Wstęp do fizyki cząstek elementarnych: część eksperymentalna

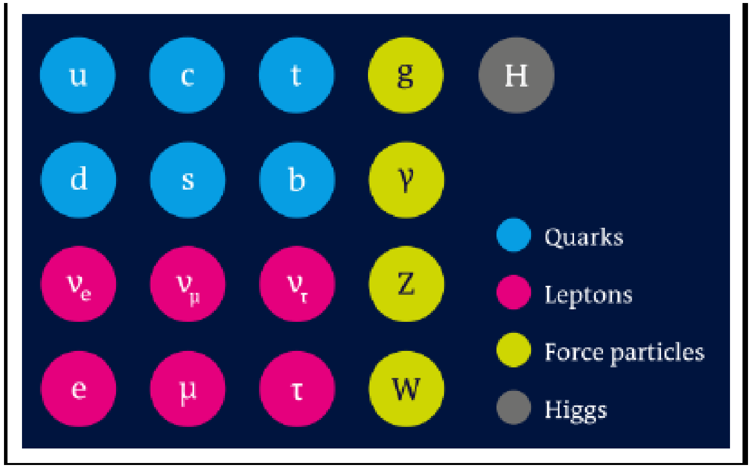
Detekcja i identyfikacja cząstek:

- ❑ Detektory śladów i pole magnetyczne
- ❑ System muonowy
- ❑ Kalorymetry

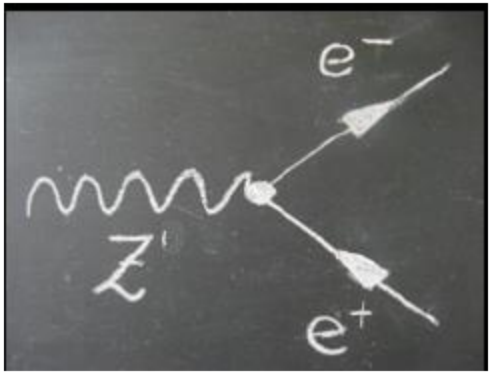
Prof. dr hab. Elżbieta Richter-Wąs

Which particles are detected?

1) **Charged leptons, photons and hadrons: e, μ,γ,π,K,p,n…** (maybe new long-lived particles, i.e. particles which enter detector)
2) B (and D) mesons and τ leptons have cτ ~ 0.09 ..0. x 10^{-3}m large enough for additional vertex reconstruction
3) Neutrinos (maybe also new particles) are reconstructed as mising transverse momentum
4) All other particles which decay or hadronise in primary vertex (top quark decays before hadronises)

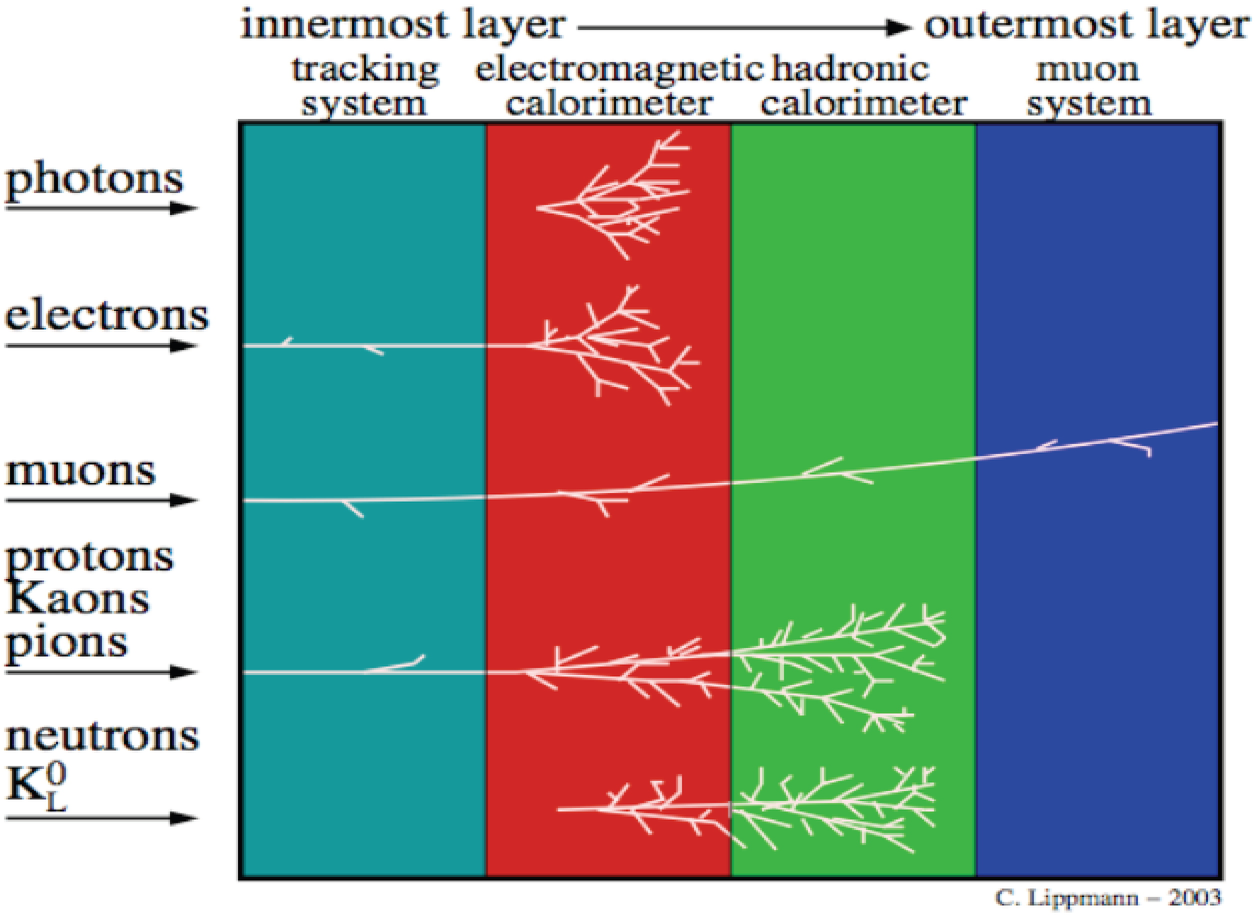


Only e, μ, γ of the fundamental Standard Model Particles are directly detected



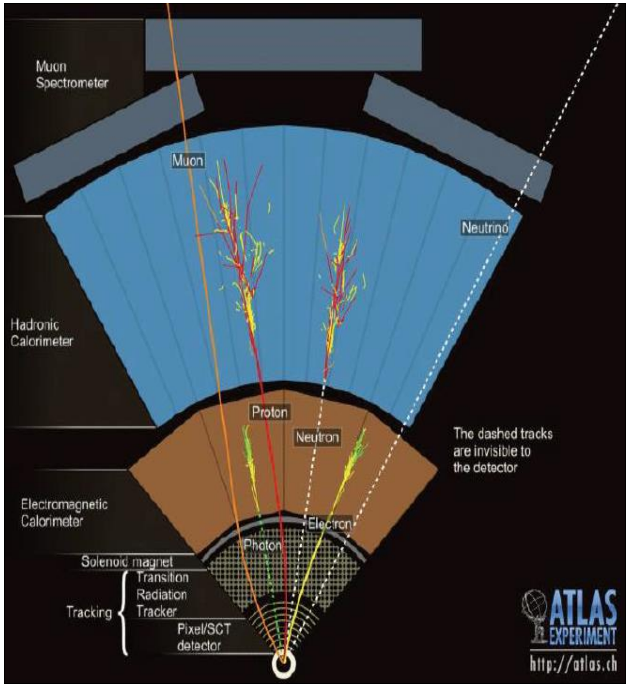
Heavy particles W, Z decay immediatelly

Sketch of particles interaction with detector



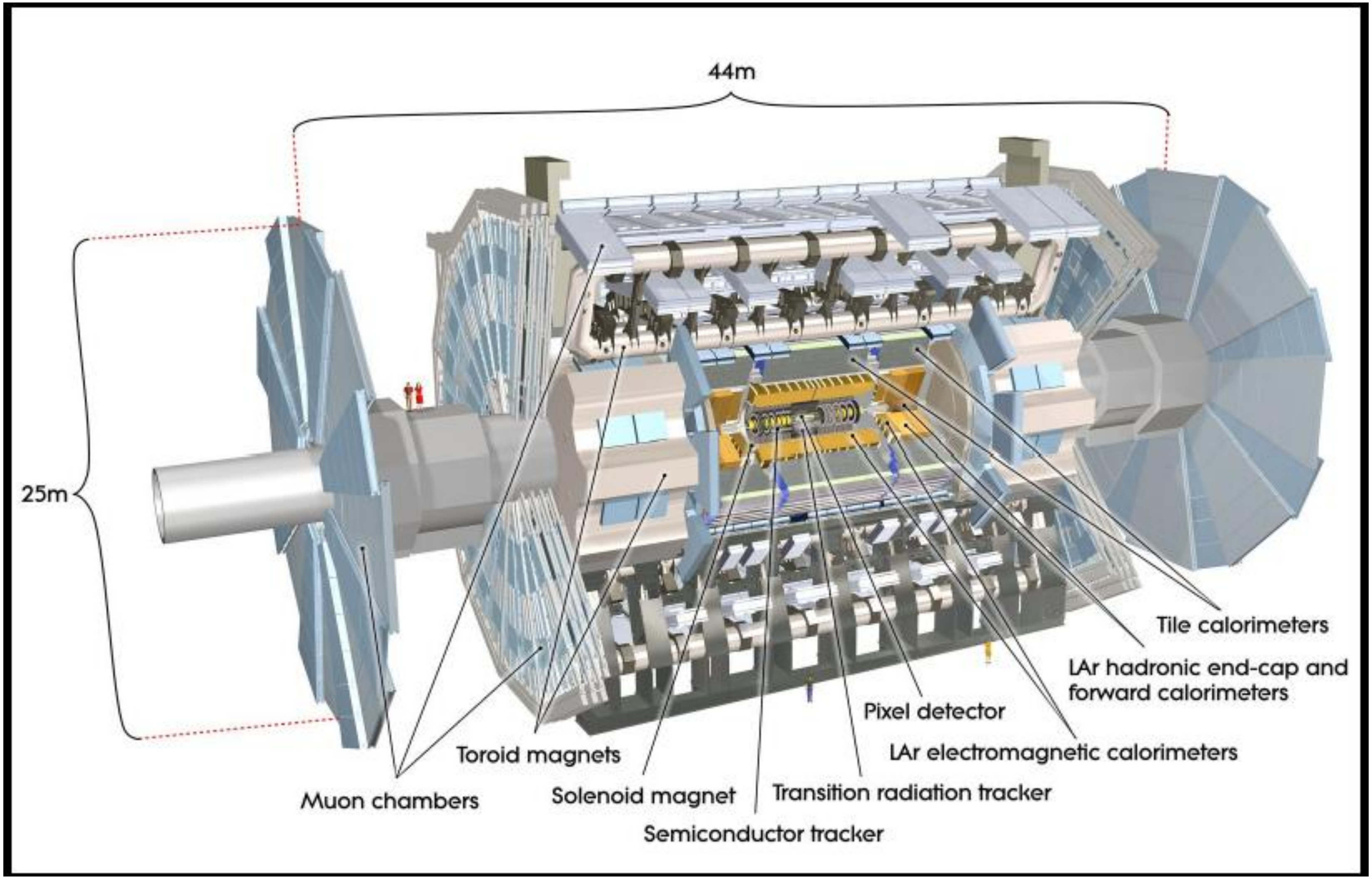
The observables?

1) Photon makes photo-efect, Compton scattering and **pair production**. It has no track but an **electromagnetic cascade** in the calorimeter.
2) Charged particles makes scattering, **ionisation**, excitation and bremsstrahlung, transition and cherenkov radiation. They produce **tracks**.
3) Electrons make **electromagnetic cascades** (clusters) in the calorimeter
4) Hadrons also interact strongly via inelastic interactions, e.g. neutron capture, induced fission, etc. They make **hadronic cascades** (clusters) int he hadronic calorimeter.
5) Only weakly interacting particles (neutrinos) are reconstructed as **missing transverse momentum** („missing energy”).



The ATLAS example

Typical 4π cylindrical onion structure



Reconstructed properties

From the hits, tracks, clusters, missing transverse momentum and vertices we reconstruct the particles properties:

1) Momentum from curved tracks
2) Charge from track curvature
3) Energy from full absorption in calorimeters and curved tracks
4) Spin from angular distributions
5) Mass from invariant mass from decay products
6) Lifetime from time of flight measurement
7) Identity from dE/dx, lifetime or special behaviour (like transition ratiation)

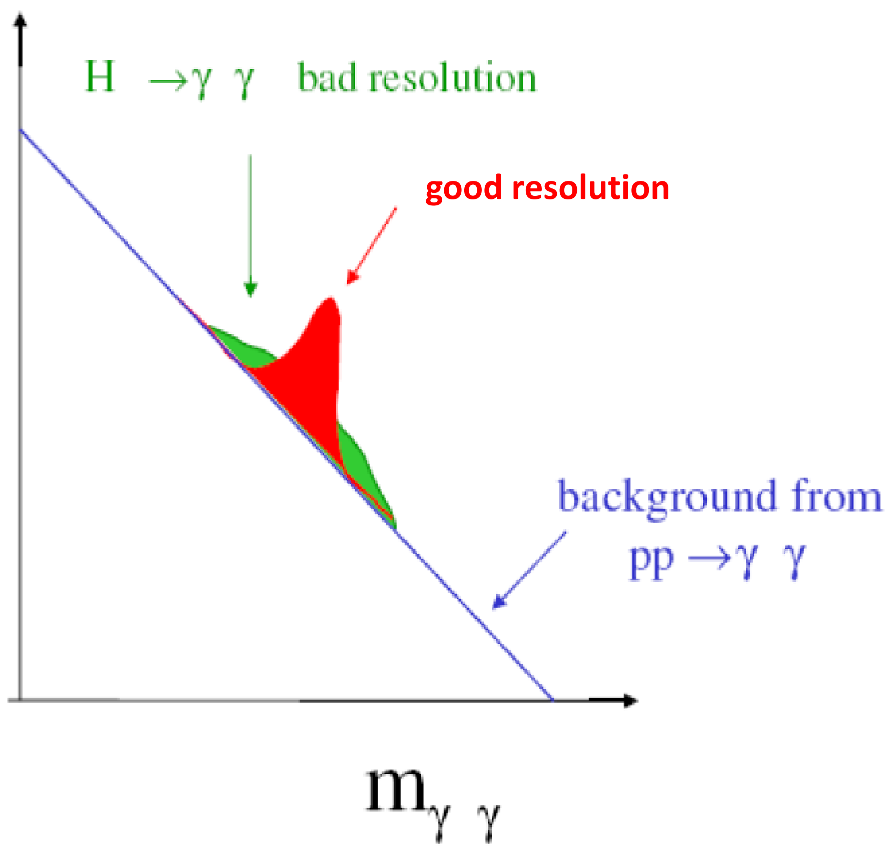
Detector design constraints (I)

- **Constraints from physics:**
  1) High detection efficiency demands minimal cracks and holes, high coverage
  2) High resolution demands little material like support structures, cables, cooling pipes, electronics etc. (avoid multiple scattering)
  3) Irradiation hard active materials to avoid degradation and changes during operation
  4) Low noise
  5) Easy maintenance (materials get radioactive)
  6) …

Example for resolution requirement

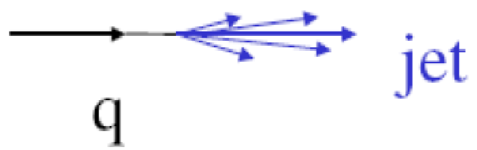
Excellent energy resolution of EM calorimeters for e/γ and of the tracking devices for μ in order to extract a signal over the backgrounds.

Example : $H \to \gamma\gamma$



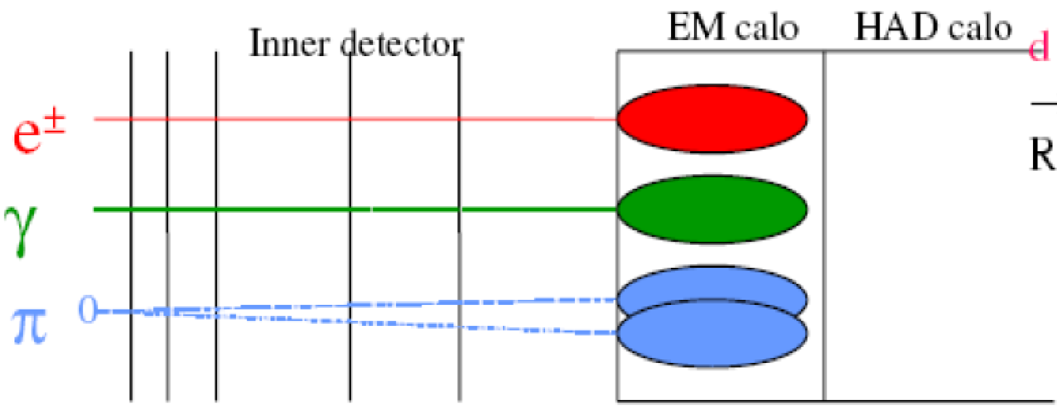
Example for particle ID requirement

Excellent particle identification capability e.g. e/jet , γ /jet separation



number and p_T of hadron in a jet have large fluctuations

in some cases: one high-p_T π^0; all other particles too soft to be detected



$d(\gamma\gamma) < 10$ mm in calorimeter

→QCD jets can mimic photons.

Rare cases, however:

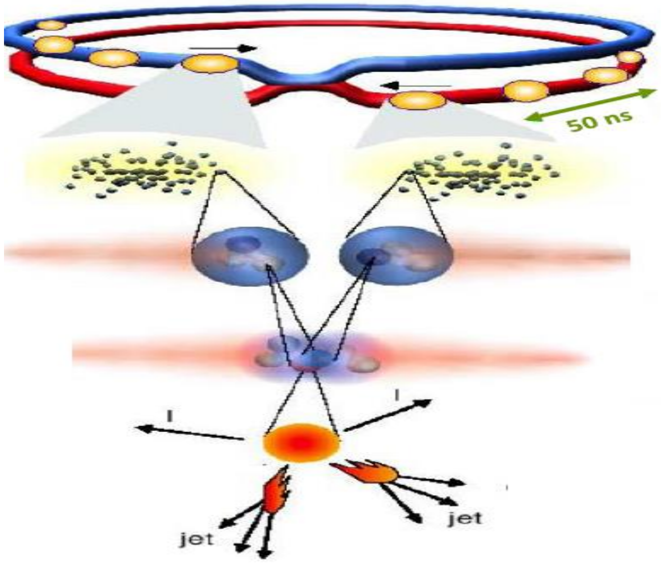
$$\frac{\sigma_{jj}}{\sigma(H \to \gamma\gamma)} \sim 10^8$$

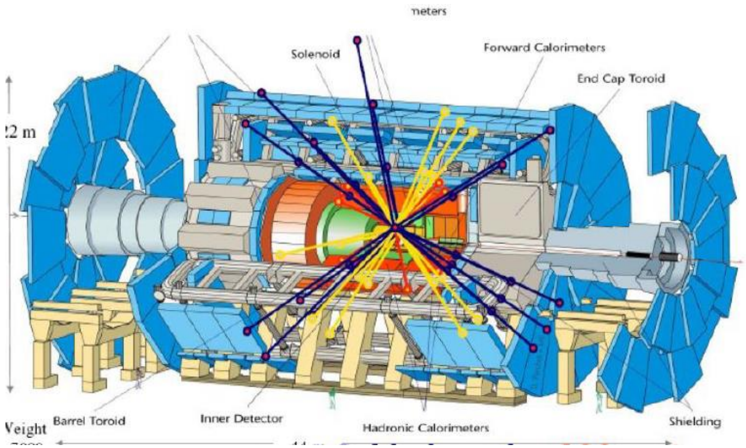
$m_{\gamma\gamma} \sim 100$ GeV

need detector (calorimeter) with fine granularity to separate overlapping photons from single photons

Detector design constraints (II)

- **Enviromental contraints, i.e. from LHC design parameters:**
  1) Collision events every ~ 25ns
  2) Muons from previous event still in detector when current enters tracker
  3) High occupancy in the inner detector
  4) Pile up (more proton proton collisions in each bunch crosing)
  5) High irradiation
  6) …



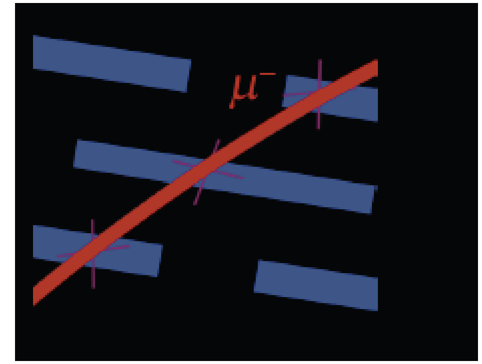


Magnet system

- Use Lorentz force to curve tracks

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

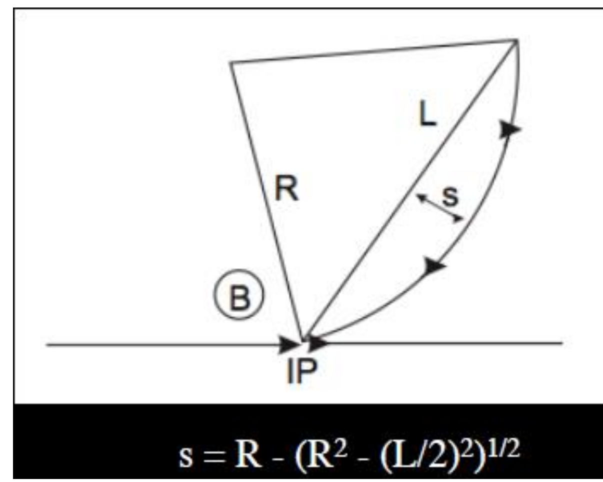
Electric force   Magnetic force



- Max E is about 50MV/m in high vacum, just B field used (5T gives ~10^3 stronger force)
- Curvature or radius: q v B = m v^2/T => p = q B R
- At least three hits needed to reconstruct a unique R of a track
- Remember solenoid resolution:

  $(\Delta p_T/p_T)_{solenoid} \sim (\Delta s/L^2 B) p_T$

(in GeV with s in μm, L in cm and B in T. Large B is good against high occupancy.



s = sagitta

Charged particle in magnetic field

Lorentz force:

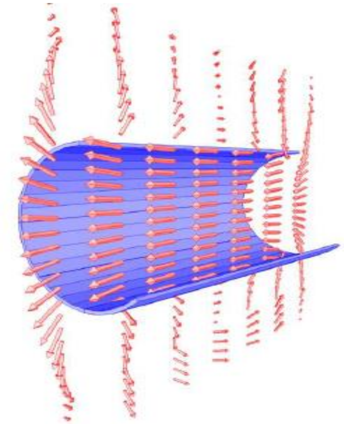
$$\vec{F} = q\vec{v} \times \vec{B}$$

↓

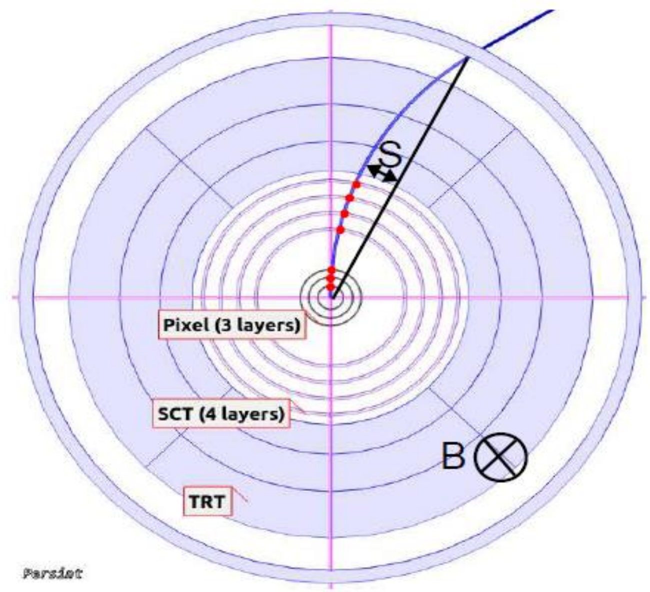
$$P \sim 0.3 \cdot R \cdot B \qquad R \rightarrow \frac{1}{S}$$

P: momentum (GeV)
R: curvature (m)
B: Magnetic field (Tesla)

Charged track => signal in detectors
=> reconstruction program
=> Sagitta (=1/R) determination



Solenoid (ATLAS Inner Tracker)



Charged particle in magnetic field

Lorentz force:

$$\vec{F} = q\vec{v} \times \vec{B}$$

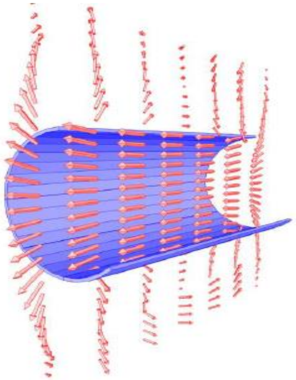
$$\downarrow$$

$$P \sim 0.3 \cdot R \cdot B \qquad R \rightarrow \frac{1}{S}$$

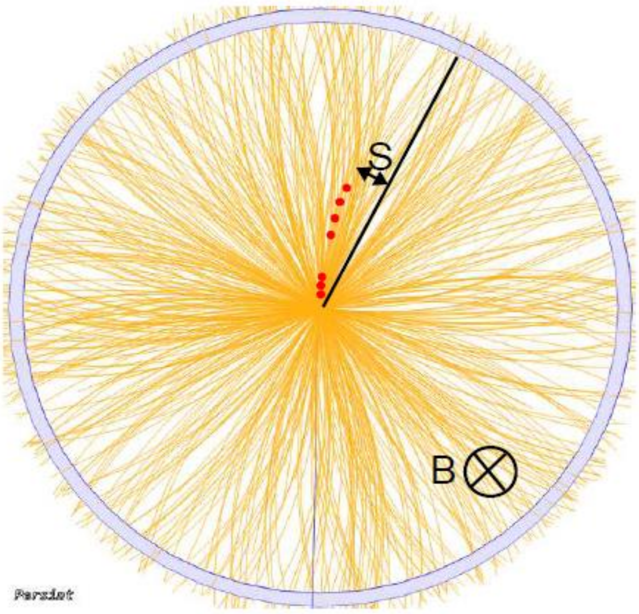
P: momentum (GeV)
R: curvature (m)
B: Magnetic field (Tesla)

Charged track => signal in detectors
=> reconstruction program
=> Sagitta (=1/R) determination

Reconstruction can be complicated



Solenoid (ATLAS Inner Tracker)



Frequent magnet designs

Solenoid (A)

Deployed in ATLAS and CMS

$(dp/p)_{solenoid} \sim p \cos theta / BR^2$

$cost \sim LR^2B^2$

Toroid (B)

Deployed in ATLAS

$(dp/p)_{toroid} \sim p \cos theta / B_{in}R_{in} \ln(R_{out}/R_{in})$

Dipole (C)

Used in fixed target / forward experiments.

Deployed in ALICE and LHCb.

$(dp/p)_{dipole} \sim p / BL$

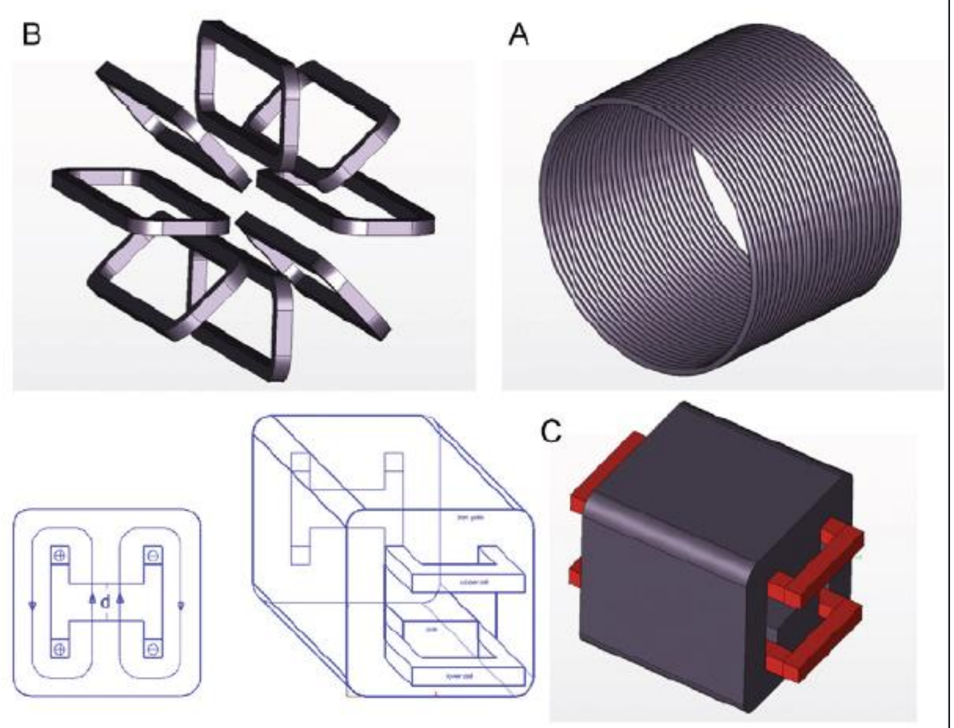
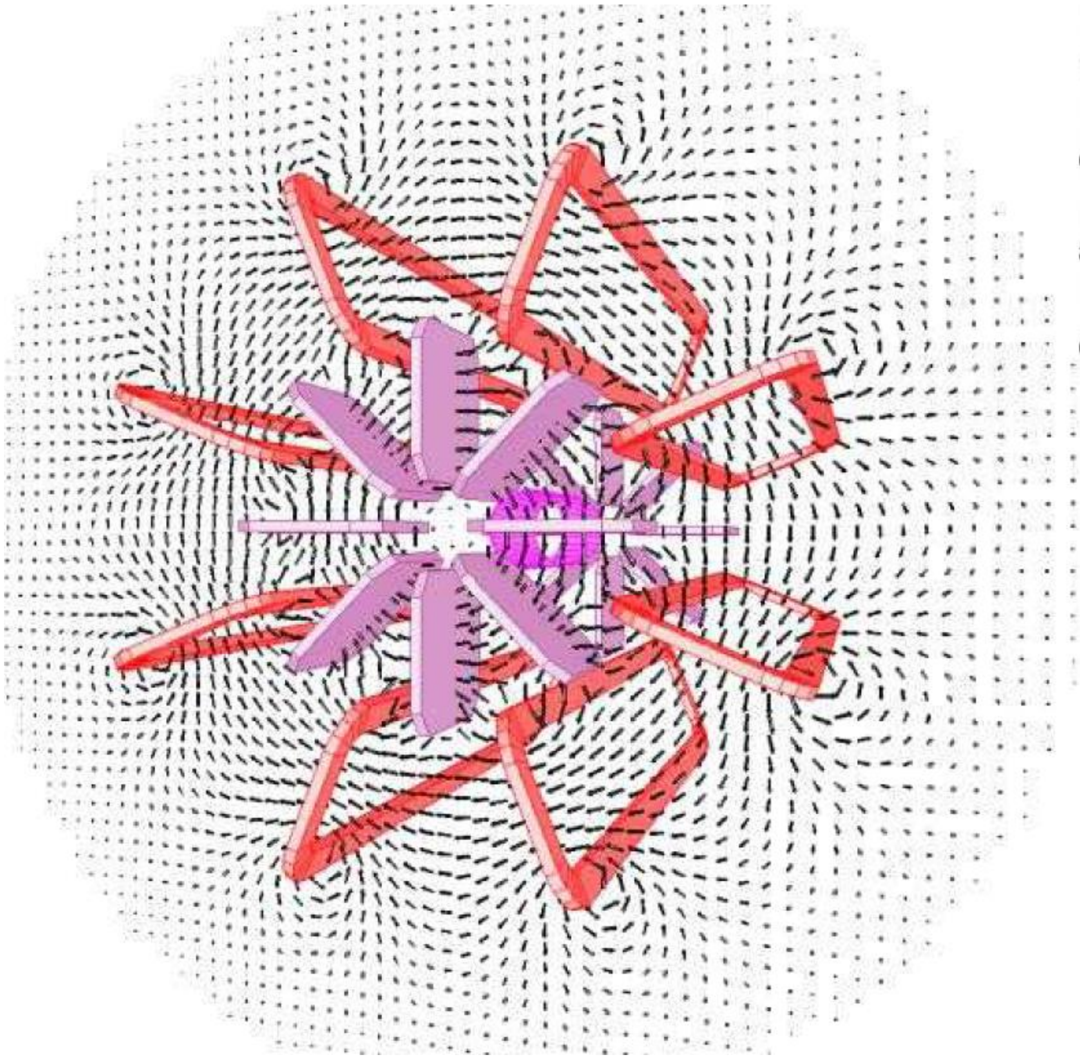
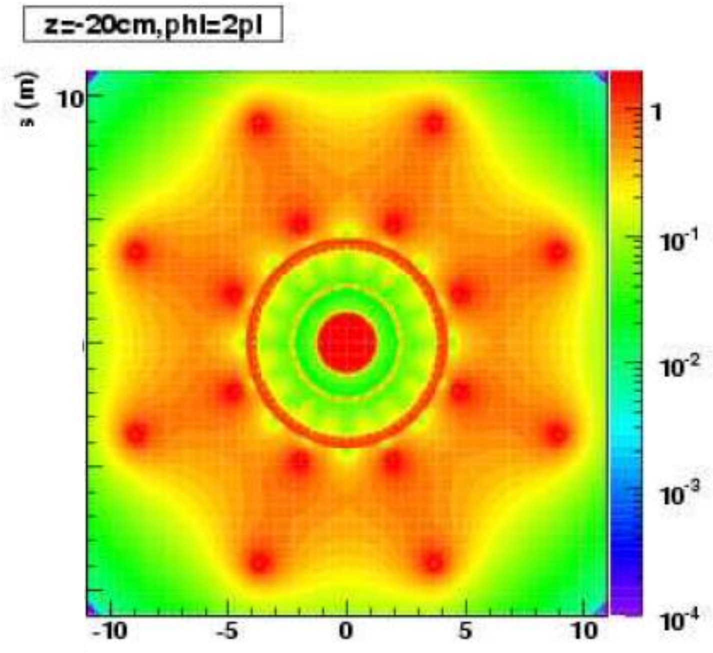


Fig. 1. Solenoid coil (A), toroid coil (B) and dipole coil (C).

Charged particle in magnetic field

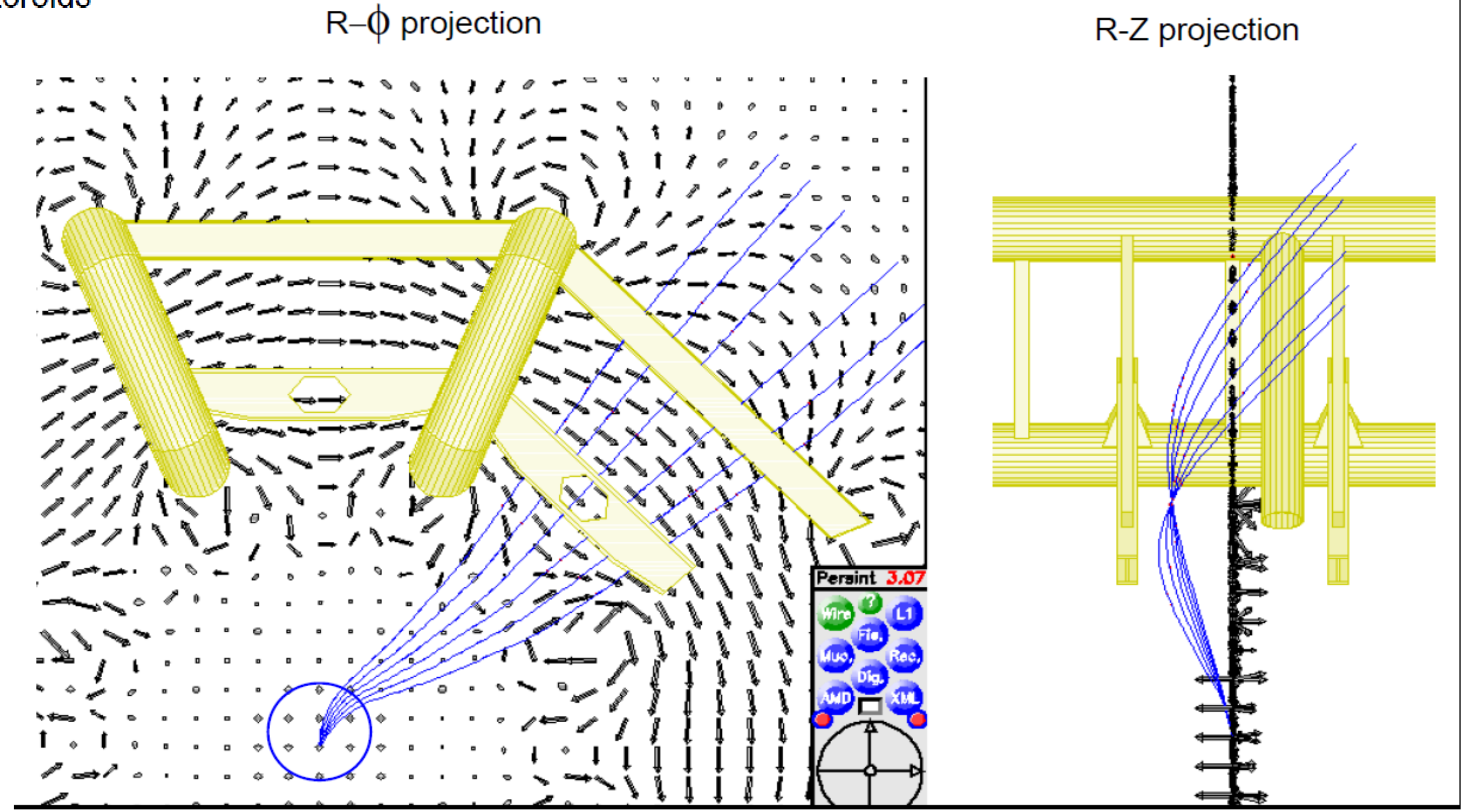




ATLAS magnetic field
1 solenoid
3 toroids

Charged particle in magnetic field

ATLAS magnetic field
1 solenoid
3 toroids



Size and field examples

ATLAS barrel toroid

20.5 kA, 3.9 T

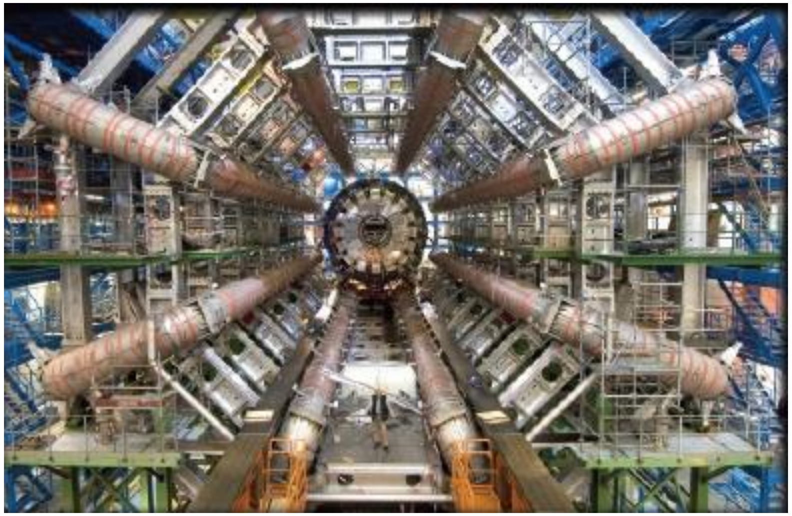


Table 1
Main parameters of some HEP detector magnets (solenoids).

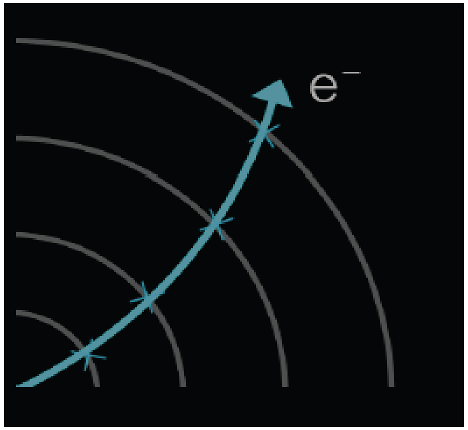
	CDF	CLEO-II	ALEPH	ZEUS	H1	KLOE	BaBar	Atlas	CMS
B (T)	1.5	1.5	1.5	1.8	1.2	0.6	1.5	2.0	4.0
R (m)	1.5	1.55	2.7	1.5	2.8	2.6	1.5	1.25	3.0
L (m)	4.8	3.5	6.3	2.45	5.2	3.9	3.5	3.66	12.5

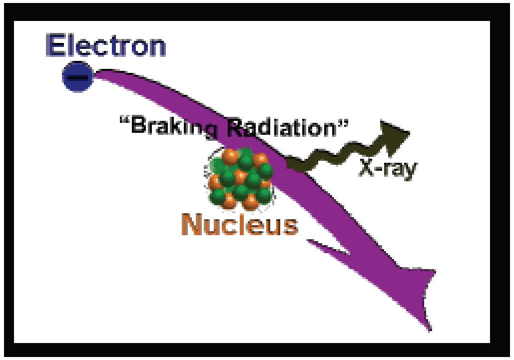
The magnet layout is a major constraint for the rest of the detector!
See A. Gadi, A magnet system for HEP experiments, NIMA 666 (2012) 10-24

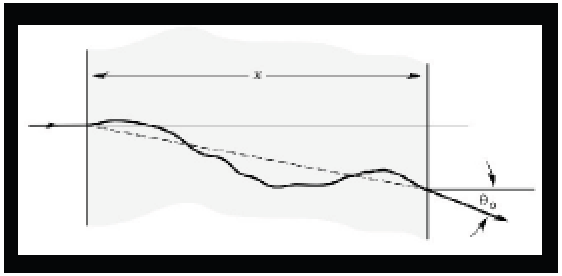
Tracking principles

- Exploit physical processes of moving charged particles in the magnetic field:

1) **Ionisation** (Bethe-Boch) is the main detection process for heavy particles ($m > m_e$)
   - ➢ Collect the charges with an electric field => hits
   - ➢ Reconstruct hits to tracks in B field => **p_T, vertices, isolation**
2) Bremsstrahlung is the main process for e^{+-} above some 100 MeV
3) Multiple scattering (unwanted, degrades the resolution)
4) Irradiation damage (unwanted, degrades efficiency)







Bethe-Bloch formula

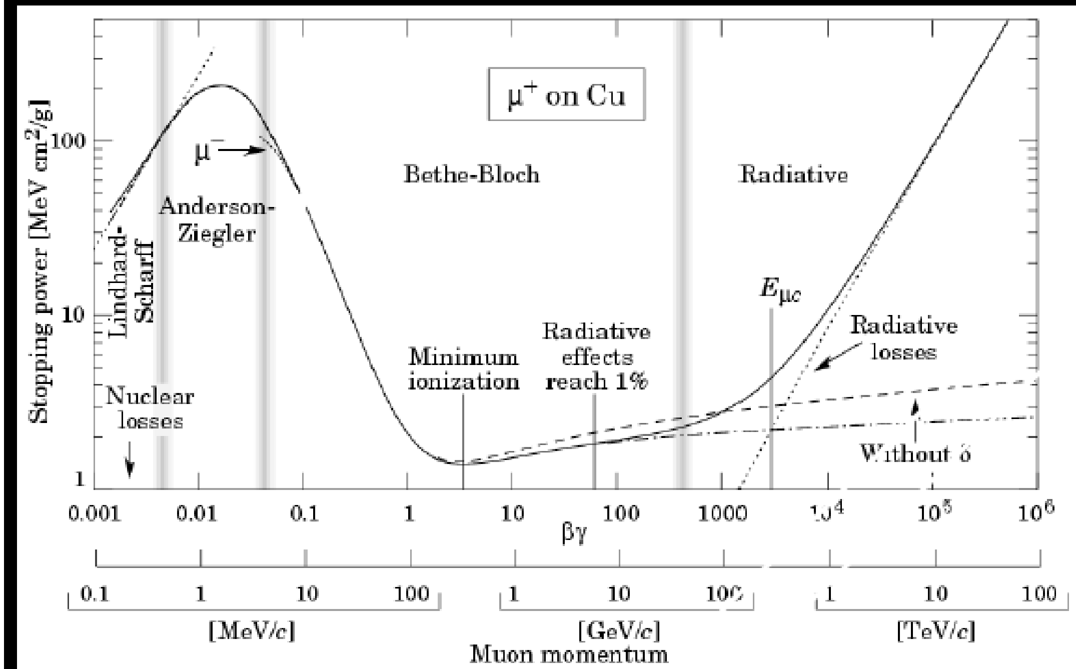
Describes stopping power of heavy charged (heavier than electron) particle in matter [MeV g^{-1} cm^2]

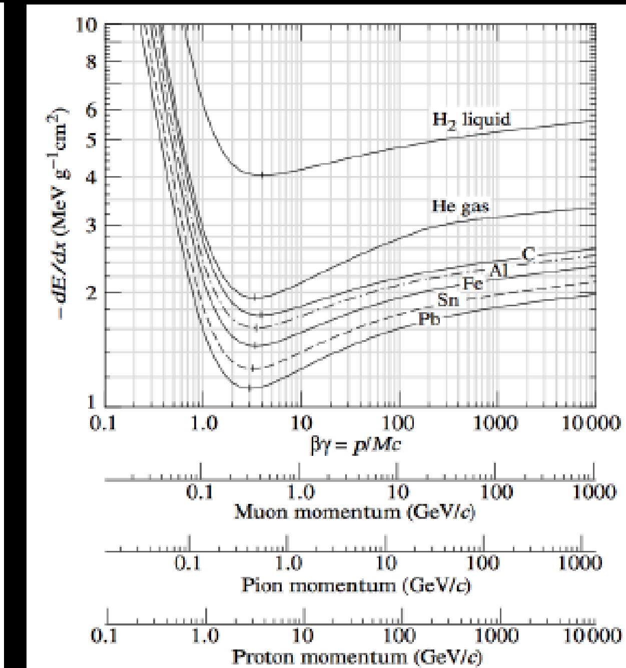
$\beta = v/c, \gamma = (1-\beta^2)^{1/2}$

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2}\right) - \beta^2 - \frac{\delta(\gamma)}{2}\right]$$

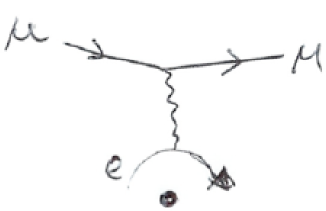
- The energy loss depends only on **charge z** and **velocity β** of the particle
- **Rest is material dependent**: I = mean ionisation/excitation energy [MeV], δ density effect correction, T_{max} is maximum energy transfer in one collision.

Muon energy loss

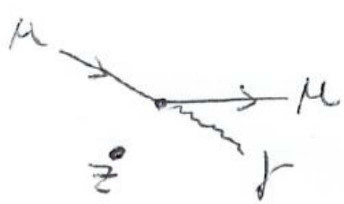




Ionization



Bremsstrahlung



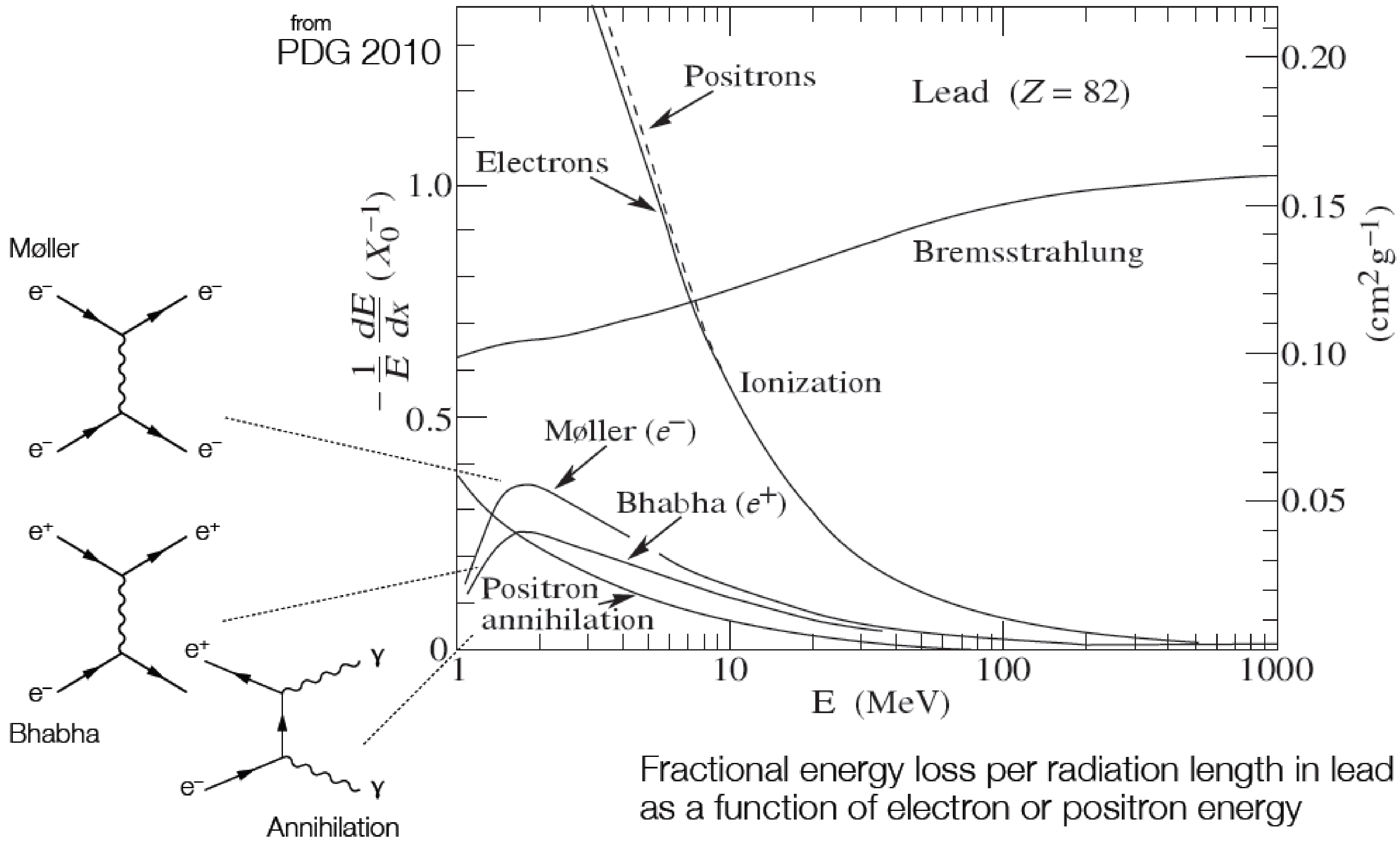
At low β : dE/dx ~ 1/β²

Minimum at βγ ~ 3..4 (minimal ionasing particle)

At high β : dE/dx slowly increasing due to relativistic enhancement of transversal E field.

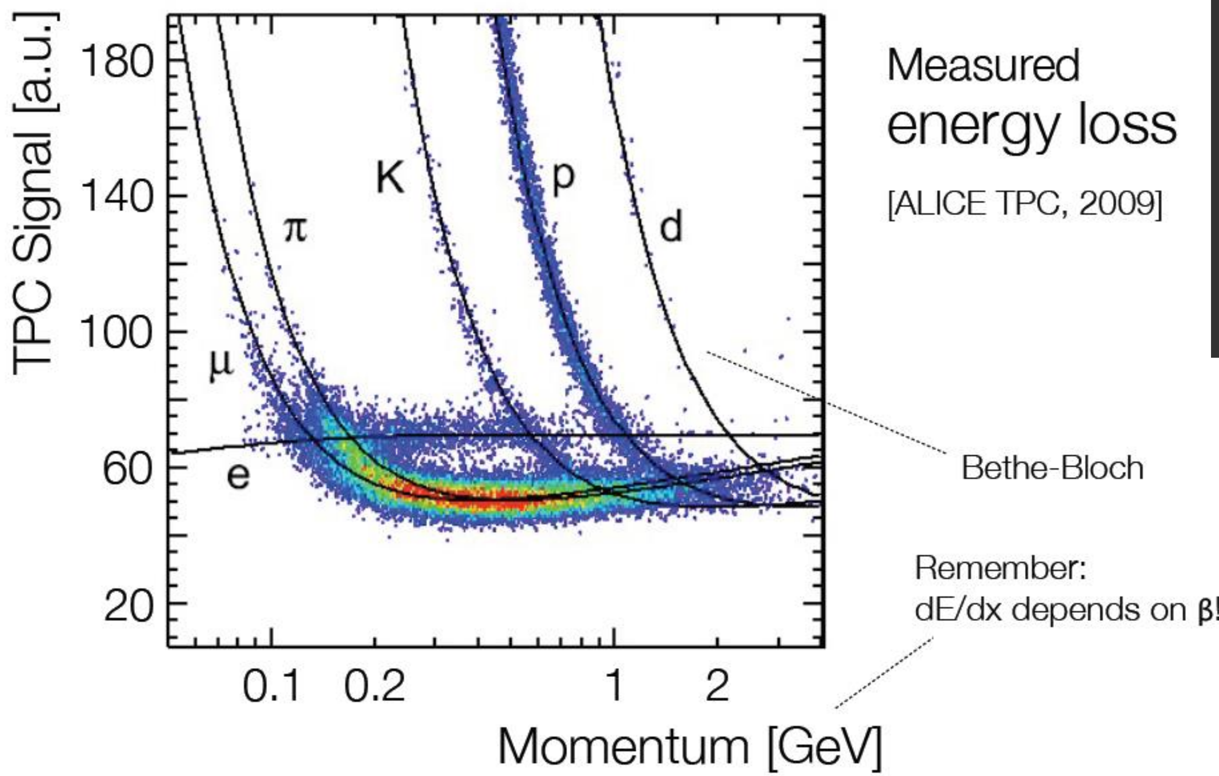
At very high β: saturation due to shielding/polarisation

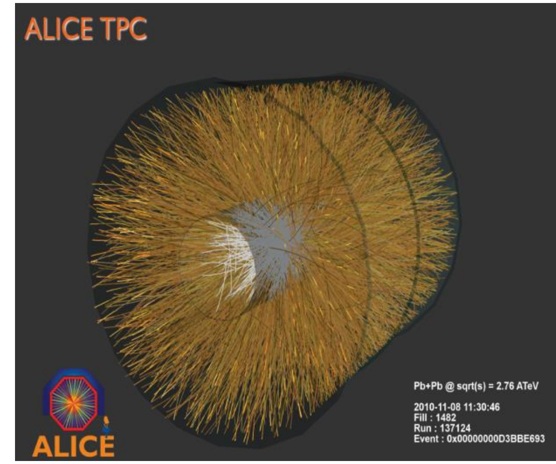
Total energy loss of electrons



Fractional energy loss per radiation length in lead as a function of electron or positron energy

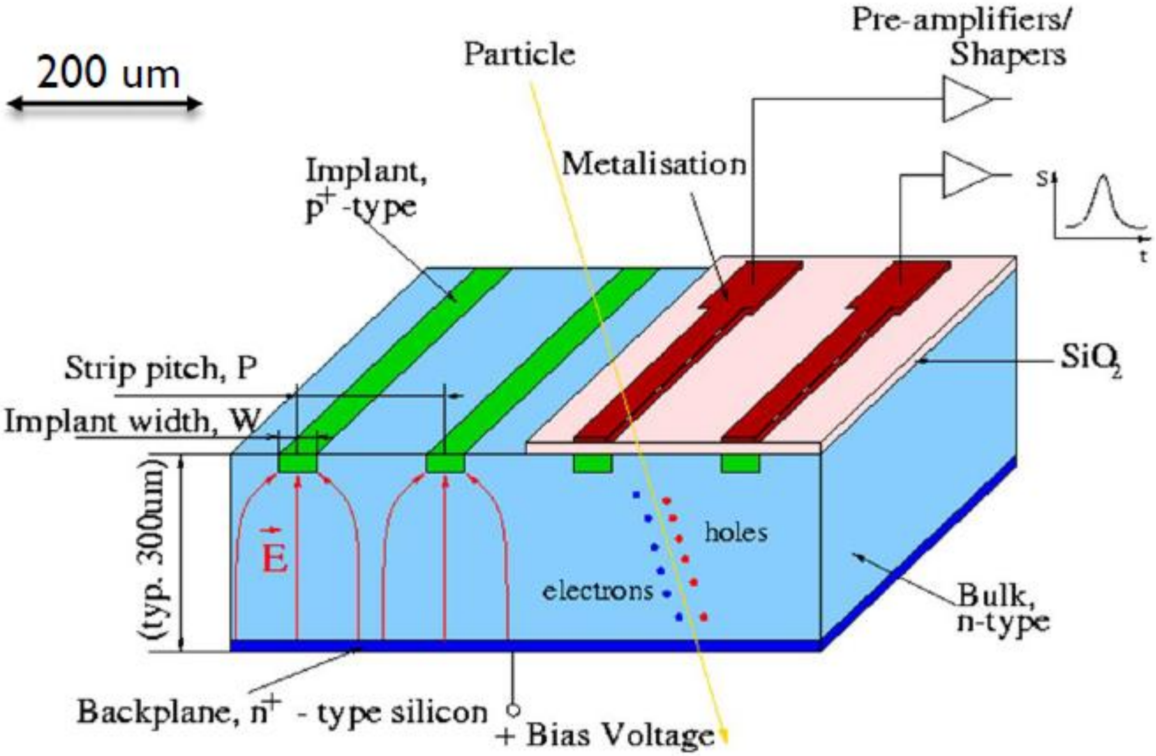
Identifying particles by dE/dx

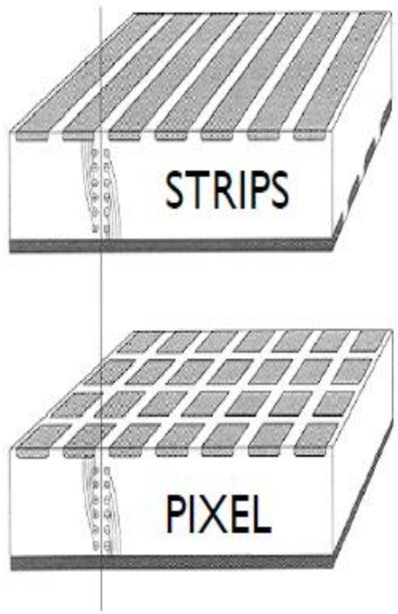




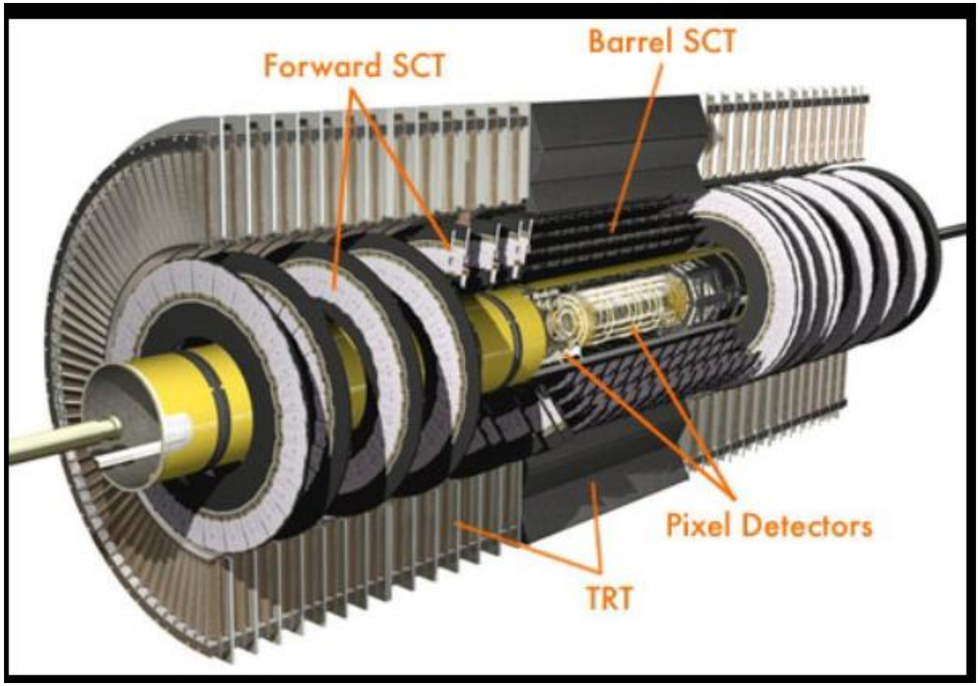
Energy loss used for particle identification

Silicon detectors





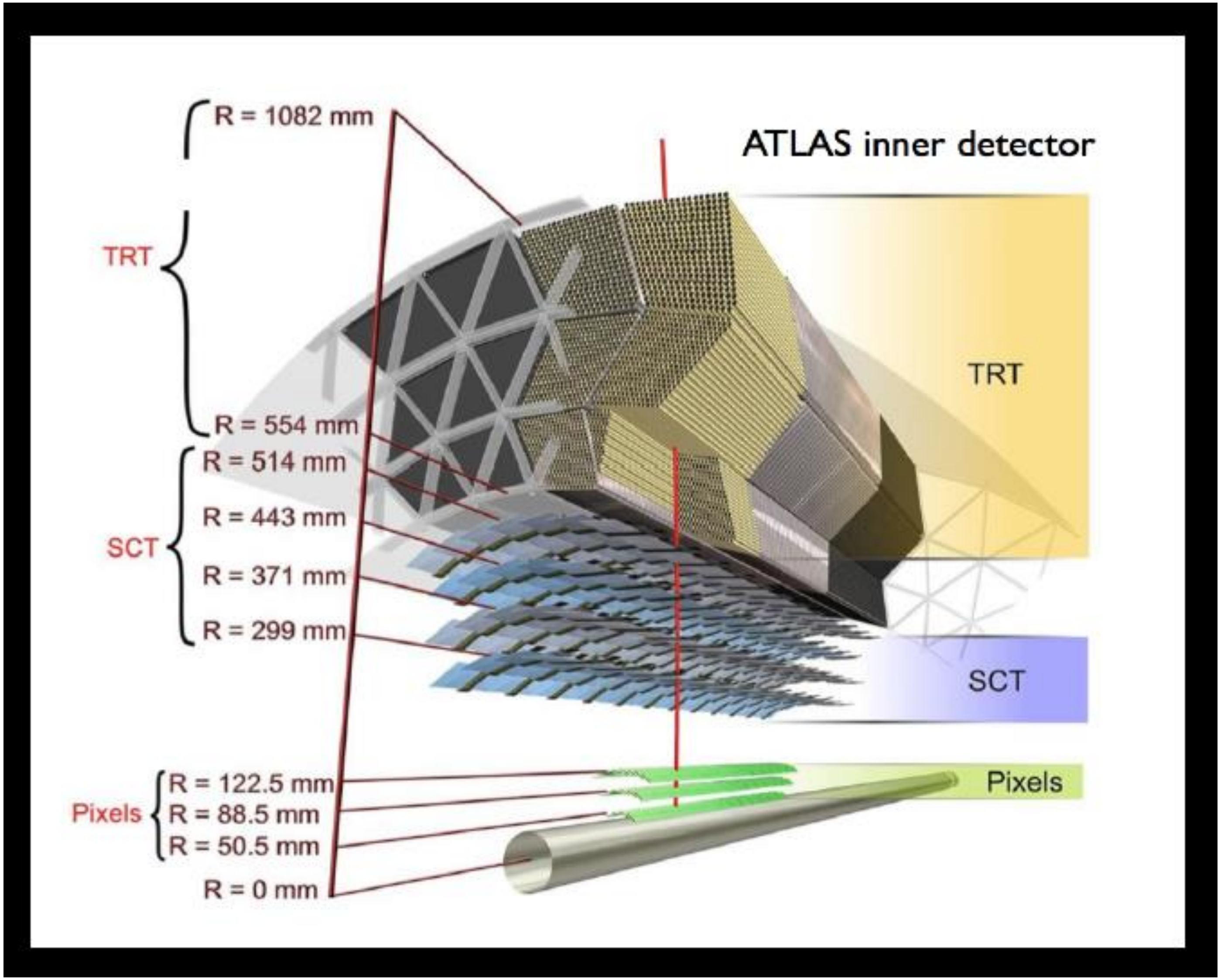
ATLAS Inner Detector



- 3 layers of pixel modules in barrel
- 2x5 disks of forward pixel disks
- 4 layers of strip (SCT) modules in barrel
- 2x9 disks of forward strip modules

Figure : ATLAS Inner detector (ID) in LHC run 1 with pixel and strip (SCT) silicon and transition radiation (TRT) detectors. The length is about 5.5 m.

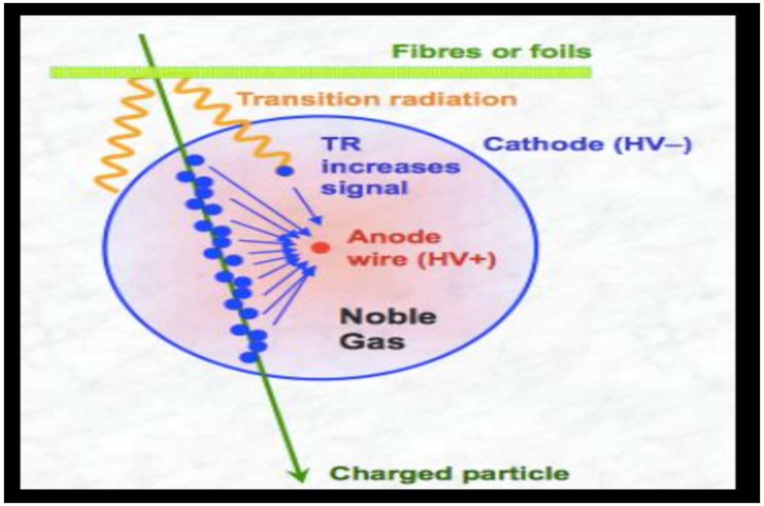
ATLAS Inner Detector

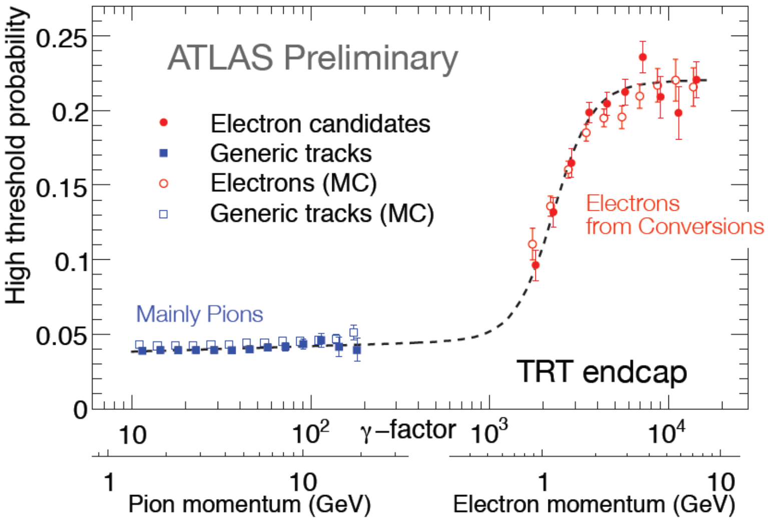


Transition Radiation Tracker

Combine tracking with particle identification (PID)

- Charged particles radiate photons when crossing material borders.
- E^{+-} radiate x-rays more than heavier particles.
- Use this particle PID, i.e. distinguis e^{+-} from hadrons.
- ATLAS has a TR detector in the inner detector. It uses gas for detection.



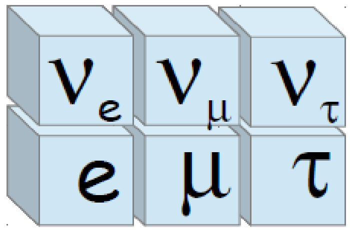


Muon

Standard Model

Leptons

fermions



Electromagnetic & weak interaction (& gravitation)

Muon

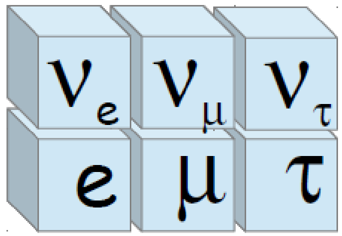
mass:	105.6583715±0.0000035 MeV
spin :	1/2
mean Life:	$(2.1969811 \pm 0.0000022)\times 10^{-6}$ s
τ^+/τ^- :	1.00002±0.00008 (CPT!)
$\mu^- \rightarrow e^- \bar{\nu}_e \; \nu_\mu$	~100%
$\mu^+ \rightarrow e^+ \nu_e \; \bar{\nu}_\mu$	~100%

Muon

Standard Model

Leptons

fermions

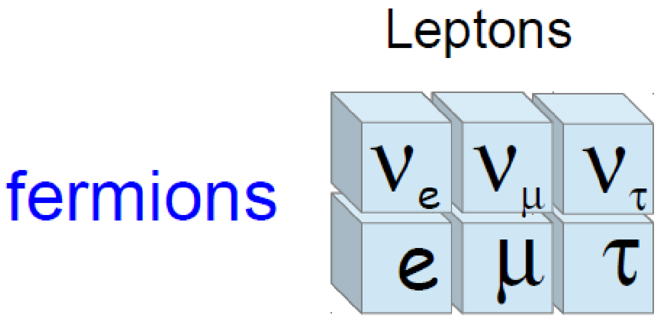


Electromagnetic & weak interaction (& gravitation)

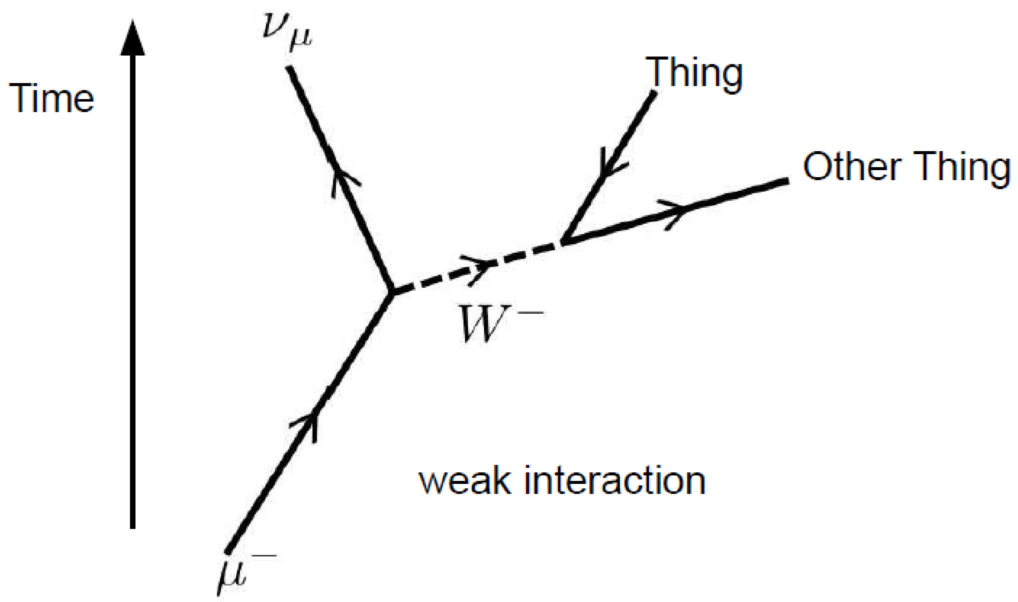
Muon

- ~207 times more massive than electron
- ~ 17 times less massive than the tau
- Unstable $c\tau \sim 660$m
  but the second longest mean life time after the neutrons
- Means: stable for some simulation in G4

Muon



Electromagnetic & weak interaction (& gravitation)



Muon detection in tracking detector

Muon has electrical charge, m_μ ~106 MeV ~ 200m_e, no strong charge, life time τ = 2.2 μs, LHC p_μ ~ 5 … 1000 GeV.

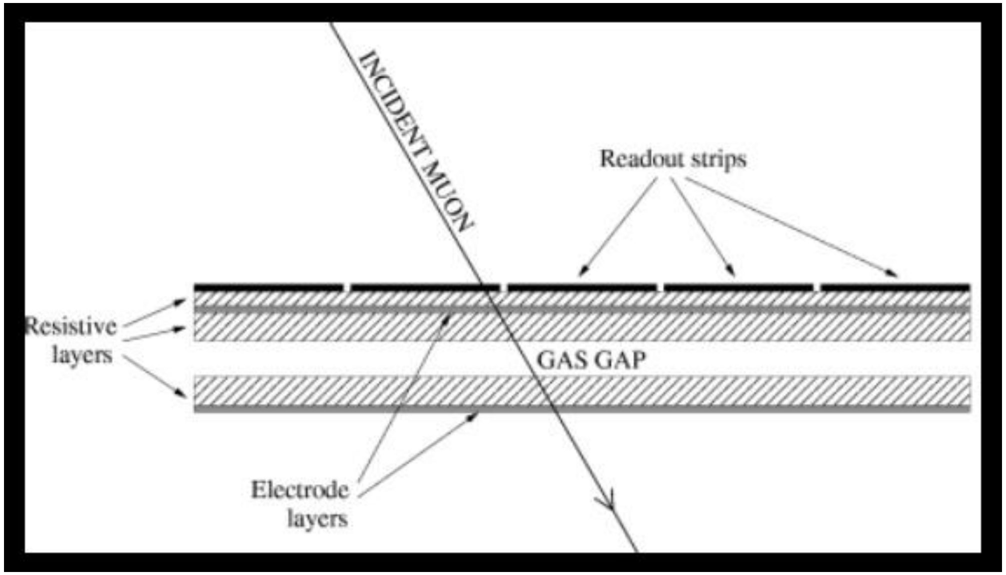
- Curves in magnetic field (charge and momentum)
- Makes track in inner detector/silicon
- Penetrates the full detector, „stable” wrt detector size
- Energy loss described by Bethe-Bloch formulae

Assume (curved) tracks outside the calorimeters to be muons. That means:

- Large detectors, i.e. usually gas
- Match with tracks from inner detector
  - Negligible processes:
    - σ_{Brems} ~ E/m^2 for low E
    - Multiple scattering $m_\mu >> m_e$
- Watch out for non muon punch through from calorimeter

Triggering muons

- Design LHC bunch spacing is 25ns, i.e. need for fast detectors:
  - Resistive Plate Chambers (RPC)
  - Thin Gap Chambers (TGC)
  - Large surface chanmbers with thin (mm) gas layers for fast detection (ps to ns)

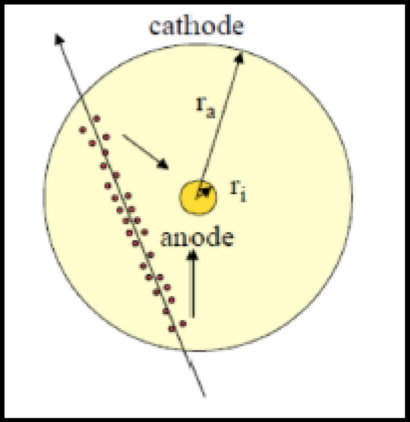


2 mm gap in ATLAS

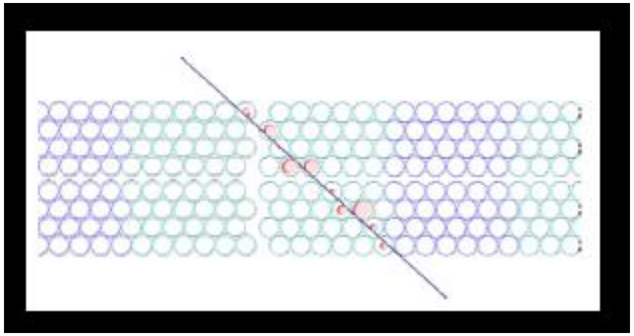
Measuring muons

For high precision position measurements:

- Drift tubes with gas, position drift time (ATLAS, CMS)
  - Array of 10^{4-5} tubes, 1-10cm^2, up to 10m long
  - 50-100 mm and ns resolution
  - Deadtime 20-100 ns
- Cathode Strip Chambers (ATLAS, CMS, LHCb)
  - Multiwire gas chamber with strip read-out
- Micro Pattern Gas Detector (LHCb)
- Time Projection Chamber (ALICE)

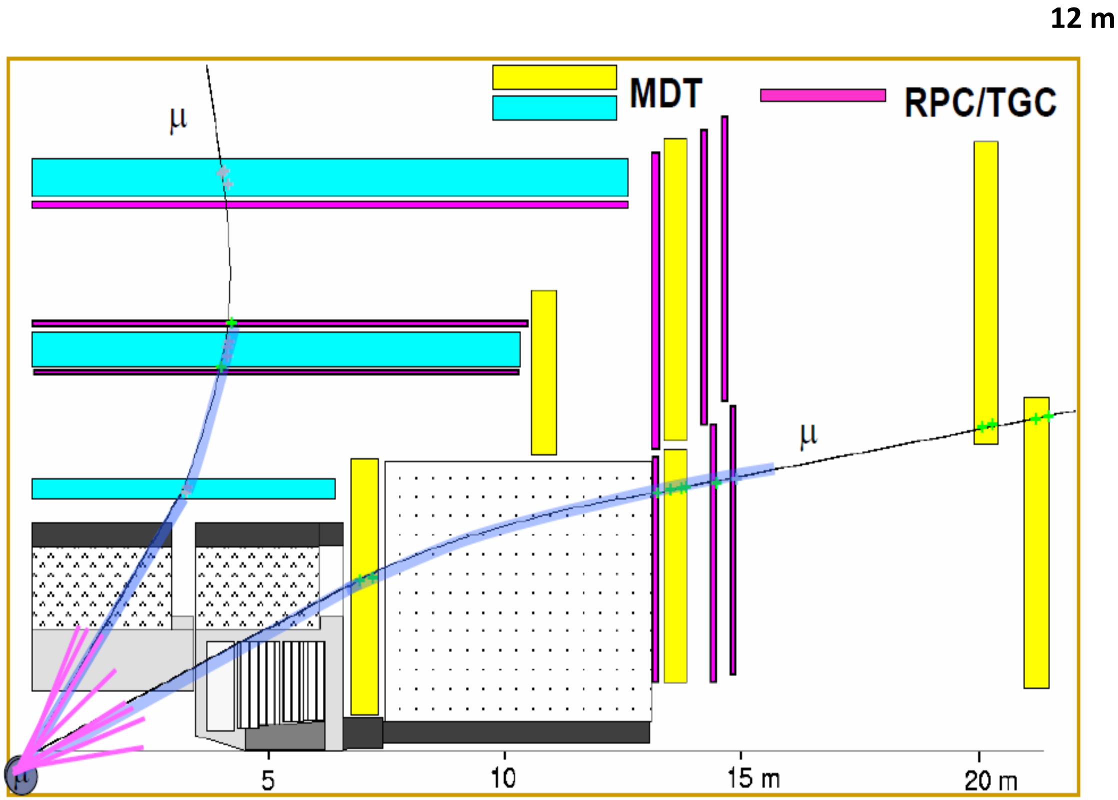


Principle of a drift tube



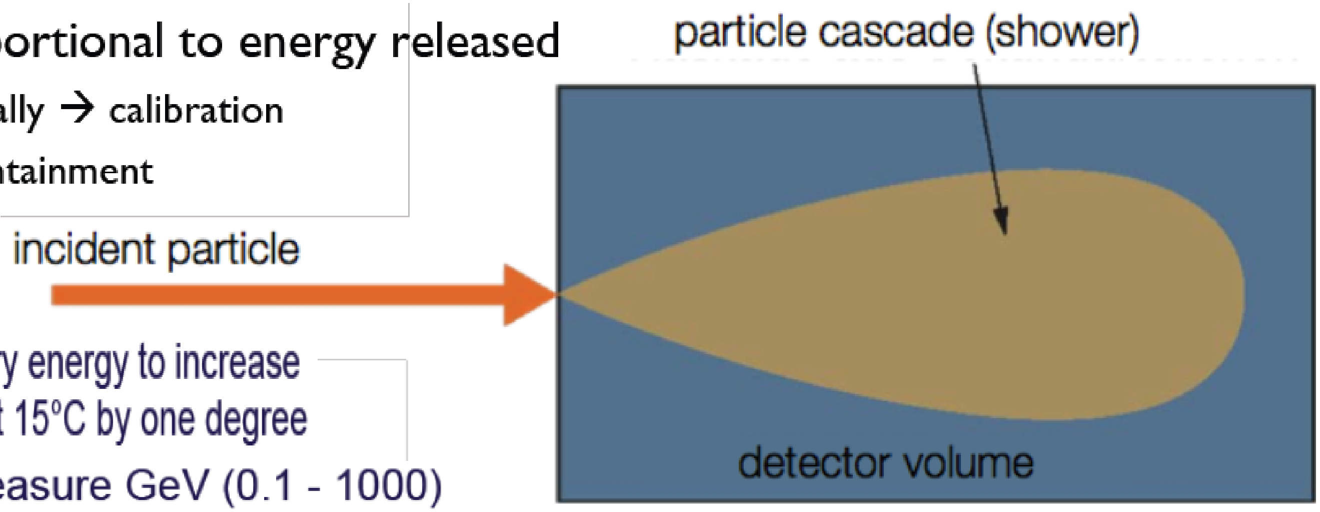

A module with 2x4 layers of drift tubes (ATLAS)

Muon system in ATLAS



Calorimeter: principle of the measurement?

- **Energy measurement via total absorption of particles**
- **Principles of operation**
  - ✓ Incoming particle initiates particle shower
    - Electromagnetic, hadronic
    - Shower properties depend on particle type and detector material
  - ✓ Energy is deposited in active regions
    - Heat, ionization, atom excitation (scintillation), Cherenkov light
    - Different calorimeters use different kind of signals
  - ✓ Signal is proportional to energy released
    - Proportionally → calibration
    - Shower containment



1 calorie (4.185J) is the necessary energy to increase the temperature of 1 g of water at 15°C by one degree

At hadron colliders we measure GeV (0.1 - 1000)

$1\ \text{GeV} = 10^9\ \text{eV} \approx 10^9 * 10^{-19}\text{J} = 10^{-10}\ \text{J} = 2.4\ 10^{-9}\ \text{cal}$

1 TeV = 1000 GeV : kinetic energy of a flying mosquito

Why calorimeters?

First calorimeters appeared in the 70's:
need to measure the energy of all particles, charged and neutral.

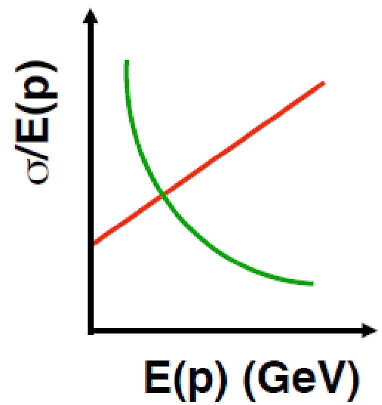
Until then, only the momentum of charged particles was measured using magnetic analysis.

The measurement with a calorimeter is destructive e.g.

$$\pi^- + p \rightarrow \pi^0 + n, \quad \pi^0 \rightarrow \gamma\,\gamma$$

Magnetic analysis

$$\frac{\sigma(p)}{p} = ap \oplus b$$



$$\frac{\sigma(E)}{E} \approx \frac{a}{\sqrt{E}}$$

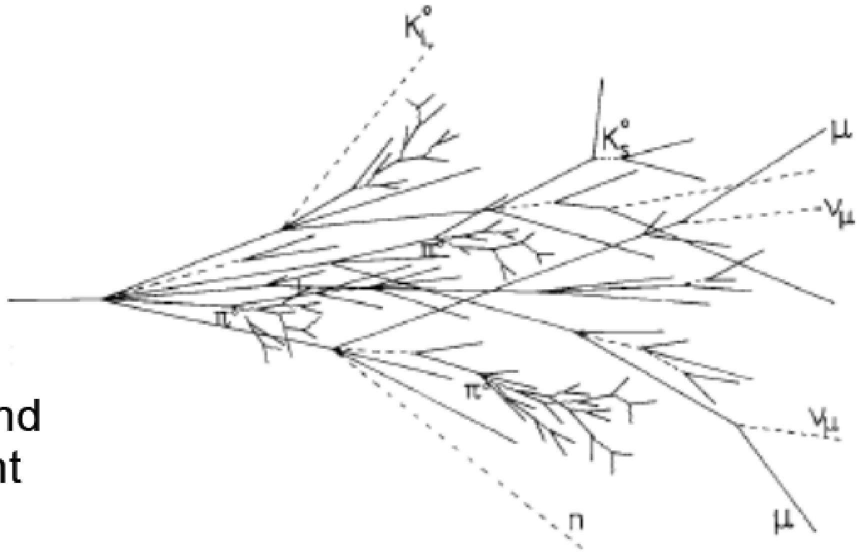
Calorimetry

Particles do not come out alive of a calorimeter

EM and hadron calorimeters

- Calorimeters are subdivided into electromagnetic and hadronic sub-detectors
- Electromagnetic interactions develop over shorter distances than hadronic interactions
- Fundamental processes of signal generation differ, calling on different optimization

cascade with EM and hadronic component



A typical HEP calorimetry system

Typical Calorimeter: two components ...

Electromagnetic (EM) +
Hadronic section (Had) ...

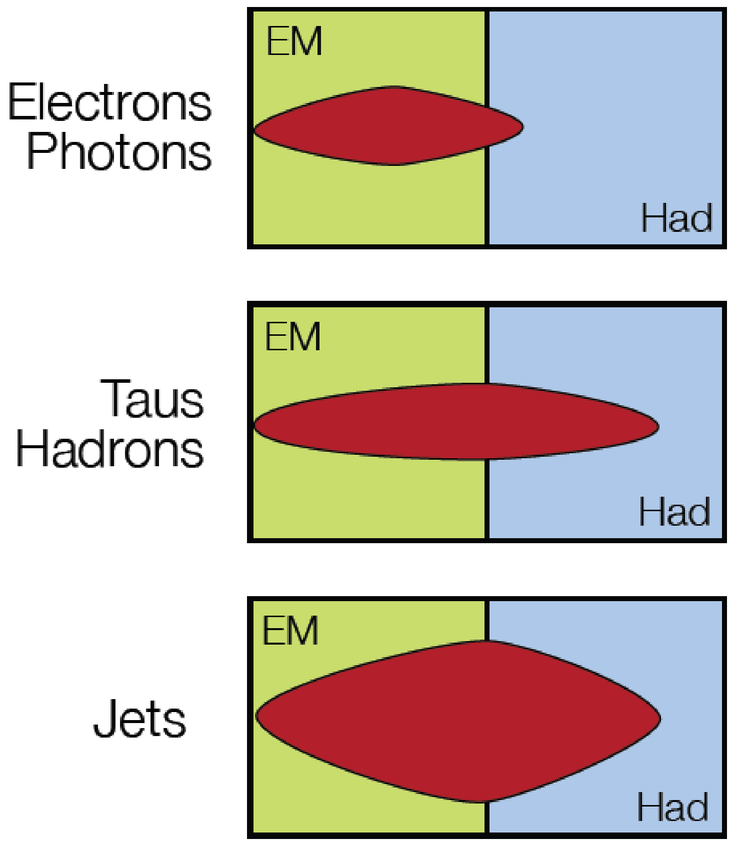
Different setups chosen for
optimal energy resolution ...

But:

Hadronic energy measured in
both parts of calorimeter ...

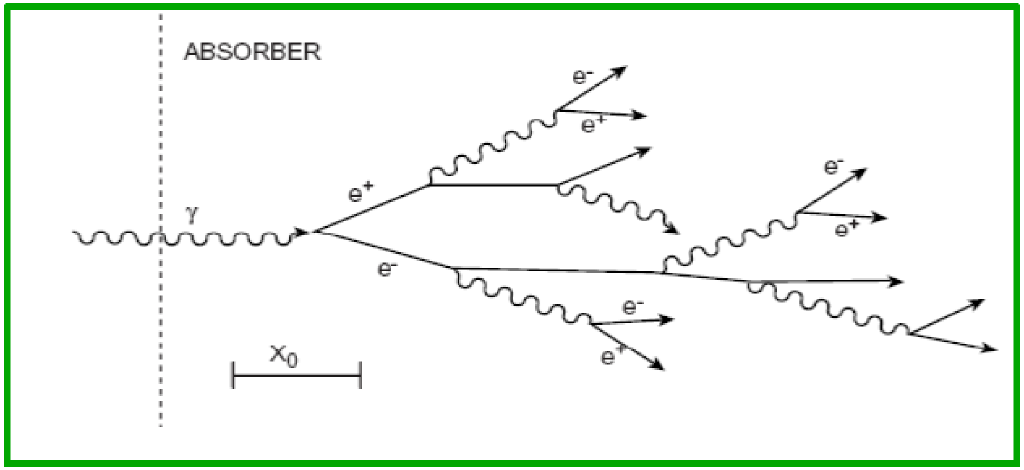
Needs careful consideration of
different response ...

Schematic of a
typical HEP calorimeter



Electromagnetic showers

At high energies, electromagnetic showers result from electrons and photons undergoing mainly bremsstrahlung and pair creation.



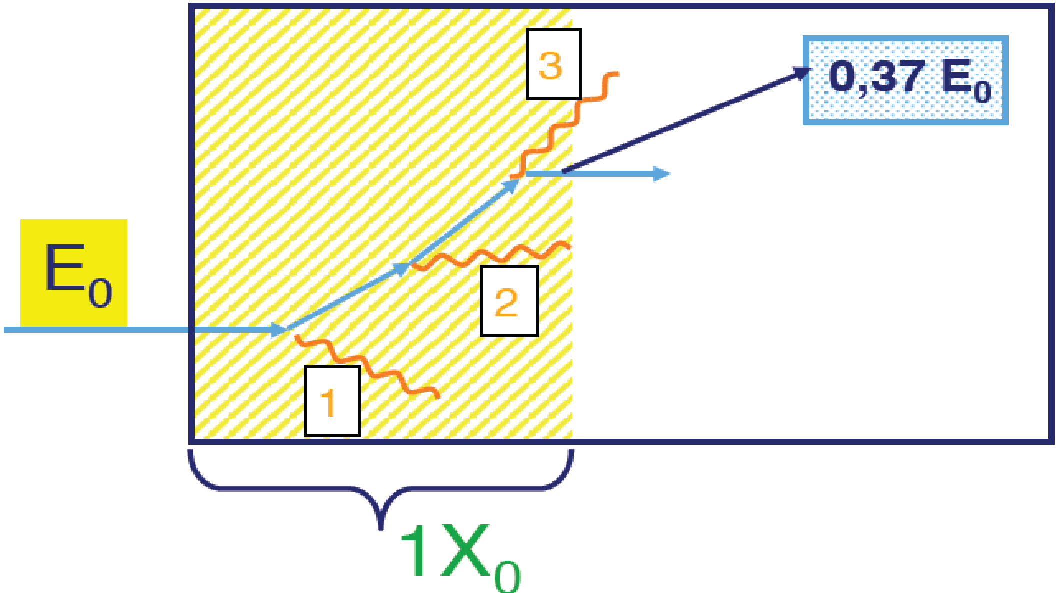
For high energy (GeV scale) electrons bremsstrahlung is the dominant energy loss mechanism.
For high energy photons pair creation is the dominant absorption mechanism.
Shower development is governed by these processes.

Radiation length

The radiation length is a "universal" distance, very useful to describe electromagnetic showers (electrons & photons)

X_0 is the distance after which the incident electron has radiated (1-1/e) 63% of its incident energy

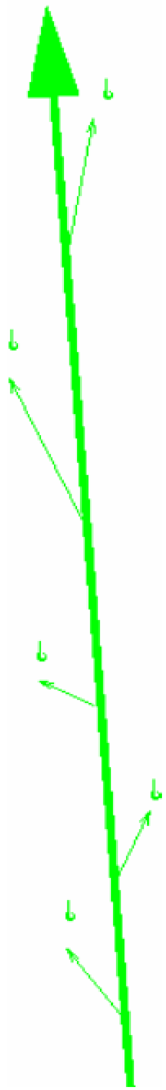
$$dE/dx = E/X_0$$
$$dE/E = dx/X_0$$
$$E = E_0 e^{-x/X_0}$$

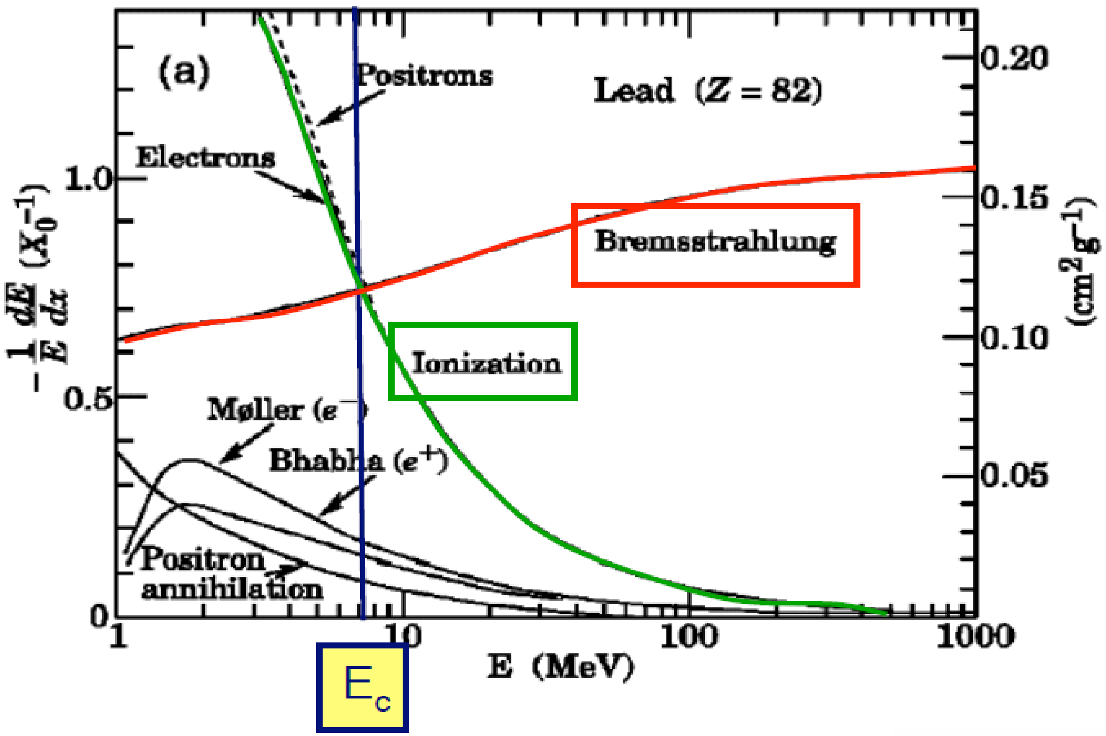


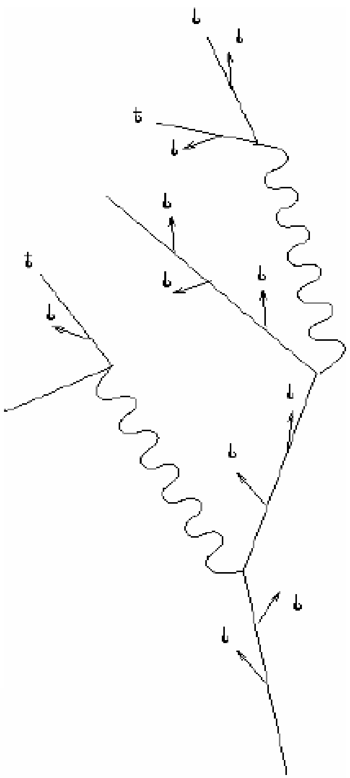
	Air	Eau	Al	LAr	Fe	Pb	$PbWO_4$
Z	-	-	13	18	26	82	-
X_0 (cm)	30420	36	8,9	14	1,76	0.56	0.89

Total energy loss of electrons

Electrons mainly loose their energy via ionization & Bremsstralung







Total energy loss for photons

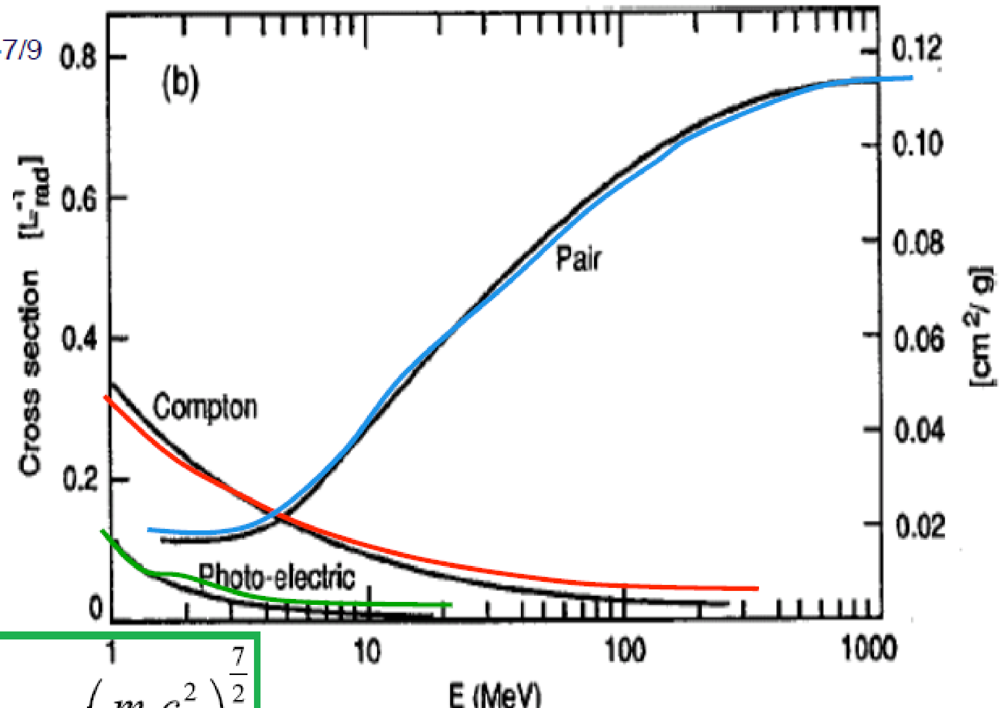
Pair Production

$$\sigma_{pair} \approx \frac{7}{9} \times \frac{A}{N_A} \times \frac{1}{X_0}$$

Probability of conversion in 1 X_0 is $e^{-7/9}$

Can define mean free path:

$$\lambda_{pair} \approx \frac{9}{7} X_0$$



Compton scattering

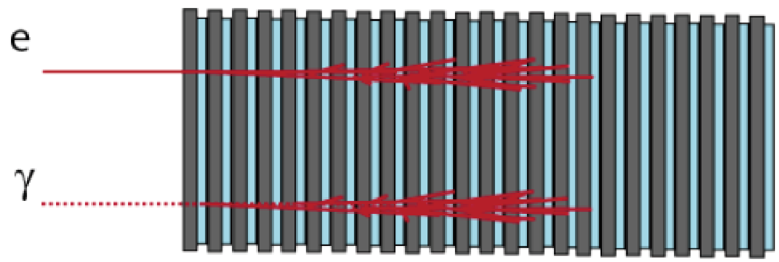
$$\sigma_C \approx \frac{\ln E_\gamma}{E_\gamma}$$

Photo-electric effect

$$\sigma_{pe} \approx Z^5 \alpha^4 \left(\frac{m_e c^2}{E_\gamma} \right)^{\frac{7}{2}}$$

EM and hadron calorimeters

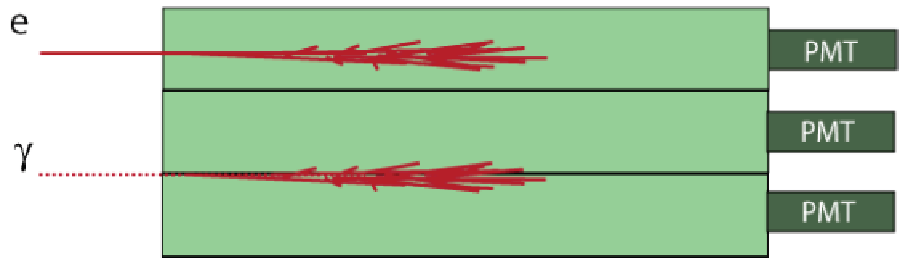
- "Lead-scintillator" calorimeter



Energy resolutions:

$\Delta E/E \sim 20\%/\sqrt{E}$

- Exotic crystals (BGO, PbW, ..)

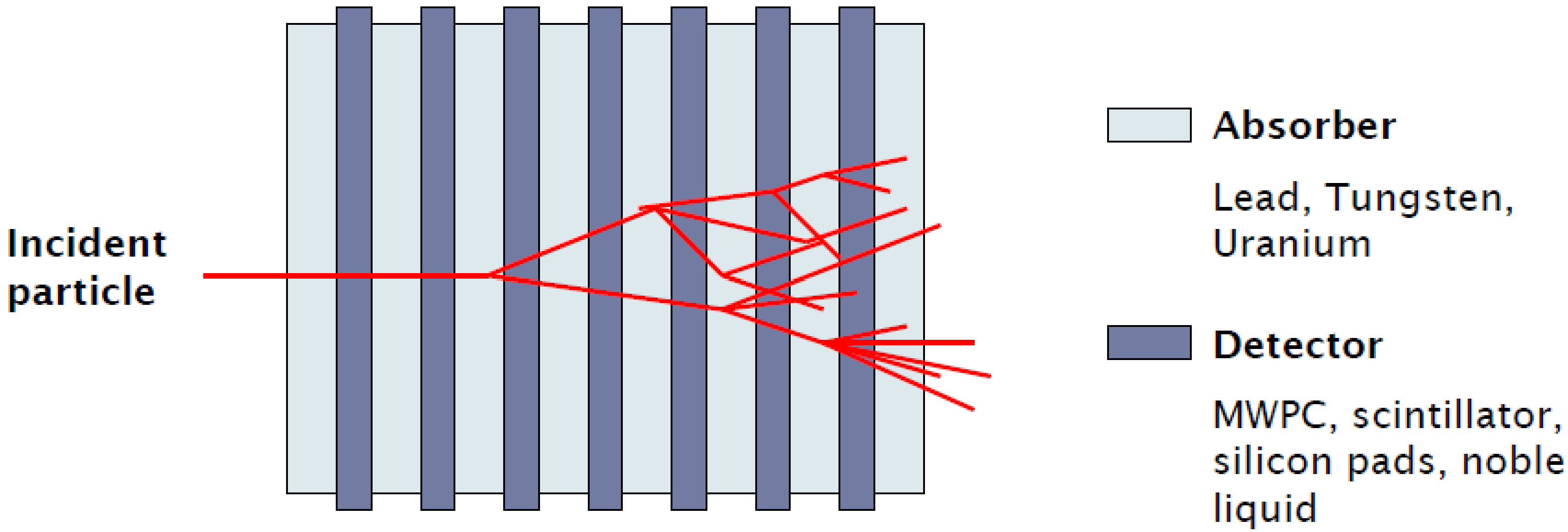


$\Delta E/E \sim 1\%/\sqrt{E}$

- Liquid argon calorimeter
  - Slow collection time (~1μsec)

$\Delta E/E \sim 18\%/\sqrt{E}$

Sampling calorimeters



- Absorber (passive) and detector (active) layers
- Fluctuations in visible energy: „sampling fluctuations” due to variations of number of charged particles in the detector

Energy resolution

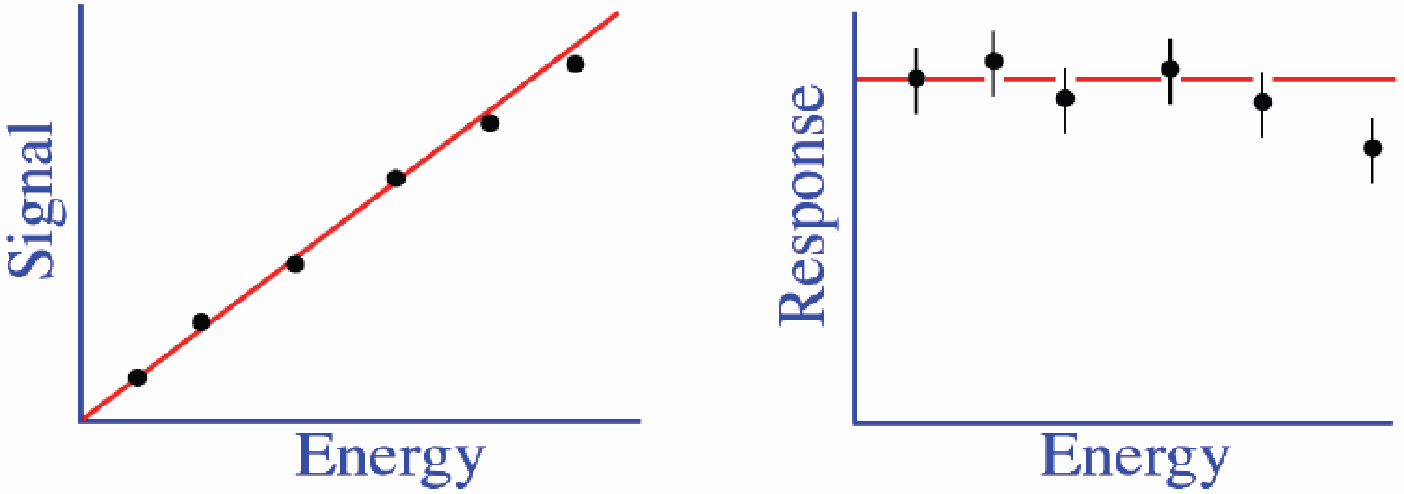
- Statistical fluctuations
  - In the number of particles in the shower
  - In the number of escaping or undetected particles
- Noise
  - Electronic noise
  - Pile up
- Constant
  - Dead material
  - Calibration errors
  - Mechanical imperfections
- **Higher energy -> better resolution**

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{\sigma_n}{E} \oplus \text{constant}$$

Linearity

Response: mean signal per unit of deposited energy
e.g. # of photons electrons/GeV, pC/MeV, µA/GeV

→ A linear calorimeter has a constant response



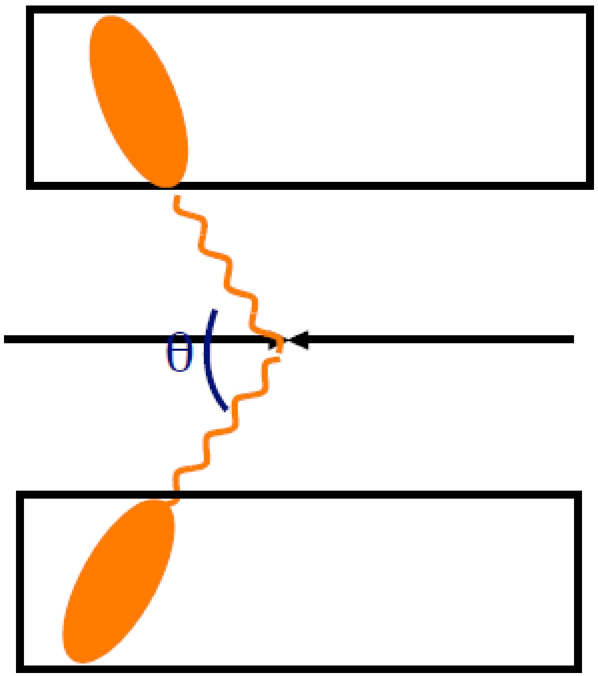
Electromagnetic calorimeters are in general linear.
All energies are deposited via ionisation/excitation of the absorber.

Position and time resolution

Higgs Boson in ATLAS

For $M_H \sim 120$ GeV, in the channel $H \to \gamma\gamma$

$\sigma(M_H) / M_H = ½ [\sigma(E_{\gamma 1})/E_{\gamma 1} \oplus \sigma(E_{\gamma 2})/E_{\gamma 2} \oplus \cot(\theta/2)\, \sigma(\theta)]$



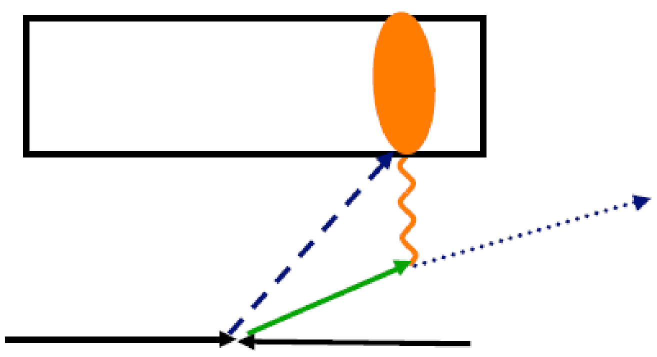
$pp \to H+x \to \gamma\gamma + x$

Time measurement

Validate the synchronisation between sub-detectors (~1ns)

Reject non-collisions background (beam, cosmic muons,..)

Identify particles which reach the detector with a non nominal time of flight (~5ns measured with ~100ps precision)



Particle identification

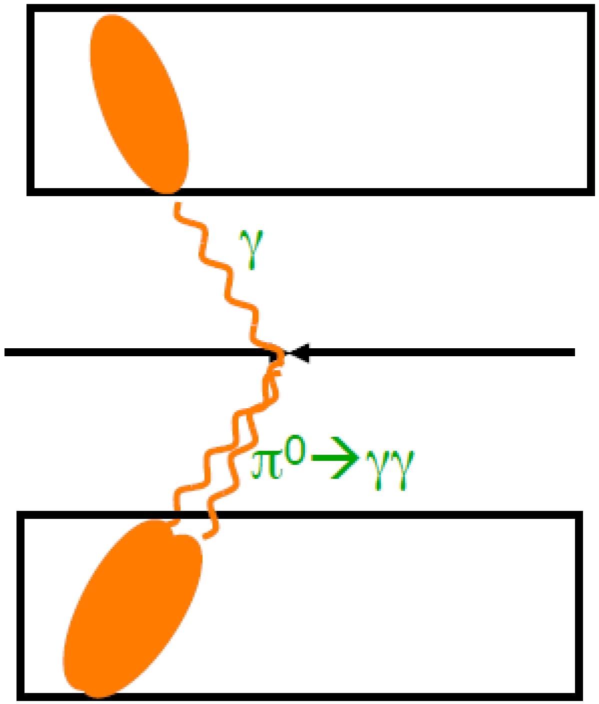
Particle Identification is particularly crucial at Hadron Colliders:

- Large hadron background
- Need to separate
  - Electrons, photons, muons from
  - Jets, hadrons

Means

- Shower shapes (lateral & longitudinal segmentations)
- Track association with energy deposit in calorimeter
- Signal time

γ/π^0 rejection



$pp \rightarrow \gamma\text{-jet} \rightarrow \gamma + \pi^0 + x$

ATLAS EM Calorimeter

Accordion Pb/LAr |η|<3.2 ~170k channels

- Precision measurement |η|<2.5

3 layers up to |η|=2.5 + presampler |η|<1.8

2 layers 2.5<|η|<3.2

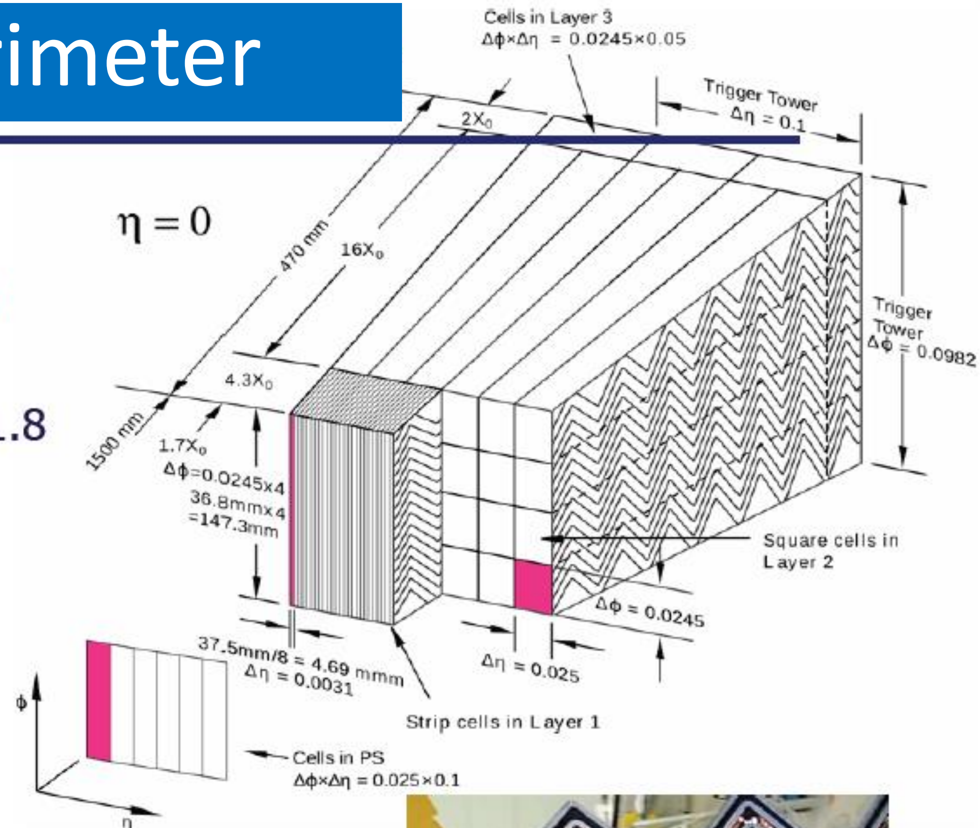
- Layer 1 (γ/π^0 rej. + angular meas.)
- Δη.Δφ = 0.003 x 0.1
- Layer 2 (shower max)
- Δη.Δφ = 0.025 x 0.0.25
- Layer 3 (Hadronic leakage)
- Δη.Δφ = 0.05 x 0.0.025

Energy Resolution: design for η~0

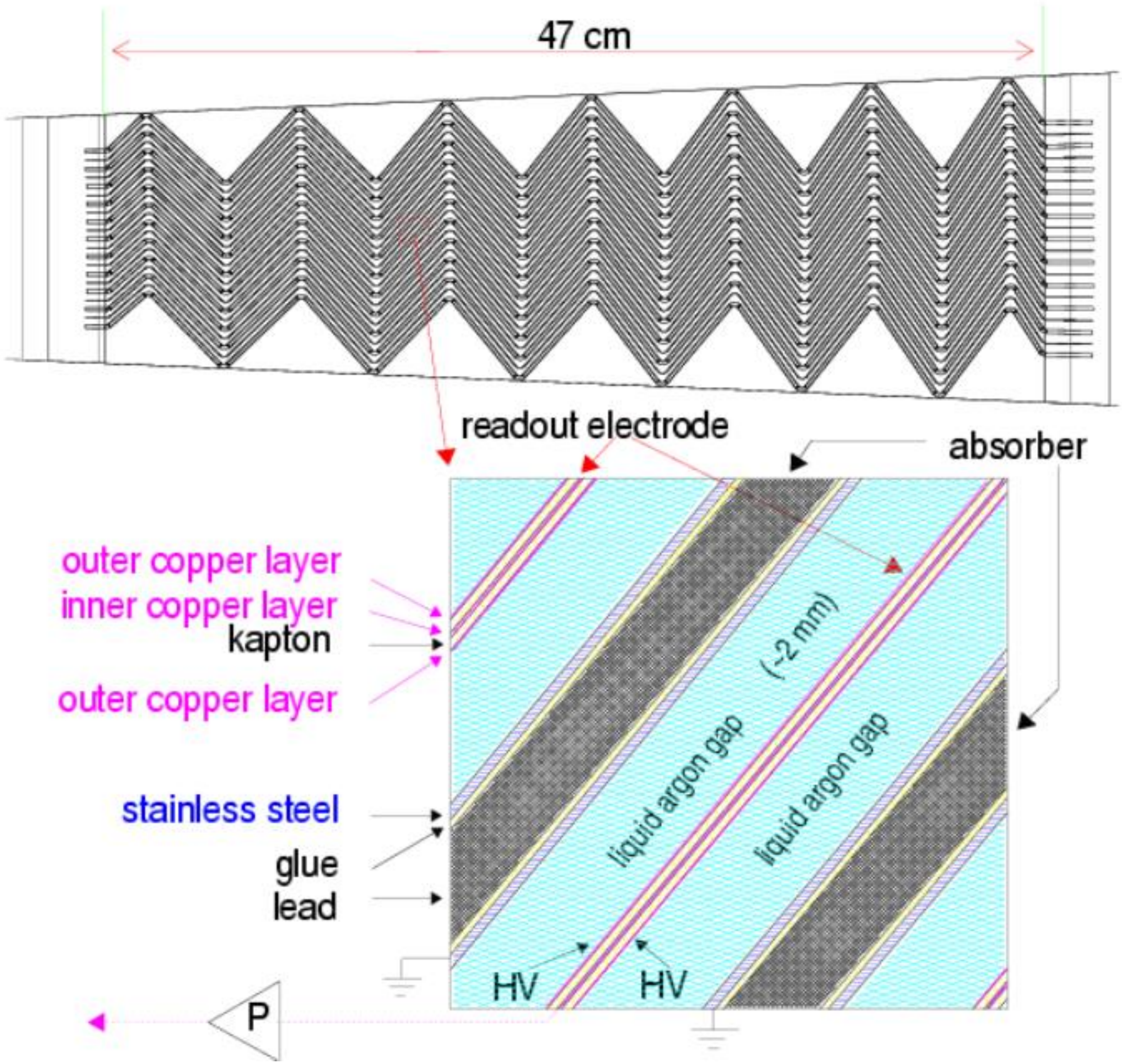
- ΔE/E ~ 10%/√E ⊕ 150 MeV/E ⊕ 0.7%

Angular Resolution

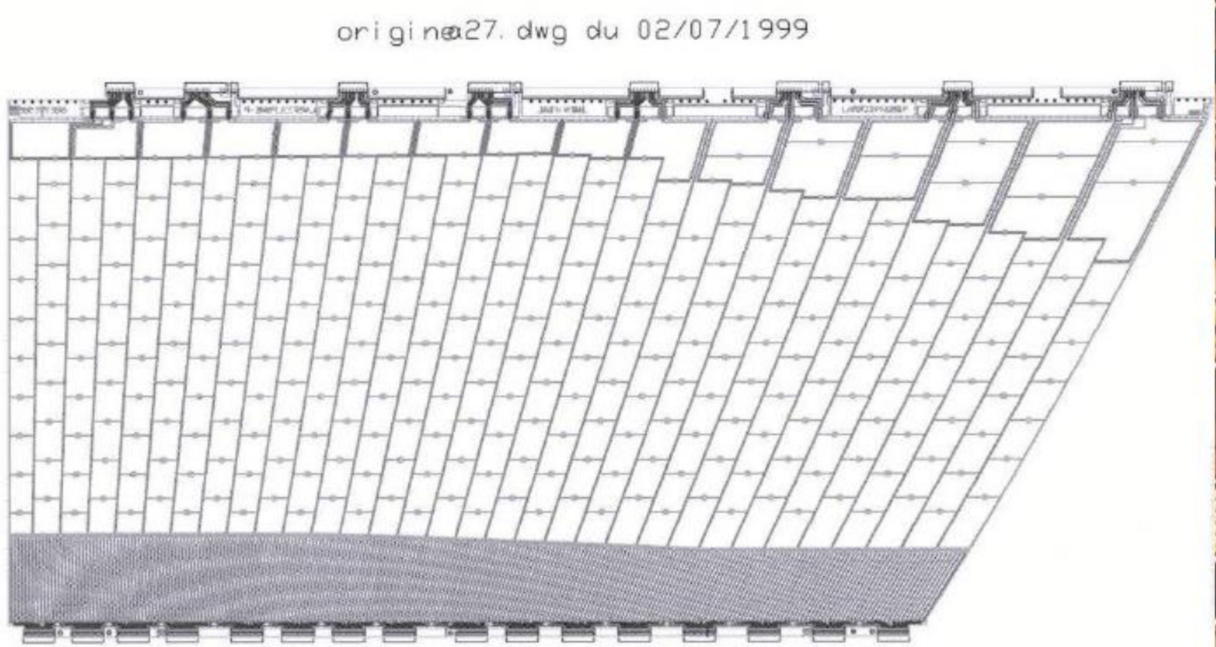
- 50mrad/√E(GeV)

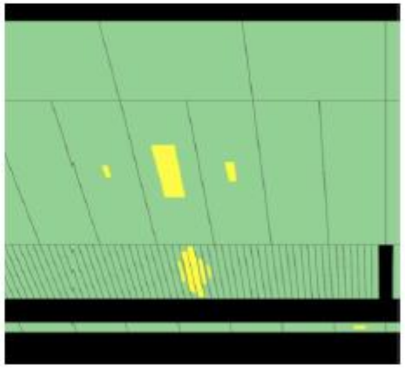


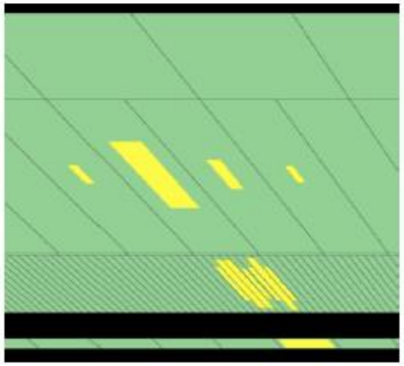
ATLAS EM Calorimeter

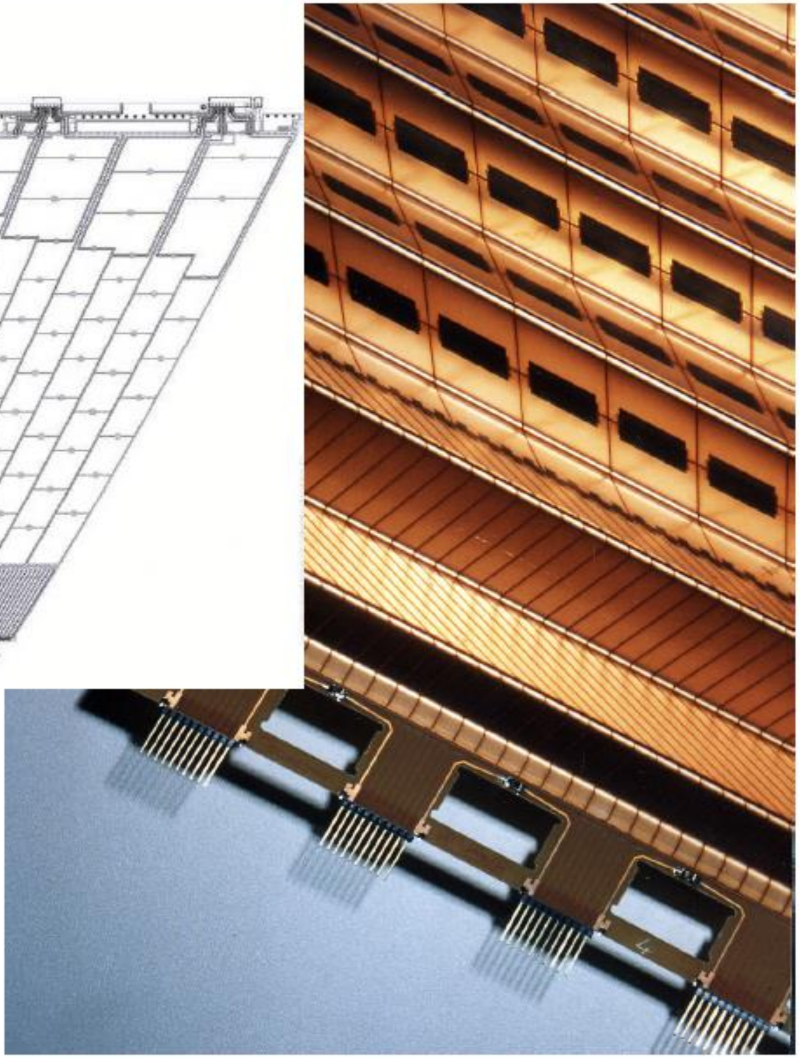


The segmentation

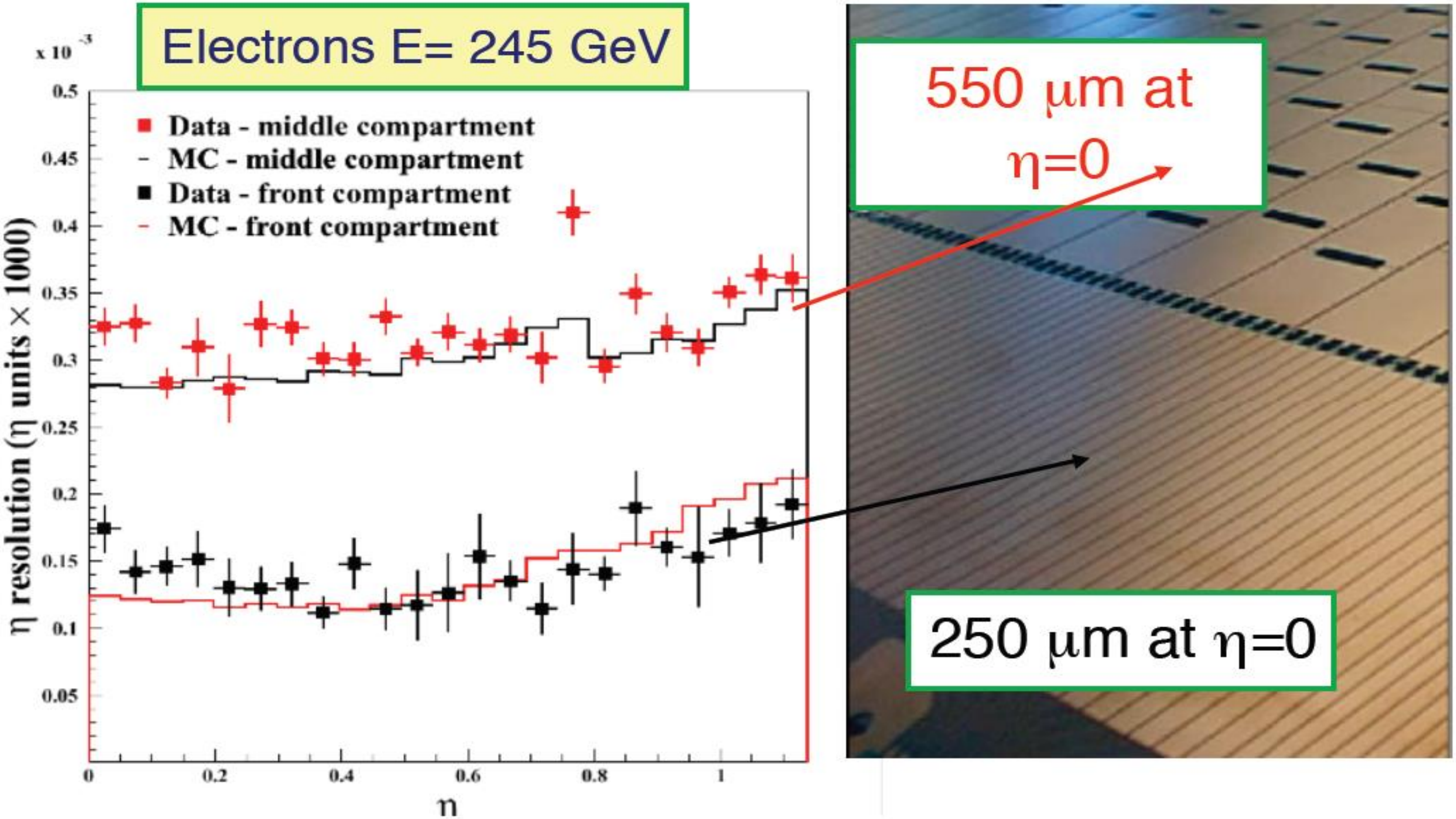




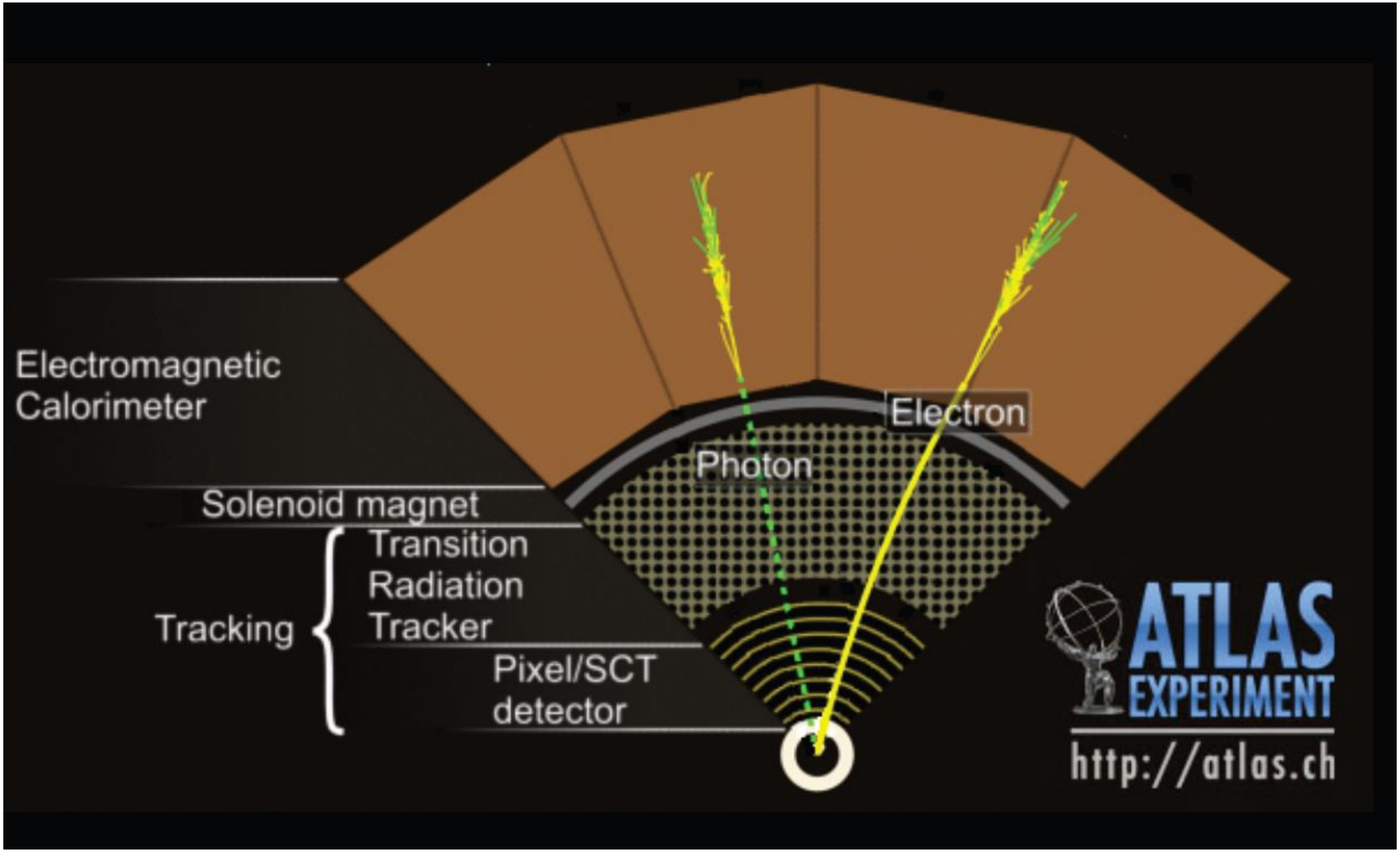




Position resolution

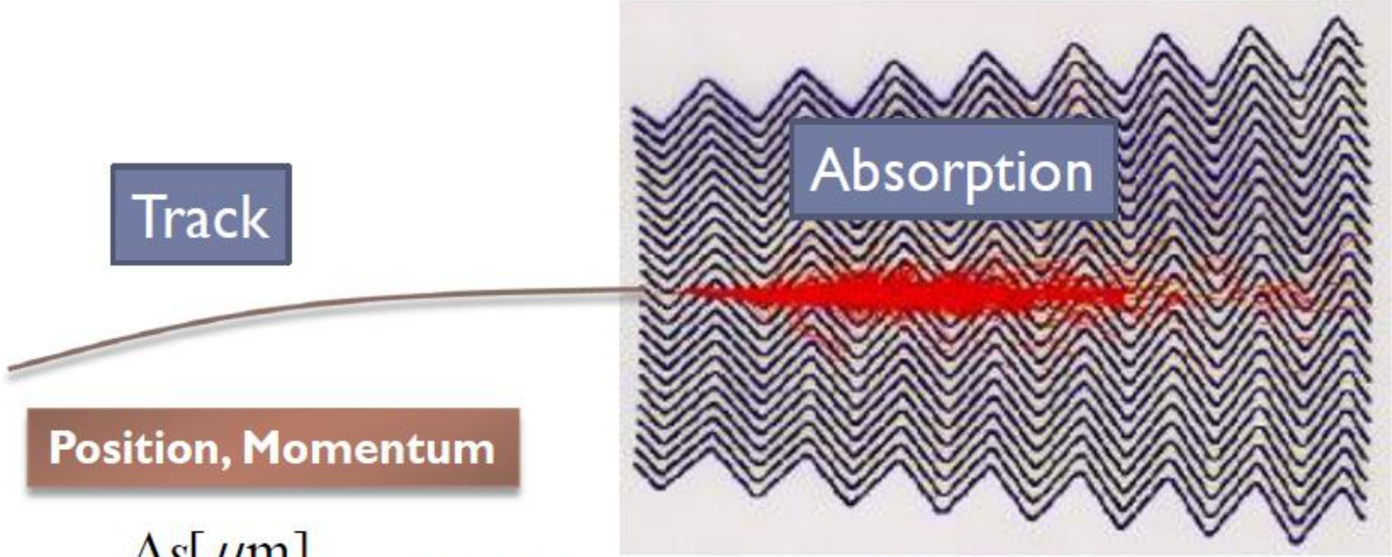


Particle identification with tracker and calo



Position, momentum, energy

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{\sigma_n}{E} \oplus \text{constant}$$



Energy

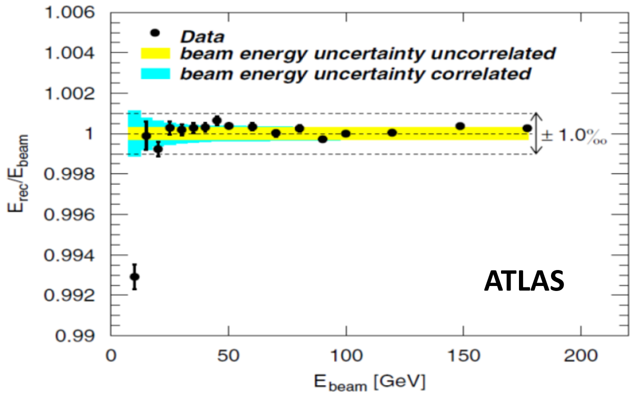
$$\frac{\Delta p}{p} \approx 0.25 \frac{\Delta s[\mu \mathrm{m}]}{(L[\mathrm{cm}])^2 B[\mathrm{T}]} p[\mathrm{GeV}]$$

$$\propto p$$

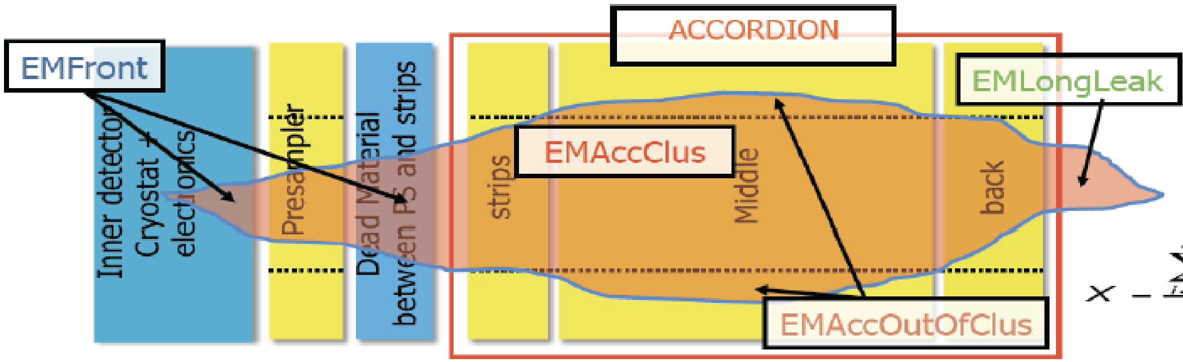
$$\propto \frac{1}{\sqrt{E}}$$

Cluster energy reconstruction

- E_{rec}: Need to correct E_{acc} for losses
  - in matter in front of calorimeter (IDl + cryostat)
  - Between Crysotat & Accordion
  - Loss outside the cluster $E_{outcluster}$
  - Rear leakage E_{leak}



- Use MC



$$X = \frac{\sum_{i=1}^{4} E_i^{LAr} X_i}{\sum_{i=1}^{4} E_i^{LAr}}$$

$$E^{reco} = F(E_{acc}^{reco},\eta)\cdot E_{ps}^{cl\ lAr} + S_{acc}(X,\eta)\cdot\left(\sum_{i=1,3} E_i^{cl\ lAr}\right)(1+C_{out}(X,\eta))\cdot(1+f_{leak}(X,\eta))$$

Energy deposited in front of calo

Energy deposited into the cluster

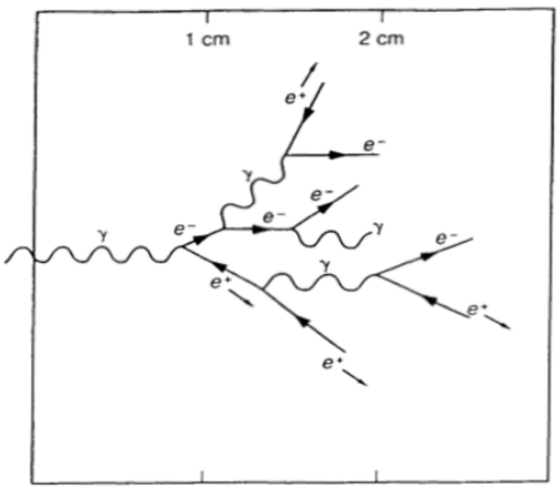
Energy deposited out of cluster

Energy deposited behind calo

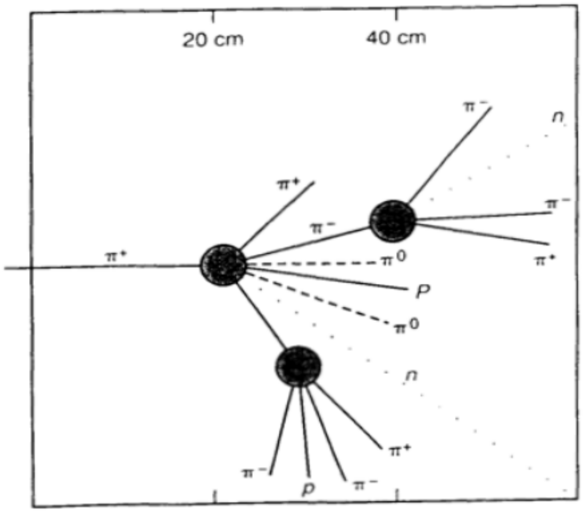
Hadron calorimetry

- Hadron Calorimeters, as EM calorimeters measure the **energy** of the incident particle(s) by fully absorbing the energy and prividing measurement of absorbed energy
- Hadronic showers are more complicated that EM ones. The **longitudinal** development is characterised by the nuclear **interaction length** (mean free path before interaction)

EM shower



Hadronic shower



Hadronic showers

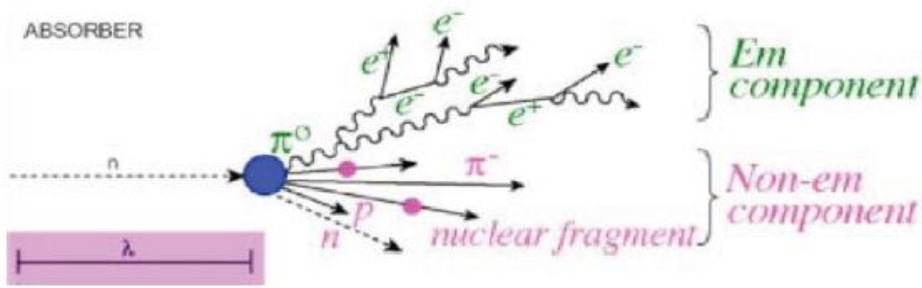
- **Nuclear interaction length**: mean free path before interaction $\lambda_{int} \approx 35\ A^{1/3} \cdot g \cdot cm^{-2}$
- Nuclear interaction length is longer than radiation lenght

Material	Atomic No. (Z)	Radiation Length (X_0) (g/cm^2)	Radiation Length (X_0) (cm)	Interaction Length (λ) (g/cm^2)	Interaction Length (λ) (cm)	X_0/λ
Beryllium	_4	65.19	35.28	75.2	40.7	1.2
Carbon	_6	42.70	18.8_	86.3	38.1	2.0
Aluminum	13	24.01	8.9_	106.4	39.4	4.4
Iron	26	13.84	1.76	131.9	16.8	9.5
Copper	29	12.86	1.43	134.9	15.1	15.1
Tungsten	74	6.76	0.35	185._	9.6	27.4
Lead	82	6.37	0.56	194._	17.1	30.5
Uranium	92	6.00	0.32	199._	10.5	33.2

higher *Z* materials separate hadronic/EM interactions better

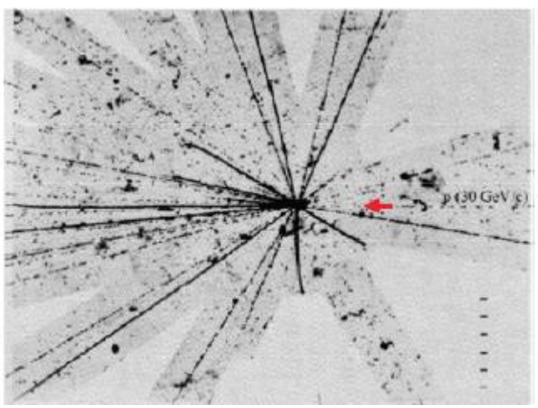
Hadronic showers

- Hadronic showers are
  - **Broader** and more penetrating
  - Subject to **large fluctuations**

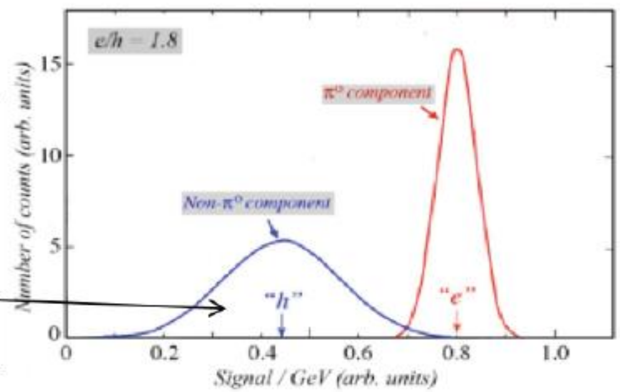


Electrons, photons
$\pi^0 \rightarrow 2\gamma$

Charged hadrons	(20%)
Nuclear fragments , p	(25%)
Neutrons, soft γ's	(15%)
Breakup of nuclei	(40%)

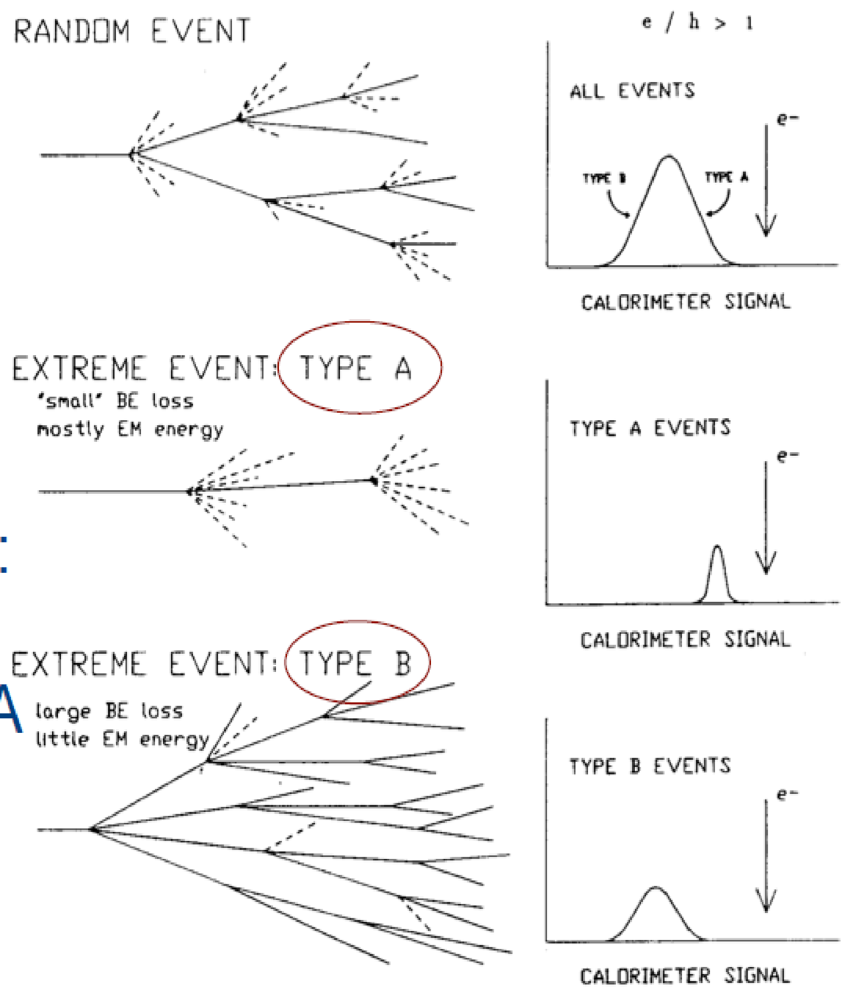


Either not detected
or often to slow to be
within detector time
window
= **Invisible energy**
e/h > 1



Hadronic showers: resolution

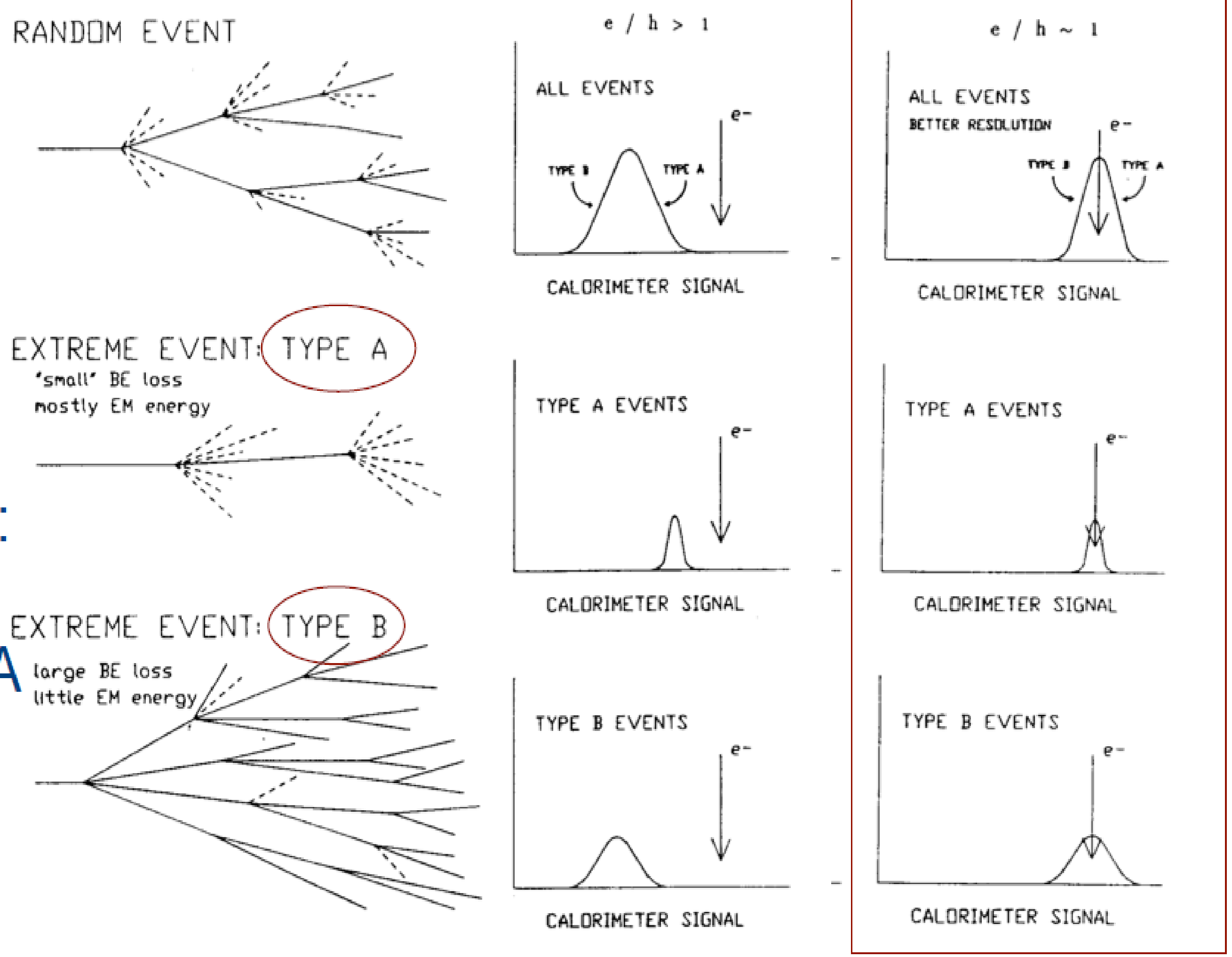
- fluctuations of en. measurement
  - the most important fluctuation: binding energy (BE) losses
  - correlated with EM shower energy fraction
- optimal resolution: need to equalize response of type A vs. type B



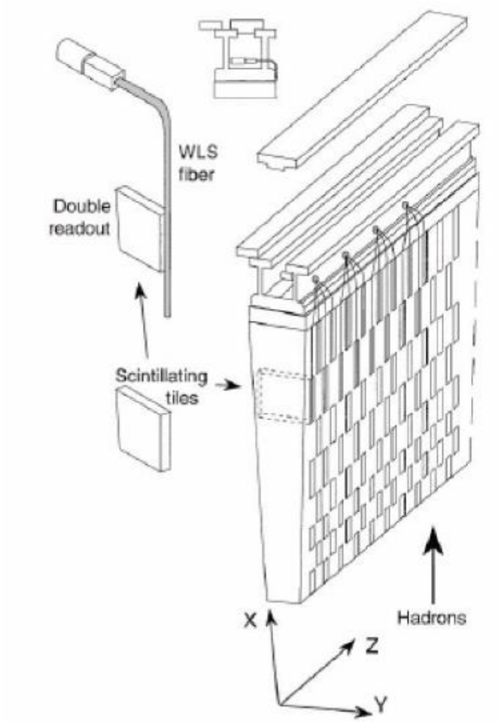
Hadronic showers: resolution

- fluctuations of en. measurement
  - the most important fluctuation: binding energy (BE) losses
  - correlated with EM shower energy fraction
- optimal resolution: need to equalize response of type A vs. type B

compensation: e/h~1



ATLAS Hadronic Calorimeter (Tile)



Fe/Scint with WLS fiber Readout via PMT

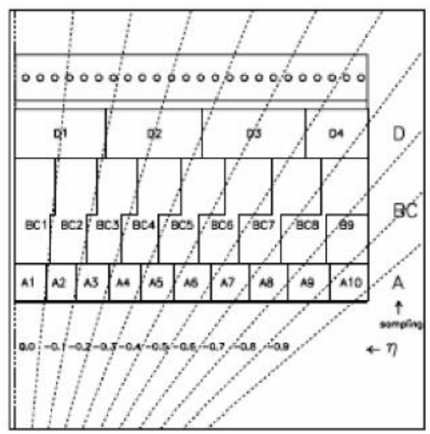


Figure 5-15 Cell geometry of half of a barrel module. The fibres of each cell are routed to one PMT.

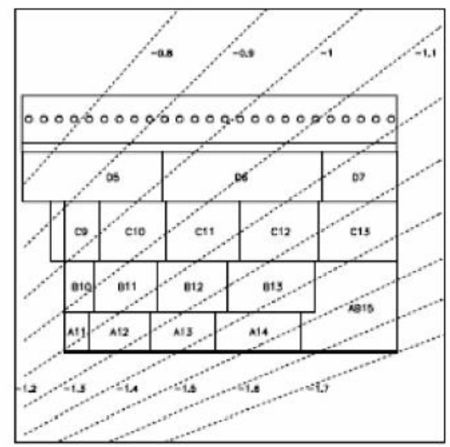


Figure 5-16 Proposed cell geometry for the extended barrel modules (version "a la barrel").

Hadronic and EM calorimeters

EM calorimeters

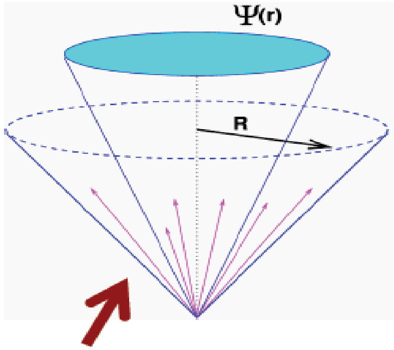
- **Very well understood theoretically**
- **Technology continue to advance**
- **Have good energy resolution (2-10%/$E^{1/2}$)**
- **EM showers develop through brems and pair production**
- **Characteristic length is radiation length X_0**

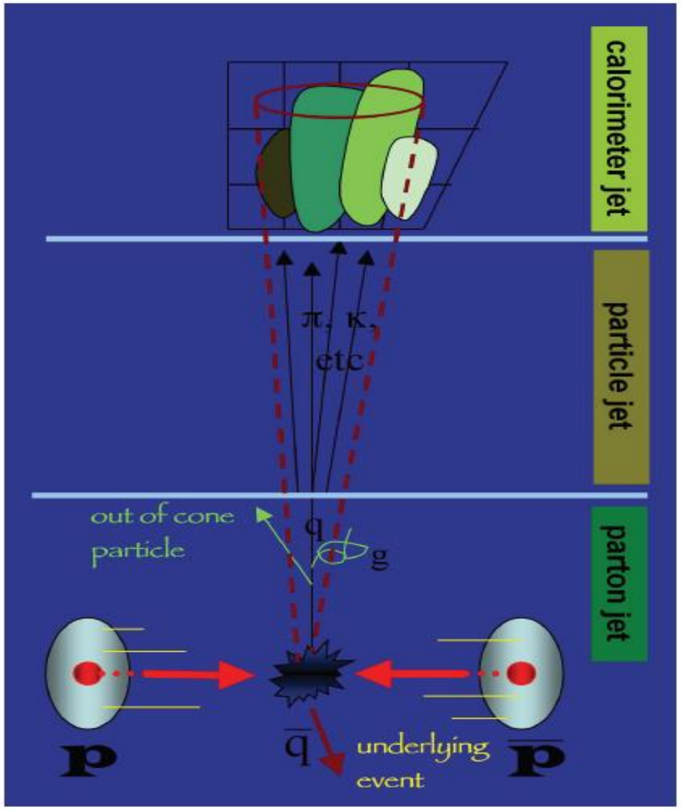
Hadronic calorimeters

- **Hadronic showers are more complex**
- **Hadronic calorimeters have worse energy resolution than EM ones (40-100%/$E^{1/2}$)**
- **Hadronic showers develop through nuclear interaction**
- **Characteristic length is interaction length λ**

Not always measure individual particles

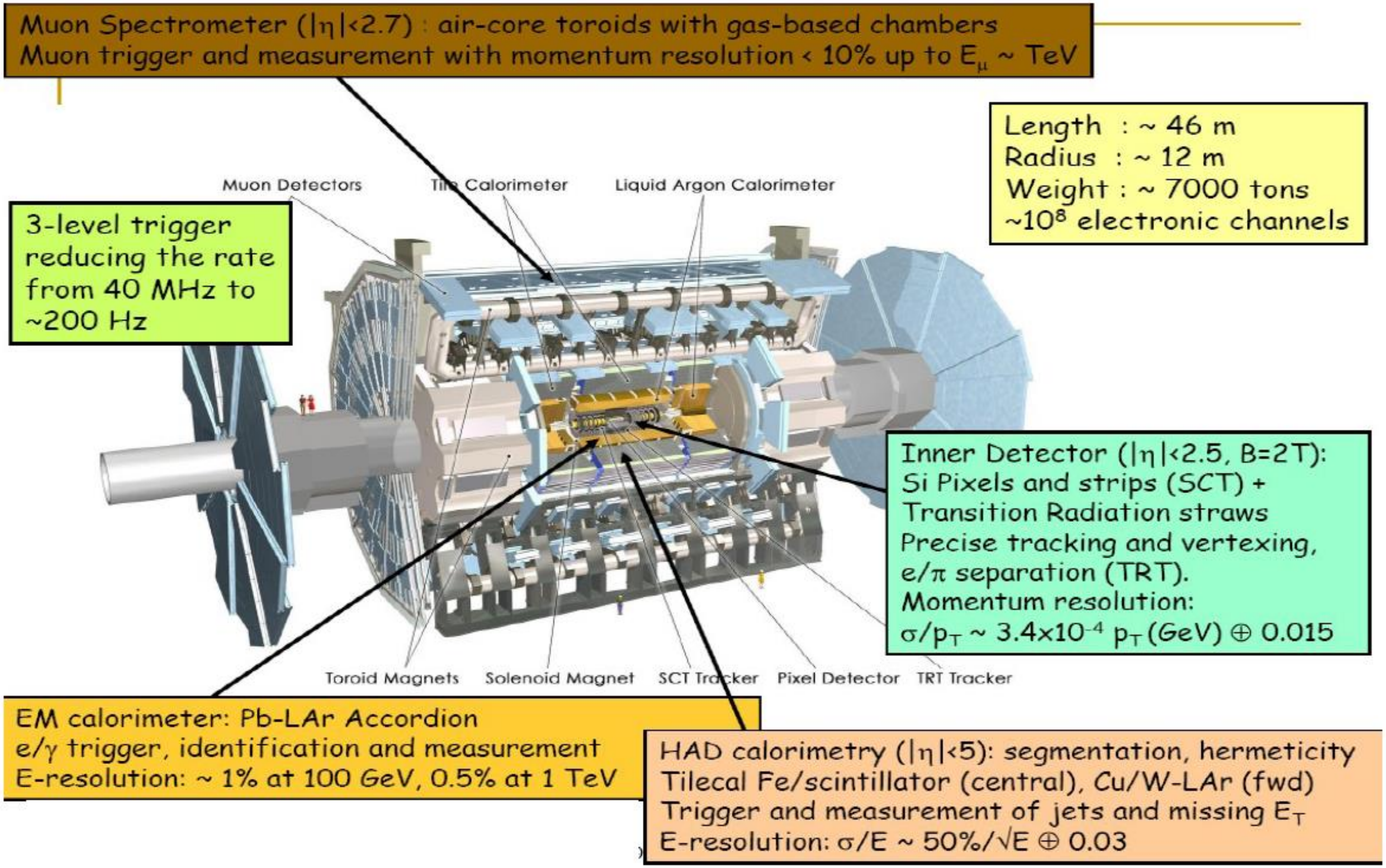
- A "jet" is a narrow cone of **hadrons** and other particles produced by the **hadronization** of a quark or gluon
- Jets are often best measured by total absorption rather than measurement of individual particles
  - Processes creating jets are complicated
    - Parton fragmentation, with electromagnetic or hadronic showering in the detector
  - Jet reconstruction is difficult
  - Jet energy scale and reconstruction is large source of uncertainty





- Measure energy in a "cone"

The ATLAS detector



Nuclear Instruments & Methods in Physics Research

topical issue

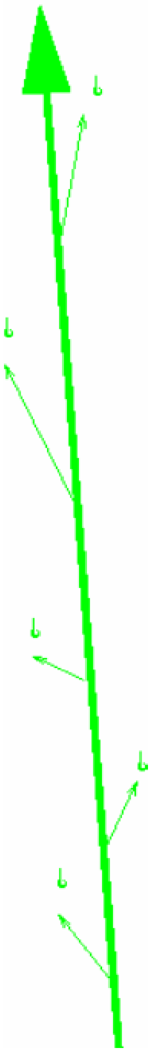
Instrumentation and detector technologies for frontier high energy physics

Volume 666, pages 1 - 222 (21 February 2012)

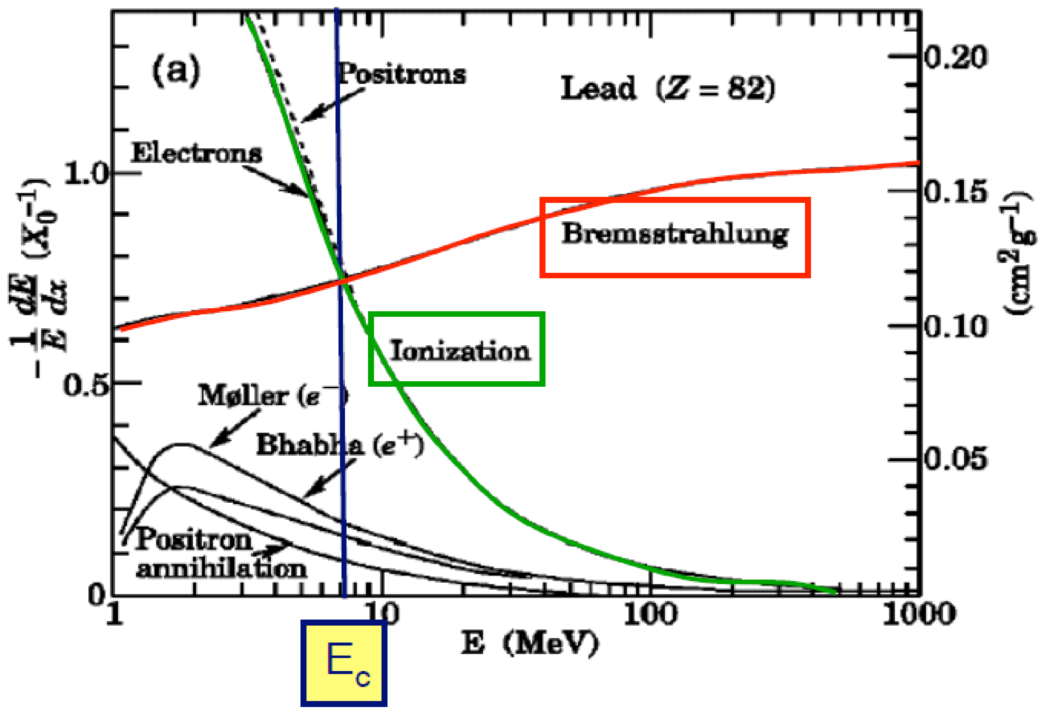
Edited by:
Archana Sharma (CERN)

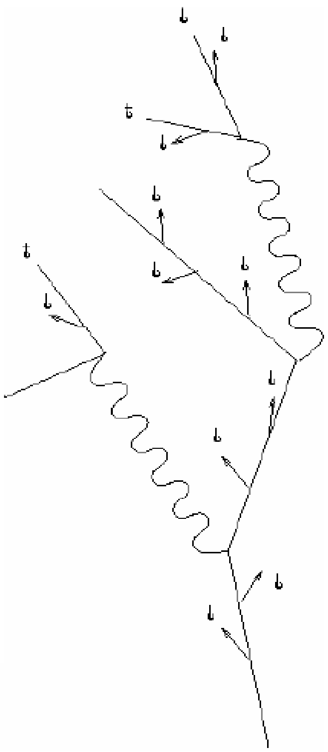
Technological advances in radiation detection have been pioneered and led by particle physics. The ever increasing complexity of the experiments in high energy physics has driven the need for developments in high performance silicon and gaseous tracking detectors, electromagnetic and hadron calorimetry, transition radiation detectors and novel particle identification techniques. Magnet systems have evolved with superconducting magnets being used in present and, are being designed for use in, future experiments. The alignment system, being critical for the overall detector performance, has become one of the essential design aspects of large experiments. The electronic developments go hand in hand to enable the exploitation of these detectors designed to operate in the hostile conditions of radiation, high rate and luminosity.
This volume provides a panorama of the state-of-the-art in the field of radiation detection and instrumentation for large experiments at the present and future particle accelerators.

Which processes contribute for electrons

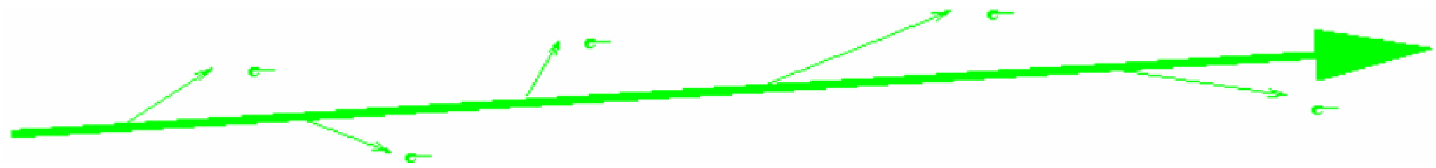


Electrons mainly loose their energy via ionization & Bremsstralung





Ionisation



Interaction of charged particles with the atomic electronic cloud.

Dominant process at low energy $E<E_c$.

The whole incident energy is ultimately lost in the form of ionisation and excitation of the medium.

Boethe-Bloch formula

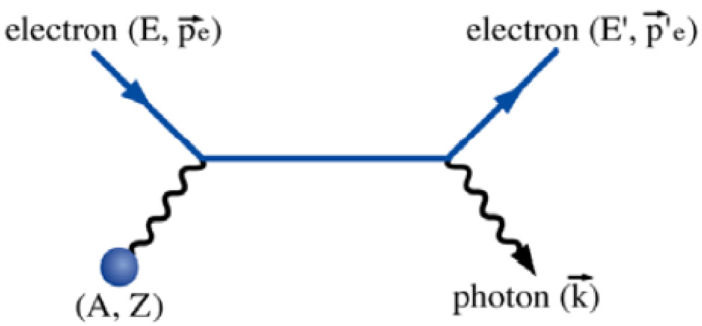
$\sigma \prec Z$

$$-\frac{dE}{dx}\bigg|_{ion} = N_A \frac{Z}{A} \frac{4\pi\alpha^2(\hbar c)^2}{m_e c^2} \frac{Z_i^2}{\beta^2}\left[\ln\frac{2m_e c^2\gamma^2\beta^2}{I} - \beta^2 - \frac{\delta}{2}\right]$$

where E is the kinetic energy of the incident particle with velocity β and charge Z_i, I ($\approx 10\times Z$ eV) is the mean ionization potential in a medium with atomic number Z.

Bremsstrahlung

Real photon emission in the electromagnetic field of the atomic nucleus



Electric field of the nucleus + of the electrons Z(Z+1)

At large radius, electrons screen the nucleus $\ln(183Z^{-1/3})$

$$d\sigma/dk = 4\,\alpha\,Z(Z+1)r_e^2 \ln(183Z^{-1/3})(4/3-4/3y+y^2)/k$$ [D.F.]

where y=k/E and $r_e = \frac{1}{4\pi\varepsilon_0}\cdot\frac{e^2}{m_e c^2} = 2.818\ 10^{-15}$ m classical radius of the electron.

→ For a given E, the average energy lost by radiation, dE, is obtained by integrating over y.

Bremsstrahlung

In this formulae $Z(Z+1) \sim Z^2$

$$-\frac{dE}{dx}\bigg|_{rad} = \left[4n\,\frac{Z^2\alpha^3(\hbar c)^2}{m_e^2c^4}\,\ln\frac{183}{Z^{1/3}}\right] E$$

where n is the number of nucleus/unit volume.

dE/dx is conveniently described by introducing the radiation length X_0

$$-\frac{dE}{dx}\bigg|_{Brem} = \frac{E}{X_0}$$

$$X_0 = \left[4n\,\frac{Z^2\alpha^3(\hbar c)^2}{m_e^2c^4}\,\ln\frac{183}{Z^{1/3}}\right]^{-1} \text{g/cm}^2$$

Approximation $X_0 \approx \frac{180A}{Z^2}\ g.cm^{-2}$

X_0 is most of the time expressed in [length] $X_0[g.cm^{-2}]/\rho$

Radiation length

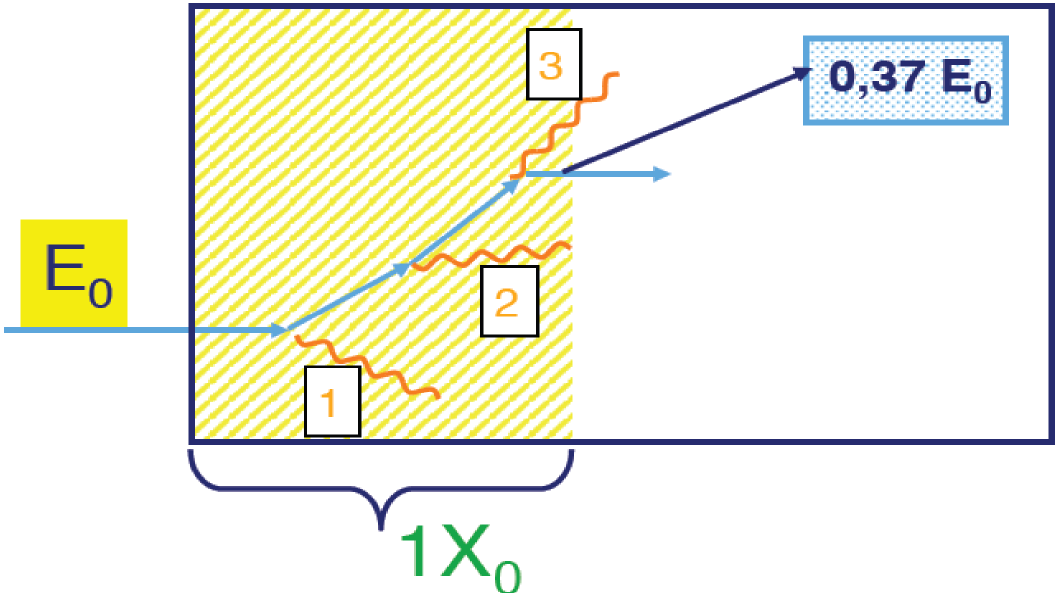
The radiation length is a "universal" distance, very useful to describe electromagnetic showers (electrons & photons)

X_0 is the distance after which the incident electron has radiated (1-1/e) 63% of its incident energy

$dE/dx=E/X_0$

$dE/E=dx/X_0$

$E=E_0e^{-x/X0}$



	Air	Eau	Al	LAr	Fe	Pb	$PbWO_4$
Z	-	-	13	18	26	82	-
X_0 (cm)	30420	36	8,9	14	1,76	0.56	0.89

Which processes contribute for photons

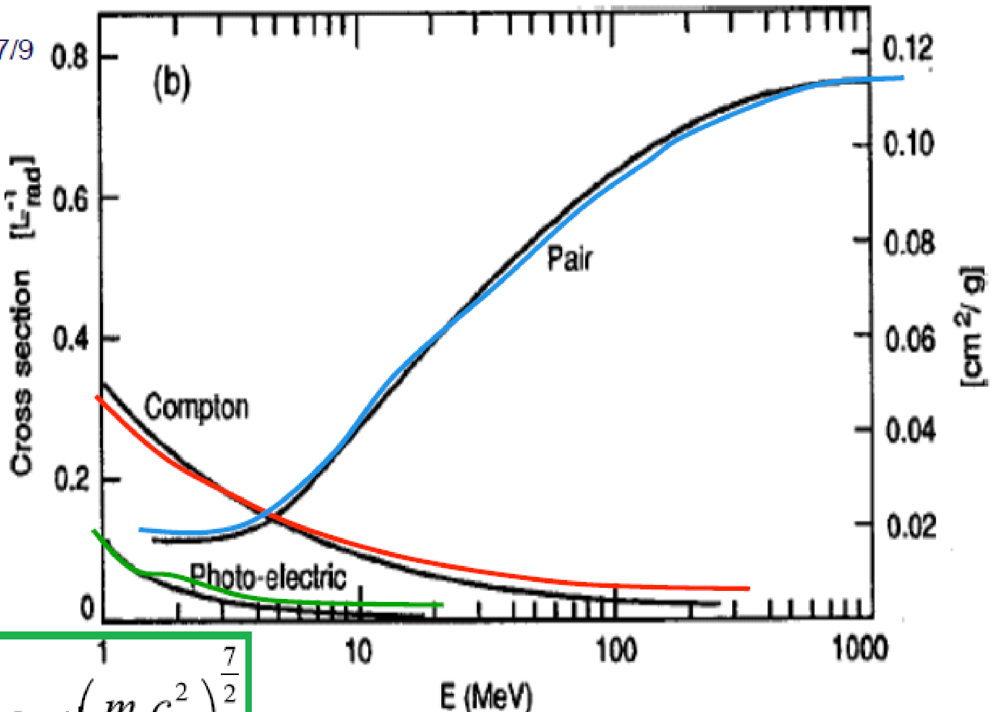
Pair Production

$$\sigma_{pair} \approx \frac{7}{9} \times \frac{A}{N_A} \times \frac{1}{X_0}$$

Probability of conversion in 1 X_0 is $e^{-7/9}$

Can define mean free path:

$$\lambda_{pair} \approx \frac{9}{7} X_0$$



Compton scattering

$$\sigma_C \approx \frac{\ln E_\gamma}{E_\gamma}$$

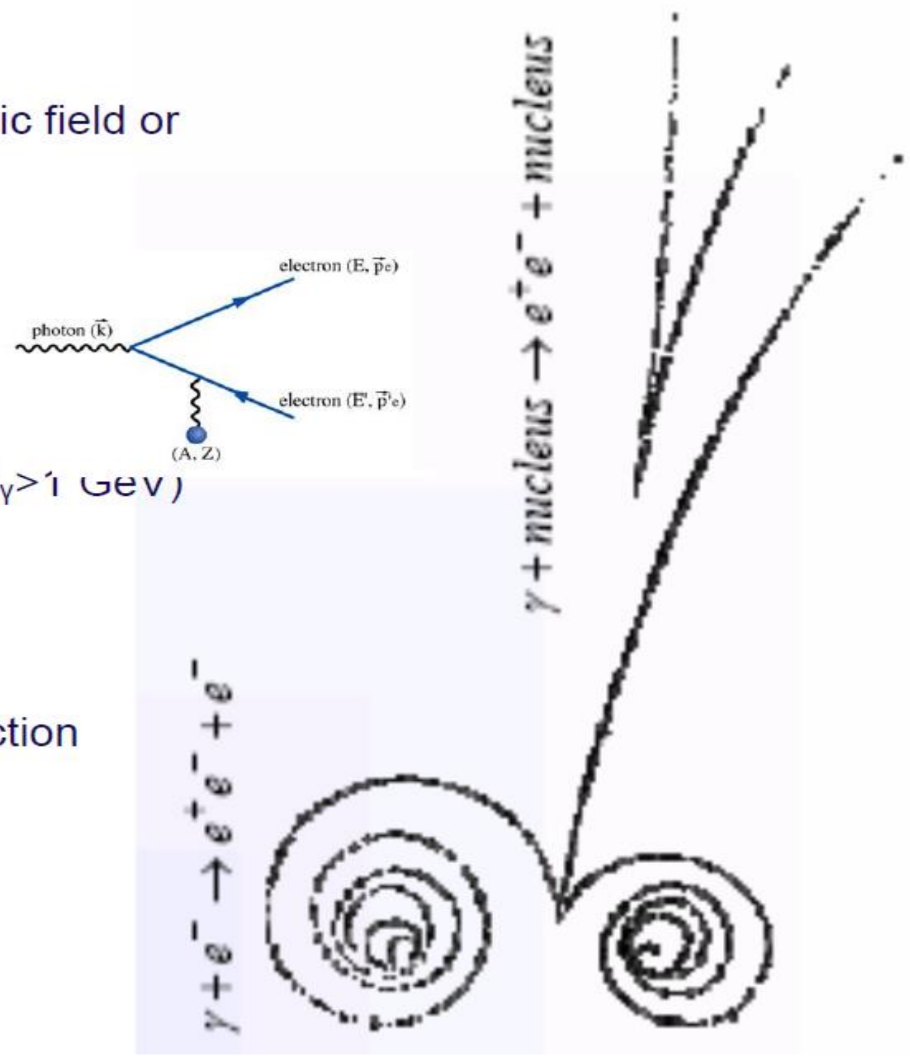
Photo-electric effect

$$\sigma_{pe} \approx Z^5 \alpha^4 \left(\frac{m_e c^2}{E_\gamma} \right)^{\frac{7}{2}}$$

Pair production

Photon interaction with nucleus electric field or electrons if $E_\gamma > 2.m_e.c^2$.

$$\sigma_{pair} \sim 7/9 \;.\; A/N_A \;.\; 1/X_0 \propto Z(Z+1)$$



Cross-section is independent of E_γ (E_γ>1 GeV)

Conversion length $\lambda_{conv} = 9/7\ X_0$

e^+e^- pair is emitted in the photon direction

$\theta \sim m_e/E_\gamma$

Photo-electric effect

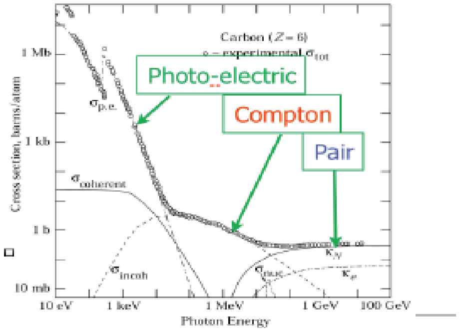
Photon extracts an electron from the atom

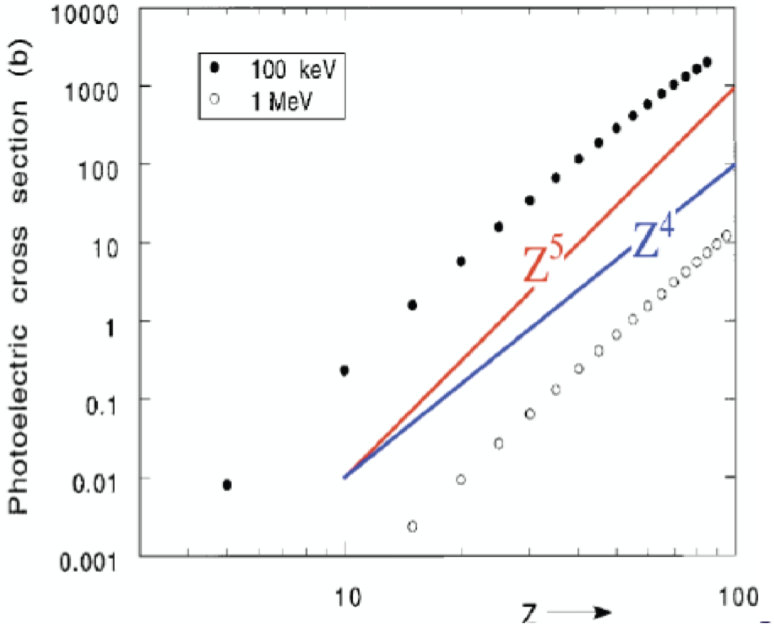
$\gamma + atom \rightarrow e^{-} + atom^{*}$

Electrons are not free → binding energy → discontinuities

Cross-section

- Strong function of the number of electrons
- Dominant at very low energy

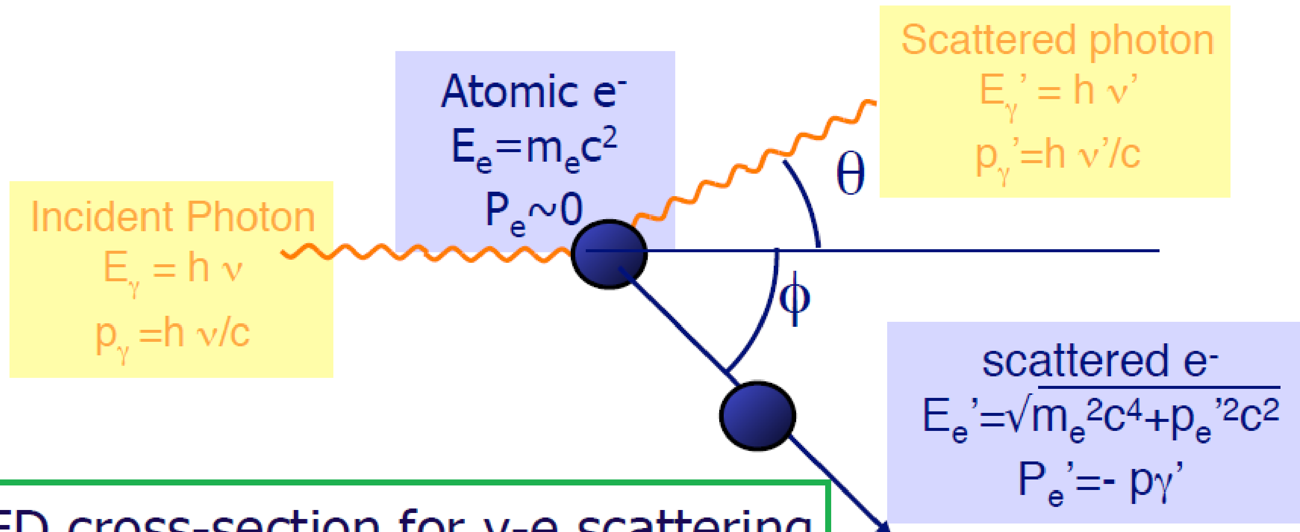




Electrons are emitted isotropically

$$\sigma \propto \frac{Z^5}{E^3}$$

Compton effect



QED cross-section for γ-e scattering

$$\sigma_{compton} \sim Z\,.\,\ln(E_\gamma)/E_\gamma$$

Process dominant at $E\gamma \simeq$ 100 keV - 5 GeV