

# Particle Physics for specialists

## Part 2 : Detectors

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Some slides/ideas taken from wonderful lectures of  
prof. Tadeusz Lesiak and F. Żarnecki, S. Gilardoni,  
P. Bechle, M. Sapinski, M. Delamastro, L. Goerlich,  
A. Salzburger, M. Krammer, D. Cockerril, M. Turata,  
H. Meinhard

# Content of the course

- The Particle Physics **for specialists** course consists of 30h of lectures
  1. Accelerators and Detectors (4h) - Anna Kaczmarska
  2. Standard Model (7h) - Andrzej Bożek
  3. Heavy flavour physics (3h) - Marcin Kucharczyk
  4. Electroweak interactions, Higgs physics and Beyond Standard Model (4h) - Paweł Bruckman
  5. Electron-proton scattering and forward physics (3h) - Rafał Staszewski
  6. Heavy ion physics (3h) - Adam Trzupek
  7. Neutrino physics (3h) - Tomasz Wachała
  8. Introduction to cosmology, cosmic rays (3h) - Dariusz Góra
- Slides will be available on indico
  - <https://indico.ifj.edu.pl/event/727/>
- Literature
  - Perkins *Introduction to High Energy Physics*
  - Griffiths *Introduction to Elementary Particles*
  - Martin, Shaw *Particle Physics*
  - Halzen & Martin: *Quarks & Leptons: an Introductory Course in Modern Particle Physics*
  - Particle Data Group: "Review of Particle Physics" [<http://pdg.lbl.gov>]
- Exam: essay min. 5 pages, topics to choose will be provided at the end of the course



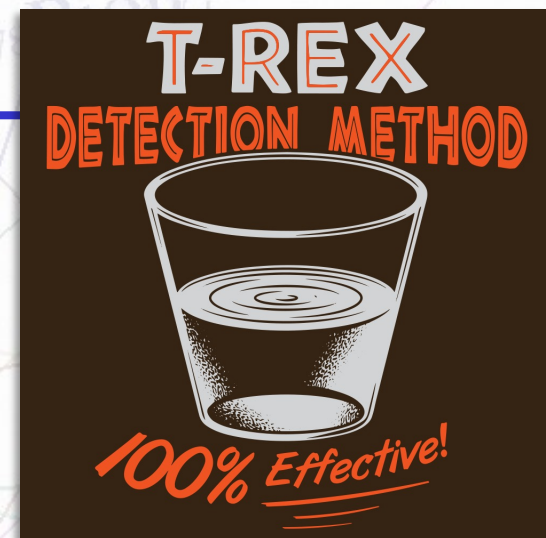
The background is a complex, abstract composition. It features a dark blue field filled with numerous thin, bright yellow and orange lines. These lines are mostly straight but many are curved, creating a sense of movement and energy. There are also larger, more diffuse yellow and orange shapes, some resembling nebulae or galaxies. The overall effect is one of a dynamic, invisible structure being revealed or visualized.

How to See Invisible



# Detection of particles

- In macro-world we can observe process without disturbing it
  - In micro-world we cannot "see" particles without changing their state
    - each measurement is connected to interaction
  - **We are not observing particles but their interactions with matter**
  - **It is not possible to observe non-interacting particle!**
- 
- In order to detect a particle, it must:
    - interact with the material of the detector == lose energy in the material it traverses
    - transfer energy in some recognizable fashion (signal)
  - **At an experiment we want to be able to detect all the particle that live long enough to interact with the detector**
  - We would like to know:
    - From where do all the particles come?
    - Are there secondary decays?
    - What are all the momenta of the charged particles
      - With help of magnetic field:  $r = p/(qB)$
    - What is the energy of all particles?
    - Identify the particles





# Passage of charged particles through matter

The main mechanisms of energy loss of charged particles

- **Ionization**

- loss of an electron after interaction with passing particle
- dominant effect for particles other than electrons
- described by **Bethe-Bloch formula**

- **Bremsstrahlung**

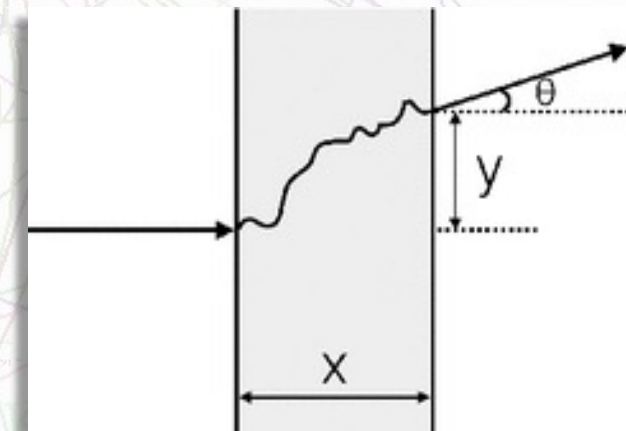
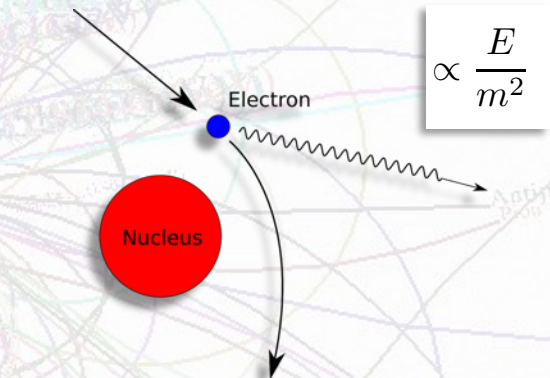
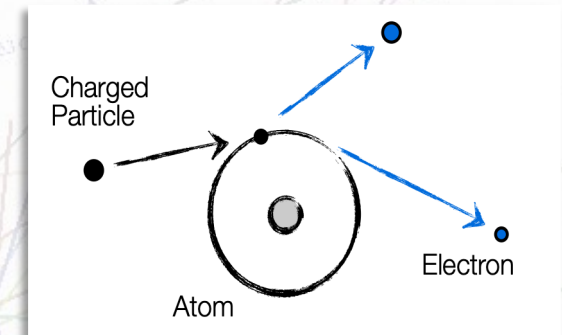
- dominant for low mass particles (electrons)
- EM radiation produced by the deceleration of a charged particle when deflected by another charged particle (e.g. electron by an atomic nucleus)

- **Multiple scattering**

- scattering in Coulomb field of nucleus
- small energy loss, but deflection

- **Excitation of atoms**

- Scintillation
- Cherenkov radiation
- Transition radiation



# Ionization (1)

- The **Bethe-Bloch** formula describes the mean rate of ionization loss of (heavy) charged particles
  - This formula is not correct for electrons because of spin, kinematics and identity of the incident electron with the electrons, which it ionizes
- Energy loss depends on charge ( $z^2$ ) and velocity ( $\beta$ ) of incident particle (but not on its mass!) and properties of medium (weakly)

Valid for heavy charged particles ( $m_{\text{incident}} \gg m_e$ ), e.g. proton,  $k$ ,  $\pi$ ,  $\mu$

$$-\left\langle \frac{dE}{dx} \right\rangle = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[ \ln \left( \frac{2m_e c^2 \beta^2 \gamma^2}{I^2} W_{\max} \right) - 2\beta^2 - \delta(\beta\gamma) - \frac{C}{Z} \right]$$

$$= 0.1535 \text{ MeV cm}^2/\text{g}$$

$$\frac{dE}{dx} \propto \frac{Z^2}{\beta^2} \ln(a\beta^2\gamma^2)$$

## Fundamental constants

$r_e$  = classical radius of electron  
 $m_e$  = mass of electron  
 $N_a$  = Avogadro's number  
 $c$  = speed of light

## Absorber medium

$I$  = mean ionization potential  
 $Z$  = atomic number of absorber  
 $A$  = atomic weight of absorber  
 $\rho$  = density of absorber  
 $\delta$  = density correction  
 $C$  = shell correction

## Incident particle

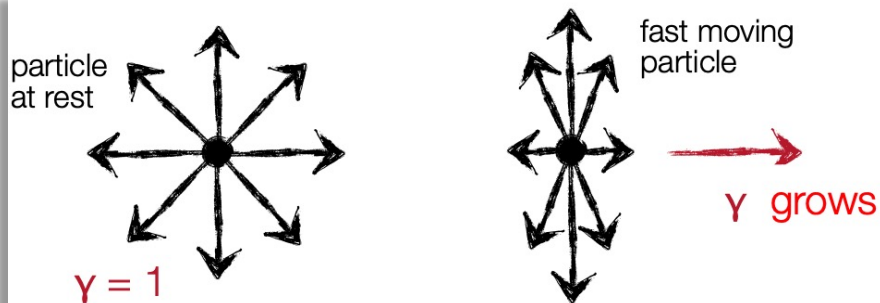
$z$  = charge of incident particle  
 $\beta$  =  $v/c$  of incident particle  
 $\gamma$  =  $(1-\beta^2)^{-1/2}$   
 $W_{\max}$  = max. energy transfer in one collision

$$r_e = \frac{1}{4\pi\epsilon_0} \frac{e^2}{m_e c^2}$$



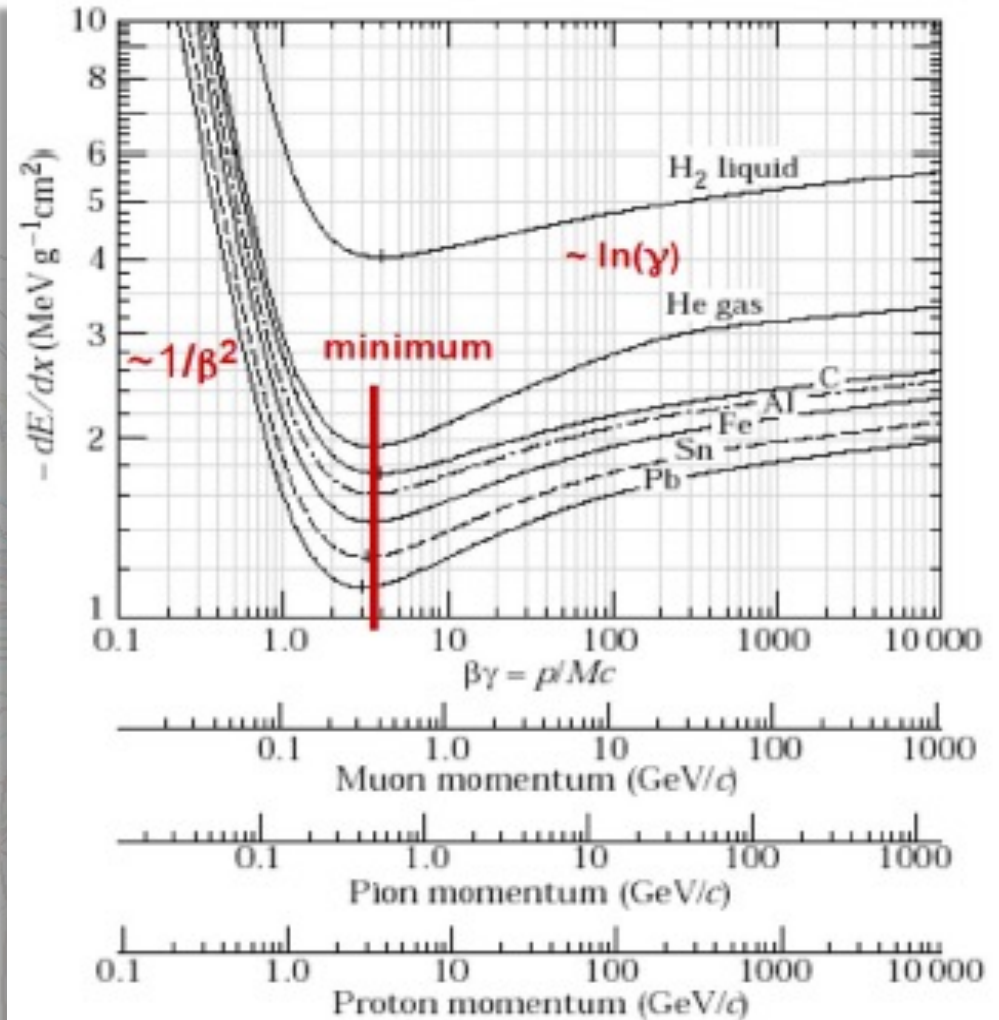
# Ionization (2)

- For small velocities  $dE/dx$  falls like  $1/\beta^2$ 
  - slower particles experience E- field for a longer time  $\rightarrow$  stronger energy loss!
- All particles have a region of minimum ionization with  $dE/dx \sim 1\text{-}2 \text{ MeV/g cm}^2$  for  $\beta\gamma \sim 3$  - minimum ionizing particles (MIP)
- As  $\beta$  continues to increase,  $\ln\gamma^2$  begins to dominate and  $dE/dx$  starts to increase
  - region of relativistic rise
  - Lorentz transformation of field lines: transversal component of E field grows with  $\gamma \rightarrow E_y \rightarrow \gamma E_y$ , larger collision distances, more ionization



Saturation for high energies  $\rightarrow$  Fermi plateau  
Due to polarization (density correction  $\delta$ )

- shielding of E-field far from particle path  $\rightarrow$  less collisions with far distant electrons

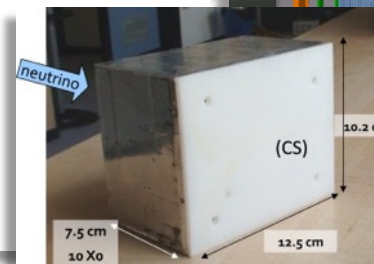
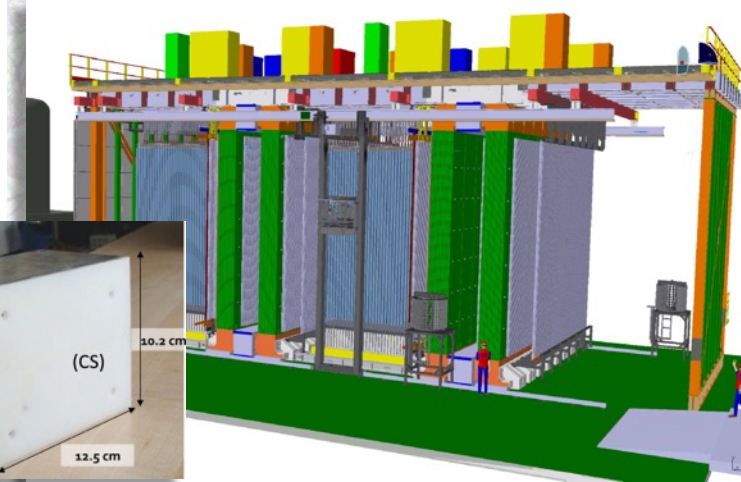
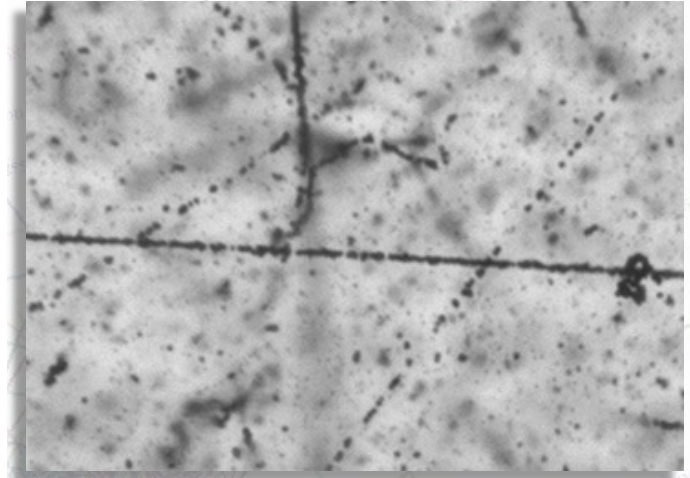


Shell correction ( $C/Z$ ) - in general small

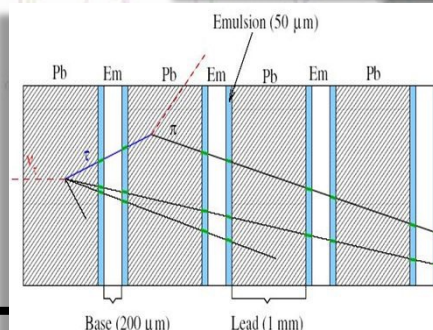
- arises if particle velocity is close to orbital velocity of e (assumption that e is at rest breaks down)

## Detectors based on ionization: emulsion

- An ionizing particle passing through the emulsion breaks up its molecules (AgBr, AgCl)
- After developing the film, the released silver grains are locked to the main body of the emulsions while the remnant part is washed away
- With the help of a microscope, these grains, can be observed as black dots
- Emulsions have been used as tracking devices since mid-1940s and are still in use
- **Exceptional (not surpassed by any other detector) spatial resolution:  $0.2\ \mu\text{m}$**
- $v$  from density of grains ( $dE/dx$ )
- $p$  can be estimated from multiple scattering
- analysis quite painful!
  - records everything (no trigger possible)



Cecil Frank Powell (1950) Nobel Prize for development of the photographic method of studying nuclear processes

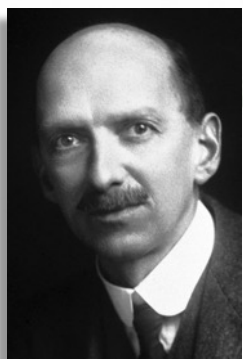


OPERA neutrinos detector: particles observed in "bricks" of photographic films interleaved with lead sheets

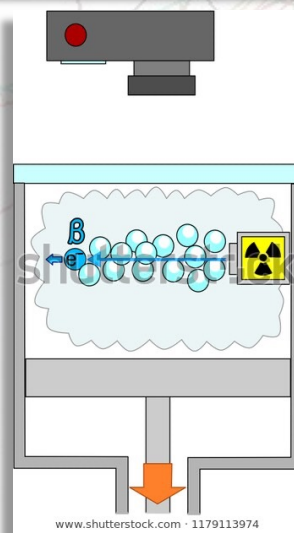
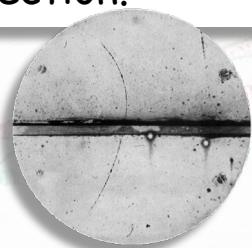


## Detectors based on ionization: cloud chamber

- **Wilson Chamber (Cloud Chamber)** is the earliest tracking detector
- In over-saturated vapor, primary ionization clusters left behind a charged particle are centers of condensation
- Droplets will follow the track of a particle
- **Used: beginning of the 20th century till mid-1950s**
  - moderate spatial resolution (mm)
  - $p$  from curvature in magnetic field,  $v$  from  $dE/dx$
  - slow, moderate volume

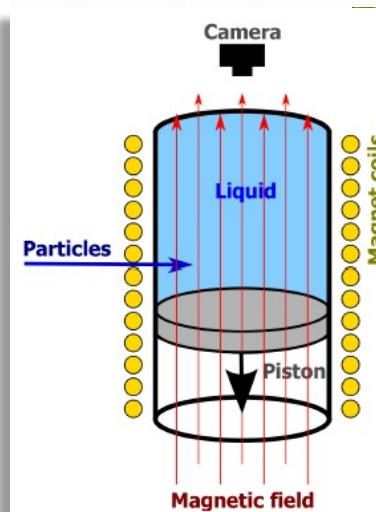


Charles Wilson  
(1927) Nobel Prize  
for his method of  
charged particles  
detection.

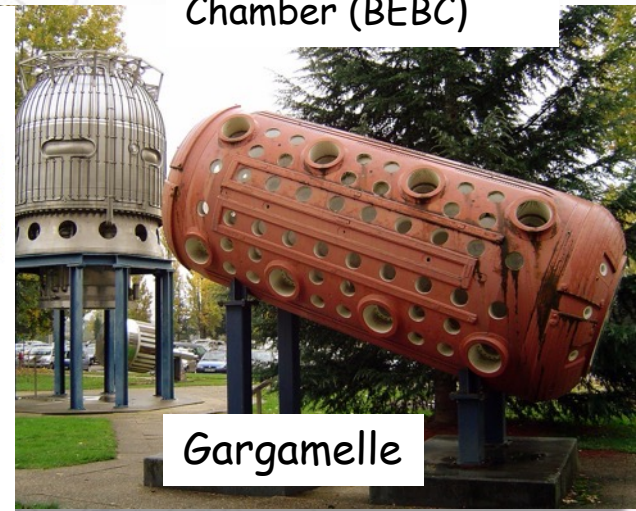


# Detectors based on ionization: bubble chamber

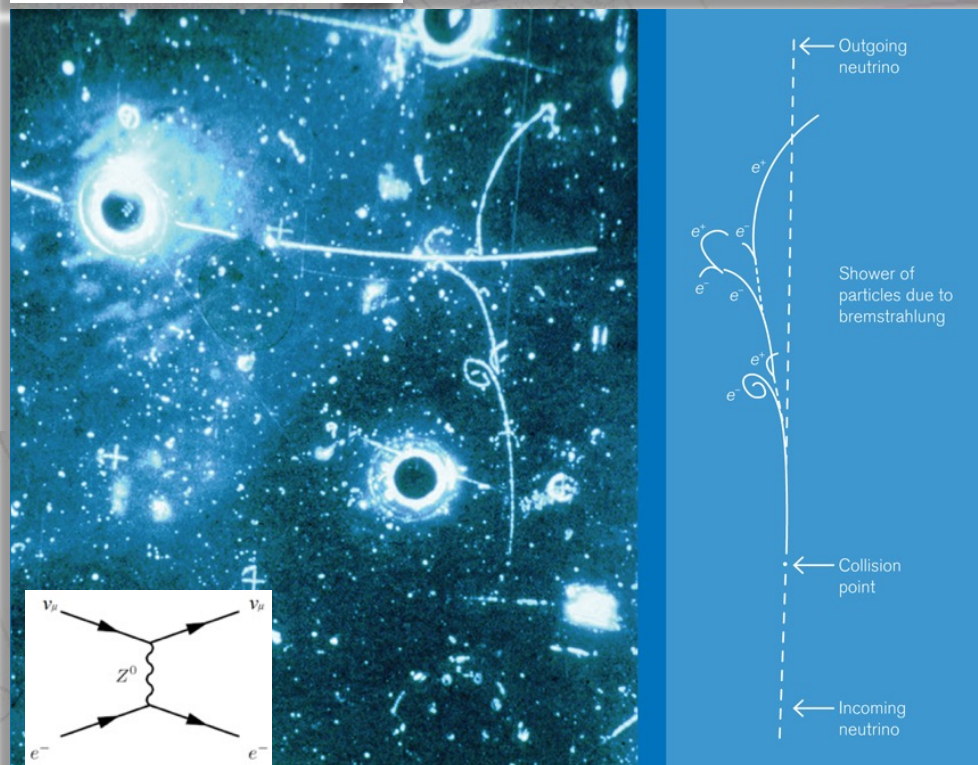
- **Bubble chamber:** a container with pressured liquid close to, but below the boiling point
- Charged particles leave cluster of ionization
- If the pressure is dropped, the boiling temperature drops and the liquid becomes overheated. Boiling is about to begin, bubbles are formed on ionization clusters
- Pictures taken from different directions allow for unambiguous 3D reconstruction
- **Used: from mid-1950s for > 25 years**
- Good spatial resolution: 100  $\mu\text{m}$
- $v$  from density of grains ( $dE/dx$ ),  $p$  from  $B$
- Large volumes (good for neutrino physics)
- Slow, practically no trigger capabilities
- Analysis is painful



Big European Bubble Chamber (BEBC)



Gargamelle

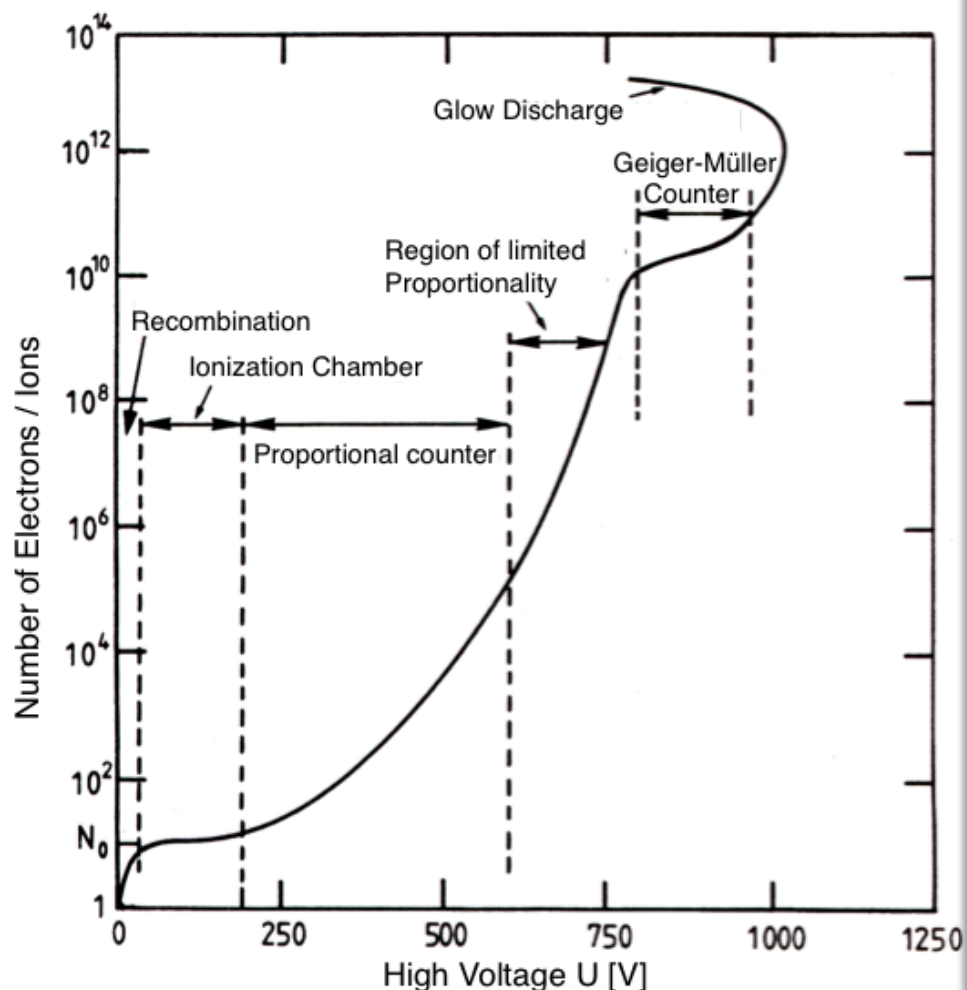


Donald Glaser (1960)  
Nobel Prize for the  
invention of the bubble  
chamber



## Detectors based on ionization: gaseous detectors

- Charged particles ionize atoms in gas volume and produce electron - ion pairs
- Electrons and ions drift in an externally applied electric field and induce the signal
- Due to the high mobility of electrons and ions, gases are ideal detectors (also cheap)



Gas counters may be operated in different operation modes depending on the applied high voltage

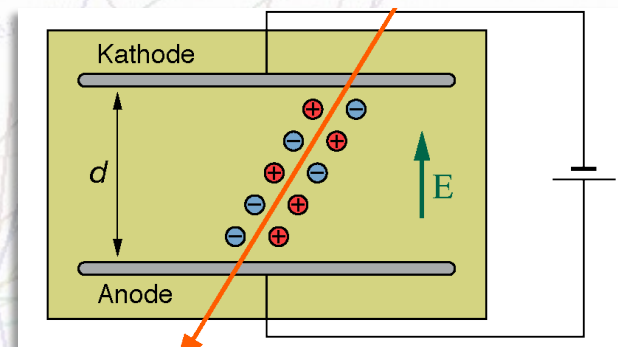
- **Recombination:** radiation creates pairs recombining before reaching electrodes
  - loss of original signal
- **Ionization Chamber:** created pairs can reach electrodes with help of voltage  $U$ 
  - signal proportional to primary ionization
- **Proportional Counter:** secondary electrons are created
  - signal proportional to primary+secondary ionization
- **Geiger-Muller Counter:** discharge in the full gas
  - same signal independent of energy



# Detectors based on ionization: ionization chamber and proportional counter

## Ionization Chamber - the simplest gas detector

- voltage allows for full collection of charges, however below the threshold of secondary ionization (no amplification)
- signal inducted by the movement of electrons and ions in the electric field



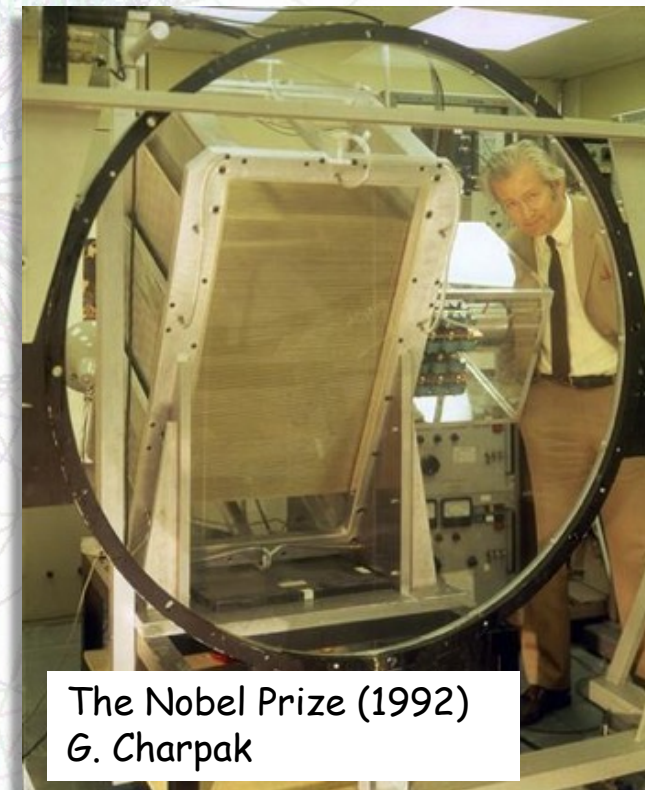
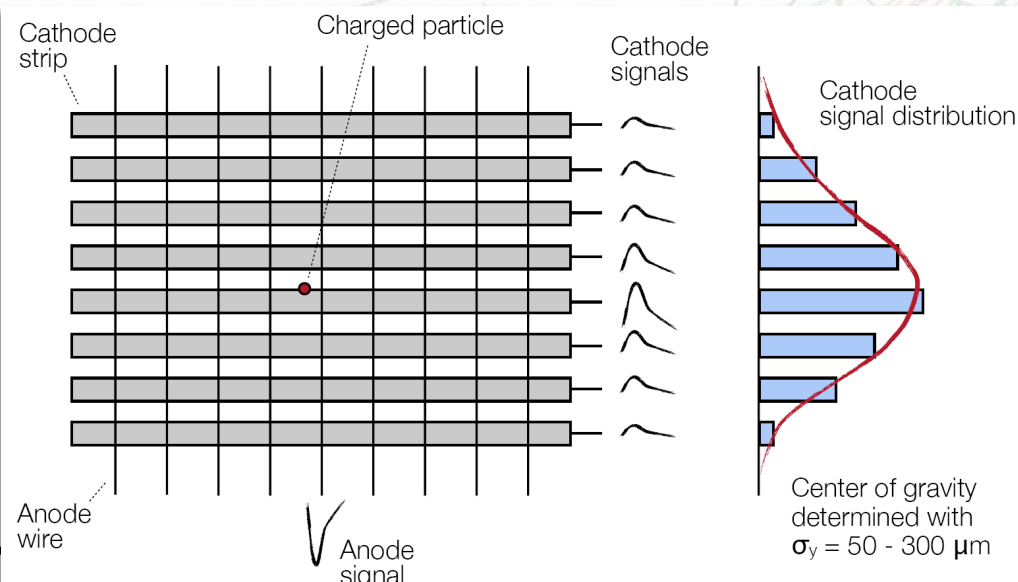
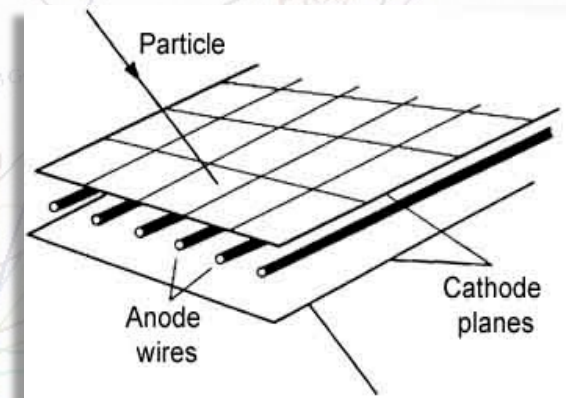
## Proportional Counter - gas-filled tube with a thin wire stretched along its axis

- Positive high voltage potential applied to the wire, large enough to accelerate drifting electrons to energies sufficient for producing secondary ionization
- The gas gain factor is constant - signal proportional to the primary ionization
- Total charge collected on the wire
  - $G(\text{gas gain}) = 10^4\text{-}10^5 \times \text{initial ionization}$
- Choice of gas: noble gases to increase ionization probability
  - The larger atomic number is, the lower the ionization potential is
  - However, Xe and Kr are expensive  $\Rightarrow$  Ar is the noble gas of choice
- Limit: with some gas photons can be created by gas de-excitation
  - Photons can create ionization elsewhere in the fill gas (photoelectric effect)
  - Help: adding "quenching gas" like methane absorbing UV photons

# Detectors based on ionization: multiwire proportional counter

**Multiwire proportional counter (MWPC)** - many parallel anode wires stretched in plane between two cathode planes

- Different anode wires act as independent detectors. **First fully electronic detector!**
  - electronics: thousands of electronic channels became affordable by 1970s
- MWPC can only measure the coordinate perpendicular to the wires. No position measurement along the wires!
- If cathode is segmented, perpendicular to the wires, can be used to determine the 2<sup>nd</sup> coordinate
- Employing a center of charge calculation, a position resolution of  $\sim 50\text{-}300\text{ }\mu\text{m}$  is achievable (by simply using the wire position  $\sim 500\text{ }\mu\text{m}$ ).





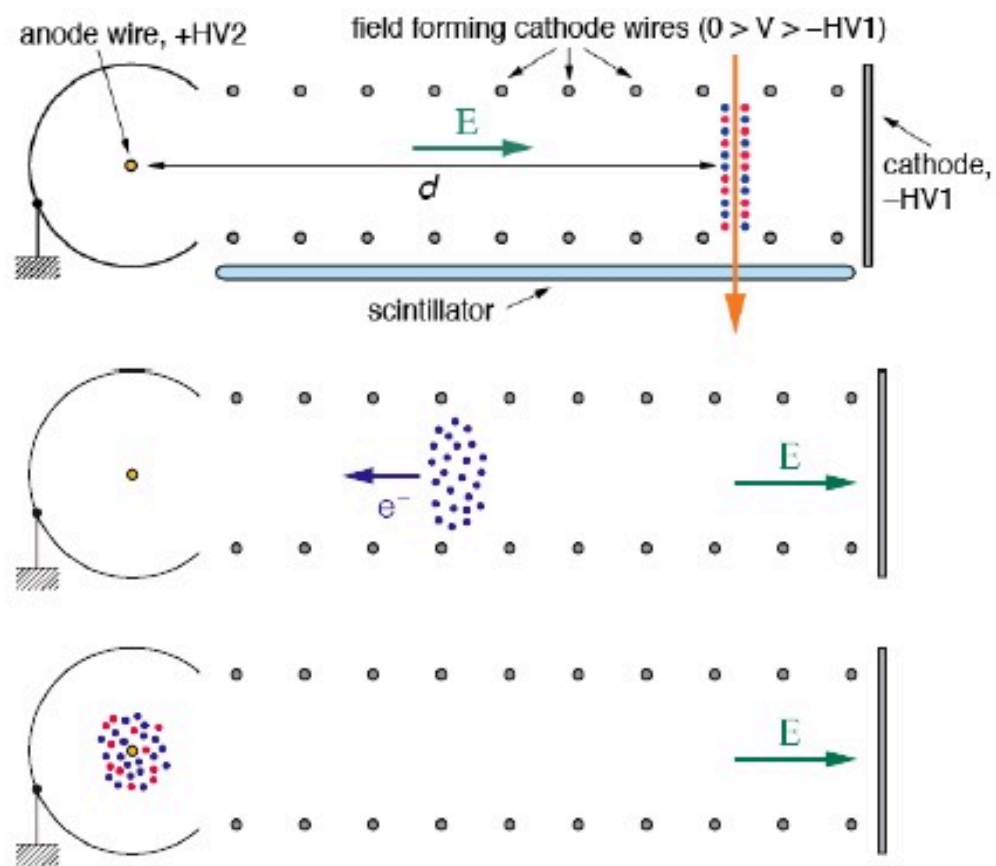
## Detectors based on ionization: drift chamber

**Drift chamber** is a multiwire chamber but with spread cathode planes

1. Charged particle traversing the chamber produce ionisation. The scintillator signal starts a timer ( $t = t_0$ ).
2. Electrons drift to the anode wire.
3. Electrons reaching the wire create secondary ionisation (avalanche) and trigger a signal ( $t = t_1$ ).

From the time difference the distance of the traversing particle to the wire is deduced.

$$\Delta t = t_1 - t_0, \quad x = v \cdot \Delta t$$

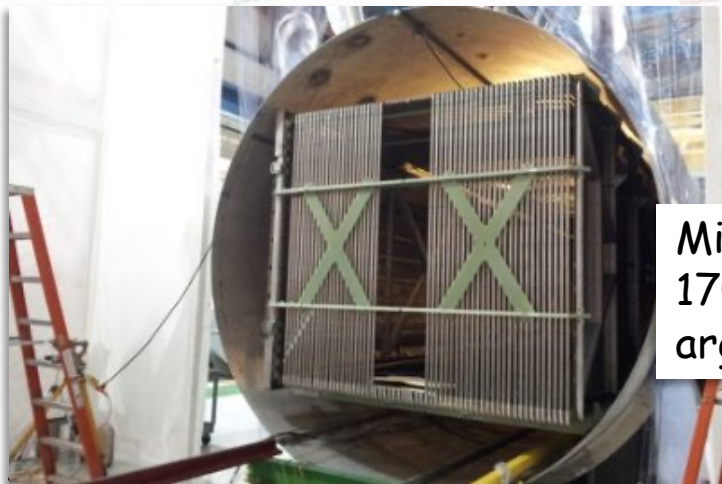
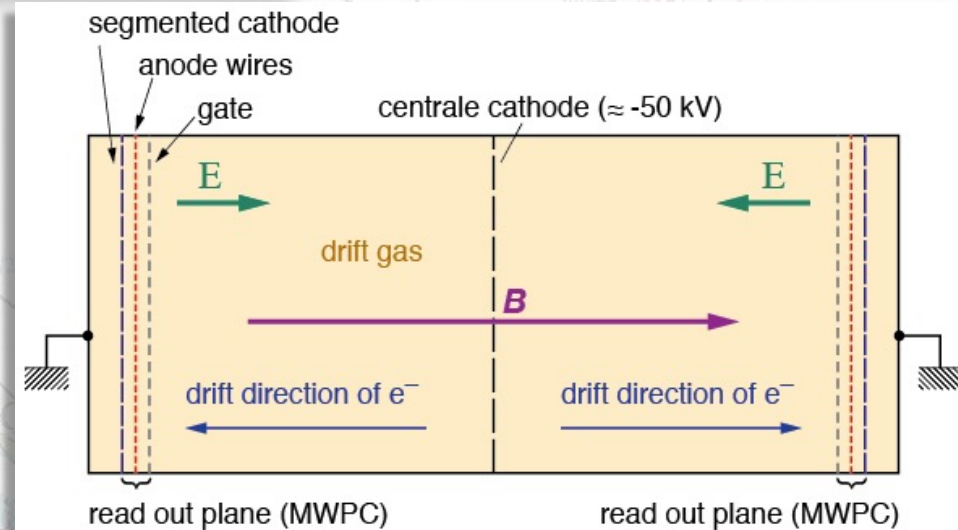


- The electric field has to be homogeneous and the drift velocity constant and known
- Position resolution for large area chambers  $\sim 200 \mu\text{m}$
- Compared to MWPC: fewer wires and electronic channels, higher precision, but slower!

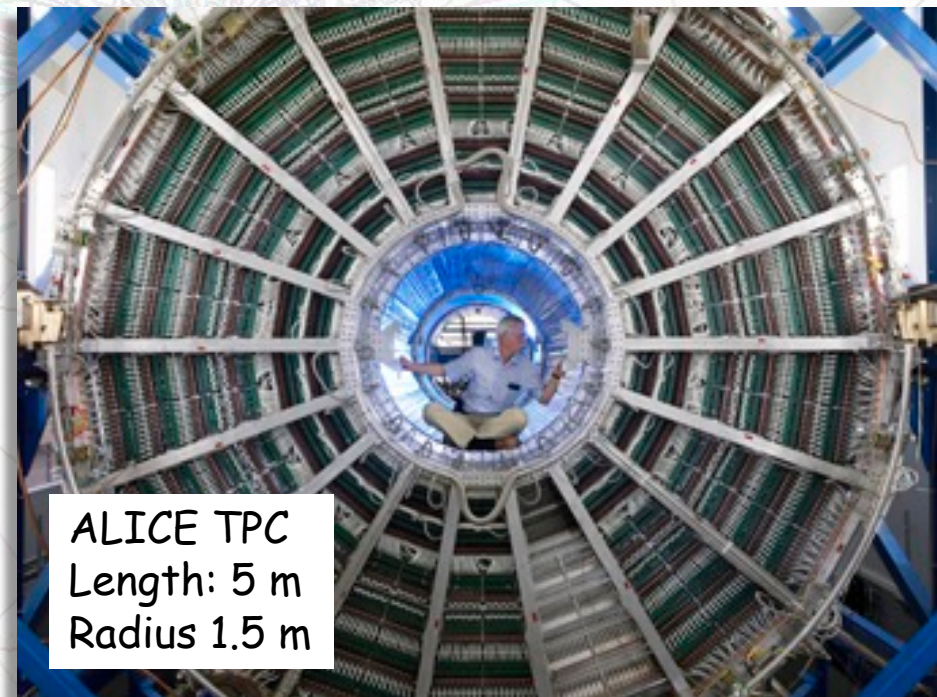
# Detectors based on ionization: Time Projection Chamber (TPC) (1)

Drift chamber with several meters drift distances

- **Electronic "bubble chamber", full 3D reco!**
- Ionization electrons drift toward endcaps where MWPCs are placed
  - $xy$  from wires and pads of MWPC
  - $z$  from drift time measurement
- $p$  measurement:  $B$  field,  $v$  from  $dE/dx$
- Position resolution of typically  $\sigma_{r,\phi} = 150\text{--}250\ \mu\text{m}$  and  $\sigma_z \approx 1\ \text{mm}$
- Due to long drift times (e.g.  $90\ \mu\text{s}$  for 2,5 m drift length ALICE TPC), TPCs are not suitable for high particle rates - but ok for HI collisions



MicroBooNE  
170-ton liquid  
argon TPC

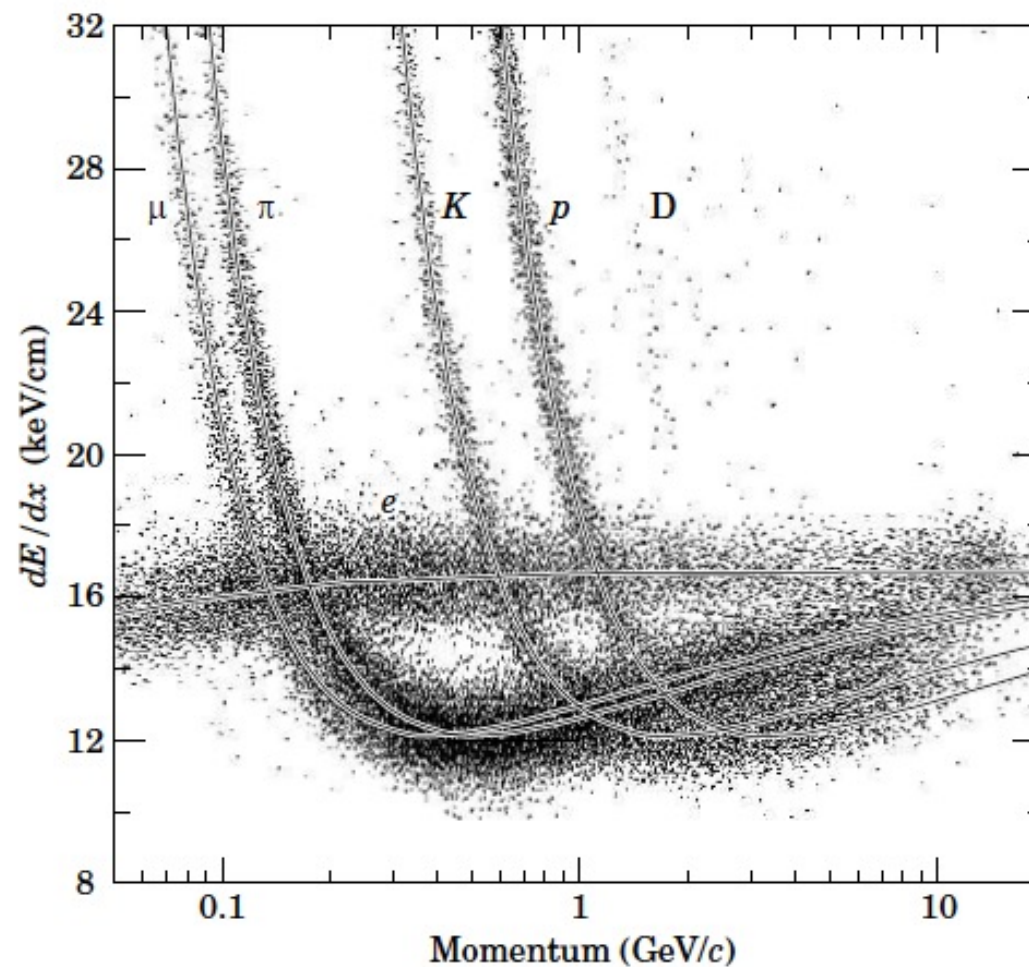


ALICE TPC  
Length: 5 m  
Radius 1.5 m



## Detectors based on ionization: Time Projection Chamber (TPC) (2)

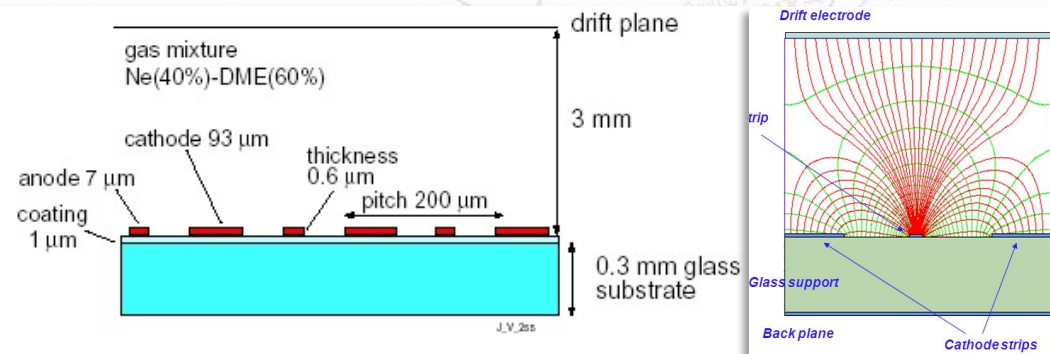
Simultaneous measurement of particle momenta (from bending in magnetic field) and ionization losses  $dE/dx$  (depending on  $v$ ) allows for identification of particles (with not very high momenta)



# Detectors based on ionization: new solutions

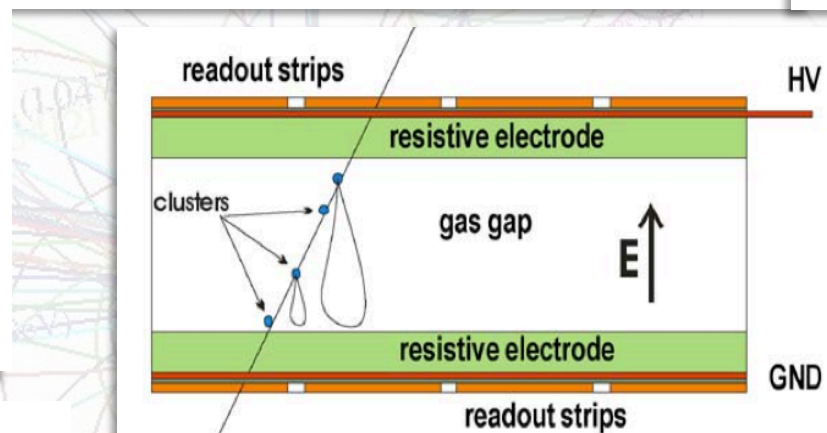
## Micro Strip Gas Chamber (MSGS)

- gain provided by metal strips on resistive electrodes
- fast ion collection  $\rightarrow$  high rate capability
- resolution 30-40  $\mu\text{m}$



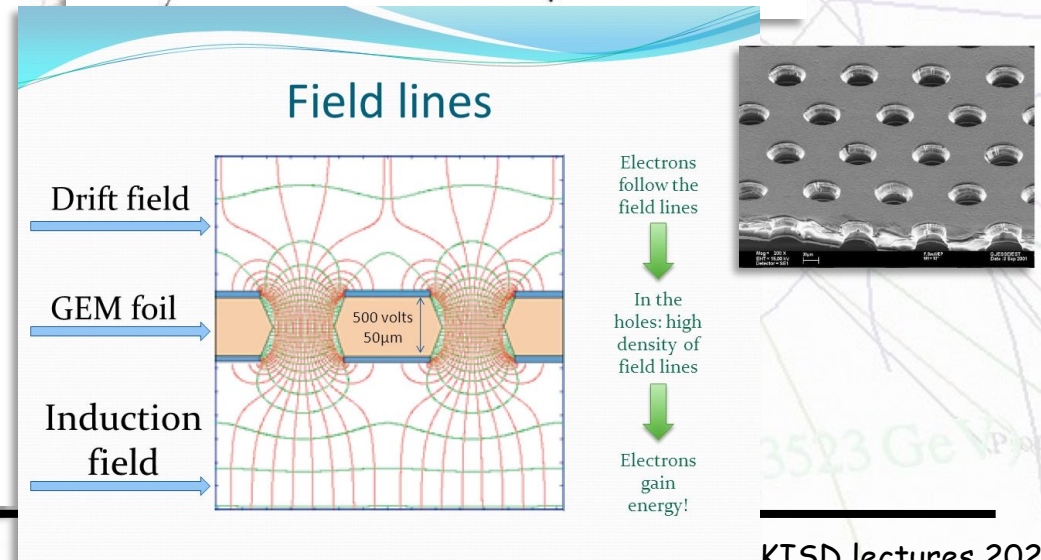
## Resistive Plate Chambers (RPC)

- modern spark chamber
- Gas gap typically 2 mm
- Operating in avalanche mode
- space resolution  $\sim$  mm
- Fast timing ( $\sim$  1 ns) and sufficient high rate capability  $\rightarrow$  **ideal as trigger detectors!**



## Gas Electron Multiplier (GEM)

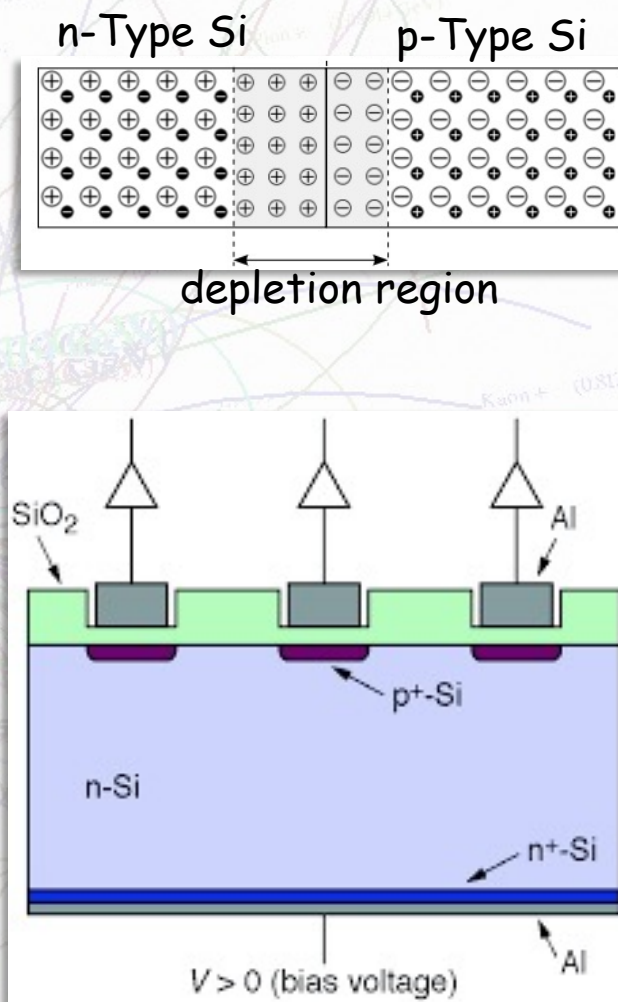
- Parallel-plate chamber with a thin insulating film in the middle, copper clad on both sides, with a pattern of micro-holes,  $O(50) \mu\text{m}$
- Two sides of the film are kept at a difference of potentials  $\rightarrow$  strong E field in the holes  $\Rightarrow$  gas amplifications
- Signal is read out from strips/pads on the plane "under" the foil
- Resolution  $\sim$  70  $\mu\text{m}$





## Detectors based on ionization: silicon detectors (1)

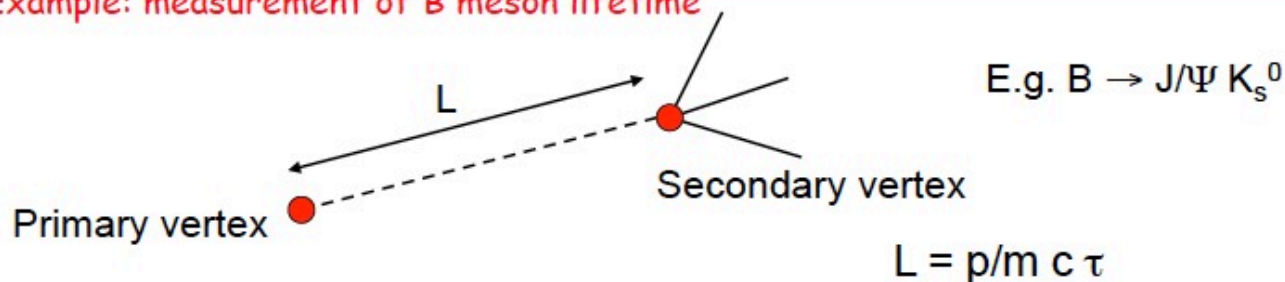
- Silicon detector is an ionization chamber with electron-hole pairs produced as a result of ionization losses
- Use of Si-diode: n-Type Si (adding donors) + p-Type Si (adding acceptors)
- Due to diffusion, region near the p-n interface forms the depletion layer  $\Rightarrow$  no free carriers
- Application of a reverse bias voltage  $\rightarrow$  the thin depletion zone gets extended over the full junction  $\rightarrow$  **fully depleted detector**
- Charged particle traversing depleted zone creates free e/hole pairs
- Under the influence of the E-field, the electrons drift towards the n-side, the holes towards the p-side  $\rightarrow$  **detectable current**.
- **Construction:** thin ( $\sim 300\text{ }\mu\text{m}$ ) layer of n-Type strips/pixels with p-Type implanted and connected to individual read-out channels
- Easily detectable signals from plain ionization—no additional multiplication mechanisms are needed because:
  - large density of electrons (a few thousand  $\times$  > than in gases)
  - small average energy needed for ionization ( $\sim 3\text{ eV}$  vs  $\sim 30\text{ eV}$  in gases)
- Resolution depends on distance from strip to strip ( $20\text{--}150\text{ }\mu\text{m}$ )



## Detectors based on ionization: silicon detectors (2)

- Silicon detectors are:
  - intrinsically fast:
    - thin
    - fast drift of both electrons and holes
  - precise: e.g.  $\sim 5 \mu\text{m}$  from center of gravity method on signals shared between  $50 \mu\text{m}$  wide strips
  - have good two-track resolution (due to small strip/pixel size).
- These features make them ideal of vertex (primary and secondary) tracking...
- Radiation hardness
- But... expensive
  - not only Silicon itself
  - high number of readout channels
  - large power consumption -  $\rightarrow$  cooling

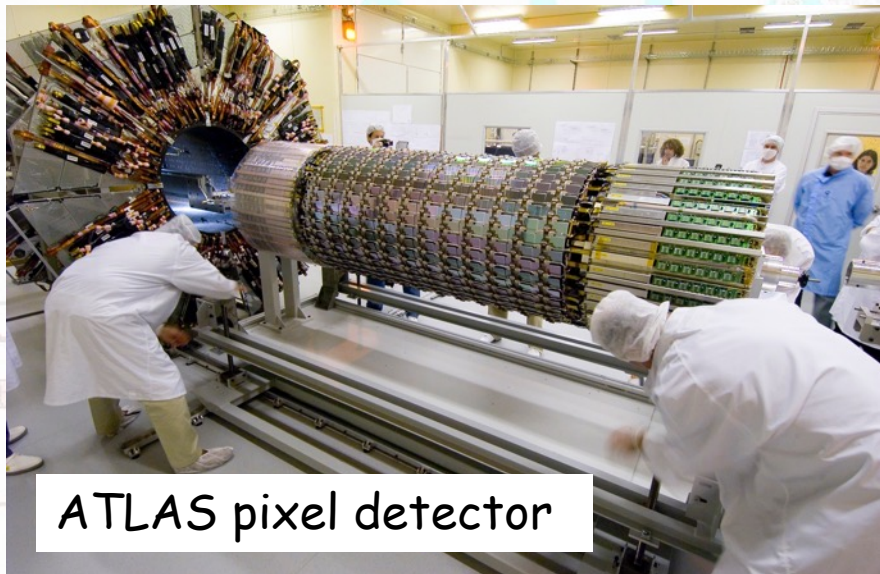
Example: measurement of B meson lifetime



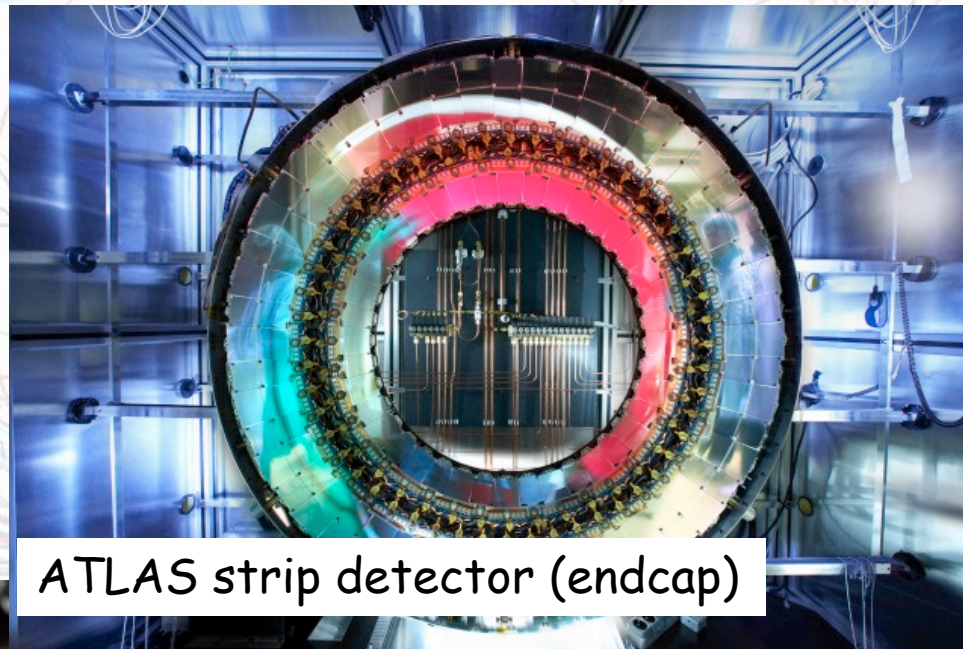
- Look for B vertex and measure decay length - dist. between primary and secondary vert.
- B mesons decay within 1-2 mm of interaction point ( $ct \sim 0.5 \text{ mm} + \text{relativistic time dilat.}$ )
- Need vertex detectors with excellent position resolution  $\sim 10 \mu\text{m}$



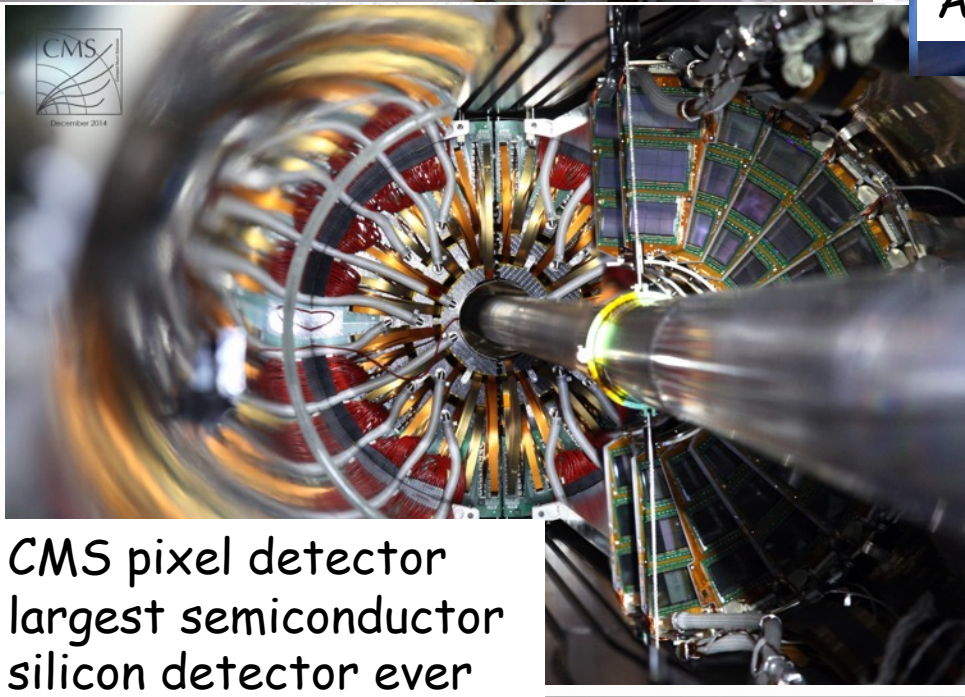
## Detectors based on ionization: silicon detectors (3)



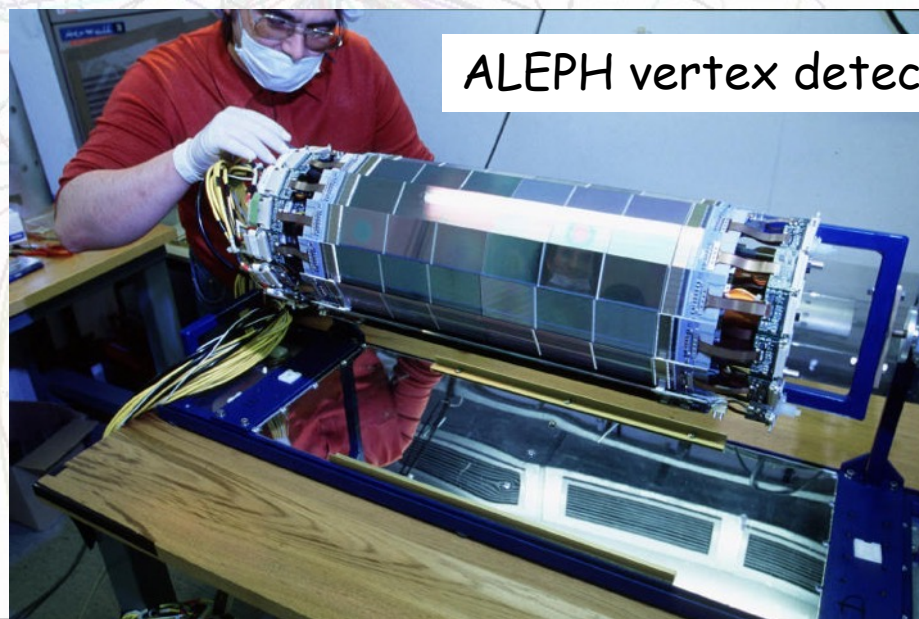
ATLAS pixel detector



ATLAS strip detector (endcap)



CMS pixel detector  
largest semiconductor  
silicon detector ever  
constructed



ALEPH vertex detector



# Detectors based on excitation of atoms: Cherenkov detectors (1)

Nobel Prize in 1958:  
Cherenkov, Frank and Tamm



- Cherenkov radiation results when a charged particle, exceeds the speed of light in a dielectric medium through which it passes
- Charged particle moving inside a polarizable medium excites its molecules
  - upon returning back to their ground state, the molecules re-emit some photons
- Emitted waves move out spherically at the (phase) light velocity in the medium
  - if particle is slow, the radiated waves bunch up slightly in the direction of motion, but they do not cross.
  - if particle moves faster than the light speed, the emitted waves add up constructively leading to a coherent radiation at angle  $\theta$  with respect to the particle direction
    - cone of emission in the direction of particle motion
- Analogy: the sonic boom of a supersonic aircraft or bullet or bow wave generated by speed boat when it travels faster than waves

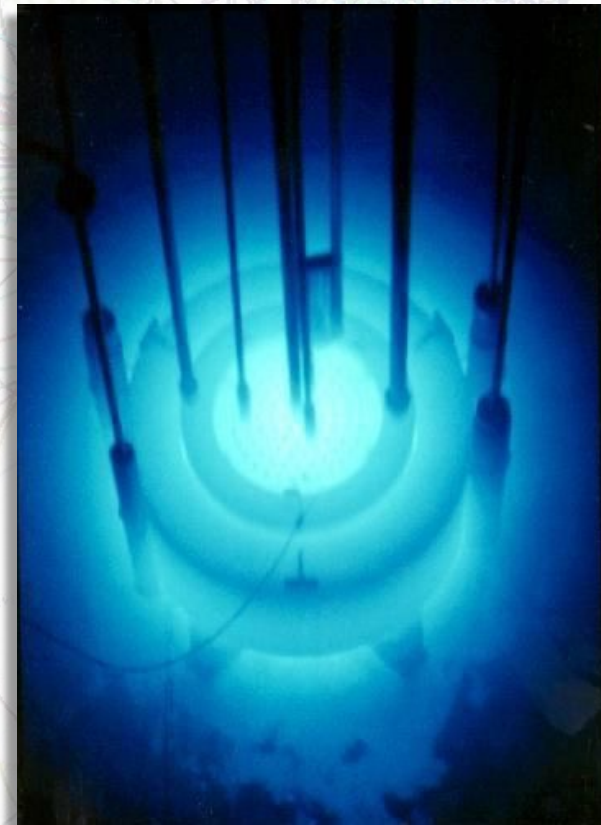
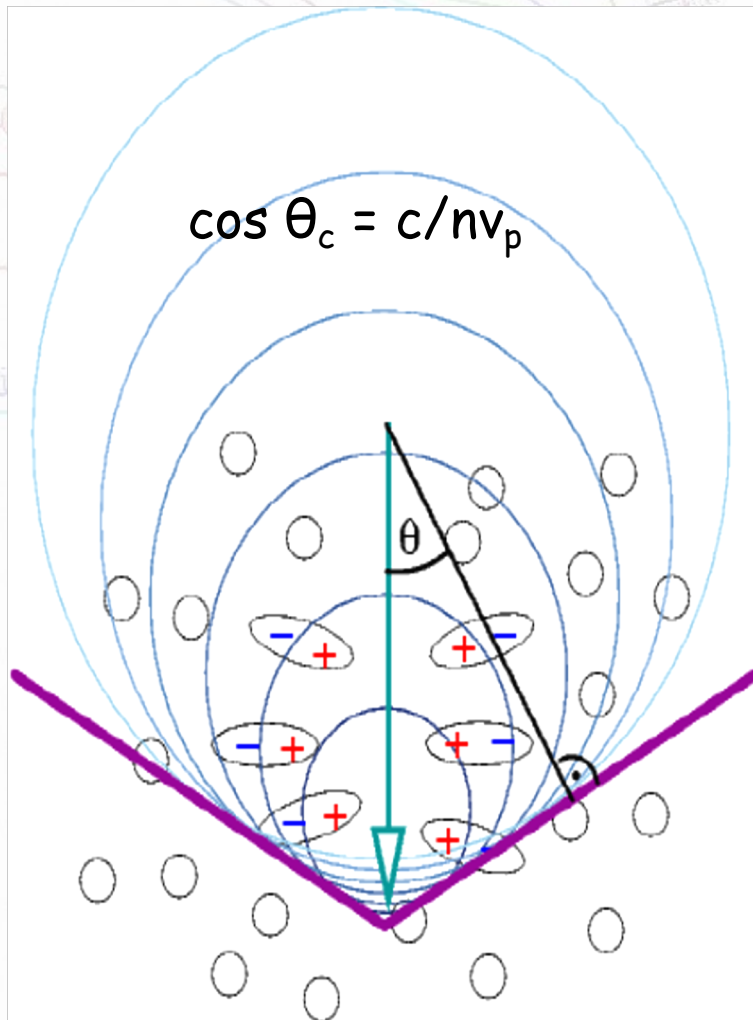




## Detectors based on excitation of atoms: Cherenkov detectors (2)

The geometry of the Cherenkov wave front is defined by the particle velocity  $v_p = \beta c$  and the speed of light in the medium  $v_l = c/n$  ( $n$  - refractive index):

- The frequency spectrum of Cherenkov radiation is given by the Frank-Tamm formula.
- Cherenkov radiation is continuous.
- Around the visible spectrum, the relative intensity per unit frequency is approximately proportional to the frequency.
  - this is why visible Cherenkov radiation is observed to be brilliant blue



Cherenkov radiation can characterize the remaining radioactivity of spent fuel rods

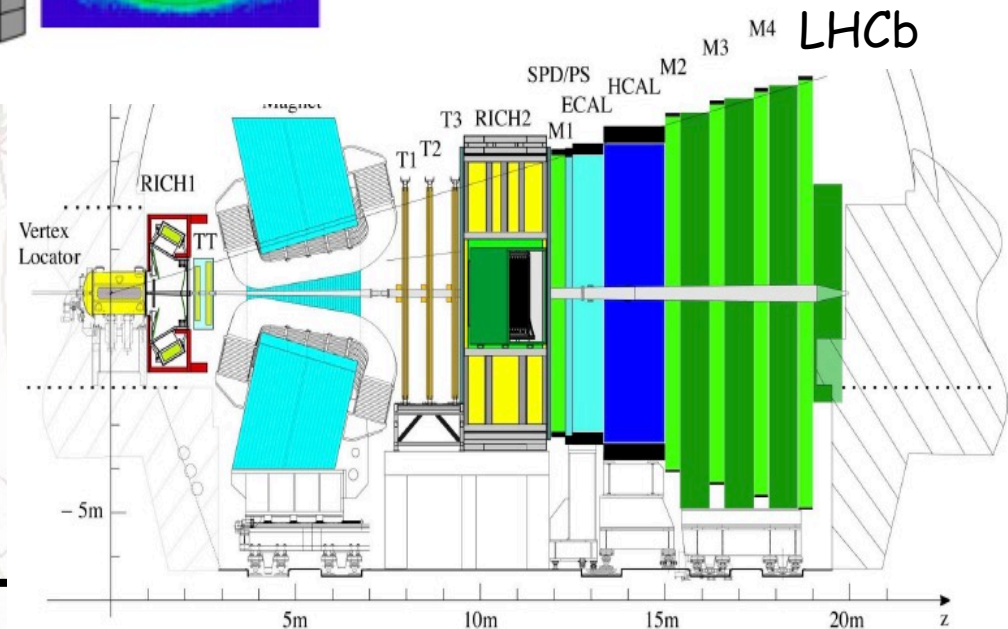
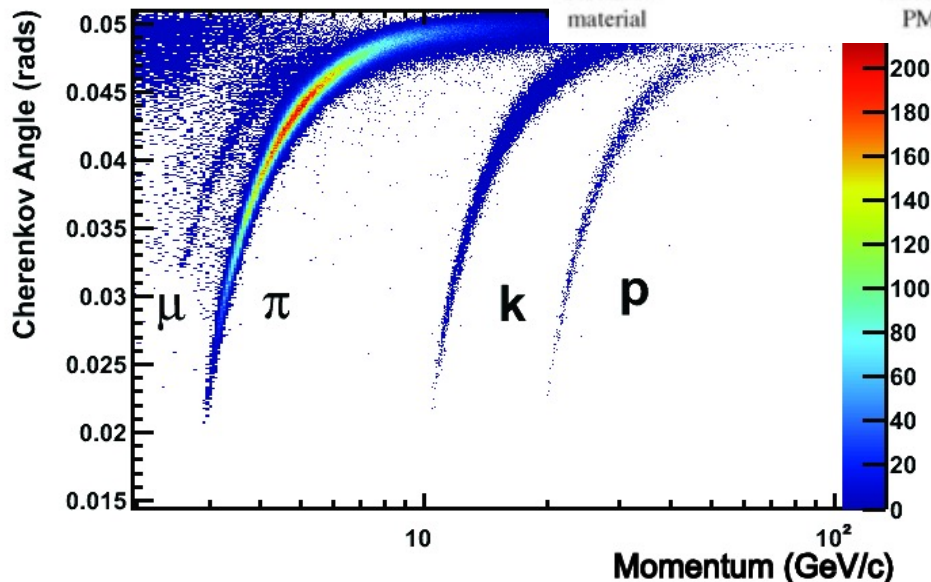
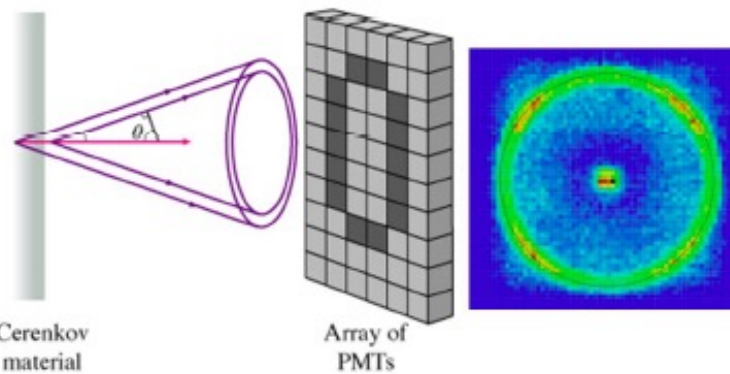
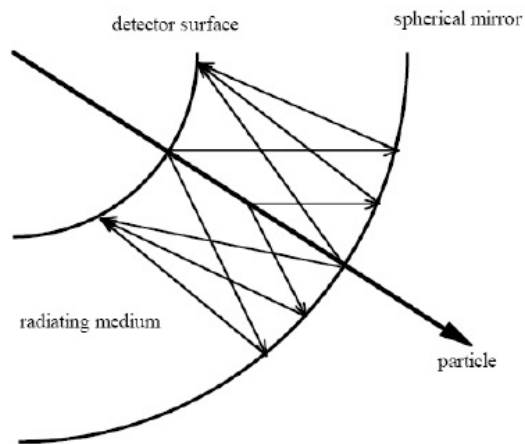
# Detectors based on excitation of atoms: Cherenkov detectors (3)

## Cherenkov Detector Designs:

- **Threshold Counters** - Yes/No decision on the existence of the particle **type**
- **Imaging Counters** - measuring  $\cos\theta_c$ 
  - E.g. Ring Imaging Cherenkov Detectors (RICH)

Via a mirror system, the light cone is imaged on the photon detector plane as a ring with its diameter proportional to  $\theta_c$

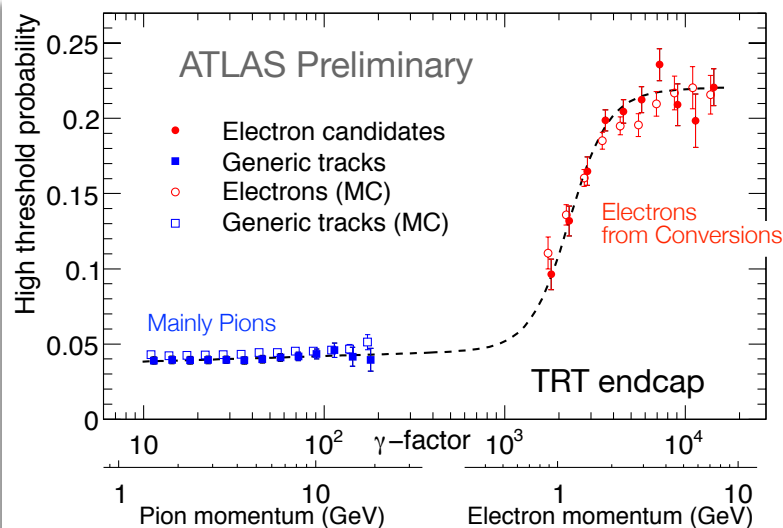
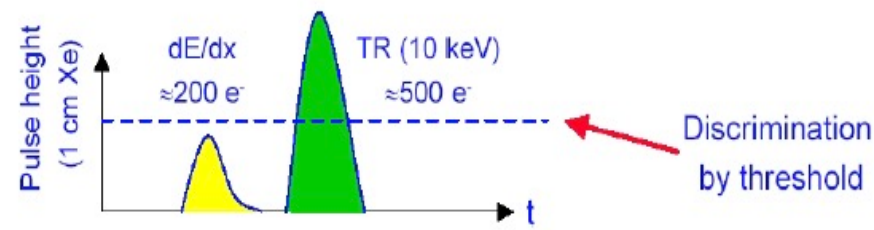
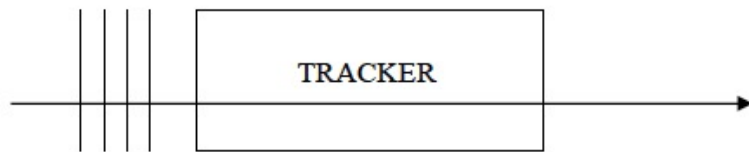
- Can be used for particle identification over large surfaces



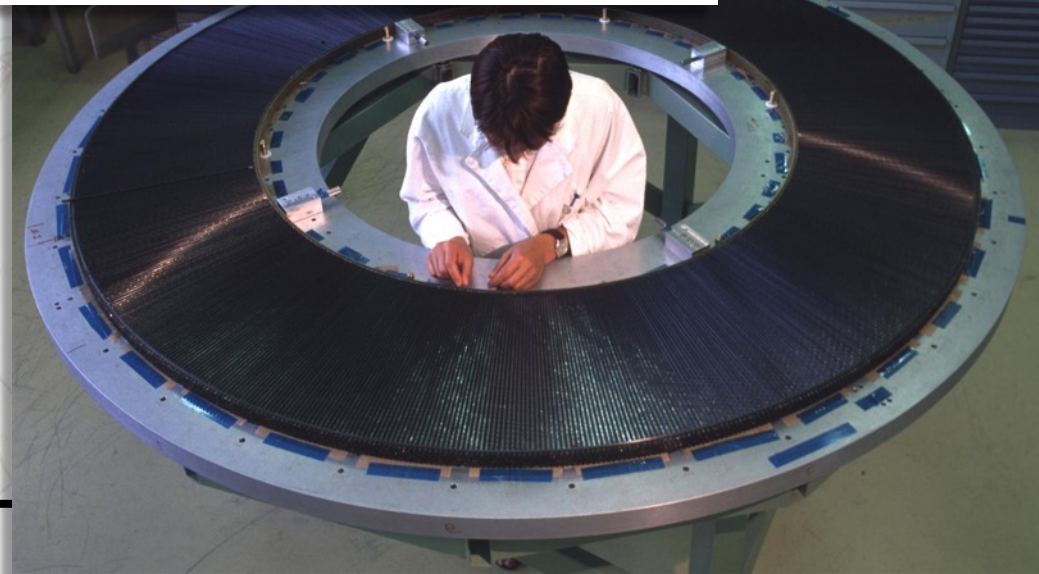


# Detectors based on excitation of atoms: transition radiation

- **Transition Radiation:** radiation in the x-ray region when ultra relativistic particles cross the boundary between two media with different dielectric constants
- Angle of emission of transition radiation photons  $\sim 1/\gamma$  of the particle
- Demonstrated theoretically by Ginzburg and Frank in 1945
- Number of emitted photons ( $E \sim$  several keV)  $\sim \gamma \rightarrow$  method effective for  $\gamma \sim 1000$
- Typical geometry of TR detector
  - a stack of many foils with gaps in between
  - behind a foil stack there is a MWPC or drift chamber where the TRD signal is detected along with the signal from the charged track

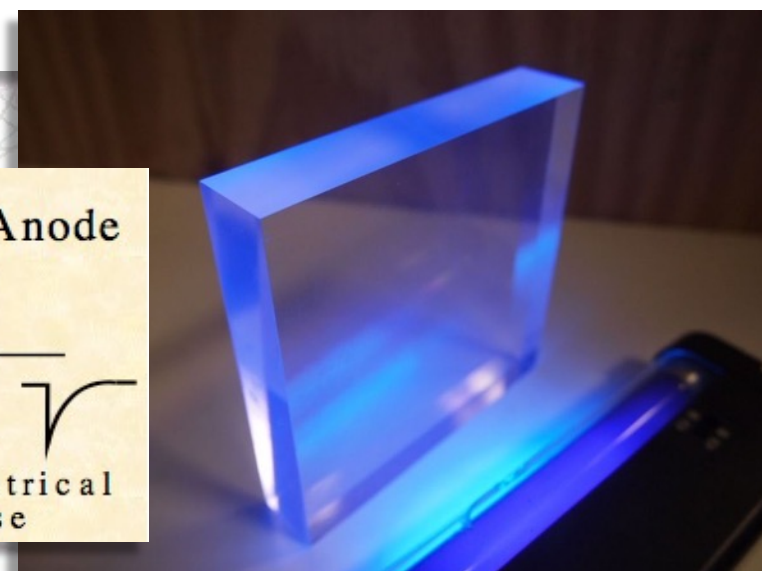
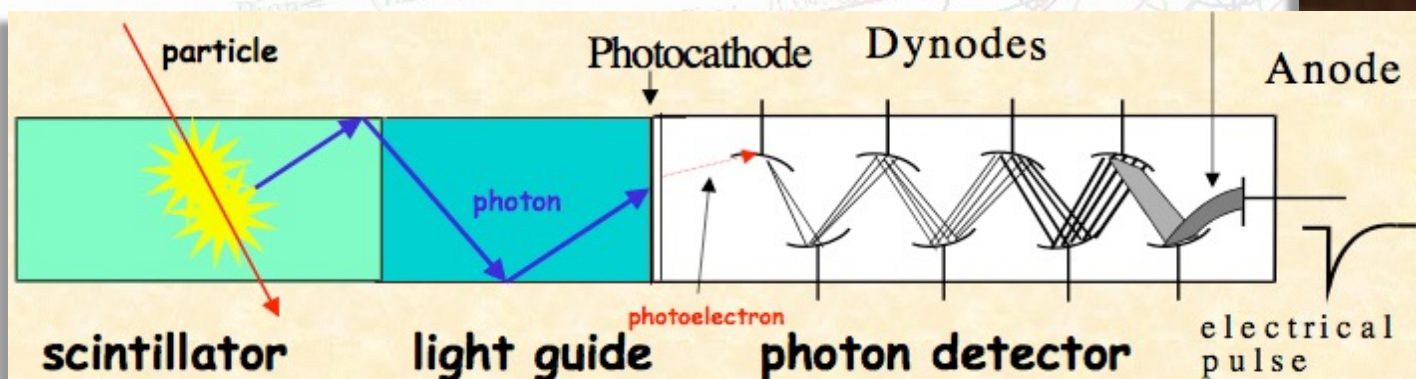


Mainly for  $e/\pi$  separation in 0.5 - 200 GeV



# Detectors based on excitation of atoms: scintillation

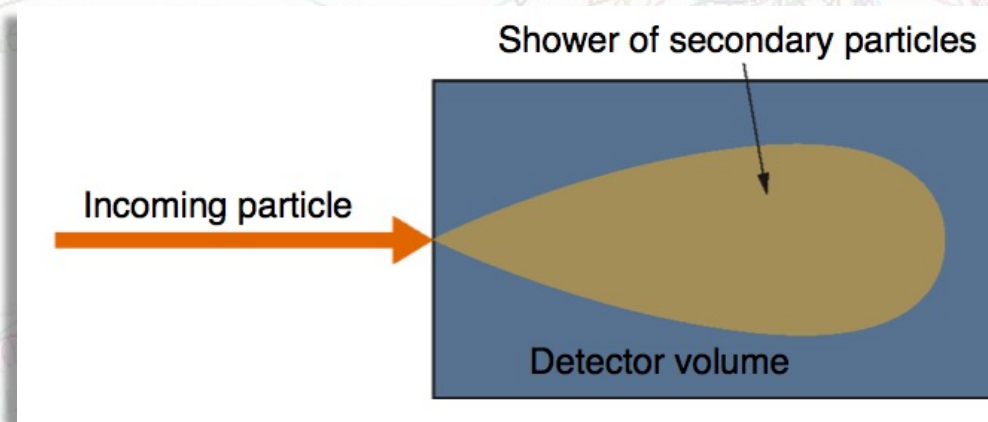
- Incident particles can excite atoms or molecules in the **scintillating medium**
- Excited states decay under emission of photons (UV and visible light)
- The **scintillator** is transparent to the scintillation light
- In photo-sensors scintillation light can be converted in a (weak) electric current
  - coupled to amplifying device such as a **photomultiplier**
  - light is transformed into electrical pulses, which can be analyzed
- One of the most common detection techniques for nuclear radiation and particles
  - most scintillators have linear response: light output  $\sim$  exciting energy
  - shape of emitted light pulses is different for different particles, in some scintillators
    - particle ID
  - fast: response and recovery time is short wrt other detectors
    - trigger!





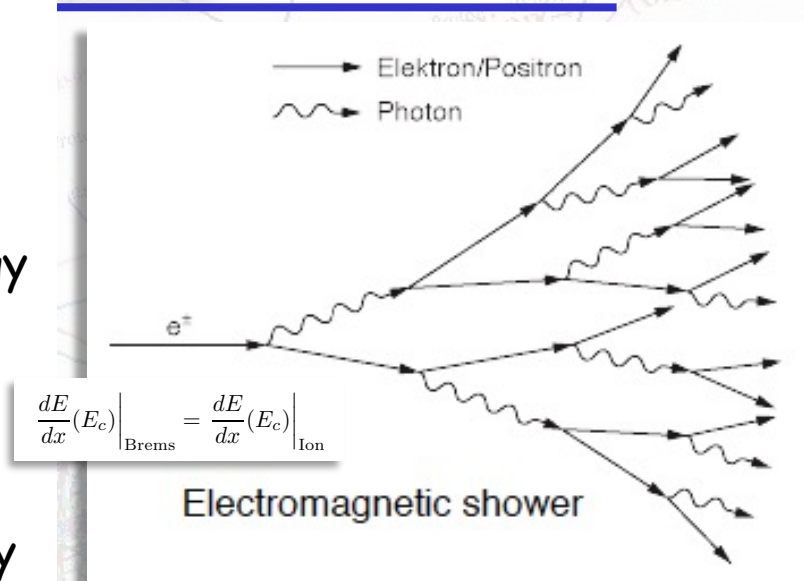
# Calorimeters

- A calorimeter is a detector which fully absorbs the particles
- The signals produced are a measure for the energy of the particle
  - Calorimeter signal  $\sim$  deposited energy  $\sim$  energy of primary particle
  - The particle initiates a particle shower
  - Each secondary particle deposits energy and produces further particles until the full energy is absorbed (hence the historical name calorimeter)
  - This destructive process, the particle's energy is converted in a detectable signal
- Note: calorimetry is addressed also to neutral particles!
- The composition and the dimensions of these showers depend on the type and energy of the primary particle ( $e^\pm$ , photons or hadrons)



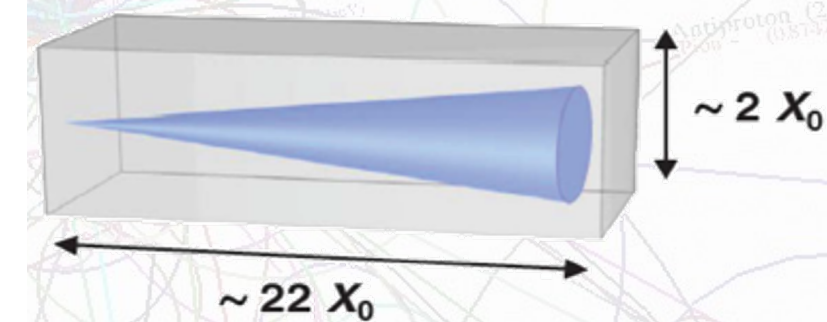
# Electromagnetic cascade

- Penetrating  $e^-/e^+$  emit  $\gamma$  through bremsstrahlung
- The high energy photon produces  $e^+e^-$  pairs
- The primary  $e^-/e^+$  may emit further  $\gamma$ 's etc...
- Particle multiplication continues until particle energy  $\sim$  the critical energy  $E_c$  at which the loss through ionization equals the loss through bremsstrahlung
- If the penetrating particle is a photon, the shower starts with pair production and continues identically



The spatial extension of a shower depends on the material

- Longitudinal dimension: **radiation length  $X_0$** 
  - $X_0$  is the distance in which the projectile loses  $1/e$  ( $\approx 63.2\%$ ) of its energy due to radiation
- Transversal (lateral) dimension: **Molière radius  $\rho_M$**



$$R(95\%) = 2\rho_M$$

$$X_0 = \frac{A \cdot 716.4 \frac{\text{g}}{\text{cm}^2}}{Z(Z+1) \ln(287/\sqrt{Z})}$$

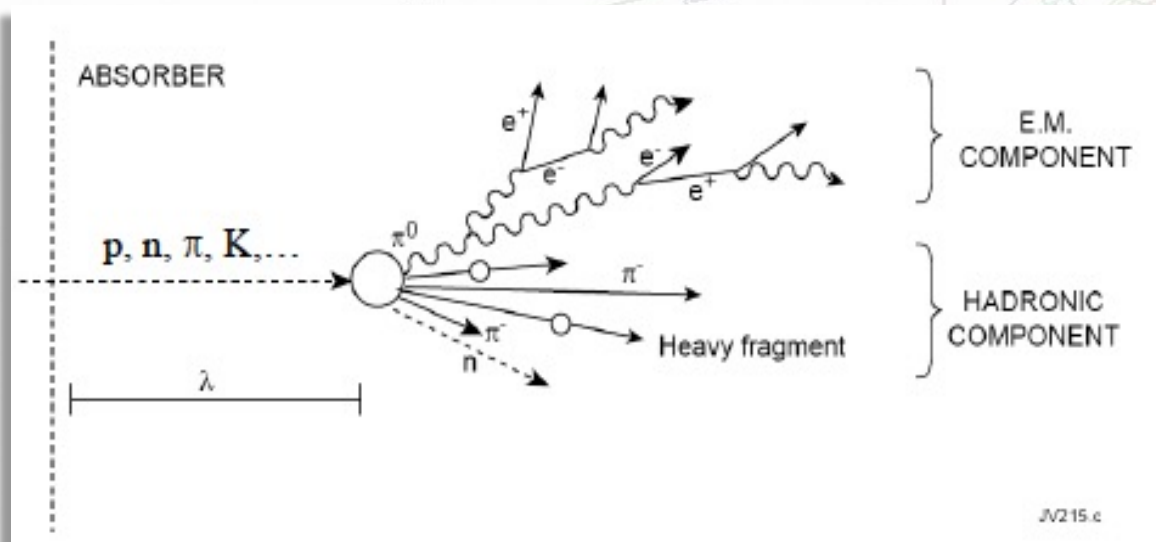
|                  |         |
|------------------|---------|
| $^{13}\text{Al}$ | 8.9 cm  |
| $^{26}\text{Fe}$ | 1.76 cm |
| $^{29}\text{Cu}$ | 1.43 cm |
| $^{82}\text{Pb}$ | 0.56 cm |

$$\rho_M = \frac{\sqrt{\frac{4\pi}{\alpha}} m_e c^2}{E_c} = \frac{21[\text{MeV}]}{E_c [\text{MeV}]} \cdot X_0$$



# Hadronic cascade

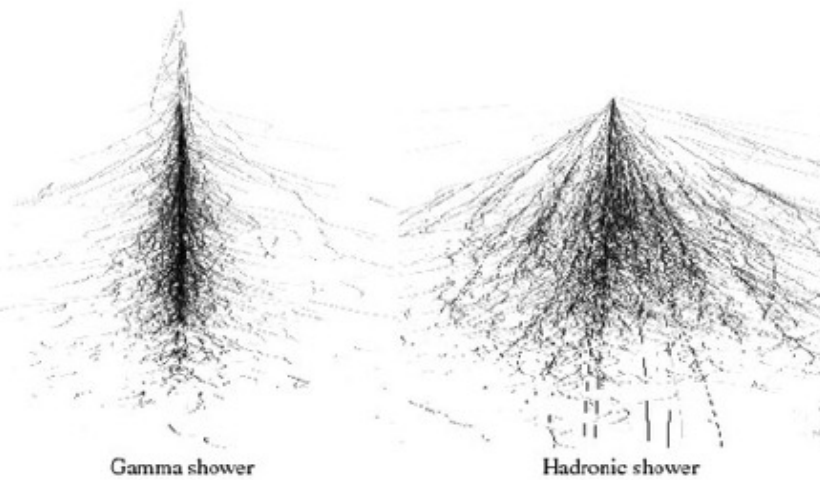
- **Hadronic shower** are a series of inelastic hadronic interactions of a primary particle with the nuclei of the target material
- Produced secondary particles (mainly  $\pi^\pm$  and  $\pi^0$ ) undergo further inelastic interactions and produce more particles
- Due to the multitude of possible processes the development of a hadronic shower is considerably more complicated compared to an EM shower
- **Created  $\pi^0 \rightarrow \gamma\gamma$  and initiate an EM shower within the hadronic shower!**
- **Hadronic shower involves energy loss processes which do not create measurable signals:** nuclear binding energy, production of neutrinos and high energy muons, kinetic energy of debris of nuclei



Hadronic shower dimensions described by the nuclear absorption length  $\lambda_a$

- 95% of a shower is contained in approximately  $7.6 \lambda_a$
- 95% of the total energy is deposited in a cylinder with radius  $\lambda_a$
- E.g. Lead  $X_0=0.56 \text{ cm}$ ,  $\lambda_a = 17 \text{ cm}$

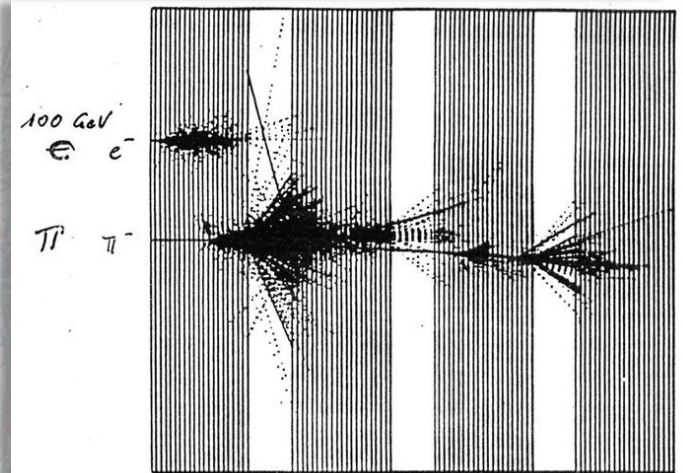
# EM and Hadronic cascades



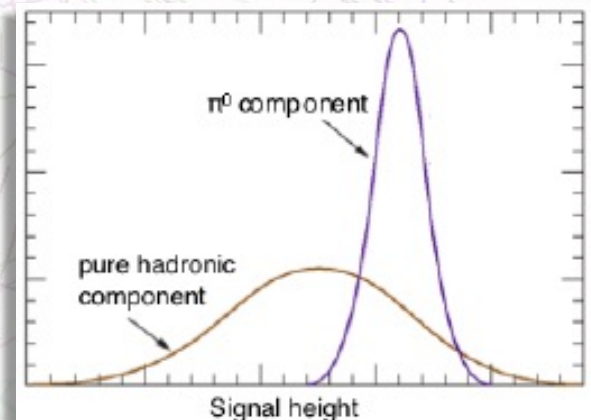
|       | $\lambda_{\text{int}}$ [cm] | $X_0$ [cm] |
|-------|-----------------------------|------------|
| Scint | 79.4                        | 42.2       |
| LAr   | 83.7                        | 14.0       |
| Fe    | 16.8                        | 1.76       |
| Pb    | 17.1                        | 0.56       |
| U     | 10.5                        | 0.32       |
| C     | 38.1                        | 18.8       |

$$\left. \begin{array}{l} X_0 \sim \frac{A}{Z^2} \\ \lambda_{\text{int}} \sim A^{1/3} \end{array} \right\} \rightarrow \frac{\lambda_{\text{int}}}{X_0} \sim A^{4/3}$$

$$\lambda_{\text{int}} \gg X_0$$



- Purely hadronic shower involves energy loss processes
- No such energy loss mechanism in the EM shower
  - response of calorimeter to EM component larger than to hadronic component  $\rightarrow$  **e/h response ratio**
- **e/h is figure of merit of hadron calorimeters**
  - $e/h > 1$ , ideal calorimeter has  $e/h=1$  (compensating calorimeter)





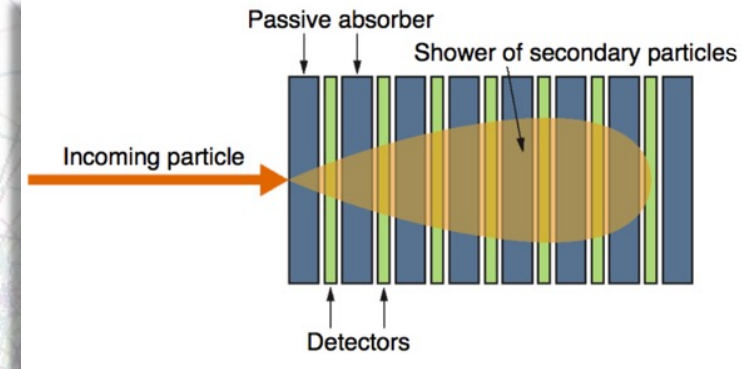
## Different types of calorimeters

- Two different applications: electromagnetic and hadronic calorimeters

### Two different calorimeters by construction:

- Homogeneous Calorimeters (only EM Calorimeter)**

- Detector material is also absorbing material (e.g. scintillator block, lead glass)
- Advantage:** Best possible E resolution achievable
- Disadvantage:** Expensive, large



- Sampling Calorimeters:** alternating layers of passive absorbers and active detectors
  - Typical absorbers are materials with high density: Fe, Pb, U
  - Typical active detectors: plastic scintillators, noble liquid ionization etc.
  - Advantages:** can optimally choose the absorber and detector material, f.e. by choosing a very dense absorber calorimeters can be made very compact, cheap
  - Disadvantages:** only part of particles energy is deposited in active detector layers and measured, energy resolution is worse than in homogeneous calorimeter

## Energy resolution of calorimeters (1)

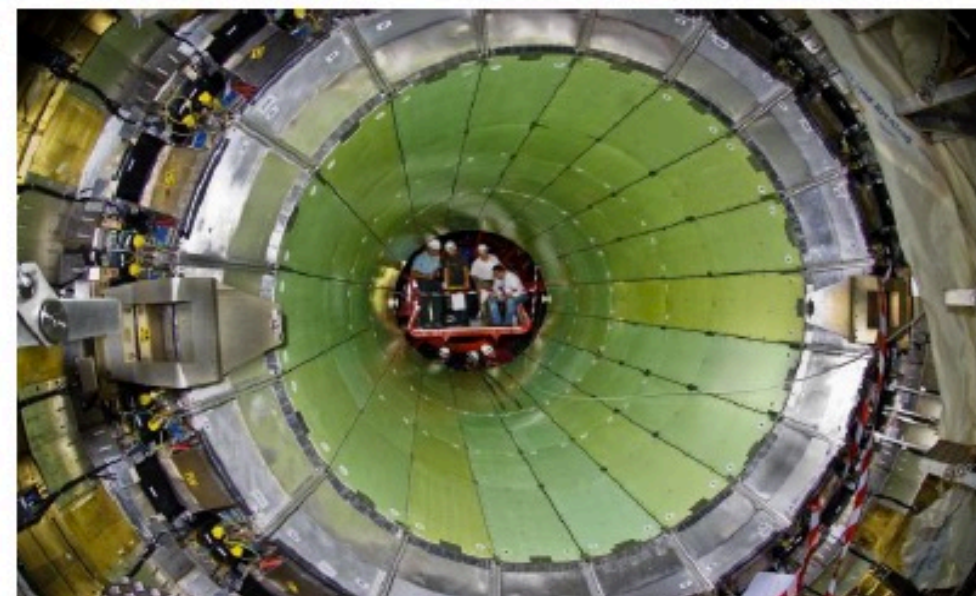
- Calorimetry is based on a statistical process. A particle produces on average  $N$  secondary particles.
- Ideally, if all shower particles counted:  $E \sim N$ ,  $\sigma \sim \sqrt{N} \sim \sqrt{E}$ 
  - the relative energy resolution improves with increasing energy
- In practice: energy resolution of a calorimeter where  $E$  is energy of incoming particle:

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \quad \leftarrow \text{added in quadrature}$$

- **$a$ , stochastic term:** the counting aspect of the measurement: simple statistical error. Scales with the square root of the number of particles.
  - **$b$ , noise term:** constant, energy-independent noise (f.e. from readout electronics) contribution to the signal
  - **$c$ , constant term:** contributions that scale with energy: imperfections in calorimeter construction (dimension variations), non-uniform detector response, channel to channel intercalibration errors, fluctuations in longitudinal energy containment, energy lost in dead material before or in detector
- Crucial to have small constant term for good energy resolution at the highest particle energies
  - Essential to CALIBRATE the calorimeter, namely establish a precise relationship between the "visible energy" detected and the energy of the incoming particle



Proton Pion



A man in a white lab coat and gloves is working on a transparent, futuristic structure that resembles a DNA helix or a complex molecular model. The structure is illuminated by blue light, and the man is focused on his work. The background is dark with some glowing elements.

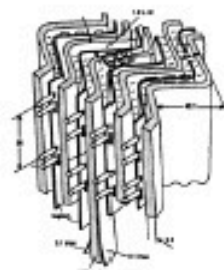
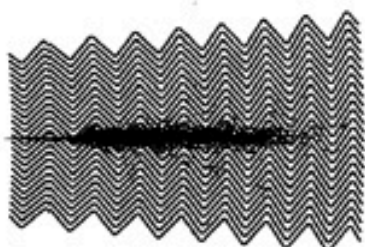
lead tungstate

**Endcaps: 4 Dees (2 per Endcap)**  
**14648 Crystals (1 type) – total mass 22.9 t**



## Example of Sampling EM Calorimeter

### ATLAS 'Accordion' sampling liquid argon calorimeter at the LHC



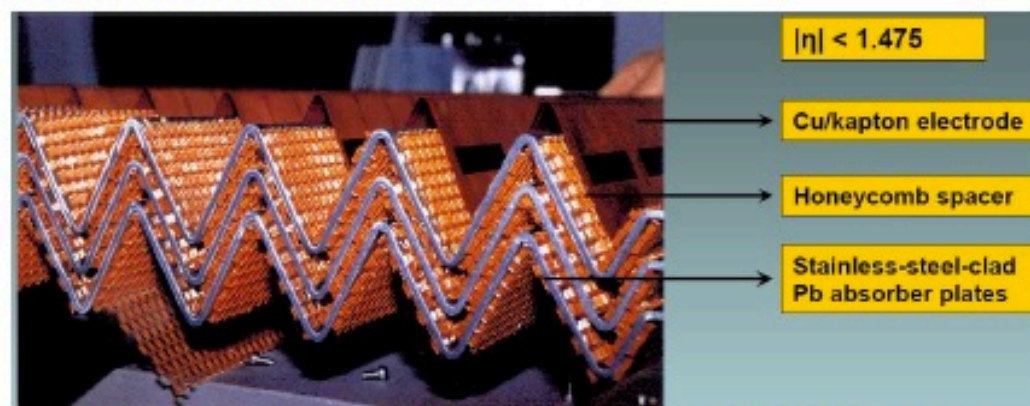
Corrugated stainless steel clad Pb absorber sheets, 1-2 mm thick

Immersed in liquid argon (90K)

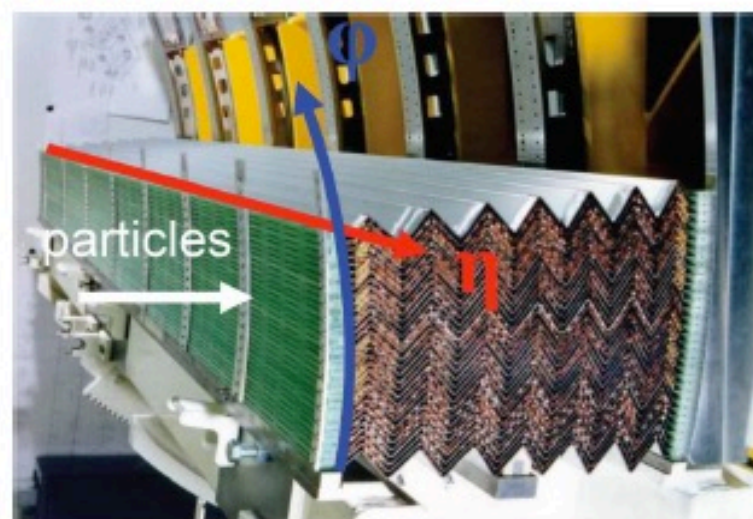
Multilayer Cu-polyimide readout boards

Collect ionisation electrons with an electric field across 2.1 mm liquid Argon drift gap

1 GeV energy deposit  $\rightarrow$  collect  $5 \cdot 10^6 e^-$



Accordion geometry minimises dead zones  
Liquid argon intrinsically radiation hard  
Readout board allows fine segmentation (azimuth, rapidity, longitudinal)

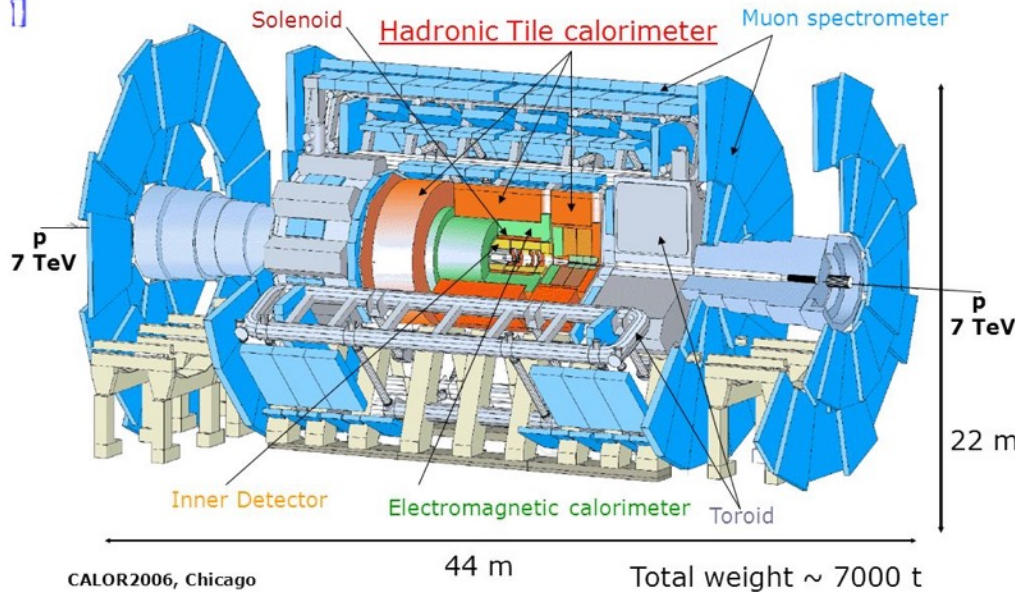




# Example of Hadronic Calorimeter: ATLAS Tile Calorimeter

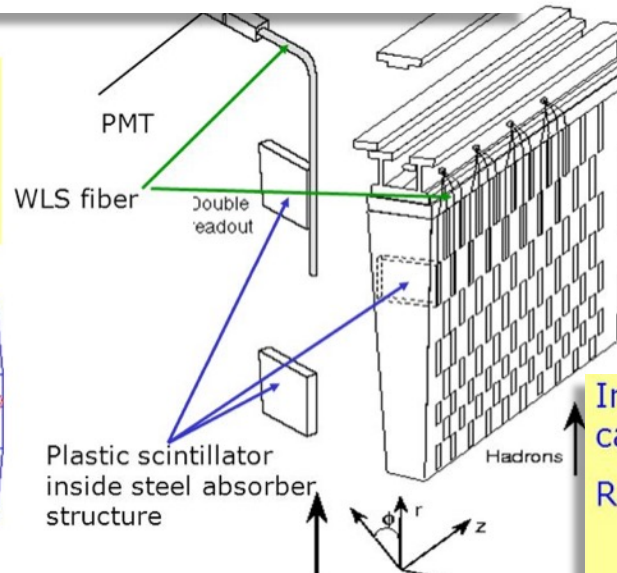
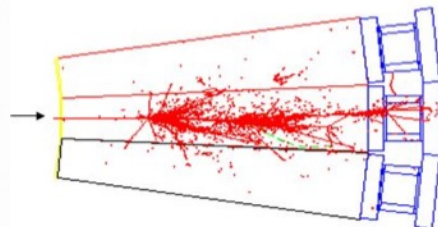


## ATLAS detector



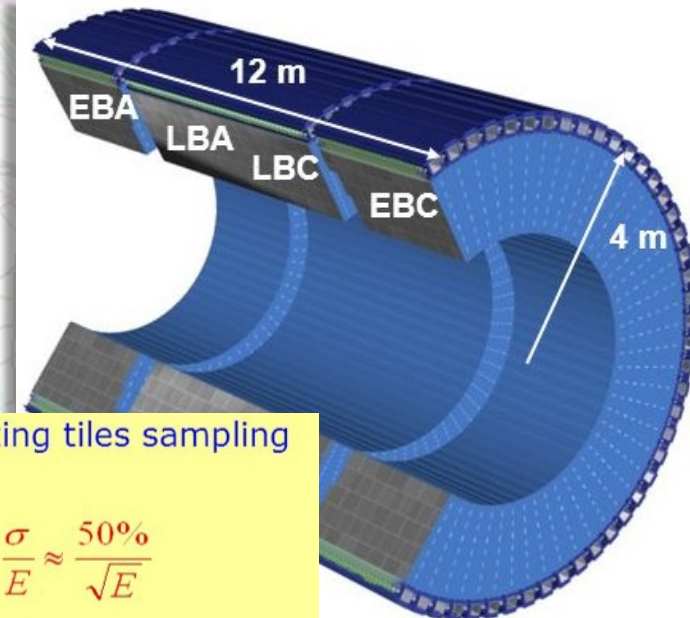
### Principle of TileCal:

Measure light produced by charged particles in plastic scintillator



Iron - scintillating tiles sampling calorimeter

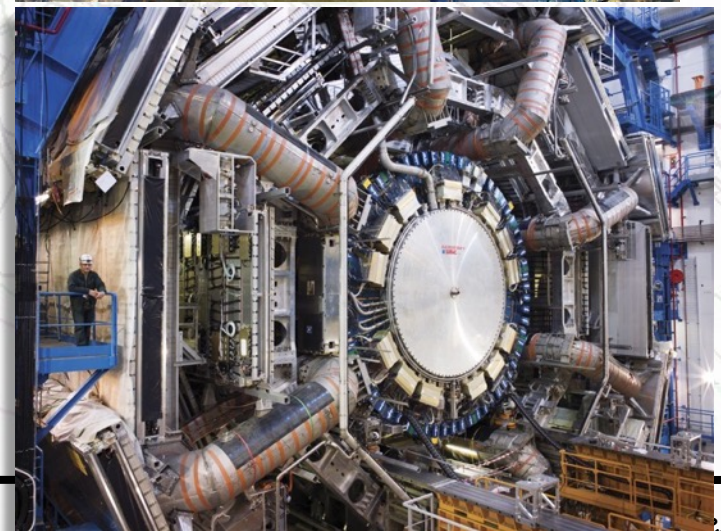
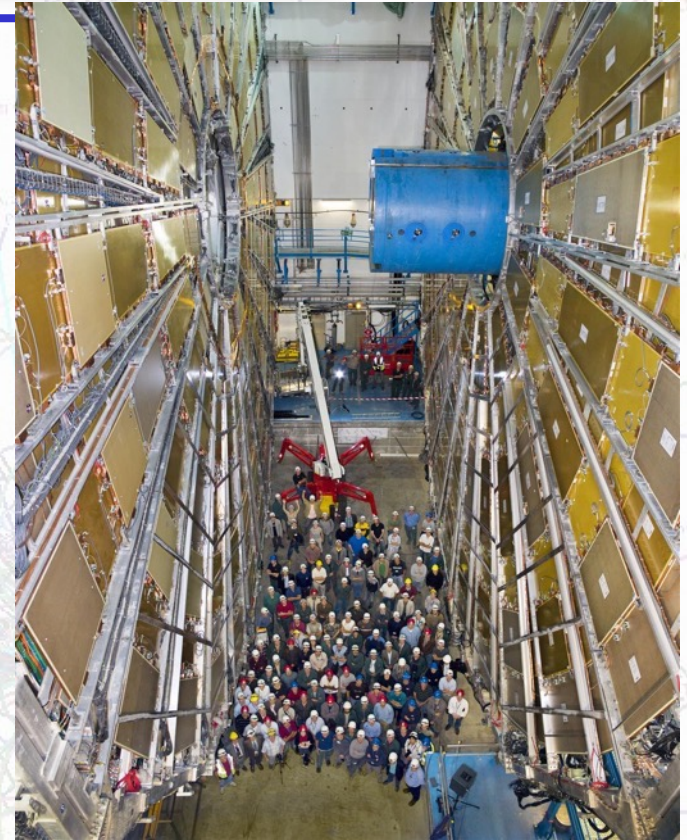
Resolution:  $\frac{\sigma}{E} \approx \frac{50\%}{\sqrt{E}}$





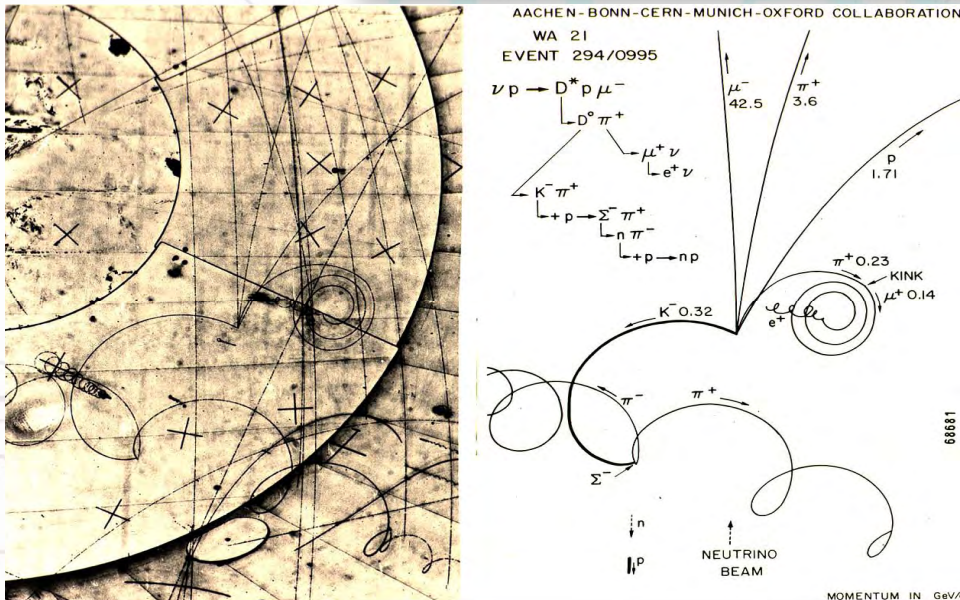
# Detection of muons

- Muons are charged particles that are not interacting strongly and also do not creating EM cascades
- Muons can penetrate several meters of iron without interacting, unlike most particles they are not stopped by any calorimeter
- Therefore, detectors, usually wire chambers, to detect muons are placed at the end of the experiment where they are the only particles likely to register a signal
- E.g. ATLAS muon spectrometer is made up of 4,000 individual muon chambers using four different technologies

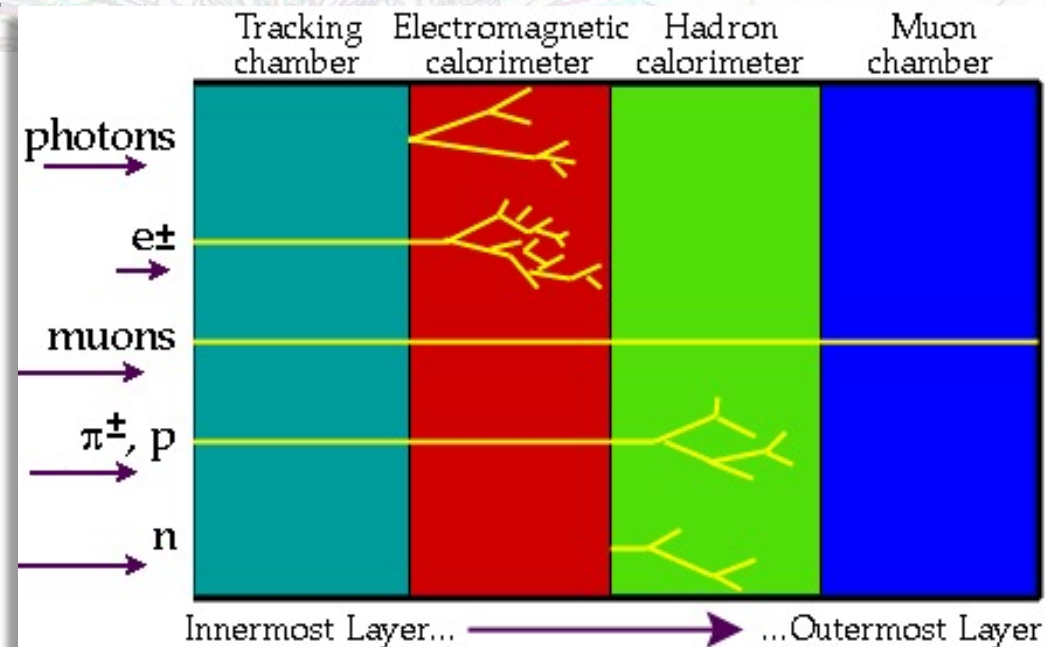




## Modern detector systems



- Modern detectors in particle physics combine several sub-detectors in layers much like an onion or like ogres 😊
- Length travelled before decay is  $L = \beta\gamma\tau c$ , anything with  $\tau \gtrsim 10^{-10}$  s might appear in detector ( $e^\pm, \mu^\pm, \pi^\pm, K^\pm, K^0, p, n, \gamma, \nu$ )
- Use series of different detection techniques to identify these particles
- Detector is generally a few centimeters from the interaction point



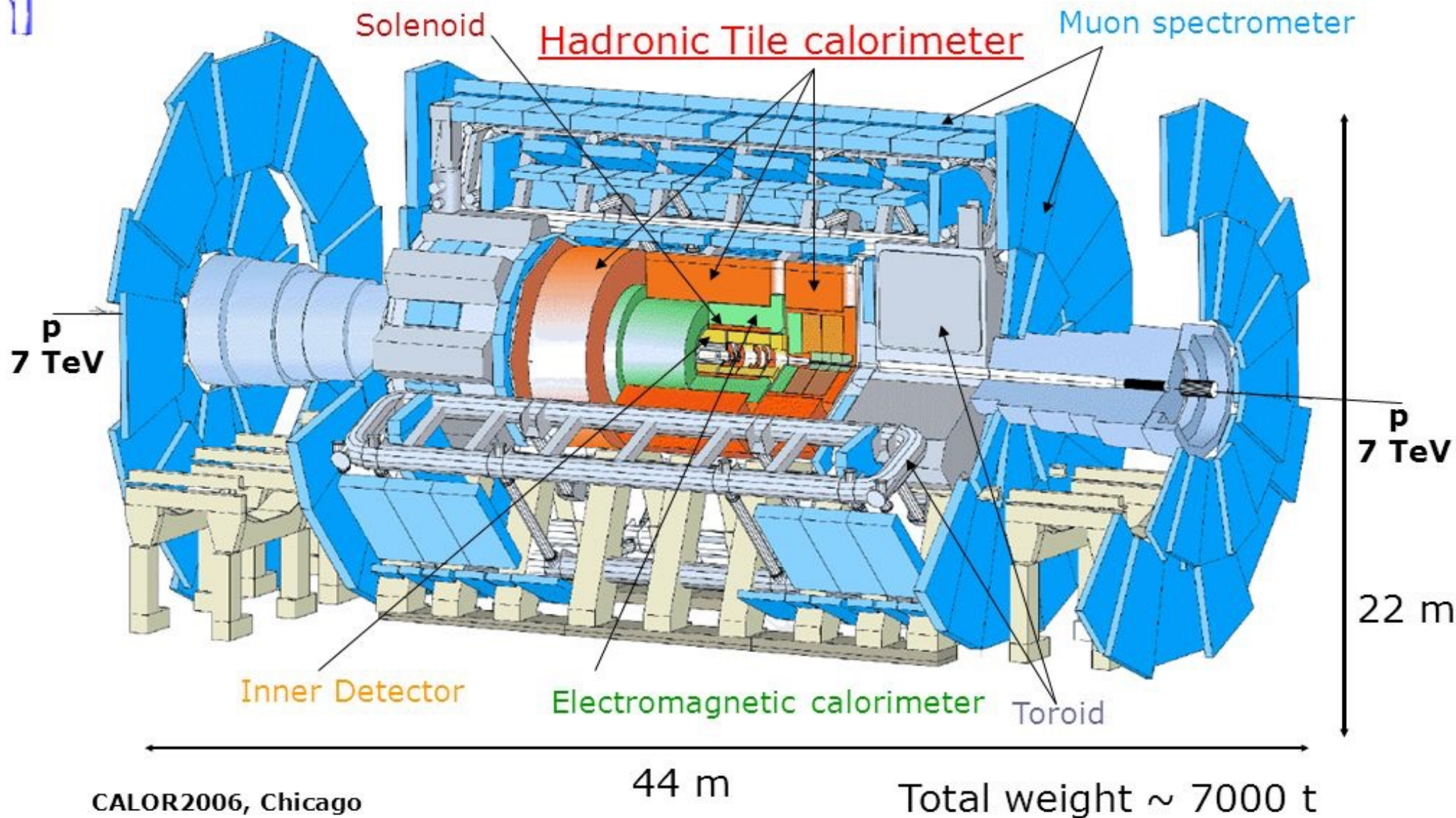


Together with CMS: The fastest and biggest digital "camera" on earth

$\sim 10^8$  electronic channels  
 $\sim 3000$  km of cables  
Cost: 450 MCHF  $\rightarrow$  65 CHF/kg



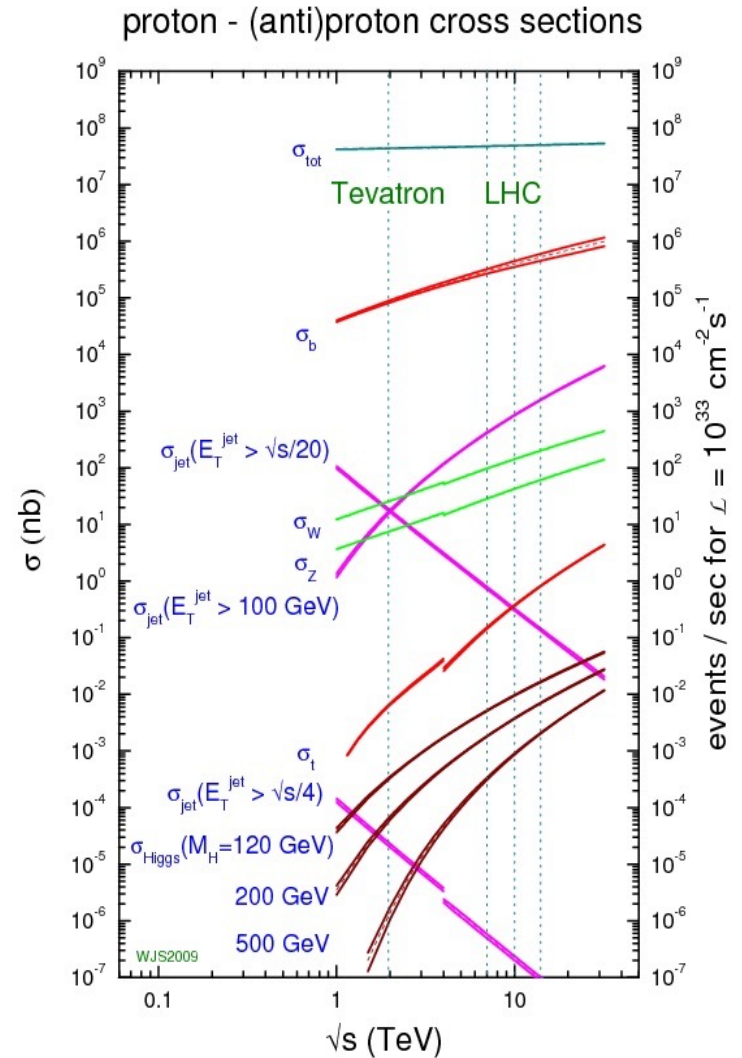
# ATLAS detector



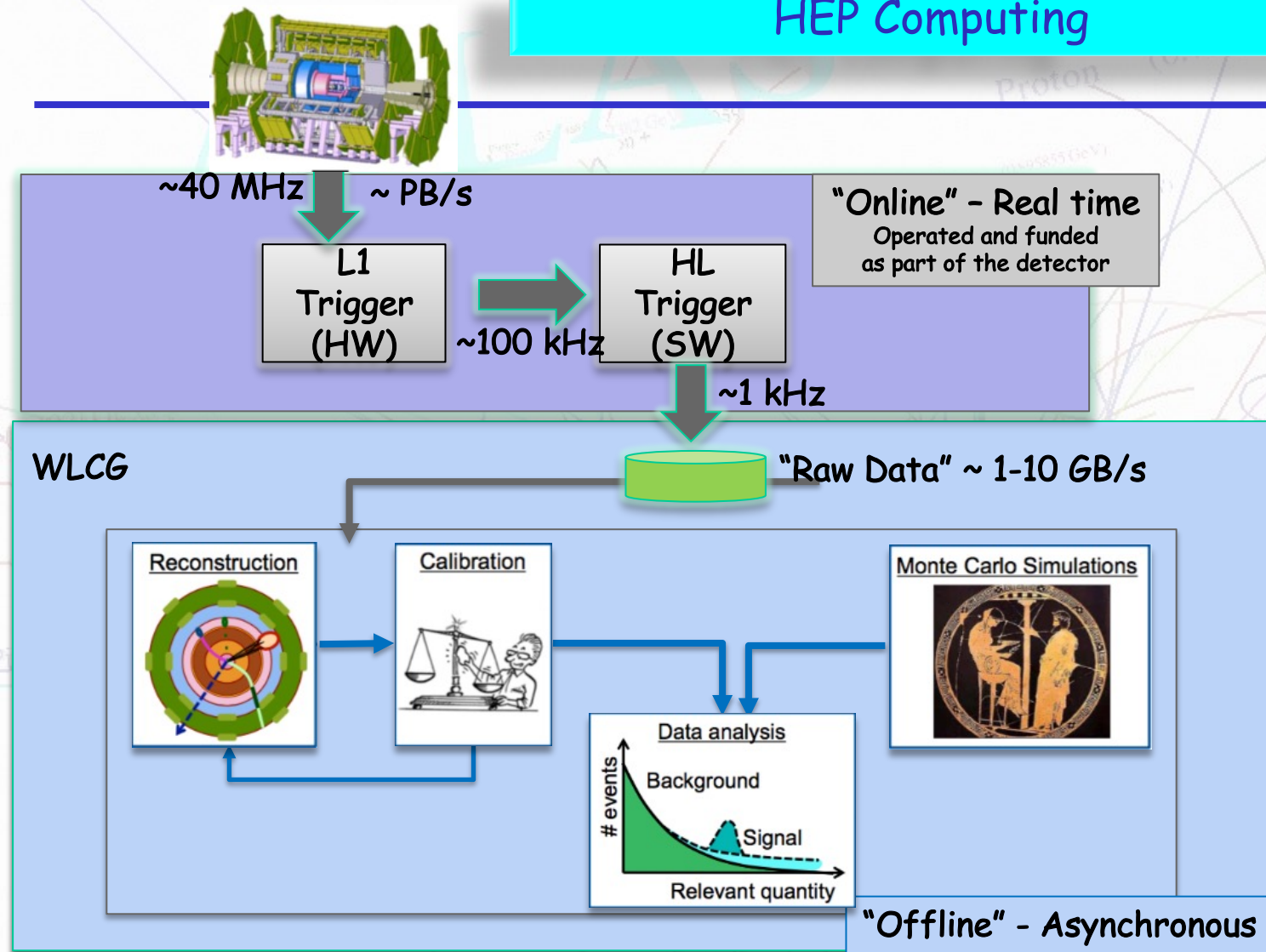


# Trigger systems - Why we need them?

- In general the cross sections of Standard Model processes is increasing with  $\sqrt{s}$
- **Total cross section is large but interesting processes (Higgs bosons, SUSY, etc.) have much lower cross sections!**
- **The trigger decides, in real-time, which data should be archived for offline analysis**
  - selects rare events and suppress background
  - rejected events are loss forever!
- **Trigger systems are necessary due to real-world limitations in computing power, data storage capacity and rates**
- **E.g. ATLAS trigger system**
  - The **Level-1 trigger** (hardware based) has to take decision in  $\sim 2 \mu\text{s}$ . Accepts less than 100k events out of 40M bunch crossings /sec
  - The **Event Filter** (software based) only about 2k events per second are passed on to a data storage system for offline analysis



# HEP Computing



- To allow the thousands of scientists scattered around the globe to collaborate on the analysis, tens of thousands of computers located around the world are being harnessed in a **distributed computing network called the Grid**



# The Worldwide LHC Computing Grid

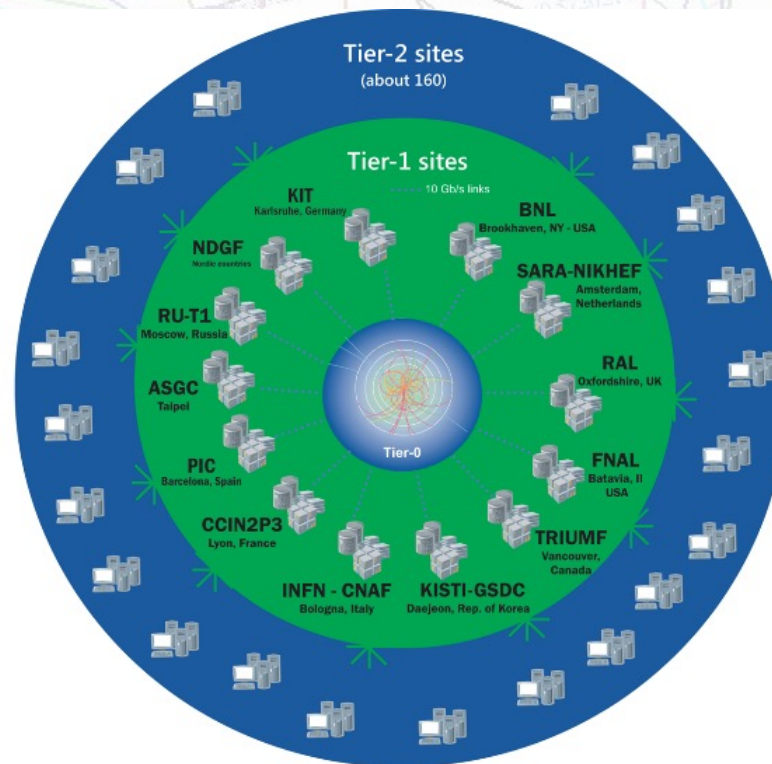
**WLCG: An international collaboration to distribute and analyse LHC data**

Integrates computer centres worldwide that provide computing and storage resource into a single infrastructure accessible by all LHC physicists

**Tier-0 (CERN):** data recording, reconstruction and distribution

**Tier-1:** permanent storage, re-processing, analysis

**Tier-2:** Simulation, end-user analysis



~170 sites,  
42 countries

~750'000 cores

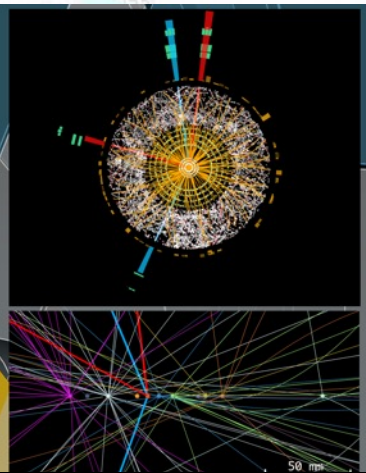
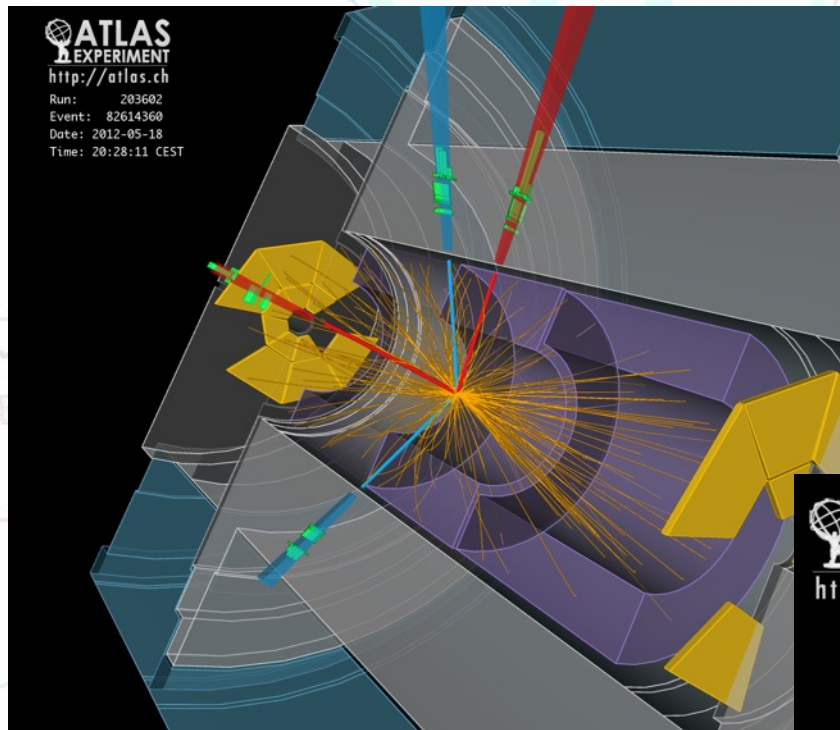
~1'000 PB of storage

> 2 million jobs/day

10-100 Gb links

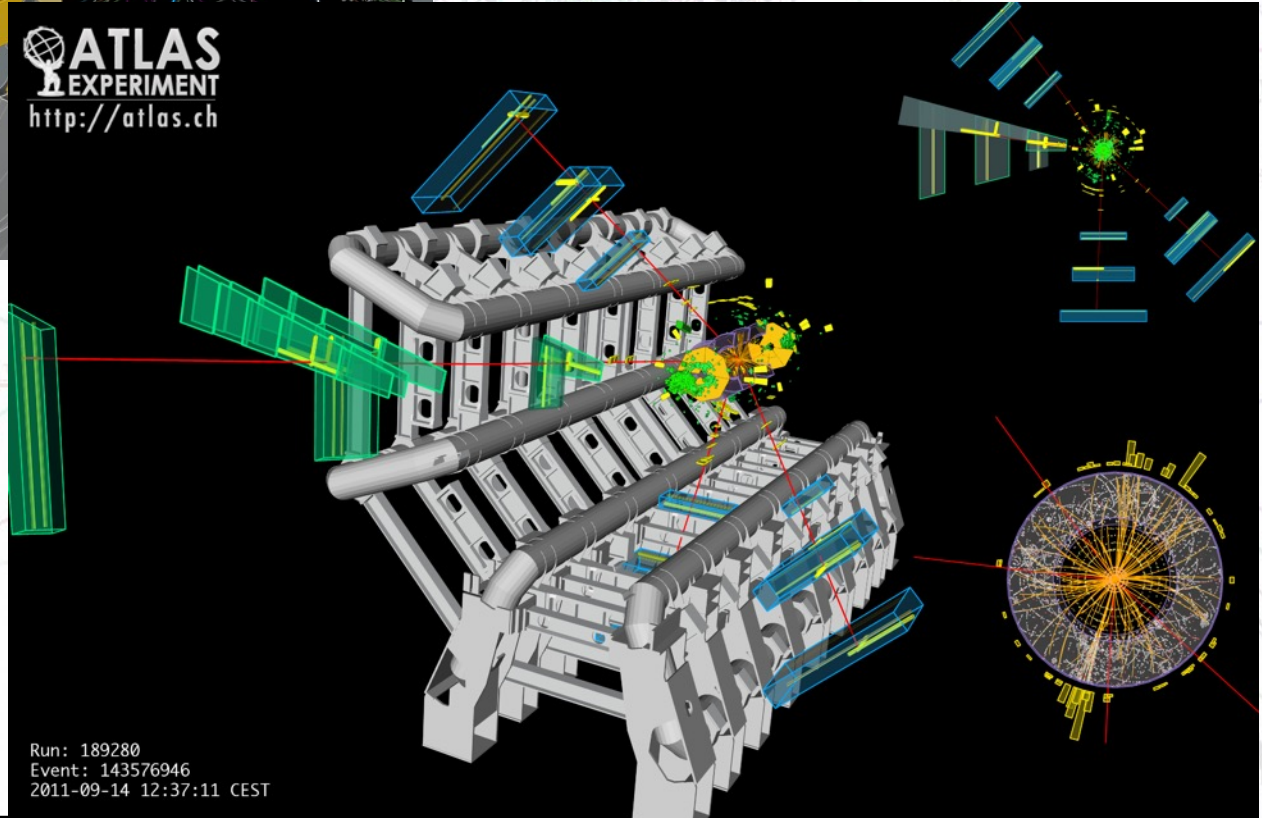
- Grid makes multiple computer centres look like a single system to the end-user
- Advanced software, called middleware, automatically finds the data the scientist needs, and the computing power to analyse it.
- Middleware balances the load on different resources. It also handles security, accounting, monitoring and much more.

# Event Display



$$H \rightarrow ZZ \rightarrow 4\mu$$

$$H \rightarrow ZZ \rightarrow 4e$$





# THE END



*A*  
WARNER BROS. —  
FIRST NATIONAL PICTURE



# Additional slides for curious kids

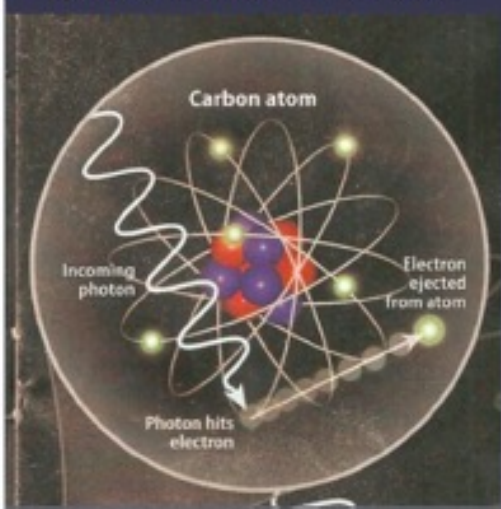




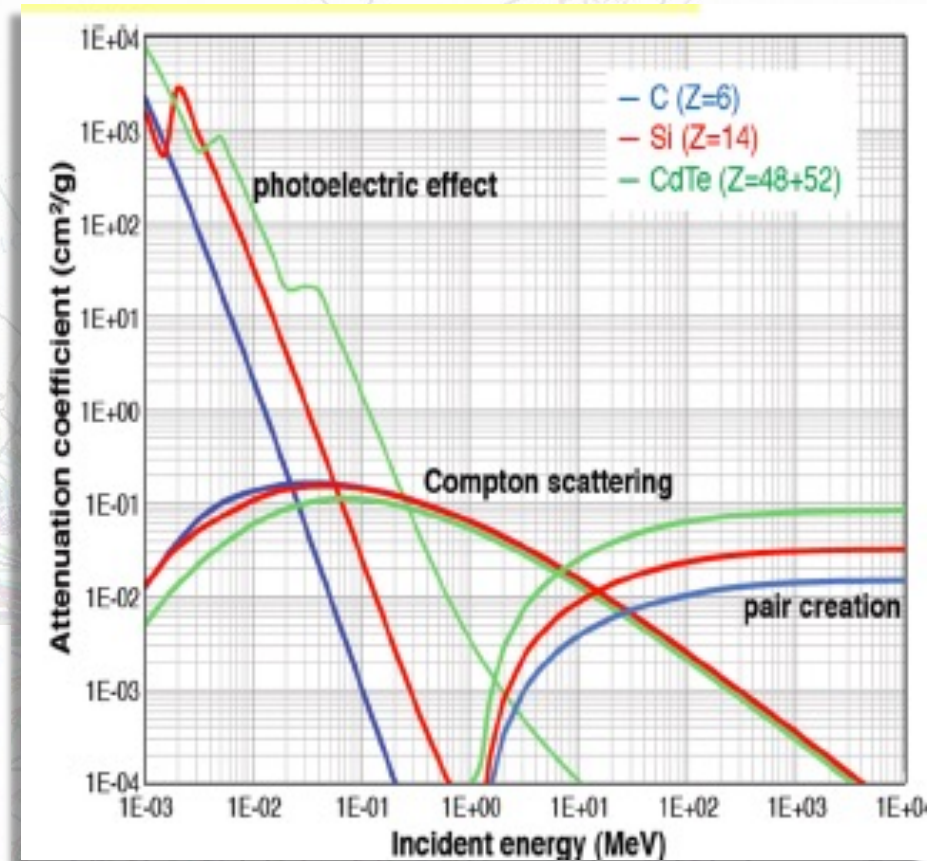
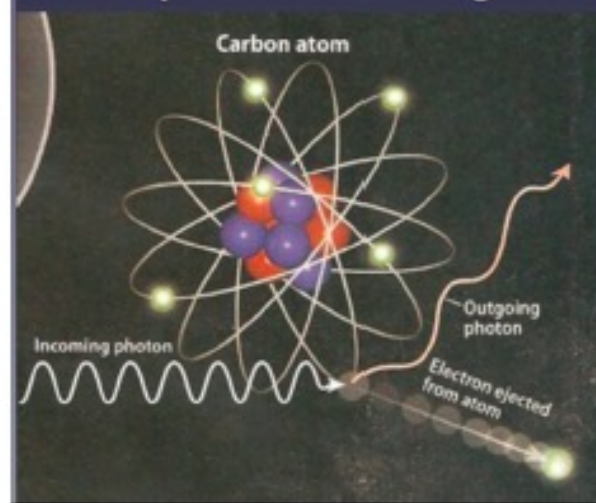
# Interaction of photons with matter

- Photons are neutral, Bethe-Bloch formula does not apply
- Photons can create charged particles or transfer energy to charged particles:
  - Low energies ( $< 100$  keV)
    - Photoelectric effect
  - Medium energies ( $\sim 1$  MeV)
    - Compton scattering
  - High energies ( $> 10$  MeV)
    - $e^+e^-$  pair production in electric field of nucleus

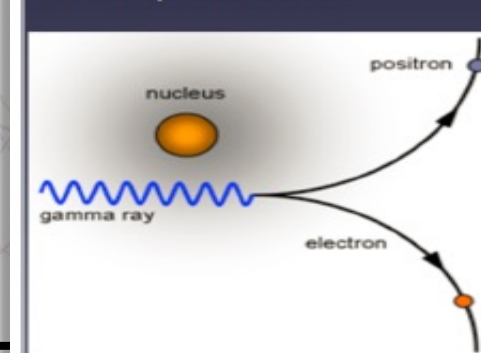
## Photoelectric Effect



## Compton Scattering



## Pair production



## Energy resolution of calorimeters (2)

| Experiment     | Detectors    | Absorber material          | $e/h$          | Energy resolution (E in GeV) |
|----------------|--------------|----------------------------|----------------|------------------------------|
| UA1 C-Modul    | Scintillator | Fe                         | $\approx 1.4$  | 80%/√E                       |
| ZEUS           | Scintillator | Pb                         | $\approx 1.0$  | 34%/√E                       |
| WA78           | Scintillator | U                          | 0.8            | 52%/√E $\oplus$ 2.6%*        |
| D0             | liquid Ar    | U                          | 1.11           | 48%/√E $\oplus$ 5%*          |
| H1             | liquid Ar    | Pb/Cu                      | $\leq 1.025^*$ | 45%/√E $\oplus$ 1.6%         |
| CMS            | Scintillator | Brass<br>(70% Cu / 30% Zn) | $\approx 1$    | 100%/√E $\oplus$ 5%          |
| ATLAS (Barrel) | Scintillator | Fe                         | $\approx 1$    | 50%/√E $\oplus$ 3%**         |
| ATLAS (Endcap) | liquid Ar    | Brass                      | $\approx 1$    | 60%/√E $\oplus$ 3%**         |

\* After software compensation

\*\* Design values

Homogeneous calorimeters:

| Experiment | Material          | Energy resolution (E in GeV) |
|------------|-------------------|------------------------------|
| NA48       | Liquid Kr         | 4.8%/√E $\oplus$ 0.22%       |
| BELLE      | CsI(Tl)           | 0.8%/√E $\oplus$ 1.3%        |
| CMS        | PbWO <sub>4</sub> | 2.7%/√E $\oplus$ 0.55%*      |

Sampling calorimeters:

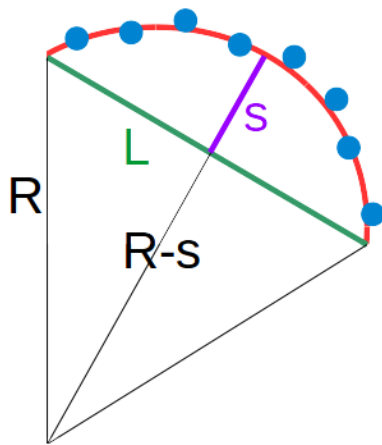
| Experiment | Detector                 | Detector thickness [mm] | Absorber material | Absorber thickness [mm] | Energy resolution (E in GeV) |
|------------|--------------------------|-------------------------|-------------------|-------------------------|------------------------------|
| UA1        | Scintillator             | 1.5                     | Pb                | 1.2                     | 15%/√E                       |
| SLD        | liquid Ar                | 2.75                    | Pb                | 2.0                     | 8%/√E                        |
| DELPHI     | Ar + 20% CH <sub>4</sub> | 8                       | Pb                | 3.2                     | 16%/√E                       |
| ALEPH      | Si                       | 0.2                     | W                 | 7.0                     | 25%/√E                       |
| ATLAS      | liquid Ar                |                         | Pb                |                         | 10%/√E $\oplus$ 0.7%*        |
| LHCb       | Scintillator             |                         | Fe                |                         | 10%/√E $\oplus$ 1.5%*        |

\* Design values



# Momenta measurement

- Immerse detector (tracker) in magnetic field  $B$  to measure track radius, and thus particle momentum  $p$ 
  - Measure sagitta  $s$  from track arc  $\rightarrow$  curvature  $R$



$$R = \frac{L^2}{8s} + \frac{s}{2} \sim \frac{L^2}{8s}$$

$$p = 0.3B \left( \frac{L^2}{8s} \right)$$

$$\frac{\sigma_p}{p} = \frac{\sigma_s}{s} = \frac{8p}{0.3BL^2} \sigma_s$$

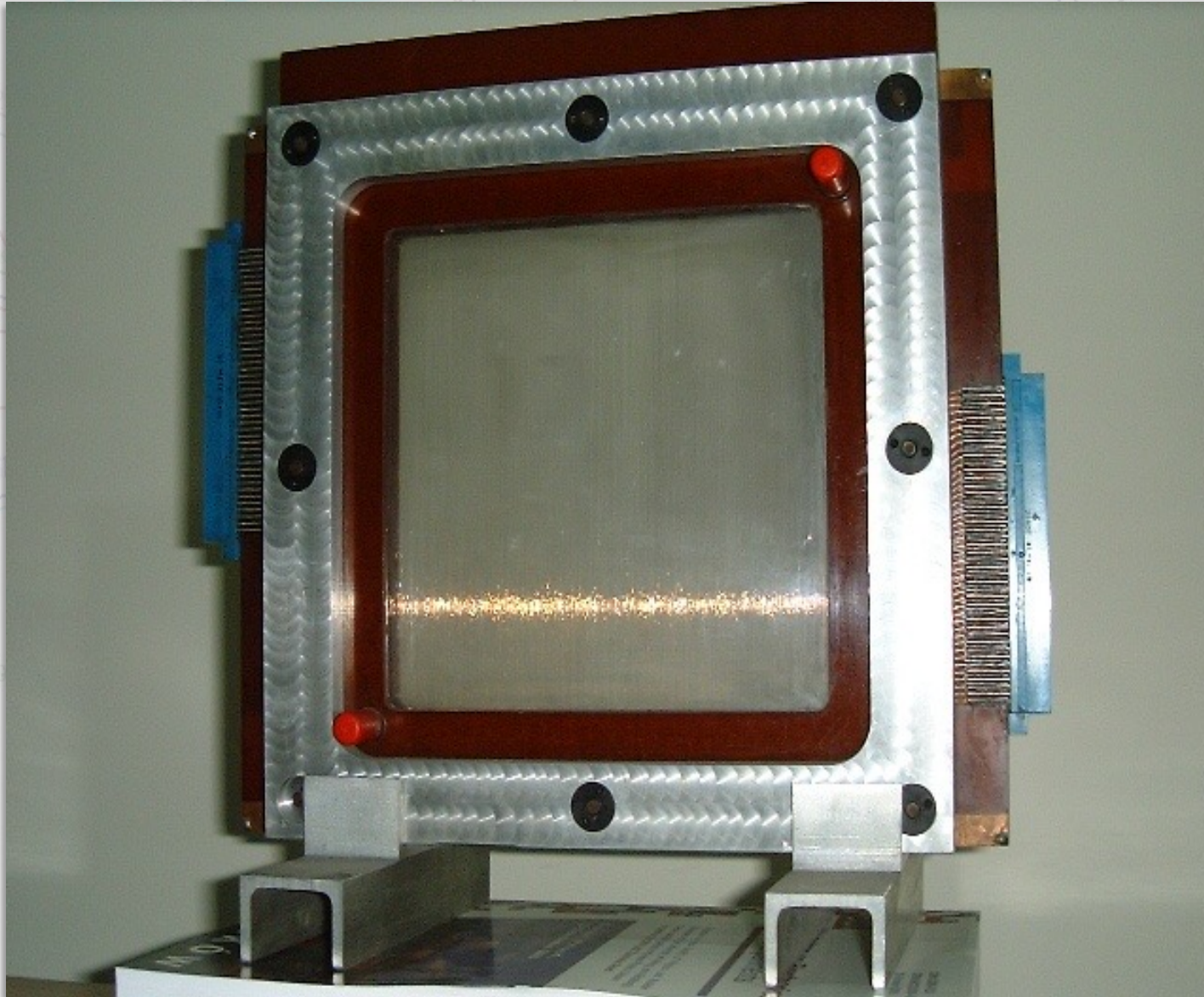
- High- $p$  particles have high radius of curvature
  - Track almost straight
- Low- $p$  particles have small radius curvature
  - Measure with high accuracy

## Relative transverse momentum resolution

- degrades linearly with momentum
- improves linearly with  $B$  field
- improves quadratically with radial extension detector

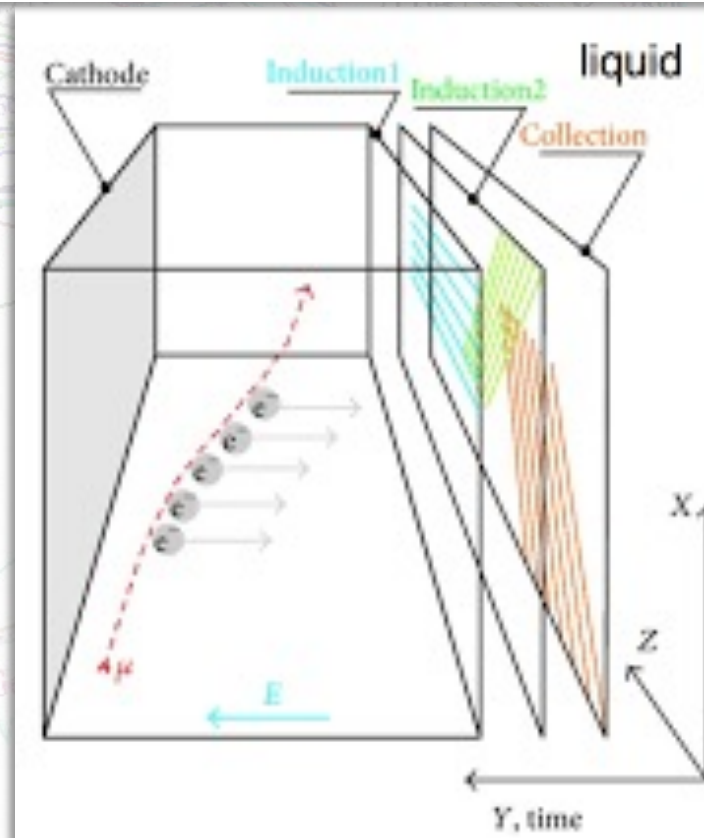
$$\frac{\sigma_{p_T}}{p_T} = \frac{8p_T}{0.3BL^2} \cdot \sigma_s \rightarrow \frac{\sigma_{p_T}}{p_T} \propto p_T$$

## First multiwire proportional chambers in Poland (1973, IFJ Kraków)



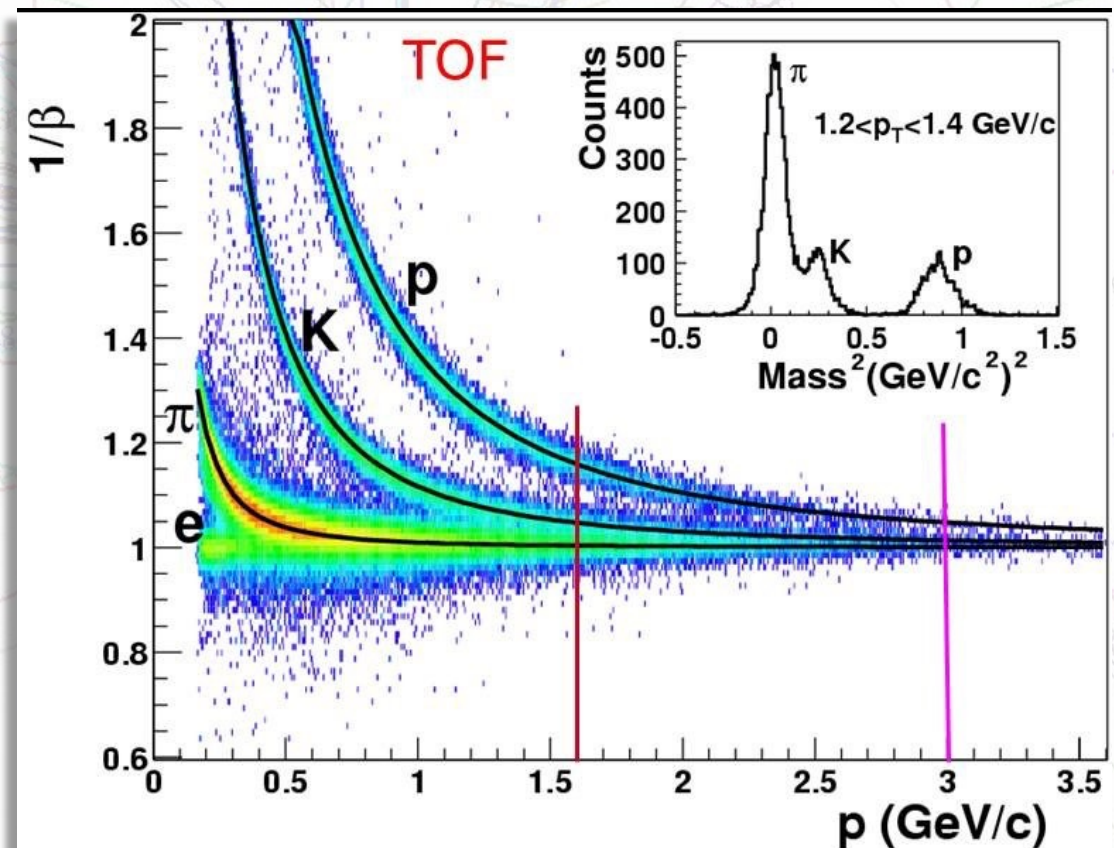
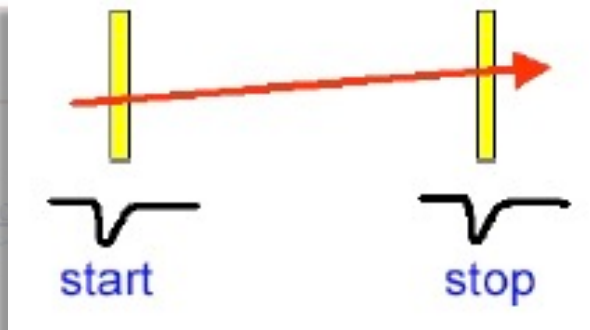


- Set of separated anode wire planes. Wires orientation varies from plane to plane.
- Together, these planes read out signals from the drift electrons.
- **Induction planes** set at lower potentials than the **collection plane**, allowing drift electrons to pass through them after inducing signals.



# Time Of Flight (ToF) detectors

- Fast detectors (scintillators) that can measure the time of flight, time it took a particle to fly a distance  $L$ :  $v=L/t$
- Combine TOF with momentum measurement to get mass of particle
- Allows to identify particles with low momenta



STAR-TOF

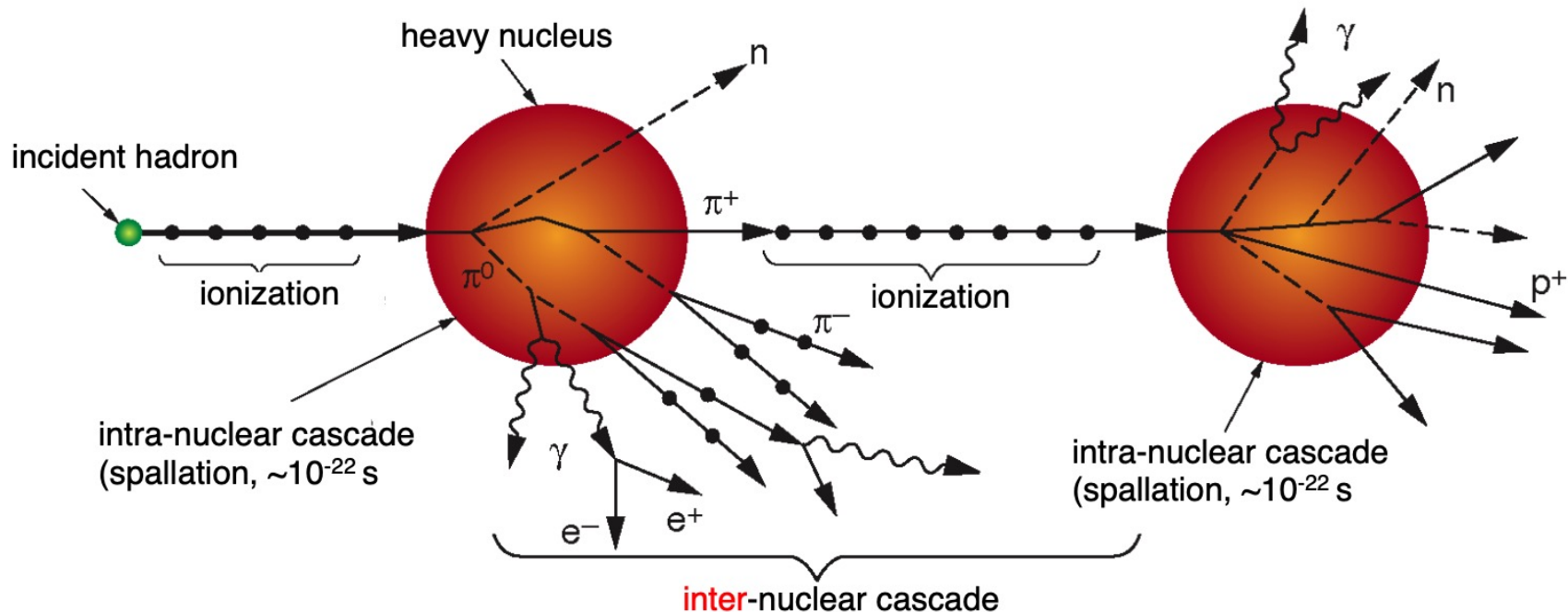


## 6.3.1 Hadronic Showers

### Hadronic interactions



- ★ **Intra-nuclear cascade:** Components of the nucleus receive enough energy to interact with each other and to produce pions or other hadrons.
- ★ **Inter-nuclear cascade:** Particles escaping the nucleus hit another nucleus.



## 6.3.1 Hadronic Showers

### Spallation

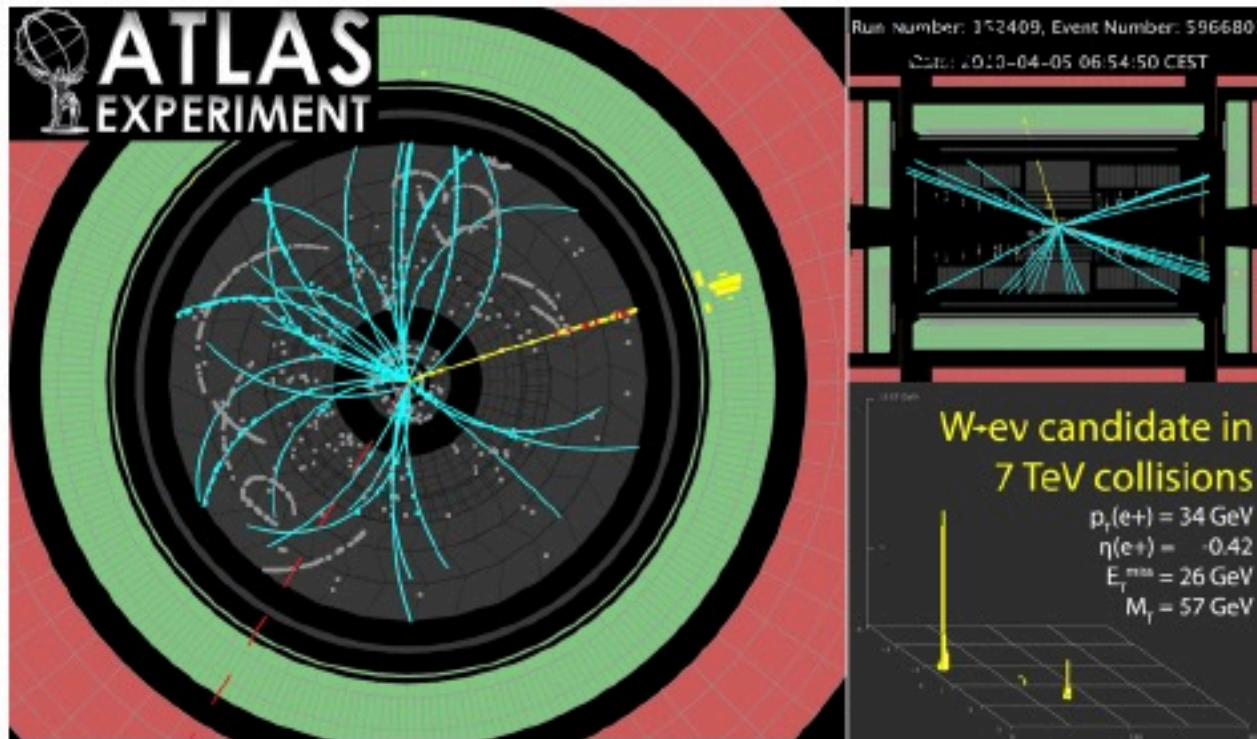


- ★ Spallation is the transformation of a nucleus caused by an incident, high energetic, hadronically interacting particle. During spallation a large number of elementary particles,  $\alpha$ -particles, and possibly larger debris of the nucleus are emitted.
- ★ Spallation is the most probable process when a hadron hits a nucleus.
- ★ Following spallation the target nucleus is in an excited state and releases further particles or undergoes fission.
- ★ The secondary particles from the spallation process have mostly enough energy to itself interact with a nucleus.



# Neutrino Identification at Colliders

- Neutrinos are not charged and only interact via the weak force  
⇒ they do not interact at all in the detector.  $\sum \vec{p}_{\text{initial}} = \sum \vec{p}_{\text{final}}$ 
  - The initial momentum of the collision is along beam direction: no initial momentum perpendicular to beam direction.
  - Total momentum of the perpendicular to the beam should sum to zero.
  - We infer neutrinos from absence of momentum seen in a particular direction.



Direction of  
momentum  
carried  
by neutrino

Reconstructed  
path of electron

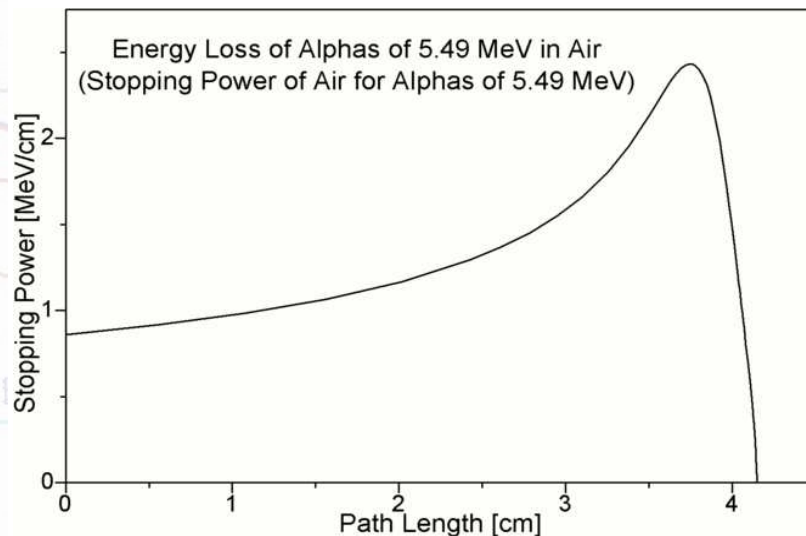
Low momentum  
charged particle

# Jonizacja

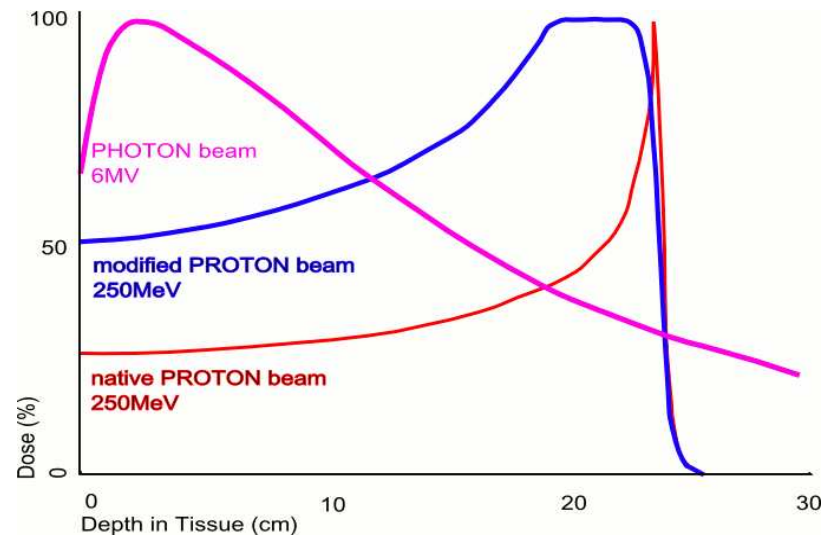
## Krzywa Bragga

Zależność strat na jonizację od długości drogi w materiale:

Cząstki  $\alpha$  w powietrzu:



Protony i fotony w tkance:



Gdy cząstka znajdzie się poniżej minimum jonizacji, straty energii gwałtownie rosną  
⇒ depozyt energii największy blisko miejsca zatrzymania cząstki (terapia hadronowa)

When a fast charged particle moves through matter, it ionizes atoms of the material and deposits a dose along its path. A peak occurs because the interaction cross section increases as the charged particle's energy decreases. Energy lost by charged particles is inversely proportional to the square of their velocity, which explains the peak occurring just before the particle comes to a complete stop.



# Typowe własności różnych detektorów

| Typ detektora                        | Zdolność przestrz.           | Zdolność czasowa                    | Czas martwy            |
|--------------------------------------|------------------------------|-------------------------------------|------------------------|
| Emulsja                              | 1 $\mu\text{m}$              | —                                   | —                      |
| Komora pęcherzykowa                  | 10-150 $\mu\text{m}$         | 1 $\mu\text{s}$                     | 50 $\mu\text{s}$       |
| Kom. strymerowa ( $\rightarrow$ RPC) | 300 $\mu\text{m}$            | 2 $\mu\text{s}$ ( $<0.5\text{ns}$ ) | 100 $\mu\text{s}$      |
| Komora proporcjonalna                | 50-300 $\mu\text{m}$         | 2 ns                                | 200 ns                 |
| Scyntylator                          | —                            | 100 ps                              | 10 ns                  |
| Komora dryfowa                       | 50-300 $\mu\text{m}$         | 2 ns                                | 100 ns                 |
| Komora dryfowa LAr                   | $\sim$ 175-450 $\mu\text{m}$ | $\sim$ 200 ns                       | $\sim$ 2 $\mu\text{s}$ |
| Paski silikonowe                     | $<25$ $\mu\text{m}$          | ograniczone przez elektronikę       |                        |

# Electromagnetic showers

Typical values for  $X_0$ ,  $E_c$  and  $R_M$  of materials used in calorimeter

|                   | $X_0$ [cm] | $E_c$ [MeV] | $R_M$ [cm] |
|-------------------|------------|-------------|------------|
| Pb                | 0.56       | 7.2         | 1.6        |
| Scintillator (Sz) | 34.7       | 80          | 9.1        |
| Fe                | 1.76       | 21          | 1.8        |
| Ar (liquid)       | 14         | 31          | 9.5        |
| BGO               | 1.12       | 10.1        | 2.3        |
| Sz/Pb             | 3.1        | 12.6        | 5.2        |
| PB glass (SF5)    | 2.4        | 11.8        | 4.3        |



# A simple shower model

## Simple shower model: [continued]

Shower characterized by:

Number of particles in shower  
Location of shower maximum  
Longitudinal shower distribution  
Transverse shower distribution

Longitudinal components;  
measured in radiation length ...

... use:  $t = \frac{x}{X_0}$

Number of shower particles  
after depth  $t$ :

$$N(t) = 2^t$$

Energy per particle  
after depth  $t$ :

$$E = \frac{E_0}{N(t)} = E_0 \cdot 2^{-t}$$

$$\rightarrow t = \log_2(E_0/E)$$

Total number of shower particles  
with energy  $E_1$ :

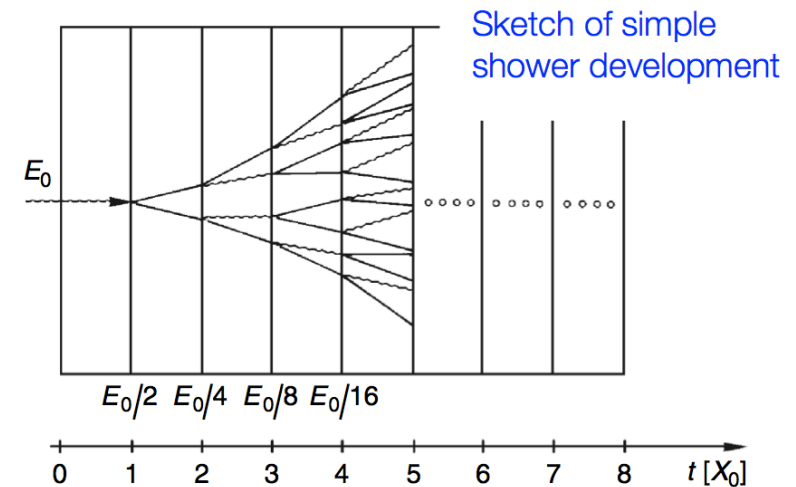
$$N(E_0, E_1) = 2^{t_1} = 2^{\log_2(E_0/E_1)} = \frac{E_0}{E_1}$$

Number of shower particles  
at shower maximum:

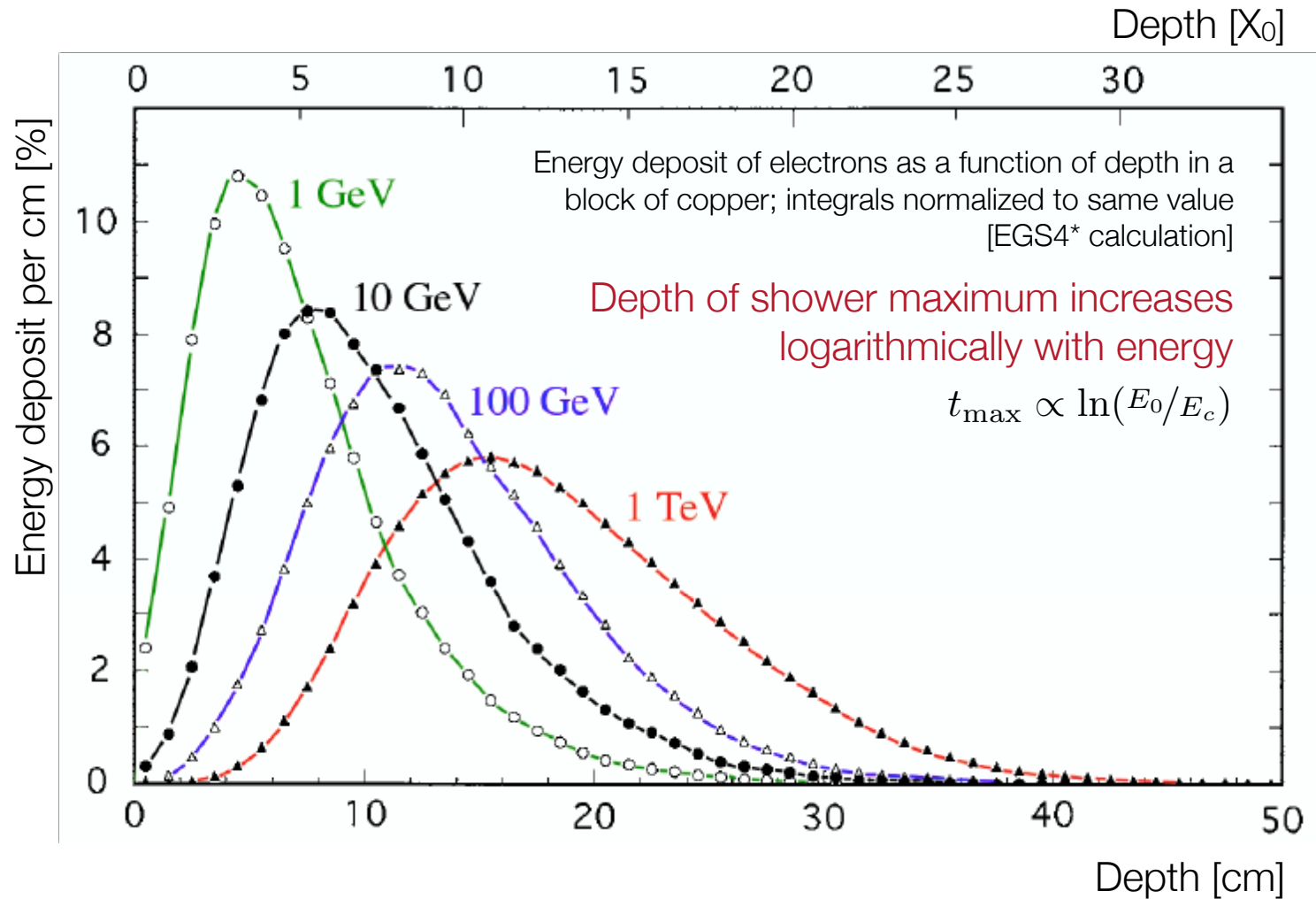
$$N(E_0, E_c) = N_{\max} = 2^{t_{\max}} = \frac{E_0}{E_c} \propto E_0$$

Shower maximum at:

$$t_{\max} \propto \ln(E_0/E_c)$$



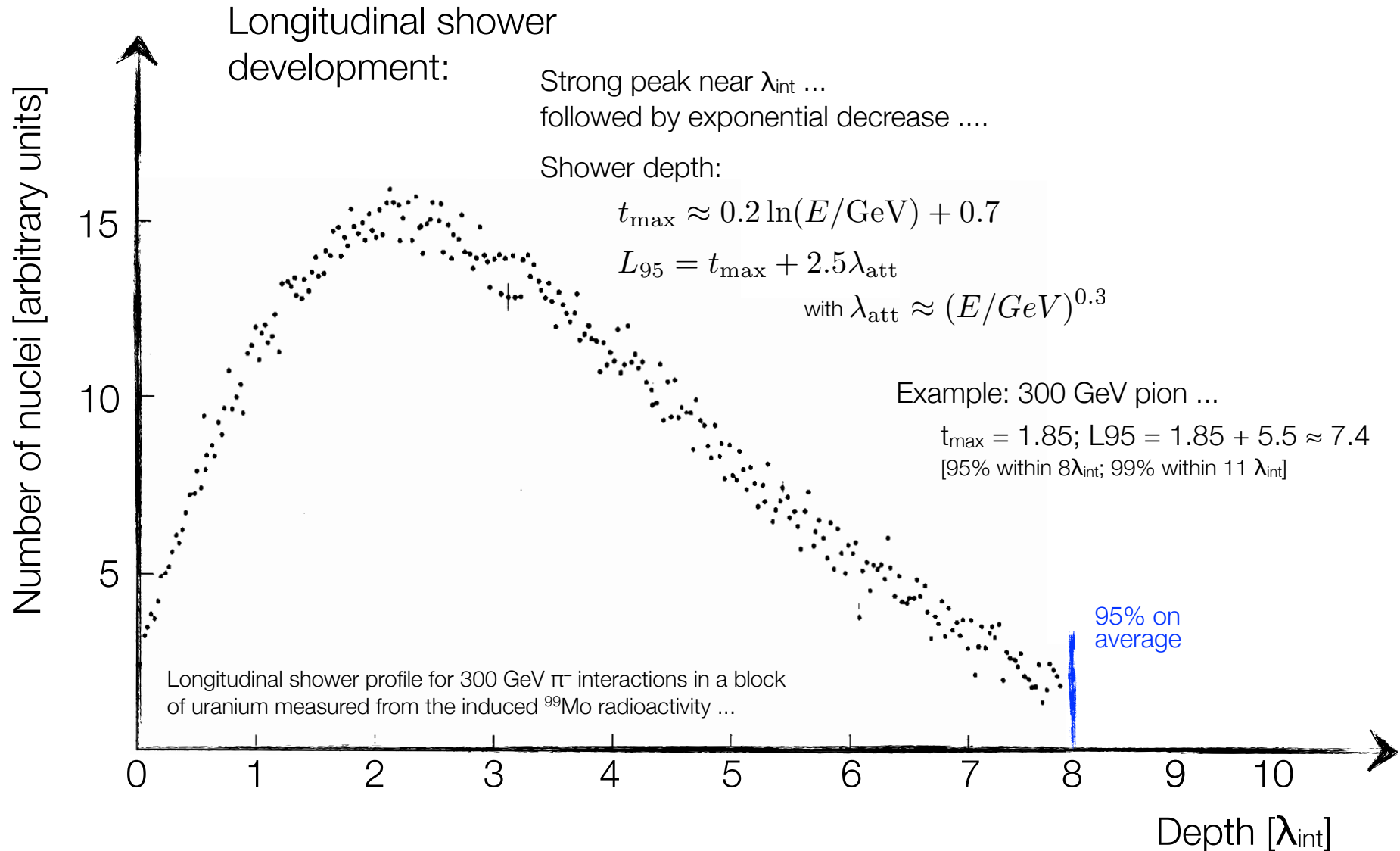
# EM shower longitudinal development



\*EGS = Electron Gamma Shower



# Hadronic shower longitudinal development



# Kalorymetry

## Kompensacja algorytmiczna

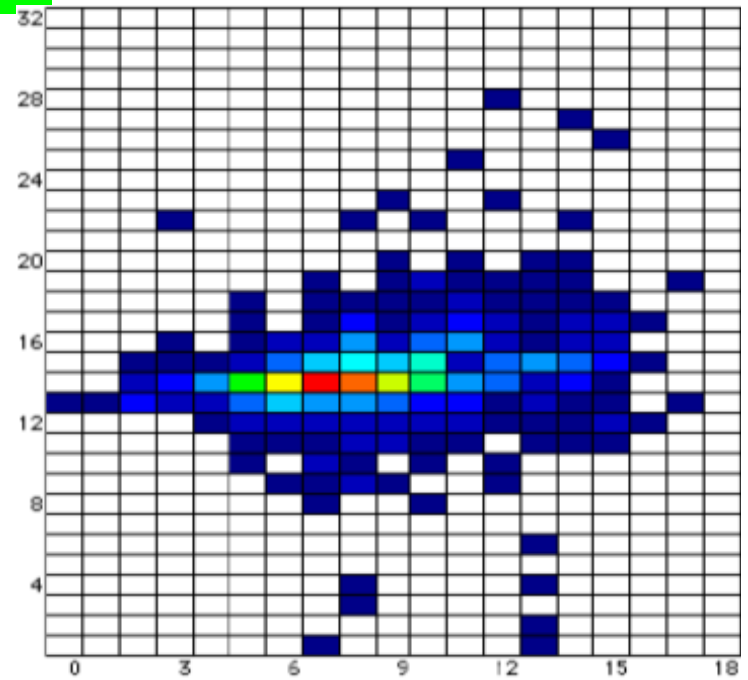
Jeśli nie dobierzemy odpowiednio materiałów absorbera i detektora odpowiedź kalorymetru na część elektromagnetyczną i hadronową kaskady będą różne.

Odpowiedź kalorymetru na pojedynczy hadron:

$$E_{meas} = (f_{em} + (1 - f_{em})/\eta_{had}) \cdot E$$

gdzie:  $f_{em}$  - ułamek energii w części EM,  
 $\eta_{had}$  - tłumienie składowej hadronowej ( $\sim 1.4$ )

Jeśli jesteśmy w stanie zrekonstruować  $f_{em}$  możemy istotnie **polepszyć dokładność pomiaru**.



W kalorymetrze od dużej segmentacji część EM kaskady widoczna jest jako

**silnie zlokalizowane depozyty**

( $X_0 \ll \lambda_{int}$ )

$\Rightarrow$  można oszacować  $f_{em}$