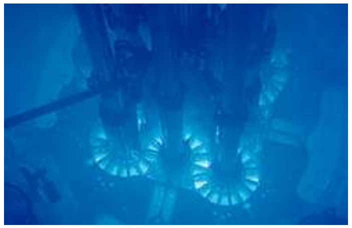
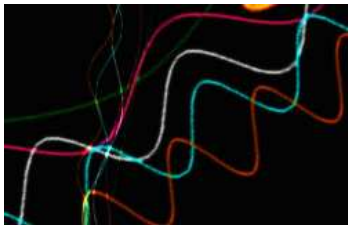
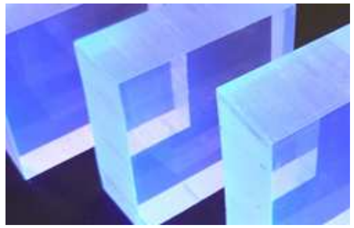
Particles detection with light

physics processes and detectors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Outline

- ✔ *light* in experiments
  - ► experiments using *light* observation techniques
- ✔ detectors *light* : scintillation, cerenkov and transition radiation, fluorescence
  - ► emission mechanisms and characteristics
  - ► scintillator/radiators
  - ► light yield
  - ► physics measurements
  - ► detectors

Light in Experiments

LHC experiments (pp collisions)

ATLAS Transition Radiation Detector, Hadronic Calorimeter (scintillators + fibers)

LHC-B Ring Imaging Cerenkov Detectors (Gas, aerogel)

neutrino experiments

SUPERKAMIOKANDE Cerenkov Detector (water)

ICECUBE Cerenkov Detector (ice)

charged and gamma cosmic rays

AMS Cerenkov Detector (aerogel, NaF), Scintill (plastic) and Transition Rad Det

AUGER Cerenkov Detector (water), Fluorescence

TELESCOPE ARRAY Scintilators (plastic), Fluorescence

MILAGRO Cerenkov Detector (water)

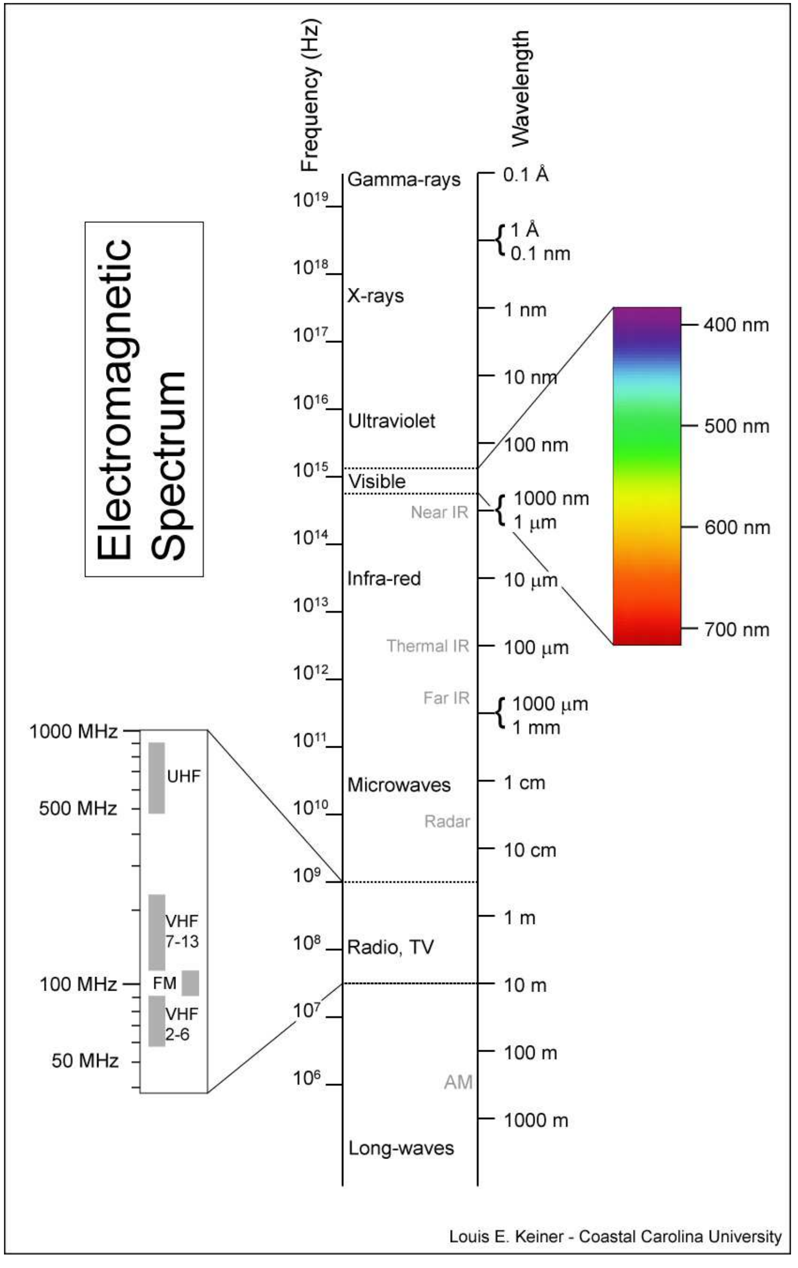
OWL Fluorescence (atmosphere)

STACEE solar array - cerenkov radiation (atmosphere)

HESS Cerenkov Detector (atmosphere)

VERITAS, CTA Cerenkov radiation (atmosphere)

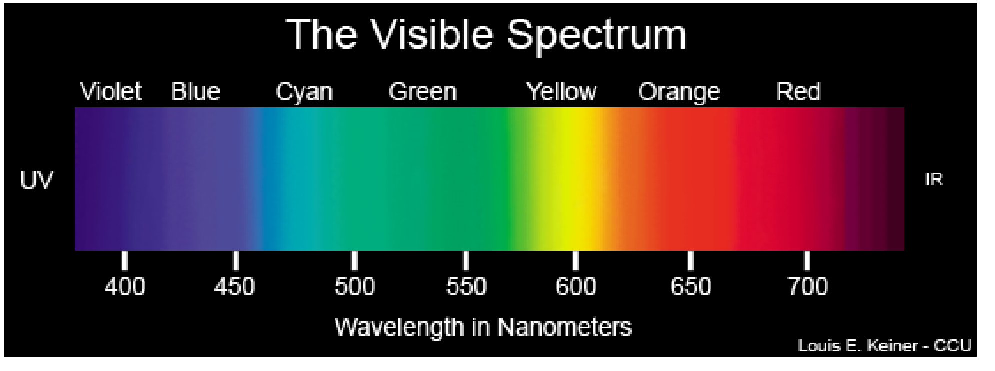
Electromagnetic spectrum



Energia : $\lambda \rightarrow$ eV

$$E\ [eV] = \frac{h\ c}{\lambda} = \frac{1.24}{\lambda\ [\mu m]} = \frac{1.24\ 10^3}{\lambda\ [nm]}$$

type)	λ [nm]	E [eV]
ultraviolet	200	6
visible	500	2.4
infrared	1000	1.24
X-rays	1	$\sim 10^3$
γ-rays	$< 10^{-3}$	$> 10^6$



Cosmic Gamma Rays (CGR)

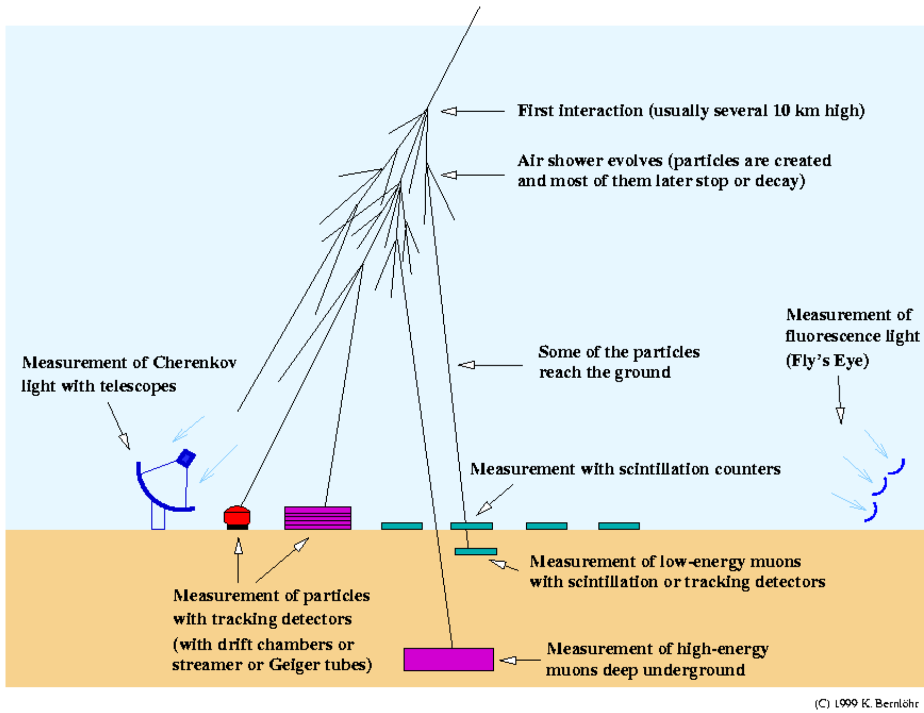
Space telescopes — *(Below 50 GeV)*

Atmospheric Cherenkov Detectors — *(50 GeV – 50 TeV)*

Air shower arrays — *(Above 50 TeV)*

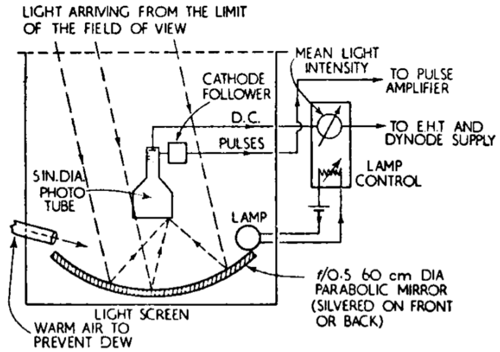
different techniques depending on γ energy

- ✔ **I**maging **A**tmospheric **C**erenkov **T**elescope -**IACT** (CTA, VERITAS, HESS)
- ✔ Water Cerenkov large surface detector (MILAGRO)
- ✔ Solar array experiment (STACEE)
- ✔ Air shower detector array (Tibet-AS)

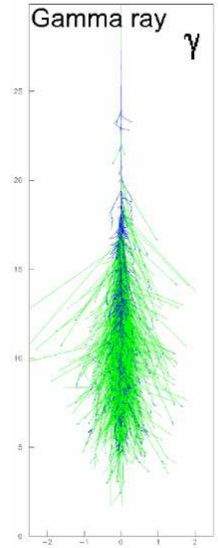


IACT detection technique

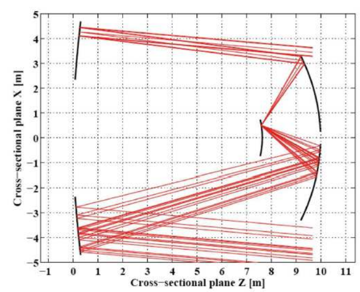
- ✔ cosmic ray shower emits Cerenkov radiation
- ✔ IACT telescopes images the Cerenkov radiation flash arriving at earth ($\sim$ nsec)
- ✔ light is collected on mirrors and reflected towards a detection camera
- ✔ the light spot allows to distinguish γ's from dominant background protons
- ✔ threshold energy (~ 10 MeV's) depends on collecting area (A)
  $E_{th} \sim \frac{1}{\sqrt{A}}$
- ✔ CTA, a ground-based Gamma Ray observatory, is a very large project currently under development in Europe and United States

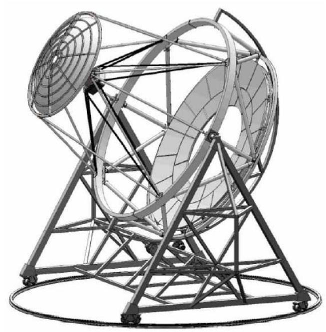


1st observation experiment (1953)



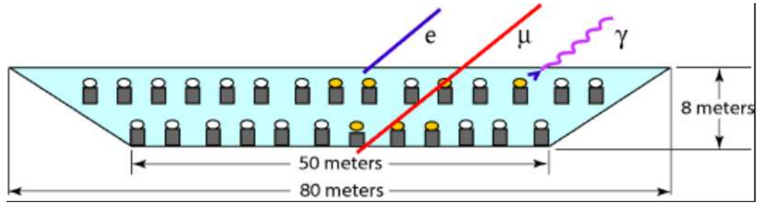

HESS telescopes, Namibia

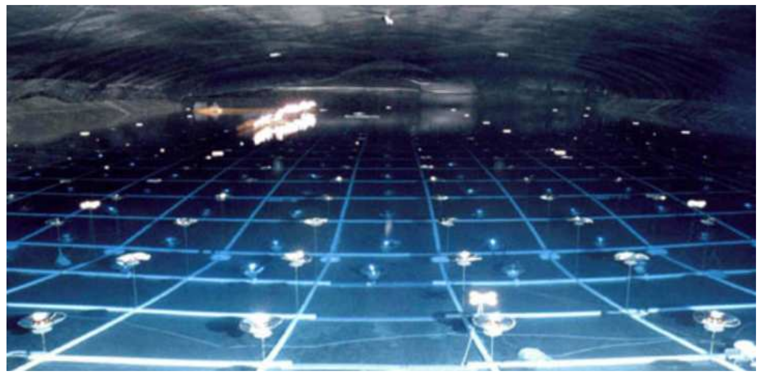




Extensive Air Shower Array (EAS)

- ✔ VHE gamma rays inciding on earth interact with the upper atmosphere and produce extensive air showers (EAS)
- ✔ most of secondary particle are photons (90%) peaking close to the shower score
- ✔ in MILAGRO the EAS is detected by converting the shower into cerenkov radiation emitted by the water medium
- ✔ rate $\sim 2 \times 10^3$ /sec
- ✔ the amplitude and arrival time of the light arriving to photodetectors can provide the comsic ray direction and energy
- ✔ large field of view (FOV) and large duty cycle (in fact, it operates continuously

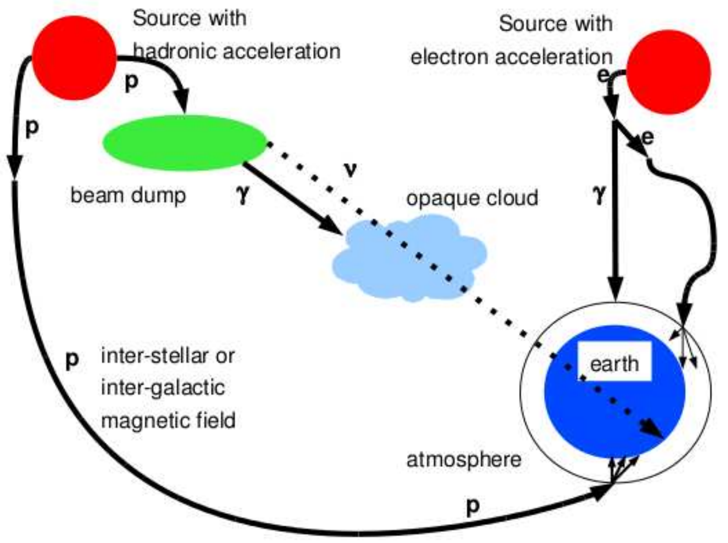




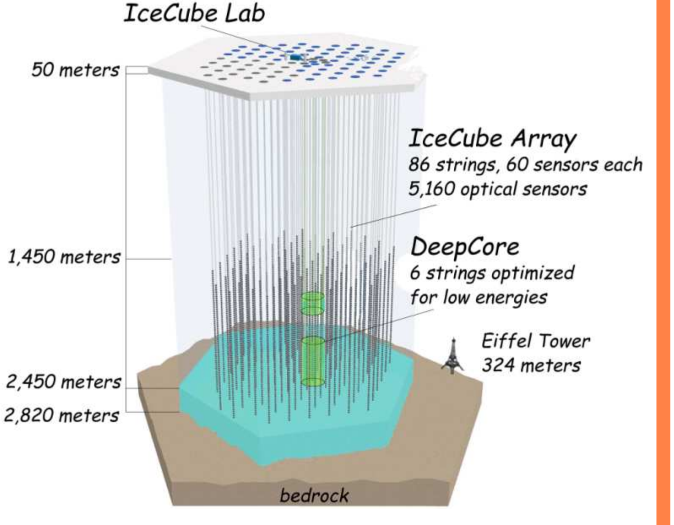
- ✔ **HAWC observatory being built in Mexico (4100 altitude)**

Neutrino detection

- ✔ neutrinos are messengers from cosmological sources
- ✔ indication of hadronic acceleration at sources
  - ► accelerated hadrons interact with matter producing charged pions which in turn decay to ν's
- ✔ insensitive to intergalactic/interstellar magnetic fields
- ✔ very small cross section

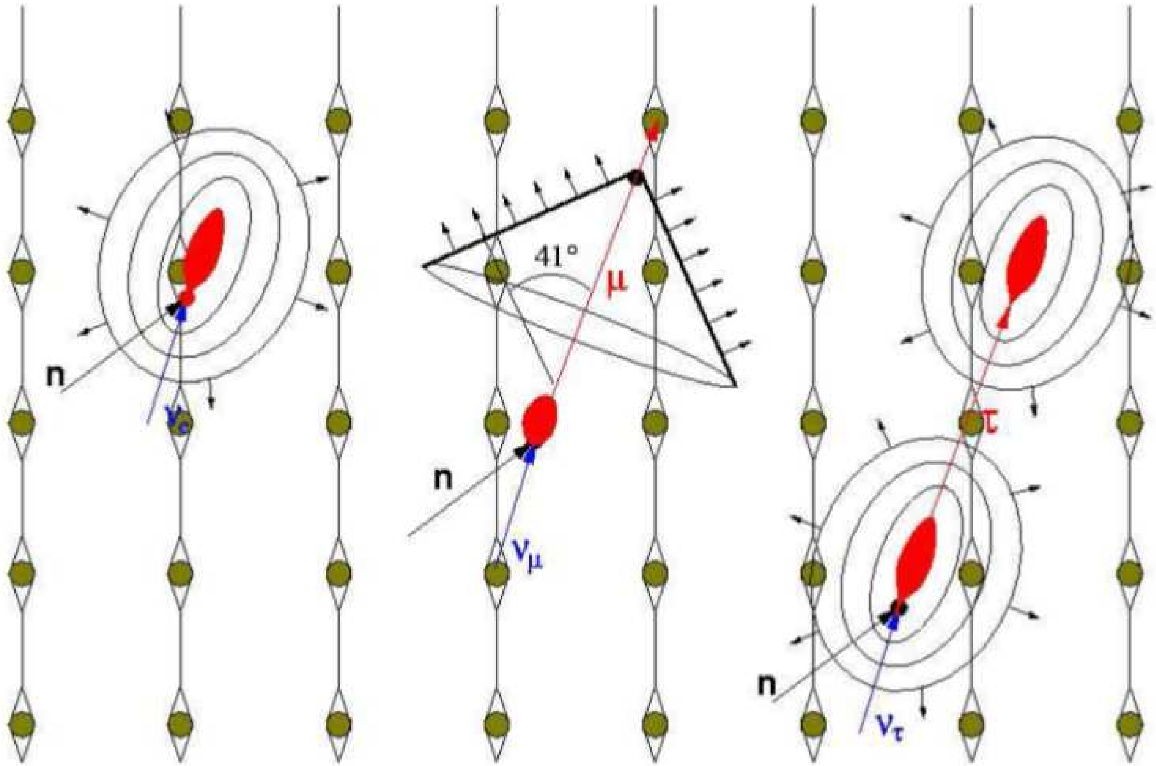


SuperK



ICECUBE : detecting HE ν's on ice

- ✔ Cerenkov radiation is emitted in ice by the products of the neutrino interaction : the hadronic cascade or the lepton
- ✔ ICECUBE is sensitive to neutrinos from sub-TeV to multi-PEV energies



ν's interact weakly with the medium nucleus :

$$\nu + N \rightarrow Z^0 \rightarrow \nu + X$$
$$\nu + N \rightarrow W^{\pm} \rightarrow \ell + X$$

$$\boxed{\Delta_{\nu\ell} \sim \frac{0.7^\circ}{(E_\nu/TeV)^{0.7}}}$$

E_ν	10 GeV	10 TeV
$\Delta_{\nu\ell}$	3.5°	0.14°

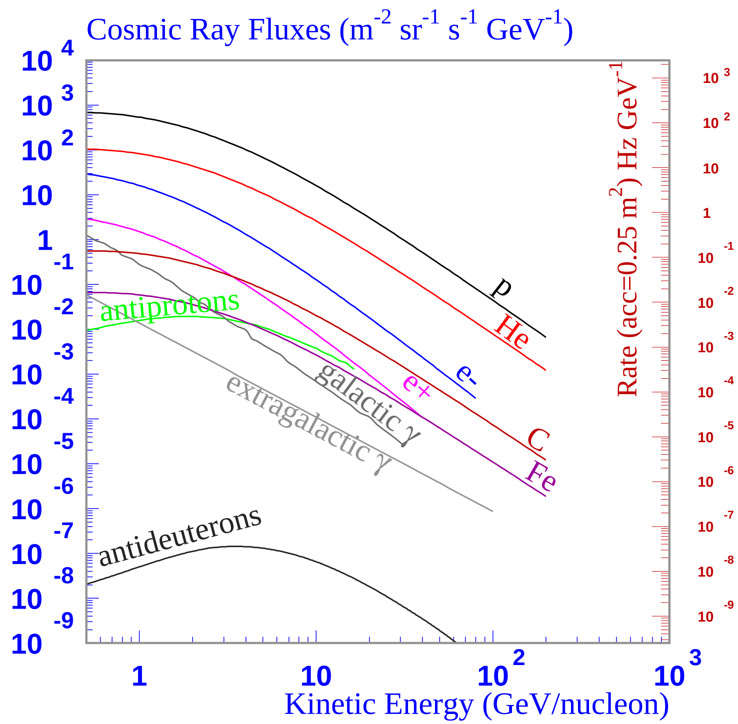
light interactions :

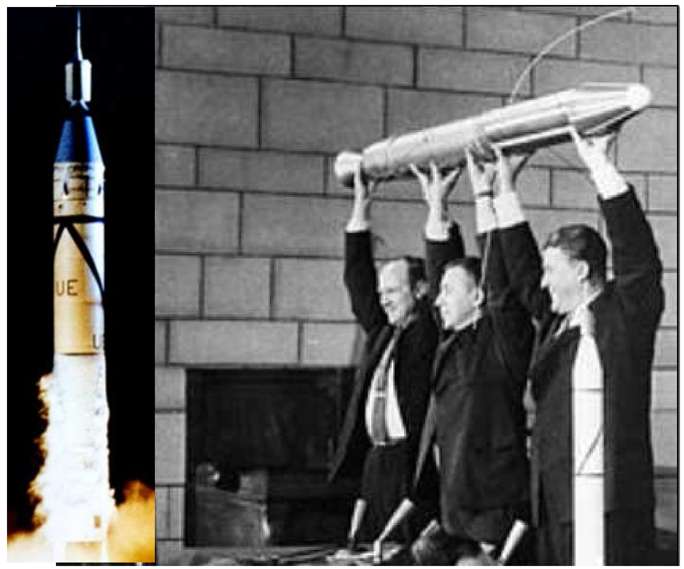
$\lambda_{abs} \sim 100$ m

$\lambda_{sca} \sim 25$ m

CRs detection on space

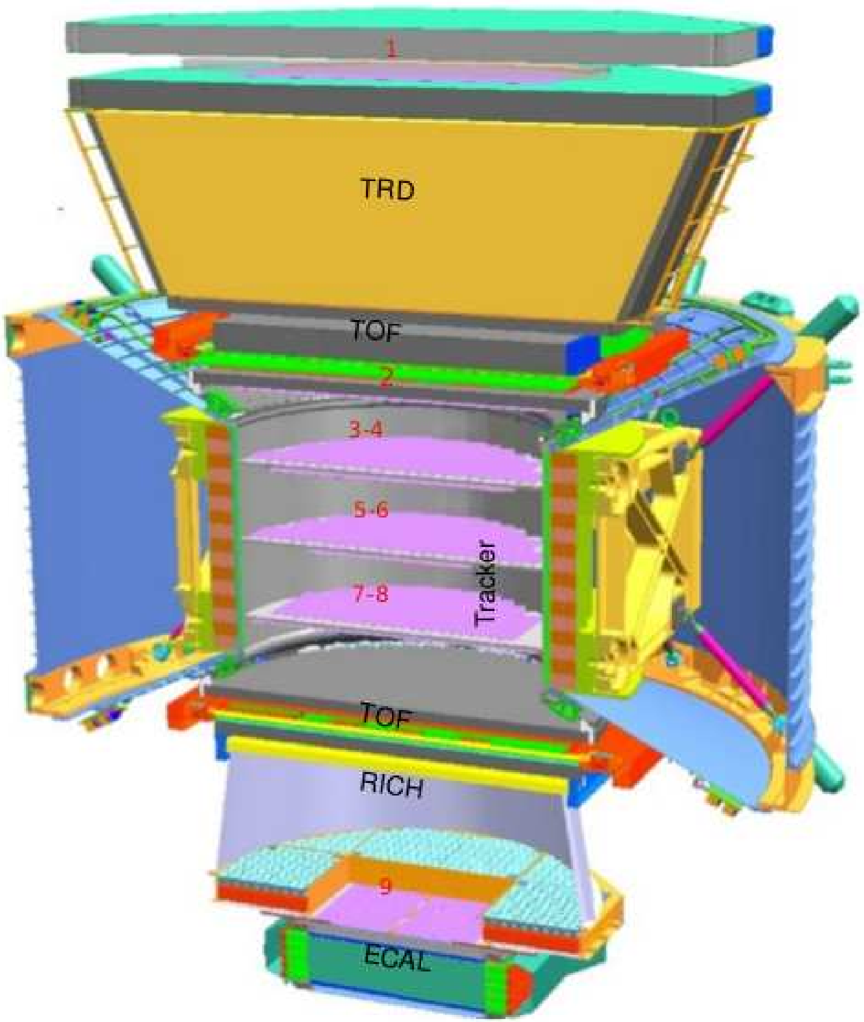
- ✔ cosmic rays (mostly protons) detection on space is feasible up to TeV's energies
  - ▶ cosmic ray flux decreases steeply with energy ($\Phi \sim E^{-2.7}$)
- ✔ a key issue on their detection is its identification ($\gamma, p, \bar{p}, e^{\pm}, he, ...$)
- ✔ a detector on space capabilities :
  - ▶ fast trigger events (event rate depends on geomagnetic detector position)
  - ▶ electric charge
  - ▶ velocity
  - ▶ rigidity ($Rig = \frac{pc}{Ze}$) and energy
- ✔ carried by satellites (ISS) or balloons
  - ▶ Explorer-I (1958) carried the 1st CR detector (Geiger counter)
  - ▶ Van Allen belts discovered



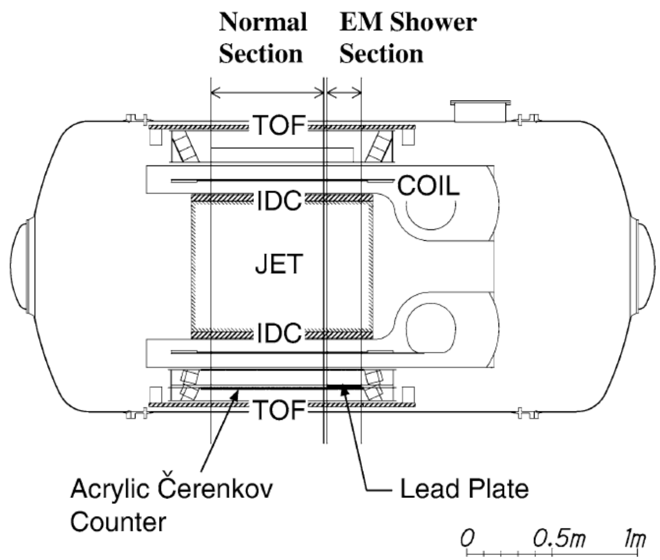


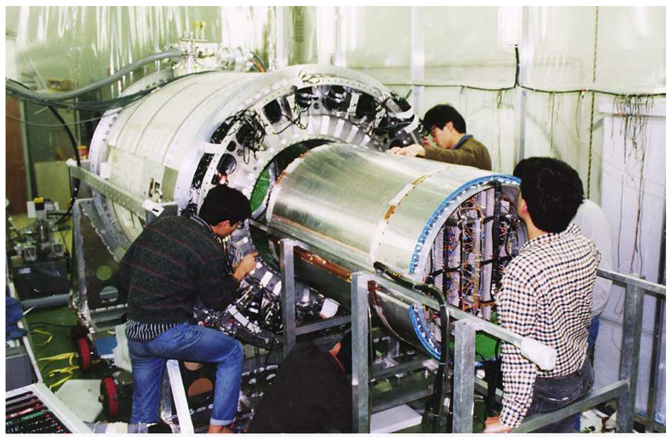
CRs space detectors

AMS detector



BESS detector





Cerenkov radiation

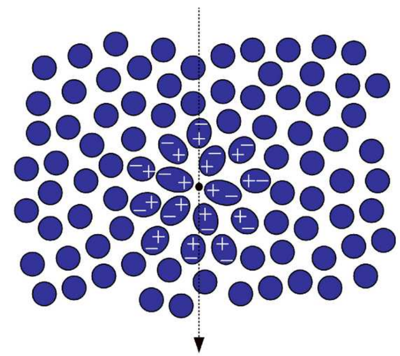
mechanisms, characteristics, measurements

Cerenkov Radiation : principles

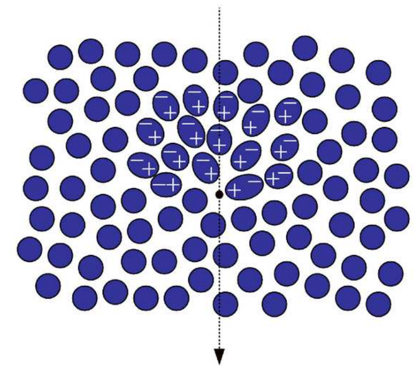
- ✔ suppose an electric charged particle crossing a dielectric medium
  - ► the region in the neighbourhood of the crossing particle will be polarized

    electric dipole : $\vec{p} = q\vec{d}_{(-\rightarrow+)}$
  - ► the electrical polarization of atoms can be seen as a displacement of the mean electrical center of the negative charge with respect to the positive charge of the nucleus, induced by the particle electric field

  For slowly moving particles, the polarization is symmetrical about the instantaneous position of the charge
  - ► no resultant dipole field at large distances

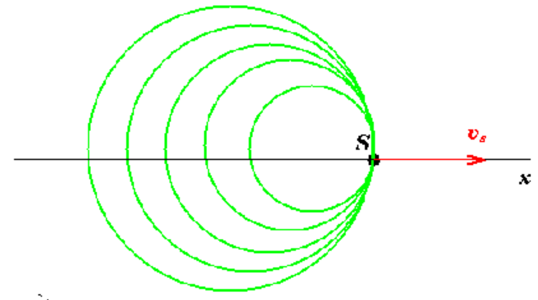


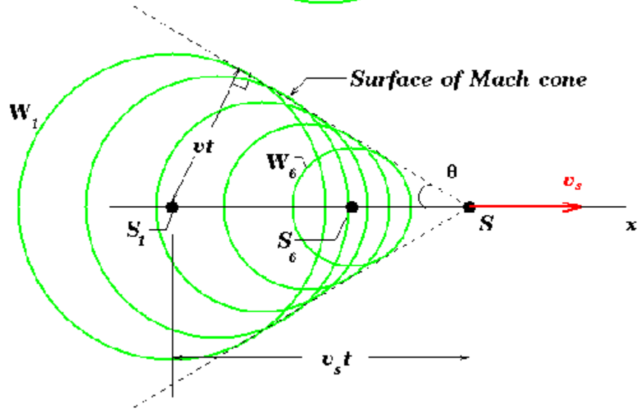
- ✔ For particles moving with speed comparable to the velocity of light in the dielectric medium, the polarization is no longer distributed symmetrically
  - ► there is a resultant dipole field



Cerenkov Radiation : characteristics

- Each elementary and transitory electric dipole will radiate while the charge moves through the dielectric medium
- The wavelets radiated by all these dipoles will interfere existing only one unique angle of emission of the radiation for which the wavelets interfere construtively for particle speed (v) above the speed of the light in the medium ($c_m = \frac{c}{n}$)
- The minimal particle velocity that triggers the Cerenkov radiation comes from the condition $\cos\theta_C < 1 \Rightarrow \beta_{th} = \frac{1}{n}$





$$\cos\theta_c = \frac{c_m t}{vt} = \frac{c}{nv} = \frac{1}{\beta n}$$

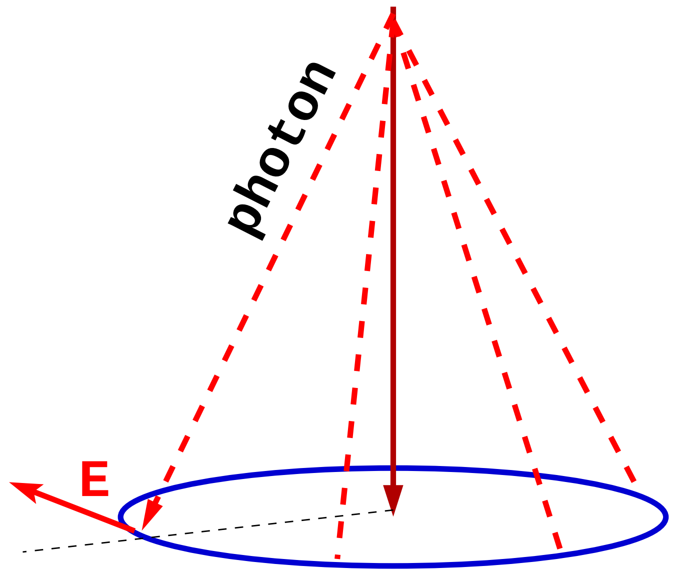
$$\cos\theta_c^{max} = \frac{1}{n}$$

$$\gamma_{th}^2 = \frac{1}{1-\beta_{th}^2} = \frac{n^2}{n^2-1}$$

Cerenkov Radiation : light yield

- ✔ The Cerenkov radiation is emitted with an aperture angle θ_c and uniforn in azimuth (φ), $\frac{dN_\gamma}{d\varphi} = c^{te}$
- ✔ It is polarized along the plane made by the particle and the emitted photon
- ✔ The number of emitted photons in a given medium of refractive index n with energies $[E_\gamma, E_\gamma + dE_\gamma]$, in a medium length thickness $d\ell$ for a particle of velocity β and electric charge Z is :

$$\boxed{d^2N_\gamma = \frac{\alpha}{\hbar c} Z^2 \sin^2\theta_c(E_\gamma) dE_\gamma d\ell}$$



- $\sin^2\theta_c = 1 - \frac{1}{\beta^2\, n^2(E_\gamma)}$
- $E_\gamma = \frac{h\,c}{\lambda} \Rightarrow dE_\gamma = -\frac{h\,c}{\lambda^2} d\lambda$
- $\frac{\alpha}{\hbar c} = \frac{1/137}{197.3\,10^{-6}\,eV.cm} \simeq$ 370/eV.cm

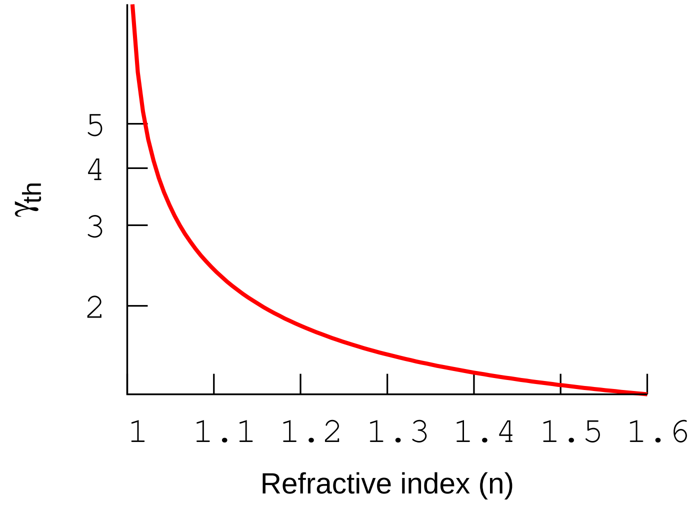
$$\boxed{\frac{dN_\gamma}{d\ell} = 2\pi\alpha Z^2 \int_{\lambda(E_\gamma^{max})}^{\lambda(E_\gamma^{min})} \left(1 - \frac{1}{\beta^2\, n^2\,(\lambda)}\right) \frac{d\lambda}{\lambda^2} \simeq 2\pi\alpha Z^2 \left(1 - \frac{1}{\beta^2\, n^2}\right) \left(\frac{1}{\lambda_{min}} - \frac{1}{\lambda_{max}}\right)}$$

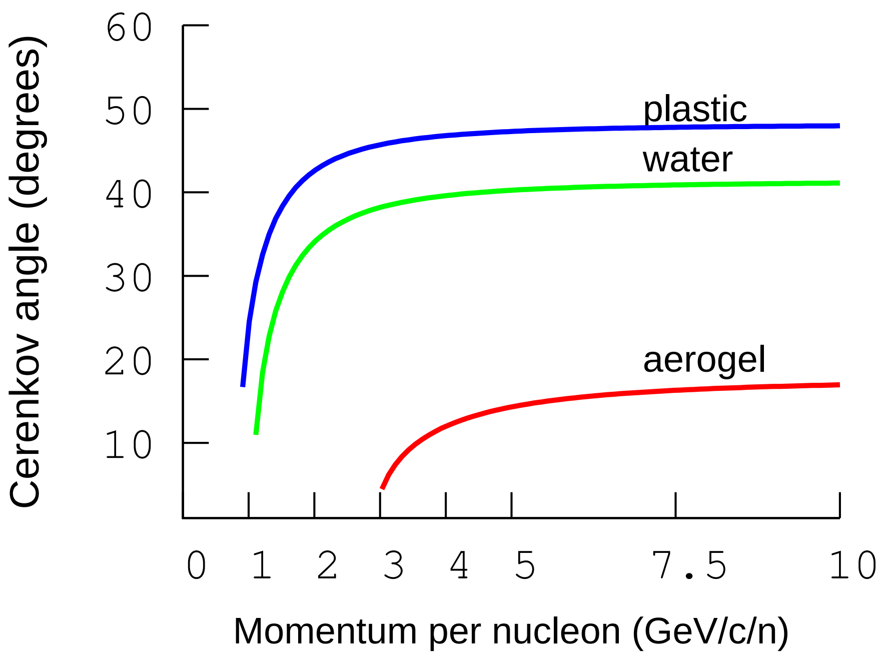
Cerenkov Radiation : radiator media

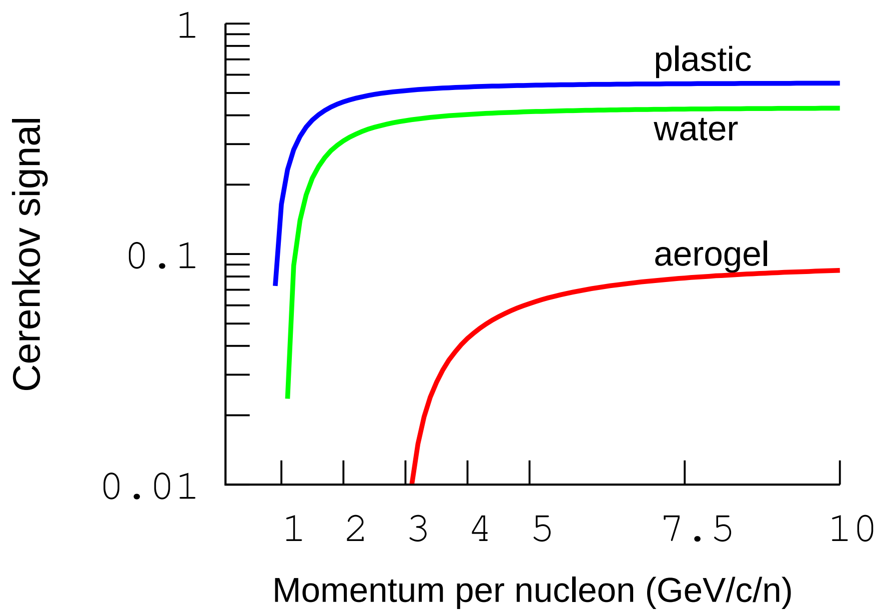
media	type	n	$\theta_c(max)$ [º]	$\sin^2\theta_c \ \ (\beta = 1)$
He	gas	1.000035	0.48	
Air	gas	1.000283	1.36	
Isobutane	gas	1.001270	2.89	
Freon	liquid	1.233	35.8	
Water	liquid	1.333	41.25	
Aerogel	solid	1.025-1.075	12.7-21.5	
NaF	solid	1.334		
Quartz	solid	1.46	46.7	
Plexiglass	solid	1.5	48.19	0.5556
Plastic scintil	solid	1.581	50.76	0.5999
BGO	solid	2.15	62.3	

Cerenkov radiation : radiators

- γ threshold
- cerenkov angle (θ_c)
- cerenkov signal $(\propto \sin^2 \theta_c)$







Cerenkov Radiation : air shower yield

- Only using the shower electromagnetic component
- air approximations $(n \sim 1; m_e/E << 1)$

$$n = 1 + \Delta n \rightarrow \boxed{\frac{1}{n^2} \simeq 1 - 2\Delta n}$$

$$\frac{1}{\beta^2} = \left[1 - \left(\frac{m_e}{E}\right)^2\right]^{-1} \rightarrow \boxed{\frac{1}{\beta^2} = 1 + \left(\frac{m_e}{E}\right)^2}$$

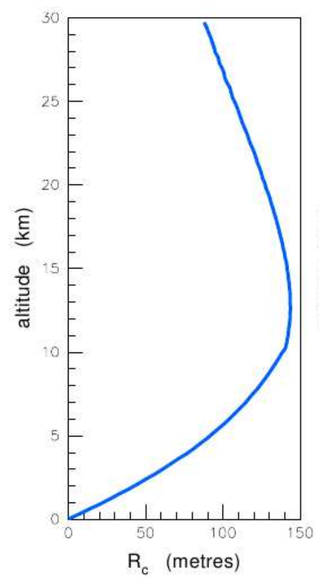
- The electrons threshold energy $\beta = 1/n$

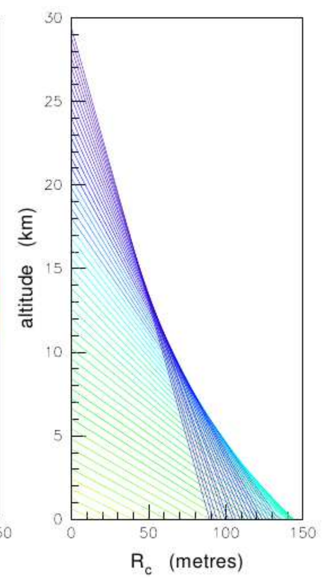
$$n^2 \simeq 1 + 2\Delta n = 1 + \left(\frac{m_e}{E_{th}}\right)^2 \rightarrow \boxed{E_{th}^2 = \frac{m_e^2}{2\Delta n}}$$

- The light yield

$$\boxed{\sin^2\theta_c = 1 - \frac{1}{\beta^2 n^2} \sim 2\Delta n - \left(\frac{m_e}{E}\right)^2}$$

- air refractive index
  $(n-1) = \Delta n \simeq 2.8 \times 10^{-4}\frac{\rho(z)}{\rho_0}$
  ($\rho_0 \simeq 1.19$ Kg/m^3)
- isothermal atmosphere
  $\rho(z) = \rho_0 e^{-z/z_0}$
  ($z_0 = 7.1$ Km)





$$\frac{dN_\gamma}{d\ell} = 4\pi\alpha Z^2 \Delta n(z)\left[1 - \left(\frac{E_{th}(z)}{E}\right)^2\right]\left(\frac{1}{\lambda_{min}} - \frac{1}{\lambda_{max}}\right)$$

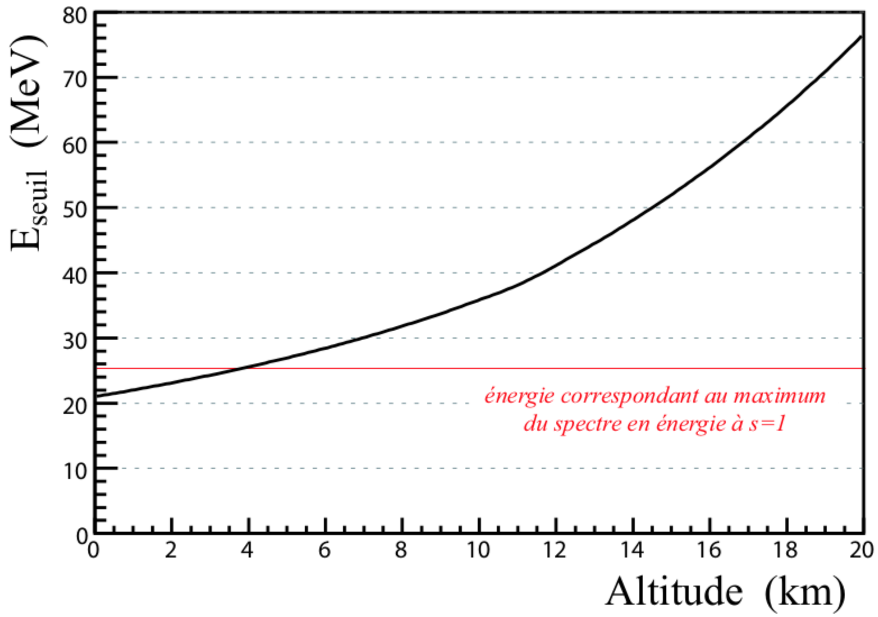
Cerenkov Radiation : air shower yield

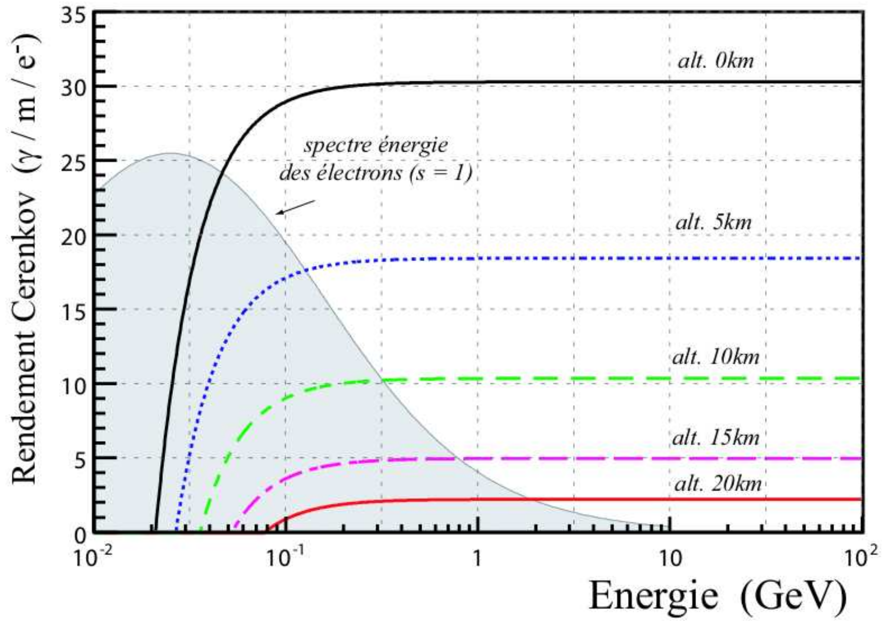
$$\Delta n(z) \simeq 2.8 \times 10^{-4} \frac{\rho(z)}{\rho_0}$$

$$\boxed{E_{th} = \frac{m_e}{\sqrt{2\Delta n(z)}} = 0.46\ 10^{-2} \frac{m_e}{\sqrt{(\rho(z)/Kg/m^3)}}}$$

$$\lambda_{min} = 300\ nm\ \lambda_{max} = 600\ nm$$

$$\boxed{\frac{dN_\gamma}{d\ell} \sim (33/m) \cdot Z^2 \cdot (\rho(z)/Kg.m^3) \left[1 - \left(\frac{E_{th}(z)}{E}\right)^2\right]}$$



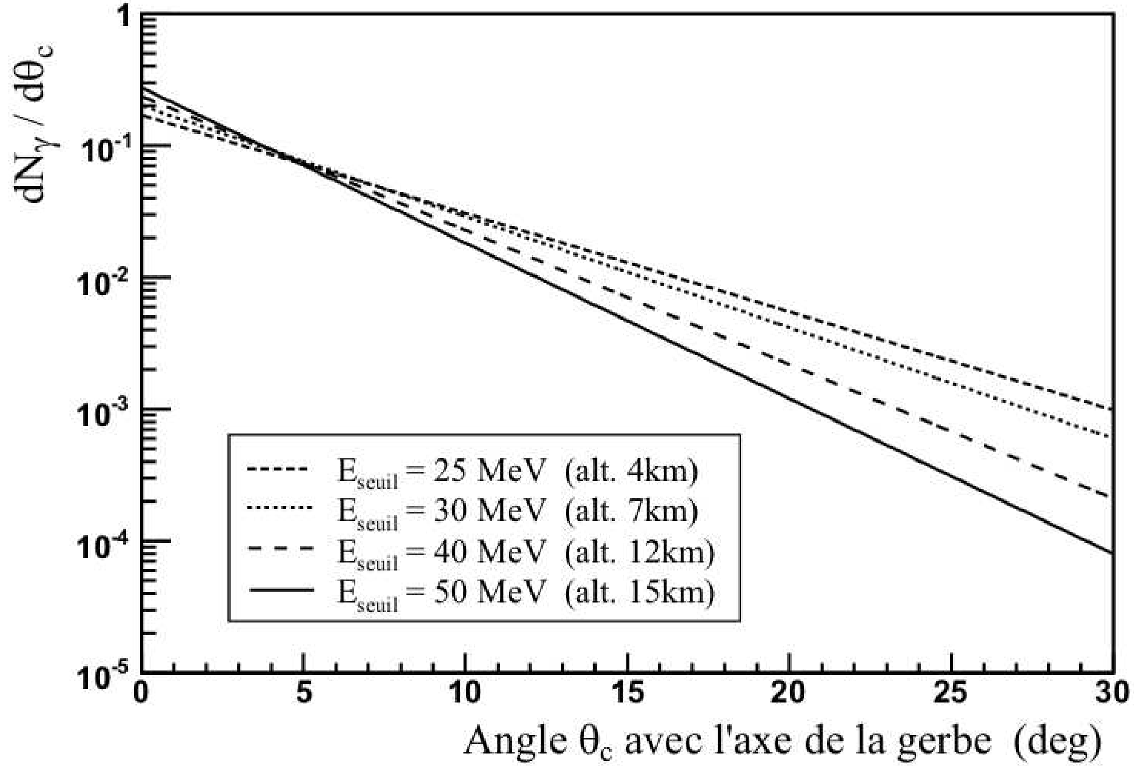


Cerenkov Radiation : angular dispersion

- ✔ the angular distribution of the Cerenkov photons is related to the intrinsic charged particle dispersion existing in the air shower
- ✔ the angular dispersion of the photons is parametrized as a function of the photon angle with respect to the shower axis θ and a parameter $\theta_0(E_{th})$

$$\boxed{\frac{dN_\gamma}{d\theta} = \frac{e^{-\left(\frac{\theta}{\theta_0}\right)}}{\theta_0}}$$

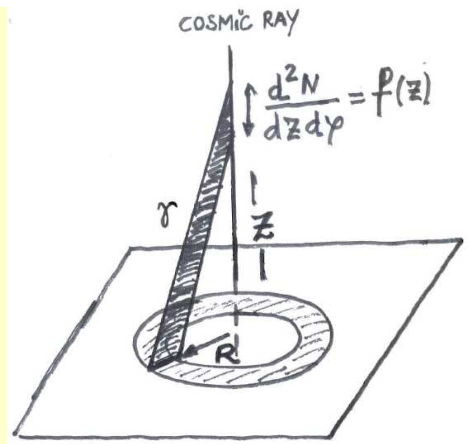
$$\theta_\theta(E_{th}) = 0.80\,\left(\frac{E_{th}}{MeV}\right)^{-0.65}$$



Cerenkov photon density at ground

- The differential number of photons radiated per interval of length (dz) and azimuth ($d\varphi$) within an angle wrt shower axis $[\theta, \theta + d\theta]$:

$$\boxed{d^3N = f(z)dzd\varphi\; P(\theta)d\theta} \qquad \left[P(\theta) = \frac{1}{\theta_0}e^{-\frac{\theta}{\theta_0}}\right]$$



- The photon distribution arriving at earth, making the transformation $\theta \simeq \frac{R}{z}$:

$$\frac{d^3N}{dzd\varphi d\theta} = z\,\frac{d^3N}{dzd\varphi dR} \;\Rightarrow\; \frac{d^3N}{dzd\varphi dR} = \frac{f(z)}{\theta_0 z}e^{-\frac{\theta}{\theta_0}}$$

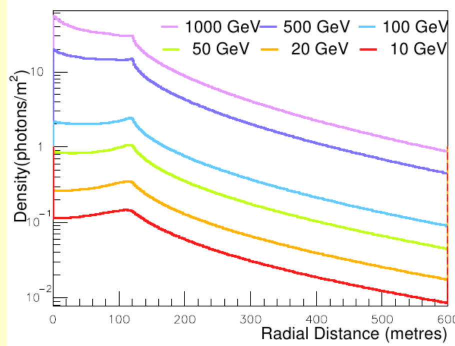
- The radial distrib integrating over the shower path and in azimuth :

$$\frac{dN}{dR} = \int_0^{2\pi} d\varphi \int_0^h dz \frac{f(z)}{\theta_0 z}e^{-\frac{\theta}{\theta_0}} = 2\pi \int_0^h dz \frac{f(z)}{\theta_0 z}e^{-\frac{\theta}{\theta_0}}$$

- The density of photons at ground :

$$dS = RdRd\varphi$$

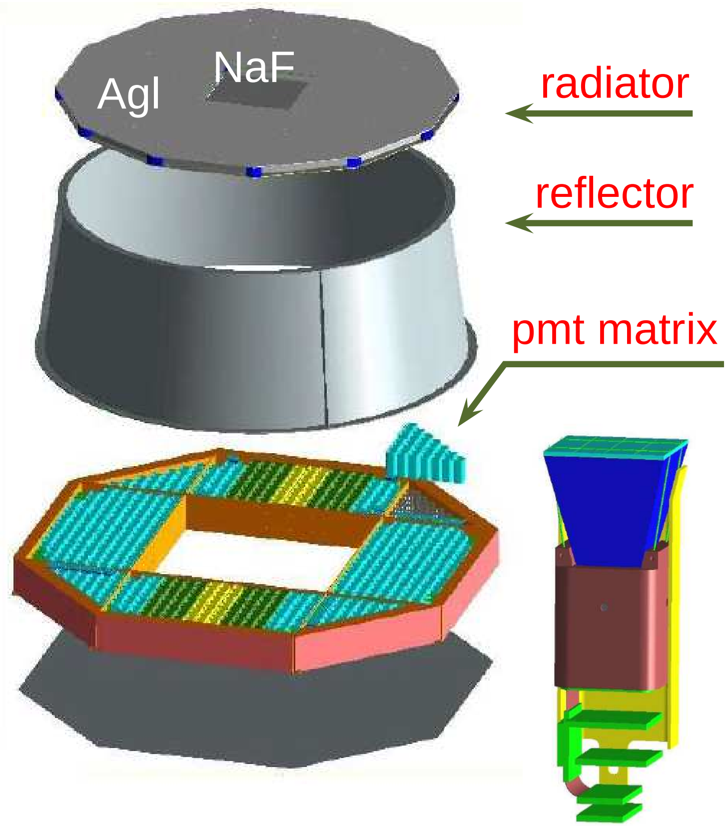
$$\boxed{\frac{dN}{dS} = \frac{1}{R}\int_z \frac{d^3N}{dzd\varphi dR}\,dz = \frac{1}{\theta_0}\frac{1}{R}\int_0^h dz \frac{f(z)}{z}e^{-\frac{R}{z\,\theta_0}}}$$



AMS : Ring Imaging Cerenkov Detector

Construction

- ✔ proximity focusing Ring Imaging Detector
- ✔ dual solid radiator configuration
  low index aerogel : $n = 1.050$, $2.5\ cm$ thickness
  sodium fluoride : $n = 1.334$, $0.5\ cm$ thickness
- ✔ conical reflector 85% reflectivity
- ✔ photomultiplier matrix
  680 multipixelized (4×4) detectors
- ✔ spatial pixel granularity : $8.5 \times 8.5\ mm^2$



It provides

- ✔ accurate particle velocity measurement
  $\Delta\beta/\beta \sim 0.1\%$ for protons
- ✔ electric charge determination
  $\Delta Z \sim 0.2$
- ✔ albedo rejection
  directional sensitivity

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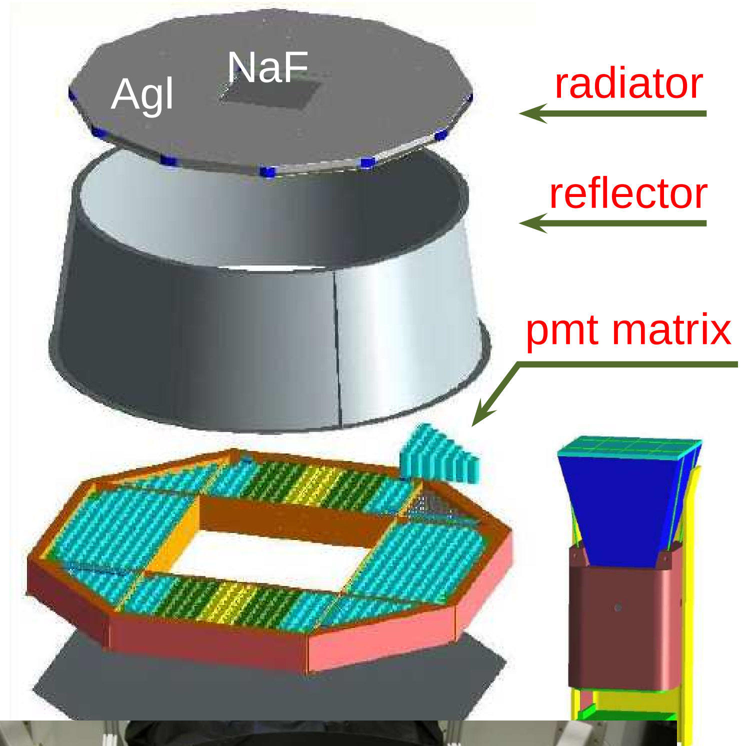
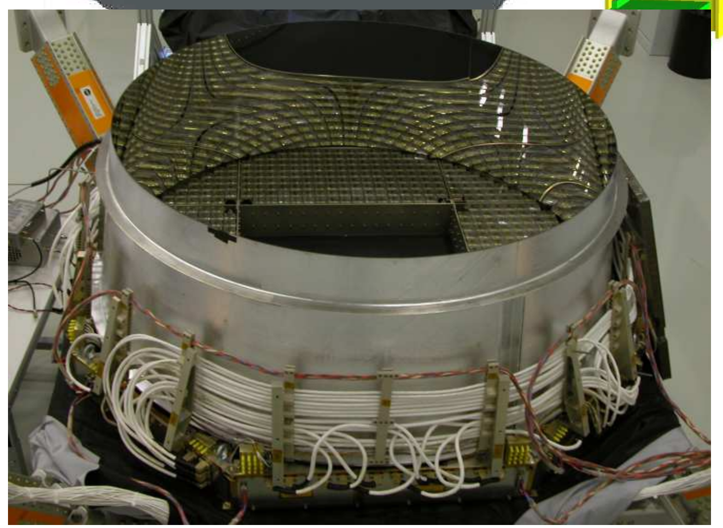
  directional sensitivity

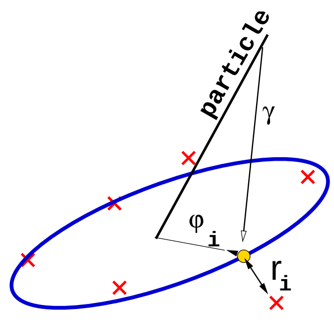


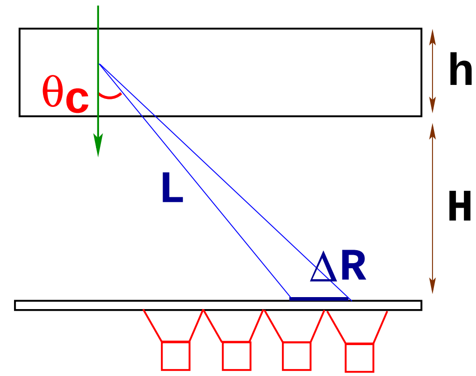


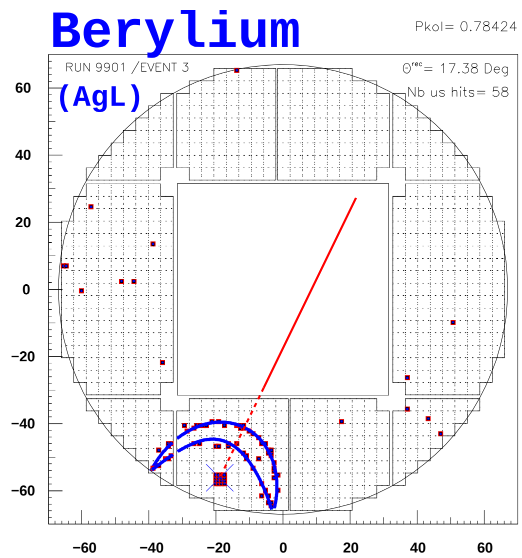
Velocity measurement with the RICH

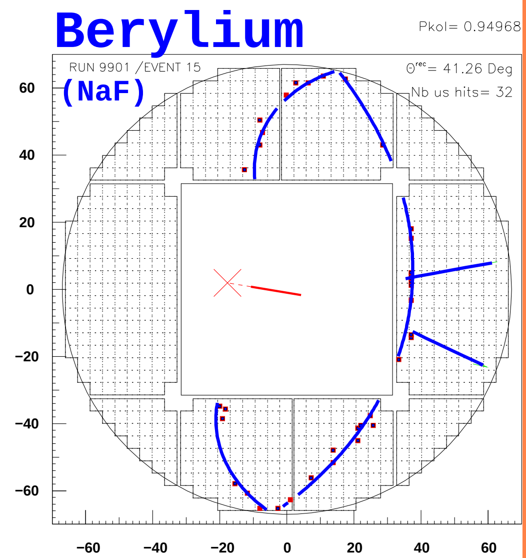
- ✔ The AMS Tracker provides the **particle direction** (θ, ϕ) and **impact point** at the RICH radiator
- ✔ **Ring of cerenkov photons** is function of θ_c
  geometrical and likelihood methods applied to reconstruct θ_c
- ✔ Velocity obtained from θ_c measurement

$$\boxed{\beta = 1/n \ \cos\theta_c}$$









Velocity measurement with the RICH

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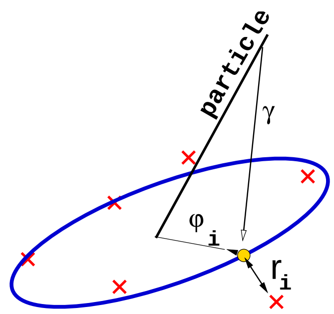
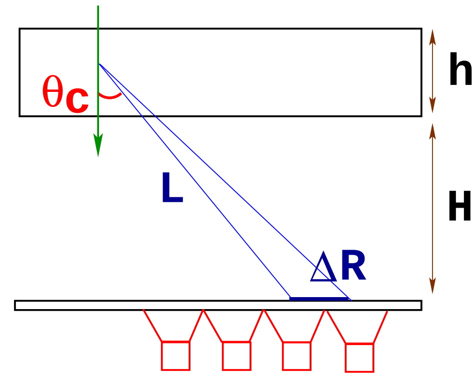




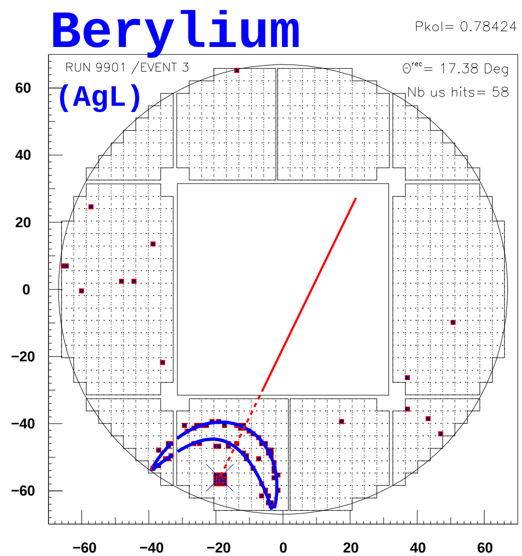
- Velocity obtained from θ_c measurement
  $\boxed{\beta = 1/n \ \cos\theta_c}$
- sources of β uncertainties :
  - pixel size (8.5 mm)
  - radiator chromaticity, $n(\lambda)$
  - radiator thickness $(h \tan\theta_c)$
    photon emission point unknown

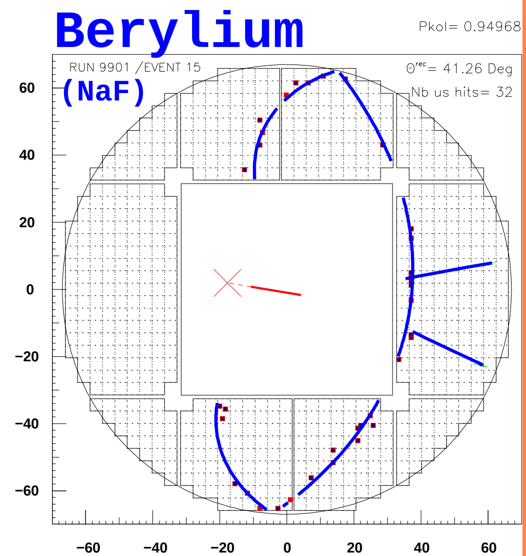
$$\boxed{\frac{\Delta\beta}{\beta} = \tan\theta_c \frac{\Delta\theta_c}{\sqrt{N_{pe}}}}$$

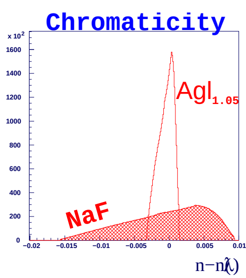
$$\boxed{\Delta\theta_c = (\Delta\theta_c)^{pixel} \oplus (\Delta\theta_c)^{thick} \oplus (\Delta\theta_c)^{chrom}}$$

$$\boxed{\Delta\theta_c^{(i)} \simeq \frac{\Delta R_i}{H}\cos^2\theta_c}$$ i=pixel,thickness

$$\boxed{\Delta\theta_c^{(i)} \simeq \frac{1}{\tan\theta_c}\frac{\Delta n}{n}}$$ i=chromat.





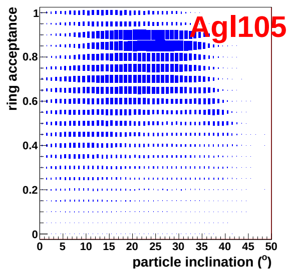


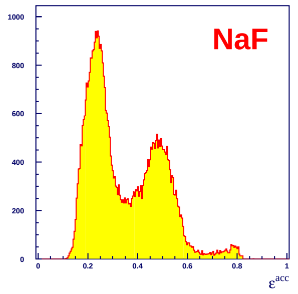
	$\Delta\theta_c^{geom}$ (mrad)		$\Delta\theta_c^{chrom}$ (mrad)	$\Delta\theta_c$ (mrad)	$(\Delta\beta/\beta)_{hit}$ $(\beta \simeq 1)$
	$\Delta\theta_c^{thick}$	$\Delta\theta_c^{pixel}$			
AGL	3.3	4.6	3.2	6.5	**$2.1\ 10^{-3}$**
NaF	0.3	0.6	4.8	4.8	**$4.2\ 10^{-3}$**

RICH velocity reconstruction : results

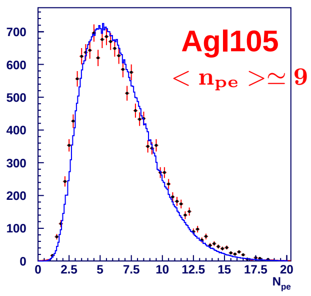
Simulation results

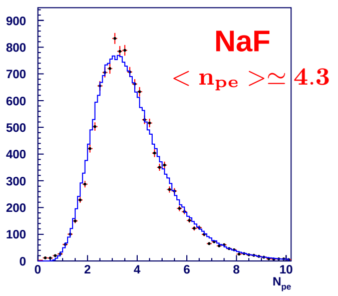
Geom acceptance



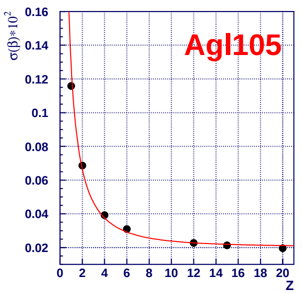


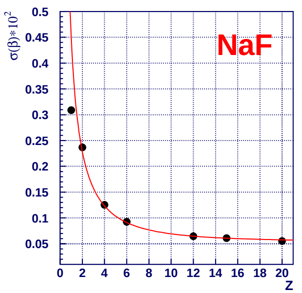
number of photoelectrons



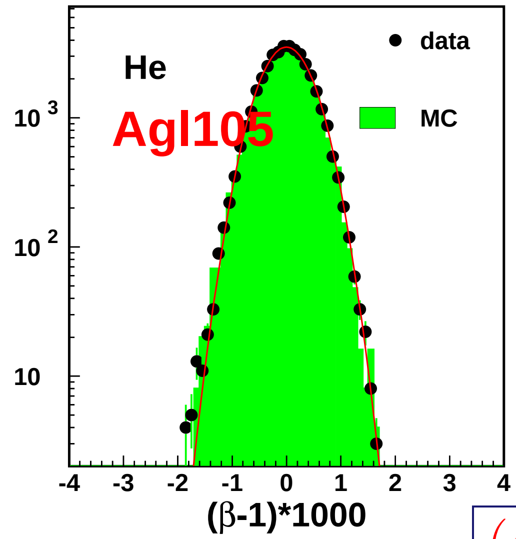


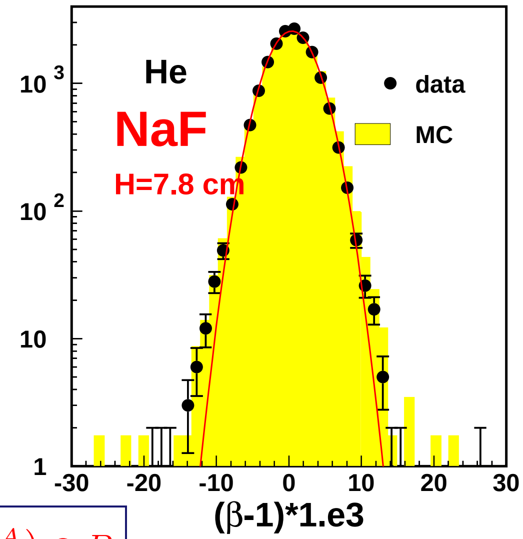
velocity reconstr error



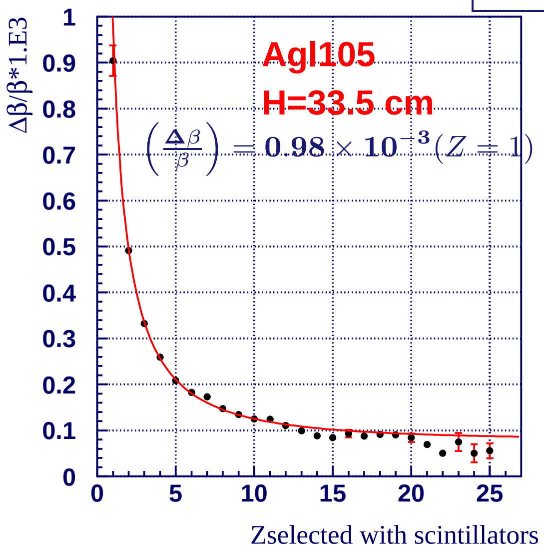


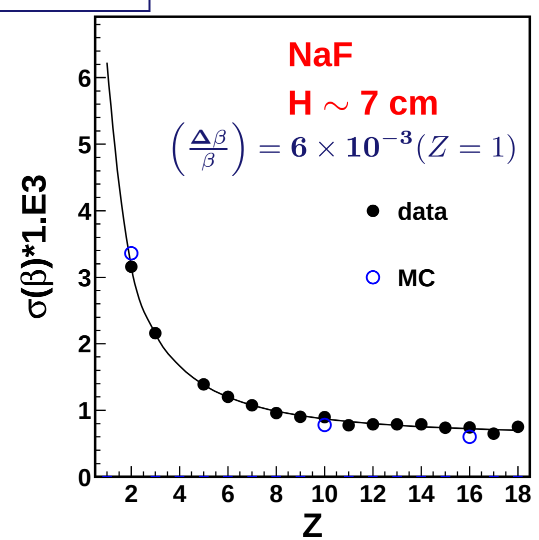
Test Beam (2003) results : fragmented ions





$$\left(\frac{\Delta\beta}{\beta}\right) = \left(\frac{A}{Z}\right) \oplus B$$





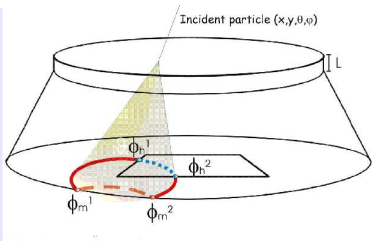
Charge determination with the RICH

- ✔ Charge determination :

  $$\boxed{Z^2 \propto \frac{N_{p.e}}{\varepsilon}}$$

  $\varepsilon \equiv$ ring efficiency

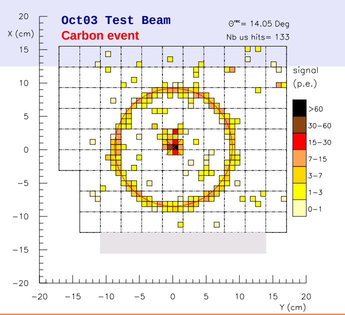
  ring acceptance, γ absorption,...

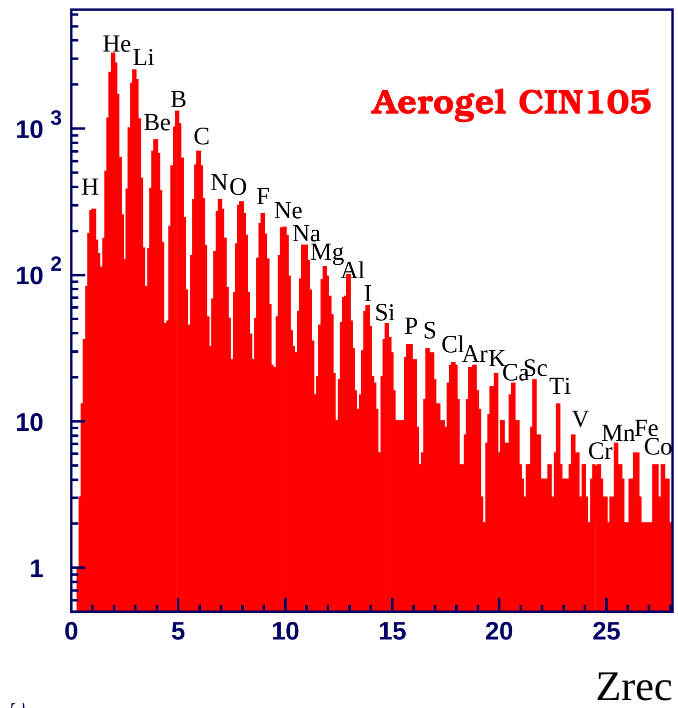


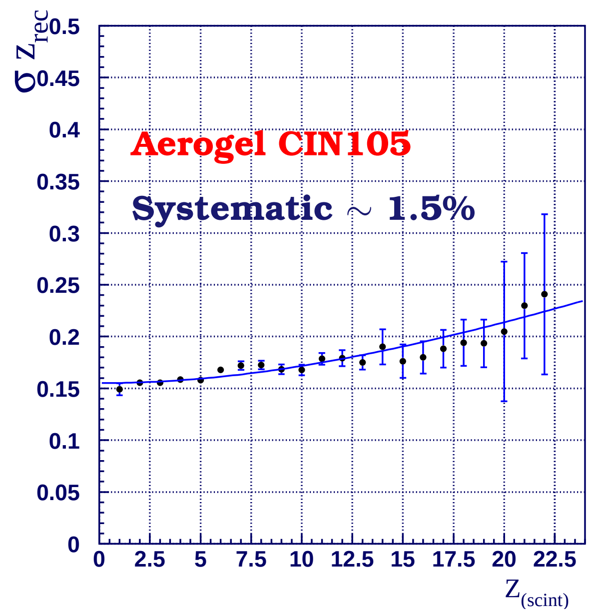
- ✔ Z Uncertainties :
  - ▶ statistical : $\Delta N_{p.e} = \sqrt{N_{p.e}\left(1+\sigma^2_{p.e}\right)}$
  - ▶ systematics from non-uniformities :
    - radiator : n, thickness, clarity, ...
    - detection : LG, PMT, temperature effects, ...

$$\boxed{\Delta Z = \frac{1}{2}\sqrt{\frac{1+\sigma^2_{p.e}}{N_0} + Z^2\left(\frac{\Delta\varepsilon}{\varepsilon}\right)^2}}$$

- ✔ results from test beam (2003) with fragmented ions







Scintillation radiation

mechanisms, characteristics, measurements

Charged particles ionization (dE/dx)

The energy lost by a charged particle while traversing a medium was obtained by Bethe and Bloch :

$$-\frac{1}{\rho}\frac{dE}{dx} \equiv -\frac{dE}{dt} = \underbrace{2\,\pi\,N_A\,r_e^2\,m_e c^2}_{0.1535\quad MeV\cdot cm^2.g^{-1}}\;\frac{Z}{A}\,\frac{z^2}{\beta^2}\left[\ln\left(\frac{2\,m_e\,\gamma^2\,v^2\,T_{max}}{I^2}\right) - 2\beta^2 - \delta\right]$$

r_e electron classical radius
($r_e = 2.817 \times 10^{-13}$ cm)
$r_e = \frac{e^2}{4\,\pi\,\varepsilon_0\,m_e c^2}$

m_e electron mass ($m_e = 0.511$ MeV/c^2)

N_A Avogradro's number ($N_a = 6.023 \times 10^{23}$ mol^{-1})

ρ medium density

z particle electric charge

Z medium atomic number (nb of electrons)

A medium mass number (nb of protons and neutrons)

I Excitation mean energy

$$\frac{I}{Z} = \begin{cases} 12 + \frac{7}{Z}\ [eV] & (Z<13) \\ 9.76 + 58.8Z^{-1.19}\ [eV] & (Z>=13) \end{cases}$$

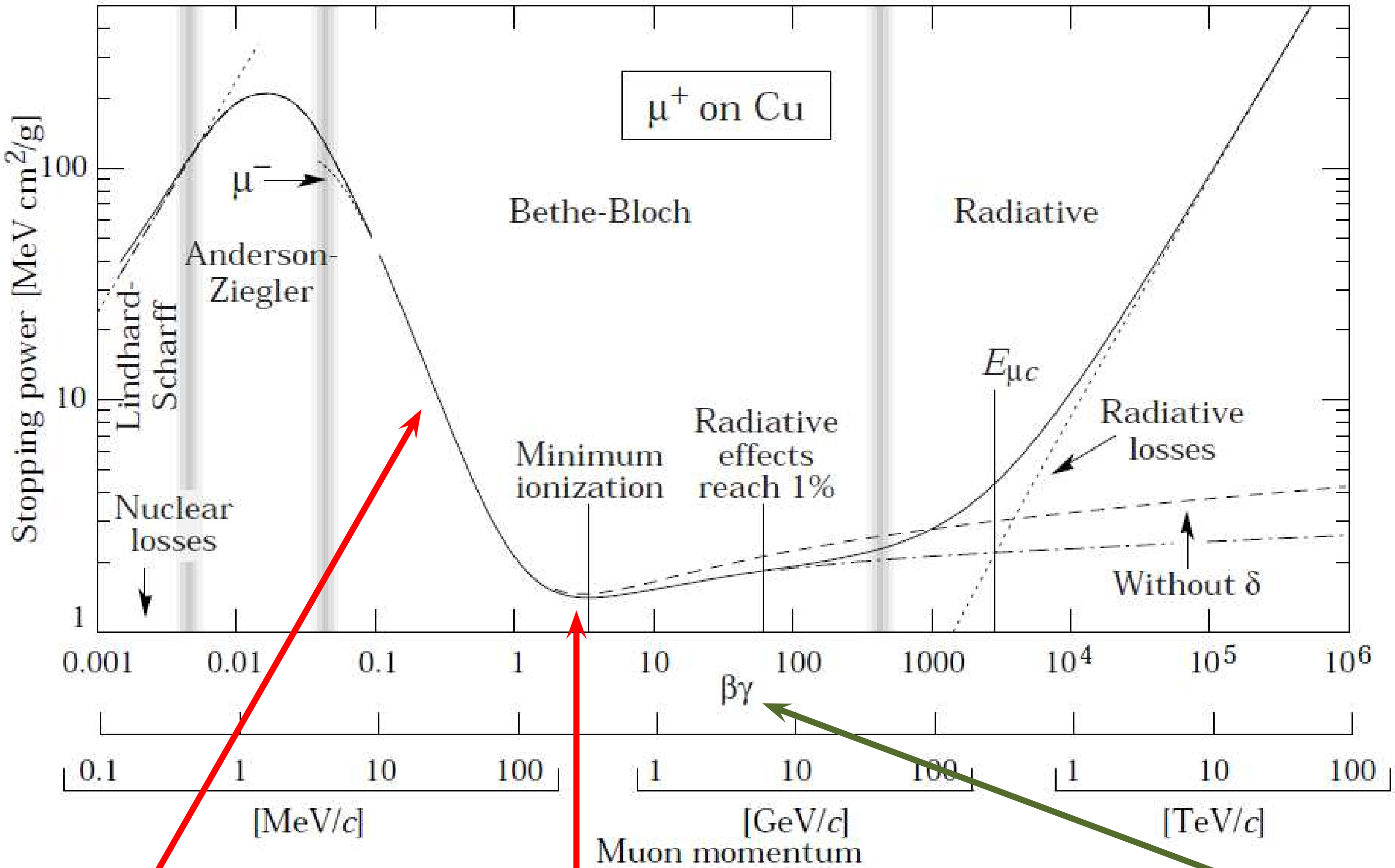
β particle velocity ($\beta = \frac{v}{c}$)

γ Lorentz factor ($\gamma^{-1} = \sqrt{1-\beta^2}$)

δ density correction

T_{max} maximal energy transfered in collision
$T_{max} \sim 2\,m_e c^2\,\beta^2\,\gamma^2 \quad (M >> m_e)$

Muon energy loss in Copper



$$\frac{dE}{dx} \propto \frac{1}{\beta^2}$$

minimum ionizing region
relativistic rise

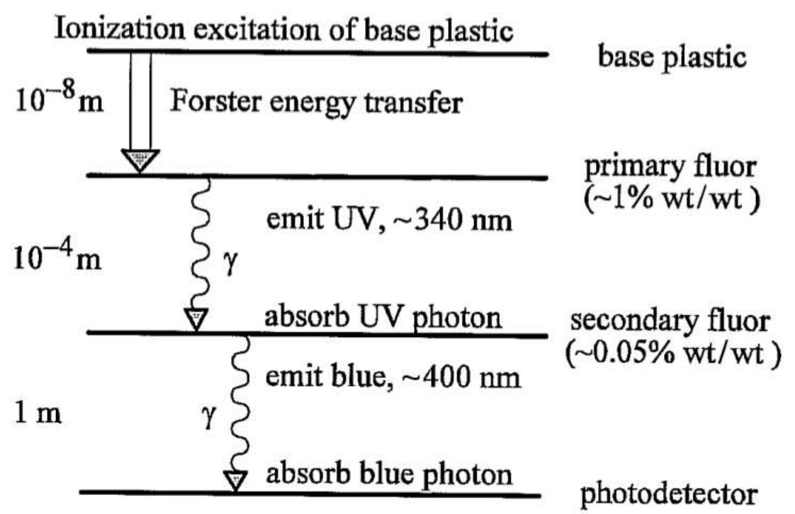
$\gamma\beta = \frac{p}{m}$
turns β scale vis

Scintillation : principles

- A particle traversing a medium causes its ionization through interaction with the atomic electrons of the medium
- Part of this ionization energy is tranformed into **excitations** that will produce **scintillation light** in the sub-sequent de-excitation process - materials are said to be **luminiscent**
- The decay of the excited sttes is made through the re-emission of the absorbed energy in terms of light
  fast decay - **fluorescence**
  slow decay - **delayed fluorescence or phosphorescence**

The light emitted in the primary fluorescence is of ultraviolet nature and easily absorbed in most organic *transparent* materials

A second fluorescent material can be introduced to make the ultraviolet light absorption and consequent re-emission at higher wavelenghths ***wavelentgh shifter***



Scintillation materials : organic

✔ **Organic**

stilbene, anthracene : hidrogen, carbon, oxygen constituents

luminiscent emission comes from molecules de-excitation

- low Z materials
- less *light yield* than inorganic
- ligth response very fast ($\sim nsec$)
  $N(t) = Ae^{-t/\tau_f} + Be^{-t/\tau_s}$
- plastic scintillators are vey popular because are easily machined
  organic scintillator dissolved in a solvent (polyvyniltoluene, polymethylmethacrylate) subsequently polimerized

  affected by aging that decreases the light yield
  can develop surface micro-cracks (contacts with solvents or oils)

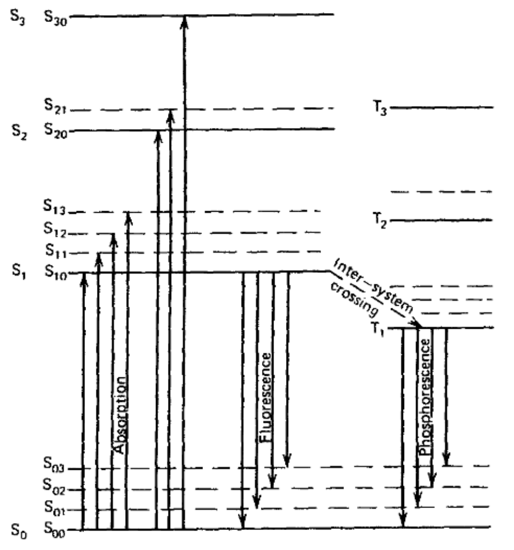
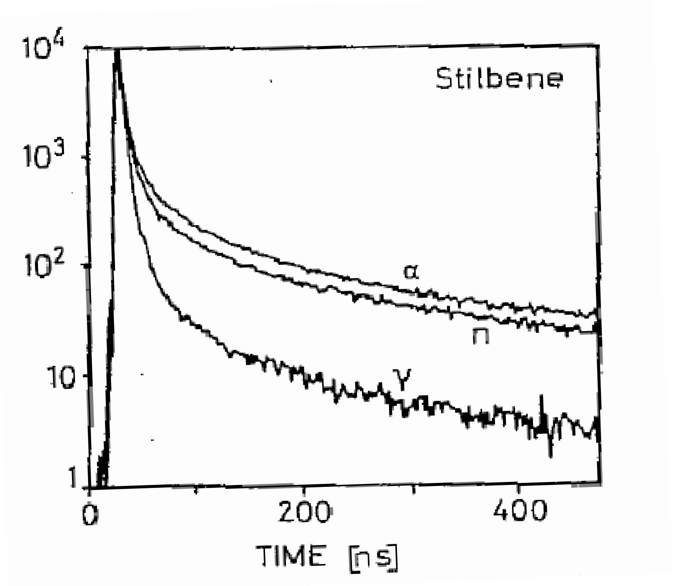


Figure 8.1 Energy levels of an organic molecule with π-electron structure. (From J. B. Birks, *The Theory and Practice of Scintillation Counting*. Copyright 1964 by Pergamon Press, Ltd. Used with permission.)



Scintillation materials

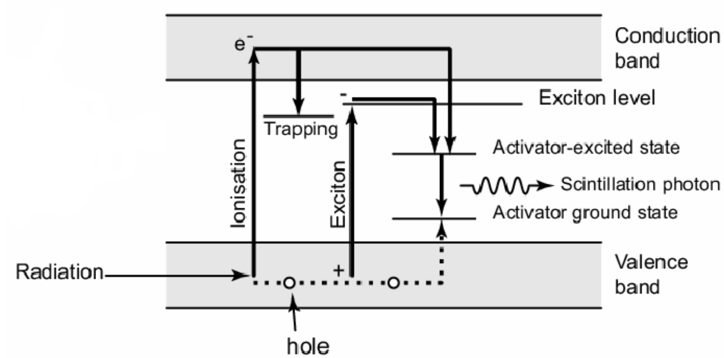
✔ **Inorganic**

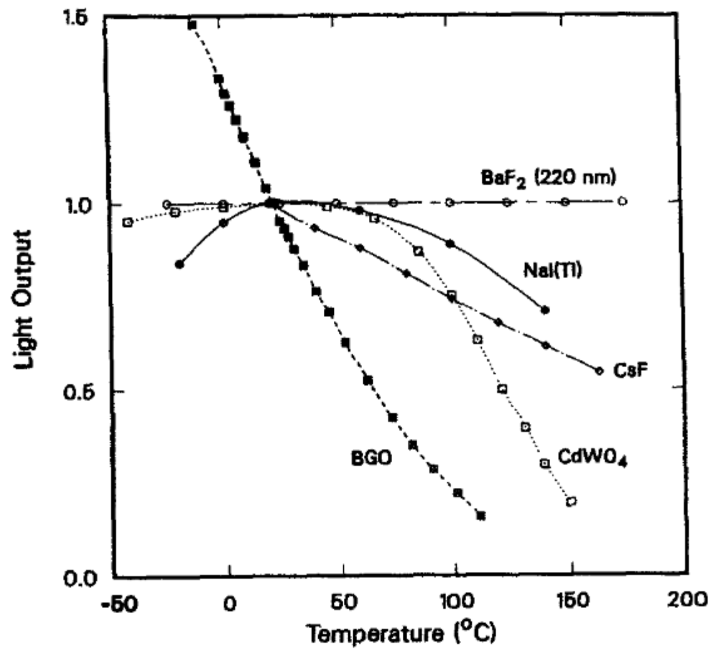
ionic crystalls doped with an activator

luminiscent emission comes from energy transitions in the crystal lattice

impurities (*activators*) are added to increase the light efficiency

- ▶ large densities and Z : cristals NaI, CsI, BGO, BaF2, ...
- ▶ good *light yield*
  better energy resolution
- ▶ larger stopping power compared to plastics
- ▶ can be hygroscopic (absorb water)
- ▶ a large component of phosphorecence light is present (~ 500 nsec)
- ▶ light output rather temperature dependent



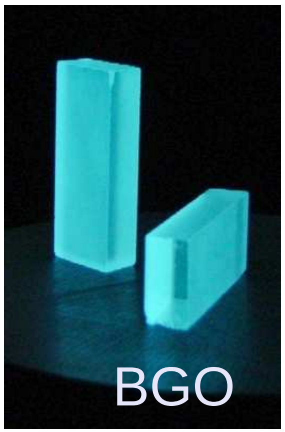


Scintillators

a good scintillator

- ✔ **large effciency** in energy conversion
- ✔ **large transparency** to the fluorescent radiation emitted
- ✔ **emission spectrum** adapted to photodetectors sensitivity
- ✔ **emission response time** small (τ_d)

PLastic coupled to LG

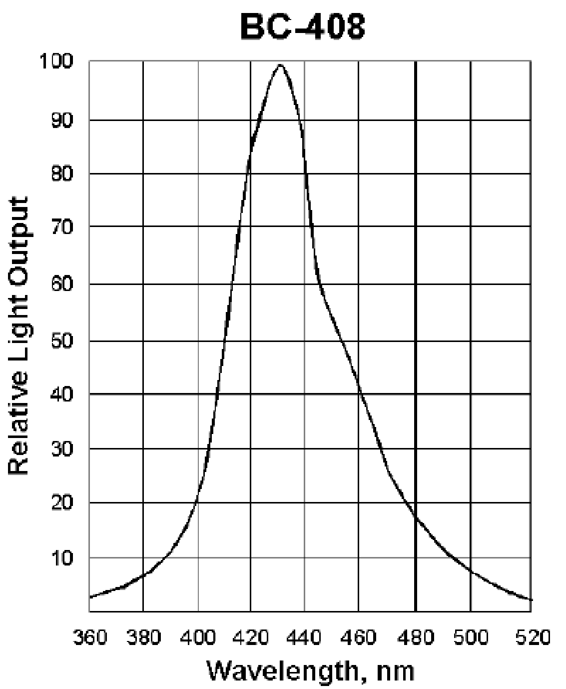


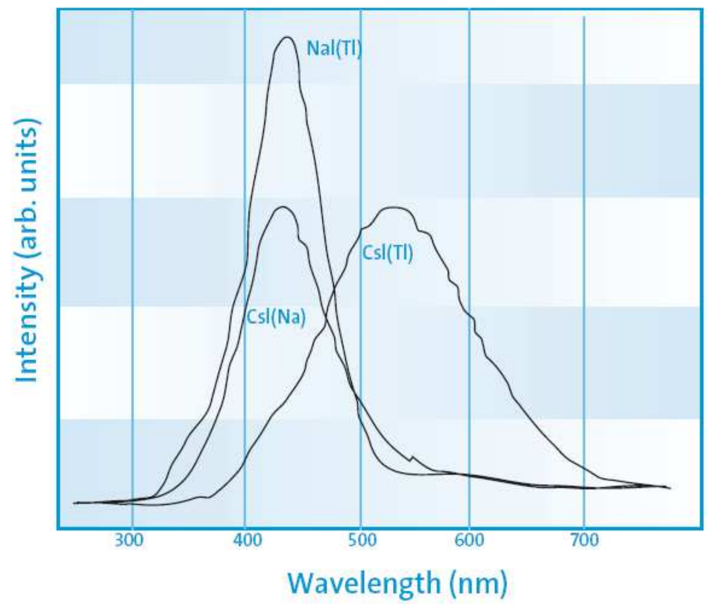
BGO

Cosmic Rays Laboratory (IST/MEFT)

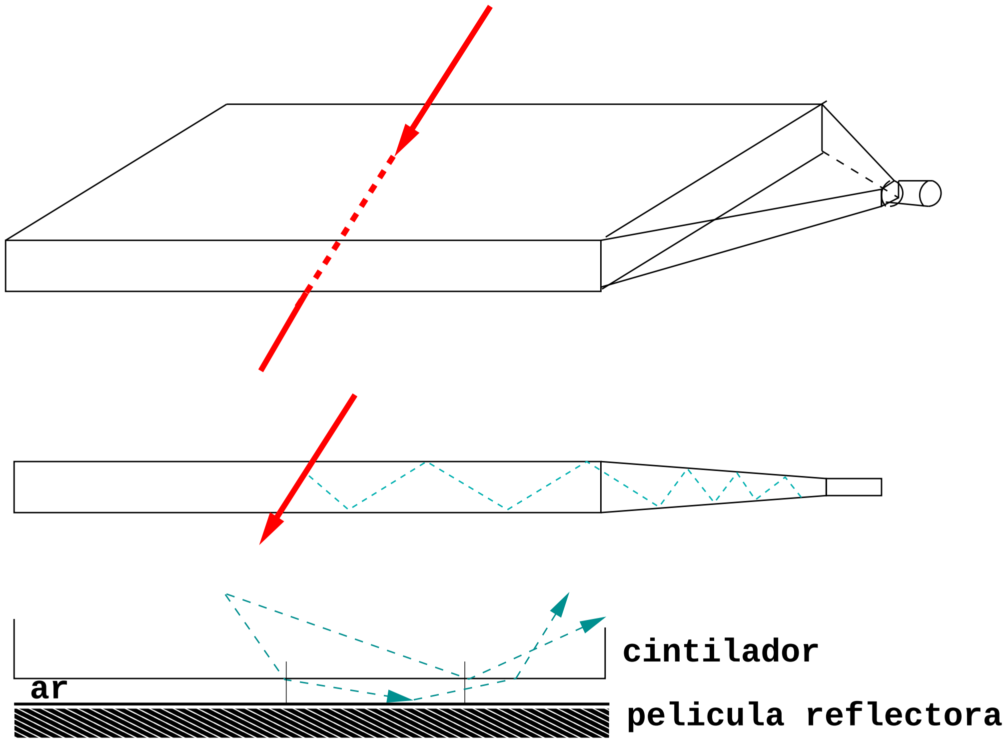
Scintillators properties

Material	eV/photon	τ [nsec]	λ_{max} [nm]	ρ [g/cm^3]	$\frac{dE}{dx}$ (mip) [MeV/cm]	n	Notes
Anthracene	60 (100%)	30	447	1.25		1.62	
Plastic NE104	88 (68%)	1.9	406	1.032	~ 2	1.58	
NaI	26 (230%)	230	413	3.67	4.8	1.85	Hygro
CsI(Na)	90 (150%)	650	420	4.51	~ 5	1.79	
BGO	173	300	480	7.13	9.2	2.20	





Scintillator counter



The plastic scintillator counter is glued to a trapezoidal light guide. All the set is wrapped loosely with an aluminium foil to assure the existence of an air layer close to the scintillator counter. The detector light tightness is assured by wrapping all the counter with black tape.

- ✔ Charged particle transfers energy to scintillator by ionization

  $$\Delta E \sim \frac{dE}{dx}\, L$$

- ✔ Photons are emitted isotropically

  $$\frac{dN_\gamma}{d\Omega} = c^{te}$$

- ✔ Total reflection for photons inciding with large angles on the scintillator-air interface (multiple internal total reflections are done at the surfaces)

  $$\theta_i > arcsin(n)$$

- ✔ There can be light attenuation for large photon distances (~ 1 m)
- ✔ Light guide coupled to scintillator carries photons to the photon detector

Plastic scintillator : light yield

What is the light output of the scintillation counter existing in the Lab Cosmic Rays having a size $100 \times 50 \times 1$ cm and 1 cm thick ?

- Energy lost by *mip* particle

  $\Delta E \sim 2\ [MeV \cdot cm^2/g] \times 1.032\ [g/cm^3] \sim 2$ [MeV/cm]

- Number of emitted photons

  1 photon emitted for every $\sim$ 90 eV of lost energy

  $N_\gamma \sim \frac{\Delta E}{90} \sim \frac{2\times 10^6}{90} \sim 2.2 \times 10^4\ \gamma$/cm

- Detector acceptance

  at 1st order let's only account for the photons that arrive directly to the light guide entrance or through total reflection $\quad \varepsilon \sim 10^{-2}$

- $\boxed{\Delta E \sim 2 \text{ [MeV/cm]}}$
- $\boxed{N_\gamma \sim 2.2 \times 10^4\ \gamma\text{/cm}}$
- $\boxed{\varepsilon \sim 10^{-2}}$

$$\varepsilon = \frac{\Delta \cos\theta\ \Delta\phi}{4\ \pi}$$

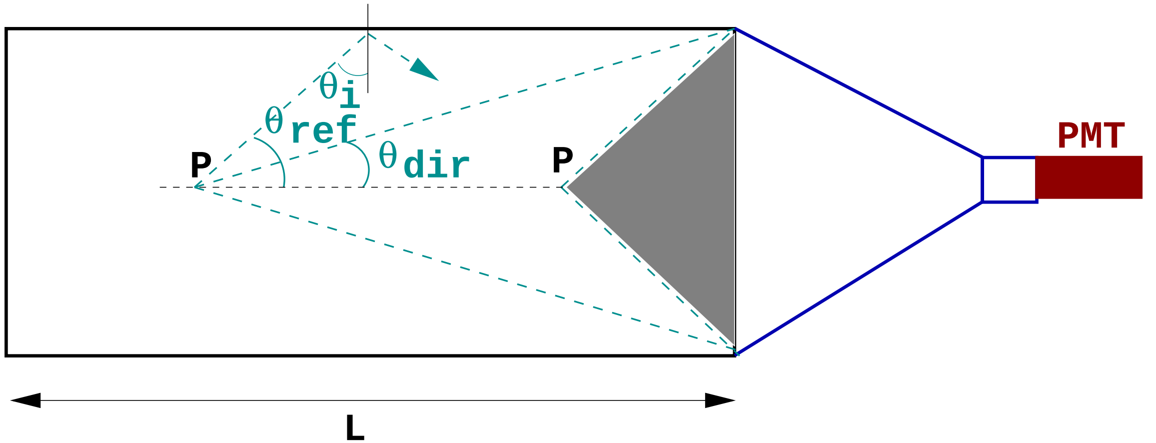
$$\Delta \cos\theta = 1 - \cos\theta_{ref}$$

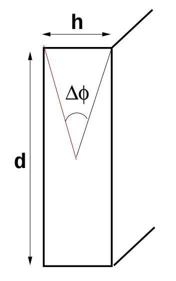
$$(\theta_{ref} + \theta_i = \tfrac{\pi}{2})$$

$$\cos\theta_{ref} = -\sin\theta_i = -\frac{1}{n}$$

$$\boxed{\Delta \cos\theta_{ref} = 1 + \frac{1}{n}}$$

$$\boxed{\Delta\phi = 2 \times \frac{h}{2\ d}}$$



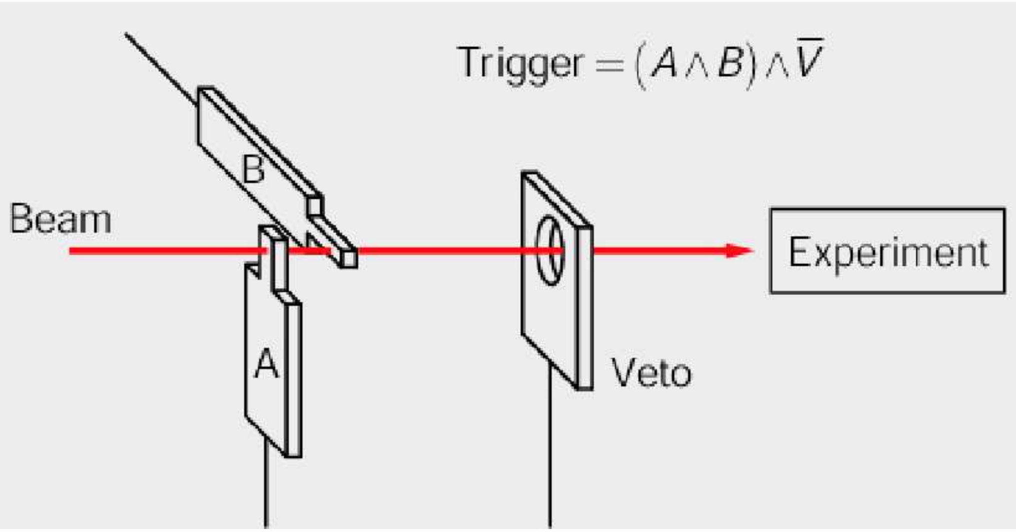


$$\varepsilon = \frac{(1+1/n)\ (h/d)}{4\ \pi}$$

Triggering with scintillators

The rapid time response of plastic scintillators (~ nsec)is used to build the fast trigger system of particle physics experiments

several counters are placed in coincidence or anticoincidence



Scintillators : velocity measurement

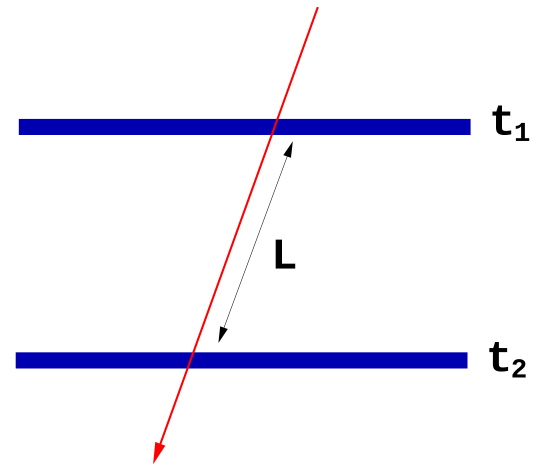
- Particle velocity can be measured from the crossing times on scintillator planes
- Usually, both scintillator ends are instrumented with photodetectors and an average time is derived : $< t >= \frac{1}{2}(t_i + t_f)$
  $\sigma_t \sim 100$ psec
- The time that particle takes to cross both planes : $t = L/\beta c$
- Velocity uncertainty for a distance $L = 1$ m :

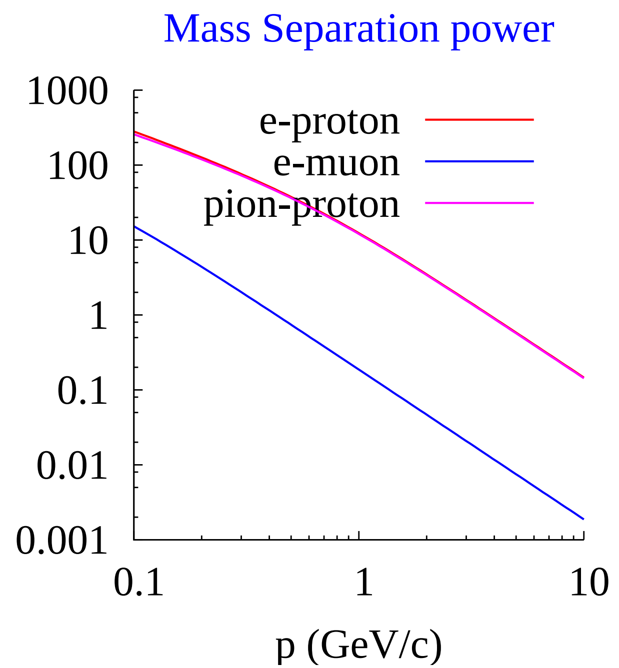
$$\frac{\sigma_\beta}{\beta} = \frac{\sigma_t}{t} \sim \frac{100\ psec}{3\ nsec} \sim 3\%$$

- Mass separation power :

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

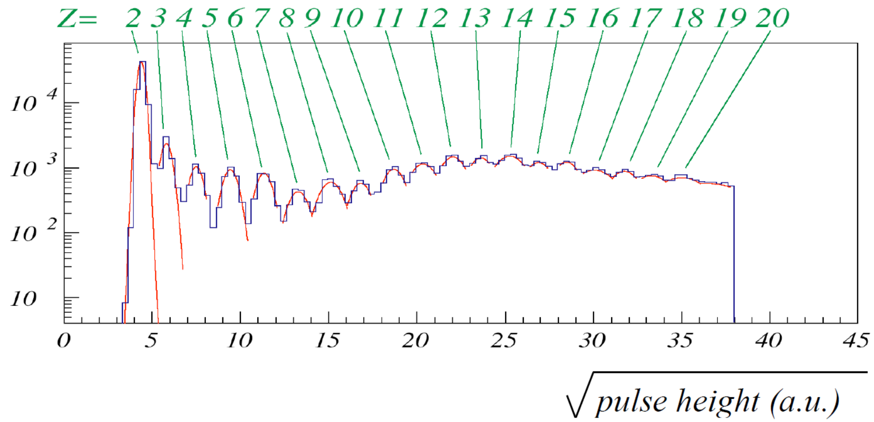
$$= \frac{L}{c\sigma_t}\left(\sqrt{1+\left(\frac{m_1}{p}\right)^2} - \sqrt{1+\left(\frac{m_2}{p}\right)^2}\right)$$



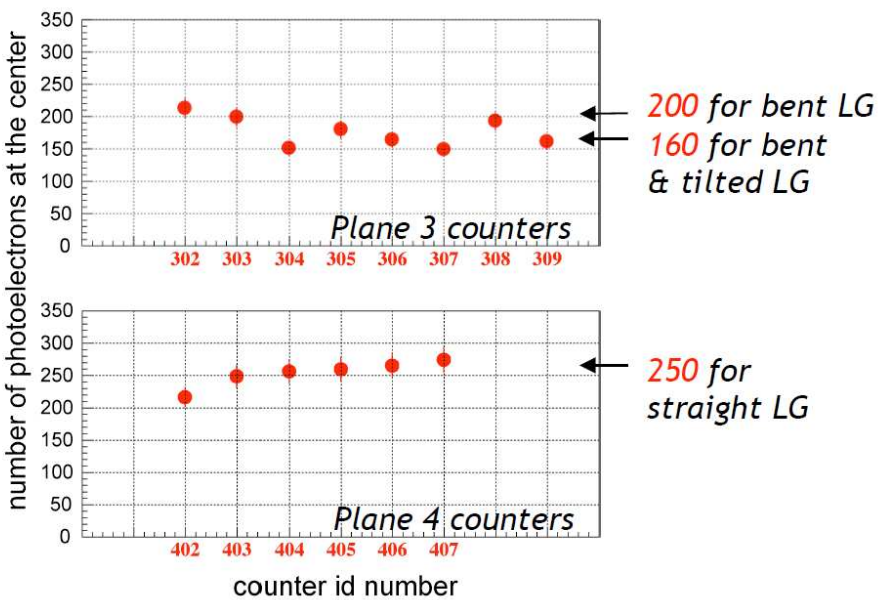


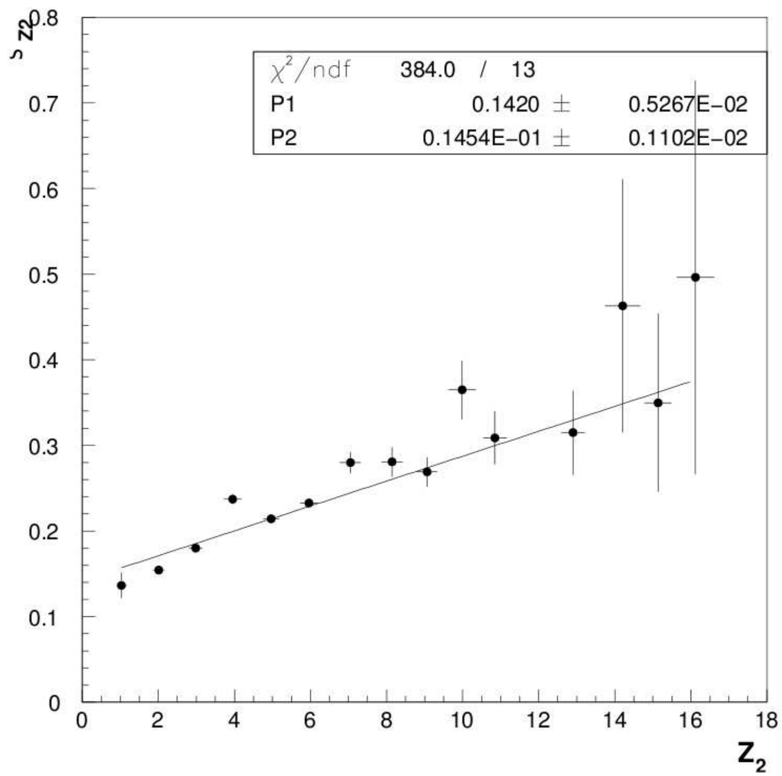
Charge measurement (Z) with TOF

- energy deposited on scintillator
  $\Delta E \propto Z^2$
- up to 4 ΔE samplings
- dominant uncertainty comes from energy deposition fluctuations
- test beam data with fragmented ions
  charge separation up to $Z \sim 15$



Measured number of photoelectrons





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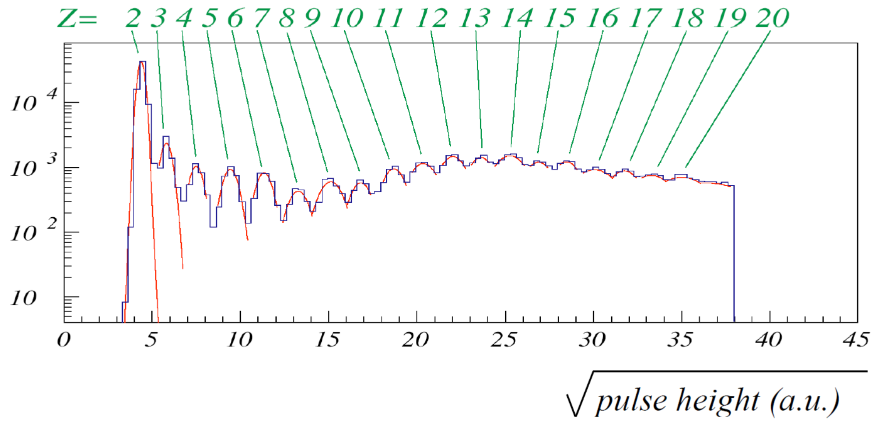
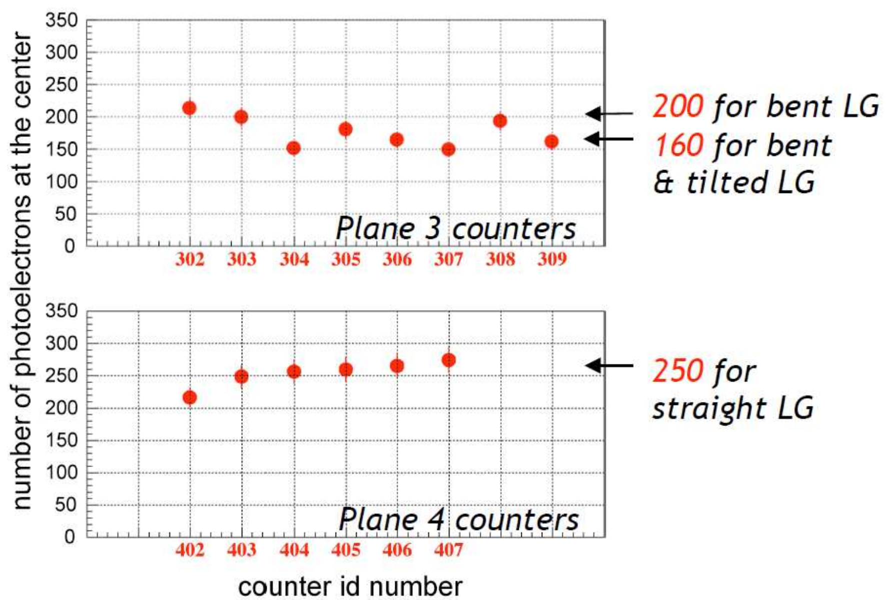
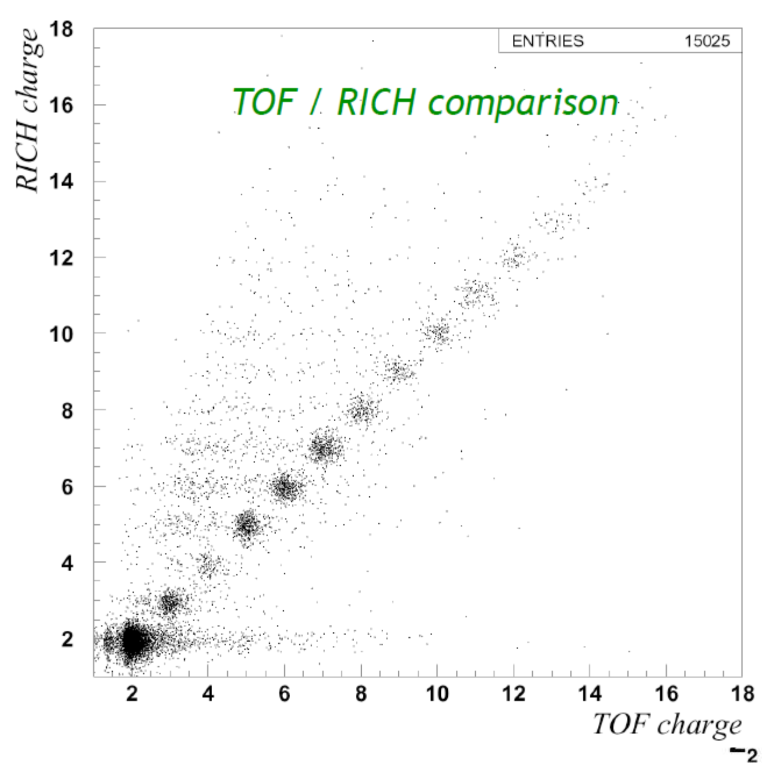


Measured number of photoelectrons





Fluorescence radiation

mechanisms, characteristics, measurements

Air fluorescence : principles

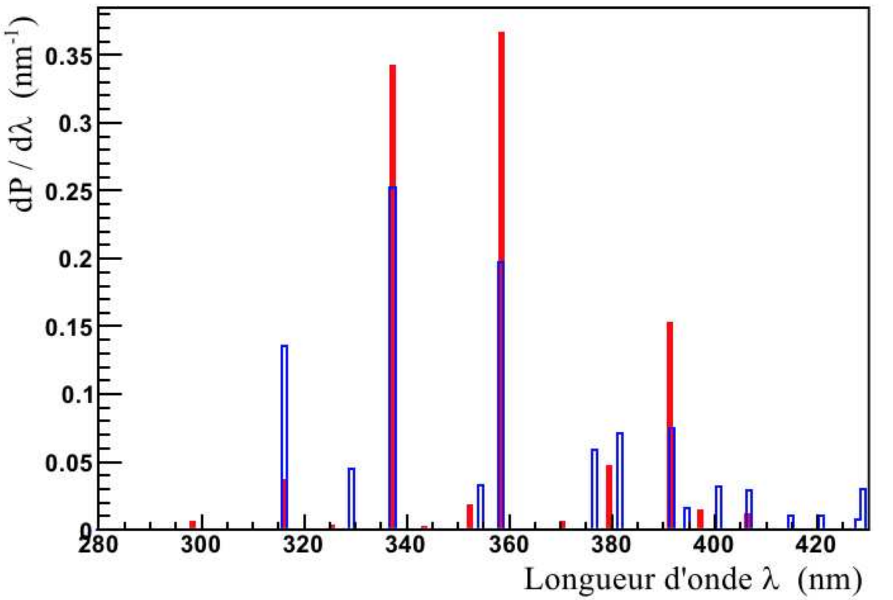
- the electrons of the cosmic ray air shower interact with the nitrogen (N) molecules bringing these to an excited state
- the nitrogen de-excitation is made with the emission of fluorescence photons essentially in the range [300, 400] nm

  isotropic radiation
- there exist the possibility of radiationless de-excitation

  collisions with neighbour molecules

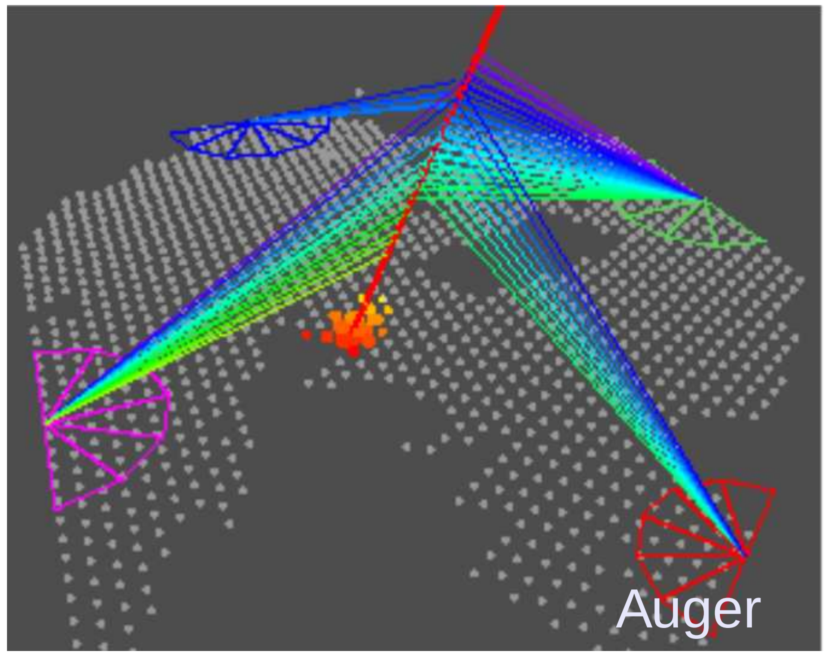
  internal transitions

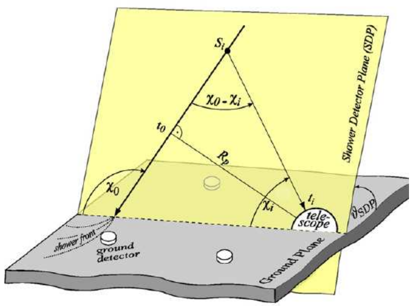
  water vapour
- the fluorescence yield depends on air temperature and pressure

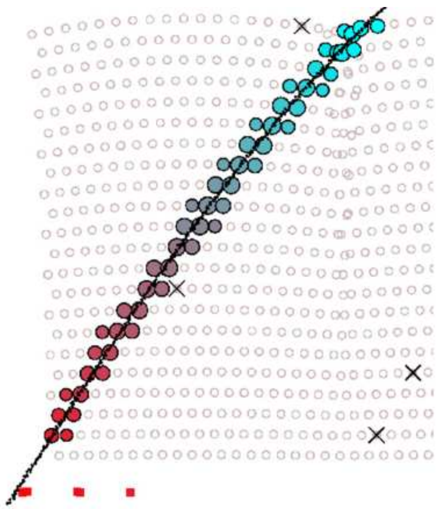


Air fluorescence : applications

- ✔ Fly's Eye detected for 1st time showers fluorescence
- ✔ AUGER experiment has 4 fluorescence detectors (FDs)
  - ▶ measurement of the shower profile
  - ▶ shower direction (time)
  - ▶ shower energy : $E = \sum_i \frac{S_i}{\varepsilon_i}$





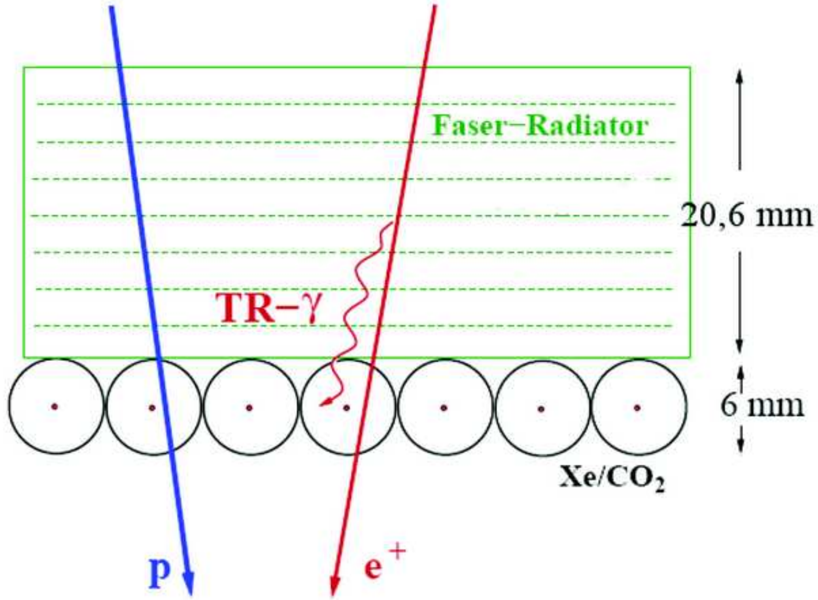


Transition radiation

mechanisms, characteristics, measurements

Transition radiation : principles

- Electromagnetic radiation is emitted when a charged particle traverses a medium with a varying dielectric permitivity (ε)
- A transition radiator will consist on a series of foils and air gaps
  - polyethilene foam
  - fleece
- X-rays are emitted
- To avoid X-ray absorption in radiator foils, its atomic number Z has to be as low as possible
- The X-rays are detected by proportional tubes filled with a mixture of Xe/CO_2 (80%/20%)



Transition radiation : characteristics

differential light yield

the photon energy spectrum in a single interface medium/1 (ω_1) to medium/2 (ω_2) and multiple interfaces.

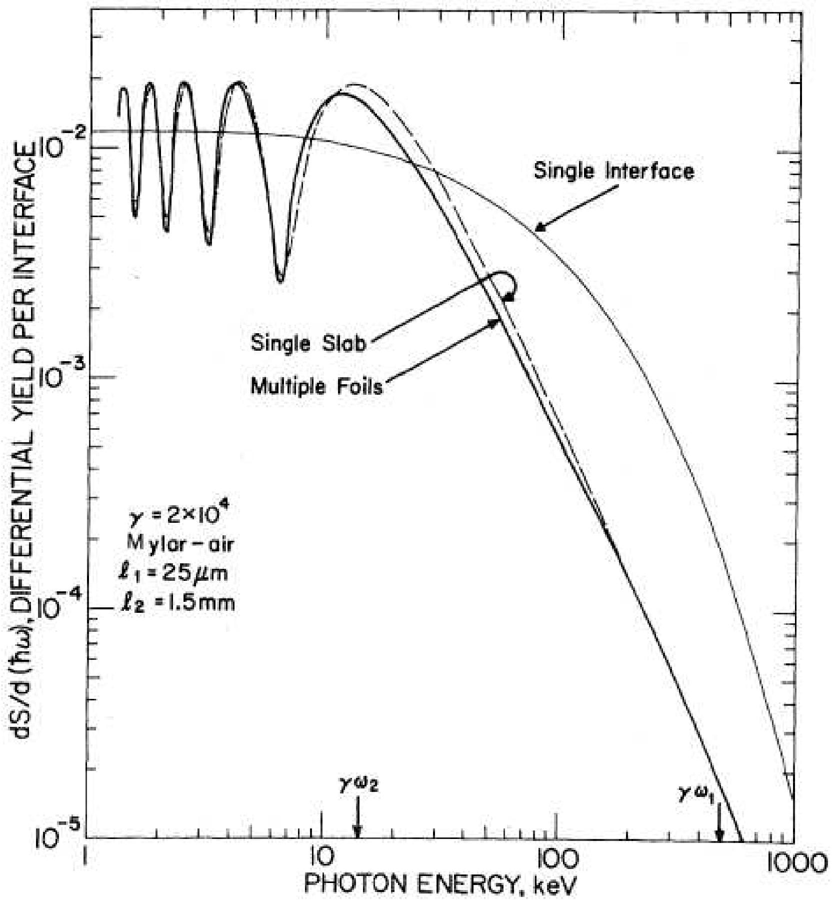
total light yield

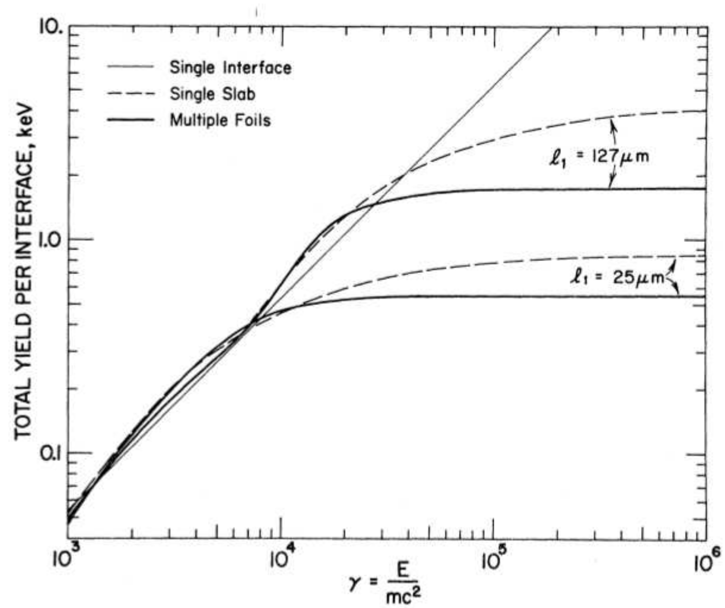
The total energy radiated in one transition medium-air is proportional to the Lorentz factor ($\gamma = \frac{E}{m}$) and depends on the medium plasma frequency (ω_P) : :

ω_P : medium plasma frequency

($\omega_P = \frac{n_e e^2}{\varepsilon_0 m_e} \sim 10^{16}$/s)

$$\boxed{E = \frac{\alpha}{3}\hbar\omega_P\gamma \sim 1.6\ 10^{-2}\ \gamma}\ \text{[eV]}$$





[Cherry et al., PRD10, 11 (1974)]

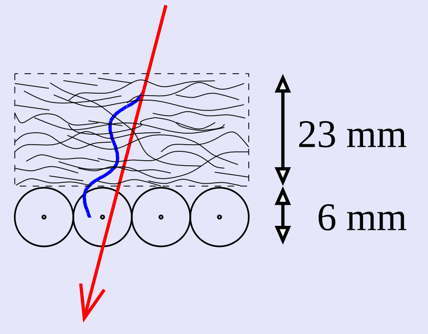
Transition Radiation Detector (TRD)

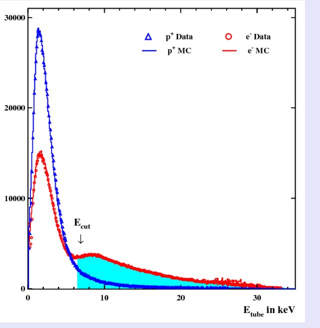
Construction

- ✔ *modules (328) made of fleece radiator and straw tubes*
  - ▶ 16 straw tubes per module
  - ▶ radiator thickness of $23\ mm$
  - ▶ straw tubes ($\Phi = 6\ mm$) filled with Xe/CO_2
- ✔ 20 *layers* assembled on a octogonal shape
  - ▶ 4 layers on upper/lower part along the bending plane
  - ▶ 12 layers on the middle transversally placed

It provides

- ✔ evaluation of the particle $\gamma \equiv \frac{E}{m}$ boost
- ✔ separation of particles with extreme mass differences

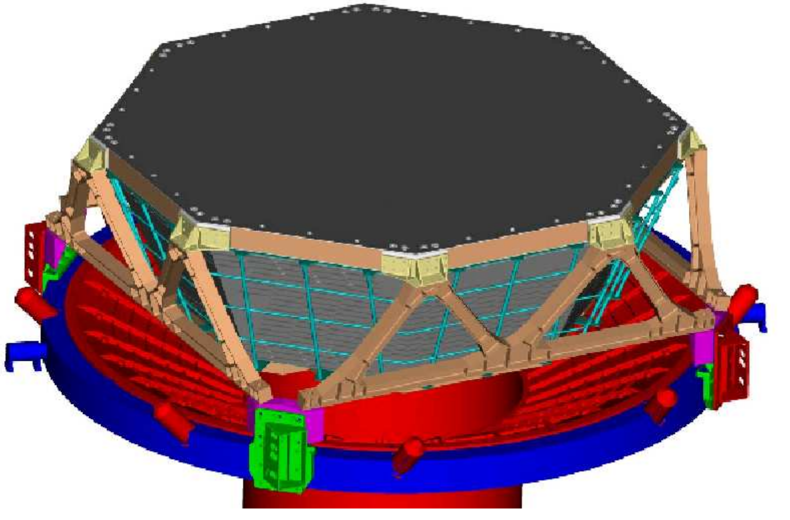




X-ray photons radiated when particle crosses radiator boundaries ($\sim 100\ transitions$)

- $E_\gamma \sim \gamma\ (eV)$
- $N_\gamma \sim \alpha\ N_{transitions}$

detectable signal for $\gamma \gtrsim 1000$



AMS TRD : positron-proton separation

separation estimator

A likelihood estimator can be set taking into account :

- number of hits detected N
- prob densities for positron $P(e)$ and proton $P(p)$

$$\boxed{L = \prod_{i}^{N} \frac{P(e)}{P(e) + P(p)}}$$