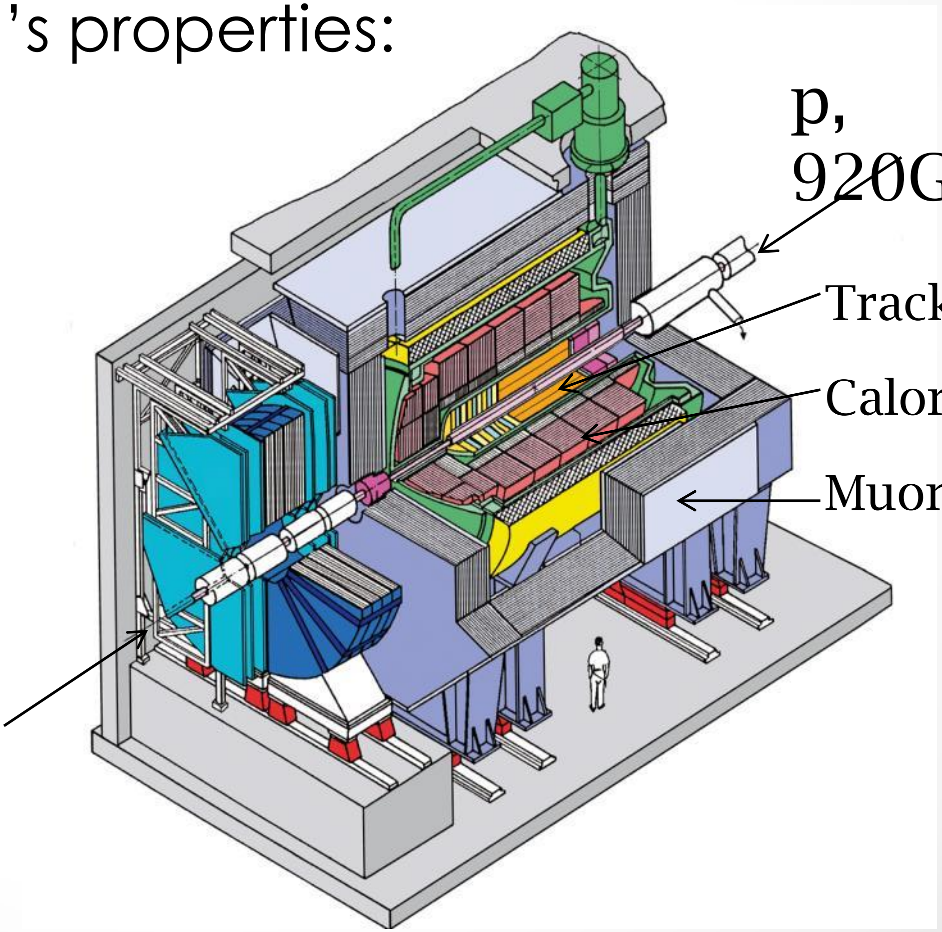
Detectors

PSI Lab Course 2014
Dirk Wiedner

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



p, 920GeV

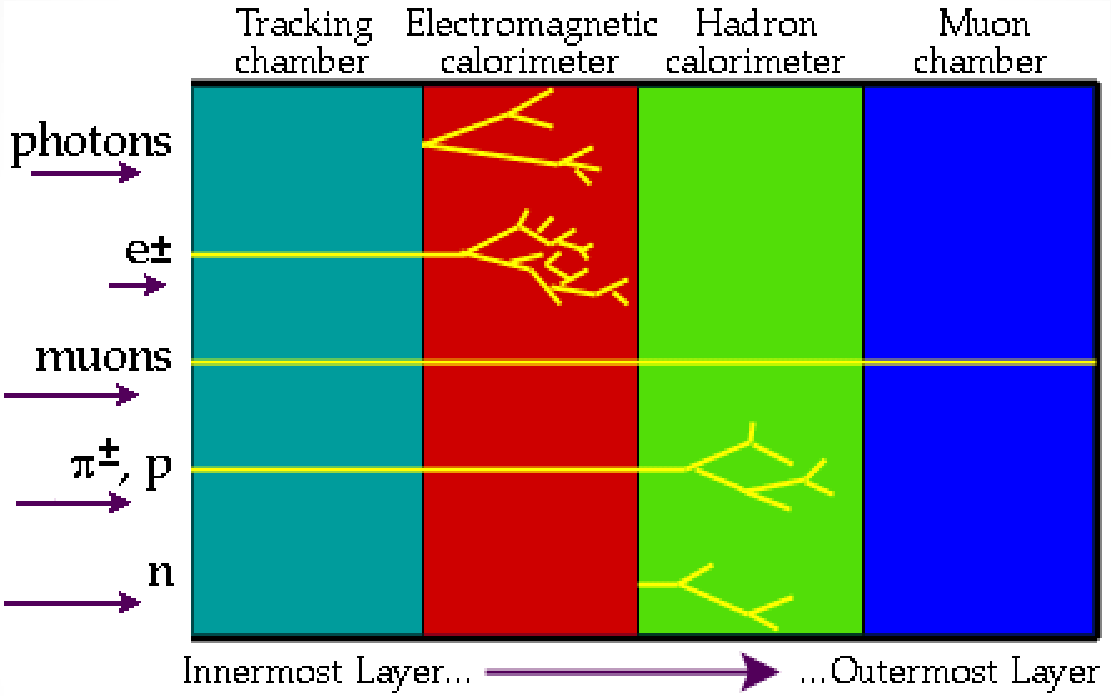
Tracking

Calorimeter

Muon System

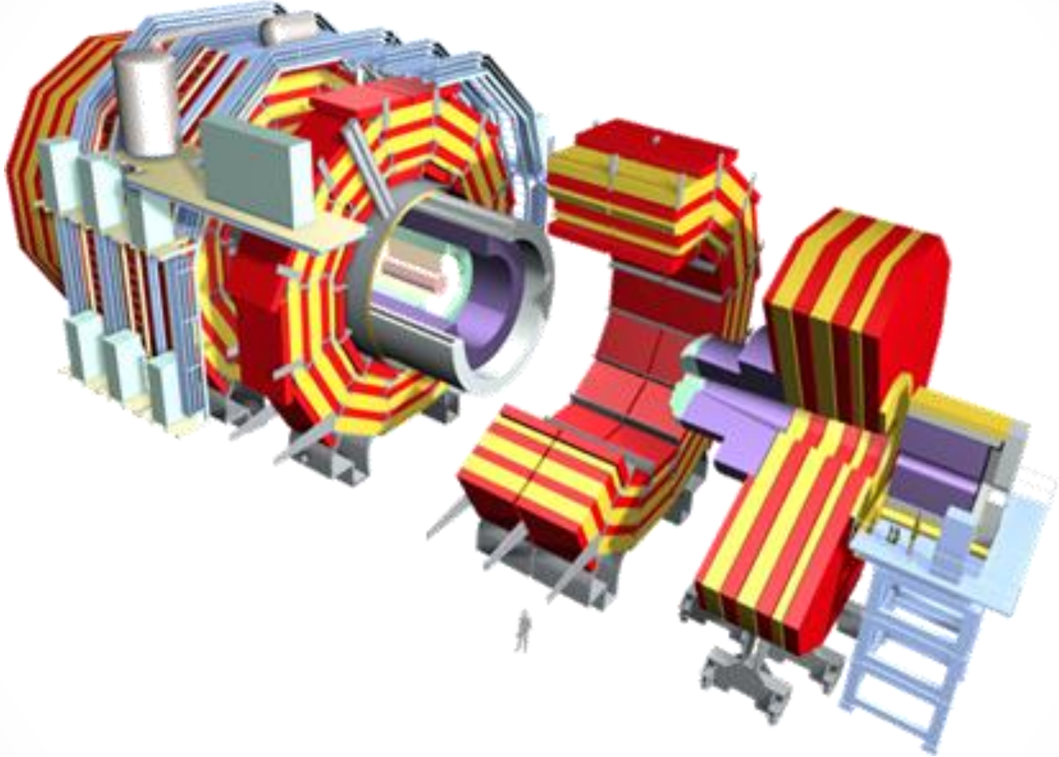
e, 27GeV

Particle Decay Signatures

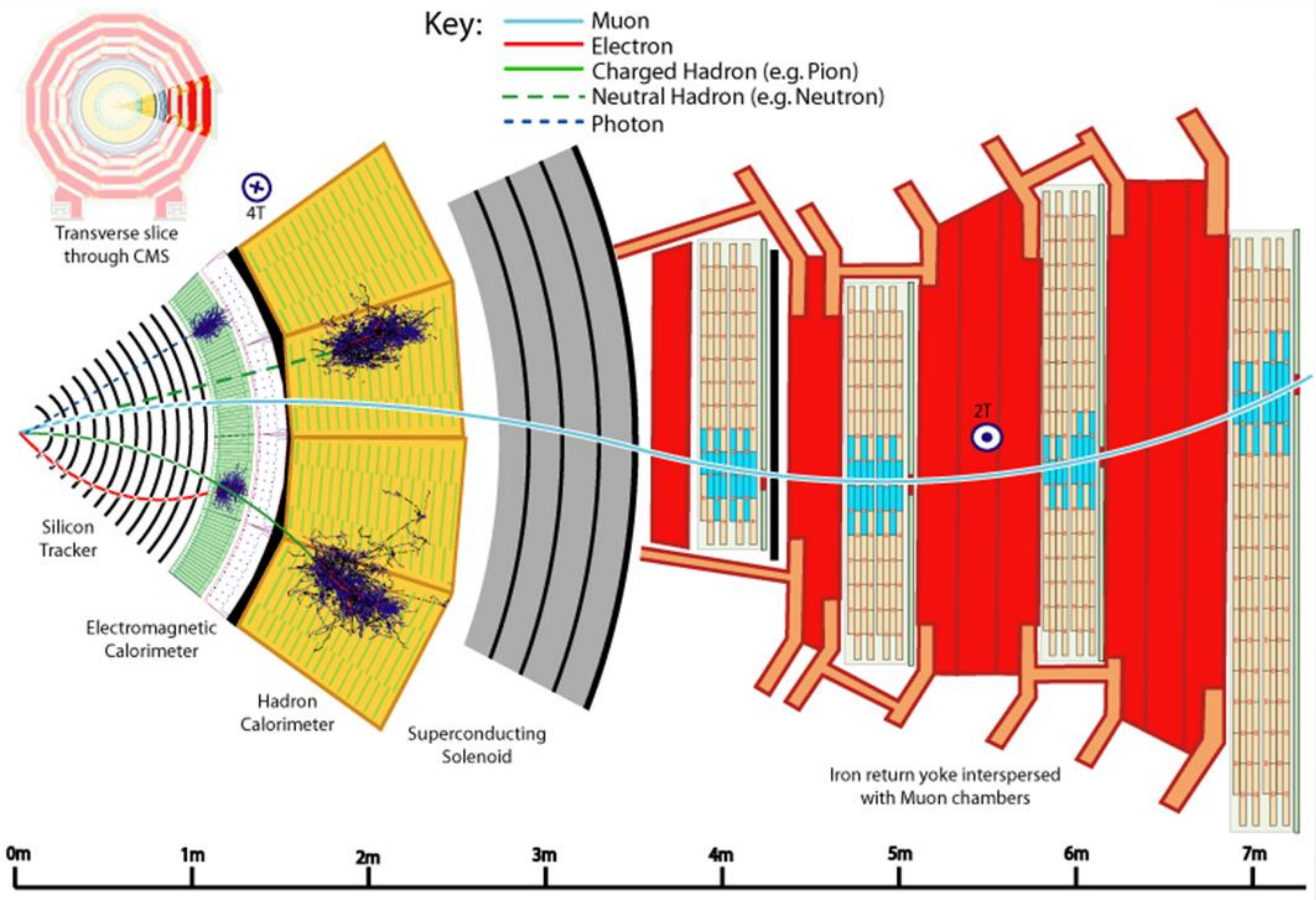


- Particles are detected via their interaction with matter.
- Many types of interactions are involved,
  - mainly electromagnetic.
- In the end, always rely on ionization and excitation of matter.

Particle Decay Signatures in CMS



Particle Decay Signatures in CMS



Energy loss by Ionization

…

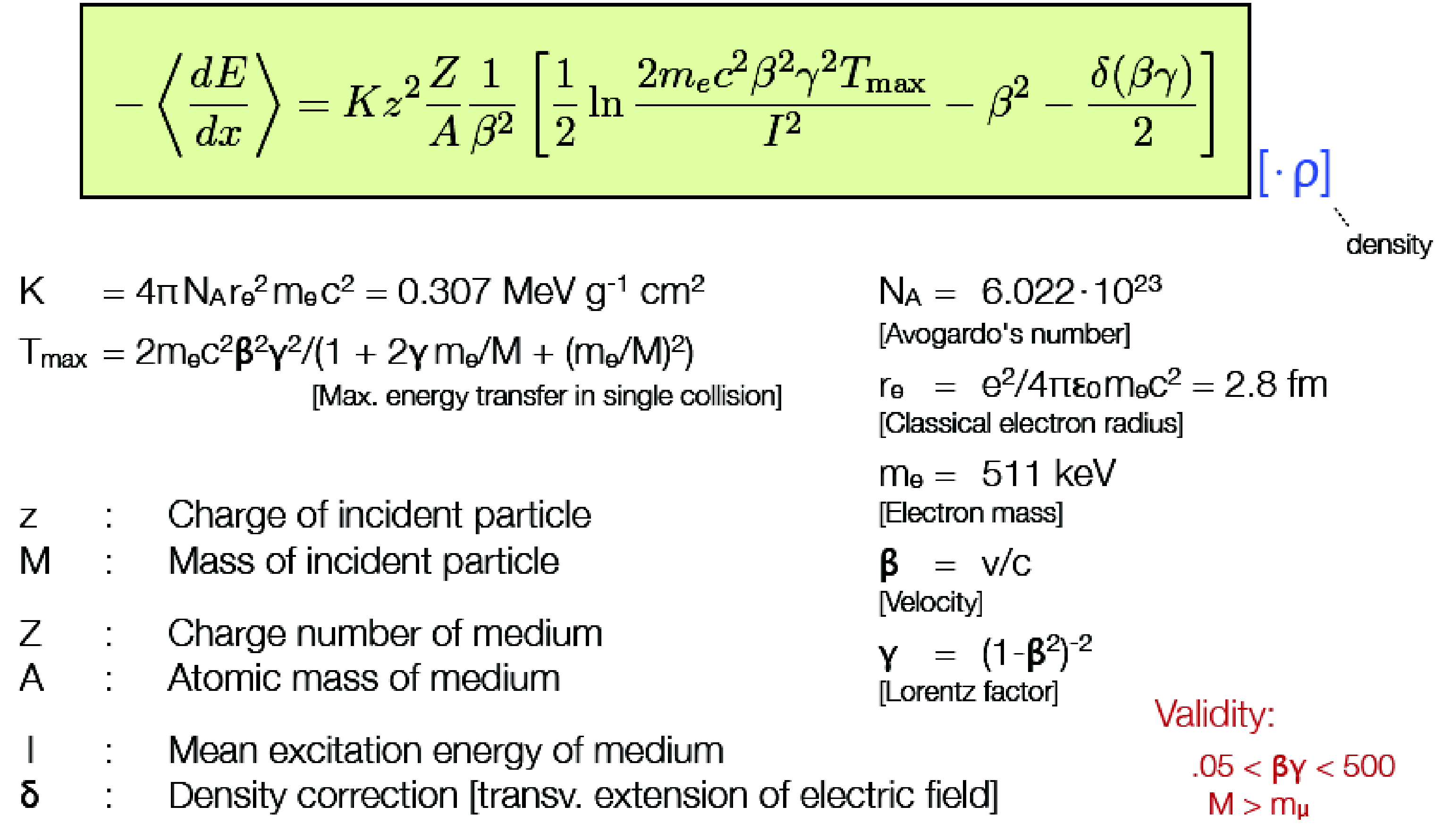
Bethe-Bloch formula

- Ionization main electromagnetic energy loss for charged particles.
  - Except when the projectile is highly relativistic
- The mean energy loss due to ionization given by the **Bethe-Bloch** formula:

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

Bethe-Bloch formula

- Ionization main electromagnetic energy loss for charged particles.
  - Except when the projectile is highly relativistic
- The mean energy loss due to ionization given by the **Bethe-Bloch** formula:



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

density

$K = 4\pi N_A r_e^2 m_e c^2 = 0.307$ MeV g^{-1} cm^2

$T_{max} = 2m_ec^2\beta^2\gamma^2/(1 + 2\gamma\, m_e/M + (m_e/M)^2)$

[Max. energy transfer in single collision]

$N_A = 6.022 \cdot 10^{23}$

[Avogardo's number]

$r_e = e^2/4\pi\varepsilon_0 m_e c^2 = 2.8$ fm

[Classical electron radius]

$m_e = 511$ keV

[Electron mass]

$\beta = v/c$

[Velocity]

$\gamma = (1-\beta^2)^{-2}$

[Lorentz factor]

z : Charge of incident particle

M : Mass of incident particle

Z : Charge number of medium

A : Atomic mass of medium

I : Mean excitation energy of medium

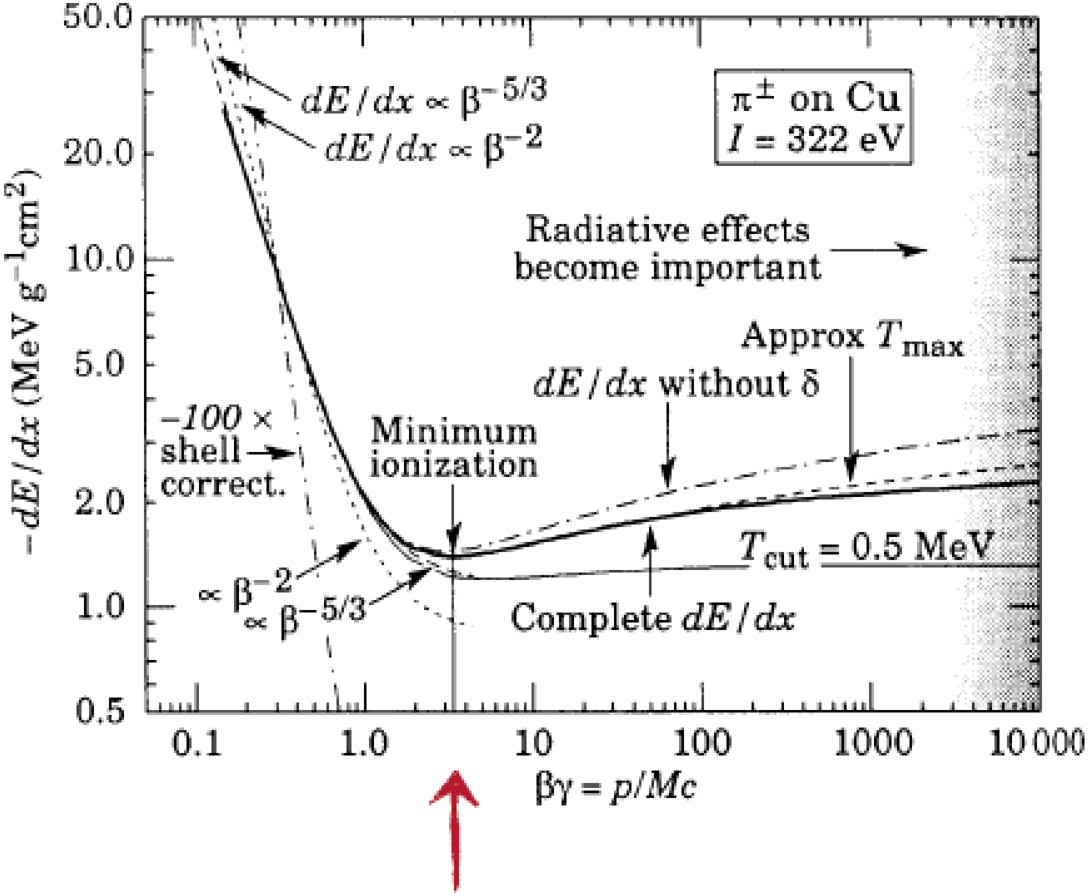
δ : Density correction [transv. extension of electric field]

Validity:

$.05 < \beta\gamma < 500$

$M > m_\mu$

Energy loss of π in Cu



$\beta\gamma = 3$-4

Minimum ionizing particles (MIP): $\beta\gamma = 3$-4

dE/dx falls ~ β^{-2}; kinematic factor
[precise dependence: – $\beta^{-5/3}$]

dE/dx rises ~ $\ln(\beta\gamma)^2$; relativistic rise
[rel. extension of transversal E-field]

Saturation at large ($\beta\gamma$) due to density effect (correction δ)
[polarization of medium]

Units: MeV g^{-1} cm^2

MIP looses ~ 13 MeV/cm
[density of copper: 8.94 g/cm^3]

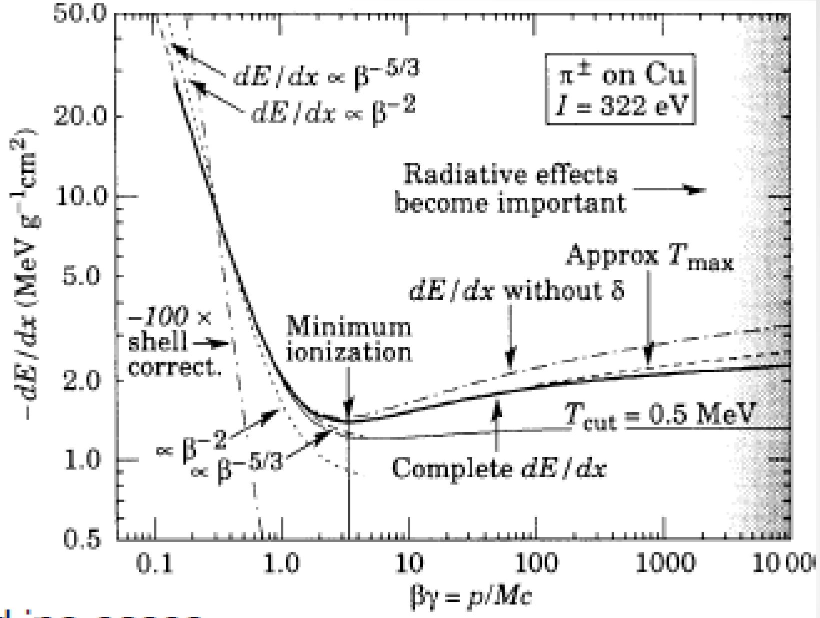
Energy loss of Pi in Cu

$1/\beta^2$-dependence:

Remember:

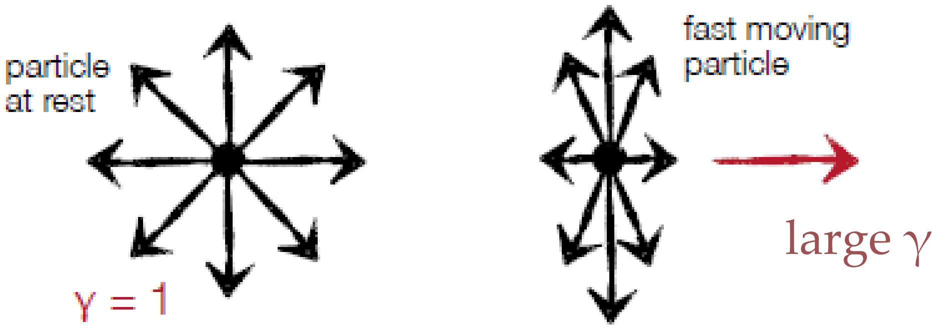
$$\Delta p_\perp = \int F_\perp dt = \int F_\perp \frac{dx}{v}$$

i.e. slower particles feel electric force of atomic electron for longer time ...



Relativistic rise for $\beta\gamma > 4$:

High energy particle: transversal electric field increases due to Lorentz transform; $E_y \rightarrow \gamma E_y$. Thus interaction cross section increases ...

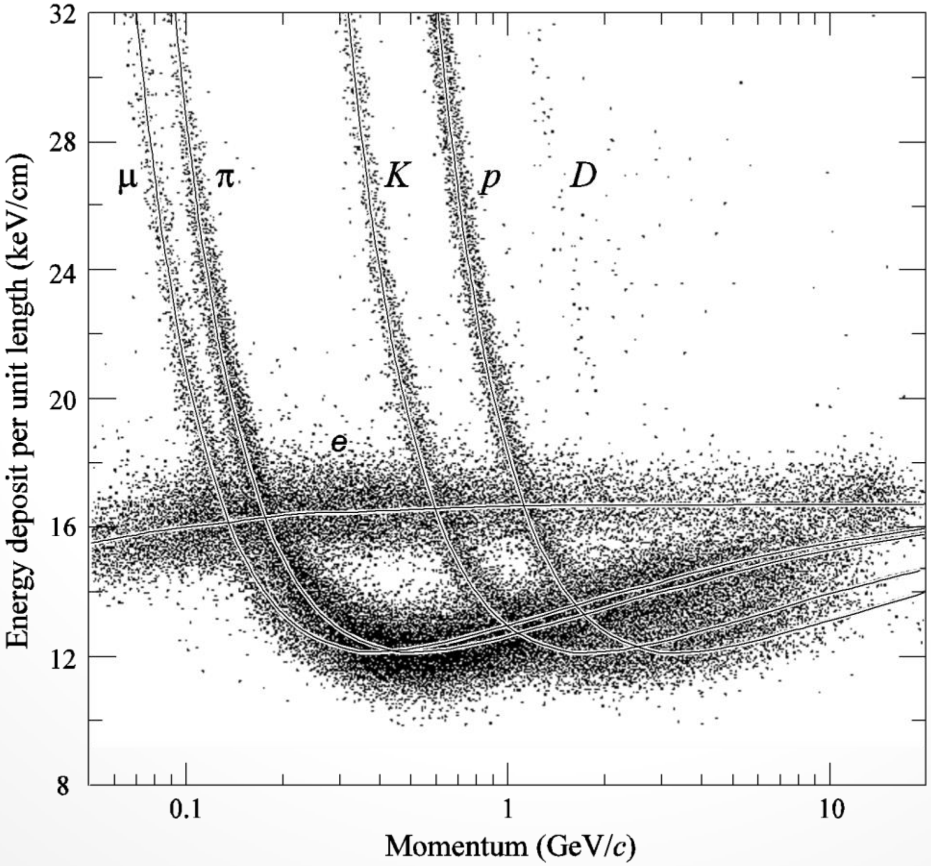


Corrections:

low energy	: shell corrections
high energy	: density corrections

dE/dx and Particle Identification

- Measurements of energy loss to identify particles
  - when giving enough care to calibration problems
- simultaneous measurement of momentum required



Calorimetry

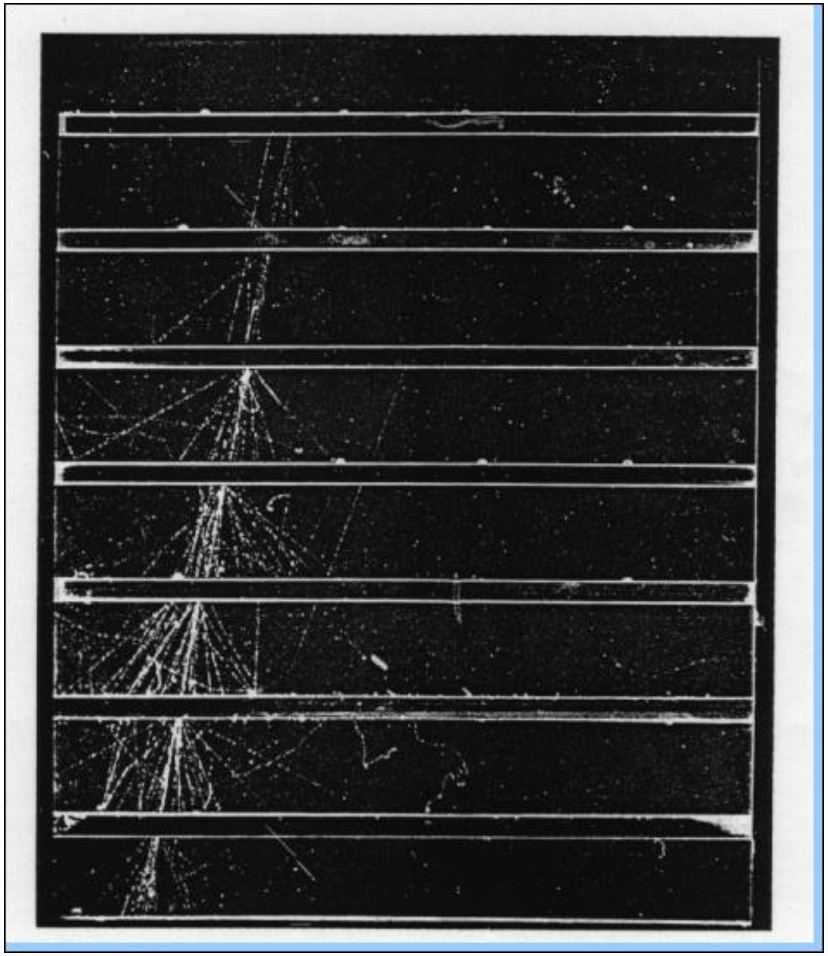
Introduction

- Energy of a particle measured destructively
- Particle must be completely stopped in detectors to measure its full energy

Introduction

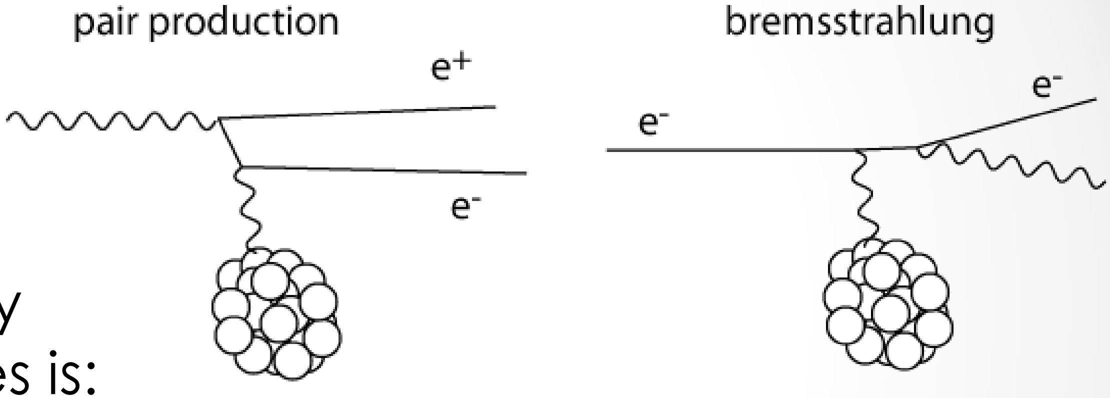
- Energy of a particle measured destructively
- Particle must be completely stopped in detectors to measure its full energy
- Energy is deposited in a localized space
  - position can be determined with accuracy dependent on:
  - transverse energy fluctuations
  - detector design.
- Accuracy of energy measurement:
  - Constant term: Uniformity of the detector medium
  - Stochastic term: Active sampling wrt total detector volume
- Calorimetry can provide momentum of a particle
  - redundantly to the inner tracking measurements
  - useful in cleaning up backgrounds.

Shower in cloud chamber



Electron and γ Interactions

- At E> 10 MeV, interactions of γs and e⁻s in matter dominated by:
  - e^+e^- pair production and
  - Bremsstrahlung
- At lower energies, Ionization becomes important.
- The ratio of the energy loss for these processes is:



$$R = \left(\frac{dE}{dx}\right)_{Brems} \Big/ \left(\frac{dE}{dx}\right)_{Ion} \approx \frac{ZE}{580MeV}$$

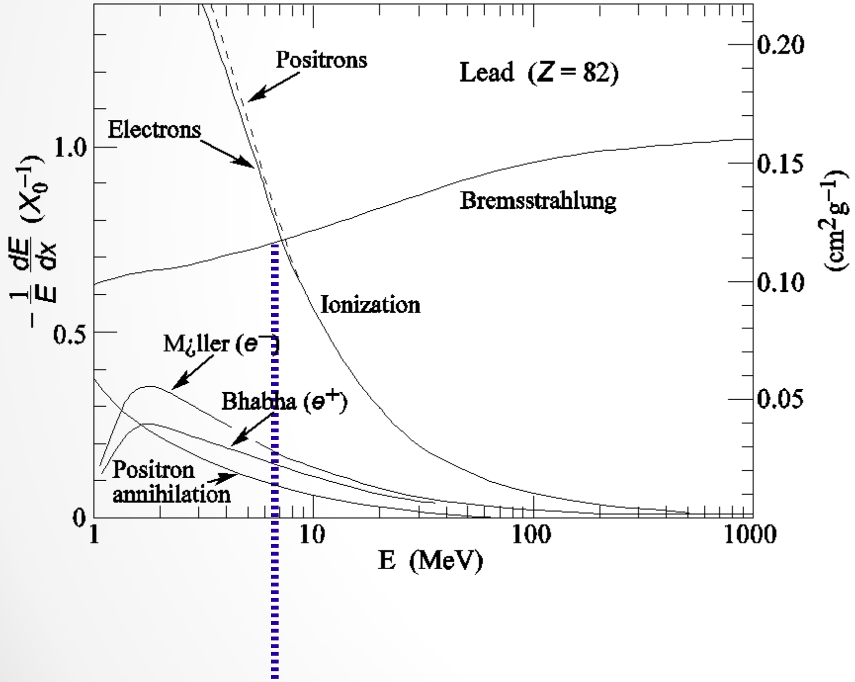
Critical Energy:

When energy loss due to Bremsst. and energy loss due to ionization are equal.

$$E_c \approx \frac{610MeV}{Z+1.24}$$

Electron energy loss and critical energy

relative energy loss for electrons



E_c = 7 MeV in Pb

- Critical energy loss due to
    - ○ Bremsstrahlung and
    - ○ ionization are equal to

$$E_c \approx \frac{610MeV}{Z + 1.24}$$

- High Z material gives more signal: shower stop later

Photon interactions in matter (A, Z)

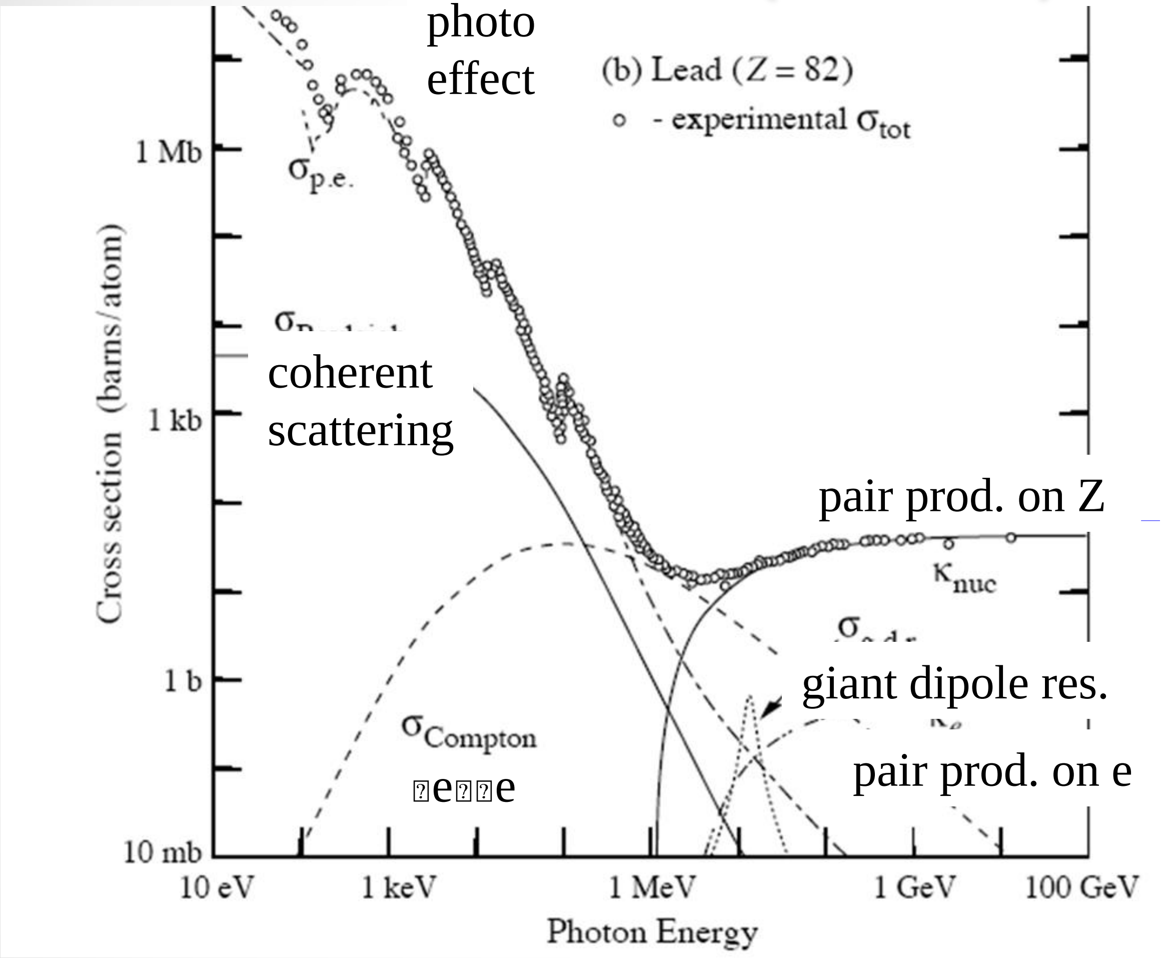


photo effect

coherent scattering

pair prod. on Z

42 barn

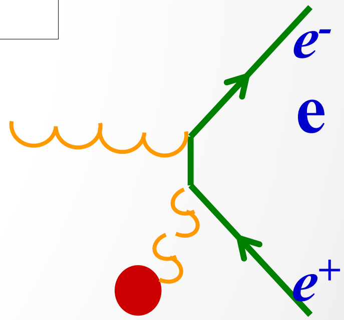
giant dipole res.

$\sigma_{Compton}$

□e□□e

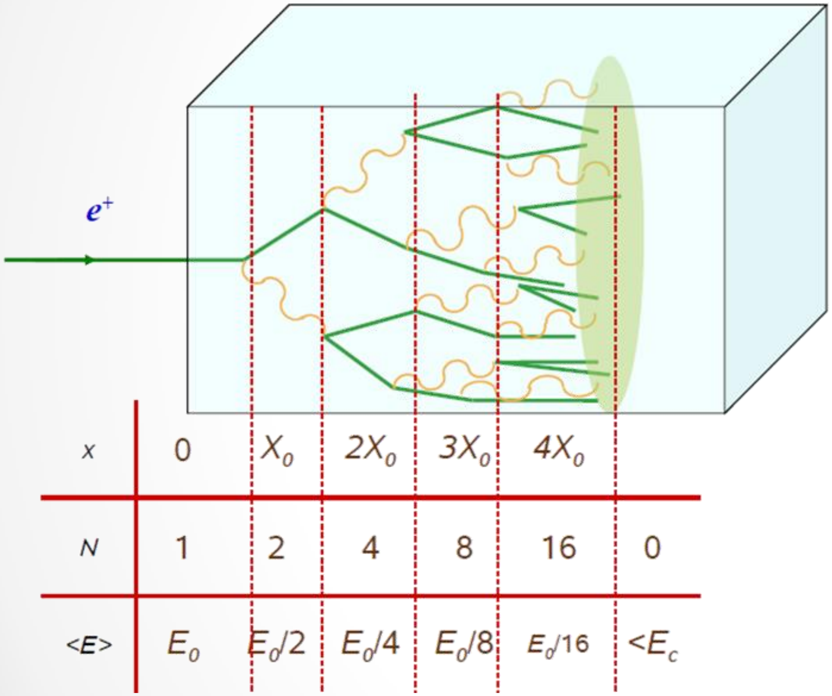
pair prod. on e

$\gamma A \rightarrow A^{*+} e^-$ $A^{*+} \rightarrow A^+ \gamma_{flour}$	photo
$\gamma A \rightarrow A \gamma'$	Rayleigh
$\gamma e \rightarrow e \gamma'$	Compton
$\gamma Z \rightarrow Z e^+ e^-$	Pair
$\gamma e \rightarrow e\, e^+ e^-$	Pair



Pair production $\gamma Z \rightarrow e^+ e^-$ dominates above ~4 MeV

Electromagnetic Showers

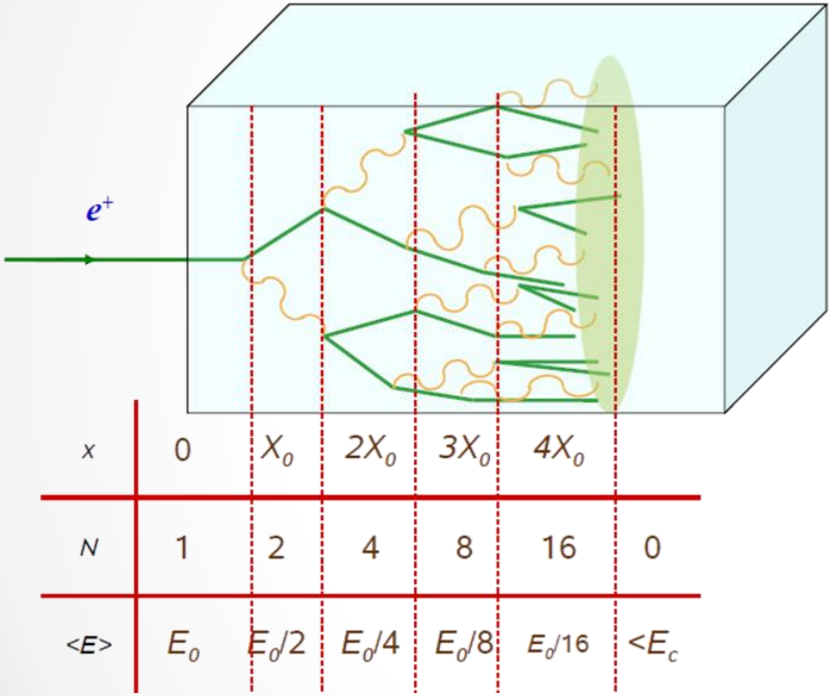


x	0	X_0	$2X_0$	$3X_0$	$4X_0$	
N	1	2	4	8	16	0
$\langle E \rangle$	E_0	$E_0/2$	$E_0/4$	$E_0/8$	$E_0/16$	$<E_c$

- Radiation Length X_0:
    - Scaling variable for the probability of occurrence of bremsstrahlung pair production
    - and for the variance of the angle of multiple scattering.
- Average energy loss due to bremsstrahlung for an electron of energy E is related to the radiation length:

$$(dE/dx)_{brems} = E/X_0$$

Electromagnetic Showers



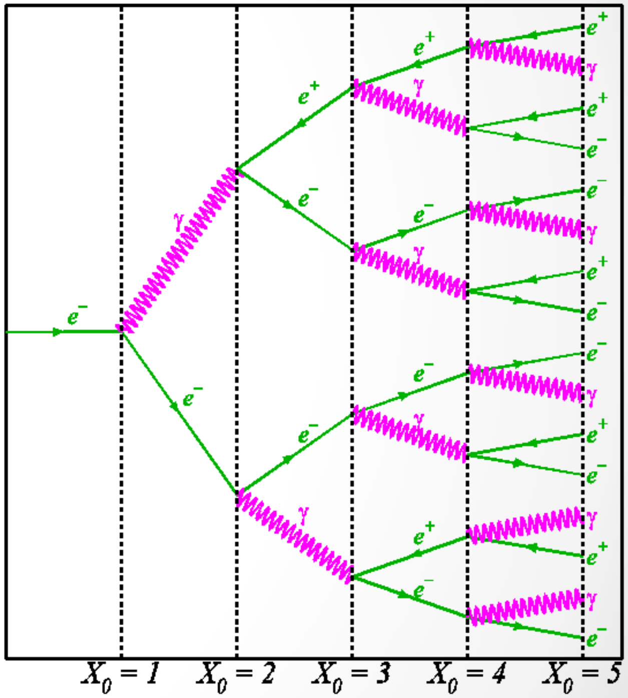
x	0	X_0	$2X_0$	$3X_0$	$4X_0$	
N	1	2	4	8	16	0
$<E>$	E_0	$E_0/2$	$E_0/4$	$E_0/8$	$E_0/16$	$<E_c$

- Radiation Length X_0:
    - Scaling variable for the probability of occurrence of bremsstrahlung pair production
    - and for the variance of the angle of multiple scattering.
- Average energy loss due to bremsstrahlung for an electron of energy E is related to the radiation length:

$$(dE/dx)_{\text{brems}} = E/X_0$$

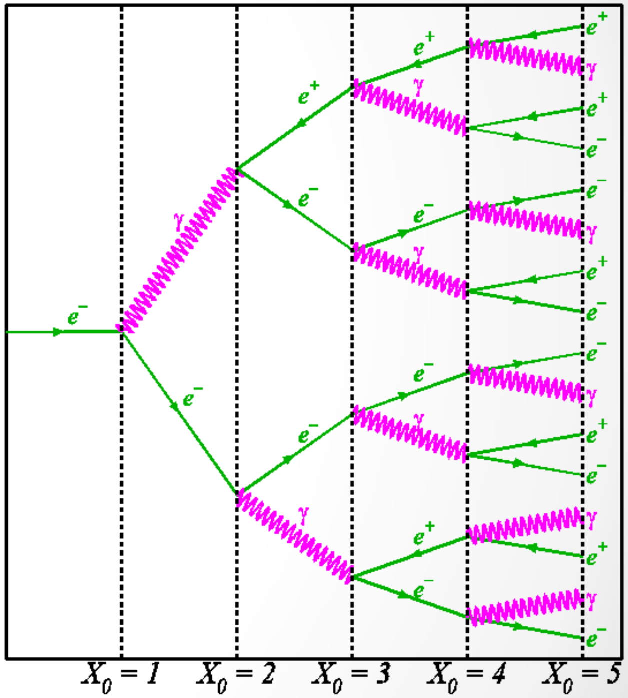
Simple Shower Model

- Start with a **high energy electron**: E0
- After 1 X_0: 1e^- and 1γ each with E0/2
- After 2 X_0: 2e^-, 1$e^+$and 1γ each with E0/4
- After kX_0: total **$N=2^k$**, each with $<E>=$**$E_0/2^k$**
- At $<E> = E_C$ pair production and bremsstrahlung stop
- Compton- or photo-effect and ionization take over.
- The shower ranges out.
- $k_{max} = lg_2(E_0/E_C) \rightarrow$ Shower depth grows logarithmically with E_0
- $N_{max} = 2k_{max} = E_0/E_C \rightarrow$ Number of shower particles grows linearly with E_0.



Simple Shower Model

- Start with a **high energy electron**: E0
- After 1 X_0: 1e^- and 1γ each with E0/2
- After 2 X_0: 2e^-, 1$e^+$and 1γ each with E0/4
- After kX_0: total $\mathbf{N=2^k}$, each with $<E>=\mathbf{E_0/2^k}$
- At $<E> = E_C$ pair production and brems-strahlung stop
- Compton- or photo-effect and ionization take over.
- The shower ranges out.
- $k_{max} = lg_2(E_0/E_c)$ → Shower depth grows logarithmically with E_0
- $N_{max} = 2k_{max} = E_0/E_C$ → Number of shower particles grows linearly with E_0.



Energy Measurement

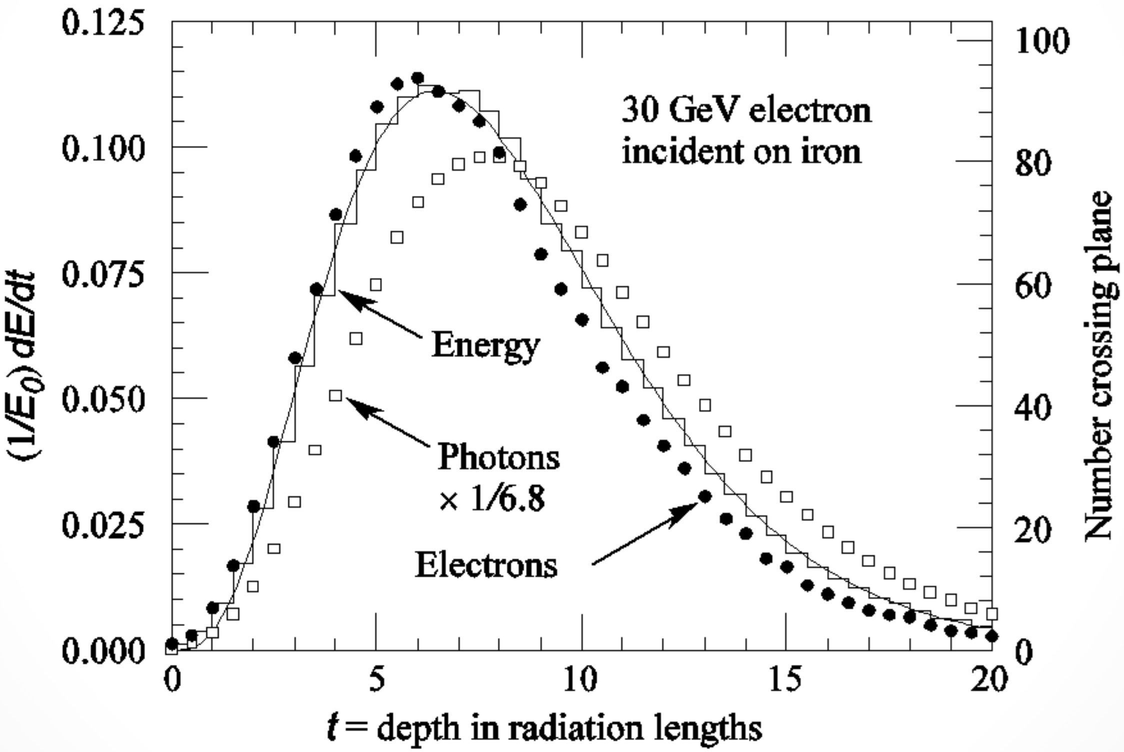
- Total number of particle in the shower in the simple model:
  $\Rightarrow \mathbf{N_{tot}} = \Sigma_k 2^k = 2\ 2^{kmax} -1 \simeq \mathbf{2\ E_0\ /\ E_c}$
- 2/3 of N_{tot} are charged (e^++e^-), $\Rightarrow N_{ch} = 4/3\ E_0/E_c$
- Each e travels 1 X0 between interactions
  $\Rightarrow$ total path length $L_{ch} \simeq 4/3\ X_0\ E_0\ /\ E_c$
- Electrons and positrons also ionize the medium, collect charge or fluorescence light. $\Rightarrow$ The measured signal $S \sim X_0\ E_0\ /\ E_c$
- After calibration, S is an energy measurement!
- Shower fluctuations: particle production is a Poisson process:
  $\Rightarrow \sigma(N) = \sqrt{N}$
- $\Rightarrow \sigma(S)\ /\ S = 1/\ \sqrt{S}$
- The relative energy resolution improves as $1/\sqrt{E_0}$

Energy Measurement

- Total number of particle in the shower in the simple model:
  ⇒ $\mathbf{N_{tot}} = \Sigma_k 2^k = 2\ 2^{kmax} - 1 \simeq \mathbf{2\ E_0 / E_c}$
- 2/3 of N_{tot} are charged ($e^+ + e^-$), ⇒ $N_{ch} = 4/3\ E_0/E_c$
- Each e travels 1 X0 between interactions
  ⇒ total path length $L_{ch} \simeq 4/3\ X_0\ E_0 / E_c$
- Electrons and positrons also ionize the medium, collect charge or fluorescence light. ⇒ The measured signal $S \sim X_0\ E_0 / E_c$
- After calibration, S is an energy measurement!
- Shower fluctuations: particle production is a Poisson process:
  ⇒ $\sigma(N) = \sqrt{N}$
- ⇒ $\sigma(S) / S = 1/ \sqrt{S}$
- The relative energy resolution improves as $1/\sqrt{E_0}$

A sophisticated shower simulation

energy profile



particle flow

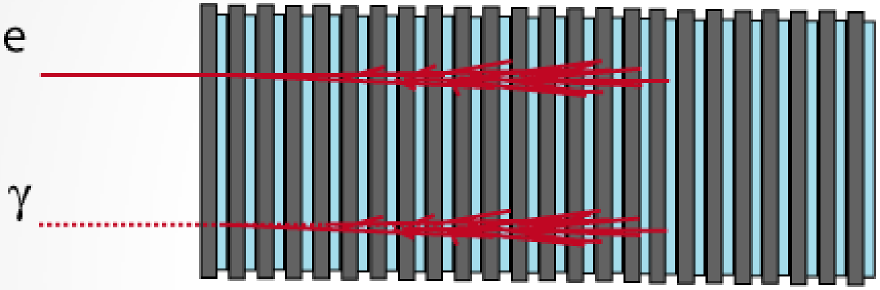
Electromagnetic Calorimeter Types

- Homogeneous “shower counters”:
    - Best performance from unorganic scintillating crystals.
    - Also use lead glass, detects Cerenkov light of electrons, limited by photoelectrons 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. LAr - Pb versions obtain ~10%/ √E. Ionization read out by electrodes attached to plates (no PMTs!).
    - Disadvantage: slow collection times (~1 μs).

Electromagnetic Calorimeter Types

- “Lead-scintillator sandwich” calorimeter

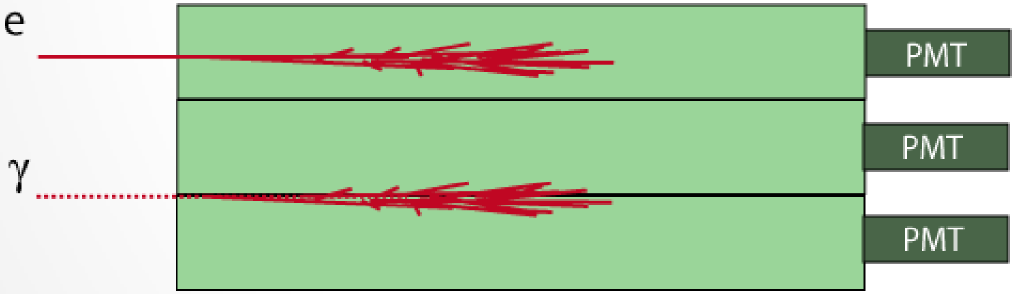
Energy resolutions:



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

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

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



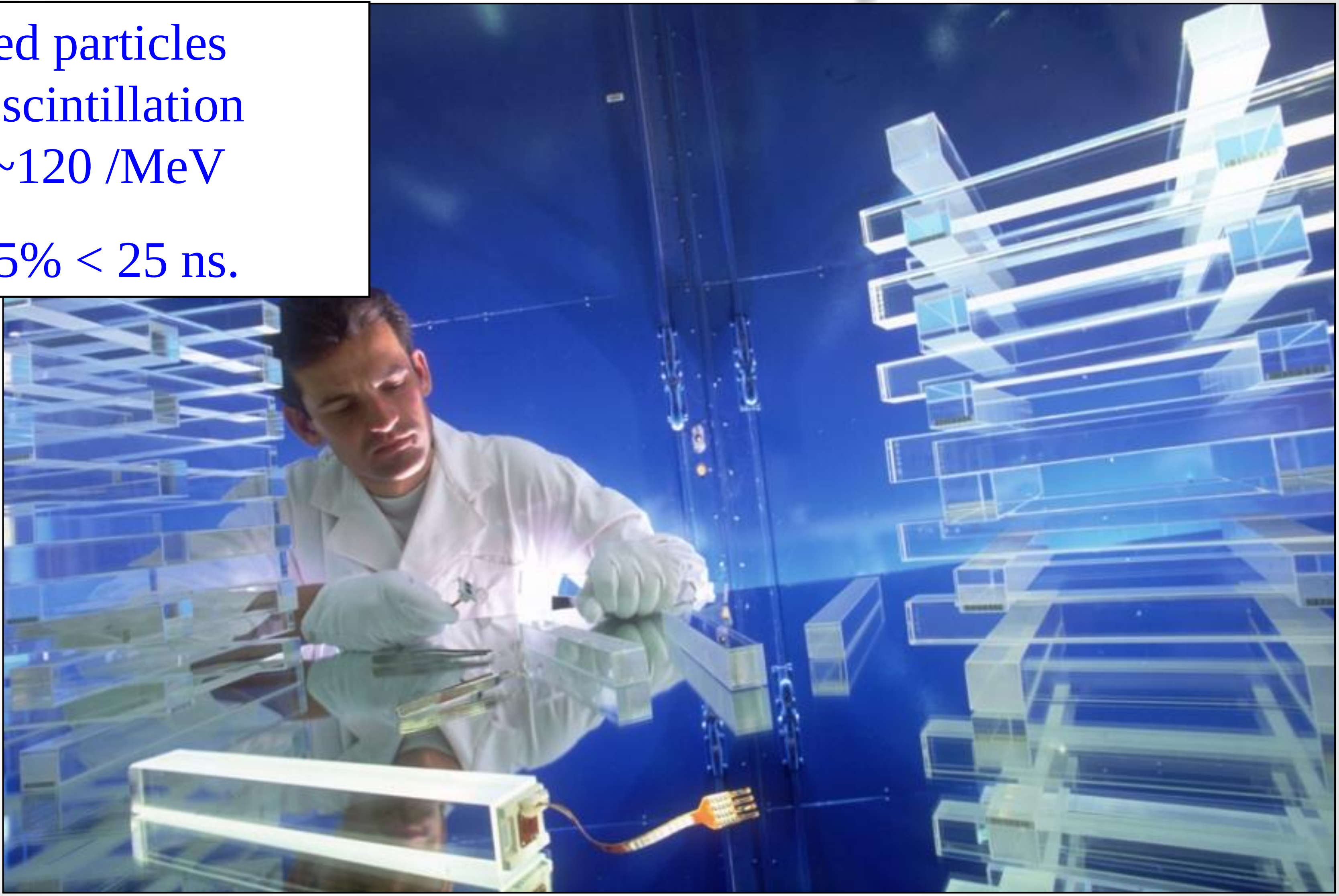
- Liquid argon calorimeter

$\Delta E/E \sim 18\%/\sqrt{E}$

CMS PbWO Crystals

Charged particles create scintillation light: ~120 /MeV

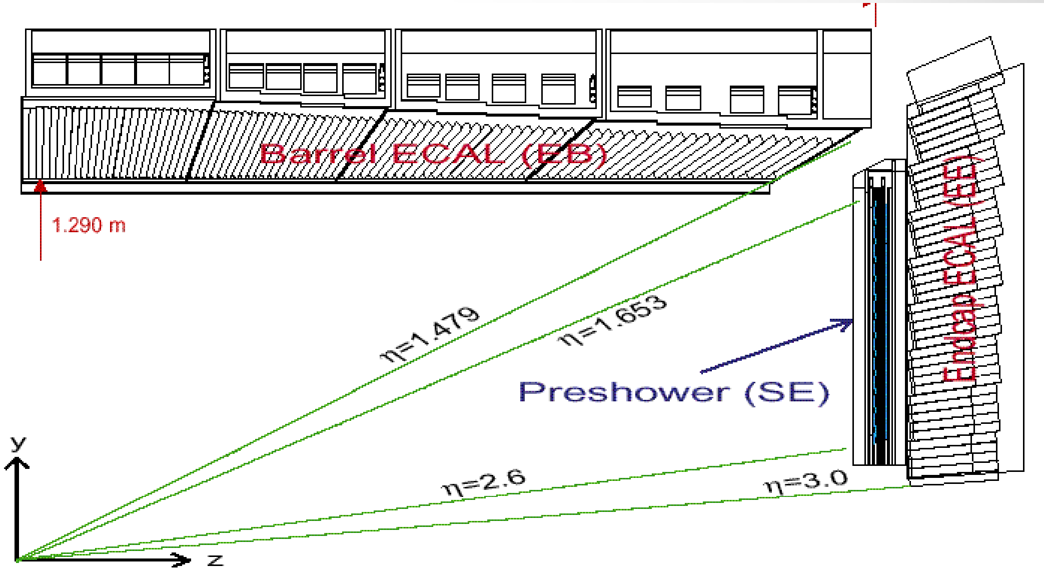
fast: 95% < 25 ns.

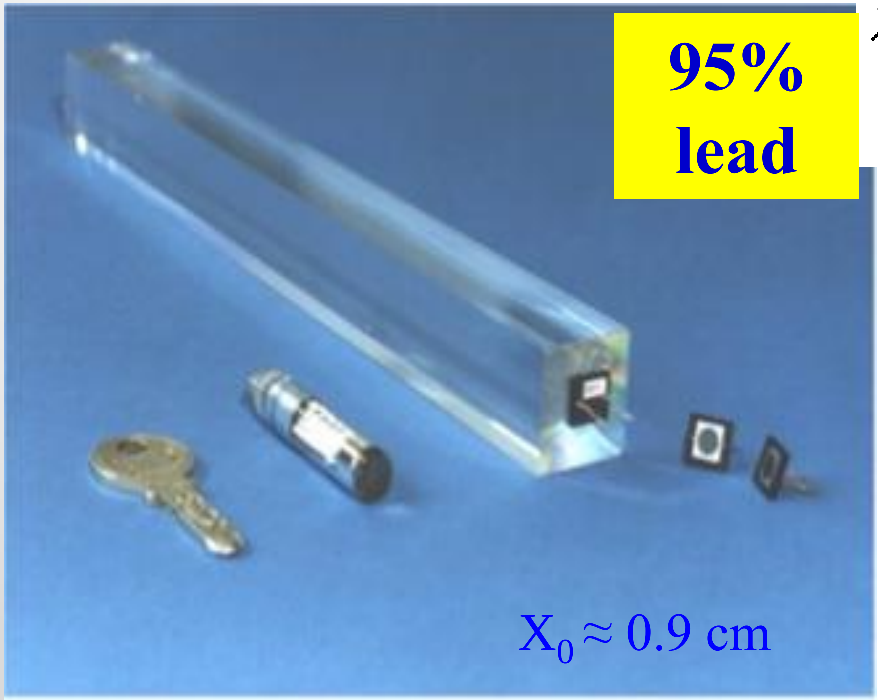


CMS ECAL

$\phi=85$mm

- CMS $PbWO_4$ crystal calorimeter



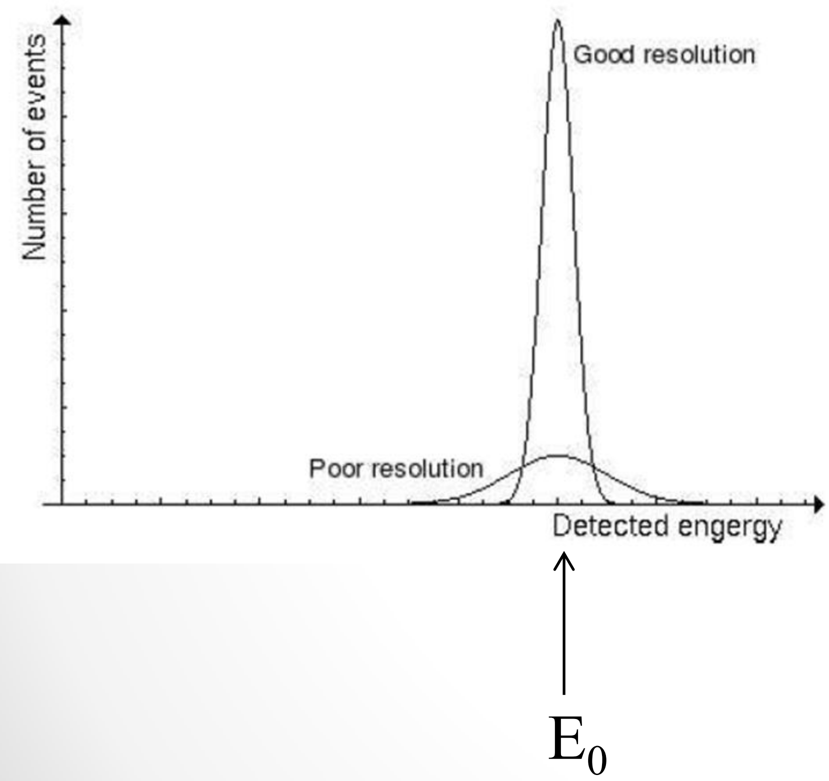


95% lead

$X_0 \approx 0.9$ cm

- **Barrel: 62k crystals 2.2 × 2.2 × 23 cm**
- **End-caps: 15k crystals 3 × 3 × 22 cm**

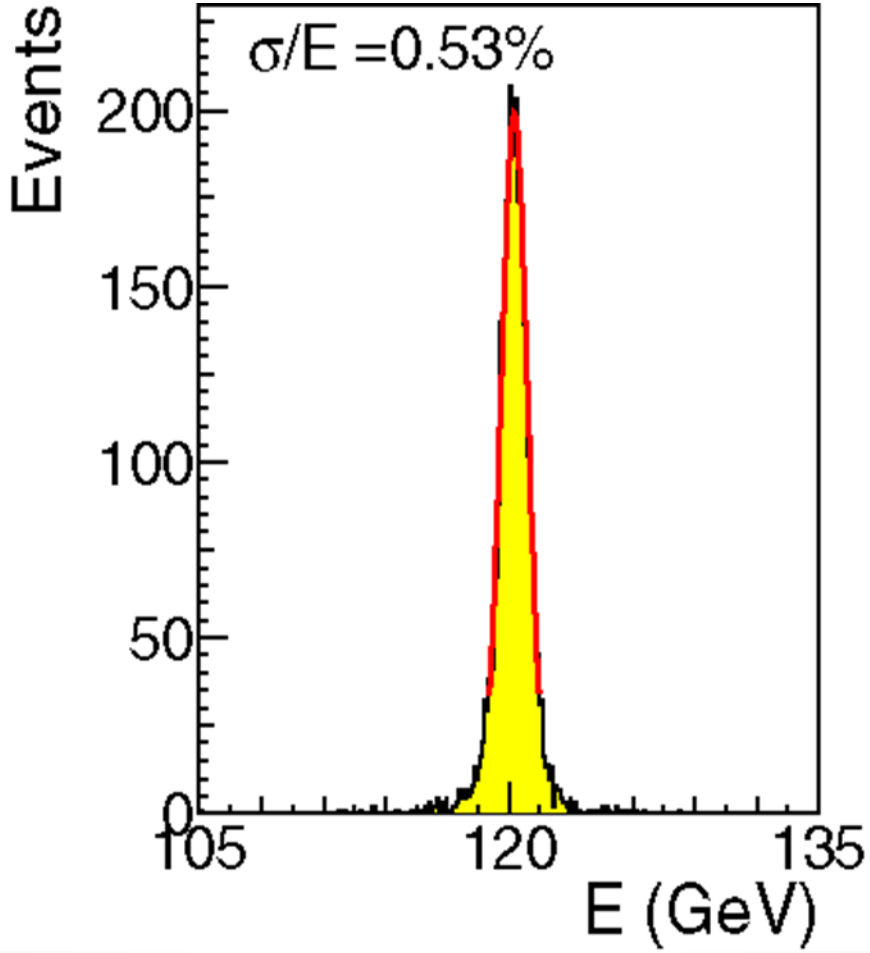
Energy Resolution



- Look at Detector Response for given energy E_0.
- For interaction following Poisson statistics
- ➢ Detector Response for many interactions become Gaussian.
- Fit Response with Gaussian and look at σ (Resolution).

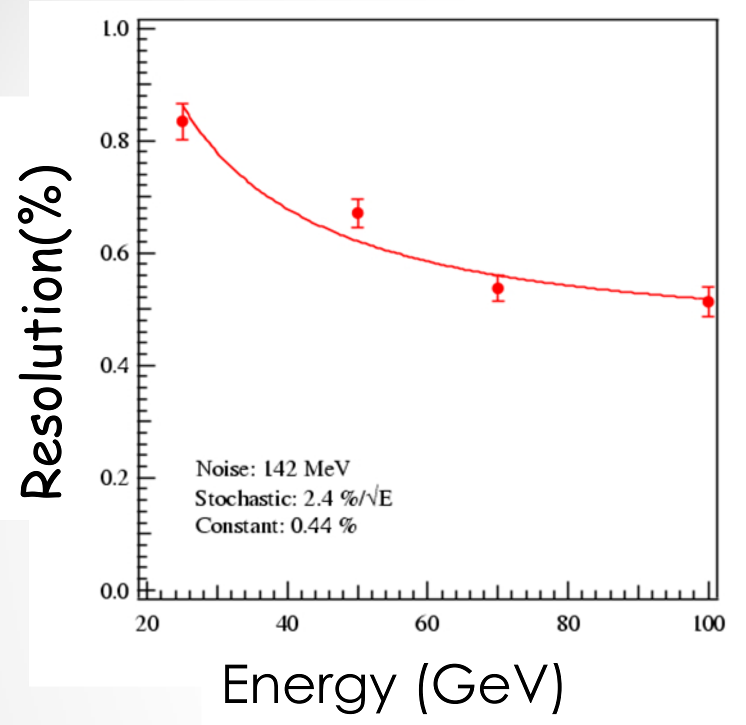
Test beam calibration

Response of a $PbWO_4$ calo to a 120 GeV e^- test beam:

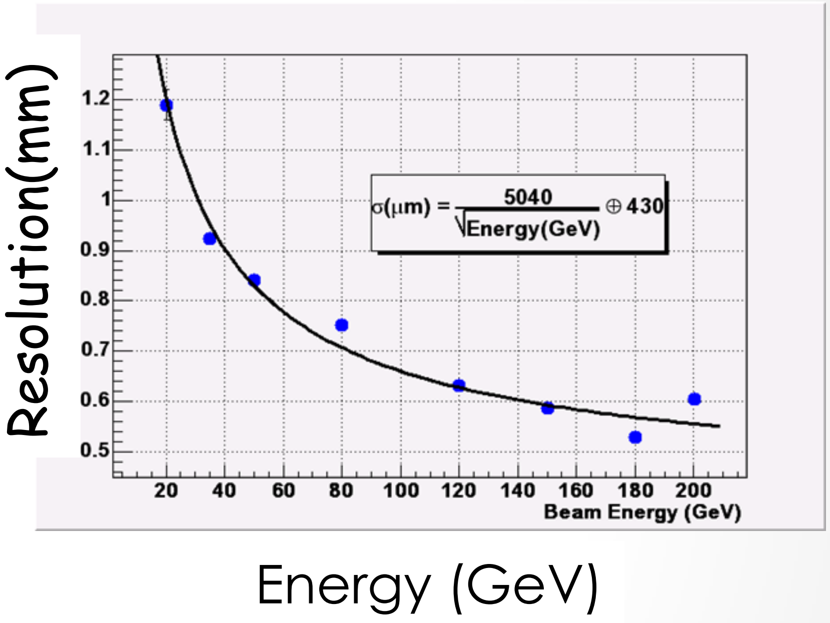


CMS ECAL Test beam with final electronics.

Energy



Position



$$\frac{\sigma(E)}{E} = \frac{2.4\,\%}{\sqrt{E}} \oplus \frac{142\ \text{MeV}}{E} \oplus 0.44\,\%$$

$$\sigma_Y\,(\mu m) = \frac{5040}{\sqrt{E}} \oplus 430$$

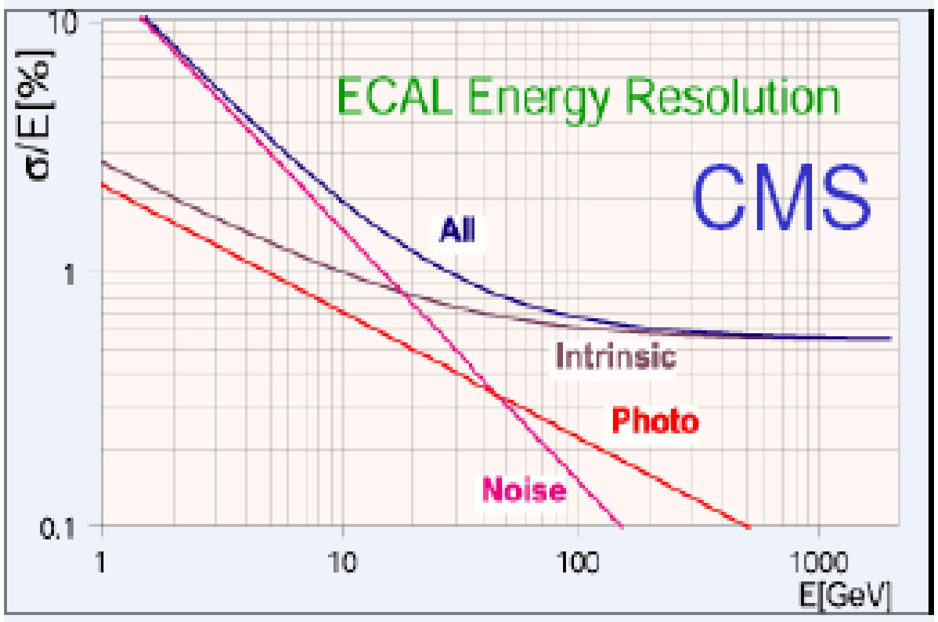
0.6% at 50 GeV.

0.85 mm at 50 GeV.

Energy resolution terms

- The intrinsic shower fluctuations give σ(E) ~ √E
- Fluctuations in the photo-electron yield also give σ(E) ~ √E
- Noise (electronics, radiation) gives a constant term: σ(E) = c
- Inhomogeneities and leakage give σ(E) ~ E

σ(E) / E
[%]



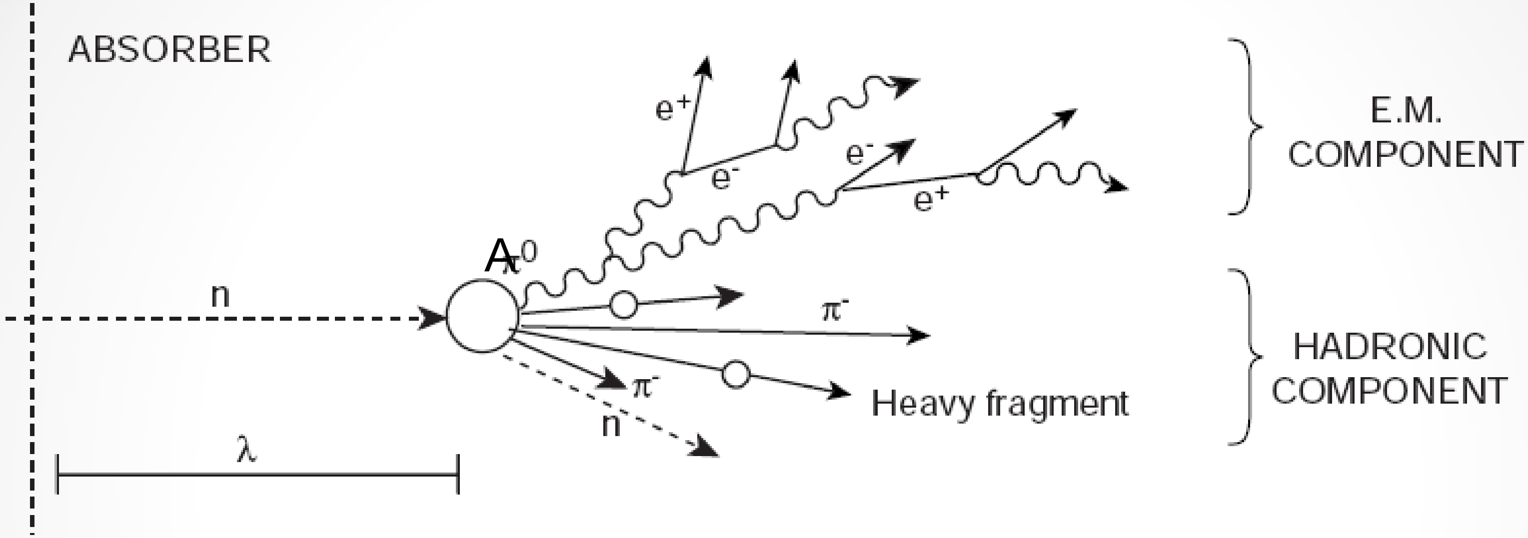
$$\frac{\sigma(E)}{E} = \frac{2.4\,\%}{\sqrt{E}} \oplus \frac{142\ \mathrm{MeV}}{E} \oplus 0.44\ \%$$

Hadron Calorimeters

- Strongly interacting particle > 5 GeV enters matter
  - inelastic and
  - elastic scattering between particles and nucleons occur.
- Cascade ceases when hadron energies small enough to
  - stop by ionization energy loss
  - or nuclear absorption.
- Hadronic Shower:
  - Spatial scale for shower development given by nuclear absorption length λN.
  - Mean free path of a particle before undergoing a non-elastic interaction in a given medium.
- Compare X_0 for high-Z materials
- hadron calorimeters large compared to EM calorimeters.

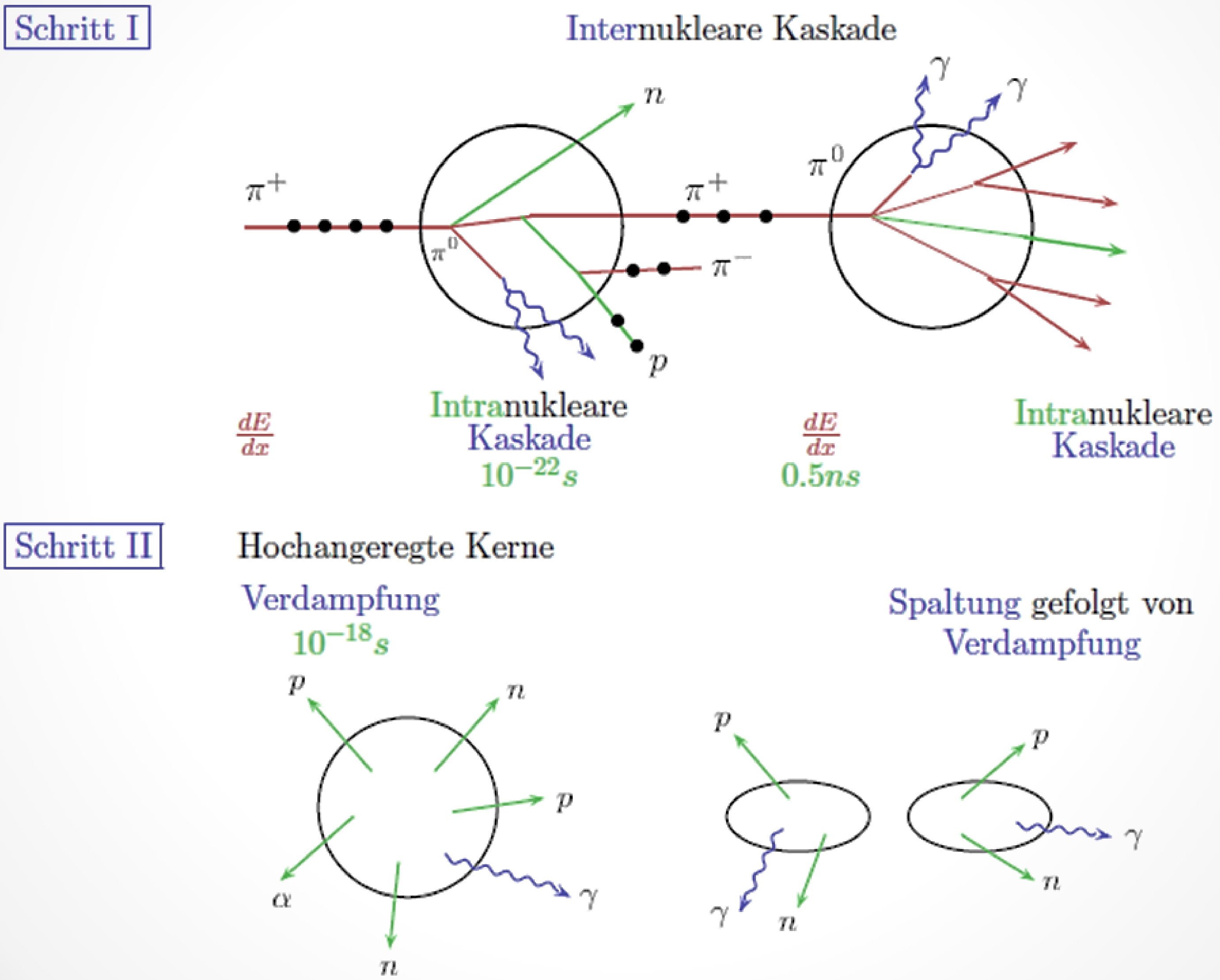
Material	**X_0 (g/cm²)**	**λ(g/cm²)**
H_2	63	52.4
Al	24	106
Fe	13.8	132
Pb	6.3	193

Hadronic showers

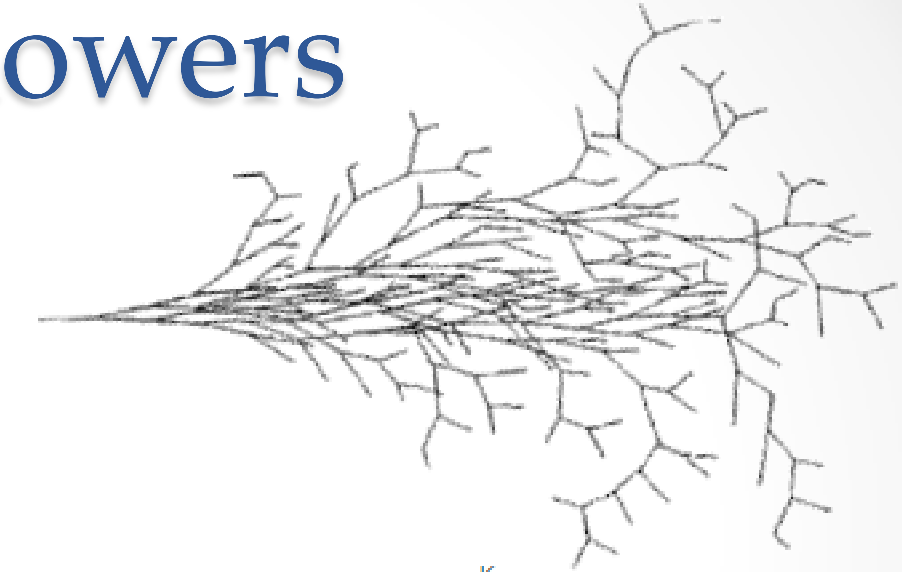


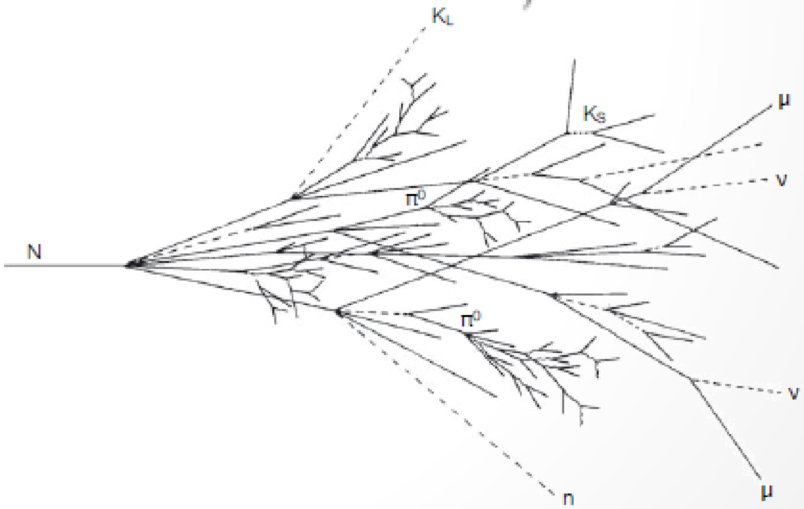
- Hadronic interaction have high multiplicity:
- Shower 95% contained in ~7λ at 50 GeV (1.2m of iron)
- Hadronic interactions produce π^0:
  - $\pi^0 \rightarrow \gamma\gamma$, leading to local EM showers ('hot spots', ~30%)
- Some energy lost in nuclear breakup and neutrons
  - 'invisible energy', 15-35%
- Stronger fluctuations in a hadronic shower:
  - Worse energy resolution

Hadronic showers

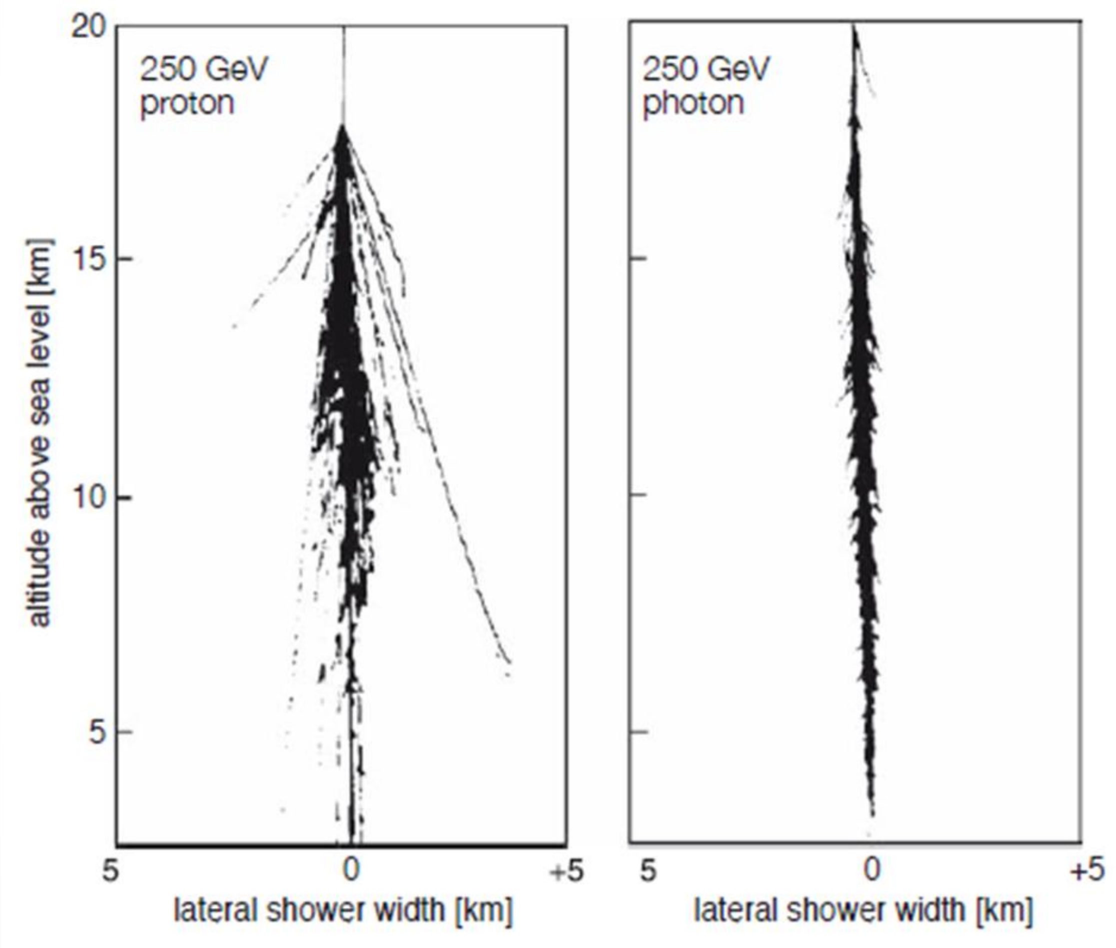


Electromagnetic & Hadronic showers

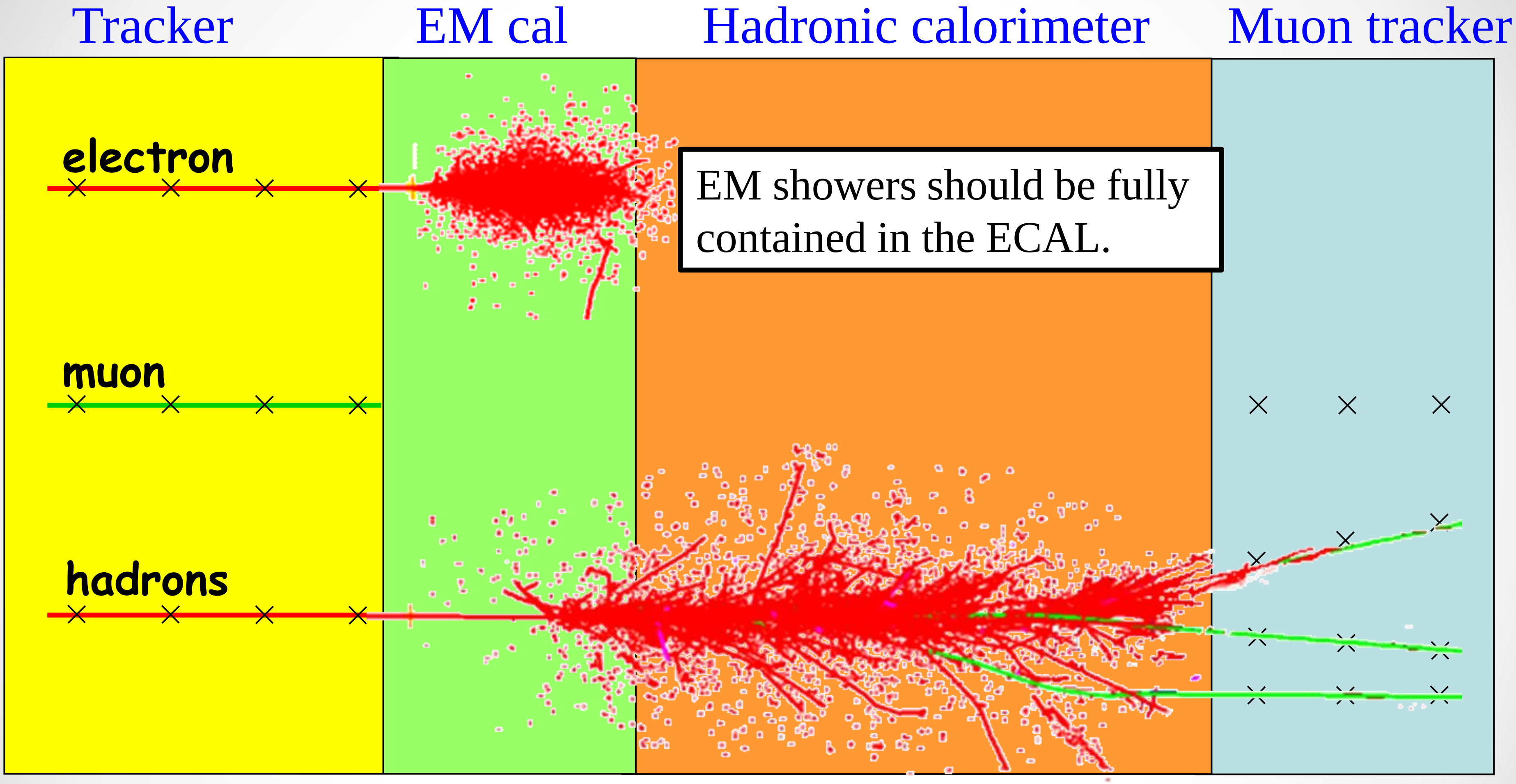




Electromagnetic & Hadronic showers



Hadronic showers



EM showers should be fully contained in the ECAL.

Hadronic showers may already
start in the ECAL and extend into the HCAL.

Hadronic interaction length

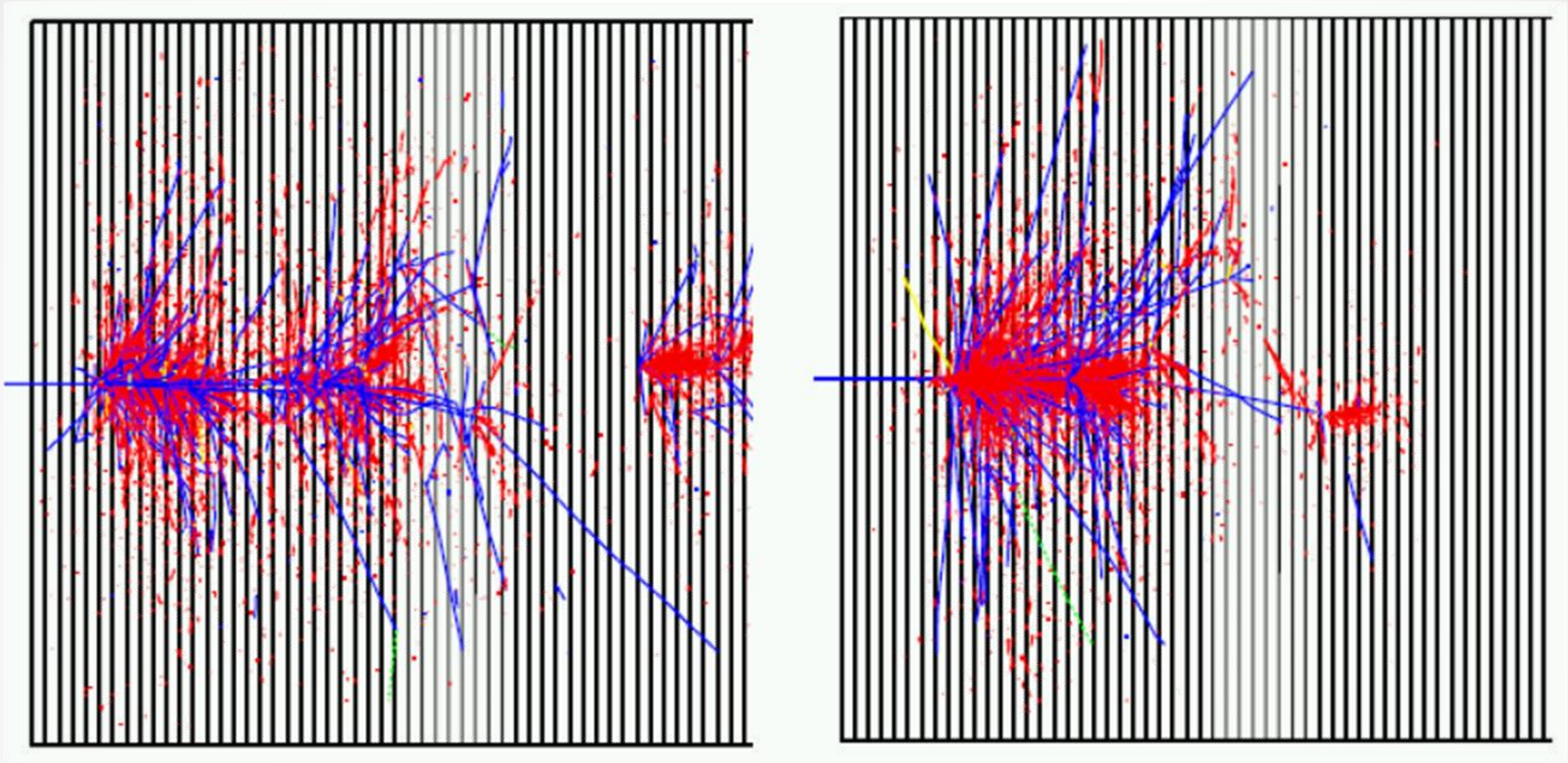
- Pion-proton cross section σ(πp) ≈ 25 mbarn above a few GeV.
- σ(πA) ≈ σ(πp) $A^{2/3}$ (black disk limit).

➢ hadronic interaction length:

$$\lambda_I = \frac{A}{\sigma N_A \rho} = \frac{35cm}{\rho} A^{1/3}$$

- λ_I = 17 cm in Fe or Pb.
- Much larger than X_0.

2 hadronic showers



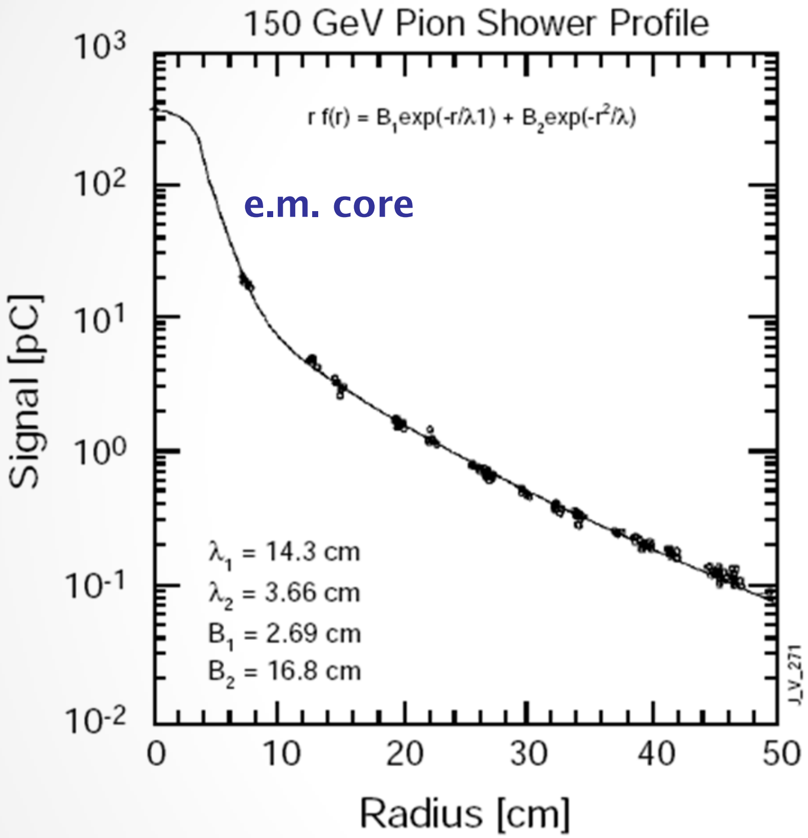
blue = hadronic component

red = electromagnetic component

A good hadron calorimeter should have

- equal response to hadrons and electrons ('hardware compensation')
- or high granularity to isolate the hot spots ('software compensation')

Hadron shower transverse



e.m. core

- Transverse shower development:
  - Secondaries have significant transverse momenta
  - They produce a wide shower
    - compared with EM showers
  - Part of the shower gets an electromagnetic nature
    - i.e. The decay of the π^0 produced in the interaction
    - remains inside a narrow cylinder:
    - two times the Moliere radius

T.S.Virdee, Proc. of the 1998 European School of High-Energy Physics, CERN 99-04

Compensating Calorimeters

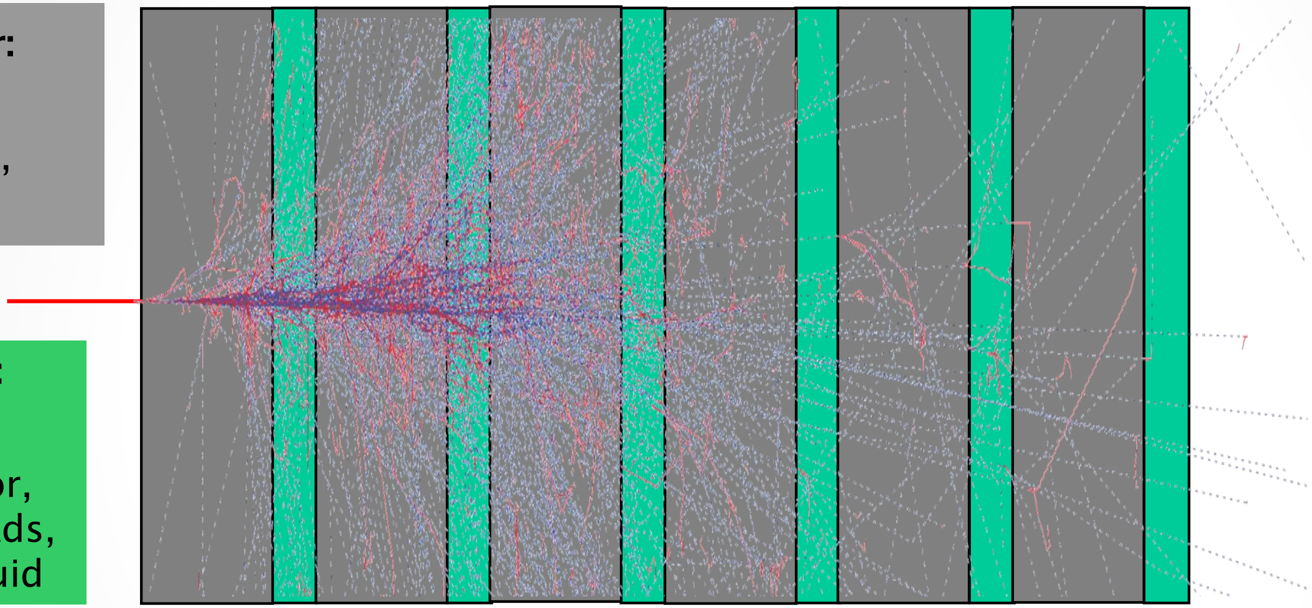
- Improvements in energy resolution can be achieved if
  - o showers induced by electrons and hadrons of same energy
  - ➢ produce same visible energy (detector response).
- Requires the losses to be "compensated"
- Three methods:
  - o Energy lost by nuclear reactions made up for by fission of ^{238}U
  - o liberating n and soft γ-rays
  - o response close to equal:
  - o proton-rich detector → em shower decreases
  - o hadron shower increases due to more nuclear reactions
- If have lots of H_2:
  - ➢ compensation achieved with high absorber material:
  - o in inelastic collision of hadrons w/ absorber nuclei,
  - o neutrons are produced → recoil protons, larger signal.
- Reduce fluctuation in EM component:
  - o weight individual counter responses
  - o even response out across the board

Sampling calorimeter

Absorber and detector are separated as passive and active layers.

Absorber:

Lead,
Tungsten,
Uranium



Detector:

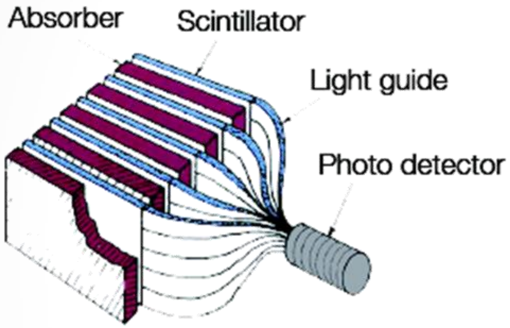
MWPC,
scintillator,
silicon pads,
noble liquid

- The active detector material **samples** a fraction F of the shower.
- The detector signal is proportional to the incident energy.
- Allows longitudinal segmentation
- Good for hadrons
- Energy resolution is degraded $\sim 1/\sqrt{F}$ ('sampling fluctuations').
- Less expensive.

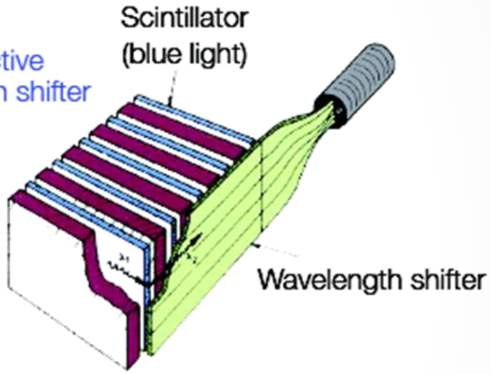
Sampling Calorimeters

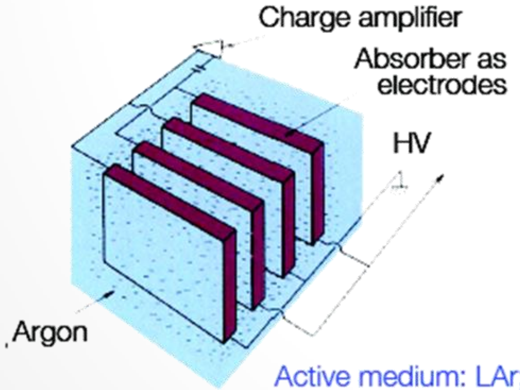
Possible setups

Scintillators as active layer;
signal readout via photo multipliers



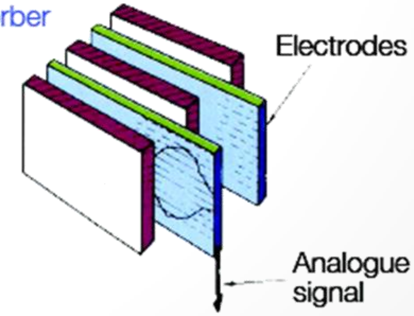
Scintillators as active layer; wave length shifter to convert light



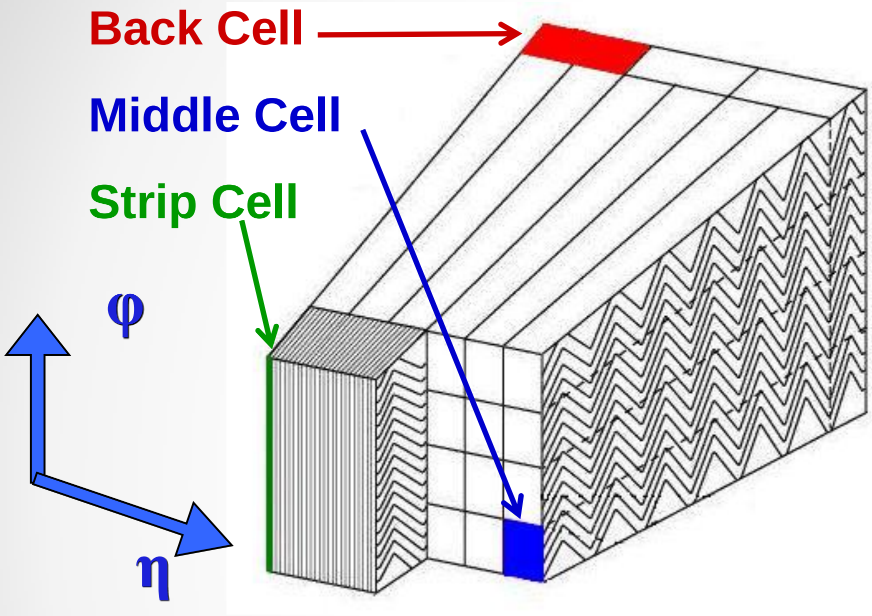


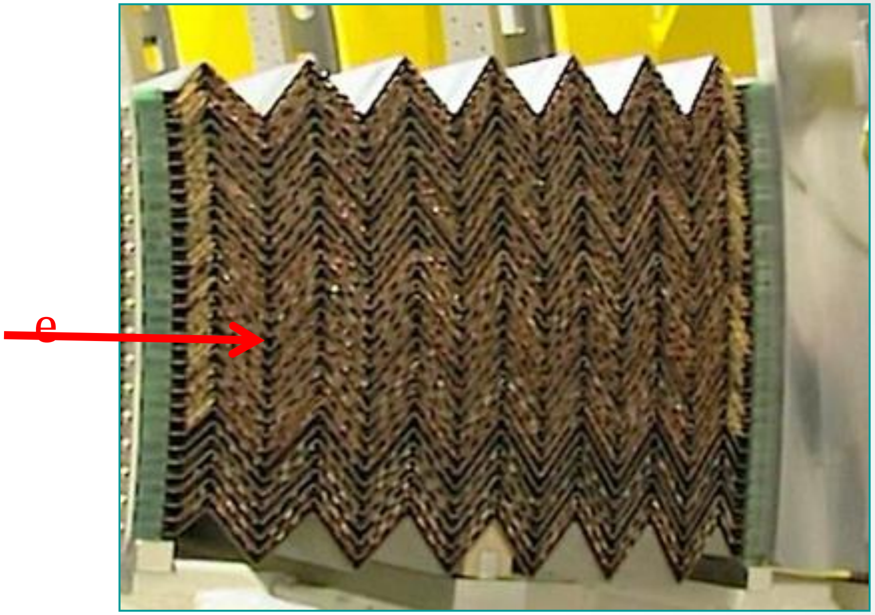
Active medium: LAr; absorber embedded in liquid serve as electrods

Ionization chambers between absorber plates



ATLAS LAr ECAL



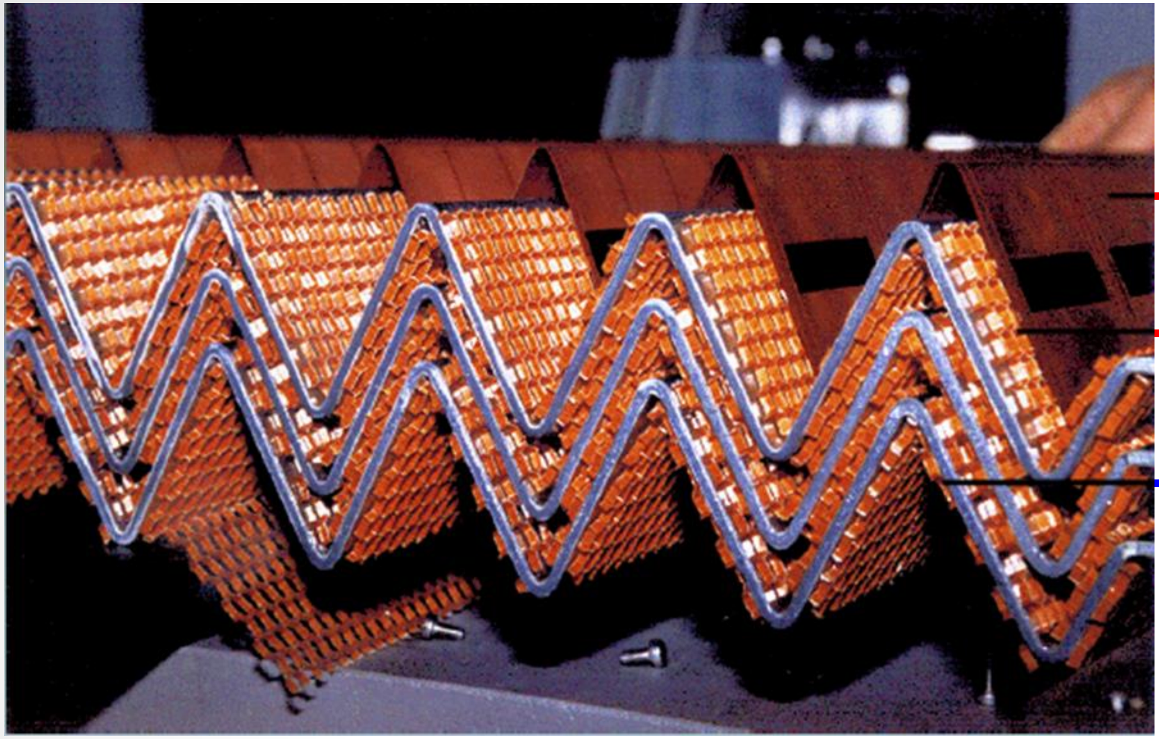


3 sections:

- strips for position resolution
- middle for energy measurement
- back for leakage control

- Pb absorber in LAr
- Accordion geometry for routing of readout signals to the back
- Allows dense packing and fine granularity.

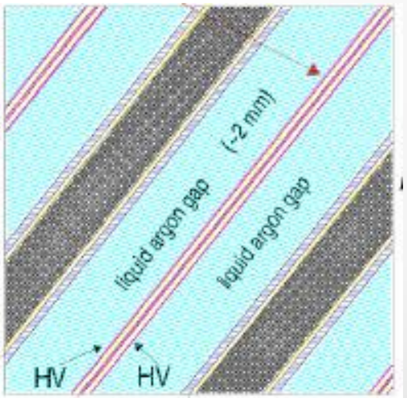
ATLAS LAr ECAL



Cu electrodes at +HV

Spacers define LAr gap
2 × 2 mm

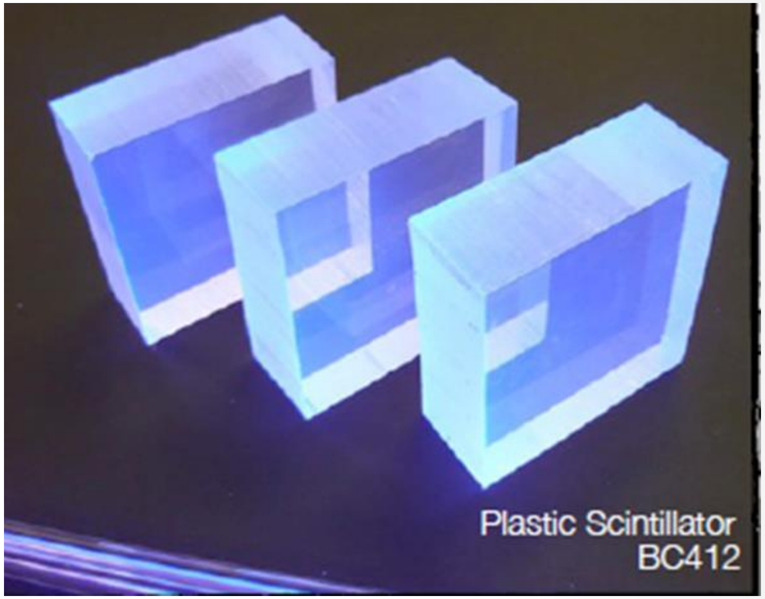
2 mm Pb absorber
clad in stainless steel.



Scintillators:

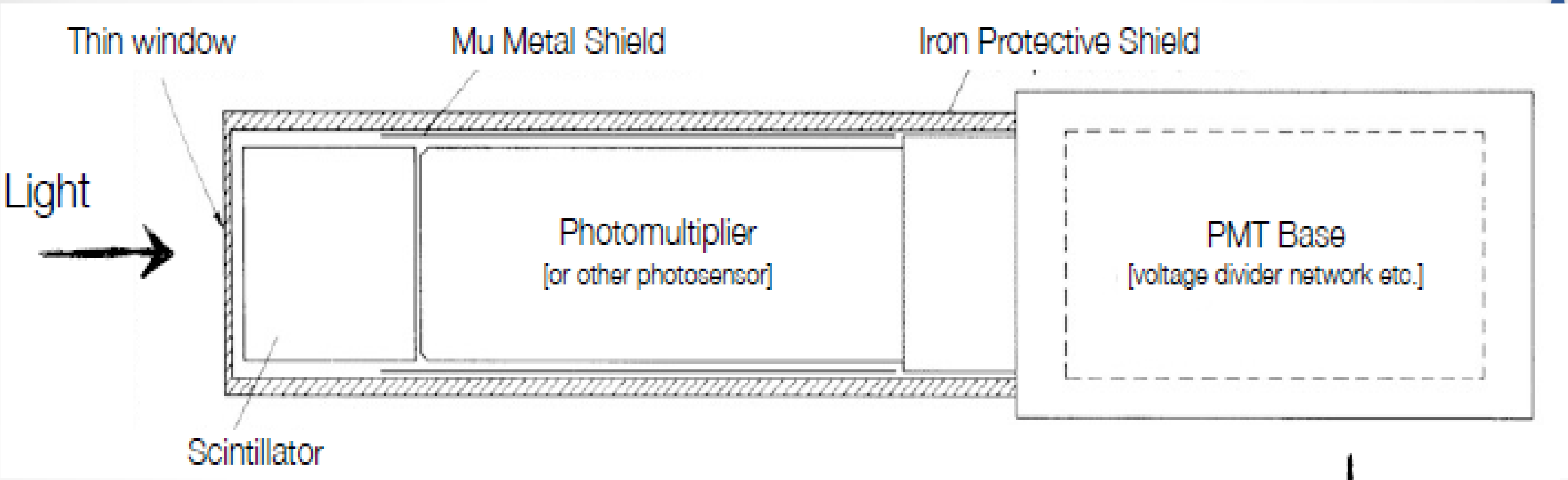
- A scintillator is a material which exhibits the property of luminescence when excited by ionizing radiation.
- Luminescent materials, when struck by an incoming particle, absorb its energy and scintillate, i.e. re-emit the absorbed energy in the form of a small flash of light, typically in the visible range.

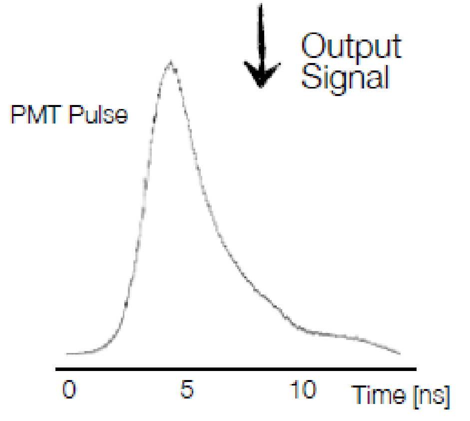
Scintillators General Characteristics



- Principle:
  - dE/dx converted to visible light
  - Light detection via photo-sensors
- Main features:
  - Sensitivity to energy of particle
  - Fast response
  - Pulse Shape discrimination
- Requirements:
  - High efficiency for the conversion of exciting energy to fluorescent radiation
  - Transparency to its fluorescent radiation to allow light transmission
  - Emission of light in a detectable spectral range
  - Short decay time to allow fast response

Scintillators - Basic Setup

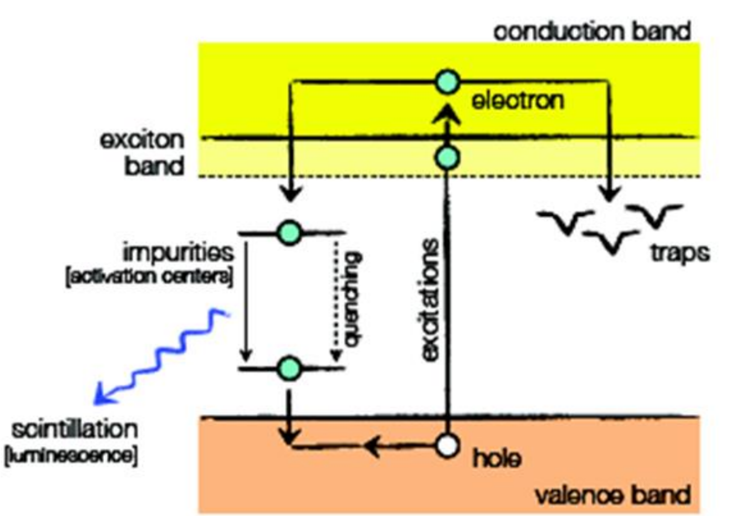




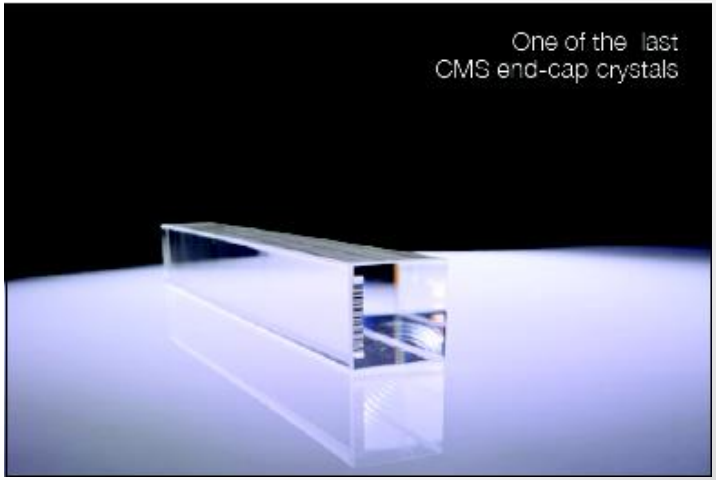
- Photo-sensors
  - Photomultiplier
  - Avalanche Photodiodes
  - ...
- Scintillator Types
  - Organic Scintillators
  - Inorganic Scintillators
  - Noble Gases

Inorganic Crystals

- Material
  - Sodium iodide (NaI)
  - Cesium iodide (CsI)
  - BGO
  - …
- Mechanism
  - Energy deposition by ionization
  - Energy transfer to impurities
  - Radiation of scintillation photons

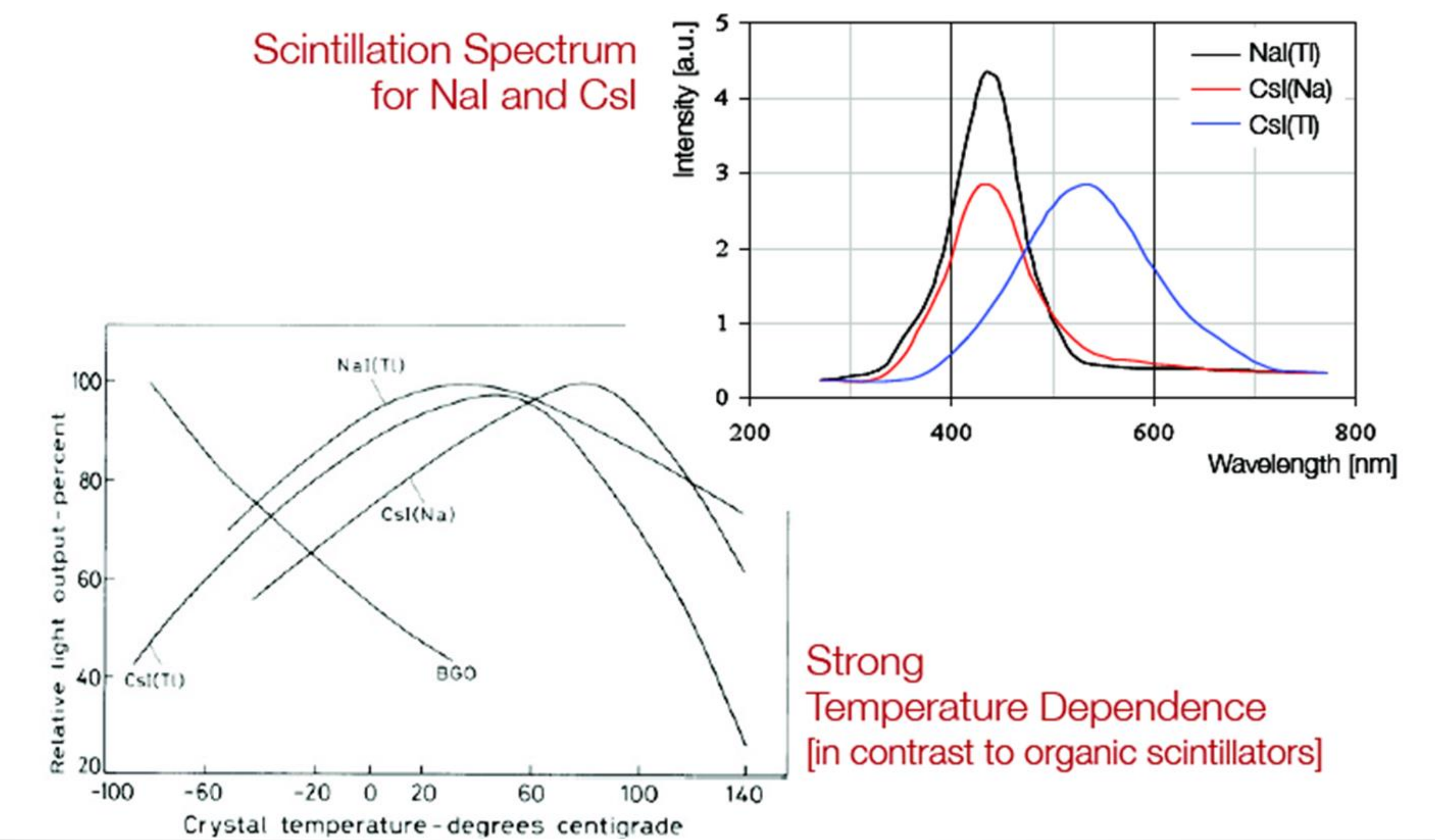


Energy bands in impurity activated crystal



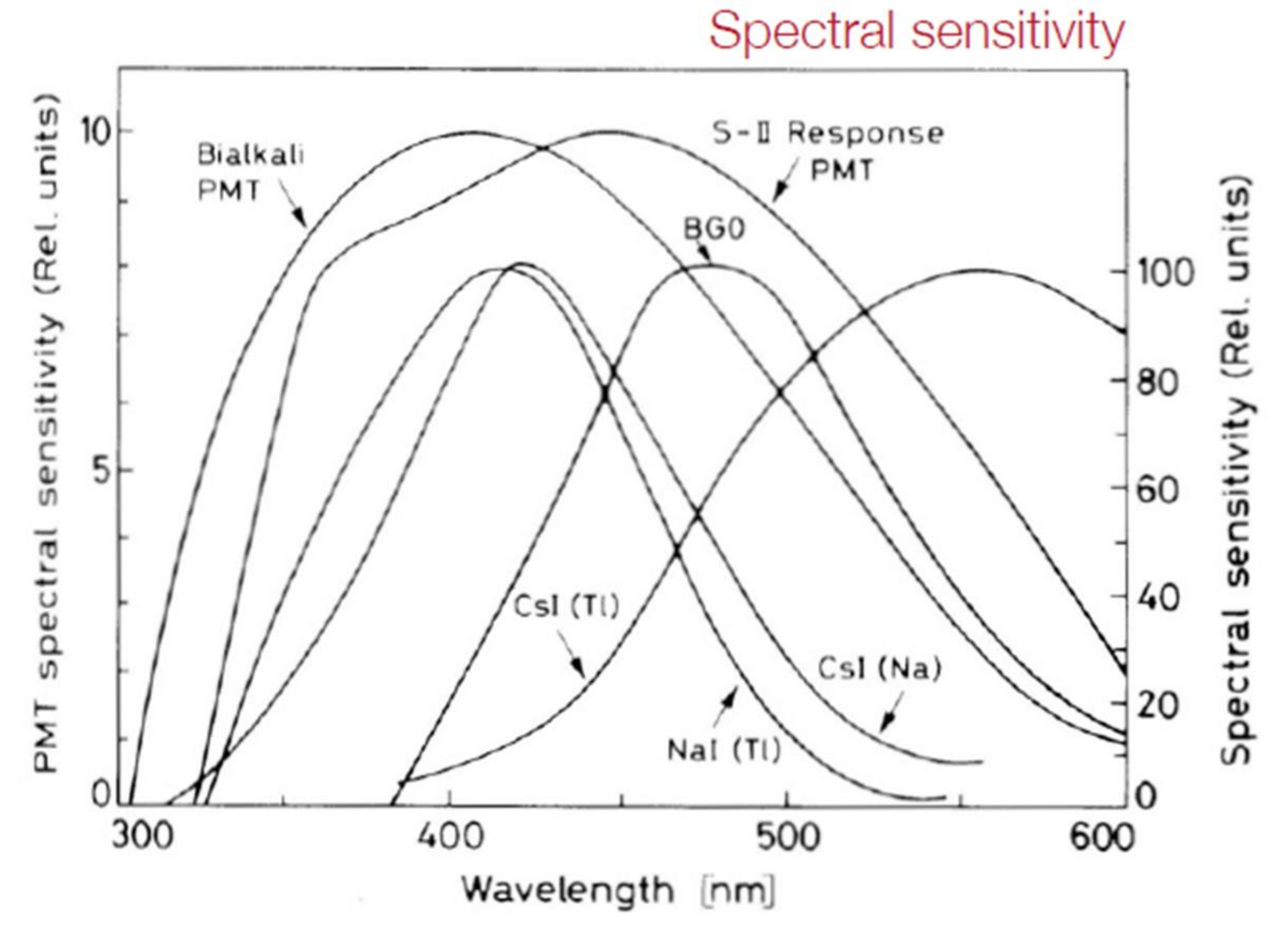
One of the last CMS end-cap crystals

Inorganic Crystals - Light Output


Scintillation Spectrum for NaI and CsI

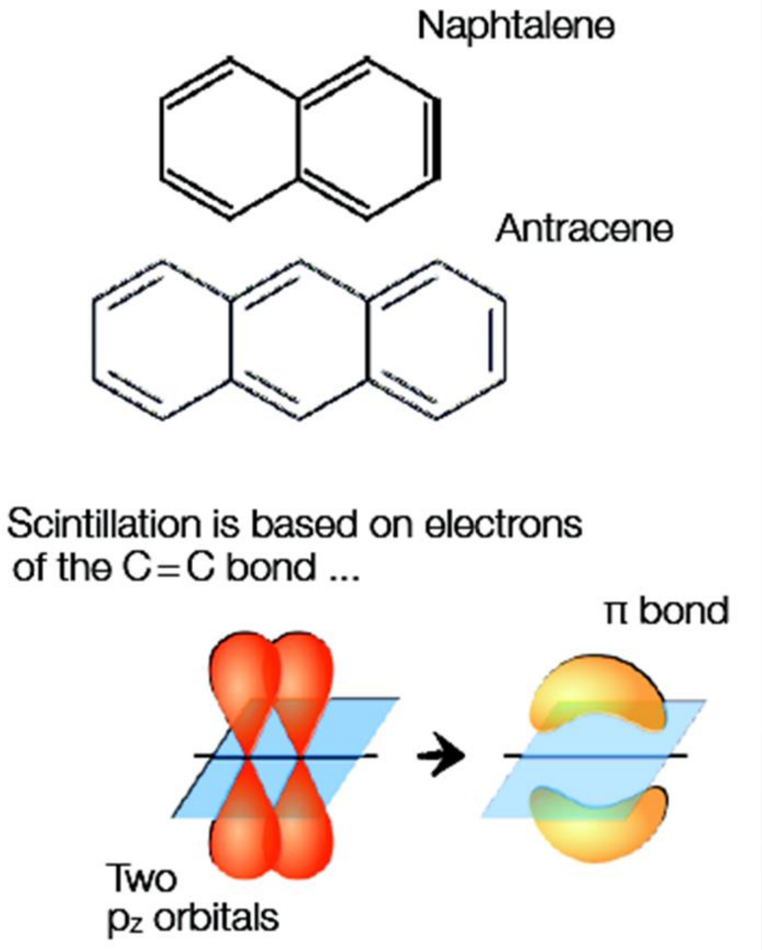
Strong
Temperature Dependence
[in contrast to organic scintillators]

Inorganic Crystals - Light Output



Organic Scintillators

- Aromatic hydrocarbon compounds:
    - Naphthalene ($C_{10}H_8$)
    - Antracene ($C_{14}H_{10}$)
    - Stilbene ($C_{14}H_{12}$)
- …
- Very fast decay time
- Scintillation light arises from delocalized electrons in π-orbitals



Scintillation is based on electrons of the C=C bond ...

Scintillators Comparison

Inorganic Scintillators

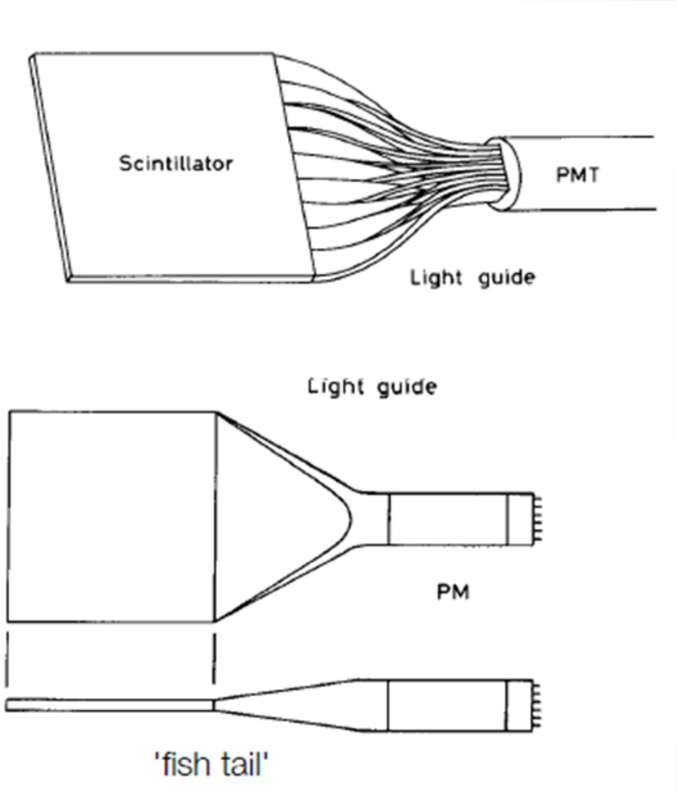
- Advantages:
  - high light yield
  - high density
  - good energy resolution
- Disadvantages:
  - complicated crystal growth
  - large temperature dependence
  - Expensive

Organic Scintillators

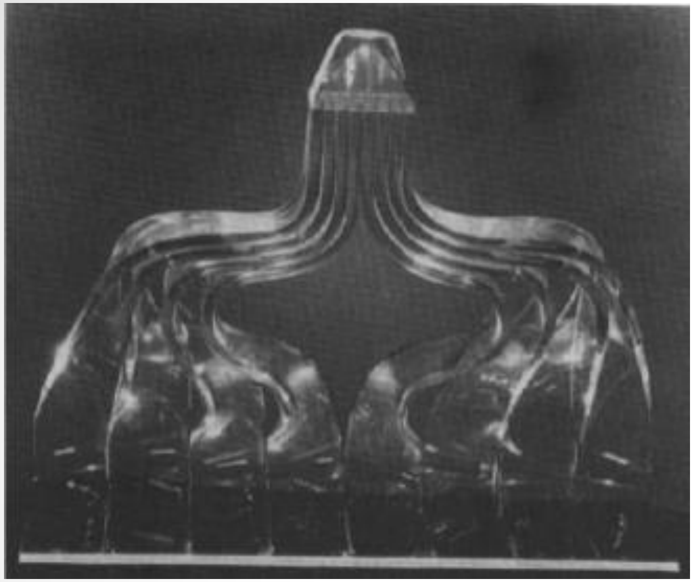
- Advantages:
  - very fast
  - easily shaped
  - small temperature dependence
- Disadvantages:
  - Lower light yield
  - radiation damage
  - Cheap

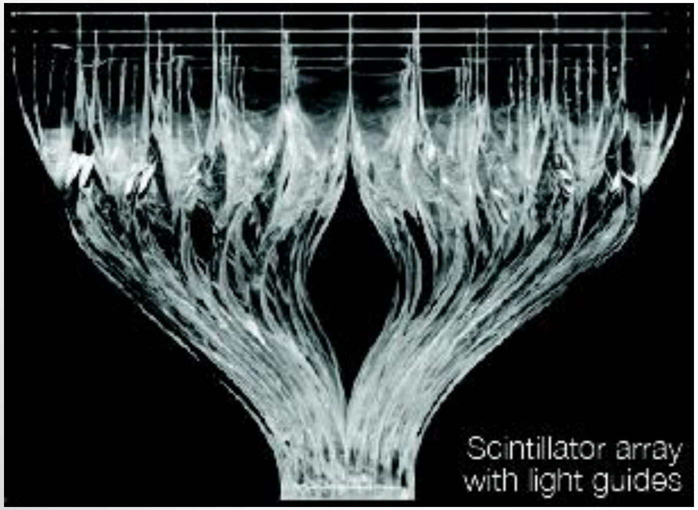
Transport of Optical Photons

- Unavoidable or desirable to have the photo-detector remote from the scintillator:
  - Space limitations
  - Photo detector out of the magnetic field
  - Couple a large scintillator surface (volume) to a single photo-detector
  - …
- Use optical wave guides:
  - Total internal reflection

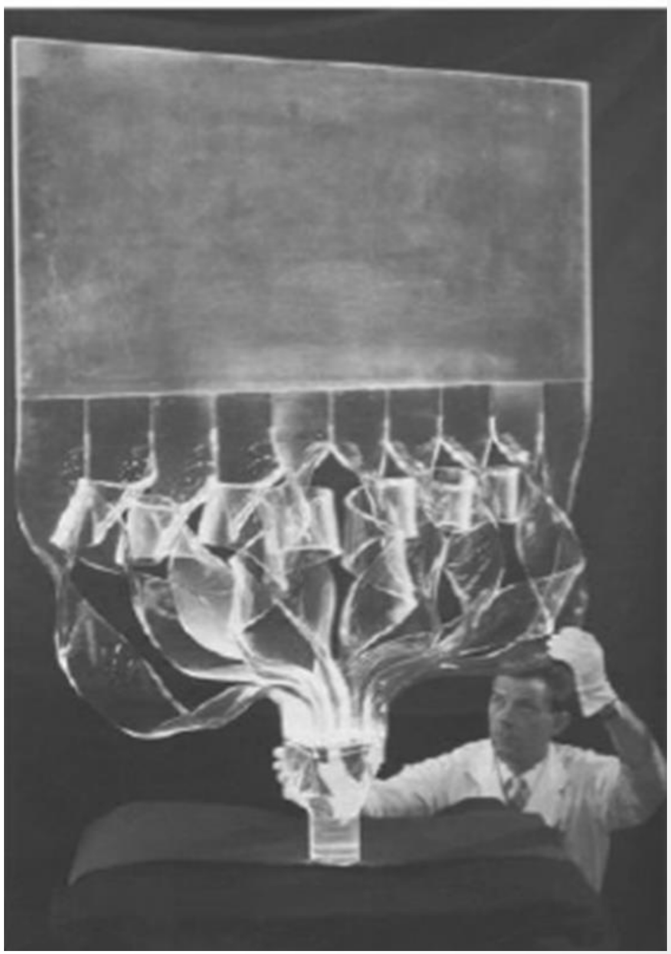


Transport of Optical Photons





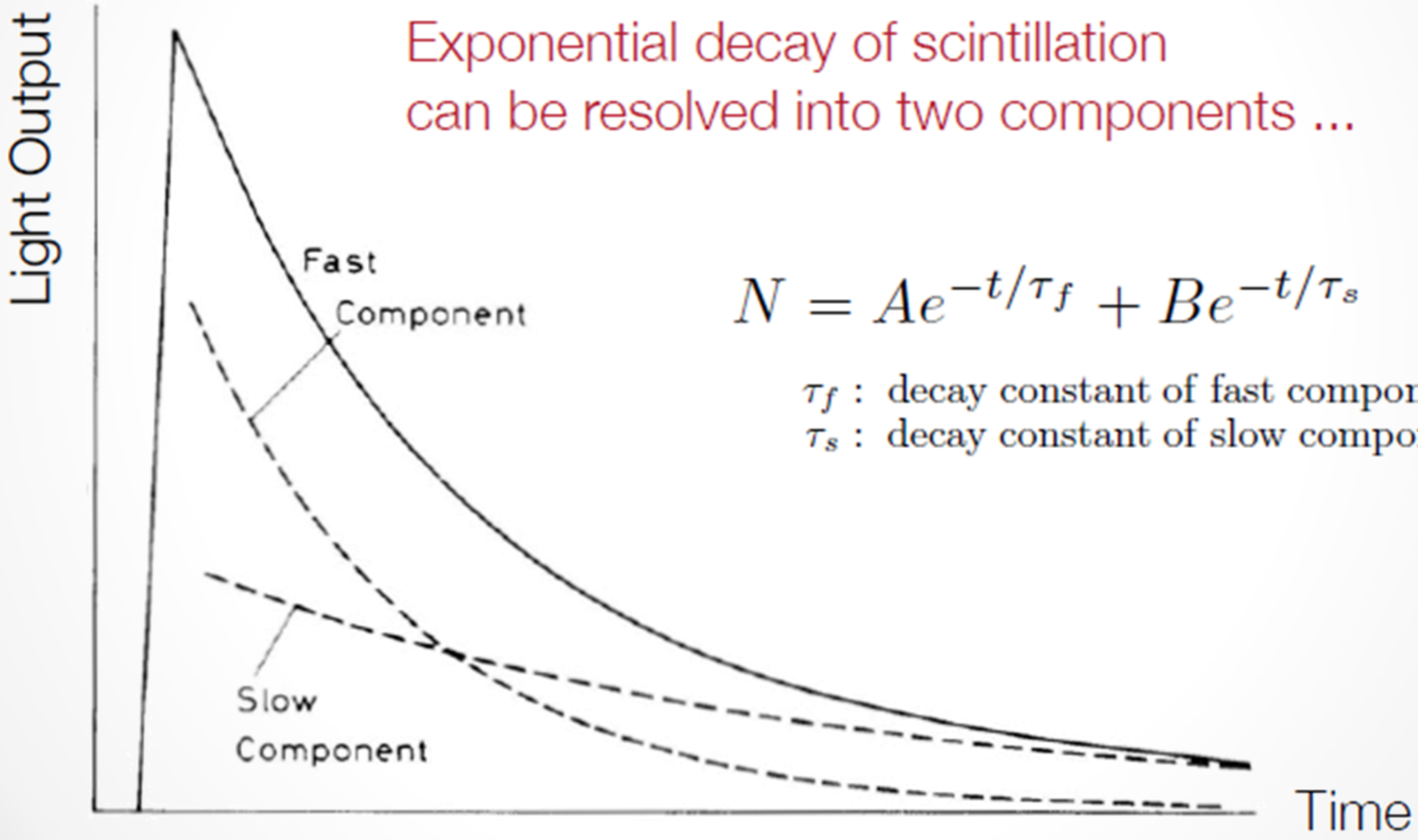
Scintillator array with light guides



CMS Hcal read out

- Scintillators coupled to readout fibers.
- Bundles of fibers coupled to an avalanche photodiode

Time Constants



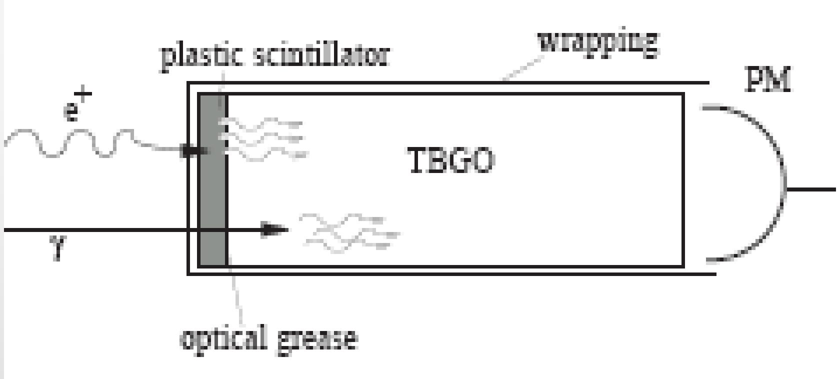
Exponential decay of scintillation can be resolved into two components ...

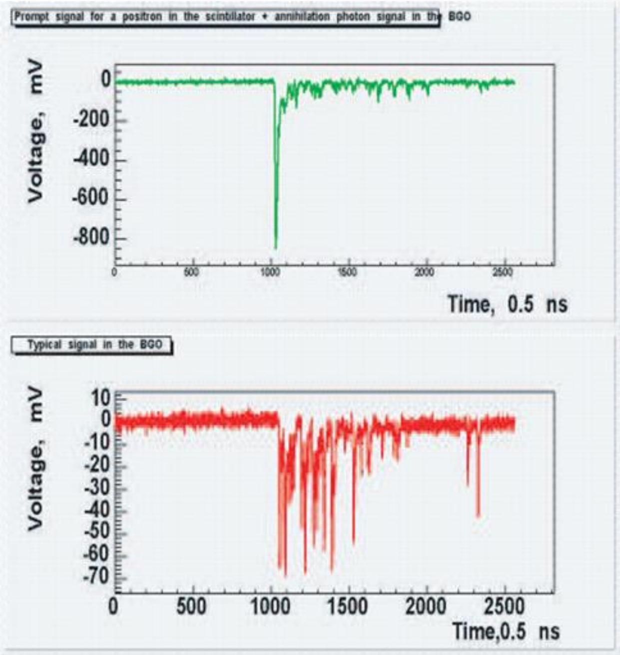
$$N = Ae^{-t/\tau_f} + Be^{-t/\tau_s}$$

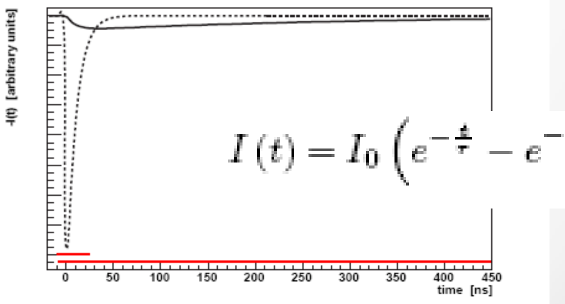
τ_f : decay constant of fast component
τ_s : decay constant of slow component

γ, e separation based on time constant

- e interacts in plastic sc.
- γ interacts in BGO
    - Decay times BGO ~300ns
    - plastic sc ~10ns
- use different integration times!



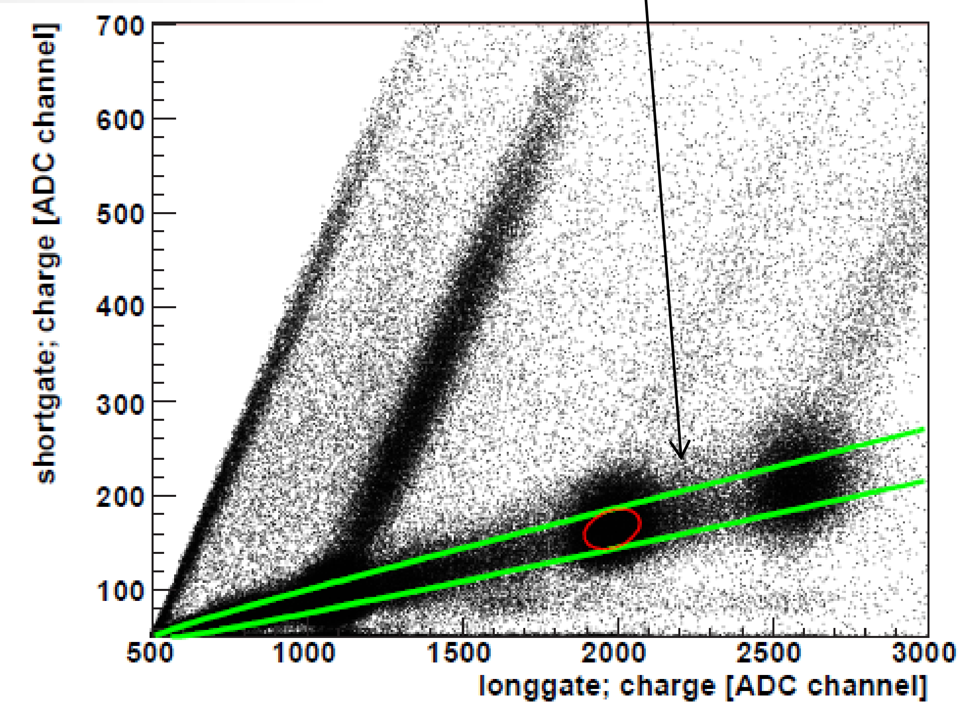




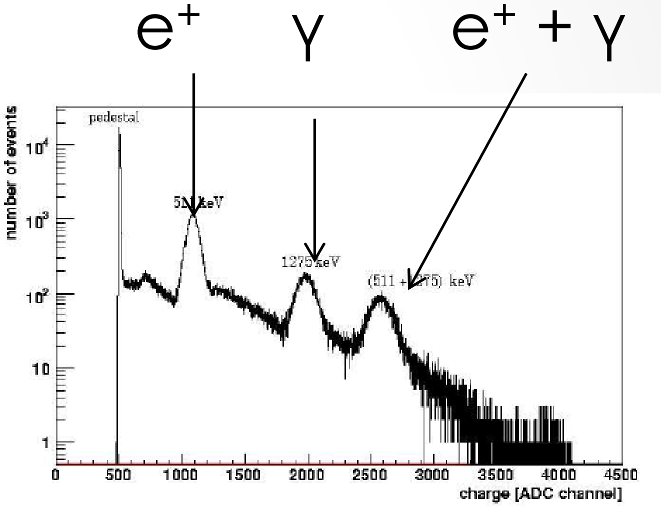
$$I(t) = I_0 \left(e^{-\frac{t}{\tau}} - e^{-\frac{t}{\tau_1}} \right)$$

γ, e separation based on time constant

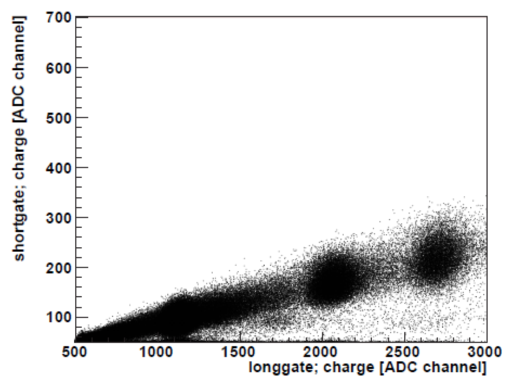
- scatter plot of 22Na decay spectrum
- no short signal for γ



- ^{22}Na decay spectrum



- only BGO, no fast signal

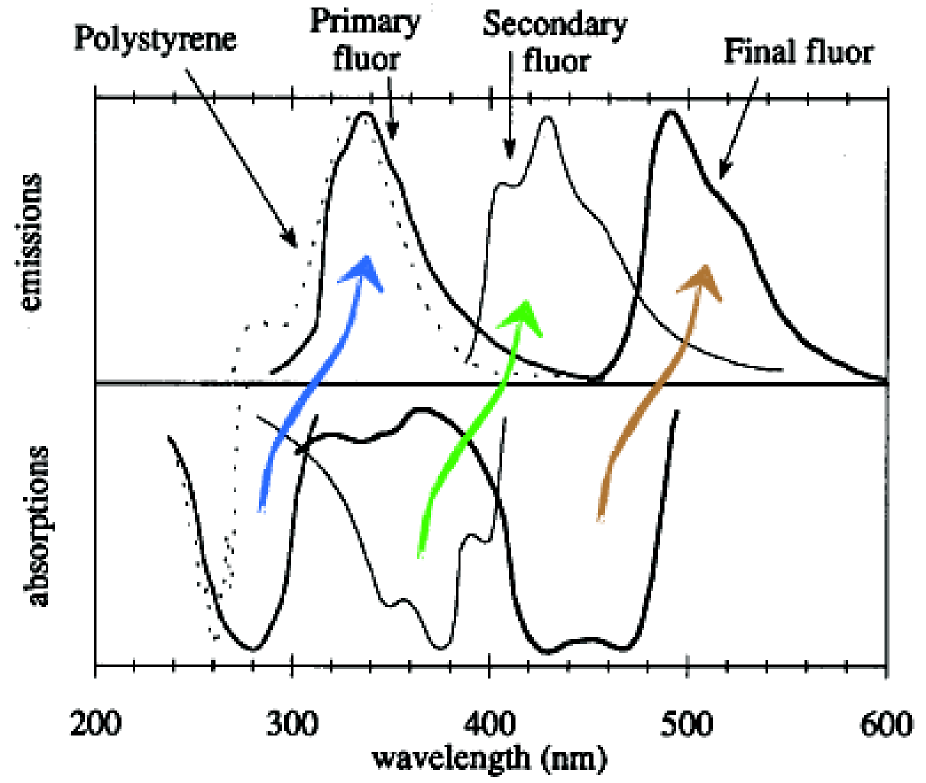


Wavelength Shifting

Principle:

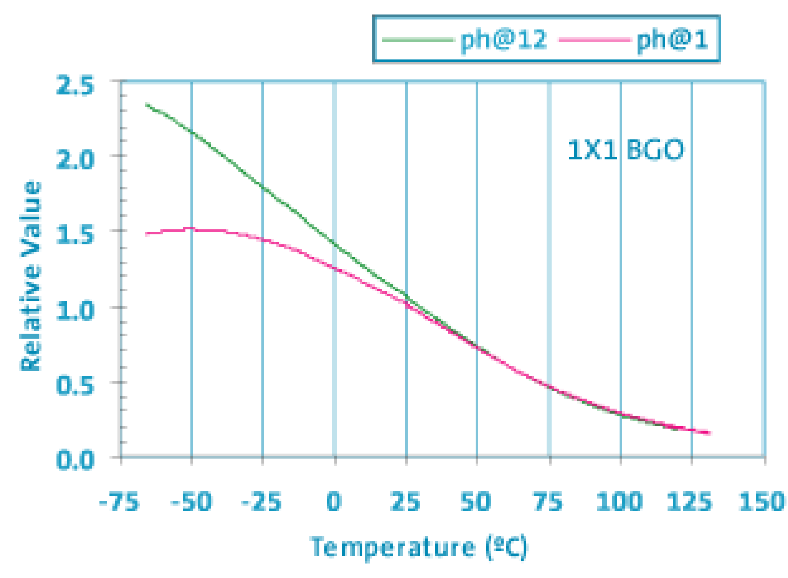
- converts the short wavelength light (λ<400nm) emitted by scintillation or Cherenkov radiation
- into a longer wavelength (blue light, λ>400nm)

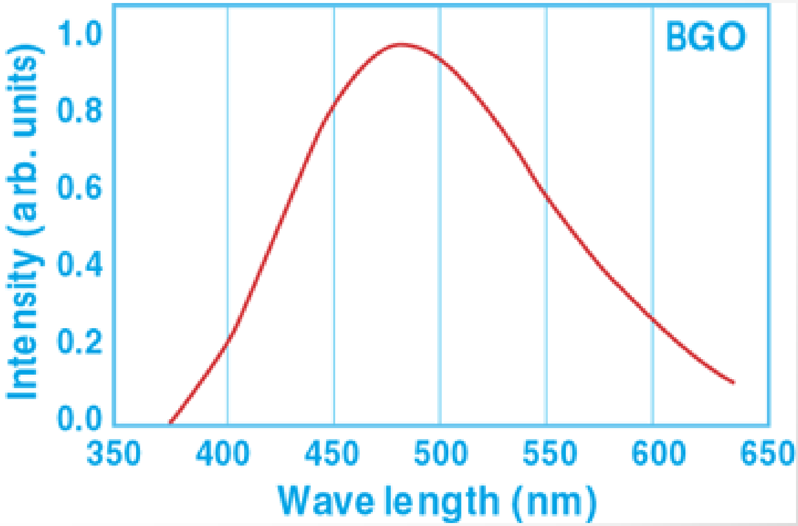
➢ Adapt light to spectral sensitivity of photosensor



BGO

- Best suited for gamma detection (high Z)
- High density
- Temperature dependence!!!

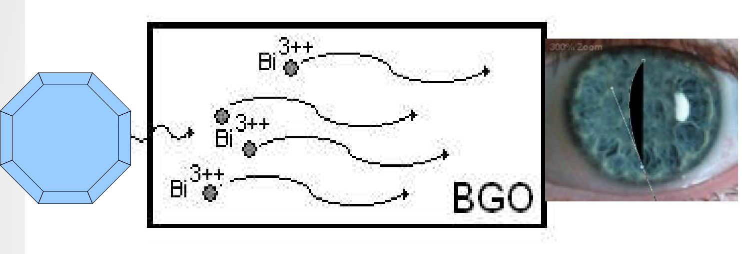




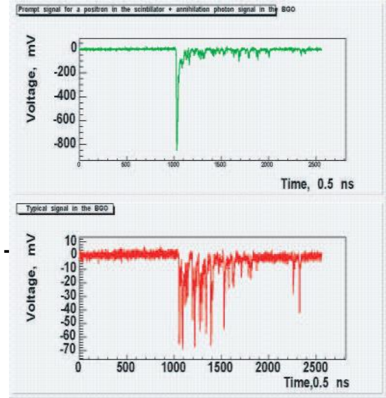
Scintillation Detector

- Couple scintillator to an electronic light sensor

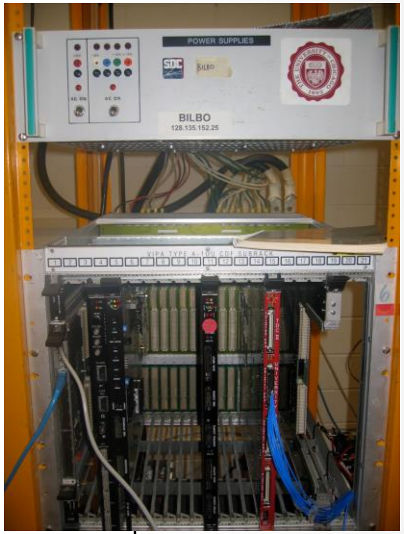
Source Scintillator Eye

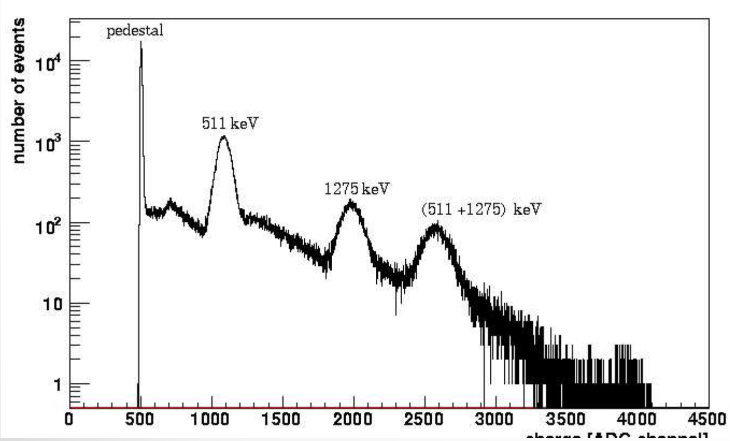


Electronic Signal



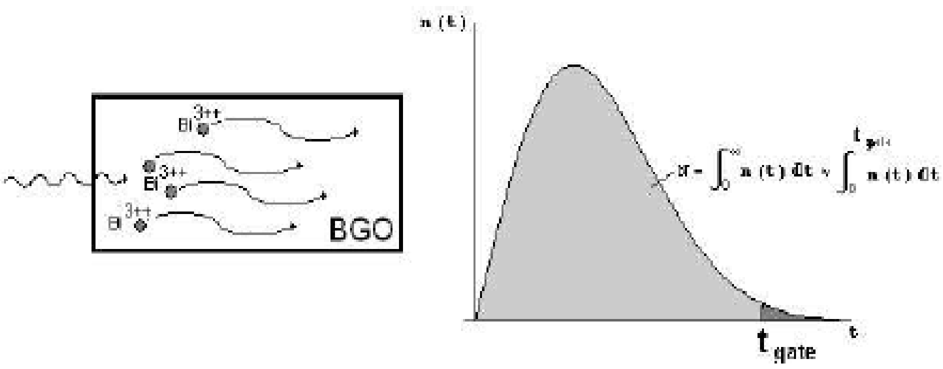
Electronic Hardware





Energy Measurement with BGO

$E_{\gamma,\mathrm{pos.}} = ?$

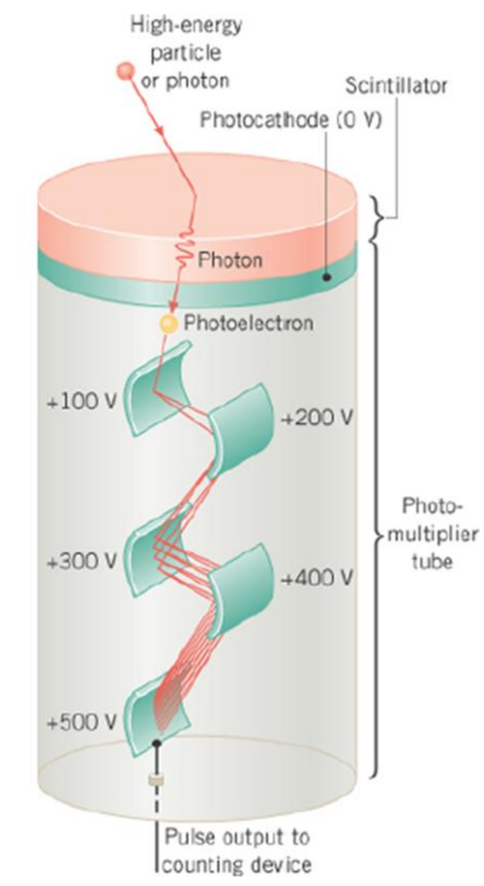


- BGO: $Bi_4Ge_3O_{12}$
- Luminescence: Optical transition of Bi^{3+} ion
- n(t): #exitedBi^{3+} ions per dt
- ==> $N = \int^{\infty} n(t)dt \approx \int^{t_{gate}} n(t)dt = N_{measured}$ N_meas. ~ 4photons/keV (BGO)
- ==> $E_{\gamma,\mathrm{pos.}} = N \alpha E_{\gamma, Bi^{3+}}$

Light Detectors

Photomultiplier Tube (PM)

- Light falls on a **photo-cathode**
- Photo-electron is emitted
  - **Photo effect**
  - Quantum Efficiency depends on
    - Cathode material and
    - Wavelength (QE ~ 25%)
- Photo-electron focused and accelerated towards the first **dynode** by electric field
- Photo-electron strikes dynode
  - Several electrons are emitted
- Several dynodes (10-15) give **hight gain** 10^7
- **High speed**: few ns transmit time
- Gain much lower in magnetic field

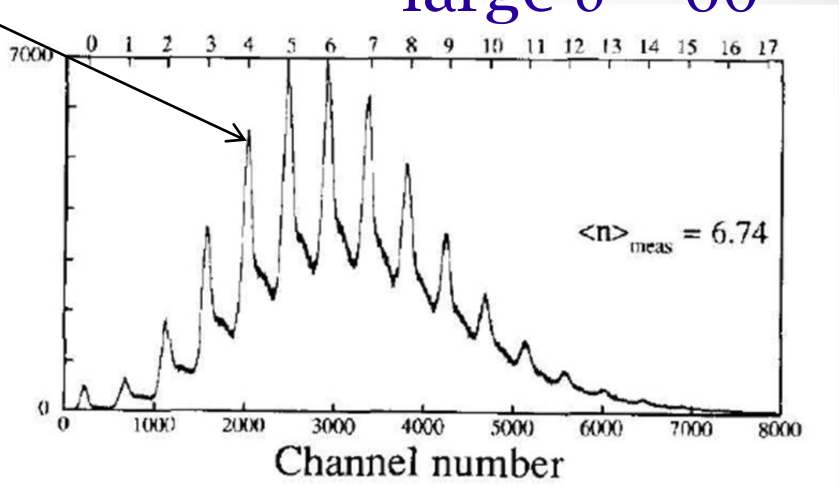


Source: Cutnell and Johnson, 7th edition image gallery

PM Response

peaks: single photo electrons

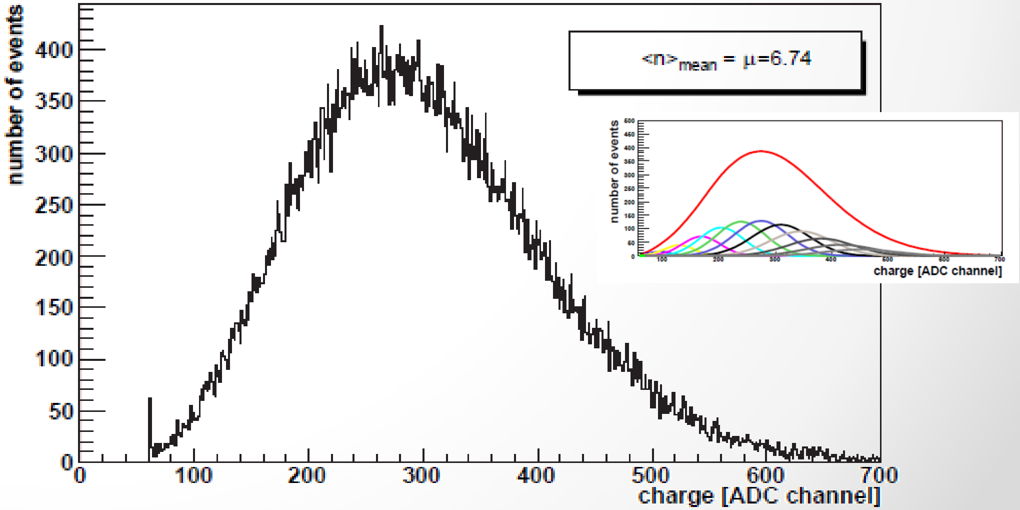
large δ ~ 60



- Integrated PM response of 2 PM with different dynode multiplication factors:

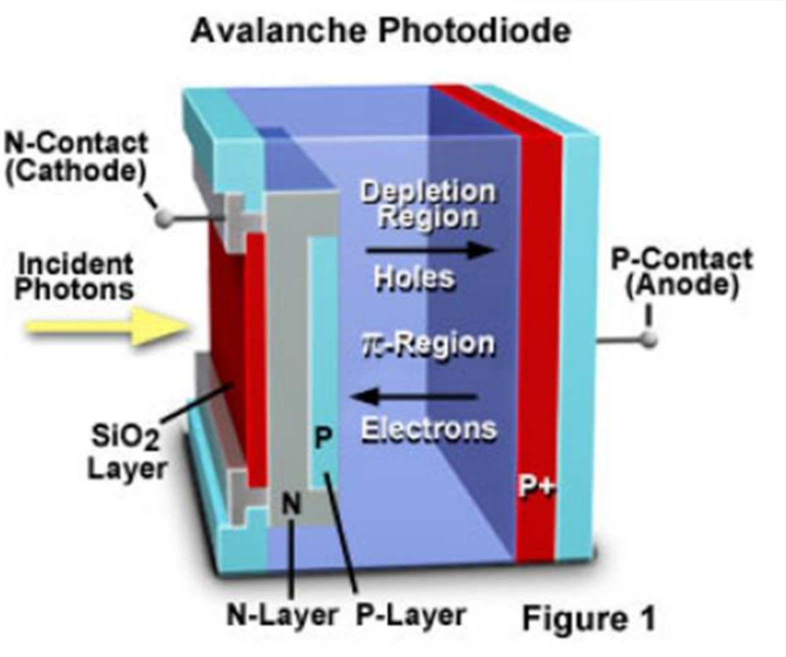
$$\delta = \frac{\text{number of secondary electrons emitted}}{\text{number of primary incident electrons}}$$

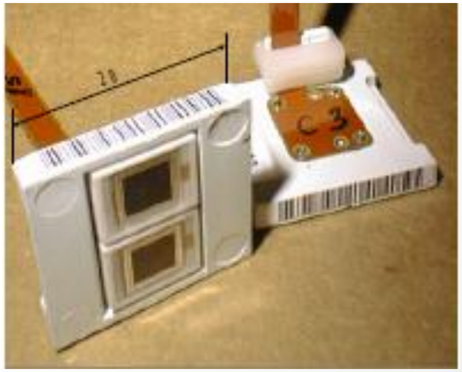
normal δ ~ 5-10



Avalanche Photodiode (APD)

- 85% quantum efficiency
- Photoelectrons create cascade of electron-hole pairs in the bulk.
- Gain ~100 in linear mode
- Low sensitivity to magnetic field.
- APD gain decreases by 2.3%/°C .
  - Need temperature stabilization within 0.1°C in ECAL!

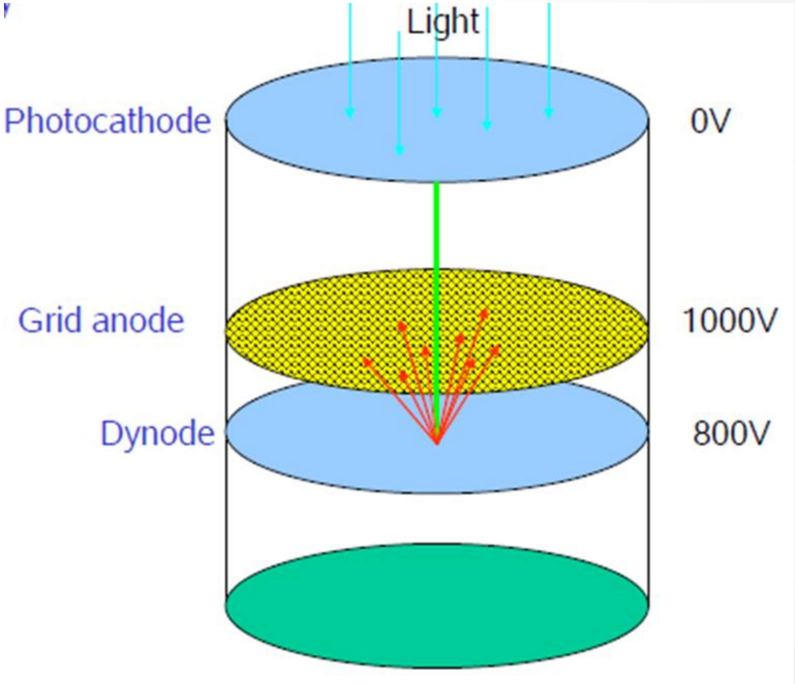




Vacuum photo-triodes

- ~20% quantum efficiency
- Single stage photomultiplier
- Gain ~ 10 at B=4T

radiation resistant UV glass
window used in CMS ECAL



Time of Flight

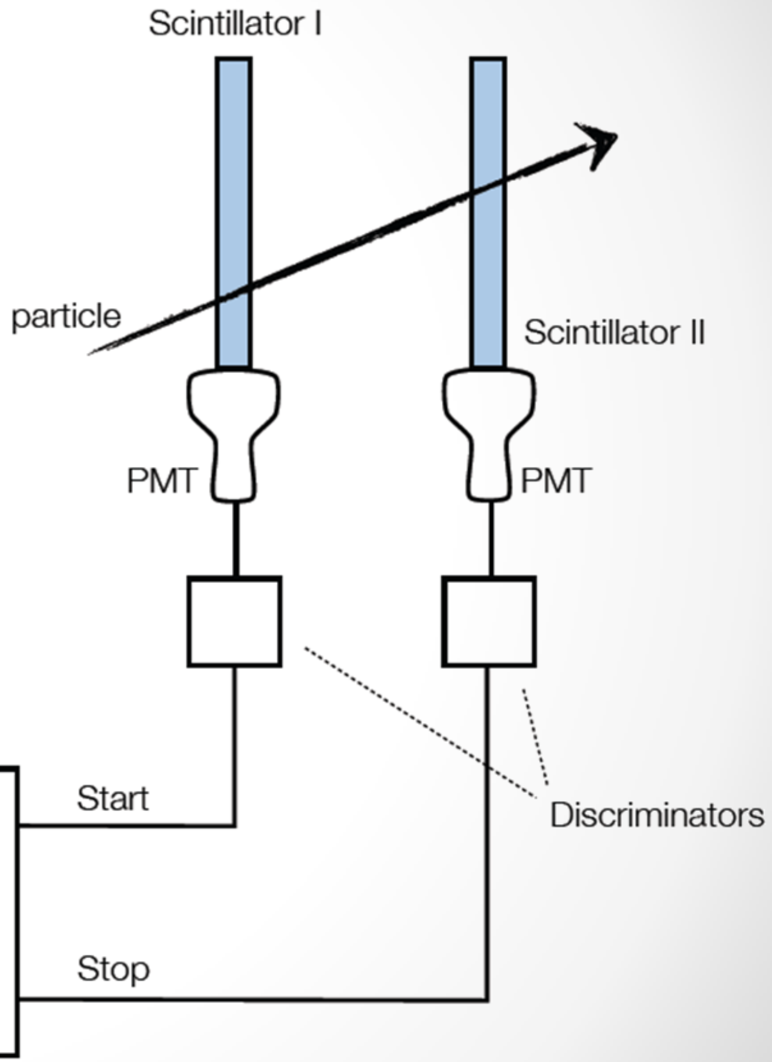
Basic idea:

Measure signal time difference between two detectors with good time resolution
[start and stop counter; also: beam-timing & stop counter]

Typical detectors:

- Scintillation counter
- Resistive Plate Chamber (RPC)

Coincidence setup or TDC measurement with common start/stop from interaction time



Time of Flight

Distinguishing particles with ToF:
[particles have same momentum p]

Particle 1 : velocity v_1, β_1; mass m_1, energy E_1
Particle 2 : velocity v_2, β_2; mass m_2, energy E_2

Distance L : distance between ToF counters

$$\Delta t = L\left(\frac{1}{v_1} - \frac{1}{v_2}\right) = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right)$$

$$= \frac{L}{pc^2}(E_1 - E_2) = \frac{L}{pc^2}\left(\sqrt{p^2c^2 + m_1^2c^4} - \sqrt{p^2c^2 + m_2^2c^4}\right)$$

Relativistic particles, $E \simeq pc \gg m_i c^2$:

$$\Delta t \approx \frac{L}{pc^2}\left[(pc + \frac{m_1^2c^4}{2pc}) - (pc + \frac{m_2^2c^4}{2pc})\right]$$

$$\Delta t = \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$

For L = 2 m:

Requiring $\Delta t \gtrsim 4\sigma_t$ K/π separation possible up to p = 1 GeV if $\sigma_t \approx 200$ ps ...

Cherenkov counter, RPC : $\sigma_t \approx 40$ ps ...
Scintillator counter : $\sigma_t \approx 80$ ps ...

Example:

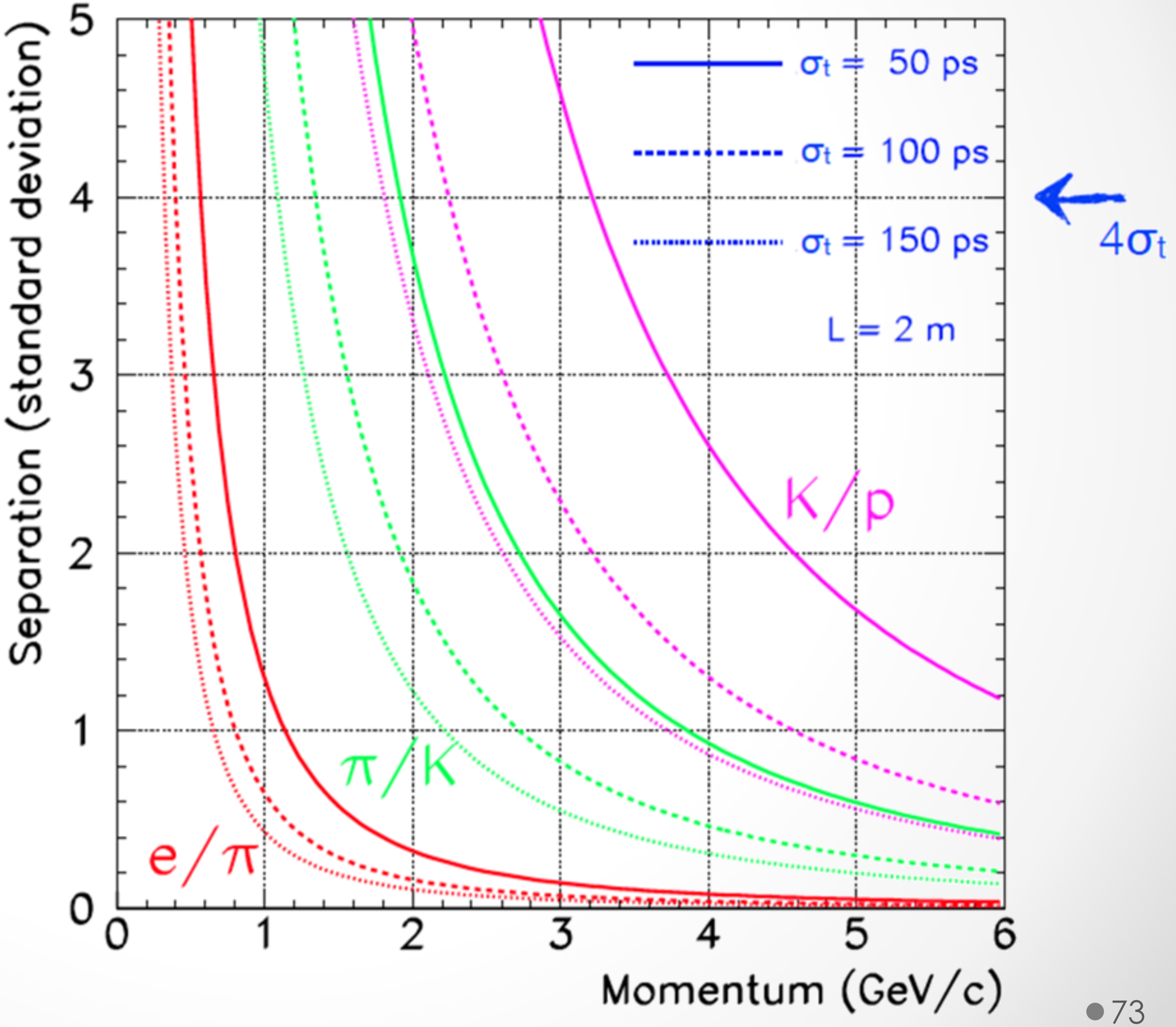
Pion/Kaon separation ...
[$m_K \approx 500$ MeV, $m_\pi \approx 140$ MeV]

Assume:
p = 1 GeV, L = 2 m ...

$$\rightarrow \quad \Delta t \approx \frac{2\ \mathrm{m} \cdot c}{2\ (1000)^2\ \mathrm{MeV}^2/c^2}\left(500^2 - 140^2\right)\ \mathrm{MeV}^2/c^4$$

$$\approx 800\ \mathrm{ps}$$

Time of Flight



Difference in time-of-flight in σ_t ...

[L = 2 m]

Time of Flight

Mass resolution ...

Use: $\beta = L/\tau$

$\gamma = (1-\beta^2)^{-1}$

$[c=1]$

$$p = \beta\gamma m$$

$$m^2 = p^2\left(\frac{1}{\beta^2}-1\right) = p^2\left(\frac{\tau^2}{L^2}-1\right)$$

$$^*\ \frac{p^2\tau^2}{L^2} = m^2 + p^2 = E^2$$

$$\rightarrow\ \delta(m^2) = 2p\,\delta p\underbrace{\left(\frac{\tau^2}{L^2}-1\right)}_{m^2/p^2} + \underbrace{2\tau\delta\tau\frac{p^2}{L^2} - 2\frac{\delta L}{L^3}p^2\tau^2}_{\text{use }^*}$$

$$= 2m^2\frac{\delta p}{p} + 2E^2\frac{\delta\tau}{\tau} - 2E^2\frac{\delta L}{L}$$

$$\rightarrow\ \sigma(m^2) = 2\left[m^4\left(\frac{\sigma_p}{p}\right)^2 + E^4\left(\frac{\sigma_\tau}{\tau}\right)^2 + E^4\left(\frac{\sigma_L}{L}\right)^2\right]^{1/2}$$

Usually:

$$\left.\frac{\delta L}{L} \ll \frac{\delta p}{p} \ll \frac{\delta\tau}{\tau}\ \right] \ \rightarrow\ \sigma(m^2) = 2E^2\frac{\sigma_\tau}{\tau}$$

Uncertainty in time measurement dominates ...

Some Literature

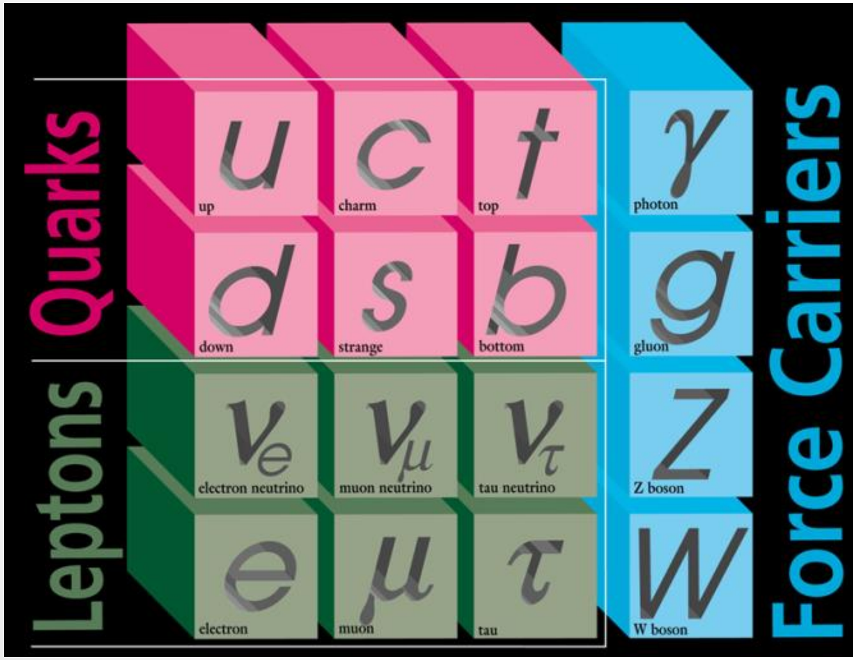
- **Web**:
  - The Particle Detector BriefBook: http://rkb.home.cern.ch/rkb/PH14pp/node1.html
  - (there is also a Data Analysis BriefBook)
  - http://pdg.lbl.gov/ --> Summary and Reviews
- **Lectures:**
  - http://wwwhephy.oeaw.ac.at/p3w/halbleiter/VOTeilchendetektoren.html
  - http://www.kip.uni-heidelberg.de/~coulon/Lectures/Detectors/
  - http://www.desy.de/~blist/vl-detektor-ws07/
  - www.physics.ucdavis.edu/Classes/Physics252b/Lectures/252b_lectureXX.ppt XX = 1,2,3,4
- **Script:**
  - http://www.physik.tu-dortmund.de/E5/E5-alt-alt/index.php?content=25&lang=de

More Literature

- **Text books:**
  - C.Grupen: Particle Detectors, Cambridge UP 22008, 680p
  - D.Green: The physics of particle Detectors, Cambridge UP 2000
  - K.Kleinknecht: Detectors for particle radiation, Cambridge UP, 21998
  - W.R. Leo: Techniques for Nuclear and Particle Physics Experiments, Springer 1994
  - G.F.Knoll: Radiation Detection and Measurement, Wiley, 32000
  - W.Blum, L.Rolandi: Particle Detection with Driftchambers, Springer, 1994
  - G.Lutz: Semiconductor radiation detectors, Springer, 1999
  - R. Wigmans: Calorimetry, Oxford Science Publications, 2000
- **Review articles:**
  - T.Ferbel (ed): Experimental Techniques in High Energy Physics, Addison-Wesley 1987
- **Web:**
  - Particle Data Group: Review of Particle Properties: pdg.lbl.gov

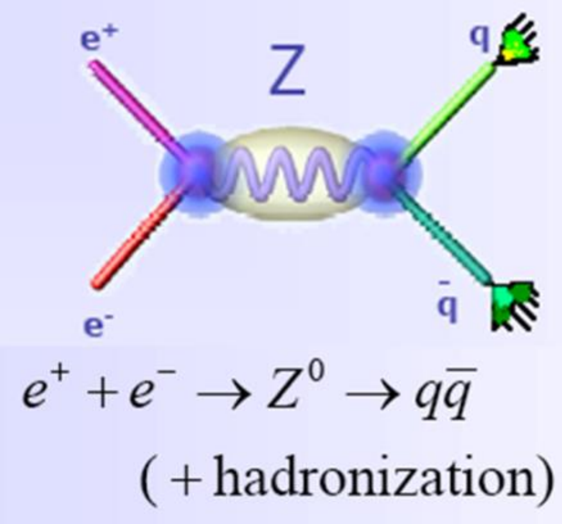
Backup Slides

The Standard Model



- The SM:
  - world is made up of **quarks** and **leptons**
  - interacting by exchanging **bosons**
  - only photons directly visible
- How do we see without seeing?
- What makes Particle Detection possible?

Particle Reactions

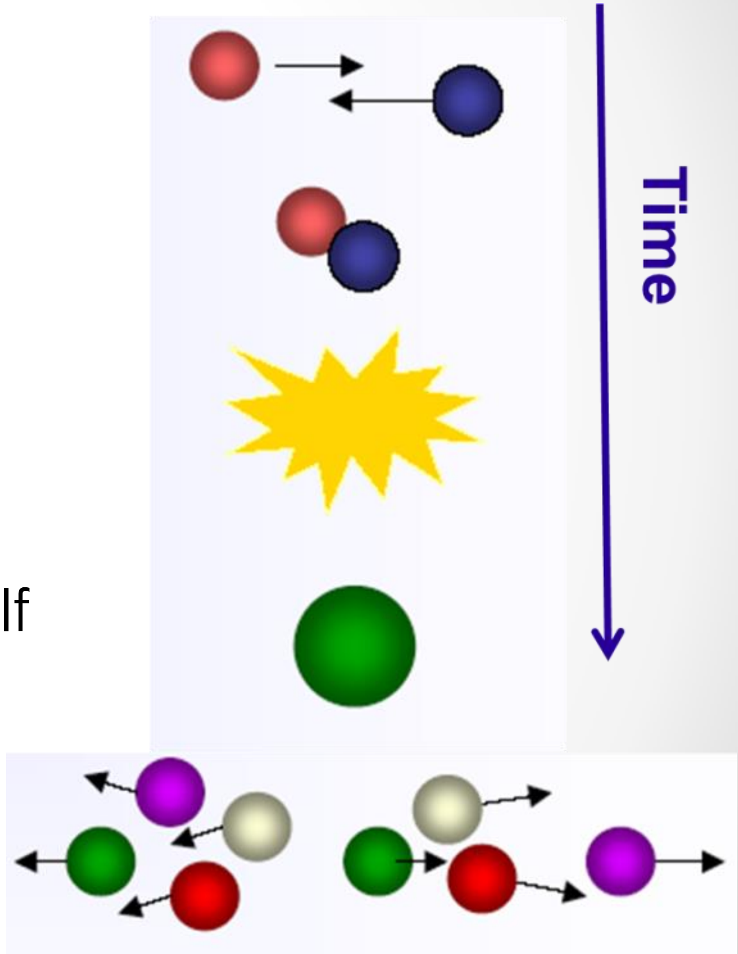


$$e^+ + e^- \rightarrow Z^0 \rightarrow q\bar{q}$$

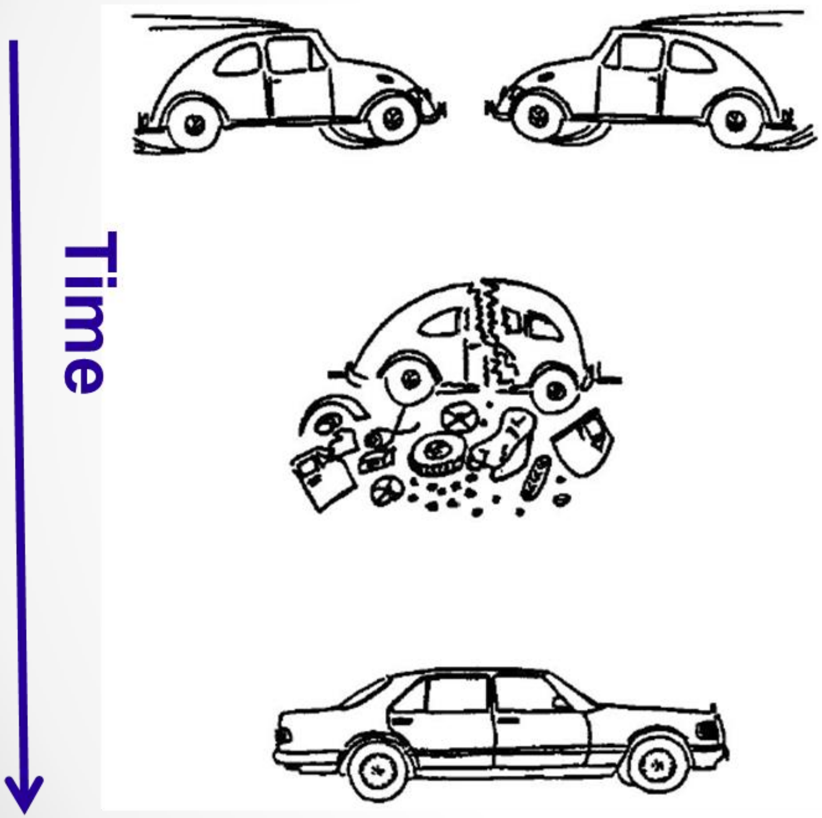
$$(+\text{hadronization})$$

- Idealistic View:
  - Elementary Particle Reaction
- Usually cannot “see” the reaction itself
- To reconstruct the
  - **process** and the
  - **particle properties**

➢ need **maximum information** about **end-products**



Principle of an Elementary Particle Measurement

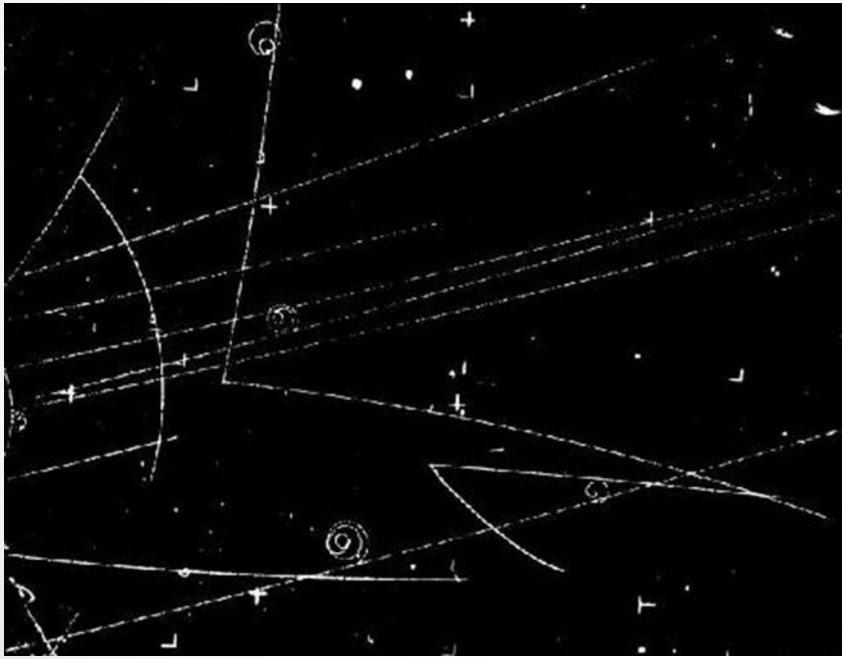


- Need good:
  - o Detectors
  - o Triggers,
  - o Readout
  - ➢ to reconstruct the mess.
- Need good:
  - o Analyzers
  - ➢ to put the raw data into a piece of physics.

Example of two Reactions

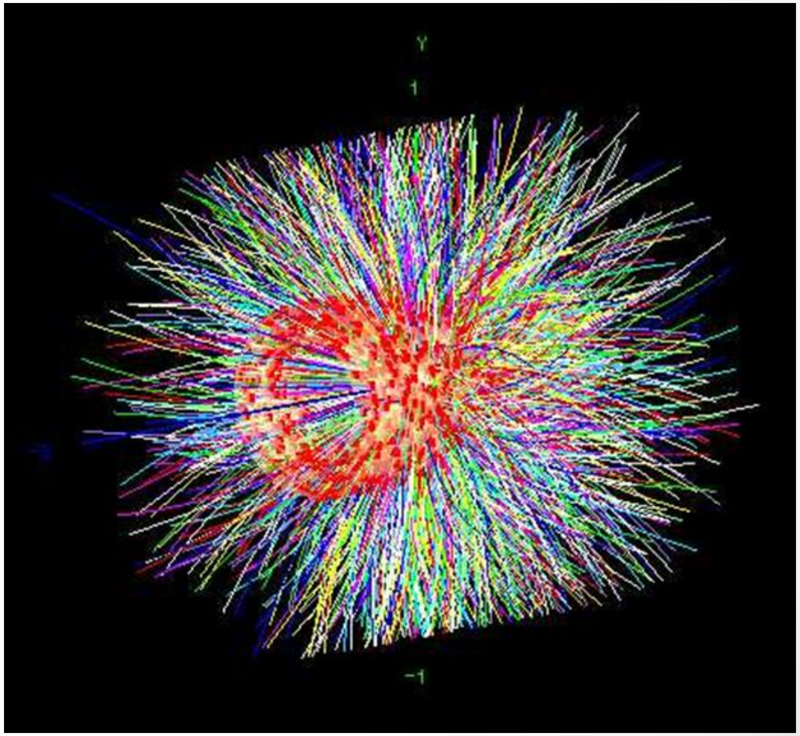
Tracks in a Bubble Chamber

(Bubble chambers are not used any more).



Simulated Super LHC event.

(People started to think about a LHC upgrade).



The decay products of elementary particle reactions can look very complicated!

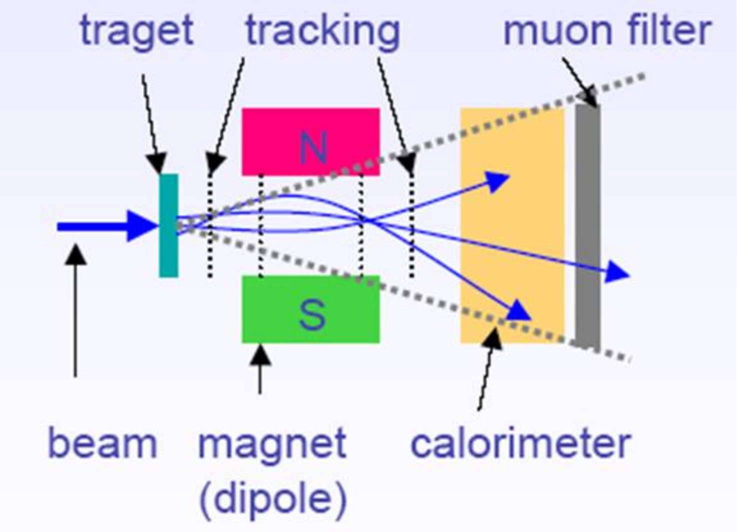
Global Detector Systems

- Overall design depends on:
    - Number of particles
    - Event topology
    - Momentum/energy
    - Particle identity

- No single detector measures it all…
- ➢ Create detector systems

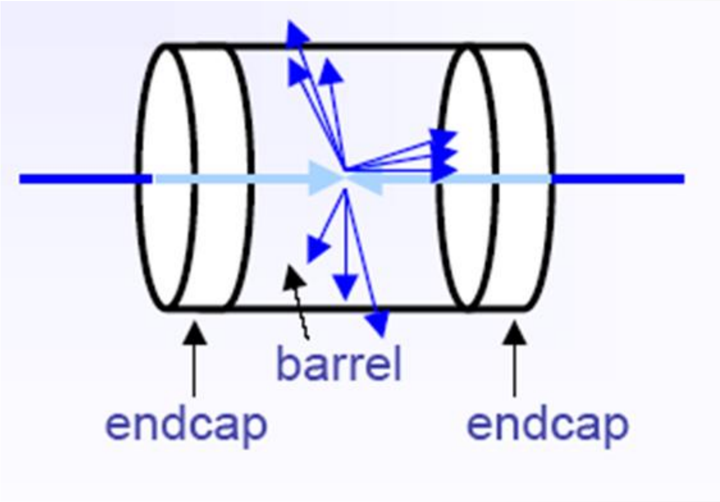
Global Detector Systems

Fixed Target Geometry



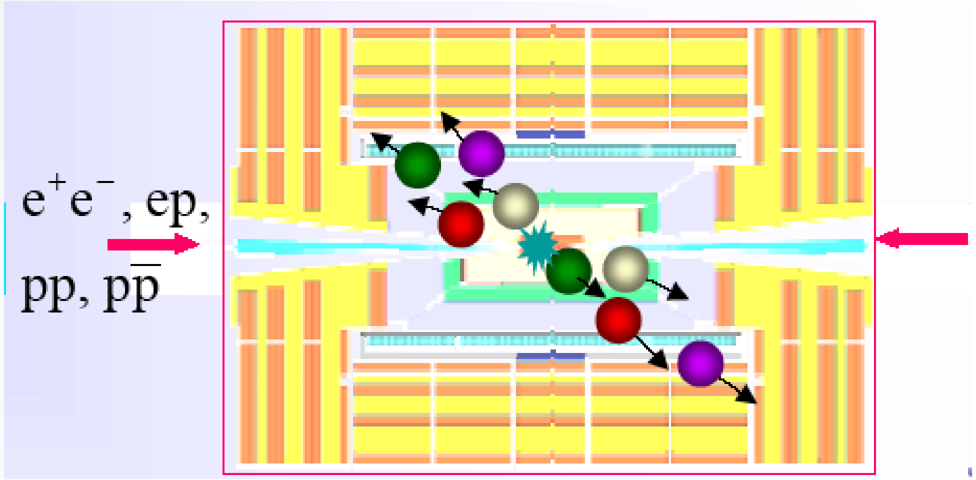
- Limited solid angle dΩ coverage
- Easy access (cables, maintenance)

Collider Geometry



- Full" solid angle dΩ coverage
- Very restricted access

Ideal Detectors

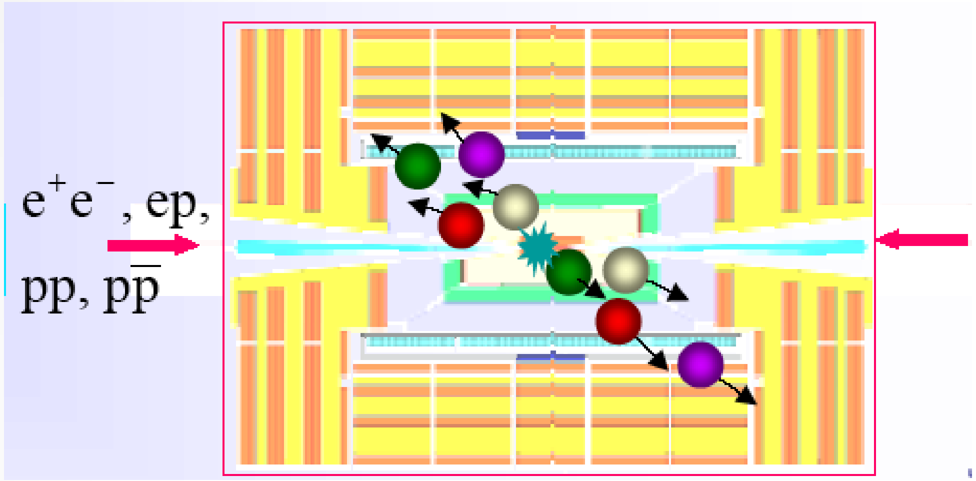


<u>End products:</u>

- charged particles
- neural particles
- photons

- An “ideal” particle detector would provide…
  - Coverage of **full solid angle**, no cracks, fine segmentation (why?)
  - Measurement of momentum and energy
  - Detection, tracking, and identification of all particles (mass, charge, lifetime)
  - Fast response: no dead time (what is dead time?)
  - Contain no dead material (what is dead material?)
- However, practical limitations:
  - Technology, Space, Budget

Ideal Detectors

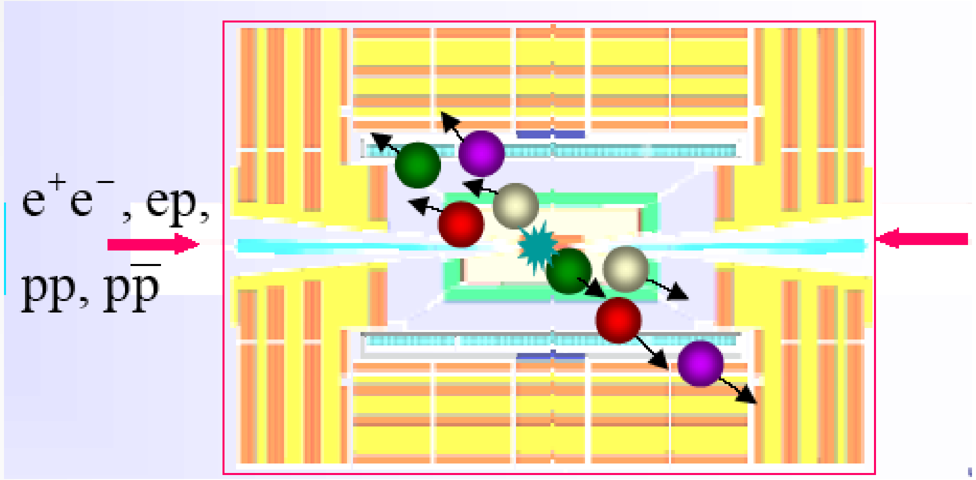


End products:

- charged particles
- neural particles
- photons

- An “ideal” particle detector would provide…
  - Coverage of full solid angle, no cracks, fine segmentation (why?)
  - Measurement of **momentum** and **energy**
  - Detection, tracking, and identification of all particles (mass, charge, lifetime)
  - Fast response: no dead time (what is dead time?)
  - Contain no dead material (what is dead material?)
- However, practical limitations:
  - Technology, Space, Budget

Ideal Detectors

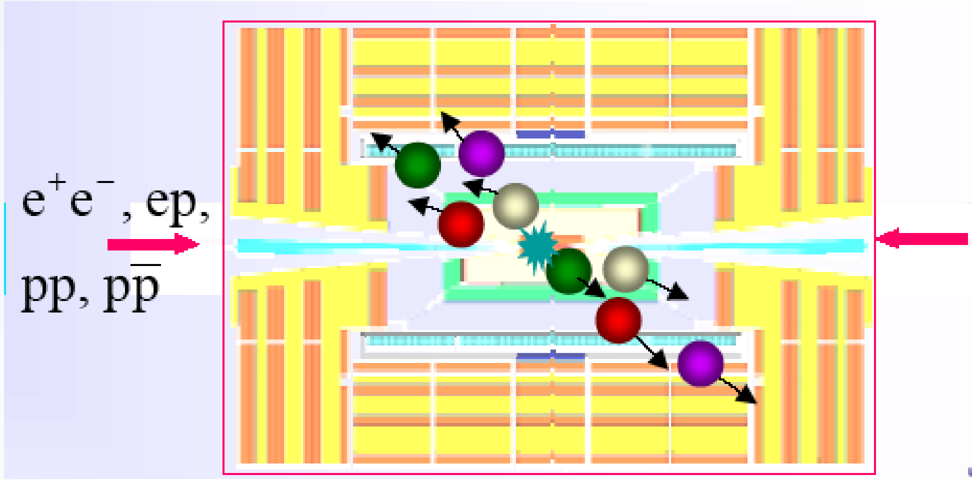


<u>End products:</u>

- charged particles
- neural particles
- photons

- An “ideal” particle detector would provide…
  - Coverage of full solid angle, no cracks, fine segmentation (why?)
  - Measurement of momentum and energy
  - **Detection**, **tracking**, and **identification** of all particles (mass, charge, lifetime)
  - Fast response: no dead time (what is dead time?)
  - Contain no dead material (what is dead material?)
- However, practical limitations:
  - Technology, Space, Budget

Ideal Detectors

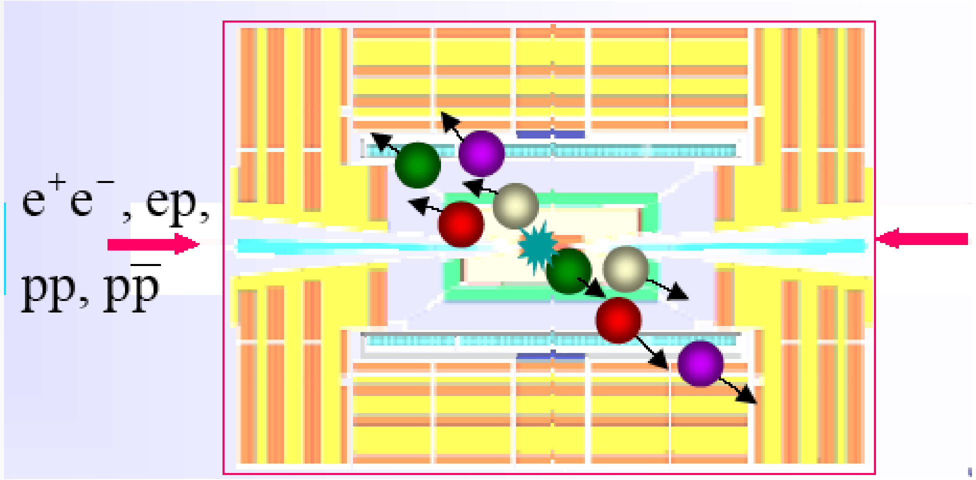


<u>End products:</u>

- charged particles
- neural particles
- photons

- An “ideal” particle detector would provide…
  - Coverage of full solid angle, no cracks, fine segmentation (why?)
  - Measurement of momentum and energy
  - Detection, tracking, and identification of all particles (mass, charge, lifetime)
  - **Fast** response: no dead time (what is dead time?)
  - Contain no dead material (what is dead material?)
- However, practical limitations:
  - Technology, Space, Budget

Ideal Detectors

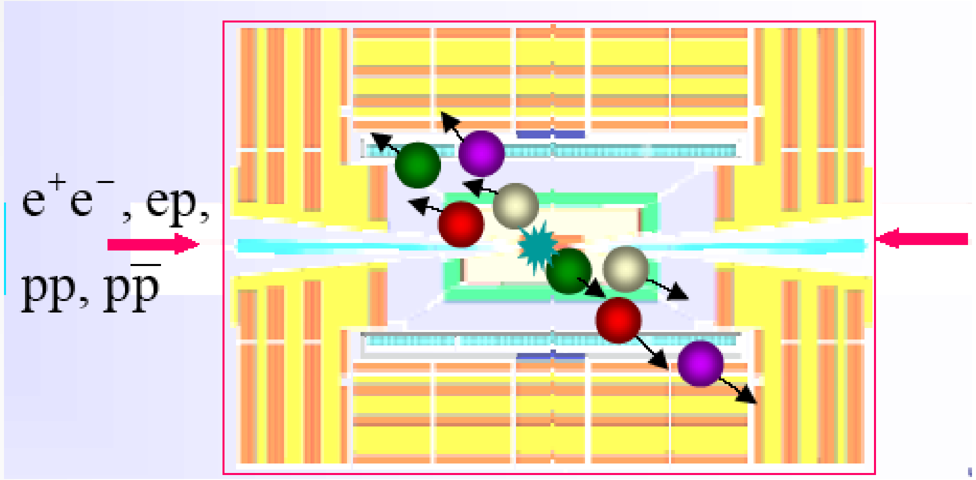


<u>End products:</u>

- charged particles
- neural particles
- photons

- An “ideal” particle detector would provide…
  - Coverage of full solid angle, no cracks, fine segmentation (why?)
  - Measurement of momentum and energy
  - Detection, tracking, and identification of all particles (mass, charge, lifetime)
  - Fast response: no dead time (what is dead time?)
  - Contain **no dead material** (what is dead material?)
- However, practical limitations:
  - Technology, Space, Budget

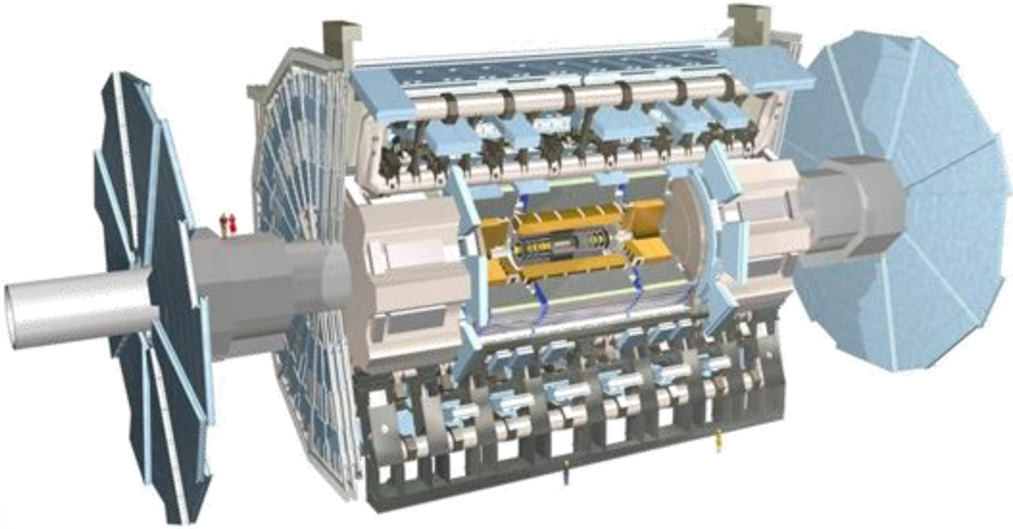
Ideal Detectors



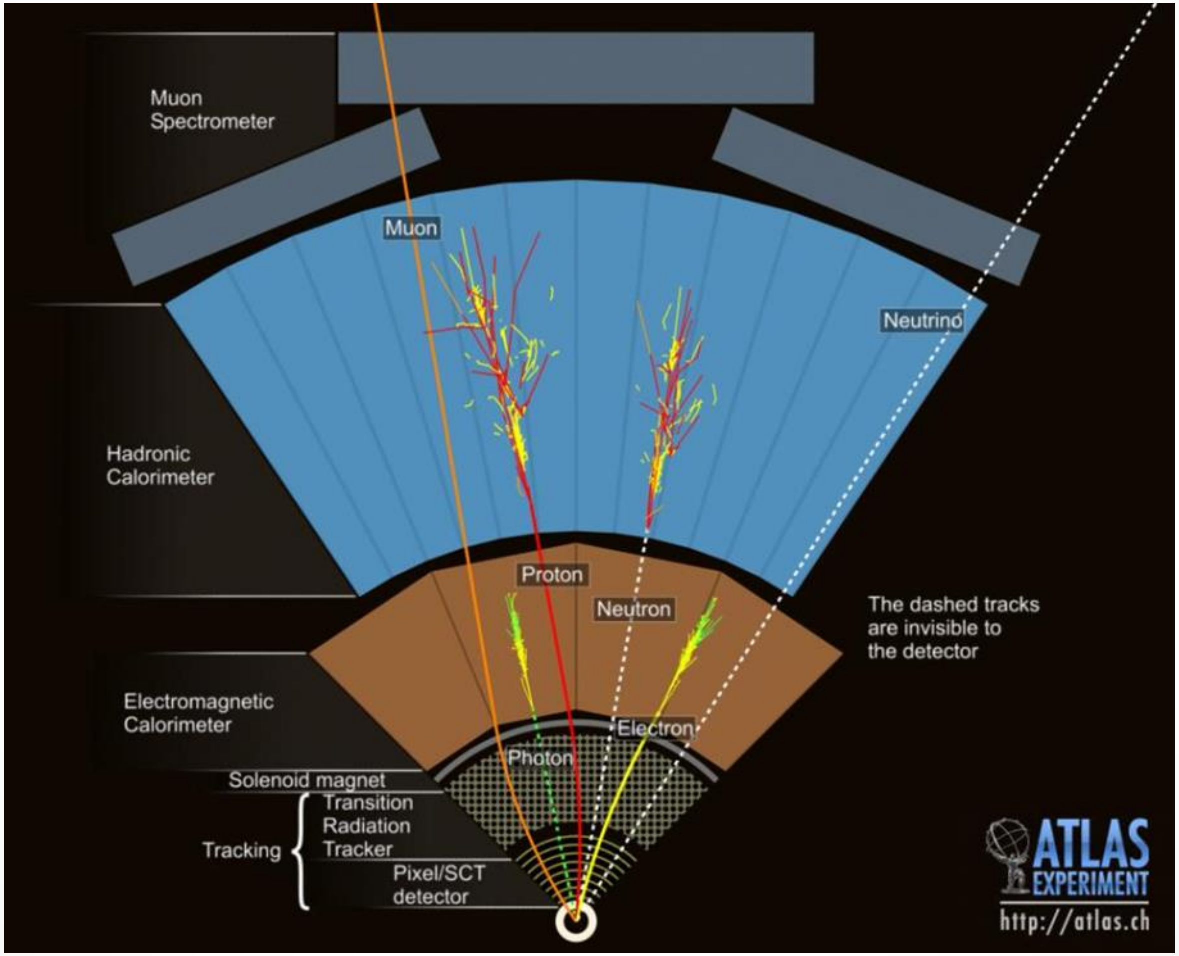
<u>End products:</u>
- charged particles
- neural particles
- photons

- An “ideal” particle detector would provide…
  - Coverage of full solid angle, no cracks, fine segmentation (why?)
  - Measurement of momentum and energy
  - Detection, tracking, and identification of all particles (mass, charge, lifetime)
  - Fast response: no dead time (what is dead time?)
  - Contain no dead material (what is dead material?)
- However, practical limitations:
  - **Technology**, **Space**, **Budget**

Particle Decay Signatures in Atlas



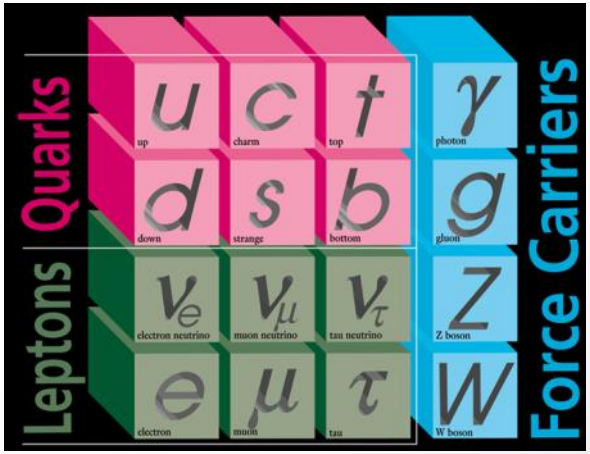
Particle Decay Signatures in Atlas



Particle Identification Methods

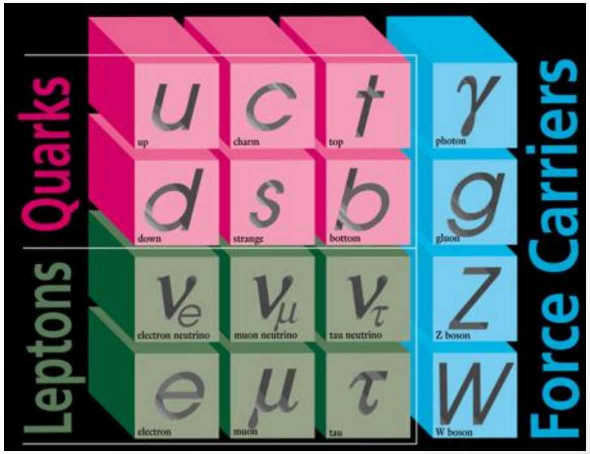
Constituante	Vertex	Track	PID	Ecal	Hcal	Muon
Electron	Primary	✓	✓	✓	-	-
Photon	Primary	-	-	✓	-	-
u, d, gluon	Primary	✓	-	✓	✓	-
Neutrino	-	-	-	-	-	-
s	Primary	✓	✓	✓	✓	-
c, b, tau	Secondary	✓	✓	✓	✓	-
Muon	Primary	✓	-	MIP	MIP	✓

- PID = Particle ID (TOF, dE/dx)
- MIP = Minimum Ionizing Particle



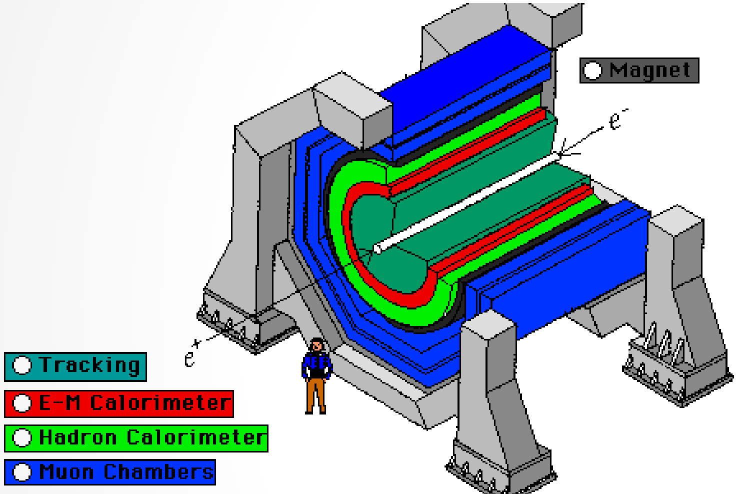
Particle Detection Methods

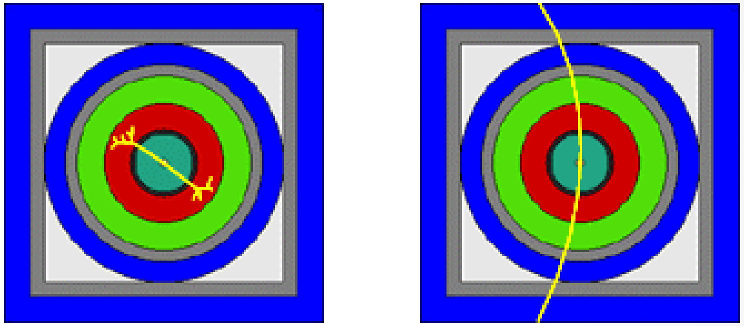
Signature	**Detector Type**	**Particle**
Jet of hadrons	Calorimeter, Tracking	u, c, t → Wb, d, s, b, g
Missing energy	Calorimeter	ν_e, ν_μ, ν_τ
Electromagnetic shower	EM Calorimeter	e, γ
Purely ionization interactions, dE/dx	Muon absorber	M, $\tau \rightarrow \mu \nu_\mu \nu_\tau$
Life time, $c\tau \geq 100$ μm	Si-Tracking	b, c, τ



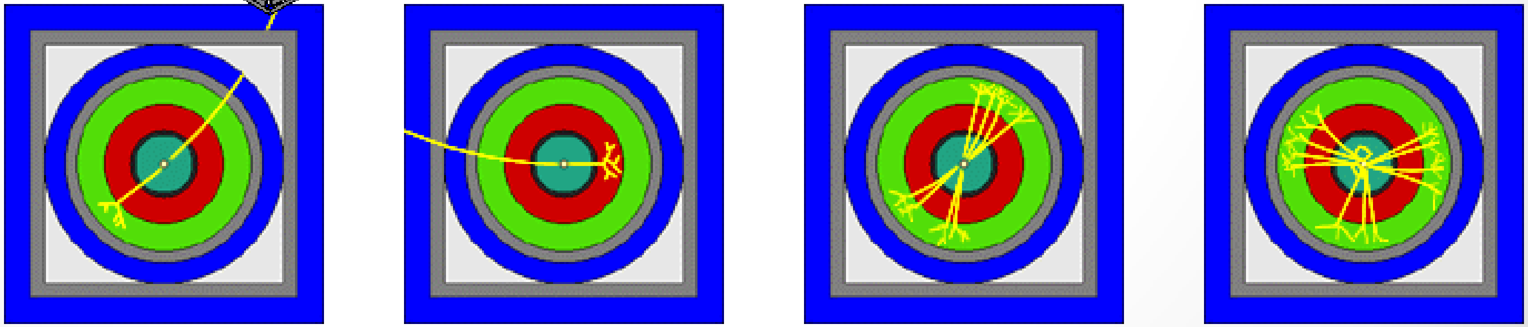
Quiz: Decays of a Z boson

- Z bosons have a very short lifetime, decaying in ~10-27 s, so that:
  - only decay particles are seen in the detector.
  - By looking at these detector signatures, identify the daughters of the Z boson.





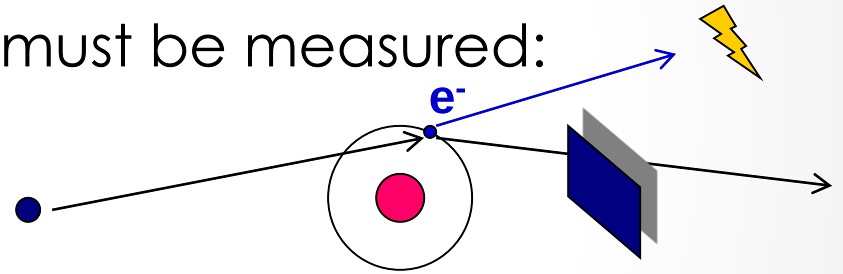
But some daughters can also decay:



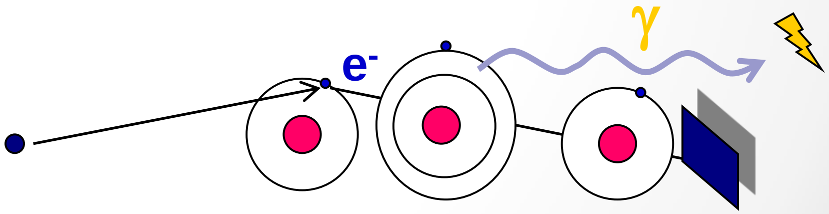
- More fun with Z bosons: http://opal.web.cern.ch/Opal/events/opalpics.html

Principles of a measurement

- The particle must **interact** with the detector material:
  - **transfer** directly or indirectly **energy** to the medium they are traversing
  - via **ionization** or **excitation** of its constituent atoms.
- An effect of the interaction must be measured:
  - Ionization:



  - Excitation and scintillation:



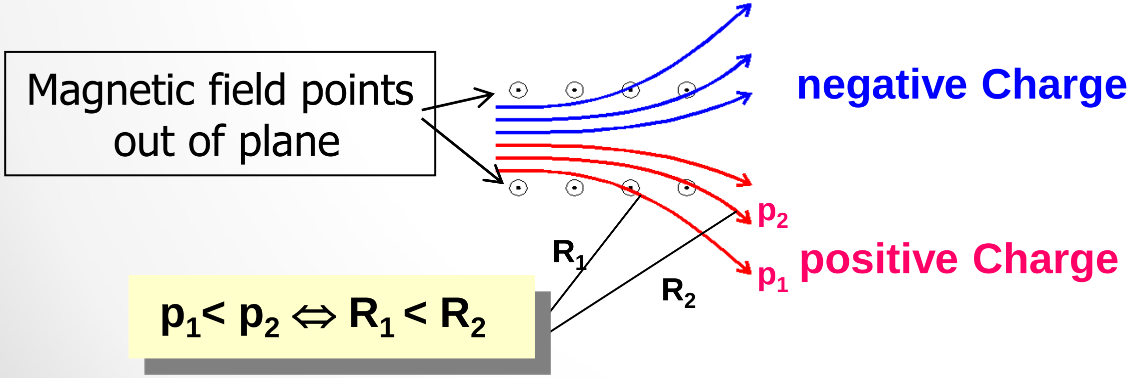
  - Cerenkov radiation
  - Signals from electron-hole pairs (Si-detectors)
- The particle may also be affected by the interaction:
  - energy loss, scattering and absorption

Measurable Properties of particles

- Production / passage of a particle
- Four-Momentum of particle
- Charge of particle
- Lifetime of particle

How does one measure the Four-Momentum?

- Energy:
  - with a "calorimeter" (see tomorrow)
- Momentum:
  - with a "magnetic field + track detector"



Magnetic field points out of plane

negative Charge

positive Charge

$p_1 < p_2 \Leftrightarrow R_1 < R_2$

Lorentz-Force

$$q\,v_T\,B = m\,v_T^2/R$$

$$\Downarrow$$

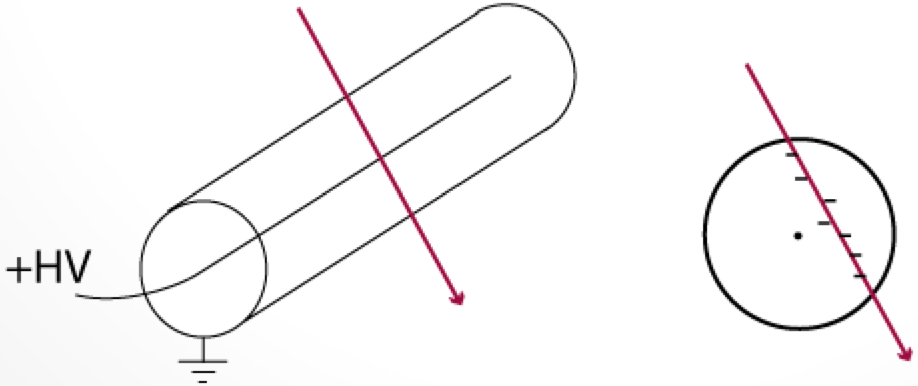
$$q\,B\,R = m\,v_T = \mathbf{p_T}$$

Tracking:

Proportional Counters
and Drift Chambers

Charged Particle Tracking

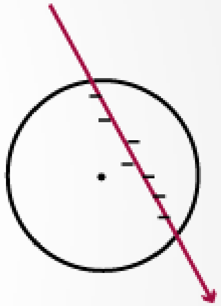
- Two main types:
  - Gas wire chambers
  - Silicon
- Innermost detectors:
  - precise tracking → use Si-Detectors!
- Outer detectors:
  - silicon too expensive!
  - (not true for LHC-detectors also use silicon).
- Basic design: ionization chamber with HV sense wire:

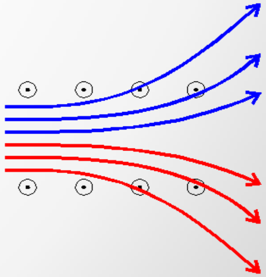


Amplification of 10^3 - 10^5 in high field near wire

Ionization Wire Chambers

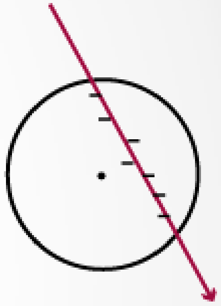
- Wire Chambers:
  - Most commonly used detection devices in high energy physics experiments.
- The Basics of Wire Chambers:
  - Charged particles travels through a gas
  - Gas is ionized by the particle
  - Ionization drifts & diffuses in an electric field toward an electrode
  - Collection and amplification of anode signal charge
  - ➢ detectable signals
  - Measurement of points on trajectory determines p





Processes in Gases

- When a charged particle passes through gases subject to an E field, it loses energy by:
  - Elastic scattering (small)
  - Excitation: gas atoms/molecules
  - Excite then de-excite by γ emission
  - **Ionization** (most important)



- Ionization:
  - One or more electrons are liberated from atoms of the medium,
  - ➢ leaving positive ions and electrons.
  - Energy imparted to atom exceeds ionization potential of gas.

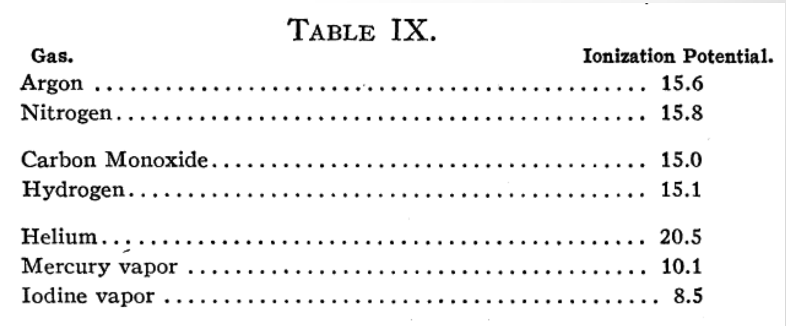
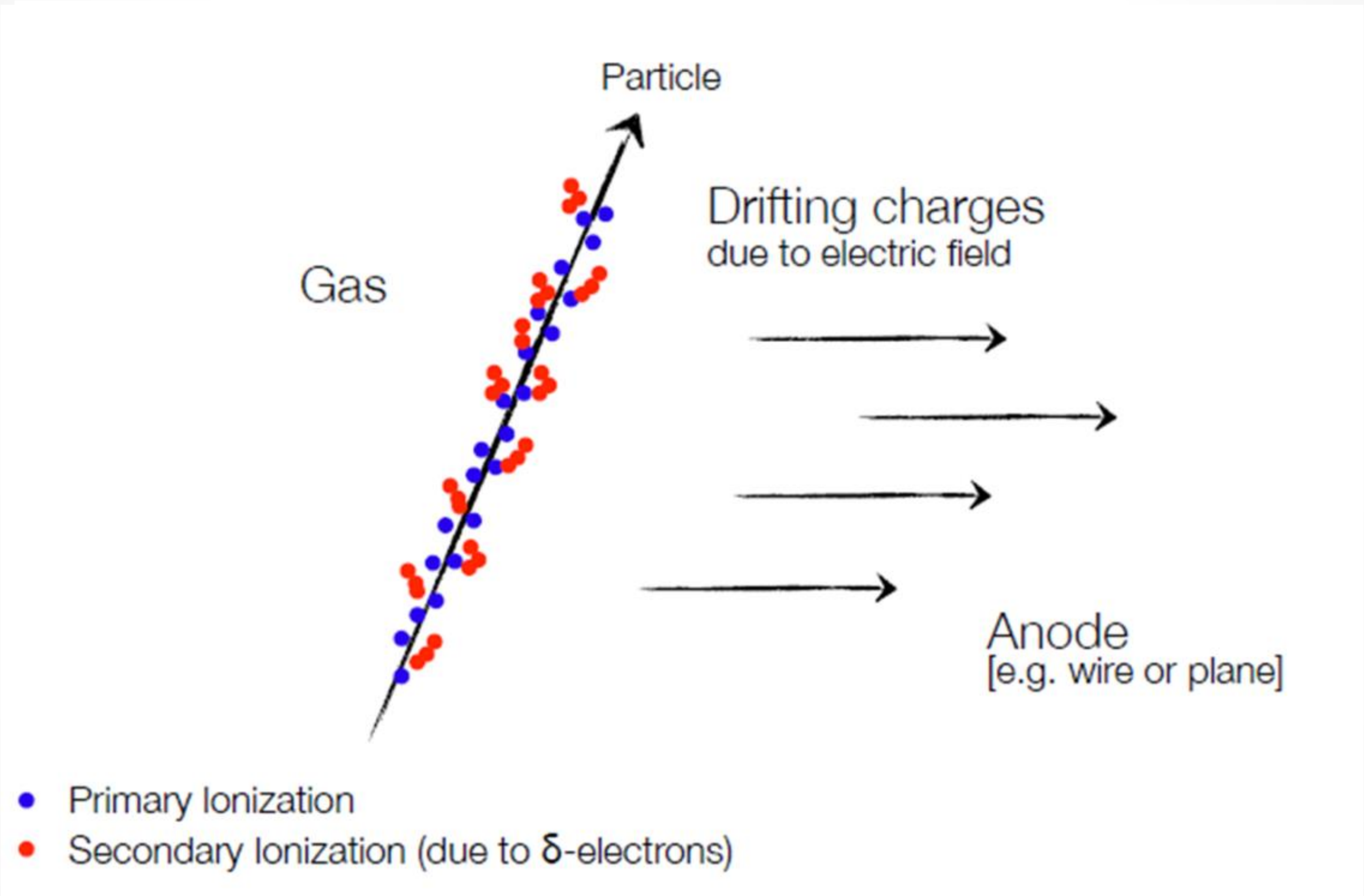


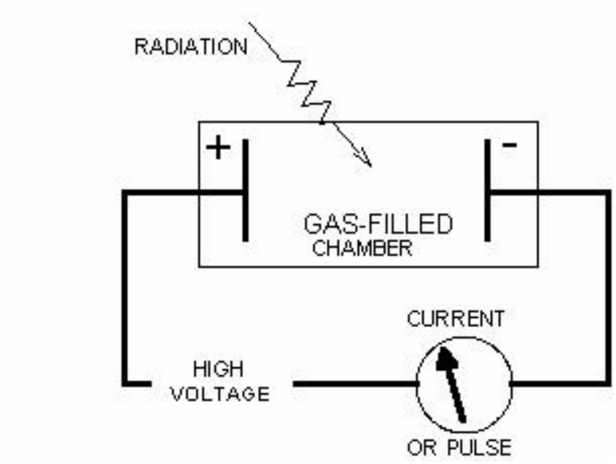
TABLE IX.

Gas.	Ionization Potential.
Argon	15.6
Nitrogen	15.8
Carbon Monoxide	15.0
Hydrogen	15.1
Helium	20.5
Mercury vapor	10.1
Iodine vapor	8.5

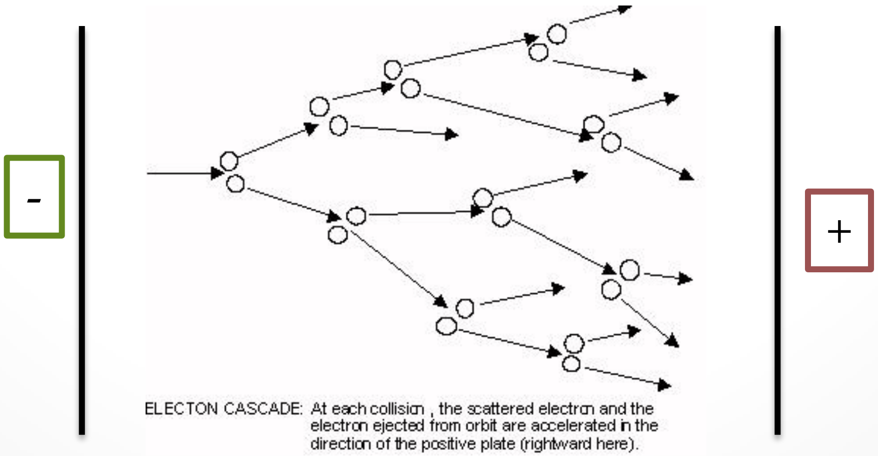
Principle of Gas Detectors



Number of Ions v. Voltage



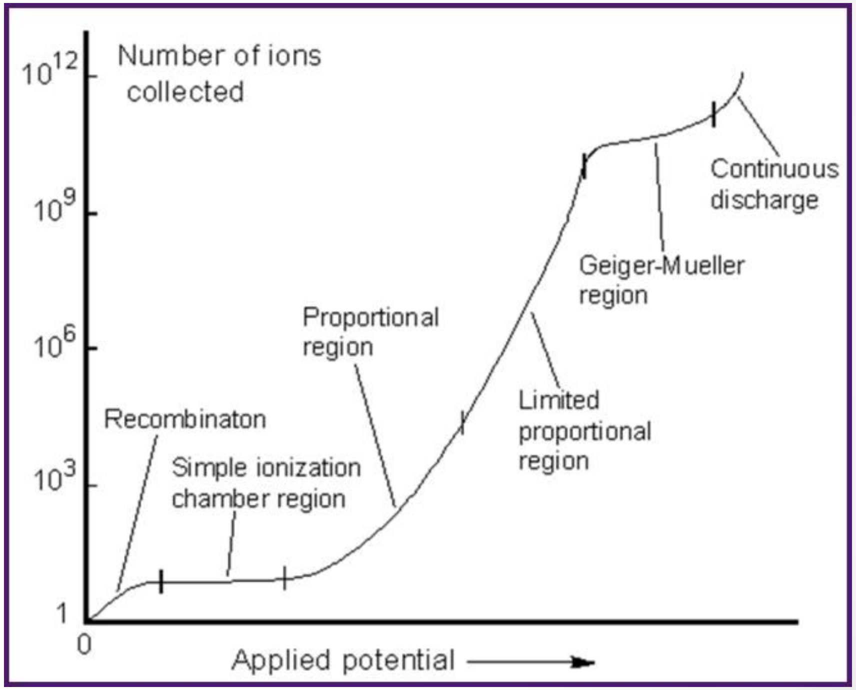
Simplest case: Parallel plate capacitor



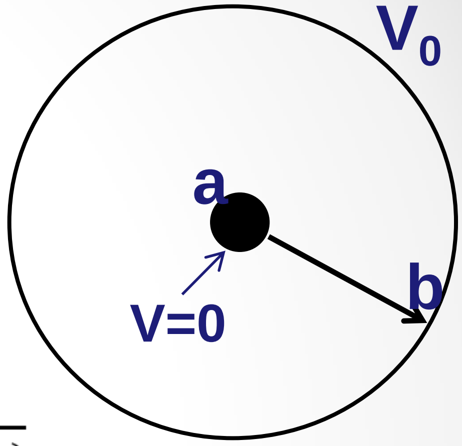
ELECTON CASCADE: At each collision , the scattered electron and the electron ejected from orbit are accelerated in the direction of the positive plate (rightward here).

Number of Ions v. Voltage

- Ionization chamber:
  - Voltage increased such that the charge arriving on plates =
  - charge formed
- Proportional region:
  - Initial electrons accelerated enough to ionize more;
  - avalanche pulse proportional to primary ionization
  - reaches ~10^8



Proportional Chambers

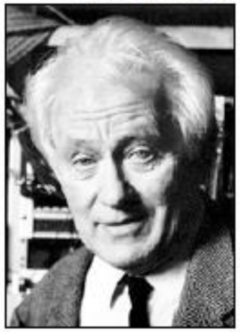


- Cylindrical proportional tube of
  - outer radius *b* at
  - voltage V_0 and
  - inner (wire) of radius *a* at voltage zero.
- Electric field inside the chamber:
- $E = \frac{2l}{r}, V_0 = 2l \ln\left(\frac{b}{a}\right), V(r) = V_0 \frac{\ln(r/a)}{\ln(b/a)},\ E(r) = \frac{V_0}{r \ln(b/a)}$
- Charged particle ->
  - Ionization.
  - e^- move toward anode
  - High fields near wire
  - Multiplication of e^-s by collisions:
  - at small r the energy gain can exceed ionization potential.
  - Runaway process, like avalanche in PMTs.
- Typical Gas gain~10^5 - 10^8, Geiger region!

Multi-wire Proportional Chambers

- MWPC invented by Charpak at CERN
  - Principle of proportional counter is extended to large areas:
  - Stack several wire planes up in different direction to get position location.

G. Charpak
Nobel Prize 1992



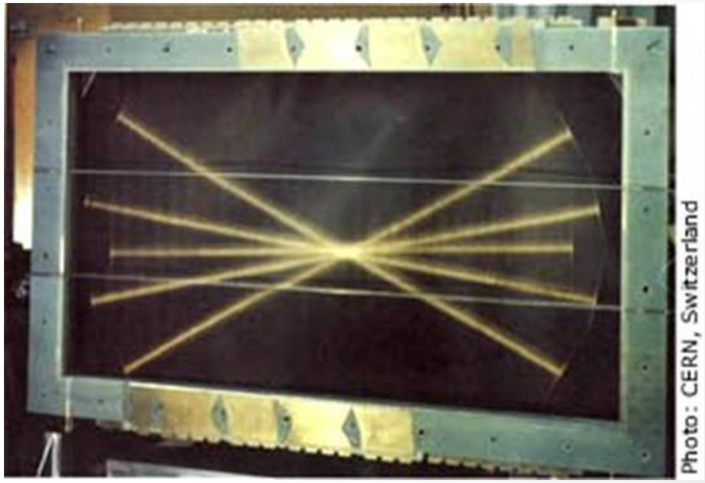
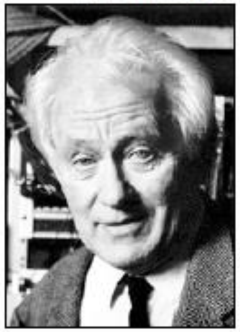
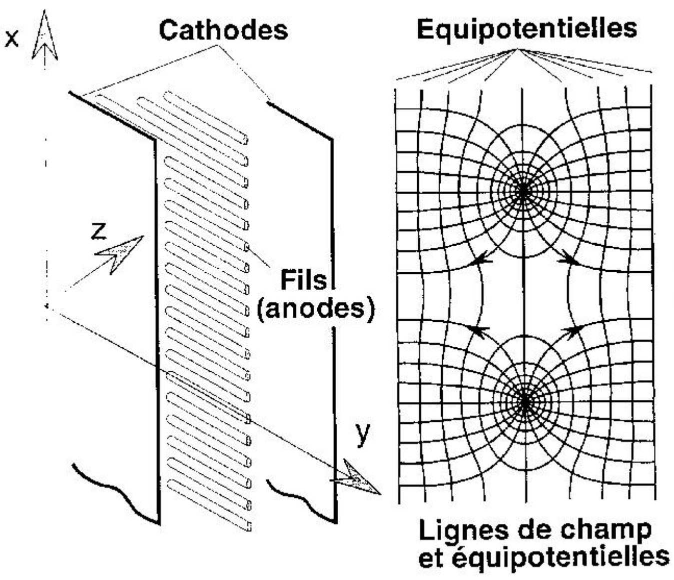


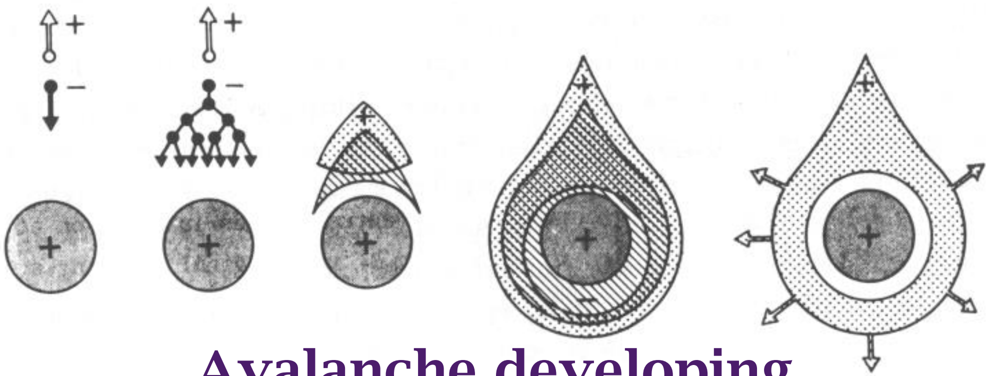
Photo: CERN, Switzerland

Multi-wire Proportional Chambers

G. Charpak
Nobel Prize 1992

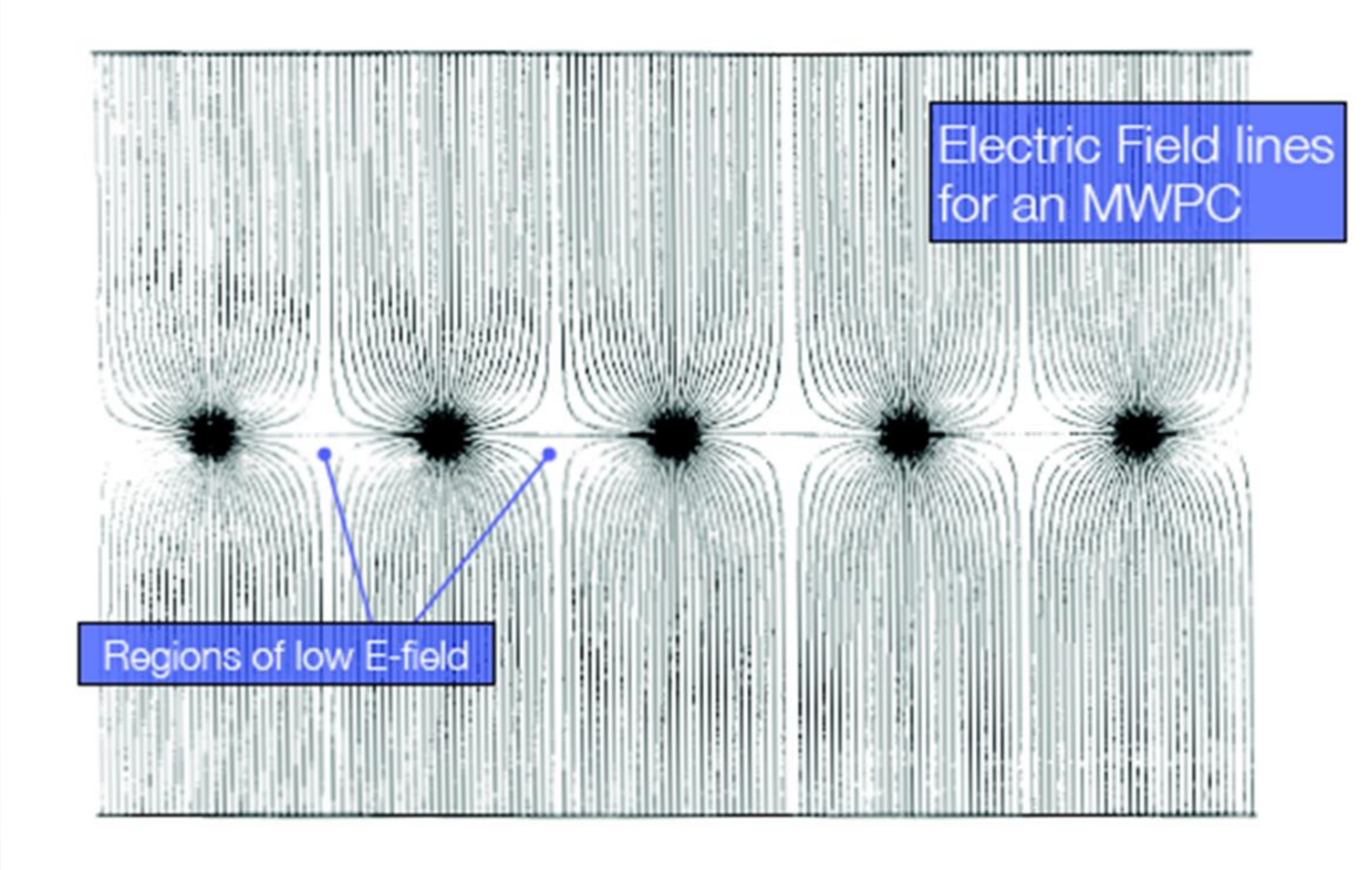






Avalanche developing

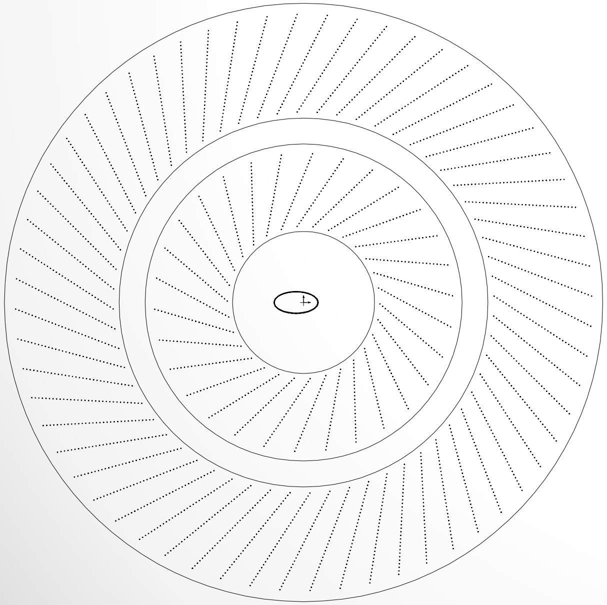
Drift Chambers - Field Formation


Electric Field lines for an MWPC

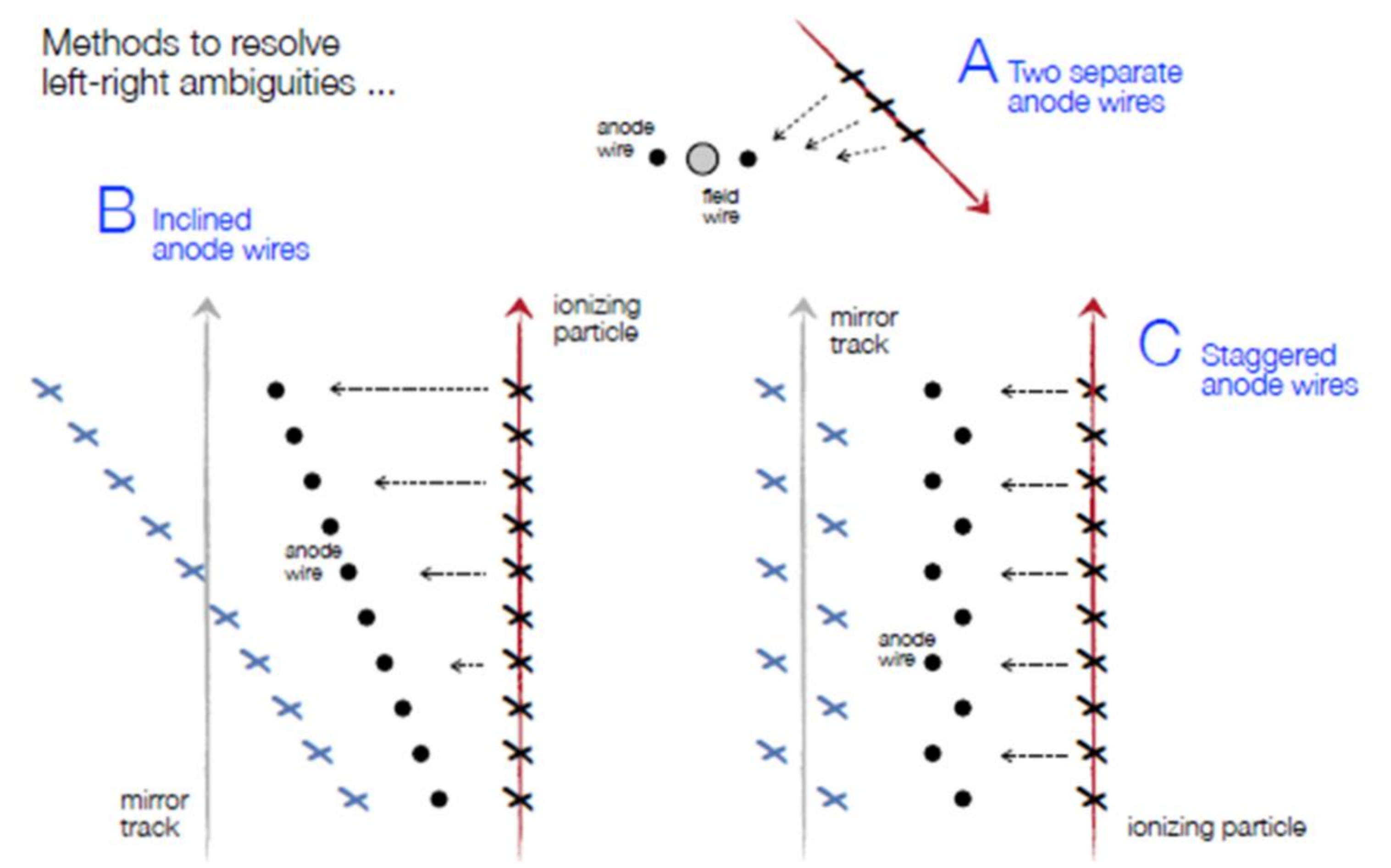
Regions of low E-field

Large Area Drift Chambers

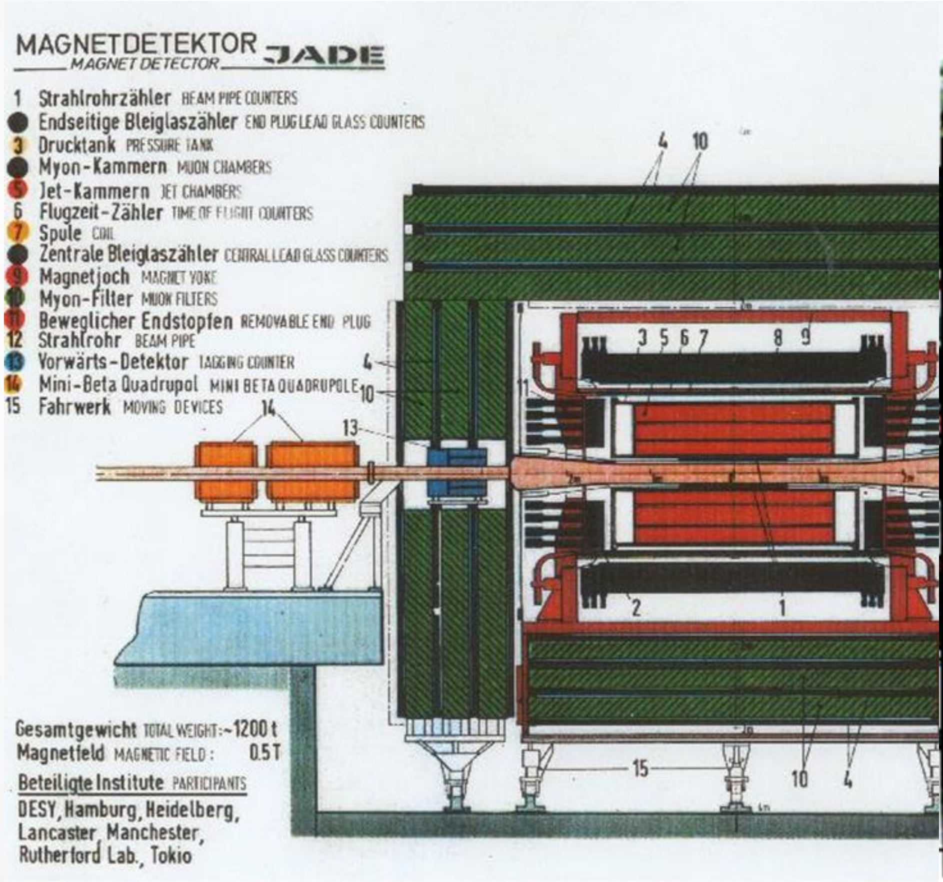
- The “open cell” drift chamber uses
    - field and sense wires:
    - field wires create shape of electric field,
    - sense wires detect time of arrival of pulse.
- Position of particle: $x = x_{wire} + v_{drift}\, t_{drift}$

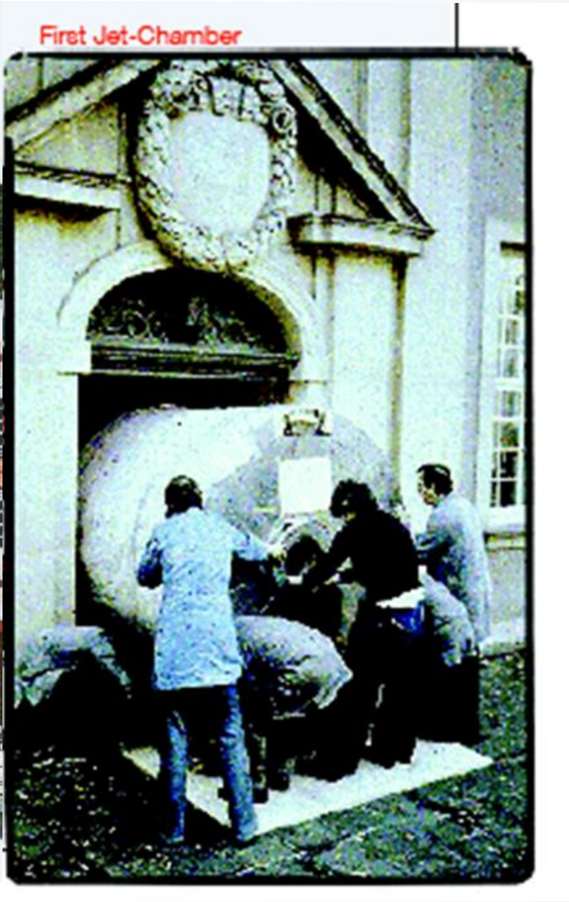


Drift Chamber - Ambiguities

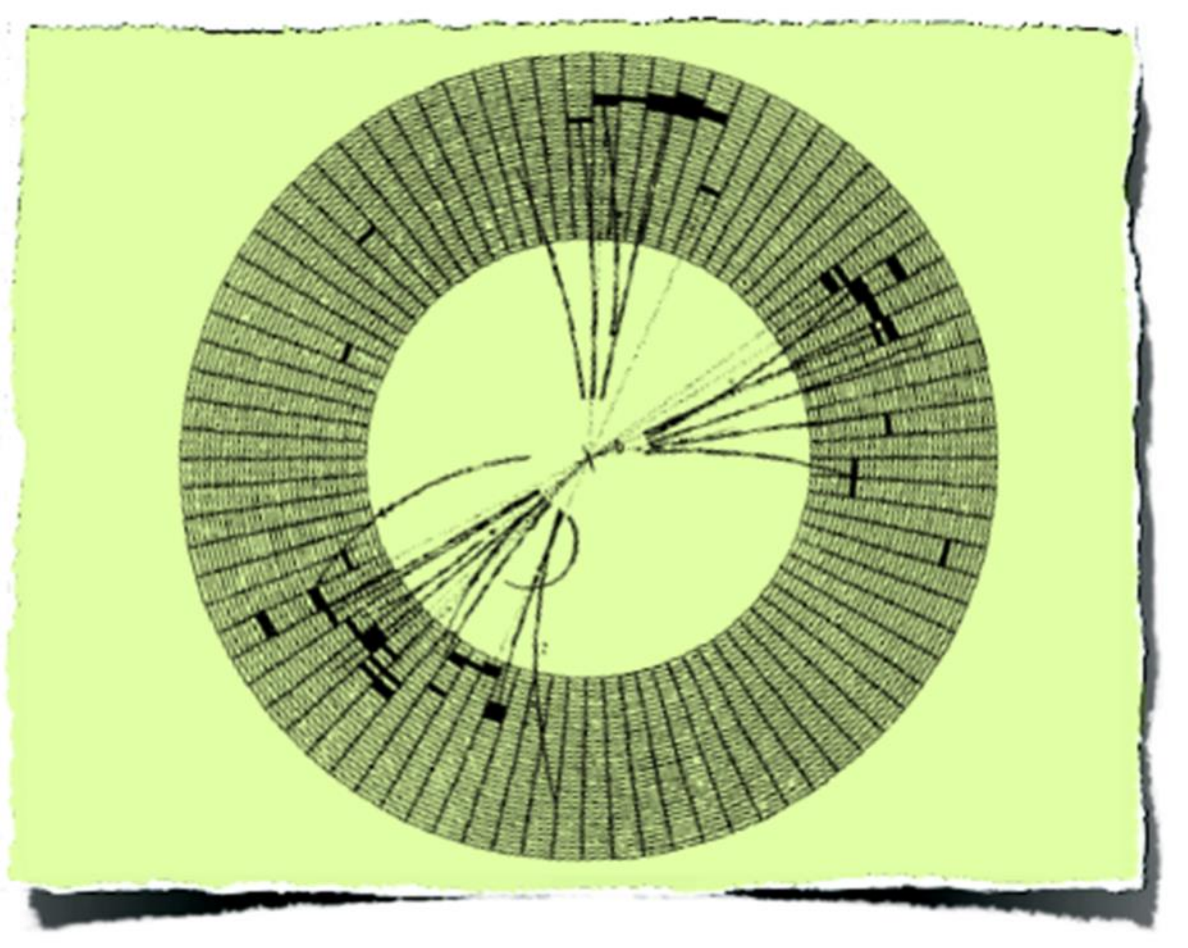


Drift Chamber - Jade

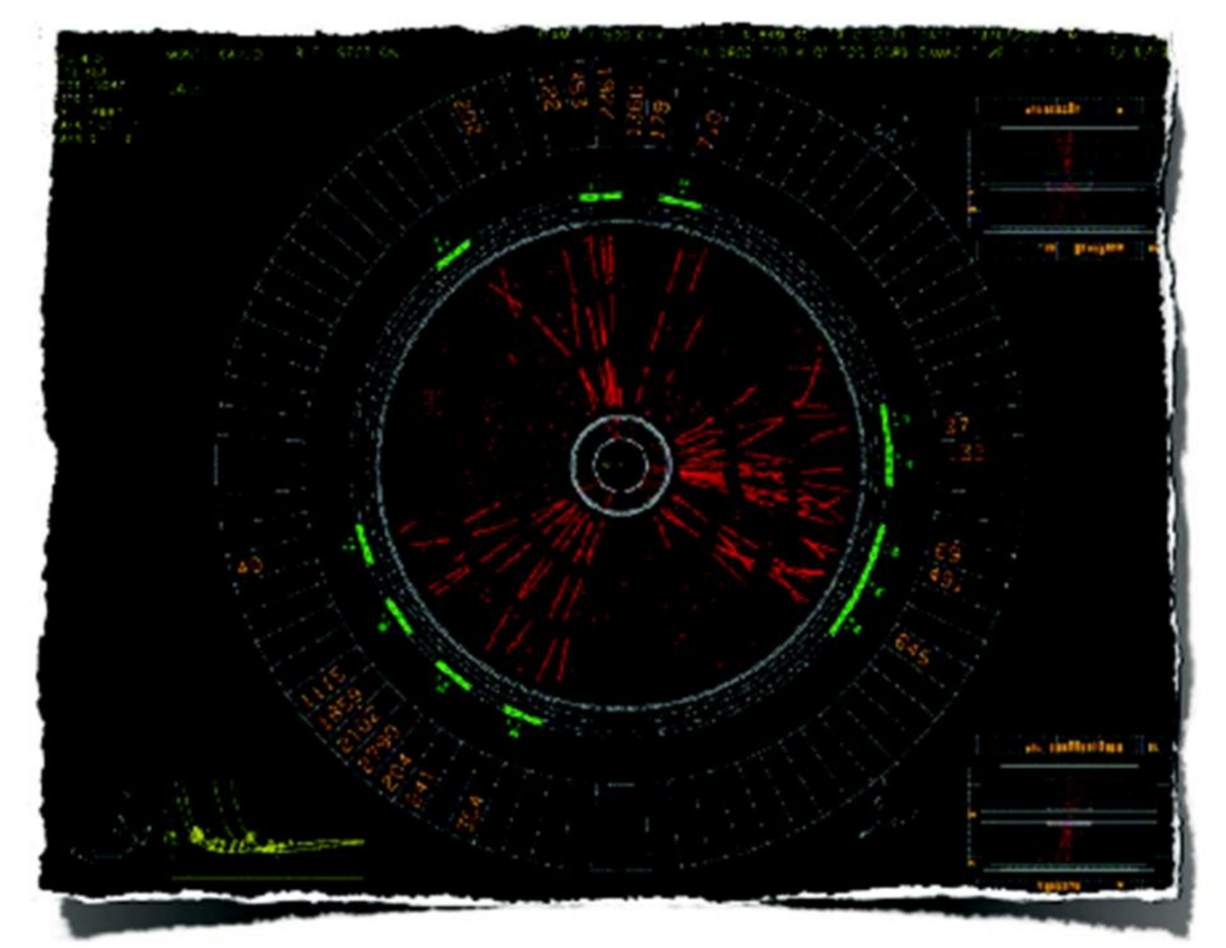




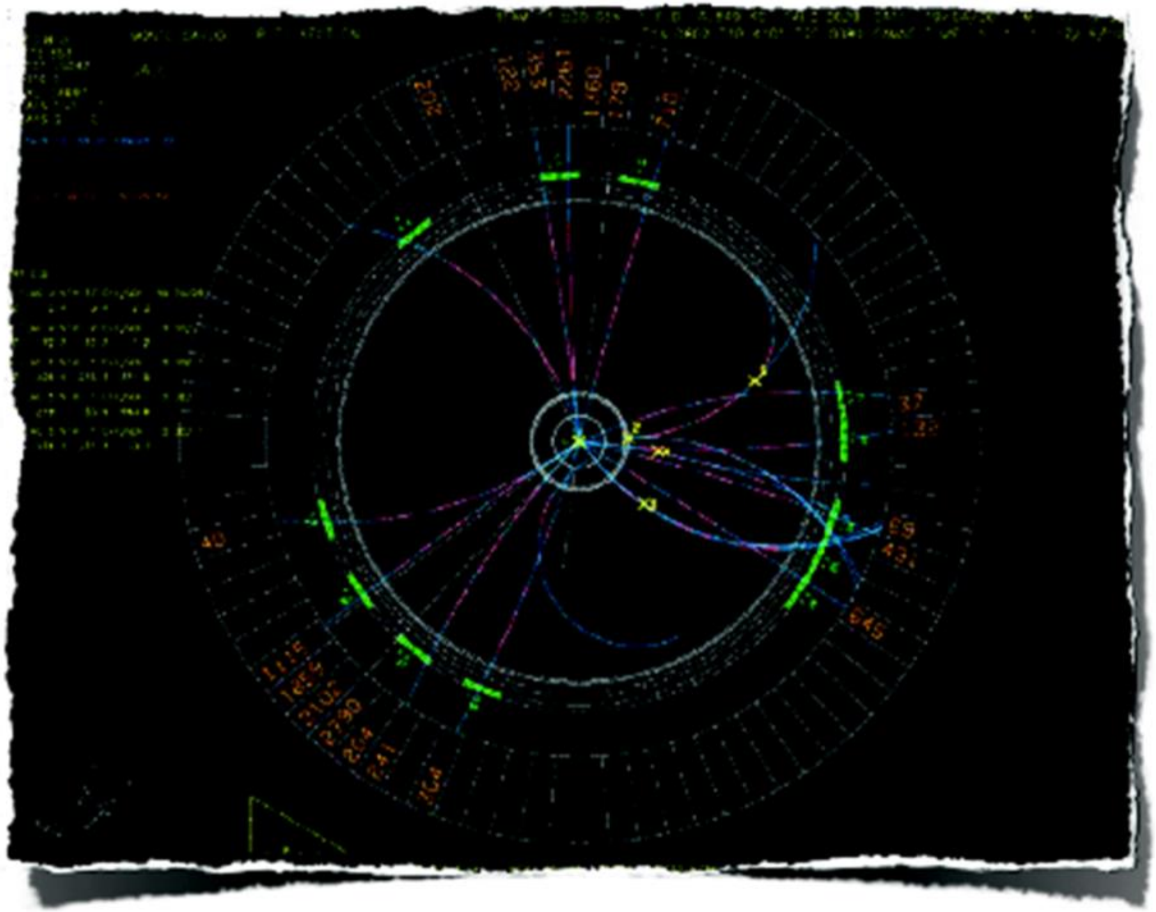
Drift Chamber - Jade



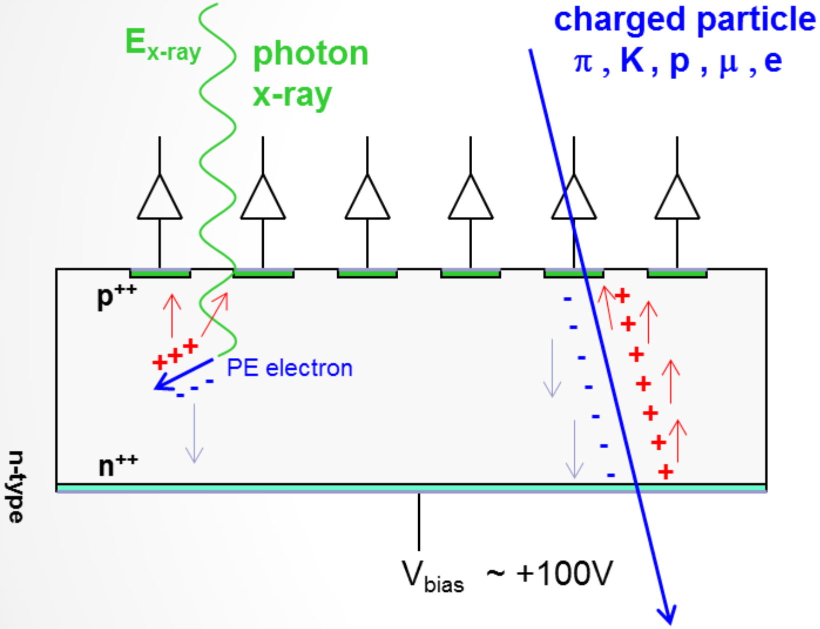
Drift Chamber - Jade



Drift Chamber - Jade

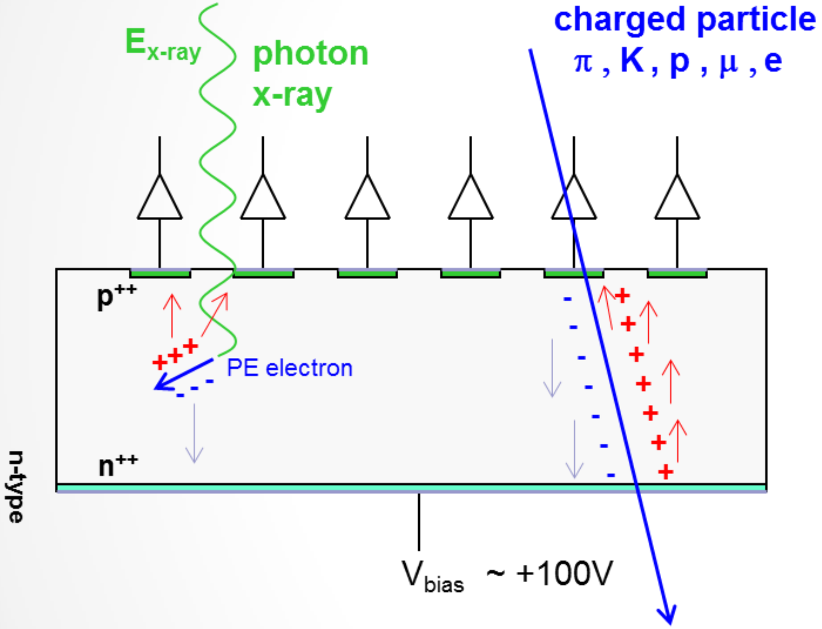


Segmented Silicon Diode Sensors for Particle Detection



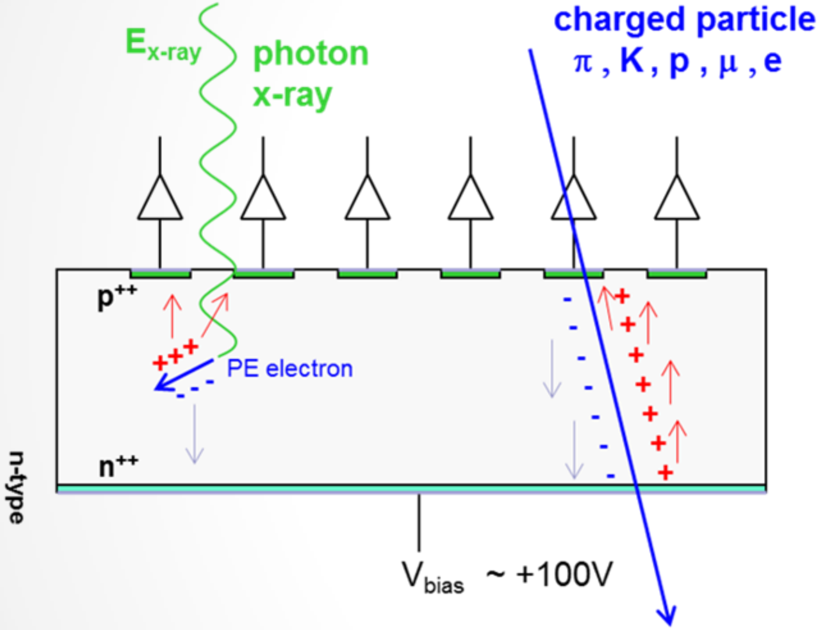
- For charged tracks resolution depend on:
  - segmentation pitch (strips, pixels)
  - charge sharing (angle, B-field, diffusion)
  - S/N performance of readout electronics
  - δ-rays

Segmented Silicon Diode Sensors for Particle Detection



- Shared Charge collection on segmented electrodes due to:
  - Diffusion during drift time
  - Lorentz angle due to presence of B-field
  - Tilted tracks
- Individual readout of charge signal on electrodes allows position interpolation that is better than pitch of segmentation.

Segmented Silicon Diode Sensors for Particle Detection

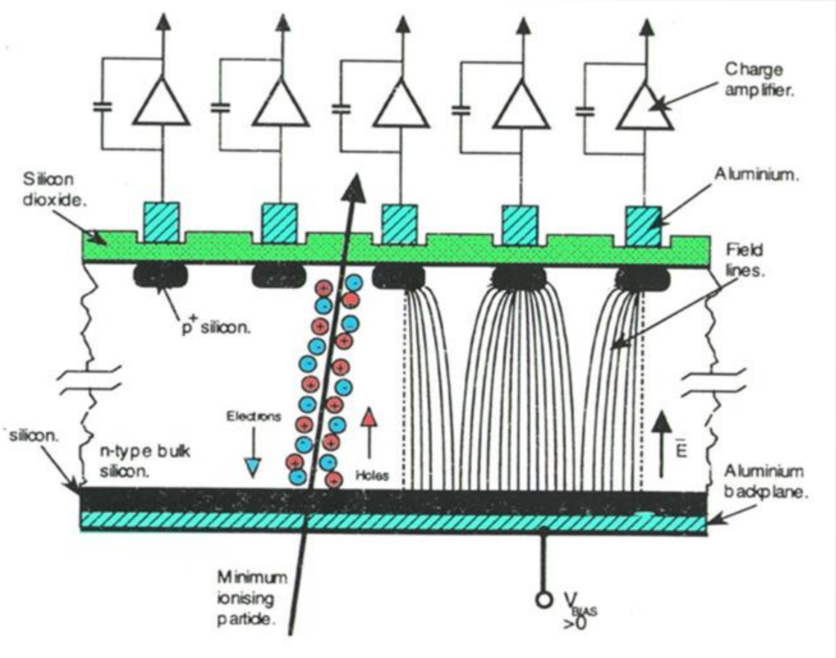


- Silicon microsrip detectors in HEP:
- Strip pitch = 50μm
- Position resolution ~1.5μm achieved

Charge collection

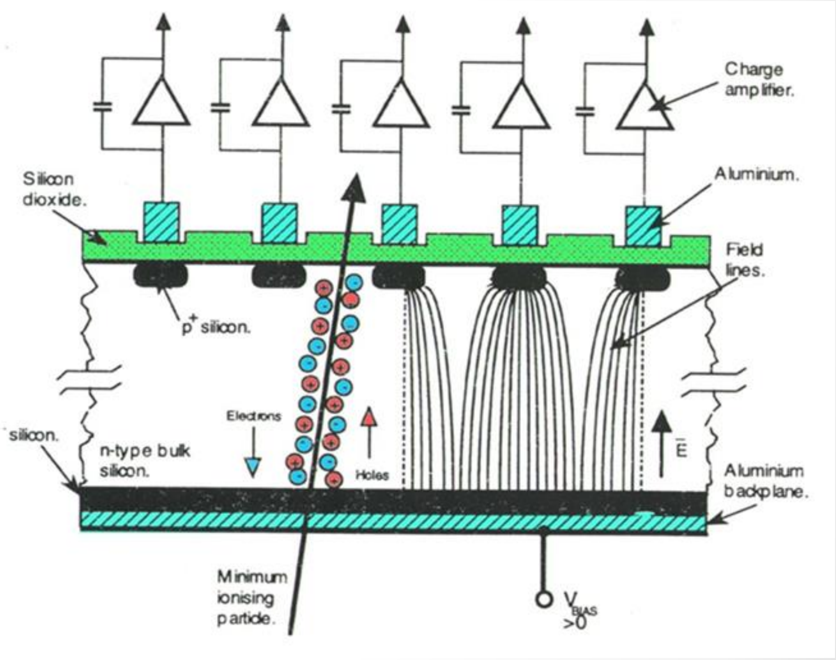
- Electrons and holes
  - separated in the electric field and
  - collected on the implanted strips:

  - Electrons drift 10 ns
  - Holes drift 25 ns
  - Need high-purity silicon to avoid trapping.



Charge collection

- Position resolution:
  - 5-30 μm
  - for strip pitch of 50-100 μm
  - better with pulse-height interpolation
- Silicon detectors are
  - fast and have
  - high resolution
- Further readout electronics required to amplify the charge
  - Need many channels to cover large areas.

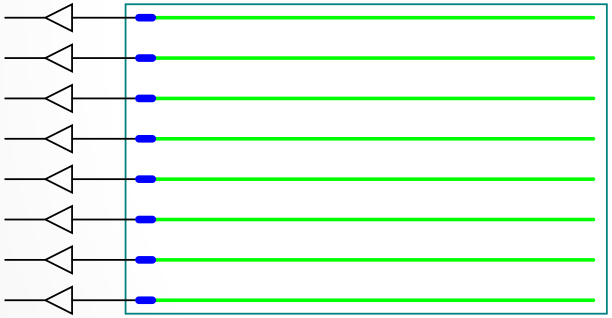


From Strips to Pixels

- very high rate & high multiplicity
  - requires 2 D – segmentation of silicon sensors.
- connection to readout electronic chips !!

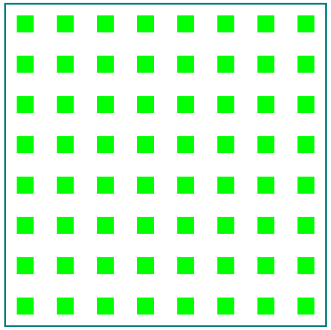
Micro strip Detectors → Pixel Detectors

LEP, HERA, Tevatron 10^5 increase **LHC**



1 D – connection

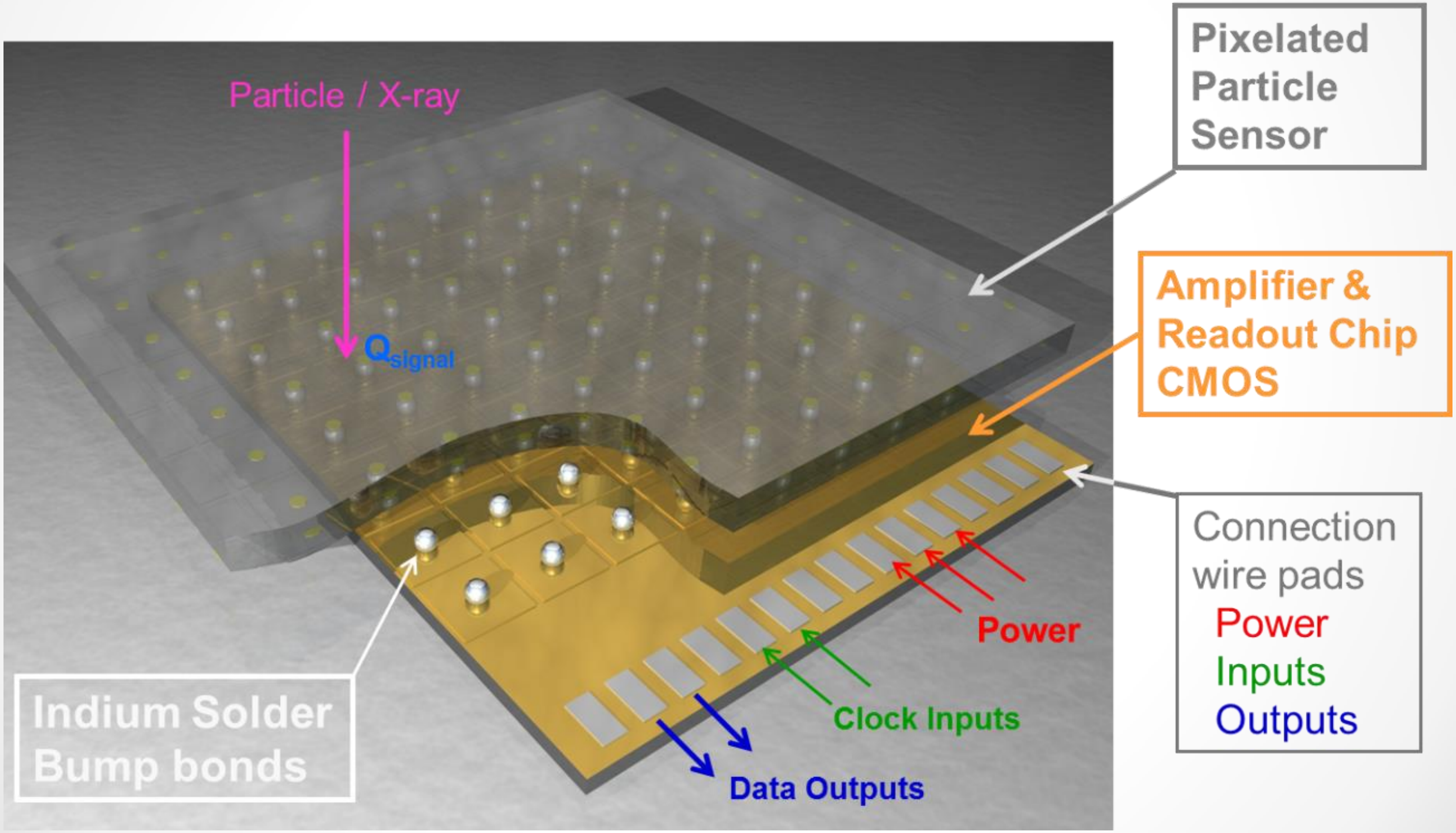
wire-bonding



2 D – connection

- bump-bonding
- wafer bonding
- 3D integration

Hybrid Pixel Detectors



Pixelated Particle Sensor

Amplifier & Readout Chip CMOS

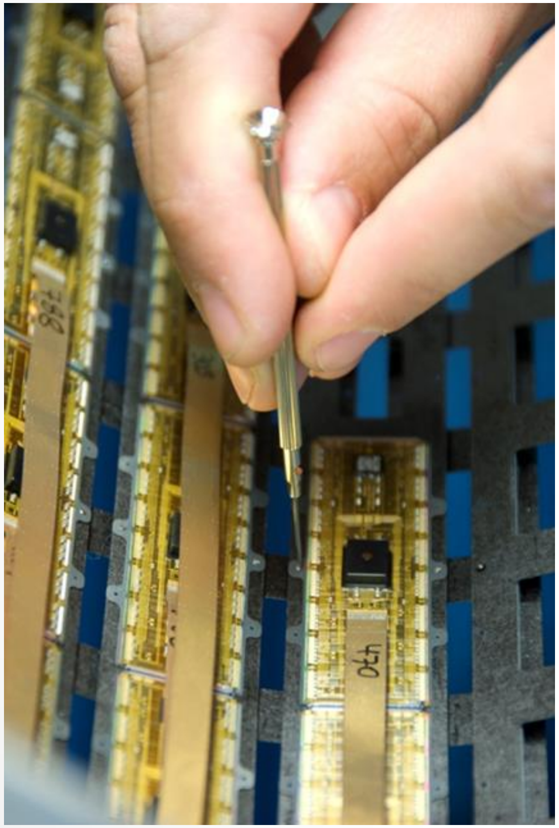
Connection wire pads
Power
Inputs
Outputs

Indium Solder Bump bonds

Particle / X-ray → Signal Charge → Electr. Amplifier → Readout → Digital Data

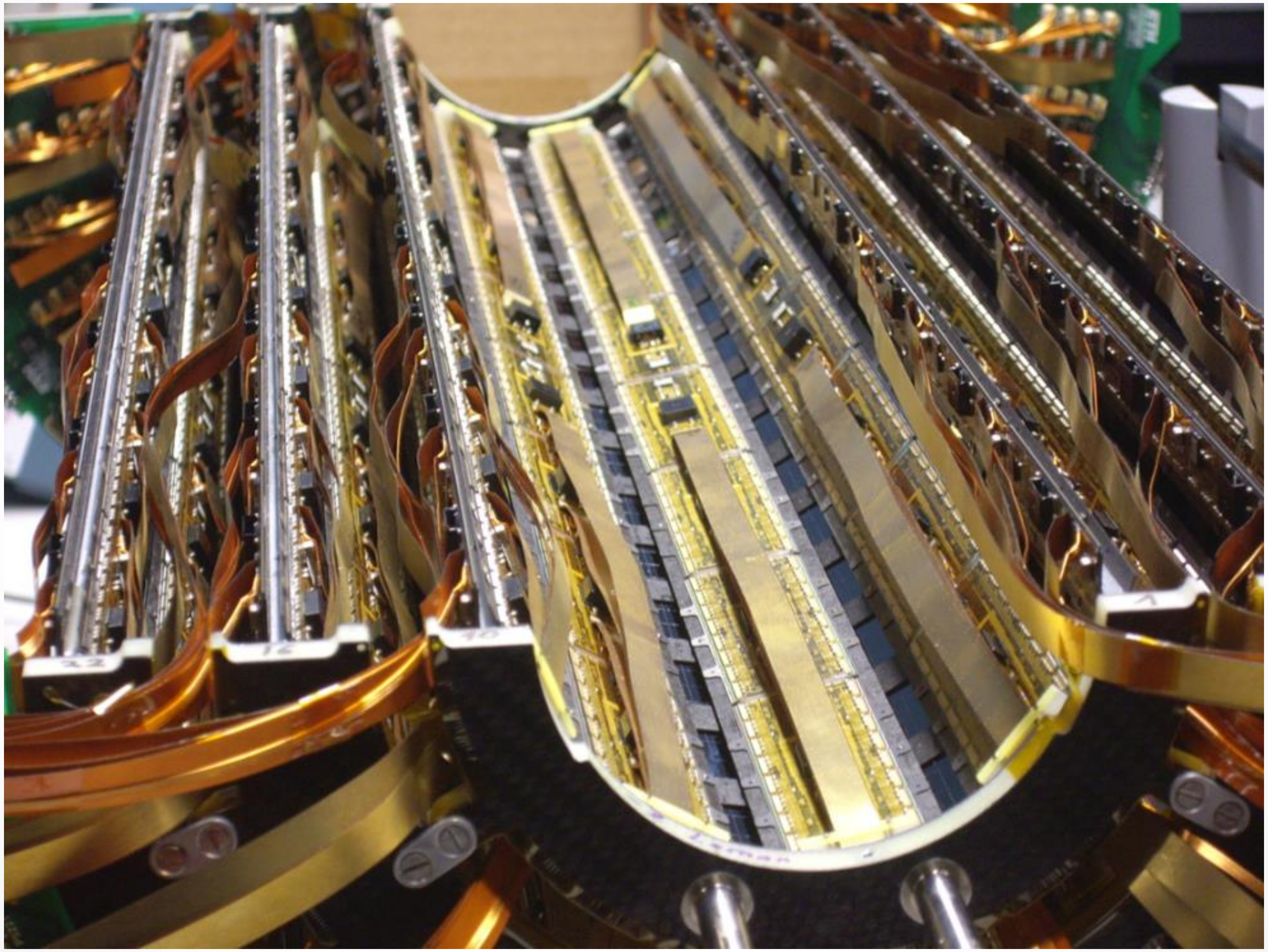
CMS Pixel Detector

for the Large Hadron Collider



768 pixel modules
~0.75 m^2

48Mega Pixel Detector with 40 MHz Frame Rate



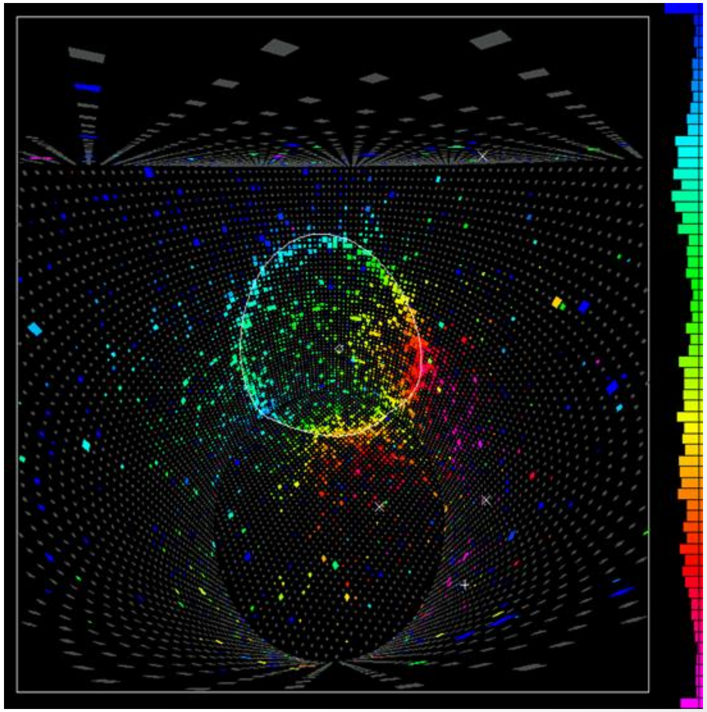
Cherenkov Radiation


P. Cherenkov: 1935
Nobelpreis 1958

A light cone, so called Cherenkov radiation is emitted

- whenever charged particles pass through matter
- with a velocity v exceeding the velocity of light in the medium.
- Measure angle of light cone -> v of particle; Particle ID possible

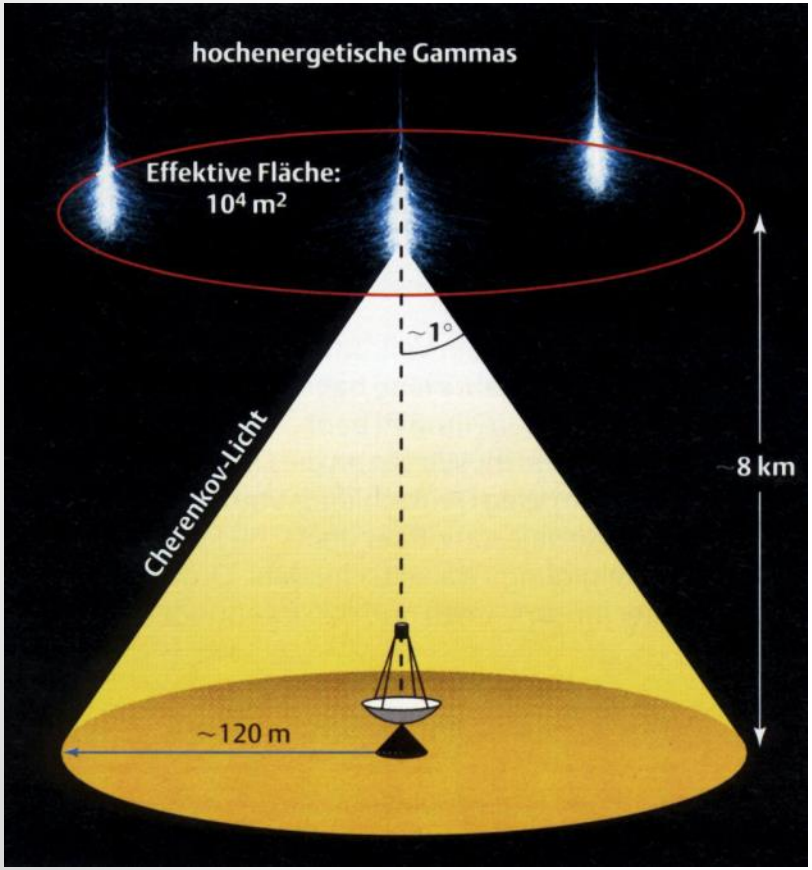

airplane passing the sonic wall


Event of Super Kamiokande

See http://webphysics.davidson.edu/applets/applets.html for a nice illustration

Application in Astroparticle Physics

- Detection of high energetic γ's via Cherenkov light in the atmosphere



Hess telescope

Magic telescope

Event Display Magic