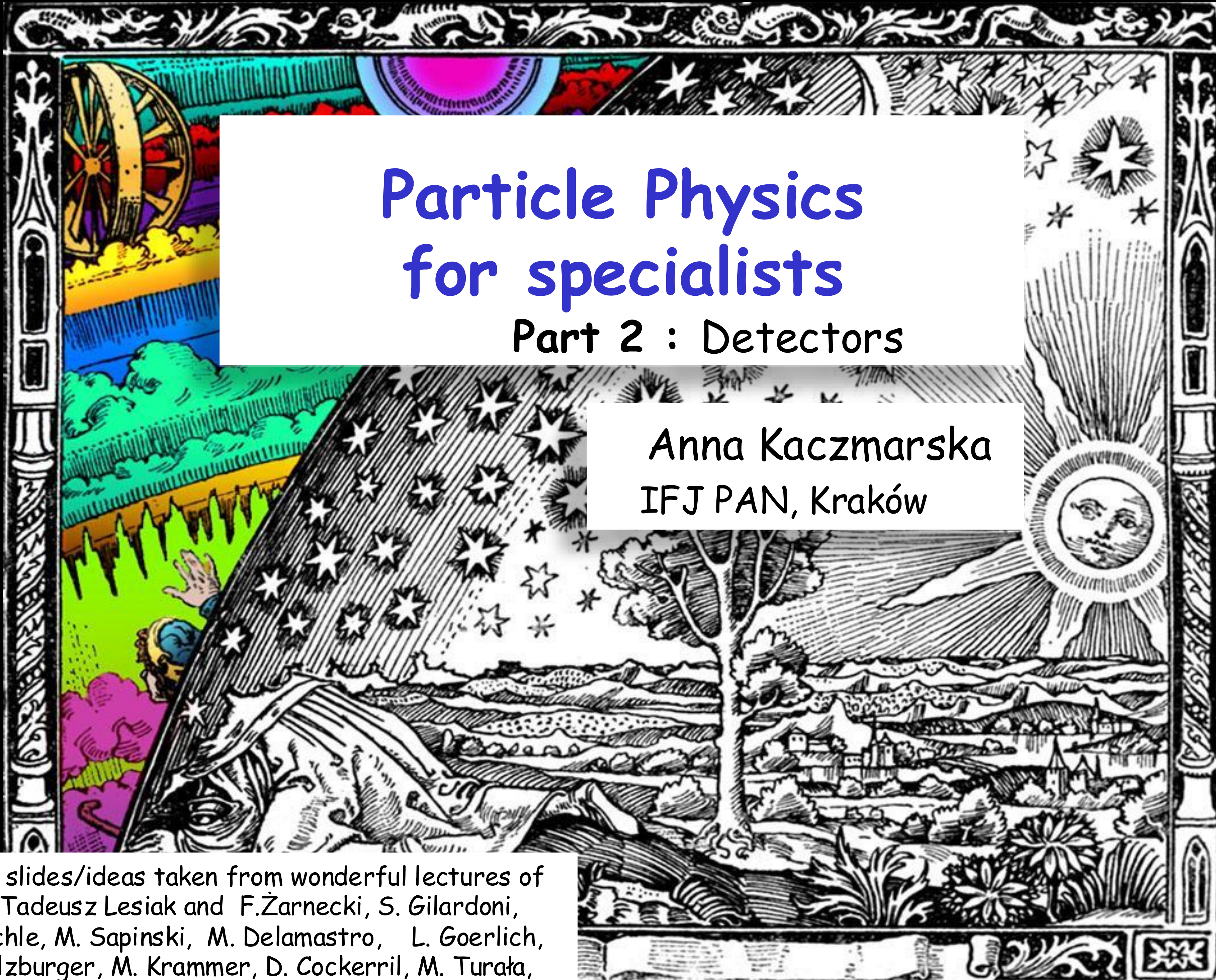


Particle Physics for specialists

Part 2 : Detectors

Anna Kaczmarska

IFJ PAN, Kraków

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. Turała, H. Meinhard

Content of the course

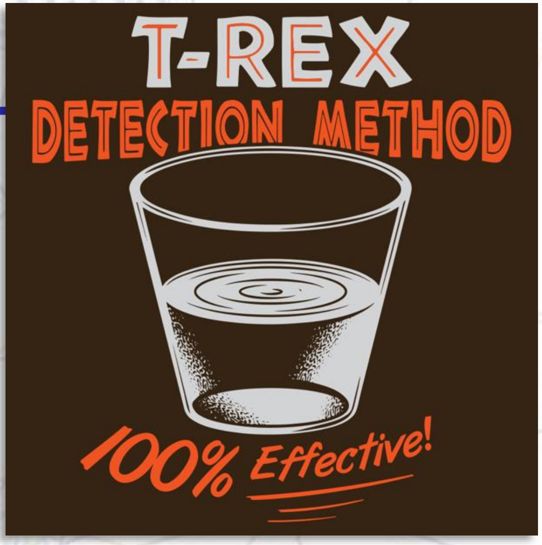
- **The Particle Physics for specialists course** consists of 30h of lectures
  1. Accelerators and Detectors (4h) – Anna Kaczmarska
  2. Standard Model (7h) – Andrzej Bożek
  3. Heavy flavour physics (3h) – Marcin Kucharczyk
  4. Electroweak interactions, Higgs physics and Beyond Standard Model (4h) – Paweł Bruckman
  5. Electron-proton scattering and forward physics (3h) – Rafał Staszewski
  6. Heavy ion physics (3h) – Adam Trzupek
  7. Neutrino physics (3h) – Tomasz Wąchała
  8. Introduction to cosmology, cosmic rays (3h) - Dariusz Góra

- **Slides will be available on indico**
  - **https://indico.ifj.edu.pl/event/1288/**
- **Literature**
  - Thomson *Modern Particle Physics (Współczesna Fizyka Cząstek)*
  - Perkins *Introduction to High Energy Physics*
  - Griffits *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: written, 3 questions randomly selected from the list of questions, the list to be provided at the end of the course

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!**

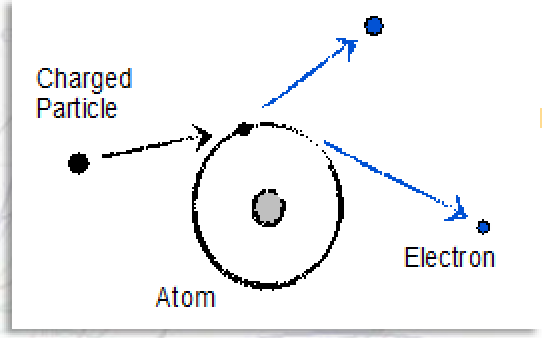
- In order to detect a particle, it must:
  - interact with the material of the detector == lose energy in the material it traverses
  - transfer energy in some recognizable fashion (signal)

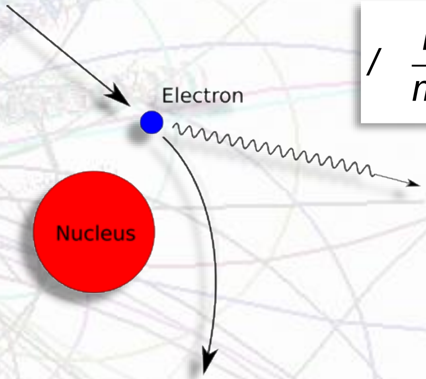
- In an experiment, we want to be able to detect all the particles that live long enough to interact with the detector
- We would like to know:
  - From where do all the particles come?
  - Are there secondary decays?
  - What are all the momenta of the charged particles
    - With help of magnetic field: $R = p/(qB)$
  - What is the energy of all particles?
  - Identify the particles

Passage of charged particles through matter

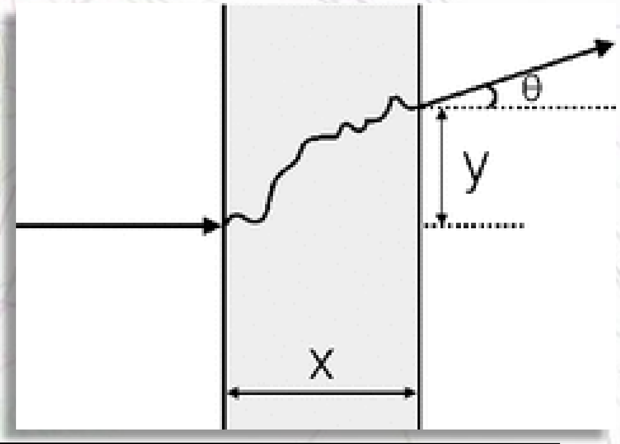
The main mechanisms of energy loss of charged particles

- **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





$/ \frac{E}{m^2}$



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 (β) of incident particle (**but not on its mass!**) and properties of medium (weakly)

Valid for heavy charged particles ($m_{incident} >> m_e$), e.g. proton, k, π, μ

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

$2\pi N_a r_e^2 m_e c^2$ =0.1535 MeV cm^2/g

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

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

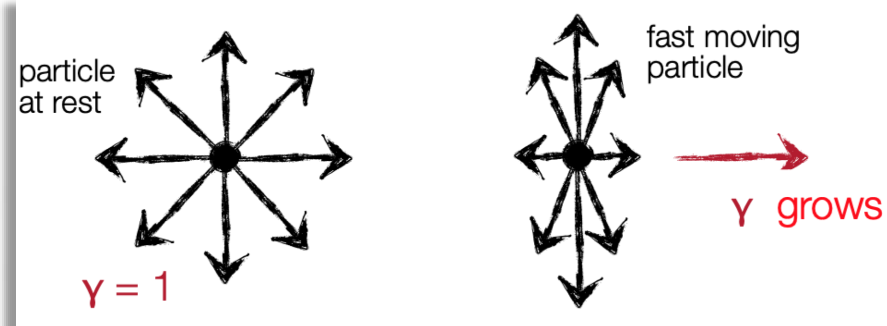
Absorber medium
- I = mean ionization potential
- Z = atomic number of absorber
- A = atomic weight of absorber
- ρ = density of absorber
- δ = density correction
- C = shell correction

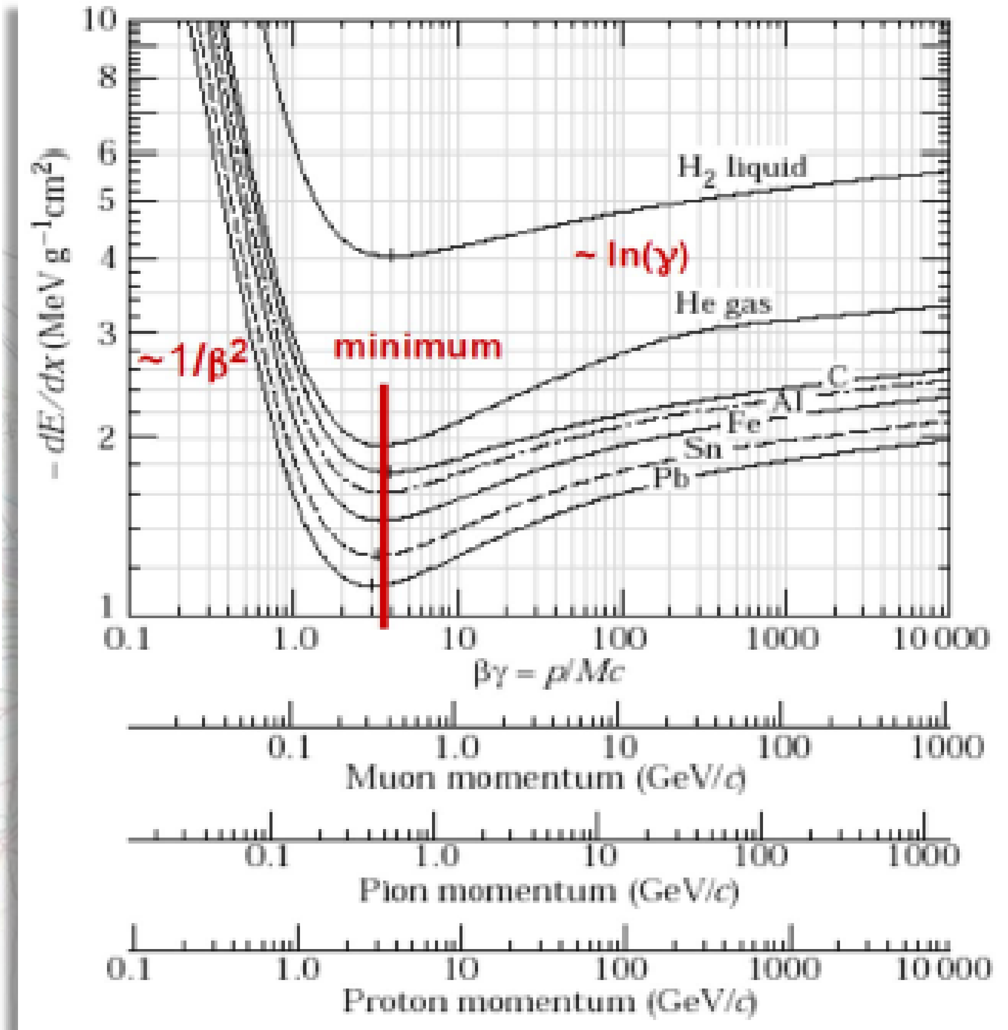
Incident particle
- z = charge of incident particle
- β = v/c of incident particle
- γ = $(1-\beta^2)^{-1/2}$
- W_{max}= max. energy transfer in one collision

$$r_e = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{m_e c^2}$$

Ionization (2)

- For small velocities dE/dx falls like $1/\beta^2$
  - slower particles experience E- field for a longer time → stronger energy loss!
- All particles have a region of minimum ionization with dE/dx ~ 1-2 MeV/g cm² for $\beta\gamma$~3 – minimum ionizing particles (MIP)
- As β 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 γ -> $E_y \rightarrow \gamma E_y$. larger collision distances, more ionization





Saturation for high energies -> Fermi plateau
Due to polarization (density correction δ)

- shielding of E-field far from particle path -> less collisions with far distant electrons

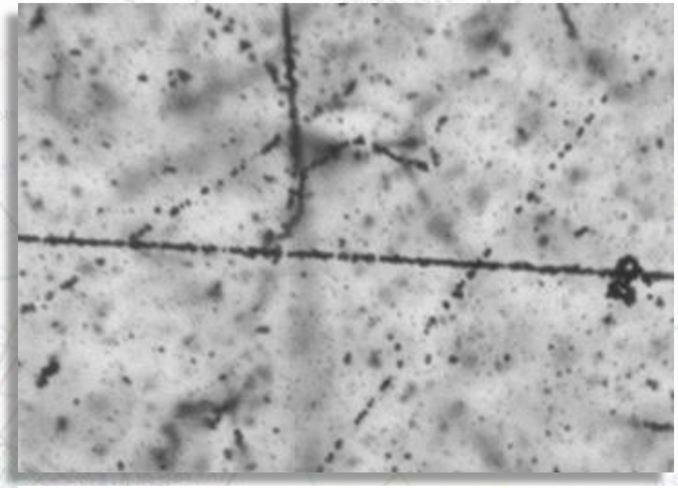
Shell correction (C/Z) – in general small

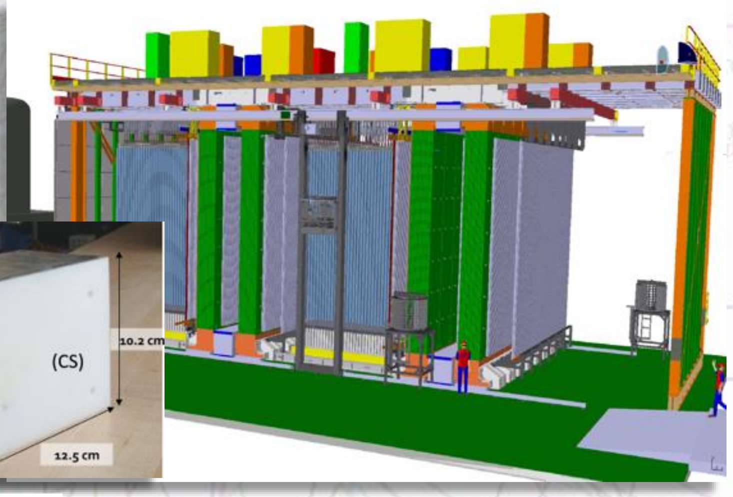
- arises if particle velocity is close to orbital velocity of e (assumption that e is at rest breaks down)

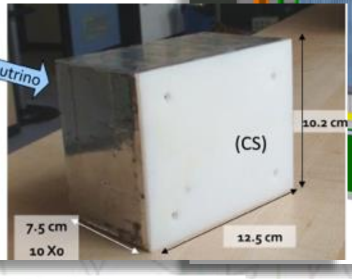
Detectors based on ionization: emulsion

- 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

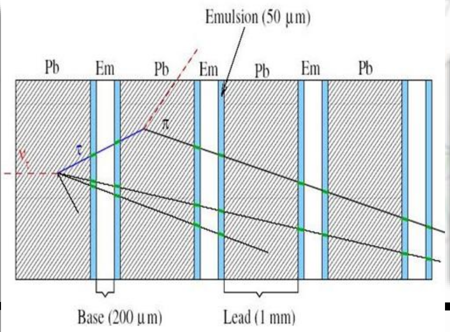
- Emulsions have been used as tracking devices since mid-1940s and are still in use
- Exceptional (not surpassed by any other detector) spatial resolution: **0.2 µm**
- v from density of grains (dE/dx)
- p can be estimated from multiple scattering
- analysis quite painful!
    - records everything (no trigger possible)







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



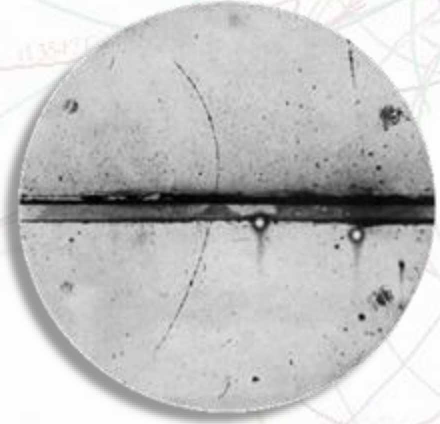
OPERA neutrinos detector: particles observed in "bricks" of photographic films interleaved with lead sheets

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.

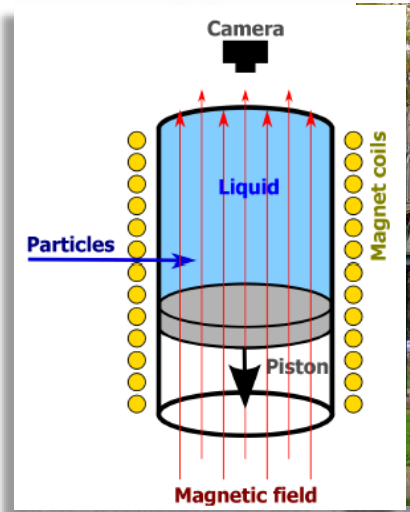


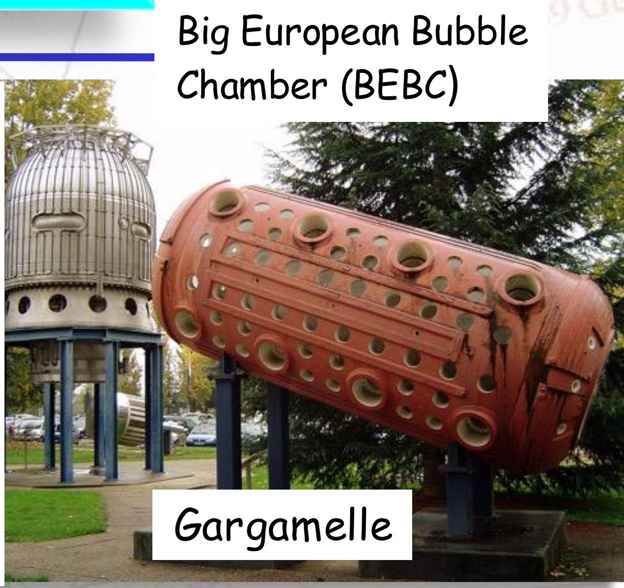
https://www.youtube.com/watch?v=i15ef618DP0&t=21s

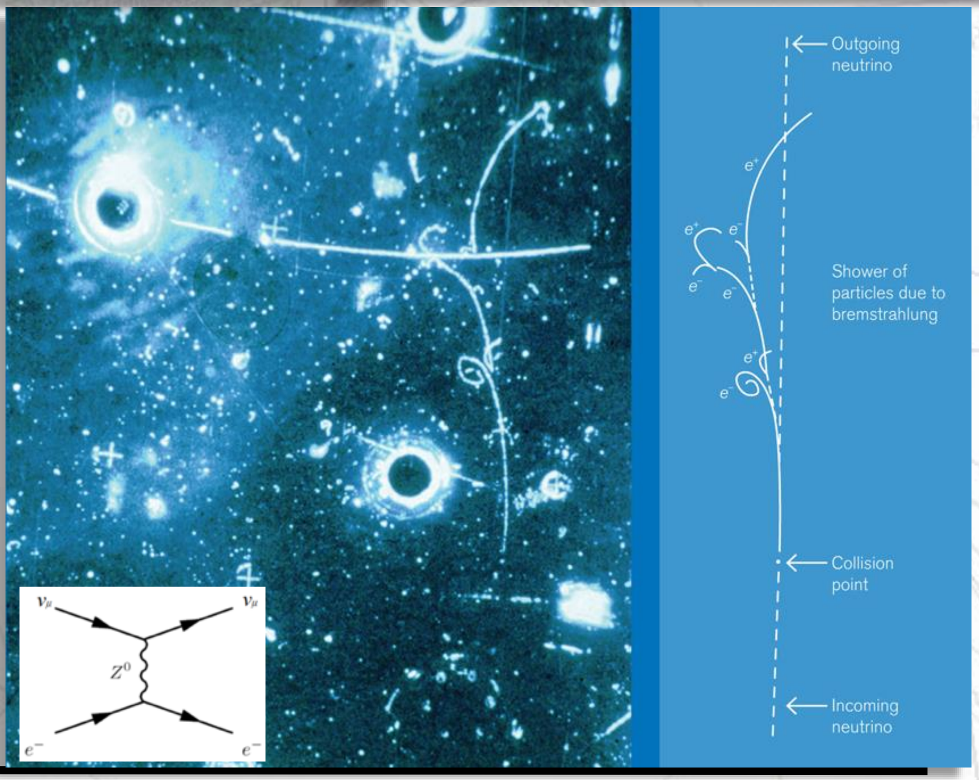
Detectors based on ionization: bubble chamber

- **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 μm**
- v from density of grains (dE/dx), p from B
- Large volumes (good for neutrino physics)
- Slow, practically no trigger capabilities
- Analysis is painful



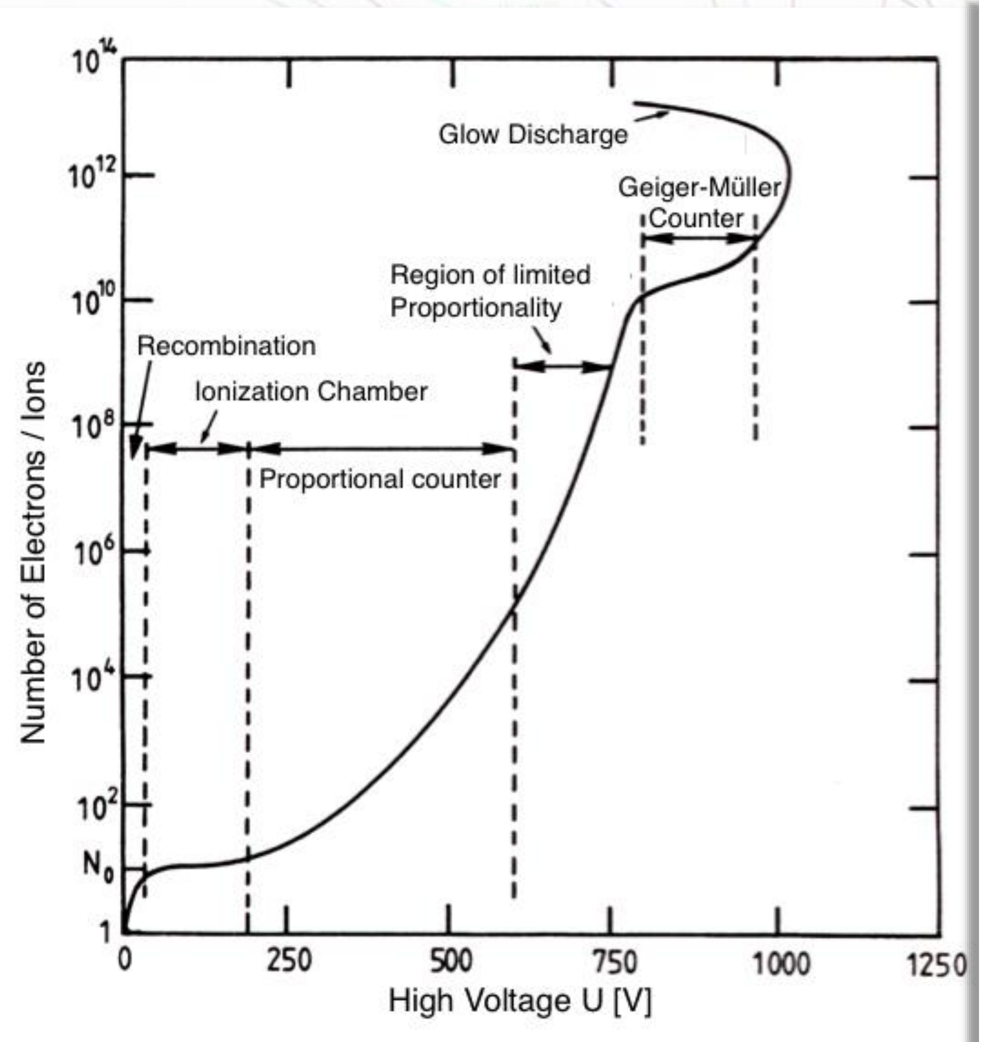




Donald Glaser (1960) Nobel Prize for the invention of the bubble chamber

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)



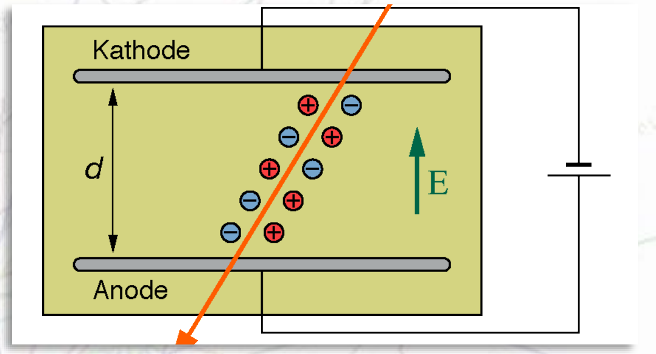
Gas counters may be operated in different operation modes depending on the applied high voltage

- 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

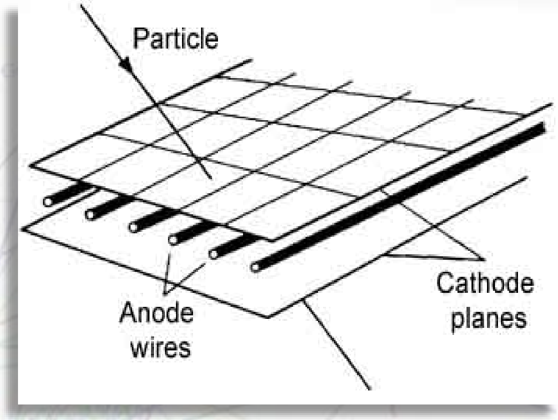
- The gas gain factor is constant – signal proportional to the primary ionization
- Total charge collected on the wire
  - G(gas gain) = 10^4-10^5 x initial ionization
- Choice of gas: noble gases increase ionization probability
  - The larger atomic number is, the lower the ionization potential is
  - However, Xe and Kr are expensive => 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

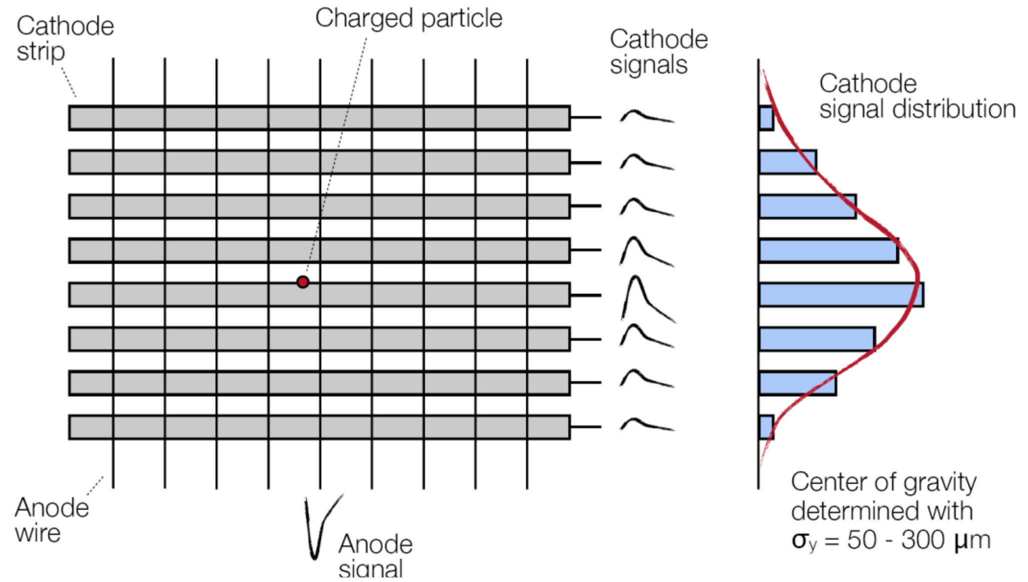
Detectors based on ionization: multiwire proportional counter

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 2nd coordinate
- Employing a center of charge calculation, a position **resolution of ~50-300 μm** is achievable (by simply using the wire position ~500 μm).



The Nobel Prize (1992)
G. Charpak



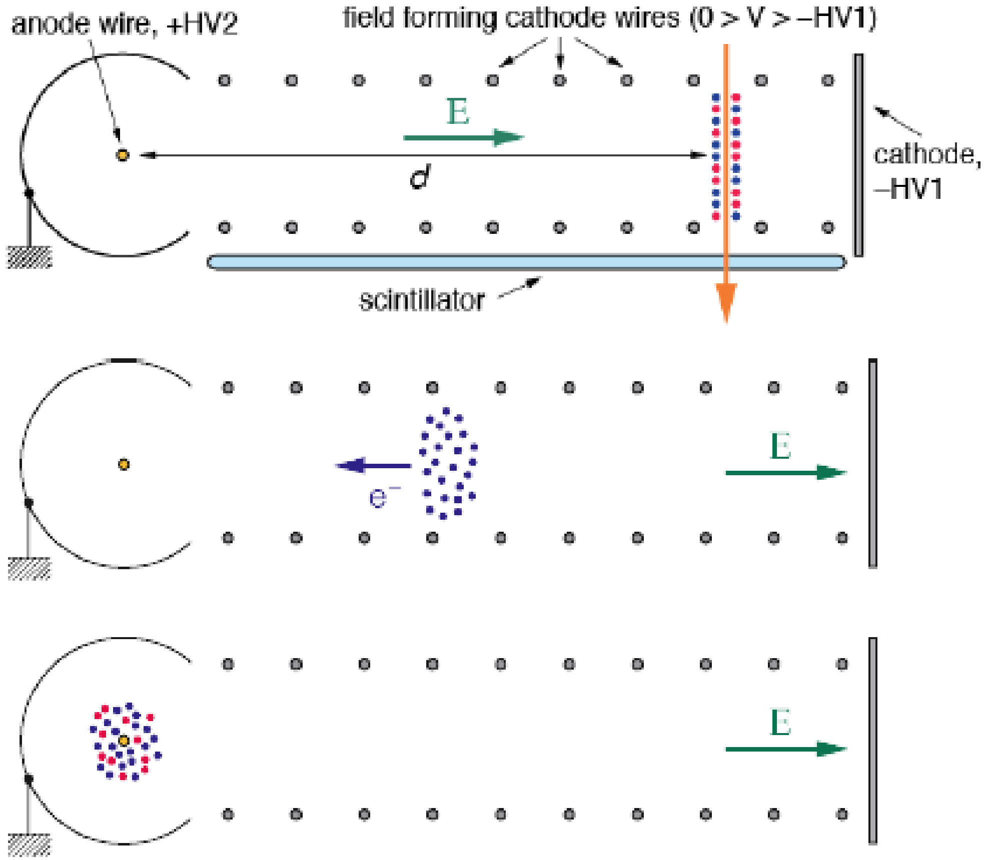
Detectors based on ionization: drift chamber

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.

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

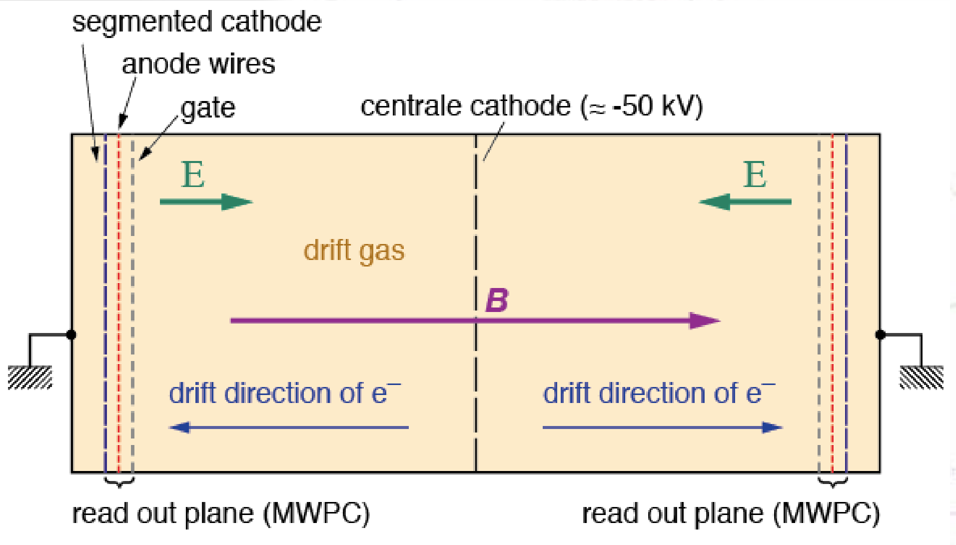


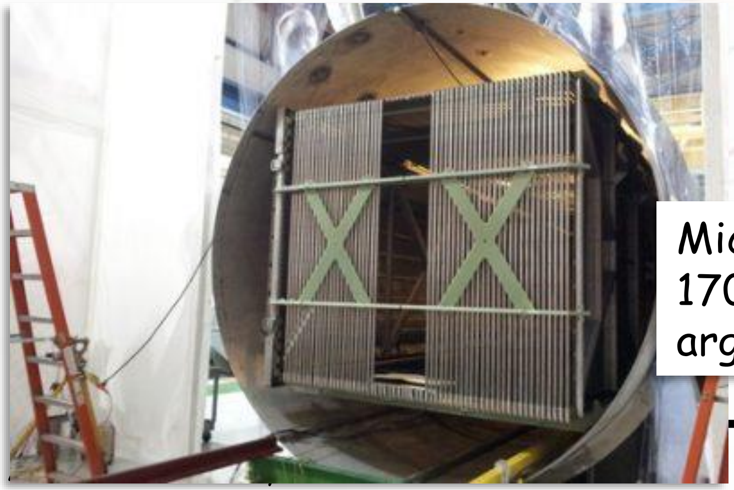
- The electric field has to be homogeneous and the drift velocity constant and known
- Position resolution for large area chambers **~200 μm**
- Compared to MWPC: fewer wires and electronic channels, higher precision, but slower!

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

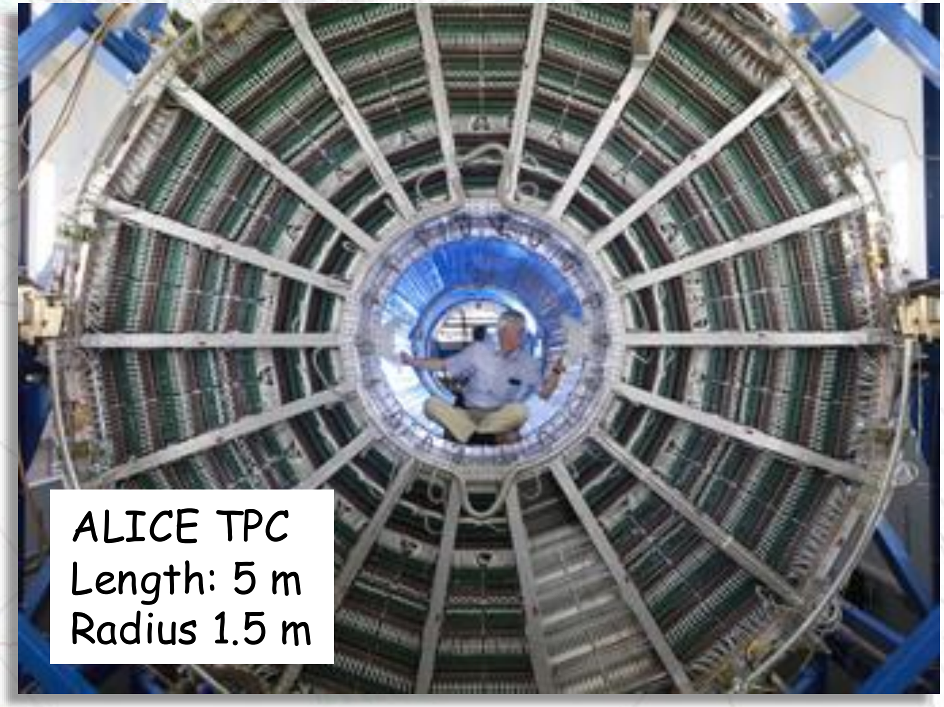
Drift chamber with several meters drift distances

- **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 $\sigma_{r,\phi}$ = 150–250 μm and $\sigma_z \approx 1$ mm
- Due to long drift times (e.g. 90 μs for 2,5 m drift length ALICE TPC), TPCs are not suitable for high particle rates – but ok for HI collisions





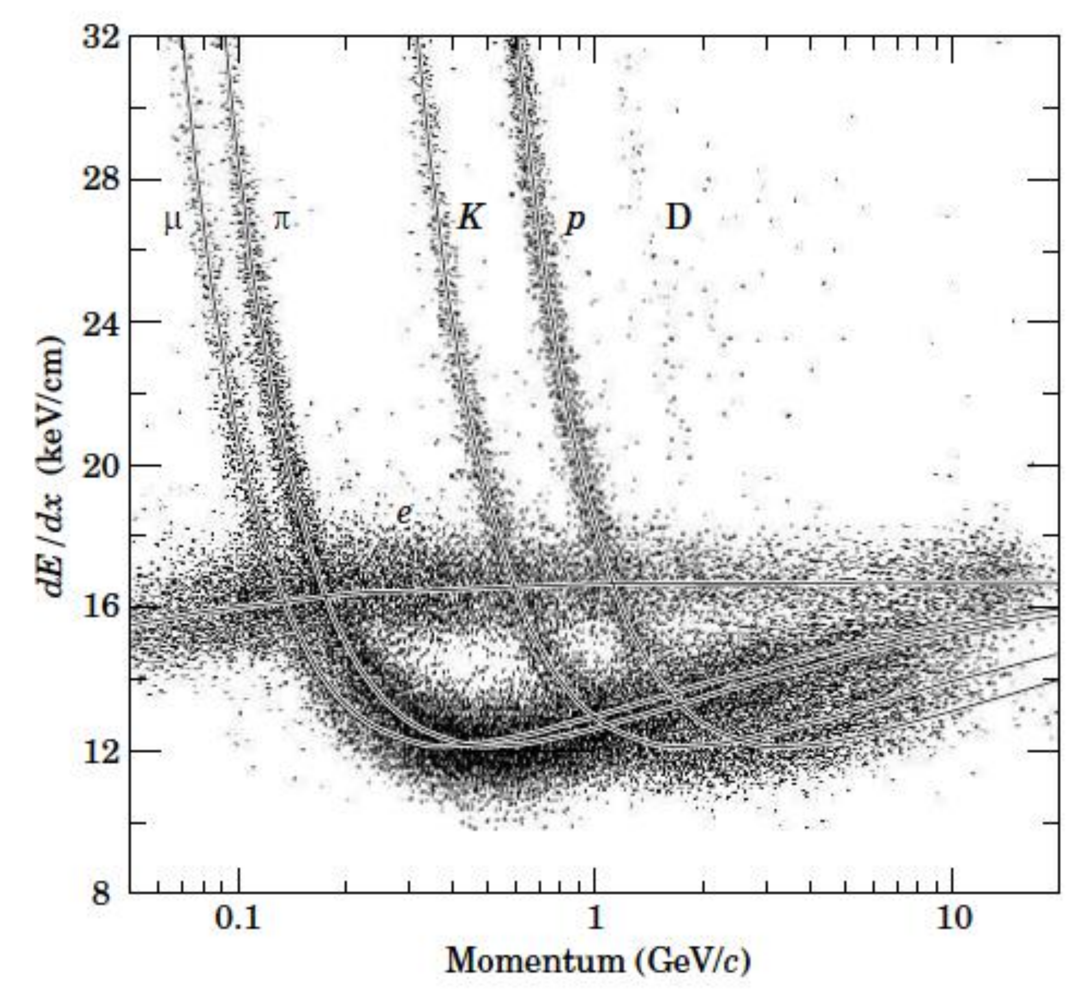
MicroBooNE
170-ton liquid argon TPC



ALICE TPC
Length: 5 m
Radius 1.5 m

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

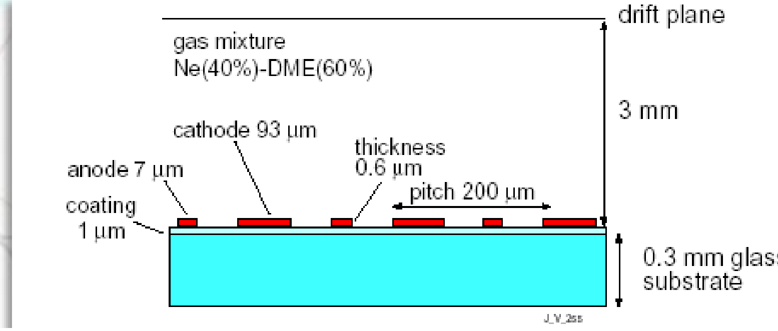
Simultaneous measurement of particle momenta (from bending in magnetic field) and ionization loses dE/dx (depending on v) allows for identification of particles (with not very high momenta)

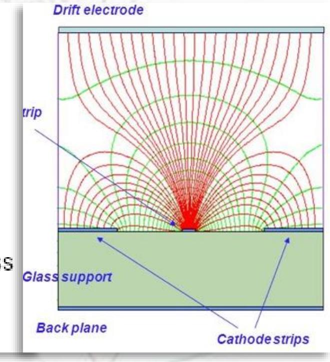


Detectors based on ionization: new solutions

Micro Strip Gas Chamber (MSGS)

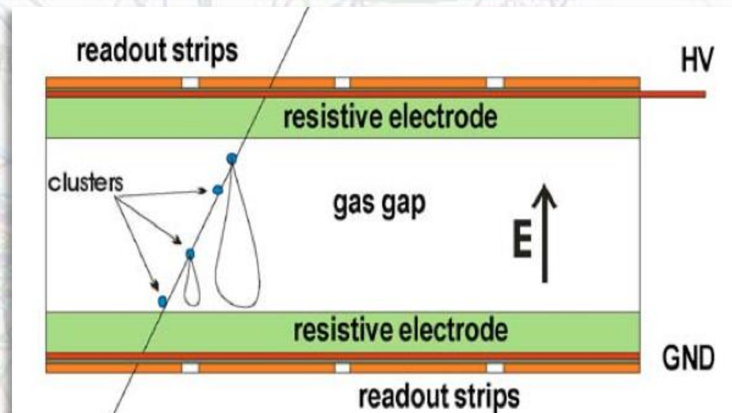
- gain provided by metal strips on resistive electrodes
- fast ion collection -> high rate capability
- resolution 30-40 μm





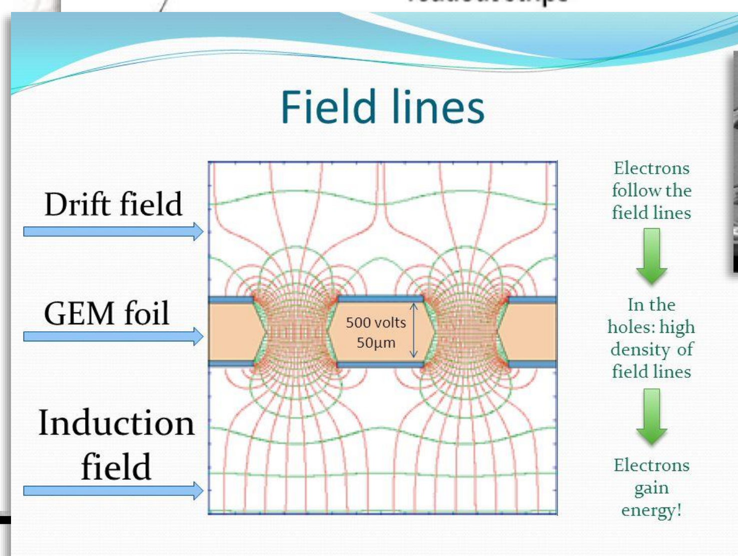
Resitive Plate Chambers (RPC)

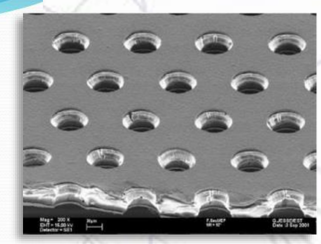
- modern spark chamber
- Gas gap typically 2 mm
- Operating in avalanche mode
- space resolution ~mm
- Fast timing (~ 1ns) and sufficient high rate capability -> ideal as trigger detectors!



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) μm
- Two sides of the film are kept at a difference of potentials -> strong E field in the holes => gas amplifications
- Signal is read out from strips/pads on the plane "under" the foil
- Resolution ~70 μm





Detectors based on ionization: silicon detectors (1)

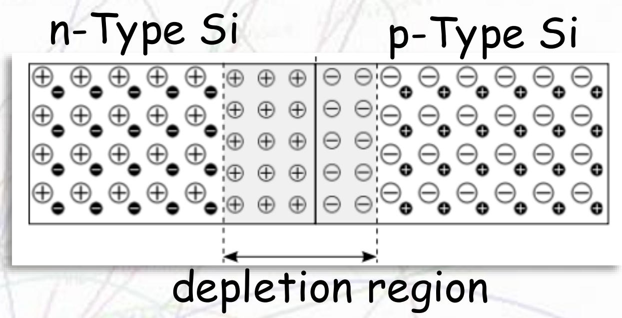
- **Silicon detector** is an ionization chamber with electron-hole pairs produced as a result of ionization losses

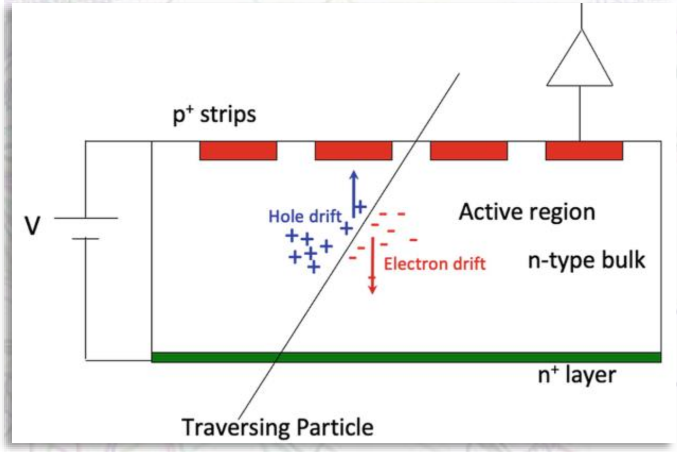
- Use of Si-diode: n-Type Si (adding donors) + p-Type Si (adding acceptors)
- Due to diffusion, region near the p–n interface forms the depletion layer => no free carriers
- Application of a reverse bias voltage → the thin depletion zone gets extended over the full junction → fully depleted detector

- 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 → detectable current

- Construction: thin (~300 μm) 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 x > than in gases)
  - small average energy needed for ionization (~3 eV vs ~30 eV in gases)
- Resolution depends on distance from strip to strip (20-150 um)

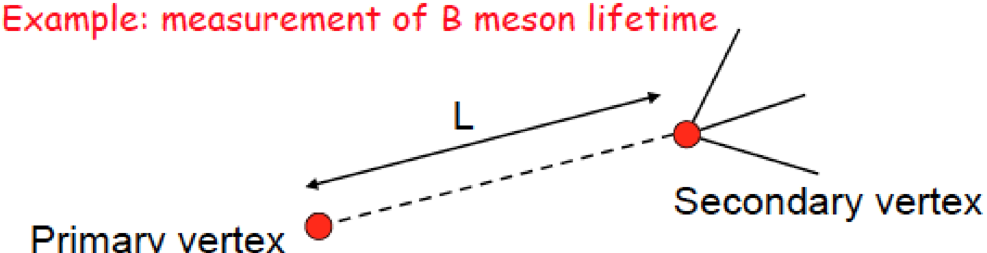




Detectors based on ionization: silicon detectors (2)

- Silicon detectors are:
  - intrinsically fast:
    - thin
    - fast drift of both electrons and holes
  - precise: e.g. ~5 µm from center of gravity method on signals shared between 50 µm 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 - > cooling

Example: measurement of B meson lifetime

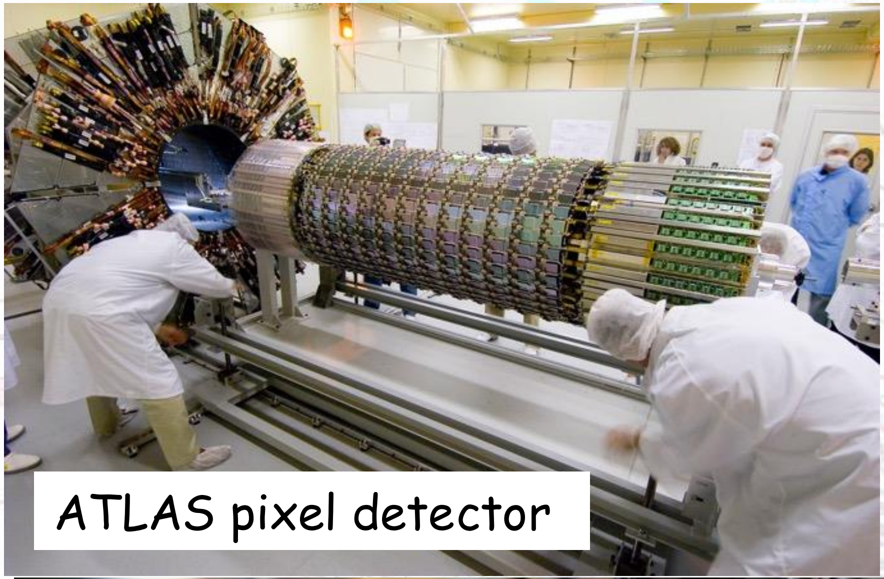


E.g. $B \rightarrow J/\Psi\, K_s^0$

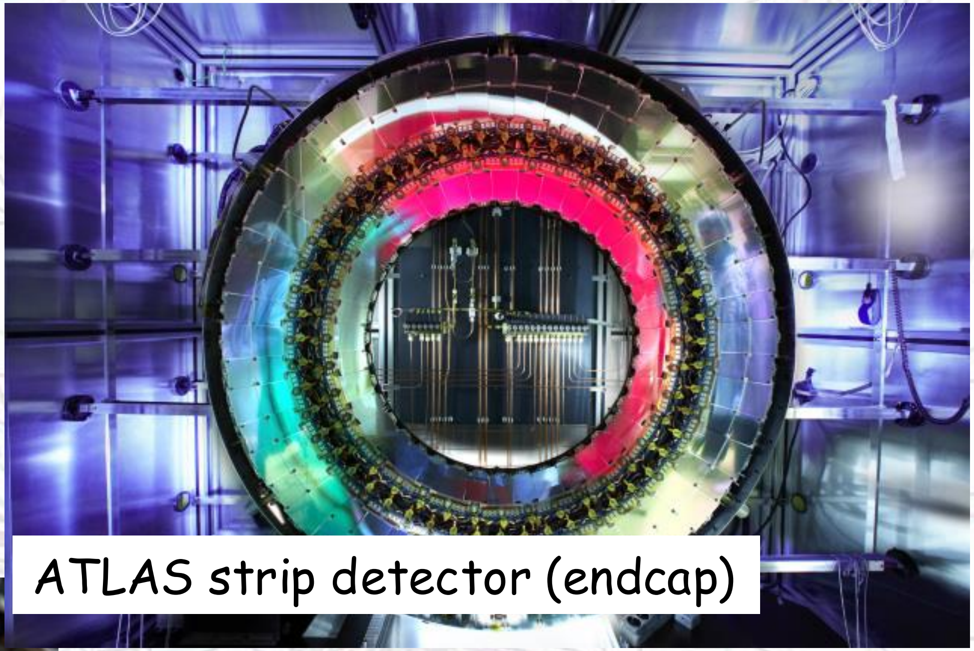
$L = p/m\, c\, \tau$

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

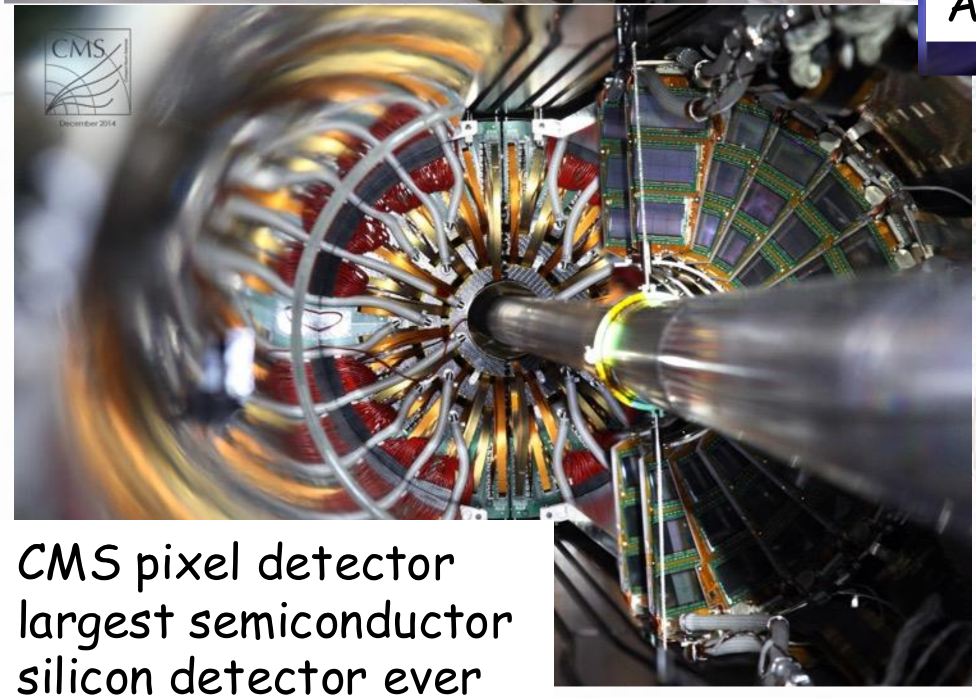
Detectors based on ionization: silicon detectors (3)



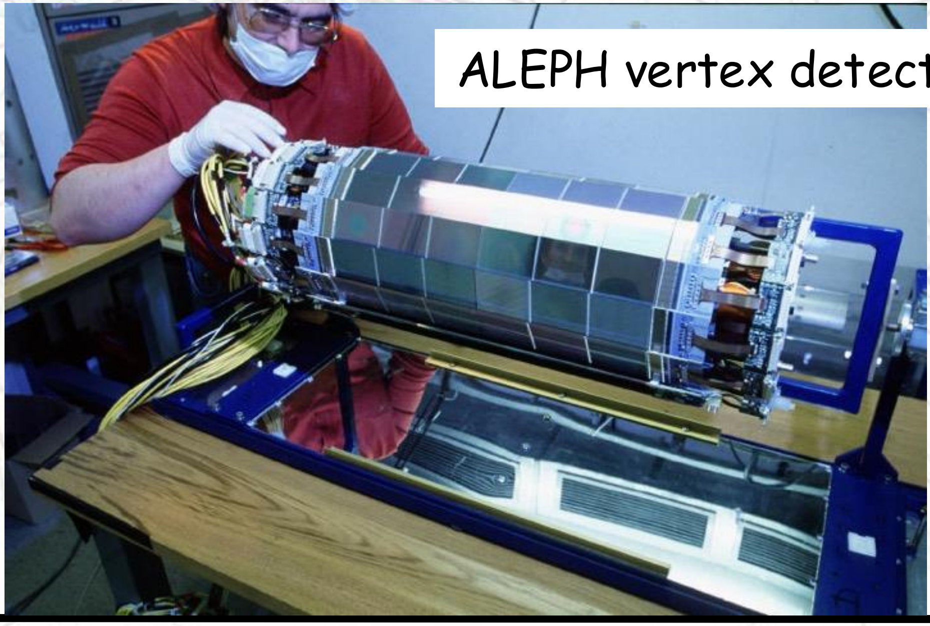
ATLAS pixel detector



ATLAS strip detector (endcap)



CMS pixel detector
largest semiconductor
silicon detector ever
constructed



ALEPH vertex detector

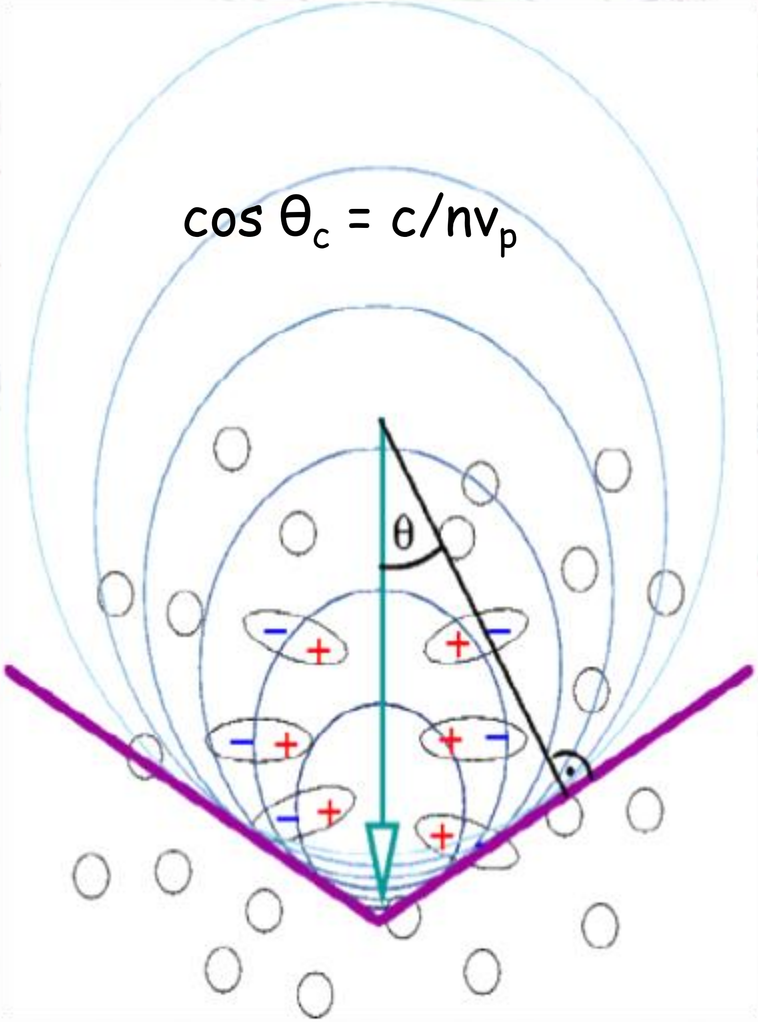
Detectors based on excitation of atoms: Cherenkov detectors (1)

Nobel Prize in 1958:
Cherenkov, Frank and Tamm

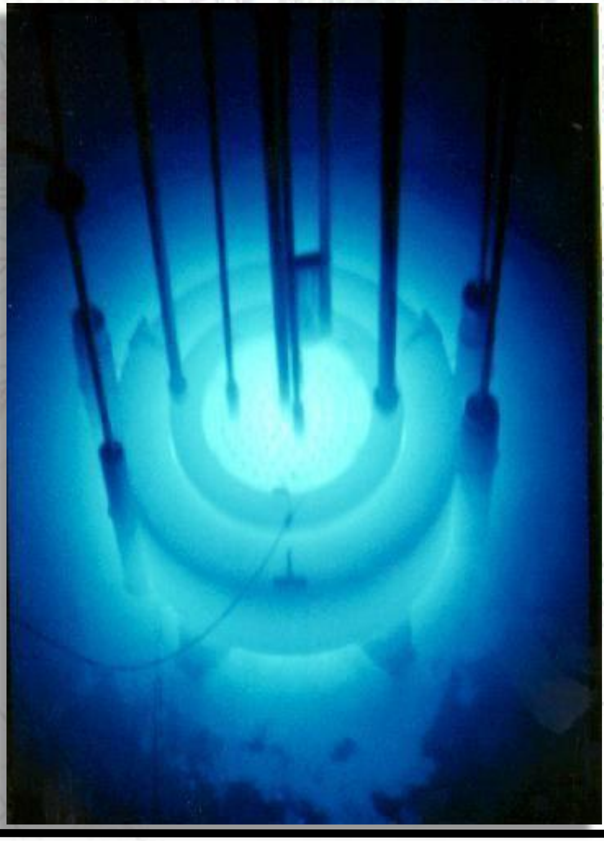
- **Cherenkov radiation** results when a charged particle, exceeds the speed of light in a dielectric medium through which it passes
- Charged particle moving inside a polarizable medium excites its molecules
  - upon returning back to their ground state, the molecules re-emit some photons (in a conductor, the disruption can be restored without emitting a photon)
- 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 θ 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 by 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

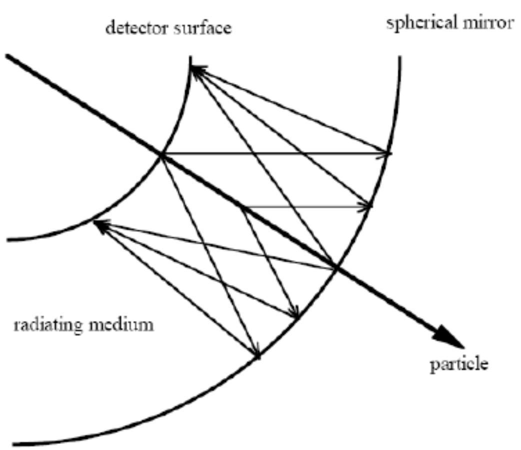


Cherenkov radiation can characterize the remaining radioactivity of spent fuel rods

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

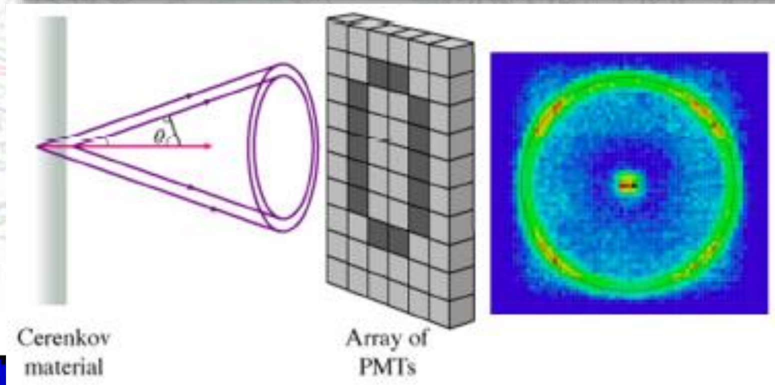
Cherenkov Detector Designs:

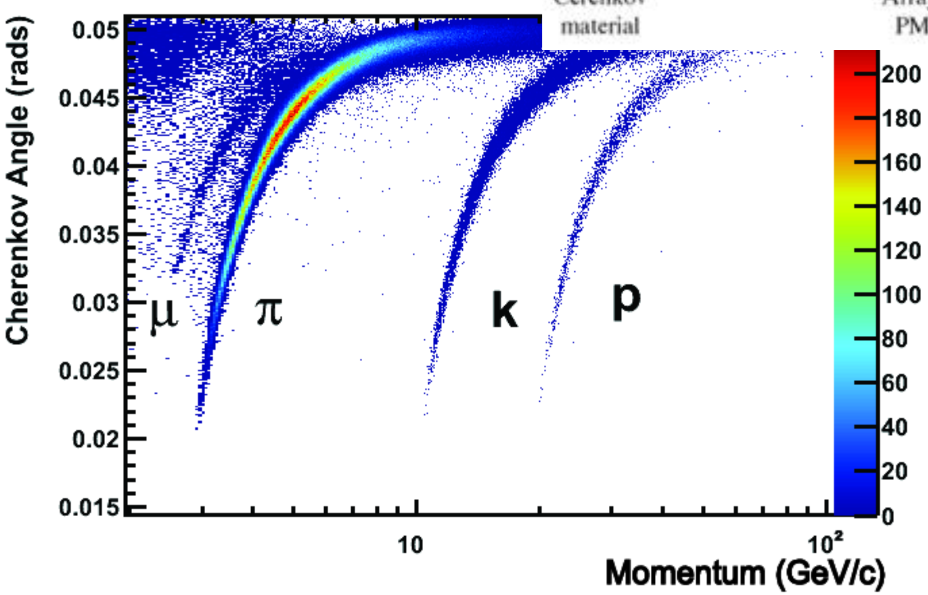
- Threshold Counters - Yes/No decision on the existence of the particle **type**
- Imaging Counters - measuring $\cos\theta_c$
  - E.g. Ring Imaging Cherenkov Detectors (RICH)

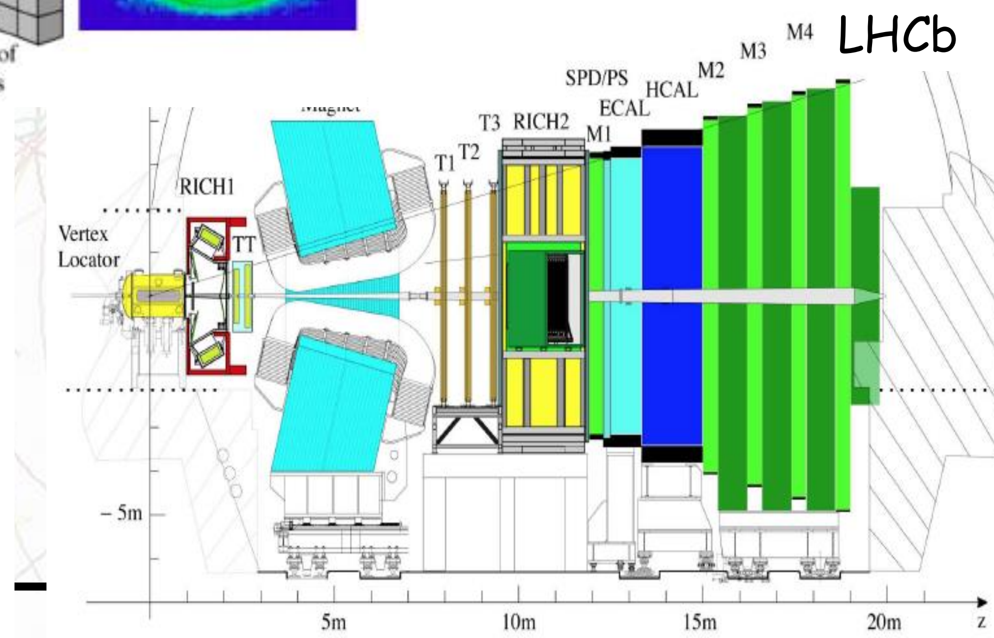


Via a mirror system, the light cone is imaged on the photon detector plane as a ring with its diameter proportional to θ_c

- *Can be used for particle identification over large surfaces*



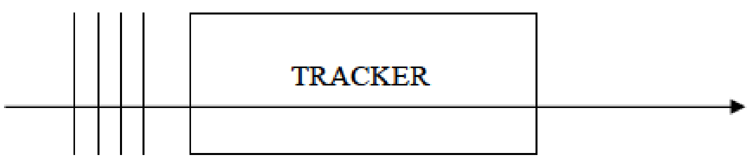


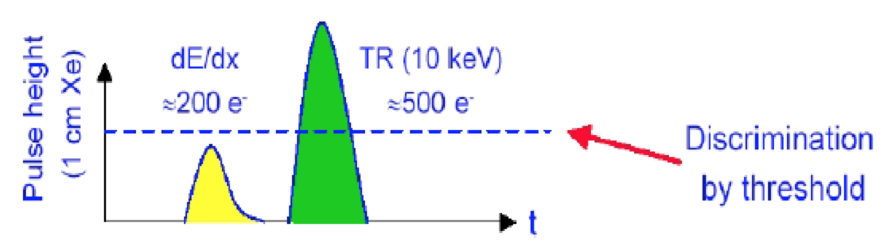


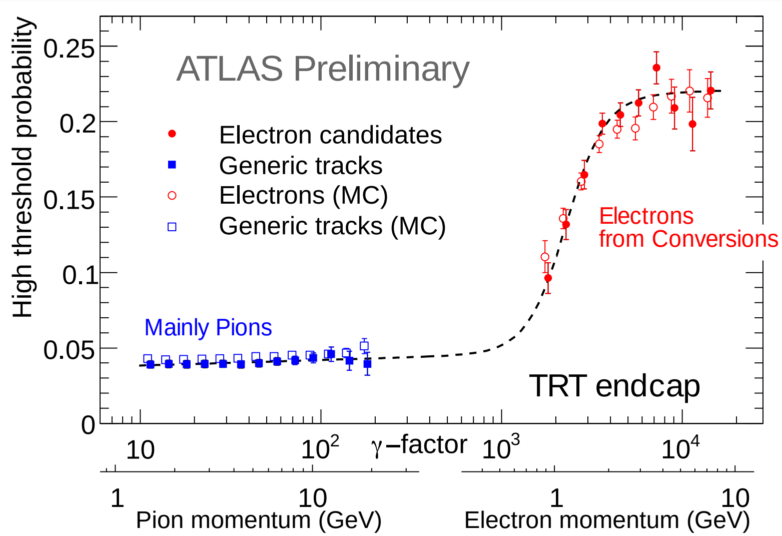
A

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 ~ $1/\gamma$ of the particle
- Demonstrated theoretically by Ginzburg and Frank in 1945
- Number of emitted photons (E ~ several keV) ~ γ -> method effective for γ ~ 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







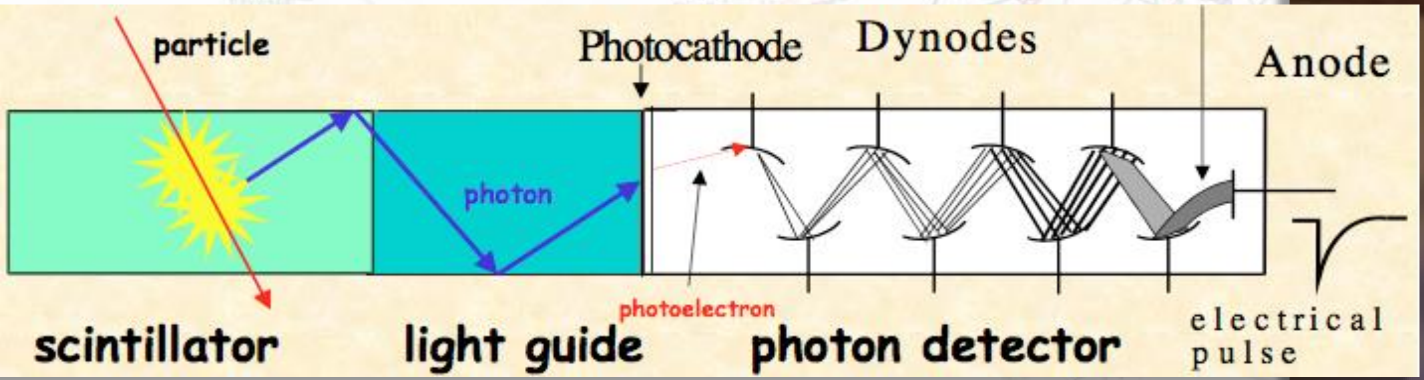
Mainly for e/π separation in 0.5 - 200 GeV

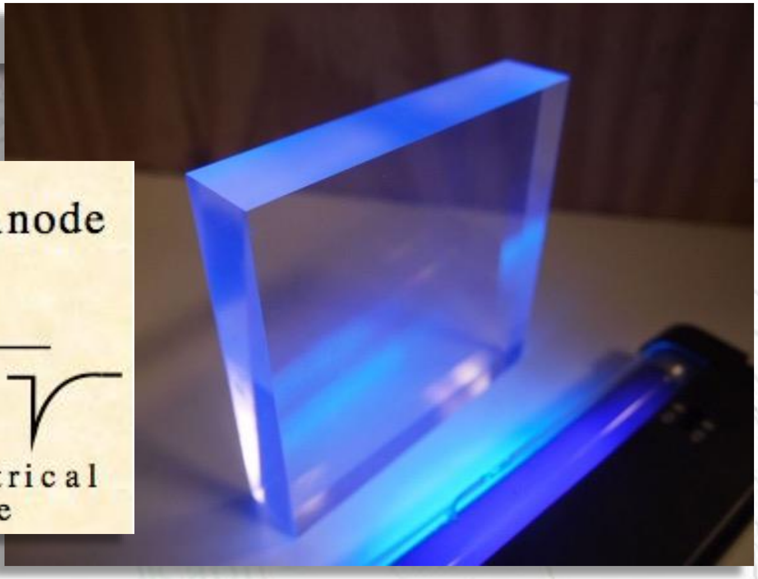
Detectors based on excitation of atoms: scintillation

- 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 ~ 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!

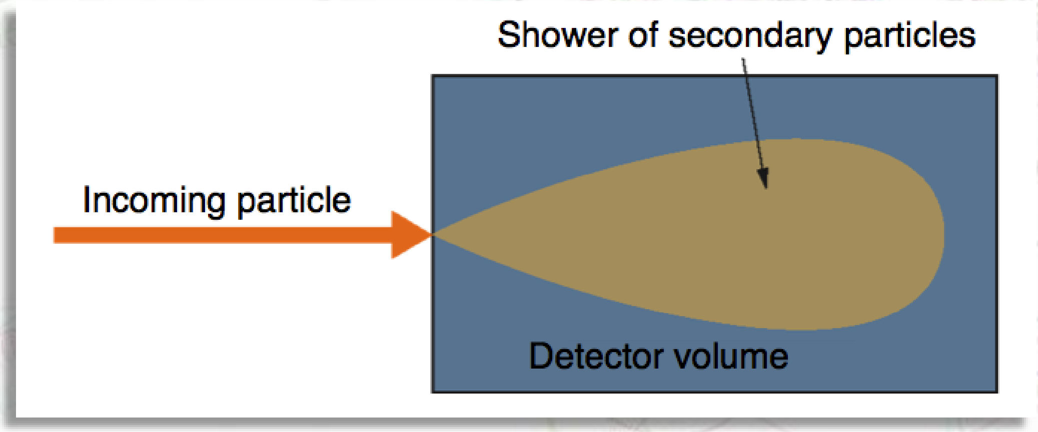




Calorimeters

- ***A calorimeter is a detector which fully absorbs the particles***
- The signals produced are a measure for the energy of the particle
  - Calorimeter signal ~ deposited energy ~ 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)

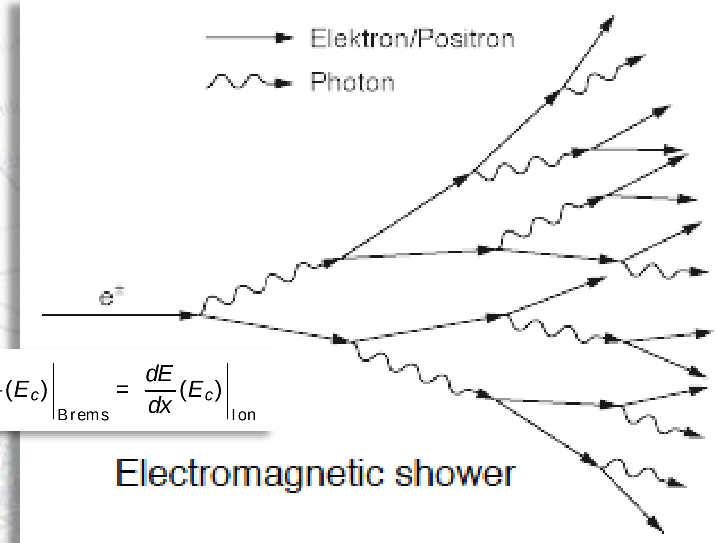


Electromagnetic cascade

- Penetrating e^-/e^+ emit γ through bremsstrahlung
- The high energy photon produces e^+e^- pairs
- The primary e^-/e^+ may emit further γ's etc…

- Particle multiplication continues until particle energy ~ the critical energy E_c at which the loss through ionization equals the loss through bremsstrahlung

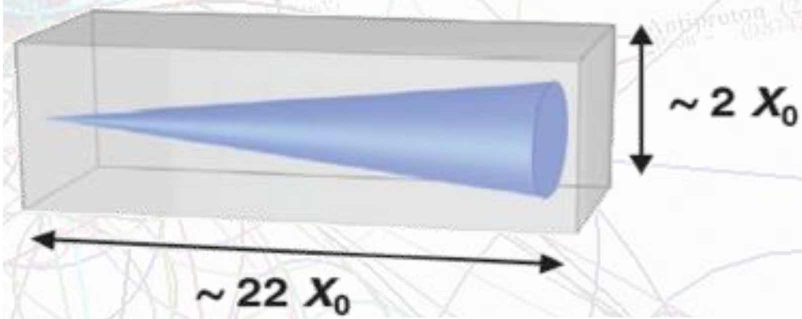
- If the penetrating particle is a photon, the shower starts with pair production and continues identically



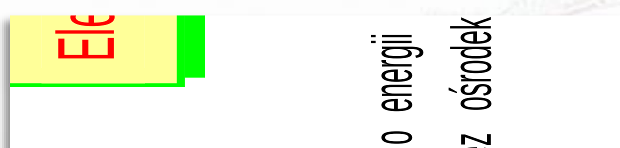
$$\frac{dE}{dx}(E_c)\Big|_{Brems} = \frac{dE}{dx}(E_c)\Big|_{Ion}$$

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 looses 1/e (≈63.2%) of its energy due to radiation
- **Transversal (lateral) dimension: Moliére radius ρ_M**



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

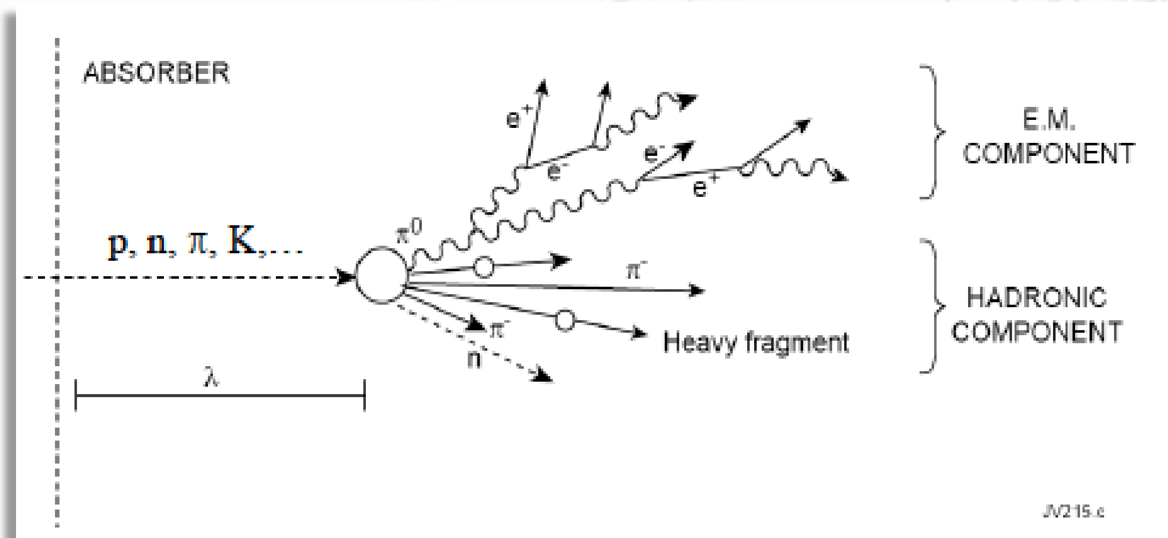


^{13}Al	8.9 cm
^{26}Fe	1.76 cm
^{29}Cu	1.43 cm
^{82}Pb	0.56 cm

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

Hadronic cascade

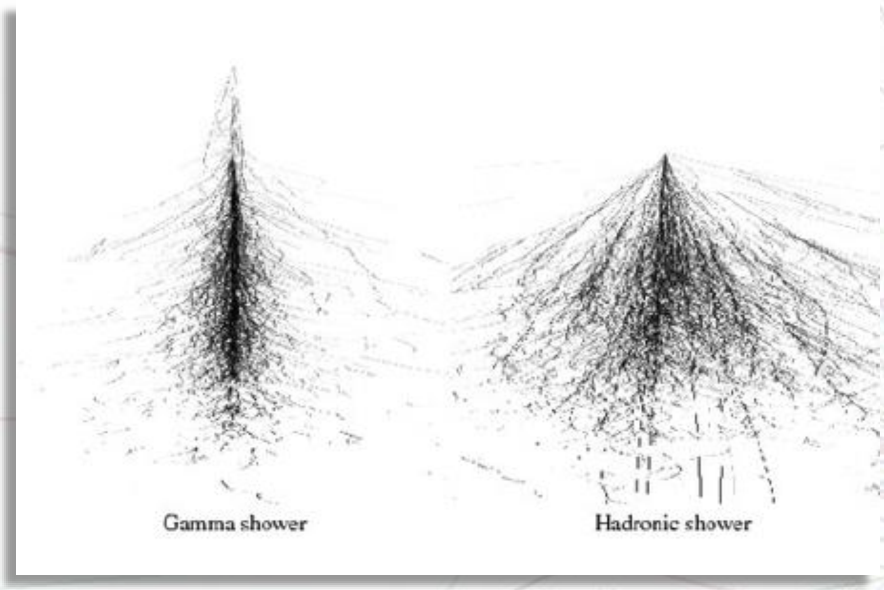
- **Hadronic shower** are a series of inelastic hadronic interactions of a primary particle with the nuclei of the target material
- Produced secondary particles (mainly $\pi^{\pm}$ and π^{0}) undergo further inelastic interactions and produce more particles
- Due to the multitude of possible processes the development of a hadronic shower is considerably more complicated compared to an EM shower
- Created π^{0} -> $\gamma\gamma$ 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 Λ_a**

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

EM and Hadronic cascades



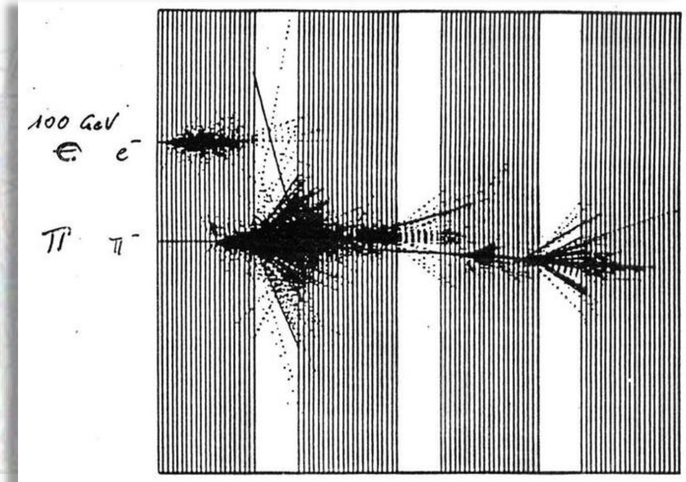
	λ_{int} [cm]	X_0 [cm]
Scint	79.4	42.2
LAr	83.7	14.0
Fe	16.8	1.76
Pb	17.1	0.56
U	10.5	0.32
C	38.1	18.8

$$X_0 \leftarrow \frac{A}{Z^2}$$

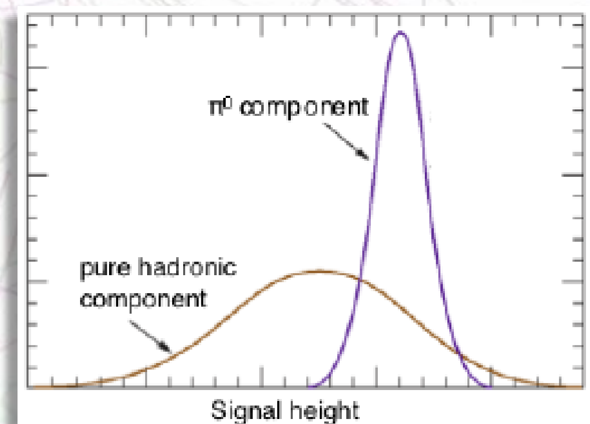
$$\lambda_{int} \leftarrow A^{1/3}$$

$$\frac{\lambda_{int}}{X_0} \leftarrow A^{4/3}$$

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



- 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 -> **e/h response ratio**
- e/h is figure of merit of hadron calorimeters
  - e/h > 1, ideal calorimeter has e/h=1 (compensating calorimeter)

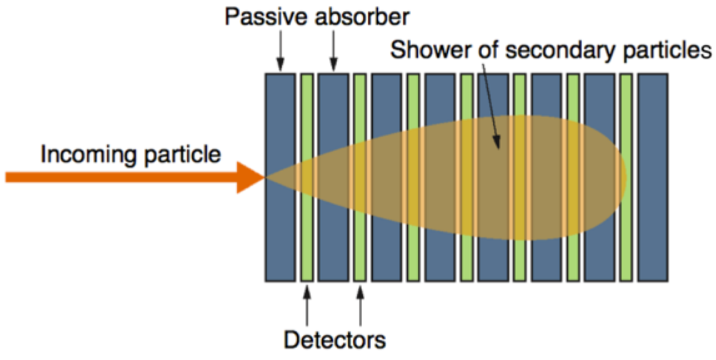


Different types of calorimeters

- 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:

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

← added in quadrature

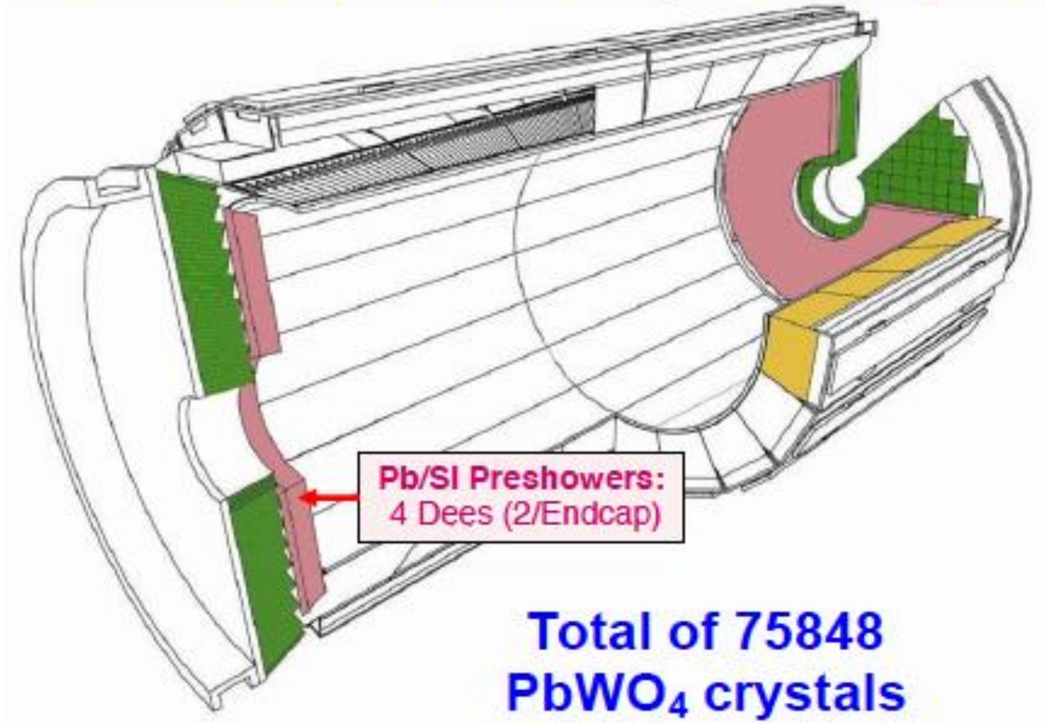
  - **a, stochastic term:** the counting aspect of the measurement: simple statistical error. Scales with the square root of the number of particles.
  - **b, noise term:** constant, energy-independent noise (f.e. from readout electronics) contribution to the signal
  - **c, constant term:** contributions 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**

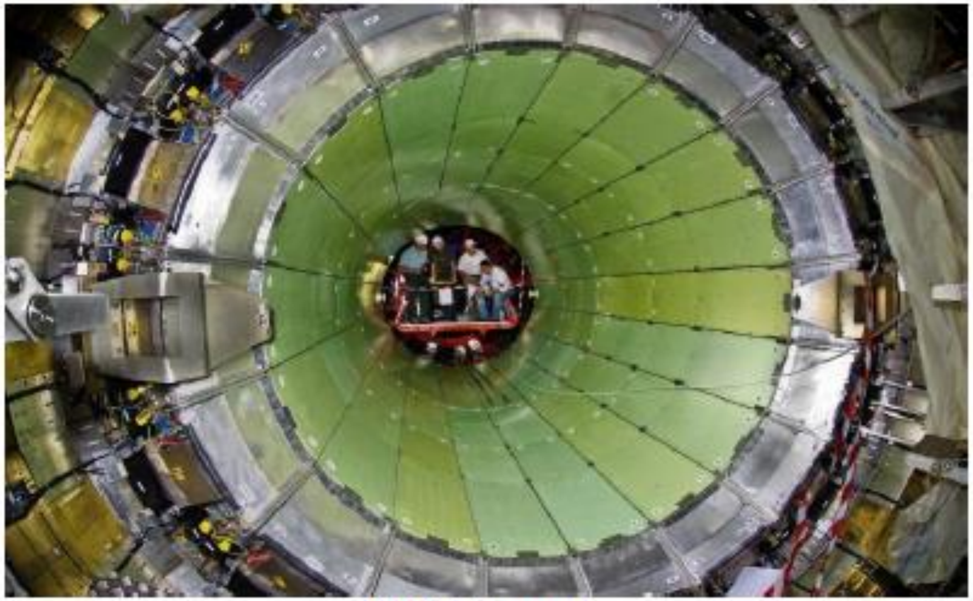
Example of Homogeneous EM Calorimeter

CMS at the LHC – scintillating $PbWO_4$ crystals



Total of 75848 $PbWO_4$ crystals

lead tungstate



CMS Barrel

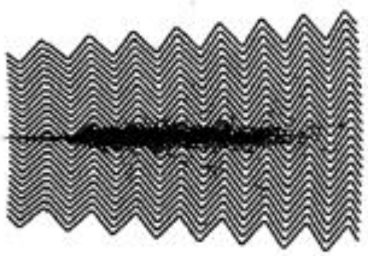
Barrel: 36 Supermodules (18 per half-barrel) **61200 Crystals** (34 types) – total mass 67.4 t

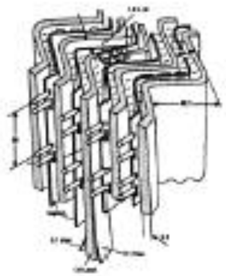
Endcaps: 4 Dees (2 per Endcap) **14648 Crystals** (1 type) – total mass 22.9 t

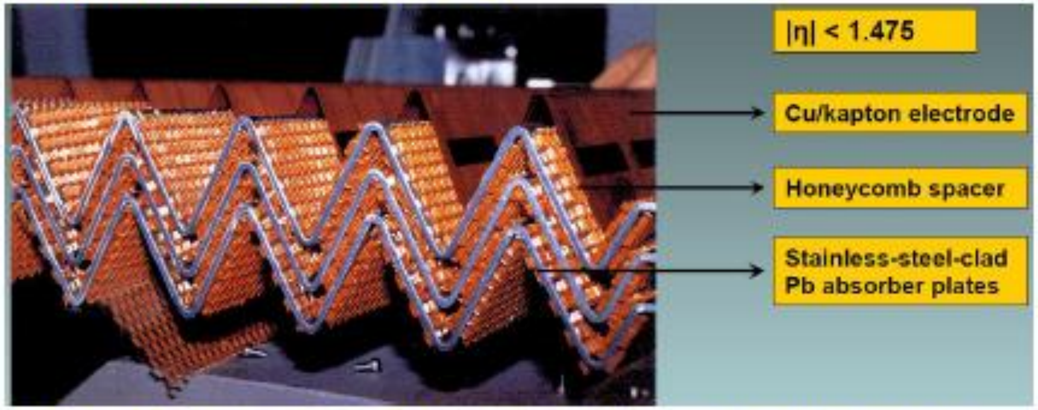
D Cockerill, RAL, STFC, UK   Introduction to Calorimeters

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)

Accordion geometry minimises dead zones

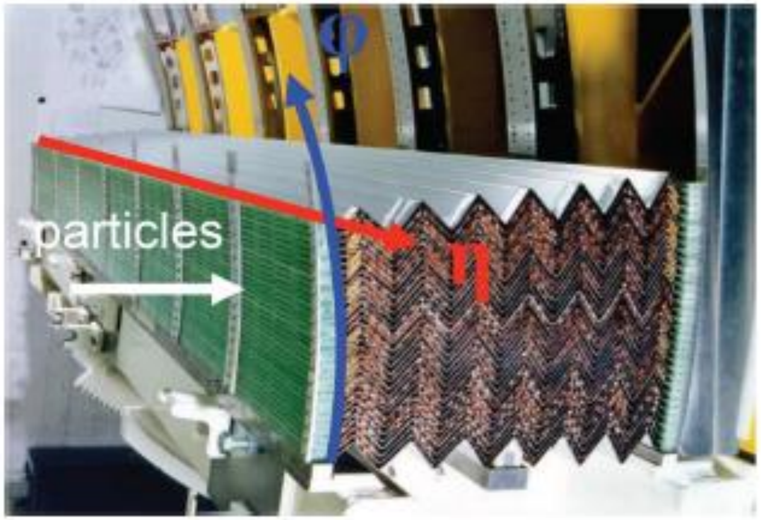
Liquid argon intrinsically radiation hard

Readout board allows fine segmentation (azimuth, rapidity, longitudinal)

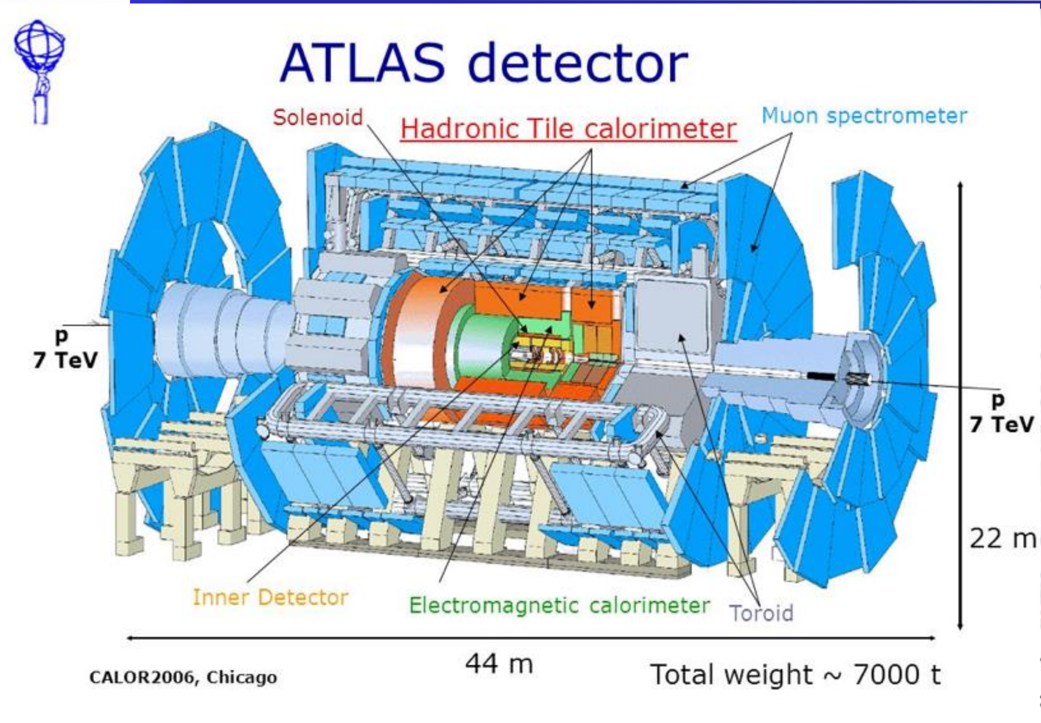
Multilayer Cu-polyimide readout boards

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

1 GeV energy deposit → collect 5.10^6 e$^-$

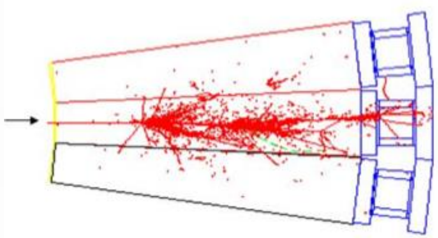


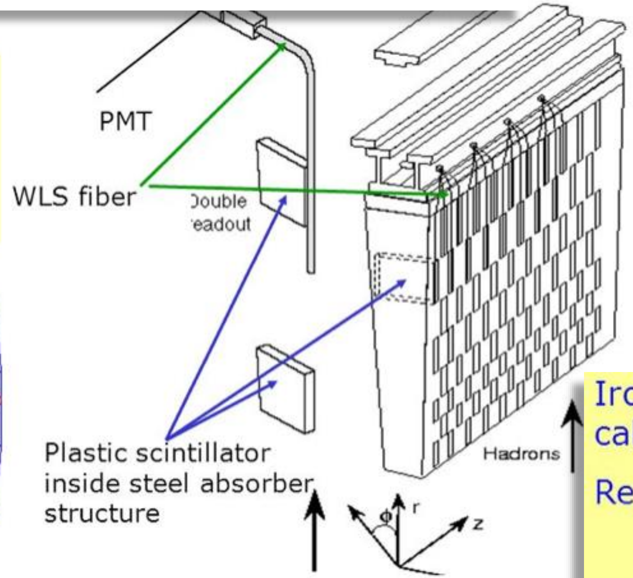
Example of Hadronic Calorimeter: ATLAS Tile Calorimeter

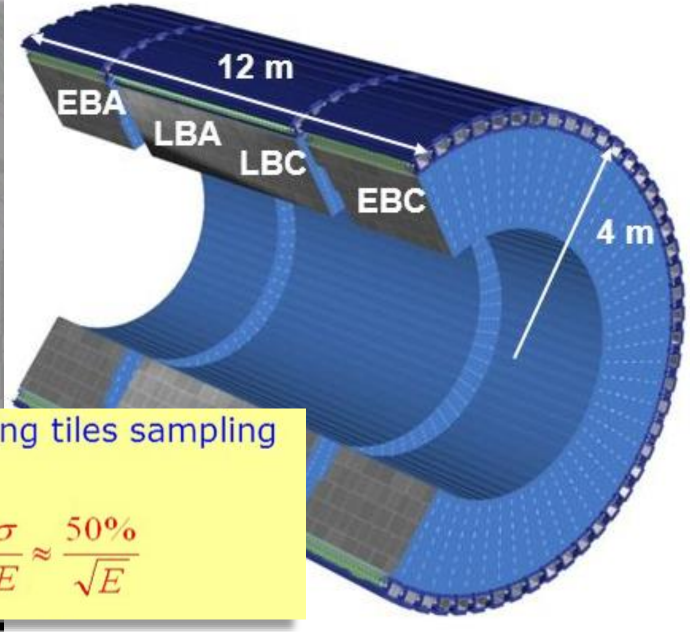


Principle of TileCal:

Measure light produced by charged particles in plastic scintillator





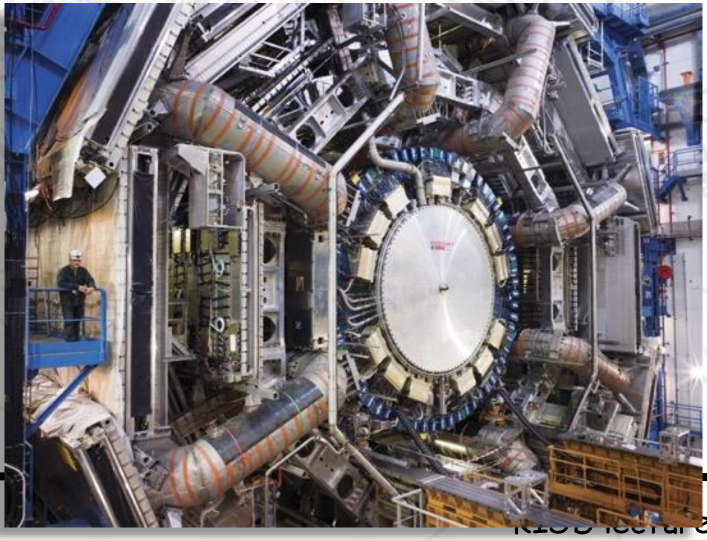


Iron – scintillating tiles sampling calorimeter

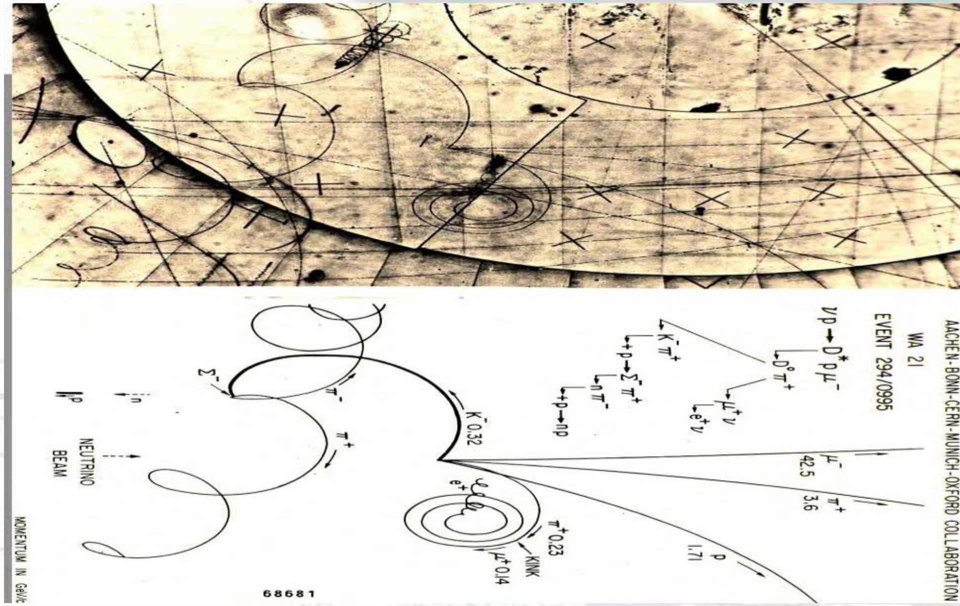
Resolution: $\frac{\sigma}{E} \approx \frac{50\%}{\sqrt{E}}$

Detection of muons

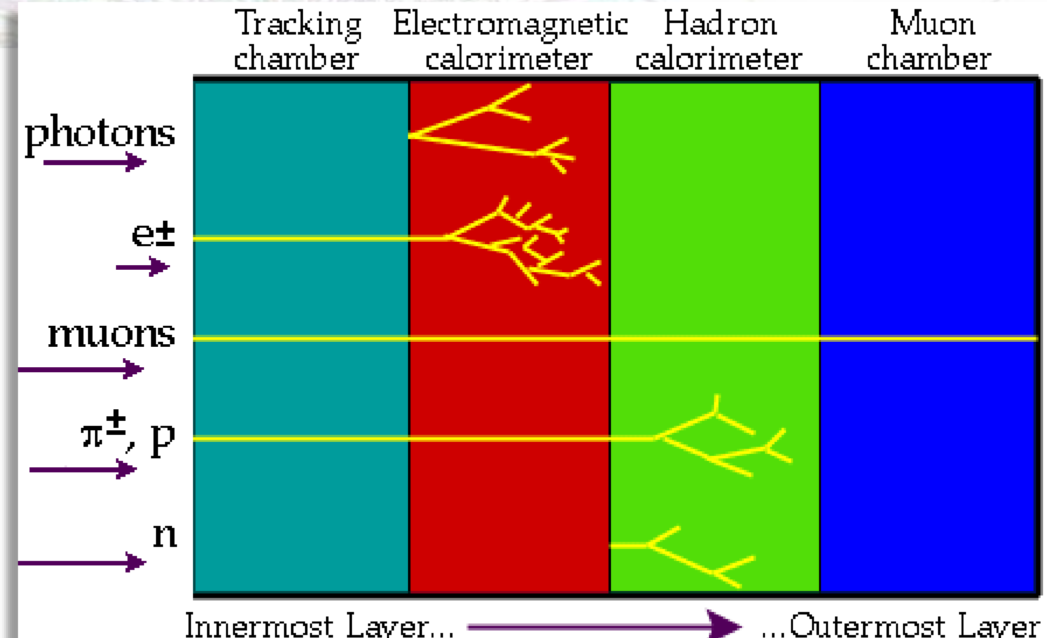
- Muons are charged particles that are not interacting strongly, and they do not create EM cascades
- Muons can penetrate several meters of iron without interacting, unlike most particles they are not stopped by any calorimeter
- Therefore, detectors, usually wire chambers, to detect muons are placed 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



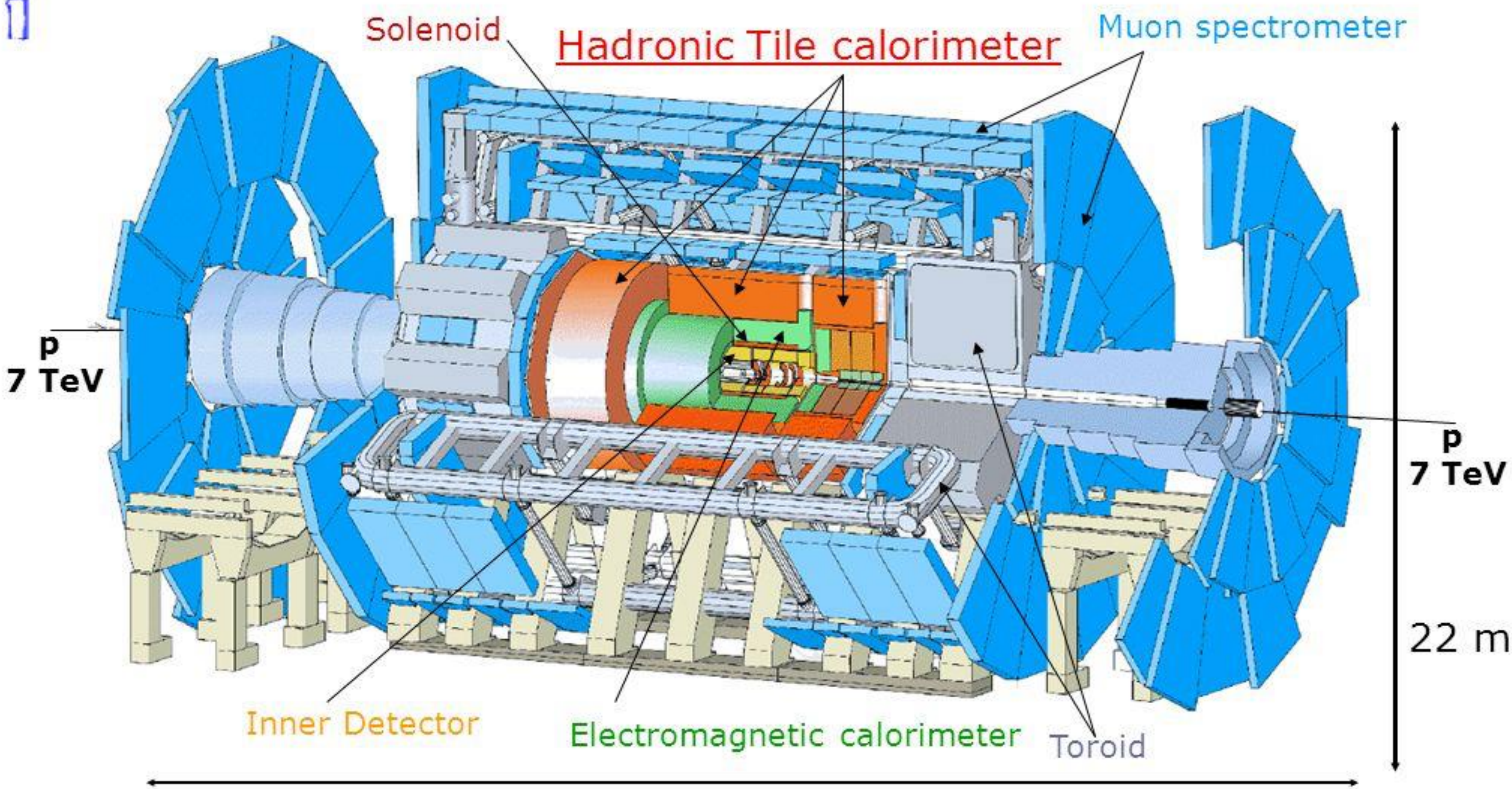
- Modern detectors in particle physics combine several sub-detectors in layers much like an onion or like ogres ☺
- Length travelled before decay is $L=\beta\gamma\tau c$, anything with τ>~10^{-10} s might appear in detector ($e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, K^0, p, n, γ, ν)
- Use series 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

~ 10^8 electronic channels
~ 3000 km of cables
Cost: 450 MCHF -> 65 CHF/kg

ATLAS detector



44 m

Total weight ~ 7000 t

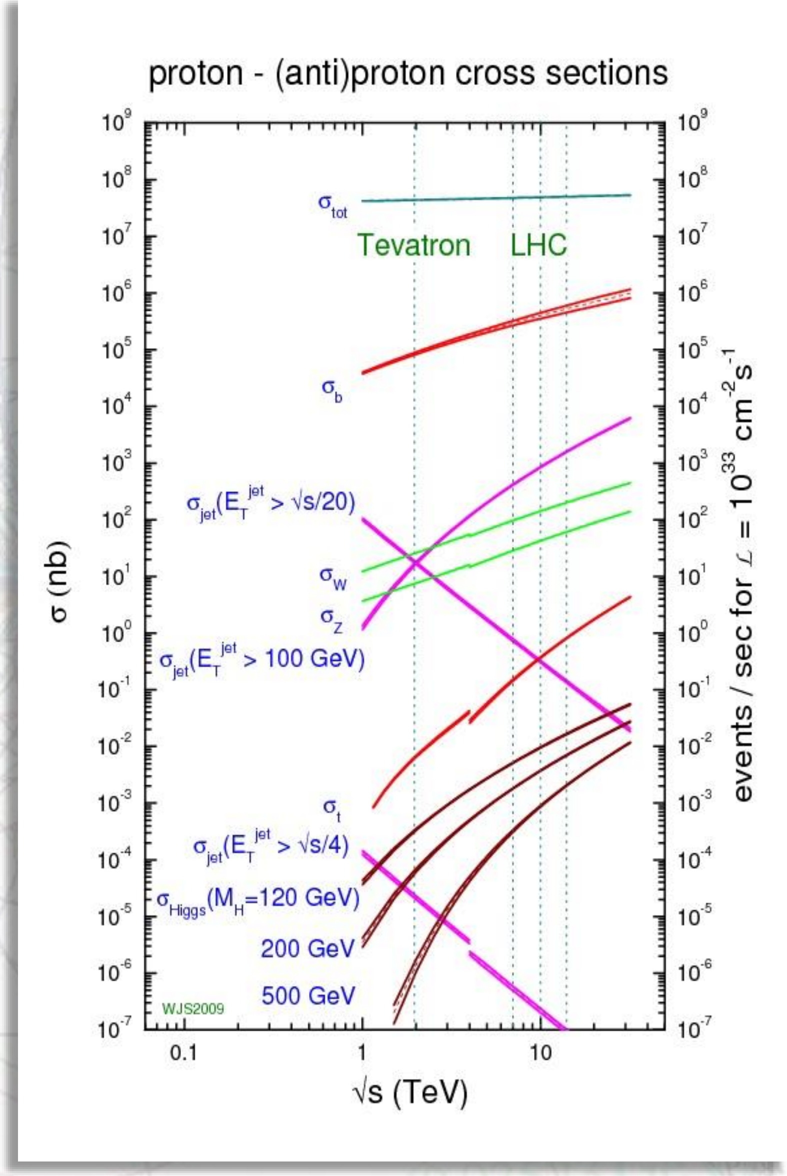
Trigger systems – Why we need them?

- 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!

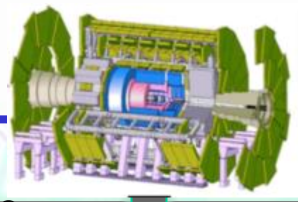
- **The trigger** decides, in real-time, which data should be archived for offline analysis
  - selects rare events and suppress background
  - rejected events are loss forever!

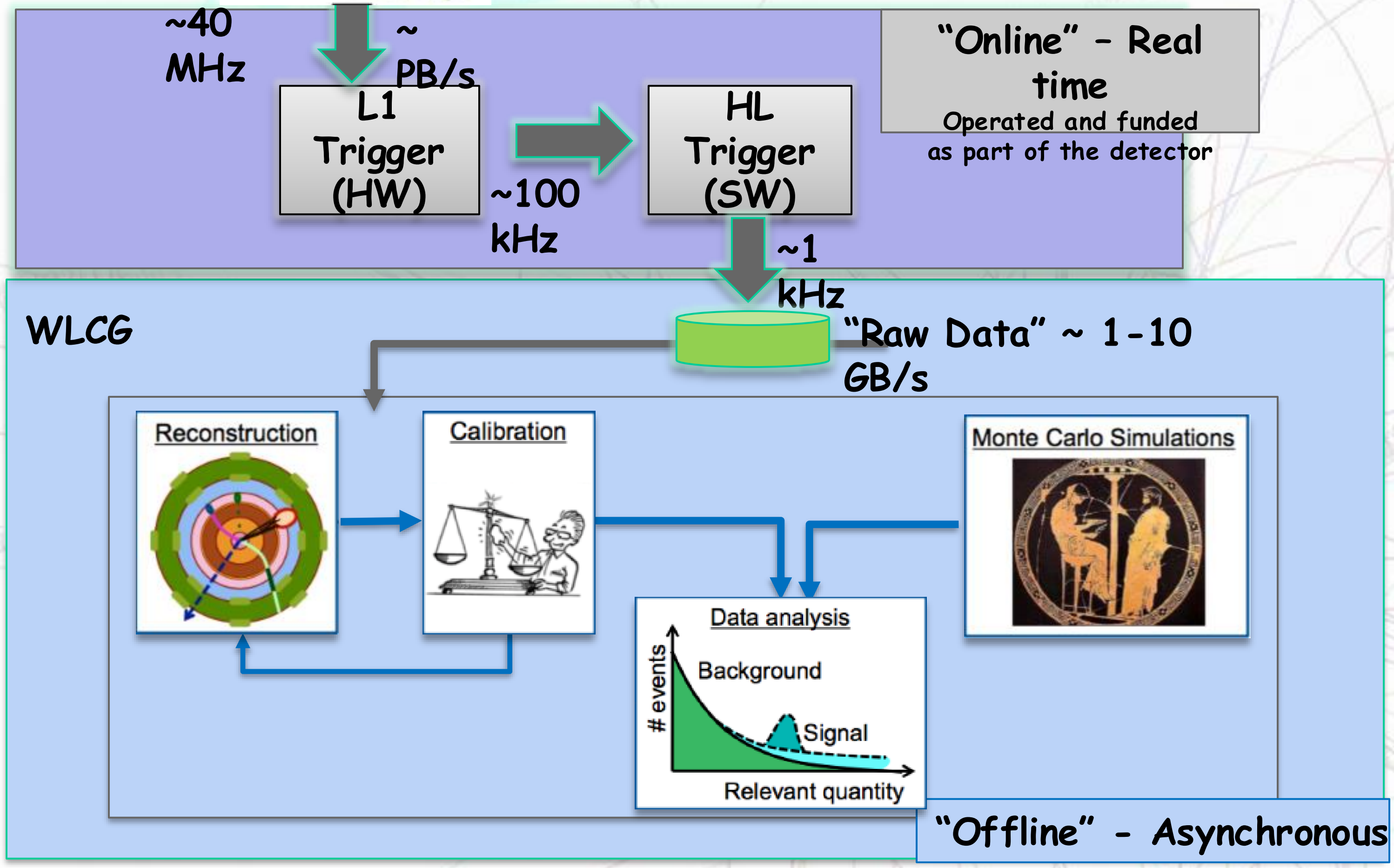
- Trigger systems are necessary due to real-world limitations in computing power, data storage capacity and rates

- E.g., ATLAS trigger system
  - The **Level-1 trigger** (hardware based) has to take decision in ~2 μs. 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

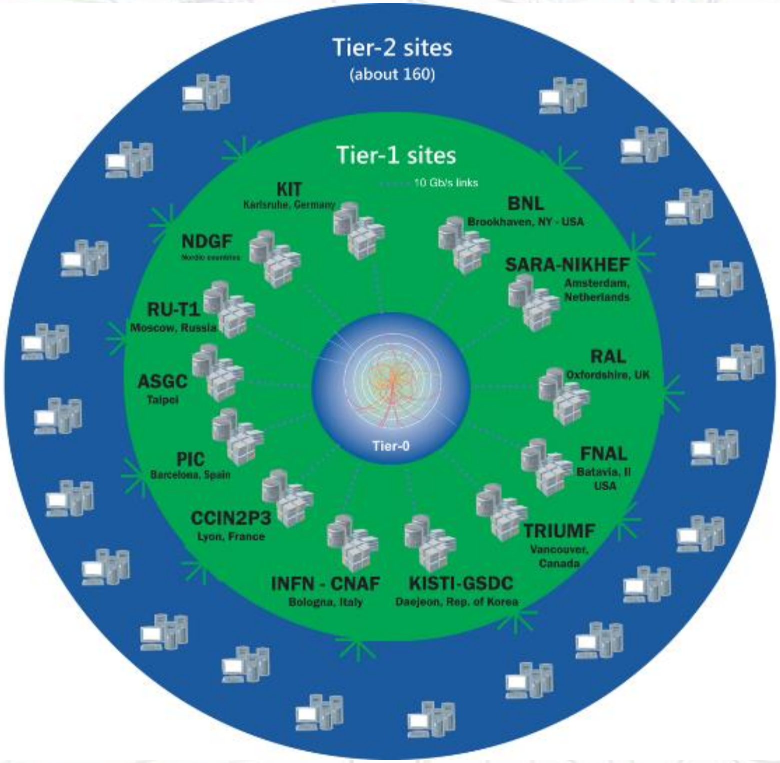
WLCG: An international collaboration to distribute and analyse LHC data

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

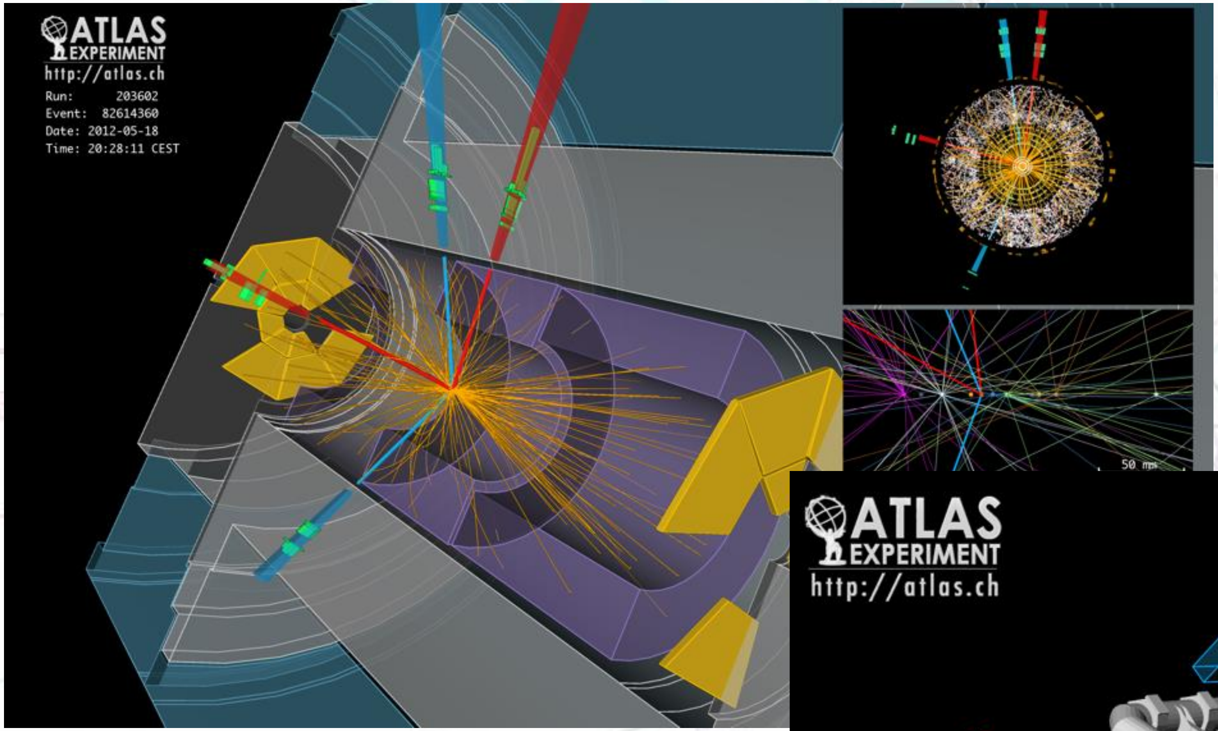
~1'000 PB of storage

> 2 million jobs/day

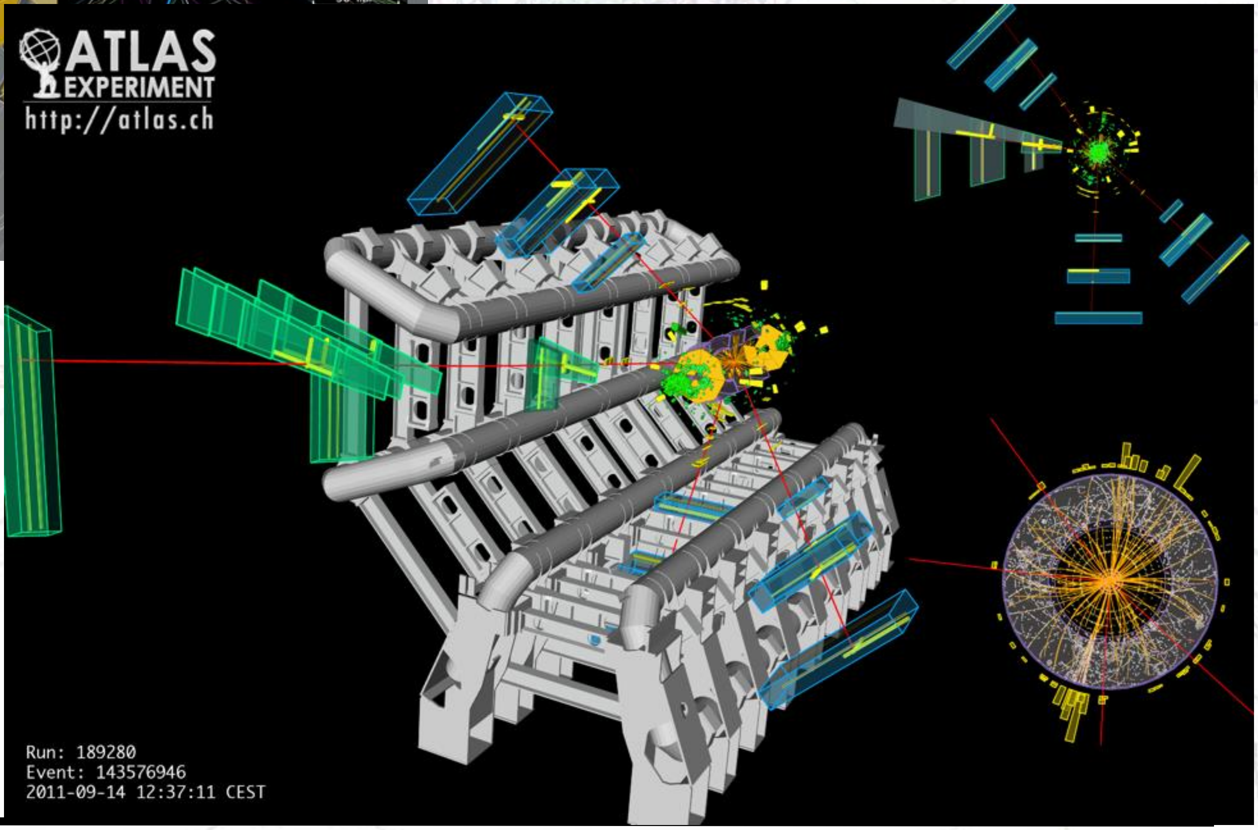
10-100 Gb links

- 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 → ZZ → 4μ



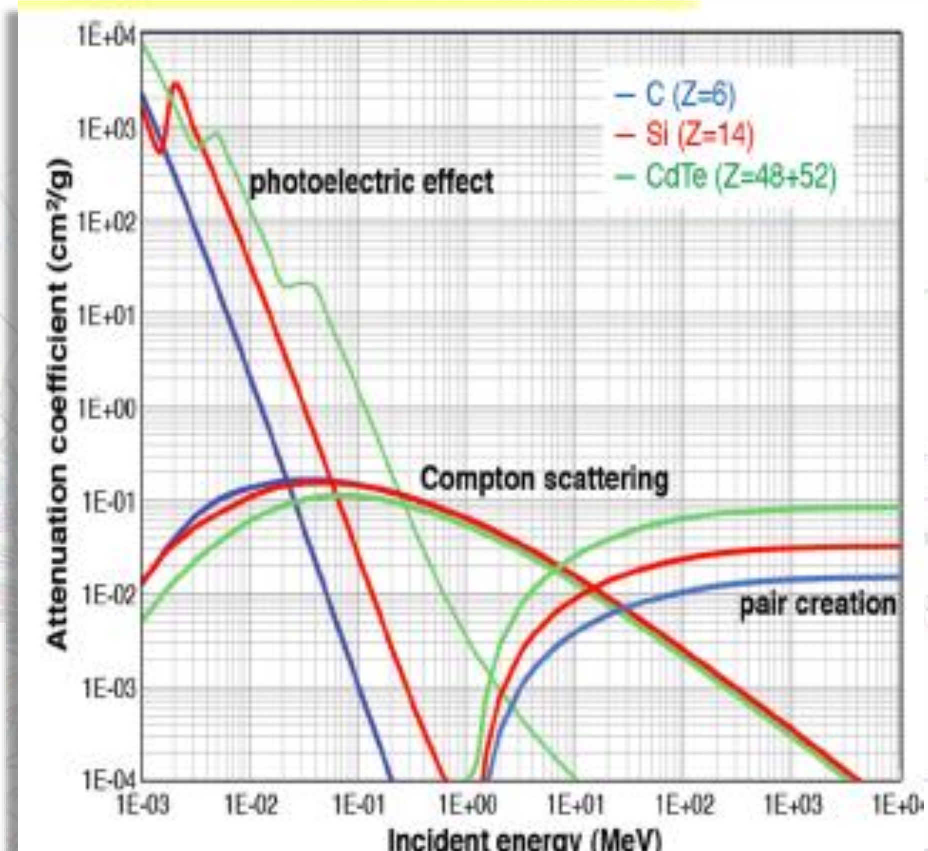
H → ZZ → 4e

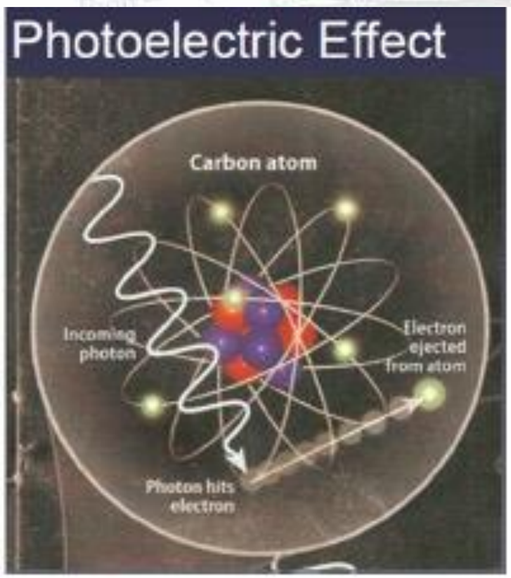

THE END
WB
A
WARNER BROS.—
FIRST NATIONAL PICTURE

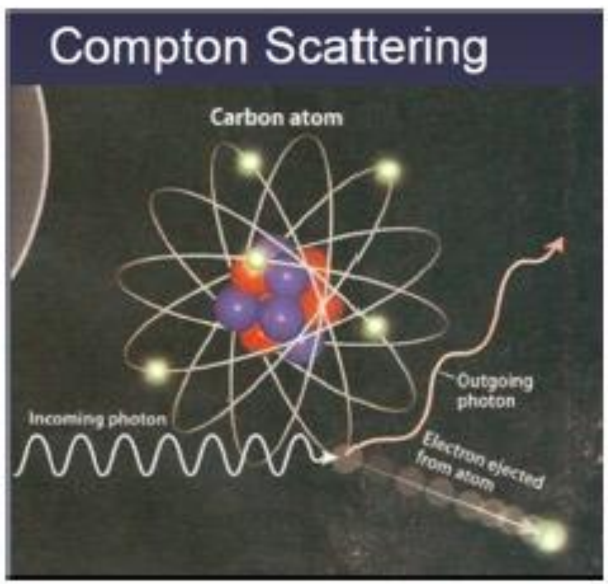
Additional slides for curious kids

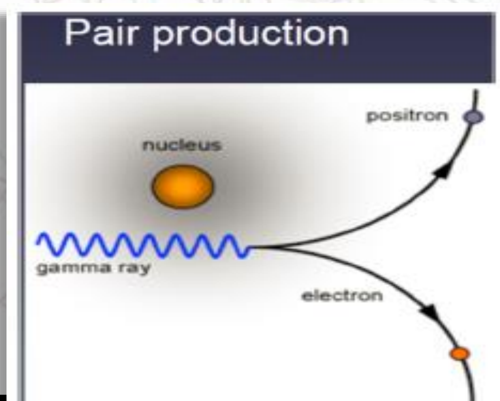
Interaction of photons with matter

- 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 (~ 1 MeV)
    - Compton scattering
  - High energies (> 10 MeV)
    - e+e- pair production in electric field of nucleus









Energy resolution of calorimeters (2)

Experiment	Detectors	Absorber material	e/h	Energie resolution (E in GeV)
UA1 C-Modul	Scintillator	Fe	≈ 1.4	80%/√E
ZEUS	Scintillator	Pb	≈ 1.0	34%/√E
WA78	Scintillator	U	0.8	52%/√E ⊕ 2.6%*
D0	liquid Ar	U	1.11	48%/√E ⊕ 5%*
H1	liquid Ar	Pb/Cu	≤ 1.025*	45%/√E ⊕ 1.6%
CMS	Scintillator	Brass (70% Cu / 30% Zn)	≠ 1	100%/√E ⊕ 5%
ATLAS (Barrel)	Scintillator	Fe	≠ 1	50%/√E ⊕ 3%**
ATLAS (Endcap)	liquid Ar	Brass	≠ 1	60%/√E ⊕ 3%**

* After software compensation
** Design values

Homogeneous calorimeters:

Experiment	Material	Energy resolution (E in GeV)
NA48	Liquid Kr	4.8%/√E ⊕ 0.22%
BELLE	CsI(Tl)	0.8%/√E ⊕ 1.3%
CMS	$PbWO_4$	2.7%/√E ⊕ 0.55%*

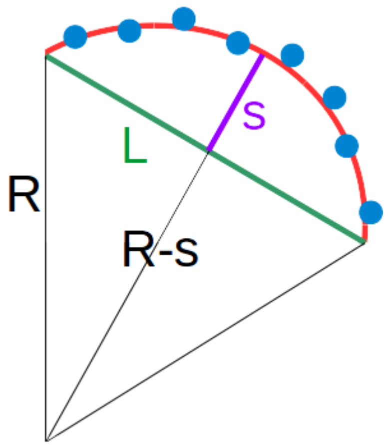
Sampling calorimeters:

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_4	8	Pb	3.2	16%/√E
ALEPH	Si	0.2	W	7.0	25%/√E
ATLAS	liquid Ar		Pb		10%/√E ⊕ 0.7%*
LHCb	Scintillator		Fe		10%/√E ⊕ 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 -> curvature R



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

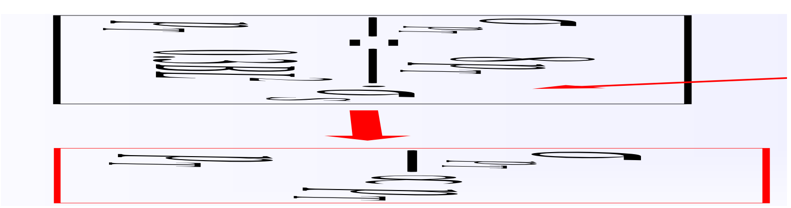
$$p = 0.3B \frac{L^2}{8s}$$

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

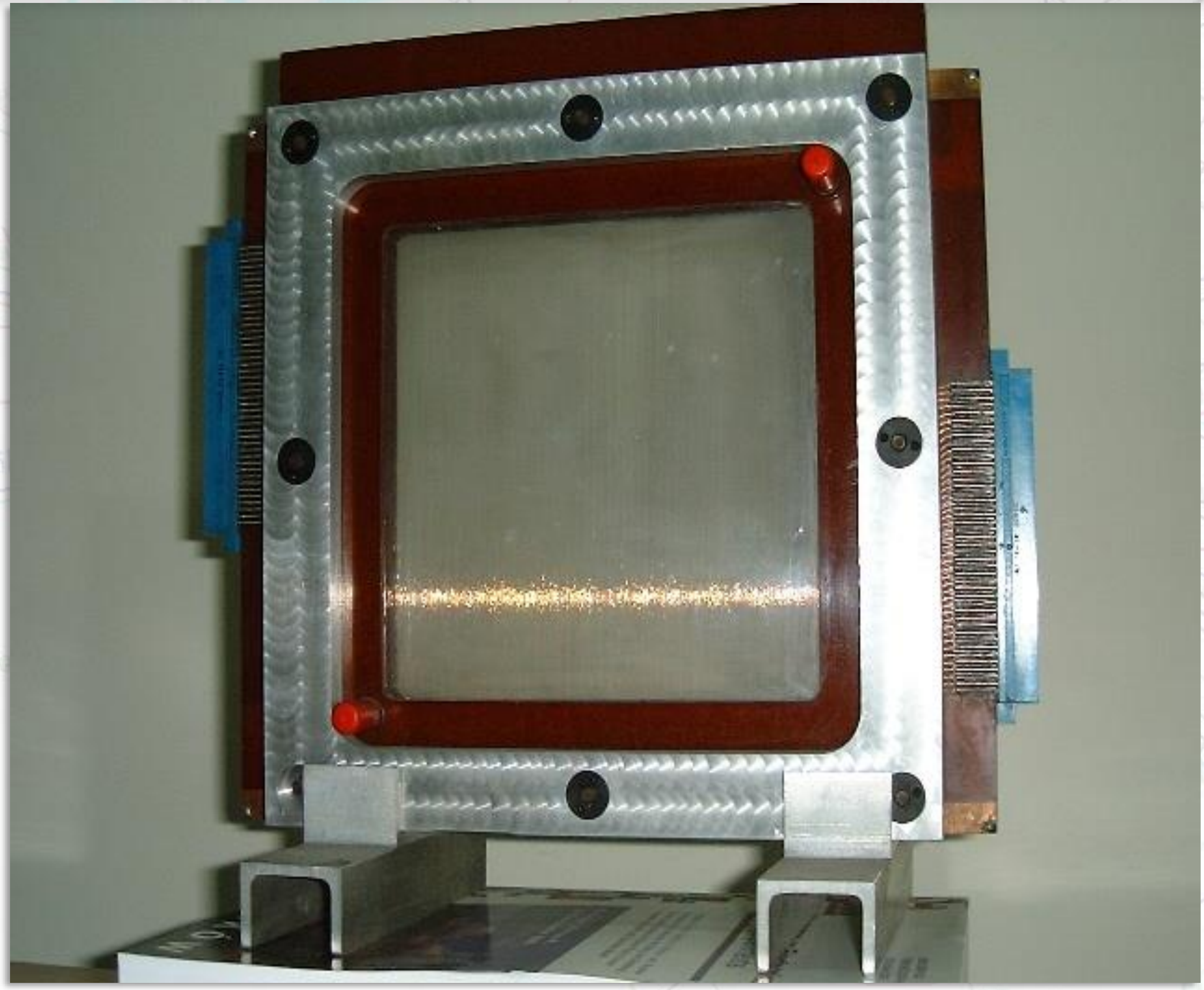
- High-p particles have high radius of curvature
  - Track almost straight
- Low-p particles have small radius curvature
  - Measure with high accuracy

Relative transverse momentum resolution

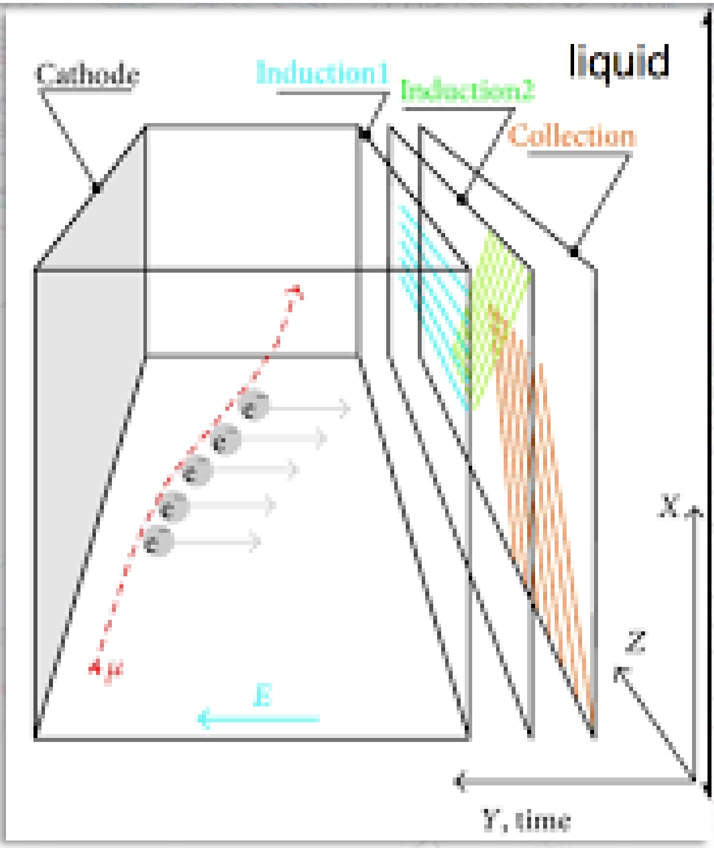
- degrades linearly with momentum
- improves linearly with B field
- improves quadratically with radial extension detector



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

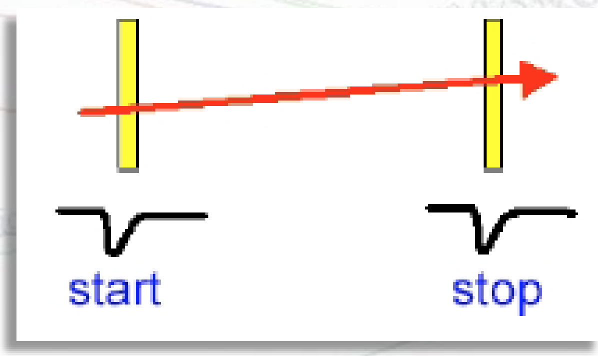


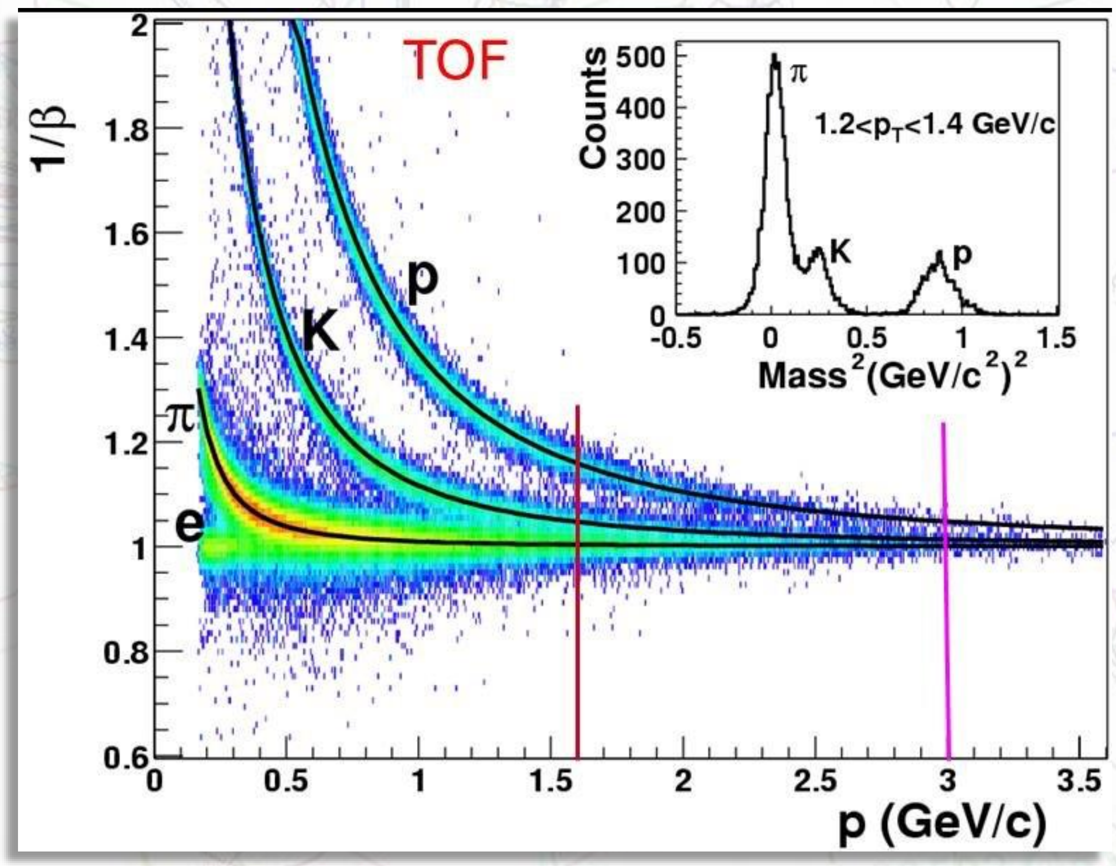
- Set of separated anode wire planes. Wires orientation varies from plane to plane.
- Together, these planes read out signals from the drift electrons.
- **Induction planes** set at lower potentials than the **collection plane**, allowing drift electrons to pass through them after inducing signals.



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



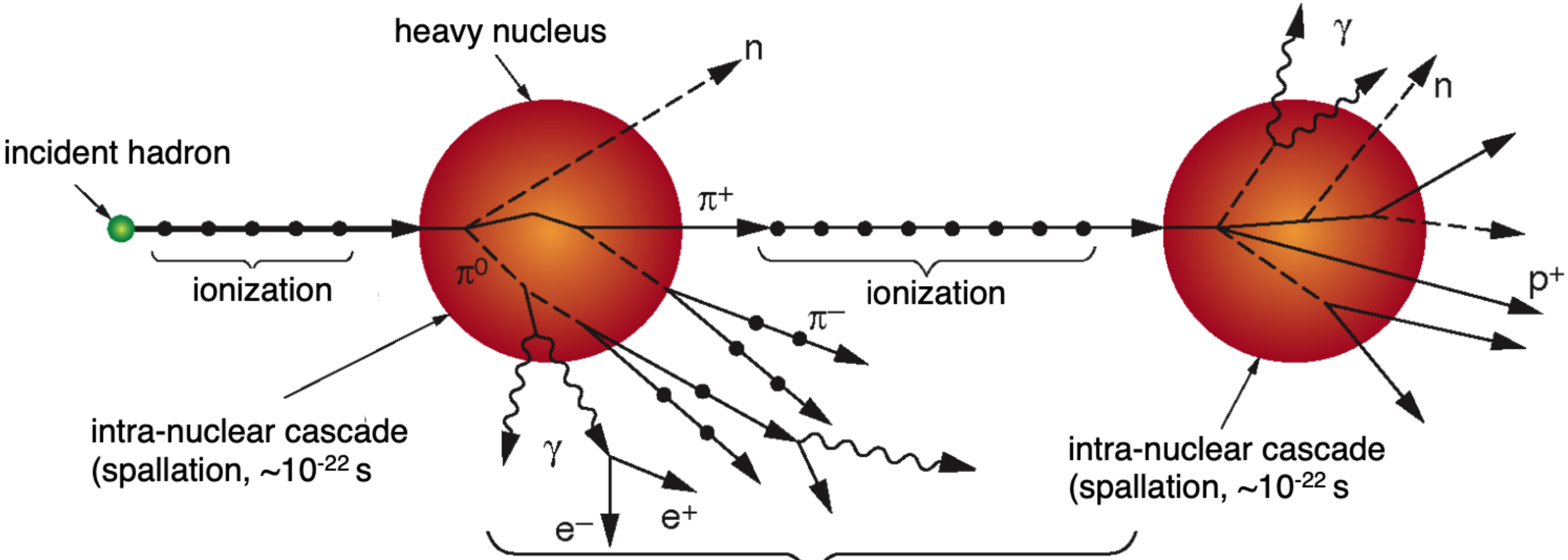


STAR-TOF

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.

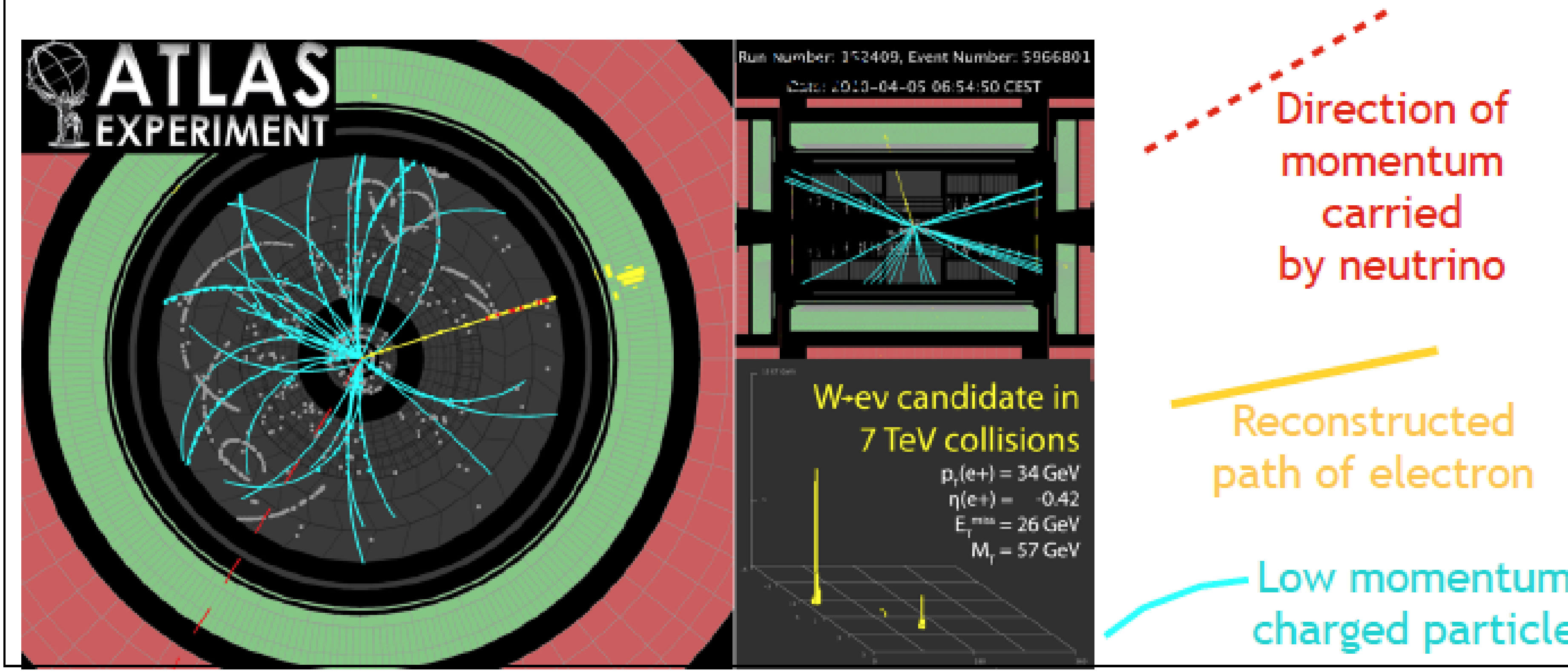


6.3.1 Hadronic Showers
Spallation

- ★ Spallation is the transformation of a nucleus caused by an incident, high energetic, hadronically interacting particle. During spallation a large number of elementary particles, α-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.

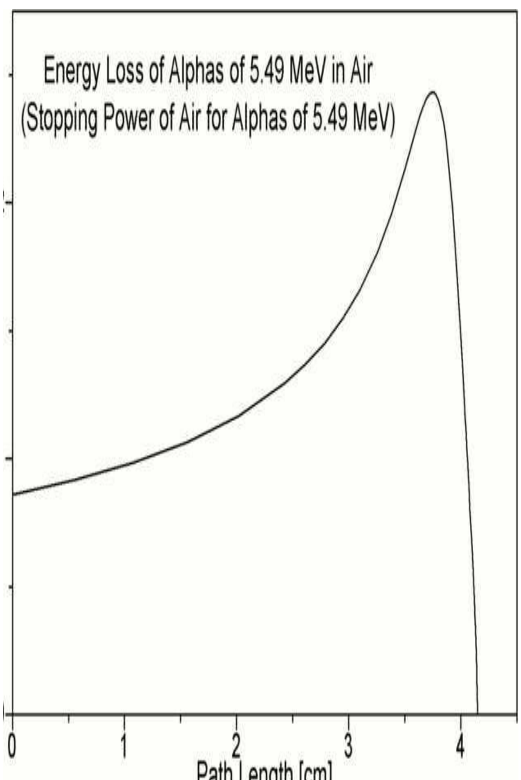


Jonizacja

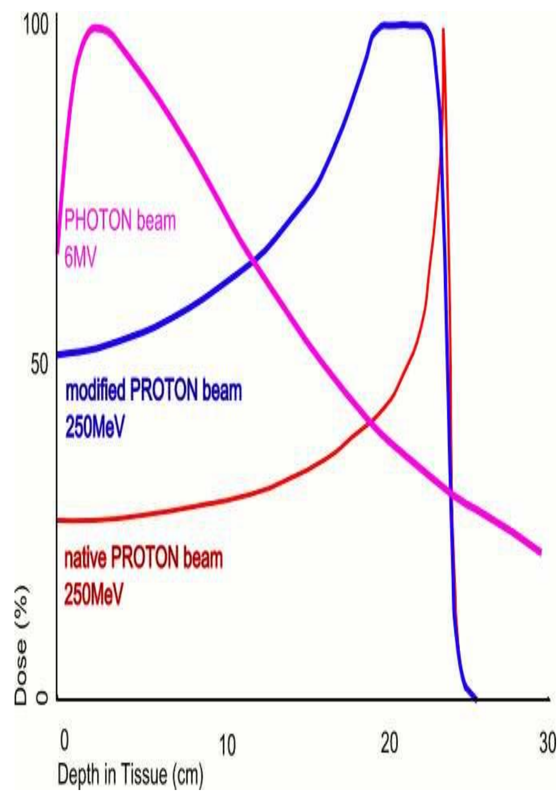
rzywa Bragga

ależność strat na jonizację od długości drogi w materiale:

ząstki α w powietrzu:



Protony i fotony w tkance:



dy cząstka znajdzie się poniżej minimum jonizacji, straty energii gwałtownie rosną

depozyt energii największy blisko miejsca zatrzymania cząstki (terapia hadronowa)

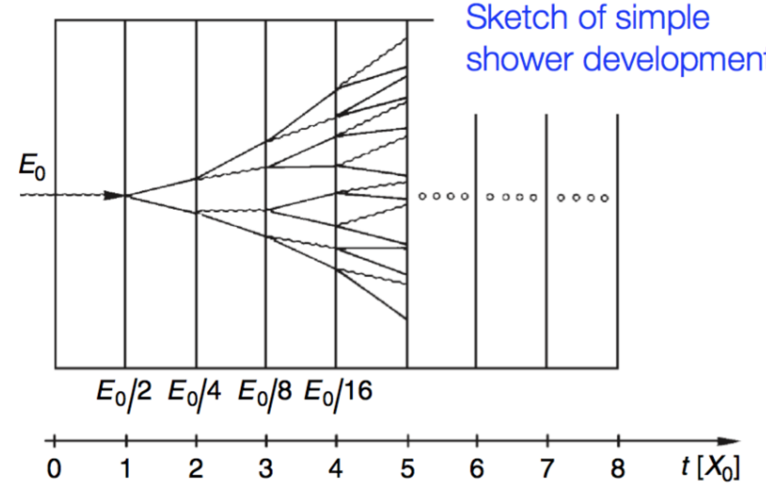
When a fast charged particle moves through matter, it ionizes atoms of the material and deposits a dose along its path. A peak occurs because the interaction cross section increases as the charged particle's energy decreases. Energy lost by charged particles is inversely proportional to the square of 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 μm	—	—
Komora pęcherzykowa	10-150 μm	1 μs	50 μs
Kom. strymerowa (→RPC)	300 μm	2 μs (<0.5ns)	100 μs
Komora proporcjonalna	50-300 μm	2 ns	200 ns
Scyntylator	—	100 ps	10 ns
Komora dryfowa	50-300 μm	2 ns	100 ns
Komora dryfowa LAr	~175-450 μm	~200 ns	~2 μs
Paski silikonowe	<25 μm	*ograniczone przez elektronikę*	

D. Kiełczewska, wykład 3

A simple shower model!



Sketch of simple shower development

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:

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

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

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:

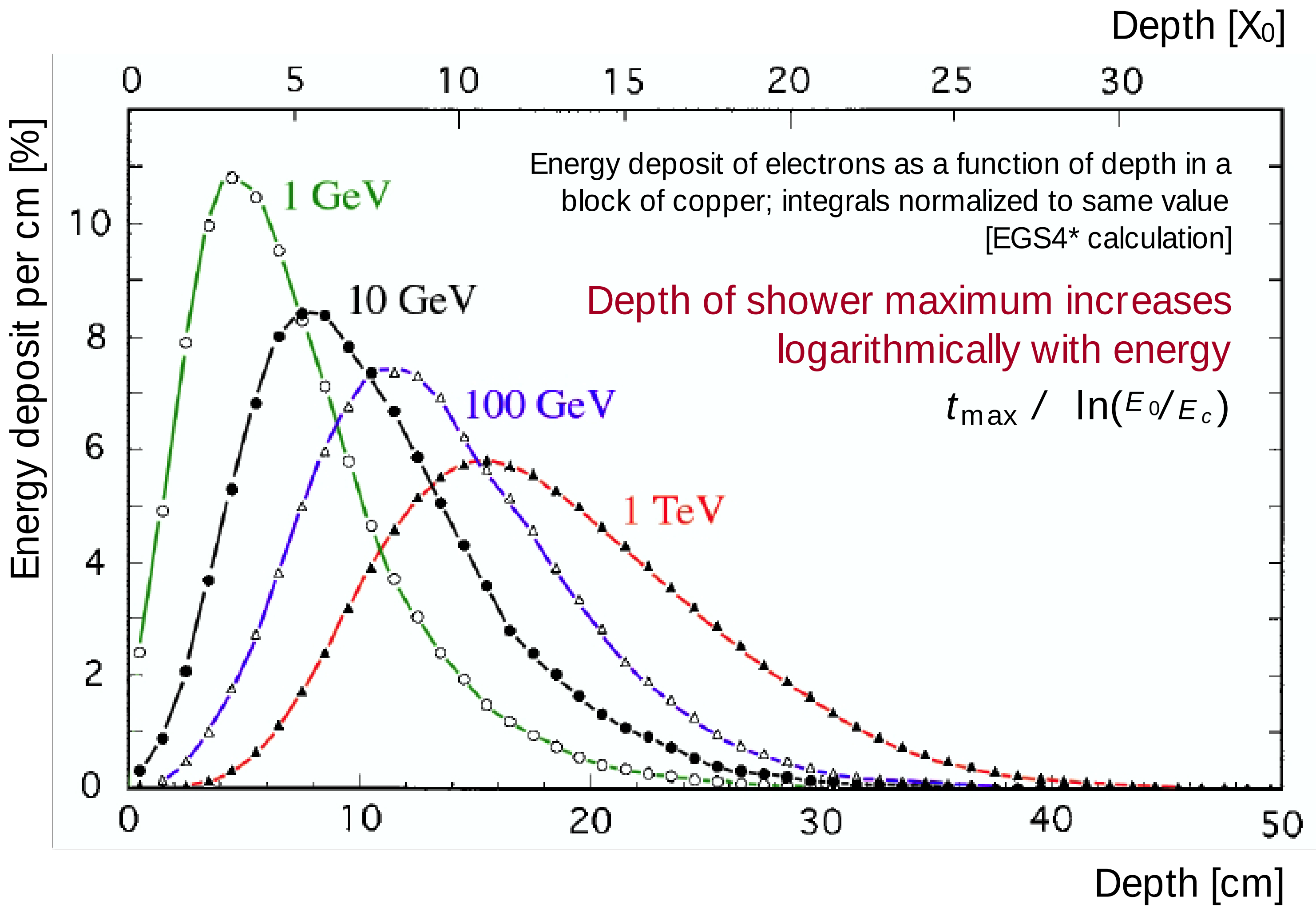
$$N(E_0, E_c) = N_{max} = 2^{t_{max}} = \frac{E_0}{E_c}$$

/ E_0

Shower maximum at:

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

EM shower longitudinal development!



*EGS = Electron Gamma Shower

Hadronic shower longitudinal development!

Longitudinal shower development:

Strong peak near λ_{int} ...
followed by exponential decrease ....

Shower depth:

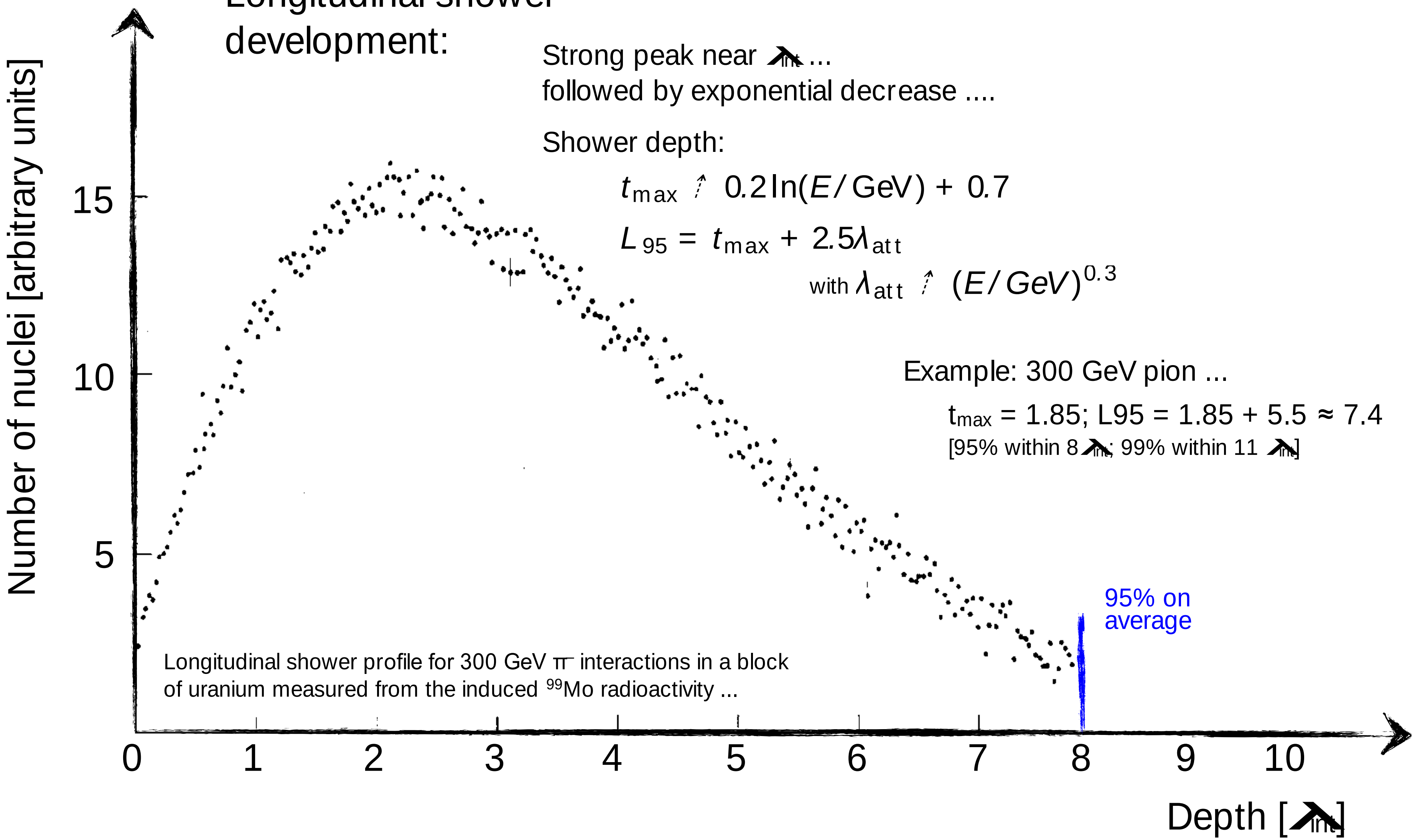
$$t_{max} \approx 0.2\ln(E/\mathrm{GeV}) + 0.7$$

$$L_{95} = t_{max} + 2.5\lambda_{att}$$

with $\lambda_{att} \approx (E/GeV)^{0.3}$

Example: 300 GeV pion ...

t_{max} = 1.85; L95 = 1.85 + 5.5 ≈ 7.4
[95% within 8 λ_{int}; 99% within 11 λ_{int}]



Kalorymetry

Kompensacja algorytmiczna

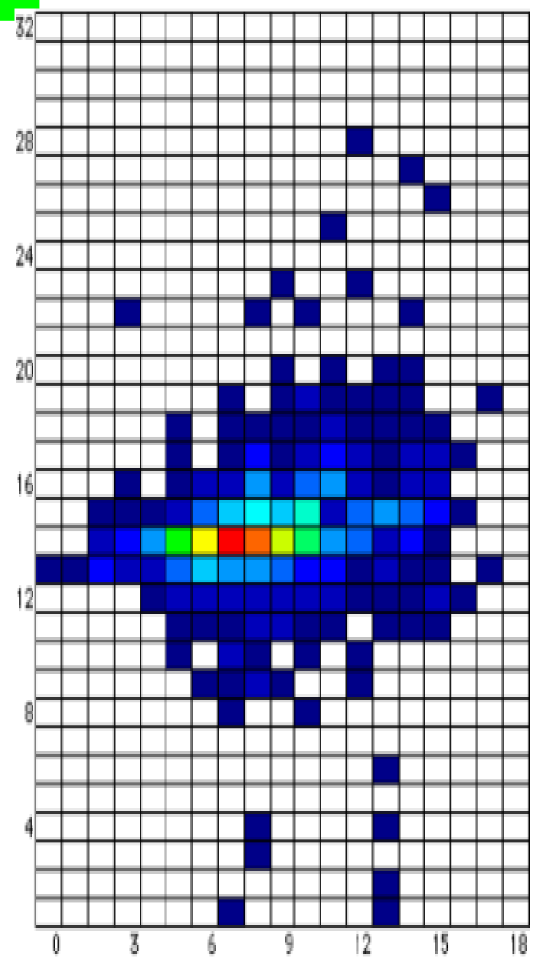
Jeśli nie dobierzemy odpowiednio materiałów absorbera i detektora odpowiedź kalorymetru na część elektromagnetyczną i hadronową kaskady będą różne.

Odpowiedź kalorymetru na pojedynczy hadron:

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

gdzie: f_{em} - ułamek energii w części EM,
η_{had} - tłumienie składowej hadronowej (~ 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}