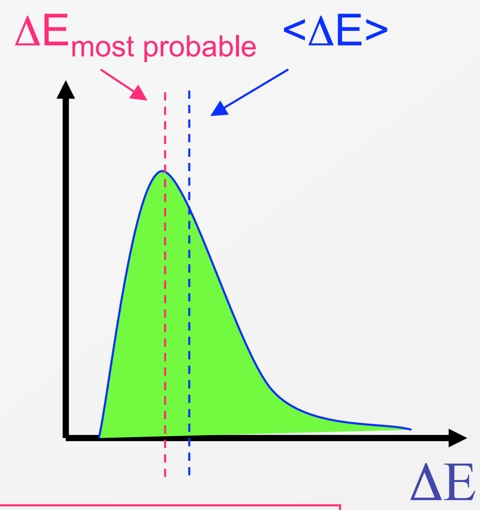
Real detector (limited granularity) can not measure $\langle dE/dx \rangle$!

It measures the energy ΔE deposited in a layer of finite thickness δx.

For thin layers or low density materials:

→ Few collisions, some with high energy transfer.

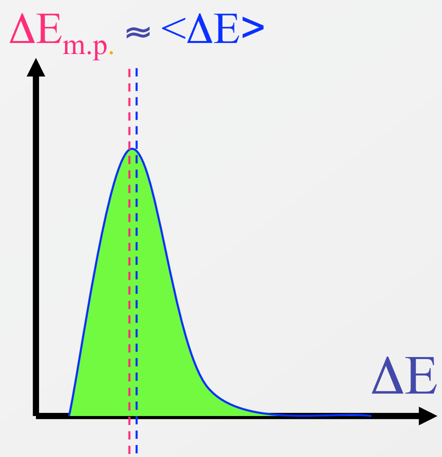




→ Energy loss distributions show large fluctuations towards high losses: "Landau tails"

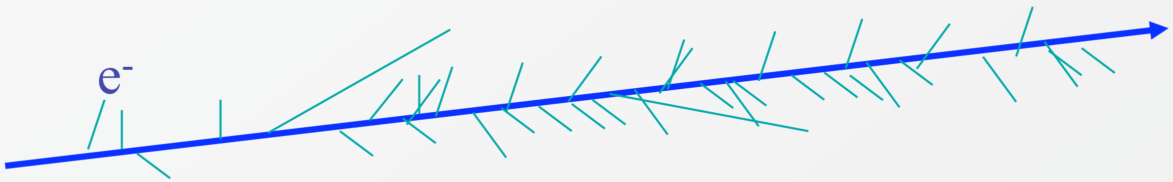
Example: Si sensor: 300 μm thick. $\Delta E_{most\ probable}$ ~ 82 keV $\langle \Delta E \rangle$ ~ 115 keV

For thick layers and high density materials:



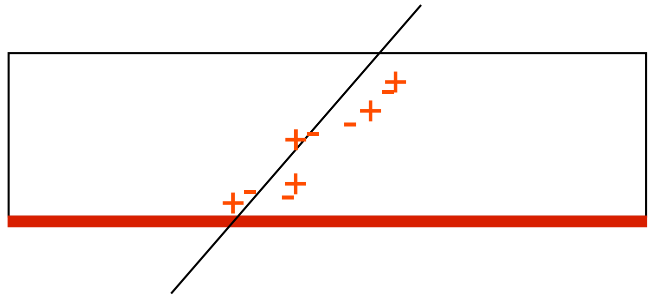
→ Many collisions.

→ Central Limit Theorem → Gaussian shaped distributions.

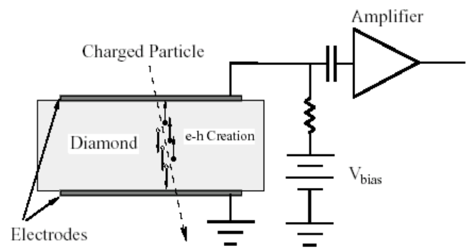


Tracking Detectors

Charged particles crossing a material loose energy by ionizing (and exciting) atoms and thus leaving along their path a trace of electron-ion pairs in gases and liquids and electron-hole pairs in solids.



Measurable electronics signals can be induced by the charges produced in this way and can be read by dedicated electronics



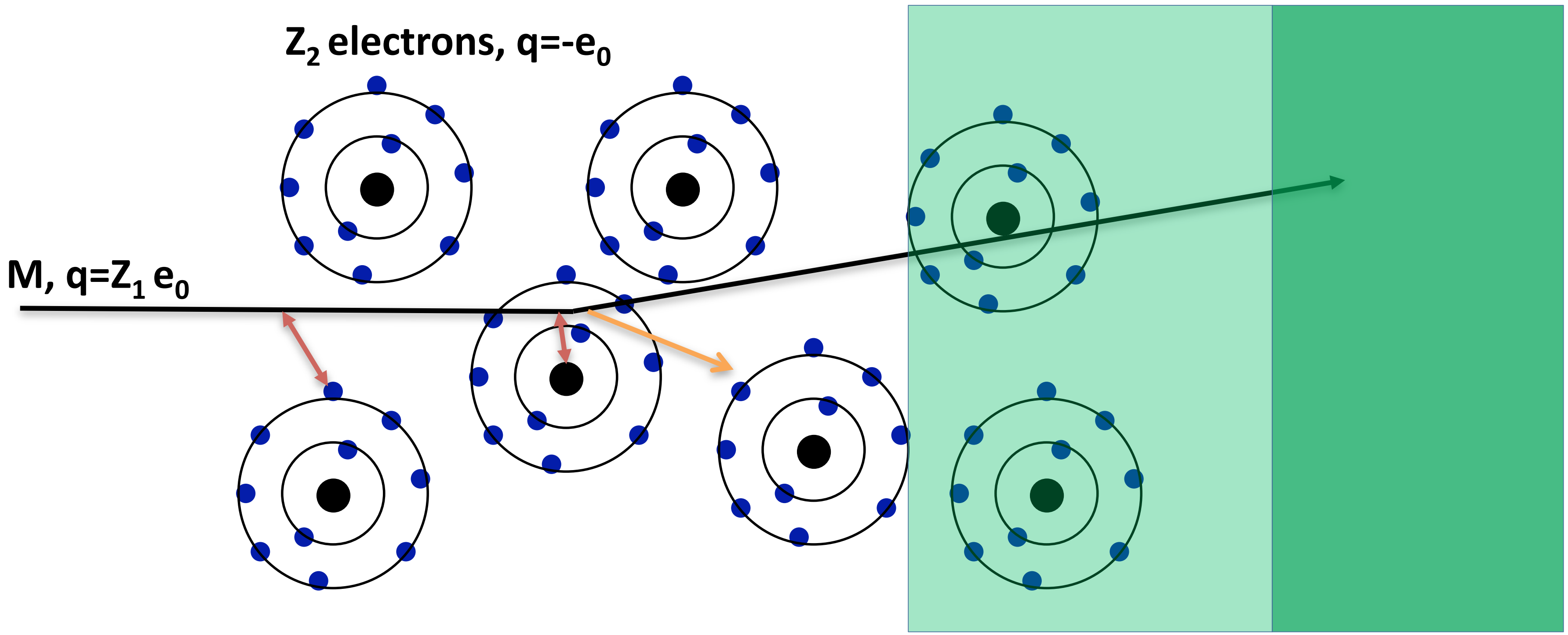
- In solid state detectors the charges produced by the ionization due to the incoming particle are sufficient to provide a measurable signal.

- Mean (most probable) energy loss: 116 (78) keV for 300μm Si thickness
- 3.6 eV to create an e-h pair
  ⇒ 72 e-h/μm (most probable)
  ⇒ 108 e-h/μm (mean)
- Most probable charge (300μm Si) ≈ 21600 e ≈ 3.5 fC

- In gas detectors the charges produced by the primary ionization due to the incoming particle need amplification in order to provide a measurable signal.

GAS)	Helium	Argon	Xenon	CH_4	DME
dE/ dx (keV/ cm)	0.32	2.4	6.7	1.5	3.9
<n>(ion-pair/ cm)	5.9	29	44	16	55

Electromagnetic Interaction of Particles with Matter



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Multiple Scattering

A particle traversing material undergoes successive deflections due to multiple elastic scattering from nuclei.

The probability that the particle is defected by an angle θ after travelling a distance x in the material is well approximated (actually tails are larger than Gaussian tails) by a Gaussian distribution with sigma of:

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

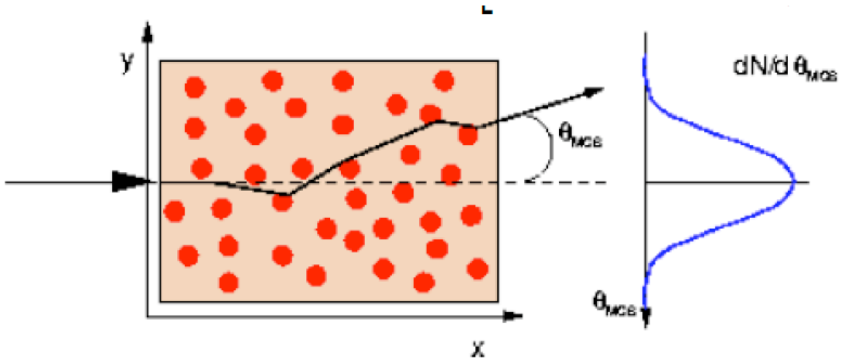
X_0 Radiation length of the material
z Charge of the particle
p Momentum of the particle

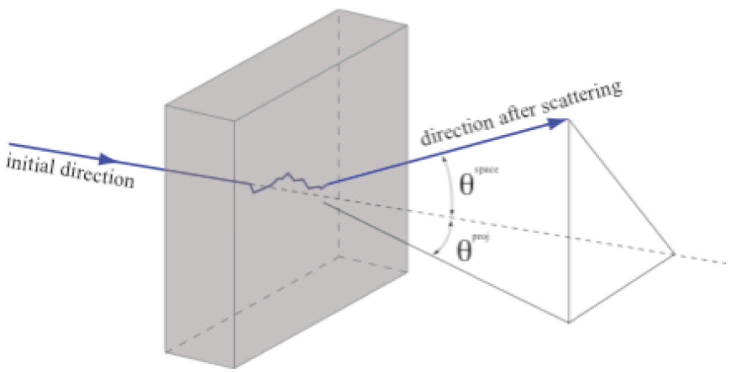
Radiation Length X_0 has 2 definitions:

◇ Mean distance over which high energy electron losses all but 1/e of its energy by Bremsstrahlung.

◇ 7/9ths of the mean free path for pair production by a high energy photon.

$$X_0 \approx \frac{716.4 g cm^{-2} A}{Z(Z+1)\ln(287/\sqrt{Z})}$$



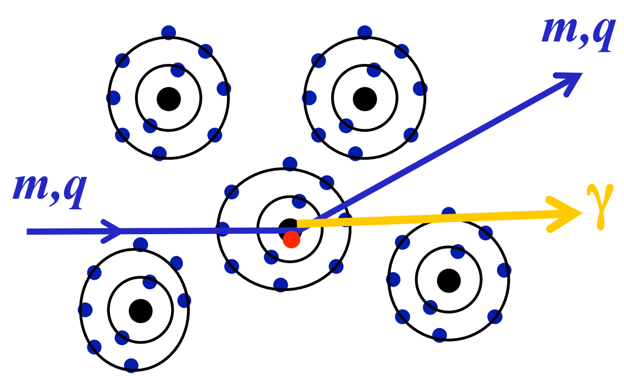


	X_0 (g cm^{-2})	X_0 (cm)
Air	37	30,000
Silicon	22	9.4
Lead	6.4	0.56

Bremsstrahlung

A charged particle of mass m and charge q traversing material not only interacts with the atomic electrons loosing energy via ionization and excitation, but also can be deflected by the atomic nuclei of charge Z of the material. This deflection (Rutherford scattering) results in an acceleration of the charge q that causes emission of photons. The radiation energy (Bremsstrahlung) emitted by the accelerated particle for a given momentum transfer can be evaluated by the Maxwell's equations and comes out to be:

- proportional $1/m^2$ of the incoming particle
- proportional to q^4 of the incoming particle
- proportional to Z^2 of the material
- proportional to ρ of the material

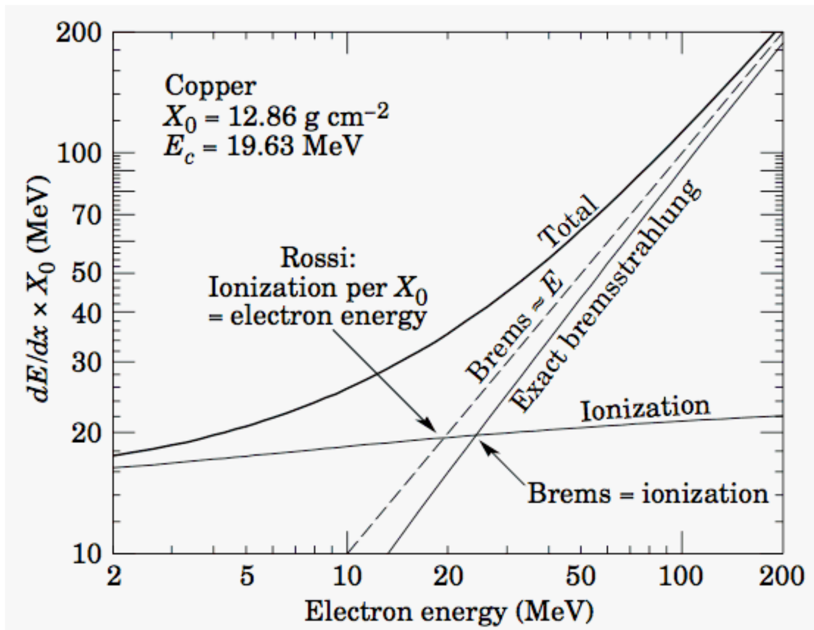


Critical Energy E_C is defined the energy at which dE/dx (Ionization)=dE/dx (Bremsstrahlung)

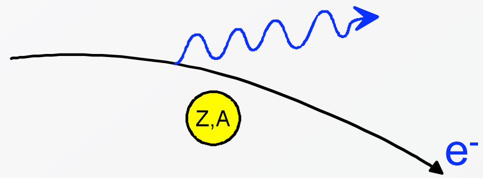
Muon in Copper: $E_C \approx$ 400 GeV

Electron in Copper: $E_C \approx$ 20 MeV

Electrons lose energy via ionization as other charged particles, however because of their small mass the Bremsstrahlung becomes the dominant process for energies ≥ 20 MeV



Interaction of charged particles



$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\varepsilon_0} \frac{e^2}{mc^2} \right)^2 E \ln \frac{183}{Z^{1/3}} \propto \frac{E}{m^2}$$

Effect is only relevant for e± and ultra-relativistic μ (>1000 GeV)

$$\frac{m_\mu^2}{m_e^2} = \frac{105^2\,\mathrm{MeV}^2}{0.5^2\,\mathrm{MeV}^2} = 4.4 \cdot 10^4$$

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

$$-\frac{dE}{dx} = \frac{E}{X_0}$$

energy loss is proportional to actual energy

$$\Rightarrow \quad E = E_0 e^{-x/X_0}$$

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

radiation length [g/cm²]

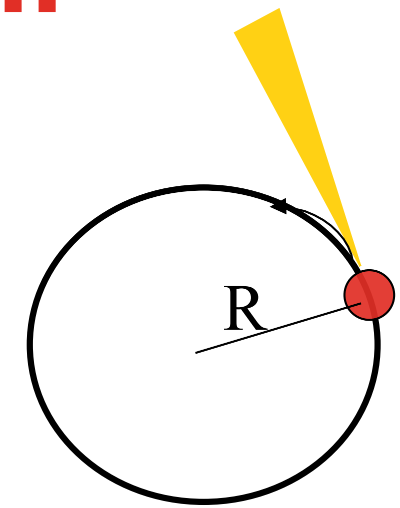
(divide by specific density to get X_0 in cm)

Synchrotron Radiation

- Energy loss per revolution

$$\Delta E = \frac{e^2}{3\varepsilon_0}\frac{\beta^3\gamma^4}{2\pi R} \qquad \beta = \frac{v}{c} \qquad \gamma = \frac{E}{m} \qquad R = \text{orbit radius}$$

$$\Delta E[GeV] = 5.7\times 10^{-7}\frac{E^4[GeV]}{R[km]}$$



- Example : LEP, $2\pi R$=27km, E=100 GeV (in 2000)
  - **ΔE = 2 GeV!!**
  - LEP at limit, need more and more energy just to compensate energy loss

- Note : for ultrarelativistic protons/electrons ($\beta \cong 1$)

$$\Delta E[p]/\ \Delta E[e] = (m_e/m_p)^4 = \mathbf{10^{-13}\ !!}$$

Interaction of charged particles

Critical energy E_c

$$\left.\frac{dE}{dx}(E_c)\right|_{Brems} = \left.\frac{dE}{dx}(E_c)\right|_{ion}$$

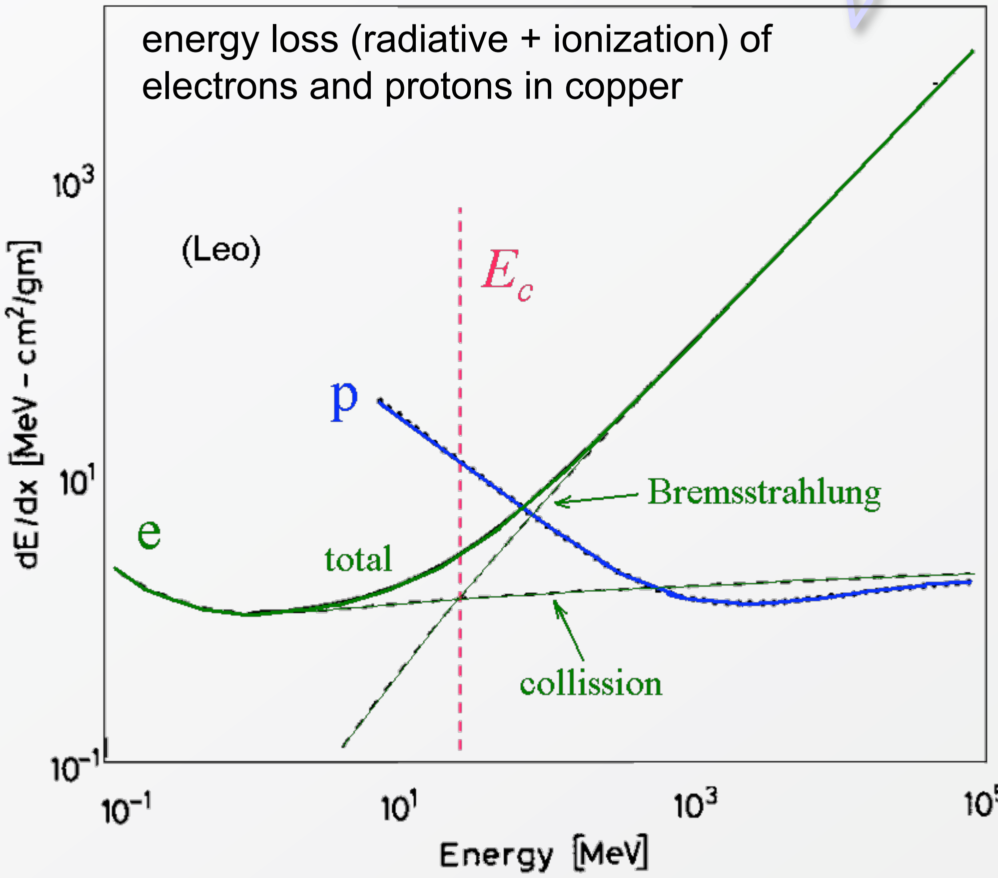
For electrons one finds approximately:

$$E_c^{solid+liq} = \frac{610\text{ MeV}}{Z+1.24} \qquad E_c^{gas} = \frac{710\text{ MeV}}{Z+1.24}$$

$E_c(e^-)$ in Cu ($Z=29$) = 20 MeV

For muons $E_c \approx E_c^{elec}\left(\frac{m_\mu}{m_e}\right)^2$

$E_c(\mu)$ in Cu ≈ 400 GeV

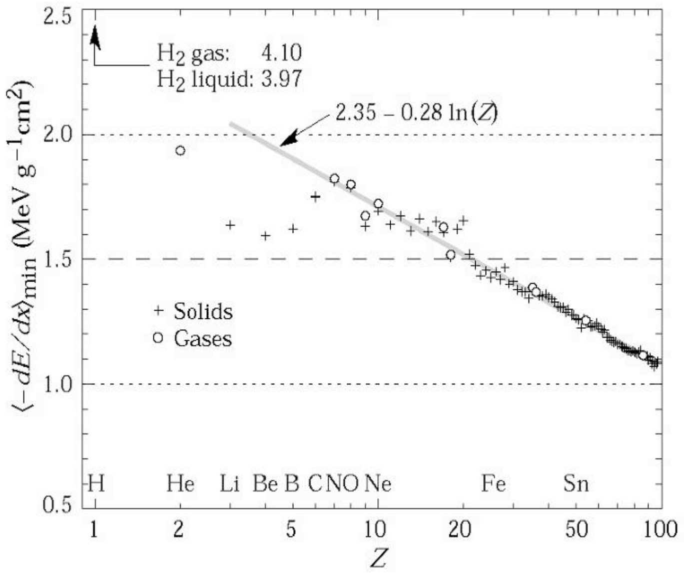


Unlike electrons, muons in multi-GeV range can traverse thick layers of dense matter.
Find charged particles traversing the calorimeter ? → most likely a muon → Particle ID

Muon Energy Loss

(Limits of applicability for Bethe Bloch)

μ at minimum ionization



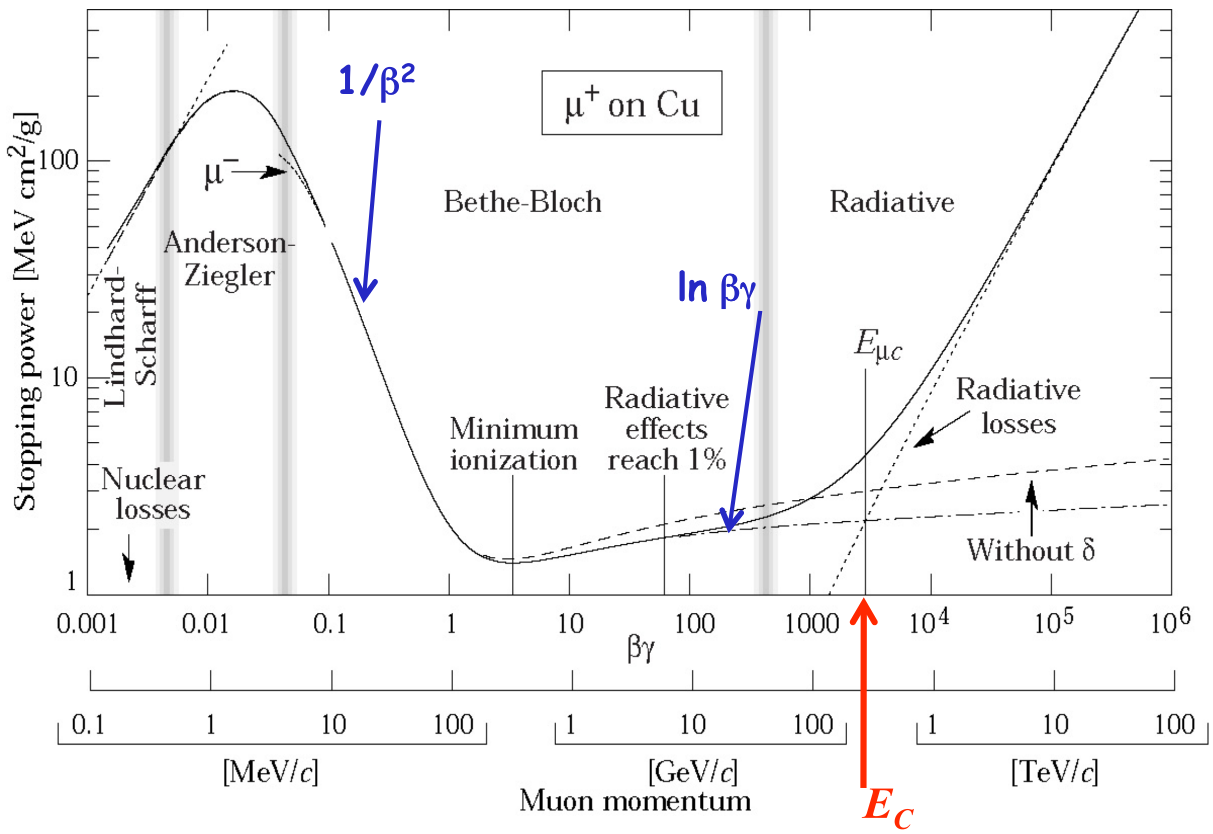
Example: a 1 GeV μ in Iron

Fe: Thickness = 100 cm; ρ = 7.87 g/cm³

dE ≈ 1.4 * 100* 7.87 = 1102 MeV

→ a 1 GeV μ can traverse 1m of Iron

a 1TeV muon hitting copper is not a MIP !



E_c = energy for which ionization matches bremsstrahlung

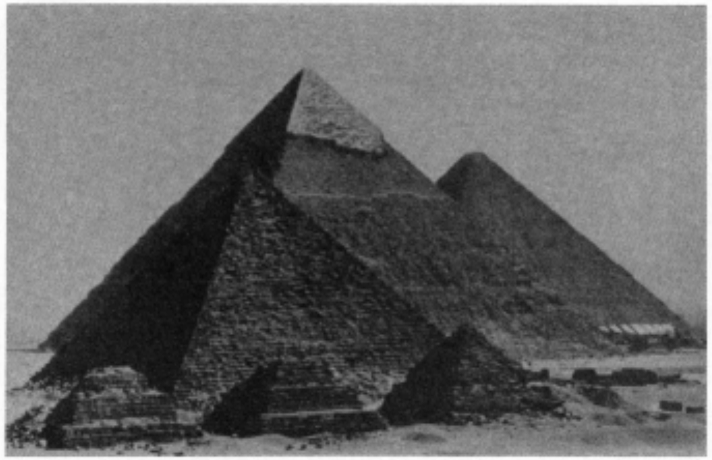
Search for Hidden Chambers in the Pyramids

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino

Fig. 2 (bottom right). Cross sections of (a) the Great Pyramid of Cheops and (b) the Pyramid of Chephren, showing the known chambers: (A) Smooth limestone cap, (B) the Belzoni Chamber, (C) Belzoni's entrance, (D) Howard-Vyse's entrance, (E) descending passageway, (F) ascending passageway, (G) underground chamber, (H) Grand Gallery, (I) King's Chamber, (J) Queen's Chamber, (K) center line of the pyramid.

6 FEBRUARY 1970



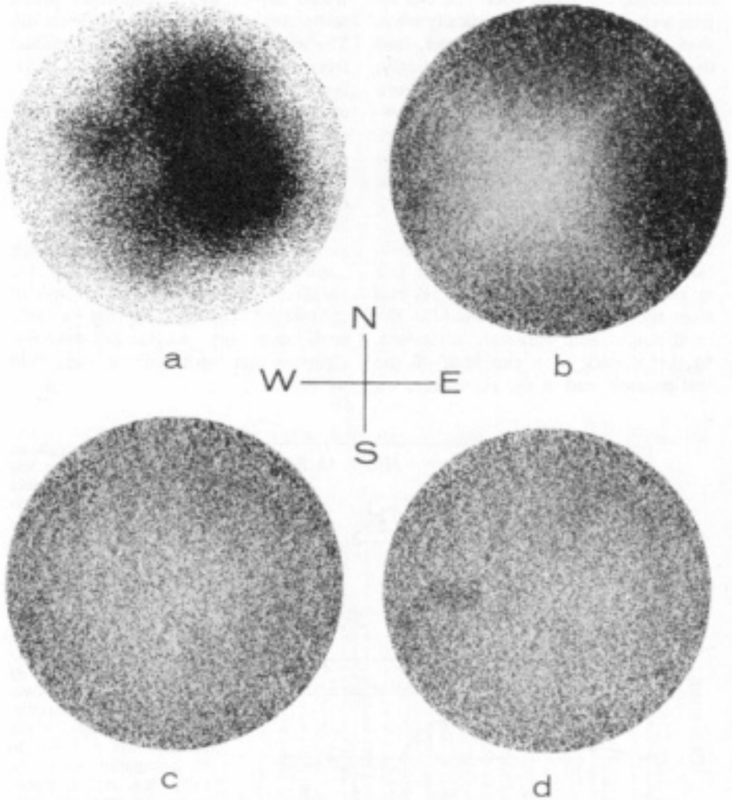
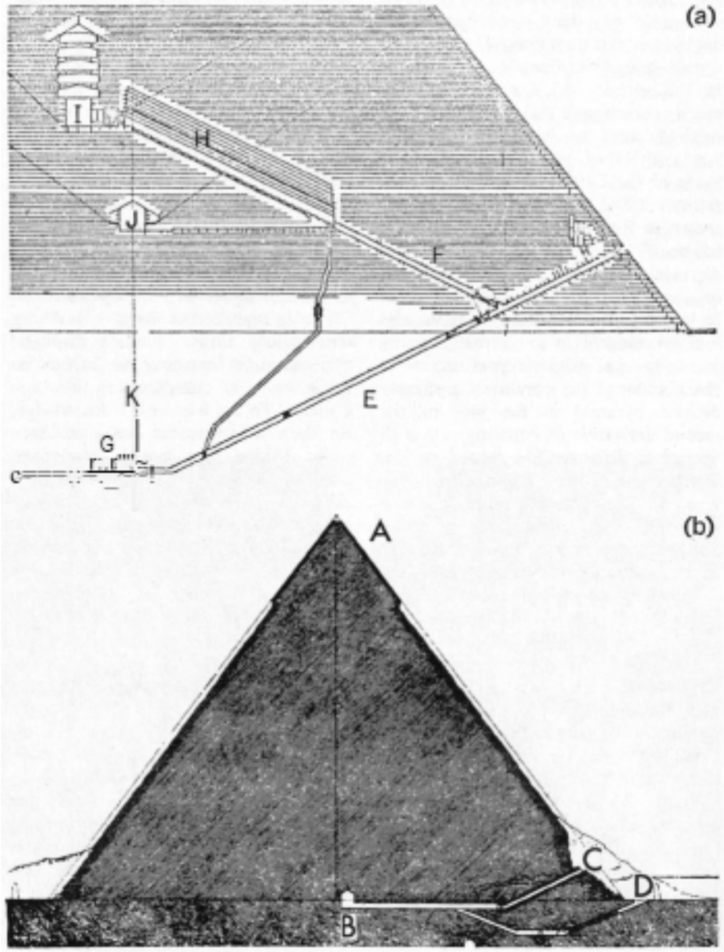


Fig. 13. Scatter plots showing the three stages in the combined analytic and visual analysis of the data and a plot with a simulated chamber. (a) Simulated "x-ray photograph" of uncorrected data. (b) Data corrected for the geometrical acceptance of the apparatus. (c) Data corrected for pyramid structure as well as geometrical acceptance. (d) Same as (c) but with simulated chamber, as in Fig. 12.



Luis Alvarez used the attenuation of muons to look for chambers in the Second Giza Pyramid → Muon Tomography

He proved that there are no chambers present.

Electrons and Positrons

Electrons and positrons lose energy via ionization just as other charged particles.
However, their smaller masses mean they lose significant energy due to radiation as well:

- Bremsstrahlung
- Elastic scattering
- Pair production and electromagnetic showers (see later)

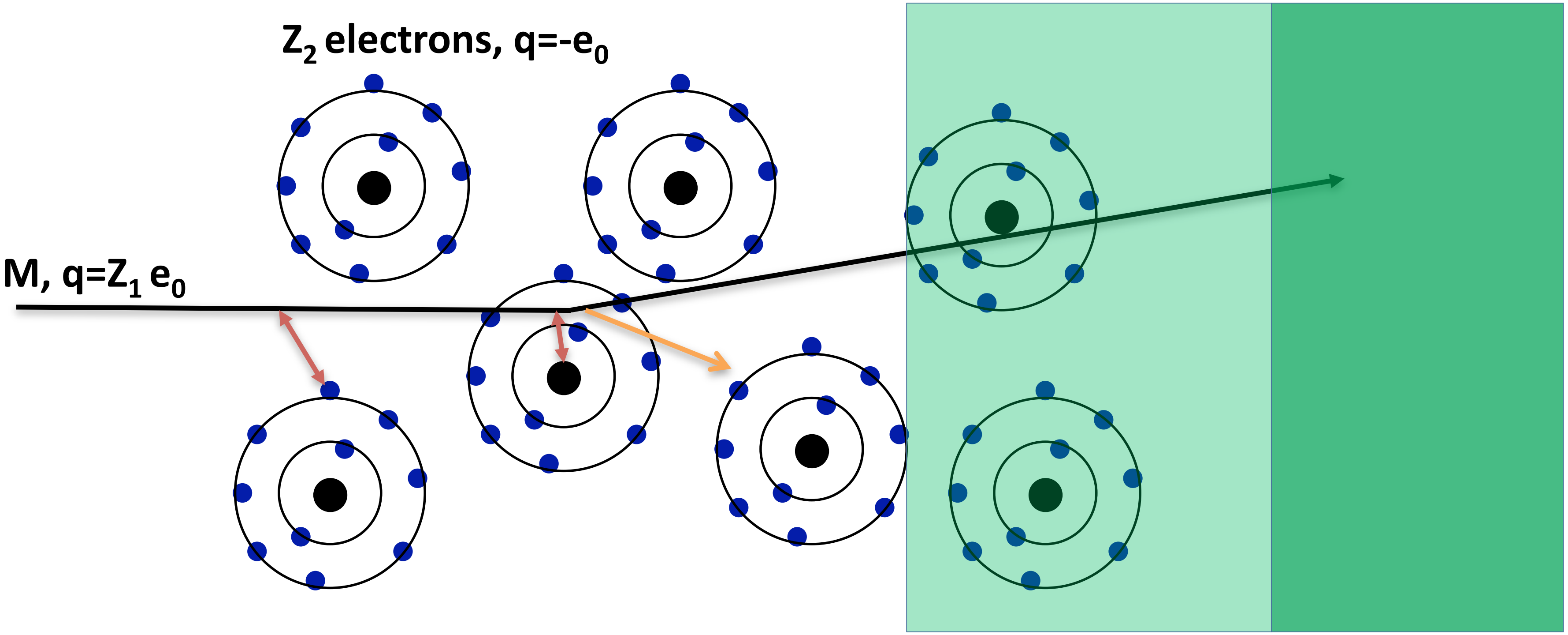
Positron Annihilation

positrons that pass through matter annihilate with an electron, to create photons:

$$e^{+} + e^{-} \rightarrow \gamma + \gamma$$

Single photons are possible if the electron is bound to a nucleus… this occurs at only 20% the rate for two photons.
A high energy positron will lose energy by collision and radiation, until it has a low enough energy to annihilate.

Electromagnetic Interaction of Particles with Matter



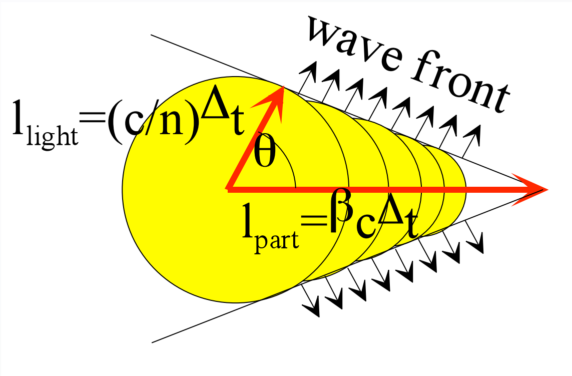
Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted.

In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called Transition radiation.

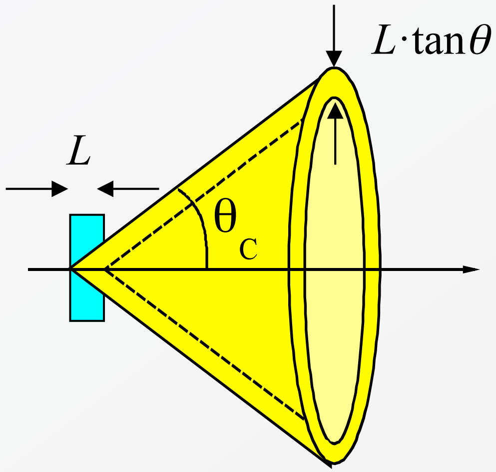
Cherenkov radiation

Cherenkov radiation is emitted when a charged particle passes through a dielectric medium with velocity $\beta \geq \beta_{thr} = \frac{1}{n}$ $\quad n$: refractive index



$$\cos\theta_C = \frac{1}{n\beta}$$

with $n = n(\lambda) \geq 1$

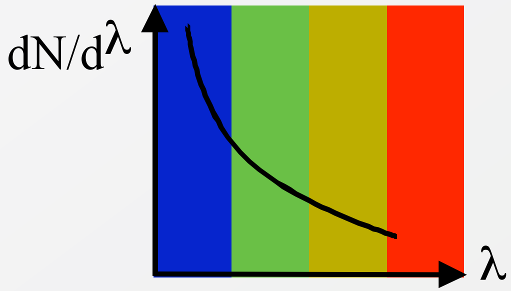


- $\beta_{thr} = \frac{1}{n} \rightarrow \theta_C \approx 0$ Cherenkov threshold
- $\theta_{max} = \arccos\frac{1}{n}$ 'saturated' angle (β=1)

Number of emitted photons per unit length and unit wavelength interval

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi z^2\alpha}{\lambda^2}\left(1-\frac{1}{\beta^2 n^2}\right) = \frac{2\pi z^2\alpha}{\lambda^2}\sin^2\theta_C$$

$$\frac{d^2N}{dxd\lambda} \propto \frac{1}{\lambda^2} \quad \text{with } \lambda = \frac{c}{\nu} = \frac{hc}{E} \quad \frac{d^2N}{dxdE} = const.$$



LHCb RICH

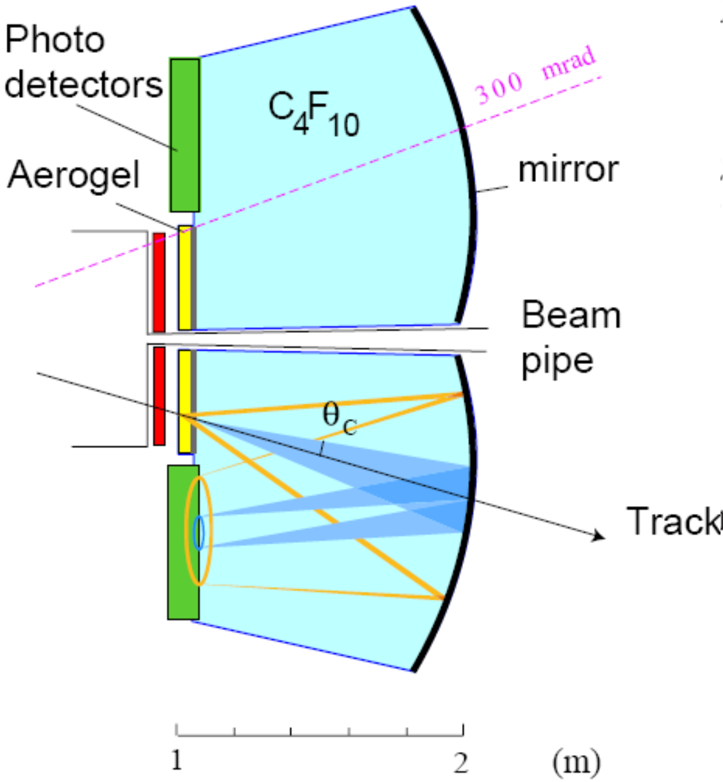
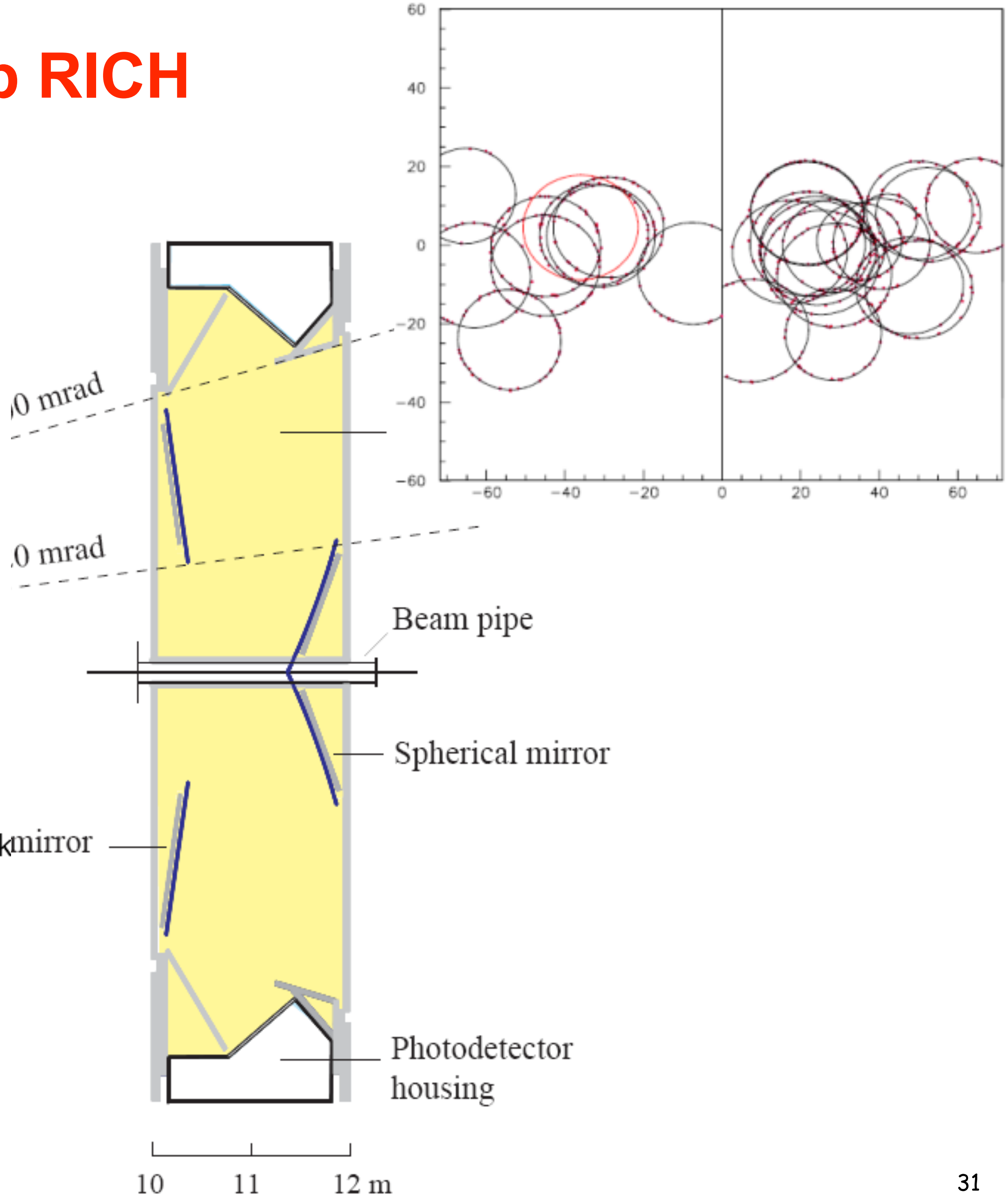
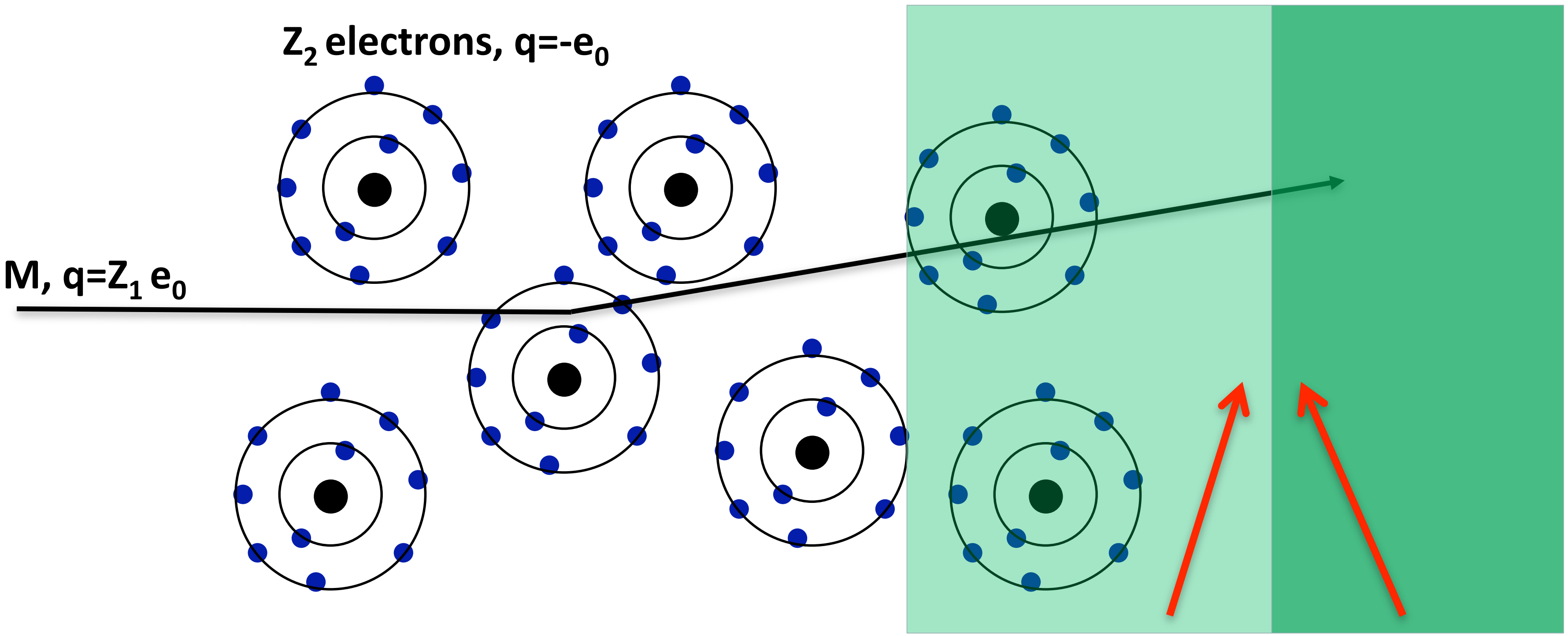


Photo detectors
Aerogel
C_4F_{10}
300 mrad
mirror
Beam pipe
θ_C
Track
1
2
(m)



Beam pipe
Spherical mirror
mirror
Photodetector housing
10
11
12 m
60
40
20
0
−20
−40
−60

Transition Radiation



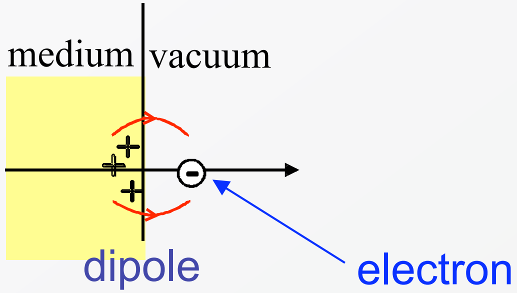
When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called Transition radiation.

Transition Radiation was predicted by Ginzburg and Franck in 1946

Relativistic theory: G. Garibian, Sov. Phys. JETP63 (1958) 1079

TR is electromagnetic radiation emitted when a charged particle traverses a medium with a discontinuous refractive index, e.g. the boundaries between vacuum and a dielectric layer.

A (too) simple picture



Medium gets polarized. Electron density displaced from its equilibrium
→ Dipole, varying in time → radiation of energy.

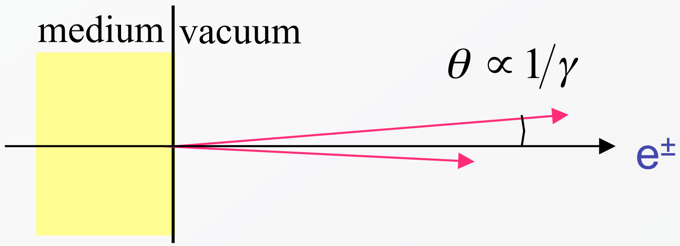
Radiated energy per medium/vacuum boundary:

$$W = \frac{1}{3}\alpha\hbar\omega_p\gamma \qquad \omega_p = \sqrt{\frac{N_e e^2}{\varepsilon_0 m_e}} \quad \begin{pmatrix}\text{plasma}\\ \text{frequency}\end{pmatrix} \qquad \hbar\omega_p \approx 20\text{eV} \text{ (plastic radiators)}$$

Radiated energy per medium/vacuum boundary:

$W = \frac{1}{3}\alpha\hbar\omega_p\gamma$ $\qquad$ $W \propto \gamma$ → only high energetic e± emit TR of detectable intensity.
→ particle ID

- Lorentz transformation makes the dipole radiation extremely forward peaked → TR photons stay close to particle track



$\theta << mrad$

- Typical photon energy: $\hbar\omega \approx \frac{1}{4}\hbar\omega_p\gamma$ $\qquad$ e± at E = 10 GeV; → γ ~ 2·10[4]

E_γ ~ 0.25 · 20 eV · 2·10[4] ~ 10 keV → X-rays

- Photons / boundary: $N_{ph} \approx \frac{W}{\hbar\omega} \propto \alpha \approx \frac{1}{137}$

- Energy loss by TR $\left.\frac{dE}{dx}\right|^{TR} = N_{ph} \cdot \mathrm{E}_\gamma = \alpha \cdot 10\,\mathrm{keV} \approx 100\,\mathrm{eV/boundary}$

(TR detectors have many boundaries!)

Electromagnetic Interaction of Particles with Matter

Ionization and Excitation:

Charged particles traversing material are exciting and ionizing the atoms.

The average energy loss of the incoming particle by this process is to a good approximation described by the Bethe Bloch formula.

The energy loss fluctuation is well approximated by the Landau distribution.

Multiple Scattering and Bremsstrahlung:

The incoming particles are scattering off the atomic nuclei which are partially shielded by the atomic electrons.

Measuring the particle momentum by deflection of the particle trajectory in the magnetic field, this scattering imposes a lower limit on the momentum resolution of the spectrometer.

The deflection of the particle on the nucleus results in an acceleration that causes emission of Bremsstrahlungs-Photons. These photons in turn produced e+e- pairs in the vicinity of the nucleus, which causes an EM cascade. This effect depends on the 2nd power of the particle mass, so it is only relevant for electrons.

Electromagnetic Interaction of Particles with Matter

Cherenkov Radiation:

If a particle propagates in a material with a velocity larger than the speed of light in this material, Cherenkov radiation is emitted at a characteristic angle that depends on the particle velocity and the refractive index of the material.

Transition Radiation:

If a charged particle is crossing the boundary between two materials of different dielectric permittivity, there is a certain probability for emission of an X-ray photon.

→ The strong interaction of an incoming particle with matter is a process which is important for Hadron calorimetry and will be discussed later.

Interaction of photons

In order to be detected, a photon has to create charged particles and / or transfer energy to charged particles

- Photo-electric effect
- Compton scattering
- Pair production

PhotoElectric Effect

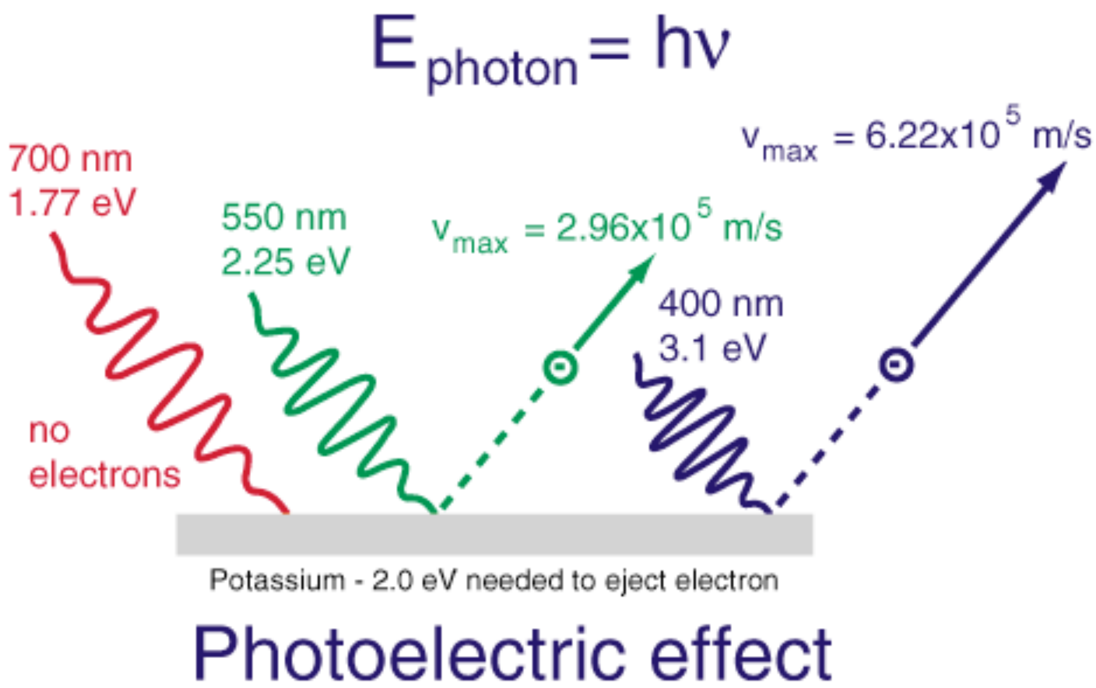
Interaction between photon and whole atom.

Photons with energies above the binding energy of an electron, can eject an atomic electron, with kinetic energy T:

$$T = h\nu - W$$

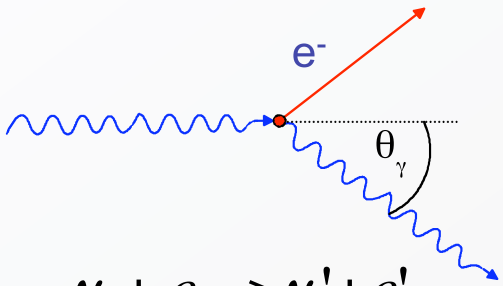
Einstein: Quantized photon energies

Feynman: QED!



Interaction of photons

Compton scattering:



$$\gamma + e \rightarrow \gamma' + e'$$

$$E'_\gamma = E_\gamma \frac{1}{1+\varepsilon(1-\cos\theta_\gamma)} \qquad \varepsilon = \frac{E_\gamma}{m_e c^2}$$

$$E_e = E_\gamma - E'_\gamma$$

Assume electron as quasi-free.

Klein-Nishina $\frac{d\sigma}{d\Omega}(\theta,\varepsilon)$ →

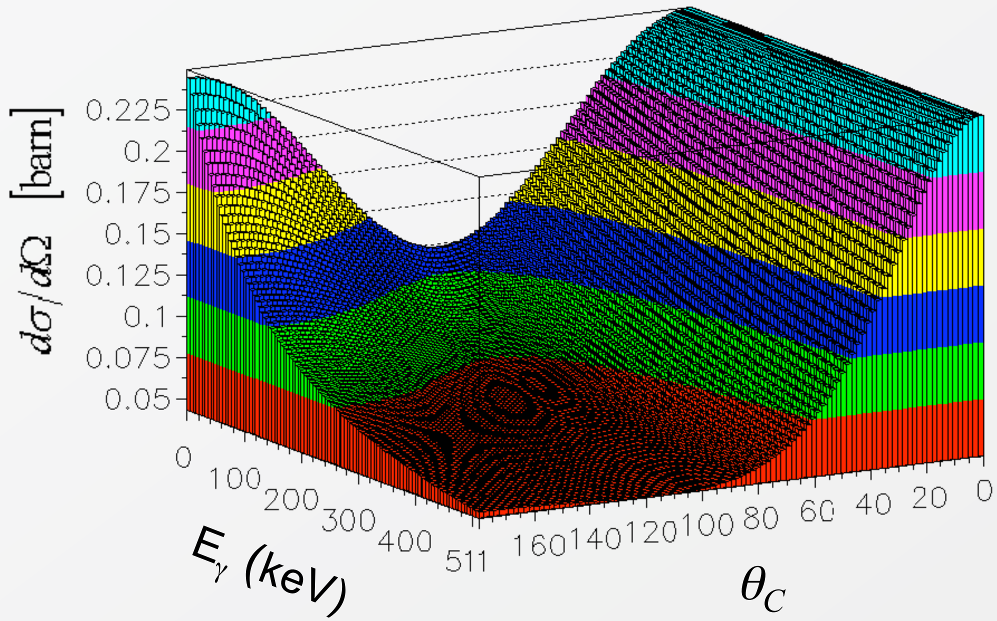
At high energies approximately

$$\sigma_c^e \propto \frac{\ln\varepsilon}{\varepsilon}$$

Atomic Compton cross-section:

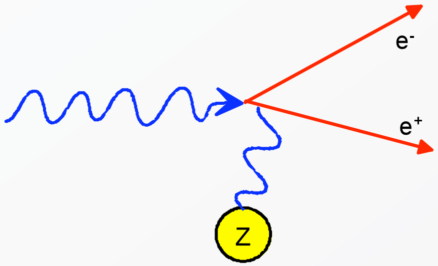
$$\sigma_c^{atomic} = Z \cdot \sigma_c^e$$

Compton cross-section (Klein-Nishina)
example: E_γ = 0 … 511 keV



Interaction of photons

Pair production



$$\gamma + nucleus \;\rightarrow\; e^+e^- + nucleus$$

Only possible in the Coulomb field of a nucleus (or an electron) if $E_\gamma \geq 2m_ec^2$

Cross-section (high energy approximation)

$$\sigma_{pair} \approx 4\alpha r_e^2 Z^2 \left(\frac{7}{9} \ln \frac{183}{Z^{\frac{1}{3}}} \right)$$

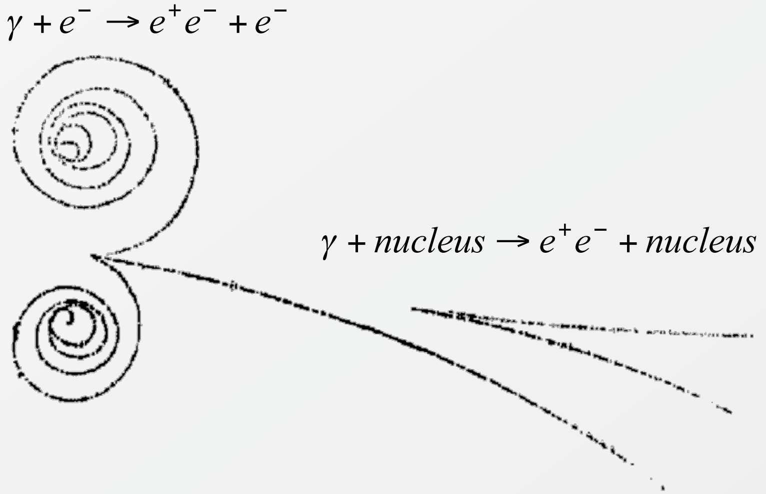
independent of energy !

$$\approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0}$$

$$\approx \frac{A}{N_A} \frac{1}{\lambda_{pair}}$$

$$\lambda_{pair} = \frac{9}{7} X_0$$

Energy sharing between e^+ and e^- becomes asymmetric at high energies.



Photon Interactions

$$I_\gamma = I_0 e^{-\mu x}$$

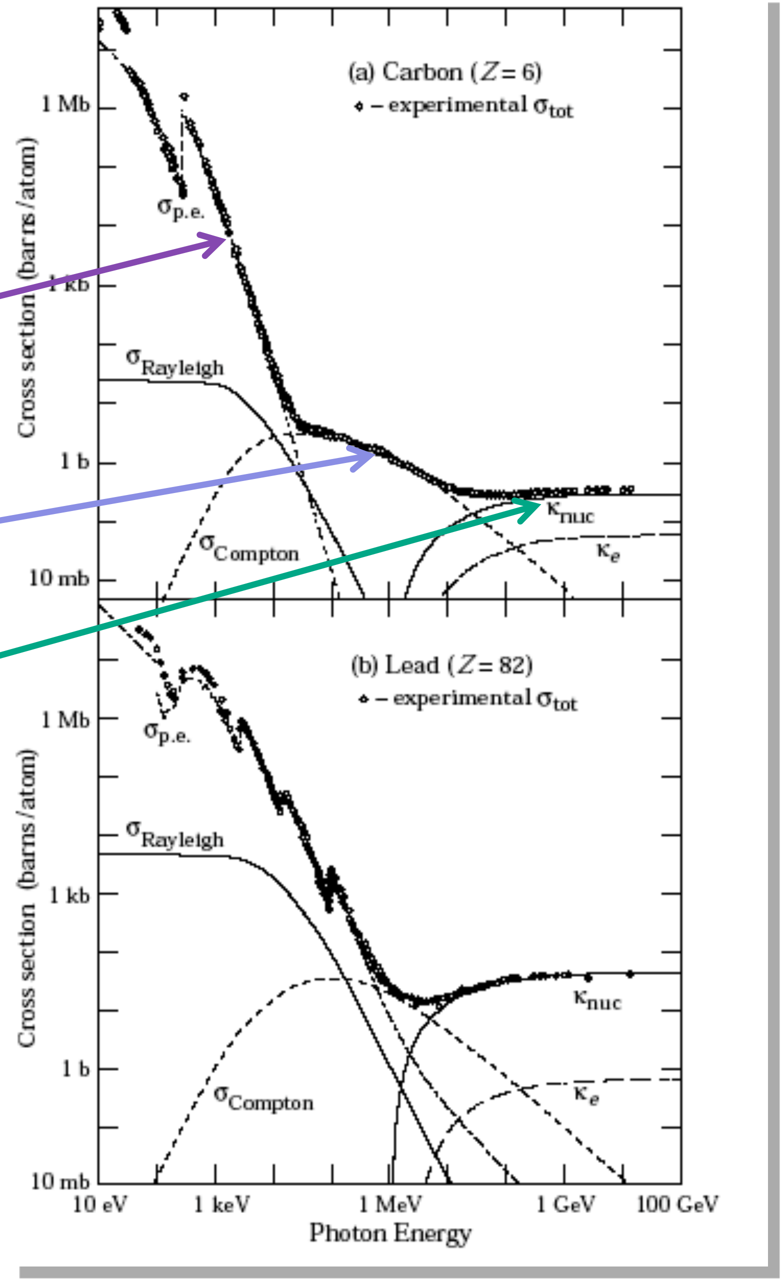
μ: attenuation coefficient :

$$\mu_i = \frac{N_A}{A}\sigma_i \quad [cm^2/g] \qquad \mu = \mu_{photo} + \mu_{Compton} + \mu_{pair} + \ldots$$

- **low energies (< 100 keV):**
Photoelectric effect

- **medium energies (~1 MeV):**
Compton scattering

- **high energies (> 10 MeV):**
e^+e^- pair production



- **Note that each of these processes leads to the ejection of electrons from atoms!**

- **"electromagnetic showers"**

Electromagnetic Interactions

Electromagnetic Interactions for charged particles (unless e^+, e^-): small perturbations.

- **Δ Energy is small**
- **slight change in trajectory**

Number of incident particles remains basically unchanged.

$\Rightarrow$ Photons: large probability to be removed upon interaction.

Beam of photons: number N removed from beam while traversing dx of material is $dN = -\mu N dx$. The beam intensity is then

$$I(x) = I_0 e^{-\mu x}$$

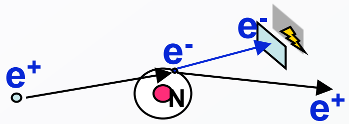
μ is the linear attenuation coefficient, dependent on the material.

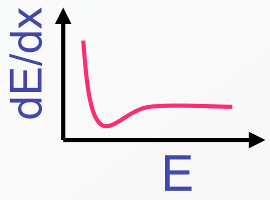
$$\mu = \frac{\sigma N_0 \rho}{A} \equiv \frac{7}{9X_0}$$

electromagnetic interactions: e^+/e^- versus γ

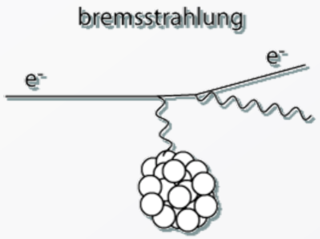
e^+ / e^-

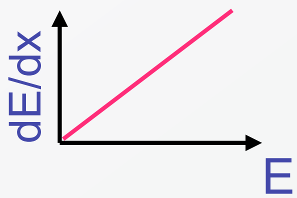
- Ionisation





- Bremsstrahlung





Brems is more important at high energies.

$$R = \left(\frac{dE}{dx}\right)_{Brem} \Big/ \left(\frac{dE}{dx}\right)_{ion} \sim \frac{ZE}{580MeV}$$

$$E_c = \frac{580MeV}{Z}$$

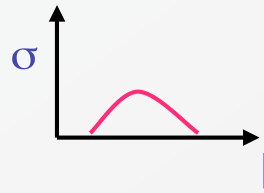
R: ratio of the energy loss for the two processes

E_c: critical energy when R=1

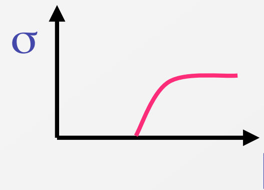
γ

- Photoelectric effect

- Compton effect



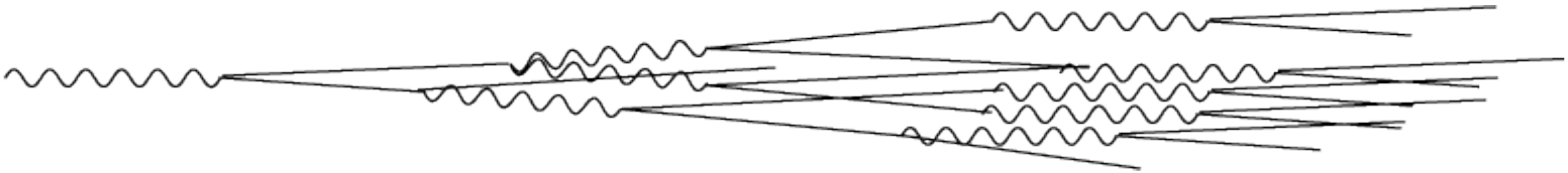
- Pair production



At high energy, when e^+/e^- interactions in matter are dominated by Brems,the interactions of γs are dominated by e^+e^- pair production.

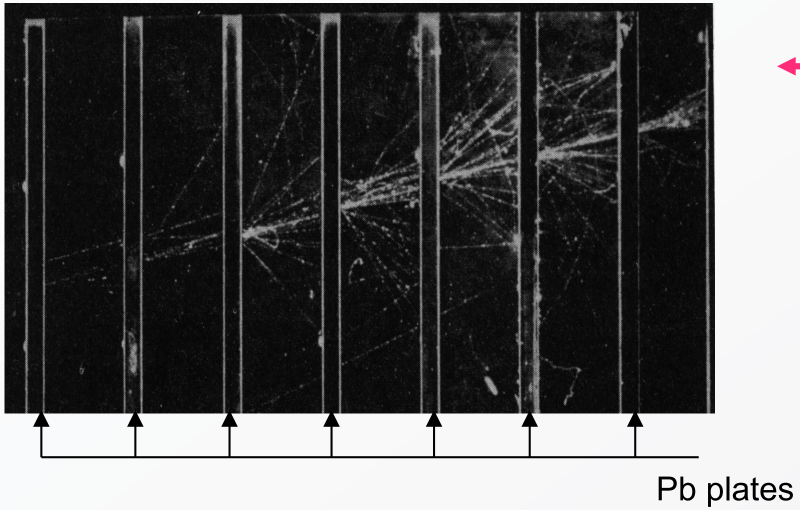
Electromagnetic Showers

- An electron (or positron) impinging on solid matter will generate a γ-Brem which in turn will produce a e^+e^- pair. Each e^+/e^- of the pair will generate a γ-Brem, and so on…(with a linear absorption coefficient of $1/X_0$
- this process repeats, giving rise to an e.m. shower:



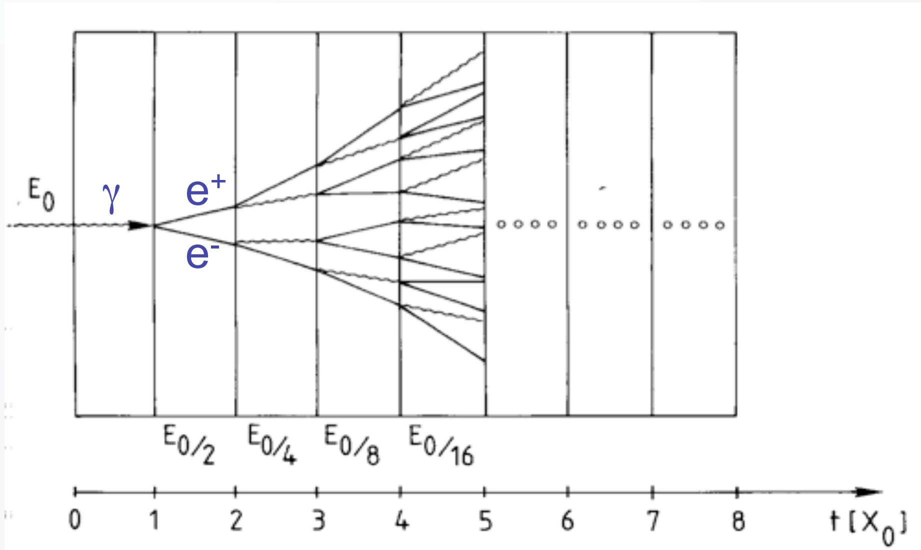
- the process continues until the resulting photons and electrons fall below threshold
- so how do we get some sort of signal out?
- the (total) ionization (scintillation) produced by the e^+e^- pairs during the e.m. shower can be detected.
- the amount of ionization (scintillation) is proportional to the energy of the incoming electro/positron

Electromagnetic cascades (showers)



Electron shower in a cloud chamber with lead absorbers

Simple qualitative model



Shower can be initiated by photon OR by electron.

- Consider only Bremsstrahlung and (symmetric) pair production.
- Assume: $X_0 \sim \lambda_{pair}$

$$N(t) = 2^t \qquad E(t)/\text{particle} = E_0 \cdot 2^{-t}$$

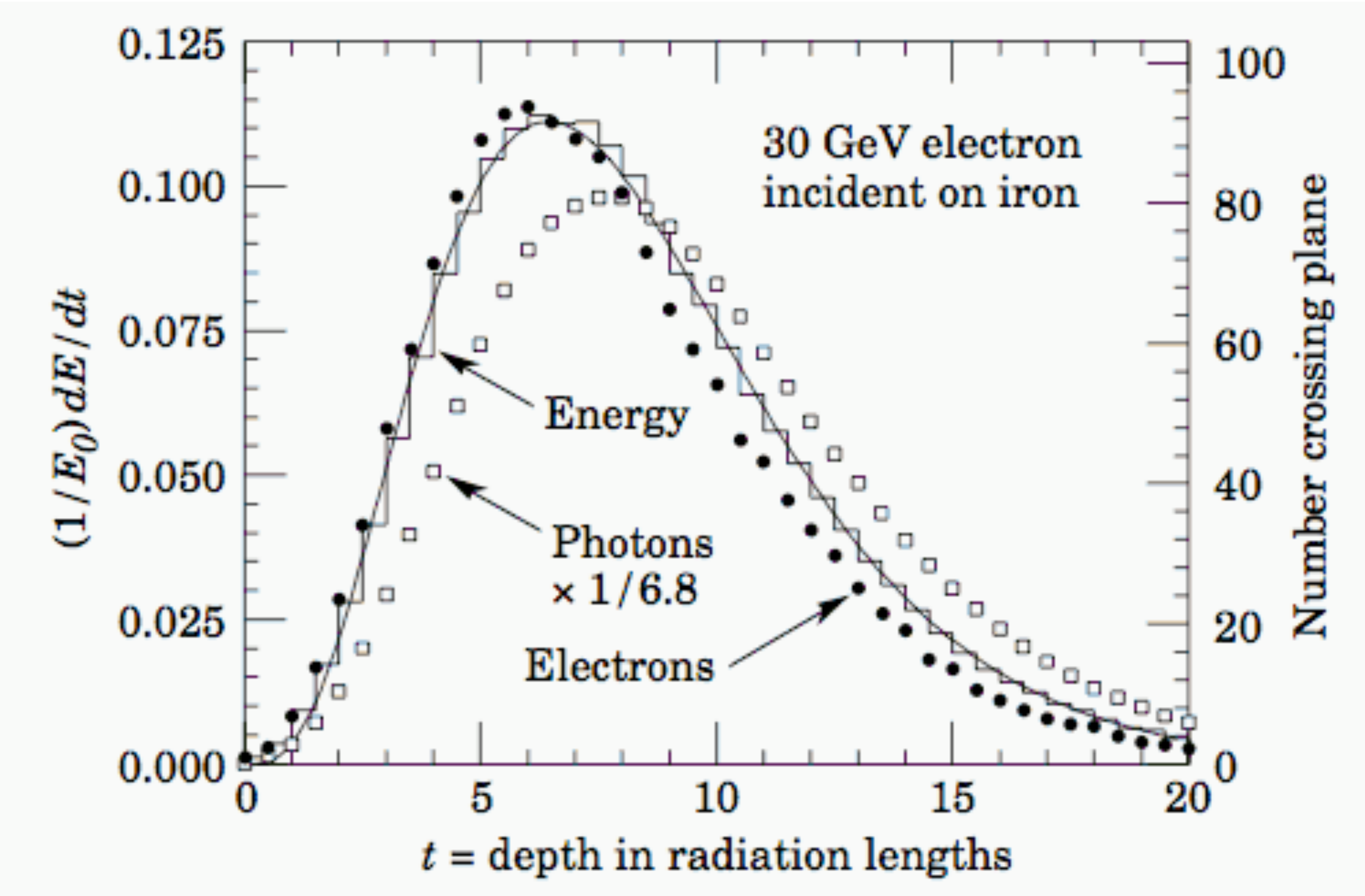
Process continues until $E(t) < E_c$

$$N^{total} = \sum_{t=0}^{t_{max}} 2^t = 2^{(t_{max}+1)} - 1 \approx 2 \cdot 2^{t_{max}} = 2\frac{E_0}{E_c}$$

$$t_{max} = \frac{\ln E_0/E_c}{\ln 2}$$

After $t = t_{max}$ the dominating processes are ionization, Compton effect and photo effect → absorption of energy.

Longitudinal profile example



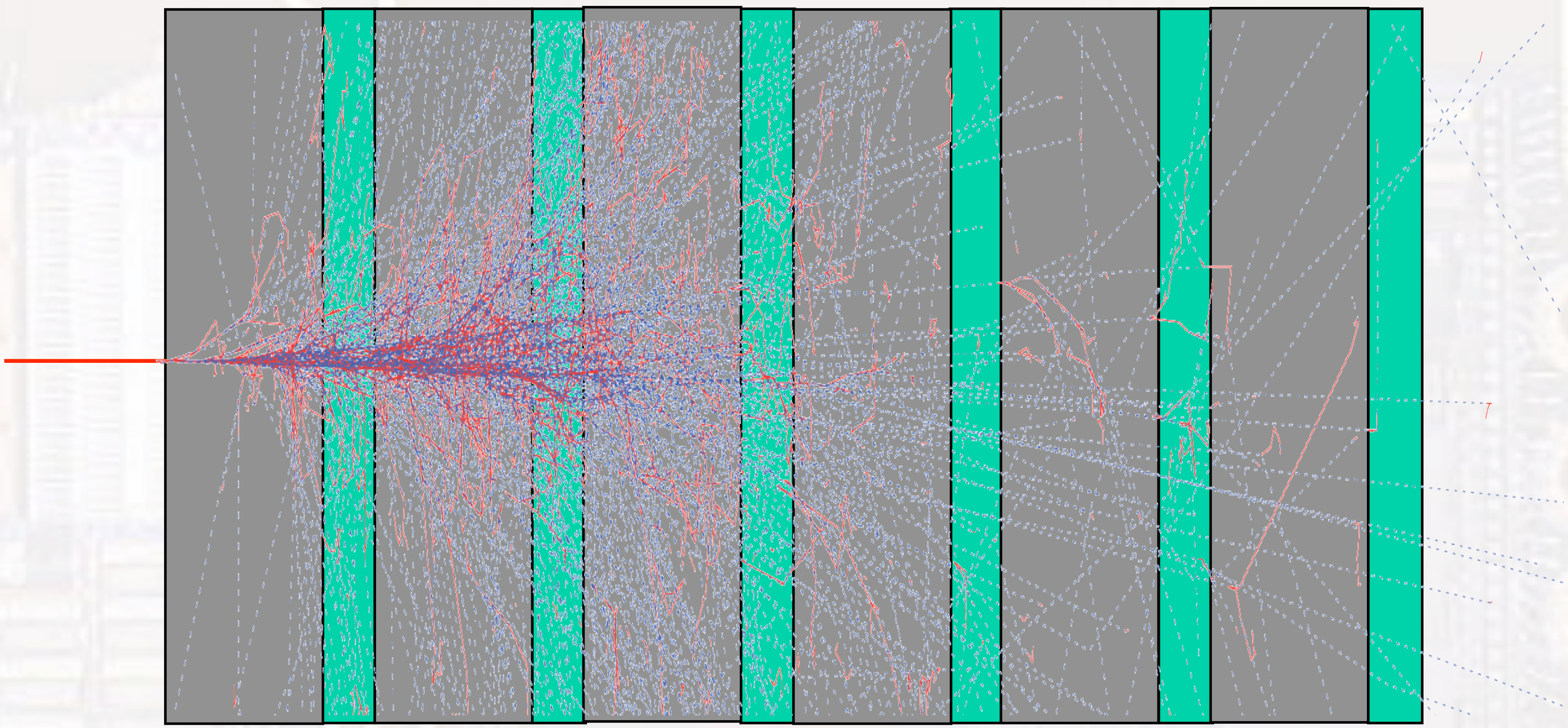
Transverse profile

- Determined by Molier radius, R_M

$$R_M = 21MeV \bullet \frac{X_0}{E_c}$$

- 99% of energy is within $3R_M$
- E_c and X_0 and thus R_M depend on material.
- Typically, transverse granularity of ECAL is chosen to match R_M .

A basic calorimeter

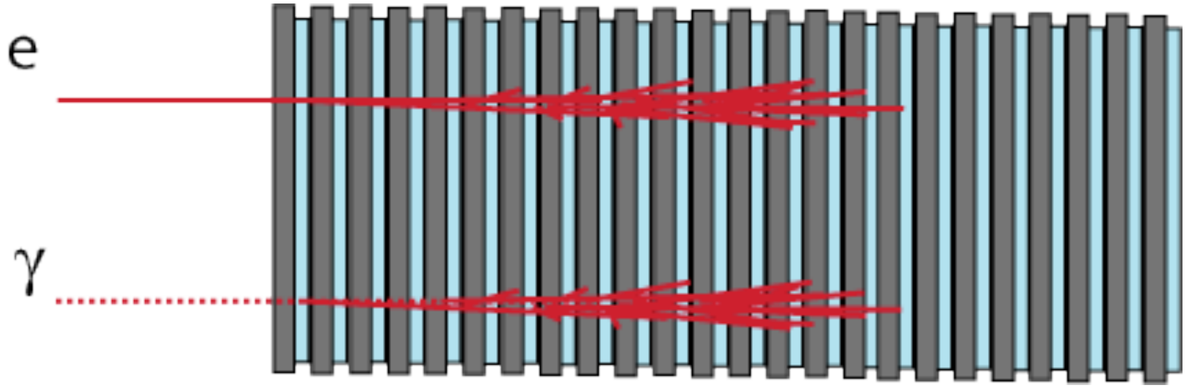


Total # of particles is proportional to energy of incoming particle

Light materials (green) produce a signal proportional to the number of charged particles traversing

Electromagnetic Calorimeter Types

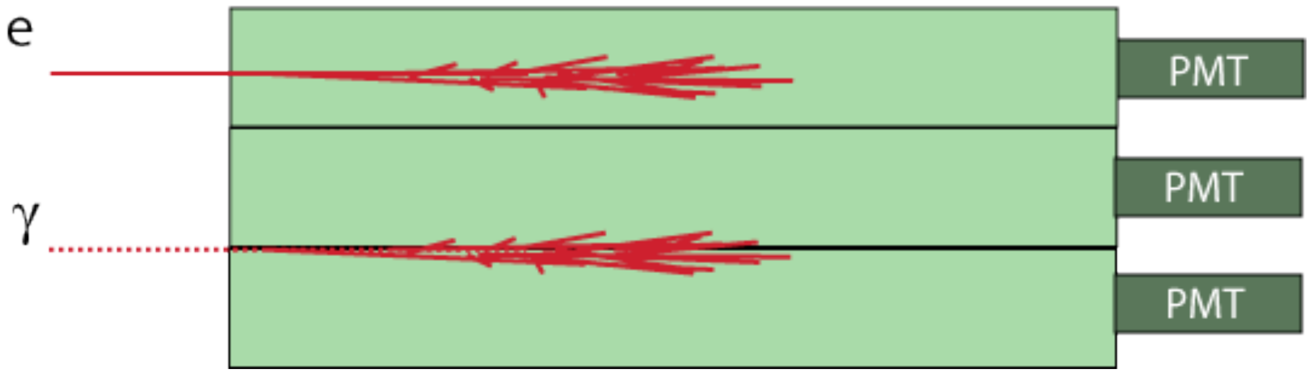
- “lead-scintillator sandwich” calorimeter



Energy resolutions:

$$\Delta E/E \sim 20\%/\sqrt{E}$$

- exotic crystals (BGO, PbW, ...)



$$\Delta E/E \sim 1\%/\sqrt{E}$$

- liquid argon calorimeter $\Delta E/E \sim 18\%/\sqrt{E}$

Electromagnetic Calorimeter Types

Homogeneous "shower counters":

Best performance from organic scintillating crystals. Example of NaI(TI) have achieved ~ $\sigma(E)/E = 0.028/\left[E(GeV)\right]^{-0.25}$. Also use lead glass, detects Cerenkov light of electrons, limited by photoelectron statistics.

Sampling calorimeters:

Layers of inactive absorber (such as Pb) alternating with active detector layers, such as scintillator or liquid. Resolutions ~7%/√E or so.

Liquid noble gases:

Counters based on liquid noble gases (with lead plates, for example) can act as ionization chambers. L Ar - Pb versions obtain ~10%/ √E. Ionization read out by electrodes attached to plates (no PMTs!). Disadvantage: slow collection times (~1 μs).

Variations in the 1990s: 'Accordion' for fast readout (front/back readout) and L Kr homogeneous detector (energy&time resolution).

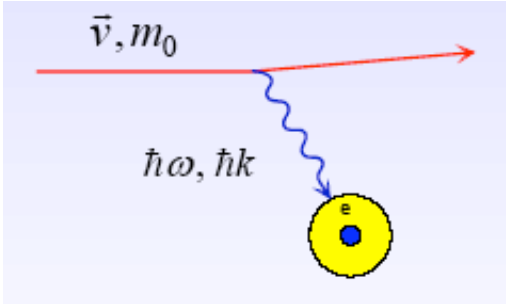
Intermezzo

Before consider strong and weak interactions of particles with matter let do a small digression on scintillators and photomultipliers (PMT)

Scintillators

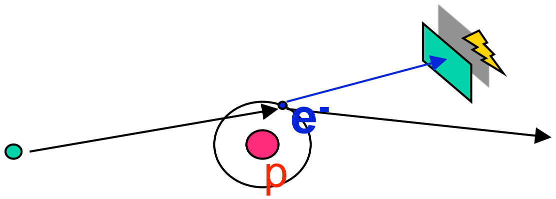
measureable signals occur via the interaction of charged particles with the detector material.

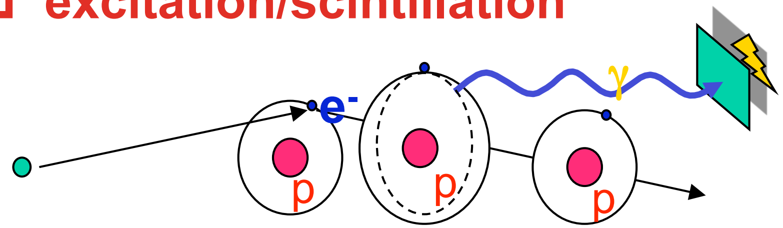
Dominant interaction is due to the coulomb interactions with the atomic *electrons* of the detector.



Depending on the $\hbar\omega$ value we may have:

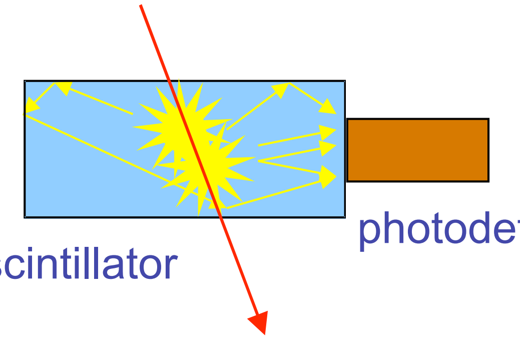
❑ **ionization** **or** ❑ **excitation/scintillation**





Ionization and excitation of atomic electrons in matter are the most common processes and allow to detect charged particles.

Introduction to Scintillators



Energy deposition by an ionizing particle or photon (γ)

→ generation
→ transmission
→ detection

} of scintillation light

Two categories

Inorganic (covered by P. Lecoq)
(crystalline structure)

- Up to 40000 photons per MeV
- High Z (good for photoeffect Z^5)
- Large variety of Z and ρ
- Undoped and doped
- ns to μs decay times
- Expensive
- Fairly Rad. Hard (100 kGy/year)

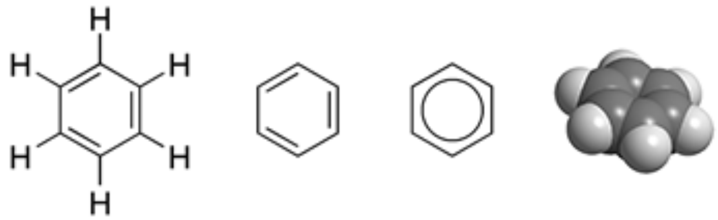
- E.m. calorimetry (e, γ)
- Medical imaging

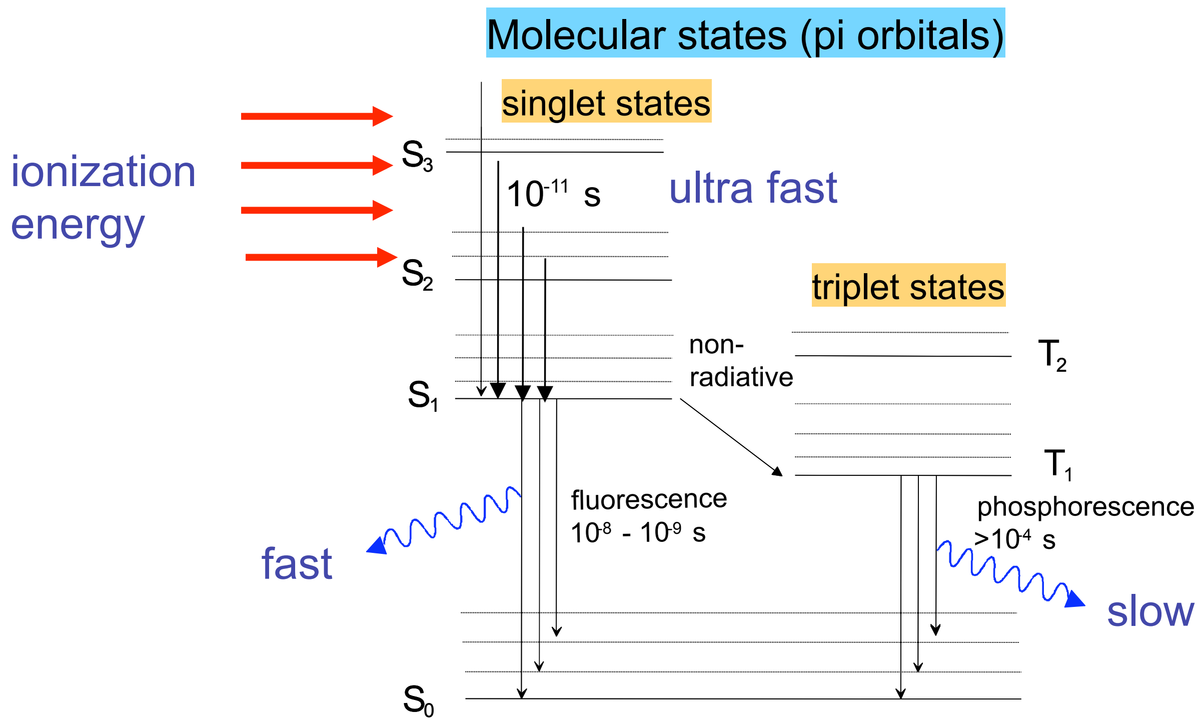
Organic
(plastics or liquid solutions)

- Up to 10000 photons per MeV
- Low Z (not good for photoeffect)
- Low density ρ~1g/cm^3
- Doped, large choice of emission wavelength
- ns decay times
- Relatively inexpensive
- Medium Rad. Hard (10 kGy/year)

Organic scintillation mechanism

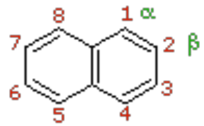
The organic scintillation mechanism is based on the pi-electrons (molecular orbitals) of the benzene ring (C_6H_6).



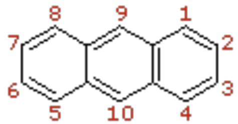


Organic scintillators exist as

crystals
(very rarely used in HEP)

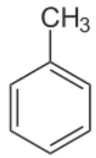


naphthalene
$C_{10}H_8$
m.p. 81° C

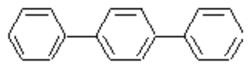


anthracene
$C_{14}H_{10}$
m.p. 217° C

liquids (solutions)
(rarely used in HEP)



e.g. toluene

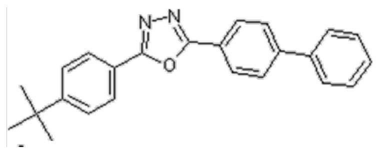


e.g. p-terphenyl

plastics (polymerized solutions)
(much used in HEP)

solvent + scintillator

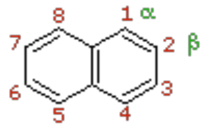
e.g. polyvinlyltoluene



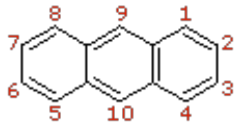
e.g. Butyl-PBD

Organic scintillators exist as

crystals
(very rarely used in HEP)



naphthalene
$C_{10}H_8$
m.p. 81° C

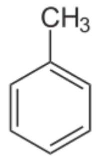


anthracene
$C_{14}H_{10}$
m.p. 217° C

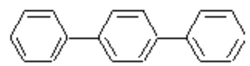
liquids
(solutions)
(rarely used in HEP)

plastics
(polymerized solutions)
(much used in HEP)

solvent + scintillator

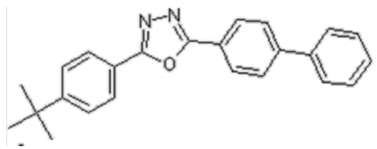


e.g. toluene



e.g. p-terphenyl

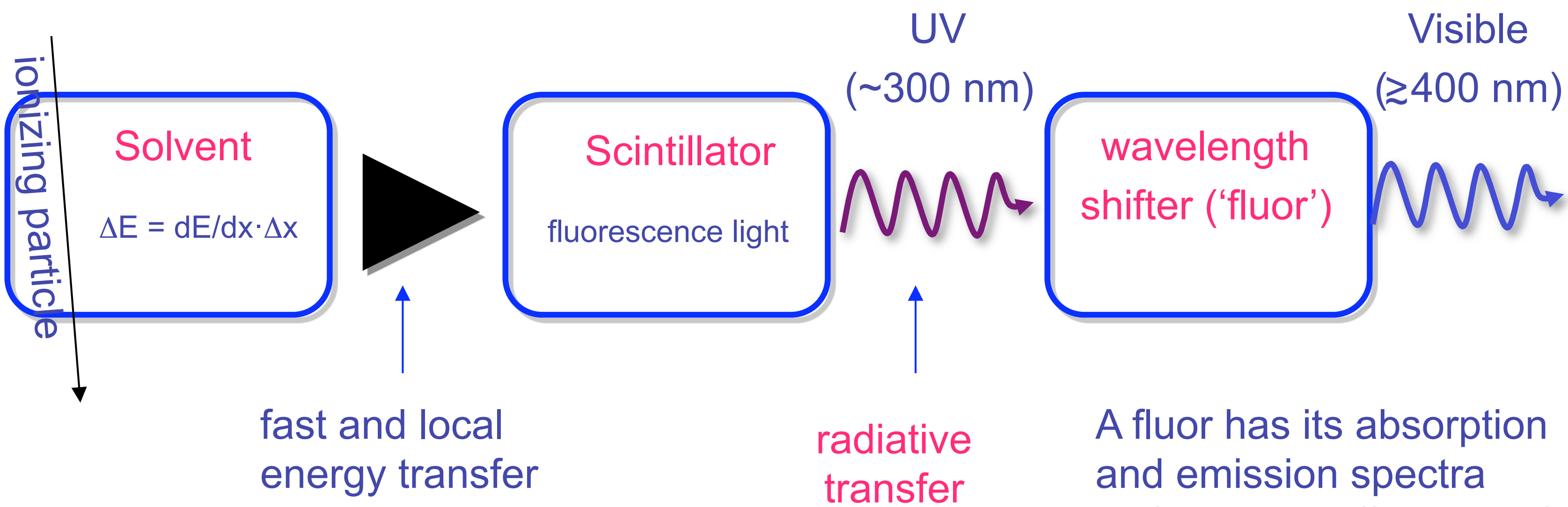
e.g. polyvinlyltoluene



e.g. Butyl-PBD

Plastic scintillators

Often they consist of a solvent + scintillator and a secondary fluor as wavelength shifter.



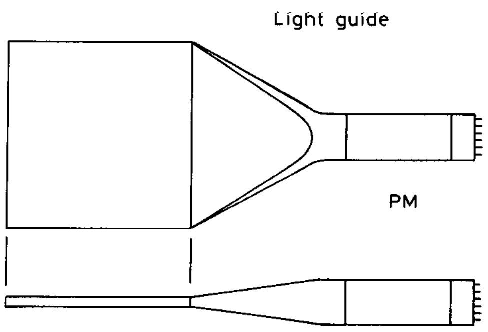
A fluor has its absorption and emission spectra shifted. The difference of the two peaks is called Stokes shift

Scintillators readout

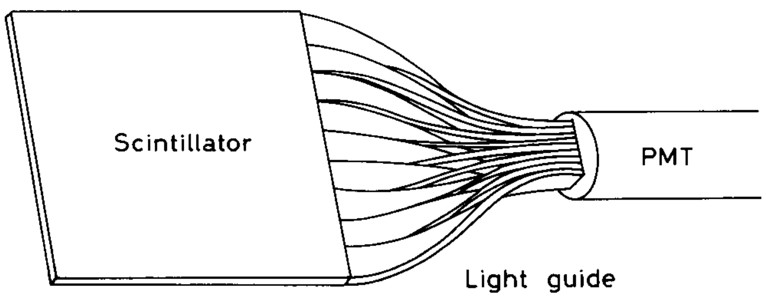
Readout has to be adapted to geometry, granularity and emission spectrum of scintillator.

Geometrical adaptation:

- Light guides: transfer by total internal reflection (+outer reflector)

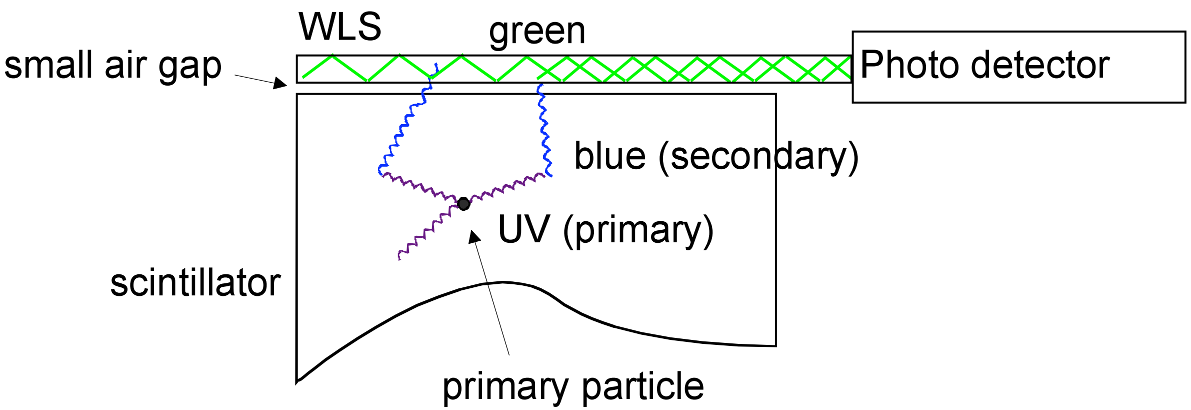


“fish tail”



adiabatic

- Wavelength shifter (WLS) bars

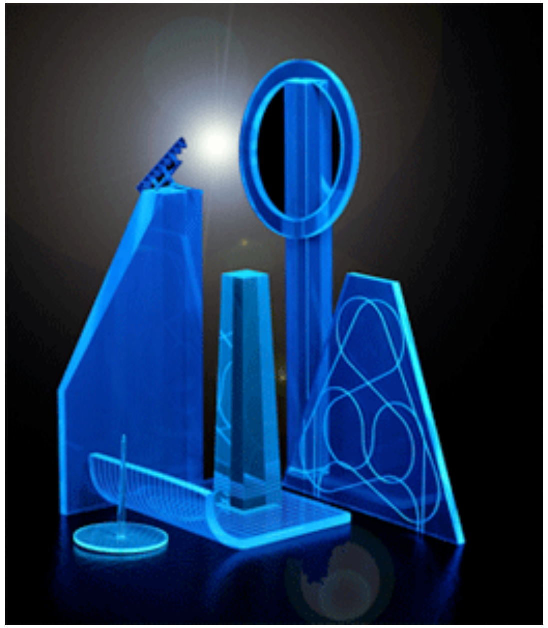


Most common applications of organic scintillators

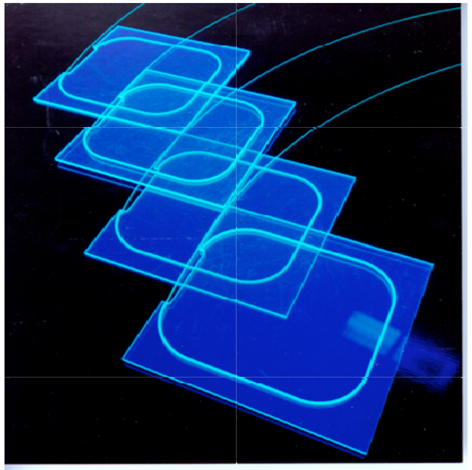
- Large volume liquid or solid detectors
- neutron detection
- underground experiments
- sampling calorimeters (HCAL in CMS or ATLAS, etc.),
- trigger counters,
- TOF counters,
- Fibre tracking

  (see below)

Michigan University: 'neutron wall'. The flat-sided glass tubes contain liquid scintillator.



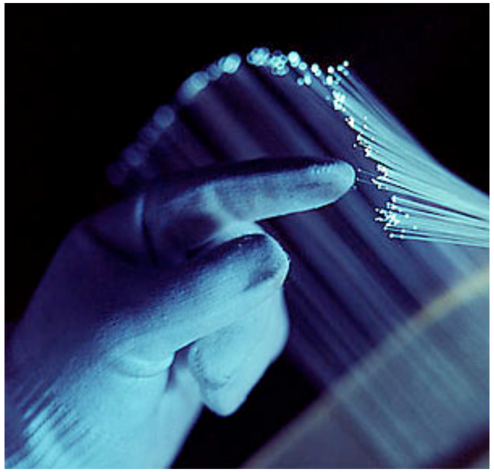
Plastic scintillators in various shapes (Saint Gobain)

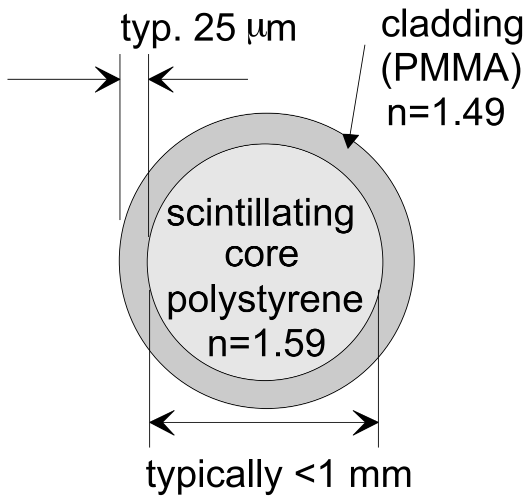


Scintillating tiles of CMS HCAL.

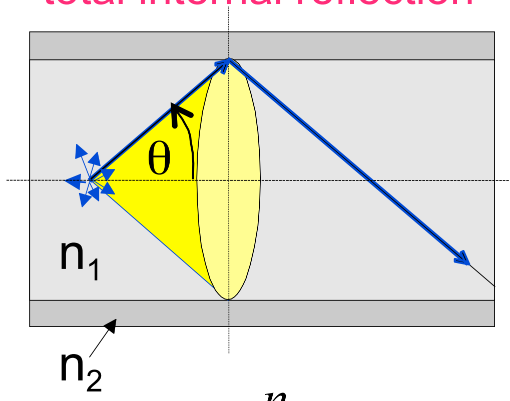
Scintillating fibres

Working principle of scintillating plastic fibres :





light transport by
total internal reflection

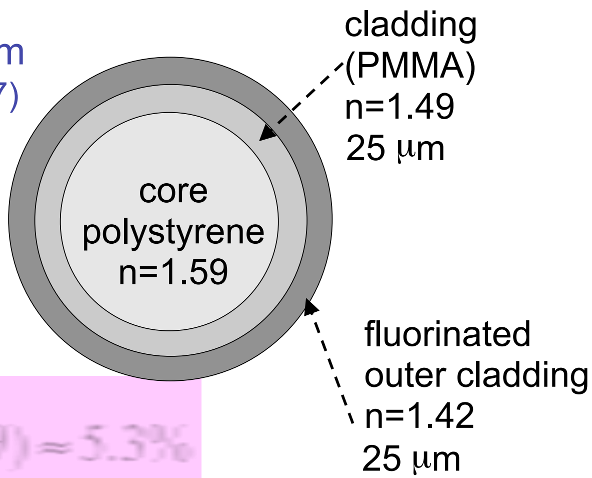


$$\theta \leq \arccos \frac{n_2}{n_1} \approx 20.4°$$

$$\frac{d\Omega}{4\pi} = 0.5\,(1 - \cos\theta) = 3\%$$

(per side)

Double cladding system
(developed by CERN RD7)



$$\frac{d\Omega}{4\pi} = 0.5\,(1 - \cos\theta) \approx 5.3\%$$

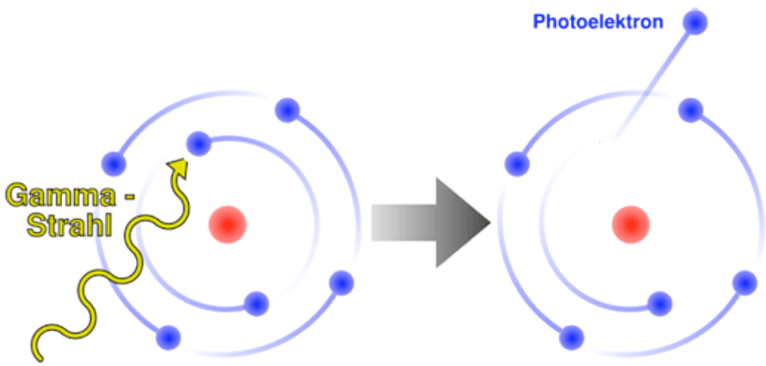
Basics of photon detection

Purpose:

- Convert light into detectable electronic signal

Principle:

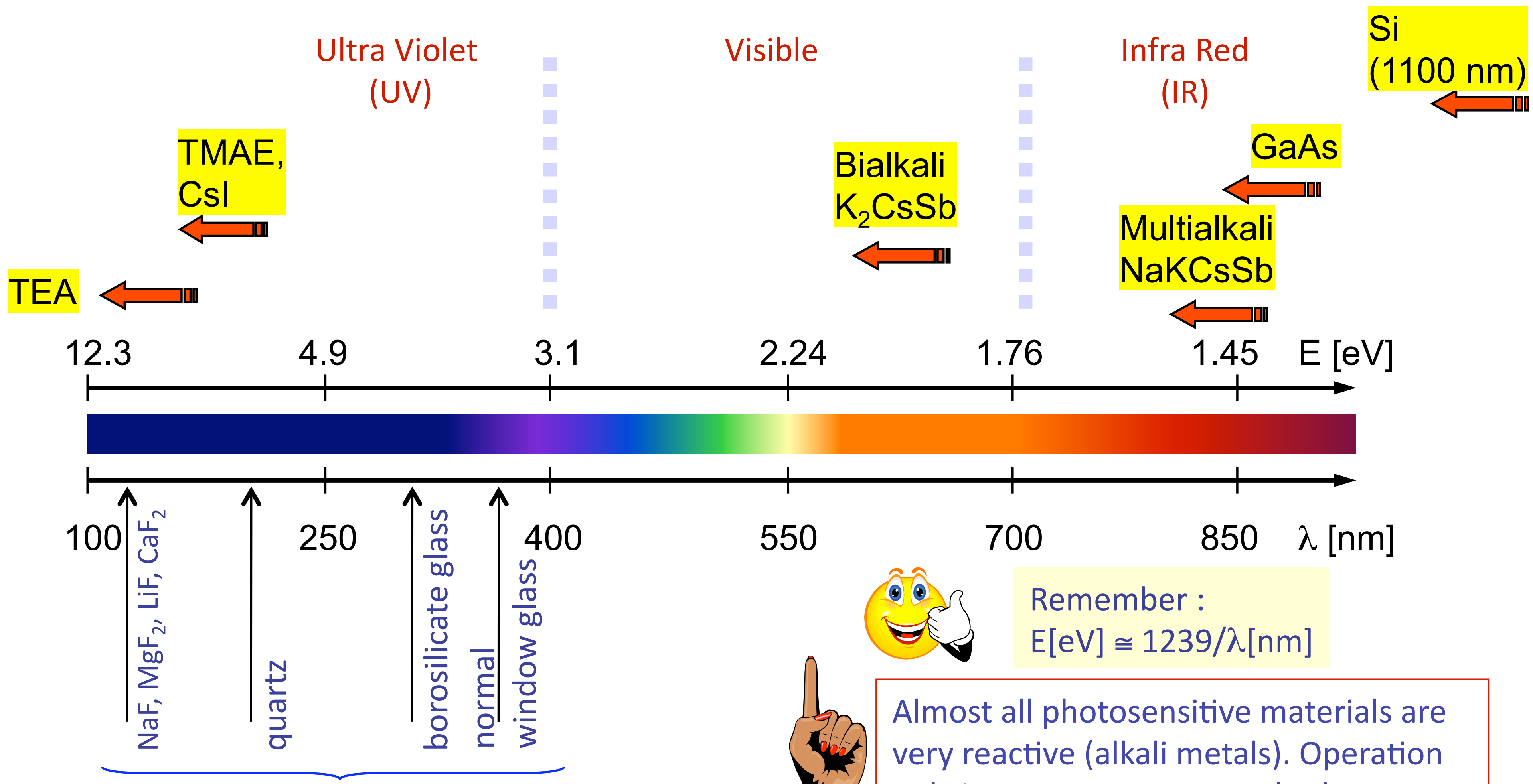
- Use photoelectric effect to 'convert' photons (γ) to photoelectrons (pe)



- Details depend on the type of the photosensitive material
- Photon detection involves often materials like K, Na, Rb, Cs (alkali metals) . They have the smallest electronegativity → highest tendency to release electrons.

Frequently used photosensitive materials / photocathodes

begin of arrow indicates threshold



Cut-off limits of window materials

Remember :
$E[eV] \cong 1239/\lambda[nm]$

Almost all photosensitive materials are very reactive (alkali metals). Operation only in vacuum or extremely clean gas. Exception: Silicon, CsI.

Requirements on photodetectors

- High sensitivity, usually expressed as:

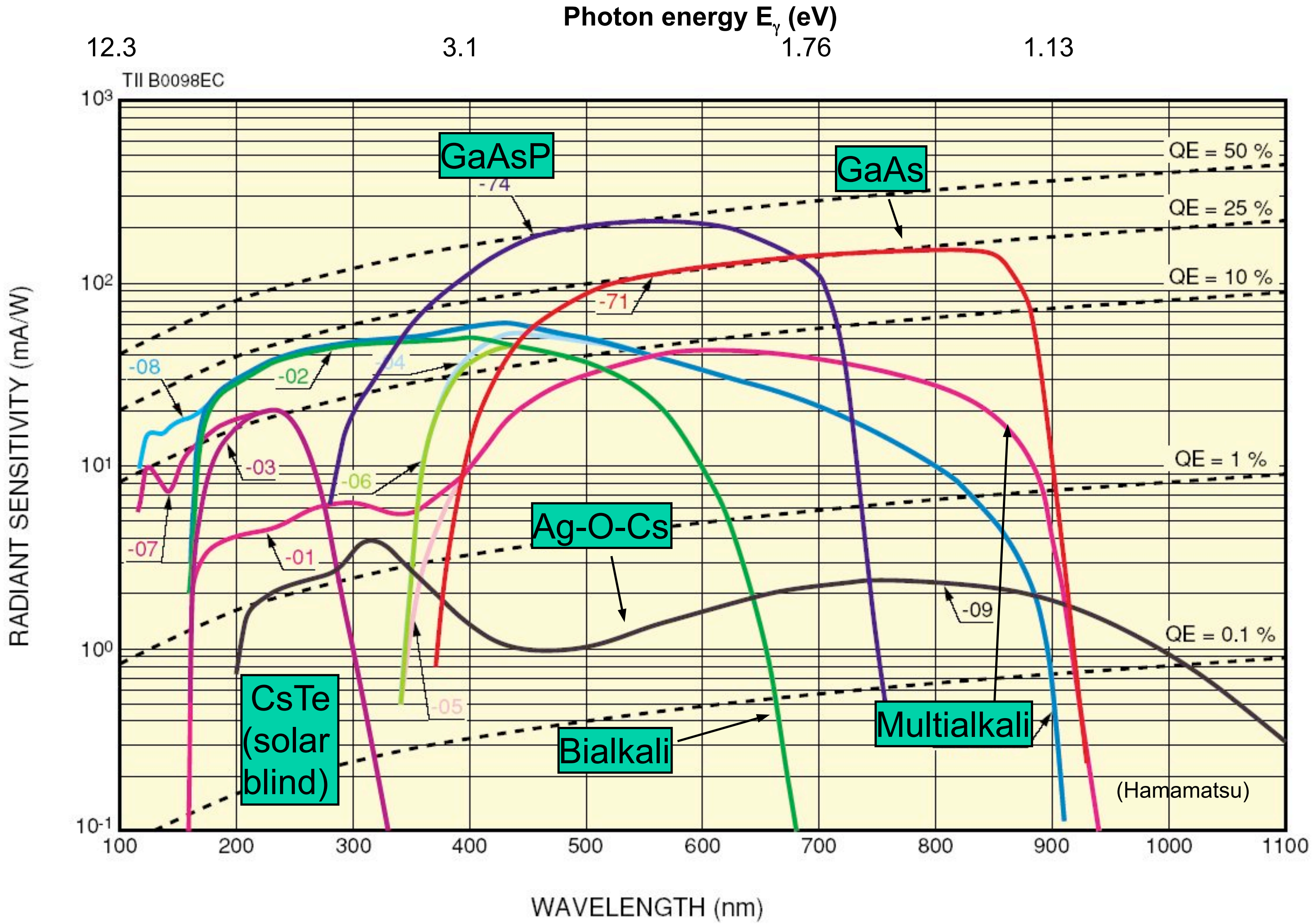
  quantum efficiency $QE(\%) = \frac{N_{pe}}{N_{\gamma}}$ or radiant sensitivity *S* (mA/W), with

  $$QE(\%) \approx 124 \cdot \frac{S(mA/W)}{\lambda(nm)}$$

QE can be >100% (for high energetic photons) !

- Good Linearity: Output signal ~ light intensity, over a large dynamic range (critical e.g. in calorimetry (energy measurment).
- Fast Time response: Signal is produced instantaneously (within ns), low jitter (<ns), no afterpulses
- Low intrinsic noise. A noise-free detector doesn't exist. Thermally created photoelectrons represent the lower limit for the noise rate ~ $A_o T^2 \exp(-eW_{ph}/kT)$. In many detector types, noise is dominated by other sources.

(External) QE of typical semitransparent photo-cathodes



Bialkali: SbKCs, SbRbCs Multialkali: $SbNa_2KCs$ (alkali metals have low work function)

Latest generation of high performance photocathodes

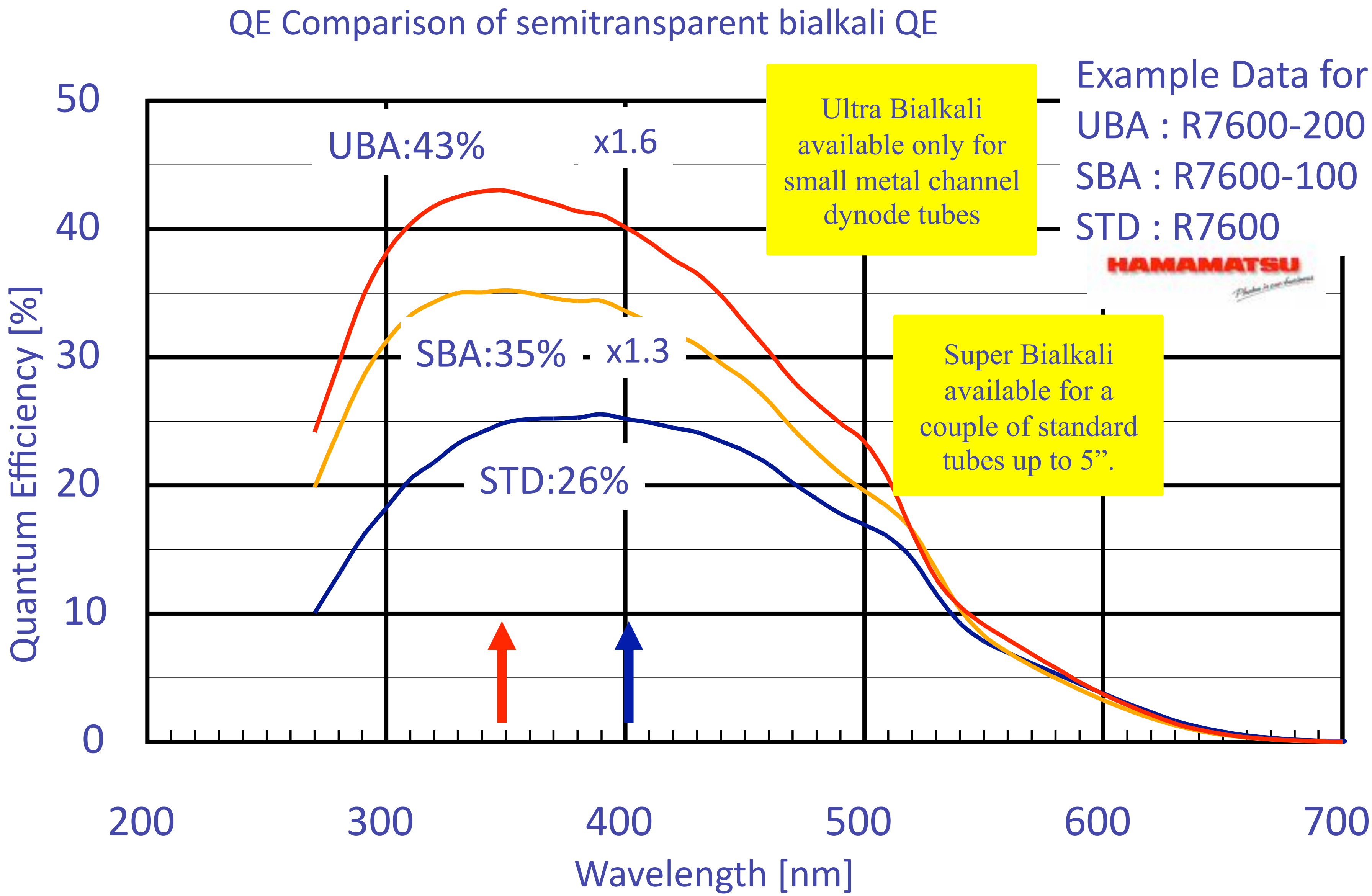


Photo-multiplier tubes (PMT's)

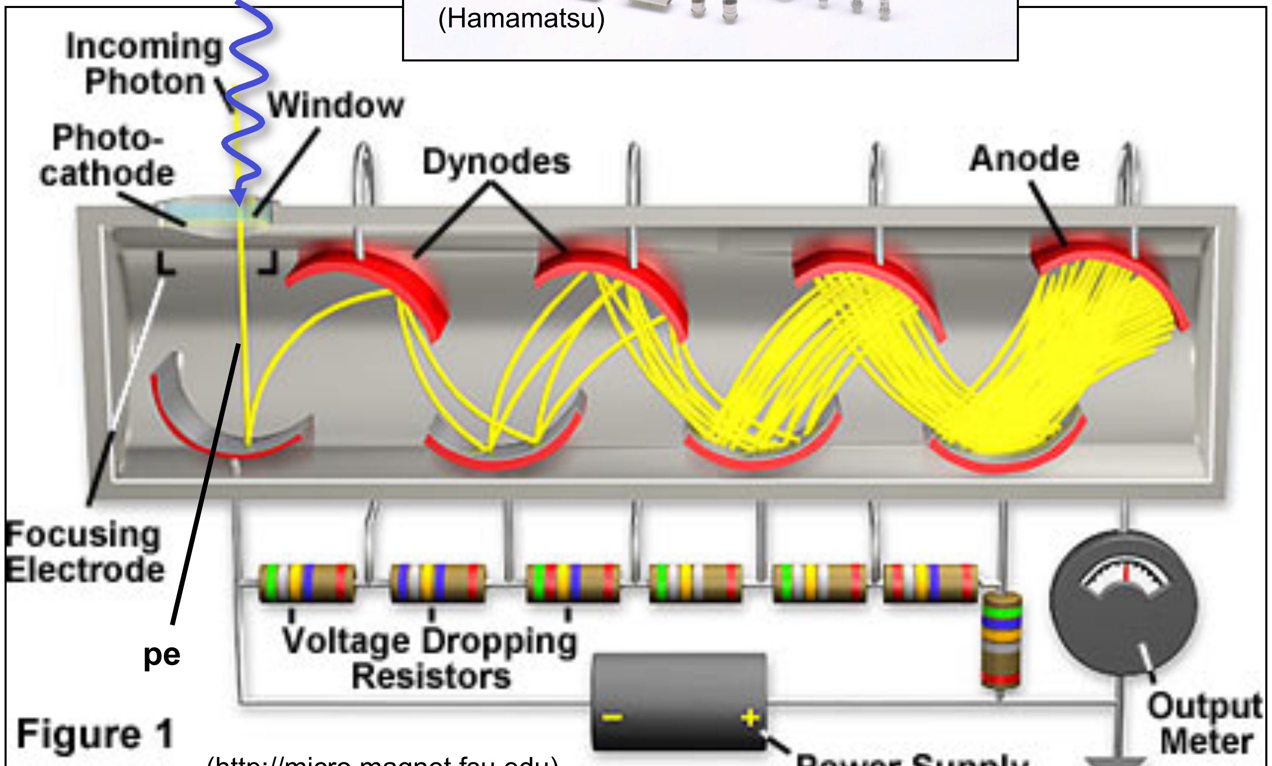
Basic principle:

- Photo-emission from photo-cathode
- Secondary emission from N dynodes:
  - dynode gain $g \approx$ 3-50 (function of incoming electron energy E);
  - total gain M:

$$M = \prod_{i=1}^{N} g_i$$

- Example:
  - 10 dynodes with $g = 4$
  - $M = 4^{10} \approx 10^6$

(Hamamatsu)

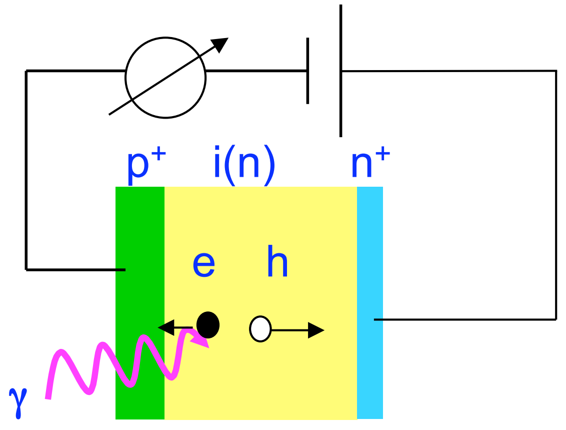


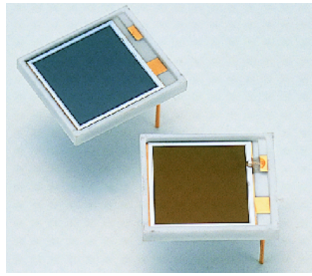
(http://micro.magnet.fsu.edu)

Solid-state photon detectors

(Si) - Photodiodes:

- P(I)N type
- p layer very thin (<1 μm), as visible light is rapidly absorbed by silicon (see next slide);
- High QE (80% @ $\lambda \approx$ 700nm);
- No gain: cannot be used for single photon detection;



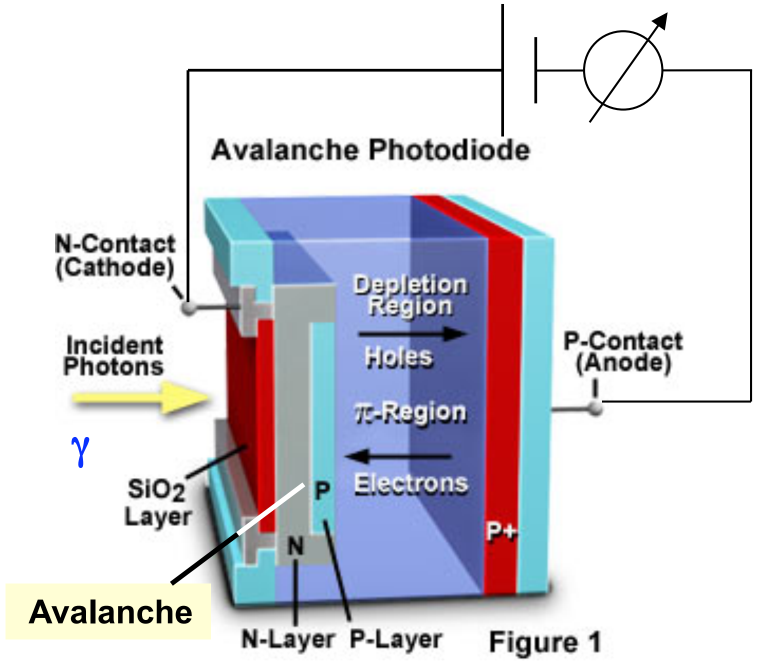


Avalanche photodiode:

- High reverse bias voltage: typ. 100-200 V

$\Rightarrow$ due to doping profile, high internal field (>10^5 V/cm) leads to avalanche multiplication;

- High gain: typ. 100-1000;
- Rel. high gain fluctuations (excess noise)

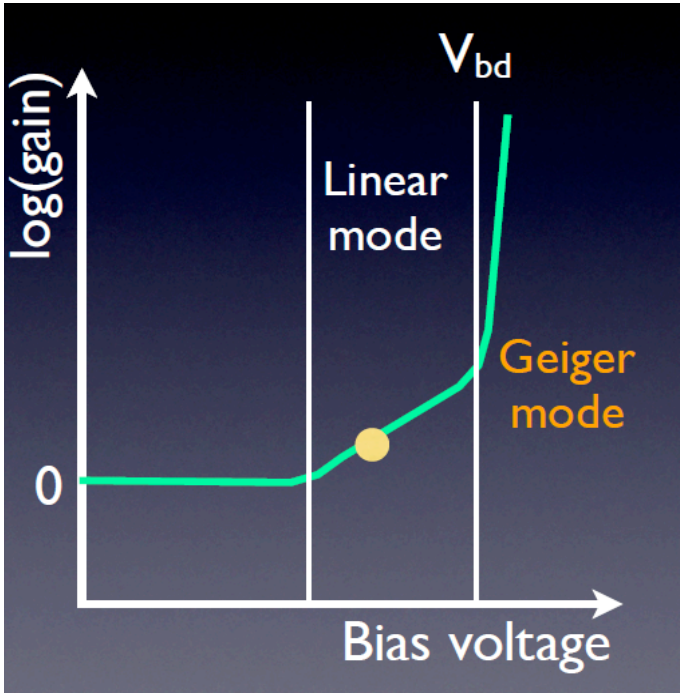


(http://micro.magnet.fsu.edu)

Solid-state … Geiger mode Avalanche Photodiode (G-APD)

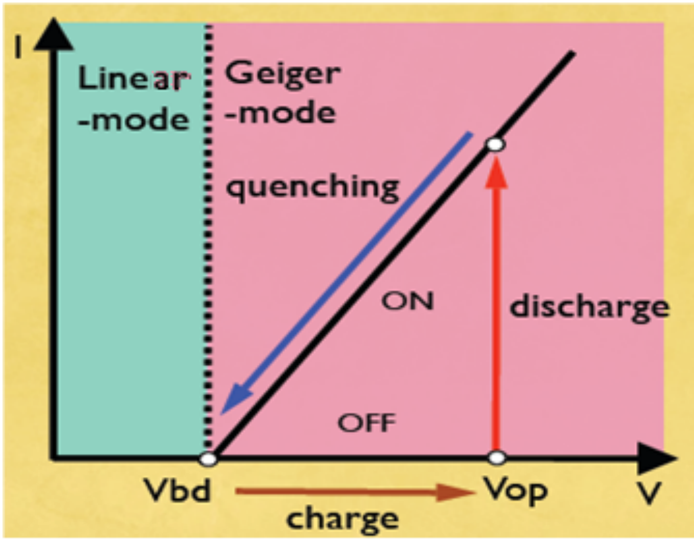
How to obtain higher gain (= single photon detection) without suffering from excessive noise ?

Operate APD cell in Geiger mode (= full discharge), however with a (passive) quenching.



J. Haba, RICH2007

J. Haba, RICH2007



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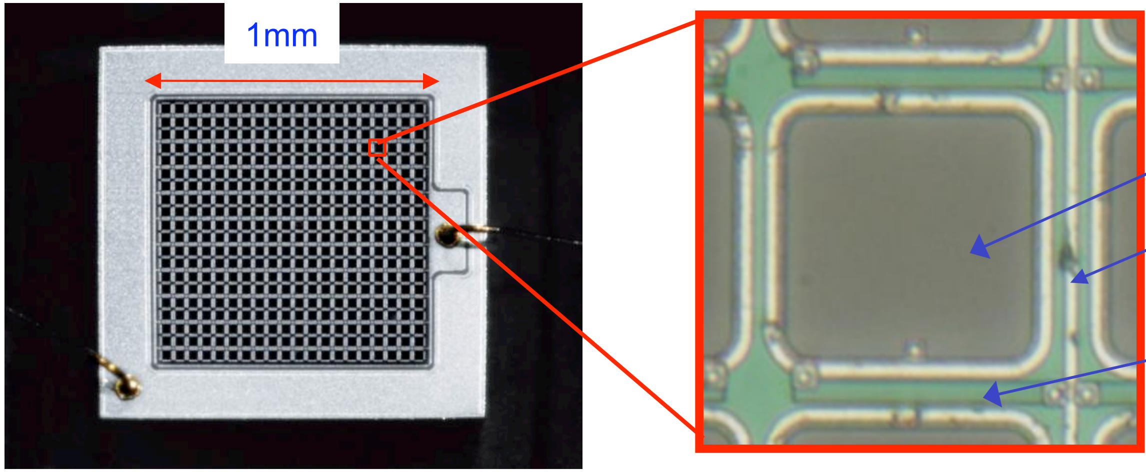
Multi pixel G-APD, called G-APD, MPPC, SiPM, …



100 – several 1000 pix / mm^2

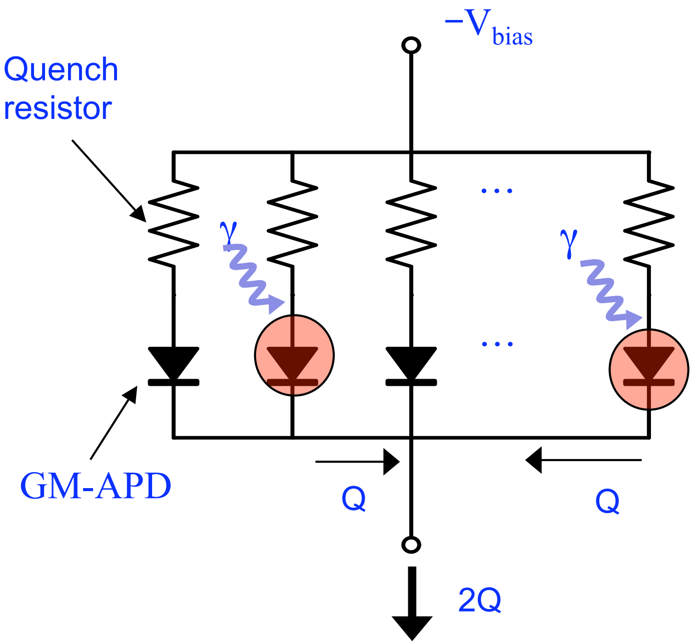
GM-APD

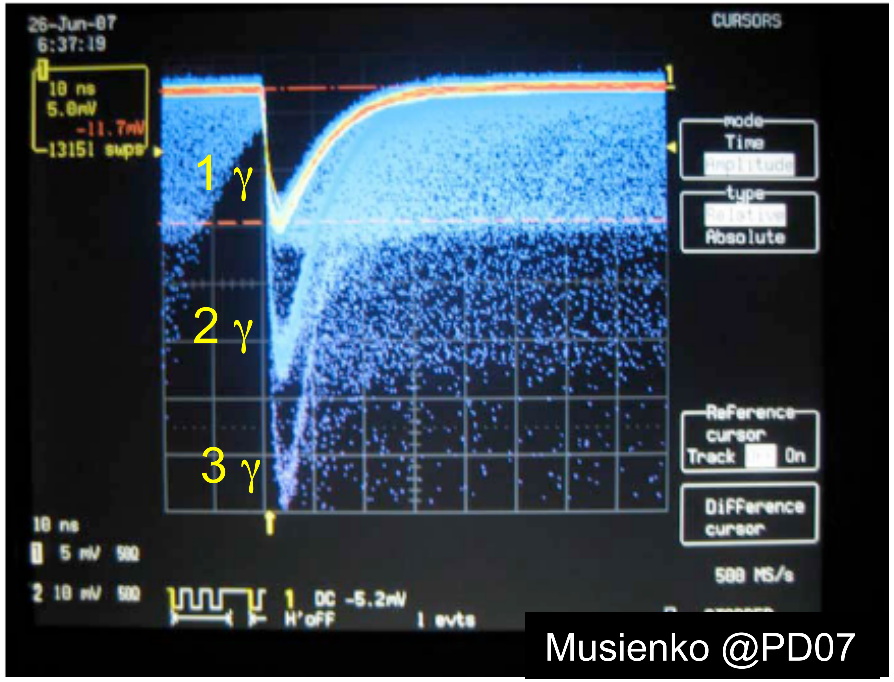
Bias bus

Quench resistor

Only part of surface is photosensitive!

Sizes up to 5×5 mm2 now standard.



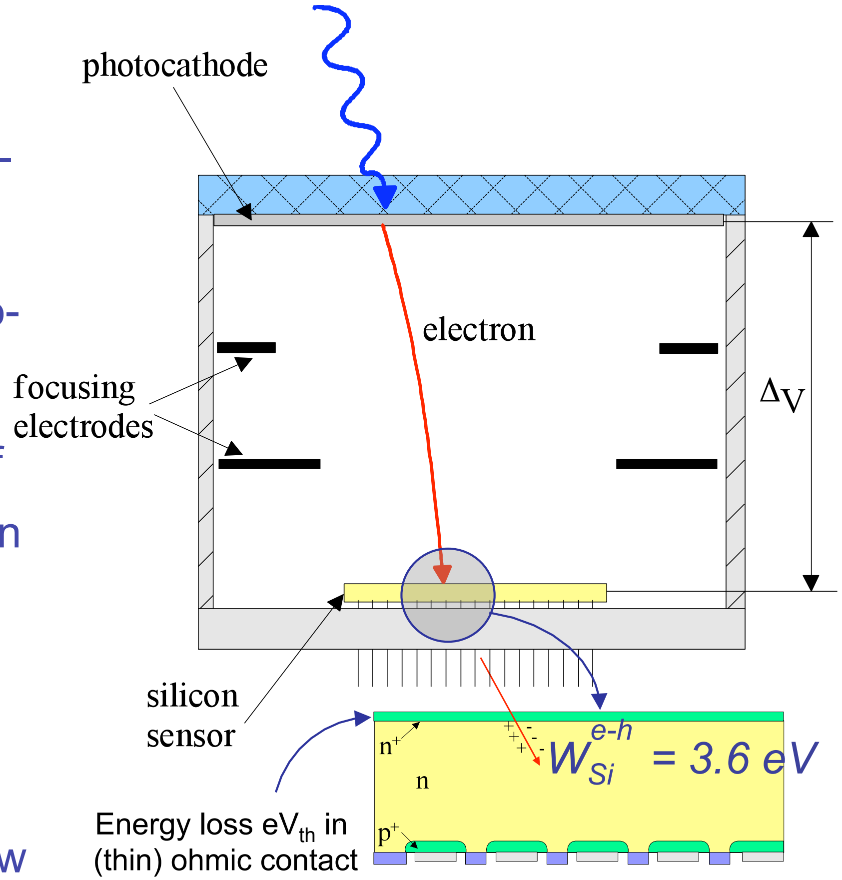


Quasi-analog detector allows photon counting with a clearly quantized signal

Hybrid Photon Detectors (HPD's)

Basic principle:

- Combination of vacuum photon detectors and solid-state technology;
- Input: collection lens, (active) optical window, photo-cathode;
- Gain: achieved *in one step* by energy dissipation of keV pe's in solid-state detector anode; this results in low gain fluctuations;
- Output: direct electronic signal;
- Encapsulation of Si-sensor in the tube implies:
  - compatibility with high vacuum technology (low outgassing, high T° bake-out cycles);
  - internal (for speed and fine segmentation) or external connectivity to read-out electronics;
  - heat dissipation issues;



$$M = \frac{e(\Delta V - Vth)}{W_{Si}}$$

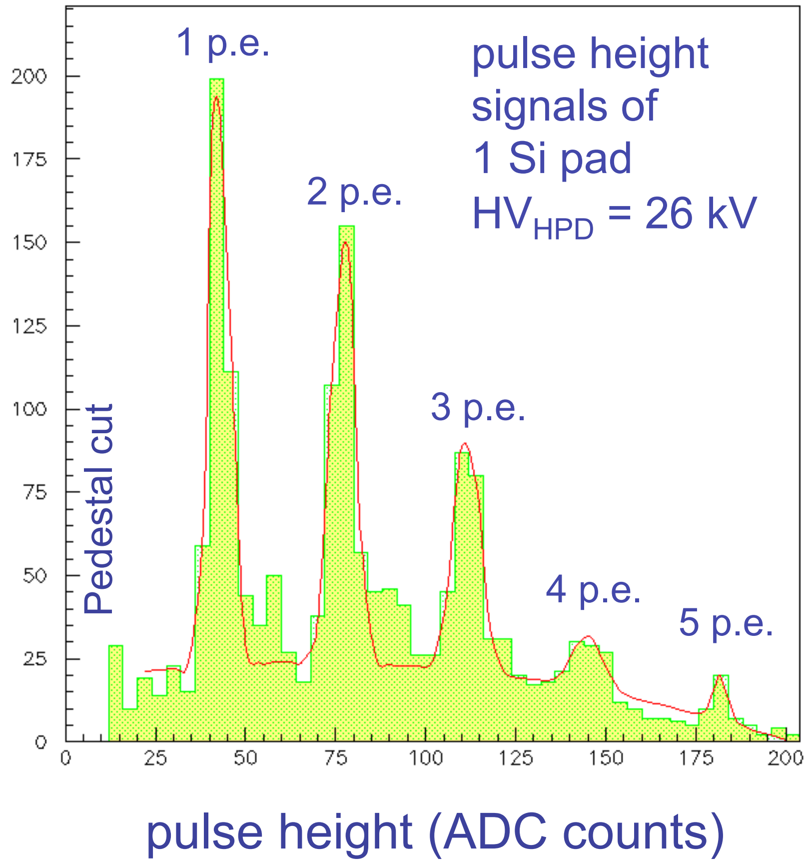
ΔV = 20 kV
→ M ~ 5000

$$\sigma_M = \sqrt{F \times M}$$

F = Fano factor
F_{Si} ~ 0.1

Hybrid Photon Detectors (HPD's)

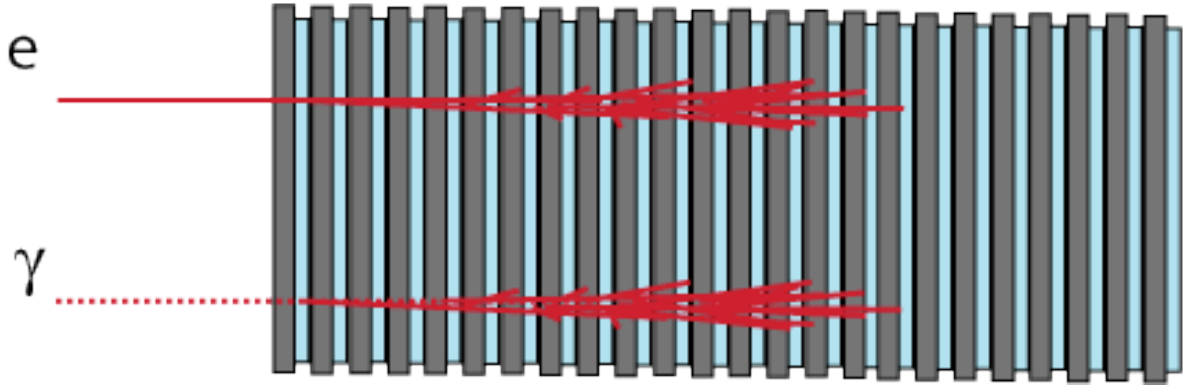
10-inch prototype HPD (CERN)
for Air Shower Telescope CLUE.



Photon counting. Continuum due to electron back scattering.

Electromagnetic Calorimeter Types

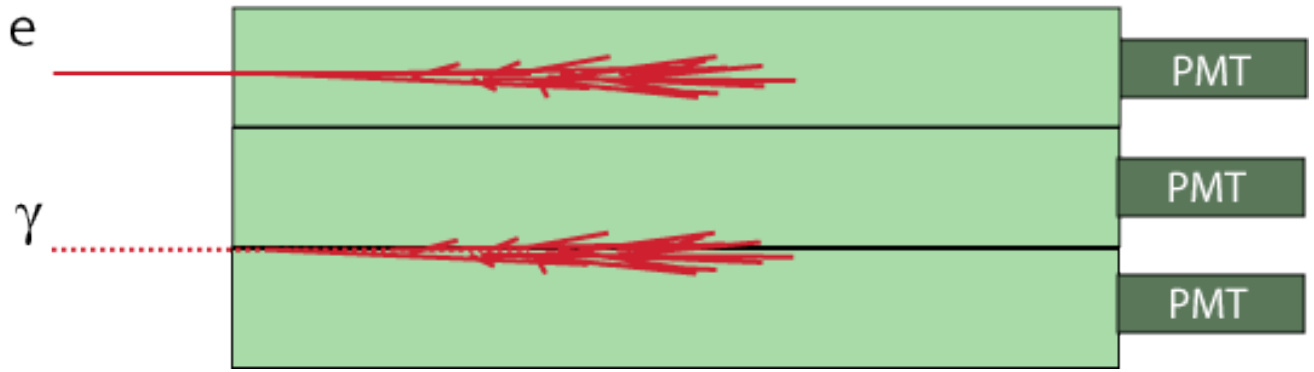
- “lead-scintillator sandwich” calorimeter



Energy resolutions:

$\Delta E/E \sim 20\%/\sqrt{E}$

- exotic crystals (BGO, PbW, ...)



$\Delta E/E \sim 1\%/\sqrt{E}$

- liquid argon calorimeter $\Delta E/E \sim 18\%/\sqrt{E}$

Interaction of Particle with Matter

Nuclear interaction

→ Much more complex than EM interactions

→ A hadron strikes a nucleus

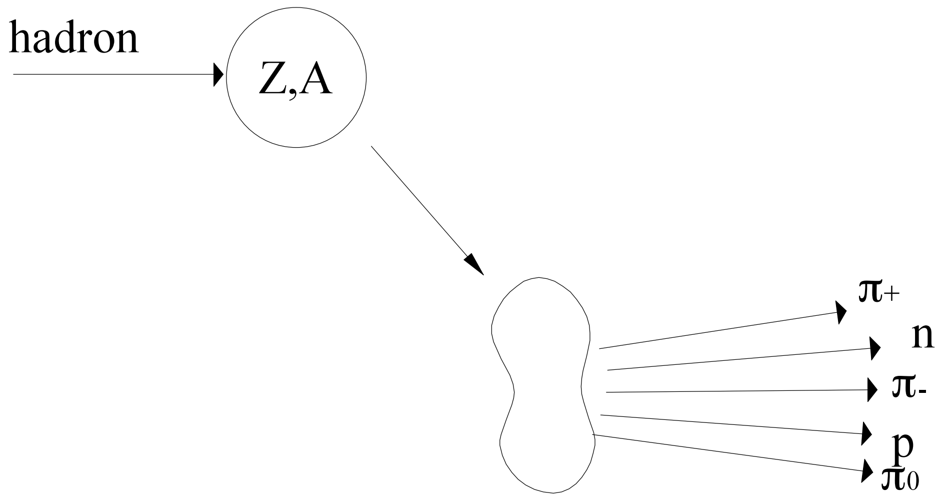
→ Interaction between partons

→ Excitation and breakup of the nucleus

→ Nucleus fragments

→ Production of secondary particles:

Charged hadrons: $\pi^{\pm}$, p, …
Neutral hadrons: n, π^0, …
Charged leptons: $\mu^{\pm}$, …
Neutral leptons: η
Low energy γ, etc…



→ Total cross-section for interaction of a hadron with matter:

$$\sigma_{tot} = \sigma_{abs} + \sigma_{el} + \sigma_q$$

σ_{tot} = total cross-section
σ_{abs} = absorption cross-section (inelastic interaction)
σ_{el} = elastic cross-section (hadron is preserved)
σ_q = quasi-elastic cross-section (hadron is preserved)

Interaction of Particle with Matter

Nuclear interaction

→ Several processes contribute to the hadron-matter interaction

→ Only (about) half of the primary hadron energy is passed on to fast secondary particles

→ The other half is consumed in production of slow pions and other process:

→ Nuclear excitation

→ Nucleon spallation → slow neutrons

→ etc..

For example, in lead (Pb):
Nuclear break-up (invisible) energy: 42%
Ionization energy: 43%
Slow neutrons ($E_K \sim 1$ MeV): 12%
Low energy λ's ($E_\gamma \sim 1$ MeV): 3%

→ Great part of this energy is "lost" : binding energy of the nucleus
production of neutrinos, etc

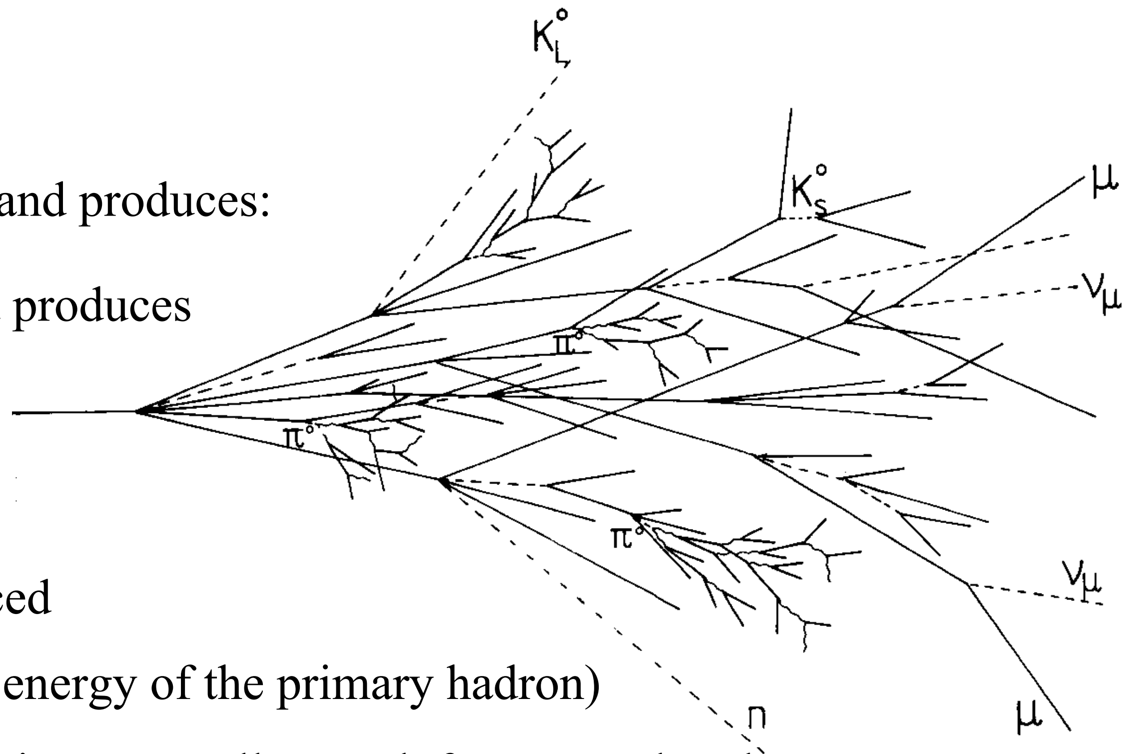
→ Part can be recovered: slow neutrons can interact with H atoms in active material like scintillator

Development of Hadronic Showers

Hadronic shower

→ Process similar to EM shower:

  → Secondary particles interact and produces:
  → tertiary particles
  → tertiary particles interact and produces
  → …… (and so forth)



→ However, processes involved are much more complex

  → Many more particles produced

  → Multiplicity $\propto \ln(E)$ (E = energy of the primary hadron)

→ Shower ceases when hadron energies are small enough for energy loss by ionization or to be absorbed in a nuclear process.

→ The longitudinal development of the shower scales with the nuclear interaction length, $\boldsymbol{\lambda_I}$:

$$\lambda_I = \frac{A}{N_A \sigma_{abs}}$$

→ The secondary particles are produced with large transverse momentum $\langle p_T \rangle > 0.35\ \text{GeV/c}$
Consequently, hadronic showers spread more laterally than EM showers.

Hadronic Interactions

- Hadrons create showers via strong interactions just like electrons and photons create them via EM.
- Mean energy of pion with initial energy E_0 after traversing material depth λ:

$$\langle E \rangle = E_0 e^{-X/\lambda}$$

- Mean energy of electron with initial energy E_0 after traversing material depth X_0 :

$$\langle E \rangle = E_0 e^{-X/X_0}$$

X_0 = radiation length

λ = interaction length or hadronic absorption length

X_0 and λ for some materials

Material	X_0	λ
H_2	63	52.4
Argon	18.9	119.7
Iron	13.8	131.9
BGO	8.0	164

Units of g/cm^2

E.g., a pion takes ~10x the depth in Iron to loose its energy than an electron with the same energy.

E.g. within the depth of X_0 in BGO, a pion looses only 5% of its energy, while an electron looses 63% of its energy, on average.

Development of Hadronic Showers

Hadronic shower

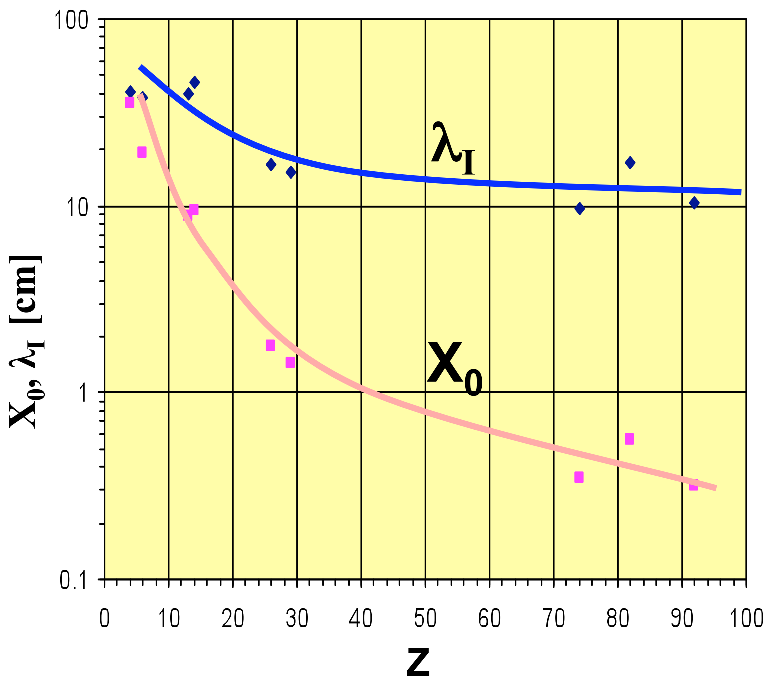
→ At **energies > 1 GeV**, cross-section depends little on energy:

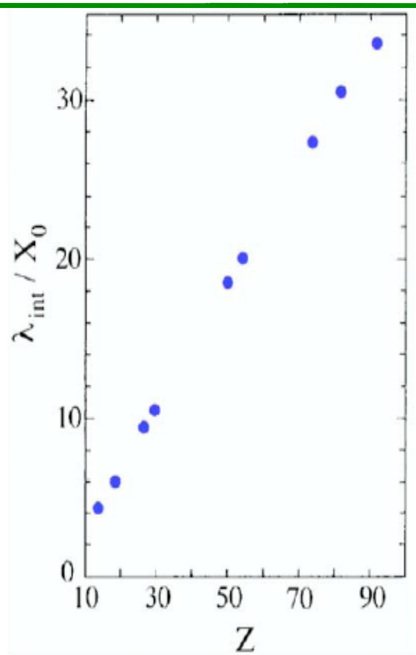
$$\sigma_{abs} \approx \sigma_0 A^{0.7} \,, \quad \sigma_0 \approx 35\ mb \quad \Rightarrow$$

$$\lambda_I \propto A^{1/3}$$

→ For $Z > 6$ → $\lambda_I > X_0$

Material	Z	A	ρ [g/cm³]	X_0 [g/cm²]	λ_I [g/cm²]
Hydrogen (gas)	1	1.01	0.0899 (g/l)	63	50.8
Helium (gas)	2	4.00	0.1786 (g/l)	94	65.1
Beryllium	4	9.01	1.848	65.19	75.2
Carbon	6	12.01	2.265	43	86.3
Nitrogen (gas)	7	14.01	1.25 (g/l)	38	87.8
Oxygen (gas)	8	16.00	1.428 (g/l)	34	91.0
Aluminium	13	26.98	2.7	24	106.4
Silicon	14	28.09	2.33	22	106.0
Iron	26	55.85	7.87	13.9	131.9
Copper	29	63.55	8.96	12.9	134.9
Tungsten	74	183.85	19.3	6.8	185.0
Lead	82	207.19	11.35	6.4	194.0
Uranium	92	238.03	18.95	6.0	199.0

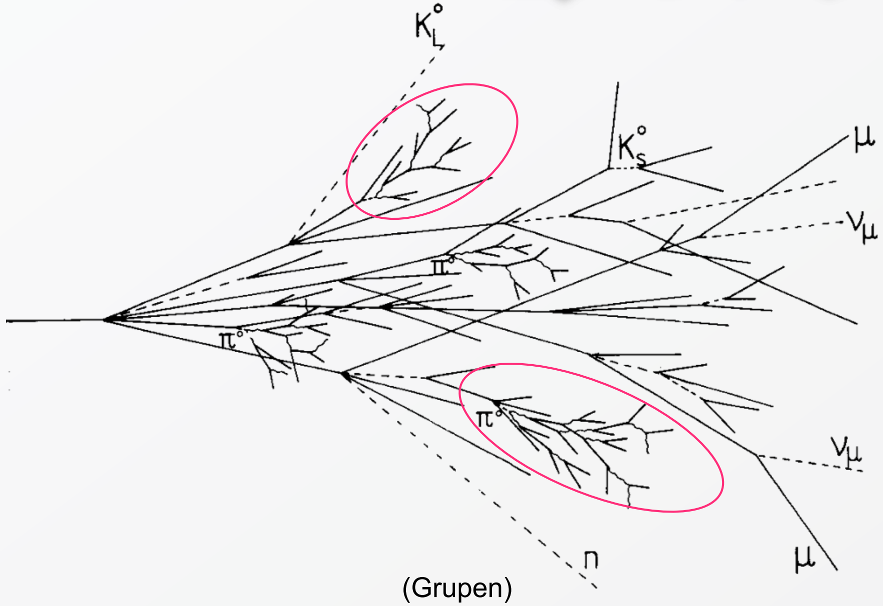




Comparing X_0 and λ_I, we understand why Hadronic calorimeters are in general larger than EM calorimeters

Hadronic cascades

Various processes involved. Much more complex than electromagnetic cascades.



(Grupen)

A hadronic shower contains two components:

hadronic + **electromagnetic**

↓

- charged hadrons p, $\pi^\pm$, $K^\pm$,
- nuclear fragmets ….
- breaking up of nuclei (binding energy)
- neutrons, neutrinos, soft γ's, muons

↓

neutral pions $\pi^0 \rightarrow 2\gamma$

→ electromagnetic cascades

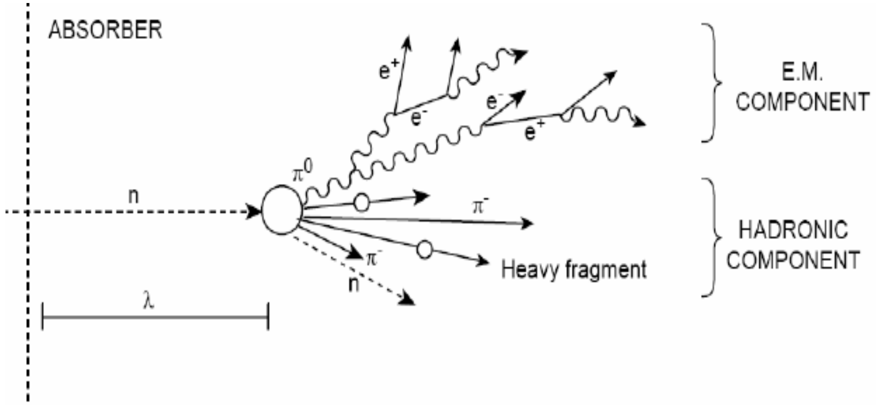
$$n(\pi^0) \approx \ln E(GeV) - 4.6$$

example $E = 100$ GeV: $n(\pi^0) \approx 18$

invisible energy → large energy fluctuations → limited energy resolution

Development of Hadronic Showers

Energy measurement



Energy measurement

→ Based on the same principle as for the electromagnetic shower

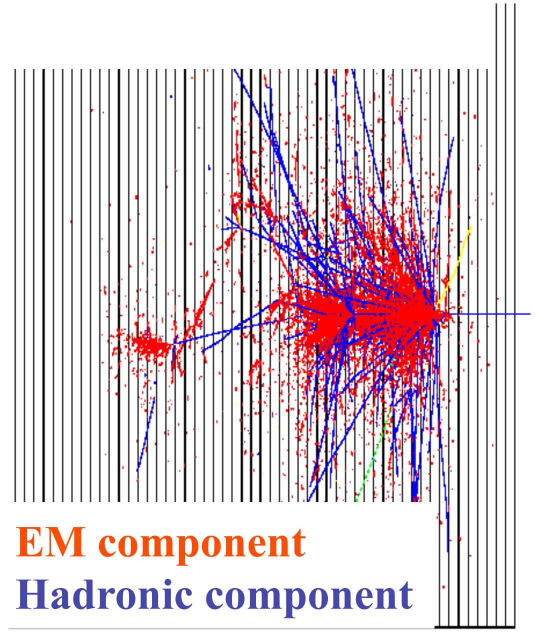
→ Shower develops until a E_{min}

→ Energy deposition by ionization ($\pi^0 \rightarrow \gamma\gamma$ and charged hadrons) and low-energy hadronic activity (fission, neutron elastic scattering off proton, etc)

→ There are two components in the mechanism of energy deposition

→ **Electromagnetic component**, due to $\pi^0 \rightarrow \gamma\gamma$ with subsequent EM photon interactions

→ **Hadronic**

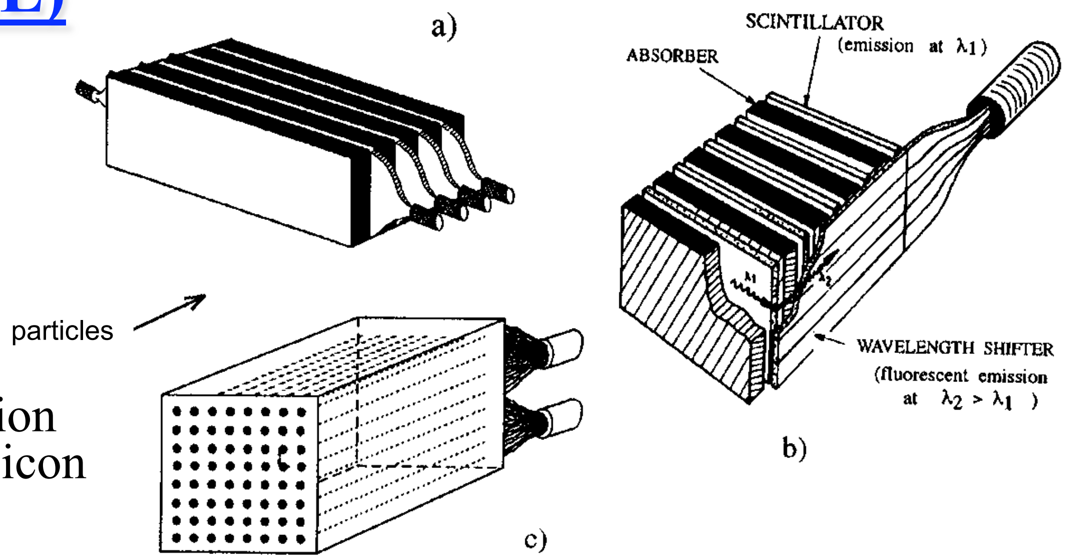


→ The end product is sampled and converted into signal.

→ The ratio between the efficiency in energy deposition due to EM interaction is and hadronic interaction is given by **e/h**

Hadronic Calorimeter

Hadronic Calorimeter (HCAL)



→ Hadronic calorimeters are usually sampling calorimeters

→ The active medium made of similar material as in EM calorimeters:

→ Scintillator (light), gas (ionization chambers, wired chambers), silicon (solid state detectors), etc

→ The passive medium is made of materials with longer interaction length λ_I

→ Iron, uranium, etc

→ Resolution is worse than in EM calorimeters, usually in the range:

$$\frac{\sigma(E)}{E} \propto \frac{(35\% - 80\%)}{\sqrt{E}}$$

→ Can be even worse depending on the goals of an experiment and compromise with other detector parameters

ATLAS tile calorimeter

Interaction of neutrinos

Neutrinos interact only weakly → tiny cross-sections. For their detection we need again first a charged particle. Possible detection reactions:

$$\nu_\ell + n \rightarrow \ell^- + p \qquad \ell = e, \mu, \tau$$
$$\bar{\nu}_\ell + p \rightarrow \ell^+ + n \qquad \ell = e, \mu, \tau$$

The cross-section for the reaction $\nu_e + n \rightarrow e^- + p$ is of the order of 10^{-43} cm^2 (per nucleon, $E_\nu \approx$ few MeV).

→ detection efficiency $\varepsilon_{det} = \sigma \cdot N_a = \sigma \cdot \rho \frac{N_A}{A} d$ $\quad (N_a$: area density $\neq N_A$: Avogadro's number)

1 m Iron: $\varepsilon_{det} \approx 5 \cdot 10^{-17}$

1 km water: $\varepsilon_{det} \approx 6 \cdot 10^{-15}$

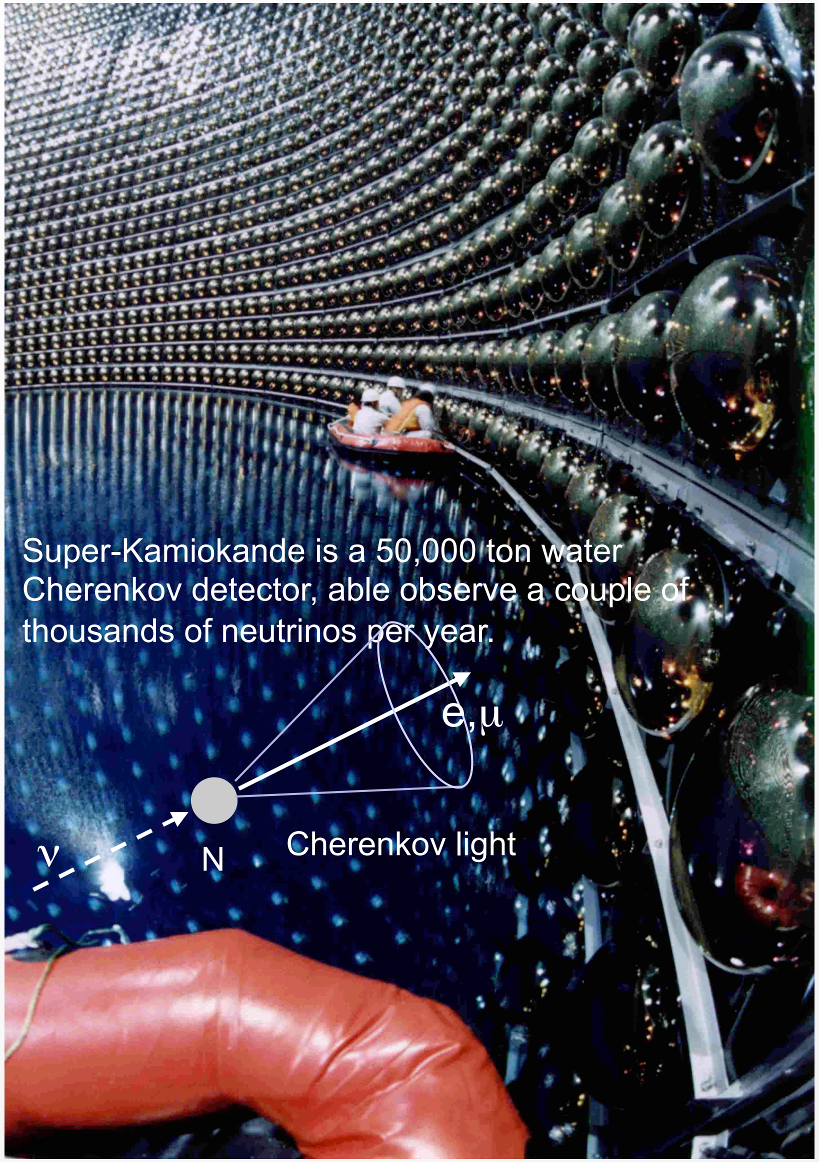
Neutrino detection requires big and massive detectors (ktons - Mtons) and very high neutrino fluxes (e.g. 10^{20} ν / yr).

In collider experiments fully hermetic detectors allow to detect neutrinos indirectly:

- sum up all visible energy and momentum.
- attribute missing energy and momentum to neutrino.

Interaction of neutrons and neutrinos

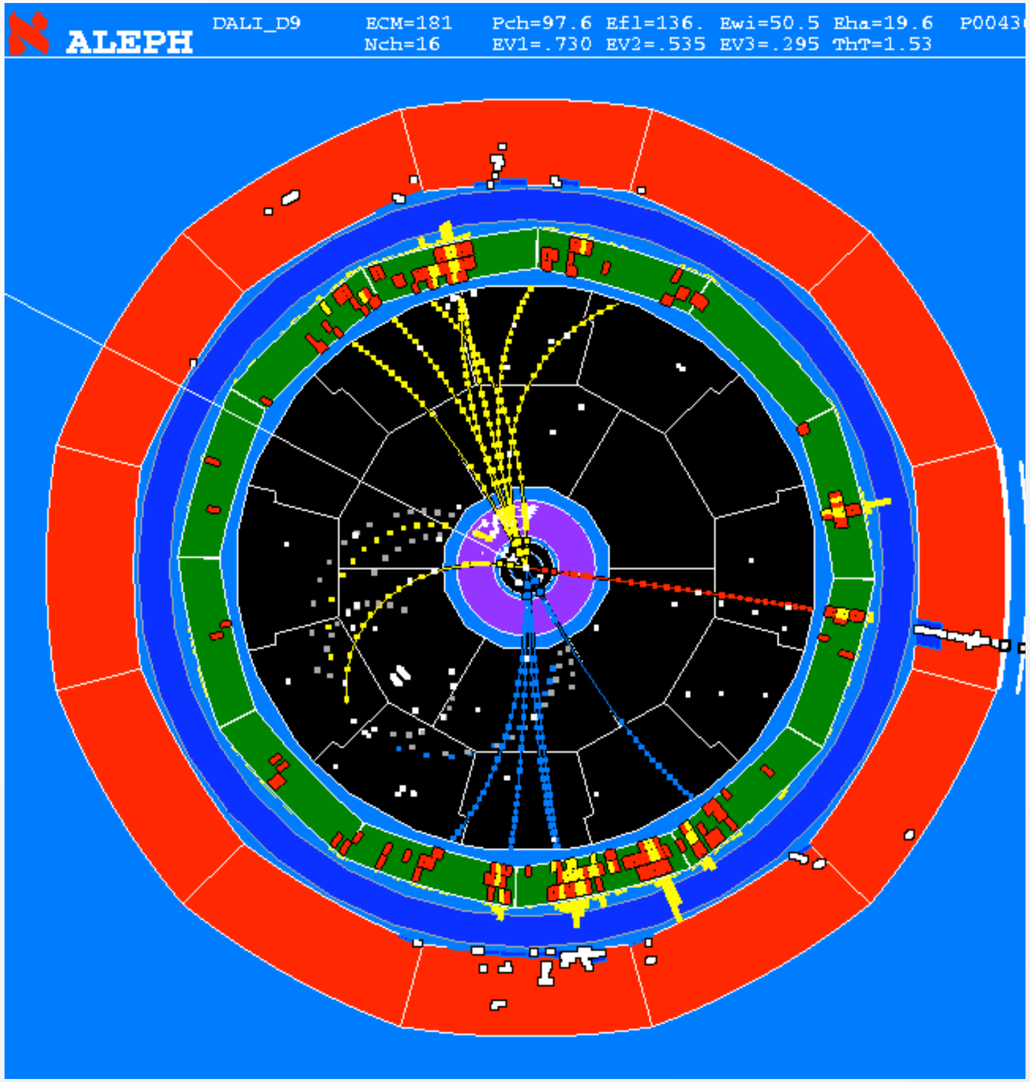
Direct neutrino detection



Indirect neutrino detection

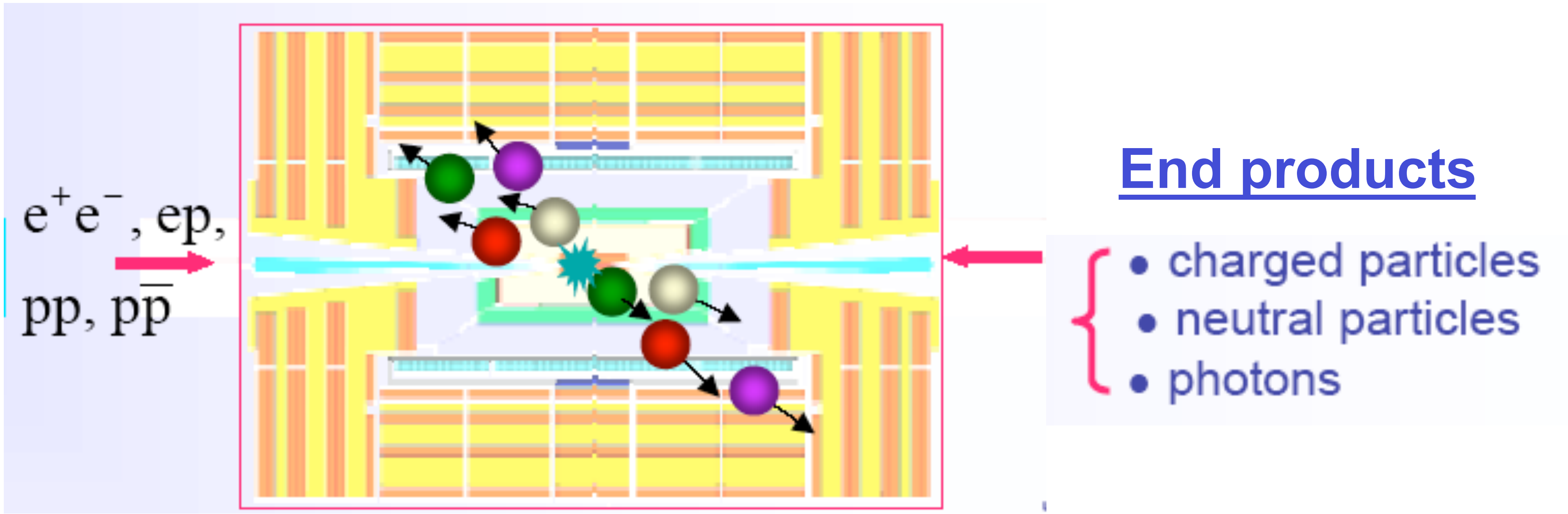
e^+e^- ($\sqrt{s}$=181 GeV) → W^+W^- → $qq\mu\nu_\mu$

→ 2 hadronic jets + μ + missing momentum



Ideal Detectors at a Collider

Now that we know all the Interactions we can talk about Detectors !



An "ideal" particle detector would provide…

- **Coverage of full solid angle, no cracks, fine segmentation**
- **Measurement of momentum and energy**
- **Detection, tracking, and identification of all particles (mass, charge)**
- **Fast response: no dead time**

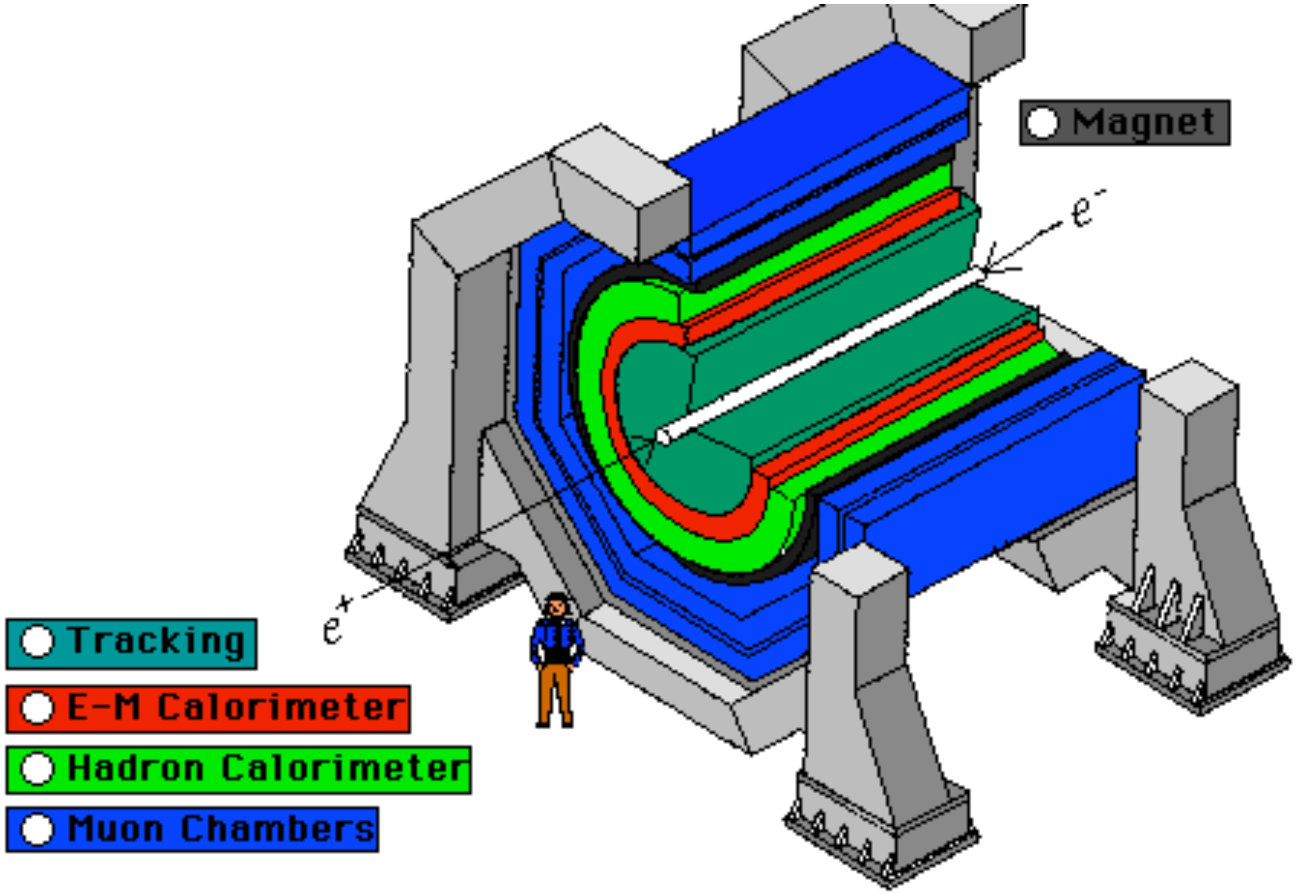
However, practical limitations: Technology, Space, Budget

Individual Detector Types

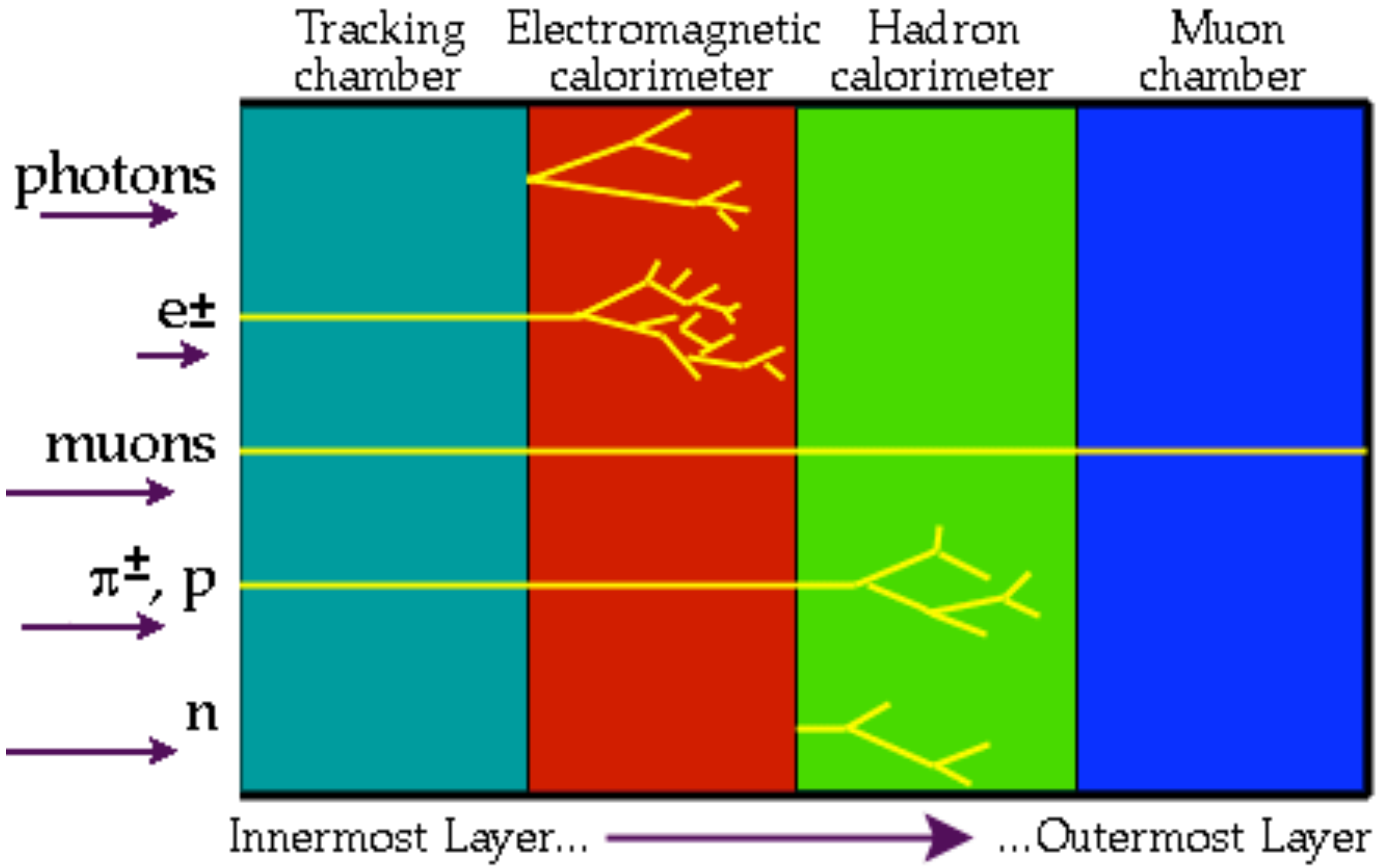
Modern detectors consist of many different pieces of equipment to measure different aspects of an event.

Measuring a particle's properties:

- → **Position**
- → **Momentum**
- → **Energy**
- → **Charge**
- → **Type**



Particle Decay Signatures



Particles are detected via their interaction with matter.

Many types of interactions are involved, mainly electromagnetic.
In the end, always rely on ionization and excitation of matter.

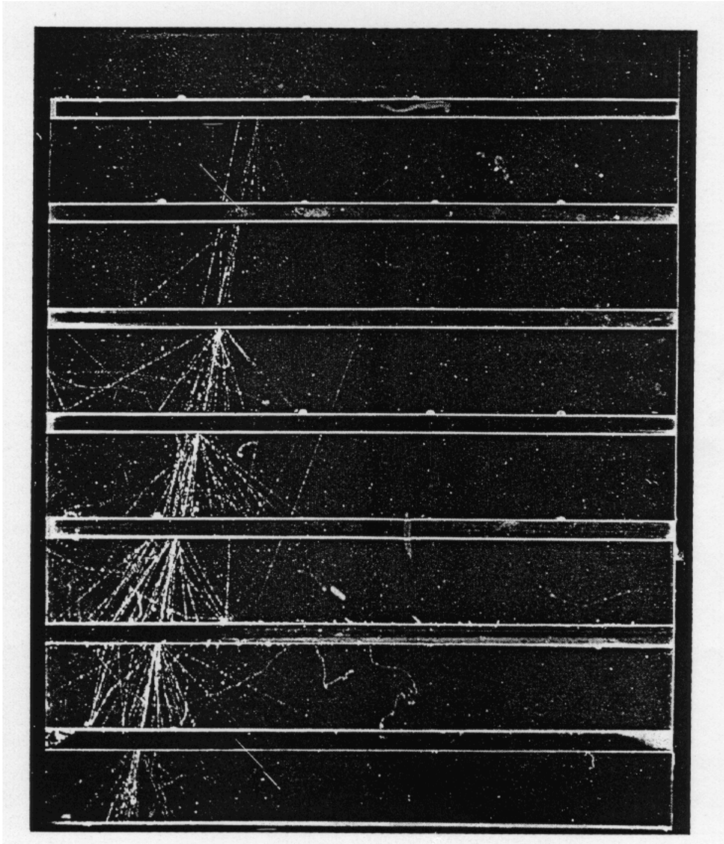
MORE

SLIDES

Electromagnetic Showers

An alternating sequence of interactions leads to a cascade:

- Primary γ with E_0 energy pair-produces with 54% probability in layer X_0 thick
- On average, each has $E_0/2$ energy
- If $E_0/2 > E_c$, they lose energy by Brem
- Next layer X_0, charged particle energy decreases to $E_0/(2e)$
- Brem of avg energy between $E_0/(2e)$ and $E_0/2$ is radiated
- Mean # particles after layer $2X_0$ is ~4
- Radiated γs pair produce again



Cloud chamber photo of electromagnetic cascade between spaced lead plates.

After n generations ($dx= nX_0$), 2^n particles, avg energy $E_0/2^n$ for shower.

Cascade stops: e^- energy → critical energy $E_c= E_0/2^n$.

Number of generations: $n=\ln(E_0/E_c)/\ln 2$.

Number of particles at shower maximum: $N_p = 2^n = E_0/E_c$.

Hadronic Calorimeter

Hadronic Calorimeter (HCAL)

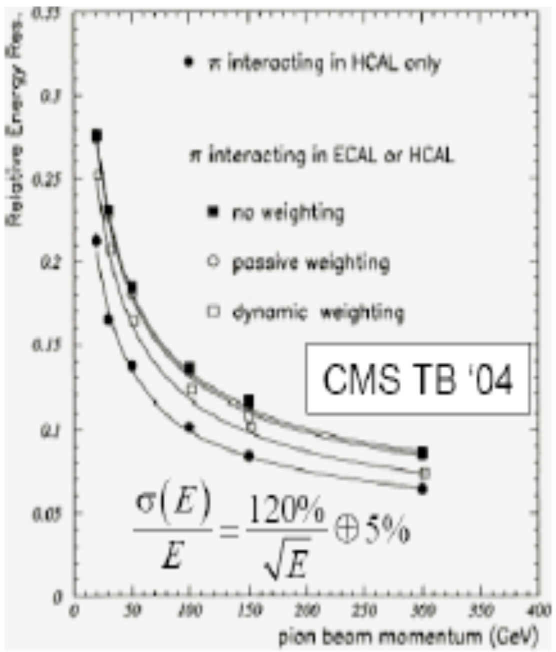
→ CMS hadron calorimeter

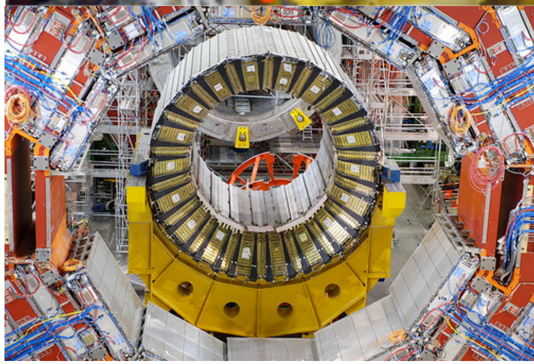
→ 16 scintillator 4 mm thick plates (active material)
Interleaved with 50 mm thick plates of brass

→ Energy resolution:

$$\frac{\sigma(E)}{E} \propto \frac{(120\%)}{\sqrt{E}} \oplus 5\%$$

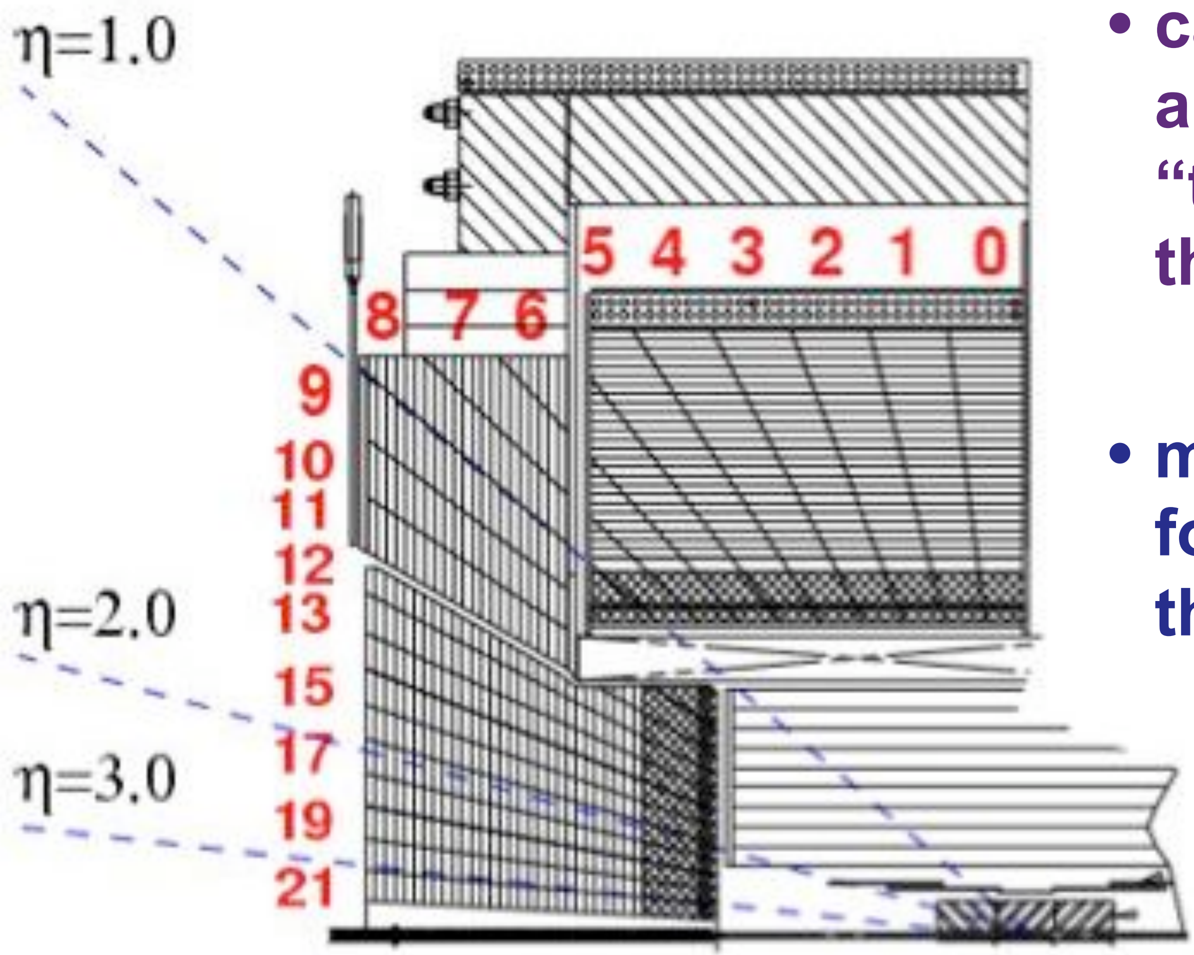
Hadronic energy resolution compromised in favor of a much higher EM energy resolution





http://www.flickr.com/photos/naezmi/365114338/

CDF Sampling Calorimeter



- calorimeter is arranged in projective "towers" pointing at the interaction region
- most of the depth is for the hadronic part of the calorimeter

CMS Hadron Calorimeter

Compensating Calorimeters

Improvements in energy resolution can be achieved if showers induced by electrons and hadrons of same energy produce same visible energy (detector response).

Requires the losses to be "compensated" in some way.

Three methods:

1) **Energy lost by nuclear reactions made up for by fission of ^{238}U, liberating n and soft γ–rays.** **Can get response close to equal: proton-rich detector em shower decreases, had shower increases due to more nuclear reactions.**
2) **If have lots of H2, compensation achieved with high absorber material:** **in inelastic collision of hadrons w/ absorber nuclei, neutrons are produced → recoil protons, larger signal.**
3) **Reduce fluctuation in EM component:** **weight individual counter responses, and even response out across the board.**