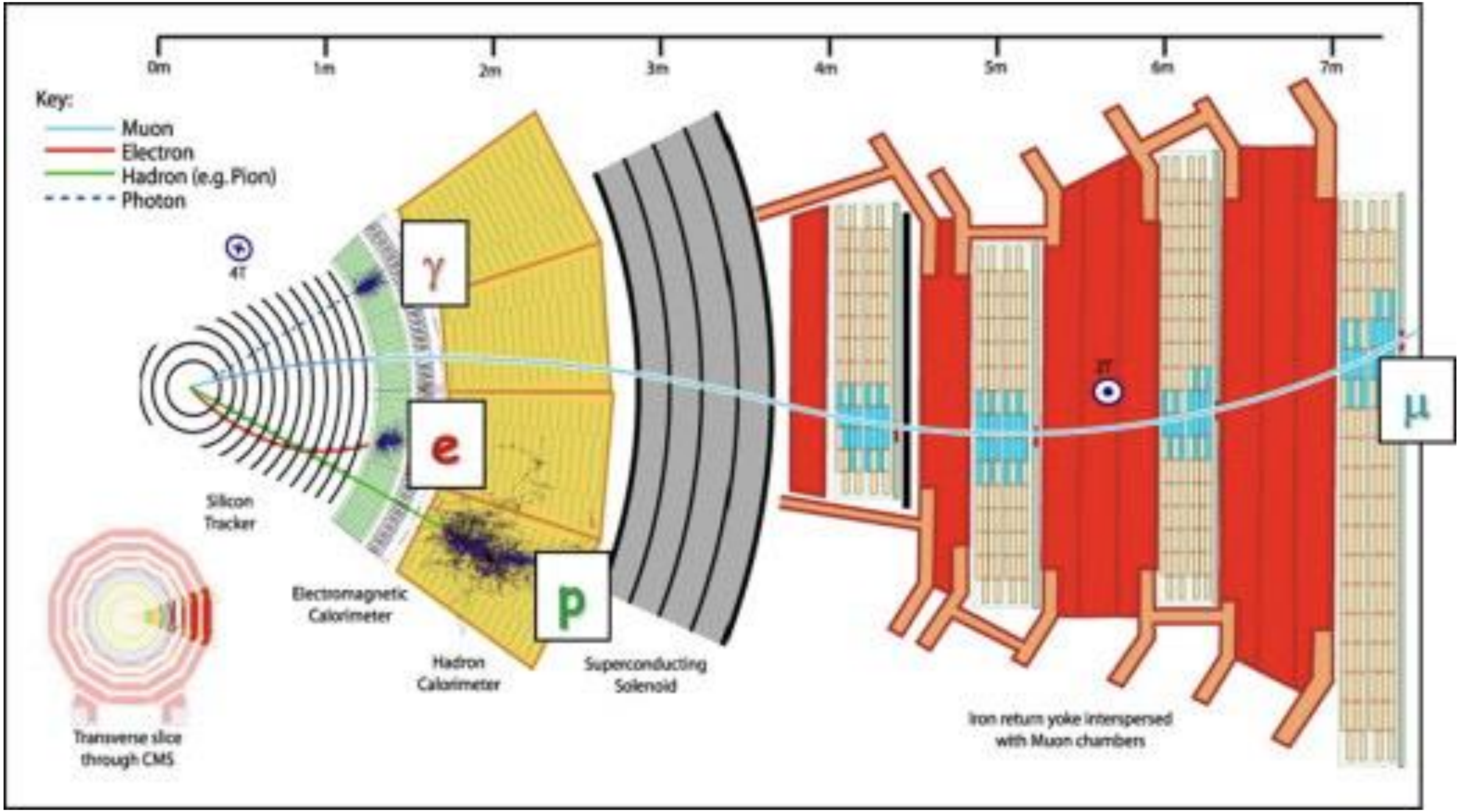
PREPARING FOR THE HANDS ON
Part 1
-
Elements of calorimetry

Concept of detectors in particle physics

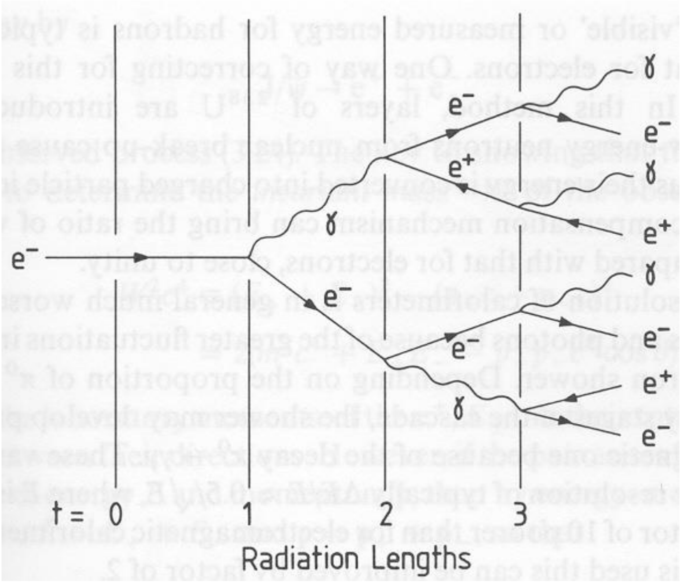
CMS @ the LHC



Calorimeters

❑ **Calorimeters** use partial or total absorption of particles and their showers to measure their energy

- Calorimeters are typically composed of small cells aligned along the direction of the incident particle, stacked up in towers
  - The alignment of these towers usually varies around the detector in order to maximize the probability of encompassing the shower at a given angle



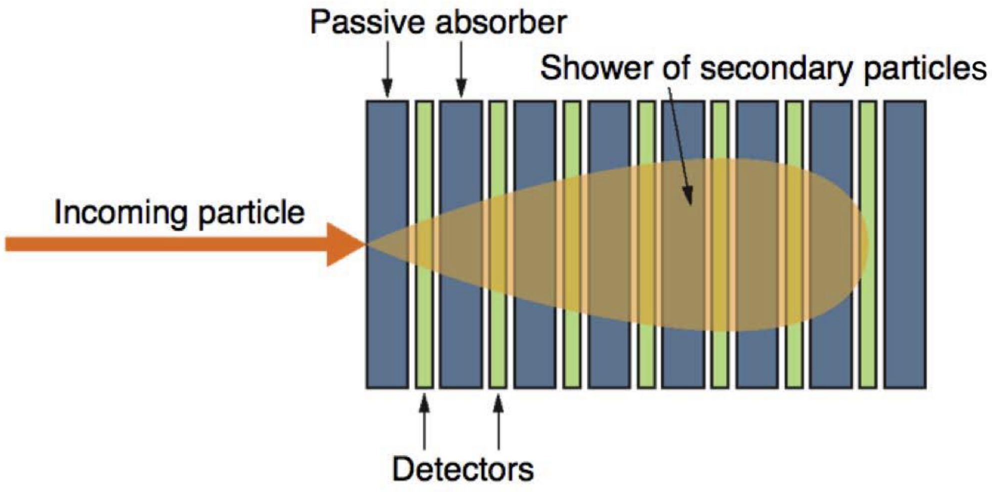
- Electrons, photons, and indeed π^0 mesons, which decay into photons, all produce electromagnetic showers
  - These showers are relatively compact and have a short shower-depth, therefore they are readily contained in a short distance by **electromagnetic calorimeters**
  - The size of an electromagnetic shower, and hence an electromagnetic calorimeter, is governed by the radiation length, X_0

Calorimeters

- Hadronic showers are generally much larger, and their shape fluctuates hugely from one event to another, hence **hadronic calorimeters** are larger than their electromagnetic counterparts
- Indeed, the response is lower, and the resolution is worse for hadrons in a hadronic calorimeter compared to electrons of the same energy in an electromagnetic calorimeter
- Most hermetic detectors use a calorimetry system that comprises both types of calorimeter
  - In such a composite calorimeter **the electromagnetic calorimeter is always the first layer the particles encounter** because whilst the heavy hadrons can pass through to the hadronic calorimeter beyond, electrons and photons would never reach their designated calorimeter if the hadronic calorimeter came first
- Although hadrons might start showering in the electromagnetic calorimeter, they can only be fully contained by the hadronic calorimeter. This is where all but the tiny fraction of energy that hadrons lost in the electromagnetic calorimeter, is deposited!

Calorimeters

- Considering what we said, the absorber material in an **electromagnetic calorimeter** should ideally **maximize the hadronic interaction length** (so as many hadrons can pass through with minimal interaction as possible) and **minimize the radiation length** (so the electromagnetic shower is fully developed within the electromagnetic calorimeter)
  - Their ratio approximately satisfies: $\lambda/X_0 \propto Z^{1/3}$
  - Maximizing this ratio means using **high-$\boldsymbol{Z}$ materials** like tungsten ($Z = 74$), lead ($Z = 82$) or uranium ($Z = 92$)
- There are two parts of any calorimeter
  - Active signal generators: the active material that measures the shower energy
  - Passive particle absorbers: the material that causes the particle to shower



Calorimeters

- There are two ways in which calorimeters can incorporate these two aspects:
  - homogeneous versus heterogeneous calorimeters
- In a **homogenous calorimeter** the active material and the absorber are the same
  - Examples of different signal exploited:

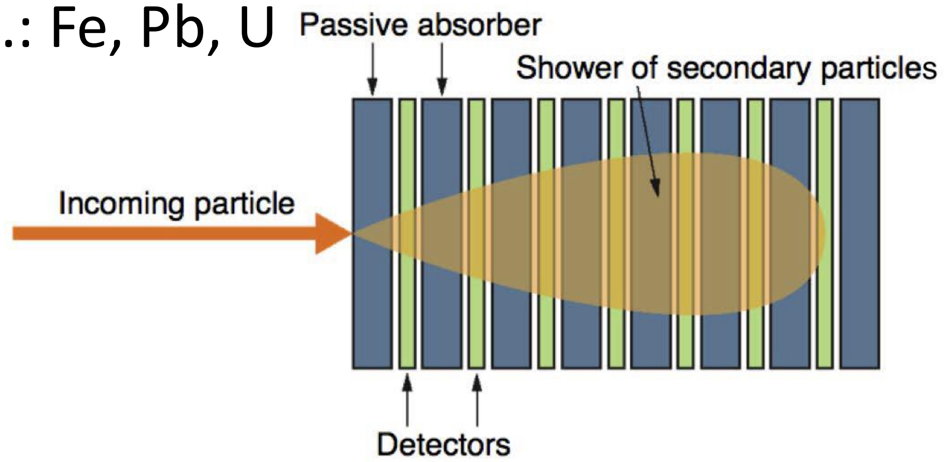
Signal	Material
Scintillation	BGO*, BaF_2, CeF_3, $PbWO_4$
Cherenkov light	Lead glass
Ionization	Liquid noble gasses (Ar, Kr, Xe), Germanium (in nuclear physics)

* Bismuth Germanate $Bi_4Ge_3O_{12}$

  - **Advantage:** Best possible energy resolution achievable
  - **Disadvantage:** Expensive
  - Homogenous calorimeters are primarily used as electromagnetic calorimeters

Calorimeters

- A **sampling calorimeter**, also known as sandwich calorimeter, consists of alternating layers of passive absorbers and active detectors
  - Typical absorbers are materials with high density, e.g.: Fe, Pb, U
  - Typical active detectors:
    - Plastic scintillators
    - Silicon detectors
    - Noble liquid ionization chambers
    - Gas detectors



- **Advantages:** can optimally choose the absorber and detector material independently and according to the application
  - By choosing a very dense absorber material the calorimeters can be made very compact
  - The passive absorber material is cheap
- **Disadvantages:** Only part of the energy is deposited in the detector layers and measured
  - Energy resolution is worse than in homogeneous calorimeter (“Sampling-Fluctuations”)

Electromagnetic showers

An ElectroMagnetic (EM) shower is a cascade of secondary electrons/positrons and photons initiated by the interaction with matter (ie, energy loss) of an incoming of electron/positron or photon.

- The main energy loss mechanism are:

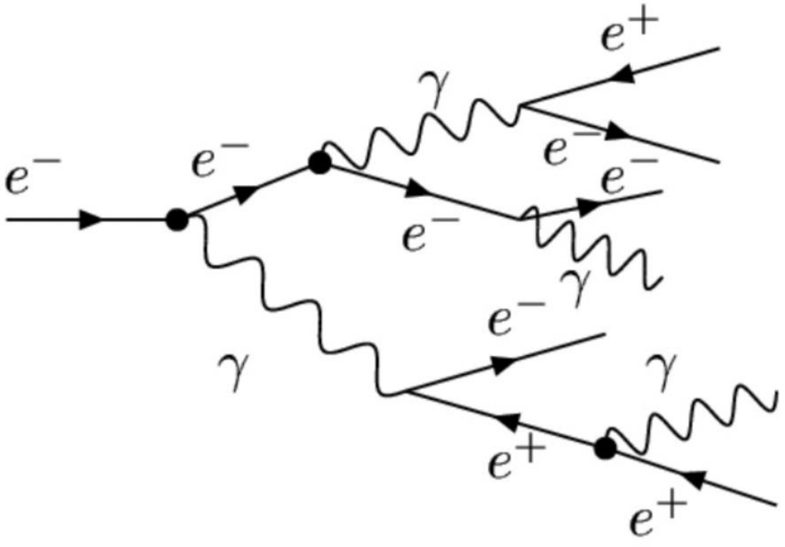
  - Ionization
  - Bremsstrahlung

  } for e+/e-

Relevant at high energy: E > ~few MeV

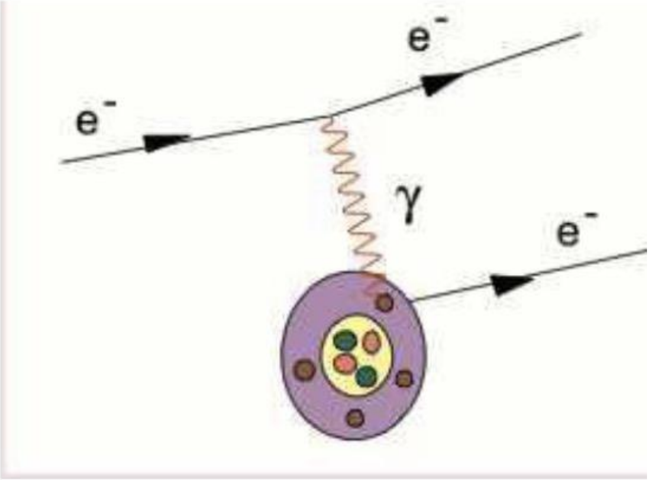
  - Compton scattering
  - Pair creation
  - Photo-electric effect

  } for γ



Electromagnetic showers - ionization

- Interaction of charged particles with electron cloud of atoms (loss of electrons, atoms -> ions)



- **Dominant process at low energy**

- **Bethe-Bloch formula** (general)

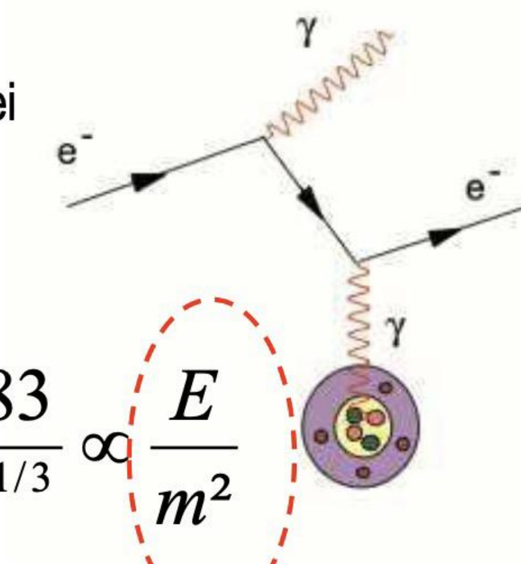
$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$ ($MeV.g^{-1}.cm^2$)

Energy loss depends:

- quadratic ally on the charge and velocity of the incident particle (but not on its mass)
- Linearly on the material (through electron density)
- Logarithmically on the material (through mean ionization I)

Electromagnetic showers - bremsstrahlung

- Radiation of real photons in the Coulomb field of the atomic nuclei
- **Dominant process at high energy**



$$\left(-\frac{dE}{dx}\right)_{rad} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{mc^2}\right)^2 E \ln\frac{183}{Z^{1/3}} \propto \frac{E}{m^2}$$

- Important for electrons, much less for muons (apart from ultra-relativistic)

$$\left(-\frac{dE}{dx}\right)_{rad} = 4\alpha N_A \frac{Z^2}{A} r_e{}^2 E \ln\frac{183}{Z^{1/3}}$$ (for electrons)

- Conveniently re-written as: $\left(\frac{dE}{dx}\right)_{rad} = \frac{E}{X_0}$

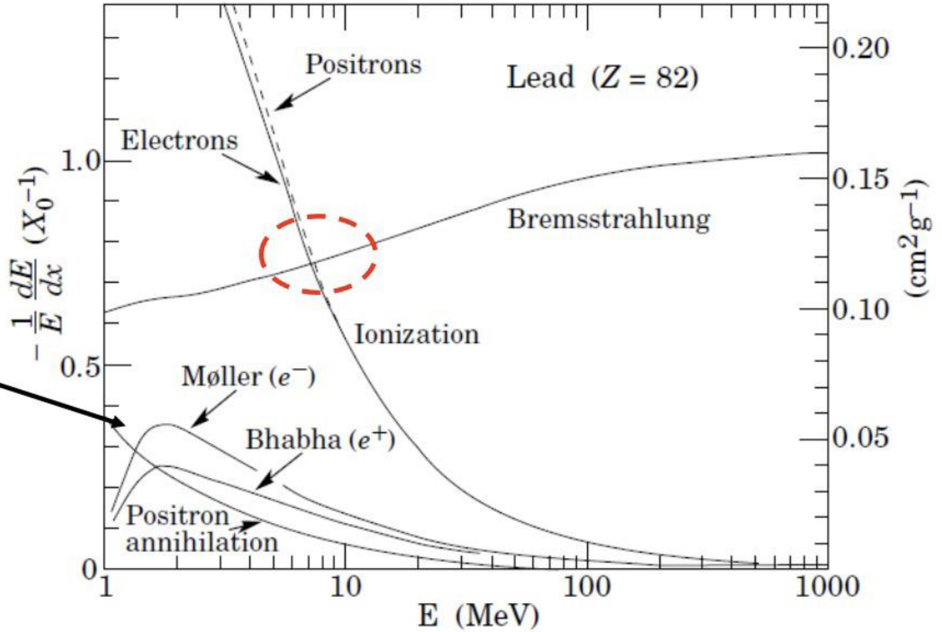
Radiation length

$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e{}^2 \ln\frac{183}{Z^{1/3}}}$$

Electromagnetic showers – critical energy

Fractional energy loss for electrons/positrons in Lead

Other processes (Bhabha, meller, …) neglected in HEP (most of the time)



- Radiation (ionization) dominant at high (low) energies
- Crossing point: $\left(\frac{dE}{dx}\right)_{rad}(E_C) = \left(\frac{dE}{dx}\right)_{ioniz}(E_C)$ E_C: **critical energy** Strongly material dependent (scales as 1/Z)

- **Examples:**

Material	W	Pb	(liquid) Ar	Cu
Z	74	82	29	13
E_C(MeV)	8,4	7,1	37	20,2

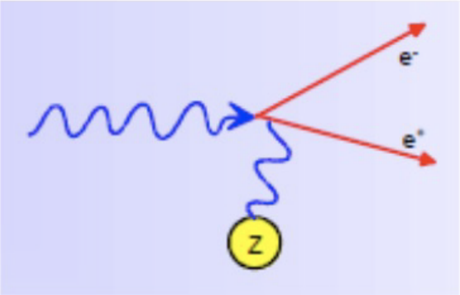
$$E_C(solid) = \frac{610\ \text{MeV}}{Z + 1.24}$$

$$E_C(liquid) = \frac{710\ \text{MeV}}{Z + 0.92}$$

Electromagnetic showers – pair production

- Can only occurs in the Coulomb field of a nucleus (or an electron) if $E_\gamma > 2m_ec^2$

$$\gamma + nucleus \rightarrow e^+e^- + nucleus$$



$$\sigma_{pair} \approx 4\alpha r_e^2 Z^2 \left(\frac{7}{9} \ln \frac{183}{Z^{1/3}} \right) \approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0}$$

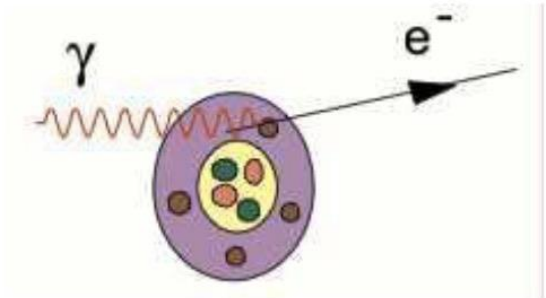
- Mean free path of photon before it creates a pair $\lambda_{pair} \approx \frac{9}{7} X_0$

- **Remarks:**
  - $\sigma_{pair} \propto Z(Z+1)$
  - Photons have a high penetrating power than electrons
  - Pair creation is independent of incident energy (for E_γ>1 GeV)
  - e+e- is **emitted in photon direction**

Electromagnetic showers – photo-electric effect

- Photon extract an electron from the atom

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



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

- **Remarks:**
  - $\sigma_{pe} \propto Z^5, E^{-3.5}$
  - Electrons are emitted (more or less) **isotropically**

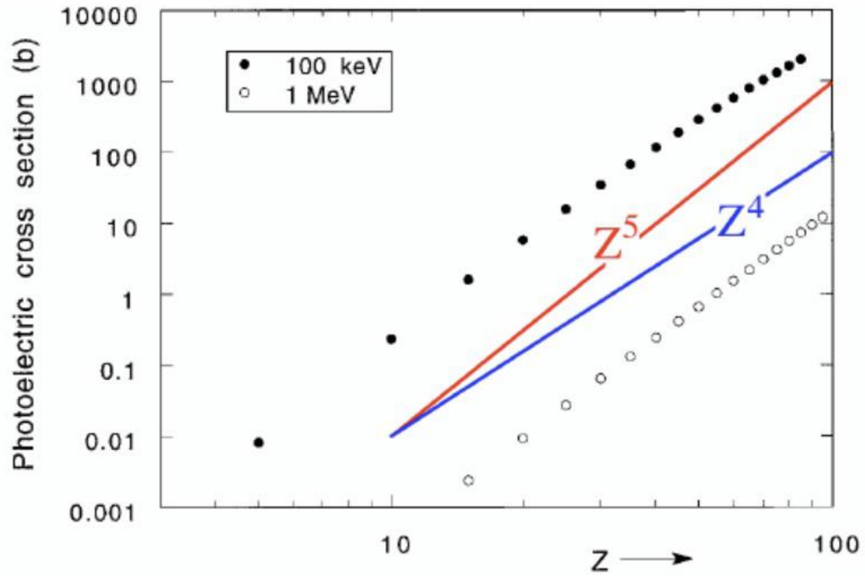
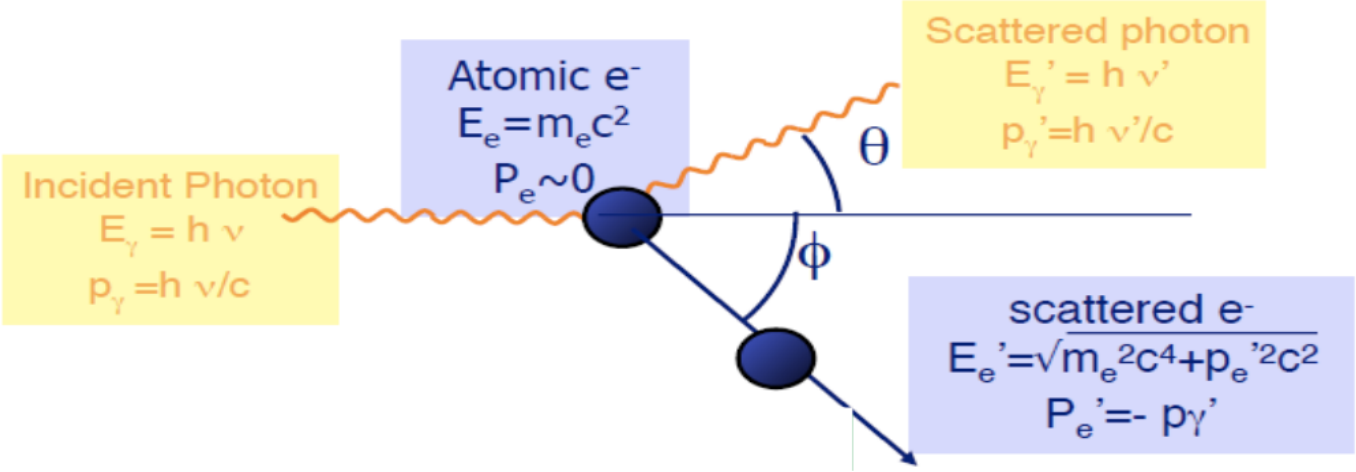


FIG. 2.3. Cross section for the photoelectric effect as a function of the Z value of the absorber. Data for 100 keV and 1 MeV γs.

Electromagnetic showers – Compton scattering

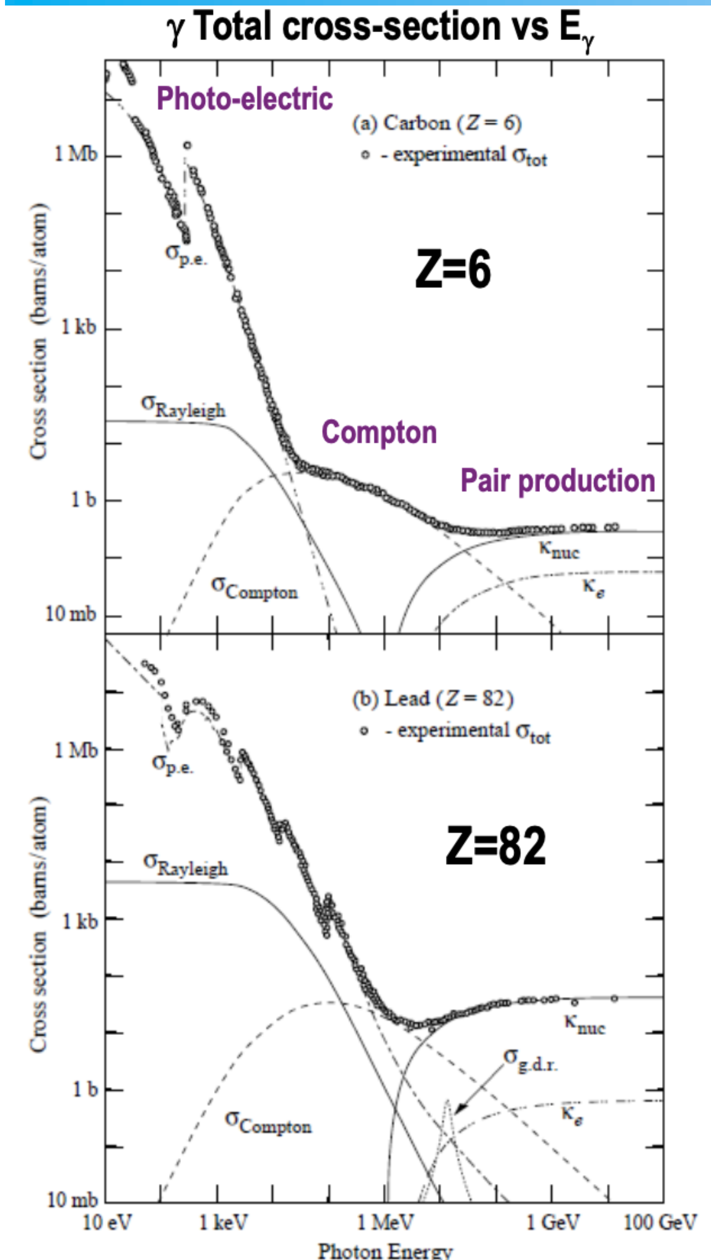
$$\gamma + e \rightarrow \gamma' + e'$$



$$\sigma_{Compton} \approx Z \frac{\ln E_\gamma}{E_\gamma}$$

- **Remarks:**
  - $\sigma_{Compton} \propto Z, E^{-1}$
  - Electrons are emitted (more or less) **isotropically**

The importance of different processes



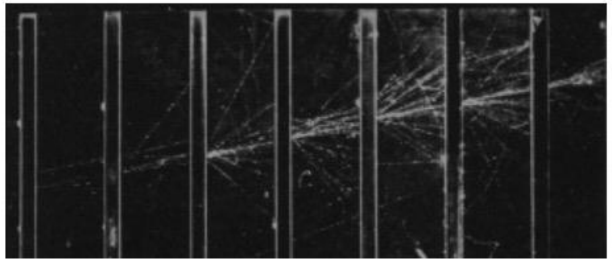
- Photo-electric: dominant at very low energy
- Compton: dominant for Eγ~100 KeV – 5 GeV
- Pair Production: dominant at higher energies

Electromagnetic showers – a simple model

Simplified model [Heitler]: shower development governed by X_0

e^- loses [1 - 1/e] = 63% of energy in 1 Xo (Brems.)

the *mean free path* of a γ is 9/7 Xo (pair prod.)



Lead absorbers in cloud chamber

Assume:

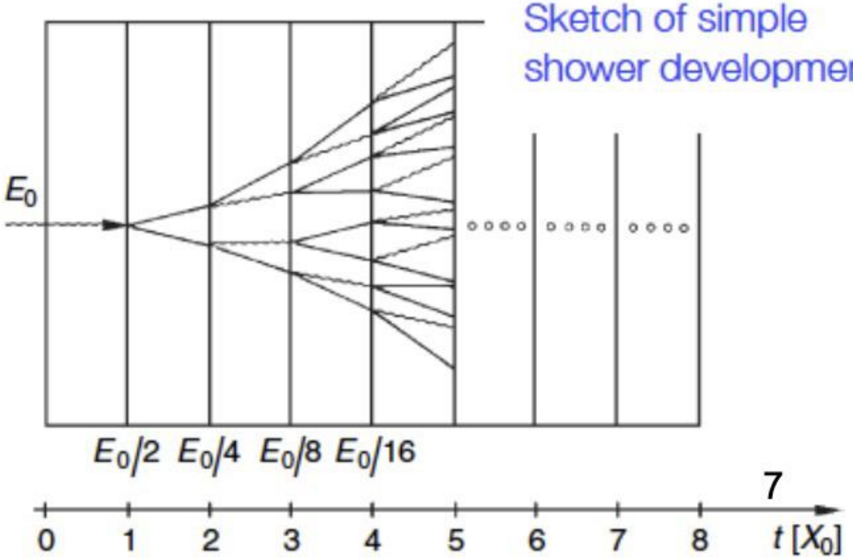
$E > E_c$: no energy loss by ionization/excitation

$E < E_c$: energy loss only via ionization/excitation

Simple shower model:

- 2^t particles after t [X_0]
- each with energy $E/2^t$
- Stops if E < critical energy ε_C
- Number of particles $N = E/\varepsilon_C$
- Maximum at $t_{\max} \propto \ln(E_0/E_c)$

Sketch of simple shower development



Electromagnetic showers – a simple model

Simple shower model quite powerful → characterized shower by:

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

$$N_{\max} = 2^{t_{\max}} = \frac{E_0}{E_c}$$

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

$$L \sim \ln \frac{E}{E_c}$$

Longitudinal shower distribution increases only logarithmically with the primary energy of the incident particle, i.e. calorimeters can be compact

Some numbers: $E_c \approx 10$ MeV, $E_0 = 1$ GeV → $t_{max} = \ln 100 \approx 4.5$; $N_{max} = 100$
$E_0 = 100$ GeV → $t_{max} = \ln 10000 \approx 9.2$; $N_{max} = 10000$

	Szint.	LAr	Fe	Pb	W
X_0(cm)	34	14	1.76	0.56	0.35

→ 100 GeV electron contained in 16 cm Fe or 5 cm Pb

Electromagnetic showers – longitudinal profile

Longitudinal profile

Parametrization:
[Longo 1975]

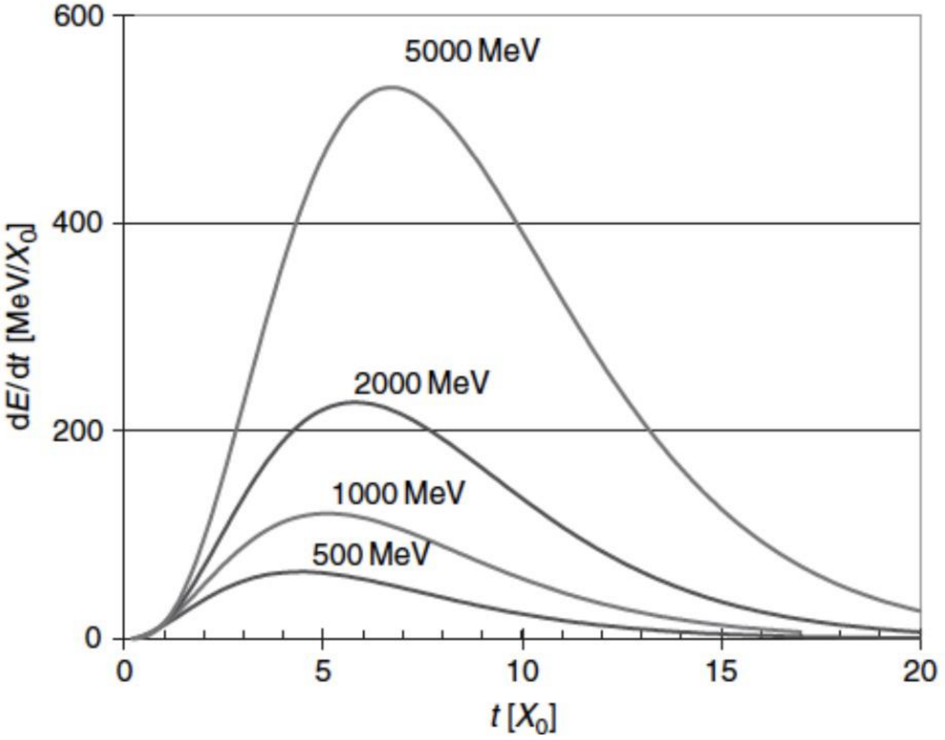
$$\frac{dE}{dt} = E_0\, t^{\alpha} e^{-\beta t}$$

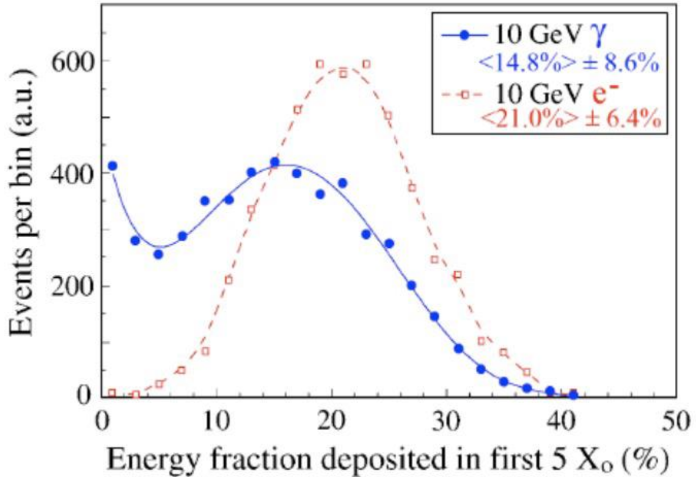
α,β : free parameters

t^{α} : at small depth number of secondaries increases ...

$e^{-\beta t}$: at larger depth absorption dominates ...

Numbers for E = 2 GeV (approximate):
$\alpha = 2$, $\beta = 0.5$, $t_{max} = \alpha/\beta$





important *differences between* showers induced by *e*, γ

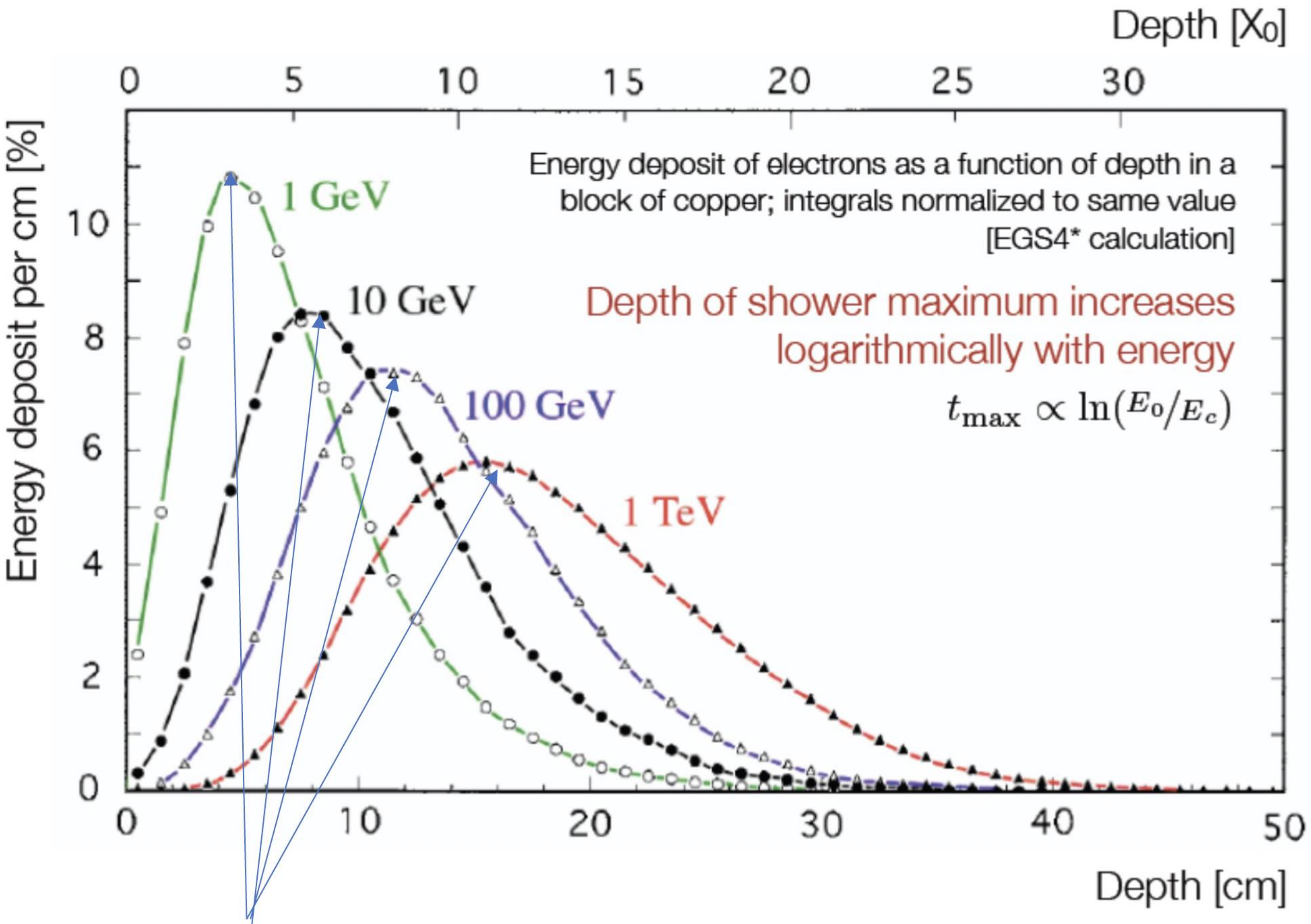
$$t_{\max} = \frac{\alpha - 1}{\beta} = \ln\left(\frac{E_0}{E_c}\right) + C_{e\gamma}$$

with:

$C_{e\gamma} = -0.5$ [γ-induced]

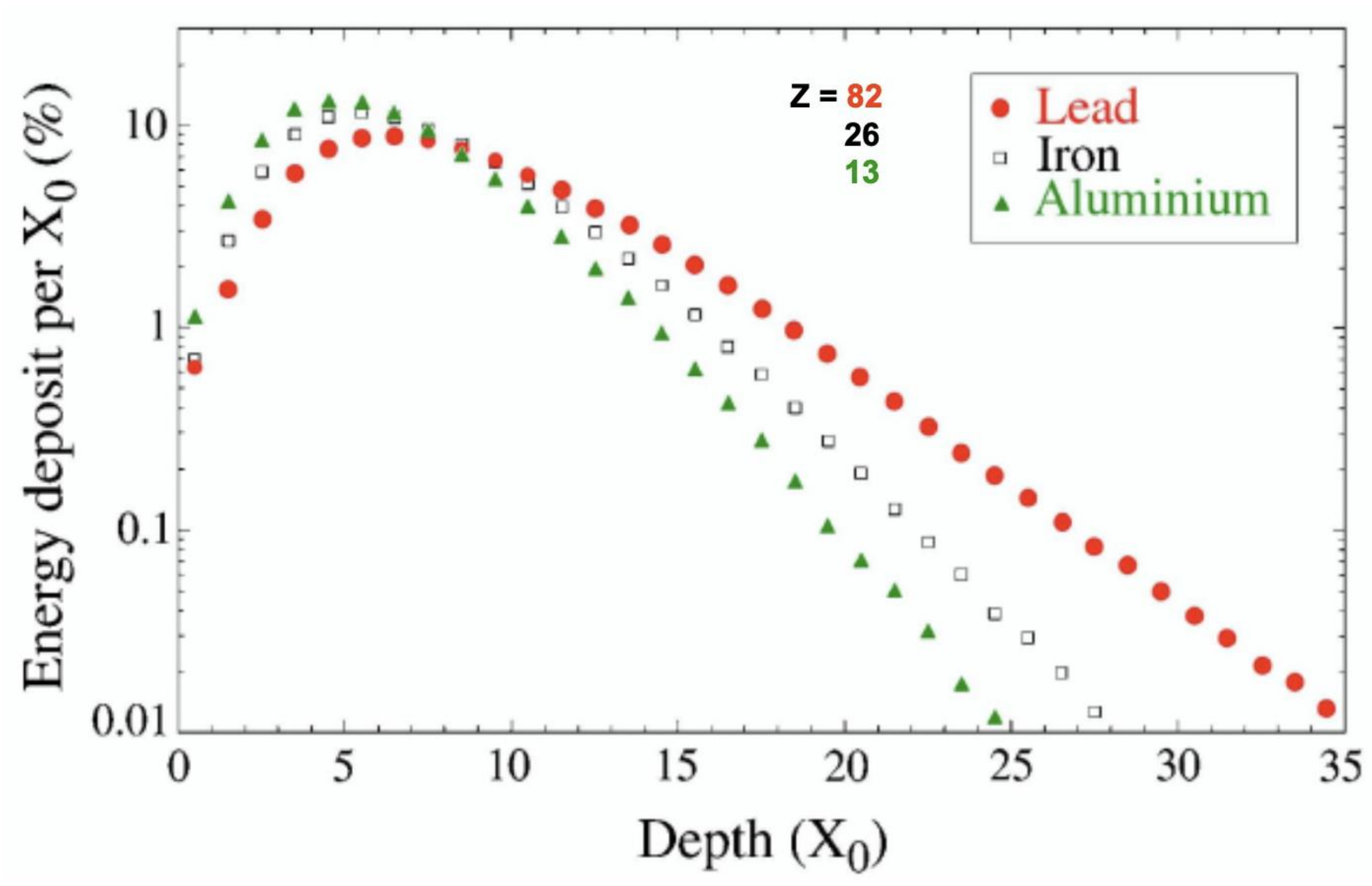
$C_{e\gamma} = -1.0$ [e-induced]

Electromagnetic showers – longitudinal profile



Shower max grows with ln(E)

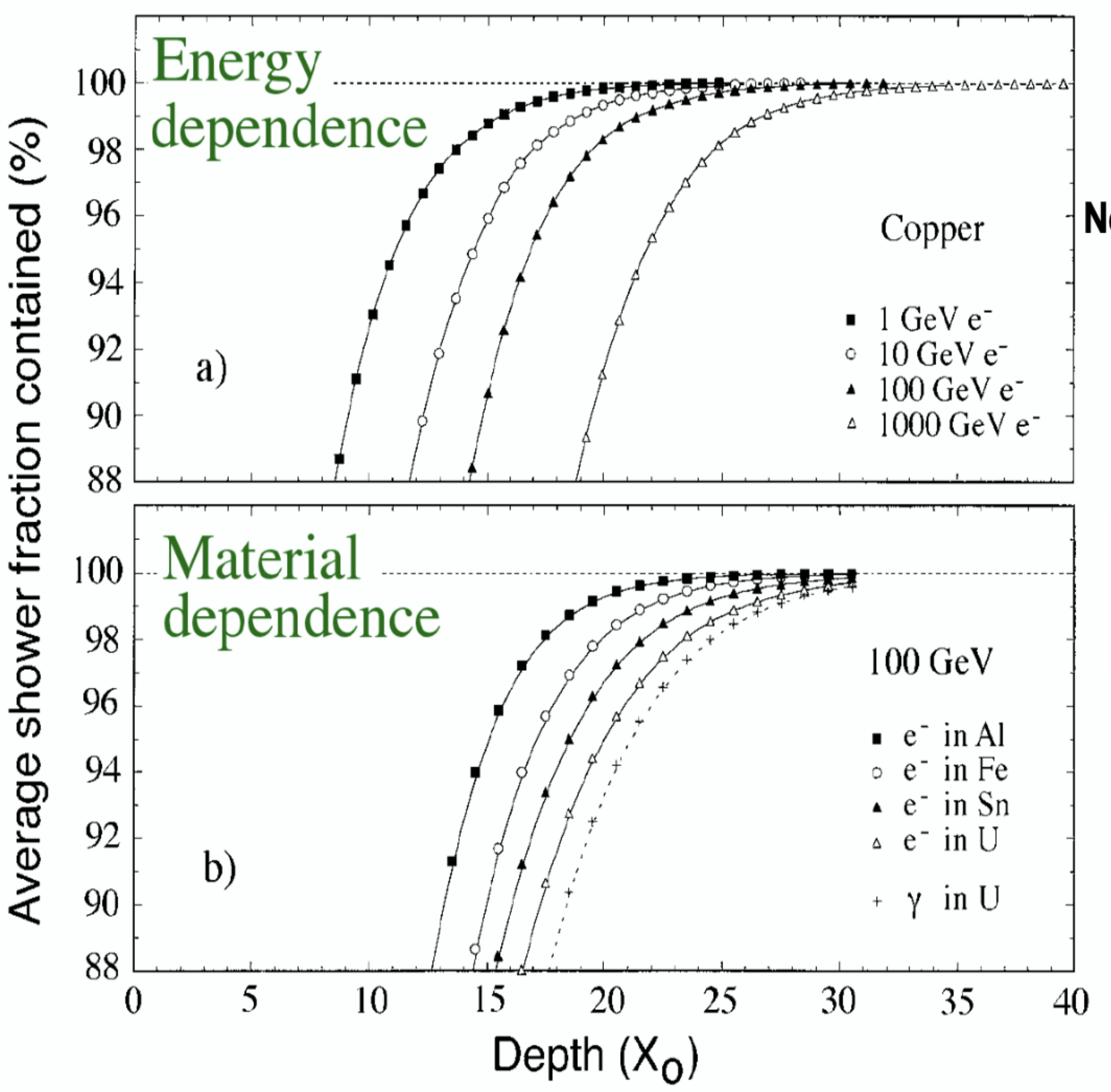
Electromagnetic showers – longitudinal profile



Shower decay:

- **after** reaching its **maximum**, the shower **decays slowly** through **ionization** and **Compton scattering**
  - ⇨ NOT proportionally to X_0

Electromagnetic showers – longitudinal containment



Need about 25-30 X_0 to contain shower
(depending on the energy of interest, material)

Longitudinal containment:

$$t_{95\%} = t_{max} + 0.08Z + 9.6$$

Calorimeter can be compact !

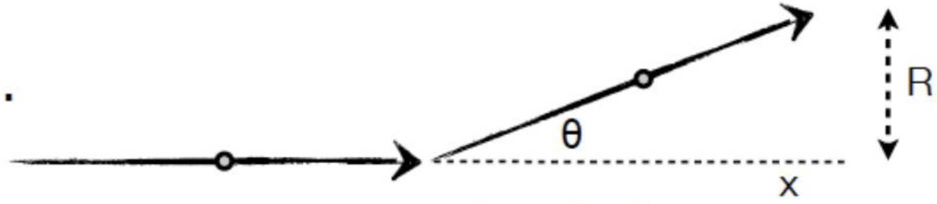
Electromagnetic showers – lateral profile

Opening angle:

1) bremsstrahlung and pair production

$$\langle\theta^2\rangle \approx (m/E)^2 = 1/\gamma^2$$

Small contribution as $m_e/E_c = 0.05$



Lateral extension: R = x·tanθ ≈ x·θ, if θ small ...

2) multiple coulomb scattering
[Mollier theory]

$$\langle\theta\rangle = \frac{21.2\ \mathrm{MeV}}{E_e}\sqrt{\frac{x}{X_0}}$$ [β = 1, c = 1, z = 1]

$$E_s = \sqrt{\frac{4\pi}{\alpha}}(m_e c^2) = 21.2\ \mathrm{MeV}$$ [Scale Energy]

Lateral spread:

Main contribution from low energy electrons as <θ> ~ $1/E_e$, i.e. for electrons with $E = E_c$

Assuming the approximate range of electrons to be X_0 yields <θ>≈ 21 MeV/E_e ➝ lateral extension: R =<θ>X_0

Mollier radius: $$R_M = \frac{E_s}{E_c}X_0 \approx \frac{21MeV}{E_c}X_0$$

Electromagnetic showers – lateral profile

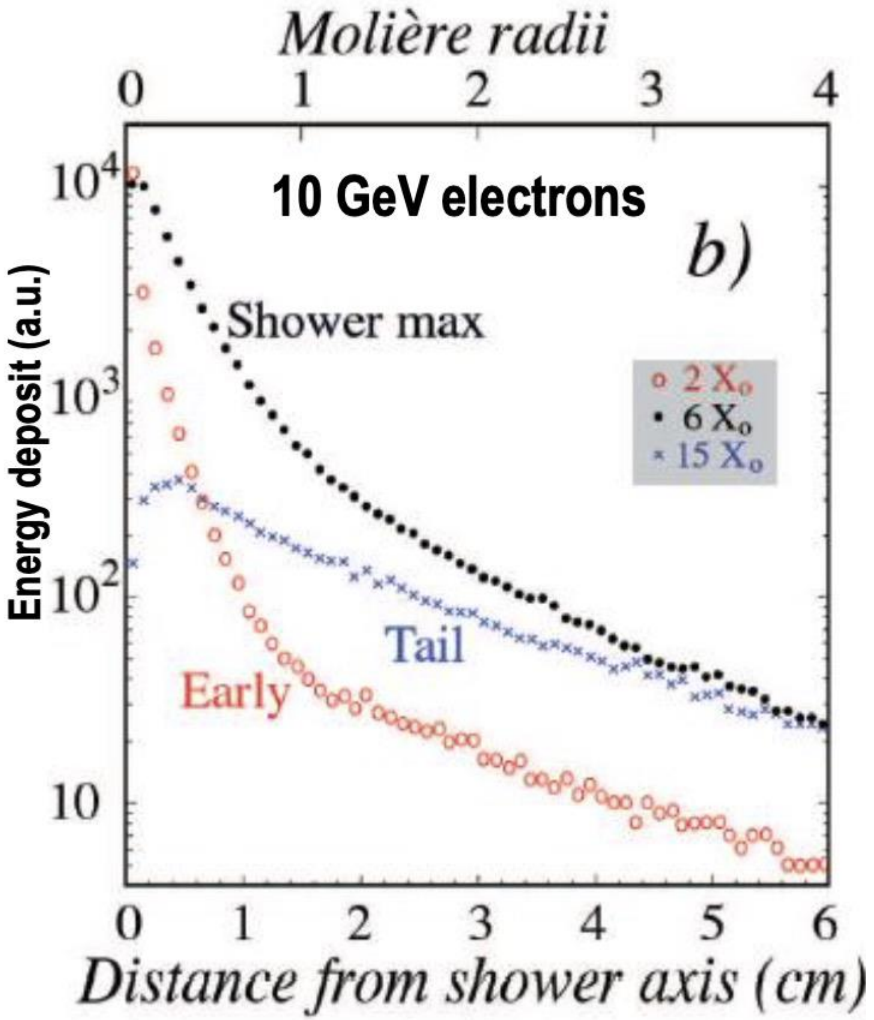
- **Moliere radius:** characteristic of a material giving the scale of the transverse dimension of an EM shower

$$R_M = \frac{21MeV}{E_C} X_0$$ (g.cm^{-2})

Scales as A/Z, while X0 scales as A/Z². much less dependent on material than X_0 !

- 90% of shower energy contained in a cylinder of $1R_m$
- 95% of shower energy contained in a cylinder of $2R_m$
- 99% of shower energy contained in a cylinder of $3.5R_m$

- Lateral shower width determined by:
  - Multiple scattering of e+/e- (early, up to shower max) => "core"
  - Compton γ away from axis (beyond shower max) => "halo"



Radial distributions of EM showers in Cu at various depth

Useful properties of some materials

Material	Z	Density [g cm^{-3}]	E_c [MeV]	X_0 [mm]	R_M [mm]	λ_{int} [mm]	$(dE/dx)_{mip}$ [MeV cm^{-1}]
C	6	2.27	83	188	48	381	3.95
Al	13	2.70	43	89	44	390	4.36
Fe	26	7.87	22	17.6	16.9	168	11.4
Cu	29	8.96	20	14.3	15.2	151	12.6
Sn	50	7.31	12	12.1	21.6	223	9.24
W	74	19.3	8.0	3.5	9.3	96	22.1
Pb	82	11.3	7.4	5.6	16.0	170	12.7
^{238}U	92	18.95	6.8	3.2	10.0	105	20.5
Concrete	-	2.5	55	107	41	400	4.28
Glass	-	2.23	51	127	53	438	3.78
Marble	-	2.93	56	96	36	362	4.77
Si	14	2.33	41	93.6	48	455	3.88
Ge	32	5.32	17	23	29	264	7.29
Ar (liquid)	18	1.40	37	140	80	837	2.13
Kr (liquid)	36	2.41	18	47	55	607	3.23
Polystyrene	-	1.032	94	424	96	795	2.00
Plexiglas	-	1.18	86	344	85	708	2.28
Quartz	-	2.32	51	117	49	428	3.94
Lead-glass	-	4.06	15	25.1	35	330	5.45
Air 20°, 1 atm	-	0.0012	87	304 m	74 m	747 m	0.0022
Water	-	1.00	83	361	92	849	1.99

Useful formulae for e.m. showers

Radiation Length:

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

Radiation Length for composite material:

$$\frac{1}{X_0} = \sum \frac{w_j}{X_j}$$

w_j: fraction of material j
X_j: radiation length of material j
(in g.cm-2)

Moliere Radius:

$$R_M = \frac{21MeV}{E_C} X_0$$

Moliere Radius for composite material:

$$\frac{1}{R_M} = \sum \frac{w_j}{R_{M\,j}}$$

w_j: fraction of material j
R_{Mj}: Moliere Radius of material j
(in g.cm-2)

Energy Resolution:

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

$\oplus$: quadratic sum
S: Stochastic
N: noise
C: constant

Useful formulae for e.m. showers

$$E_C(solid) = \frac{610\,\text{MeV}}{Z+1.24}$$

$$E_C(liquid) = \frac{710\,\text{MeV}}{Z+0.92}$$

E_C: critical energy

Shower maximum

$$t_{max} = \frac{\ln E_0 / E_C}{\ln 2}$$

$$N(t_{max}) \approx \frac{E_0}{E_C}$$

Longitudinal containment:

$$t_{95\%} = t_{max} + 0.08Z + 9.6$$

$$\frac{\sigma_E}{E} = 3.2\% \sqrt{\frac{E_c\,[\text{MeV}] \cdot t_{abs}}{F \cdot E\,[\text{GeV}]}}$$

(stochastic contribution)

t_{abs}: thickness of absorber (in units of X_0)

F: factor (~0.2 for liquid noble gaz, 0.06 for Si, ~1 for scintillators)

Energy resolution

- The accuracy with which a calorimeter reports the energy of a particle is usually expressed as a fraction of the **particle's energy**, and comprises four separate contributions added in quadrature:

$$\left(\frac{\sigma}{E}\right)_{total} = \left(\frac{\sigma}{E}\right)_{statistical} \oplus \left(\frac{\sigma}{E}\right)_{instrumental} \oplus \left(\frac{\sigma}{E}\right)_{systematic} \oplus \left(\frac{\sigma}{E}\right)_{sampling}$$

Contribution	Scales as	Origin of errors and their scaling	Energy range
Statistical	$\propto \frac{1}{\sqrt{E}}$	Showers are inherently statistical processes, thus the energy deposited varies according to a Poisson distribution: $\sigma/E = \sqrt{N}/N = 1/\sqrt{N}$. Since the energy deposited is proportional to the number of hits ($N \propto E$), this can be written as $\sigma/E \propto 1/\sqrt{E}$.	This contribution is the most significant and dominates over most of the useful range of calorimeters.
Instrumental	$\propto \frac{1}{E}$	The effect of noise and stray capacitance is largely energy independent, hence the relative contribution (σ/E) scales as $1/E$.	This contribution tends to dominate at low energies.
Systematic	constant	Systematic errors include calibration errors and non-uniformity of the calorimeter. Non-uniformity at high energies can limit accuracy to no-better than 2%. Usually, some average fraction of the energy leaks out of the calorimeter as it fails to completely contain the shower. These scale with energy, hence the relative contribution is energy independent.	This contribution usually sets the limit for performance at high energies.
Sampling	$\propto \sqrt{\frac{\Delta E}{E}}$	In sampling calorimeters the sampling fluctuations have to be added, with ΔE the energy loss of one particle in one layer.	This is only of significance in sampling calorimeters.

Energy resolution in e.m. calorimeters

- In **electromagnetic calorimeters** the statistical errors result from variations in the track length of the charged particles:

$$\left(\frac{\sigma}{E}\right)^{e.m.}_{statistical} \approx \frac{0.5\%}{\sqrt{E(\mathrm{GeV})}}$$

  - Some electromagnetic calorimeters are sampling calorimeters, for these the sampling fluctuations are given by

$$\left(\frac{\sigma}{E}\right)^{e.m.}_{sampling} \approx 0.4\% \sqrt{\frac{1000\ \Delta E}{E}}$$

  - Total energy resolution below $\sigma/\sqrt{E} \simeq 1\%$ is easily achieved in homogeneous e.m. calorimeters for particles of high energy
    - Such levels are more difficult to achieve in an e.m. sampling calorimeter

Energy resolution in hadronic calorimeters

- In **hadronic calorimeters** the statistical errors result from fluctuations in energy deposition due to energy loss through non-hadronic mechanisms such as photons and leptons from pion decay and slow neutrons
  - These fluctuations are much larger than the main statistical errors in e.m. calorimeters:

$$\left(\frac{\sigma}{E}\right)_{statistical}^{hadronic} \approx \frac{45\%}{\sqrt{E}}$$

  - **Compensating calorimeters** (e.g. the one used by the ZEUS experiment at HERA) are hadronic calorimeters with enhancements such as adjusted absorber layer and active layer widths and U-238 absorbers for slow neutron capture. These calorimeters reduce the statistical errors by around 20%: $\left(\frac{\sigma}{E}\right)_{statistical}^{compensated} \approx \frac{25\%}{\sqrt{E}}$
  - All hadronic calorimeters are sampling, but the contribution to the total energy resolution due to sampling effects is small compared to the statistical errors:

$$\left(\frac{\sigma}{E}\right)_{sampling}^{e.m.} \approx 9\%\sqrt{\frac{1000\,\Delta E}{E}}$$

Energy resolution

- typical energy resolutions for various **electromagnetic calorimeters** are given below

Electromagnetic detector	Experiment	Energy resolution
Lead glass	OPAL	$5\%/\sqrt{E}$
Liquid krypton	NA48	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$
Liquid argon and lead	NA31	$7.5\%/\sqrt{E} \oplus 0.50\% \oplus 0.10/E$
Liquid argon and lead	ATLAS	$10\%/\sqrt{E} \oplus 0.40\% \oplus 0.30/E$
Depleted uranium scintillator	ZEUS	$18\%/\sqrt{E}$

Energy resolution

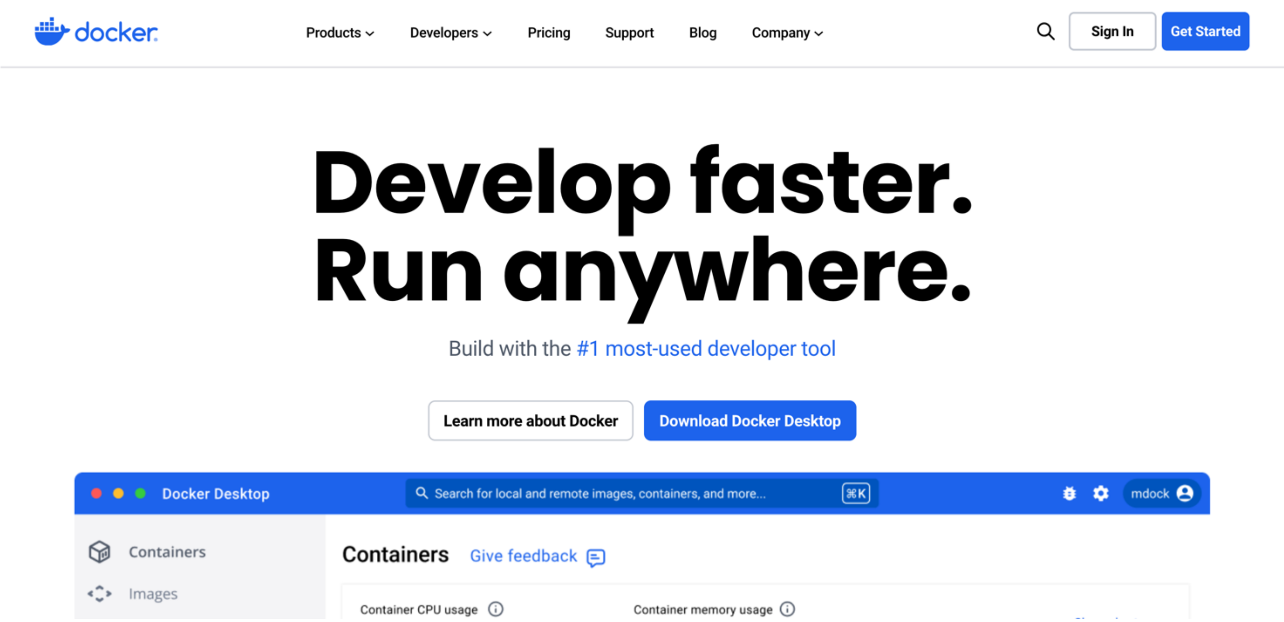
- typical energy resolutions for various **hadronic calorimeters** are given below

Absorber and thickness	Plastic scintillator	Experiment	Energy resolution
6 mm uranium and 5 mm copper	2.5 mm	AFS	$35\%/\sqrt{E}$
80 mm marble	30 mm	CHARM	$45\%/\sqrt{E}$
25 mm iron	5 mm	CDHS	$58\%/\sqrt{E}$
50 mm iron	10 mm	UA-1	$80\%/\sqrt{E}$
15 mm iron	5 mm	UA-2	$60\%/\sqrt{E}$

PREPARING FOR THE HANDS ON
Part 2

The Docker container

https://www.docker.com/



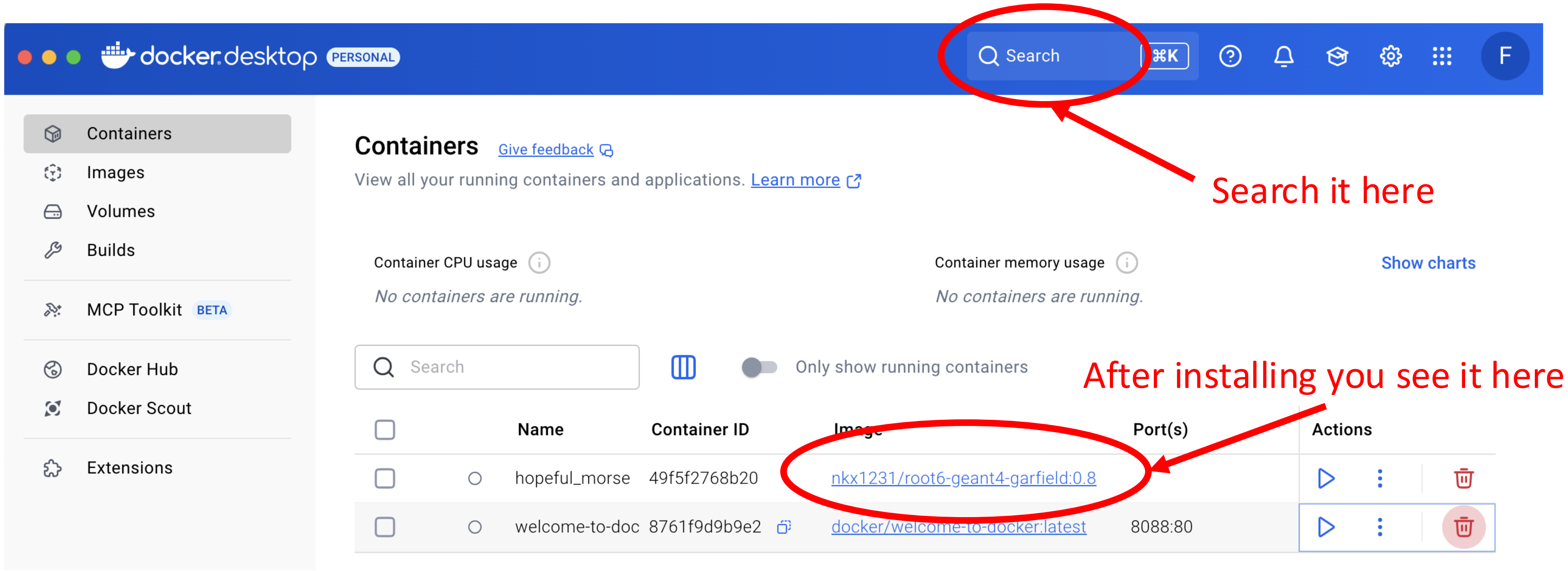
- A Docker is a container of a whole PC environment
- It allows one to run a stand-alone environment with all libraries and software preinstalled

- Download and install Docker desktop
  - Products -> Docker Desktop
- On Unix-like systems (MacOS, Linux,…) enable your **X Window System (X11)**
  - On a terminal run the following
    - `ip=$(ifconfig en0 | grep inet | awk '$1=="inet" {print $2}')`
    - `echo $ip`
    - `xhost + $ip`
  - You should get a message like:

    $ip being added to access control list
- You should now be able to run the Docker app

Install the image

- Run your Docker app
- Search and load the Image: `nkx1231/root6-geant4-garfield:0.8`



- On unix-based systems, run your Image via prompt terminal:

```
docker run -it -v /tmp/.X11-unix:/tmp/.X11-unix -e DISPLAY=$ip:0 nkx1231/root6-geant4-garfield:0.8 /bin/bash
```

Build the GEANT4 example

- You should now enter a virtual machine environment as a “root”, like:

```
[root@ccacff8eefa2:~# pwd
/root
```

- Inside `/root`, create a test directory:
  - `mkdir TestEm2_build`
  - `cd TestEm2_build`
- Build the GEANT4 directory containing the “extended” examples and chose the one named TestEm2:
  - `cmake -DGeant4_DIR=/usr/local/geant4/lib/Geant4-10.4.2 /usr/local/geant4/share/Geant4-10.4.2/examples/extended/electromagnetic/TestEm2`

Compile the GEANT4 example

- You should get a message like:

```
-- The C compiler identification is GNU 5.4.0
-- The CXX compiler identification is GNU 5.4.0
-- Check for working C compiler: /usr/bin/cc
-- Check for working C compiler: /usr/bin/cc -- works
-- Detecting C compiler ABI info
-- Detecting C compiler ABI info - done
-- Detecting C compile features
-- Detecting C compile features - done
-- Check for working CXX compiler: /usr/bin/c++
-- Check for working CXX compiler: /usr/bin/c++ -- works
-- Detecting CXX compiler ABI info
-- Detecting CXX compiler ABI info - done
-- Detecting CXX compile features
-- Detecting CXX compile features - done
-- Configuring done
-- Generating done
-- Build files have been written to: /root
```

- Compile the extended example TestEm2:

```
› make -j 2 TestEm2
```

Compile the GEANT4 example

- You should get a message like:

```
Scanning dependencies of target TestEm2
[  5%] Building CXX object CMakeFiles/TestEm2.dir/TestEm2.cc.o
[ 10%] Building CXX object CMakeFiles/TestEm2.dir/src/SteppingAction.cc.o
[ 15%] Building CXX object CMakeFiles/TestEm2.dir/src/StepMax.cc.o
[ 21%] Building CXX object CMakeFiles/TestEm2.dir/src/PrimaryGeneratorAction.cc.o
[ 26%] Building CXX object CMakeFiles/TestEm2.dir/src/PhysicsList.cc.o
[ 31%] Building CXX object CMakeFiles/TestEm2.dir/src/StepMaxMessenger.cc.o
[ 36%] Building CXX object CMakeFiles/TestEm2.dir/src/EventAction.cc.o
[ 42%] Building CXX object CMakeFiles/TestEm2.dir/src/SteppingVerbose.cc.o
[ 47%] Building CXX object CMakeFiles/TestEm2.dir/src/TrackingAction.cc.o
[ 52%] Building CXX object CMakeFiles/TestEm2.dir/src/PhysicsListMessenger.cc.o
[ 57%] Building CXX object CMakeFiles/TestEm2.dir/src/DetectorMessenger.cc.o
[ 63%] Building CXX object CMakeFiles/TestEm2.dir/src/EmAcceptance.cc.o
[ 68%] Building CXX object CMakeFiles/TestEm2.dir/src/ActionInitialization.cc.o
[ 73%] Building CXX object CMakeFiles/TestEm2.dir/src/DetectorConstruction.cc.o
[ 78%] Building CXX object CMakeFiles/TestEm2.dir/src/PhysListEmStandard.cc.o
[ 84%] Building CXX object CMakeFiles/TestEm2.dir/src/RunActionMessenger.cc.o
[ 89%] Building CXX object CMakeFiles/TestEm2.dir/src/Run.cc.o
[ 94%] Building CXX object CMakeFiles/TestEm2.dir/src/RunAction.cc.o
[100%] Linking CXX executable TestEm2
[100%] Built target TestEm2
```

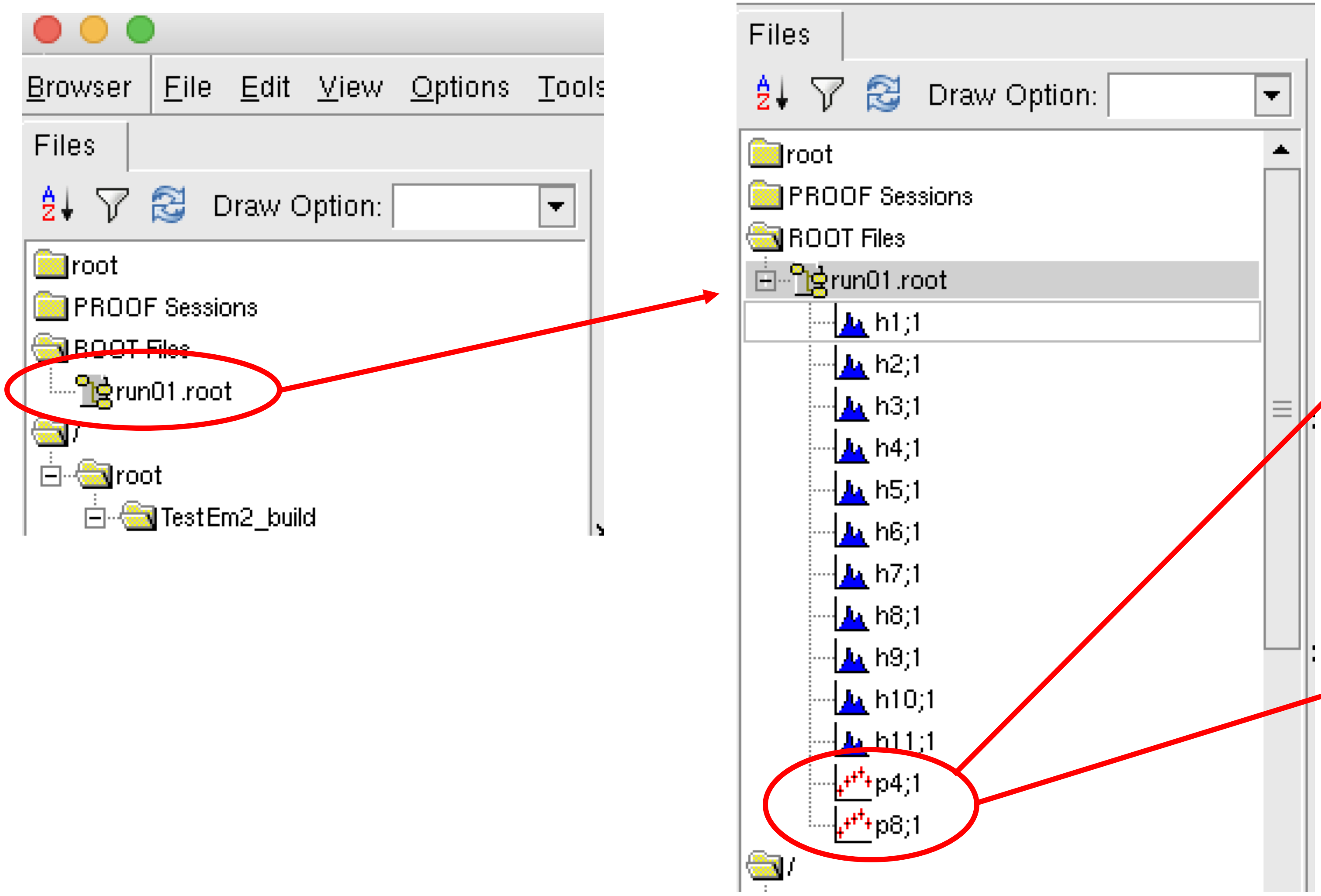
- You are now good to go!
- Remember: when you close the image all work is lost

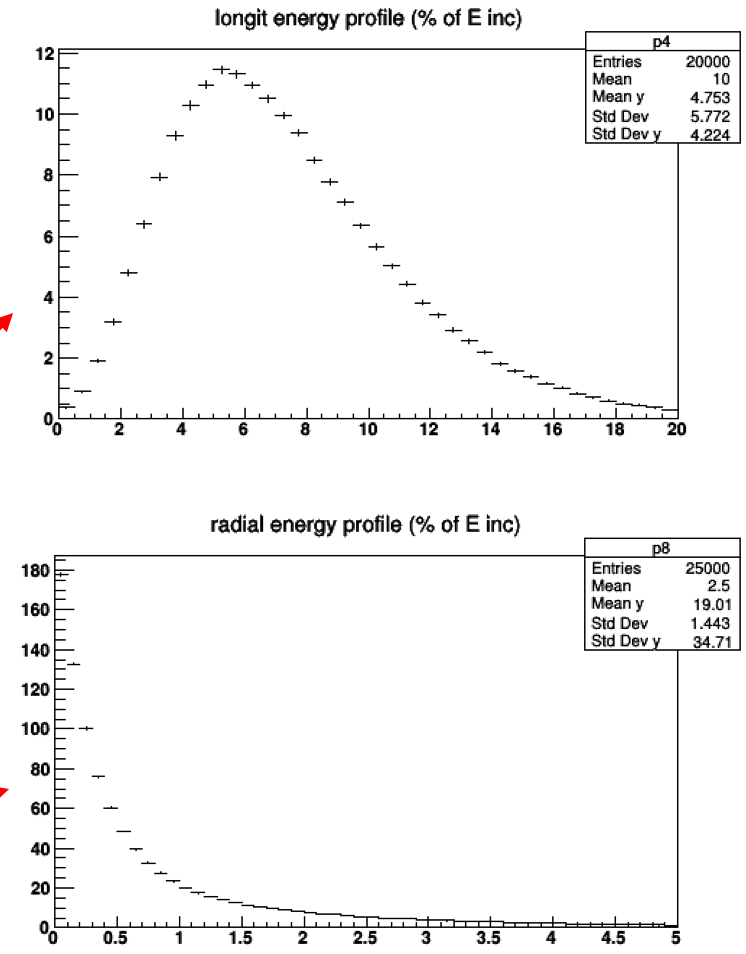
Run the GEANT4 example

- You will find three examples of run cards:
  - `run01.mac, run02.mac, run03.mac`
- Inspect them and their contents. They simulate and E.M. Cal for different:
  - Energy on an incident electron
  - material
  - …
- Run one configuration. E.g. the first one: `./TestEm2 run01.mac`
- The output is a root ntuple: `run01.root`
- Our image contains the ROOT analysis toolkit. Open the file:
  - `root run01.root`
- On the ROOT prompt, launch a TBrowser app:
  - `new TBrowser`

Run the GEANT4 example

- From the TBrowser app you can now graphically navigate the output file





Get your hands on the code

- Familiarize with the cards
- Familiarize with the code files in:

  ```
  /usr/local/geant4/lib/Geant4-10.4.2
  /usr/local/geant4/share/Geant4-10.4.2/examples/extended/electromagnetic/TestEm2/src/
  ```

- Output files, e.g. root trees, can be downloaded from the docker image to your local PC if you prefer to analyze the in your local environment
- If you just work inside the docker, remember: **DO NOT** close the image, or all the work is lost
  - You can also save the image giving a new version number
- The example used here is **TestEm2** in the extended electromagnetic examples directory

gitlab.cern.ch/geant4/geant4/-/raw/master/examples/extended/electromagnetic/TestEm2/README

TestEm2 – geometry

How to do shower profiles in a homogenous medium

GEOMETRY DEFINITION

- The geometry consists of a cylinder of homogenous material
- The default geometry is constructed in DetectorConstruction class, but all of the above parameters can be modified interactively via the commands defined in the DetectorMessenger class
- Material can be chosen: Air, Water, lAr, Al, Fe, BGO, PbWO4, Pb
- The cylinder is virtually sliced longitudinally (slice) and radially (ring). The size of the slices and rings are expressed in radiation length units and can be changed. E.g.:
  - /testem/det/setLbin 20 1. ---> 20 slices of 1. radl
  - /testem/det/setRbin 5 0.25 ---> 5 rings of 0.25 radl
  - /testem/det/update ---> rebuild the geometry

  (MaxBin = 500 in both directions)
- A uniform magnetic field along the cylinder axis can be set. eg:
  - /globalField/setValue 0 0 5 tesla

TestEm2 – physics list

- PHYSICS LISTS - are based on modular design. Several modules are instantiated:
    1. Transportation
    2. EM physics
    3. Decays
    4. StepMax - for step limitation

- EM physics builders can be local (eg. in this example) or from G4 kernel physics_lists subdirectory
- Local physics builders: - "local" standard EM physics with current 'best' options setting. These options are explicited in PhysListEmStandard
- From `geant4/source/physics_lists/builders`:
    - "emstandard_opt0" recommended standard EM physics for LHC
    - "emstandard_opt1" best CPU performance standard physics for LHC
    - "emstandard_opt2" similar fast simulation
    - "emstandard_opt3" best standard EM options - analog to "local" above
    - "emstandard_opt4" best current advanced EM options standard + lowenergy
    - "emstandardWVI" standard EM physics and WentzelVI multiple scattering
    - "emstandardSS" standard EM physics and single scattering model
    - "emlivermore" low-energy EM physics using Livermore data
    - "empenelope" low-energy EM physics implementing Penelope models
    - "emlowenergy" low-energy EM physics implementing experimental low-energy models

TestEm2 – Visualization

- AN EVENT: THE PRIMARY GENERATOR
  - The primary kinematic consists of a single particle which hits the cylinder perpendicular to the input face
  - The type of the particle and its energy are set in the PrimaryGeneratorAction class and can changed via the G4 build-in commands of G4ParticleGun class (see the macros provided with this example)
  - A RUN is a set of events
- VISUALIZATION
  - The Visualization Manager is set in the main() (see TestEm2.cc).
  - The initialisation of the drawing is done via the commands `/vis/..` in the macro `vis.mac`
  - In interactive session:
    - `PreInit` or `Idle > /control/execute vis.mac`
    - The detector has a default view which is a longitudinal view of the cylinder
    - The tracks are drawn at the end of event and erased at the end of run
      - Optionally one can choose to draw all particles, only the charged one, or none. This command is defined in `EventActionMessenger` class

TestEm2 – How to run?

PHYSICS DEMO

- The particle's type and the physics processes which will be available in this example are set in `PhysicsList` class
- In addition, a build-in interactive command (`/process/inactivate procname`) allows to activate/inactivate the processes one by one
- The threshold for producing secondaries can be changed
  - E.g.: `/testem/phys/setCuts 100 microm /run/initialize`
- The shower profiles are histogramed, if histograming is activated. They can be also printed with the command: `/testem/run/verbose 1`

HOW TO START?

- Execute TestEm2 in 'batch' mode from macro files. `TestEm2 run01.mac`
- Execute TestEm2 in 'batch' mode using multi-threading. `TestEm2 run01.mac 4` (4 is # of threads)
- Execute TestEm2 in 'interactive mode' with visualization.
  - `TestEm2`
  - `....`
  - `Idle>` type your commands
  - `....`
  - `Idle> exit`

TestEm2 – macros (*cards*)

- Macros provided in this example:
  - **egs4.mac:**
    - Fe; L = 20 radl; R = 5 radl; electron 30 GeV (EGS4 simulation: Particle Data Group - Phys.Rev.D 50-3 - August94)
  - **run01.mac:** PbWO4; L = 20 radl; R = 5 radl; electron 5 GeV
  - **run02.mac:** Al; L = 13.5 radl; R = 1.35 radl; electron 1 GeV (Electron-induced cascade showers: J&H Crannel - Phys. Rev. 184-2 - August69)
  - **run03.mac:** H2O; L = 9.97 radl; R = 0.665 radl; electron 1 GeV (Electron-induced cascade showers: J&H Crannel - Phys. Rev. 184-2 - August69)
  - **test.mac:** PbWO4; L = 20 radl; R = 5 radl; electron 5 GeV
  - **stepMax.mac:** chargedgeantino in PbWO4; To illustrate step max mechanism;
  - **vis.mac:** to activate visualization

TestEm2 – Histograms

HISTOGRAMS

- TestEm2 produces several histograms. Content of these histo:
    1. energy deposit per event
    2. charged track length per event
    3. neutral track length per event
    4. longitudinal energy profile
    5. rms of longitudinal energy profile
    6. cumulated longitudinal energy profile
    7. rms of cumulated longitudinal energy profile
    8. radial energy profile
    9. rms of radial energy profile
    10. cumulated radial energy profile
    11. rms of cumulated radial energy profile
- Define the output file name with histograms via UI command : "`/analysis/setFileName name`"
- The histogram file format can be: **root (default),** xml, csv, by selecting `g4nnn.hh` in `RunAction.hh`

Example cards: `run01.mac`

```
# $Id: run01.mac 83431 2014-08-21 15:49:56Z gcosmo $
#
# Macro file for "TestEm2.cc"
# (can be run in batch, without graphic)
#
# PbWO4 L = 20 radl  R = 5 radl; electron 5 GeV
#
/control/verbose 2
/run/verbose 2
#
/testem/det/setMat G4_PbWO4
/testem/det/setLbin 40 0.5
/testem/det/setRbin 50 0.1
#
/testem/phys/addPhysics  emstandard_opt0
#
/run/setCut 1 mm
#
/run/initialize
#
/gun/particle e-
/gun/energy 5 GeV
#
# histogram file
/testem/histo/setFileName run01
#
/run/printProgress 50
/testem/run/verbose 1
#
/run/beamOn 500
```

The example describes an e.m. calorimeter with the following setup:

- A homogeneous medium of cylindrical shape
  - length has been fixed to 20 radL
  - radius value corresponds to 5 radL
- The cylinder has been divided into 100 slices longitudinally (0.2 radL each) and into 50 rings radially (0.1 radL each)
- 500 electrons with beam energy fixed at 5 GeV, entering the detector along its main axis
- G4 Physics List: emstandard_opt0

Example of a ROOT macro

```
{
    gStyle->SetOptTitle(0);
    gStyle->SetOptStat(0000);

    TFile* f1 = new TFile("run01-1gev.root");
    TFile* f2 = new TFile("run01-10gev.root");
    TFile* f3 = new TFile("run01-100gev.root");

    f1->cd();
    TH1D* h_0 = p4->ProjectionX();
    h_0->GetYaxis()->SetTitle("Energy");
    h_0->GetXaxis()->SetTitle("L (X0)");
    h_0->SetMarkerSize(0.8);
    h_0->SetMarkerStyle(20);
    h_0->SetMarkerColor(2);
    h_0->Draw();

    f2->cd();
    TH1D* h_1 = p4->ProjectionX();
    h_1->SetMarkerSize(0.8);
    h_1->SetMarkerStyle(20);
    h_1->SetMarkerColor(3);
    h_1->Draw("same");

    f3->cd();
    TH1D* h_2 = p4->ProjectionX();
    h_2->SetMarkerSize(0.8);
    h_2->SetMarkerStyle(20);
    h_2->SetMarkerColor(4);
    h_2->Draw("same");

    TLegend *legend = new TLegend(0.5616046,0.7052632,0.8925501,0.8905263,NULL,"brNDC");
    legend->AddEntry(h_0,"Ee = 1 GeV","p");
    legend->AddEntry(h_1,"Ee = 10 GeV","p");
    legend->AddEntry(h_2,"Ee = 100 GeV","p");
    legend->Draw();
}
```

Possible studies

- longitudinal energy profile – at different particle energy, measure:
  - Energy fraction (%) vs depth in radiation length (X_0)
- radial energy profile – for different materials, measure:
  - energy fraction (%) vs depth radiation length (X_0)
- Example of possible particles: electron, photon
- Example of possible energies: 0.1 MeV, 1 MeV, 1 GeV, 10 GeV, 100 GeV, 1 TeV
- Example of possible materials:
  - lead tungstate PbWO4, a scintillating crystal with X0 = 0.89 cm RM = 2.2 cm, characterised by a quick response
  - bismuth germanate Bi4Ge3O12
  - liquid Argon
  - liquid Xenon
  - liquid Kripton