Experimentele Technieken

in de Hoge Energie Fysica en verdere toepassingen

Deel 4: kalorimeters en andere detektoren

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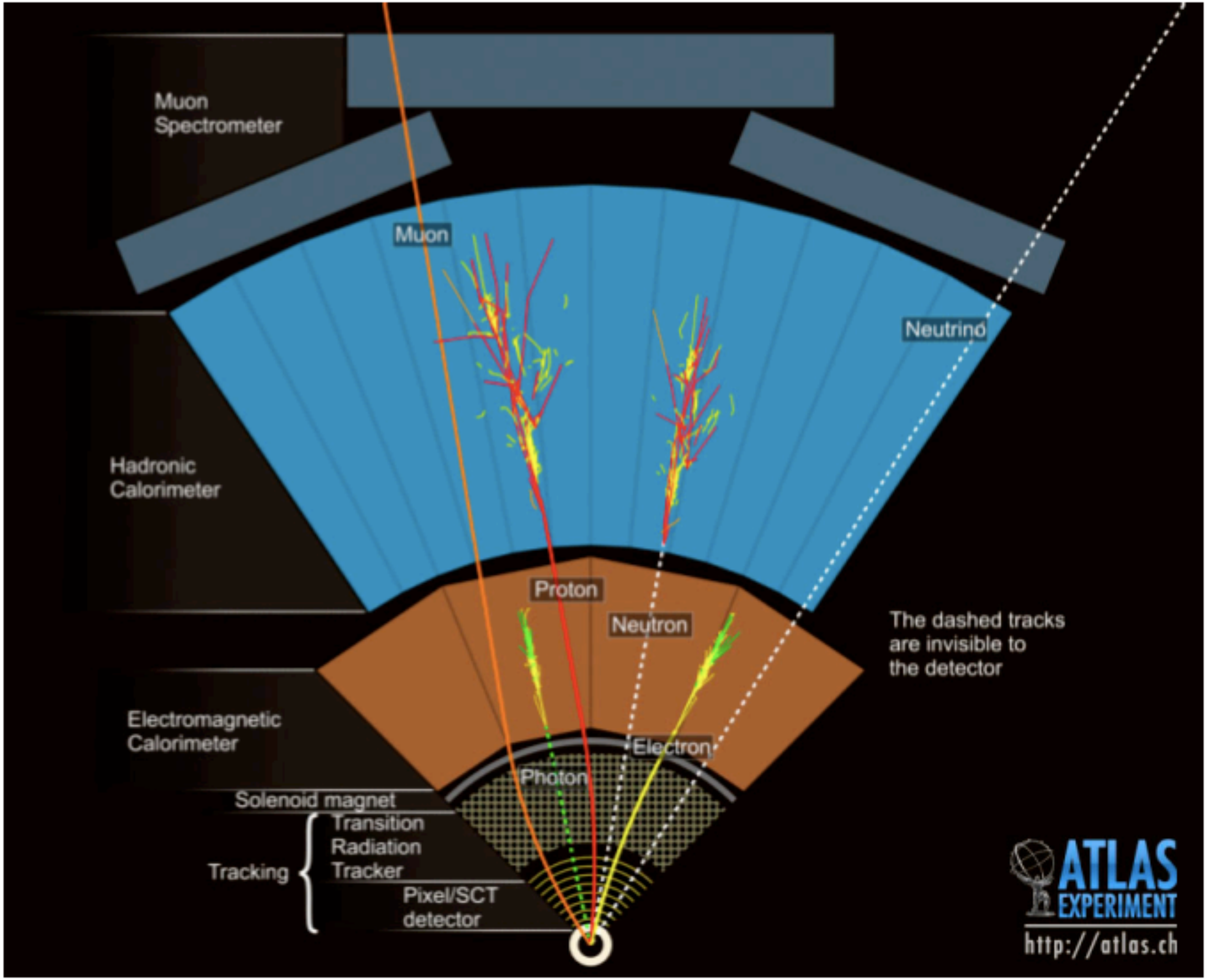

Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT
detector
Muon
Proton
Neutron
Electron
Photon
Neutrino
The dashed tracks
are invisible to
the detector
ATLAS
EXPERIMENT
http://atlas.ch

Interactions with Matter

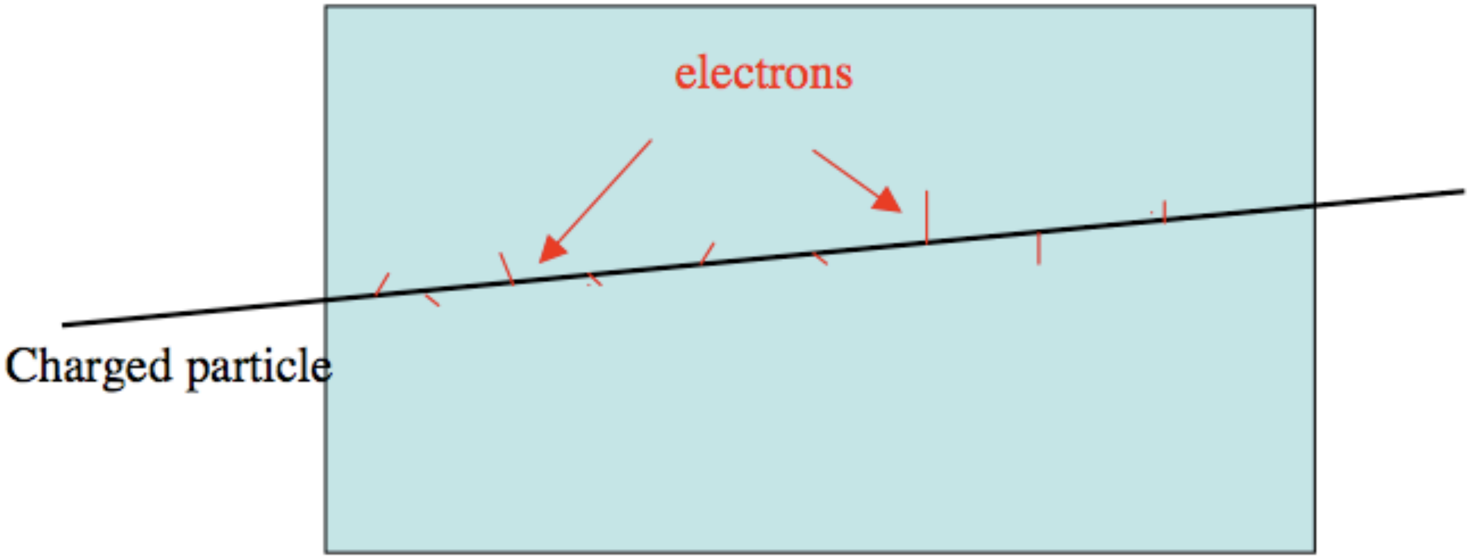
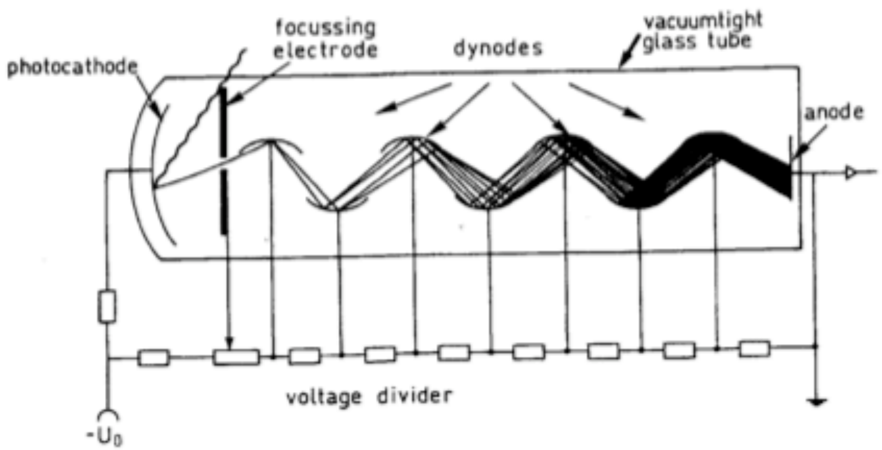
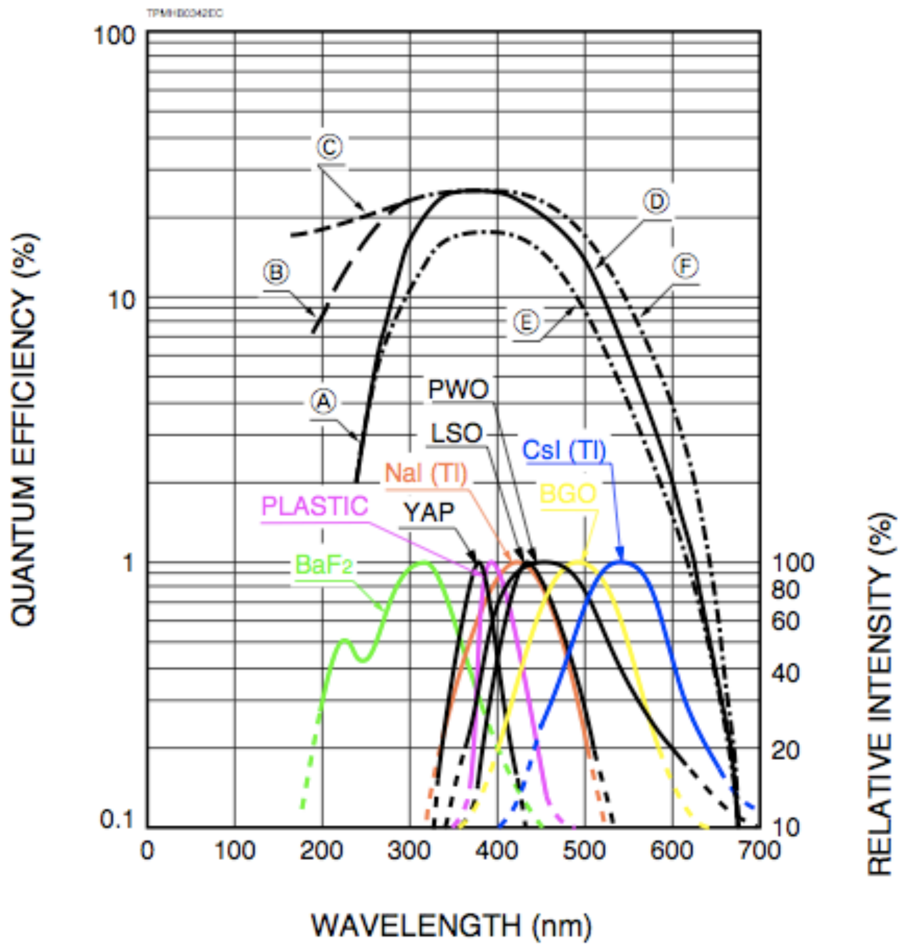


Photo-multipliers

Photomultipliers





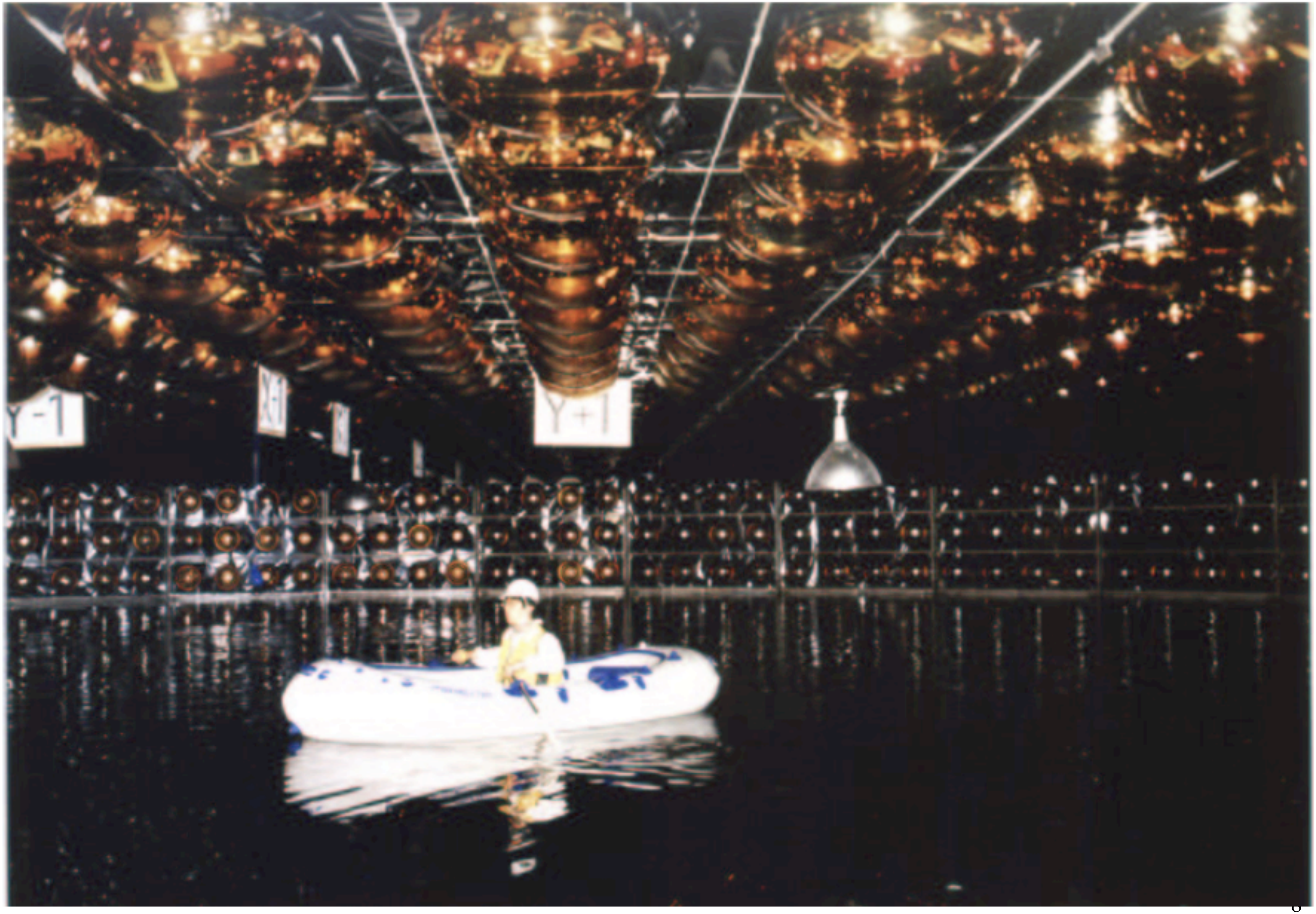
Conversion via photoelectric effect:

One photon to one electron, electrons multiplied

Typical efficiencies: up to 25%

Photomultipliers

Available from 3/8 inch diameters to ≈ 40cm diameter.
Entrance windows on top ("head on") or on sides ("side on")


Y-1
Y+1

Calorimeters

Calorimeters: Why?

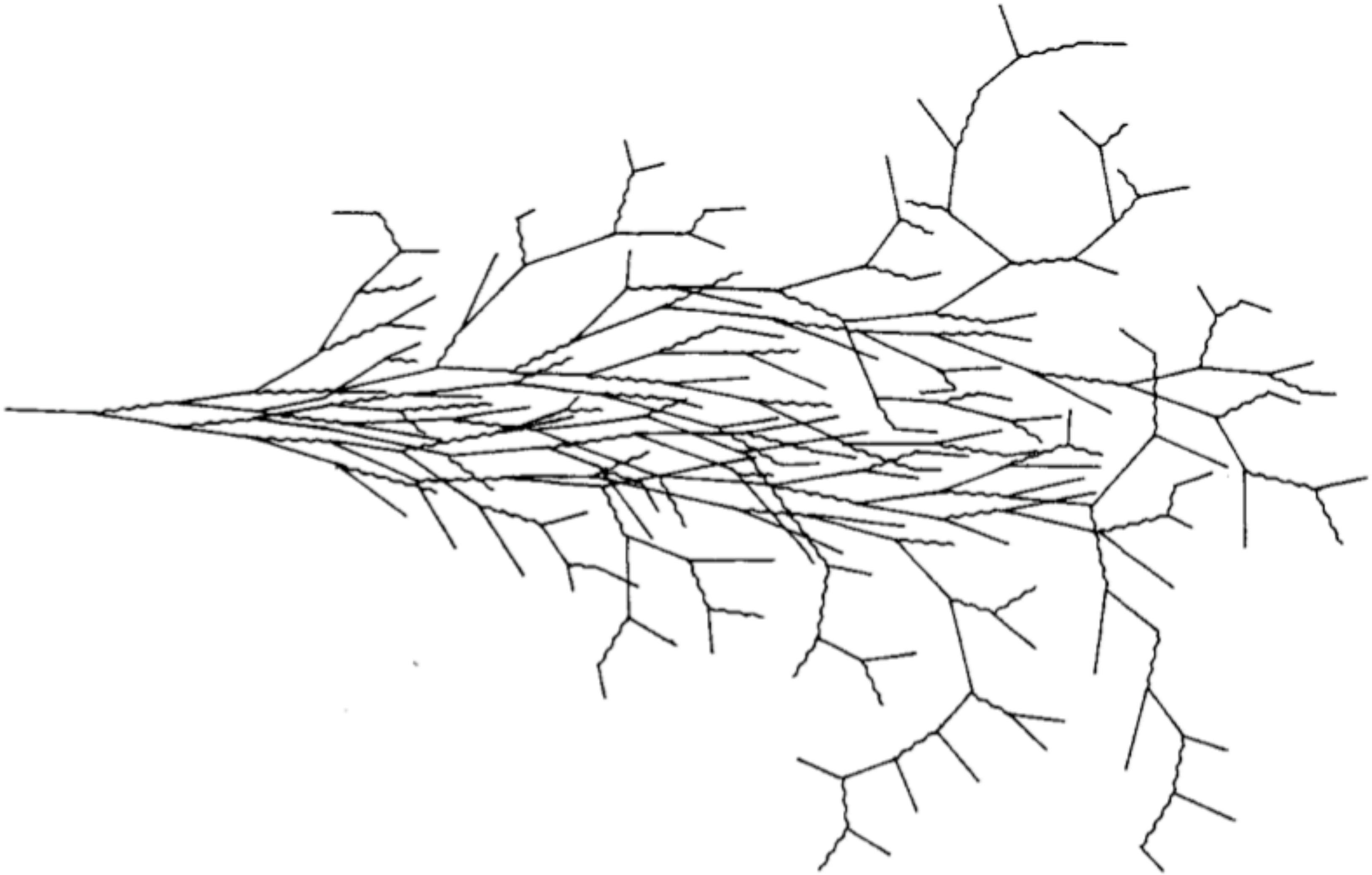
- Measure *charged + neutral* particles

- Obtain information on *energy flow*:
  Total (missing) transverse energy, jets, *etc.*

- Obtain information *fast*
  → recognize and select interesting events in real time *(trigger)*

- Performance of calorimeters *improves with energy*
  (~ $E^{-1/2}$ if statistical processes are the limiting factor)

A Shower…



Calorimeters

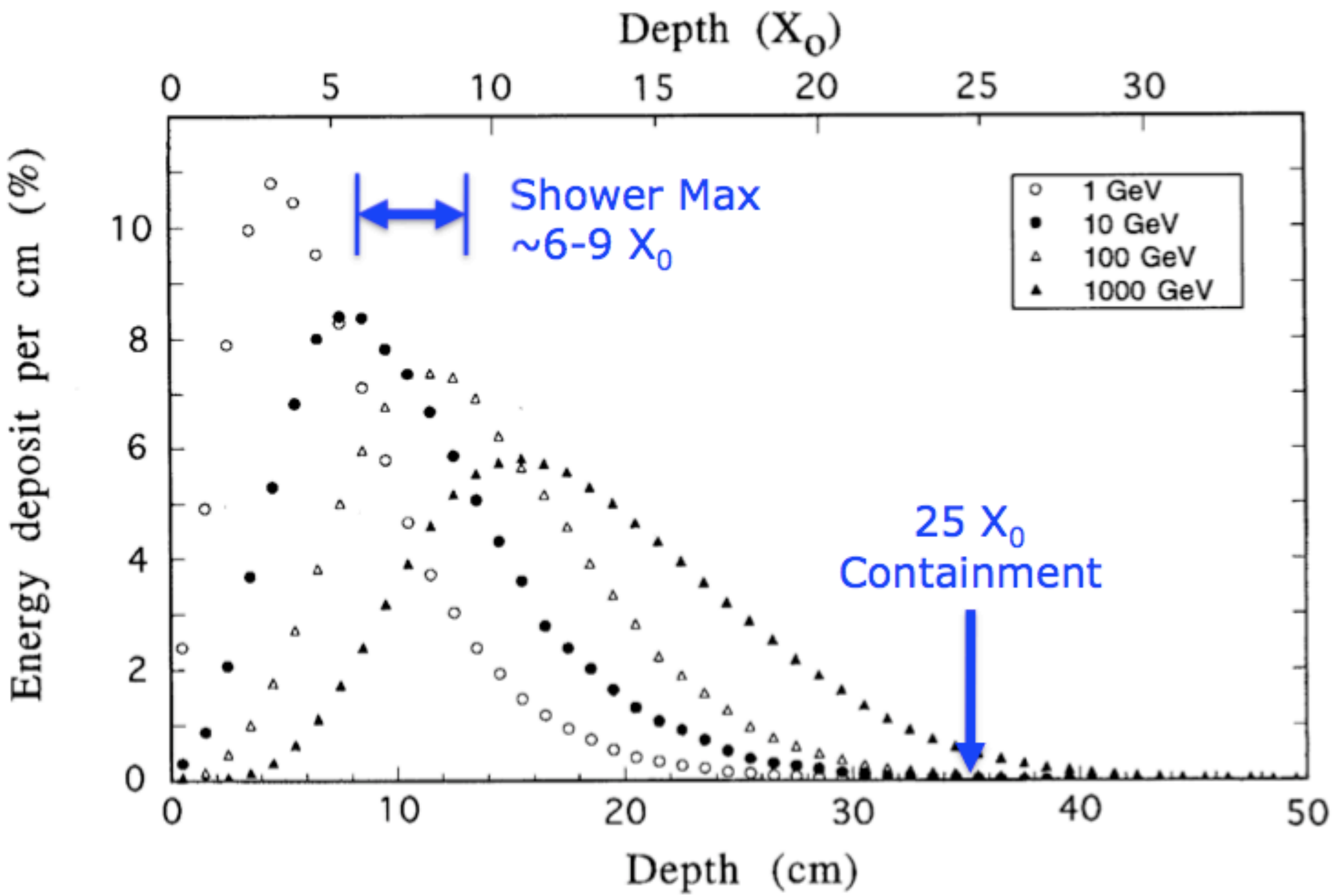
- Shower has to be absorbed totally. If not: reduced resolution due to fluctuations

- different optimization needed for electrons/photons and hadrons

- for electrons/photons: governed by Radiation Length X_0
- for hadrons: governed by Interaction Length λ_I

- for hadrons in addition: Need "compensation" due to electromagnetic part of shower.

Electromagnetic Showers



Electromagnetic Showers

Photon → Pair Production   Electron / positron → Bremsstrahlung (Photon)

- Simple Model, measured in "steps" t (one conversion, related to Radiation length X_0):
  Number of Particles: $N(t) = 2^t$
  Energy of particles: $E(t) = E_0 \cdot 2^{-t}$
  Multiplication stops if $E(t) < E_c$ $E_c = E_0 \cdot 2^{-t_{\max}}$ $E_c :\approx$ Pair production threshold

$$t_{\max} = \frac{\ln E_0/E_c}{\ln 2} \propto \ln E_0$$ position of shower maximum

Total number of shower particles:

$$S = \sum_{t=0}^{t_{\max}} N(t) = \sum 2^t = 2^{t_{\max}+1} - 1 \approx 2 \cdot 2^{t_{\max}} = 2 \cdot \frac{E_0}{E_e} \propto E_0$$

Electromagnetic Showers

Project: EM Calorimeters

Total track length (sampling step t, measures in units of X_0)

$$S^\star = \frac{S}{t} = 2 \cdot \frac{E_0}{E_c} \cdot \frac{1}{t}$$

Energy Resolution $\frac{\sigma(E_0)}{E_0} = \frac{\sqrt{S^\star}}{S^\star} = \frac{\sqrt{t}}{\sqrt{2E_0/E_c}} \propto \frac{\sqrt{t}}{\sqrt{E_0}}$

Realistic description of longitudinal shower development:

$$\frac{dE}{dt} = \text{const} \cdot t^a \cdot e^{-bt} \qquad (a, b \text{ – fit parameter})$$

Lateral spread, caused by multiple scattering:

Molière Radius $R_m = \frac{21\,\text{MeV}}{E_c} X_0[\text{g/cm}^2]$

95 % of shower energy is contained in a cylinder of radius $2\,R_m$

for homogeneous calorimeters: $R_m = \begin{cases} \text{Fe: } 14\,\text{g/cm}^2 \triangleq 1.8\,\text{cm} \\ \text{Pb: } 18\,\text{g/cm}^2 \triangleq 1.6\,\text{cm} \end{cases}$

Shower Profile and Containement

- At the shower maximum, the average amplification rate in the shower goes to unity, and we have:
  - Average Particle Energy at Shower Max:

    E_c (Pb = 7.4 MeV, Fe = 22 MeV)
  - Number of Particles at Shower Max:

    $N_{max} = E_0/E_c \propto E_0$
  - Total "Path Length" of Showering Particles:

    $L_{tot} \sim N_{max}X_0/\ln 2 \propto E_0$
  - Depth of Shower Max:

    $L_{max} \sim \ln(E_0/E_c)\ X_0 \sim 6\text{-}9\ X_0$

- Clearly, from above, if one sampled the total path length or a known fraction of the total path length (every X_0), then there is direct proportionality between the sampled energy and the incident particle energy E_0

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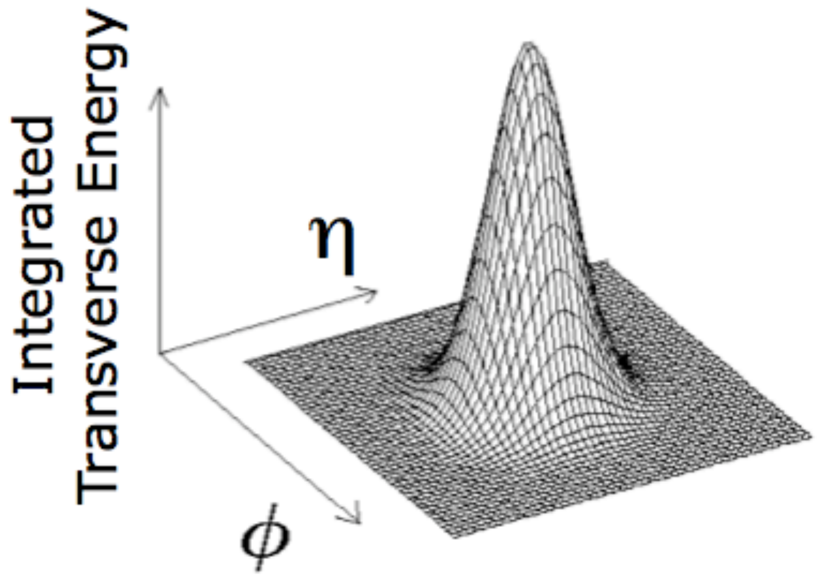
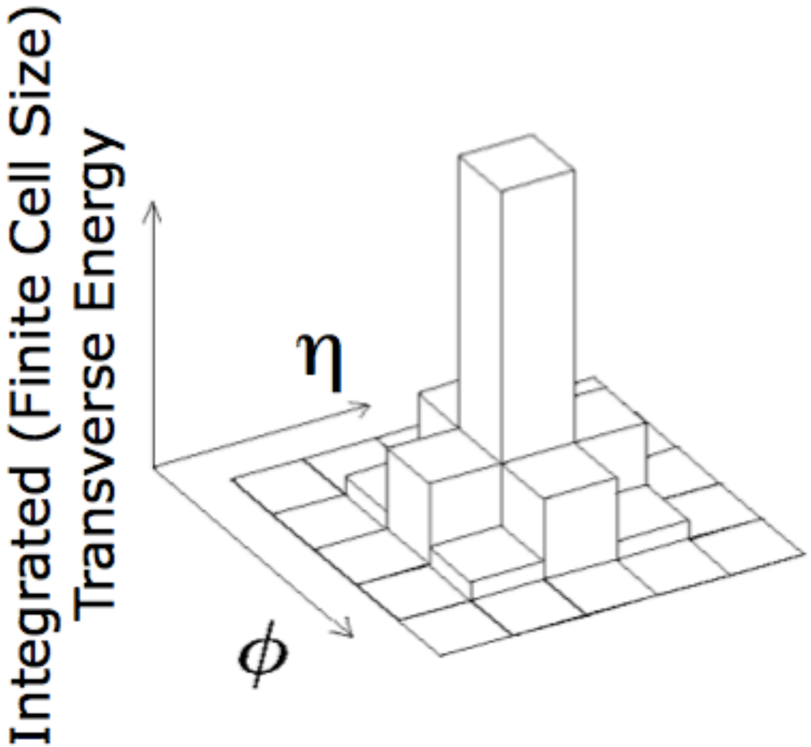
Electromagnetic Shower

- The Characteristic Transverse Size of the EM Shower is given by the Moliere Radius

$\rho_M = (21 \text{ MeV}/E_c)\, X_0$ (99% of shower in $3\rho_M$)





Choose Cell Granularity a bit Smaller than One Moliere Radius

Energy Resolution

- The energy resolution for a calorimeter can be written in the general form:

$$\frac{\sigma_E}{E} = \frac{N}{E} \oplus \frac{S}{\sqrt{E}} \oplus C$$

  - "N" is the electronic noise term and is set by the square root of the number of detector cells being summed (for incoherent noise) and the RMS electronic noise per channel **in units of energy**, i.e. ~6000e^- of preamp electronic noise is to be compared with the number of photoelectrons times the photodetector gain collected per MeV of deposited energy
  - "S" is the stochastic term and is a form of 1/√N counting statistics (signal quanta counting within a fixed volume)
  - "C" is the constant term and comes from intrinsic non-uniformities in how one computes the incident particle energy, i.e. variations in the mean response that depend on parameters that are not tracked (temperature, etc.)

Project: derive the resolution formula in calorimeters

Shower Position

- Two common methods for computing the position of a shower within a fraction of the cell size
  - Correction to the center-of-gravity:

$$x_{cog} = \sum_i x_i E_i \Big/ \sum_i E_i$$

$$x_{corr} = A \tan^{-1}(B x_{cog})$$

  - Logarithmic Weighting:

$$x = \sum_i x_i w_i \Big/ \sum_i w_i \qquad w_i = w_0 + \ln\left(\frac{E_i}{\sum_i E_i}\right)$$

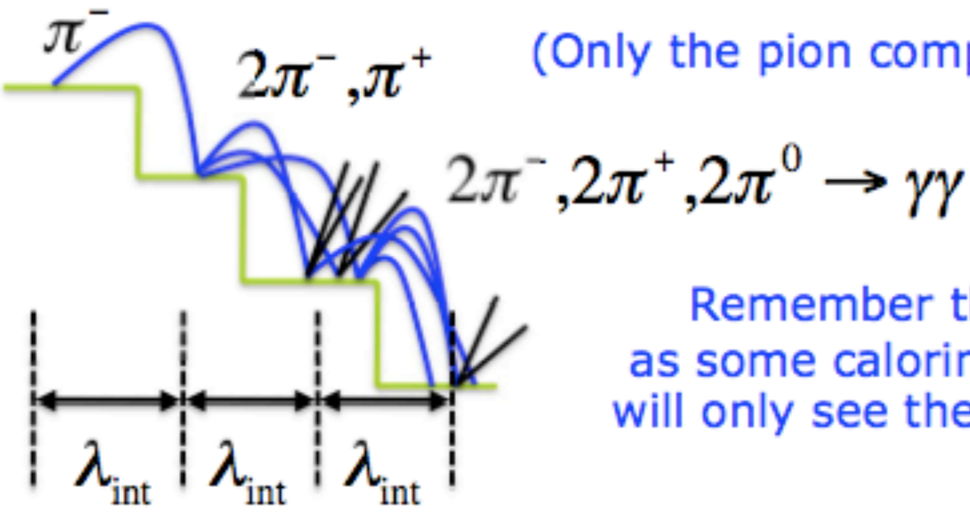
- At energies of ~45 GeV, an electron impacting on a 20mm crystal can have its impact point determined to better than 1mm in both coordinates

Interaction Lenght

- For the pion component, however, the behavior is a bit more clear (though erratic)
  - Pions are in a (nuclear) isospin triplet and therefore "tumble in isospin" with every nucleon they hit – once a charged pion tumbles into a neutral pion, the neutron pion rapidly decays to two photons and initiates an electromagnetic shower "one-way street"

(Only the pion component)

Similarly,
$\pi^+ / \pi^0 / \pi^-$
are produced in equal amounts on average



Remember this, as some calorimeters will only see the $\pi^0 \rightarrow \gamma\gamma$

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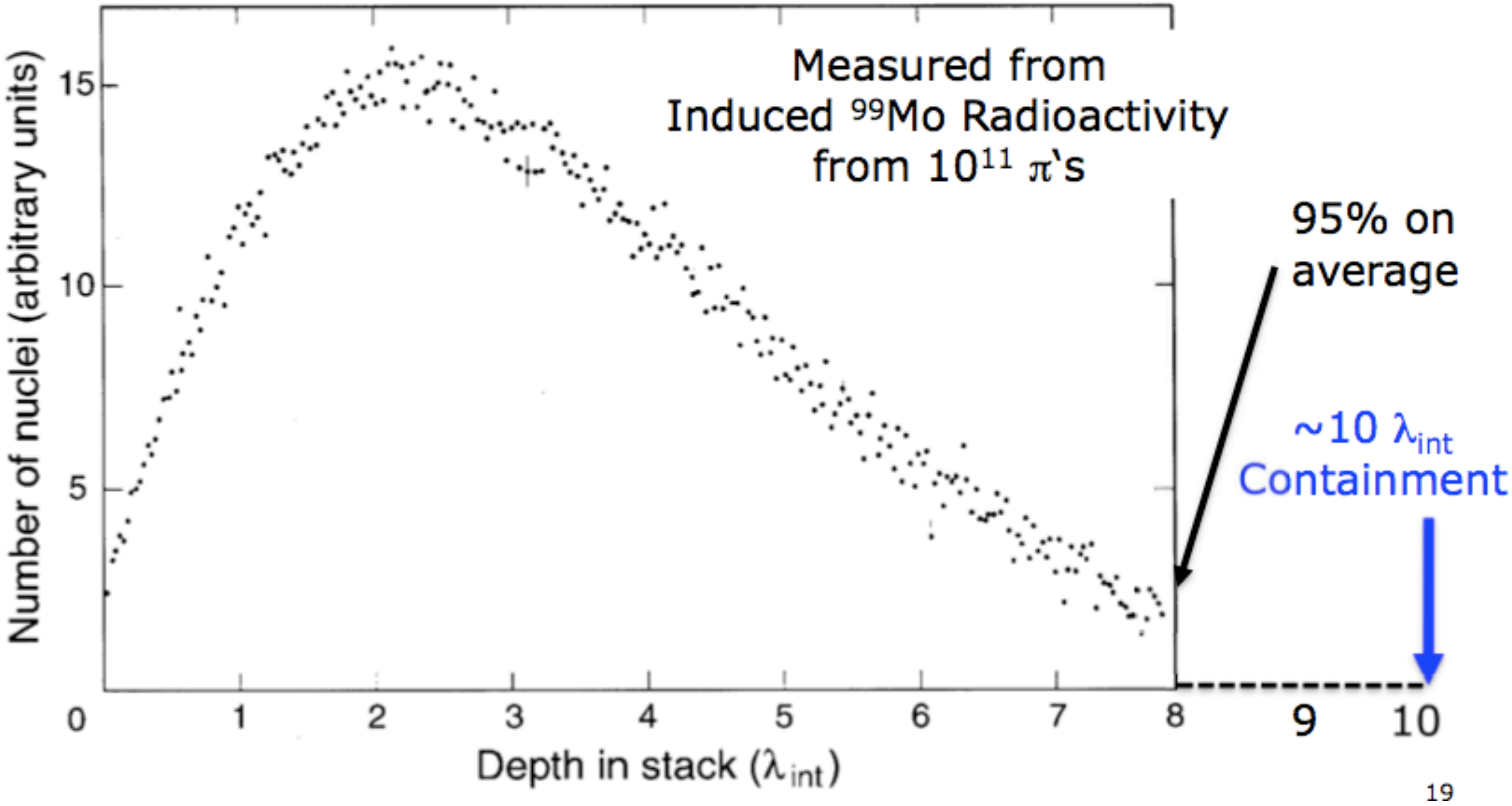
Hadronic Shower

- 300 GeV π^- in Uranium



Hadronic Showers

- What do we notice about hadronic showers besides the order of magnitude difference between X_0 and λ_{int} ?
  - 300 GeV π^- shower looks like an equiv. ~1 GeV electron shower in longitudinal profile with shower max at 2-3 λ_{int}
  - Multiplicity of interaction $\propto$ ln s

    1 → N ~ 9 processes in the first λ_{int},

    dropping with ln s to 1 → 6 in the second step,

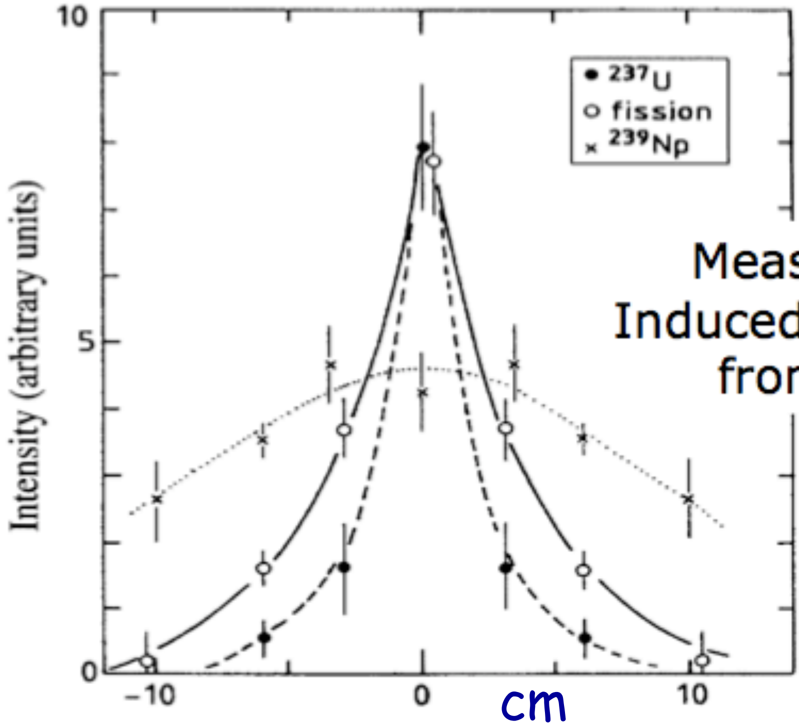
    1 → 3 in the 3rd step, and

    then mainly 1 → 1 processes after that (shower max)
  - Also, recall π^0's are falling out of the shower **(at that energy)** at a multiplicity fraction of 1/3 per interaction
- Another important feature of the pion is that it can remain a MIP for many λ_{int}
  - Although the probability drops off exponentially, there are many pions per event and many events to sort through

Hadronic Shower

- Transverse Profile is Shower Particle Species Dependent and Depth Dependent
  - Narrow EM core in the first few λ_{int}
  - Broad linear drop off after several λ_{int}

- More π^0's γ's in core
- Energetic neutrons and charged pions form a wider core
- Thermal neutrons generate broad tail

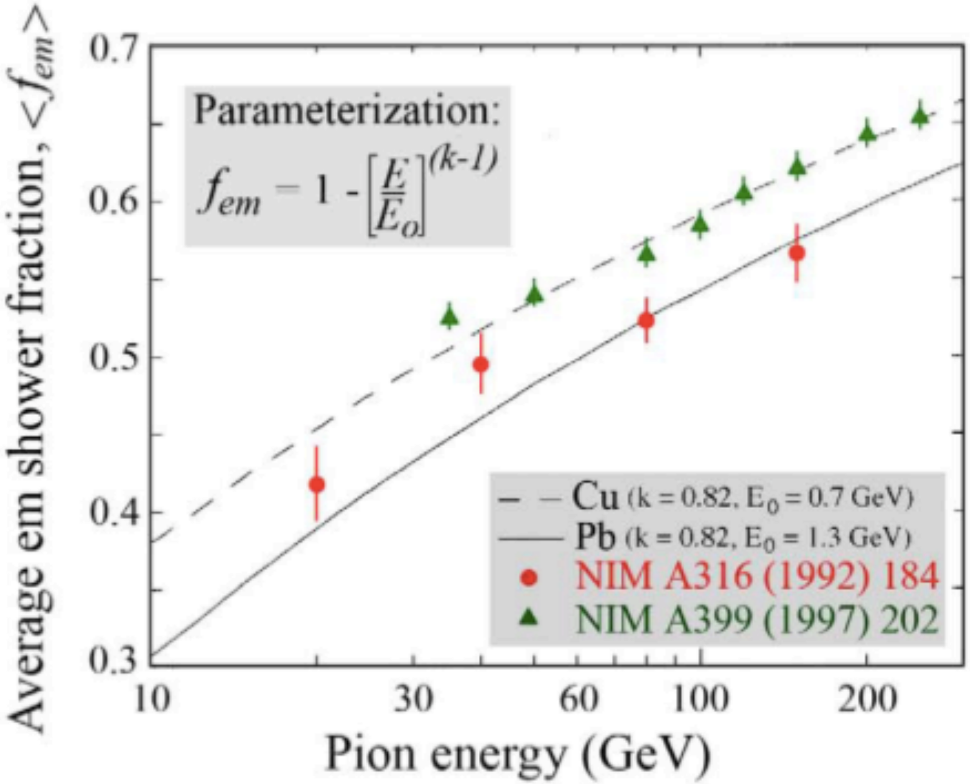


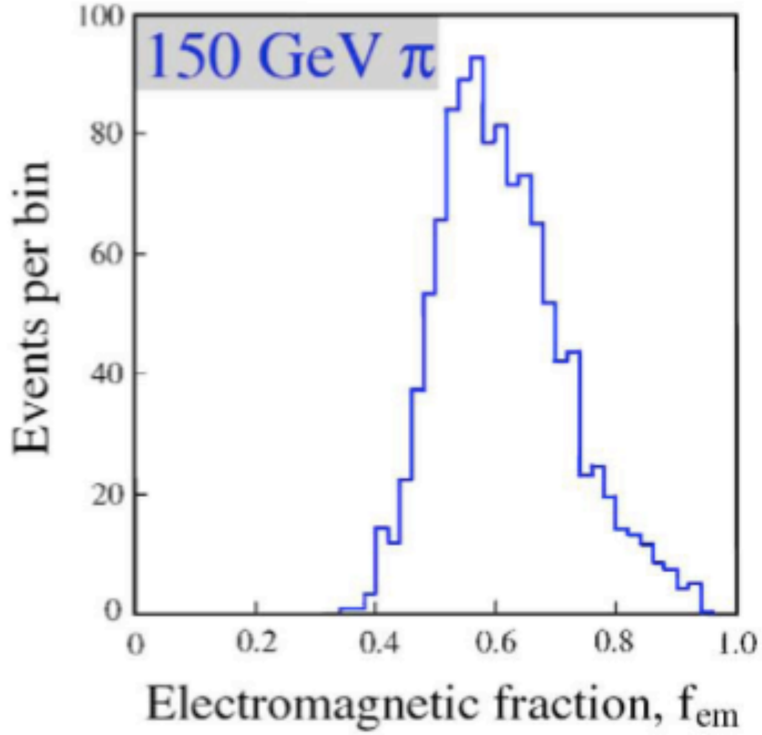
Measured from Induced Radioactivity from 10^{11} π's

(Courtesy of R. Wigmans)

EM Fraction of Charged Pion Showers

- Growth of EM Fraction with Energy
  - Non-trivial fluctuations of EM fraction





Types of Calorimeters

- Particle showers are measured with (modern) fast, low-power instrumentation, but the adage is still true, what you see is what you get
  - One quickly finds that there are two major movements in the calorimeter world: the total absorptionists and the samplers
- A **total absorption calorimeter** is a (usually homogeneous) material in which the entire volume is sensitive to energy depositions
- A **sampling calorimeter** in an interleaving of absorber/dead material and active layers used to periodically sample the particle flow in the shower

Total Absorption Calorimeter

- The resolution of an energy measurement will depend on counting statistics of the quanta released by the active material and collected by a counting device
  - In a depleted solid-state detector (Si, Ge(Li)), an electron-hole pair can be liberated with ~3.8 eV on average (band gap of Si is 1.1 eV) with most of the deposited energy going into electron-hole pair creation
  - In a scintillator, visible light with energies 2-3 eV can be emitted for a given amount of energy deposition in the crystal (not all energy goes into light)

$$E(\mathrm{eV}) = \frac{1240}{\lambda[\mathrm{nm}]}$$

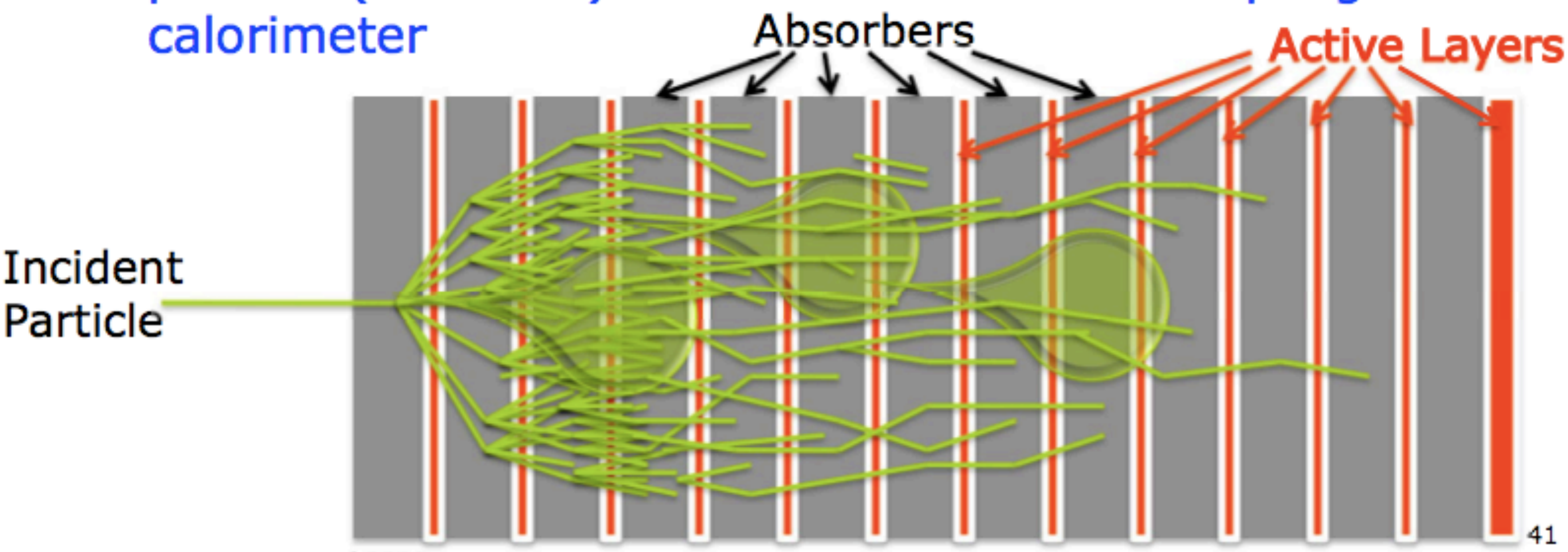
  - A Cherenkov radiator, such as Lead-Glass or Quartz, will emit in the UV (~3-6 eV) for relativistic charged particles

Total Absorption Calorimeter

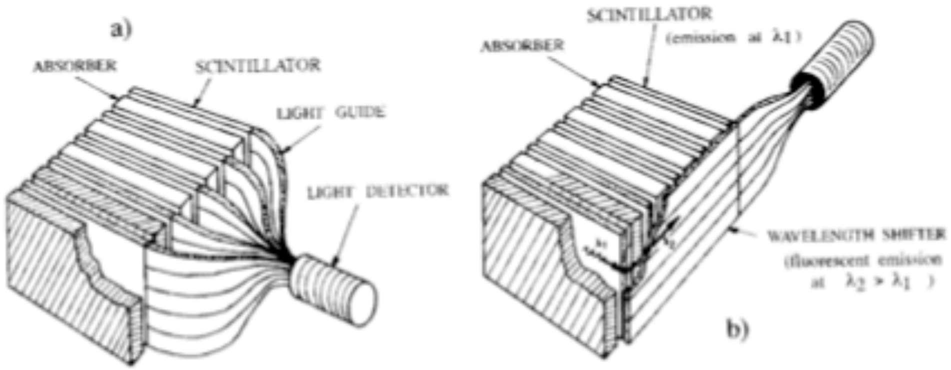
- For a total absorption calorimeter, the stochastic term of the energy resolution is largely due to the counting statistics of light collection, but it's a little more involved:
  - Take $PbW0_4$ with ~100,000 photons/GeV, gives 0.3%
  - Apply the photodetection area and quantum efficiency of photodetector, now one has 4000 photoelectrons/GeV and 1.6%
  - Include the excess noise factor F=2 for amplification shot noise from the APD, 1.6%*√2=2.2%
  - Now limit the lateral sum to keep the number of channels contributing to the electronic noise to 25, the containment fluctuations add 1.5% in quadrature, giving a total stochastic term of S=2.7%

Sampling Calorimeters

- There are no known total absorption detectors that can stop hadronic showers ($10\lambda_{int}$) in a finite thickness (~few meters or less) and for finite cost
  - There are materials (Fe, Cu, Pb, W, ^{238}U) than can do this in 1-2 meters, but they are passive materials
  - One can therefore consider interleaving active and passive (absorber) materials to form a "sampling" calorimeter



Sampling Calorimeters



- Something "heavy", inactive:
  lead, uranium, iron (steel), . . .
- Something "light", active:
  plastic scintillator, wire chamber, liquid (ionization chamber), . . .

- Problem: How to choose thicknesses?

- Problems to consider:
  1. Inactive part absorbs some of the produced shower particles, different for hadrons and electrons
  2. Some part of hadronic response is lost due to neutron absorption
  3. $\pi^0 \to \gamma\gamma$: All hadronic showers have electromagnetic component, responses (physics effects) are different.

Compensation

- Calorimeters can have greatly different efficiency for detecting electromagnetic as opposed to hadronic (mainly sensitive to MIP part) energy depositions
  - The ratio of the efficiencies is known as e/h
  - The "h" means the hadronic energy in a shower, not the energy from the shower of a hadron!
  - An incident charged pion will generate both electromagnetic and hadronic energy depositions in the calorimeter (EM fraction is energy dependent and fluctuates from shower-to-shower)
- Compensation means to design a calorimeter that has equal efficiency for both types of deposition e/h=1
  - We don't have this luxury anymore
  - Bunch crossings are too frequent to "wait" for neutrons
  - Can the EM and hadronic energies be measured separately for each shower?

Project!

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Sampling Calorimeter Design

- Electromagnetic part was understood and good simulation software available (EGS)
- In the 1980's: First systematic studies for hadronic response

- First: Uranium / Scintillator. Very good resolution of first prototype.
- Idea was that fission gives back some of "lost" neutron energy.
- Later: By accident the first prototype was "compensated".

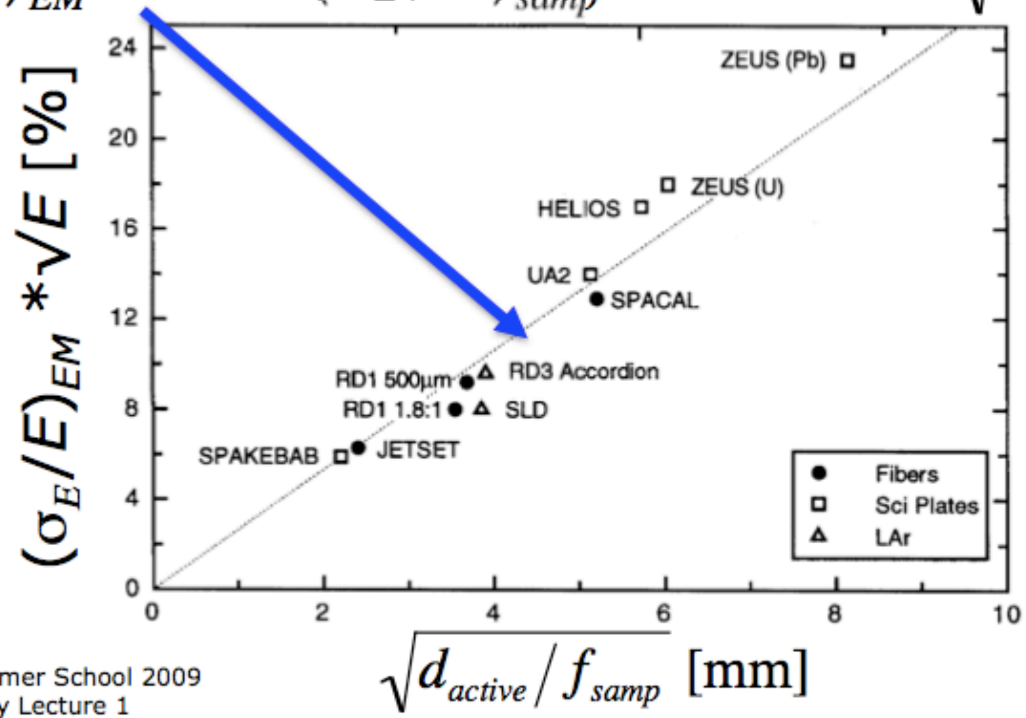
- mid-1980's: Systematic studies hadronic shower profiles, absorptions, by Wigmans et al.

- Result: One can tune **any** material combination to give identical responses to electrons and hadrons ("compensate"), due to different dependencies on Z of physics processes.
- Best resolution for hadrons only if calorimeter is compensated.
- Hadron resolution before: $\sigma_E/E \approx 100\,\%/\sqrt{E}$
- Best hadron resolution achieved (ZEUS, SPACAL): $30 - 35\,\%/\sqrt{E}$

Sampling Calorimeters

- For EM showers in a sampling calorimeter, the energy resolution is dominated by the sampling fluctuations:

$$(\sigma_E/E)_{EM}\cdot\sqrt{E}\approx(\sigma_E/E)_{samp}\cdot\sqrt{E}=2.7\%\sqrt{d_{active}/f_{samp}}$$



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Sampling Calorimeter

- The relative size of the sampling fluctuation energy resolution term for hadronic showers can be estimated for similar calorimeter geometries from the relative thickness of the absorber layers in units of λ_{int}
  - For example, a calorimeter with a 45%/√E stochastic term from hadronic shower sampling fluctuations would compare with a 80%/√E resolution calorimeter with 3 times the absorber thickness t_{had} in units of λ_{int}

$$\sigma_E^{had,samp}(t_{had}=0.33)/\sigma_E^{had,samp}(t_{had}=0.11) \approx \sqrt{t_{had}^{rel}} = \sqrt{3}$$

	X_0 (cm)	λ_{int}(cm)
Pb	0.56	17.0
$PbWO_4$	0.89	18.0
Fe	1.76	16.8
Cu	1.43	15.1

	t_{em}	t_{had}
ATLAS, Tilecal (Fe)	1.0	0.11
CMS HCAL (Cu)	3.5	0.33

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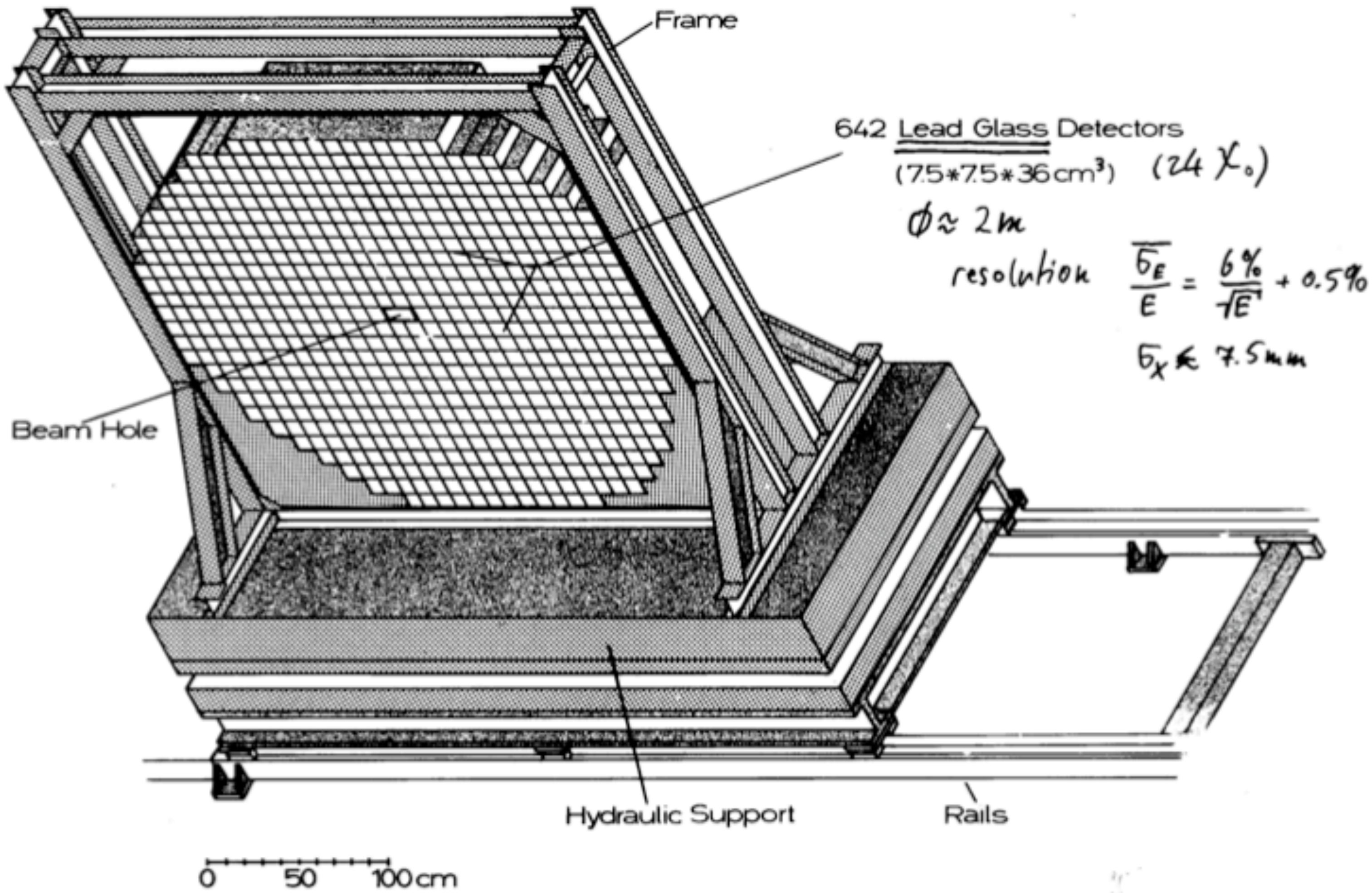
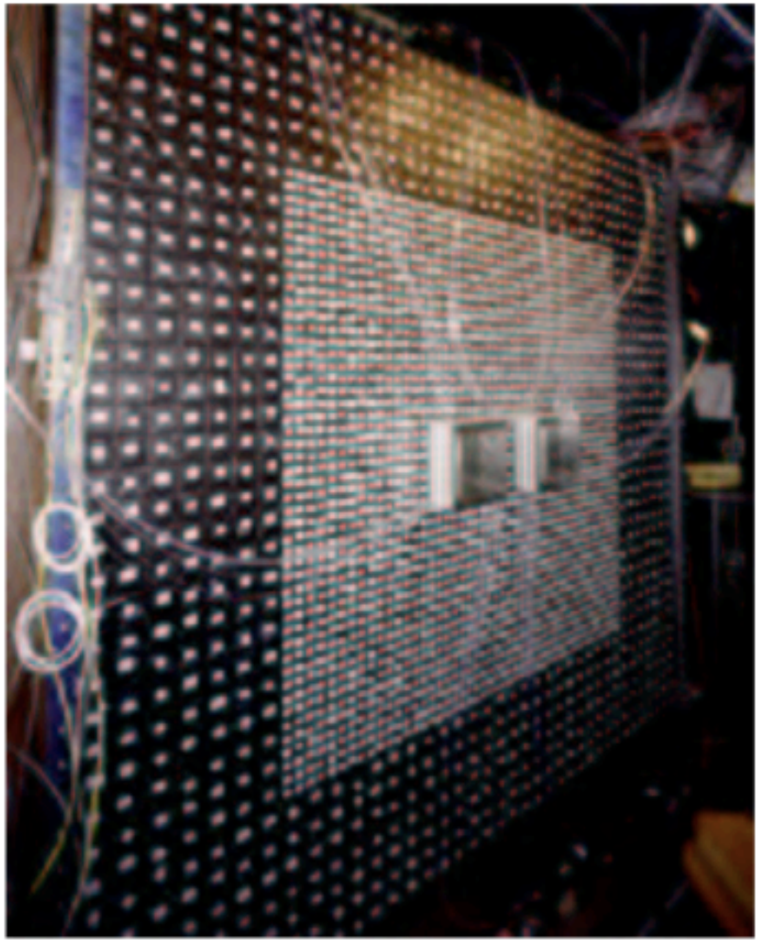
Sampling Calorimeters

- However, sampling fluctuations are not the whole story, and several other terms contribute to the energy resolution. Other contributions include:
  - Visible Energy Fluctuations (Nuclear Binding Energy and Escaping Neutrons)
  - Electromagnetic Fraction Fluctuations (for non-compensating calorimeters)
  - Containment (Longitudinal and Lateral) Fluctuations
  - Electronic Noise (at low Energy)
  - Counting Statistics of Signal Quanta (for very low yield active layers)
  - Excess Noise Factor in the Gain Mechanism of the Signal Quanta Detector
- Tevatron/LHC calorimeter examples will be covered in Lecture 2

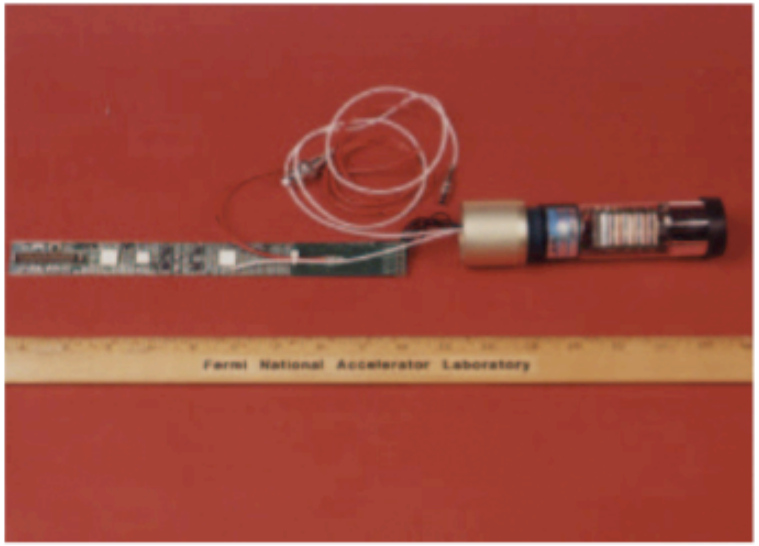
Lead Glass Calorimeter (WA79)



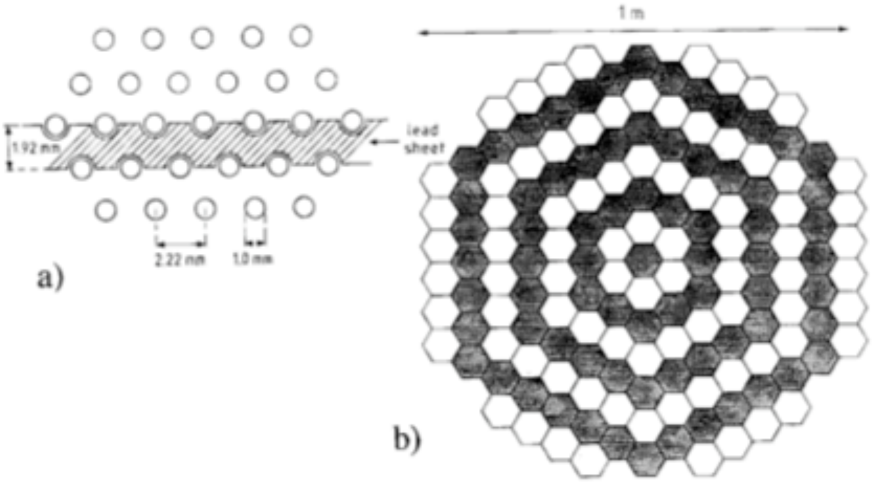
CsI Crystals (KTeV)

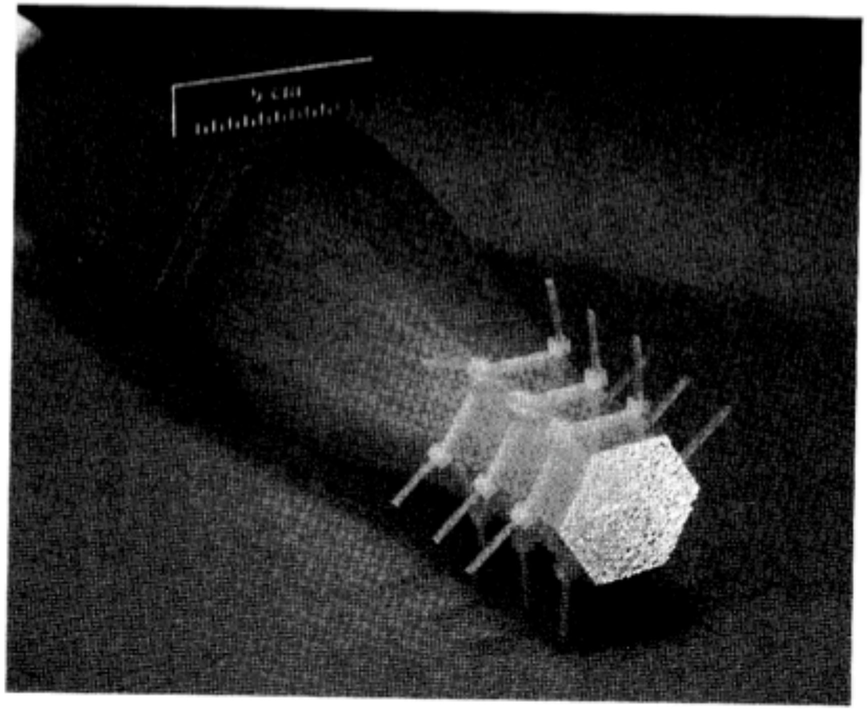


3100 CsI crystals



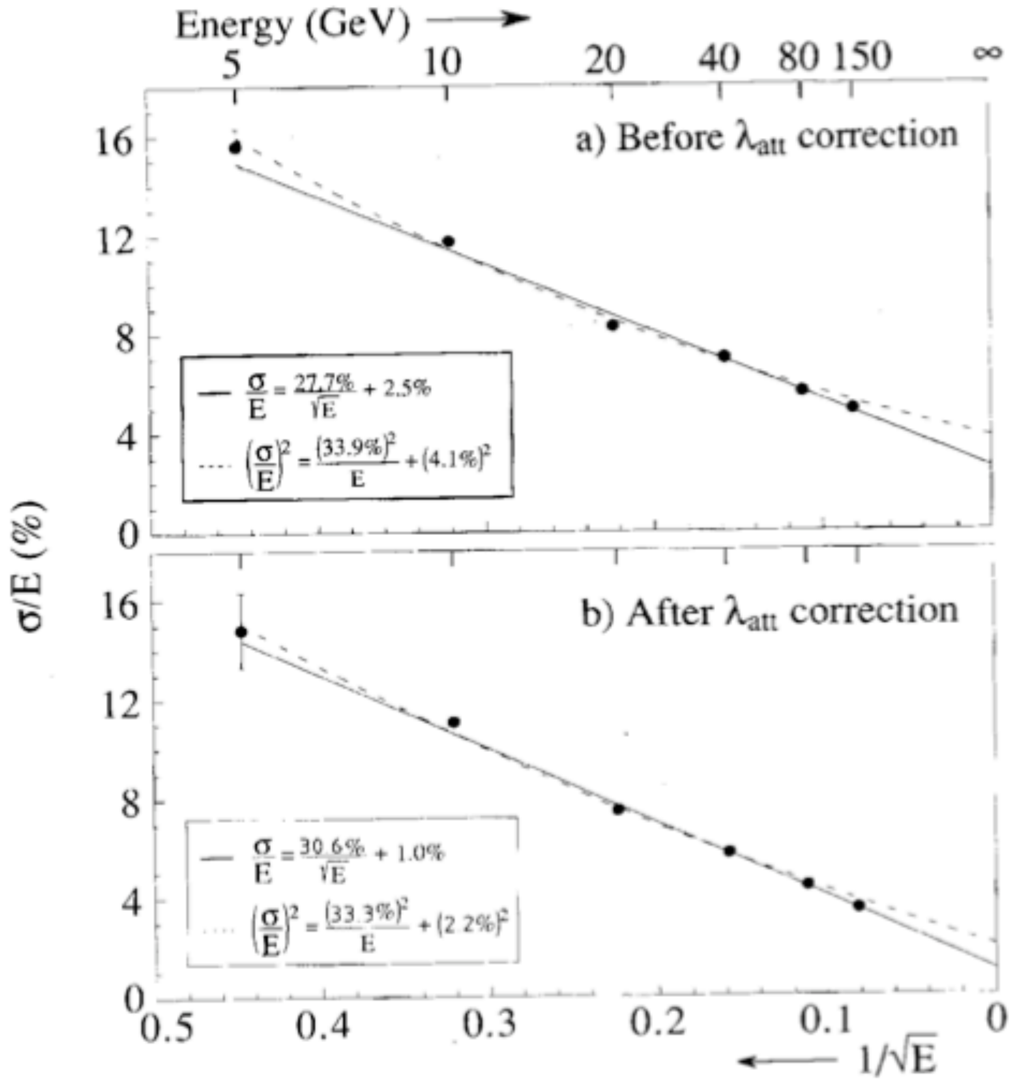
Spaghetti Calorimeter (SpaCal)





R.Wigmans, Colorimetry (Oxford Science, 2000)

Spacal Resolution



R.Wigmans, Colorimetry (Oxford Science, 2000)

Particle Identification

Particle Idenfication

- Identification of neutral particles
- Identification of charged particles

Neutral particles

- Measure total energy (Calorimeter)
- If no charged track points to signal in Calorimeter: It's a neutral
- Usually not too many possibilities left.
  Example: Hadron calorimeter, no track: most likely a neutron (or K_L^0)
- Electromagnetic calorimeter, track, signal: Measure "E/p".
  $E/p = 1$ for electrons, $E/p < 1$ for pions

- Long-lived neutral particles (Hyperons), short lived particles (charm, beauty):
  Measure 4-vector of decay products and calculate invariant mass.

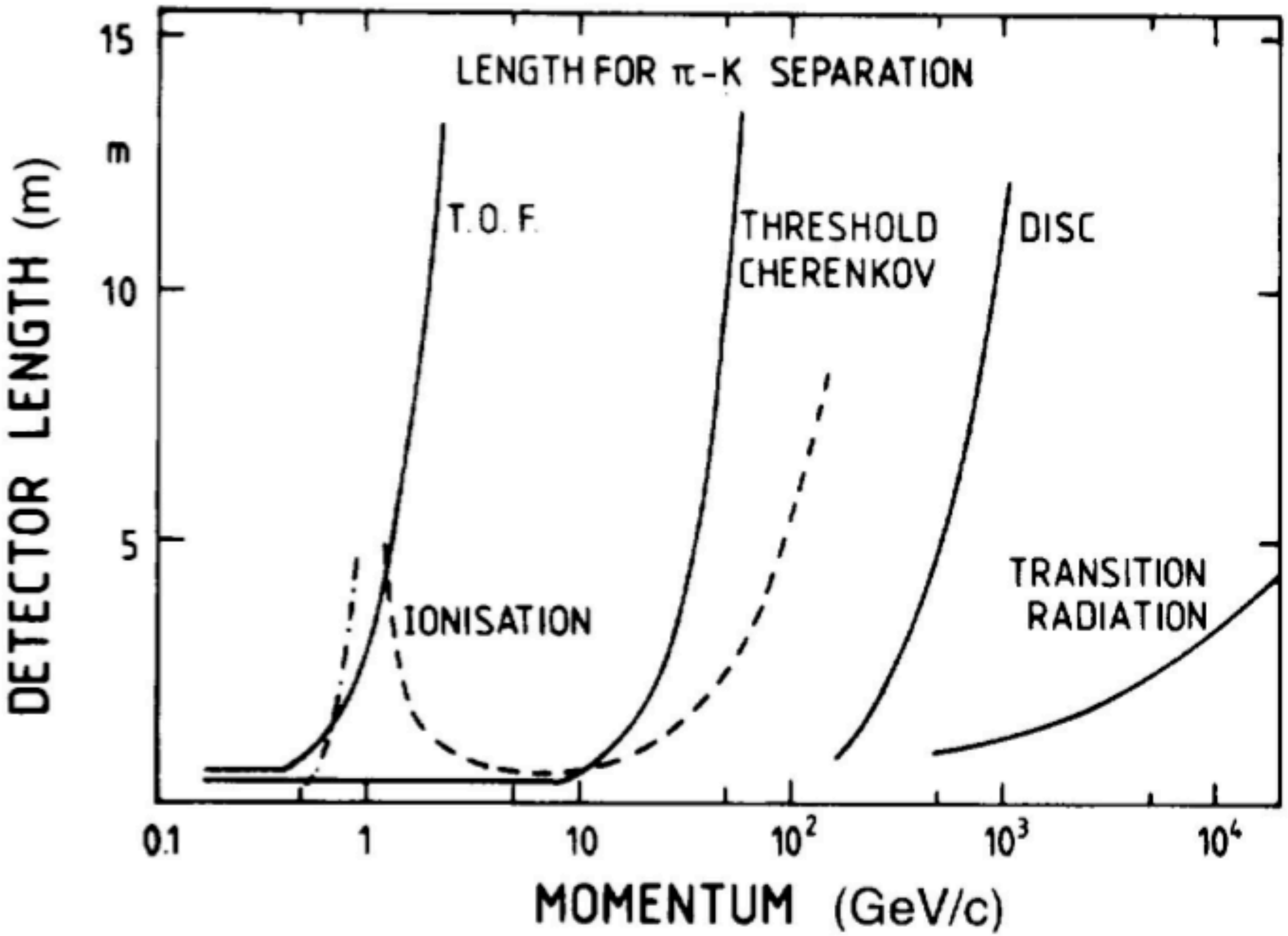
Radiation of Charged Particles

Radiation is emitted by a charge particle if:

1. $v > c/n$: Cherenkov radiation
2. $\vec{v}/c_{\text{ph}} = \vec{v} \cdot n/c$ changes
   (a) $|\vec{v}|$ changes: Bremsstrahlung
   (b) direction of $\vec{v}$ changes: Synchrotron radiation
   (c) n changes: Transition Radiation

Particle Idenfication

Fig. 5.30. Length of detectors needed for separation of π and K mesons.



Time of Flight

- Put two Scintillation Counters at a known distance
- Measure time difference between the two signals

Good time resolution: 150 psec.
Maximum distance: $\approx 10\,\mathrm{m}$ (detector), $\approx 100\,\mathrm{m}$ (beamline).
$\Longrightarrow$ Can measure difference between Kaons and Pions up to a few GeV/c
Also has problem at higher rate and/or multiple particles hitting the same scintillator

Transition Radiation

Transition Radiation: Reformation of particle field while traveling from medium with $\epsilon = \epsilon_1$ to medium with $\epsilon = \epsilon_2$.

Energy of radiation emitted at a single interface

$$S = \frac{\alpha \hbar z^2}{3} \frac{(\omega_1 - \omega_2)^2}{\omega_1 + \omega_2} \gamma$$

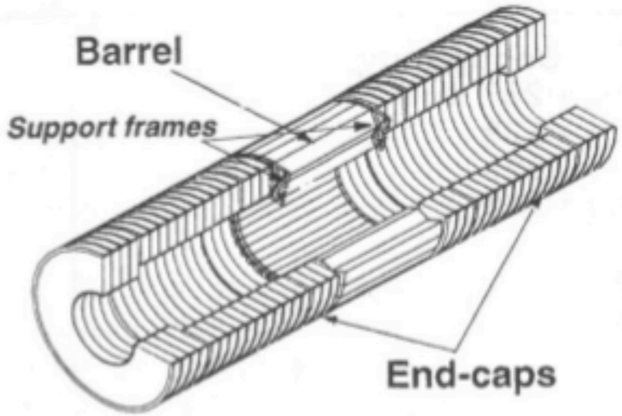
$\alpha = 1/137$, ω_1, ω_2 plasma frequencies, $\gamma = E/mc^2$.
Typical values: Air $\omega_1 = 0.7\,\mathrm{eV}$, polypropylene $\omega_2 = 20\,\mathrm{eV}$

Spectral and angular dependence of Transition Radiation:

$$\frac{d^2}{d\vartheta d\omega} = \frac{2e^2}{\pi c} \left(\frac{\vartheta}{\gamma^{-2} + \vartheta^2 + \omega_1^2/\omega^2} - \frac{\vartheta}{\gamma^{-2} + \vartheta^2 + \omega_2^2/\omega^2} \right)^2$$

$\Longrightarrow$ Most of radiation in cone with half angle $1/\gamma$: forward in particle direction.

Transition Radiation Detector



Length:	Total	6802 cm	N straws:	Total	372032
	Barrel	148 cm		Barrel	52544
	End-cap	257 cm		End-cap	319488
Outer diameter		206 cm	N electronics channels		424576
Inner diameter		96-128 cm	Weight		~ 1500 kg

Fig. 11. ATLAS Transition Radiation Tracker (TRT) conceptual design [2].

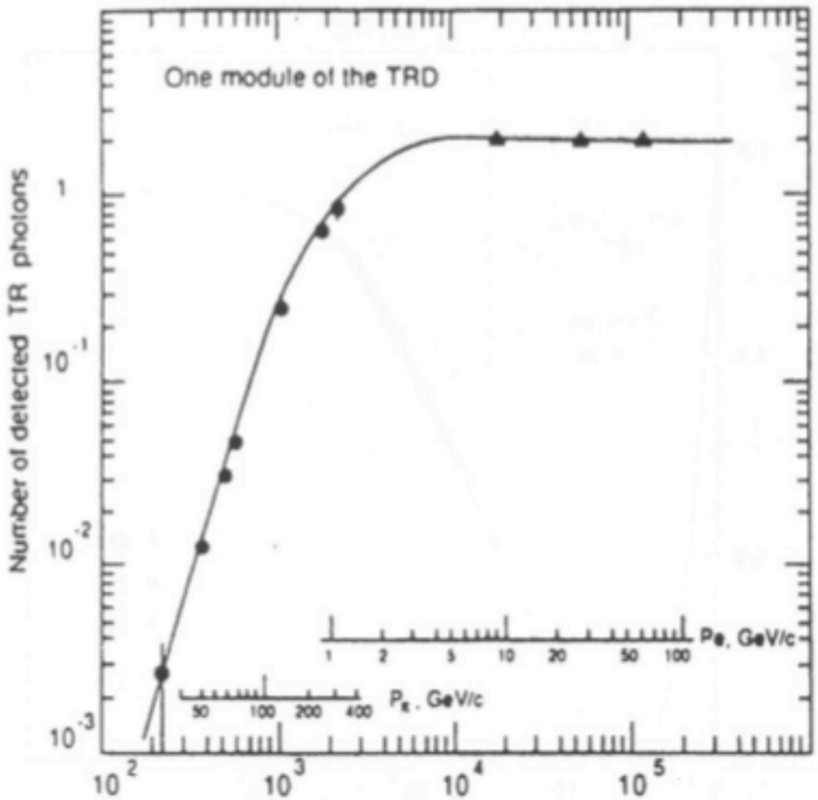


Fig. 8. The detected number of the TR photons for different Lorentz factors [4].

Cherenkov Radiation

A charged particle with a velocity v larger than the velocity of light in a medium emits light.

Angle of emission: $$\cos\theta_c = \frac{1}{\beta n} = \frac{1}{\frac{v}{c} n}$$

Number of photons: $$\frac{d^2N}{dEdl} = \frac{\alpha z^2}{\hbar c}\left(1 - \frac{1}{(\beta n)^2}\right) = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c$$

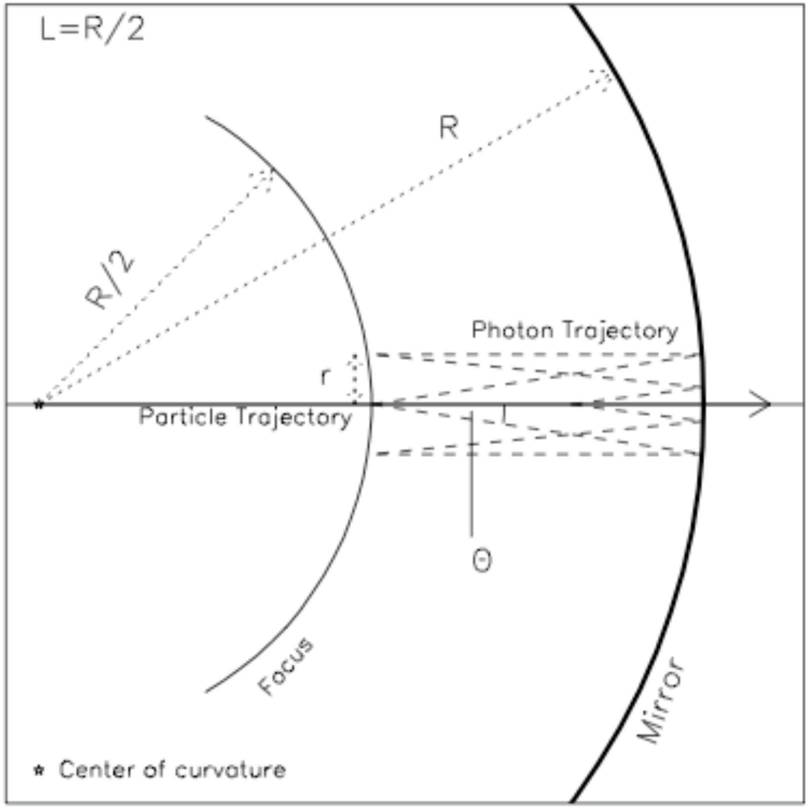
$$\frac{d^2N}{d\lambda dl} = \frac{2\pi\alpha z^2}{\lambda^2}\sin^2\theta_c$$

First (obvious) application: Threshold Cherenkov Detectors

For fixed momentum and only 2 particles to separate (beam line)

More than 2 particles and/or wider momentum range: Several counters at different thresholds

Ring Imagine Cherenkov



$$\cos\theta_c = \frac{1}{\beta \cdot n}$$

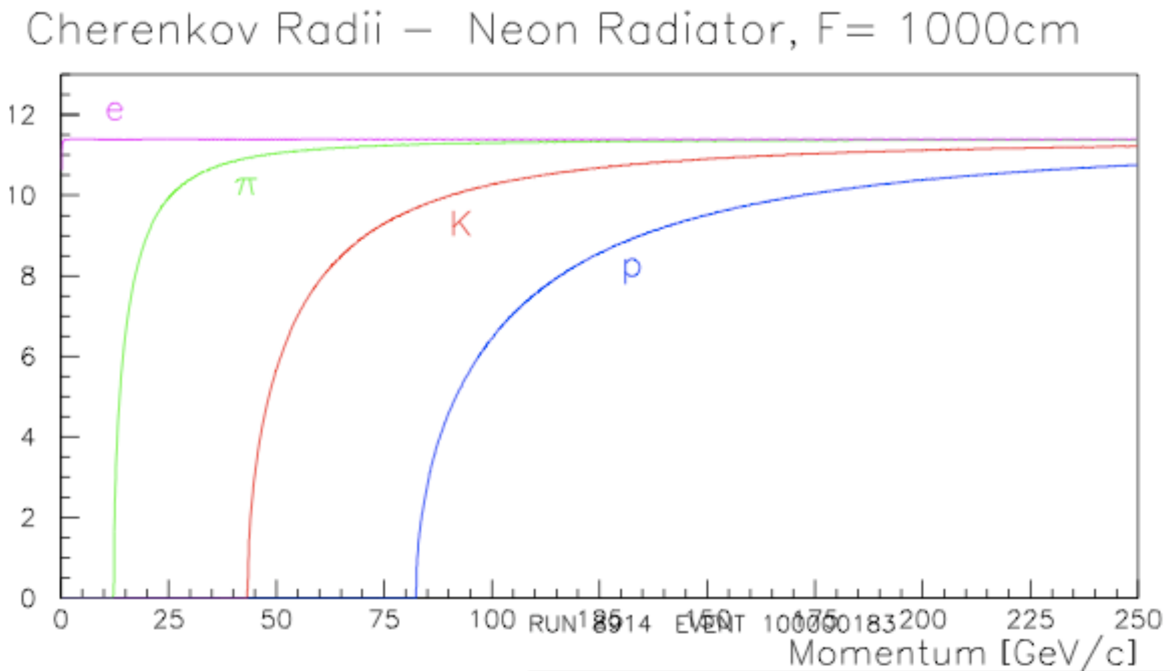
$$r = F \cdot \theta_c = \frac{R}{2} \cdot \theta_c$$

$$N_{ph} = N_0 \cdot L \cdot \sin^2\theta_c$$

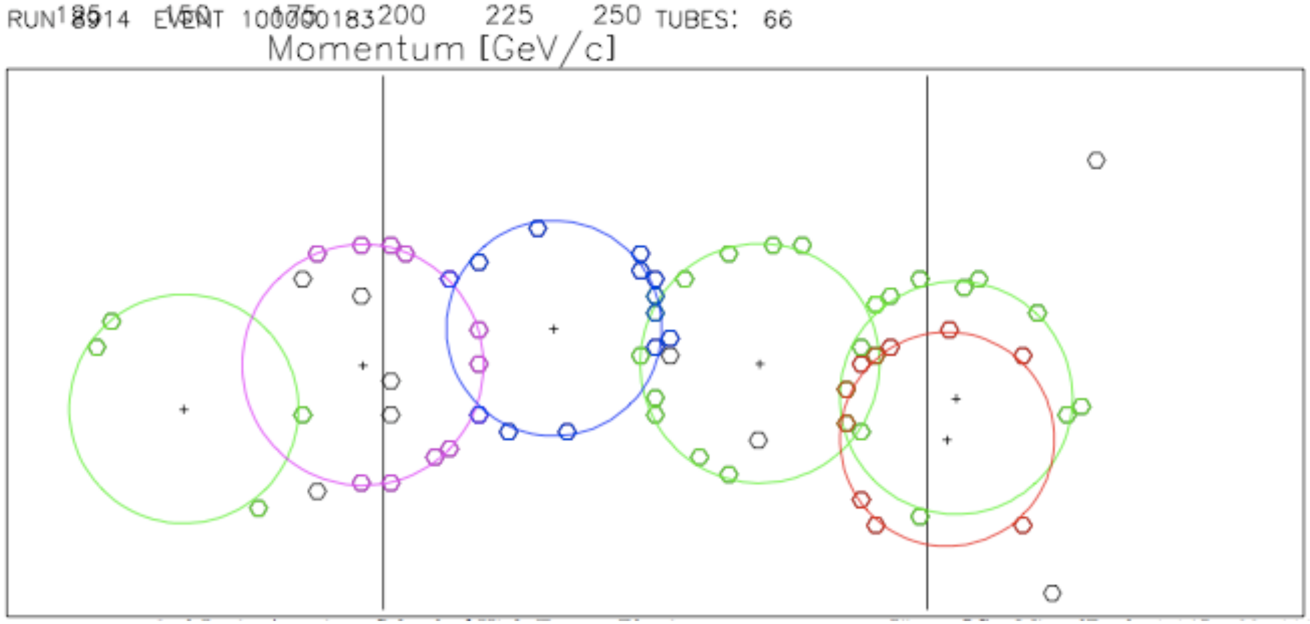
θ_c: Cherenkov angle
β: velocity
n: refractive index
r: Radius of ring on focal surface
R: Radius of curvature of spherical mirror(s)
F: Focal length ($F = R/2$)
L: Radiator length (usually $L = F$)

Parallel particles have the same ring image

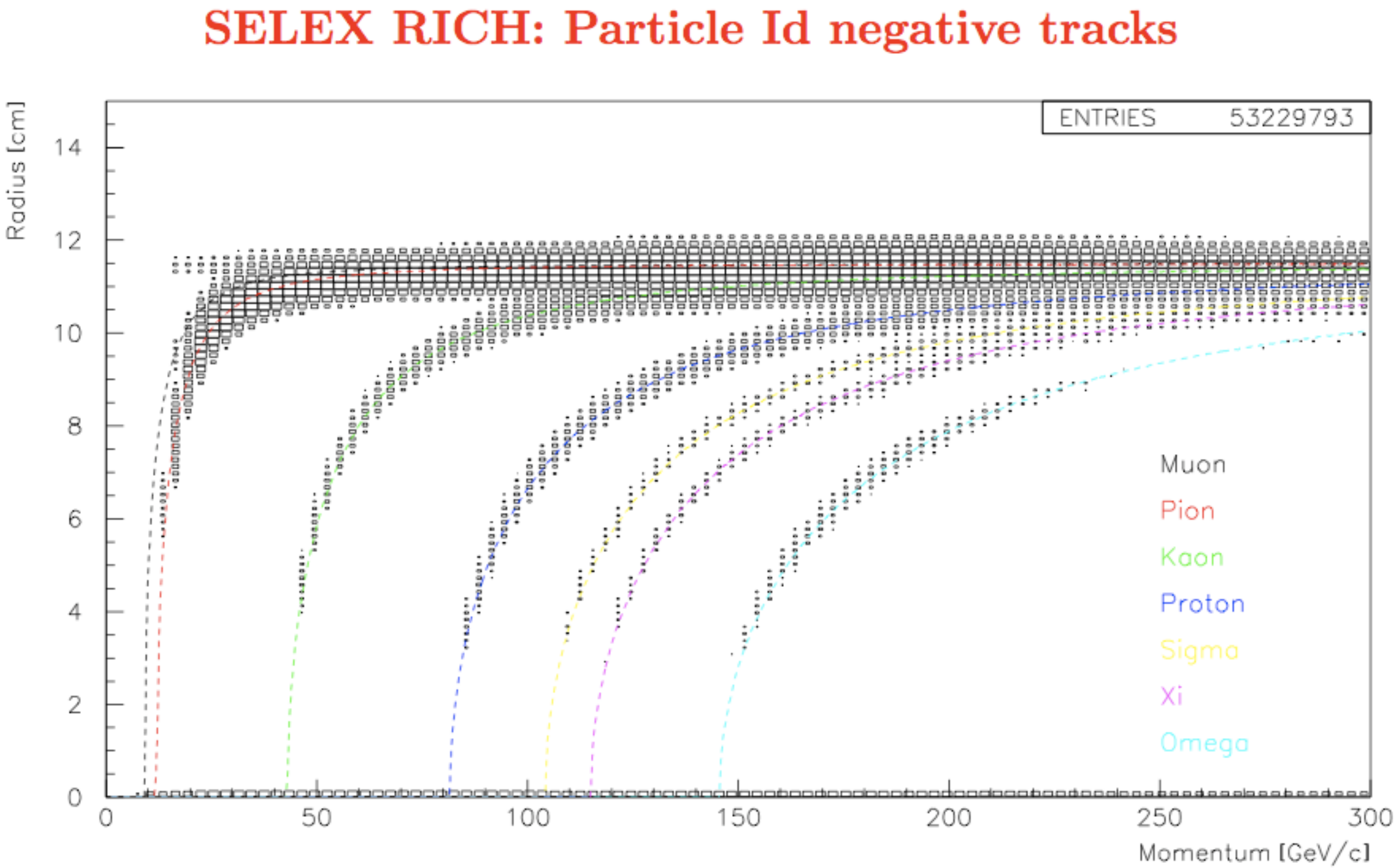
Ring Imagine Cherenkov



$$r = \frac{R}{2}\sqrt{2 - \frac{2}{n}\sqrt{1 + \frac{m^2c^2}{p^2}}}$$



Ring Imagine Cherenkov



RHIC

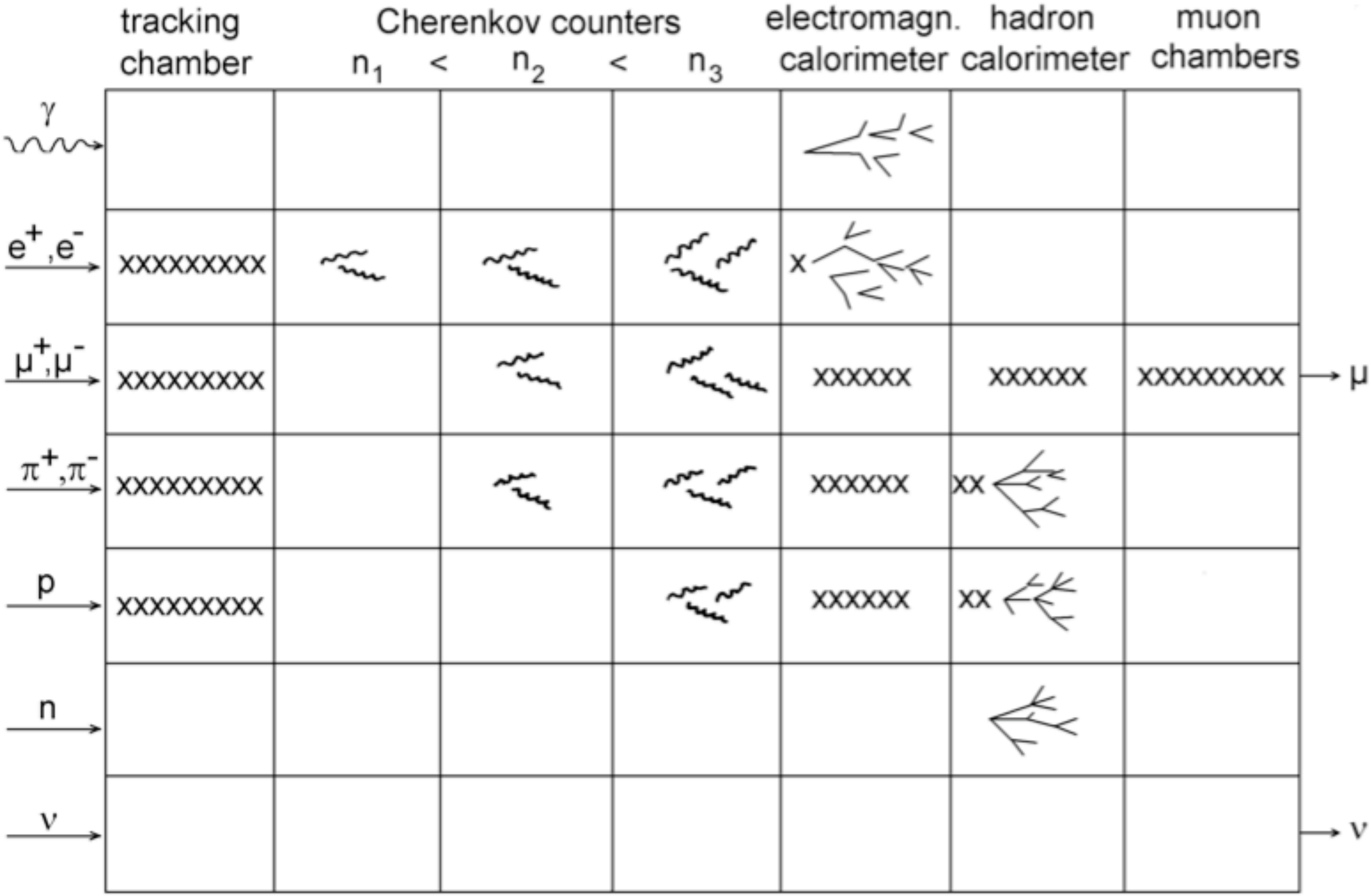
- Center of ring depends on track angle $\Longrightarrow$ large detector surface (up to square meters)
- good resolution of photon position $\Longrightarrow$ large number of "pixels" (up to 100000 or more)
- Spectrum of Cherenkov photons

$$\frac{dN}{d\lambda} = \frac{2\pi\alpha}{\lambda^2} L \sin^2 \theta_c$$

  $\Longrightarrow$ Ultraviolet

- refractive index $n = n(\lambda) \Longrightarrow$ Chromatic dispersion
- Detection of UV-photons: convert photon in electron (photoeffect)
  1. small (up to a few thousand) number of pixels: Photomultipliers
  2. large number of pixels or area: Time Expansion Chambers with TEA or TMAE
- When using TEC: particle pass through the chambers: dE/dx
- When using TEC: response (memory) time limit rate

Summary Particle Identification (cont.)



END