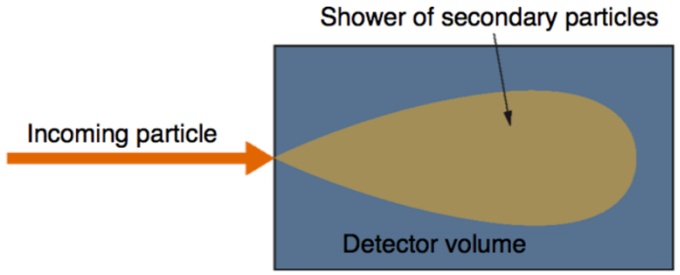
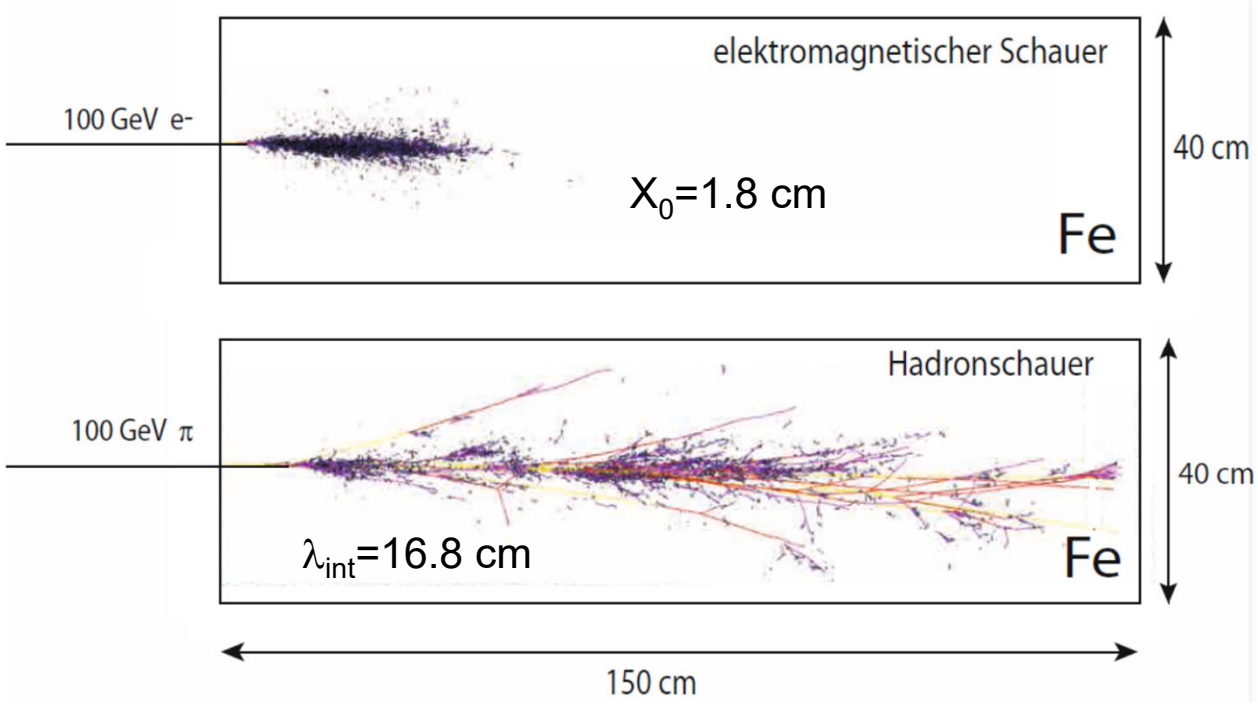
3. Calorimeters – energy measurement



Particles shower (secondary particles) and deposit their whole energy into the detector volume.

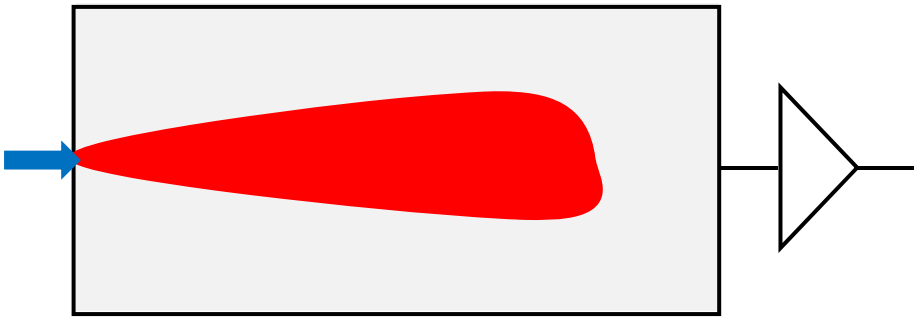


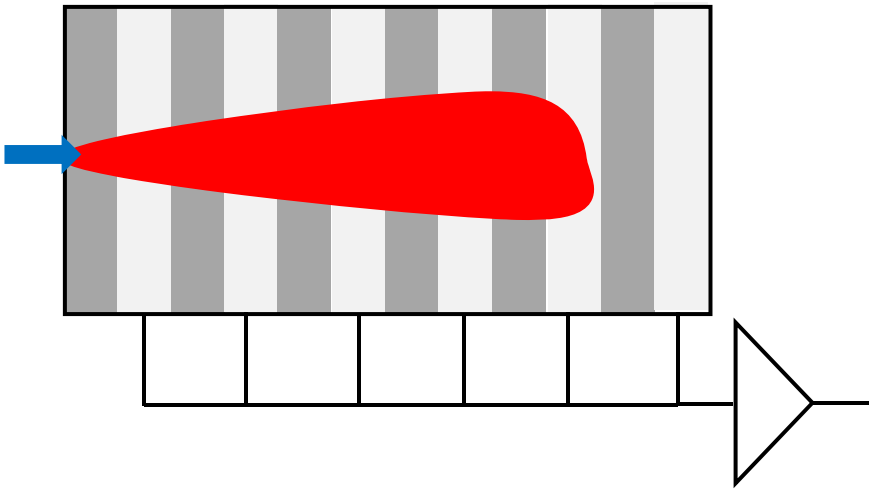
Electromagnetic shower: length scale determined by radiation length

Hadronic shower: length scale determined by hadronic interaction length (much larger)

Because of the very different shower development one distinguishes between electromagnetic calorimeters (ECAL) to measure electrons and photons and hadronic calorimeters (HCAL) to measure the energy of hadrons and jets.

Two types of calorimeters:





Homogenous calorimeters:

- "Absorber" / shower material is active and provides a measurable signal.
- All the deposited energy is transferred into the signal → best possible resolution.
- expensive
- Used only for "compact" electromagnetic calorimeters.

Sampling calorimeters:

- "Absorber" / shower material is not active but interleaved with active material (e.g. scintillators) to provide signals.
- Only a fraction of the deposited energy converted into signal → sampling fluctuations (degrades res.)
- Used for hadronic calorimeters (always) and electromagnetic calorimeters.

Homogenous calorimeter:

In homogenous calorimeter the active detector material and the absorbing material is the same. As these calorimeters are typically used for ECALs the material should have a large Z to keep the calorimeter compact ($X_0 \sim A/Z^2$).

The following detection mechanisms and materials are used:

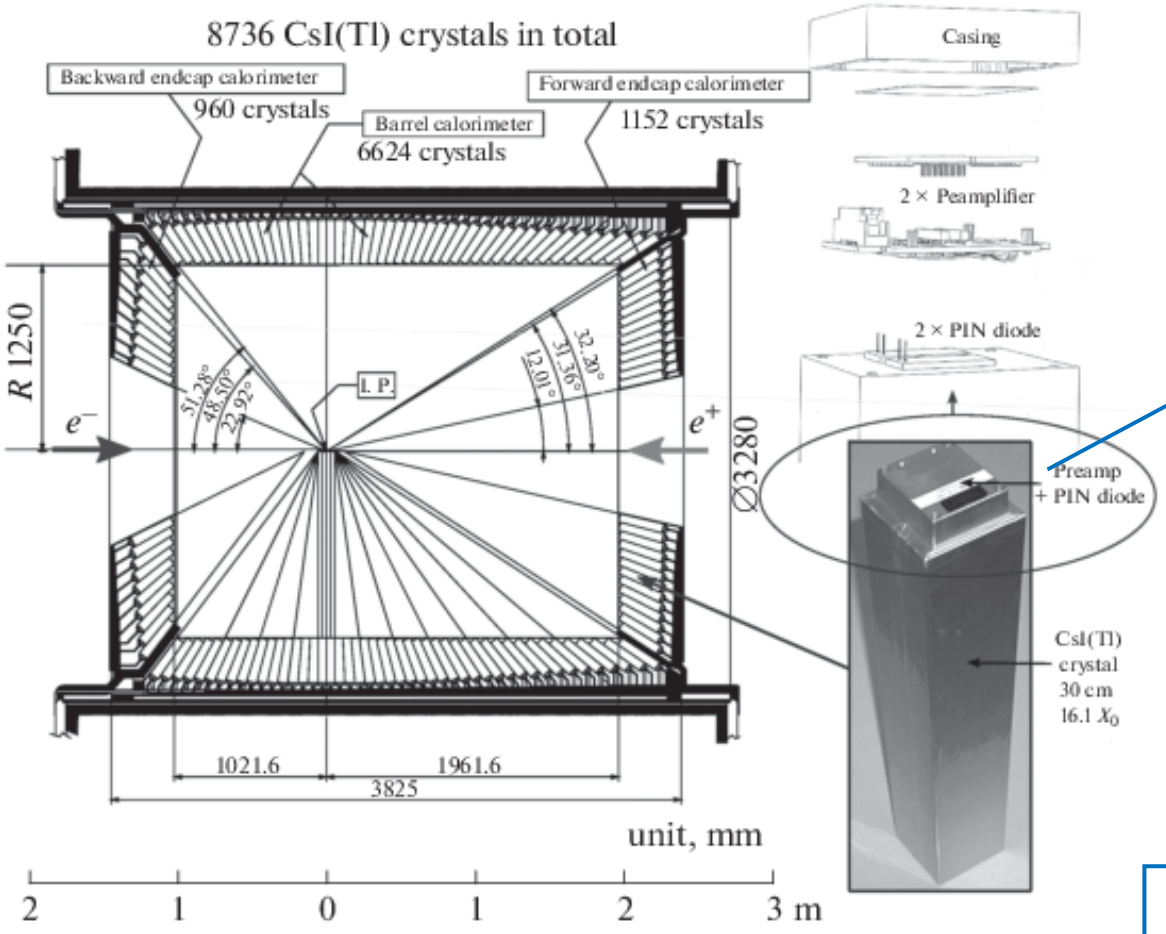
Detection mechanism	Material
Scintillation	CsJ, BGO*), BaF_2, CeF_2, $PbWO_4$
Cherenkov light	Lead glass (e.g. OPAL exp.)
Ionization	Liquid nobel gases (Ar, Kr, Xe), Semiconductors: Germanium

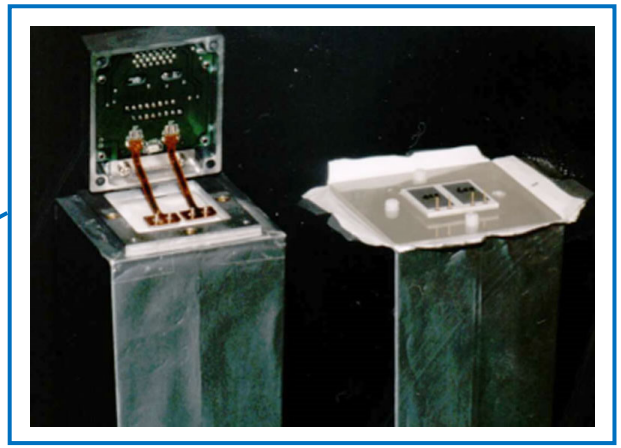
*) Bismuth Germanate $Bi_4\ Ge_3\ O_{12}$

Signal detection:

- Light of scintillators is read-out using photo-detectors: photo-multiplier tubes (expensive) or silicon photo-multiplier (cheap)
- Cherenkov light: photo-detectors (see above)
- Ionization: charge collection using E field to drift the charges to collecting electrodes

Example of homogenous electromagnetic calorimeter: Belle II calorimeter





https://doi.org/10.1134/S1063779618040494

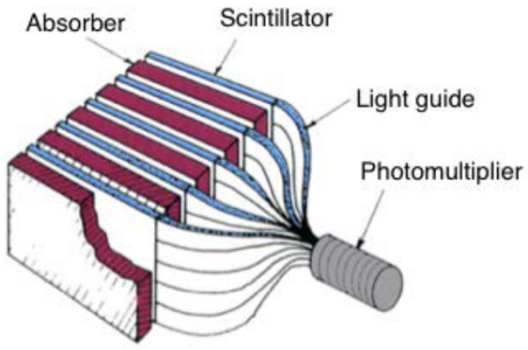
Resolution:
σ_E/E ~ 2% for E above 1GeV
σ_x : 5~10mm at incident point

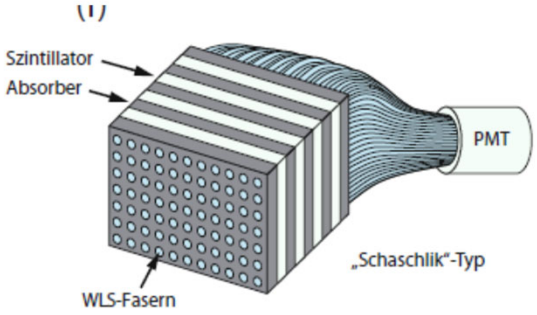
Sampling calorimeter:

Advantages:
One can optimally choose the absorber and detection 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.

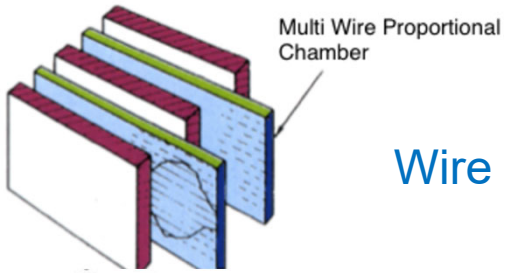
Disadvantages:
Only part of particles' energy is deposited in the detection layers. Measured energy resolution is worse than in homogenous calorimeters ("Sampling-Fluctuations")

Scintillators:

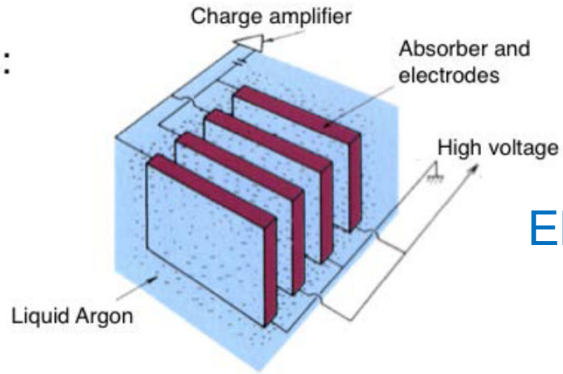




Kolanoski, Wermes 2015

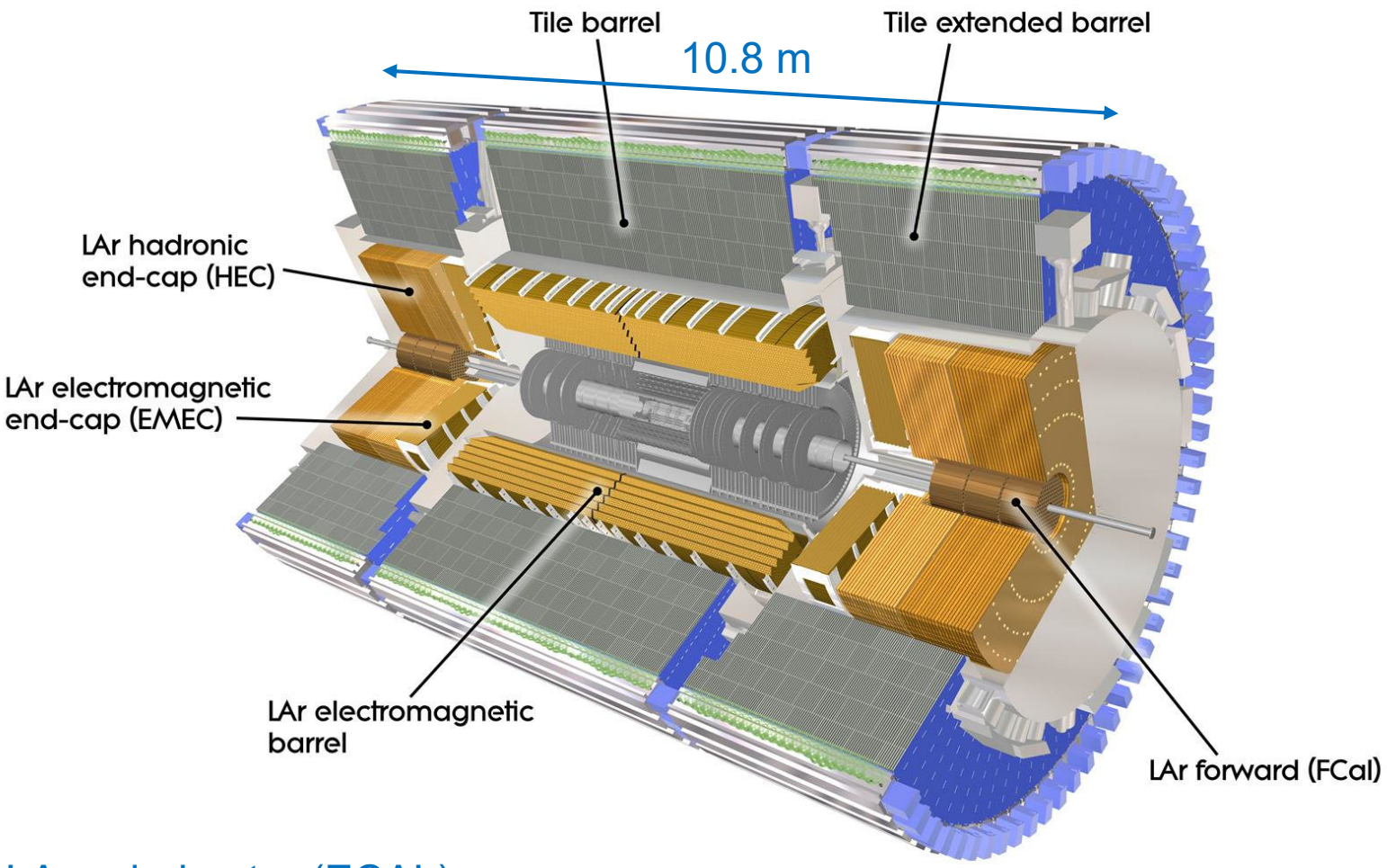


Wire chambers



Electrodes

Example: ATLAS Calorimeter System

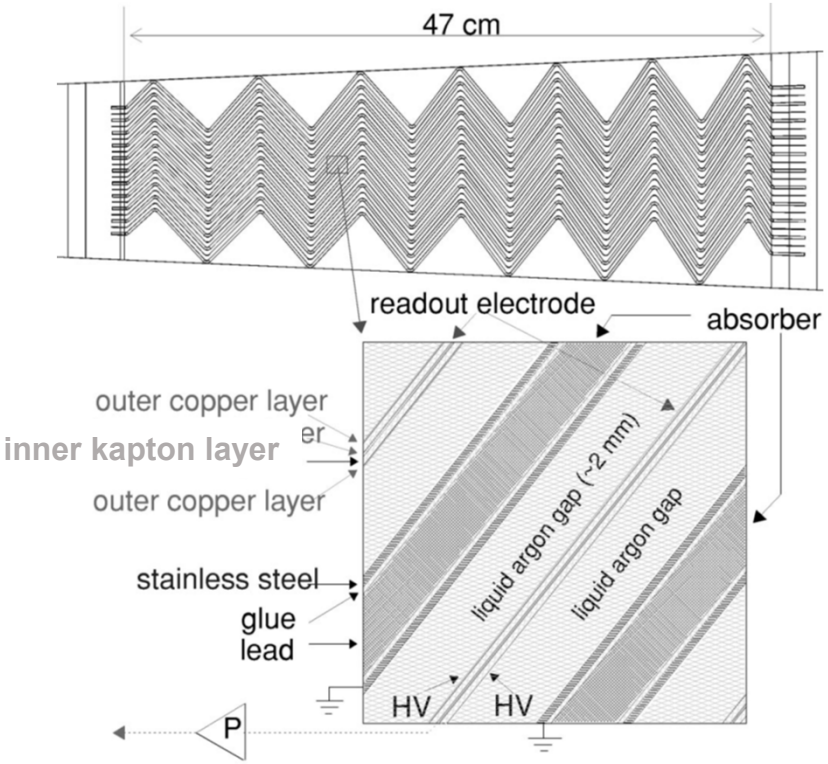


Barrel LAr calorimeter (ECAL):
6.4 m long, 53 cm thick, 110 000 channels

Tile calorimeter (HCAL):
500000 scintillator tiles

LAr Electromagnetic Calorimeter:

Absorber: thin lead plates in accordion structure in LAr as active material.

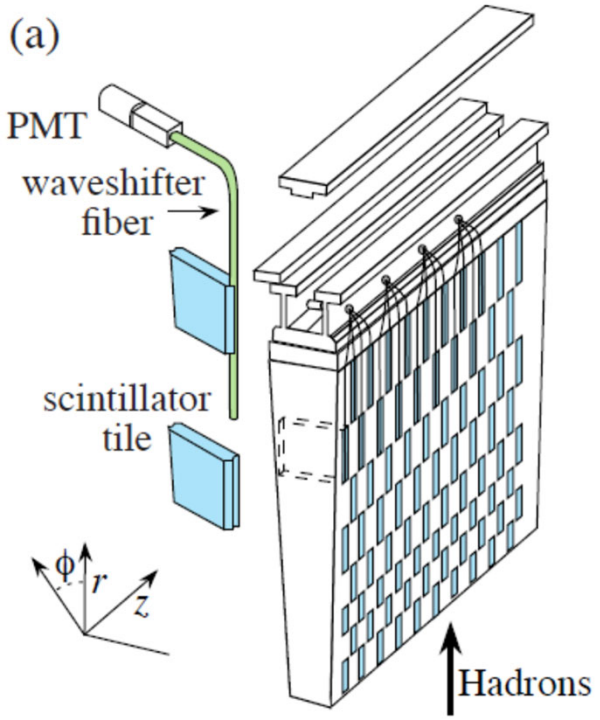


$$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{2\%}{E} \oplus 0.2\%$$

Noise term at larger energies negligible.

Tile Hadron Calorimeter:

Iron (absorber) tiles and plastic scintillator tiles as active detector.



$$\frac{\sigma_E}{E} \approx \frac{45\%}{\sqrt{E}} \oplus \frac{2..5\%}{E}$$

For hadrons w/ E=16…30GeV

https://arxiv.org/pdf/2102.04088

Electromagnetic shower: (see simple shower model)

Using detailed Monte Carlo simulations

Shower maximum in units of X_0:

$$t_{\max} = \ln\left(\frac{E}{E_c}\right) + B$$

B=-0.5 for $e^{\pm}$, B=+0.5 for γ

95% longitudinal shower containment

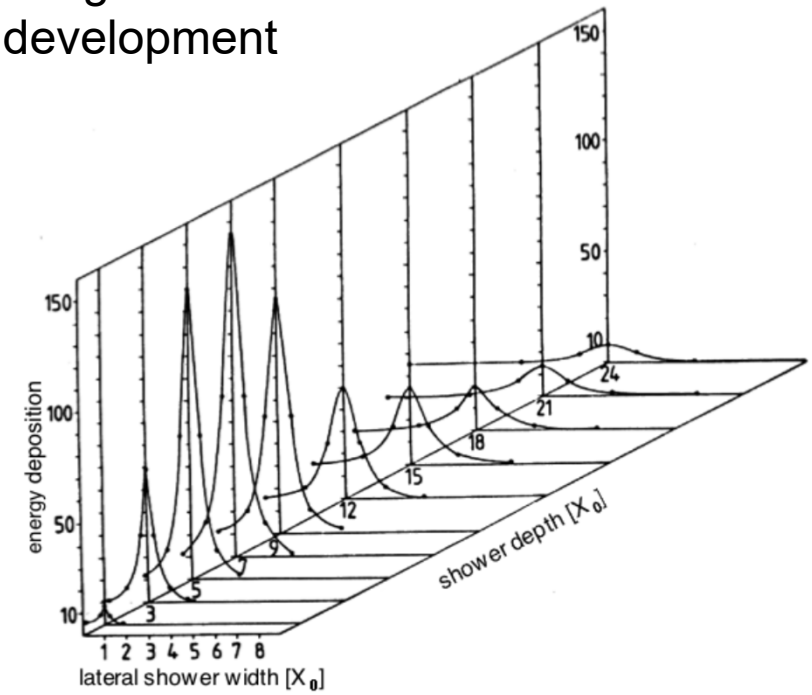
$$t_{95\%} = t_{\max} + 0.08Z + 9.6$$

Rule of thumb: ~25 X_0

95% lateral shower containment:

$$R_{95\%} = 2\rho_M$$

Longitudinal and lateral shower development



Moliere radius ρ_M: (material parameter)

$$\rho_M \approx \frac{21\text{MeV}}{E_c} X_0$$

Material	X_0 [cm]	ρ_M [cm]
Fe	1.76	1.77
Pb	0.56	1.60
U	0.32	1.00

Energy resolution of electromagnetic calorimeters:

Intrinsic resolution (homogeneous calorimeter)

In an ideal homogenous calorimeter the energy resolution is determined by the statistical fluctuations of the number of detectable signal particles N ~ E:

$$\frac{\sigma_E}{E} \sim \frac{\sigma_N}{N} \approx \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}} \sim \frac{1}{\sqrt{E}}$$

Usually called "stochastic term"

Sampling fluctuations (sampling calorimeters):

In sampling calorimeters only a small part of the deposited energy is measured. The fractions of how much energy is deposited in the absorber and in the active detector varies from event to event → these fluctuations cause a degradation of the energy resolution:

$$\frac{\sigma_E}{E} \sim \sqrt{\frac{\Delta E}{E}}$$

ΔE is the average energy deposition in an absorber layer, ratio is a measure of number of samplings (the more samplings, the better)

Sampling fluctuations: $\frac{\sigma_E}{E} \sim \frac{1}{\sqrt{E}}$

Additional contributions (for real calorimeters):

- Noise in the detector or the electronics N_{noise} → fake energy: $\Delta E_{fake} \sim N_{noise}$

  Effect on resolution: $\frac{\sigma_E}{E} \sim \frac{\Delta E_{fake}}{E} \sim \frac{1}{E}$

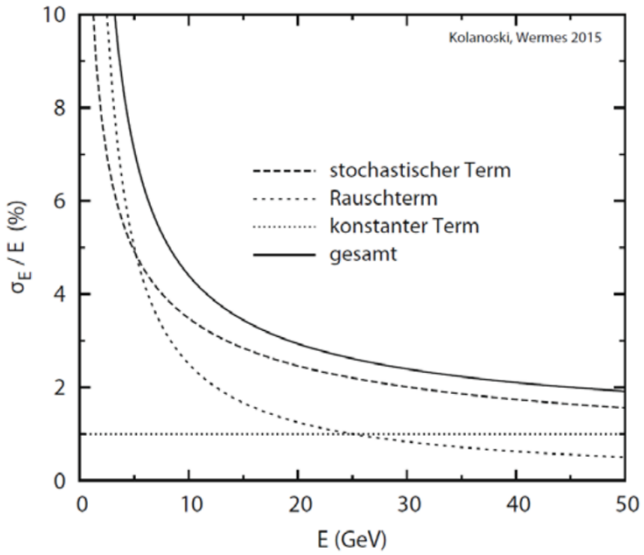
- Constant term: Channel-to-channel response calibration: $\frac{\sigma_E}{E} \sim C$

Parametrisation of the energy resolution of a real calorimeter:
The total energy resolution is the quadratic sum of different contributions

$$\frac{\sigma_E}{E} \sim \sqrt{\left(\frac{b}{E}\right)^2 + \left(\frac{a}{\sqrt{E}}\right)^2 + c^2}$$

$$\frac{\sigma_E}{E} \sim \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

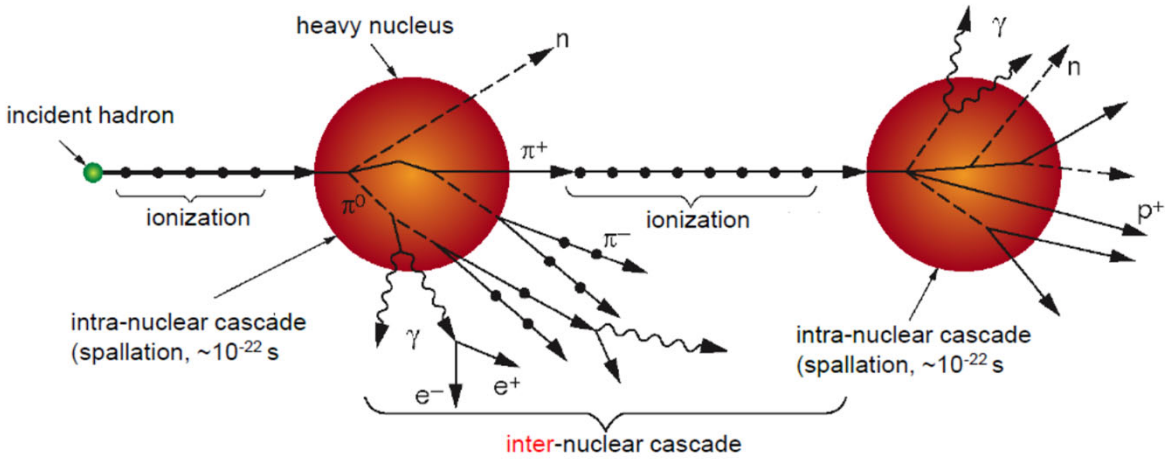
$\oplus$ =quadratic sum

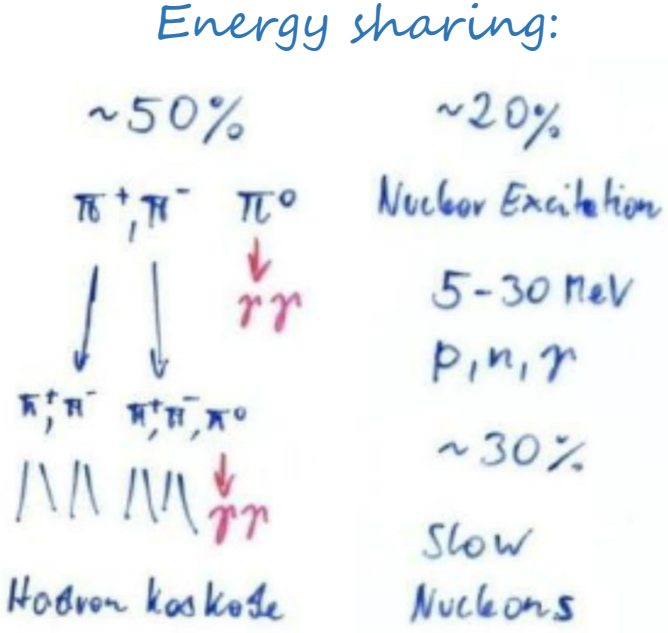


Different behaviour than spectrometer

At very high energy the calibration dominates.

Hadronic shower:

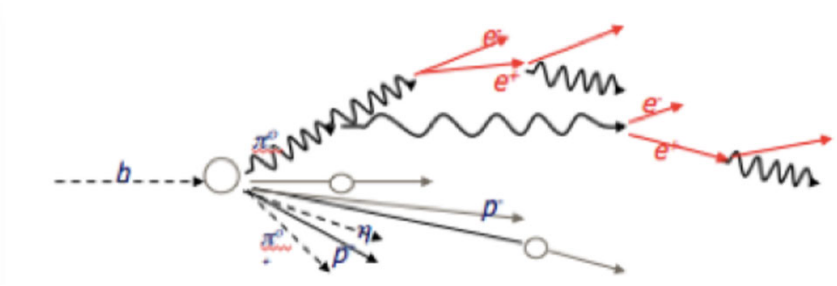




Significant fraction of deposited energy does not lead to a detectable signal in active detector: neutrons, K^0s , nuclear excitations, pion decays $\pi \rightarrow \mu\nu$ w/ minimal ionizing muons and undetectable neutrinos escaping the calorimeters.

Additional problem: fluctuating electromagnetic component from $\pi^0 \rightarrow \gamma\gamma$ decays.

e/h ratio (electromagnetic / hadronic response) :

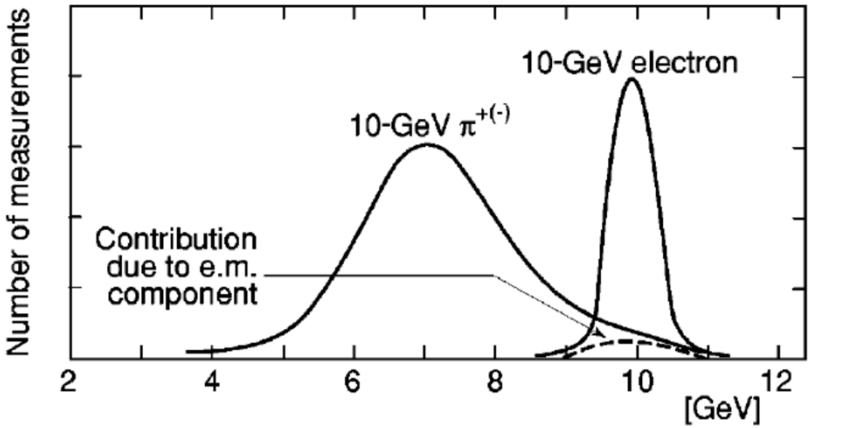


Electromagnetic component

Hadronic component

Large variations from event to event

10 GeV e/π →



Signal (in energy units) obtained for a 10 GeV energy deposit

The electromagnetic component in a shower is over-weighted. To reduce the effect of fluctuation of the electromagnetic component people tried to build “compensated calorimeters” with an e/h ratio close to 1. E.g.: ZEUS uranium / plastic scintillator calorimeter (not too successful). Alternatively software compensation is used (needs longitudinal segmentation): works!

Energy resolution of hadron calorimeters:

A fluctuating e.m. shower component together with $e/h \neq 1$, fluctuations in the shower composition w/ muon and neutrinos escaping the calorimeter, and undetected energy from neutrons and spallation leads to an energy resolution for hardon calorimeters which is significantly worse than the one for electromagnetic calorimeters.

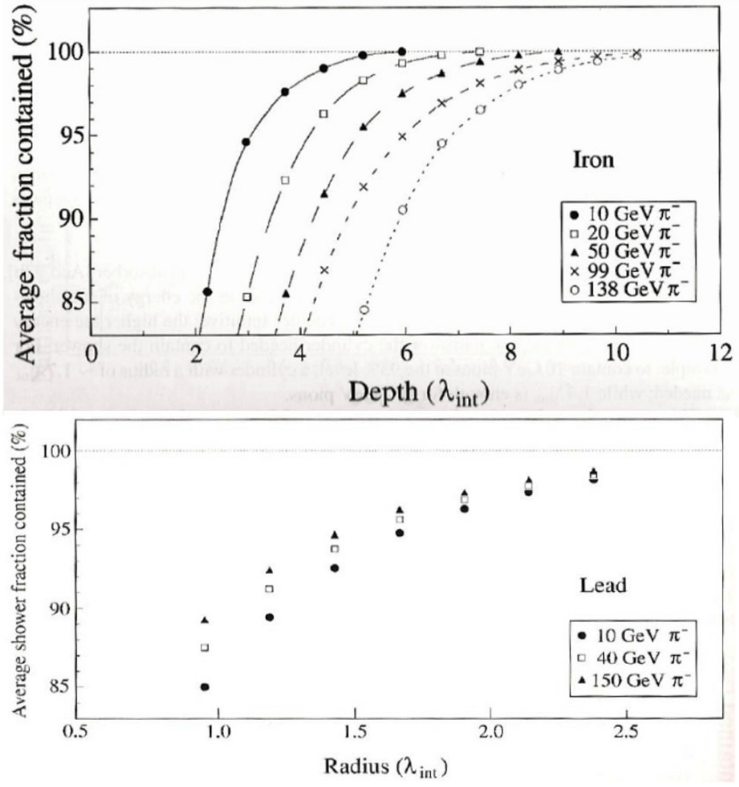
For the stochastic term of HCALs one usually finds values of 40-60%/$\sqrt{E}$ [GeV]

Shower containment:

Longitudinal shower extension:
For high energy hadrons 8…10 interaction lengths are needed to contain the shower

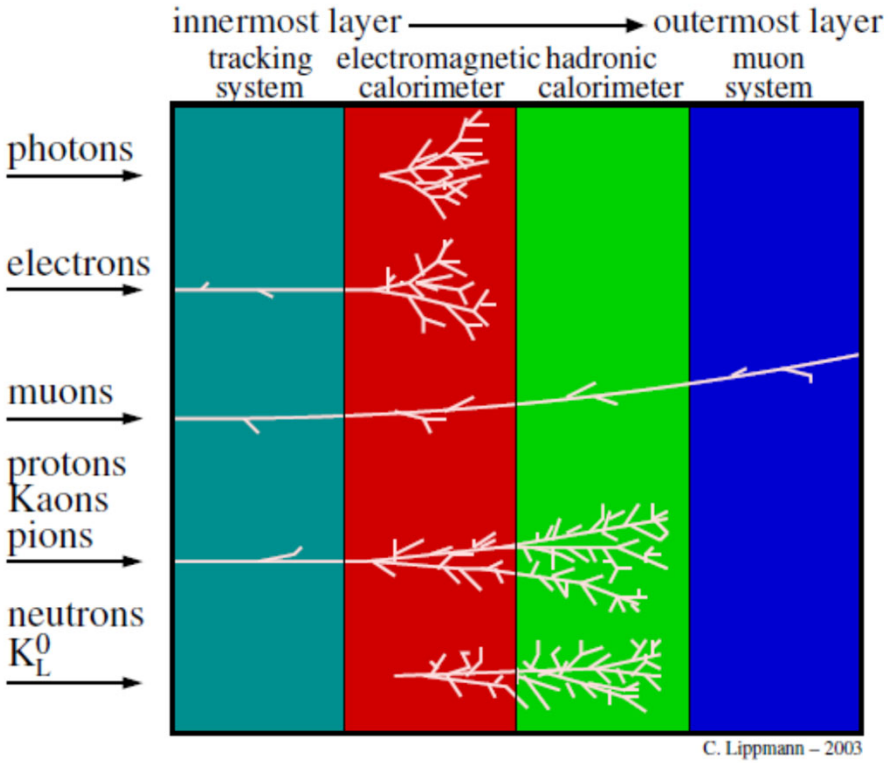
Lateral shower extension:
95% of shower contained within a cylinder with R≈1.5 λ_{int}

Reminder: λ_{int}(Fe) = 17 cm



4. Particle identification (PID)

Specific signatures of photons, electrons, muons, charged hadrons, neutral hadrons:



Particle identification using these signatures.

However, some experiments are also interested to distinguish **different charged hadrons:** K, π, p are "pseudo" stable and the end-product of many heavier hadron decays. To reconstruct these decays PID knowledge of their daughters (K, π, p) is necessary.

Hadron PID: (identification of p, K, π)

General idea: In addition to the measured particle's **momentum** one determines the particle's **velocity** (or the particle's $\beta\gamma$ value). An independent determination of momentum and velocity allows to estimate the **mass** of the particle.

Three different techniques are used to determine the particles velocity:

- Measurement of the specific energy-loss dE/dx from ionization
- Time-of-flight measurement for a given flight-distance
- Measurement of the angle θ_c of the of the Cherenkov light-cone

Specific energy-loss dE/dx

Specific energy loss of different particles as function of the particle momentum: see Bethe-Bloch formula

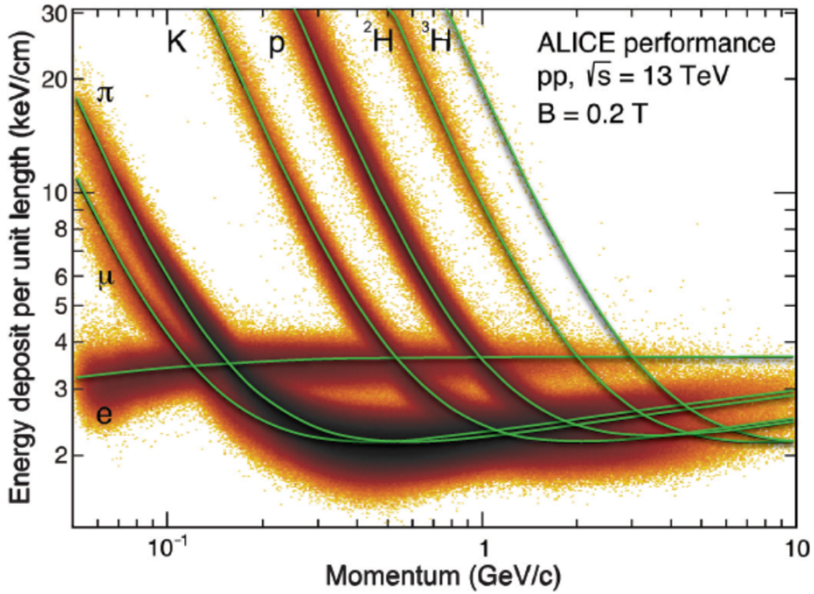
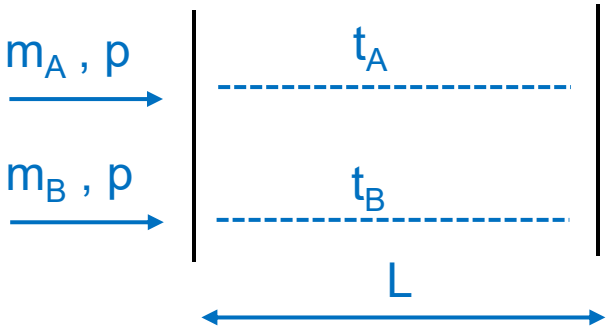


Figure 35.16: Energy deposit versus momentum measured in the ALICE TPC.

Time of flight measurement:

Time of flight (ToF)



One finds w/ p=γβcm

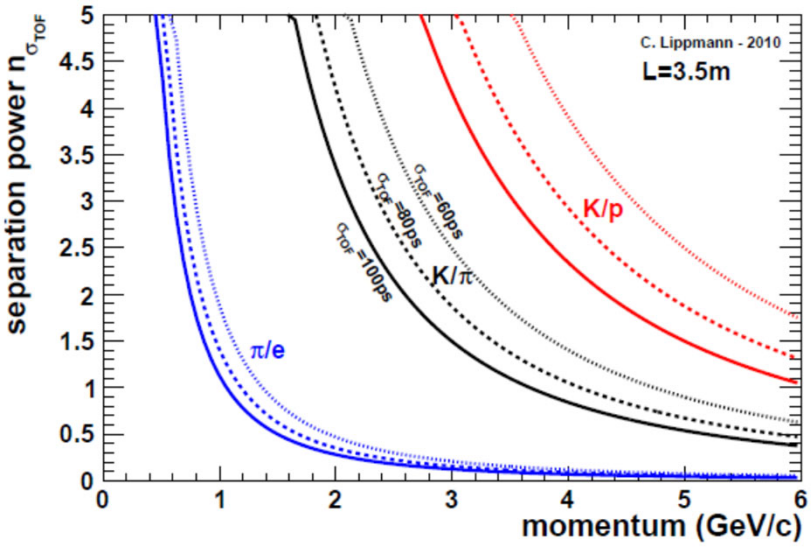
$$m = \frac{p}{c}\sqrt{\frac{c^2t^2}{L^2} - 1}$$

$$|t_A - t_B| = \frac{L}{c}\left|\sqrt{1+\left(\frac{m_A c}{p}\right)^2} - \sqrt{1+\left(\frac{m_B c}{p}\right)^2}\right|$$

Assuming a finite time resolution σ_{TOF} and approximating $\sqrt{1+(mc/p)^2} \approx 1 + (mc)^2/2p^2$ for p >> mc, one finds for the flight-time separation in sigmas (n_σ):

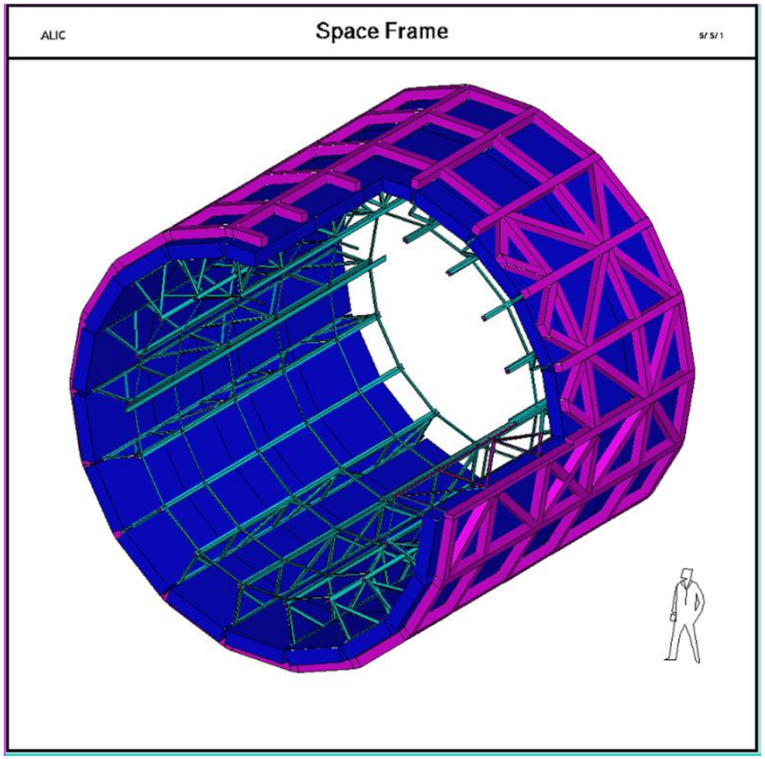
$$n_{\sigma_{TOF}} = \frac{|t_A - t_B|}{\sigma_{TOF}} = \frac{Lc}{2p^2\sigma_{TOF}}|m_A^2 - m_B^2|$$

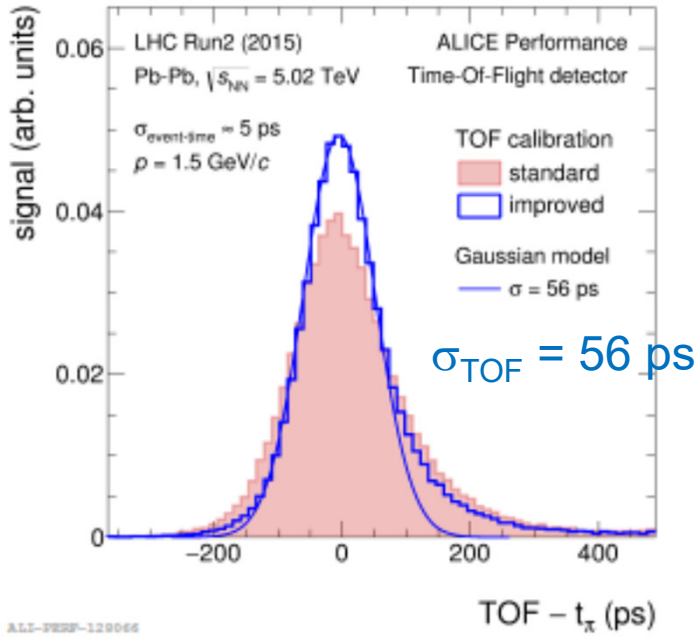
The plot shows for which momenta a separation between π/e, K/π, K/p is possible.



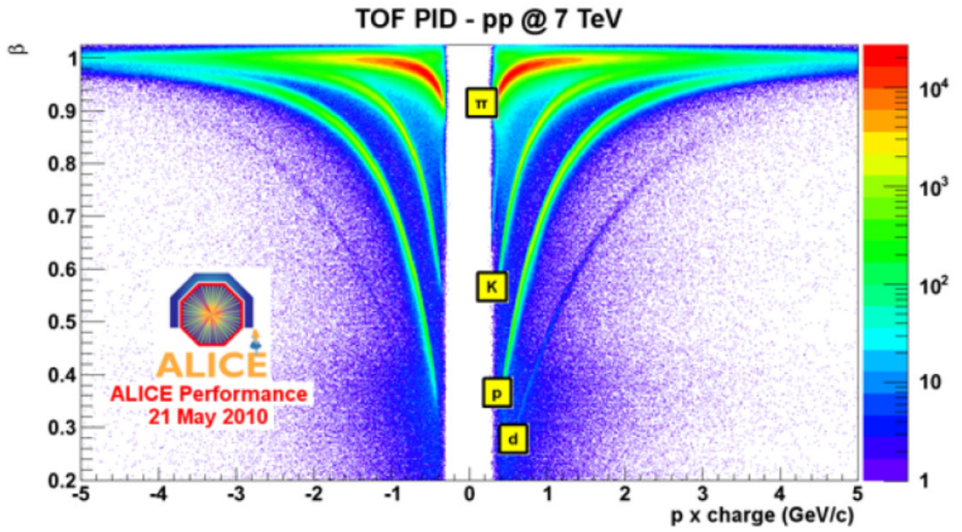
Example: ALICE TOF system

Multi-gap Resistive Plate Chambers

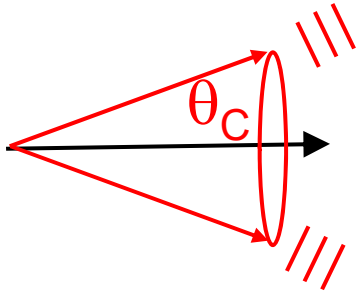




σ_{TOF} = 56 ps



Measurement of Cherenkov angle:



$$\cos\theta_C = \frac{1}{\beta n}$$

With $$\beta = \frac{1}{\sqrt{\left(\frac{mc}{p}\right)^2 + 1}}$$

one finds for the mass:

$$m = \frac{p}{c}\sqrt{n^2\cos^2(\Theta_C) - 1}$$

Average measurement error $\left\langle \sigma_{\theta_C} \right\rangle$

(several effects contribute)

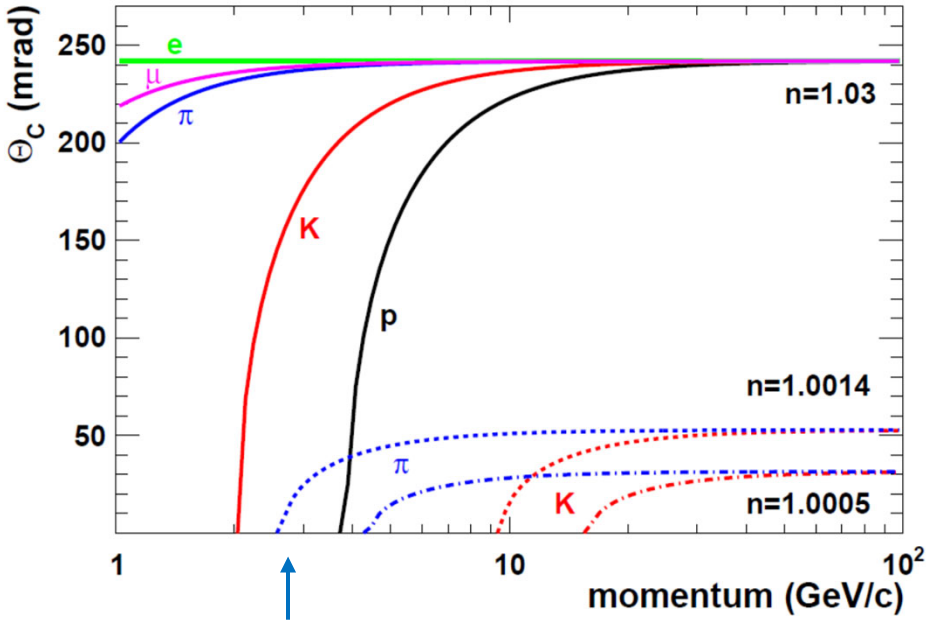
Separation in sigmas:

$$n_{\sigma_{\Theta_C}} = \frac{\Theta_{C,A} - \Theta_{C,B}}{\langle \sigma_{\Theta_C} \rangle}$$

One can derive the mass separation for $\beta \approx 1 > \beta_{Thresh}$ as function of the angular resolution to measure θ_C

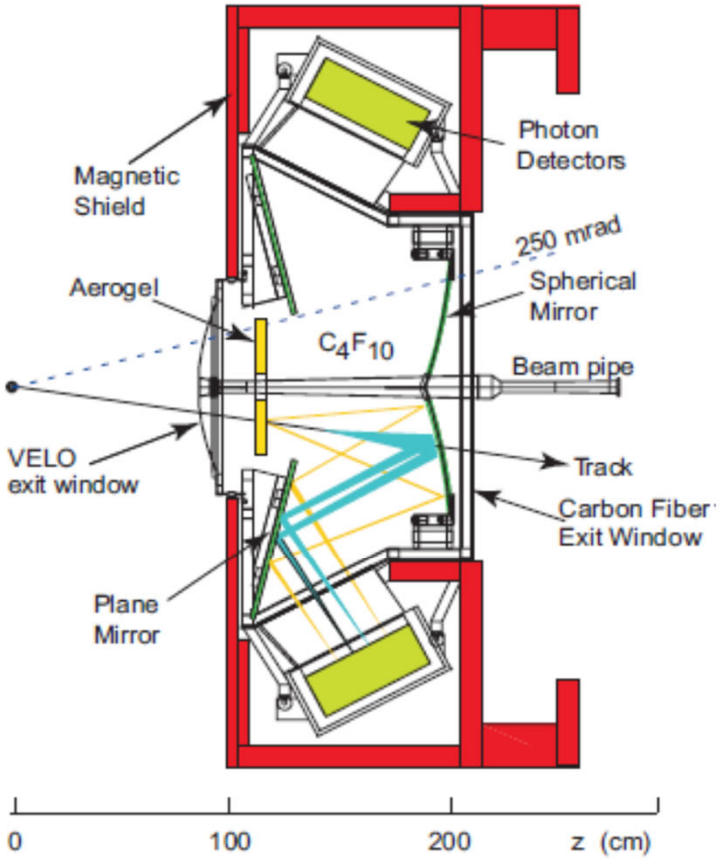
$$n_{\sigma_{\Theta_C}} \approx \frac{c^2}{2p^2\langle \sigma_{\Theta_C} \rangle \sqrt{n^2 - 1}} |m_B^2 - m_A^2|$$

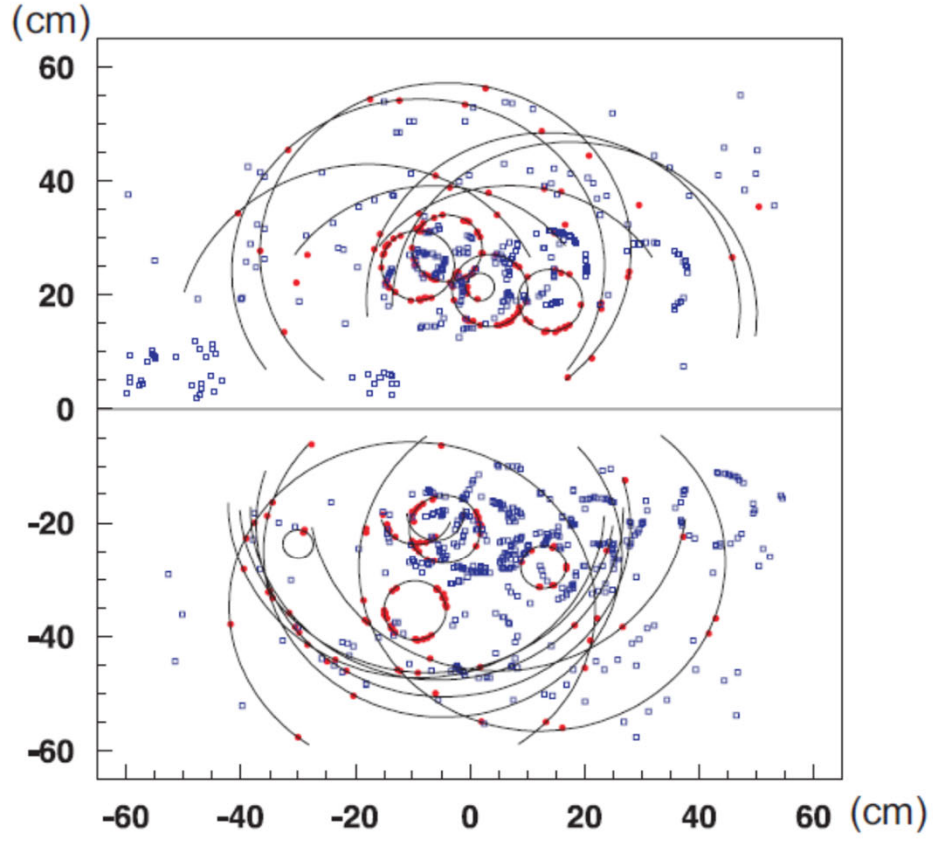
(see for example C. Amsler et al. (PDG), Phys. Let. B667 (2008) 1.)



Threshold given by $\beta > 1/n$

Example: LHCb Ring Imaging Cherenkow Detector

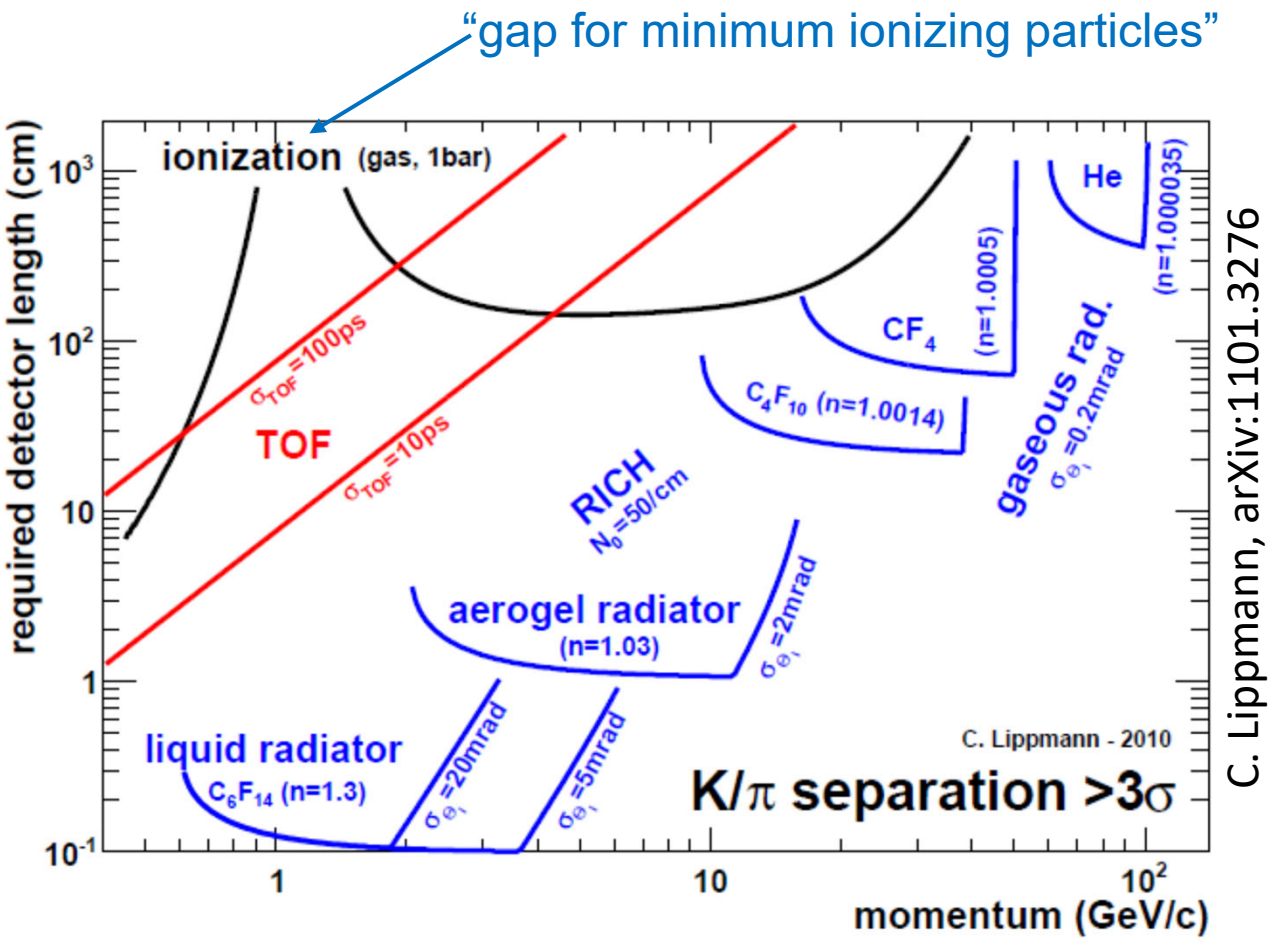




Refractive index: Aerogel n=1.037 → large rings

C_4F_{10} n=1.0015 → small rings

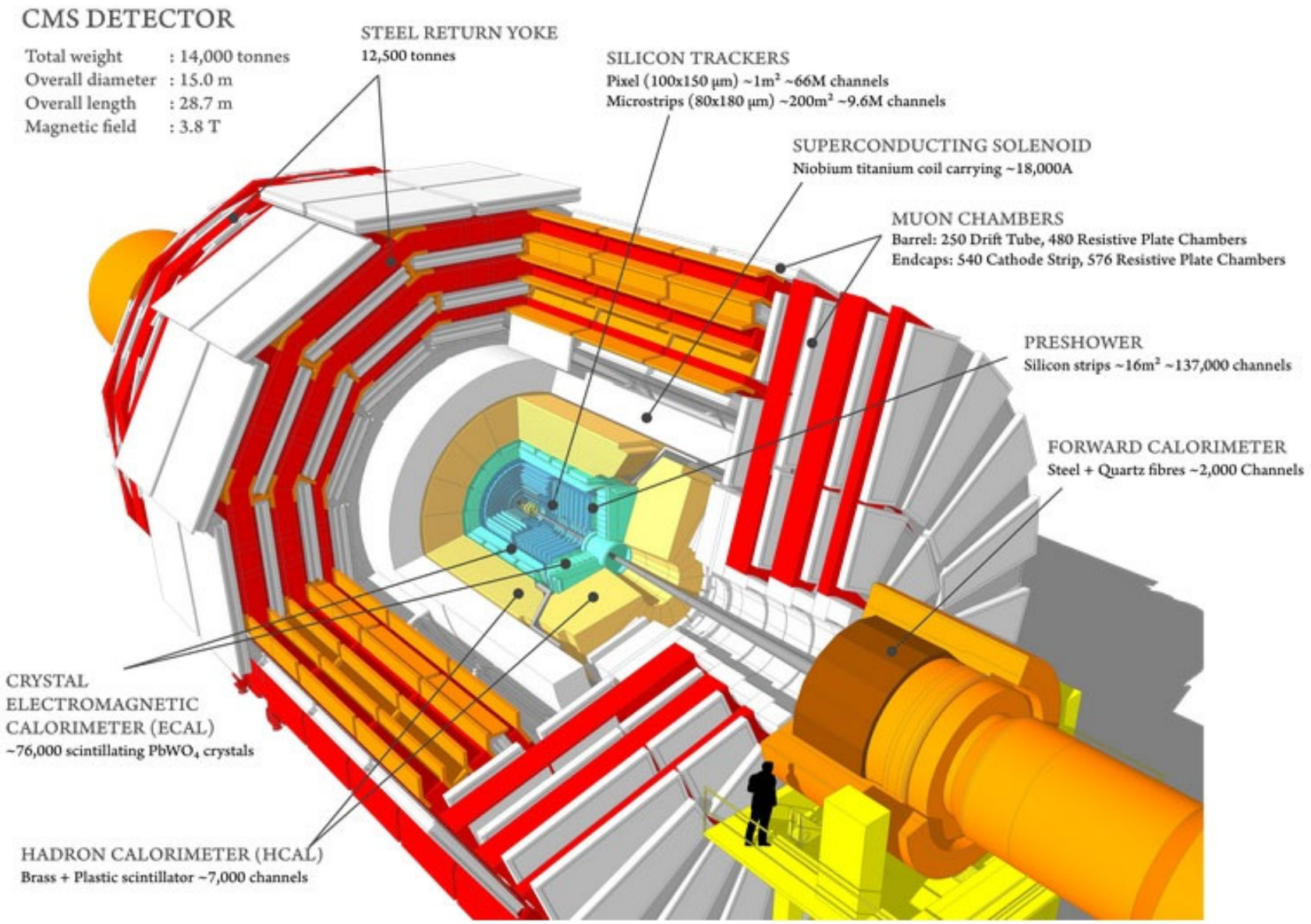
Comparison: Different PID systems and there ability to seprate K/π



C. Lippmann, arXiv:1101.3276

5. Detector systems

(only one example: CMS detector)



Particle signatures in the CMS detector:

