# Detector Development for the

with focus on Calorimeters

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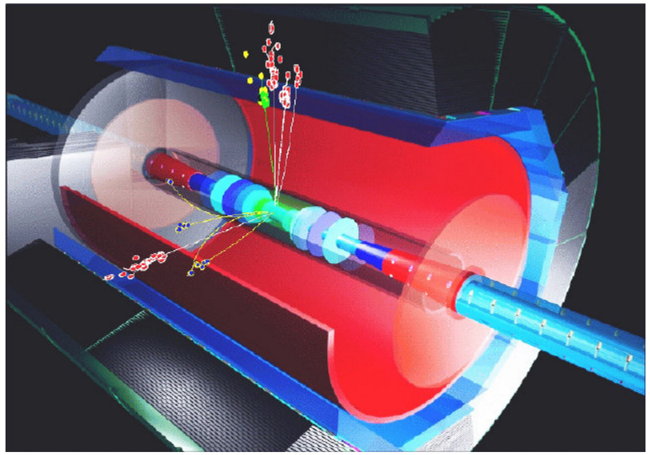


Part I : Introduction to the Physics of Particle Detectors
Part II : Detector Concepts and the Concept of Particle Flow
Part III: Calorimetry R&D for the ILC

# Part I

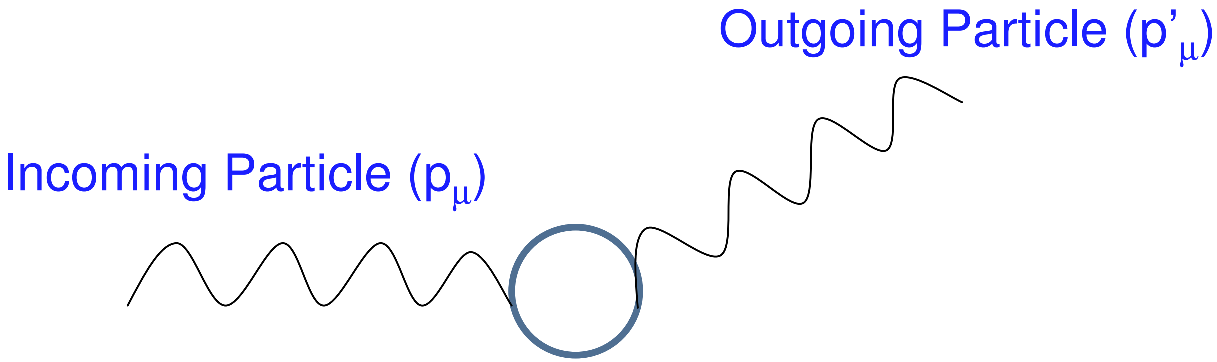
## Introduction to the Physics of Particle Detectors

# Outline

- Interactions of Particles with Matter
- Gaseous Detectors (very brief!)
- Shower Counters
  - Electromagnetic Counters
  - Hadronic Counters

- Detectors based on Semi-Conductors

# Interactions of Particles with Matter




Scattering Center:
Nucleus or Atomic Shell

Detection Process is based on Scattering of particles while passing detector material

Energy loss of incoming particle: $\Delta E = p_0 - p'_0$

# Energy Loss of Charged Particles in Matter

Regard: Particles with $m_0 >> m_e$

$\Delta E = 0$: Rutherford Scattering

$\Delta E \neq 0$: Leads to Bethe-Bloch Formula

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

z - Charge of incoming particle
Z, A - Nuclear charge and mass of absorber
$r_e$, $m_e$ - Classical electron radius and electron mass
$N_A$ - Avogadro's Number = $6.022 \times 10^{23}$ $Mol^{-1}$
I - Ionisation Constant, characterizes Material
typical values 15 eV
$\delta$ – Fermi's density correction

$T_{max}$ - maximal transferrable energy (later)

# Discussion of Bethe-Bloch Formula I

Describes Energy Loss by Excitation and Ionisation !!

We do not consider lowest energy losses

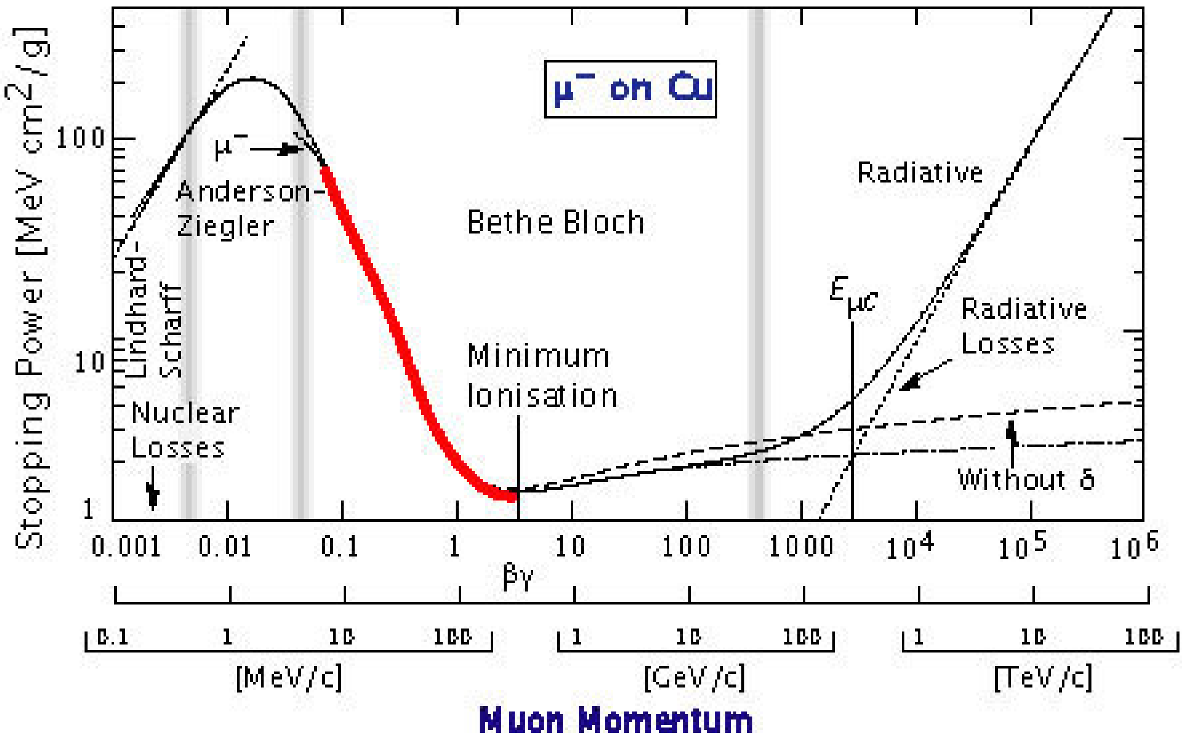
<u>'Kinematic' drop</u>

~ $1/\beta^2$

Scattering Amplitudes:

$$f_i(\theta) \propto 1 \big/ (\vec{p} - \vec{p}')^2, (\vec{p} - \vec{p}')^2 \propto v^2$$

Large angle scattering becomes less probable with increasing energy of incoming particle.

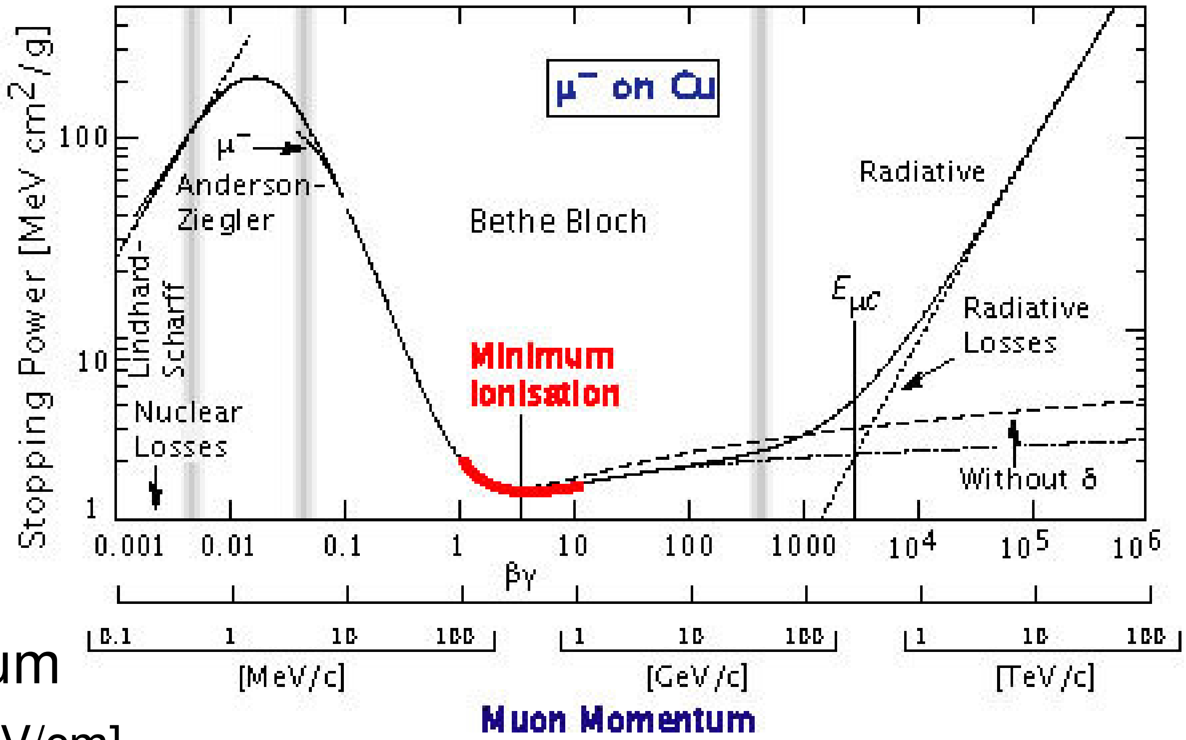



Drop continues until βγ ~ 4

# Discussion of Bethe-Bloch Formula II
# Minimal Ionizing Particles (MIPS)

dE/dx passes
broad Minimum @
$\beta\gamma \approx 4$

Contributions from
Energy losses
start to dominate
kinematic dependency
of cross sections




typical values in Minimum

| | [MeV/(g/cm²)] | [MeV/cm] |
|---|---|---|
| Lead | 1.13 | 20.66 |
| Steel | 1.51 | 11.65 |
| O2 | 1.82 | $2.6 \cdot 10^{-3}$ |

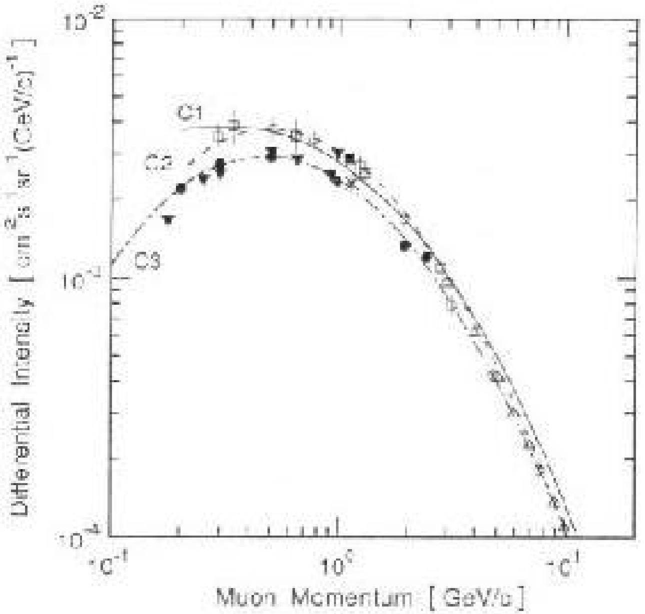
Role of Minimal Ionizing Particles ?

# Intermezzo: Minimal Ionizing Particles

Minimal Ionizing Particles deposit a well defined energy in an absorber

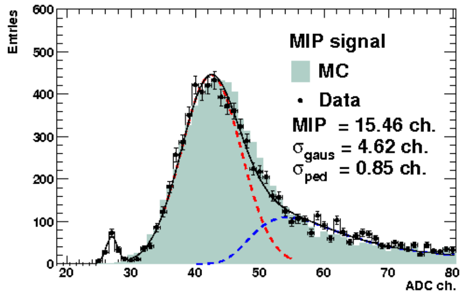
Typical Value: 2 MeV/(g/cm$^2$)

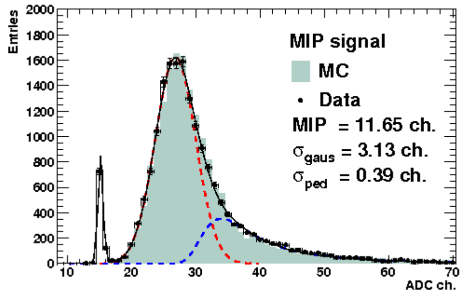
Cosmic-Ray $\mu$ have roughly $\beta\gamma \approx 4$ $\Rightarrow$ Ideal Source for Detector Calibration




Cosmic $\mu$ spectrum at
Sea Level

Rate ~ 1/(dm$^2$sec.)




Cosmic Muons detected in ILC Calorimeter Prototype

Signals show Landau-Distribution:

$\Delta E_{Average}$ (à la Bethe-Bloch) $\neq \Delta E_{Real}$

Typical for thin absorbers

Thick Absorbers:

$\Delta E_{Average} = \Delta E_{Real}$

Landau Distribution $\rightarrow$Gauss-Distribution

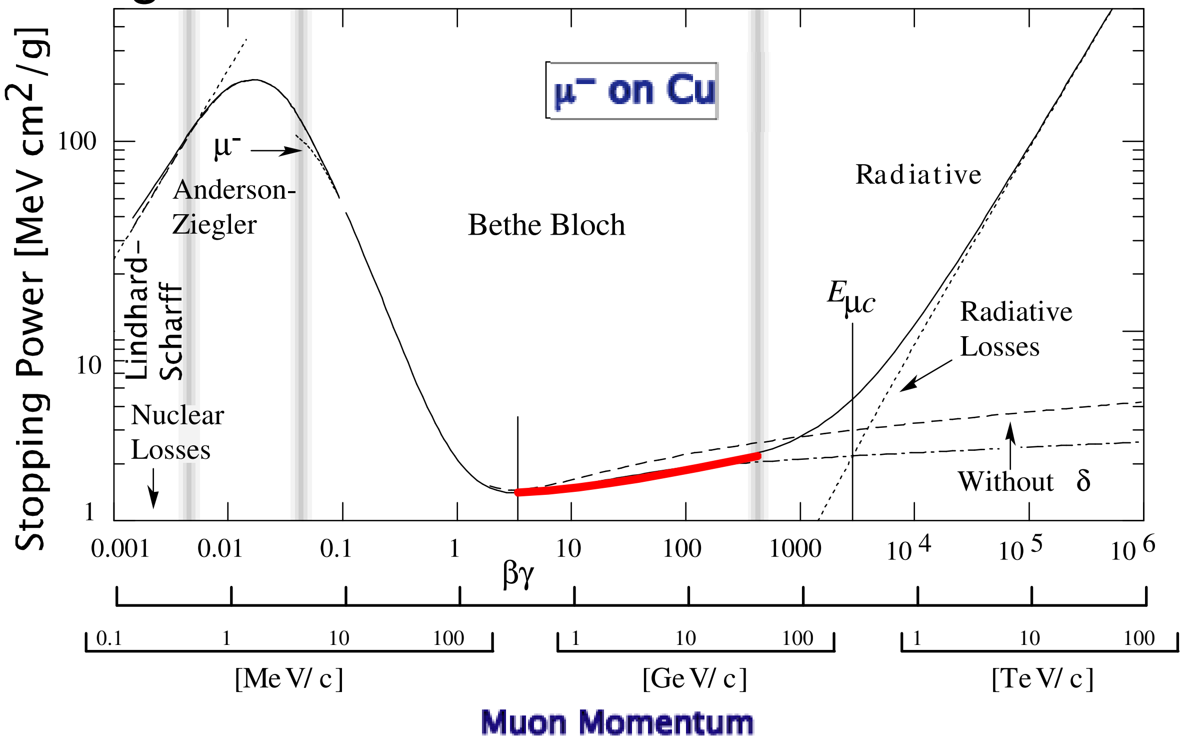
# Discussion of Bethe-Bloch Formula III

'Visible' Consequence of Excitation and Ionization Interactions.

Dominate over kinematic drop

Interesting question: Energy distribution of electrons created by Ionization.

Logarithmic Rise




## δ-Electrons

Non relativistic: $E_1 \approx M$

$$T_{\max} = 4\frac{m}{M_{Abs.}} \bullet \frac{\vec{p}_1^{\,2}}{2M_{Abs.}}$$

Relativistic: $|p_1| \approx M$

$$T_{\max} \approx \frac{2mc^2\beta^2\gamma^2}{1+2\frac{m\gamma}{M}+\left(\frac{m}{M}\right)^2}$$

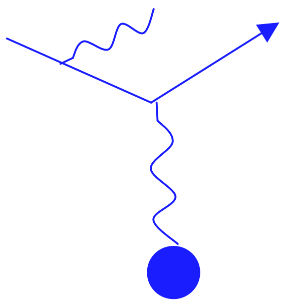
In the relativistic case an incoming particle can transfer (nearly) its whole energy to an electron of the Absorber

These δ-electrons themselves can ionize the absorber !

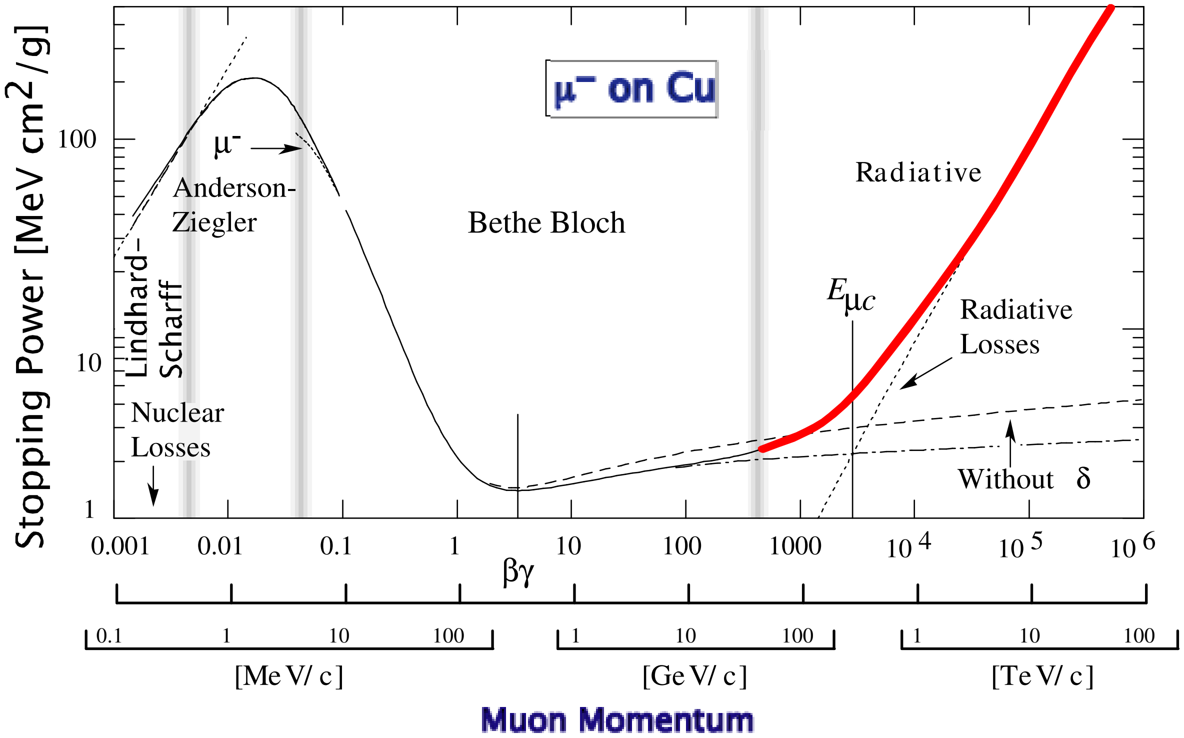
# Discussion of Bethe-Bloch Formula IV

## Radiative Losses - Not included in Bethe-Bloch Formula

Particles interact with Coulomb Field of <u>Nuclei</u> of Absorber Atoms



Energy loss due to Bremsstrahlung

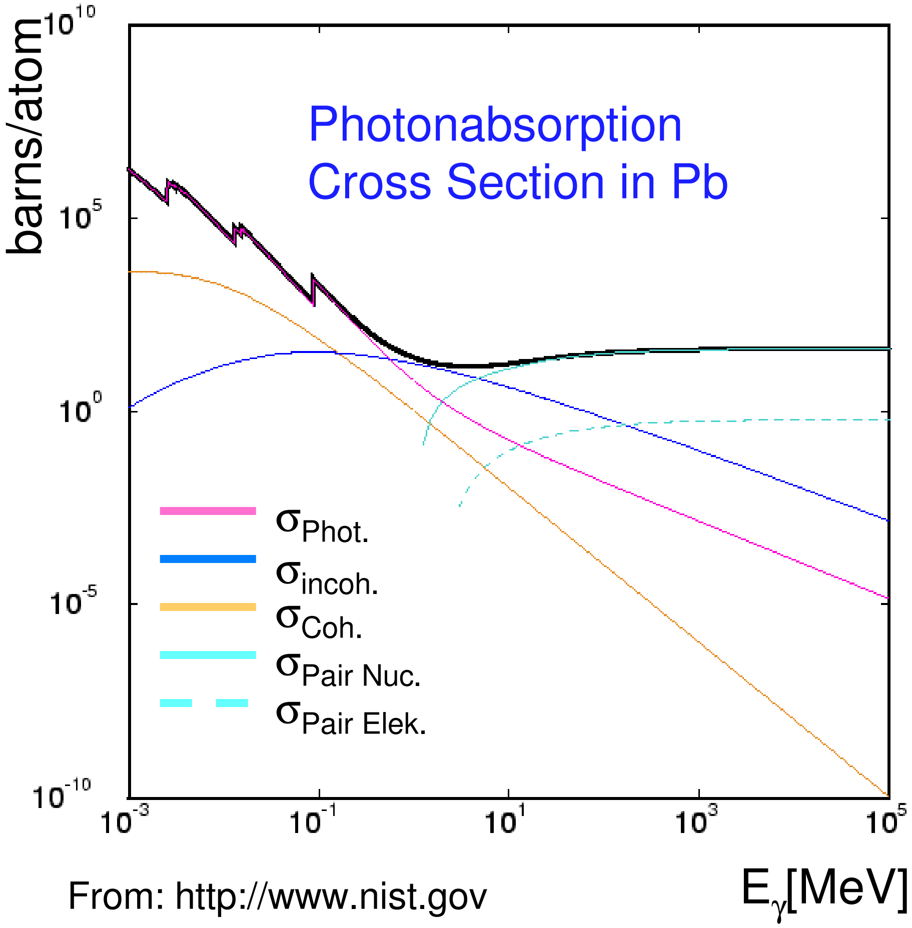



Important for e.g. Muons with E > 100 GeV
Dominant energy loss process for electrons (and positrons)

Detailed discussion later

# Interactions of Photons with Matter

General: Beer's Absorption Law: $I = I_0 e^{-\mu x}$, $\mu$ = Absorptioncoefficient




From: http://www.nist.gov

Three main processes

Photoeffect: $\sigma_{Phot.}$ $\gamma$+Atom → Atom$^+$ + $e^-$

$E_\gamma \gg m_e c^2$ $\quad \sigma_{Phot.} = 2\pi r_e^2 \alpha^4 Z^5 \frac{mc^2}{E_\gamma}$

$I_0 \ll E_\gamma \ll m_e c^2$ $\quad \sigma_{Phot.} = \alpha \pi a_B^2 Z^5 \left(\frac{I_0}{E_\gamma}\right)^{7/2}$

$a_B$ = Bohr radius, $r_e$ = class. Electronradius

Compton Effect: $\sigma_{coh.}$, $\sigma_{incoh.}$

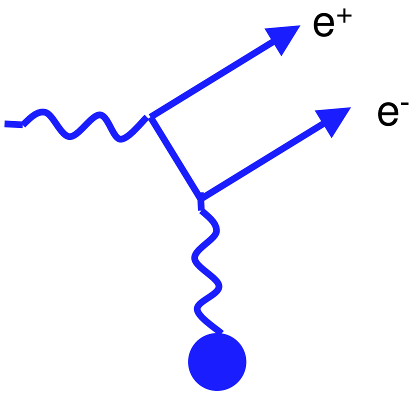
$\gamma + e^- \rightarrow \gamma + e^-$

Klein-Nishina:

$E_\gamma \ll m_e c^2$ $\quad \sigma_c = \frac{8\pi}{3} r_e^2 \left(1 - \frac{2E_\gamma}{mc^2}\right)$

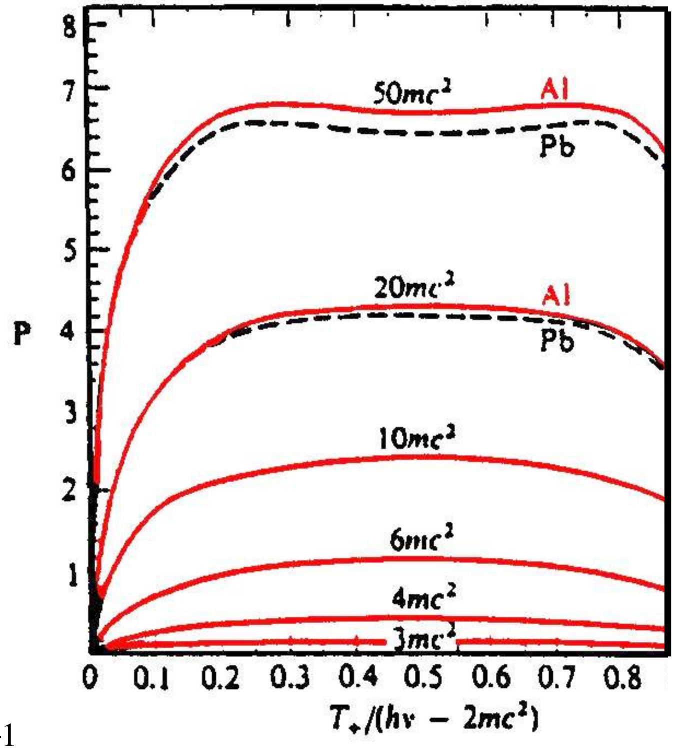
$E_\gamma \gg m_e c^2$ $\quad \sigma_c = \pi r_e^2 \frac{mc^2}{E_\gamma}\left\{\ln\left(\frac{2E_\gamma}{mc^2}\right) + \frac{1}{2}\right\}$

# Pair Production Process




Photon interacts
in Coulomb Field
of Nucleus
(or Shell Electron)

Energy Spectrum of e+e-




From Kinematics:

$$E_\gamma^{Min.} = 2m_e c^2$$

Threshold Energy 1.2 MeV

Absorption Coefficient

$$\mu(E >> m_e c^2) = \frac{28}{9} nZ^2 \alpha r_e^2 \ln\frac{183}{Z^{1/3}} = \frac{7}{9} X_0^{-1}$$

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

Radiation length

Characterizes the behavior of high energetic γ and e in Matter

Some Values:

$X_{0,Air}$=30 420 cm

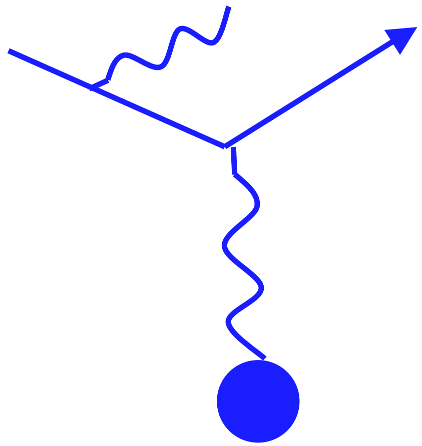
$X_{0,Al}$ = 8.9 cm

$X_{0,Pb}$ = 0.56 cm

# Bremsstrahlungs Process

Energy Loss for High Energetic electrons (and muons)

$$\frac{dE}{dx} = -4Z^2 \frac{L\rho}{A} \alpha r_e^2 E_e \ln\frac{183}{Z^{1/3}} = -\frac{E_e}{X_0}$$



Molière Radius $R_M$:

$$R_M = \frac{21 MeV}{\varepsilon_c} X_0$$

Transversal deflection of e- after passing $X_0$ due to multiple scattering

$\varepsilon_c$ = critical Energy

Energy where energy losses due to ionization excitation start to dominate

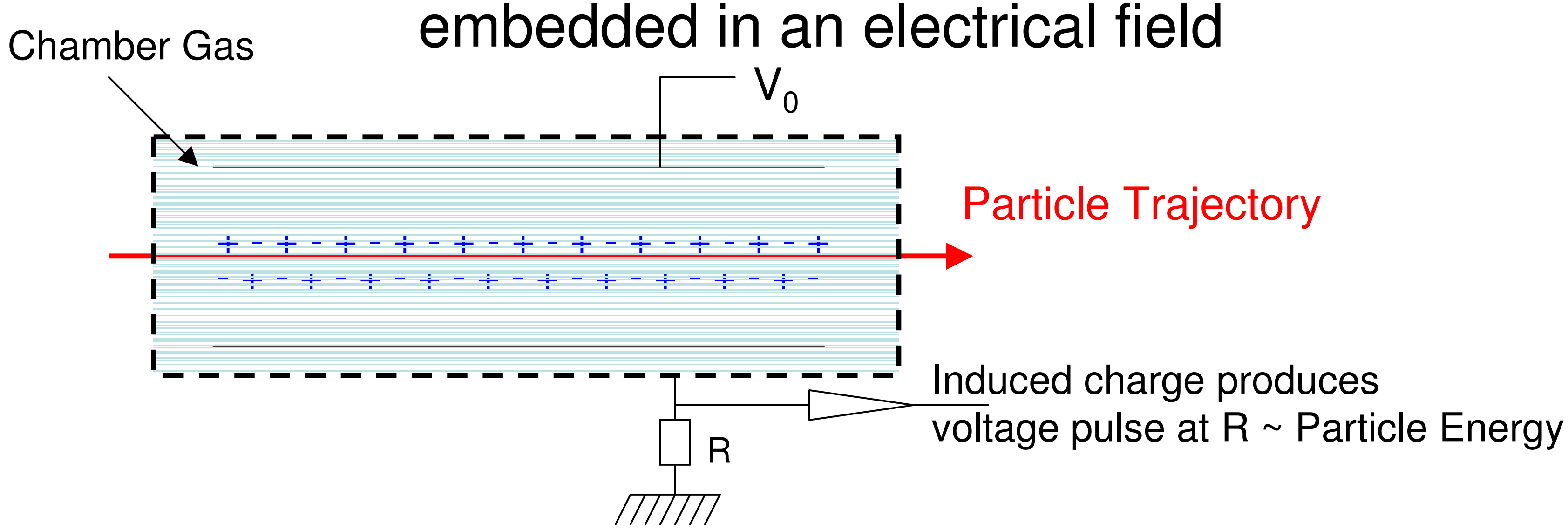
Typical Values for Pb:

| | $\varepsilon_c$[MeV] | $R_M$ [cm] |
|---|---|---|
| Pb | 7.2 | 1.6 |
| NaJ | 12.5 | 4.4 |

$X_0$, $R_M$ and $\varepsilon_c$ are most important characteristics of electromagnetic shower counters

# Gaseous Detectors

Basic Principle: Charged particle ionizes gas embedded in an electrical field

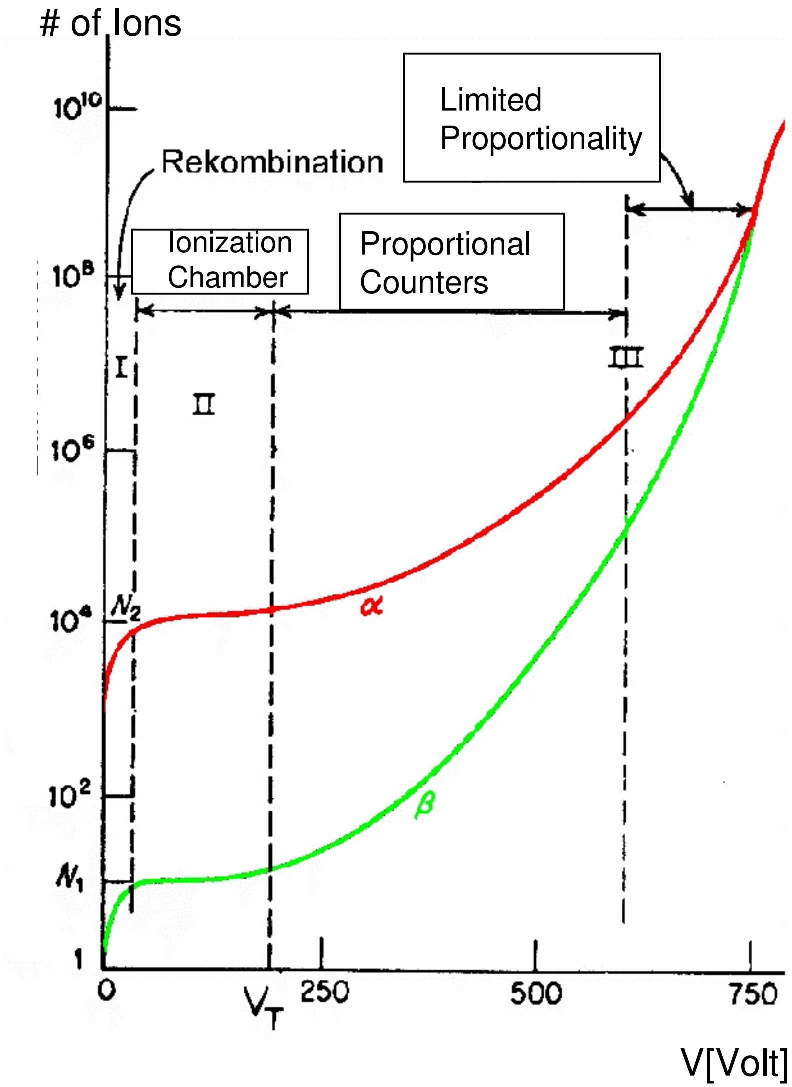



Classical Application:

Track Finding of charged particles

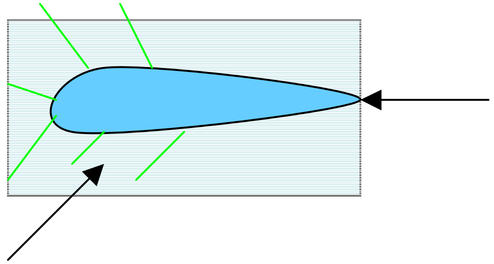
R&D for employment as sensitive device for Calorimeters (this lecture)

# Operation Modes of Gaseous Detectors



# Calorimetry

Basic Principle: High energetic particle is stopped in a dense absorber.
Kinetic energy is transferred into detectable signal




- Only way to measure to measure electrically neutral particles
- Only way to measure particles at high energies (although … see later)

Need to distinguish: Electromagnetic Calorimeters
Hadronic Calorimeters

Creation and readout of detectable Signals ?

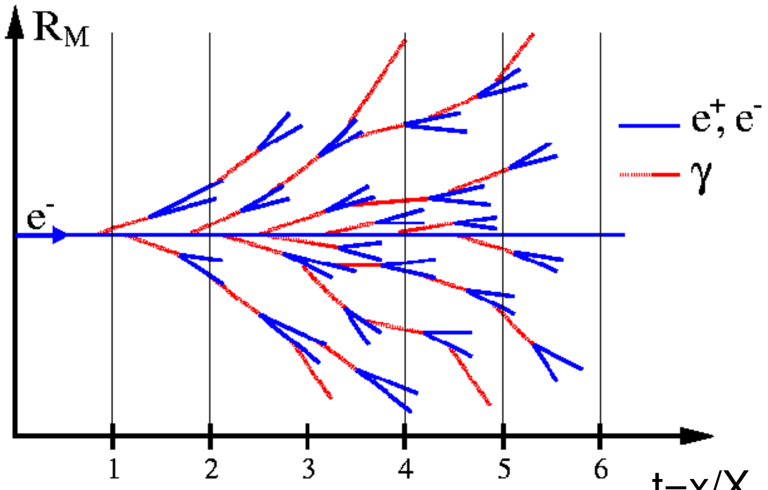
# Electromagnetic Calorimeters - Shower Development

Energy loss of electron by Bremsstrahlung:
Photons convert into $e^+e^-$-Pairs

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

## Simple Shower Model

(see Longo for detailed discussion)




- Energy Loss after $X_0$: $E_1 = E_0/2$
- Photons -> materialize after $X_0$
  $E_{\pm} = E_1/2$

Number of particles after t: $N(t) = 2^t$
Each Particle has energy

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

Shower continues until particles reach critical energy (see p. 16) where $t_{max} = \ln(E_0/\varepsilon_c)$

Shower Maximum increases logarithmically with Energy of primary particle
(Important for detector design !!!)

N.B.: Some relevant numbers:

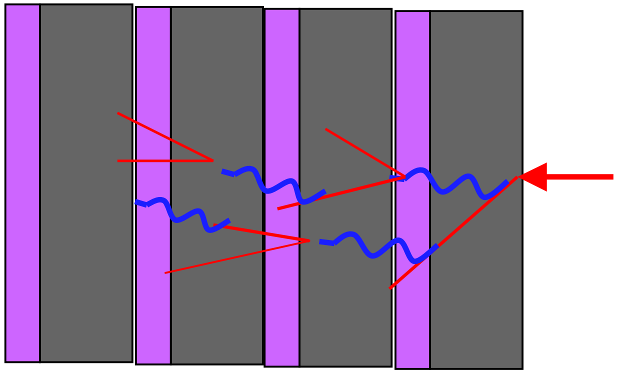
$$X_0 = \frac{180\,A}{Z^2}[g/cm^2] \quad L(95\%) = \ln\frac{E_0}{\varepsilon_c} + 0.08Z + 9.6[X_0]$$

$$\varepsilon_c = \frac{550\,MeV}{Z} \quad R(95\%) = 2R_M$$

$$t_{MAX} = \ln\left(\frac{E_0}{\varepsilon_c}\right) - \begin{cases}1 & \text{for e induced showers}\\ 0.5 & \text{for } \gamma \text{ induced showers}\end{cases}$$

# (Electromagnetic) Calorimeter - Classical Readout

Example: Sampling Calorimeters  Homogenous Calorimeters → Homework



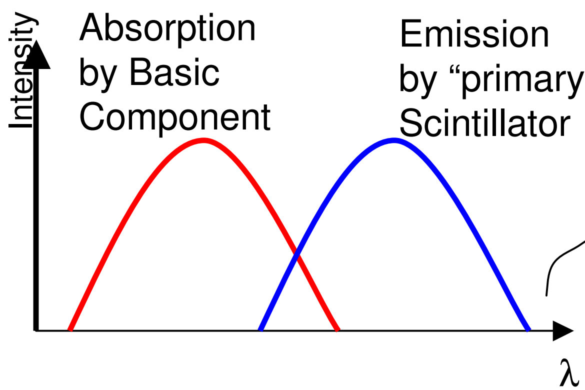
Only sample of shower passes active medium
Production of shower particles is statistical process
with N (t) ~ E ⇒ $\sigma(E) \sim \sqrt{E}$

Indeed e.g. BEMC (H1 detector): $\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus 1.7\%$

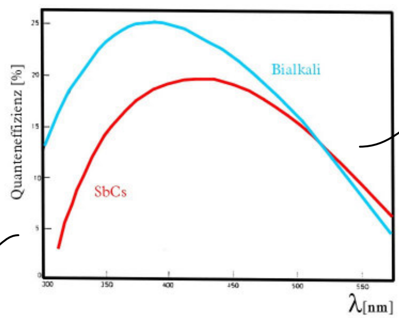
Alternating structure of Absorber and Scintillation medium
Light is generated by charged particles with $E < \varepsilon_c$

## Plastic Scintillators

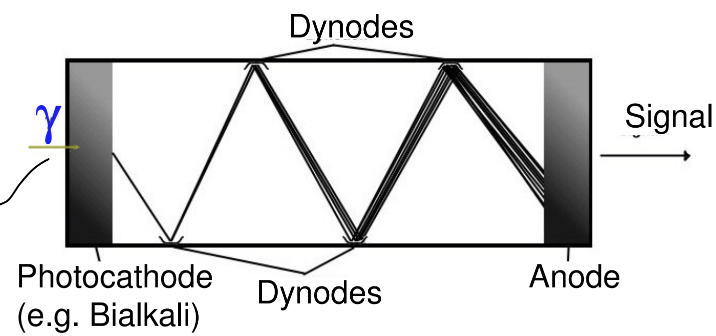
Two Component
organic Material (Benzole Type)




Spectral sensitvity of
Photocathodes




## Photomultiplier



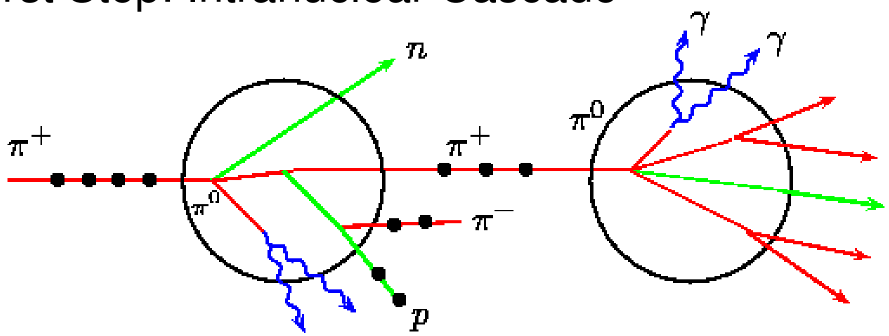

Photoeffect at Cathode: ≈ 0.2e-/γ
Amplification by Dynodes
$\delta \approx$ (10 outgoing e-/incoming e-)
Total Amplifcation:
$G \sim \delta^n$, n = Number of Dynodes

# Hadronic Showers

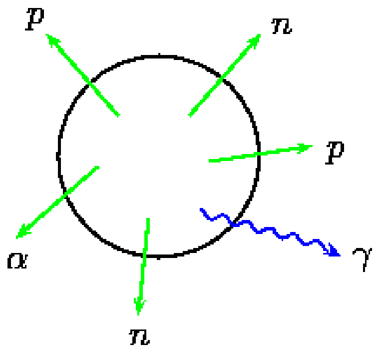
Hadronic Showers are dominated by strong interaction !

$$p + Nucleus \rightarrow \pi^{+} + \pi^{-} + \pi^{0} + \ldots + Nucleus^{*}$$

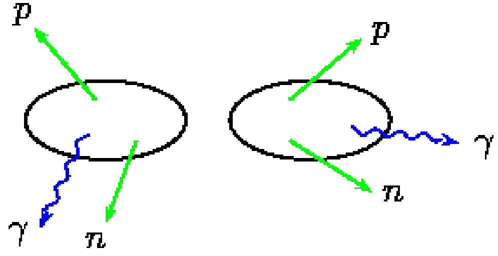
1st Step: Intranuclear Cascade




2nd Step: Highly excited nuclei
Evaporation




Fission followed
by Evaporation




Distribution of Energy
Example 5 GeV primary energy

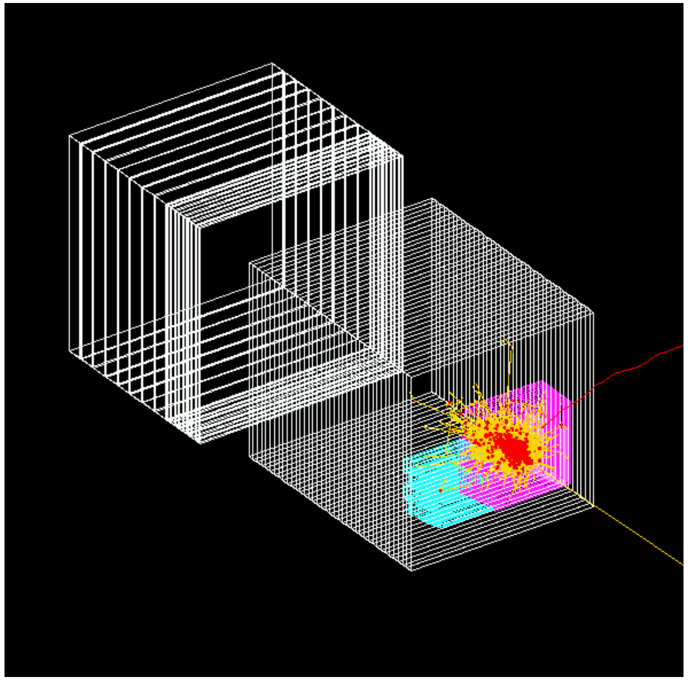
| | |
|---|---|
| - Ionization Energy of charged particles | 1980 MeV |
| - Electromagnetic Shower (by $\pi^0$->$\gamma\gamma$) | 760 MeV |
| - Neutron Energy | 520 MeV |
| - g by Excitation of Nuclei | 310 MeV |
| - Not measurable E.g. Binding Energy | 1430 MeV |
| | 5000 MeV |

Distribution and local deposition of energy varies strongly
Difficult to model hadronic showers
e.g. GEANT4 includes O(10) different Models

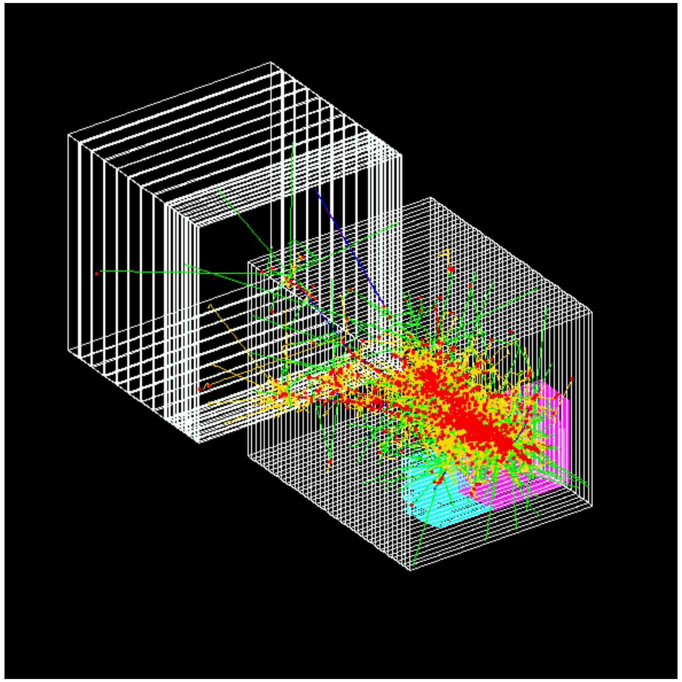
Further Reading:
R. Wigman et al. NIM A252 (1986) 4
R. Wigman NIM A259 (1987) 389

# Comparison Electromagnetic Shower - Hadronic Shower

elm. Shower



hadronic Shower



Characterized by
Radiation Length: $X_0 \propto \frac{A}{Z^2}$

$$R_M \propto \frac{21MeV}{\varepsilon_c} \bullet X_0$$

Characterized by
Interaction Length: $\lambda_{\text{int}} = \frac{A}{\sigma_{pN} A^{2/3} L \rho} \propto A^{1/3}$

$\frac{\lambda_{\text{int}}}{X_0} = \frac{A^{1/3} Z^2}{A} \propto A^{4/3} \Rightarrow$ $\text{Size}_{\text{Hadronic Showers}} >> \text{Size}_{\text{elm. Showers}}$

# Response to energy depositions

Important Relation:

$$\frac{S(e)}{S(h)} = \frac{e/mip}{f_{em}\frac{e}{mip} + (1-f_{em})\frac{h_i}{mip}}$$

S(e), S(h) = Signal created by electron, hadron

e/mip ($h_i$/mip) = Visible energy deposition of electrons (hadrons) normalized to energy deposition by mip

$f_{em}$ = Electromagnetic Component of hadronic shower

e.g. Non linear response to hadrons since

$f_{em} \sim \ln(E/1\text{ GeV})$

with a considerable fluctuation of $f_{em}$

Goal for detector planning: e/mip = h/mip ⇔ S(e) = S(h)

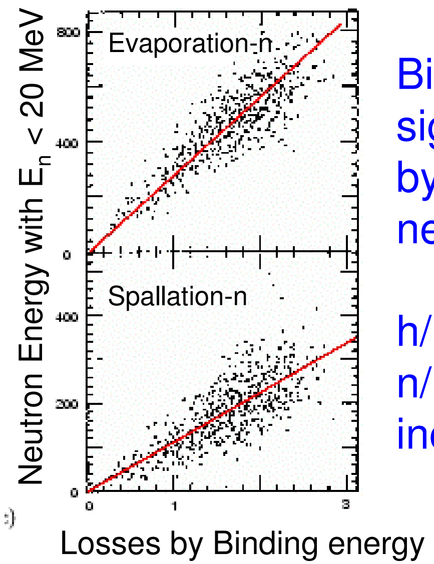
$$\frac{h_i}{mip} = f_{ion}\frac{ion}{mip} + f_n\frac{n}{mip} + f_\gamma\frac{\gamma}{mip} + f_B\frac{b}{mip}$$

$f_{ion}$: hadronic component of hadronic shower which is deposited by by charged particles

$f_n$: fraction deposited by neutrons

$f_\gamma$: fraction of energy deposited by nuclei γ

$f_B$: fraction of binding energy of hadronic component




Binding energy "lost" for signal can be compensated by detecting neutrons

h/mip increases if e.g. n/mip and/or $f_n$ is increased

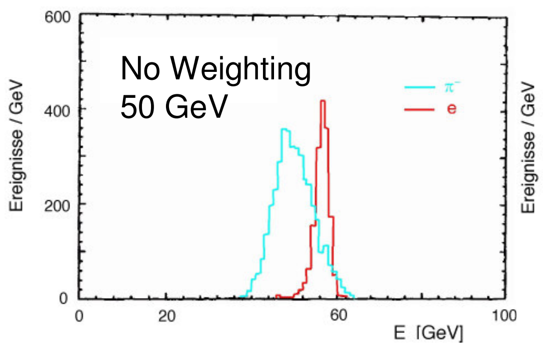
# Compensation Calorimetry

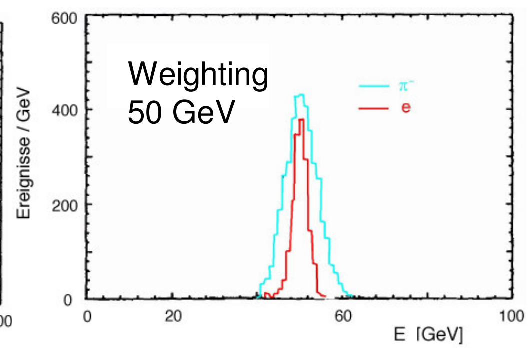
Goal: $$\frac{e}{mip} = \frac{h}{mip}$$

## Software Weighting

Correct energy response 'offline'

reduce e/mip
→Apply small weight to
signal component induced
by electromagnetic
part of hadronic shower




## Hardware Weighting

e.g. increase number of neutrons by
selecting absorber with high Z ⇒falling Z/A

⇒Higher neutron yield in nuclear reactions

Need to detect n
⇒Choose active medium with high fraction of hydrogen

# Detectors Based on Semi Conduction

Employed in: High Precision Gamma Spectroscopy
Measurement of charged particles with $E < 1$ MeV

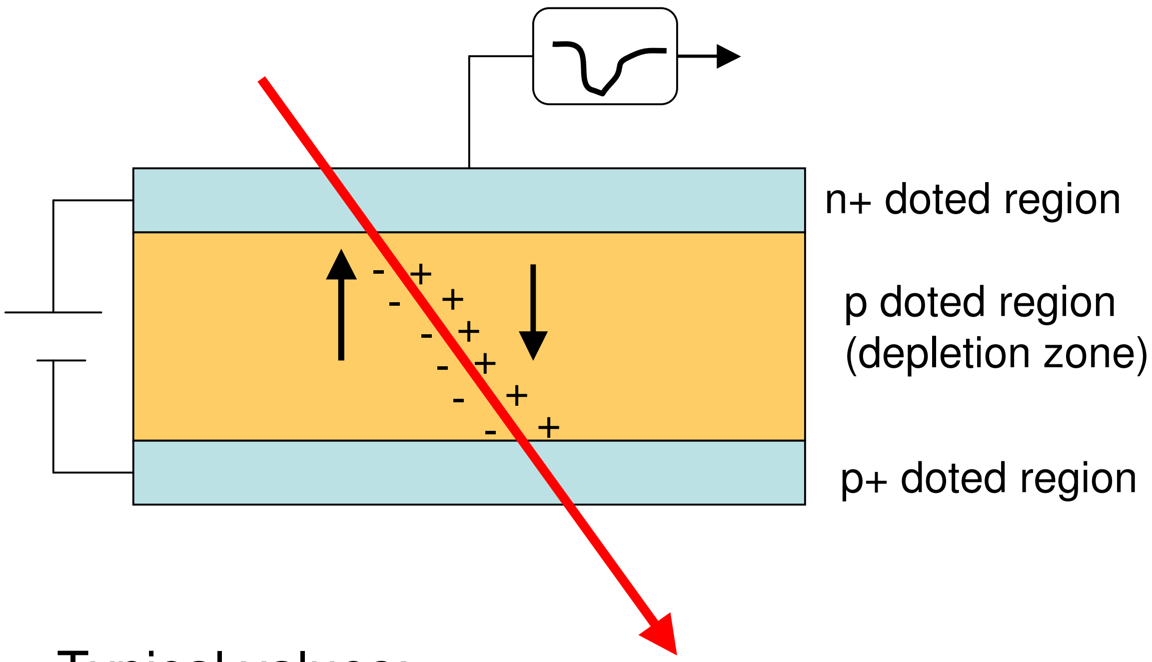
Vertex finding, I.e. determining the interaction
of a high energy reaction
General: “Pixelization” detectors
Application in Calorimetry see later

Takes relatively small energy deposition to create a signal

Comparison: O(100 eV) to create a $\gamma$-quant in a scintillator
3.6 eV to create a electron-hole pair in Silicium

# Principle of Particle Detection

Base Material e.g. Si
doted with e.g. As → n-doted (Donator)
B → p-doted (Acceptor)




Typical values:
Dotation $N_D = 10^{12}$ cm$^{-3}$, $N_A=10^{16}$ cm$^{-3}$
Extension of depletion zone 300 μm
Specific resistance of depletion zone 10kΩm

à la Lutz Feld

Universität Freiburg

Ionization of the detector material - Bethe Bloch

Charge Collection in an electrical field

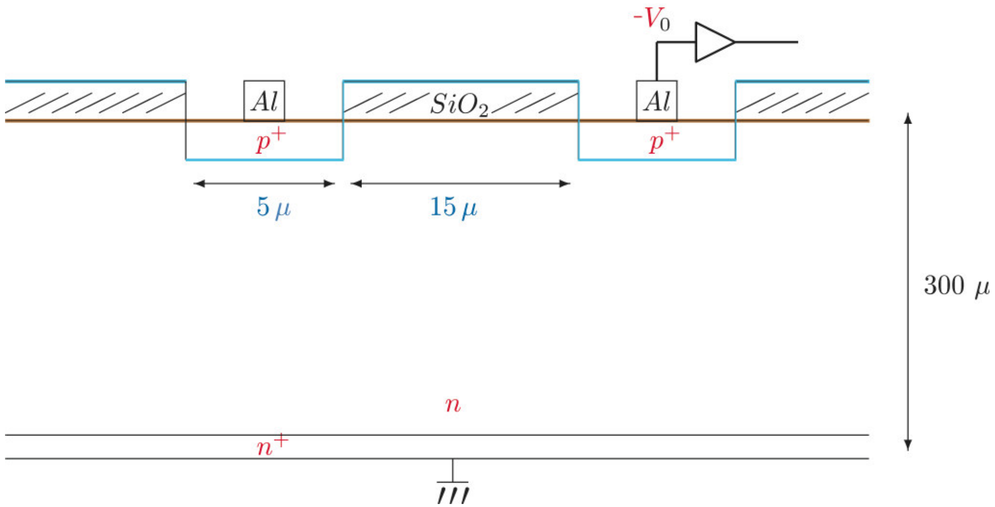
(E-Field extends over depletion zone, capacitance)

Electronic Amplification and measurement of the signal

Number of charges is proportional to deposited energy

Segmentation of electrodes allows for high spatial resolution

# Spatial Resolution - μ Strip Detector

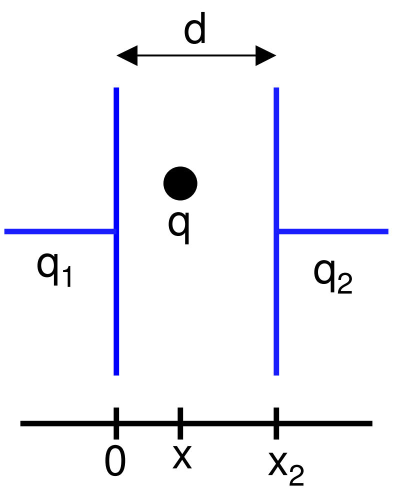



MIP creates roughly 80 e/hole pairs
⇒Q = 24000 e- in 300μm Si

⇒Application of electrostatical model
since Collection Time 20 ns
Integration Time 120 ns
Losses by Capture 1ms S

Spatial Resolution: typ. 15μm

Simple Model: Signals only on neighbored strips
Readout current those of a capacitance




Induced Charges: $q_1 = -\frac{d-x}{d} \bullet q \qquad q_2 = -\frac{x}{d} \bullet q$

if q=q(x) ⇒ $q_1 = -\int \frac{d-x}{d} q(x)dx \qquad q_2 = -\int \frac{x}{d} q(x)dx$

$$q_1 + q_2 = -q_\Sigma = -\int q(x)dx$$

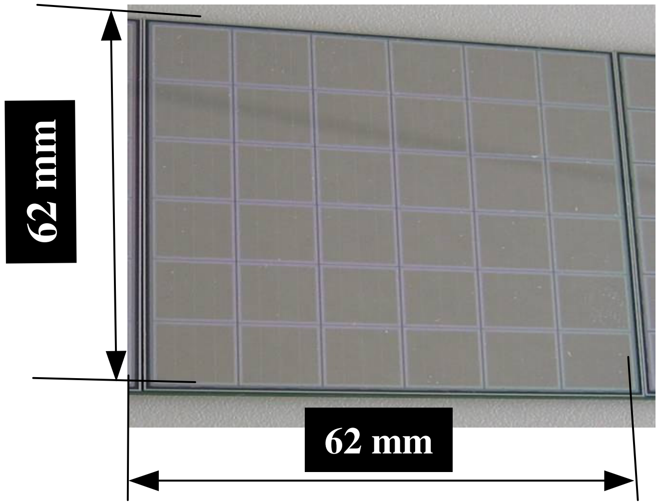
$$\langle x \rangle = \frac{1}{q_\Sigma} \int xq(x)dx = \frac{q_2}{q_1 + q_2} \bullet d$$

if q(x) = const.

# Silicon sensors for ILC electromagnetic Calorimeter

- 4" High resistive wafer : 5 KΩcm
- Thickness : 525 microns ± 3 %
- Tile side : 62.0 $^{+0.0}_{-0.1}$ mm
- 1 set of guard rings per matrix
- In Silicon ~80 e-h pairs / micron ⇒ 42000 $e^-$ /MiP
- Capacitance : ~21 pF (one pixel)
- Leakage current @ 200 V : < 300 nA (Full matrix)
- Full depletion bias : ~150 V
- Nominal operating bias : 200 V
- Break down voltage : > 300 V

Si Wafer :
6×6 pads of detection
(10×10 mm²)




Important point : manufacturing must be as simple as possible to be near of what could be the real production for full scale detector in order to :

- Keep lower price (a minimum of step during processing)
- Low rate of rejected processed wafer
- good reliability and large robustness

Wafers passivation Compatible with a thermal cooking at 40° for 12H, while gluing the pads for electrical contact with the glue we use (conductive glue with silver).