pp physics, RWTH, WS 2003/04, T.Hebbeker

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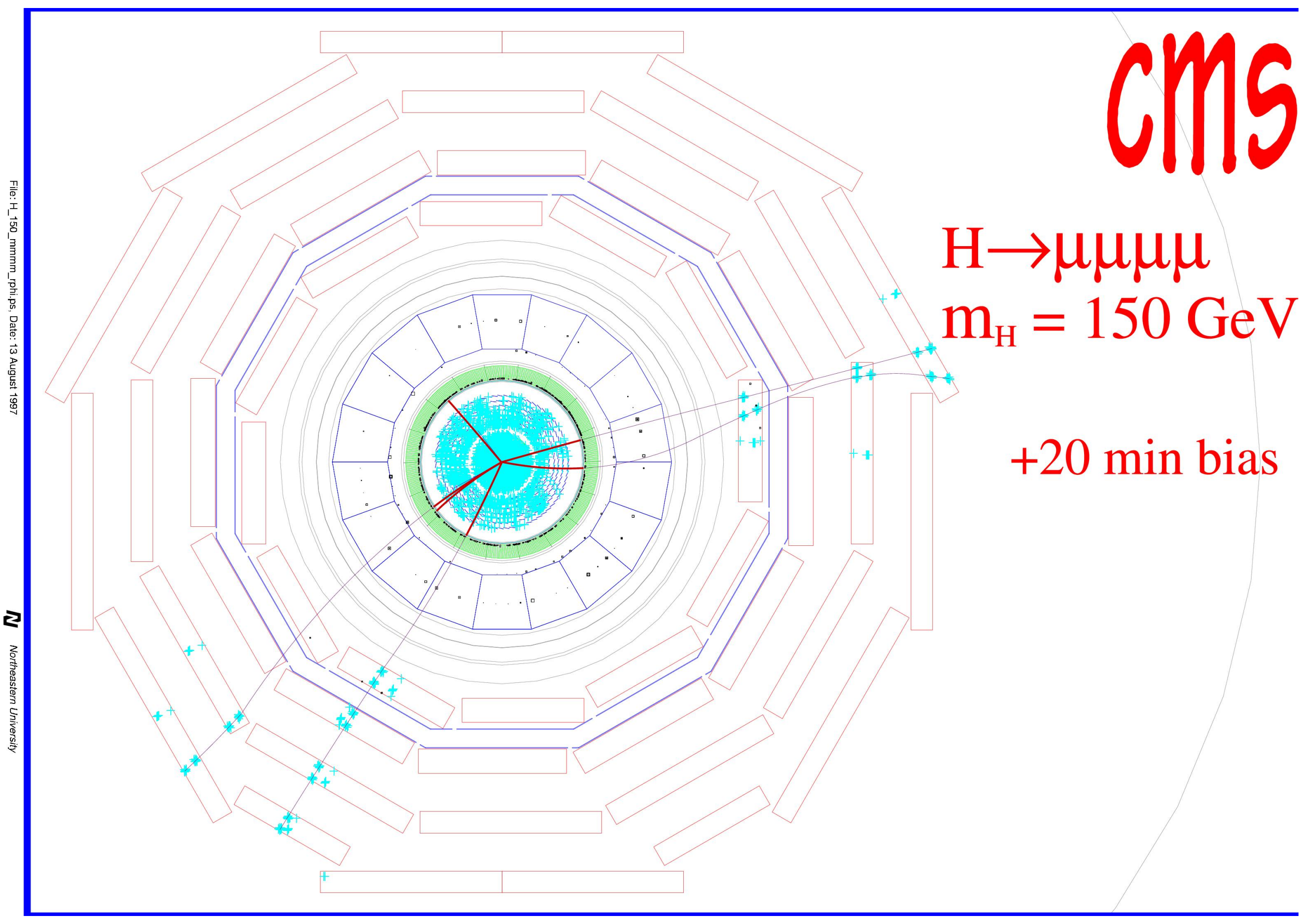
1.2.5. Muons

A clean identification of muons is possible with track detectors, 'muon chambers', outside the hadron calorimeter + absorber material (assuming enough absorption lengths so that only few 'punch through' hadrons remain).

Example: Simulated 'Higgs event' in the CMS detector:

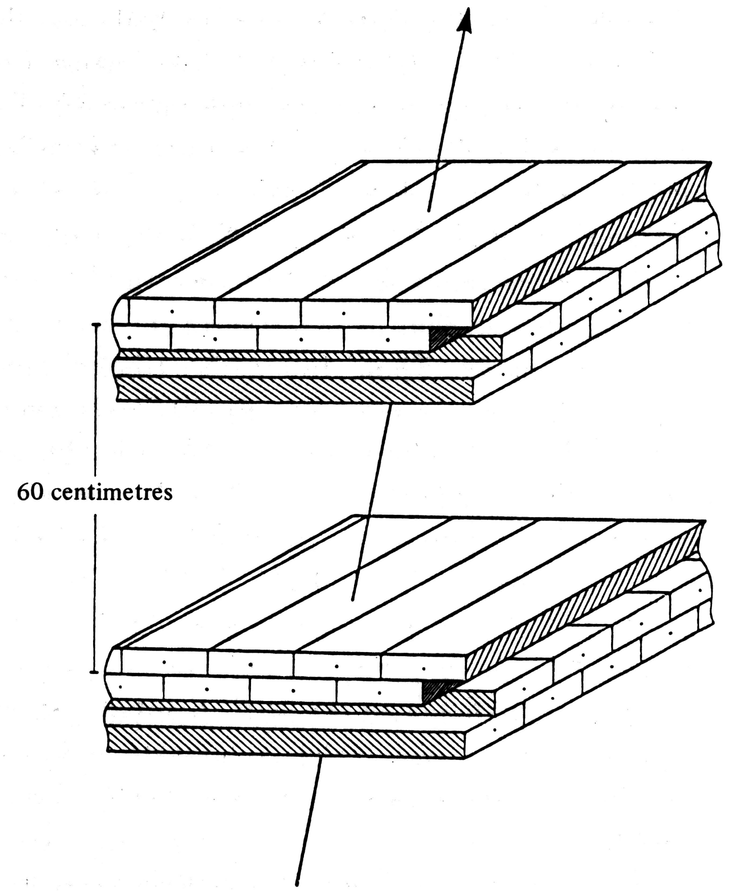


The momentum can be meausured 'stand alone' with these muon detectors, and/or by 'matching' the muon track with the corresponding one seen in the inner tracker.

Also for triggering purposes these detectors are very important.

Due to the large surface to be covered, only relatively 'cheap' gas detectors can be used, silicon devices or scintillating fibres are not (yet) a realistic alternative.

UA1 used large area drift chambers[1], enclosing the magnet yoke in the barrel region and in the end-caps. In total $350\,\mathrm{m}^2$ were covered (2 layers a 4 planes):

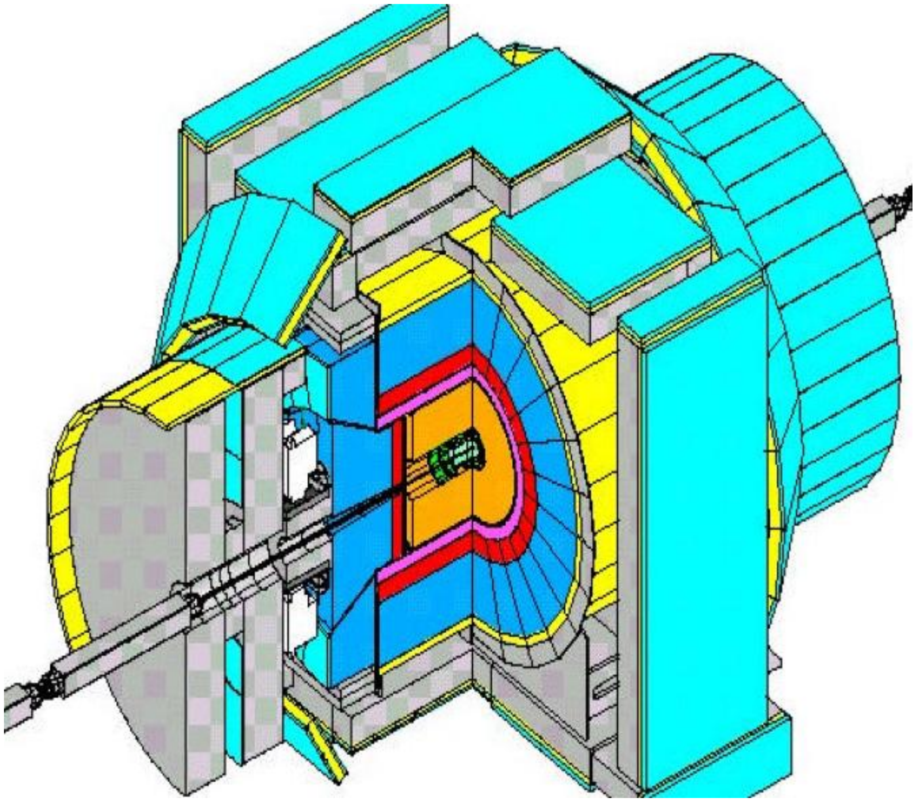


Obviously a stand-alone momentum measurement is not possible (no B-field), also a severe vertex constraint (R-z plane) is unavailable. The main purpose is the identification of muons via matching tracks seen in the other detector components; since the punch through fraction is substantial (one particle per 30 GeV hadronic shower at $\eta = 0$), this is an important task! The drift cells had a cross section of $15\,\mathrm{cm} \times 5\,\mathrm{cm}$ and gave a position resolution of $400\,\mu\mathrm{m}$. Later both UA1 magnet and muon chambers were reused in the NOMAD neutrino detector.

The **UA2** apparatus did not have outer muon detectors; thus the W (and Z) could only be studied in the $e\,\nu$ (e^+e^-) decay mode.

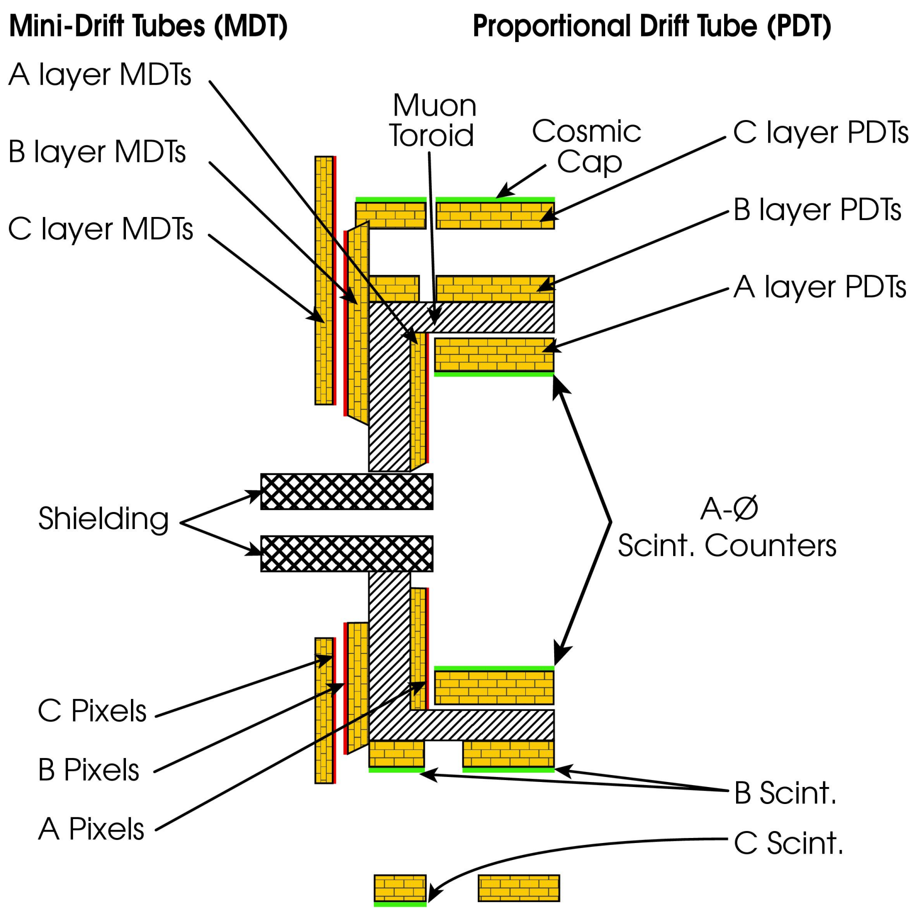
The **CDF** muon chambers cover the barrel, the intermediate region (45^0) and surround the forward toroids. Apart from drift chambers (yellow) also scintillators (light blue) are employed:

[1]built in Aachen

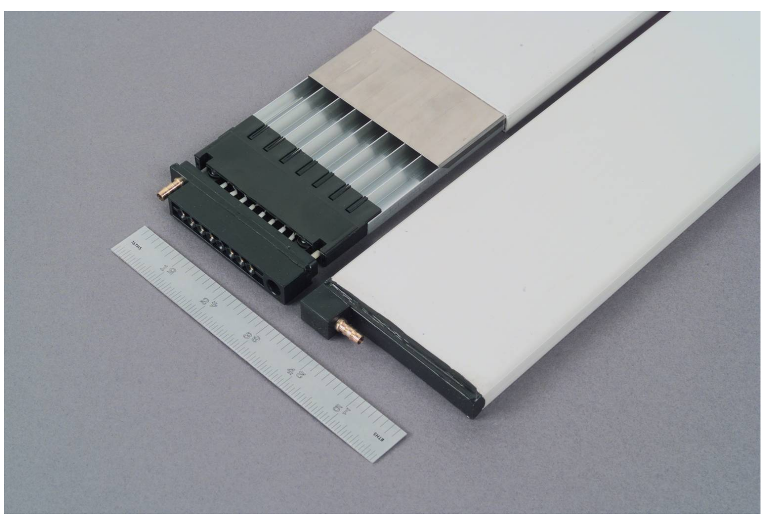


The very forward region is not covered. For small values of $|\eta|$ a nonmagnetic steel layer reduces the punch through in the outer of two separate chamber layers. The role of the muon chambers is similar to UA1, also the cell size is comparable, eg $15\,\mathrm{cm} \times 2.5\,\mathrm{cm}$ in the outer barrel region. The max. drift time is quite long, $1.4\,\mu\mathrm{s}$, but since the occupancy is low, this is acceptable. The scintillators are used to determine the corresponding beam crossing.

D0 uses two types of muon chambers (barrel and endcap regions) and scintillators (many in form of tiles):



The PDTs (Proportional Drift Tubes) cover the barrel, the MDT (Mini Drift tubes) have been added for run II in the forward regions:



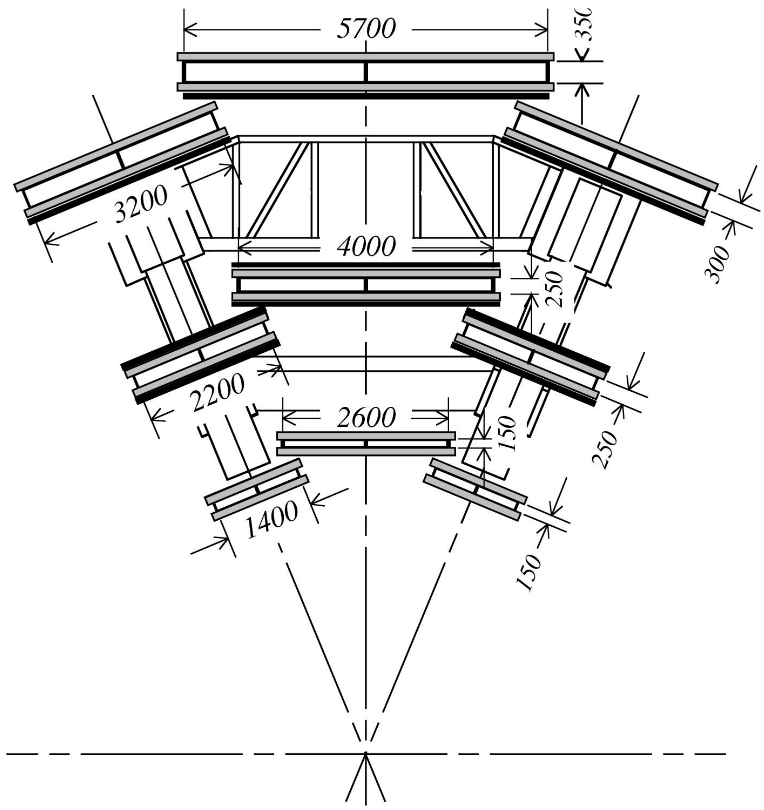
Due to the small size ($\sim 1\,\mathrm{cm}$) the max. drift time is only $60\,\mathrm{ns}$.

Since the inner layer of both the PDTs and MDTs is inside the toroid magnets, a stand alone momentum measurement is possible, but not very precise. At $\eta = 0$:

$$\frac{\Delta p}{p} = 0.3\% \cdot p/\mathrm{GeV} \oplus 18\% \tag{1}$$

The most ambitious muon detector (together with the air toroid) is being built by the **ATLAS** collaboration. They use MDTs (Monitored Drift Tubes), RPCs (Resistive Plate Chambers) and other species, which we will not discuss here.

In the barrel region the arrangement looks like this:

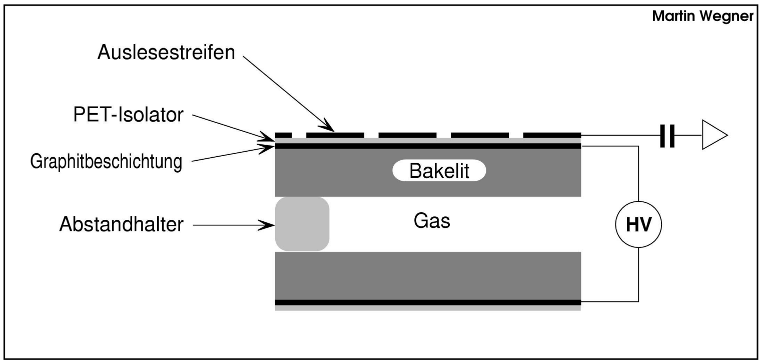


(light grey: MDT, black: RPC).

The MDT tubes have a diameter of $3\,\mathrm{cm}$ and should reach a single cell resolution of $< 100\,\mu\mathrm{m}$. They are operated at a pressure of $3\,\mathrm{bar}$ (Ar CO_2) and a voltage of $3.1\,\mathrm{kV}$. The good resolution is due to the short drift distance, the cell symmetry and the pressure (less charge diffusion, higher ionisation). One completed chamber:

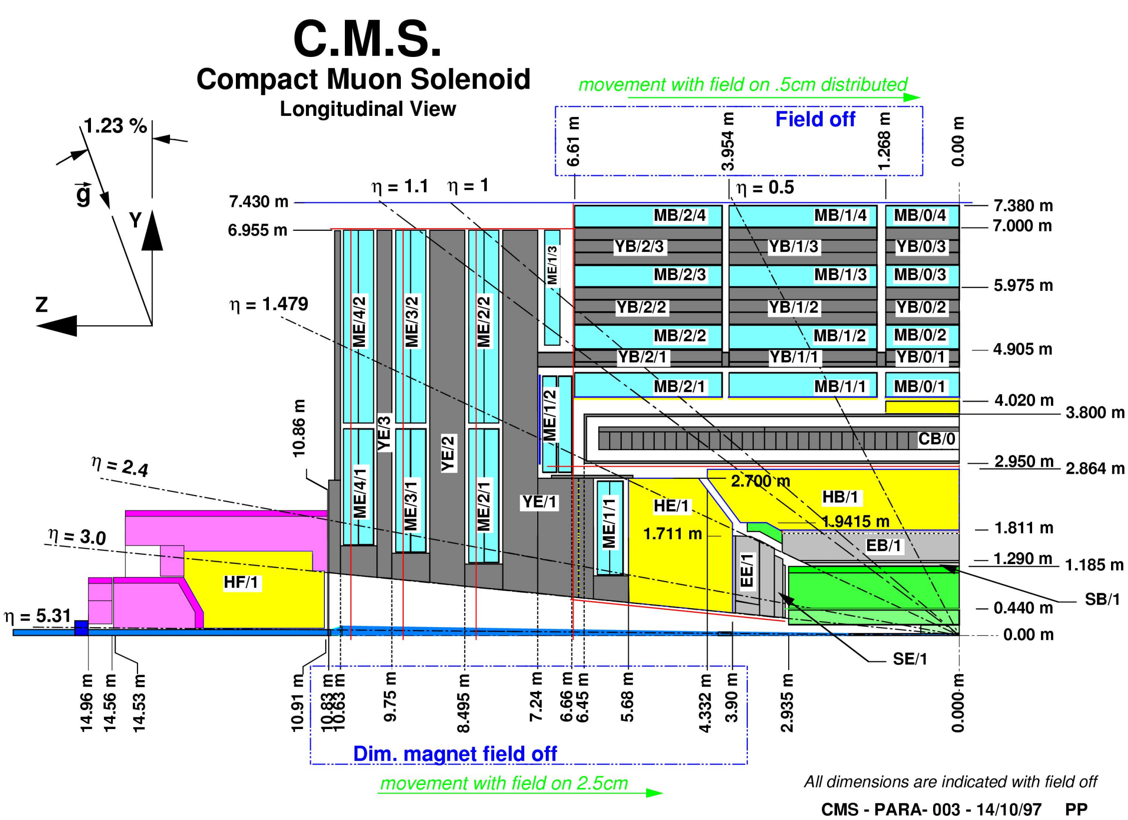
In total more than 300000 tubes will be produced, covering a surface of more than $5000\,\mathrm{m}^2$. To be able to exploit the excellent resolution, a very precise chamber alignment is crucial.

RPCs are made out of two parallel plates with a small gas gap in between (few mm) and are operated at several kV:

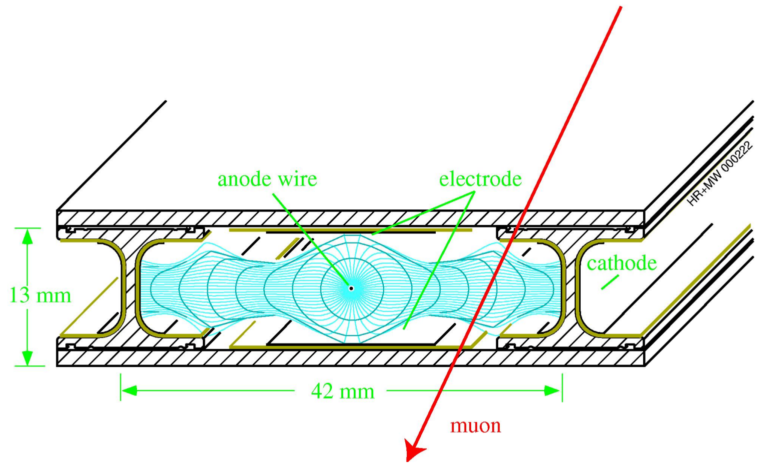


A charged particle initiates an avalanche, which induces charges on the readout strips. Important: the bakelite plates have a very high resistivity, so that locally the field collapses at this moment, thus the avalanche is interrupted and does not spread out. They are relatively simple to fabricate, since they don't use wires. Their high speed (some ns pulse length) make them ideal detectors for triggering purposes.

Also the **CMS** muon spectrometer uses RPCs, but the precision devices are again wire chambers, DTs (Drift Tubes) in the barrel region and CSCs (Cathode Strip Chambers) in the endcap region (high track density, high rate):

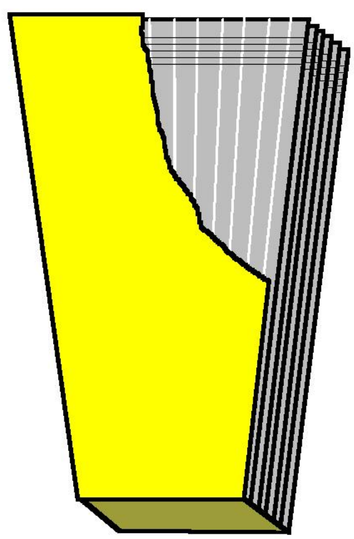


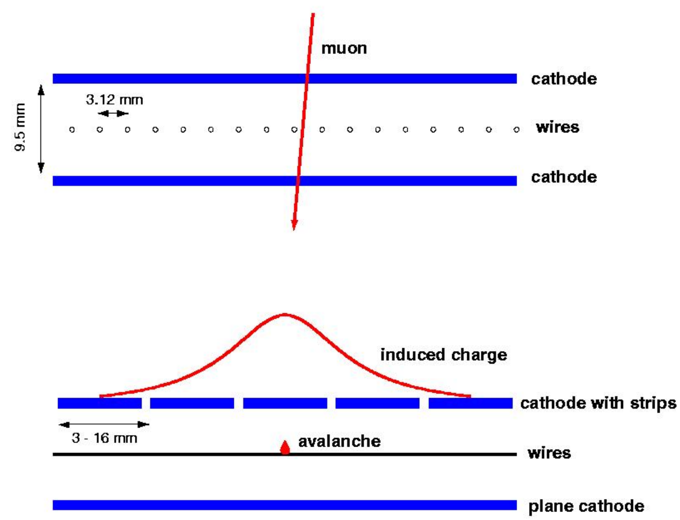
The barrel chambers consist of 190000 rectangular drift cells of typical size $4\,\mathrm{mm} \times 1.5\,\mathrm{mm} \times 2.5\,\mathrm{m}$:



They are operated at standard pressure (Ar CO_2) and reach a single wire resolution of $200\,\mu\mathrm{m}$.

The working principle of CSCs is illustrated here:





Both cathodes and anodes (no drifttime measurement) are read out.

They have several advantages compared to DTs,

- both coordinates measured
- relatively insensitive to magnetic field
- small cell size $\longrightarrow$ high rate capability

but they are more expensive.

Comparison of muon detectors:

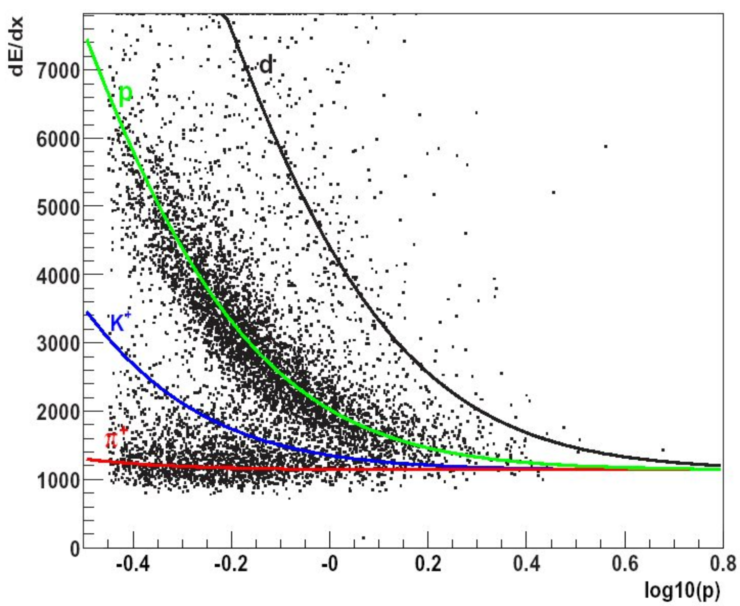
detector	type	pos. resol. $/\mu\,\mathrm{m}$	channels
UA1	drift	400	7000
CDF	drift	200-300	7000
D0	drift	500 -700	23000
ATLAS	drift	100	400000
CMS	drift	200	700000

1.2.6. Particle identification

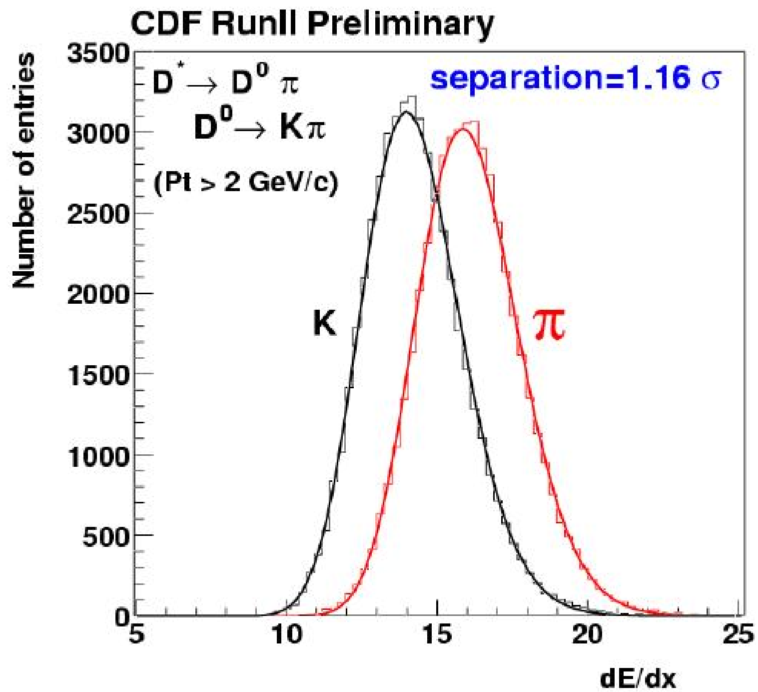
We have already encountered several examples of particle identification in the previous sections, making use of transition and Cerenkov radiation and - for muons - range!

A few more comments on dE/dx measurements in the central tracker, allowing to distinguish between charged hadrons of different type (π, K, p):

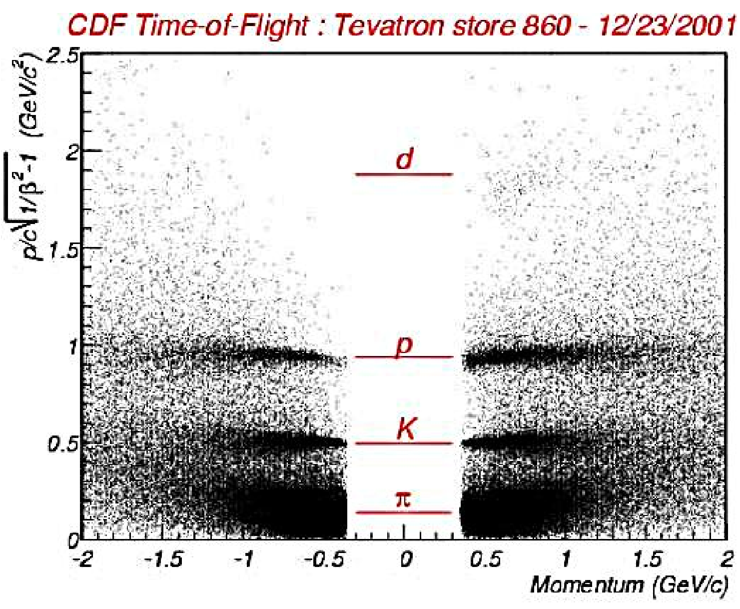
- The LHC silicon strip detectors are not foreseen for a dE/dx measurement (work only at low momenta - curl up; too few measurements; ATLAS: pulse height not read out!)
- CDF has demonstrated that in principle a silicon detector can be used:



- High quality dE/dx measurements are possible in the wire chambers of UA1 and CDF, both sampling with $\geq\sim 100$ cells:



Another tool in particle identification is TOF (Time of Flight), as used for example in CDF; their scintillators + PMs, installed behind the COT, reach a resolution of 100 ps:



The quantity plotted on the vertical axis is (apart from factors c^n):

$$p\,\sqrt{1/\beta^2-1} = m\,\gamma\,\beta\,\sqrt{1/\beta^2-1} = m \tag{2}$$

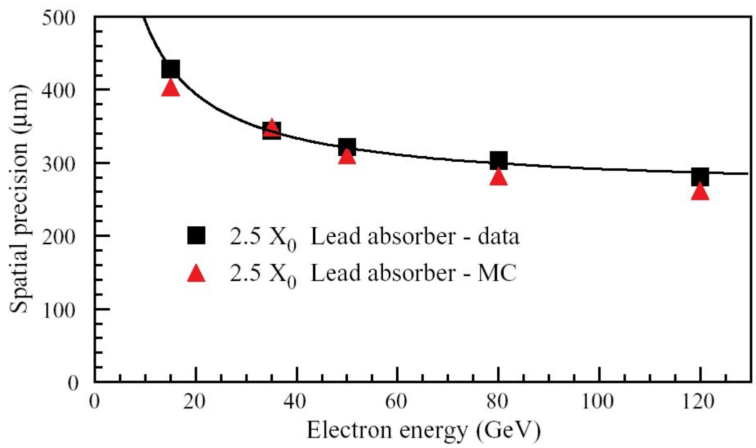
where p is measured in the tracker and β in the TOF system.

Finally the preshower detectors should be mentioned, which are used by CDF, D0, ATLAS and CMS.

These are thin position measuring detectors with absorber material ($\sim 1 - 3\,X_0$), located in front of the electromagnetic calorimeters. Thus they measure the transverse profile in the first shower part. Their purpose is twofold:
- Distinction between an electron, a single photon and a $\pi^0 \rightarrow \gamma\gamma$
- Precise measurement of shower starting point ($\longrightarrow$ photon direction, electron track matching)

They can be realised in different ways: wire chambers, scintillators (CDF), silicon strips (CMS), scintillating fibres (D0), or a high granularity compartment of a LAr calorimeter (ATLAS).

This graph shows the simulated and measured (test beam) position resolution for the CMS preshower apparatus:



The transverse shower (maximum) position resolution by the crystals is somewhat less good (factor 1.7). Combining both measurements gives the shower direction without assumption on the event vertex.