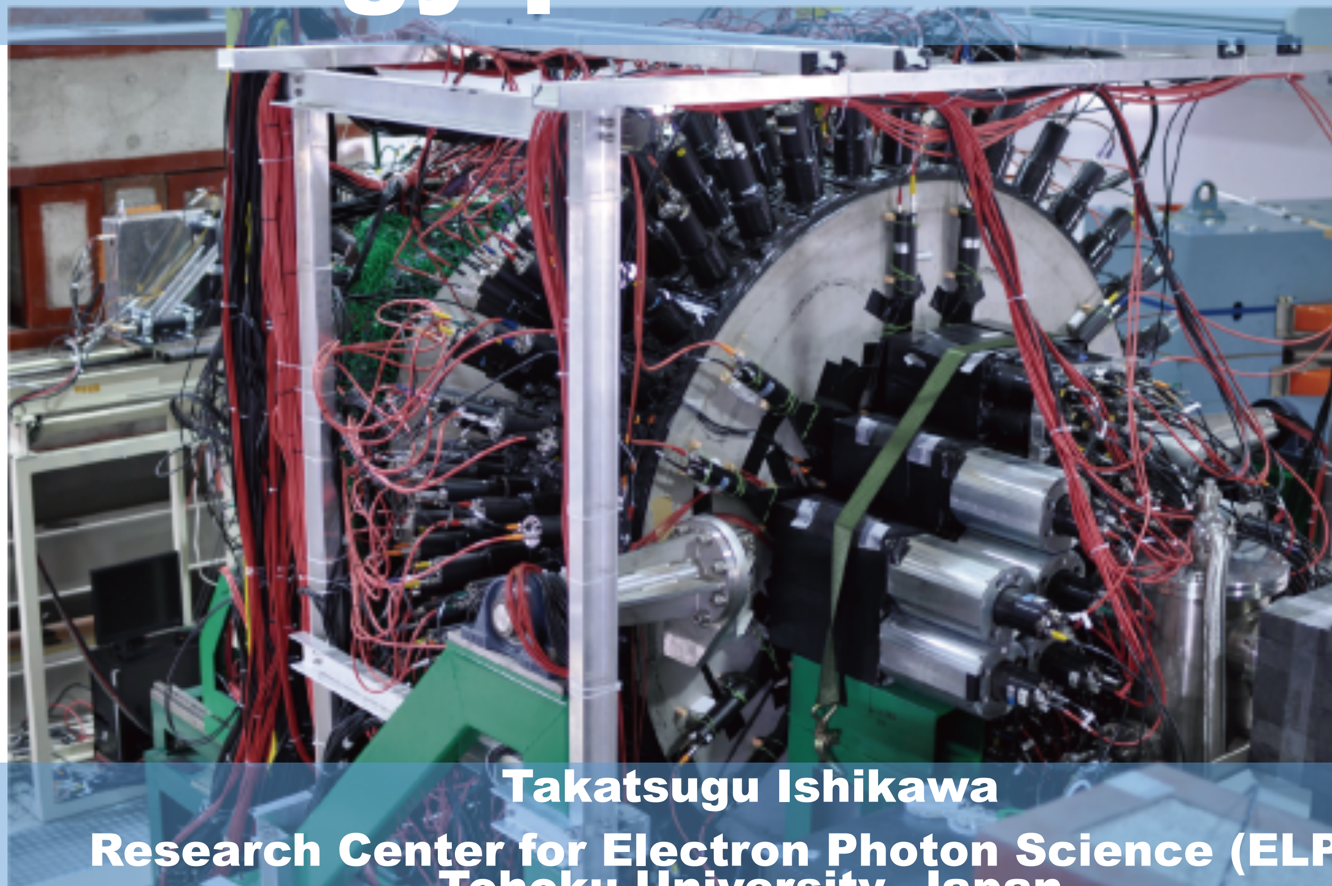
EM calorimeter for detecting high-energy photons



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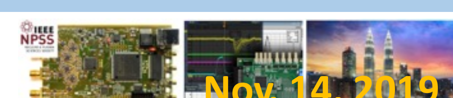


Nov. 14, 2019

Unit of the energy

electron volt (eV)

- **amount of kinetic energy gained by an electron accelerating from rest through an electric potential difference of 1 V in vacuum**

eV ~ energy of a visible photon

keV=1000 eV

MeV=1000 keV ~ minimum energy loss in a certain thickness g/cm^2

GeV=1000 MeV ~ energy corresponding to the rest mass of a proton (neutron)

What is different

	EM calorimeter	γ-ray measurement
energy of interest	10 MeV ~ GeV ~	~ MeV
photon interaction	pair production	photoelectric effect
energy deposit	shower	point-like
detector size	large	small

Outline ~ 1st lesson

- introduction ~ hadron physics
- getting started ~ calorimetry & EM shower
- physics processes in EM showers
- EM shower profile
- light source
- light detection
- energy response of a calorimeter
- FOREST detector
- summary

Introduction

hadron physics

dibaryon (B=2 hadron object)

Hadron physics

hadron

- experiences a strong interaction governed by quantum chromodynamics (QCD)
- QCD color-singlet quark and gluon many-body system
- qqq baryons and $\bar{q}q$ mesons are ordinary hadron, and others are exotic hadrons

hadron physics

- structure and interaction of hadrons in free space and nuclear medium
- non-perturbative domain of QCD

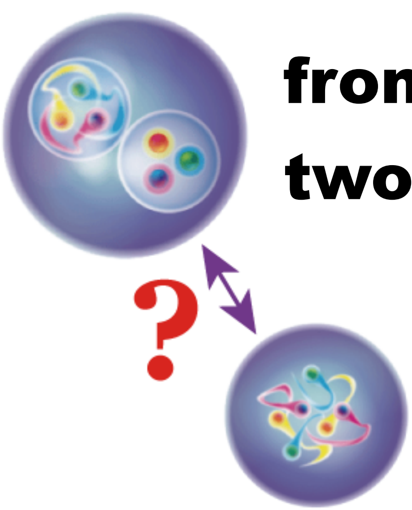
Dibaryon

dibaryon

an object with baryon number $B = 2$

the quark picture of dibaryons are of interest

a phase change of its basic configuration



from a molecule-like state consisting of two baryons such as the deuteron

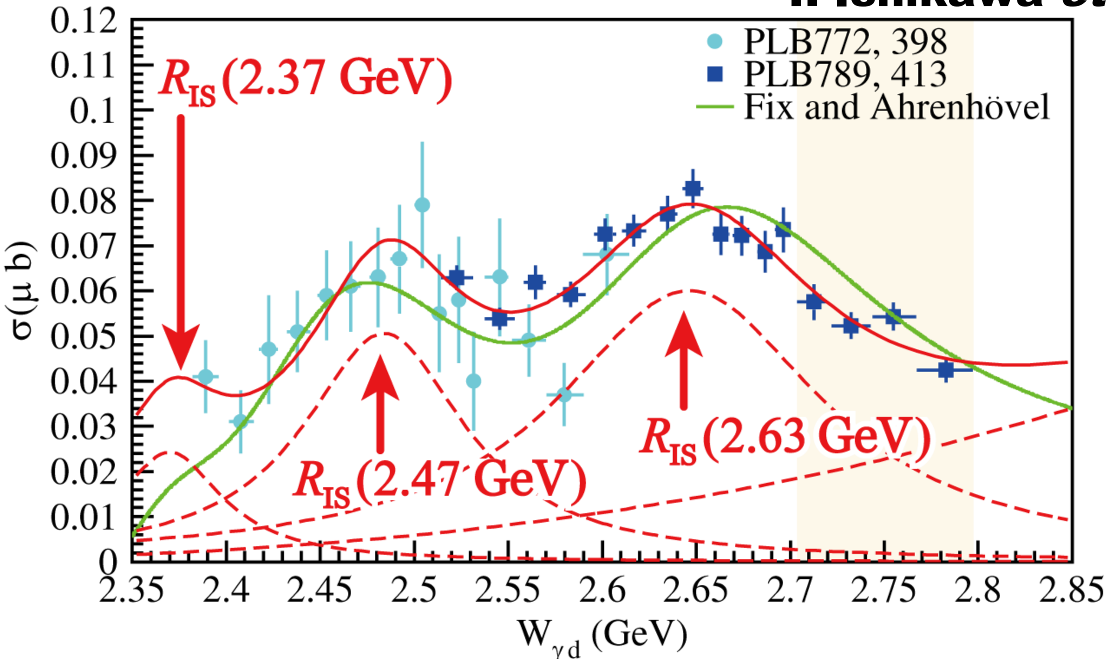
a hexaquark hadron state

Dibaryon

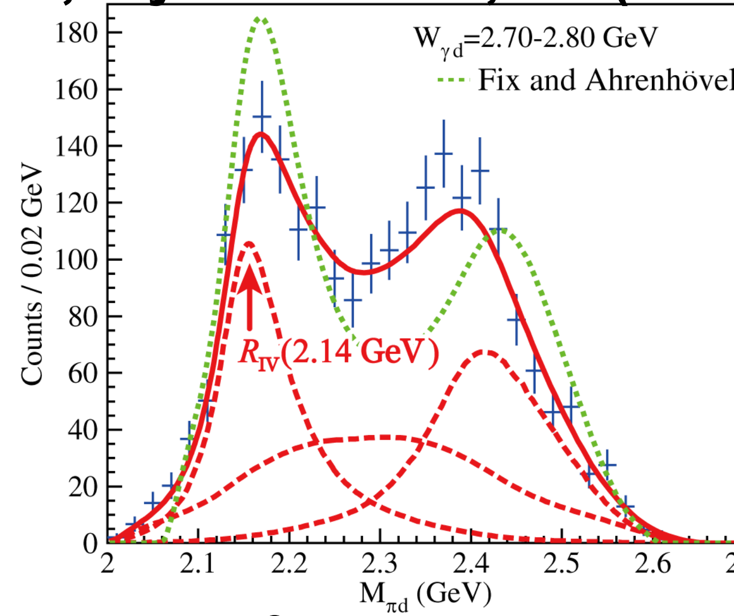
our measurement of cross sections for the $\gamma d \to \pi^0\pi^0 d$ reaction, suggesting

the $\gamma d \to R_{IS} \to \pi^0 R_{IV} \to \pi^0\pi^0 d$ sequential process is dominant

T. Ishikawa *et al.*, Phys. Lett. B 789, 413 (2019).



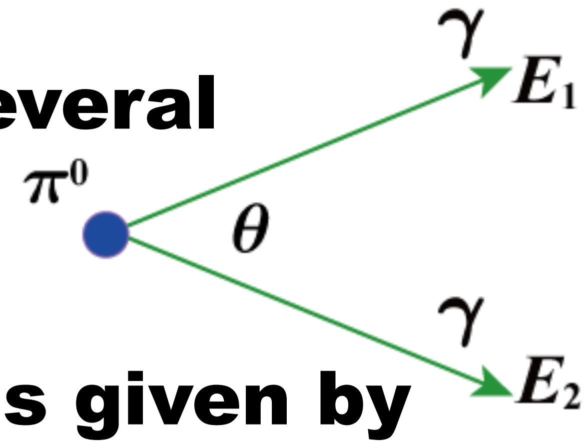
$\pi^0\pi^0 d$ system



$\pi^0 d$ system

Dibaryon

neutral mesons decay into several photons



$$\pi^0 \to \gamma\gamma$$

Four-momentum of a meson is given by a sum of that for the daughter photons

$$E^2 = M^2c^4 + p^2c^2$$

$$P_\pi = P_1 + P_2$$

$$= (E_1, p_{x,1}, p_{y,1}, p_{z,1}) + (E_2, p_{x,2}, p_{y,2}, p_{z,2})$$

$$E_i^2 = p_{x,i}^2c^2 + p_{y,i}^2c^2 + p_{z,i}^2c^2$$ **a photon is massless**

$$M_\pi c^2 = \sqrt{2E_1E_2(1-\cos\theta)}$$

high-energy photon detection is important!

Getting started

calorimetry

electromagnetic shower

Calorimetry

in thermodynamics

measuring the heat transfer

in nuclear physics

measuring the energy of a particle through total absorption in a block of matter (the energy of the particle is eventually converted into heat)

the calorimeter must have a destructive feature

Electromagnetic shower

shower

a cascade of secondary particles produced as the result of a high-energy particle interaction with dense matter

electromagnetic (EM) shower

produced by a photon, electron, or positron

hadronic shower

produced by a hadron

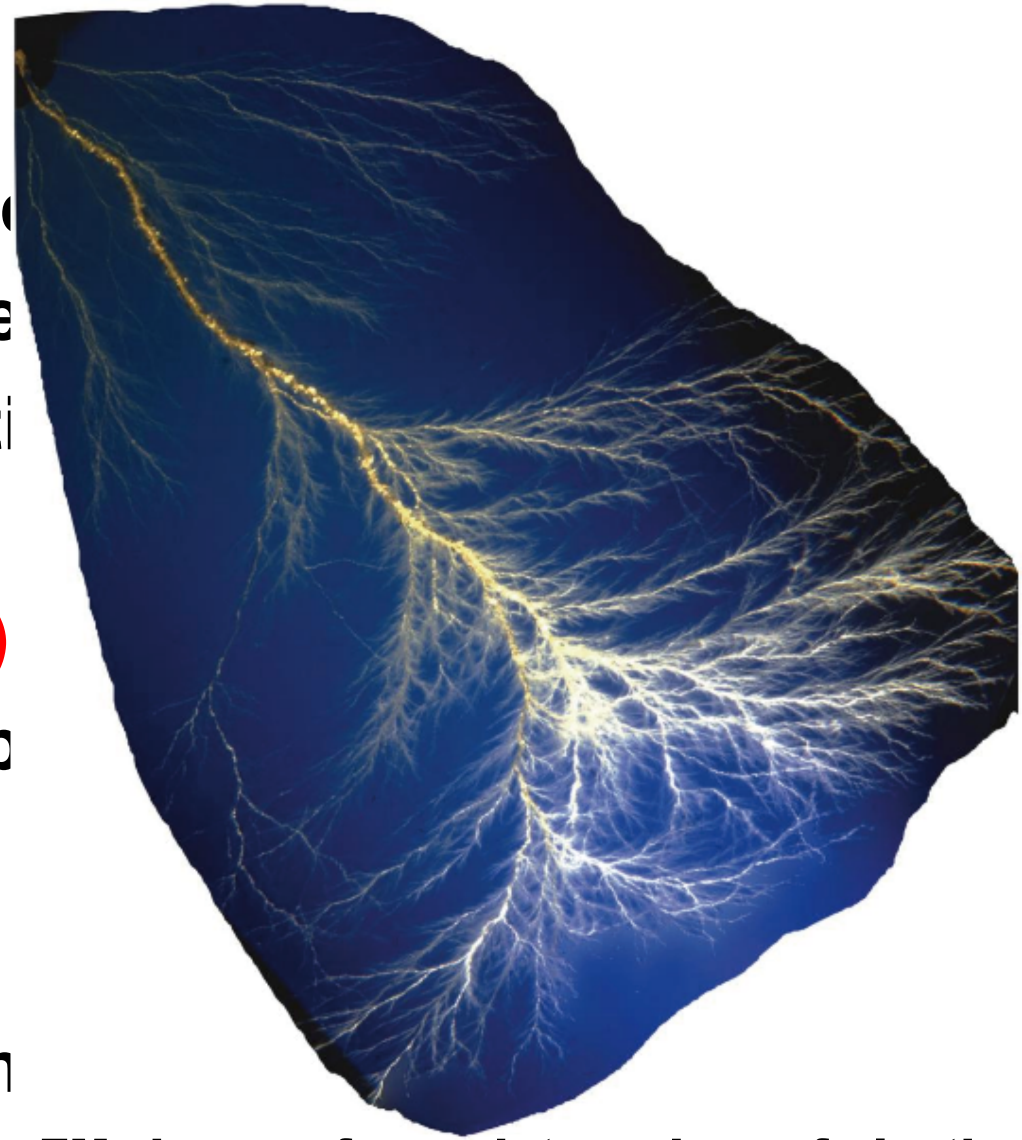
Electromagnetic shower

shower

a cascade of se

produced as the

particle interacti



electromagnetic (EM)

produced by a p

positron

hadronic shower

produced by a h

R. Wigmans, beam tree created by EM showers frozen into a piece of plastic

Electromagnetic shower

EM shower

cascade of the following two processes

pair production

a high-energy photon is converted into an electron and positron pair

bremsstrahlung

a high-energy electron (positron) emits a photon

Electromagnetic shower

EM shower

cascade of the following two processes

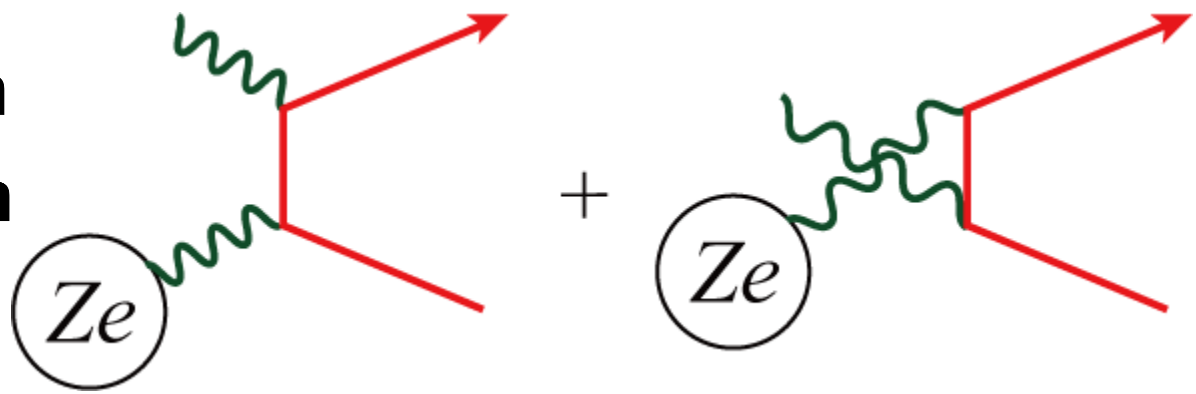
pair production

a high-energy photon is converted into an electron and positron pair

bremsstrahlun

a high-en

a photon



Electromagnetic shower

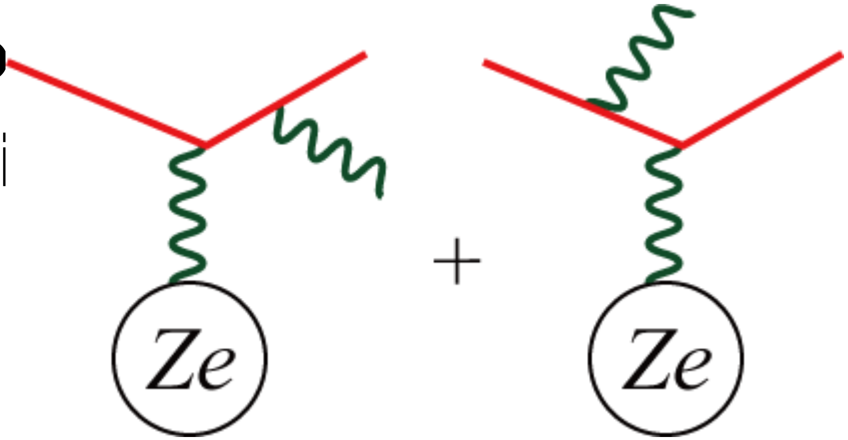
EM shower

cascade of the following two processes

pair production

a high-energy photo

an electron and posi



bremsstrahlung

a high-energy electron (positron) emits a photon

Physics processes in EM showers

energy loss of a charged particle

critical energy

Photon interaction

Energy loss of a charged particle

EM interaction

- ionizing the medium

  energy transfer is sufficient to release a bound electron

  principle on which many detectors are based

- exciting atoms or molecules

  de-excitation from these metastable states may yield scintillation light

- emitting Cherenkov light
- producing energetic knock-on electrons (δ ray)
- producing bremsstrahlung
- nuclear reaction

Critical energy

traditional definition

energy loss of the radiation process

= energy loss of the ionization

Rossi definition using the radiation length X_0

$$\left(\Delta E\right)_{\text{ion}} = \left(\frac{dE}{dx}\right)_{\text{ion}} X_0 = E$$

this definition is equivalent when

$$\left(\frac{dE}{dx}\right)_{\text{brems}} = \frac{E}{X_0}$$

(high energy limit)

Critical energy

traditional definition

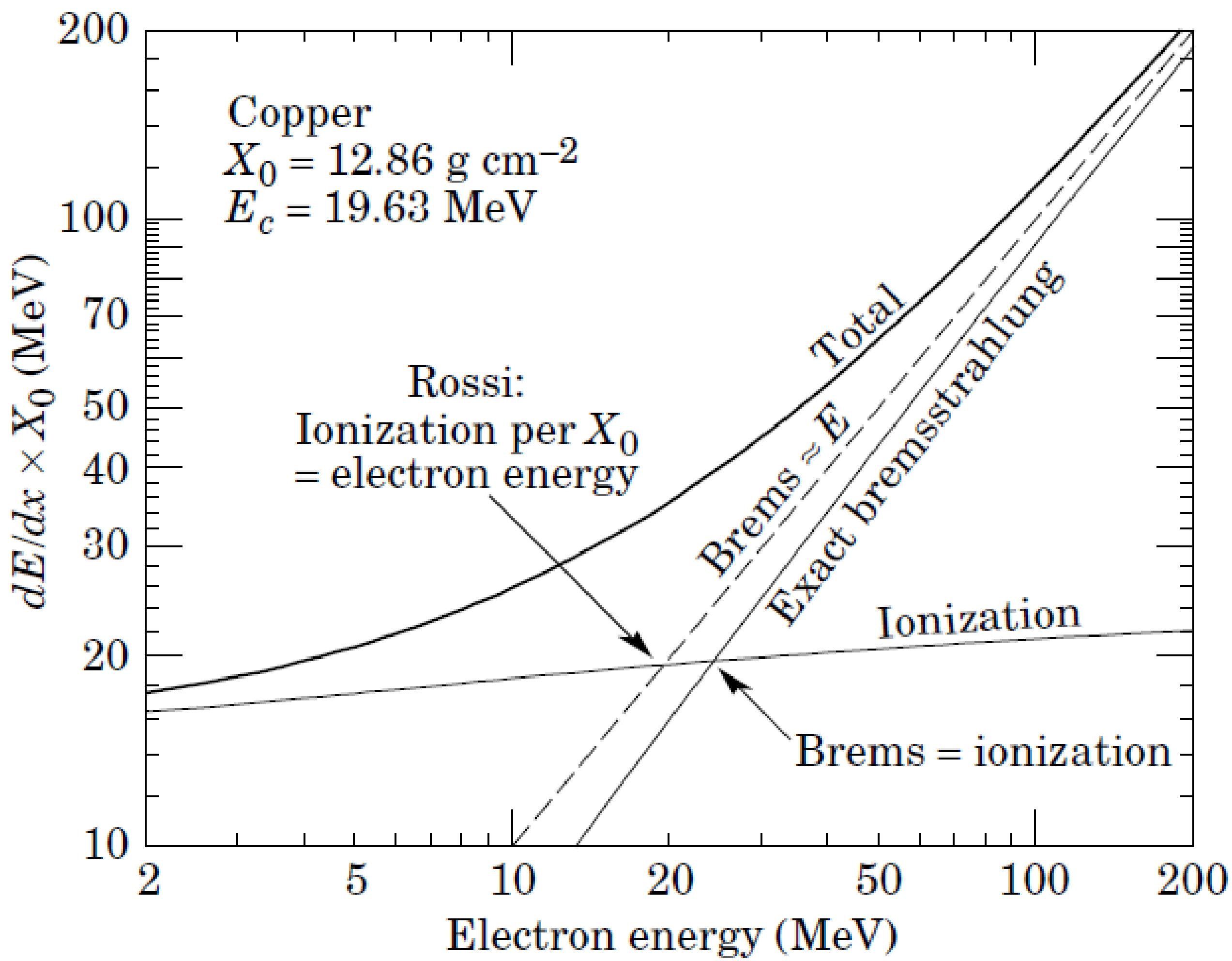
energy l

= energy

Rossi definitio

$$\left(\Delta E\right)_{\mathrm{i}}$$

this defi

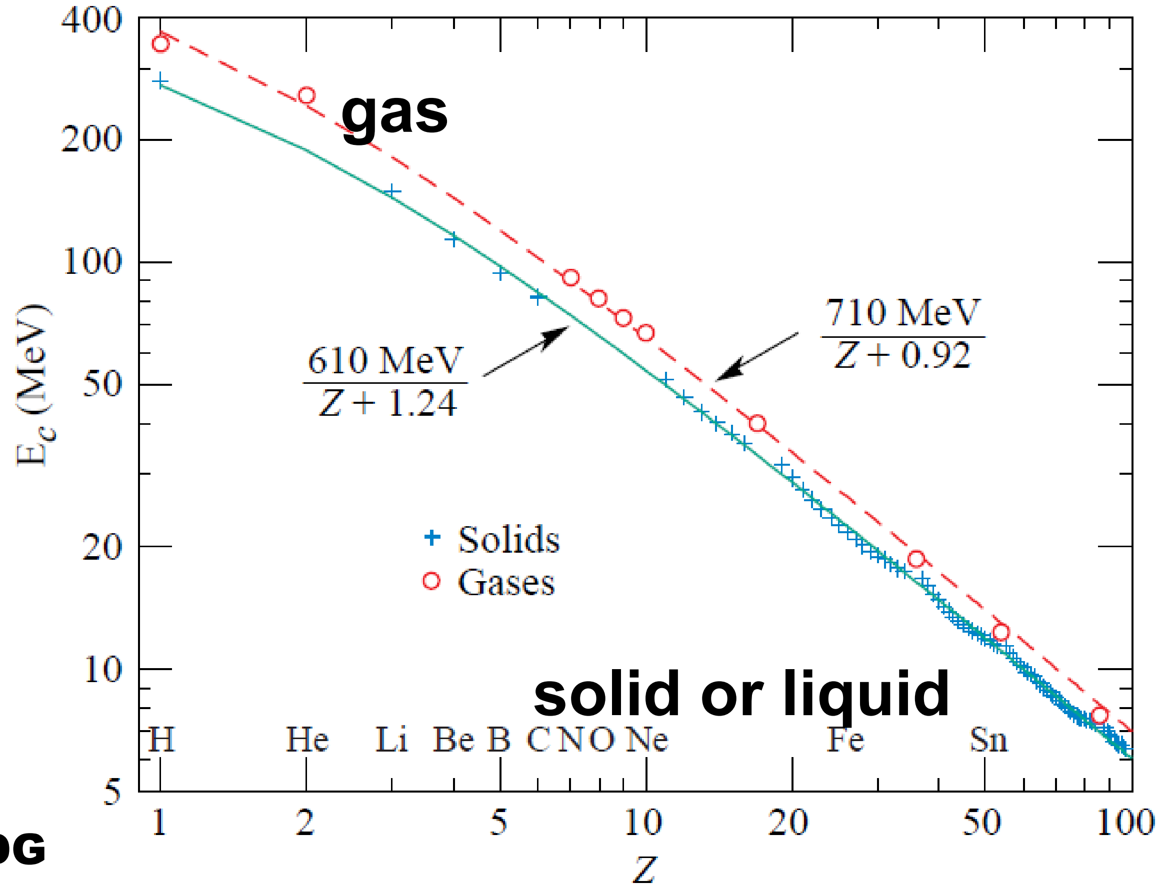


T. Ishikawa

Critical energy

Rossi definition E_c

radiation is more likely to occur for $E > E_c$



PDG

Exercise 1

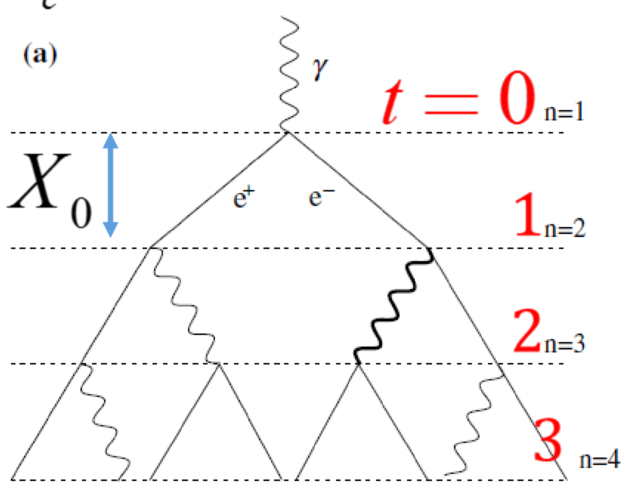
Obtain the shower maximum (depth giving the maximum energy deposit) in the following simple shower model.

bremsstrahlung / pair production at each step (=depth)

energy sharing is symmetric after each process

no energy loss by ionization (excitation) for $E > E_c$

full energy loss by ionization for $E \leq E_c$



1. **number of particles after depth t**
2. **energy per particle after depth t**
3. **number of shower particles with E_c**
4. **shower maximum in t**

Photon interactions

photoelectric effect

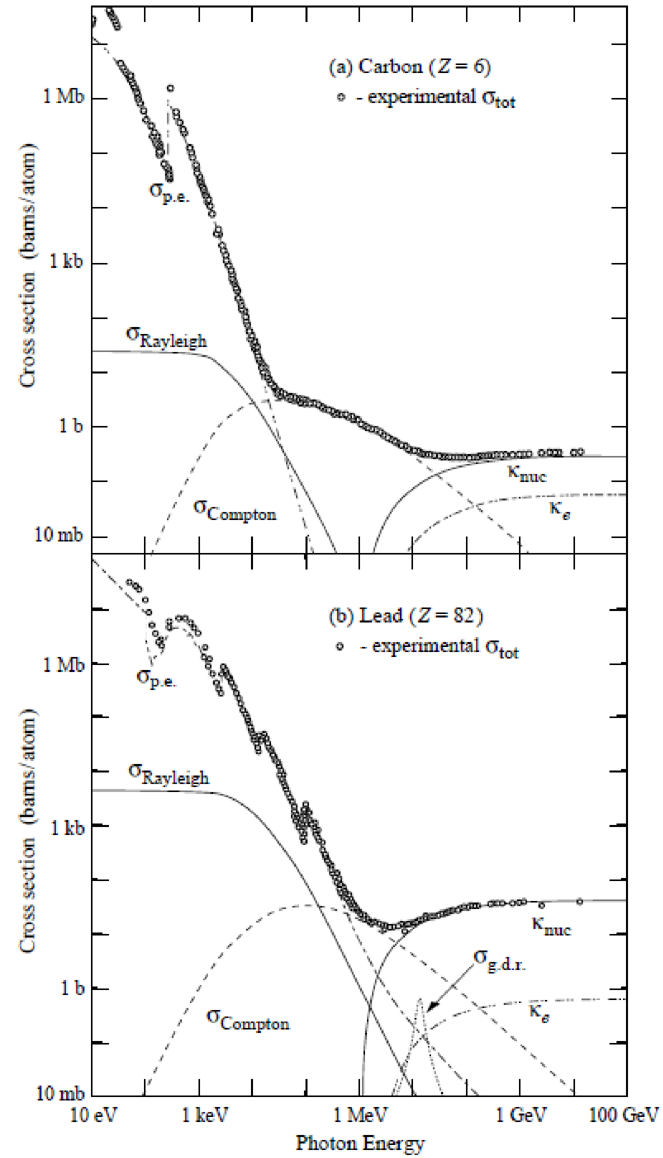
Rayleigh scattering

Compton scattering

pair production

photonuclear reaction

PDG



Photon interactions

photoelectric effect

most likely to occur at low energies

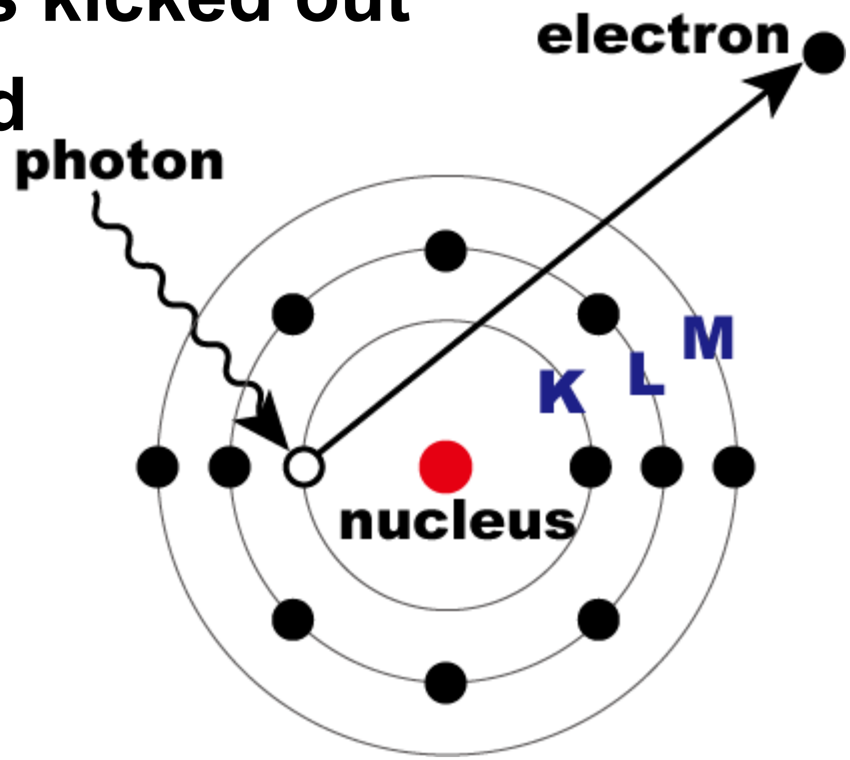
a bound electron is kicked out

photon is absorbed

complicated

$$\sigma \sim Z^n, n = 4 \sim 5$$

$$\sigma \sim E_\gamma^{-3}$$



Rayleigh scattering

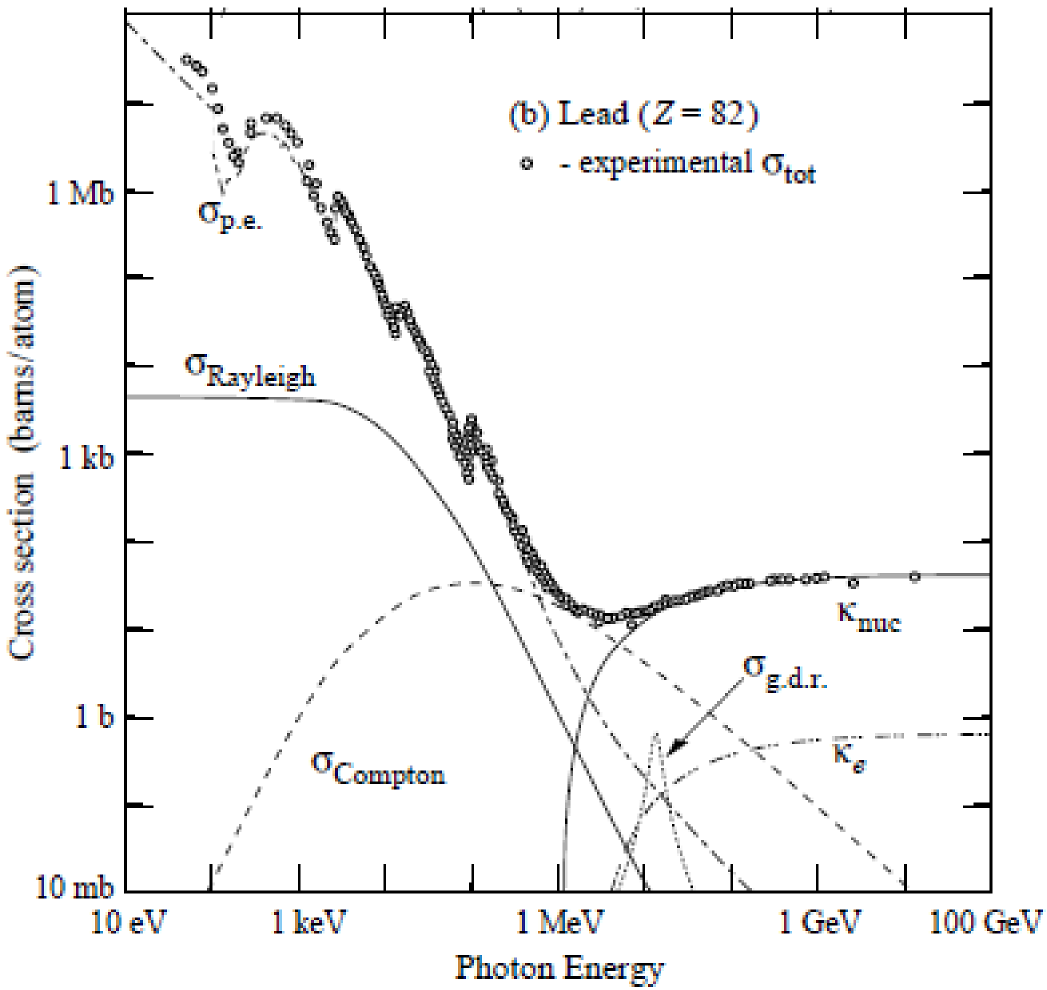
Compton scattering

pair production

Photonuclear reaction

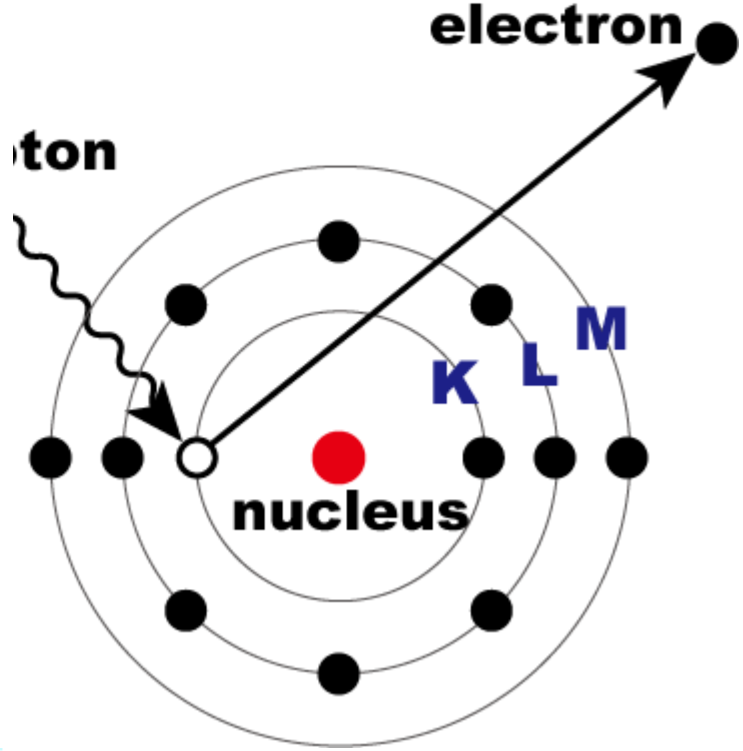
Photon interactions

photoelectric effect



: low energies

cked out



Photon interactions

photoelectric effect

Rayleigh scattering [coherent]

- **important at low energies**
- **photon is deflected by atomic electrons**
- **without losing its energy**
- **only affects the spatial distribution of the energy deposit**

Compton scattering [incoherent]

pair production

photonuclear reaction

Photon interactions

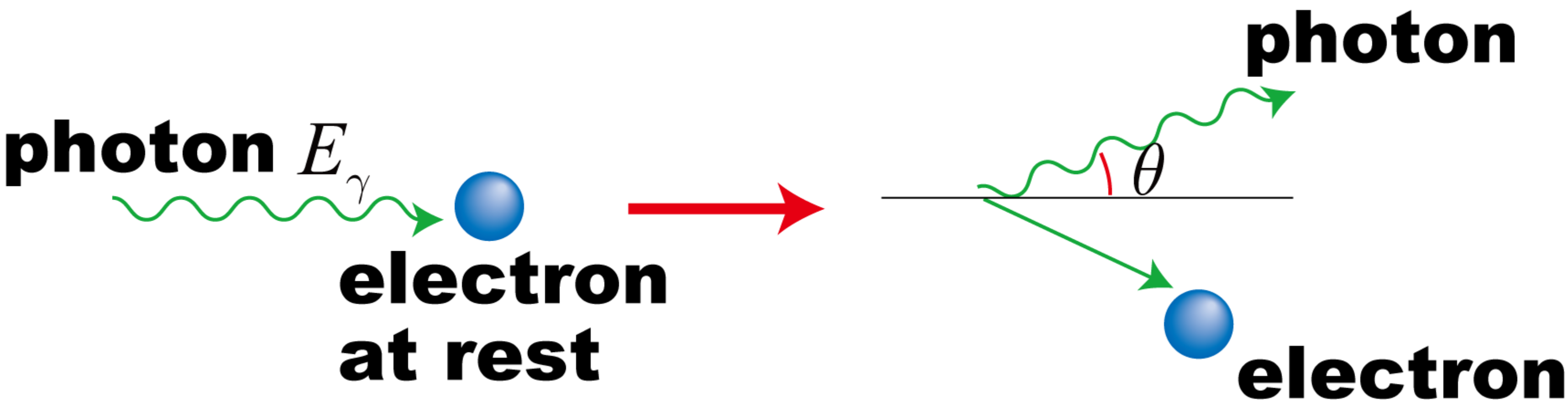
photoelectric effect

Rayleigh scattering [coherent]

Compton scattering [incoherent]

a bound electron is kicked out

photon is not absorbed



pair production

photonuclear reaction

Photon interactions

photoelectric effect

Rayleigh scattering [coherent]

Compton scattering [incoherent]

a bound electron is kicked out

photon is not absorbed

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2} \frac{1+\cos^2\theta}{\{1+\gamma(1-\cos\theta)\}^2} \left\{ 1 + \frac{\gamma^2(1-\cos\theta)^2}{(1+\cos^2\theta)\{1+\gamma(1-\cos\theta)\}} \right\}$$

$$\gamma = E_\gamma / m_e c^2$$

energy transfer $T = E_\gamma \frac{\gamma(1-\cos\theta)}{1+\gamma(1-\cos\theta)}$

pair production

photonuclear reaction

Photon interactions

photoelectric effect

Rayleigh scattering [coherent]

Compton scattering [incoherent]

many MeV photon are absorbed finally in a sequence of Compton scattering

angular distribution disappears quickly in this sequence

$$\sigma \sim Z, \sigma \sim E_{\gamma}^{-1}$$

more likely to occur than photoelectric effect at energies

$$E_{\gamma} > 20 \text{ keV for } Z = 6$$

$$E_{\gamma} > 700 \text{ keV for } Z = 92$$

pair production

photonuclear reaction

Photon interactions

photoelectric effect

Rayleigh scattering

Compton scattering

pair production

threshold $2m_e c^2$

increasing with energy

reaching an asymptotic value at high energies

$$\sigma \sim \frac{7}{9} \frac{A}{N_A \rho X_0}$$

related **to the radiation length** X_0

photonuclear reaction

Photon interactions

photoelectric effect

Rayleigh scattering

Compton scattering

pair production

photonuclear reaction

- **at energies 5~20 MeV**
- **giant dipole resonance (GDR)**
- **less than 1% of the total**

Photon interactions

photoelectric effect

Rayleigh scattering

Compton scattering

pair production

photonuclear reaction

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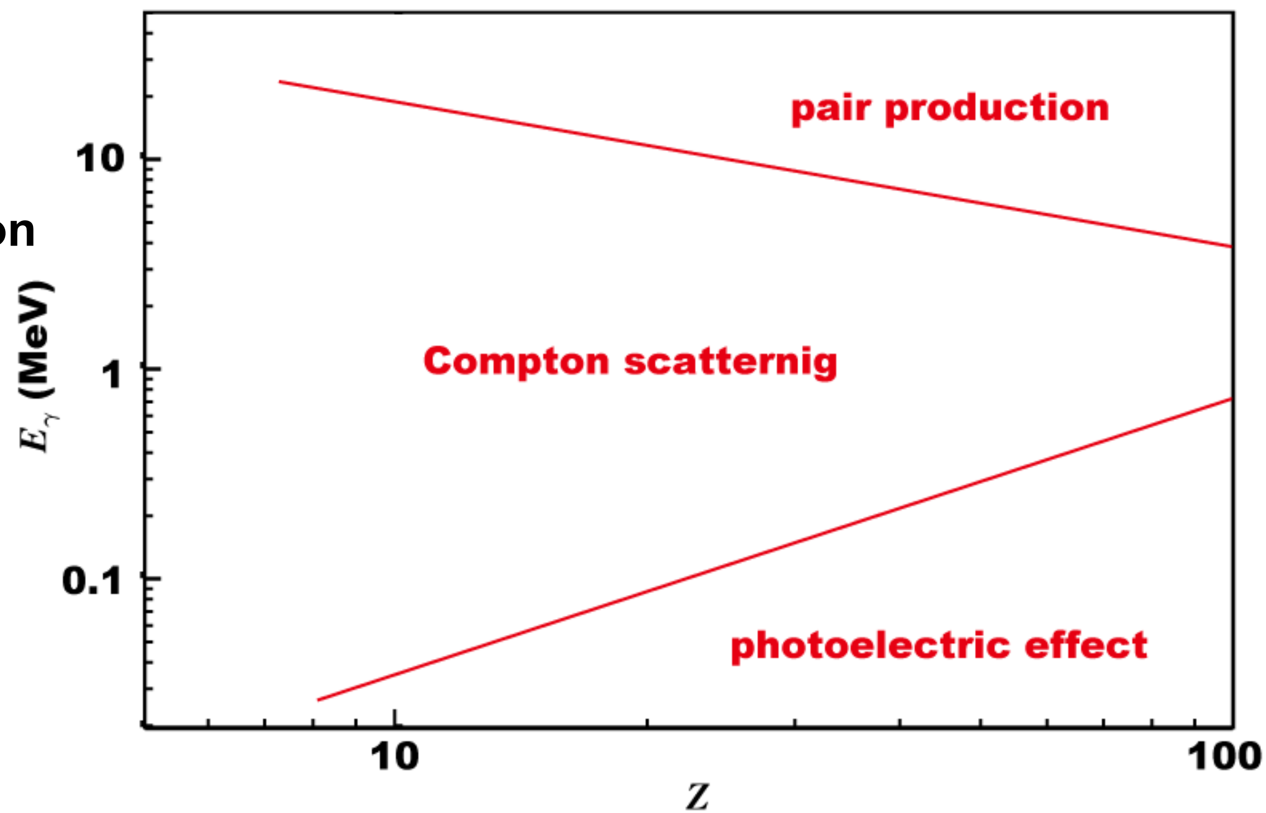

Energy domain in which each process is most likely to occur

Exercise 2

What is the main process in the total energy deposit (more than 2/3) ?

Outline ~ 2nd lesson

- introduction ~ hadron physics
- getting started ~ calorimetry & EM shower
- physics processes in EM showers
- EM shower profile
- light source
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EM shower profile

- **scaling variables**
  - **radiation length**
  - **Molière radius**
- **shower development**
  - **longitudinal**
  - **transverse**

Radiation length

mean distance X_0 over which a high-energy electron or positron loses all but e^{-1} of its energy

high-energy electrons lose the same fraction of their energy in the same number in X_0
material-dependent effects are eliminated

$$\sigma(E \to \infty) = \frac{7}{9}\frac{A}{N_A \rho X_0}$$

for photon interactions (pair production)

Radiation length

usually ρX_0 is expressed simply by X_0

namely $\mathrm{g{\cdot}cm^{-2}}$ is used as a unit for X_0

calculation by Tsai

$$\frac{1}{X_0} = 4\alpha r_e^2 \frac{N_A}{A}\left\{Z^2\left(L_{\rm rad} - f(Z)\right) + Z L'_{\rm rad}\right\}$$

$$4\alpha r_e^2 \frac{N_A}{A} = \left(716.408\ \mathrm{g{\cdot}cm^{-2}}\right)^{-1} \text{ for } A = 1\ \mathrm{g{\cdot}mol^{-1}}$$

$$f(Z) = a^2\left\{\left(1+a^2\right)^{-1} + 0.20206 - 0.0369a^2 + 0.0083a^4 - 0.002a^6\right\}$$

$$a = \alpha Z$$

Element	Z	$L_{\rm rad}$	$L'_{\rm rad}$
H	1	5.31	6.144
He	2	4.79	5.621
Li	3	4.74	5.805
Be	4	4.71	5.924
Others	> 4	$\ln(184.15\, Z^{-1/3})$	$\ln(1194\, Z^{-2/3})$

PDG

mixture or compound

$$\frac{1}{X_0} = \sum \frac{w_j}{X_j}$$

fraction by weight (w_j)

X_0 **is measured in** $\mathrm{g{\cdot}cm^{-2}}$

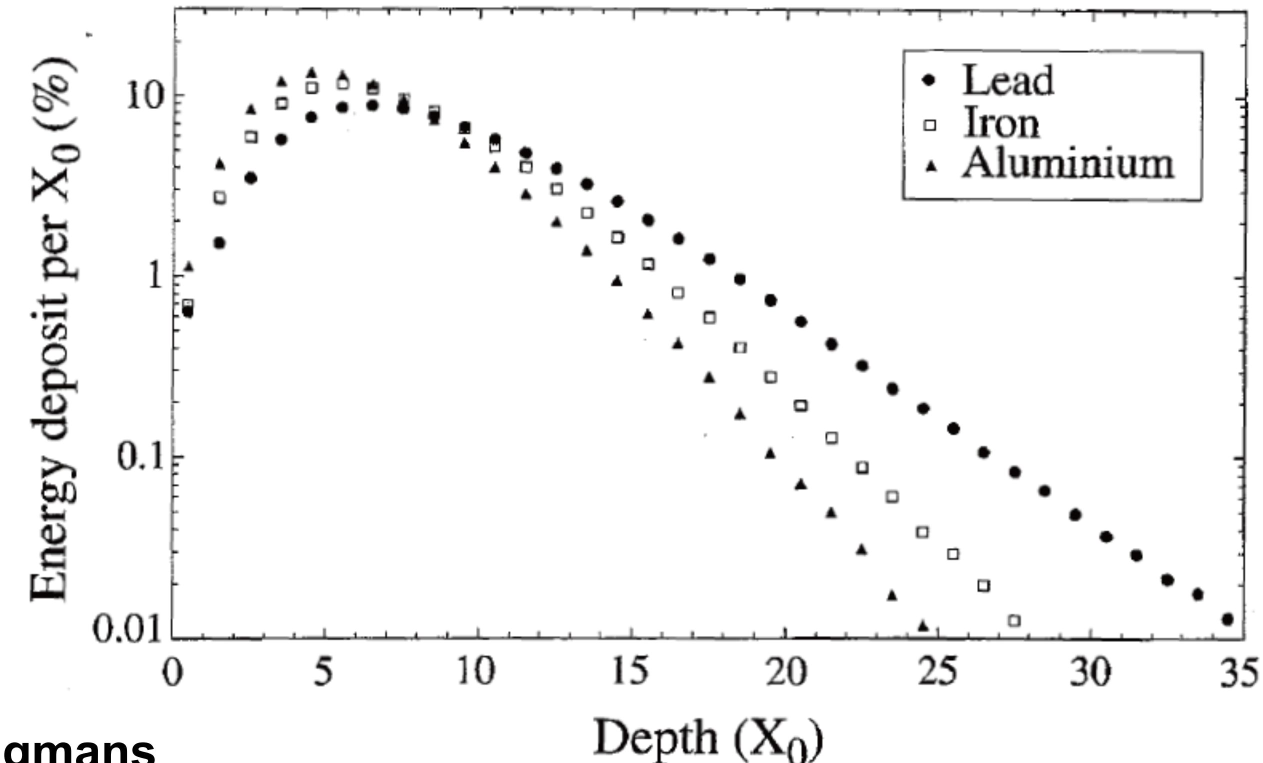
Radiation length

typical X_0 values

material	Z	A	X_0 [g/cm^2]	ρ [g/cm^3]	X_0 [cm]
H2 (liq)	1	1.008	63.05	0.071	888
D2 (liq)	1	2.014	126.0	0.169	746
C	6	12.01	42.70	$\sim$ 1.53	$\sim$27.9
Al	13	26.98	24.01	2.70	8.90
Cu	29	63.55	12.86	8.96	1.44
W	74	183.8	6.76	19.3	0.35
air			36.62	1.205×10^{-3}	3.04×10^{4}
polyvinyl toluene			43.90	1.03	42.6

Longitudinal development

energy deposit as a function of depth
expressed by the radiation length
almost material-independent



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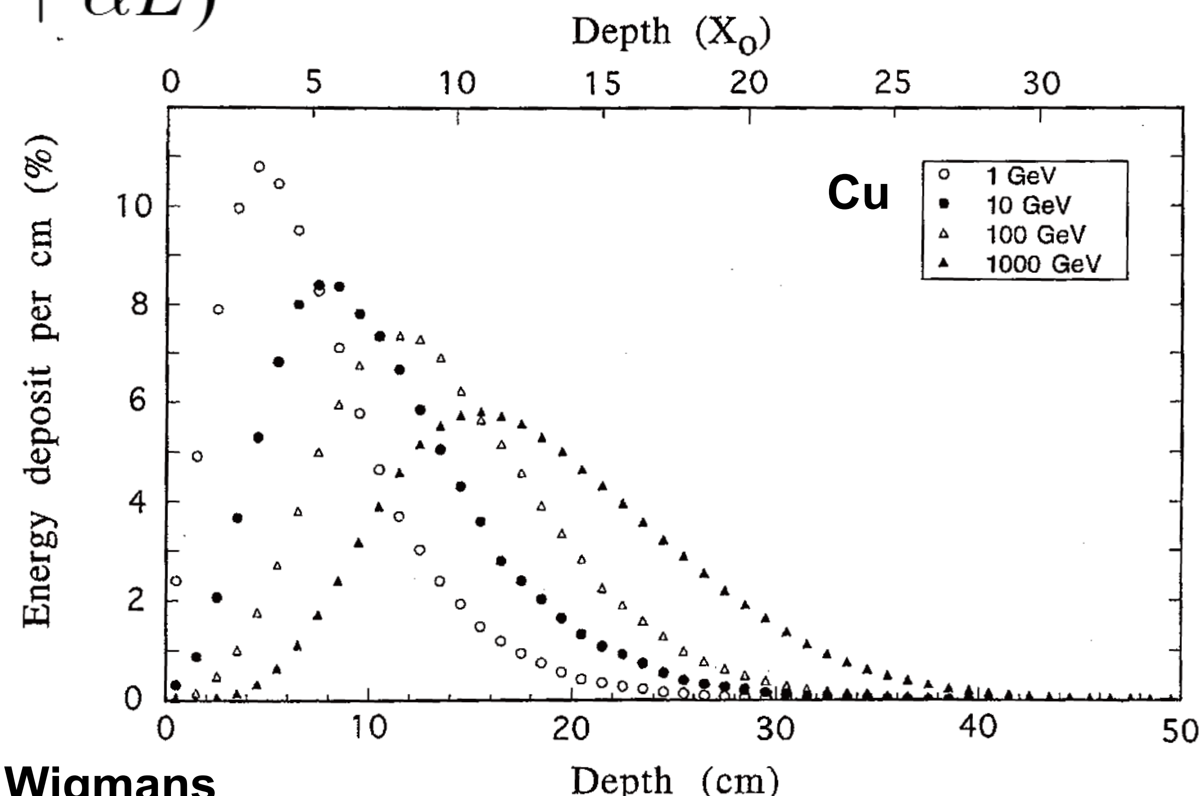
Longitudinal development

shower maximum

depth giving the maximum energy deposit

$$\propto \log(1+\alpha E)$$



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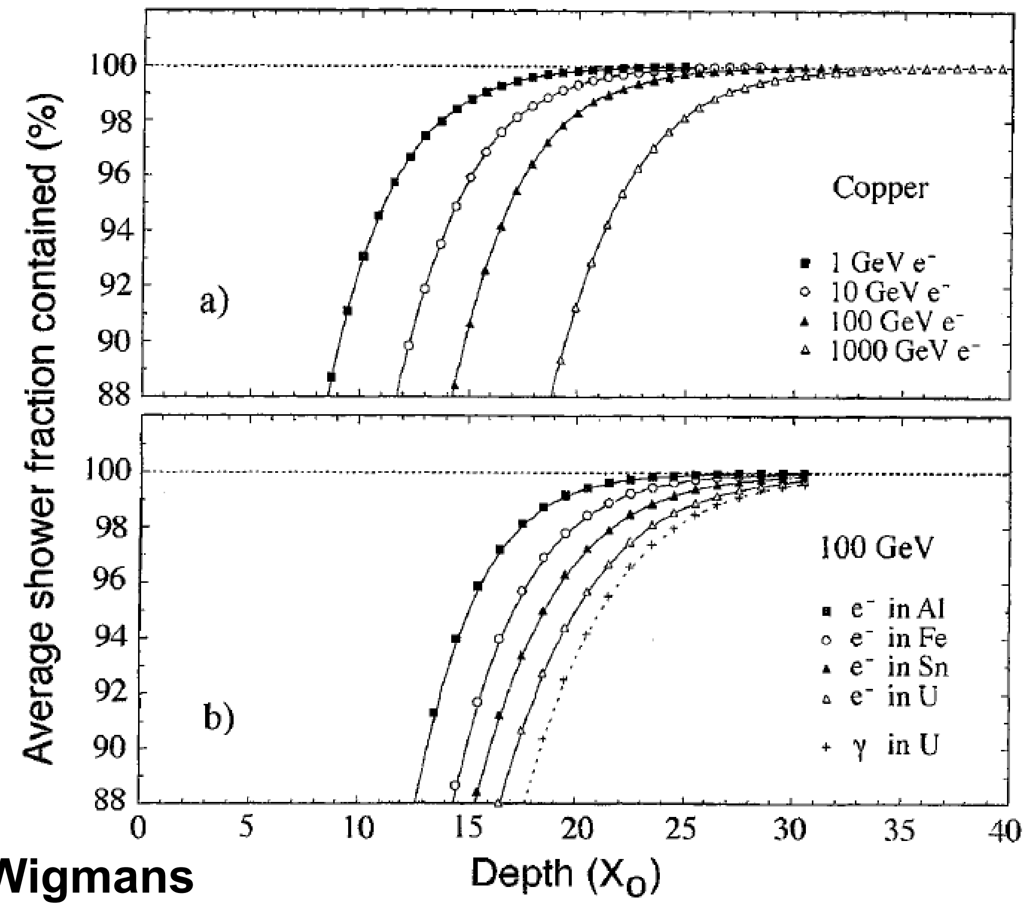
Longitudinal development

average energy fraction contained in a block of matter with infinite transverse dimensions



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Molière radius

transverse development of EM showers

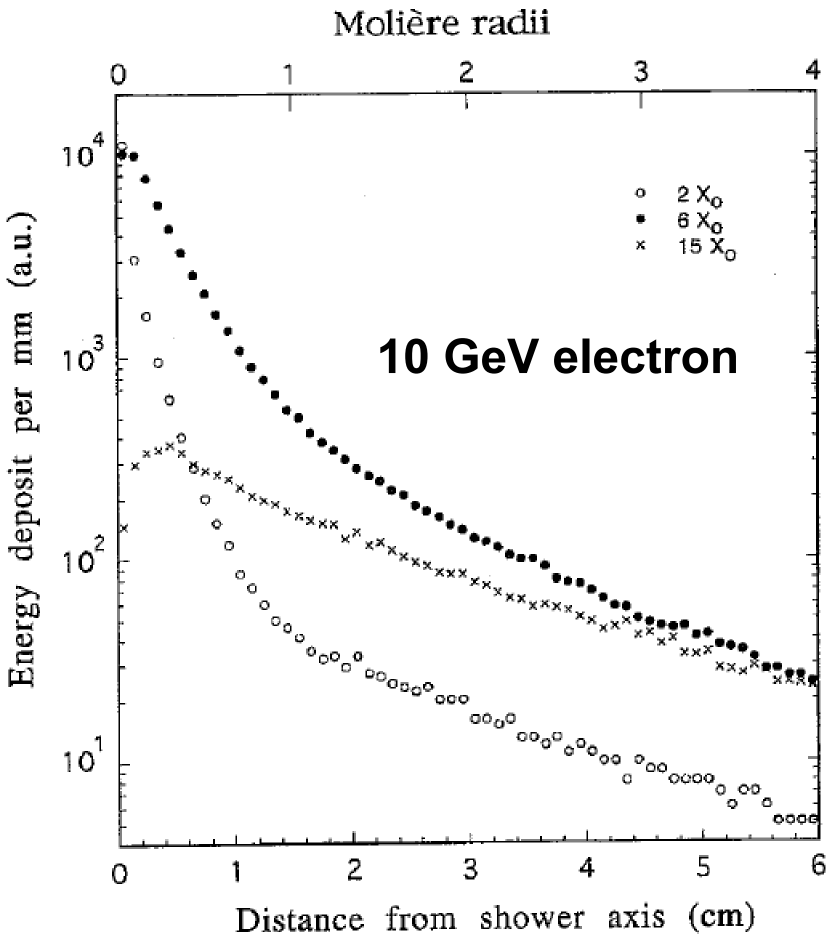
$$\rho_M = E_s \frac{X_0}{E_c}$$

$$E_s = m_e c^2 \sqrt{\frac{4\pi}{\alpha}} = 21.2\ \mathrm{MeV}$$

80% of the shower energy is deposited in a cylinder with a radius of ρ_M against the momentum direction of the primary high-energy particle

Transverse development

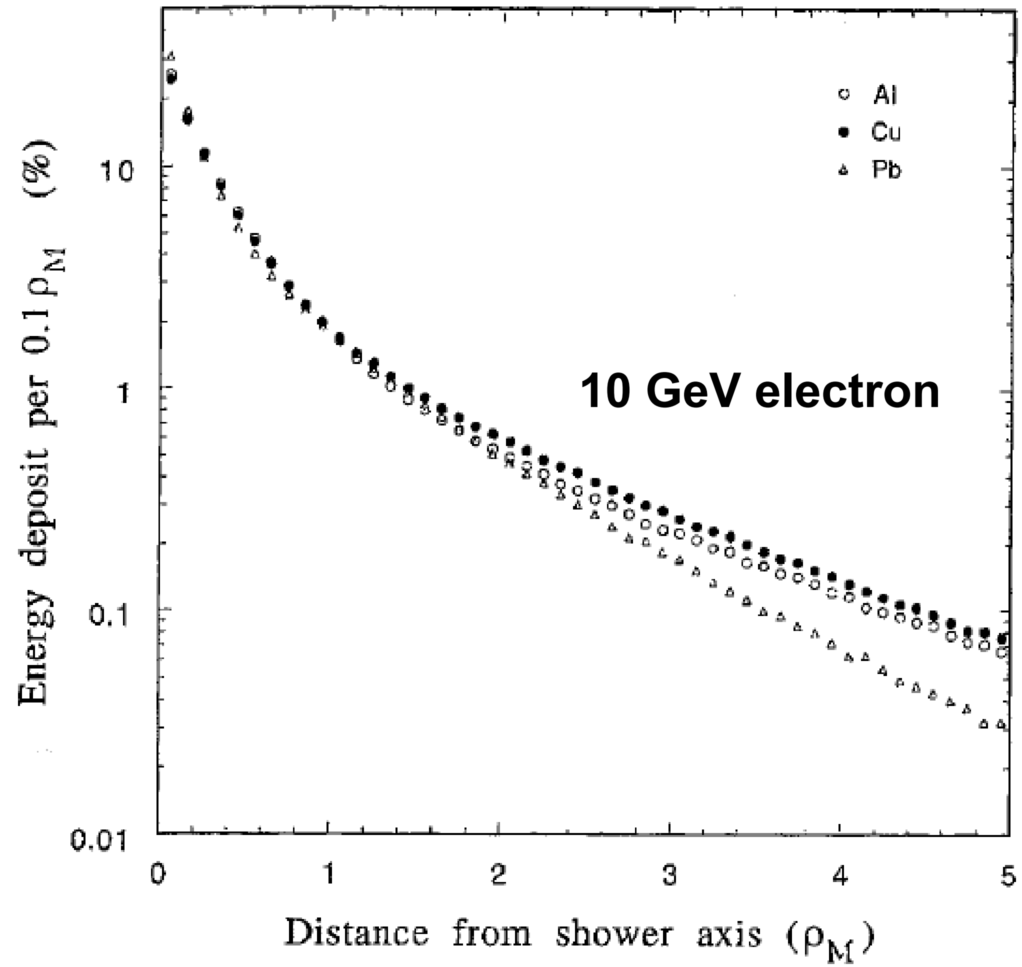
radial distribution of energy deposits for some depths



Transverse development

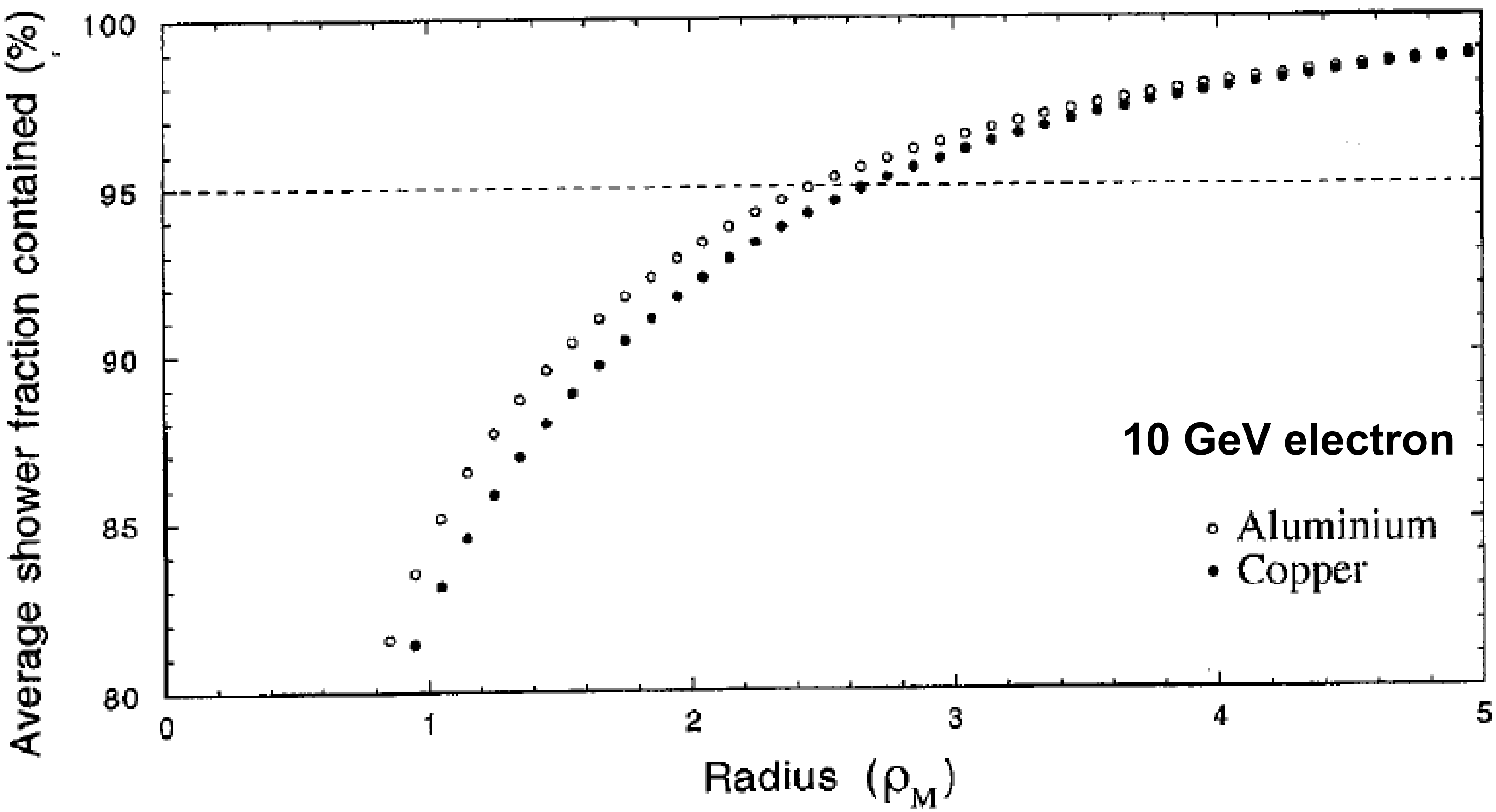
radial distribution of energy deposits for some materials

material-independent



Transverse development

average energy fraction contained in an infinitely long cylinder



Exercise 3

Consider the minimum length of the calorimeter module for 1, 10 GeV, 100 GeV photons? Here, 99% of the total energy deposit is assumed to be measured, and the module has a infinite transverse dimension.

R.
Wigmans

Light source

Cherenkov light

scintillation light

Cherenkov light

emitted when a charged particle travels through the medium faster than the speed of light

threshold

$$\beta = \frac{v}{c} > \frac{1}{n}$$

angle

$$\cos\theta = \frac{1}{\beta n}$$ ***n***: refractive index

number

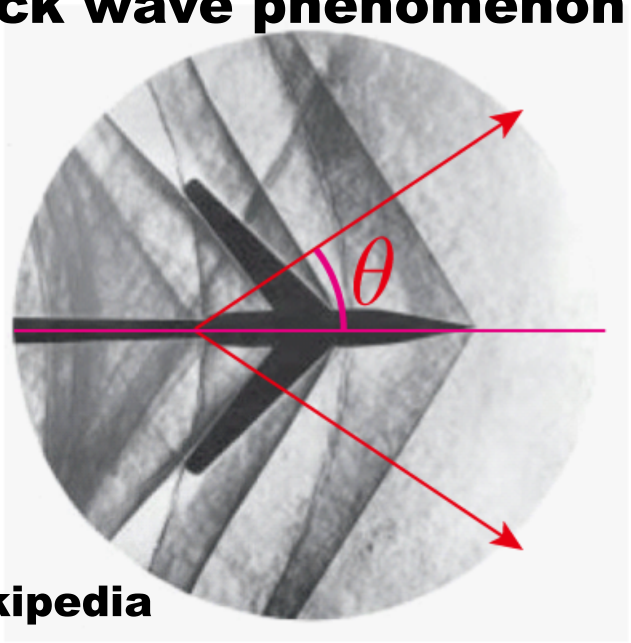
$$\sim 370 \sin^2\theta \ \mathrm{eV}^{-1}\mathrm{cm}^{-1} \ \text{for } z = 1$$

low #photons, mainly UV

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

prompt emission, polarized

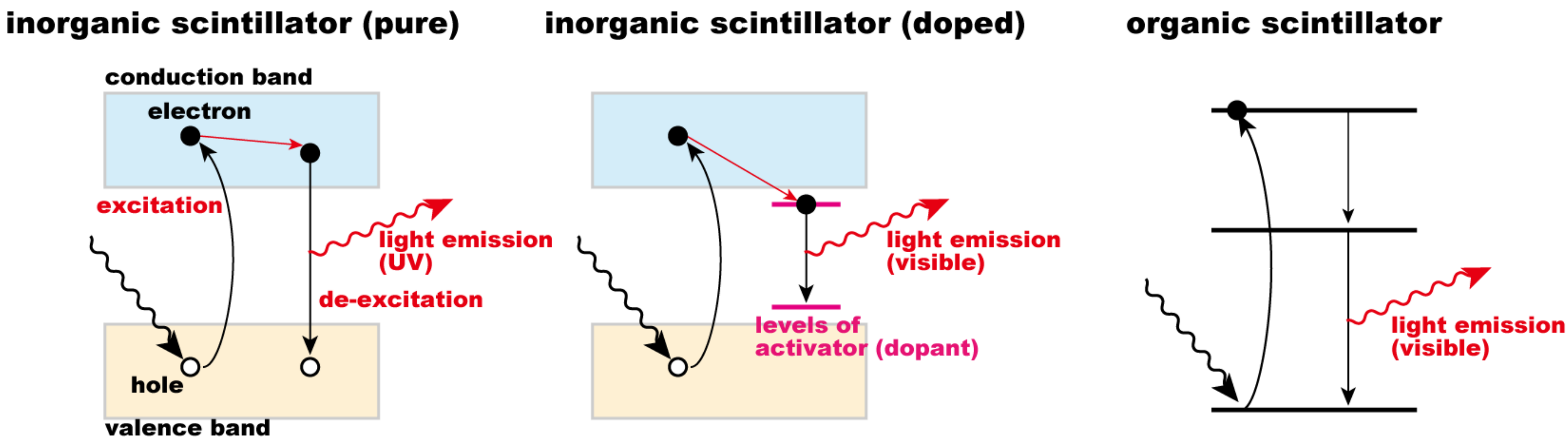
shock wave phenomenon



Wikipedia

Scintillation light

different light emission mechanisms



inorganic scintillator is often used for calorimeters

short radiation length

long decay time

Scintillation light

NaI(Tl): 45000 photons /MeV

scintillator	ρ [g/cm^3]	n	λ_{em} [nm]	τ [ns]	relative yield
NaI(Tl)	3.67	1.85	410	250	100
CsI(pure)	4.51	1.95	310	10	6
CsI(Tl)	4.51	1.79	565	1000	45
BGO $Be_3Ge_4O_{12}$	7.13	2.15	480	300	10
BSO $Be_3Si_4O_{12}$	6.80	2.06	480	100	2
PWO $PbWO_4$	8.28	2.16	480	< 30	0.8
EJ-212	1.023	1.58	423	2.4	22

plastic scintillator

green-light emission materials are often used

decay time: organic scintillator is shorter

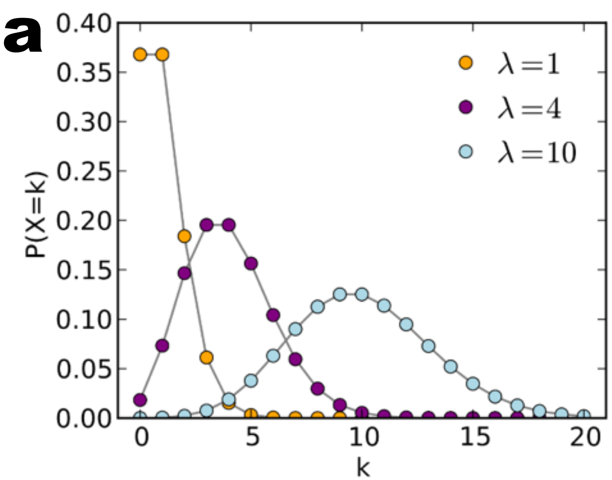
time resolution: number of photons at the leading edge

Exercise 4

What is the width of the photoelectric peak in response to the ^{137}Cs radioactive source for NaI(Tl), BGO, and PWO? Here, all the emitted scintillation light is assumed to be converted into a electric signal.

^{137}Cs: 0.662 MeV

counting number N having a fluctuation (standard deviation) of $\sqrt{N}$ (Poisson distribution)



Light detection

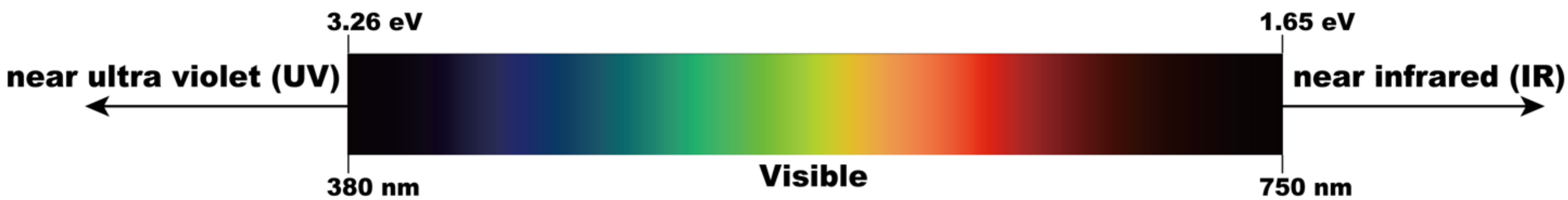
photo-sensitive material

photo-multiplier tube

Photo-diode

Photo-sensitive material

photo-detectors sensitive to visible or near visible light



Wikipedia

photon energy:

$$E_\gamma = h\nu = \frac{hc}{\lambda} \simeq \frac{1239\ \mathrm{eV \cdot nm}}{\lambda}$$

Photo-sensitive material

energy transfer of a photon to a free electron:
forbidden

- low sensitivity of metals to photons

photoconductive effect

electrons in the material are lifted to the conduction band from the valence band

- electrons and holes
- produce a photo-current

→ photodiode

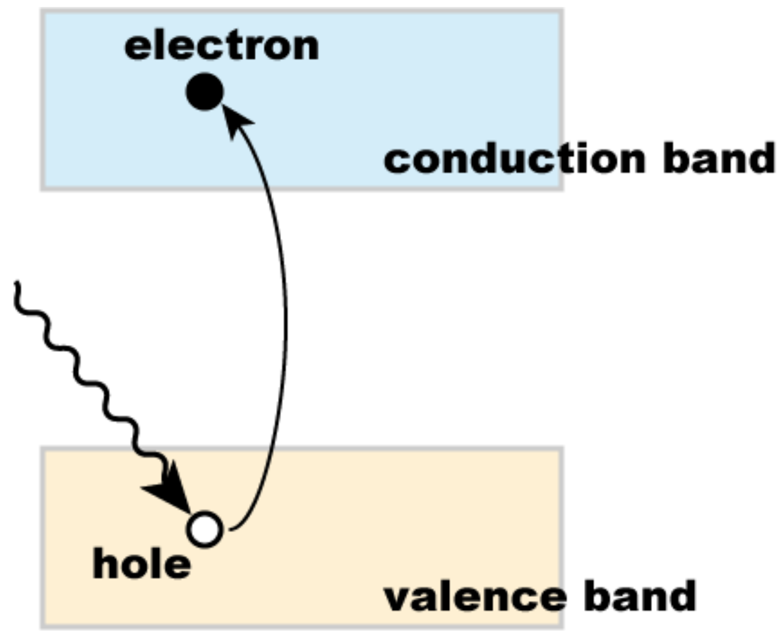


Photo-sensitive material

photoelectric effect

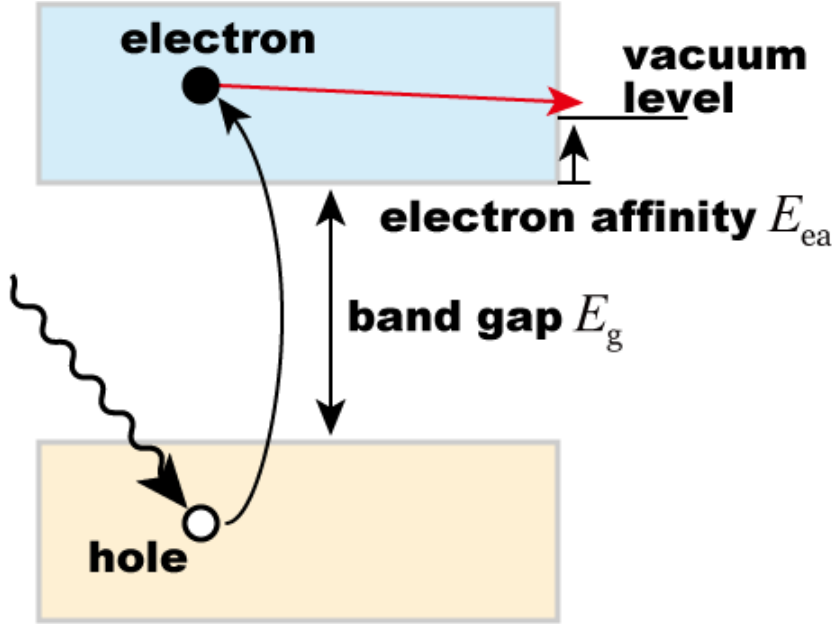
energized electrons diffuse through the material

0.05 eV loss for each electron-phonon scattering

(mean free path: a few nm)

electron arriving at the surface with a sufficient excess energy can escape from the material

$$E_\gamma > E_g + E_{ea}$$



the work function: fermi level and vacuum level

Photo-sensitive material

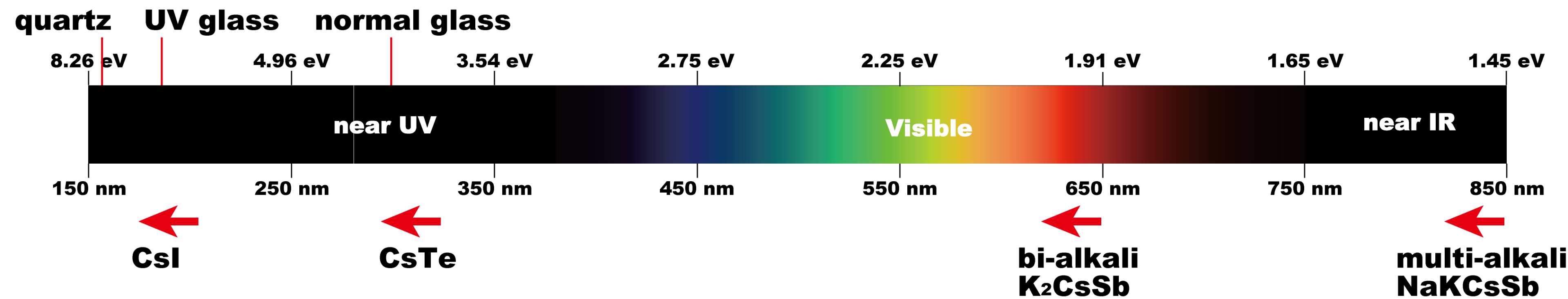
almost all the photo-sensitive materials are reactive (made up of alkali metals)

operation must be in vacuum

window materials are required

transparent to the light of interest

cut-off limits of window materials

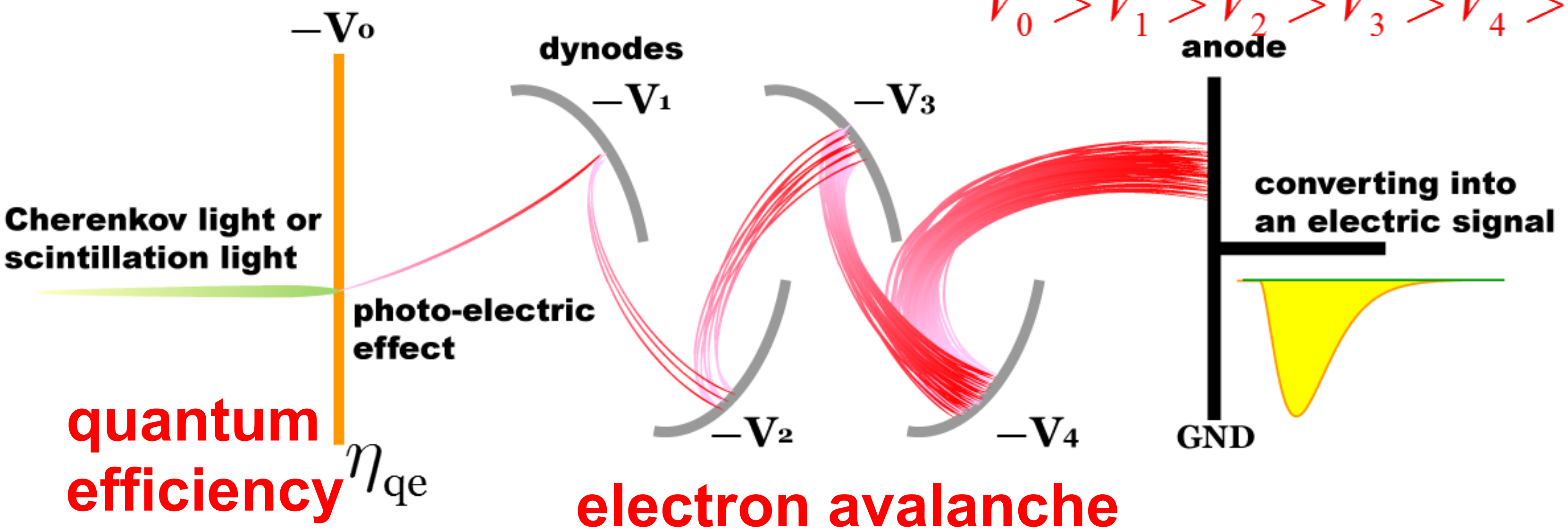


less than 1100 nm for Si

Photo-multiplier tube

almost all the photo-sensitive materials are reactive (made up of alkali metals)

$$V_0 > V_1 > V_2 > V_3 > V_4 > 0$$



electrons are accelerated in each step

several secondary electrons are emitted at each dynode

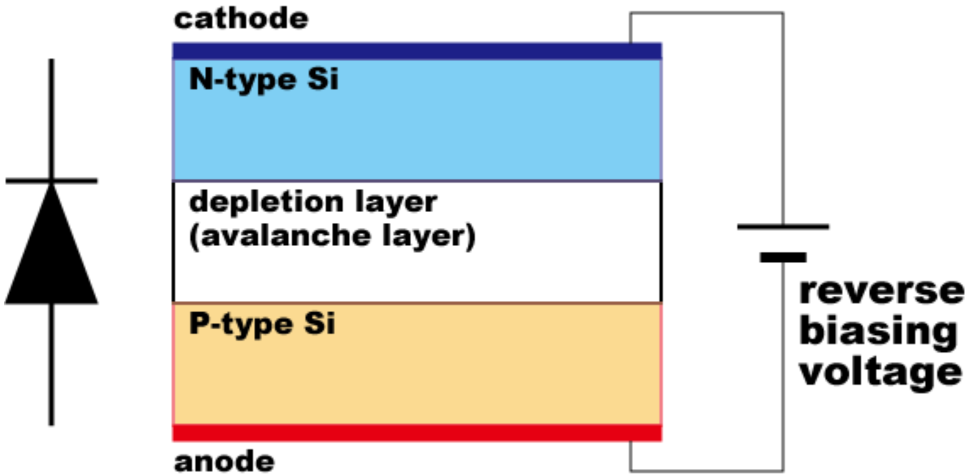
$$\text{gain} \propto V^{kn}$$

$$10^5 \sim 10^6 \qquad k = 0.7 \sim 0.8, \quad n: \text{number of dynodes}$$

Photo-diode

electron-hole pair is produced by a photon

electrons moves to the anode



PN or PIN photo-diode

avalanche photo-diode

semiconductor
- N-type … donors (electrons)
- I-type
- P-type … acceptors (holes)

avalanche layer
- low-density acceptors

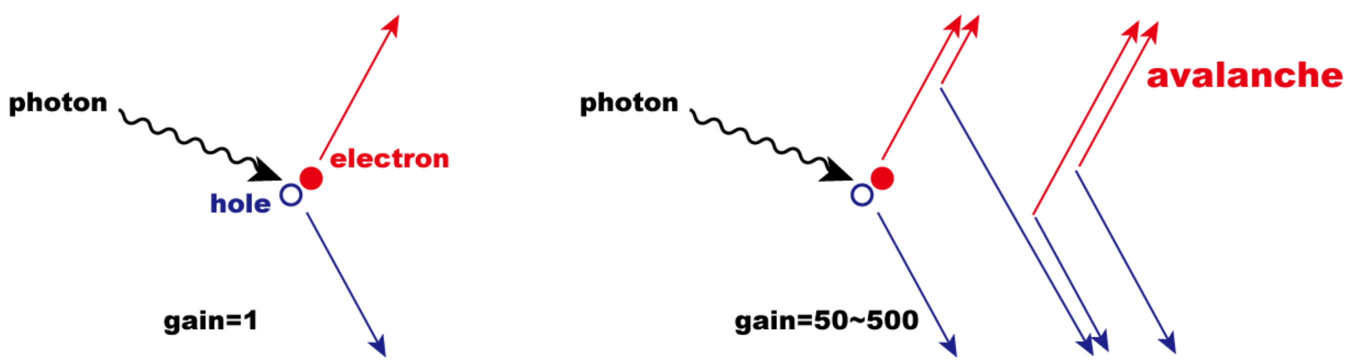
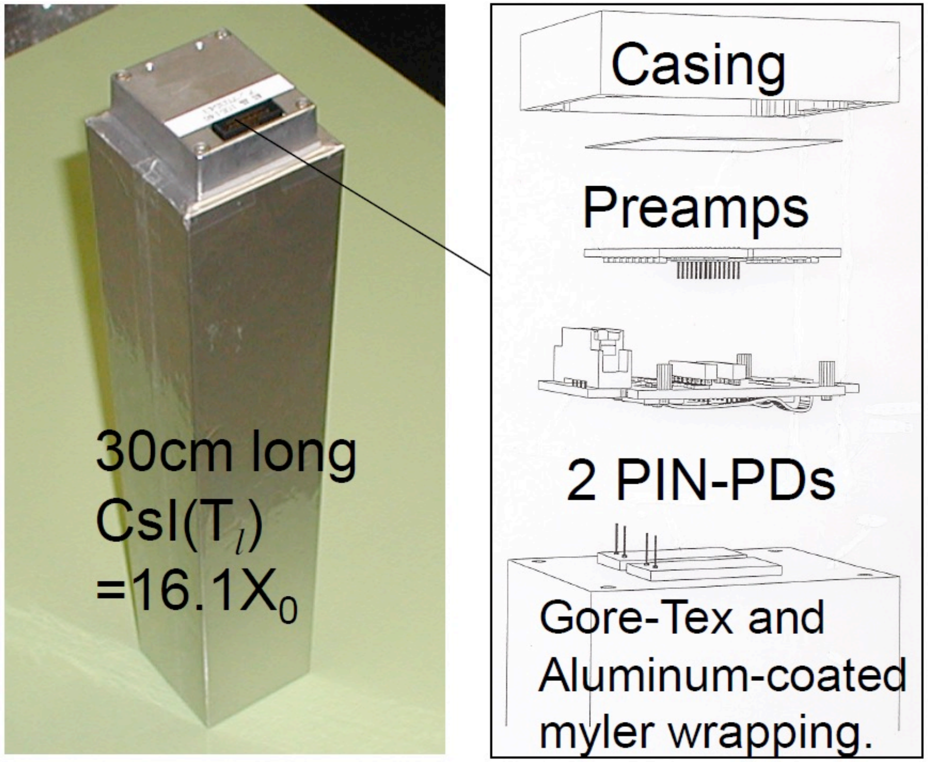


Photo-diode

lower gain as compared with PMT

additional amplifier is needed

operation is also available in high magnetic fields



K. Miyabayashi
Belle at KEK
used in a solenoidal magnetic field

Energy response of a calorimeter

- **types**
  - **homogeneous**
  - **sampling**
- **performance**
  - **energy resolution**
  - **non-linearity**

Homogeneous calorimeters

Entire kinetic energy of shower particles gives a signal

inorganic scintillator is the best

- energy response is intrinsically linear
- large number of photoelectrons

non-linearity

- saturation effects in PMTs
- saturation effects in scintillator
- shower leakage
- light attenuation
- non uniformity of scintillator
- non uniformity of PMT

Sampling calorimeters

inactive part [lead]

develop the EM shower

active part [plastic scintillator]

convert the kinetic energies of shower particles into a photon

energy resolution is not so high

sampling fraction

small number of photoelectrons

energy response is different between

electron, positron, photon, [linear] and

the others [non-linear]

Energy resolution

empirical formula

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{c_2}{E\,/\,\mathrm{GeV}}\right)^2 + \left(\frac{c_1}{\sqrt{E\,/\,\mathrm{GeV}}}\right)^2 + c_0^2$$

1st term (σ_E: independent of the energy) [noise]

electric noise

2nd term (σ_E: proportional to $\sqrt{E}$) [statistics]

photo-electron statistics

photon yield & conversion

3rd term (σ_E: proportional to E) [constant]

Energy resolution

constant term

- shower leakage from the back, side, front (albedo)
- calibration errors for modules
- non-uniformities
  - non-uniformity in scintillator (emission, and light collection)
  - non-uniformity in PMTs

Exercise 5

Consider the best geometry of a calorimeter for the photon beam energy measurement? Here, all the photons are assumed to come on the z axis.

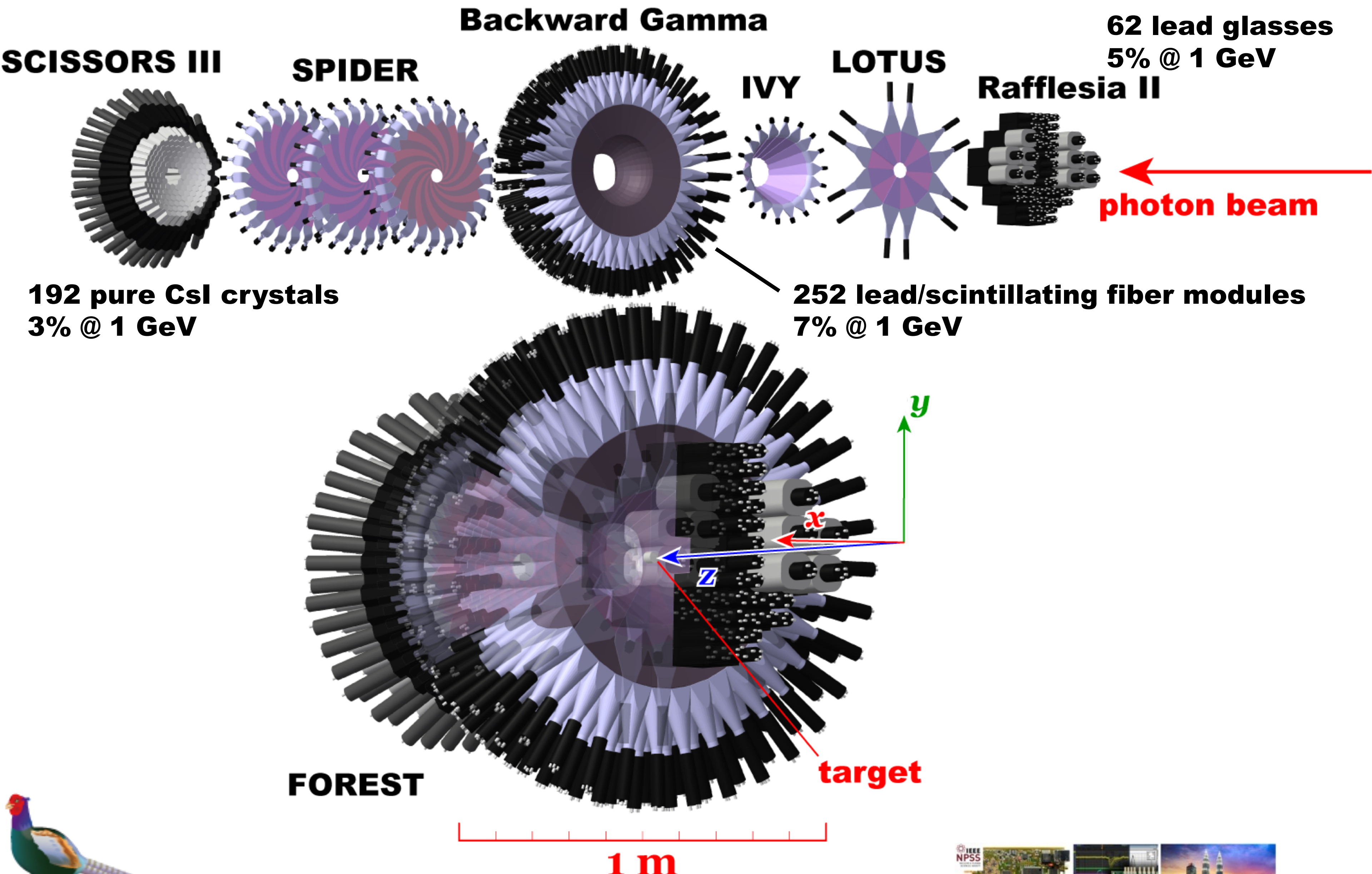
FOREST detector

EM calorimeters

forward calorimeter
central calorimeter
backward calorimeter

plastic scintillator hodoscopes

FOREST detector

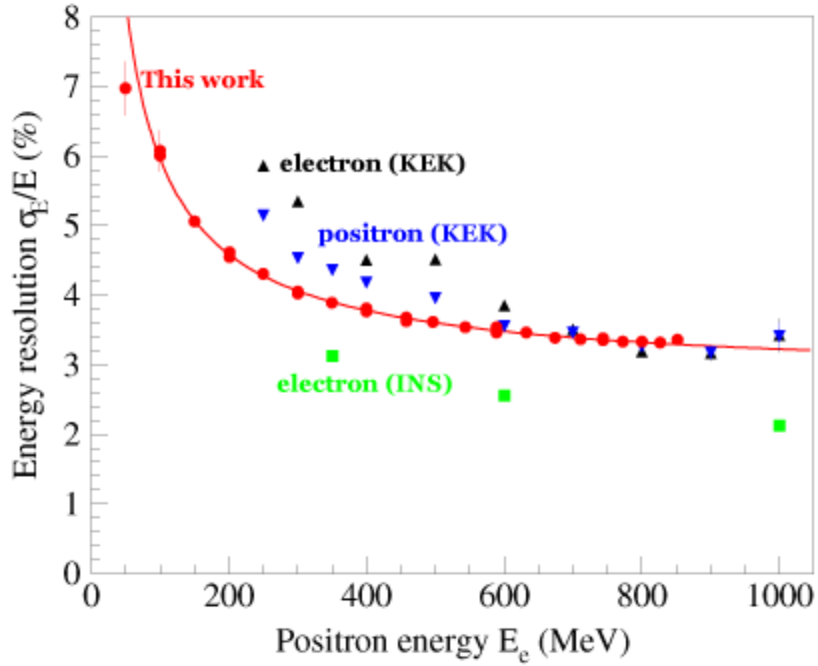


Forward calorimeter

inorganic scintillator

- high Z and high density
- active material only
- high energy resolution
- expensive

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{0.2\%}{E/\mathrm{GeV}}\right)^2 + \left(\frac{1.6\%}{\sqrt{E/\mathrm{GeV}}}\right)^2 + (2.8\%)^2$$

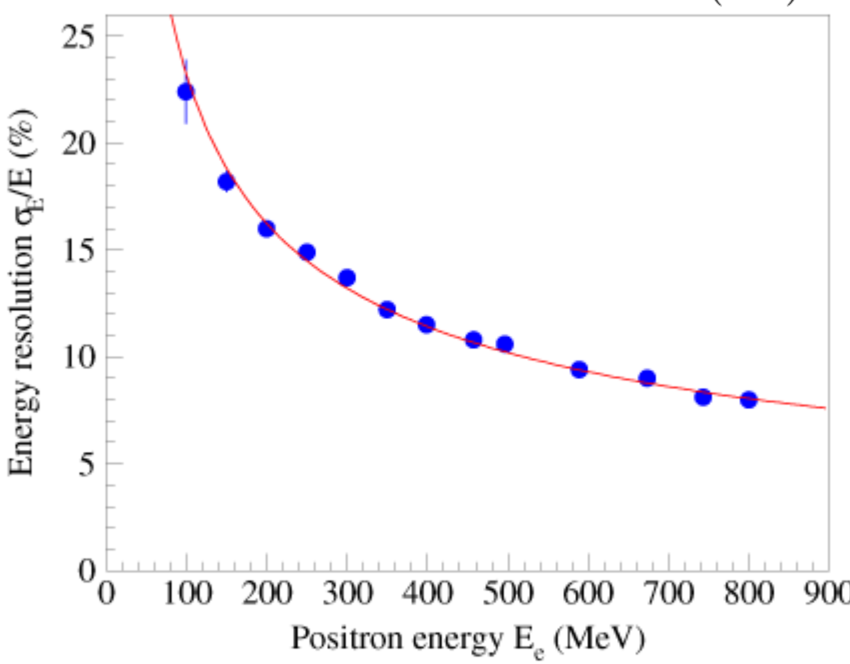


Central calorimeter

sampling calorimeter

- **heavy material (lead) & active scintillator (scintillating fiber)**
- **poor energy resolution**
- **cheaper**

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{0.5\%}{E\,/\,\mathrm{GeV}}\right)^2 + \left(\frac{7.2\%}{\sqrt{E\,/\,\mathrm{GeV}}}\right)^2 + (0.0\%)^2$$

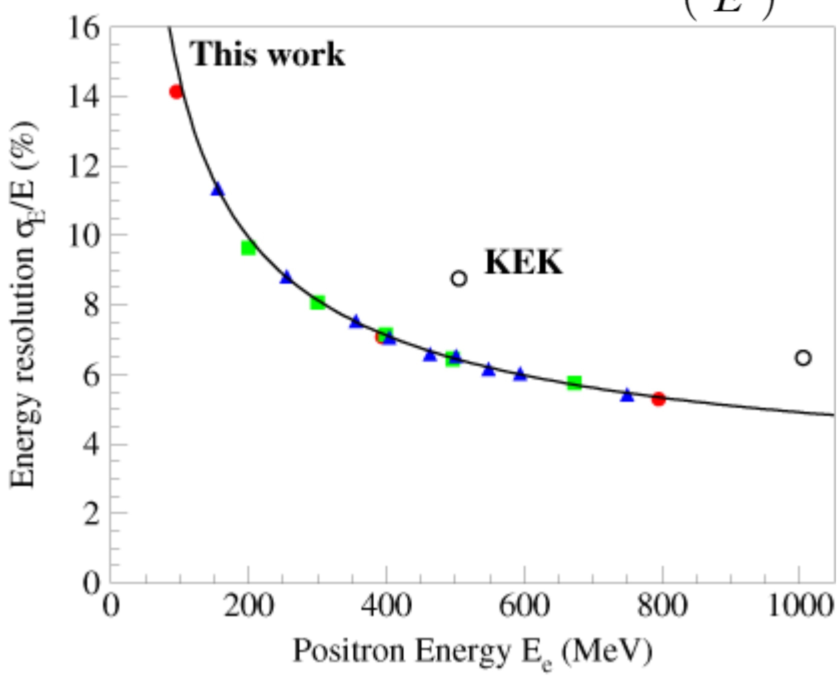


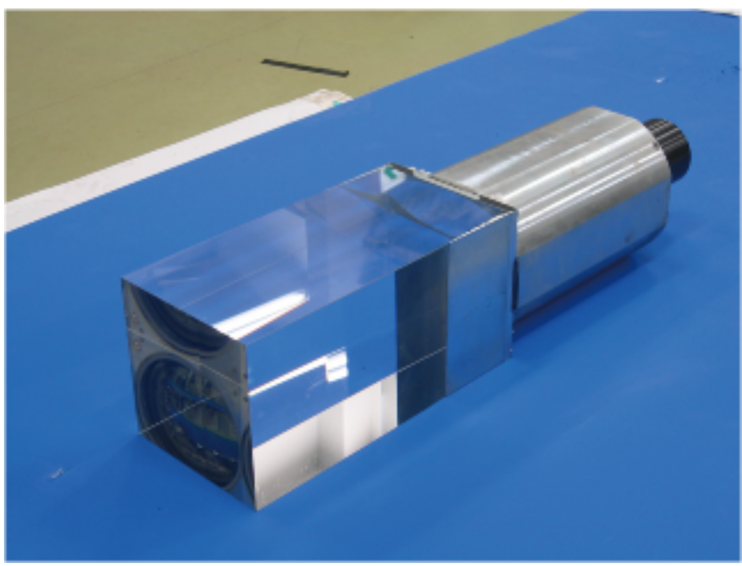
Backward calorimeter

Cherenkov calorimeter

- **heavy transparent material**
- **poor energy resolution**
- **cheaper**

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{0.5\%}{E\,/\,\mathrm{GeV}}\right)^2 + \left(\frac{4.1\%}{\sqrt{E\,/\,\mathrm{GeV}}}\right)^2 + (2.7\%)^2$$



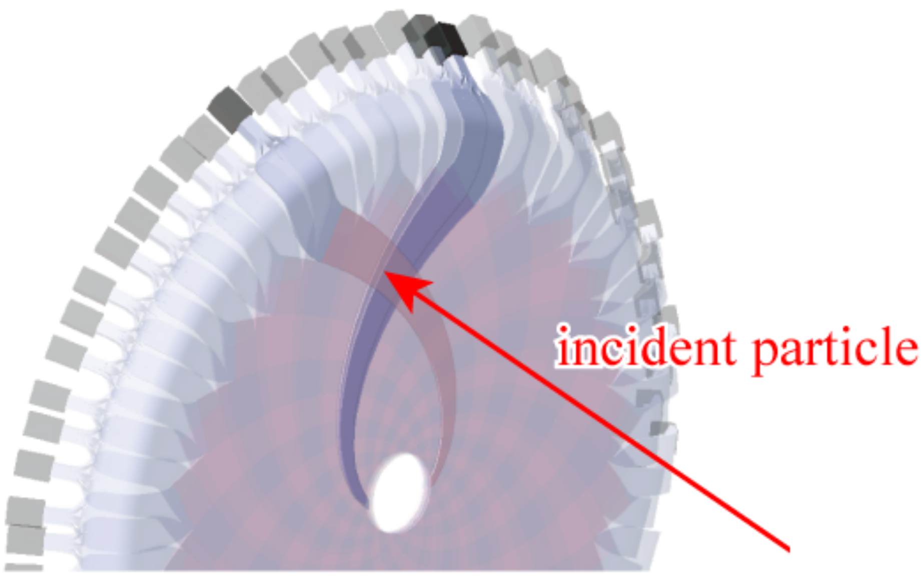


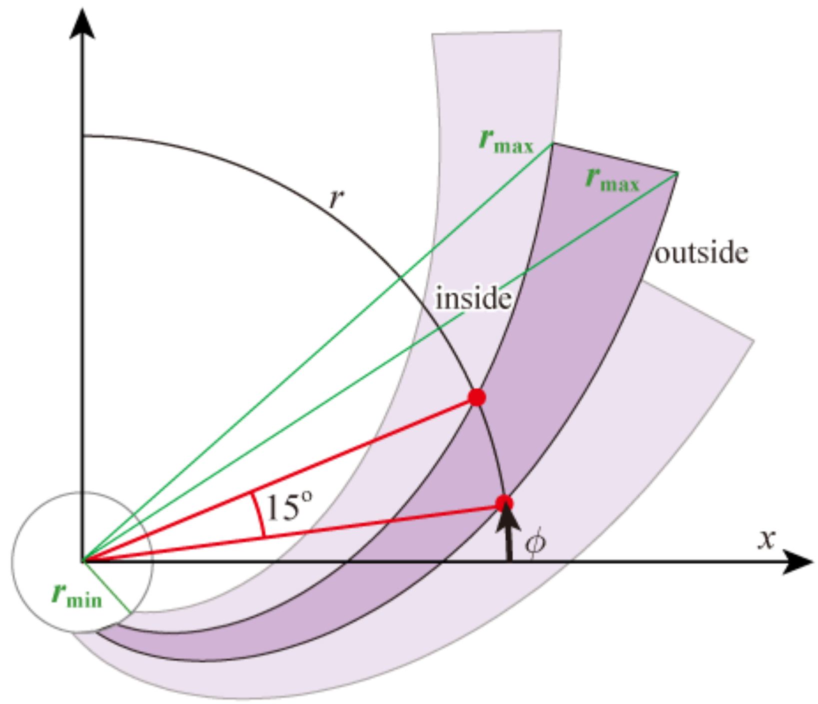
Plastic scintillator hodoscopes

placed in front of each calorimeter

to identify charged particles

forward hodoscope can determine the position of impact





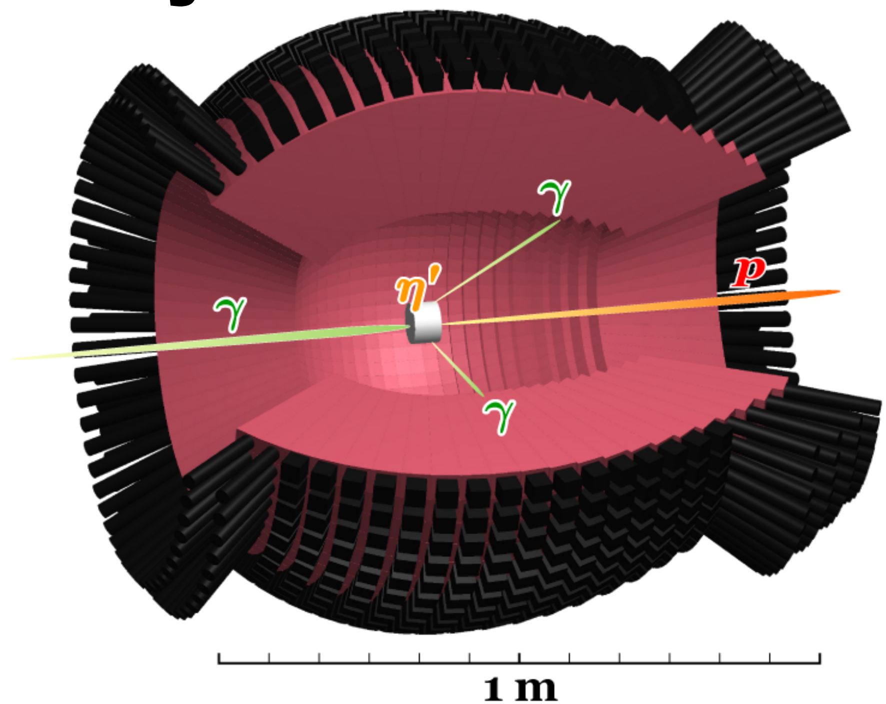
FOREST detector

EM calorimeters in FOREST

- **energy resolution is not so high, yet**
- **solid angle is large (88% in total)**
- **giving an opportunity for hadron physics studies**

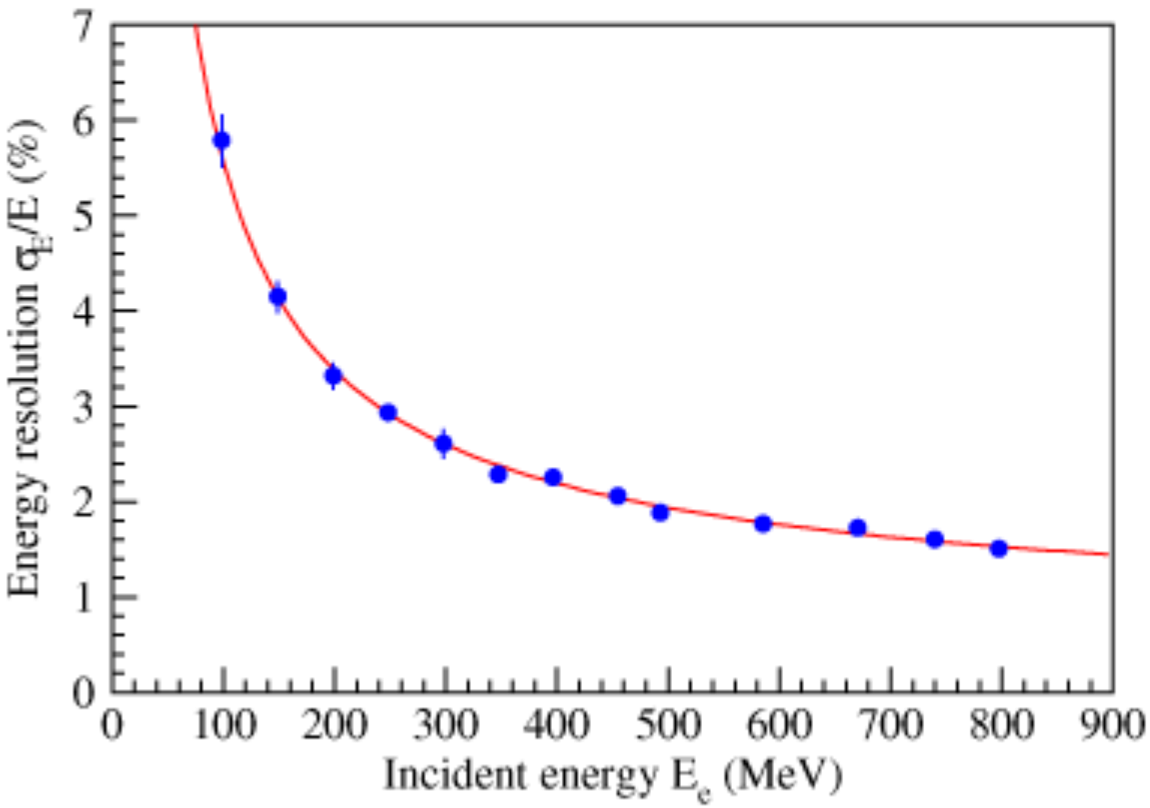
new calorimeter

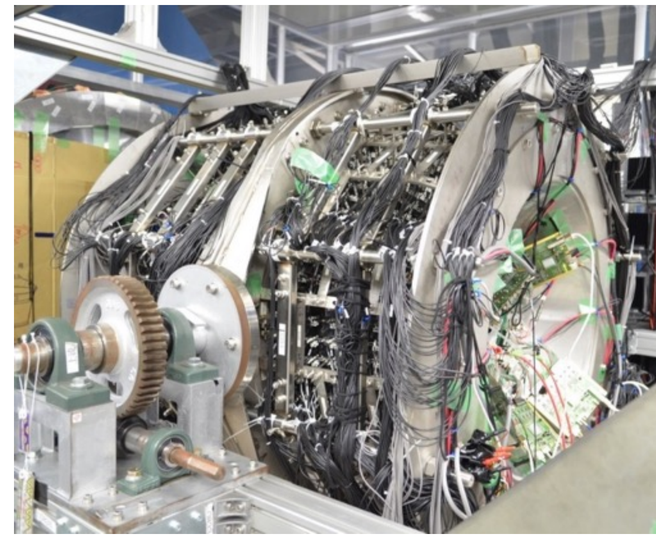
BGOegg at SPring-8



FOREST detector

new calorimeter BGOegg at SPring-8





1320 BGO crystals
1.38% @ 1 GeV

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{0.42\%}{E/\mathrm{GeV}}\right)^2 + \left(\frac{1.15\%}{\sqrt{E/\mathrm{GeV}}}\right)^2 + (0.63\%)^2$$

Exercise 6

What is the mean number of photo-electrons for 1 MeV energy deposit for BGOegg calorimeter?

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{0.42\%}{E\,/\,\mathrm{GeV}}\right)^2 + \left(\frac{1.15\%}{\sqrt{E\,/\,\mathrm{GeV}}}\right)^2 + (0.63\%)^2$$

Suppose quantum efficiency is 20%, what is the light collection efficiency in a BGO crystal?

NaI(TI): 45000 photons /MeV

relative photon yield of BGO

with respect to Na(TI): 10%

Summary

omitted items

clustering

energy reconstruction

position reconstruction

energy calibration

most important

π^0 peak in the $\gamma\gamma$ invariant mass
is used in the FOREST experiments

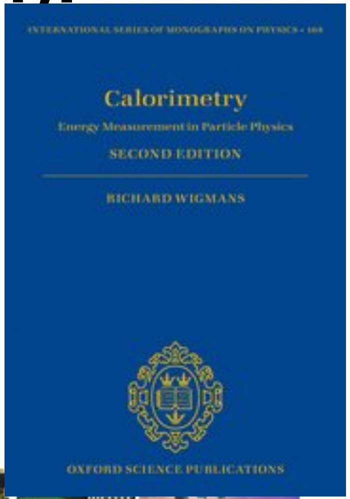
Summary

references

M. Tanabashi *et al*. (Particle Data Group), Review of Particle Physics, Phys. Rev. D 98, 030001 (2018). [PDG]

G. Gratta, H. Newman, and R.Y. Zhu, Crystal Calorimeters in Particle Physics, Ann. Rev. Nucl. Part. Sci. 14, 453 (1994).

R. Wigmans, Calorimetry
Energy Measurements in Particle Physics,
Oxford Univ. Press (2000).



Summary

our papers describing EM calorimeters

**T. Ishikawa *et al.*,
Testing a prototype BGO calorimeter with 100-800 MeV positron beams,
Nucl. Instrum. Meth. A 837, 109 (2016).**

**T. Ishikawa *et al.*,
The FOREST detector for meson photoproduction experiments at ELPH,
Nucl. Instrum. Meth. A 832, 108 (2016).**

**T. Ishikawa *et al.*,
A detailed test of a BSO calorimeter with 100-800 MeV positrons,
Nucl. Instrum. Meth. A 694, 348 (2012).**