Calorimetry I

Ted Kolberg (FSU)

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Overview

- My background
- Origins of calorimetry
- Physics of showers
- Homogenous vs. sampling calorimeters

The age of calorimetry

Until the late 1970s bubble chambers and similar devices were the main technique used in particle physics experiments. The advent of high energy colliders ushered in an 'age of calorimetry':

- High event rates → calorimeters can be fast detectors, suitable for use in triggering.

- High energies → calorimeter performance improves at high energy, and amount of material needed scales favorably as log(E).

- W, Z, top, and Higgs all have photons/electrons, jets and MET in their decays → need sensitivity to charged and neutral particles, hermeticity.

- Calorimeters play an important part in producing a comprehensive view of collision events, e.g. particle flow algorithm.

In these lectures I will explain the physics of calorimeters, review and compare some different designs, and give some examples of their role in discoveries.

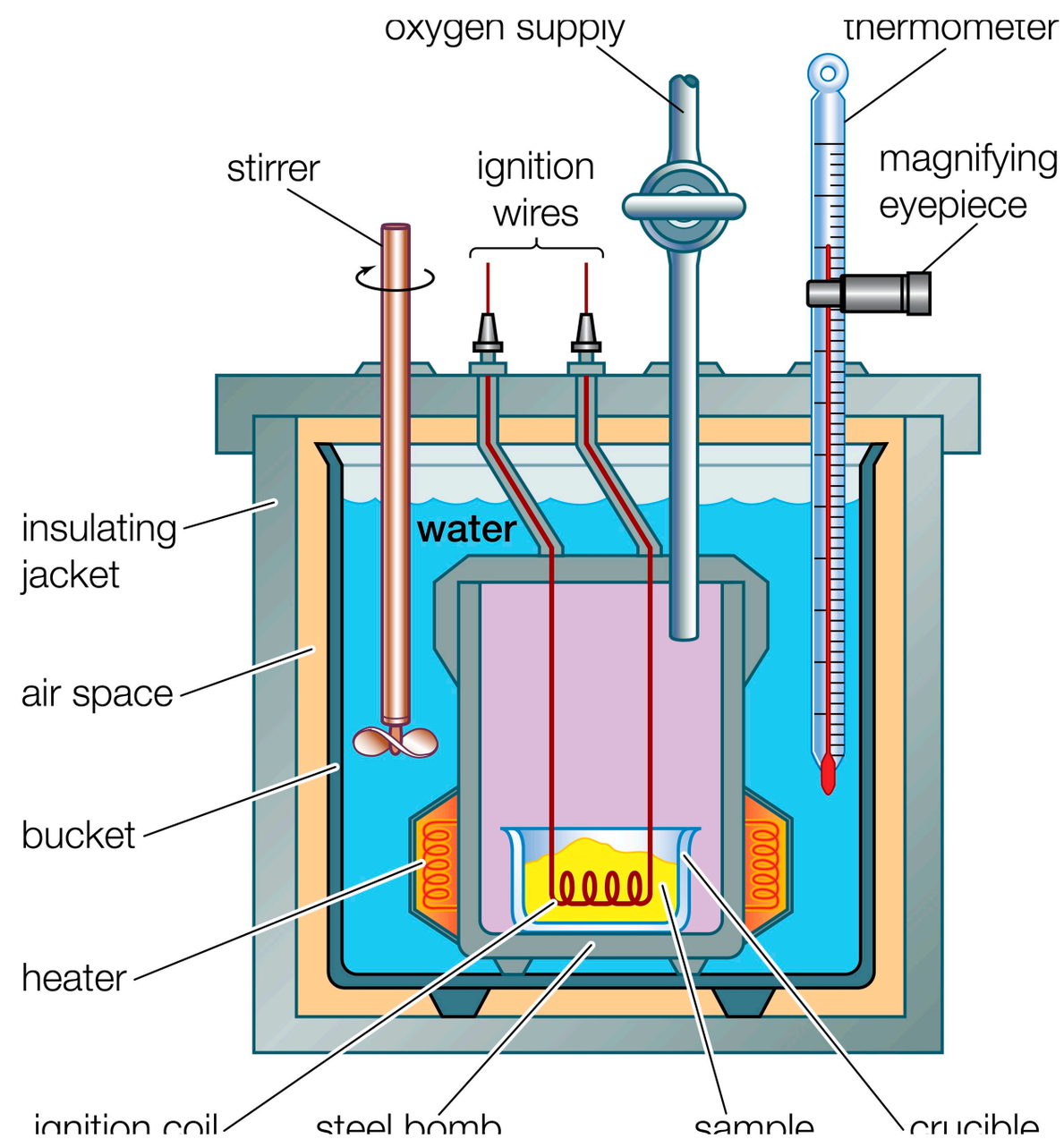
Origins of calorimetry

- The term ‘calorimeter’ is borrowed from chemistry and thermodynamics, where they are used to measure the energy released by a chemical process (burning).

- This technique is also used in assays of radioactive material, where the heat generated by radioactive decays (few mW/g) can be accurately measured.

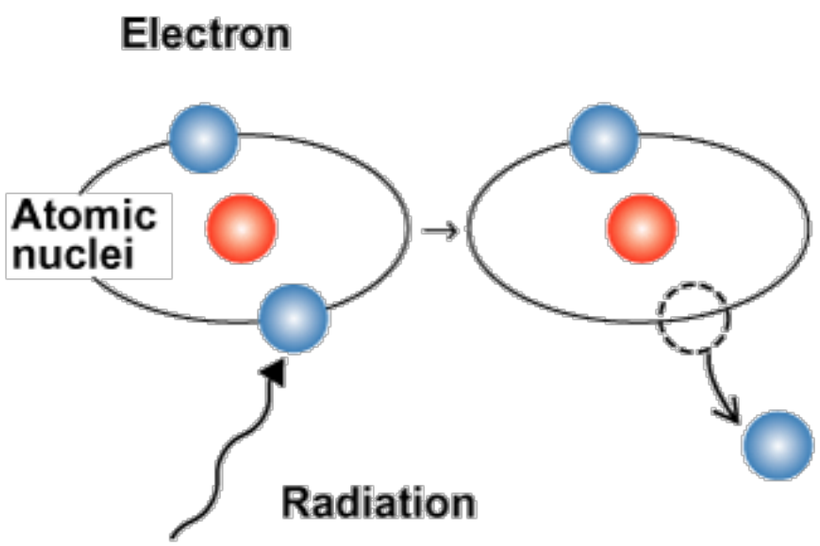
- The energy measured by calorimeters in high energy physics is tiny by comparison: 1 kcal = 2.6×10^{22} eV.

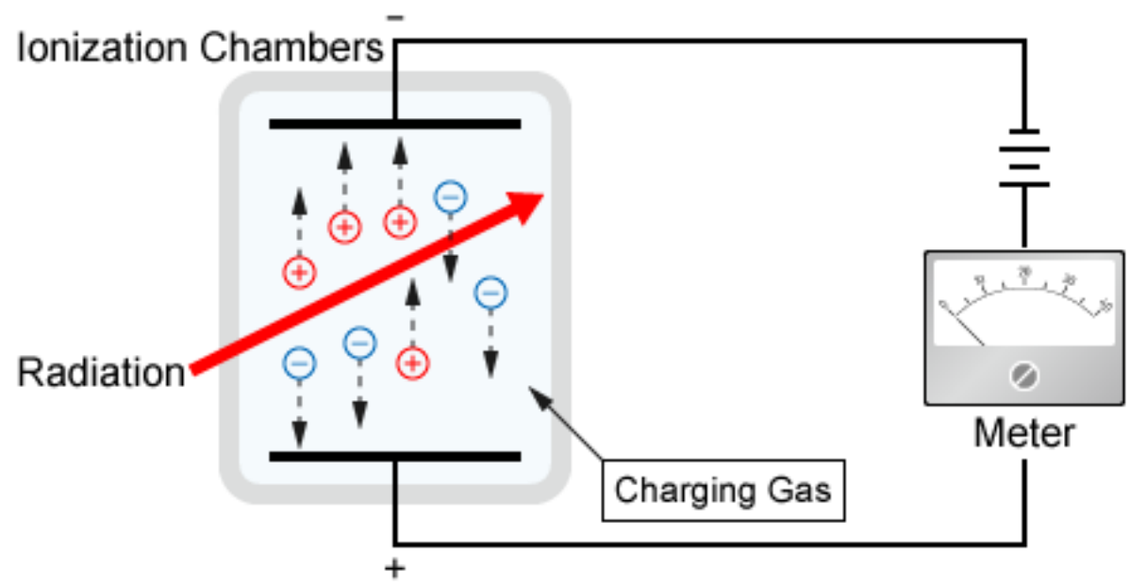
- Direct temperature measurements have no hope of detecting individual particles, so more sophisticated techniques are needed. But we keep the name.



Physics of showers

Ionization

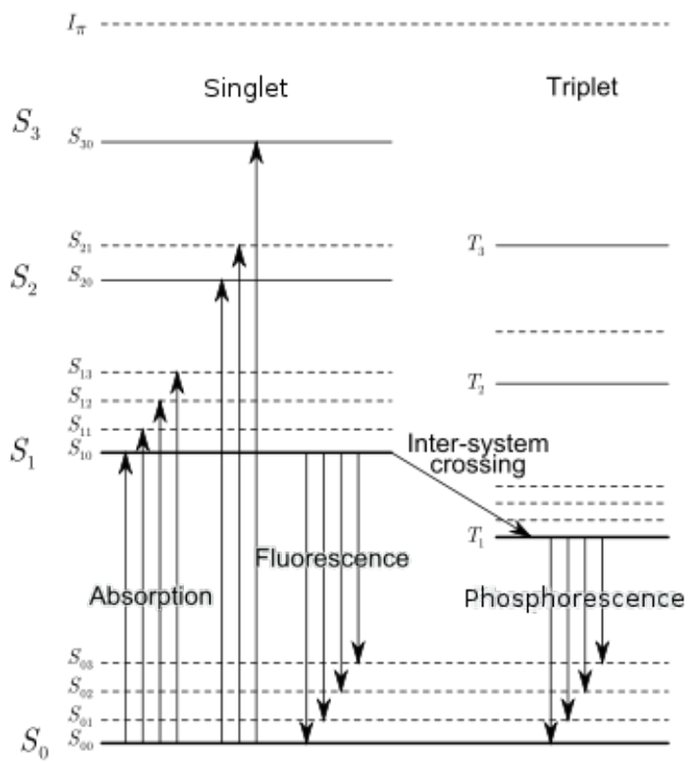


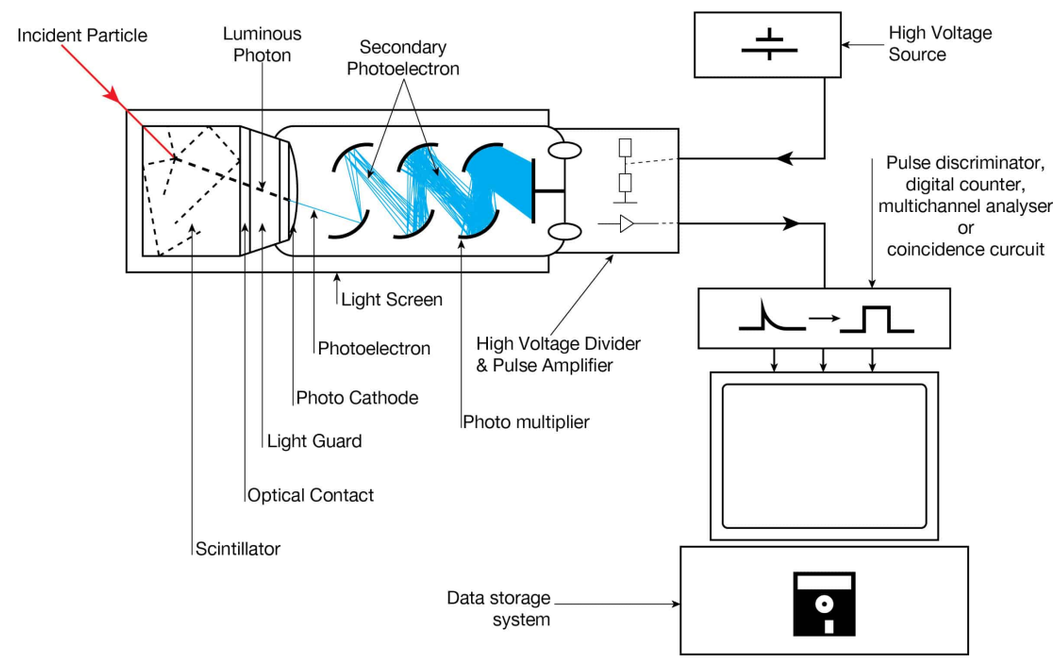


Charged particles traveling through material lose energy by interacting with the electrons in the material. For lower energies, this will mostly take the form of *ionization*.

The ionized electrons can be collected by means of an electric field and the resulting current can be measured electronically.

Scintillation

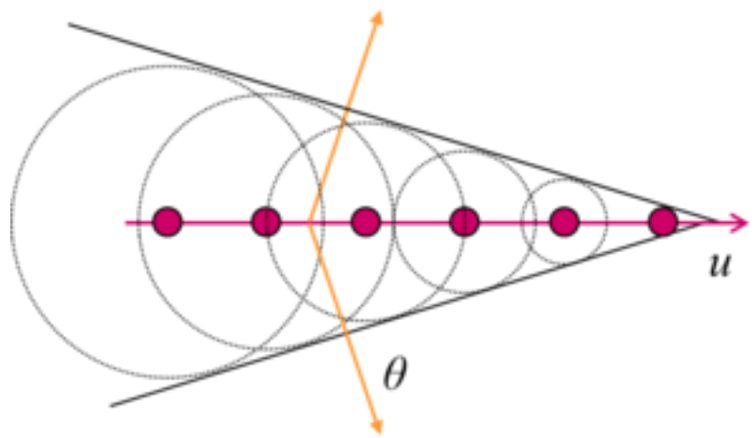


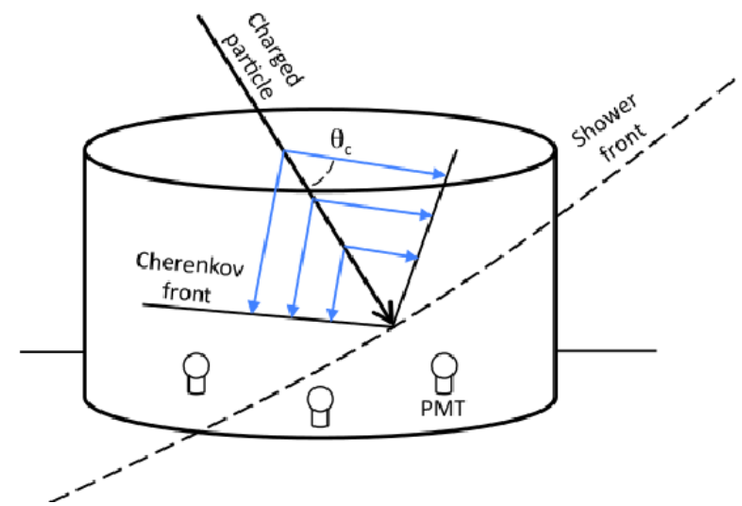


Some materials can be excited by interactions with charged particles and then decay back to a lower energy state via emission of a photon, known as *scintillation*.

These photons can be measured by a photodetector (PMT, SiPM, …) and converted into an electronic signal.

Cherenkov radiation





Charged particles traveling faster than the speed of light in a medium will emit *Cherenkov radiation*, in a cone with a characteristic opening angle related to their speed.

The Cherenkov photons can be collected by a photodetector and a suitable arrangement can be used to determine the momentum of the particle.

Other interactions

- Electrons can be ionized with such energy that they in turn further ionize the material: *δ-rays*.

- Charged particles undergoing acceleration in material will emit photons known as *bremsstrahlung*.

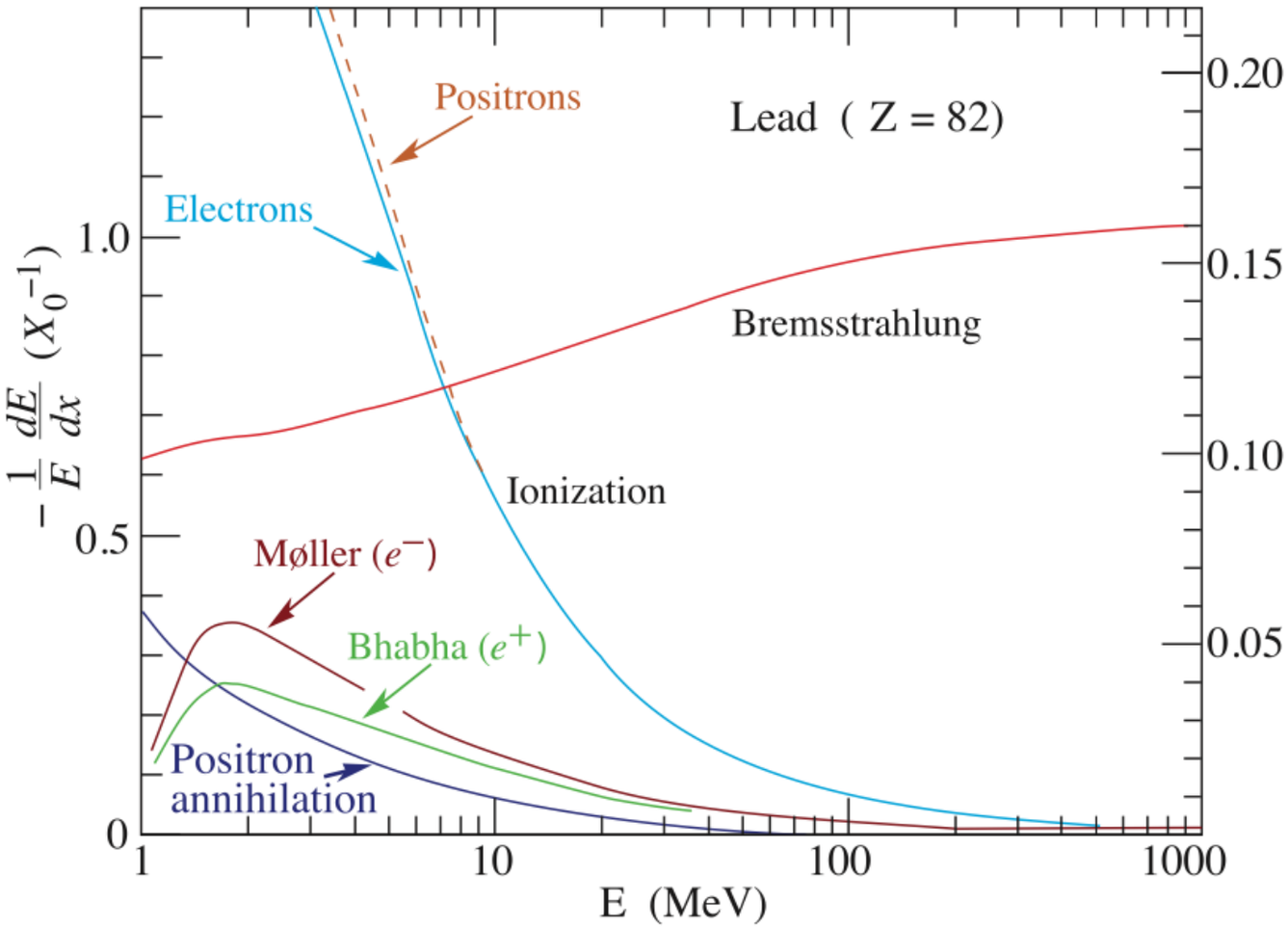
- At very high energies, charged particles can interact with the nuclei of the material and produce *nuclear reactions*.

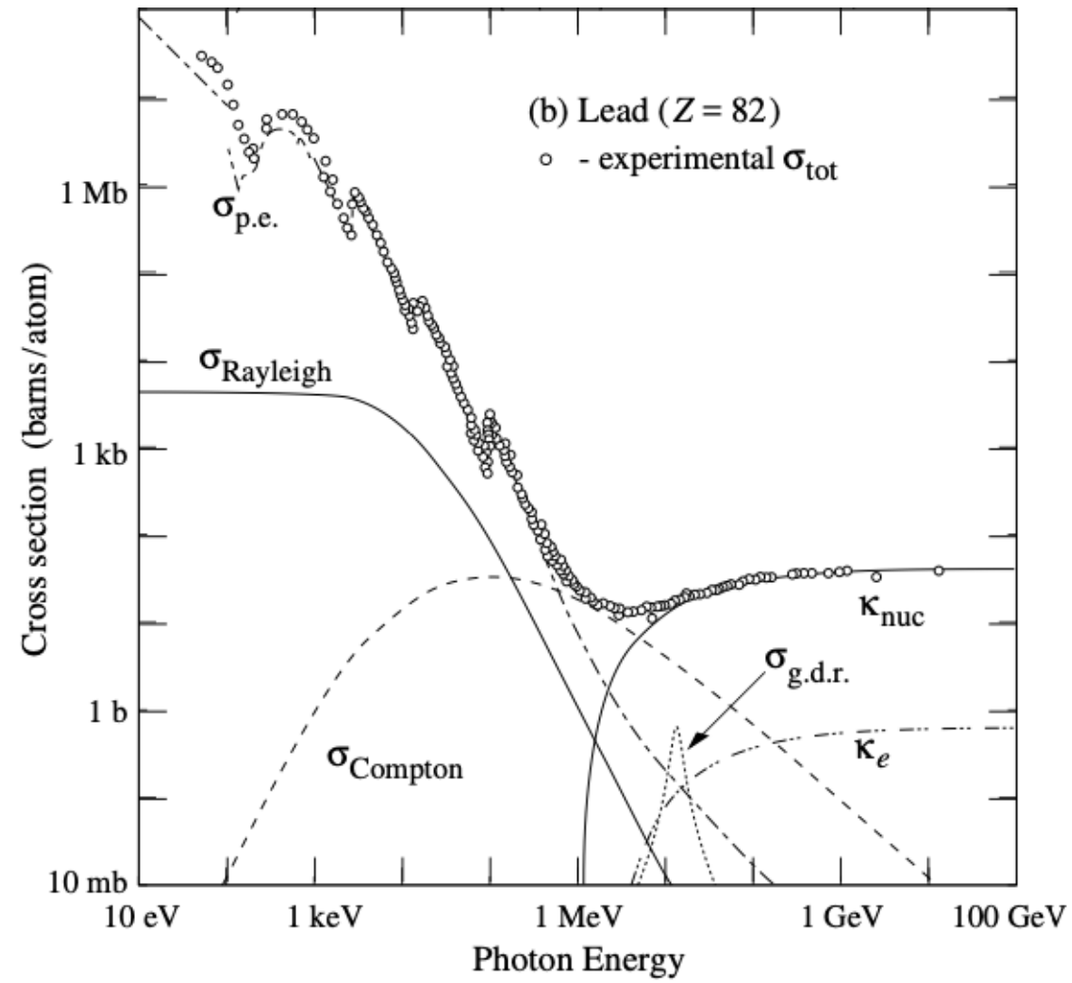
Photon interactions

Photons, being electrically neutral, have a different set of interactions:

- At low energies, *photoelectric effect* and *Rayleigh scattering* dominate.
- At higher (~MeV) energies, *Compton scattering* dominates.
- Above a few MeV, photons mostly convert into *e+e-* pairs.
    - Overwhelmingly, this happens in the Coulomb field of the nucleus, since it is so much stronger than the electronic fields for all but the lightest elements.

Electrons and photons

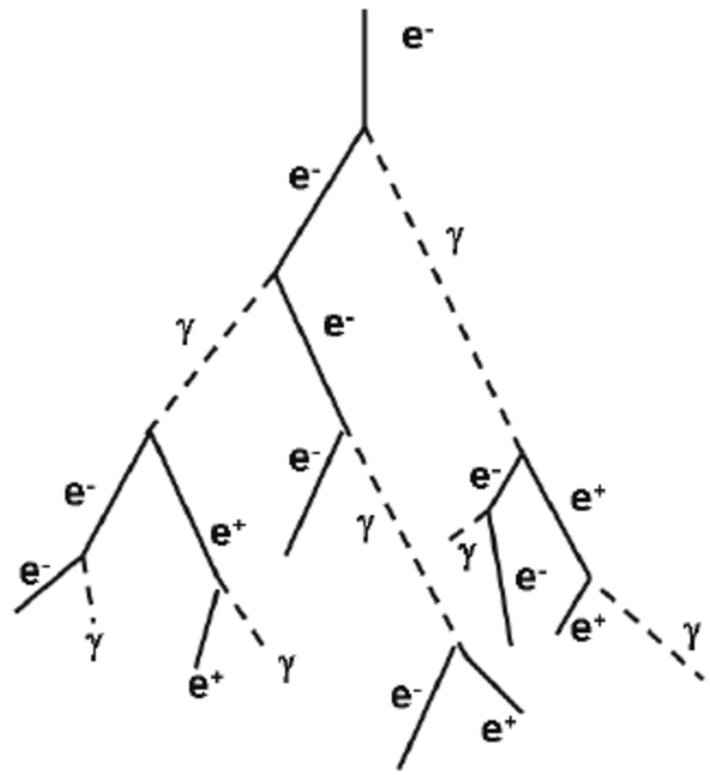




- At HEP energies, electrons (left) interact primarily by bremsstrahlung.

- Photons (right) interact by conversion into electron-positron pairs in the Coulomb field of the nucleus.

Electromagnetic showers



- Electrons produce more photons, and photons produce more electrons, in a cascade of reactions known as an *electromagnetic shower*.

- Interactions continue until the shower particles lack sufficient energy to produce further interactions of these kinds, and the remaining energy is deposited by ionization, Compton scattering, and the photoelectric effect.

Describing EM showers

EM shower development can be described by the *radiation length* X_0 and the *Molière radius* ρ_M (or ρ_0).

- The radiation length is defined as the distance over which a high-energy electron (positron) loses $1 - e^{-1}$ (63.2%) of its energy. NB that photons have a mean free path of $\frac{9}{7}X_0$ in the same material. In lead, about 0.56 cm.

- The Molière radius is derived from the radiation length and represents the radius of a cylinder around the shower axis within which 90% of the energy is contained. In lead, about 1.60 cm.

Both are important inputs to good calorimeter design: longitudinal (along shower axis) depth needed to contain showers is determined by the radiation length, while the transverse size is determined by the Molière radius.

NB residual dependence on *Z*

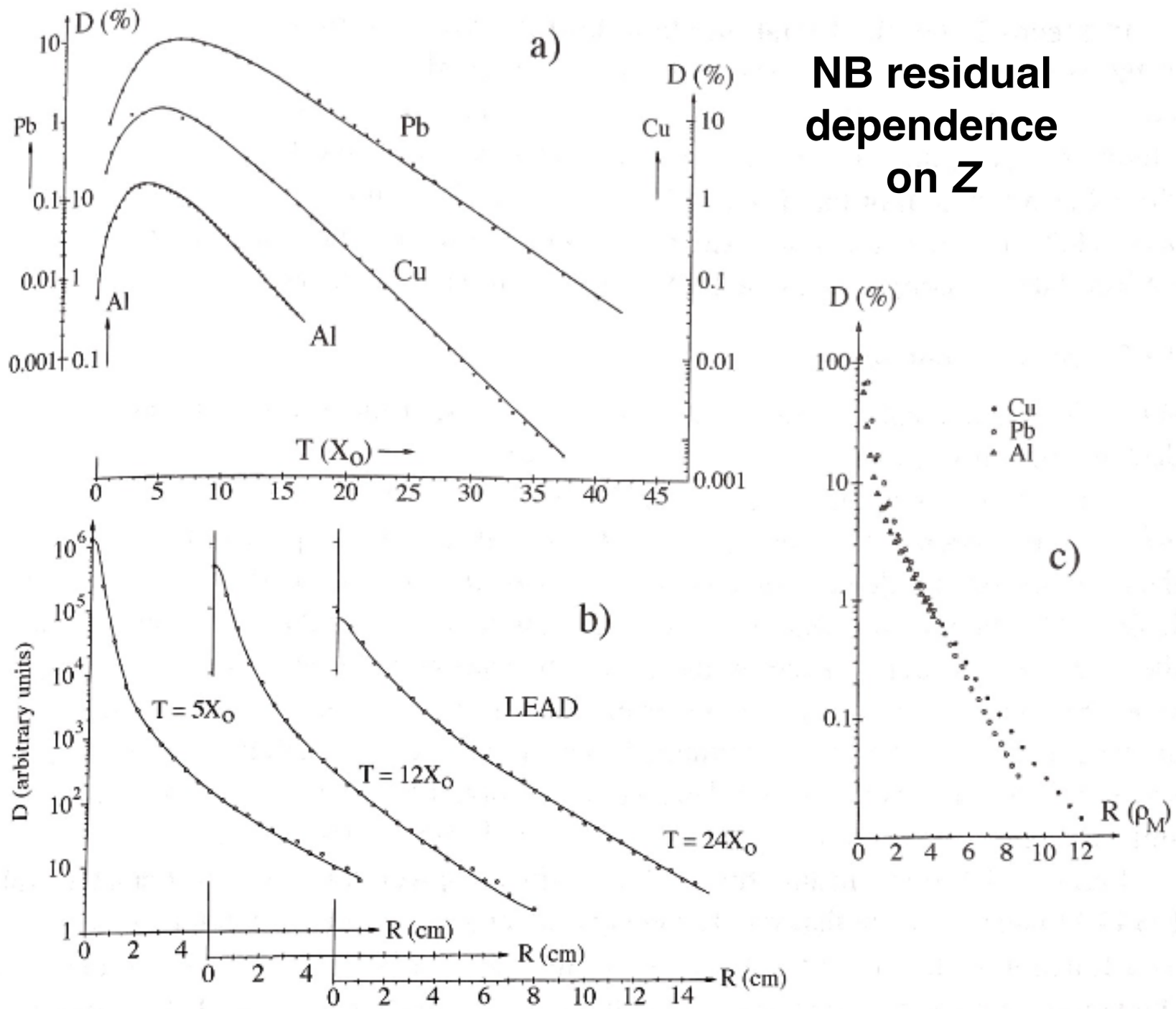
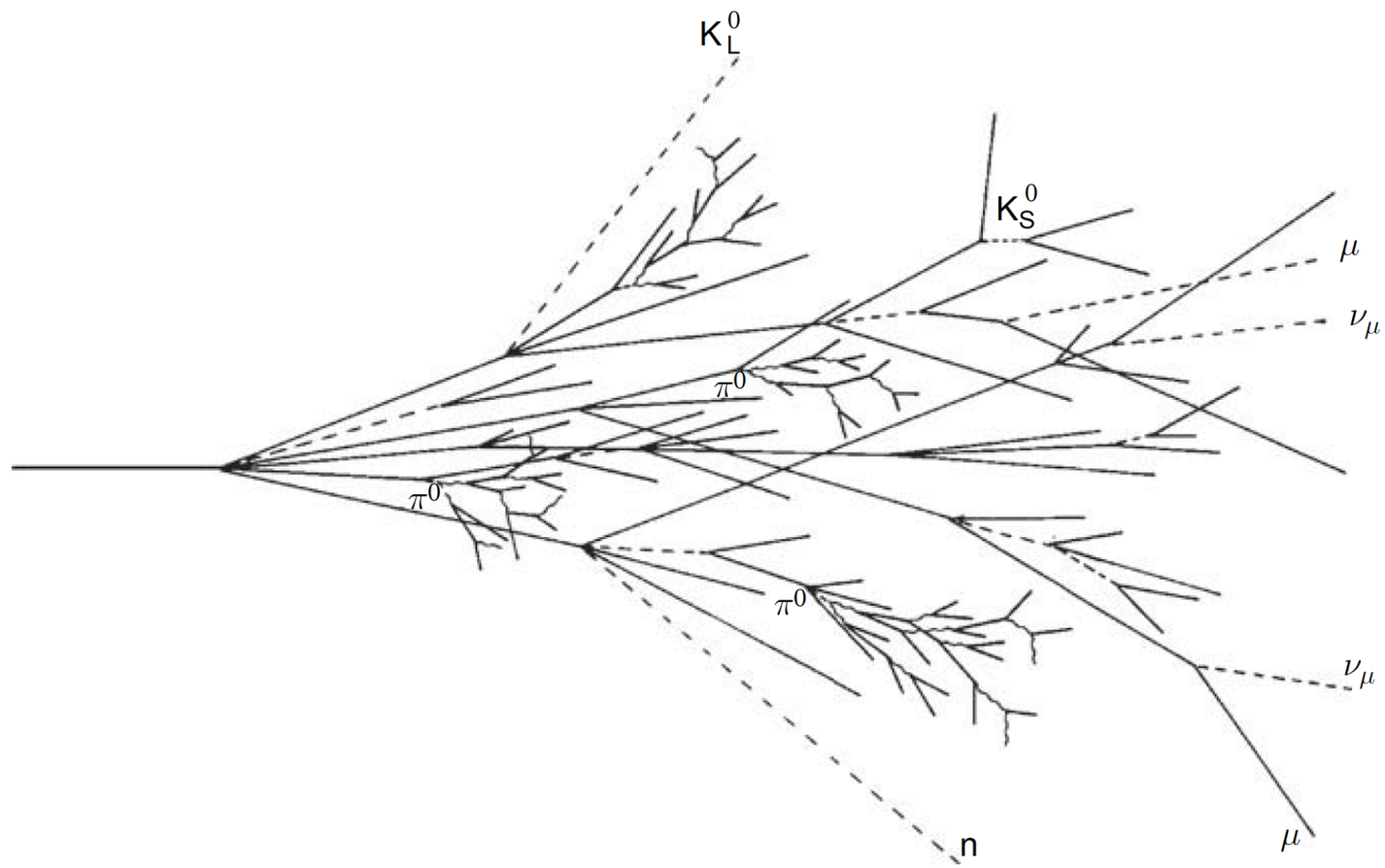


FIG. 2.16. Experimental results on the shower profiles of 6 GeV electrons in aluminium, copper and lead. Shown are the longitudinal profiles in these three materials (*a*), the lateral profiles in lead, measured at 3 different depths (*b*), and the integrated lateral profiles for copper and lead (*c*). Data from [Bat 70].

Hadronic showers



Hadrons (e.g. pions, protons) also initiate showers in material, but the physics is rather different.

- Strong interactions between the shower particles and the nuclei in the material are involved.

Hadronic interactions with matter

- Charged hadrons lose energy continuously via ionization while traversing material, while neutral hadrons do not.

- Both charged and neutral hadrons will eventually interact with a nucleus, and many different particles can be released from this interaction (large multiplicity of hadrons).

    - Hadron-nucleus interactions can create a large multiplicity of different hadrons, and may also drastically change the target nucleus.

- There are electromagnetic showers inside of hadronic showers (e.g. $\pi^0 \rightarrow \gamma\gamma$) but the overall scale of hadronic showers is set by the hadron-nucleus cross sections (smaller) and hadronic showers are physically much larger than EM ones, in the same material.

EM fraction with energy

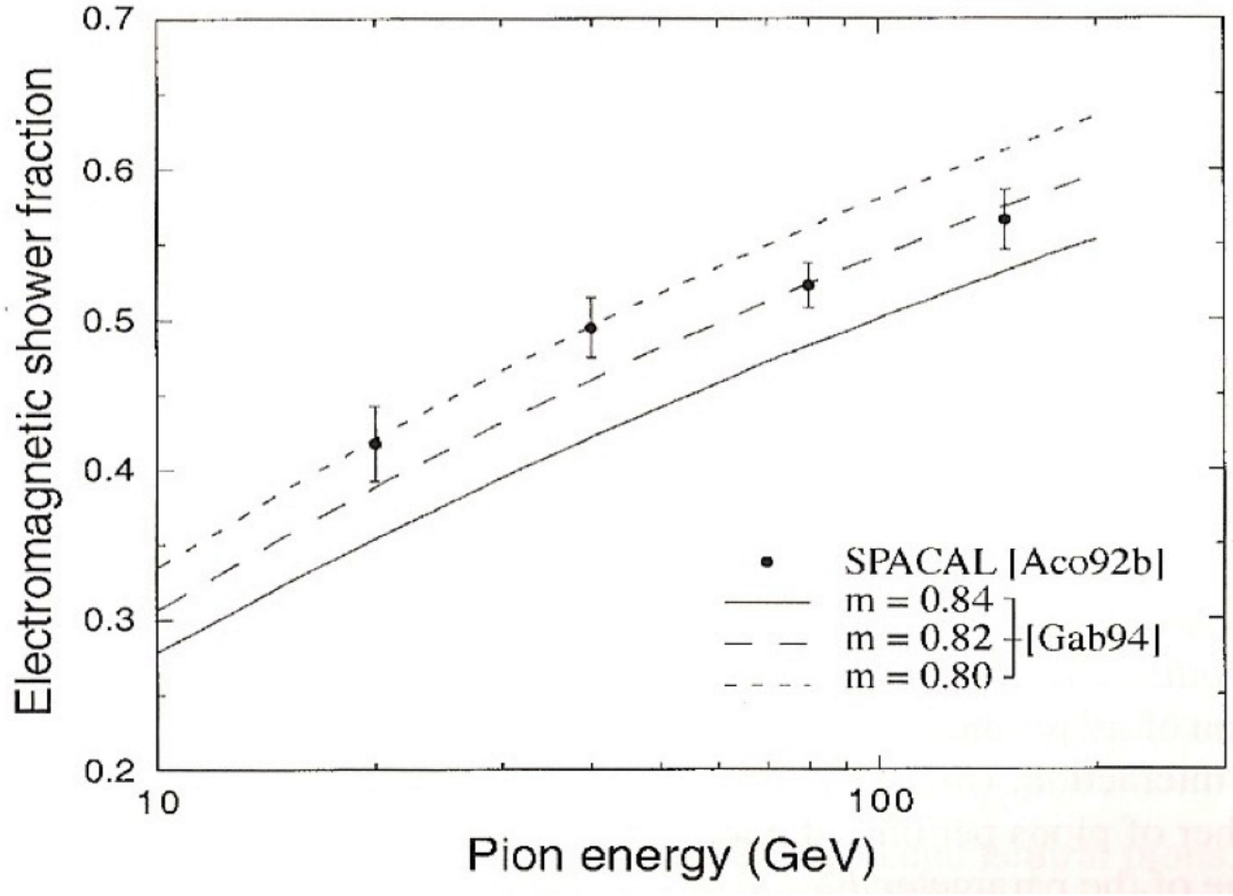
- On average, about 1/3 of produced hadrons are neutral pions, which initiate electromagnetic showers. In each successive hadronic shower generation, this 1/3 probability occurs again, such that higher energy showers (more generations) should have higher EM fractions.

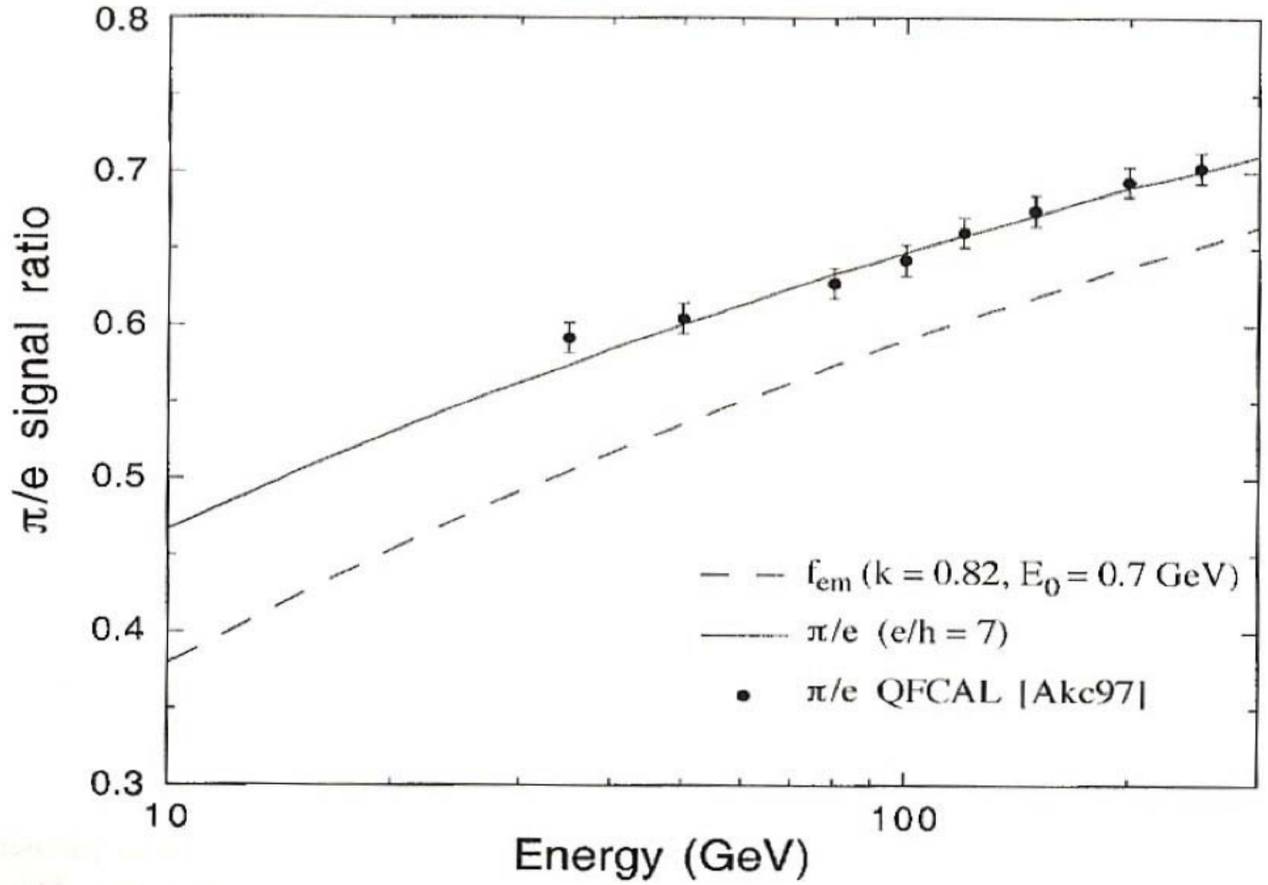
- After accounting for factors like energy loss by ionization and nuclear excitation, we find (Gabriel et al. 94) that the EM fraction goes as:

$$f_{EM} = 1 - \left(\frac{E}{E_0}\right)^{(k-1)}$$

- E_0 is the energy required to make a new pion: typically several hundred MeV. The slope *k* is related to the fraction of neutral pions in the shower and is typically 0.8, with a shallow dependence on average multiplicity.

- A representative value is EM fraction of 58% for 100 GeV showers in lead. Fraction increases with energy. This means that a sampling calorimeter should not be too coarse, even if the hadronic interaction length is long.





- SPACAL measured the EM fraction by mapping the transverse profile of showers, and decomposing into long (hadronic) and short (EM) components.

- QFCAL was a prototype calorimeter sensitive to mostly the EM components of the showers (e/h ~ 7).

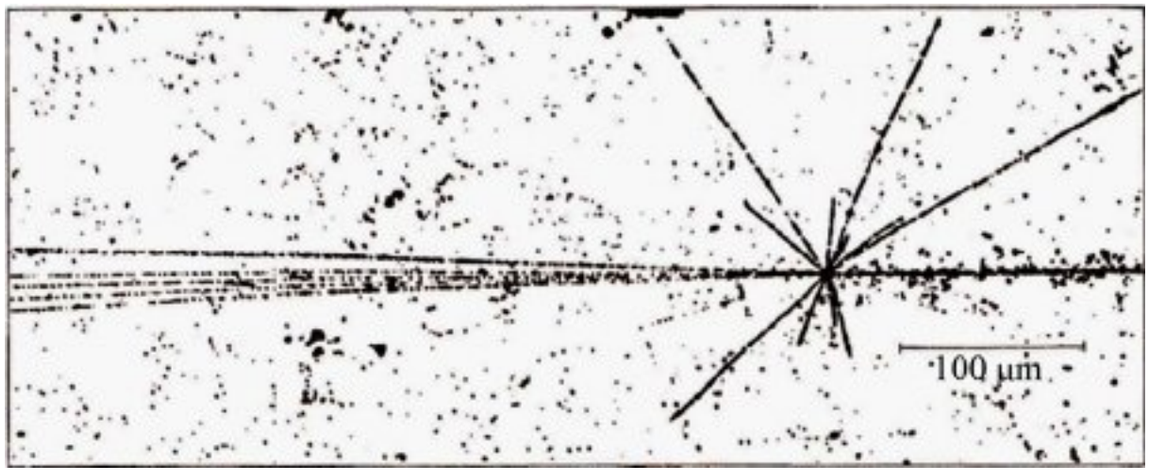
Particle multiplicities

To get a feel for the processes involved, consider an example: 100 GeV pions incident on copper (lead). Where does the energy go?

E_π (GeV)	$\langle f_{\mathrm{em}} \rangle$	$\langle \#\pi^{\pm}, K \ldots \rangle$	$\langle \#\pi^{0} \rangle$
10	0.380 (0.307)	9 (5)	3 (2)
20	0.453 (0.389)	16 (9)	5 (3)
30	0.492 (0.432)	22 (13)	7 (4)
50	0.536 (0.482)	33 (20)	11 (7)
80	0.574 (0.524)	49 (29)	16 (10)
100	0.591 (0.542)	58 (35)	19 (12)
150	0.619 (0.575)	82 (49)	27 (16)
200	0.639 (0.596)	103 (62)	34 (21)
300	0.664 (0.624)	144 (87)	48 (29)
400	0.681 (0.643)	182 (110)	61 (37)
500	0.694 (0.657)	219 (132)	73 (44)
700	0.712 (0.678)	288 (173)	96 (58)
1000	0.730 (0.698)	386 (232)	129 (77)

Wigmans, Table 2.3

Energy loss via nuclear interactions



- High energy hadrons typically cause “spallation” when they hit a target nucleus: a fast, intranuclear cascade initiated by the incoming hadron, followed by a slower de-excitation of the resulting nucleus.

- NB that since the nucleus changes into a number of fragments, some energy is lost due to the change in nuclear binding energy. This energy is invisible for calorimetric purposes.

- Typically this energy is ~40% of the non-EM fraction, but varies a lot. But anywhere from 0-60% of the **total incident energy** can be absorbed invisibly in extreme cases.

Neutrons

- Depending on the nucleus involved, neutrons may be more or less commonly produced in spallation reactions (5-10% of non-EM component carried by kinetic energy of neutrons, on average).

- Neutron interactions can occur via scattering (elastic or inelastic) and may result in the production of heavily ionizing slow protons or α particles.

    - Depending on the detector, these may produce very large signals that can interfere with calorimeter performance.

    - …or, the materials can be carefully chosen such that they are well measured and used to ‘compensate’ for energy lost to invisible processes.

- Neutrons can also cause nuclear excitations, but this depends a lot on the shell structure of the target nucleus.

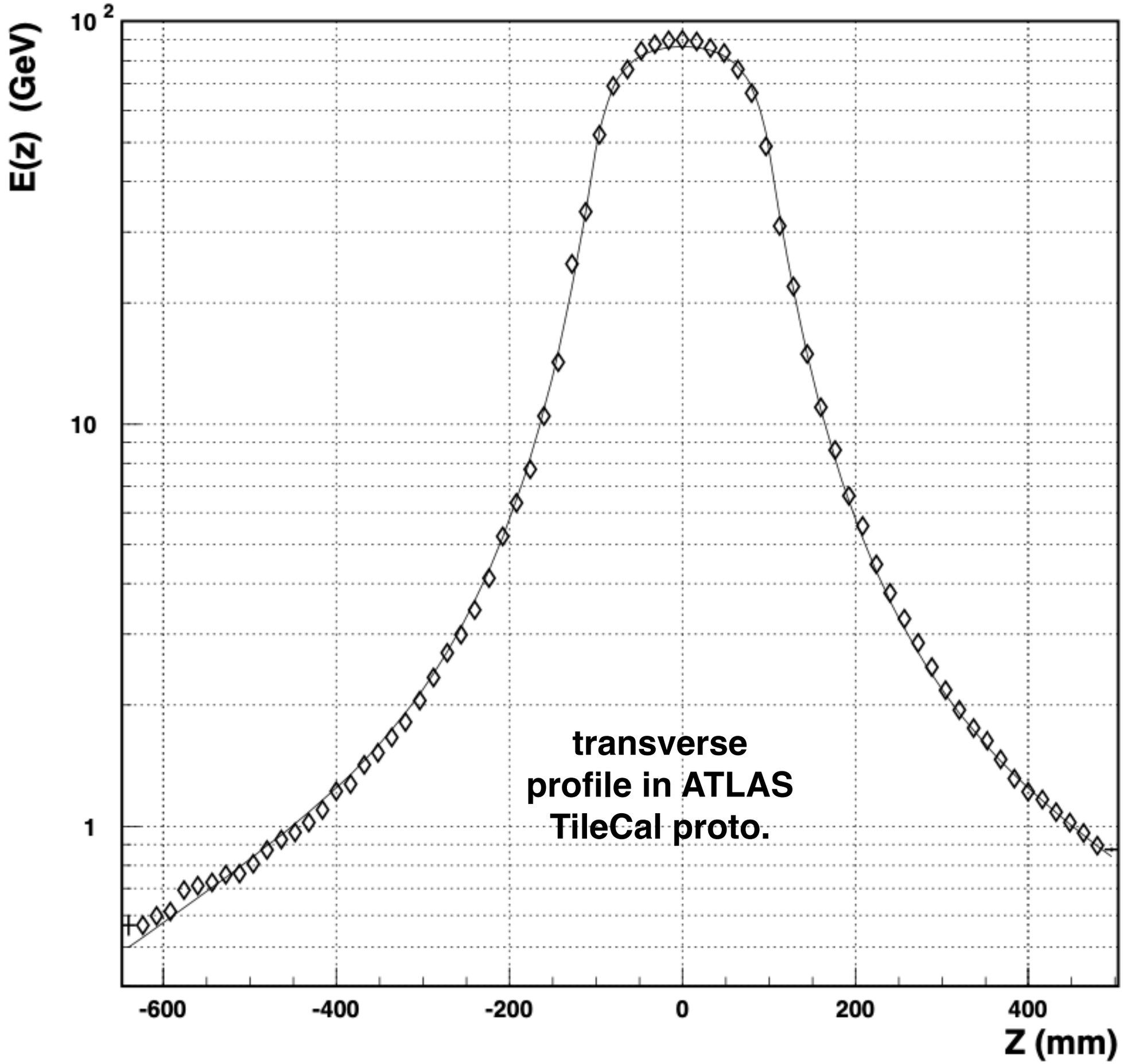
Describing hadronic showers

We have seen that there is a lot of interesting physics inside a hadronic shower, but we can try to parameterize in a general way, similar to our description of EM showers.

- Since the main non-EM process is nuclear interactions, define a *nuclear interaction length* λ_{int} such that the probability of traveling a distance *z* without interacting is $P = e^{-z/\lambda_{int}}$.

- The nuclear interaction length is determined by the identity of the incoming hadron, and the size of the target nucleus. In general, nuclear interaction lengths are 3-30 times larger than the radiation length in the same material, larger at high *Z*. Lead ≈ steel ≈ 17 cm.

- So hadronic showers start later, are larger, and have a lower energy density. They have localized EM showers within them ("EM core").


E(z) (GeV)
10 2
10
1
-600
-400
-200
0
200
400
Z (mm)
transverse
profile in ATLAS
TileCal proto.

Fluctuations

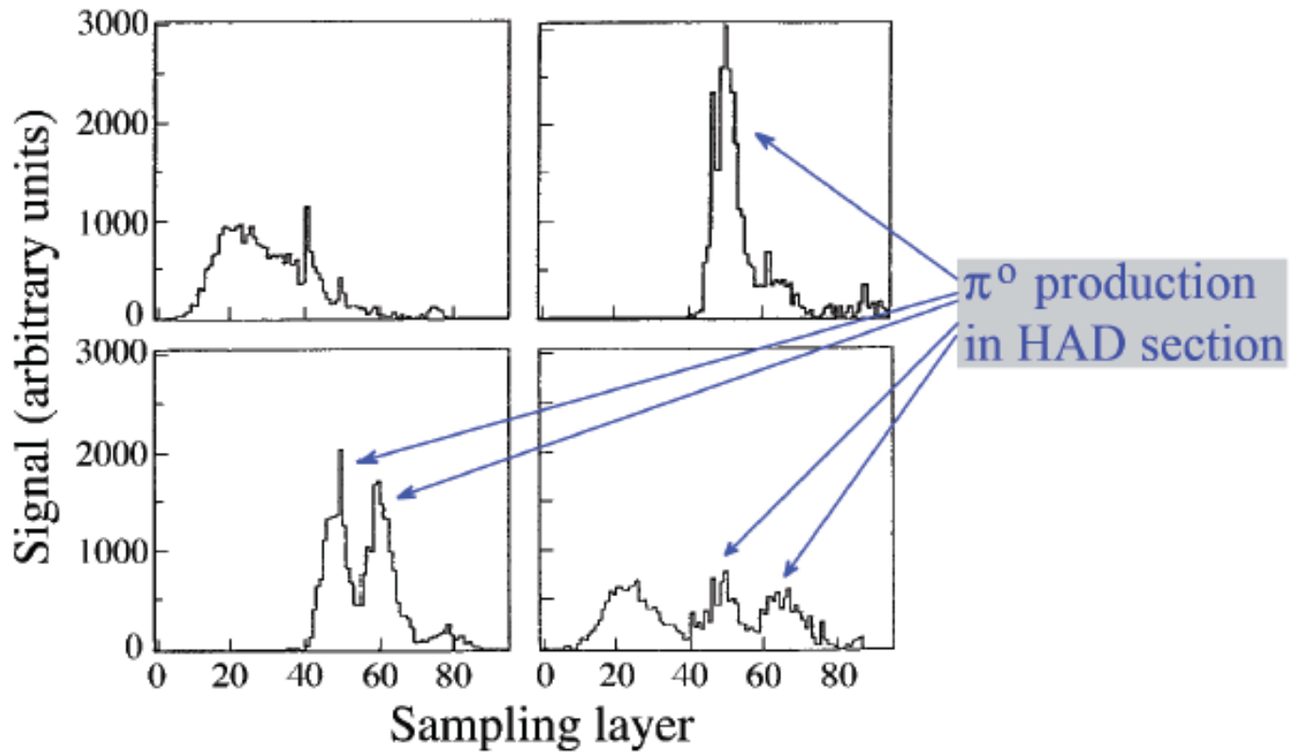


Fig. 7: Longitudinal profiles for 4 different showers induced by 270 GeV pions in a lead/iron/plastic-scintillator calorimeter [5].

- Since the number of possible interactions is larger, and result in rather different phenomena inside the shower, event-to-event fluctuations play a larger role in hadronic calorimetry.

- For the same incident particle, different numbers of high-energy neutral pions may be generated in the shower, with each giving rise to a distinct high-energy-density EM shower.

Summary of showers

- Showers develop as a high-energy particle loses energy and produces successive generations of lower-energy particles, until a threshold is reached. Shower size (transverse and longitudinal) and number of particles in the final generation depend on the incident particle type and energy, which makes calorimetry possible.

- While the overall shower develops along the axis of the incoming particle, the majority of the energy is measured by means of the relatively soft particles in the final generations of the shower. These can be traveling in any random direction.

- EM and non-EM showers have a very different phenomenology. EM showers are more compact and can be understood more easily from first principles. Non-EM showers are very complex, diffuse, and lumpy. But their features can be cleverly exploited by particular experimental designs.

Energy response

- In comparing various choices of calorimeter design, it will be useful to talk about the calorimeter **response**.
    - Response is the average calorimeter signal divided by the energy of the incoming particle.
- A closely related concept is **linearity**.
    - A calorimeter response is linear if the response is the same for different energies of incoming particles. In general, this makes interpretation of the calorimeter signals easier and more accurate.
- A useful standard candle is the response to MIPs, particles which lose a constant amount of energy per unit length by ionization, e.g. high-energy muons.

Energy resolution

- For a perfectly linear calorimeter, large enough to fully contain the showers, the only event-to-event fluctuation in the measured signal would be due to the Poisson statistics in the signal quanta:

$$\sigma_E/E = \frac{a}{\sqrt{E}}$$

- We call the event-to-event spread in the measured energy for a given incoming particle the **energy resolution**.

- There can (will) be other sources of fluctuations that makes the energy resolution worse than this limit, but it provides a good benchmark for comparing different choices.

Calorimetry II

Ted Kolberg (FSU)

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Review from yesterday

- Calorimeters are a critical piece of the modern collider experiment due to their **speed**, favorable performance with **high energy** particles, and the need to **fully reconstruct events** containing photons, electrons, jets, and MET.

- Calorimeters measure the energy of particles via a destructive process — inducing a shower in material and measuring the **shower products**.

- EM and hadronic showers are superficially similar, but hadronic showers have far more **complex physics** and are inherently difficult to measure well, due to **invisible energy**.

- The ideal calorimeter is linear in its response to electrons and hadrons, with small fluctuations event-to-event (good resolution). **Challenging to realize**.

Homogenous vs. sampling

Most calorimeters can be separated into two categories:

- **Homogenous** calorimeters consist of a dense material that initiates showers, and also produces a signal for measurement. Typically, this is scintillation light, though in principle it can also be ionization charge.

- **Sampling** calorimeters have two or more types of material. A dense material (“absorber”) initiates the shower and most shower development occurs within it. Scintillation or ionization layers (“active”) are interspersed with the absorber.

Homogenous: pros and cons

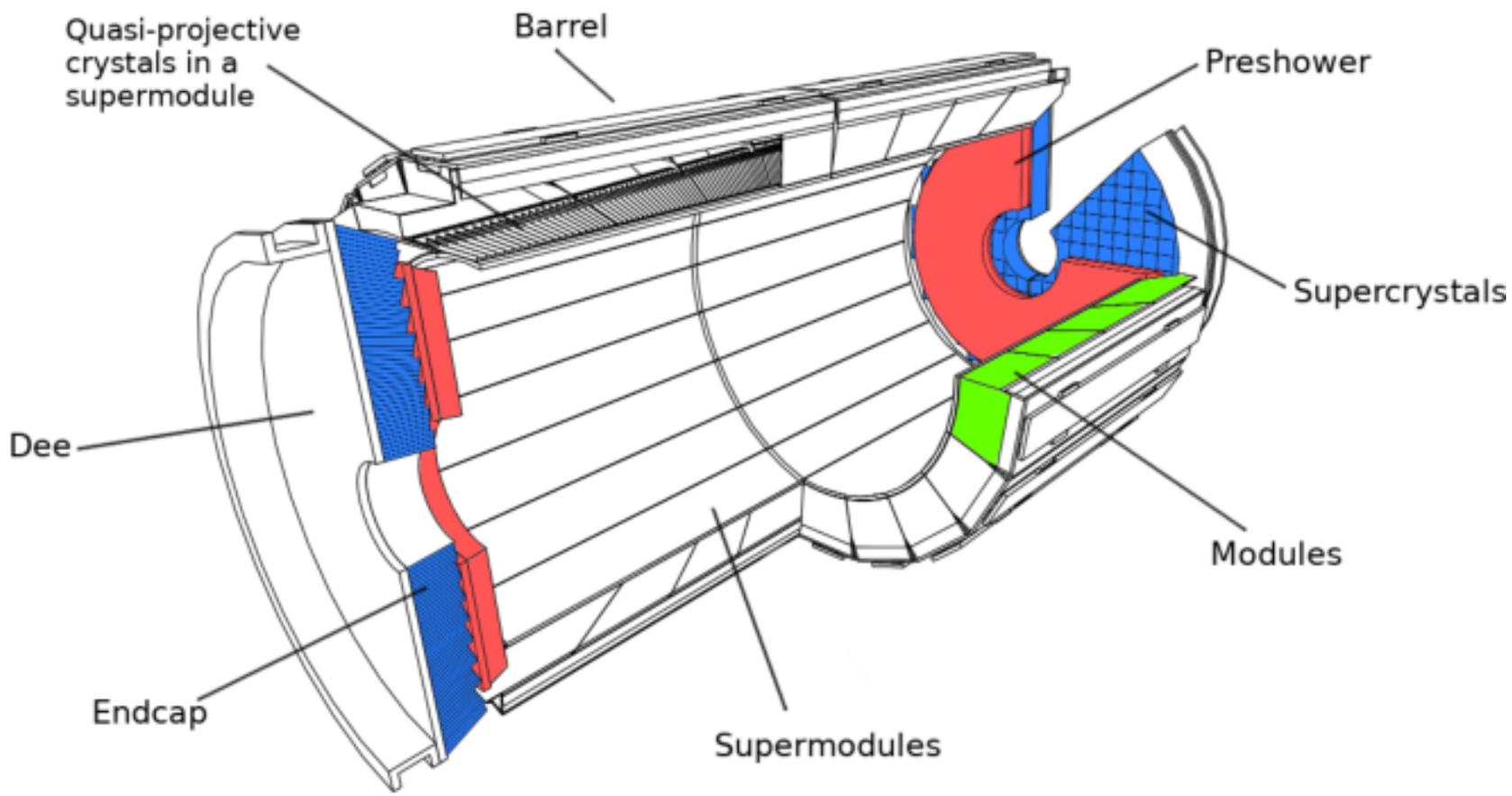
Since the whole volume is active material, there are no fluctuations in terms of how much energy is deposited in an absorber.

- Good energy resolution, can be **less than 1%** for 100 GeV particles.
- Should be intrinsically linear for EM showers.

Active material is more expensive to manufacture than absorber, leading to **large construction costs**.

- Intrinsic linearity and good resolution can be **spoiled** by a number of experimental effects if not carefully controlled (next slides).

A homogenous calorimeter



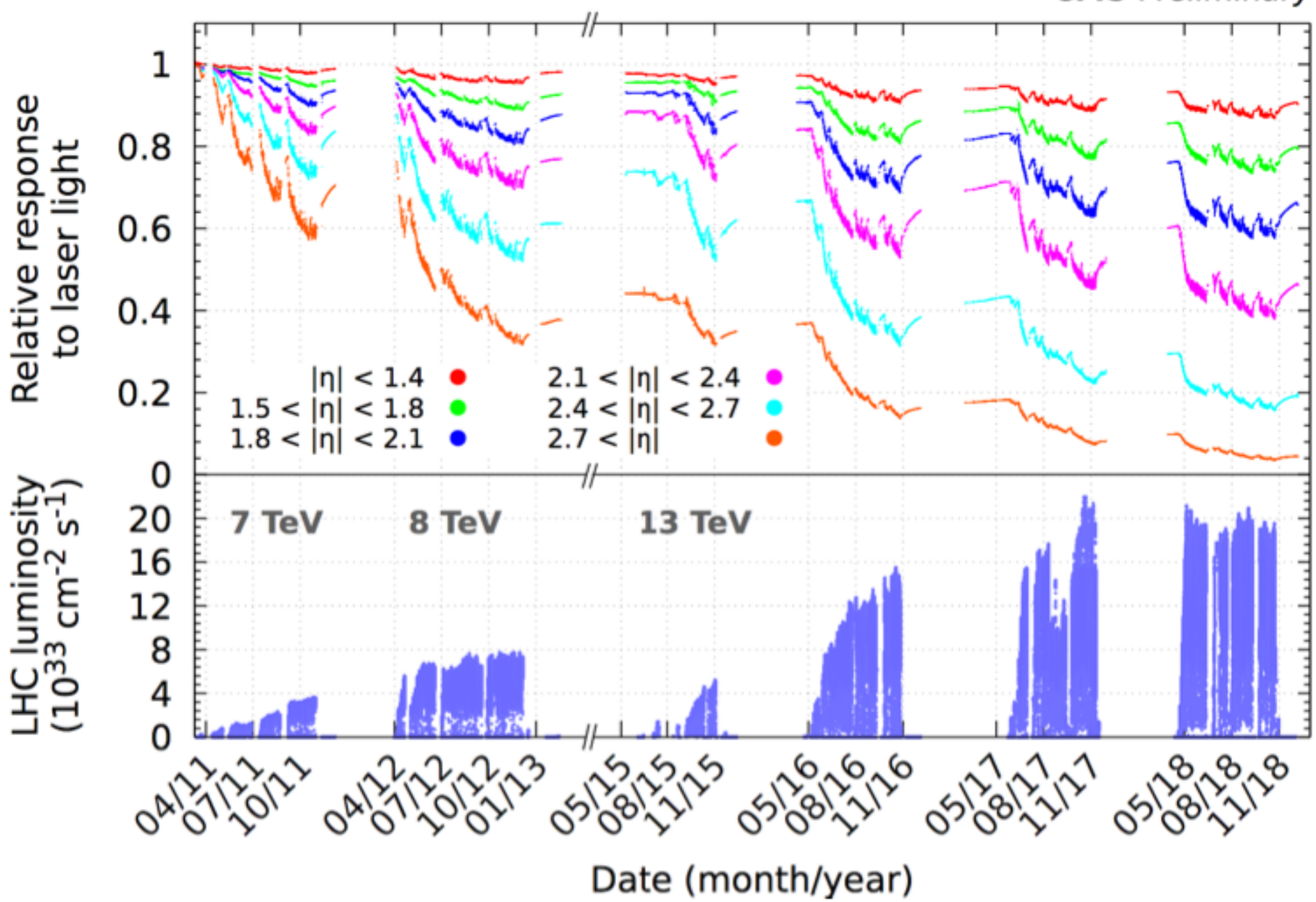
- CMS ECAL is a homogenous crystal calorimeter ($PbWO_4$). Crystal light yield is low but crystals are intrinsically radiation-hard. Crystals have a strong light yield dependence on temperature, and radiation damage 'anneals' over time and must be tracked.

- 76k channels with a total volume of 11 m^3.

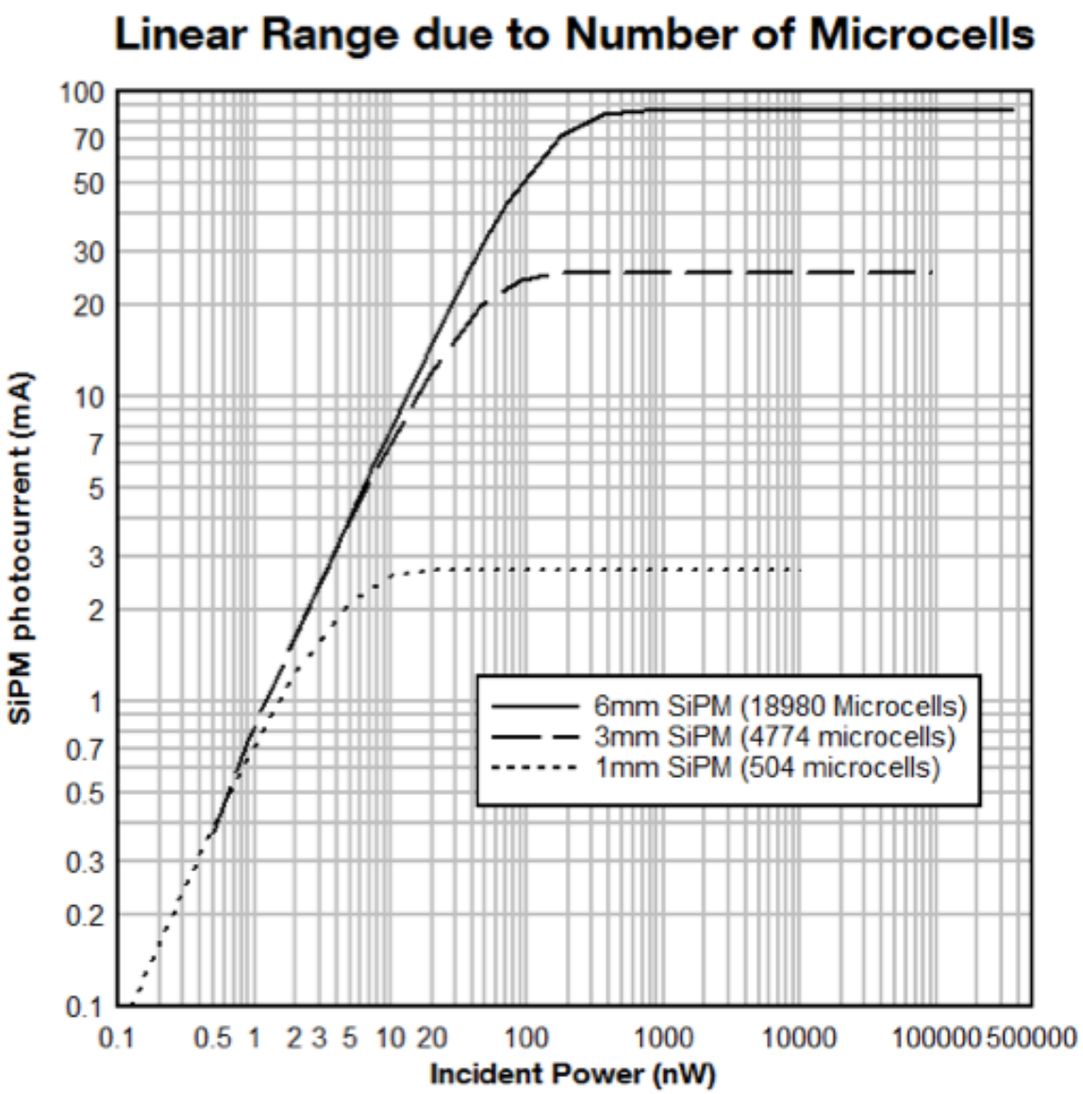
- Crystals are ~25 X_0 (25 × 0.9 cm) deep with a transverse size ~ Molière radius (2.2 cm).

- Photosensor: Avalanche photodiodes (APDs) glued on the rear of each crystal.

[CMS DP-2019/005]



Saturation effects



The active material may be completely linear but the measured signal may not be, if the photodetector or the electronics chain has a limited dynamic range.

- PMTs and semiconductor detectors will saturate with sufficiently large signals.
- Lowering the gain can reduce saturation, at the cost of reducing sensitivity for small signals.
- Digitization of analog signals into a finite bandwidth can affect linearity and resolution, if not done carefully. Balance between efficient use of bandwidth and maximum performance.

For ionization-based detectors, there can be a saturation effect at high particle densities, as well as other non-linear effects like recombination.

Shower leakage

Homogenous calorimeters will lose their linearity if the shower is not completely contained.

- Due to the large cost there is a pressure to reduce the volume of material → sufficiently high energy showers will escape through the back.

- Homogenous calorimeters still require a support structure of some kind and therefore some dead material must be present.

- Gaps and cracks needed for electronics, cooling water, etc. to pass through the calorimeter. In a collider experiment, the calorimetry can only be so close to the beam pipe.

Anomalous signals

Some effects can cause the response to **increase** with high energies:

- Non-uniform transparency loss can cause shower particles near the rear of the calorimeter to be over-sampled, causing response to increase with energy.

- Direct interactions of shower particles with photodetector (PMT glass, nuclear counter effect) can cause anomalously high signals. CMS APDs show this effect.

e/mip ratio

- MIPs (e.g. high energy muons) lose energy by ionization via the same process as the charged component of the EM showers, by exciting molecules of the medium.

- For a homogenous calorimeter, we should expect the response to be the same. I.e. if a muon loses 500 MeV of energy in passing through the calorimeter, it should produce the same response as a 500 MeV electron (photon) shower.

  - MIPs can be used for calibration as the energy loss in the material can be accurately measured.

$$e/\text{mip} = 1$$

Response to hadrons

- Due to the presence of invisible energy in hadronic showers, the response of a homogenous calorimeter to hadrons (jets) will necessarily be less than for EM showers:

$$\pi/e < 1$$

- As we have seen, the EM fraction of hadronic showers is intrinsically energy dependent. So even with a linear, homogenous calorimeter, the response to hadronic showers will vary with energy. π/e **increases with energy**.

- However the fraction of **non-EM energy** (*h*) going to various nuclear processes should not strongly depend on the incident energy. The response is less than the EM response. We call such a calorimeter **non-compensating**. A typical value might be 2, but particular designs may be even higher.

$$e/h > 1$$

Response to jets

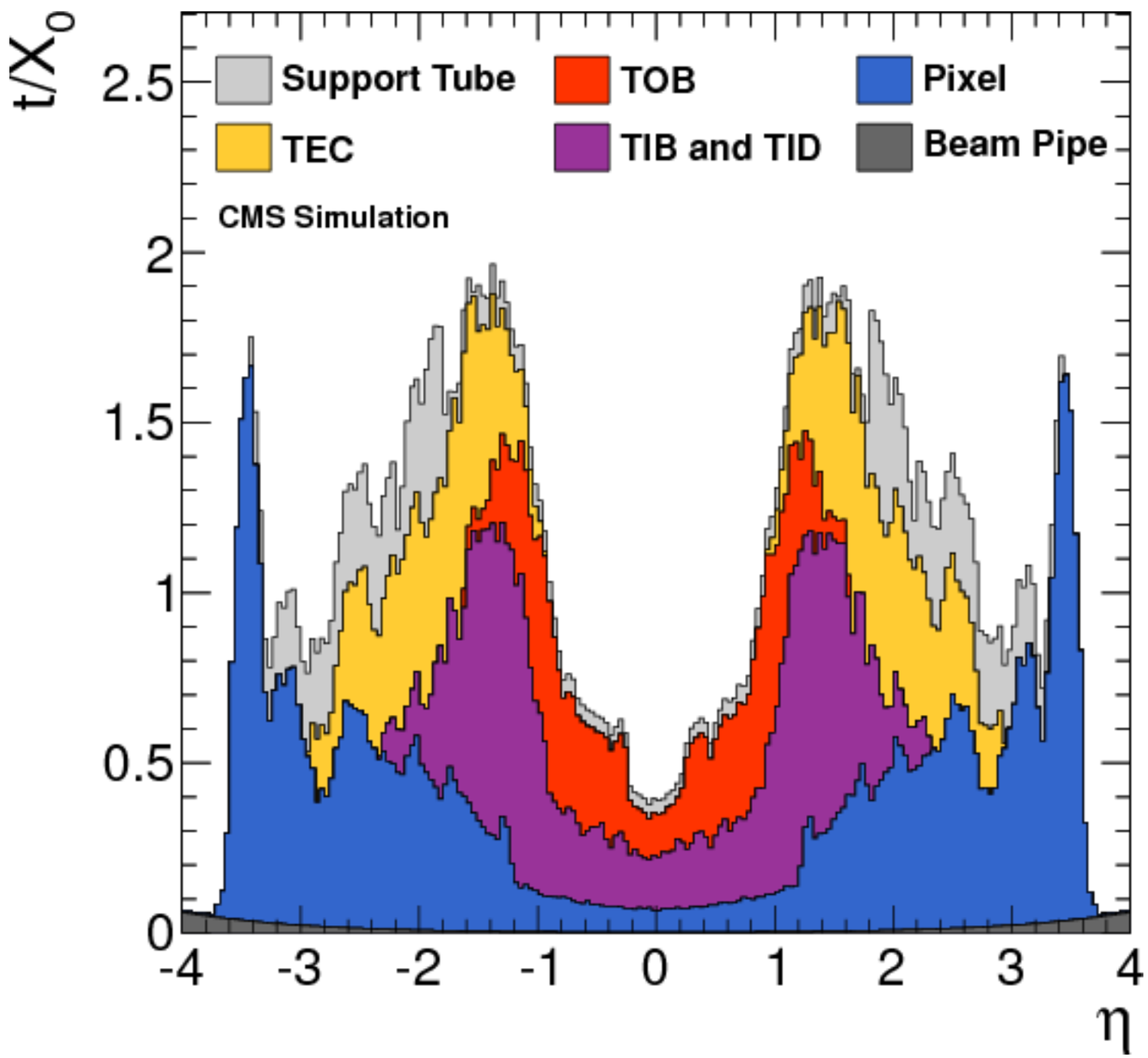
- The response to jets should be similar to the response to single hadrons, since the underlying processes are the same.

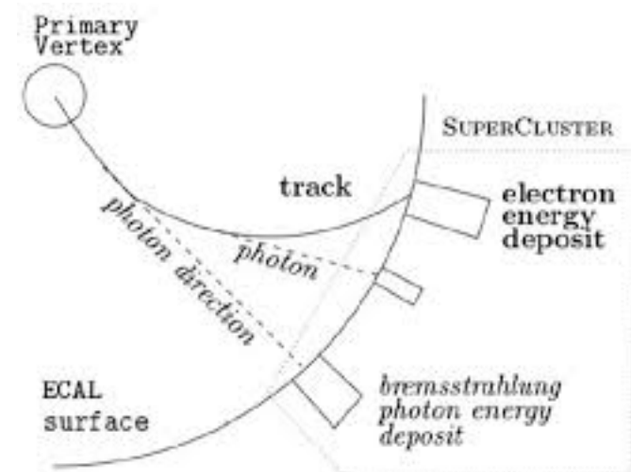
- The fragmentation process of the jet leads to additional fluctuations in the fraction of EM vs non-EM energy.

    - Quark flavor impacts the production of neutral pions (heavy quarks tend to fragment into fewer π^0s).

- While this complicates the single-hadron picture somewhat, we still have a response for jets that is less than that of electrons, by an energy-dependent amount.

“Dead” material





- Some showers start before the calorimeter due to material in the way (e.g. tracker and supporting infrastructure).
- Can try to recover some of this with clever reconstruction, but it is an ugly business best avoided.
- It may not make sense to park a really expensive state-of-the-art calorimeter behind a massive tracker.

Temperature dependence

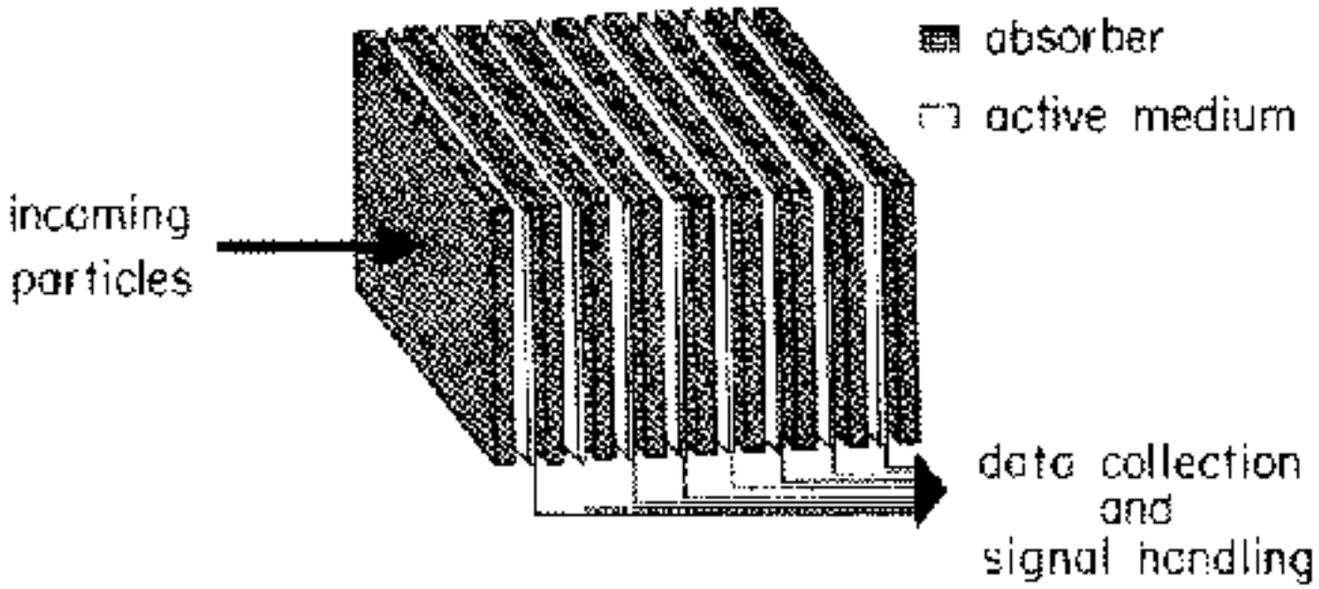
- Light yield of scintillators can be strongly temperature-dependent ($PbWO_4$ -2.0% / °C) as are the gain of both PMTs and silicon photodetectors (CMS ECAL APD -2.3% / °C).

- Operating temperatures of calorimeter can fluctuate locally due to operational conditions, electronics heat load, self-heating of radiation damaged photodetectors. Even a stable room temperature can be hard to maintain.

    - Some designs have readout electronics inside the detector volume, heat load management is critical. Power pulsing.

- Temperatures below freezing (-30 °C for radiation damaged silicon, -185 °C for LAr) require environmental control to avoid condensation or icing, additional material and complexity.

Sampling: pros and cons

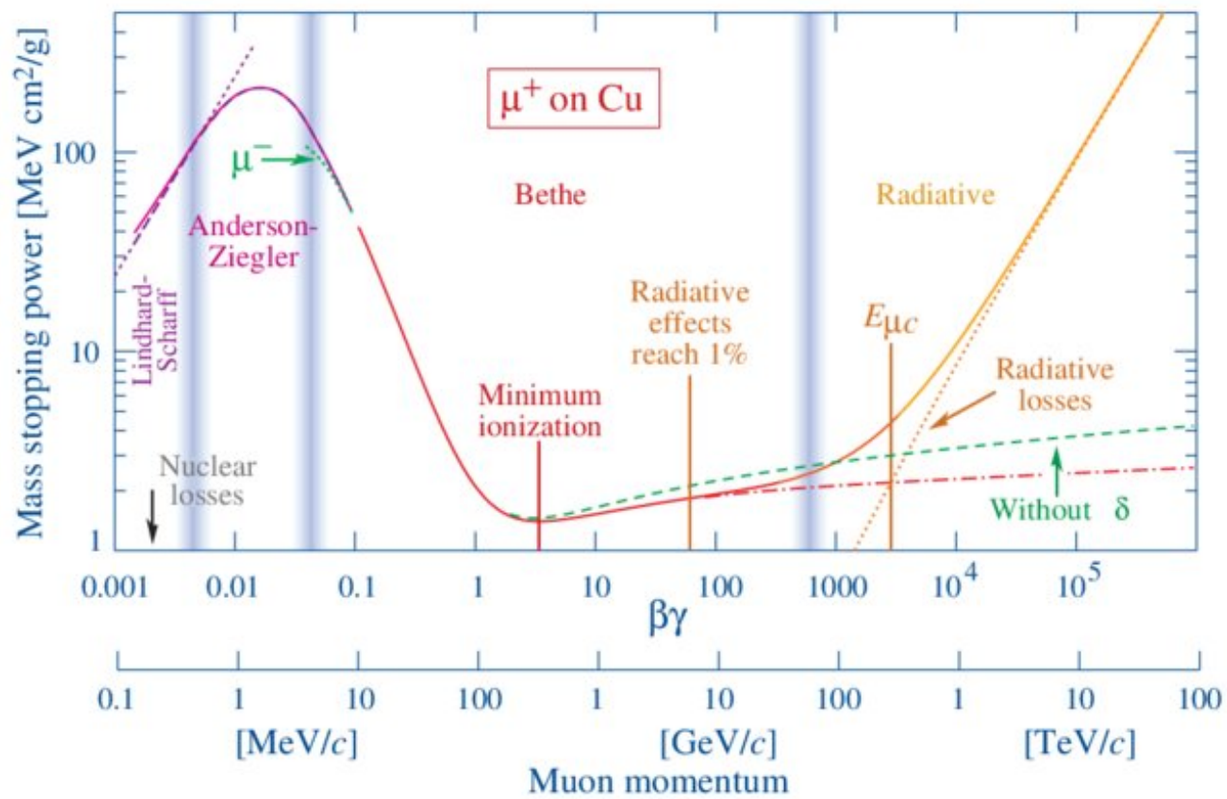


Sampling calorimeters are typically cheaper to construct, due to using a smaller volume of active material.

Inherent to the sampling concept, there are fluctuations in the fraction of energy deposited in active material vs. absorber, worsening the energy resolution. Typically, they are a few times worse at the same energy than homogenous calorimeters.

Combinations of different material types can be used to fine-tune the response to *e* vs *h*, opening the possibility of **compensating** calorimeters with e/h ~ 1.

Sampling fraction



- An important parameter of sampling calorimeters is the **sampling fraction**, or the fraction of MIP energy deposited in the active material compared with the whole calorimeter.

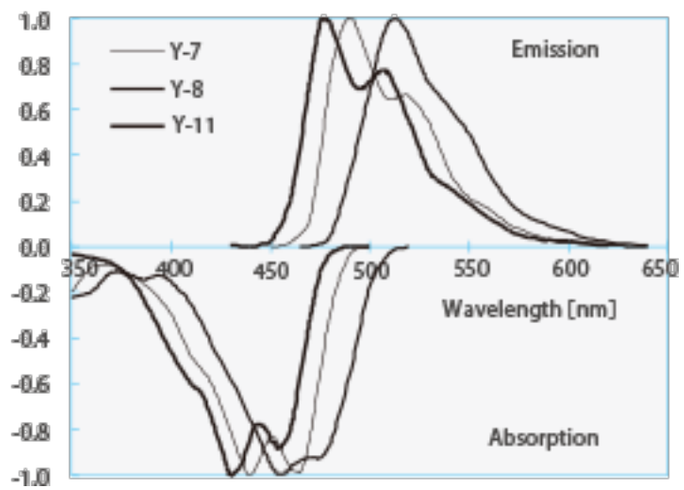
    - Not so important — orientation of the sampling layers.

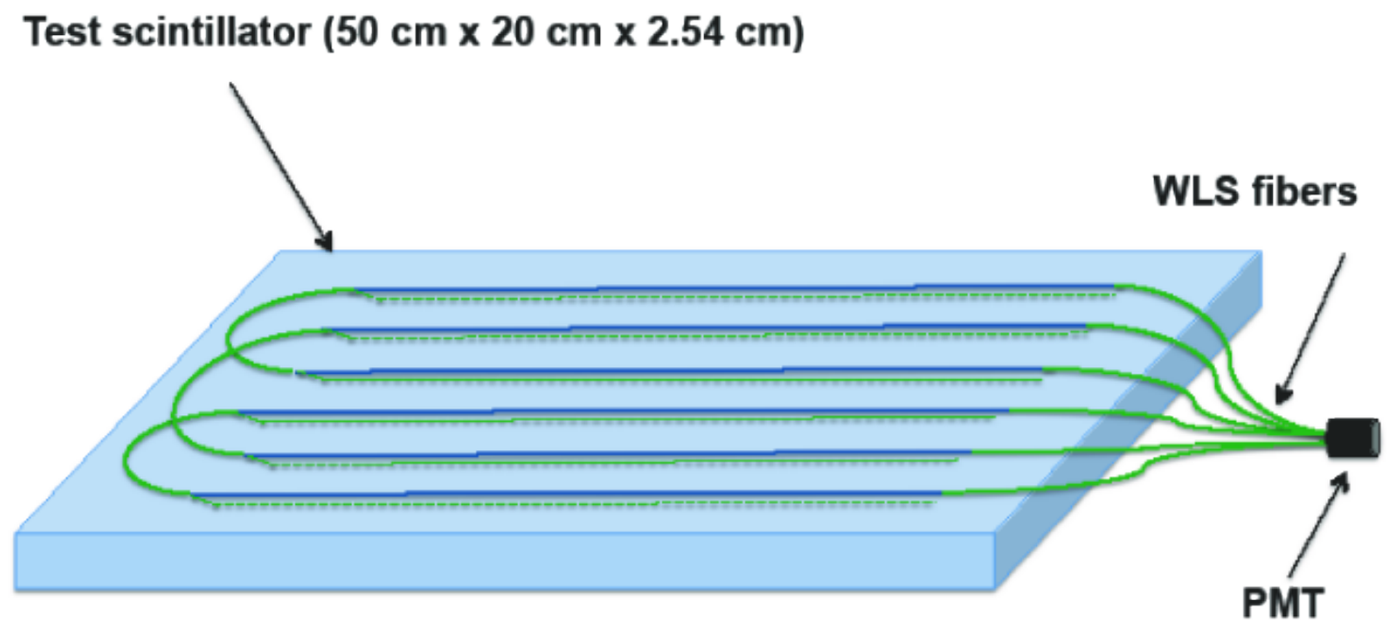
- NB that a MIP is a **hypothetical particle**. As soon as a MIP starts to lose energy, its dE/dx changes as well. Experimentally, once can measure for a spectrum of muon energies and try to extract the MIP component of the response.

Plastic scintillators

- Plastic scintillators are cheap and effective.
- Machining plastic is difficult and one can inadvertently destroy surface quality by mishandling.
- Plastics can outgas and ignite when heated (fire hazard).
- Concerns about aging/yellowing over time.
- Vulnerable to crazing/cracking under temperature cycles.

Wave length shifters

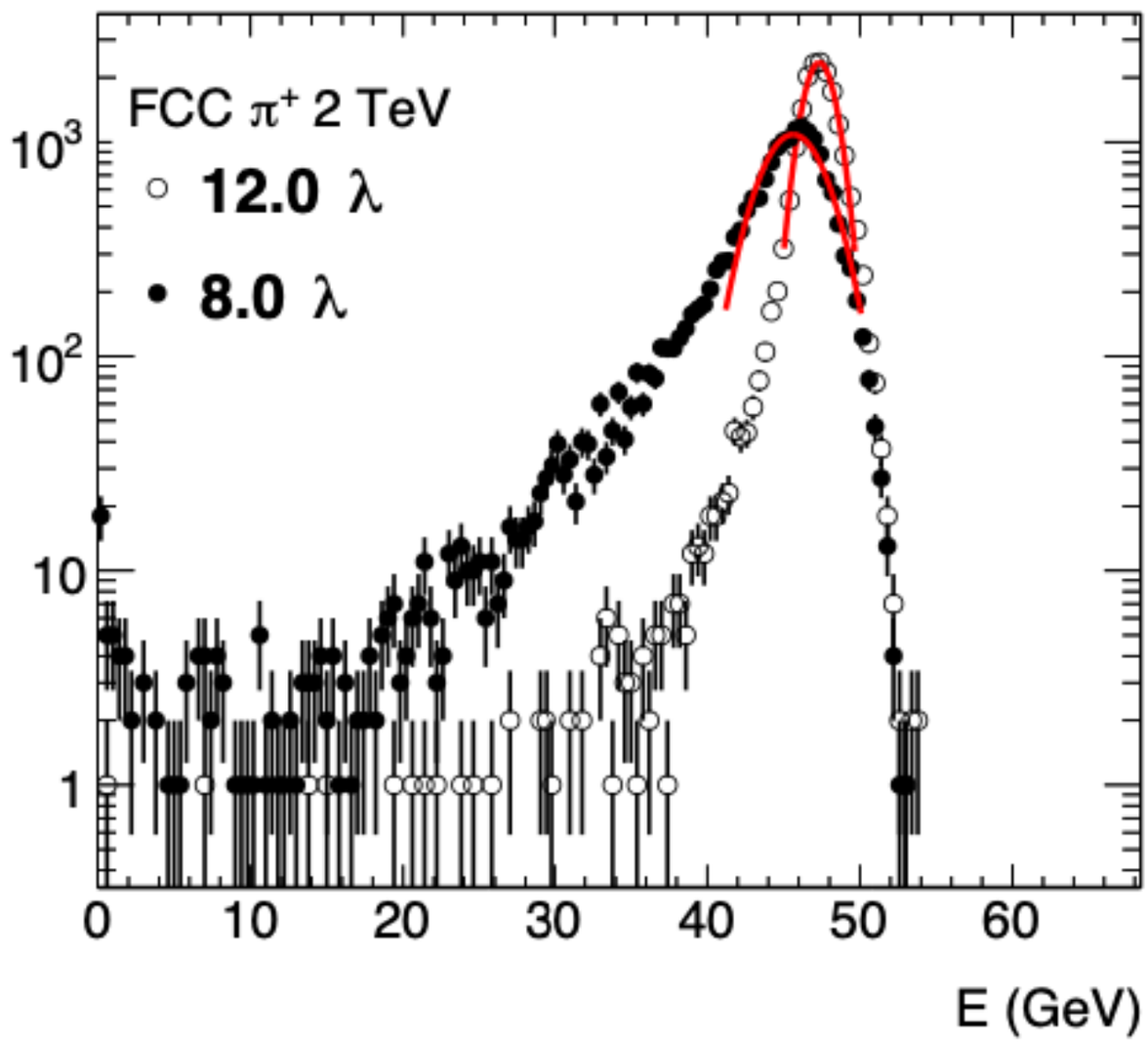




Wave length shifters are a common component of sampling calorimeters using large plastic scintillators.

- Absorb blue scintillation light and emit green shifted light.
- Improve attenuation length so that light can be routed to photodetectors, typically at the back of the calorimeter.
- Fibers give a flexible means of ganging readout channels and putting photodetectors in an optimal environment.

Containment



- A deeper calorimeter more fully contains showers, especially high-energy showers.
- For hadrons, it also does a better job of protecting the muon system from hadronic "punch-through."
- In a cylindrical geometry, each additional radiation (interaction) length requires more and more material (goes as r^2).
- There may be upper limits on the space available for the calorimeter system in the experiment.

Response to electrons

Experimental data from many sampling calorimeters shows that the response to electrons (photons) is **less** than the response to MIPs, by up to 40% in extreme cases. This is surprising as MIPs only lose energy by EM interaction!

- A clue as to the reason can be found in the fact that the larger the Z difference between active material and absorber, the lower the $e/$mip ratio.

- The majority of the signal from EM showers is carried by low-energy photons, produced by Compton scattering and the photoelectric effect. But these particles have a very short range O(1 mm) in high-Z materials. They tend to be under-sampled in the active layers.

- The response can be equalized by going to very thin layers → but this is impractical.

Response to hadrons

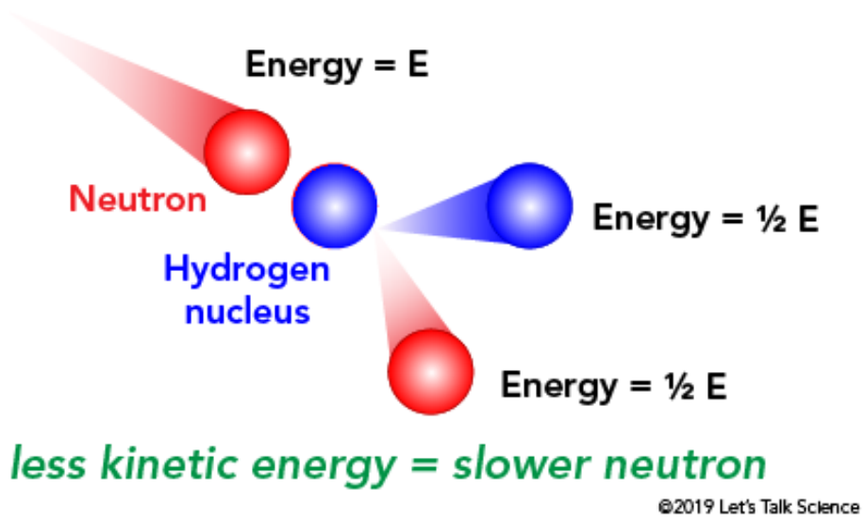
Like homogenous calorimeters, sampling calorimeters are non-linear by default, due to the changing EM fraction of the showers as a function of energy.

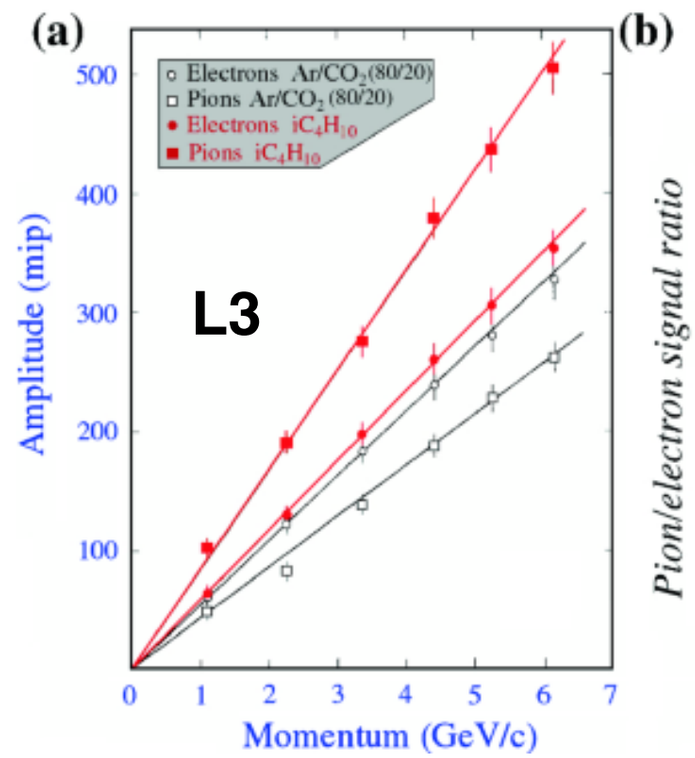
However, unlike homogenous calorimeters, we have additional degrees of freedom in designing a sampling calorimeter (absorber material, active material, sampling fraction, geometry). By cleverly choosing these, we can selectively amplify the response to hadrons in order to aim for $e/h \approx 1$.

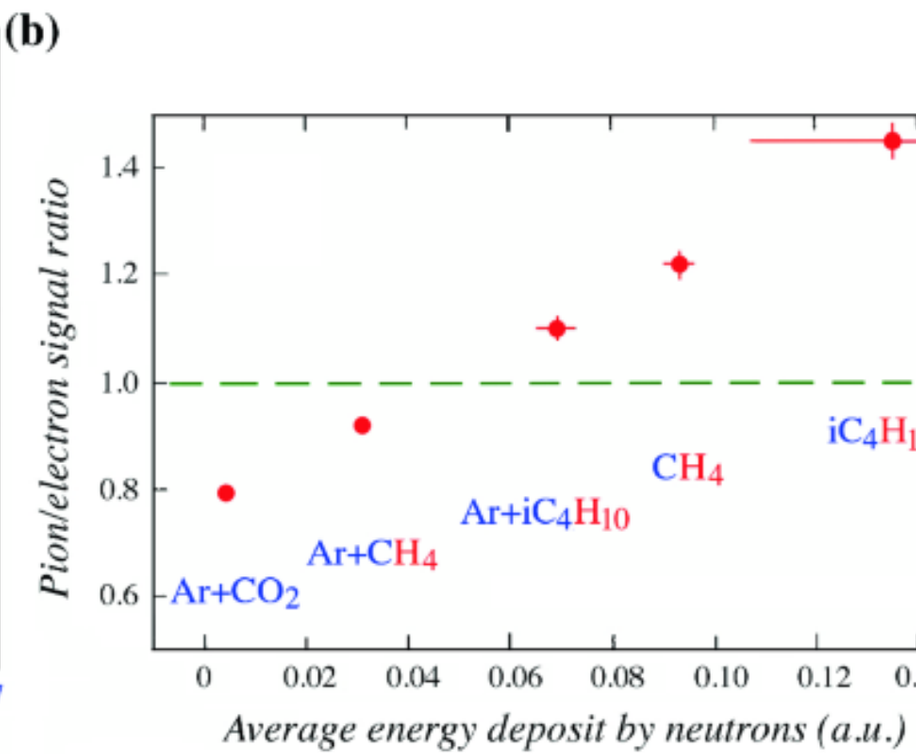
This can be done in a number of ways:

- Reduce the response to electrons, e.g. by choosing a high-*Z* absorber material.
- Enhancing the response to hadrons, by using materials containing hydrogen.

Neutron energy loss

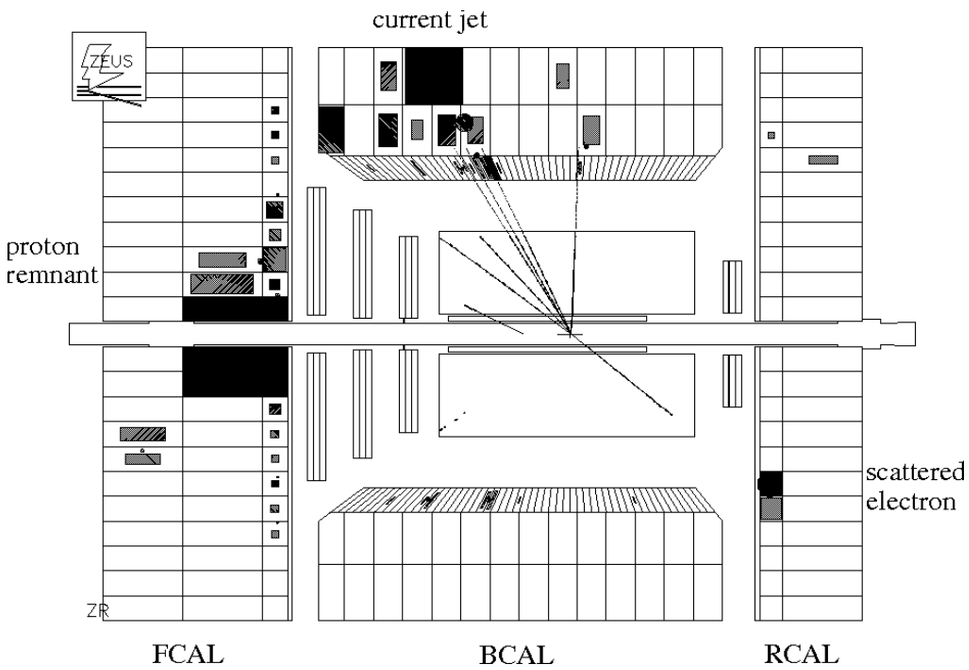


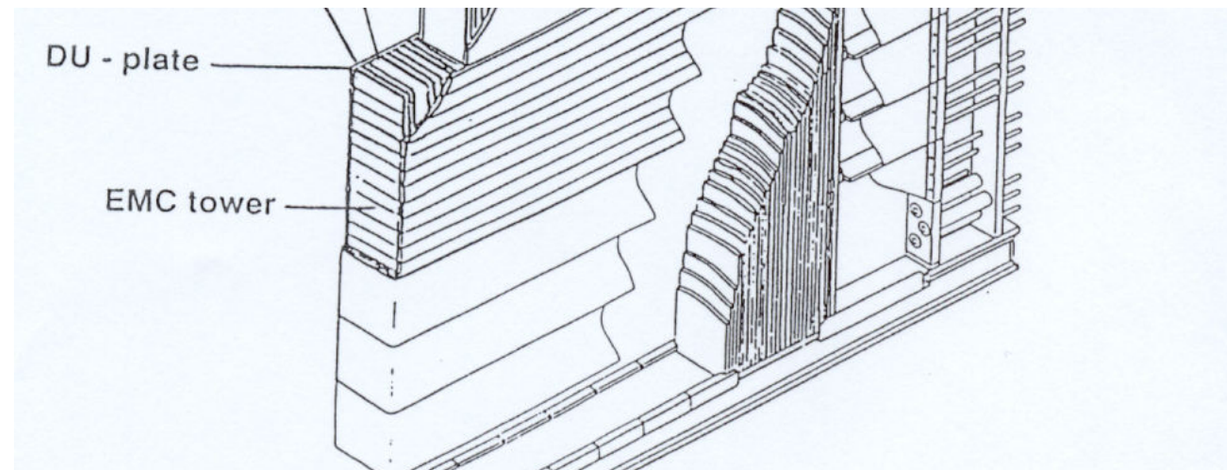




- If hydrogen is present in the active material, neutrons will very efficiently lose energy by scattering off the hydrogen nuclei.
- This reaction produces protons that rapidly range out, depositing all their energy in the active material.
- This selective enhancement of the hadron response can be tuned by the choice of material and sampling fraction.

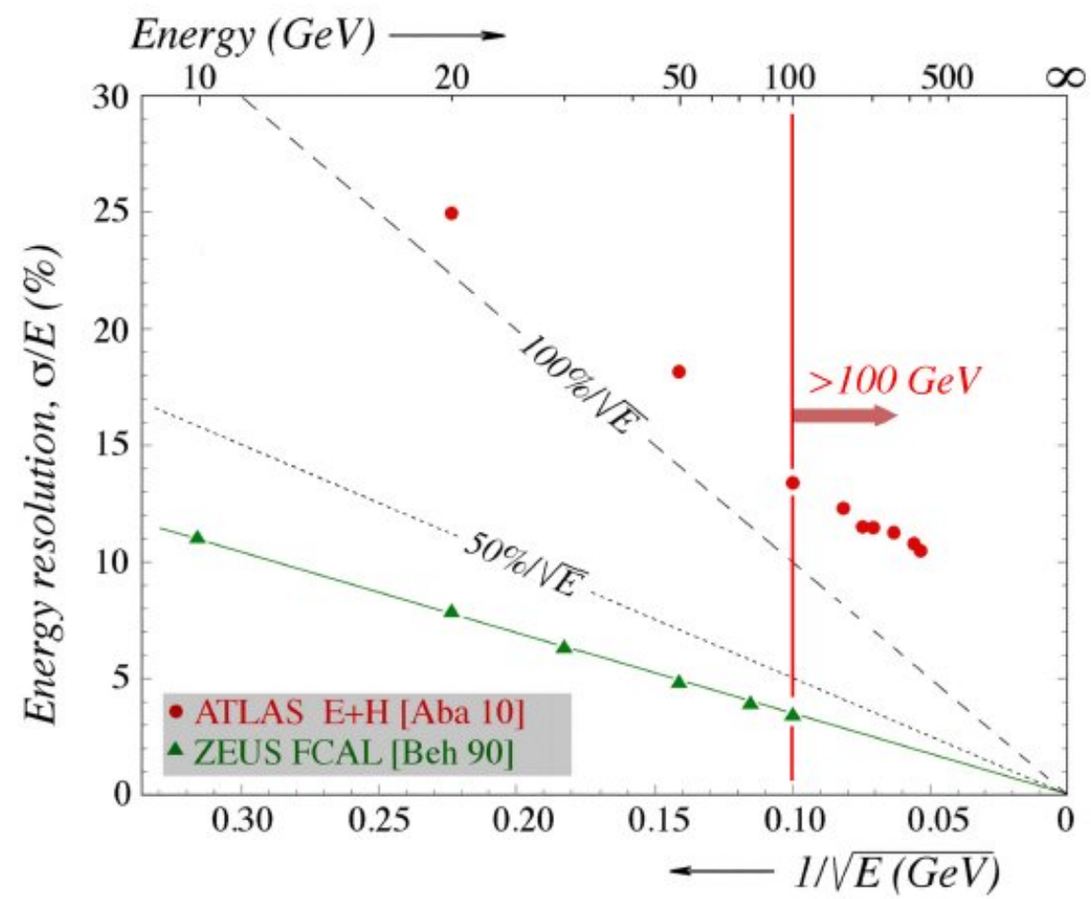
A sampling calorimeter





- ZEUS calorimeter was a sampling calorimeter made of plastic scintillator and depleted uranium.

- Calorimeter system had excellent hadron and jet energy resolution, better than any of the LHC experiments.



Cons: compensation w/neutrons

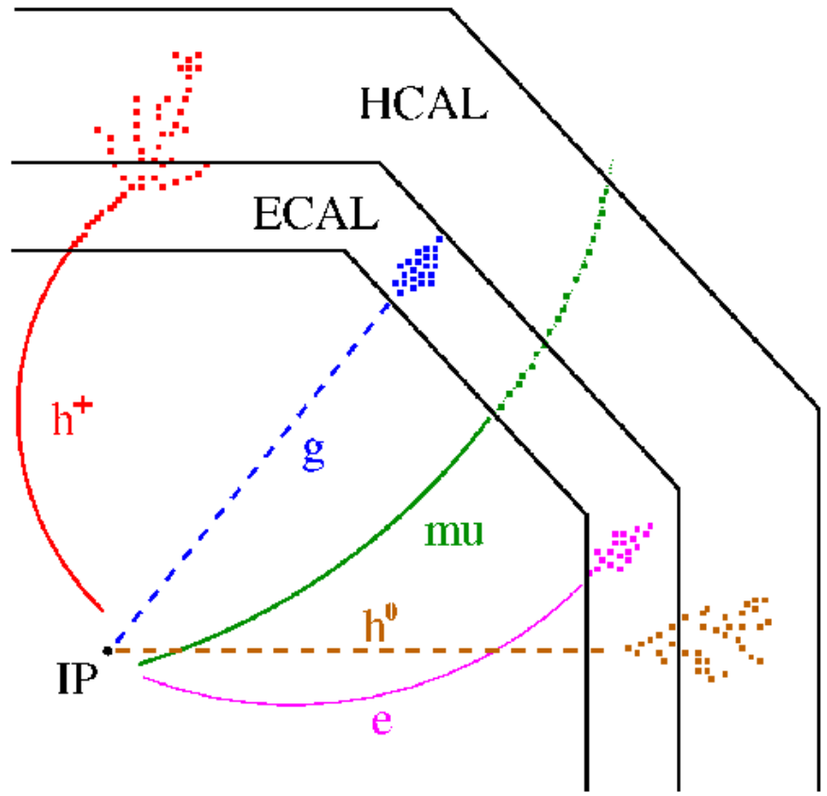
- Neutron energy loss is a slower process O(100 ns) [material dependent] and therefore the e/h approaches one after a relatively long time → this can be in tension with time resolution (high collision rates and out-of-time pileup).

- Neutrons travel far from the shower core O(50 cm) [material dependent] and so we need to integrate over a large spatial area → this can be in tension with spatial resolution of physics objects (high multiplicities, in-time pileup, jet substructure).

- Compensation does not work as well for low momentum (< 10 GeV) particles (highly ionizing).

- Depending on materials, compensation comes at the expense of good EM resolution, since it results in a low sampling fraction O(1%).

Particle flow algorithm



- Hadron calorimetry is challenging, and the requirements of a good hadron calorimeter are often in tension with other goals.

- Particle flow concept: match calorimeter deposits to tracks from the experiment's tracking systems. Identify each type of particle and choose the best measurement, leaving only neutral hadrons to be measured by the hadron calorimeter.

    - "Software compensation" concept may bring further improvements.

- PF will work best in detectors which are specifically designed to leverage it. In particular, high granularity of the calorimeter readout, such that shower overlaps are minimized and are more easily matched to tracks.

PF detectors for ILC

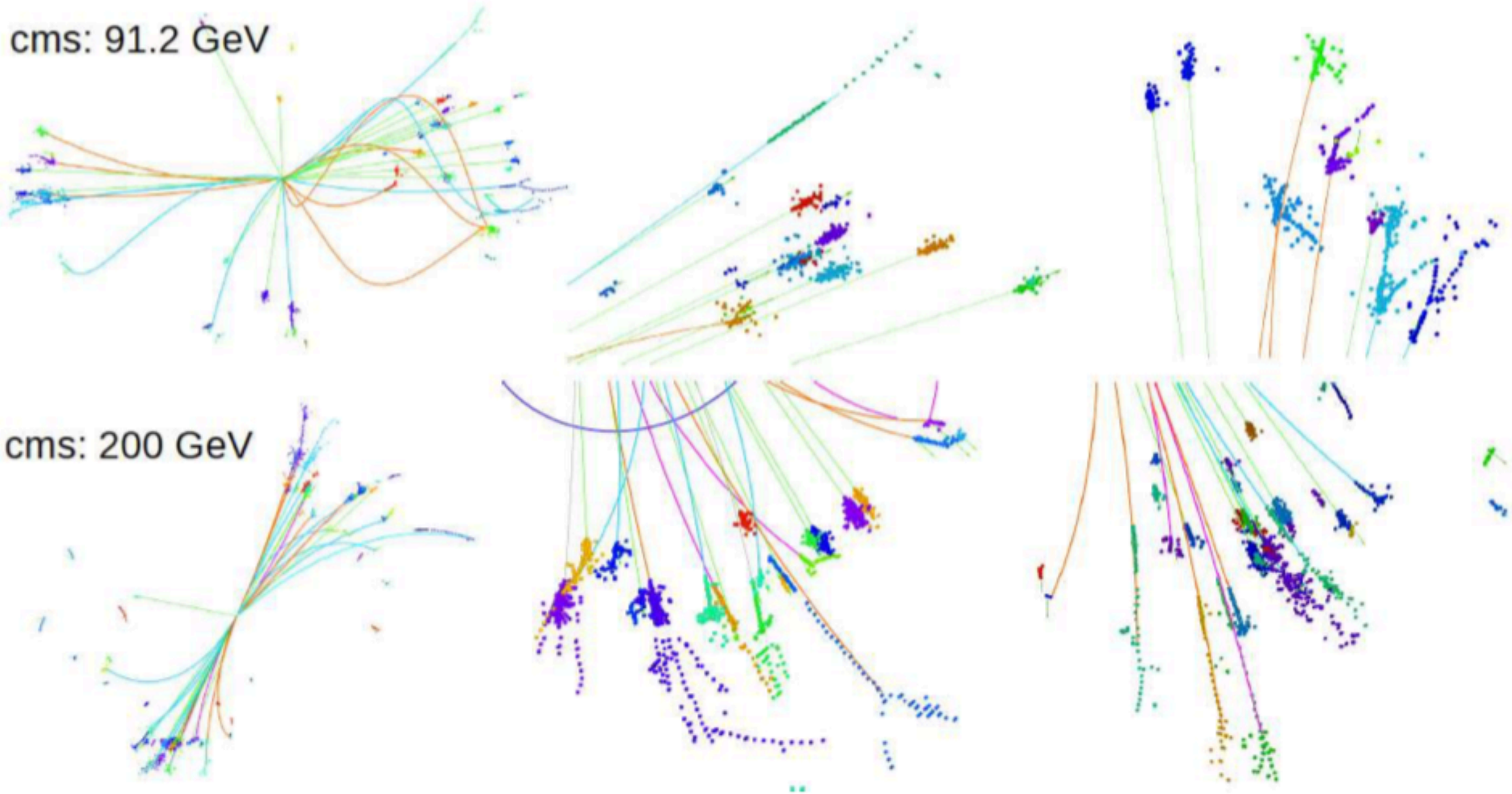
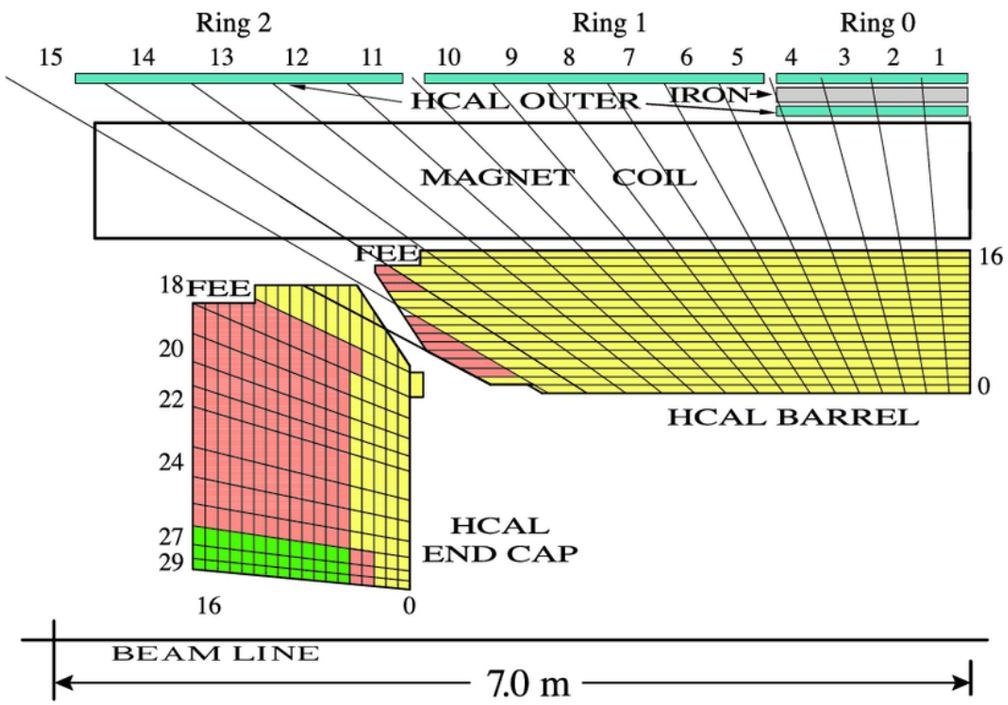
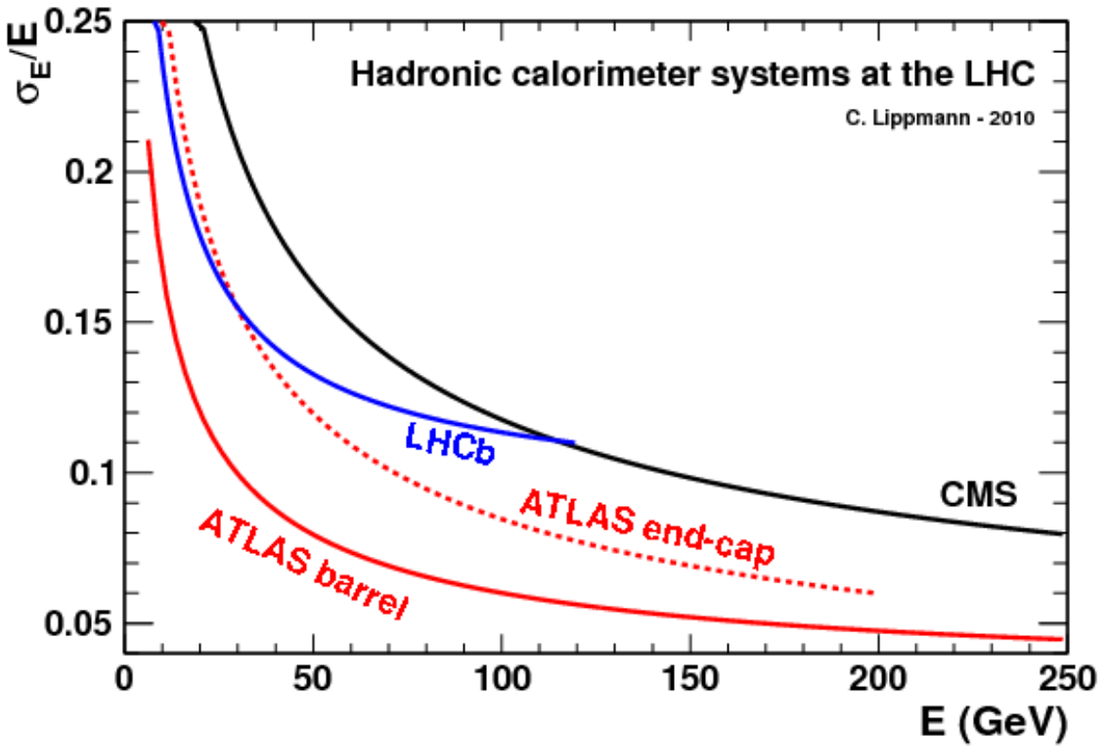
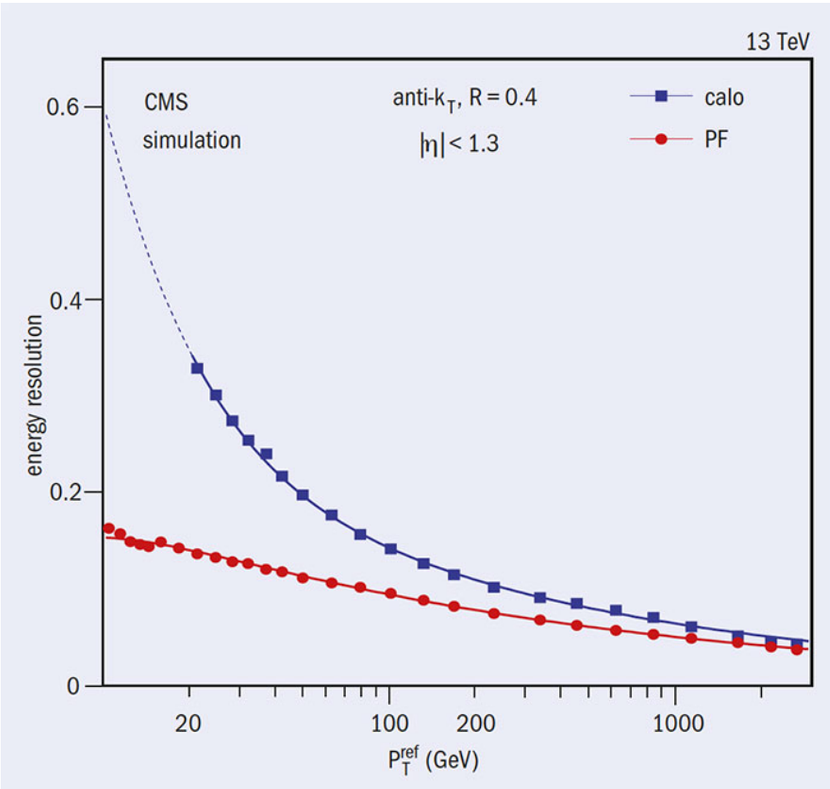


Figure 9: QQ events reconstructed with Arbor. Above plots corresponding to qq event at Z threshold, below shows that at center of mass energy of 200 GeV

Particle flow at CMS (current)

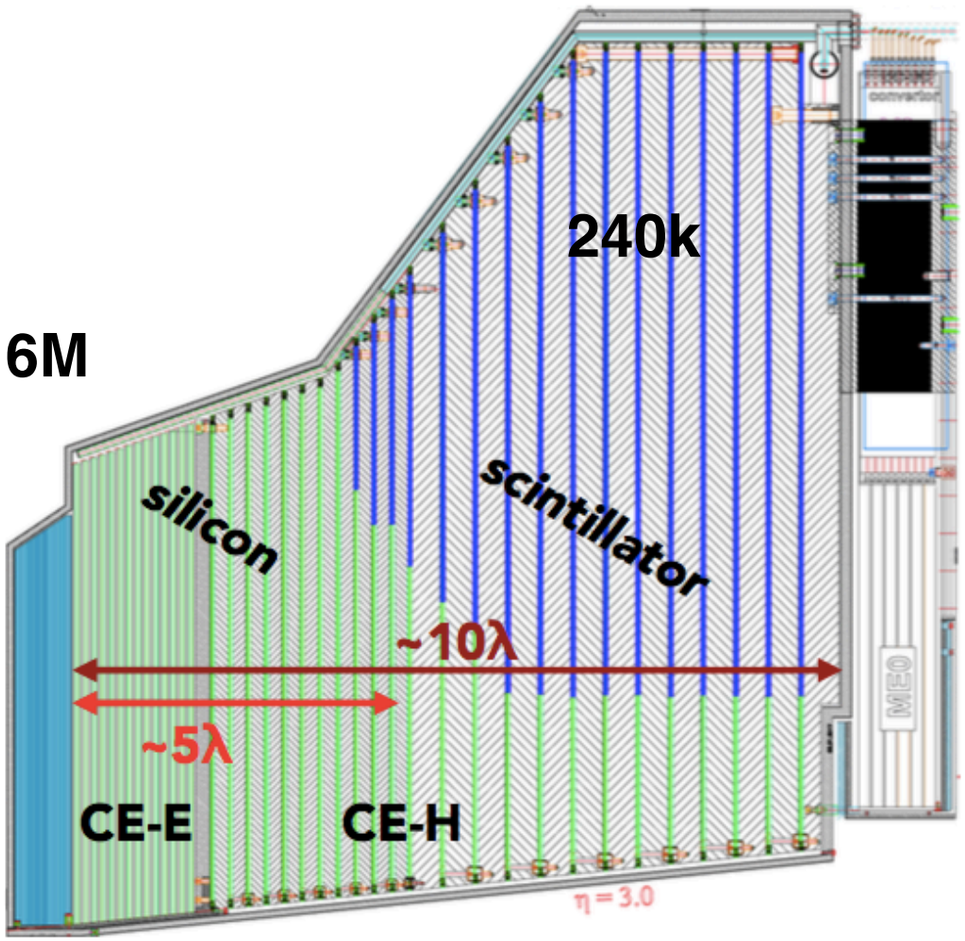


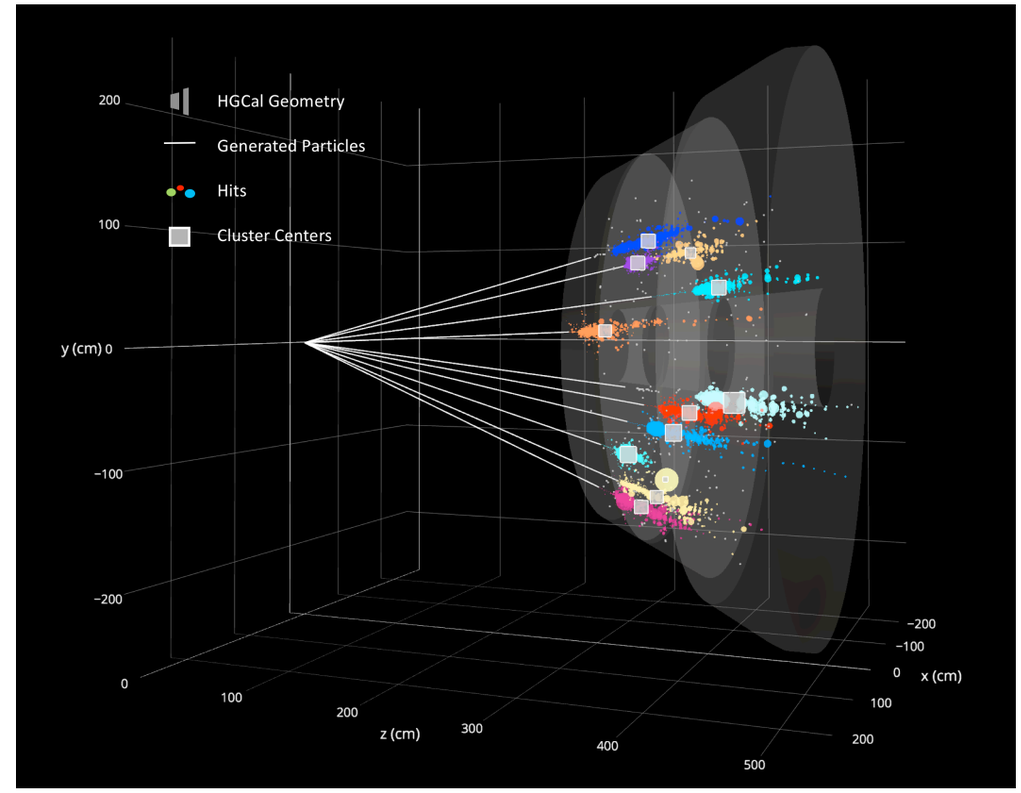


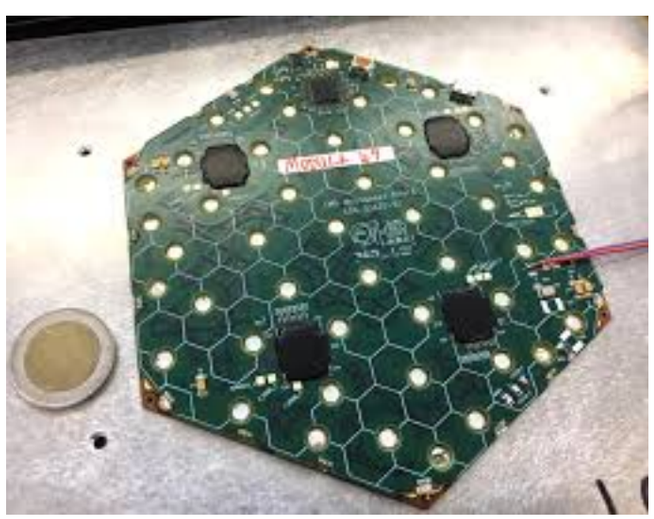


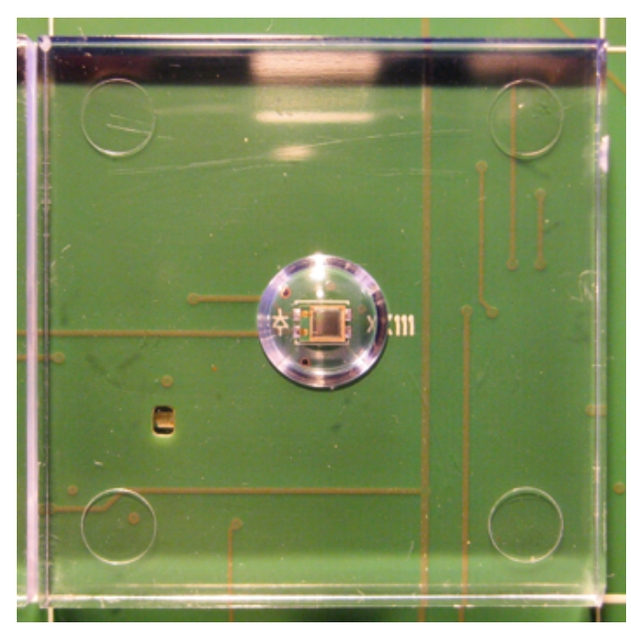
- CMS HCAL performance is pretty horrible (by design).
- Even though the channels are quite coarse, PF approach still improves the resolution by a lot, since we no longer need the HCAL for most particles.

Particle flow at CMS (future)

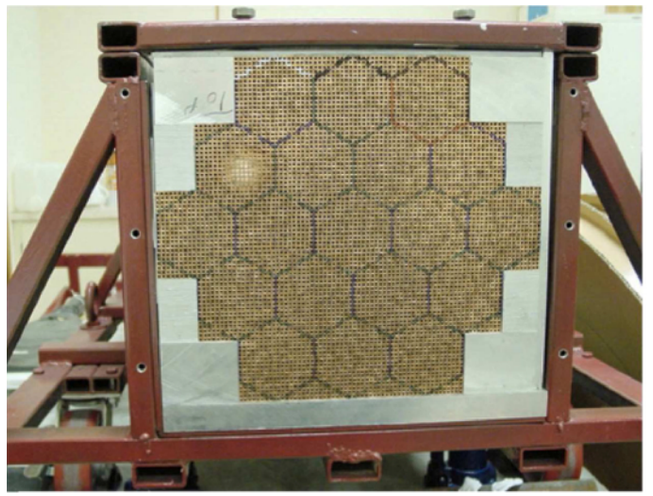


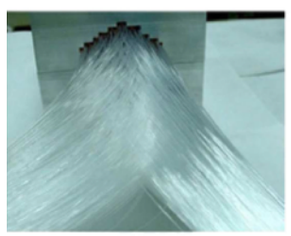


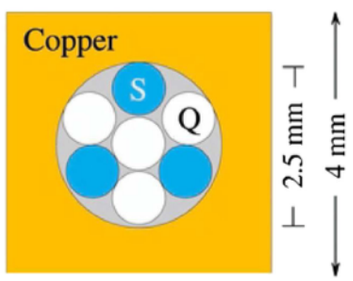


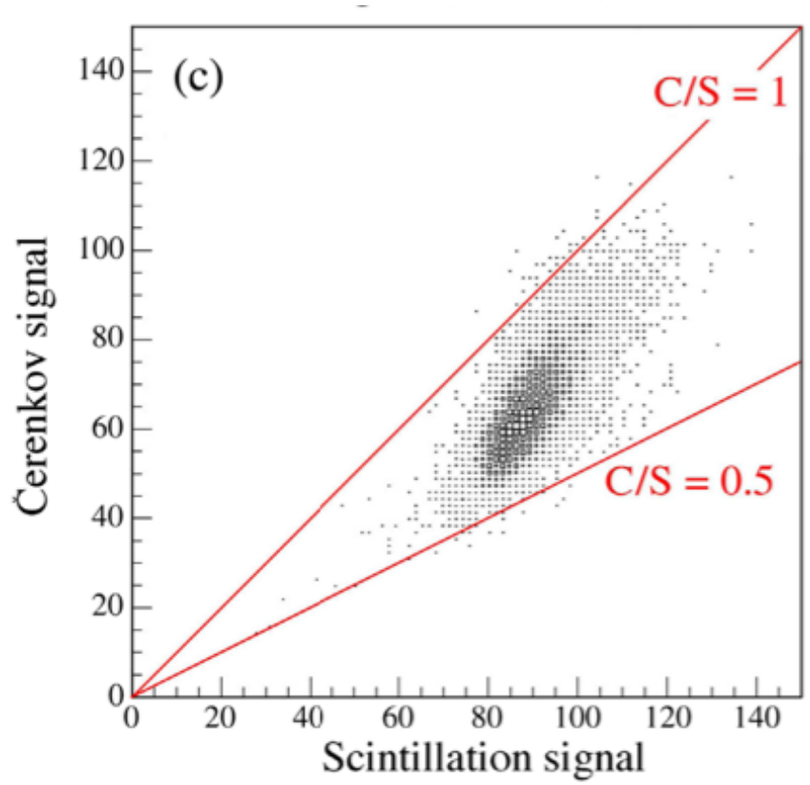


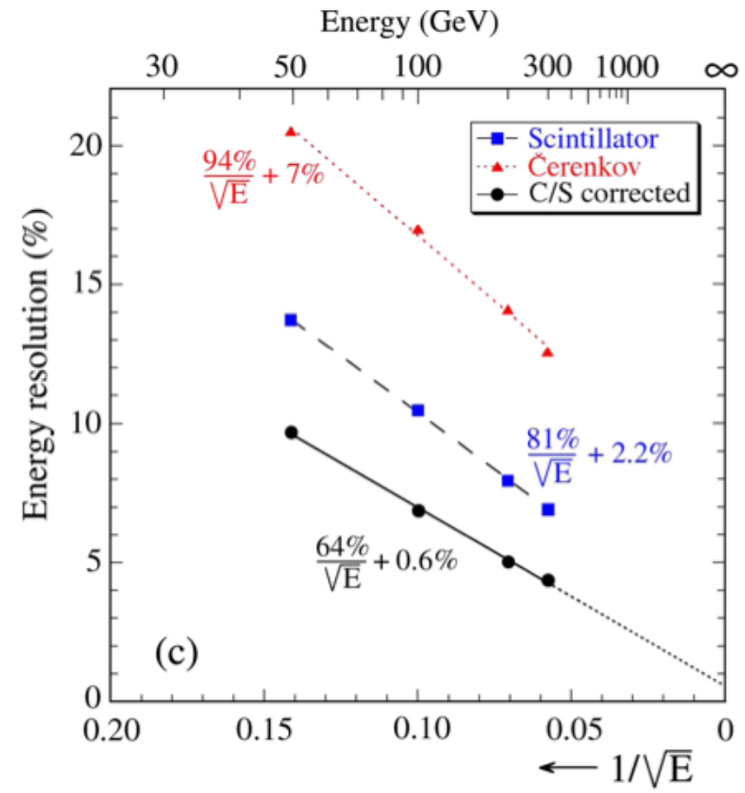
Dual readout











Another (not mutually exclusive) idea for improving the performance of calorimeter systems is **dual readout**. Not yet realized in a collider experiment.

- Dual readout works by having sensitivity to scintillation signals (e.g. from a plastic scintillator) and Cherenkov signals (e.g. from quartz fibers). (Can also be done with homogenous calorimeter.)

- Cherenkov light is produced mostly by the EM component of the shower, whereas both EM and non-EM contribute to the scintillation signal.

- The ratio of the Cherenkov and scintillation signals therefore enable an event-to-event compensation scheme, resulting in a better combined resolution than either component alone.

Summary

- Calorimetry is a critical component of collider detectors, we are living through the “age of calorimetry.”
- There are a huge number of concepts and approaches, with their own strengths and weaknesses, that lead to the large diversity of approaches taken by various experiments.
- Calorimetry, especially hadron calorimetry, is difficult and has many subtleties. Lots of interesting challenges in the field.
- Next generation accelerators will likely see the full deployment of ideas which are currently being developed (particle flow, dual readout, …)

Suggested reading

- Calorimetry: Energy Measurement in Particle Physics, Wigmans (Oxford 2000)

- PDG review 33. “Passage of Particles Through Matter,” Groom & Klein, 2019