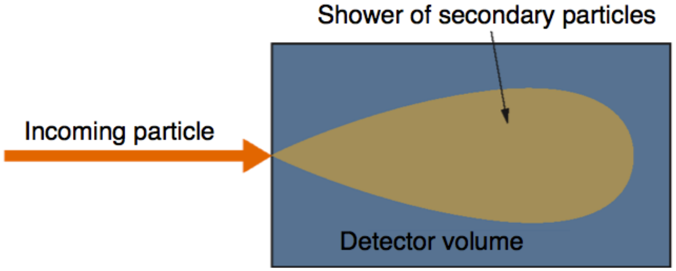
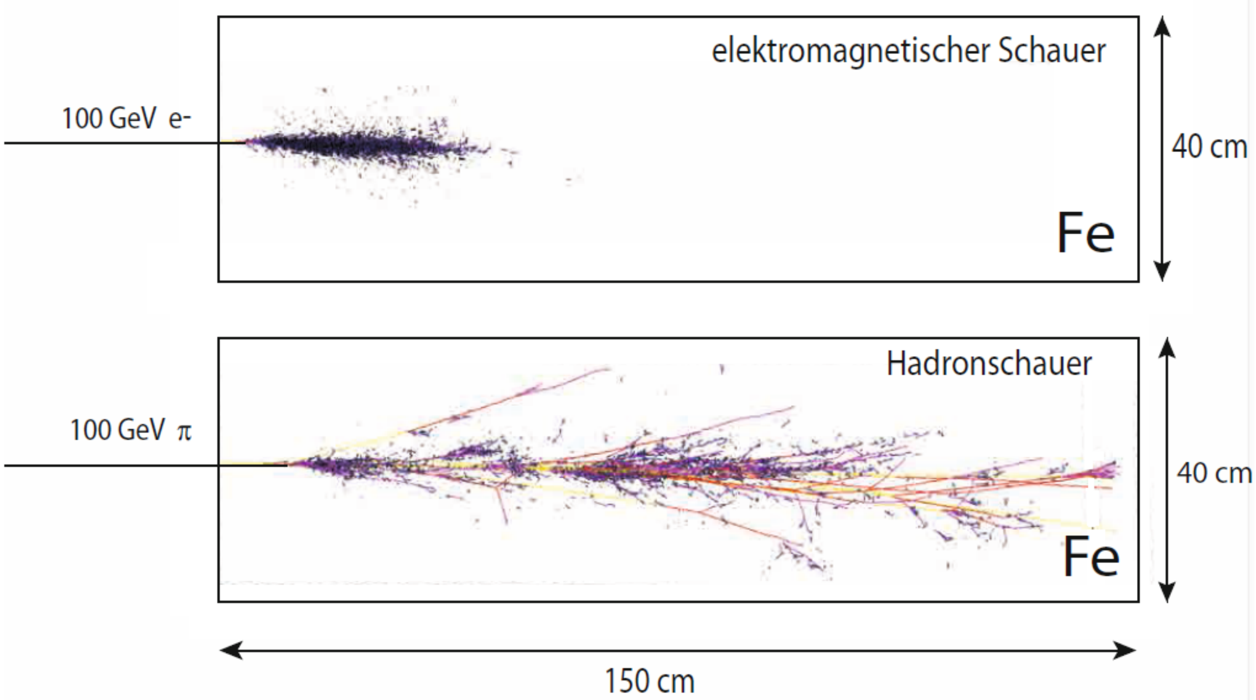
3. Calorimeters – energy measurement



Particle to measure shower (secondary particles) and deposit their whole energy into the detector volume,

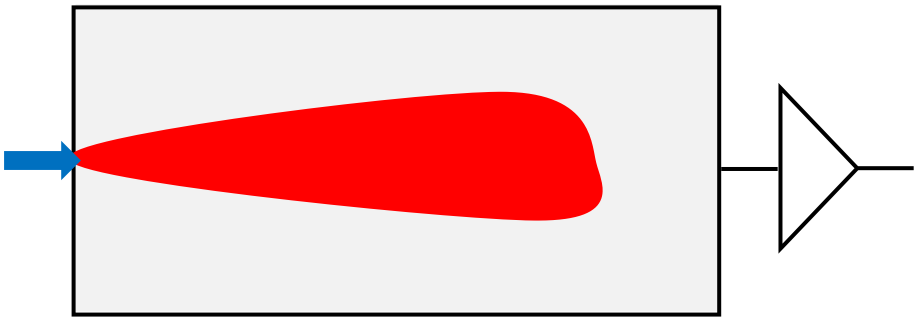


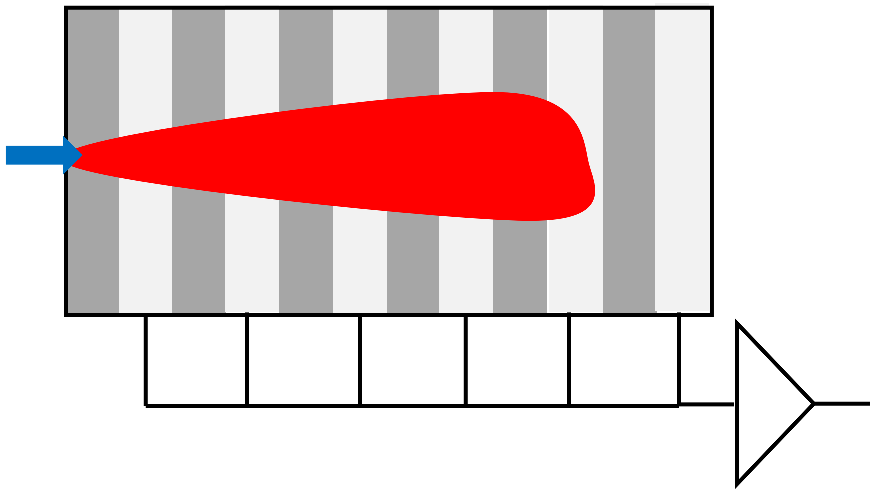
Electromagnetic shower: length scale determined by radiation length

Hadronic shower: length scale determined by hadronic interaction length

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 and interleaved with active material (e.g. scintillators) to provide signals.
- Only a fraction of the deposited energy converted into signal → sampling fluctuations (degrades res.)
- Hadronic calorimeters and for 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.

The following detection mechanisms and materials are used:

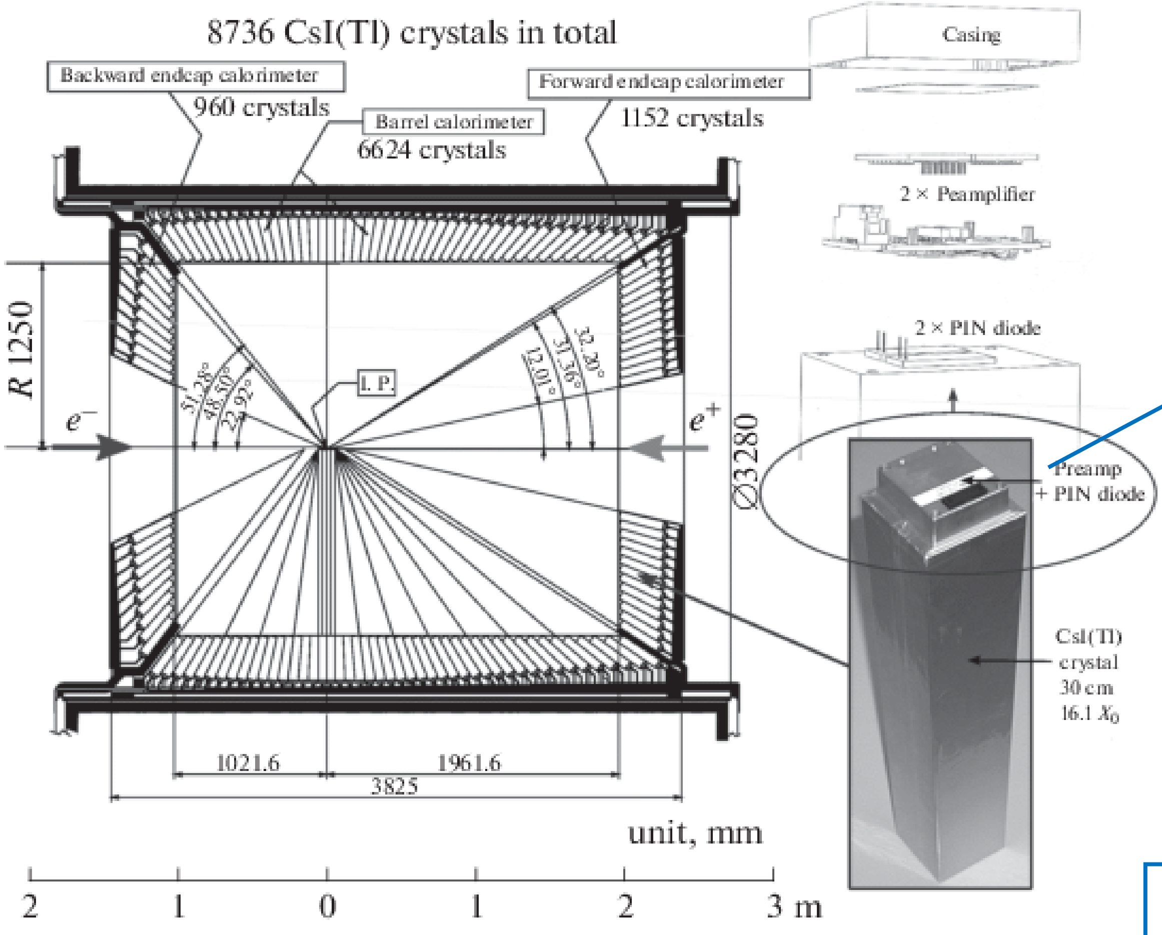
Detection mechanism	Material
Scintillation	CsJ, BGO*), BaF_2, CeF_2, $PbWO_4$
Cherenkov light	Lead glass (OPAL exp.), water (Kamiokande)
Ionization	Liquid nobel gases (Ar, Kr, Xe), Semiconductors: Germanium

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

Signal detection:

- Light of scintillators read-out using photo-detectors: photo-multiplier tubes or silicon photo-multiplier (very cheap)
- Cherenkov light: photo-detectors
- 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

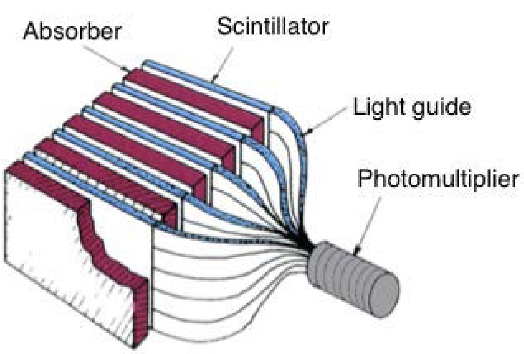
Resolution:
σE/E ~ 2% for E above 1GeV
σx : 5~10mm at incident point

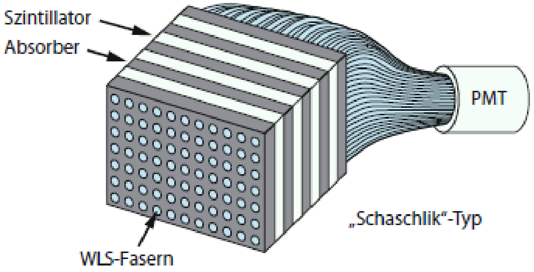
Sampling calorimeter:

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

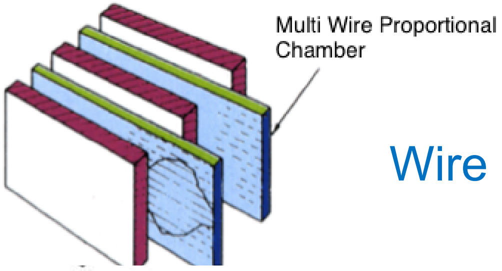
Disadvantages:
Only part of particles energy is deposited in the detector layers. Measured Energy resolution is worse than in homogenous calorimeter ("Sampling-Fluctuations")

Scintillators:

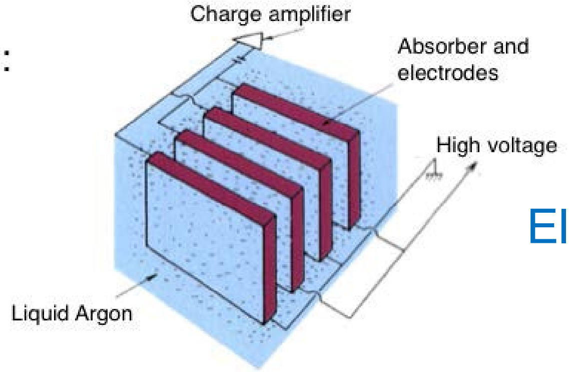




Kolanoski, Wermes 2015

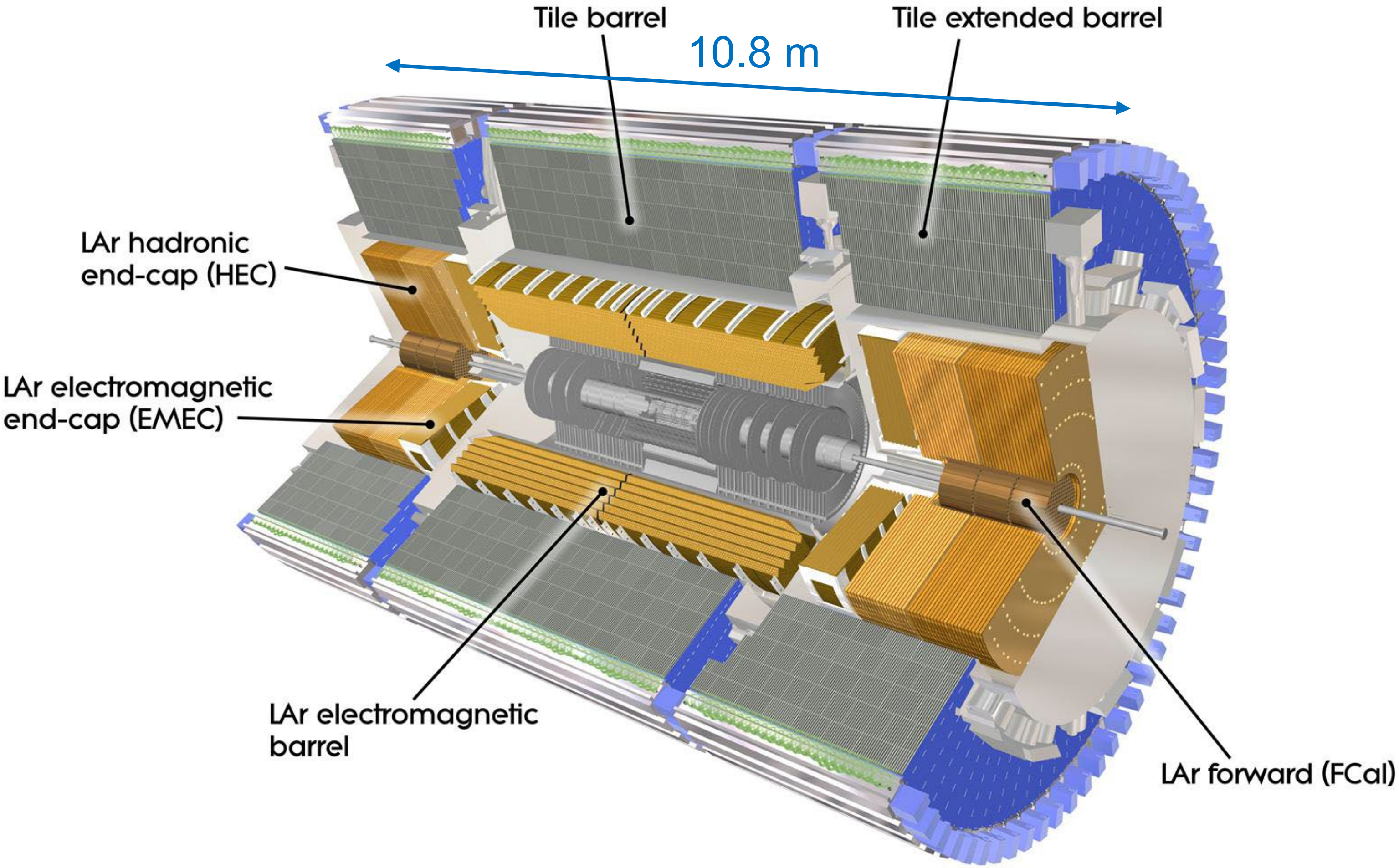


Wire chambers



Electrodes

Example: ATLAS Calorimeter System

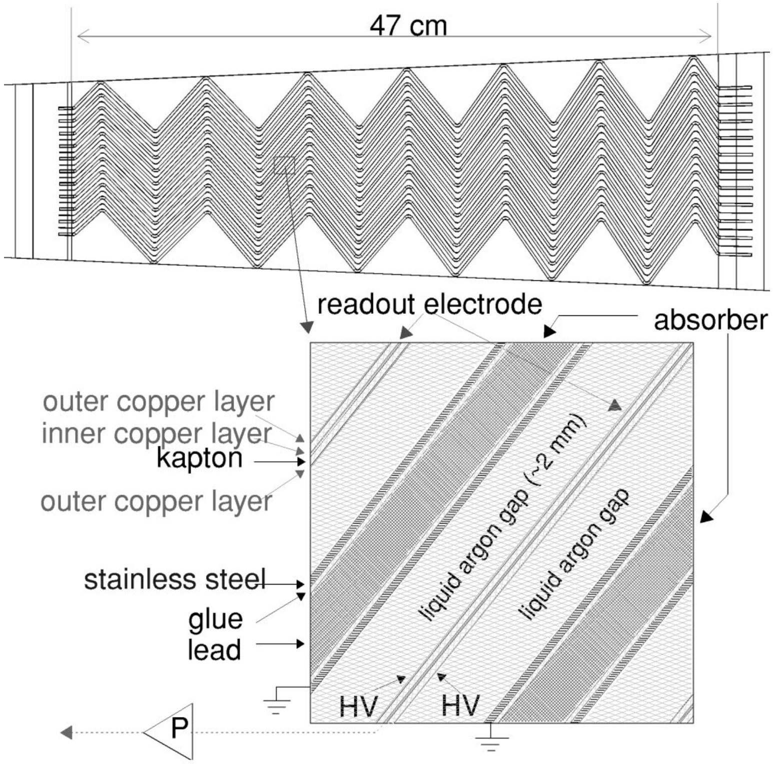


Barrel LAr calorimeter (ECAL):
6.4 m long, 53 cm thick, 110 000 channels

Tile calorimeter (HCAL):
500000 scintillator tiles

LAr Electromagnetic Calorimeter:

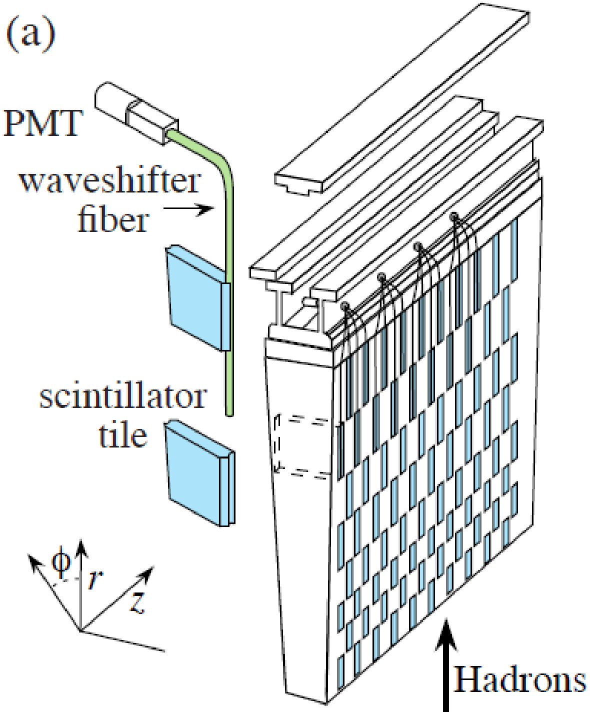
Absorber: thin lead plates in accordion structure in LAr as active material.



$$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.25}{E} \oplus 0.4\%$$

Tile Hadron Calorimeter:

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



$$\frac{\sigma_E}{E} = \left(\frac{0.42}{\sqrt{E}} + \frac{0.018}{E}\right) \oplus \frac{1.8}{E}$$

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±, B=+0.5 for γ

95% longitudinal shower containment

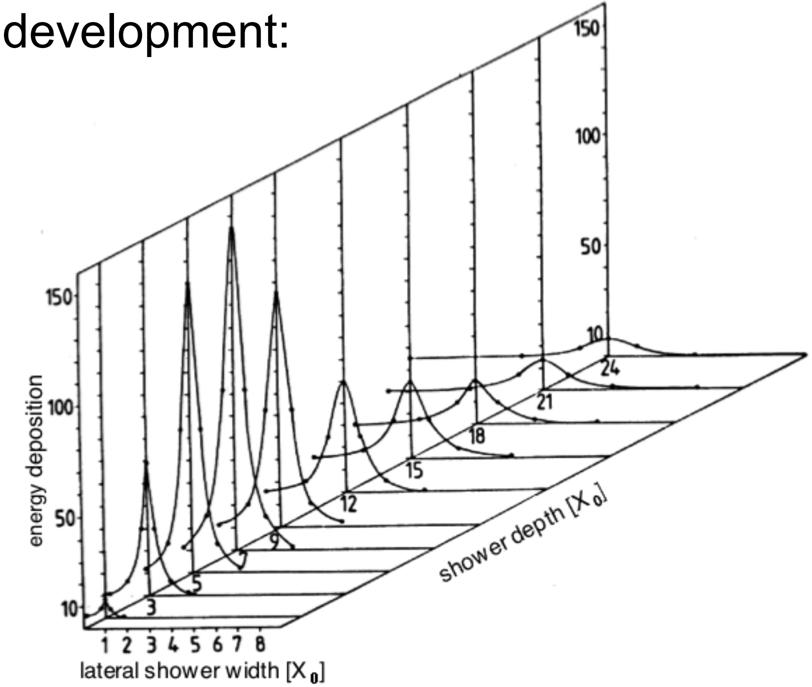
$$t_{95\%} = t_{\max} + 0.08Z + 9.6$$

Rule of thumb: ~25 X_0

95% lateral shower containment:

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

Longitudinal and lateral shower development:



Moliere radius ρ_M: $\rho_M \approx \frac{21\,\text{MeV}}{E_C} X_0$

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 higher, 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: $E_{fake} \sim N_{noise}$

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

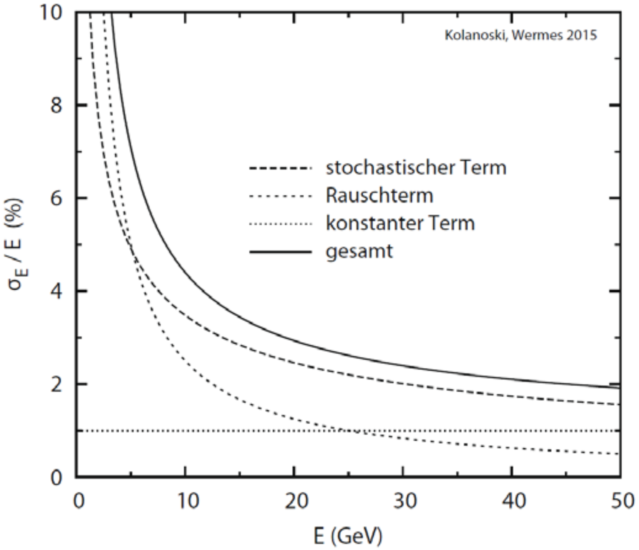
Channel-to-channel response calibration: $$\frac{\sigma_E}{E} \sim C$$

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

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

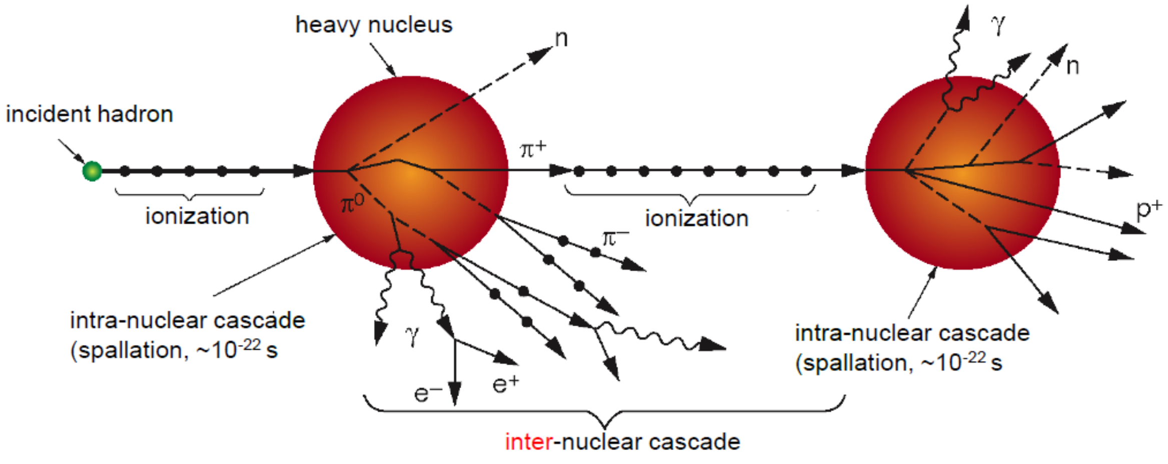
$$\frac{\sigma_E}{E} \sim \frac{b}{\sqrt{E}} \oplus \frac{a}{E} \oplus c$$

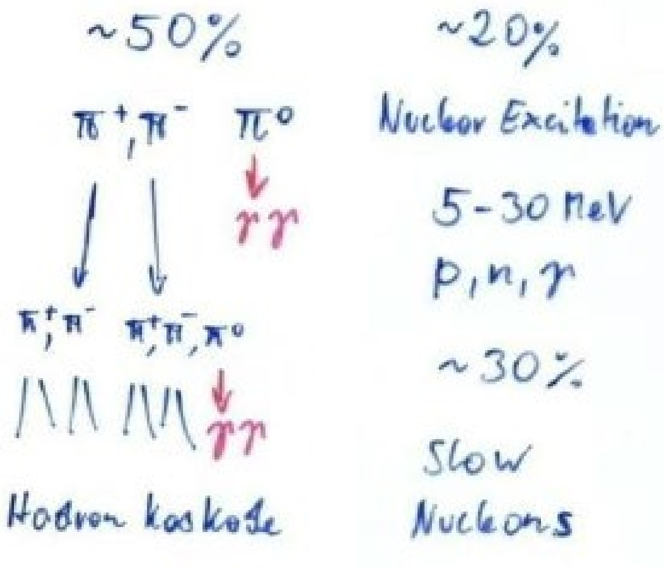
$\oplus$ =quadratic sum



Different behaviour than spectrometer

Hadronic shower:

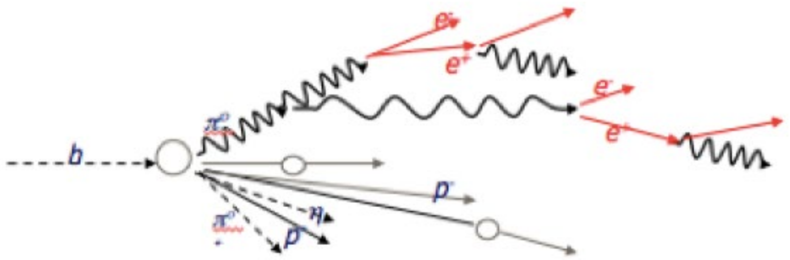




Significant fraction of deposited energy does not lead to a detectable signal in active detector: neutrons, K^0 , nuclear excitations, pion decays $\pi \rightarrow \mu\nu$ w/ minimal ionizing muons and undetectable neutrinos escaping the calorimeters.

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

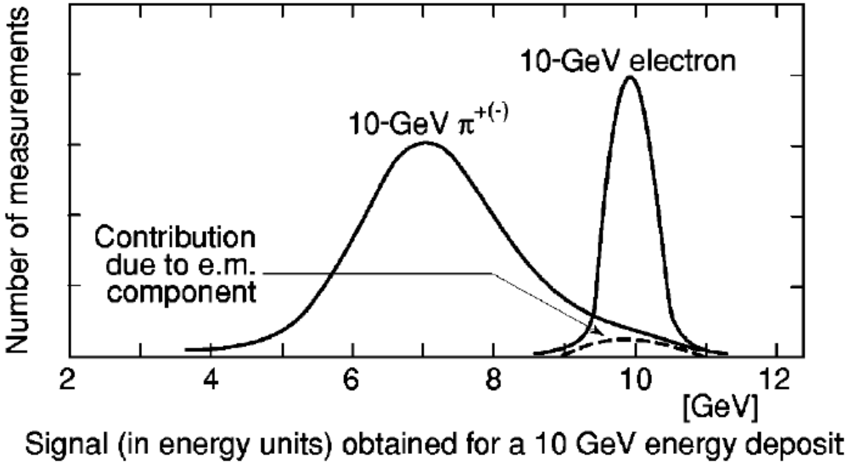
e/h ratio (electromagnetic / hadronic response) :



Electromagnetic component

Hadronic component

Large variations from event to event



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.

Energy resolution of hadron calorimeters:

A fluctuating e.m. shower component together with $e/h \neq 1$, fluctuations in the shower compositions 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.

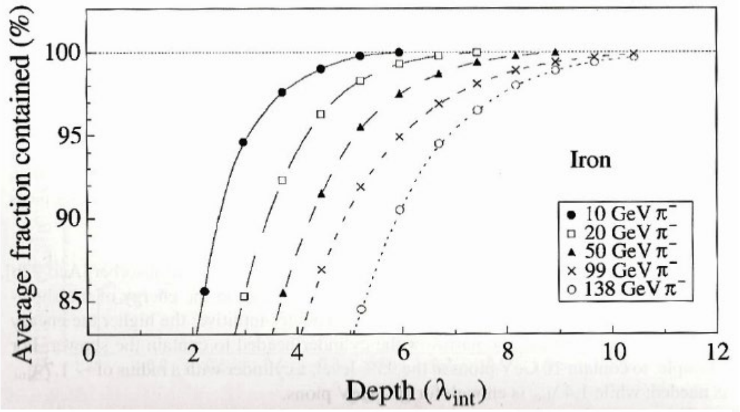
For the stochastic term of HCALs one usually finds values of $50\text{-}60\%/\sqrt{E}$ [GeV]

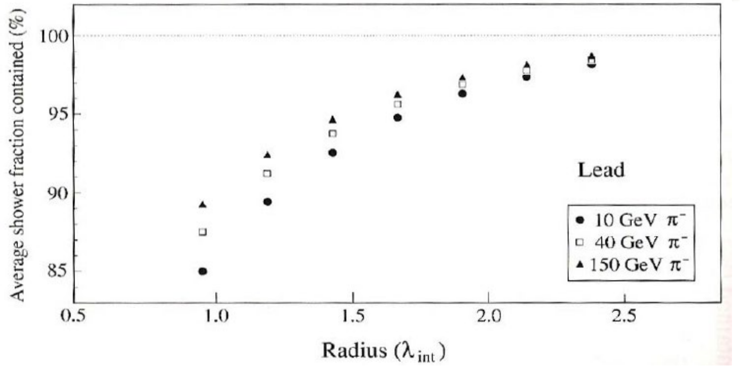
Shower containment:

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 $R \approx 1.5\ \lambda_{int}$

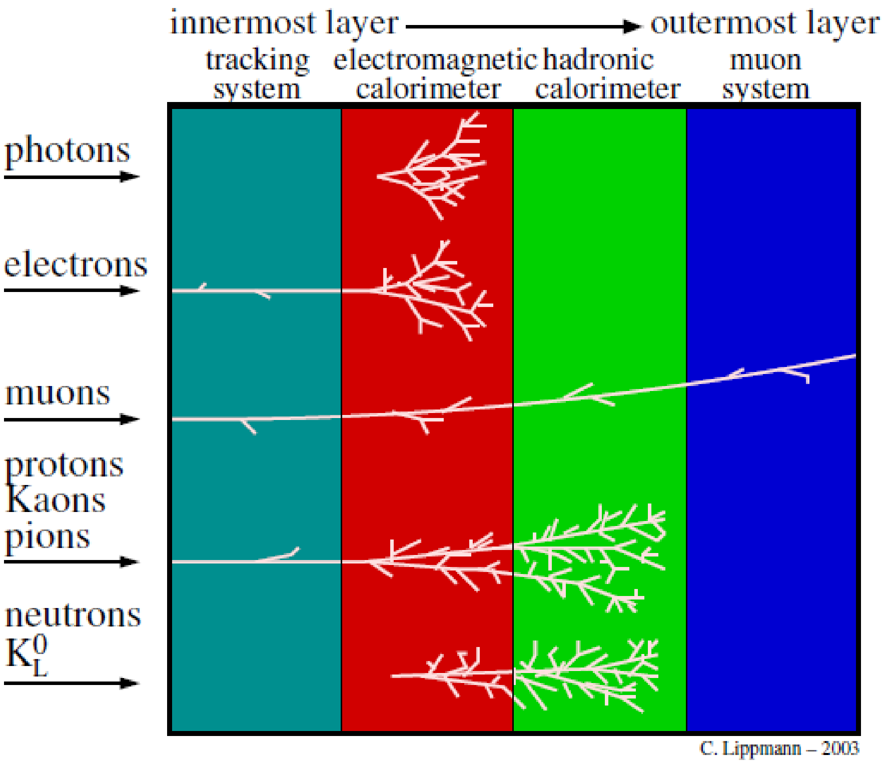
Reminder: $\lambda_{int}(Fe) = 17$ cm





4. Particle identification (PID)

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



C. Lippmann – 2003

⇨ 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

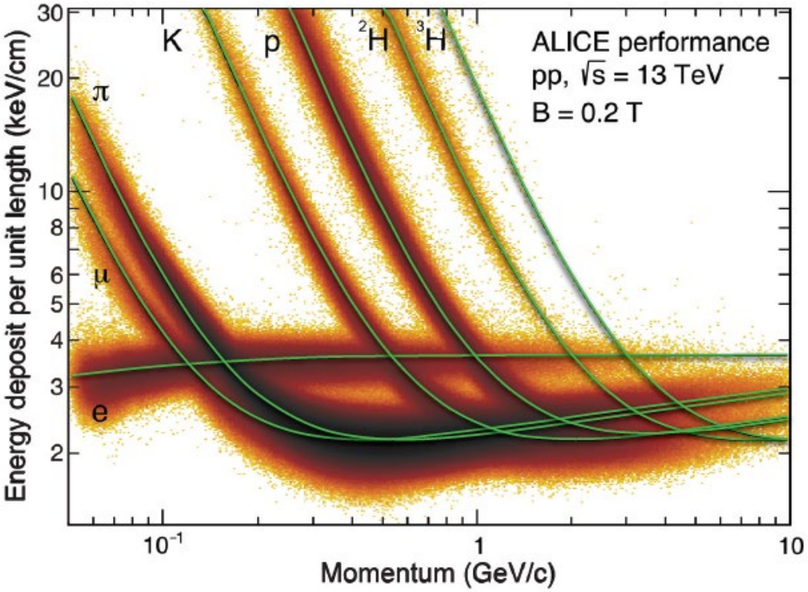
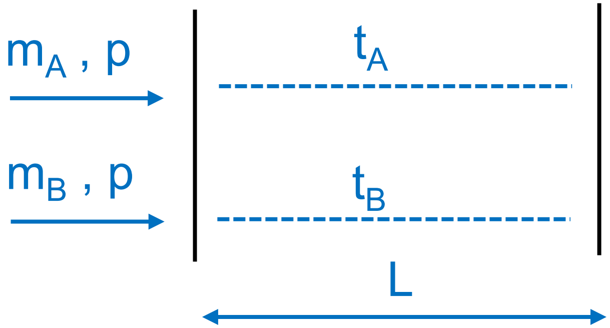


Figure 35.16: Energy deposit versus momentum measured in the ALICE TPC.

Time of flight measurement:

Time of flight (ToF)



One finds w/ $p = \gamma\beta c m$

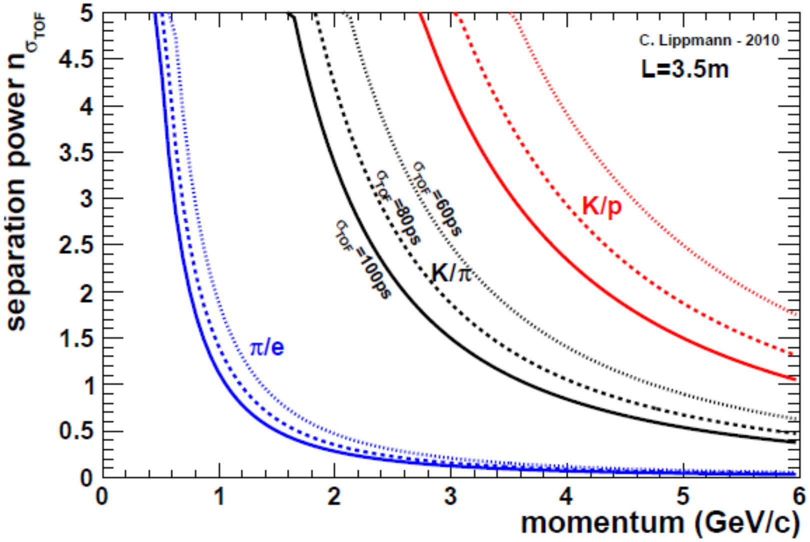
$$m = \frac{p}{c}\sqrt{\frac{c^2t^2}{L^2} - 1}$$

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

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 separation in sigmas (n_σ):

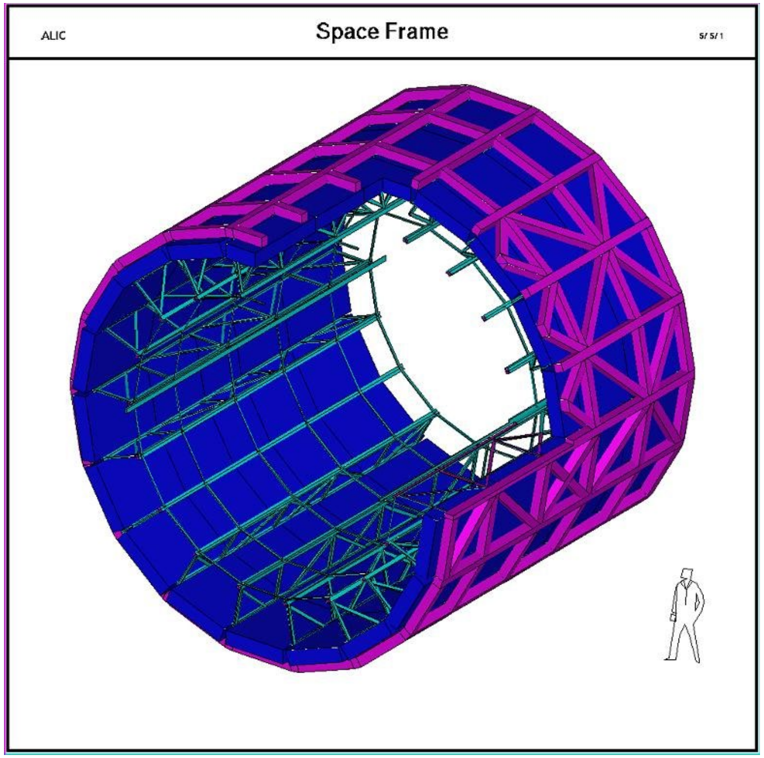
$$n_{\sigma_{TOF}} = \frac{|t_A - t_B|}{\sigma_{TOF}} = \frac{Lc}{2p^2\sigma_{TOF}}|m_A^2 - m_B^2|$$

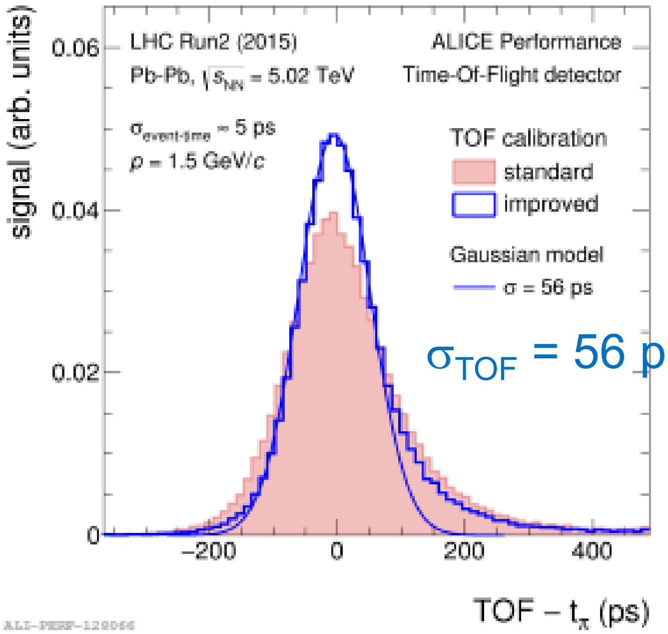
The plot shows for which momenta a separation between π/e, K/π, K/p is possible.



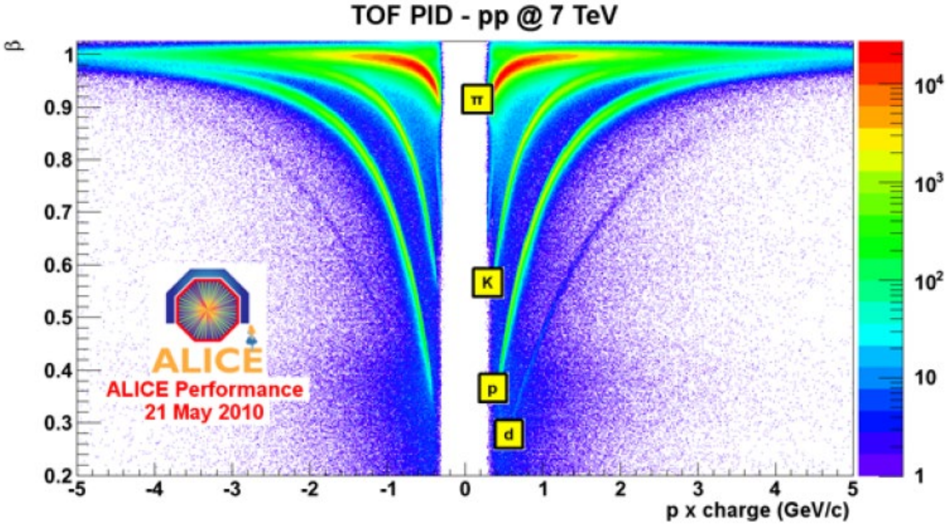
Example: ALICE TOF system

Multigap Resistive Plate Chambers

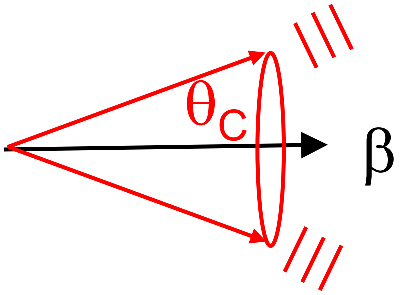




σ_{TOF} = 56 ps



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)

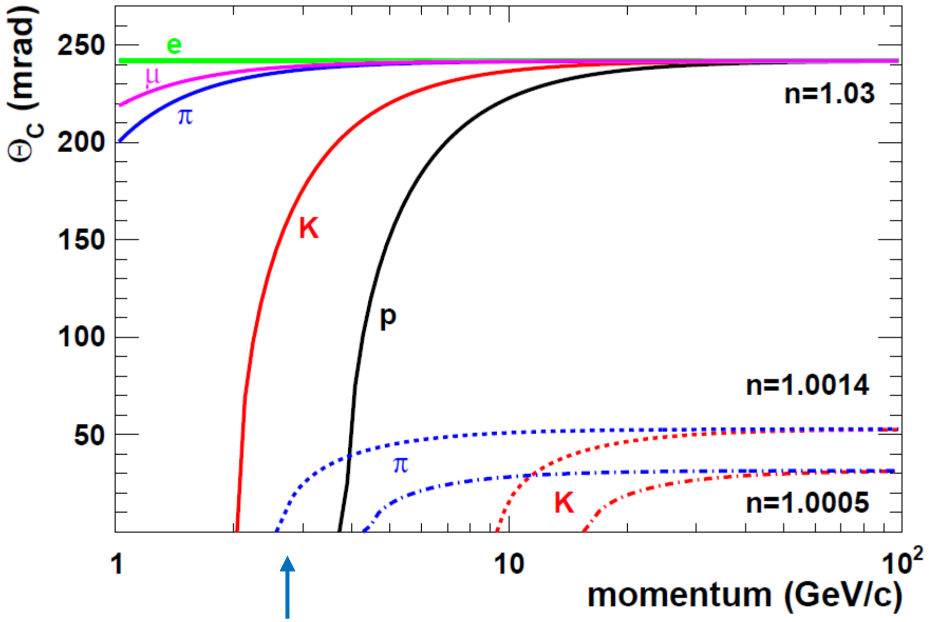
Separation in sigmas:

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

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

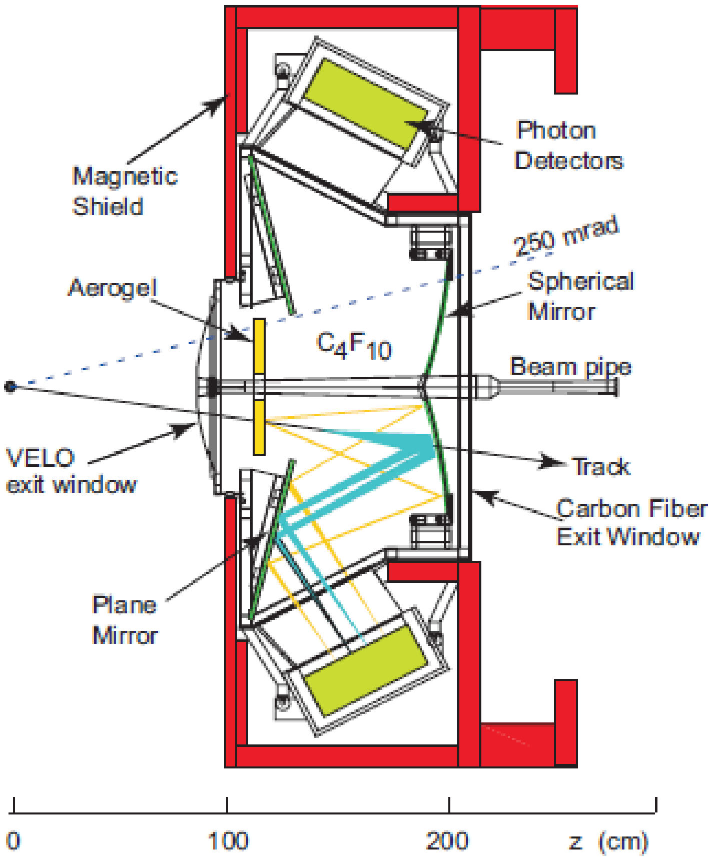
$$n_{\sigma_{\Theta_C}} \approx \frac{c^2}{2p^2 \langle \sigma_{\Theta_C} \rangle \sqrt{n^2 - 1}} \left| m_B^2 - m_A^2 \right|$$

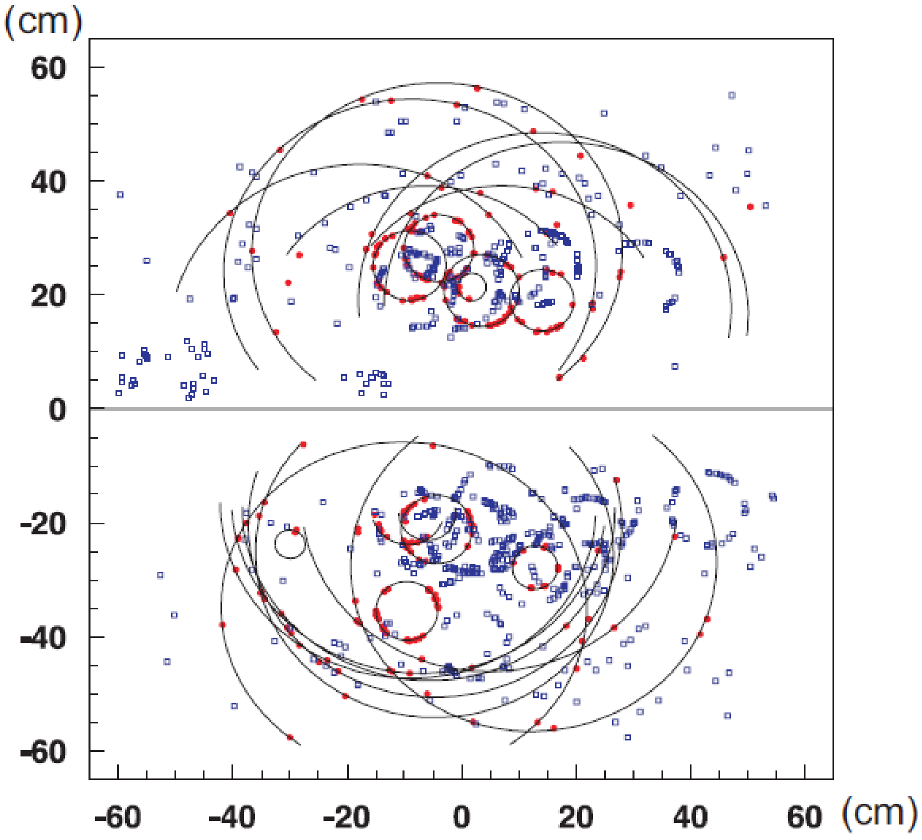
(see for example C. Amsler et al. (PDG), Phys. Let. B667 (2008) 1.)



Threshold given by $\beta > 1/n$

Example: LHCb Ring Imaging Cherenkow Detector

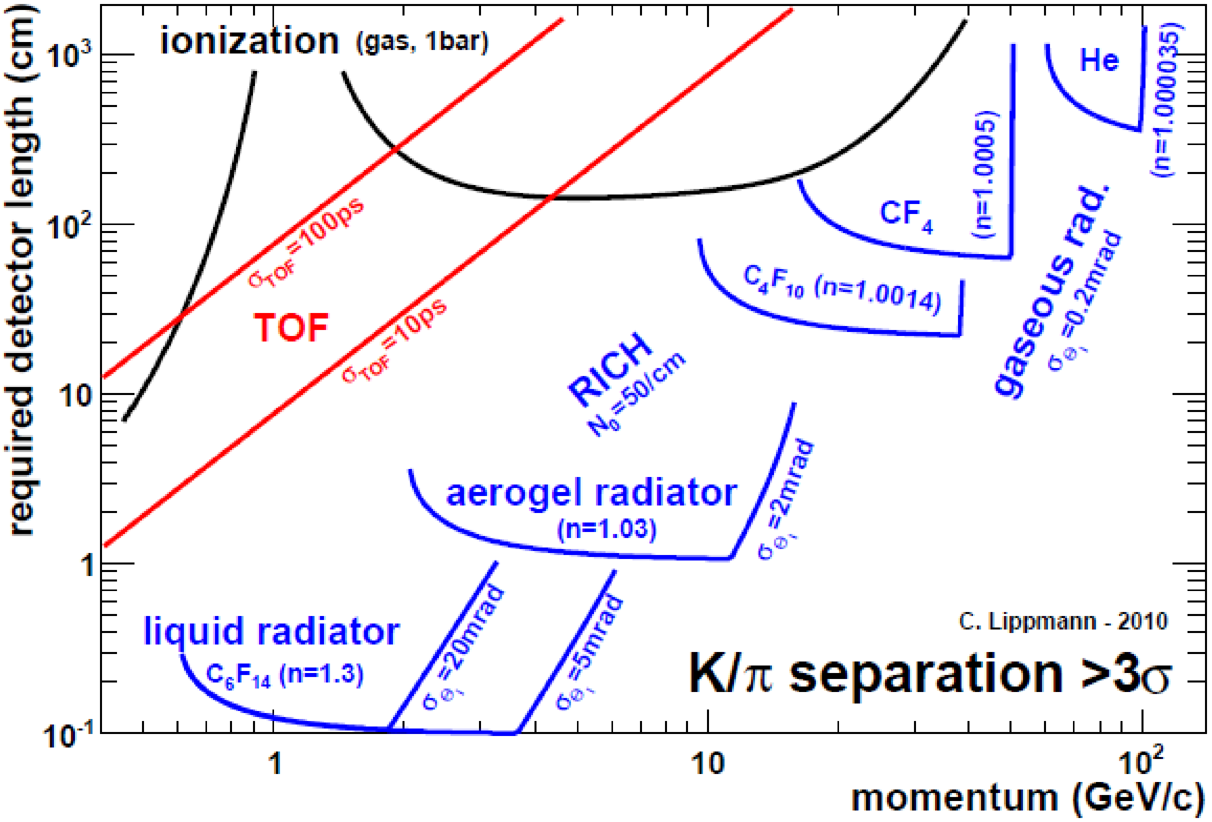




Refractive index: Aerogel n=1.037 → large rings

C_4F_{10} n=1.0015 → small rings

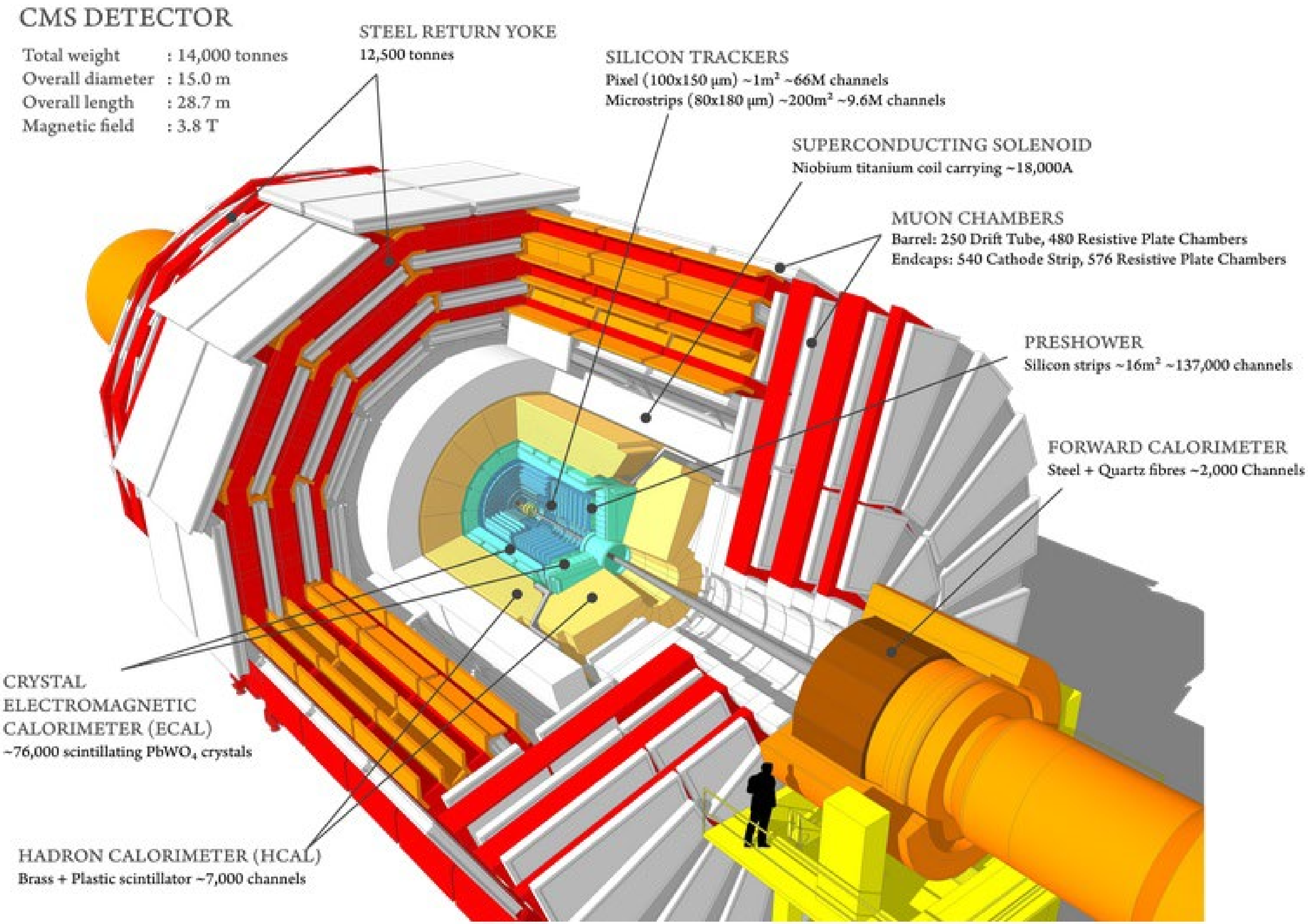
Comparison: Different PID systems



C. Lippmann, arXiv:1101.3276

5. Detector systems

(only one example)



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm) ~1m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

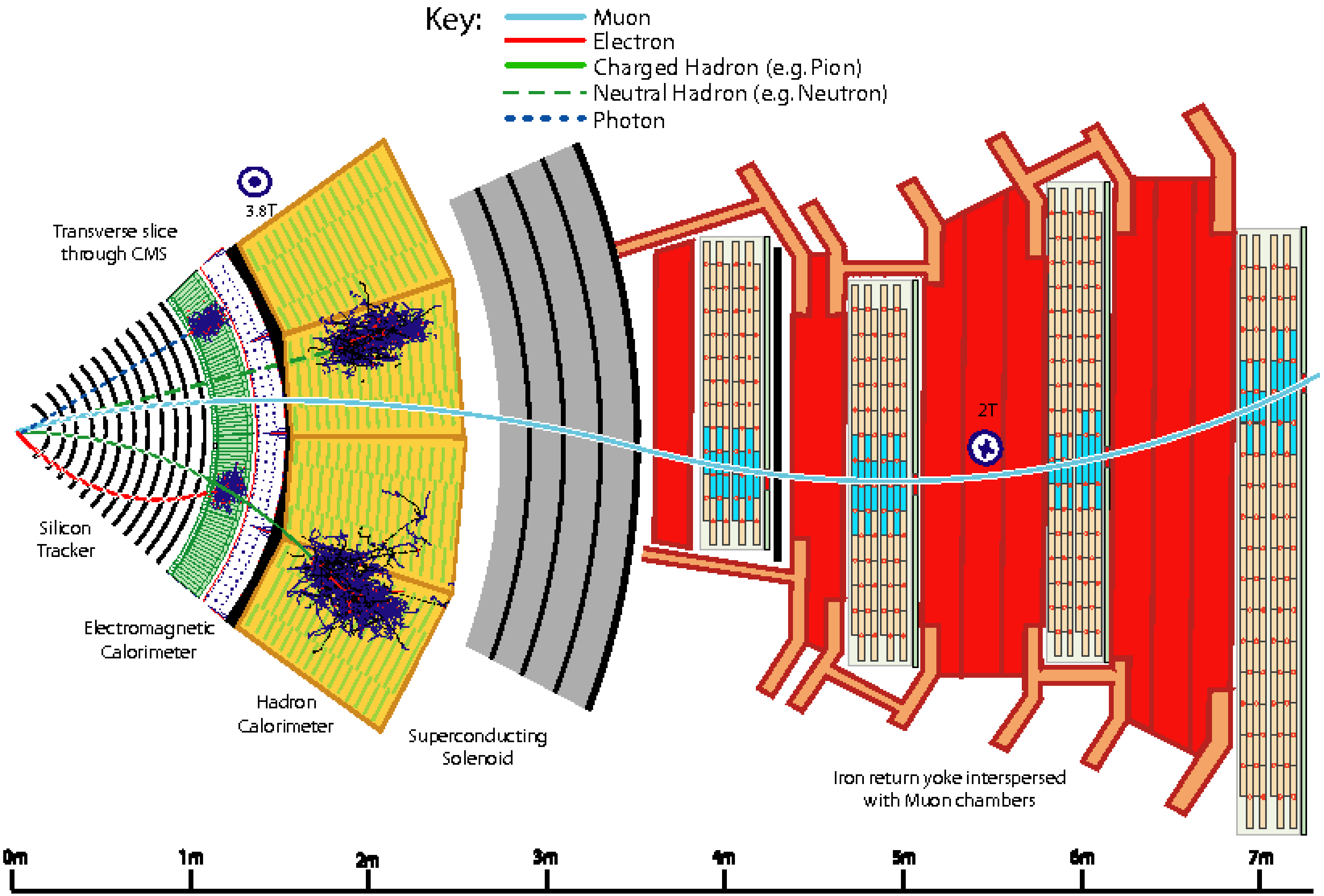
PRESHOWER
Silicon strips ~16m² ~137,000 channels

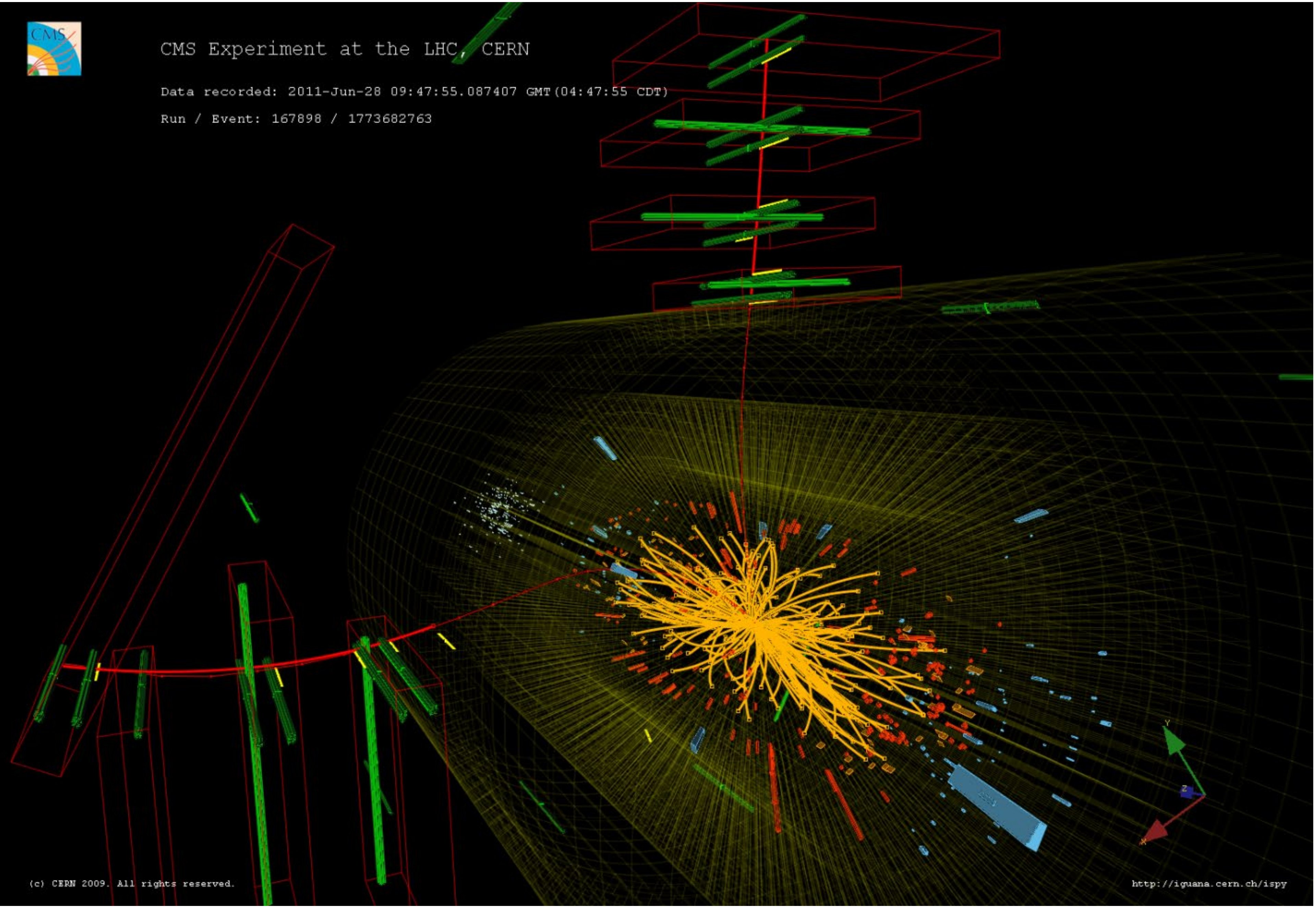
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

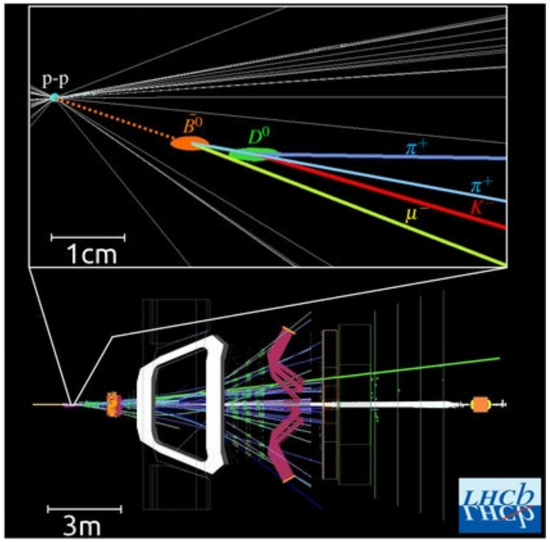
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

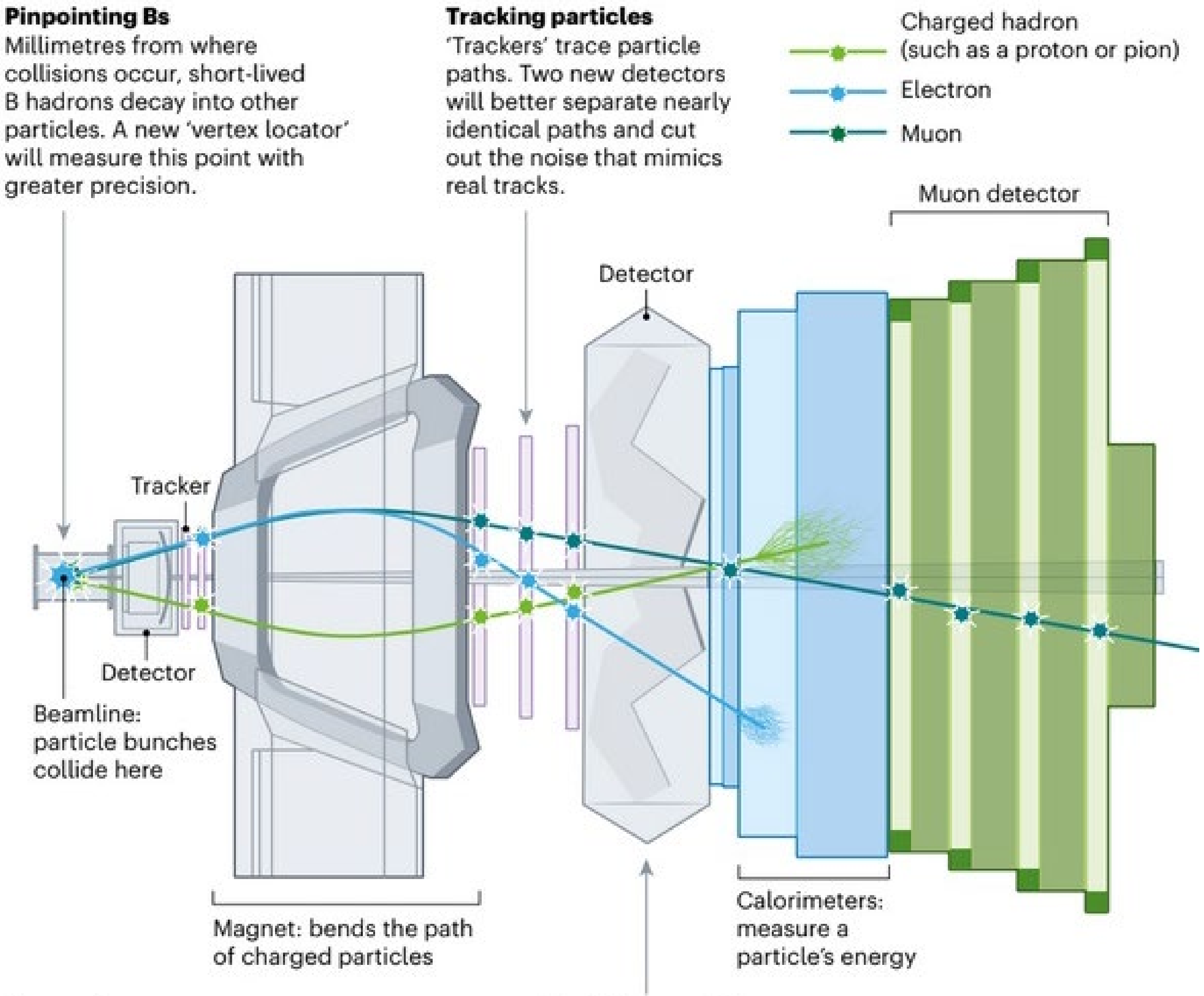
Particle signatures in the CMS detector:




CMS Experiment at the LHC, CERN
Data recorded: 2011-Jun-28 09:47:55.087407 GMT(04:47:55 CDT)
Run / Event: 167898 / 1773682763
Y
Z
X
(c) CERN 2009. All rights reserved.
http://iguana.cern.ch/ispy

LHCb Detector





Pinpointing Bs
Millimetres from where collisions occur, short-lived B hadrons decay into other particles. A new 'vertex locator' will measure this point with greater precision.

Tracking particles
'Trackers' trace particle paths. Two new detectors will better separate nearly identical paths and cut out the noise that mimics real tracks.

Beamline: particle bunches collide here

Magnet: bends the path of charged particles

Calorimeters: measure a particle's energy

Electronics
Renovated electronics mean that LHCb can now use software to scan through 40 million events per second. Previously, a coarser hardware filter first triaged these to identify one million to be scanned.

Identifying particles
Other detectors measure the velocity of charged particles; combining this information with a particle's path reveals its identity. Upgraded detectors are more sensitive to velocity and can cope with higher data rates.