Electronics and Data Acquisition

To achieve optimal performance (resolution, timing, etc.) the detector and its readout electronics have to form a well matched unit.

Signal Acquisition:
- signal amplitude, shape > energy deposit in detector
- signal time > time of particle passage

Signals are usually
- small (order of pC $\approx 10^6$ e-, PMT, wire chambers)
- very small (order of fC $\approx 10^3$ e-, Si or micro gas detectors)
- short (order of μs, scintillators, thick detectors)
- very short (order of ns, thin detectors)
- and the detector is at a certain distance from readout unit (can be up to 100m)

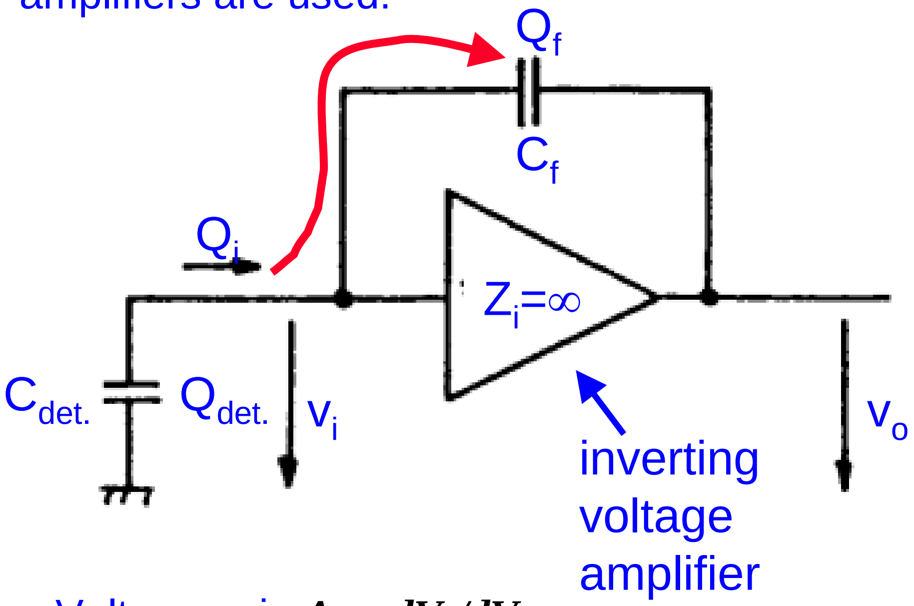
Signals need to be
- amplified
- shaped
- discriminated
- digitized
- transferred

Signals are subject to distortions
- intrinsic, noise
- external (pickup, voltage instabilities, bad grounding)

Often the ratio signal / noise (S/N) is the figure of merit !

Amplification of signals

To be independent of signal shape often charge sensitive amplifiers are used:

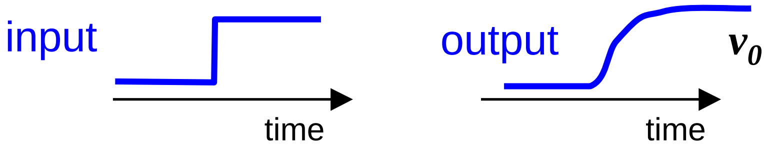


Helmuth Spieler
LBNL

- Voltage gain $A = -dV_0/dV_i$
- $Q_f = Q_i$ because $Z_i = \infty$
- Effective input capacitance $C_i = Q_i/v_i = C_f(A+1)$
- Gain $A_Q = dV_0/dQ_i = A/C_i = A/(A+1)/C_f \approx 1/C_f$

- A certain fraction of the charge stays on the detector and will not be detected: $Q_i/Q_{det.} = (1+C_{det}/C_i)^{-1}$
- C_i must be >> $C_{det.}$

- An amplifier is automatically also a shaper

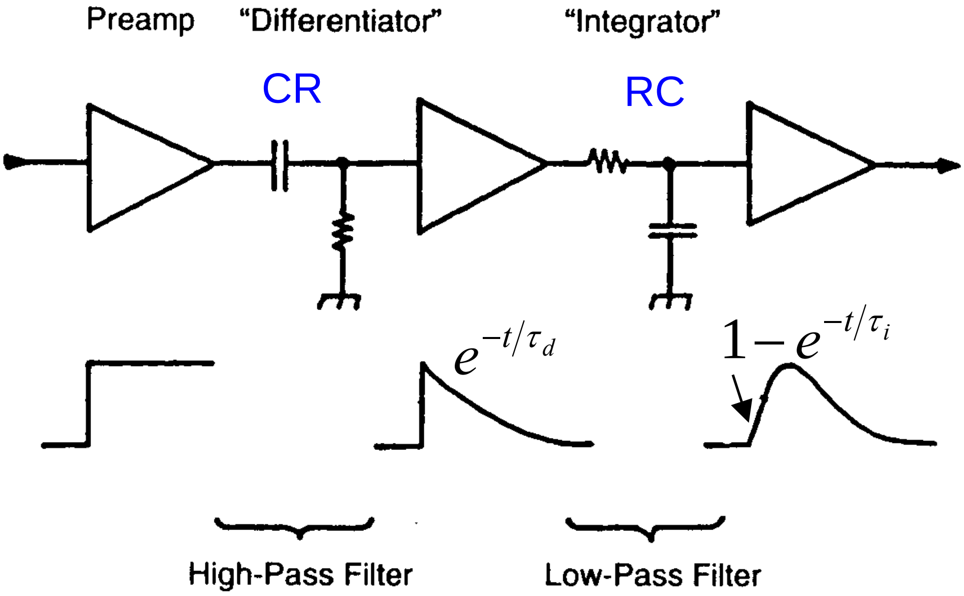


$v_0(1-e^{-t/\tau})$

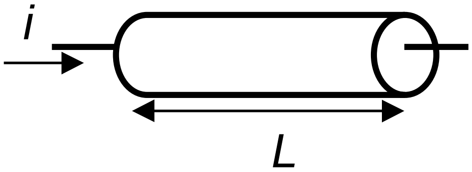
$\tau = C_D/\omega_0 C_f$

- Every detector needs its properly designed amplifier.

Shaping of signals



Noise



$$i = \frac{nev}{l}$$

current i through a sample

$$\langle di \rangle^2 = \left(\frac{ne}{l} \langle dv \rangle \right)^2 + \left(\frac{ev}{l} \langle dn \rangle \right)^2$$

current fluctuations di due to
- velocity fluctuations dv
- number fluctuations dn

- ***dv*** → thermal noise
- ***dn*** → shot noise, ***1/f*** noise

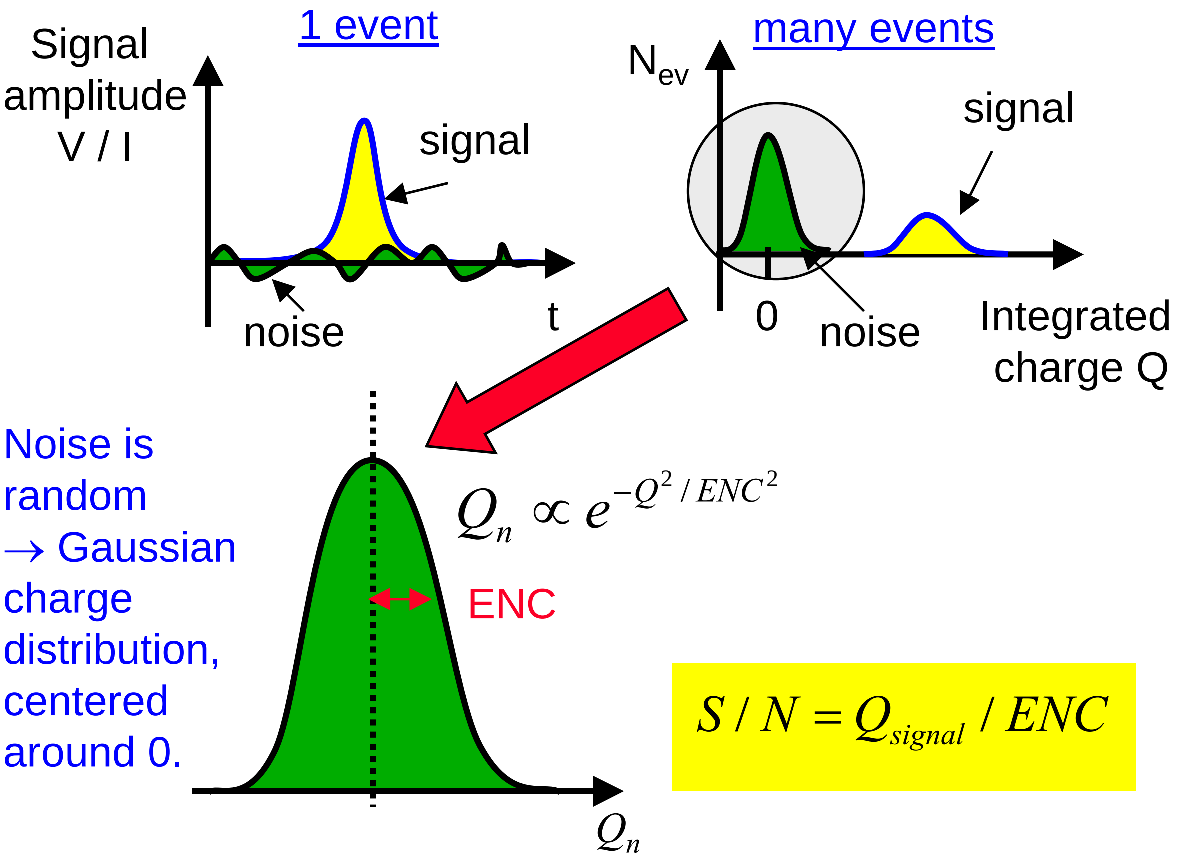
Very useful quantity for characterization of systems:

the equivalent noise charge ENC

$$ENC = F_v \cdot v_n \cdot C_i \cdot \frac{1}{\sqrt{\tau}} \oplus F_i \cdot i_n \cdot \sqrt{\tau}$$

F_v and F_i are numerical factors depending on the details of the noise filtering in the filtering network.

τ (ns)	peaking time of the shaper
C_i (pF)	total input capacitance both from detector and amplifier
v_n(nV/√Hz), i_n(pA/√Hz)	equivalent spectral current / voltage noise densities



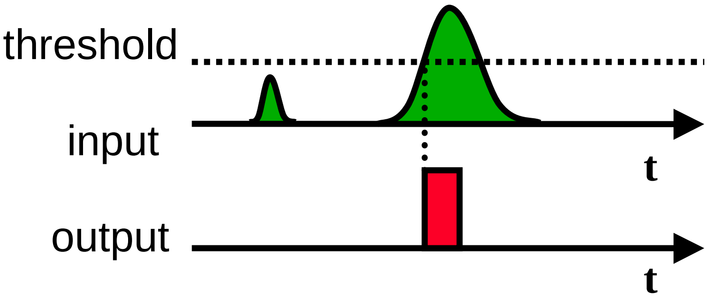
$$Q_n \propto e^{-Q^2/ENC^2}$$

Noise is random → Gaussian charge distribution, centered around 0.

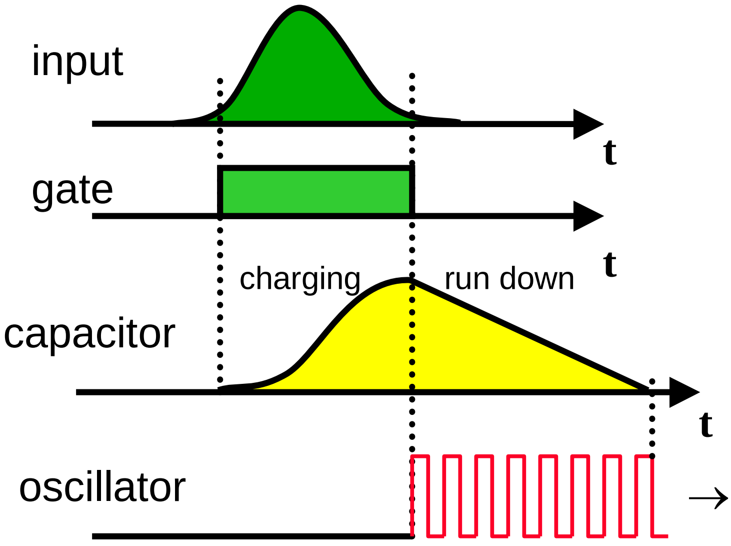
$$S/N = Q_{signal} / ENC$$

Some other frequently used elements

- Discriminator



- Analog-to-Digital Converter (ADC)



→ scaler → 001100101

- similarly: Time-to-Digital Converter (TDC)

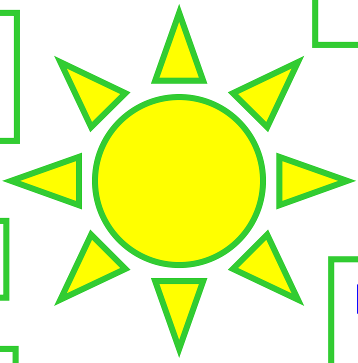
Electronics systems: Some design issues

Mode (Analog / Binary)

Radiation hardness
LHC → dose ≈ 100 kGy

Speed (peaking time)
LHC → 25 ns

Technology
(Bipolar, CMOS,...)



Noise
typ. ≈ 1000e$^-$ ENC

Dynamic range

Power consumption
few mW / channel

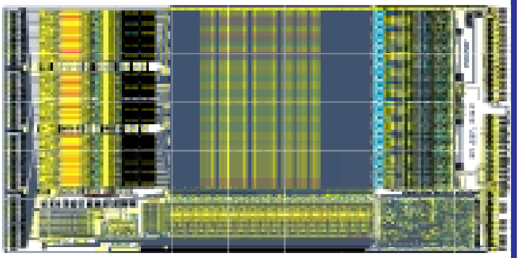
Cost

Robustness

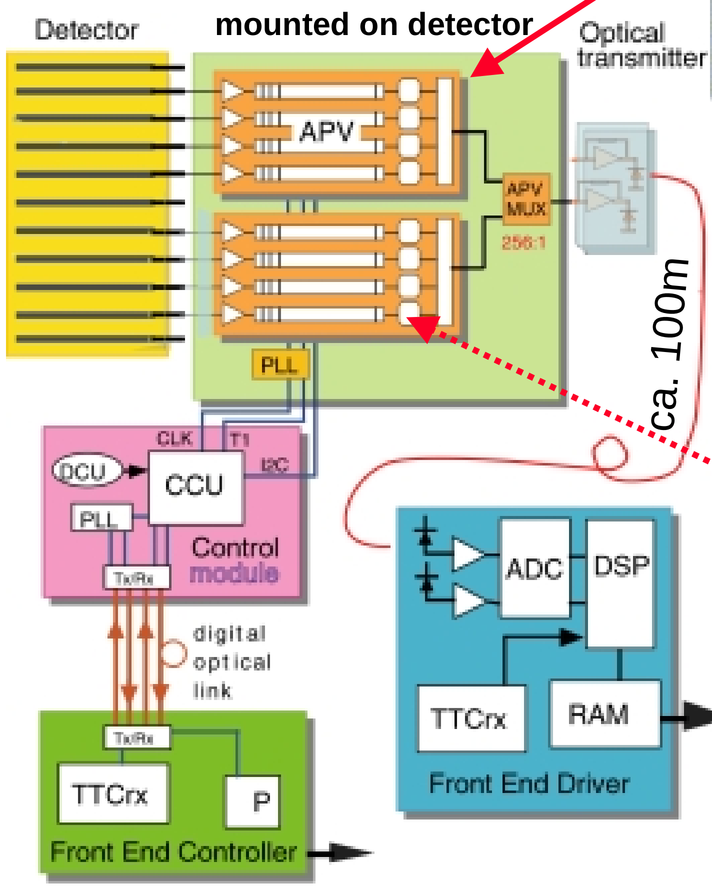
- Some parameters are conflicting, e.g. speed ⇔ power consumption or analog mode ⇔ cost.
- Every subdetector (Si-tracker, e.m. or hadron calorimeter, muon system, etc.) will weight constraints differently.

Overview of an acquisition front end

- CMS inner tracker electronics



Front End Module mounted on detector

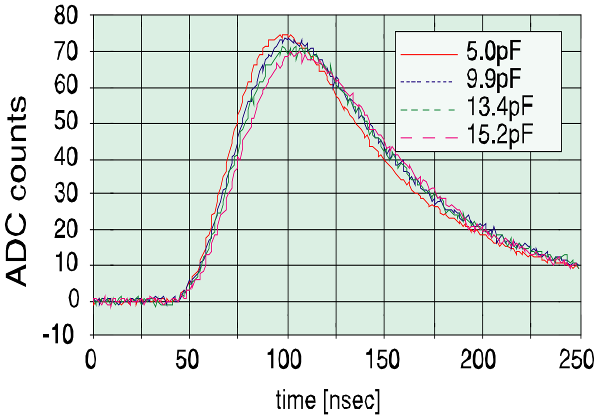


APV6 chip (128 channels)

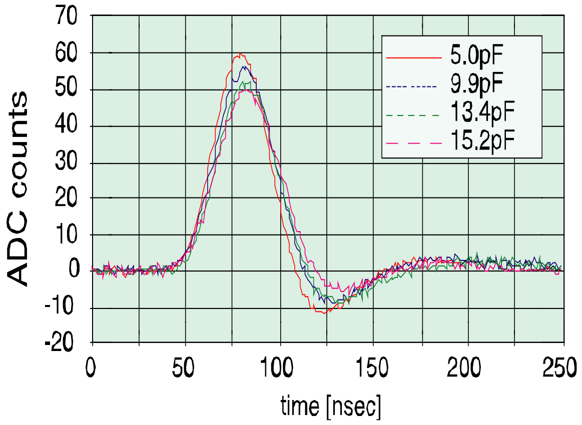
τ_{peak} = 50 ns

needs to work in de-convolution mode to determine bunch crossing unambiguously.

Peak mode



Deconvolution mode



Trigger (much more details in Clara Gaspar's lectures)

What is it ? A system defining the conditions under which an event shall be recorded.

Why is it needed ?

- Selection of interesting events
- Suppression of background
- Reduction of recorded data size

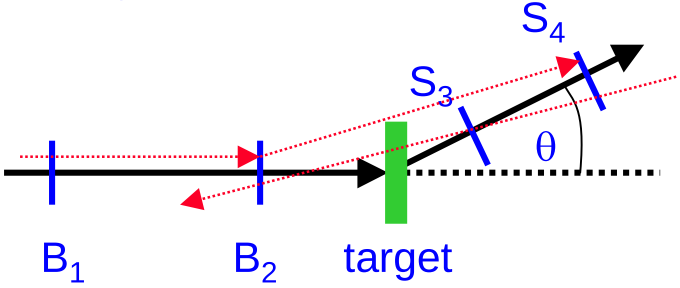
- Recording data takes time τ_{rec}, typically several ms / event.
- If rate R of selected events is not small compared to $1/\tau_{rec}$, deadtime will be produced. The recorded event rate will then be smaller than the real event rate:

$$\frac{R'}{R} = 1 - R'\tau_{rec}$$

R : real event rate

R' : recorded event rate

A very simple example of a trigger: A scattering experiment where only beam particles scattered from the target under the angle θ shall be recorded



S_4

S_3

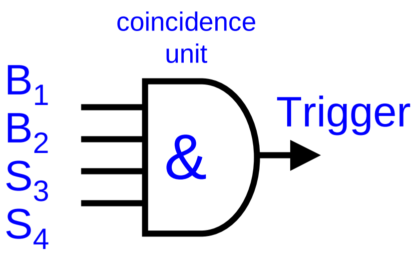
θ

B_1 B_2 target

Condition for recording:

$T = B_1 \cap B_2 \cap S_3 \cap S_4$

All other events → will be rejected.



coincidence unit

B_1

B_2

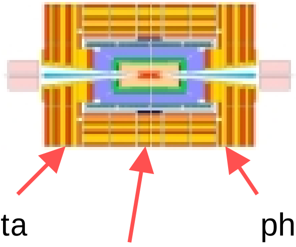
S_3

S_4

&

Trigger

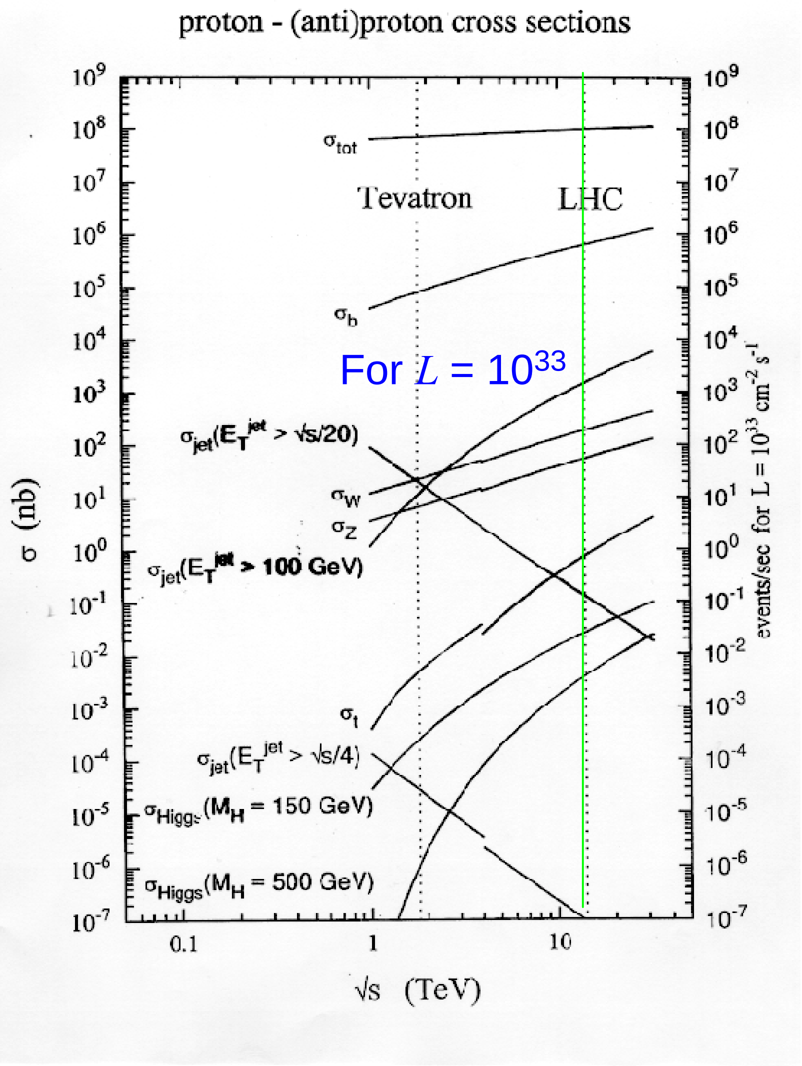
In modern experiments, trigger systems must be much more selective.

Trigger = f ()

event data

physics channel

detector parameters



LHC

Interaction rate:
~ 10^{9} events/second
An experiment can record
~ 100 events/second
(event size 1 MB)

⇒ necessary trigger rejection
~ 10^{7}

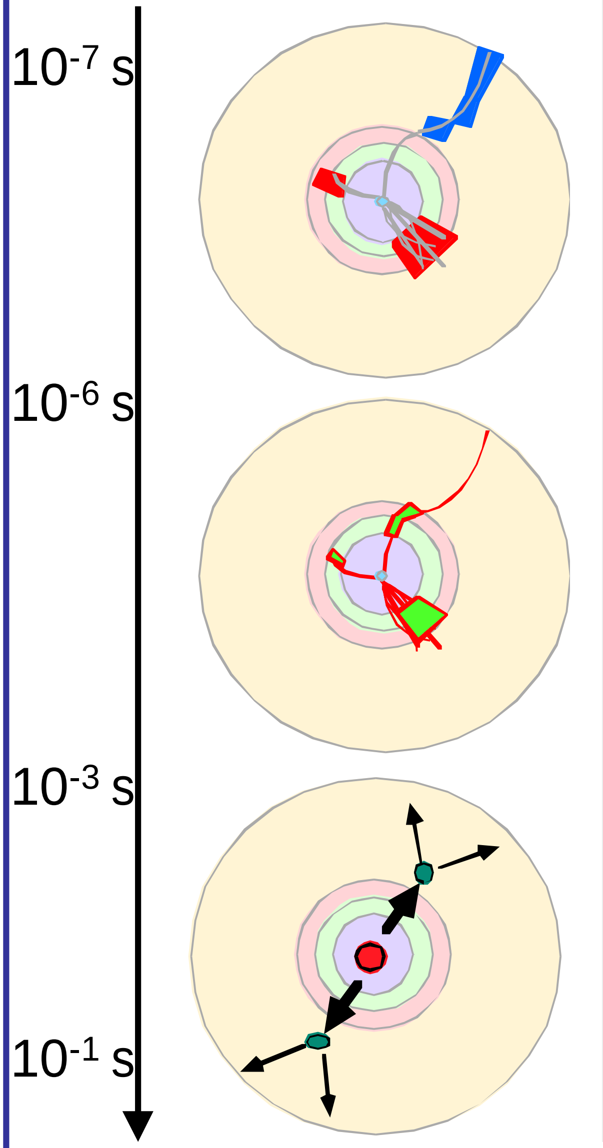
“interesting” event rate (H, t, Susy):
very few events/sec.

Electronics and Data Acquisition (backup)

Trigger decision is taken on several (usually 3) levels.
Increasing complexity and selectivity.

All data of previous level has to be stored until subsequent trigger decision has been taken.

Level “0”: Event rate: 10^9 Hz. Detector channels: 10^7 - 10^8
DAQ is running constantly at 40 MHz. Data flow $\approx 10^{16}$ bit/sec

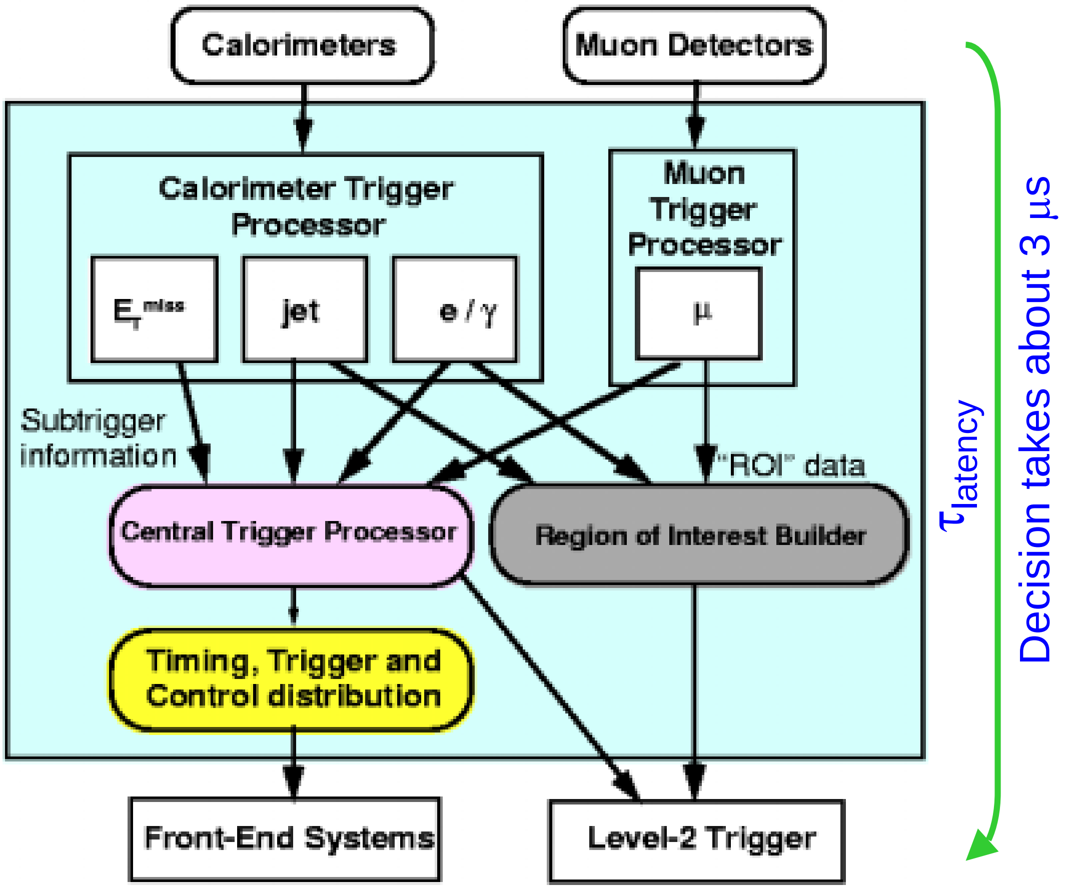


Level-1 trigger: coarse selection of interesting candidate events within a few μs. L1-rigger output rate $\approx$ 100 kHz
Implementation: specific hardware (ASICS, FPGA, DSP)

Level-2 trigger: refinement of selection criteria within $\approx$ 1 ms.
L2 output rate: $\approx$ 1 kHz
Implementation: fast processor farms.

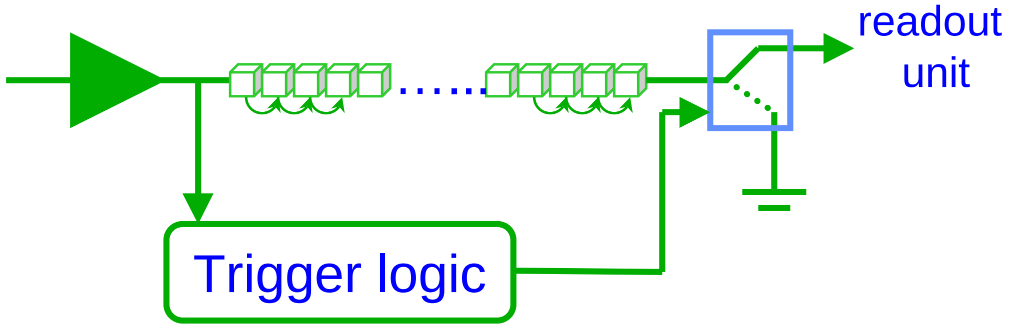
Level-3 trigger: identification of the physical process. Writing data to storage medium.
L3- output rate: 10 - 100 Hz
Event size: $\approx$ 1 Mbyte.
Implementation: fast processor farms.

Example: ATLAS level-1 trigger



The L1 trigger is deadtimeless. The trigger decision must be taken every 25 ns!

During the trigger latency time the data of each single detector channel must be stored in pipelines of 128 cells length.



Detector Systems

Remember: we want to have info on...

- number of particles
- event topology
- momentum / energy
- particle identity

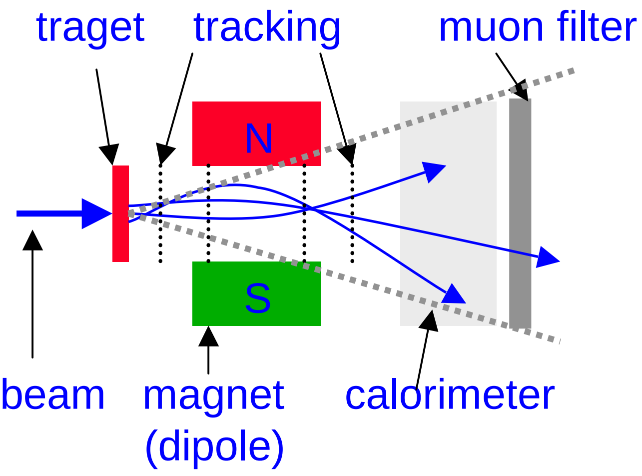
Can't be achieved with a single detector !

⇒ integrate detectors to detector systems

Geometrical concepts

Fix target geometry

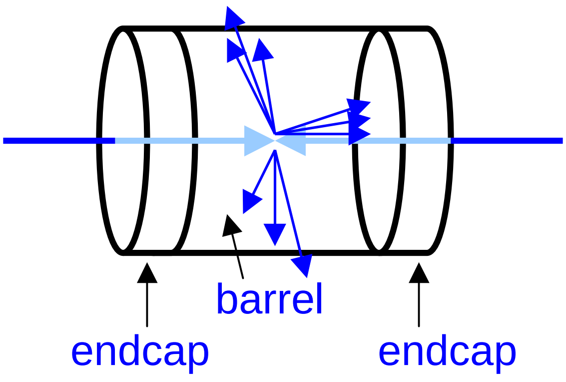
"Magnet spectrometer"



- Limited solid angle dΩ coverage
- rel. easy access (cables, maintenance)

Collider Geometry

"4π Multi purpose detector"

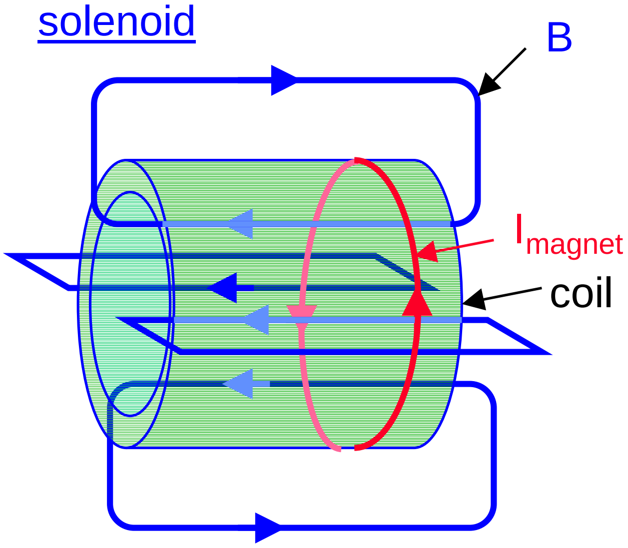


- "full" dΩ coverage
- very restricted access

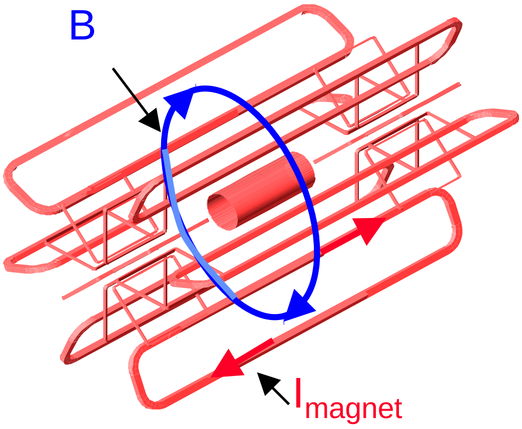
collider geometry cont.

Magnetic field configurations:

solenoid



toroid



- \+ Large homogenous field inside coil
- \- weak opposite field in return yoke
- \- Size limited (cost)
- \- rel. high material budget

Examples:

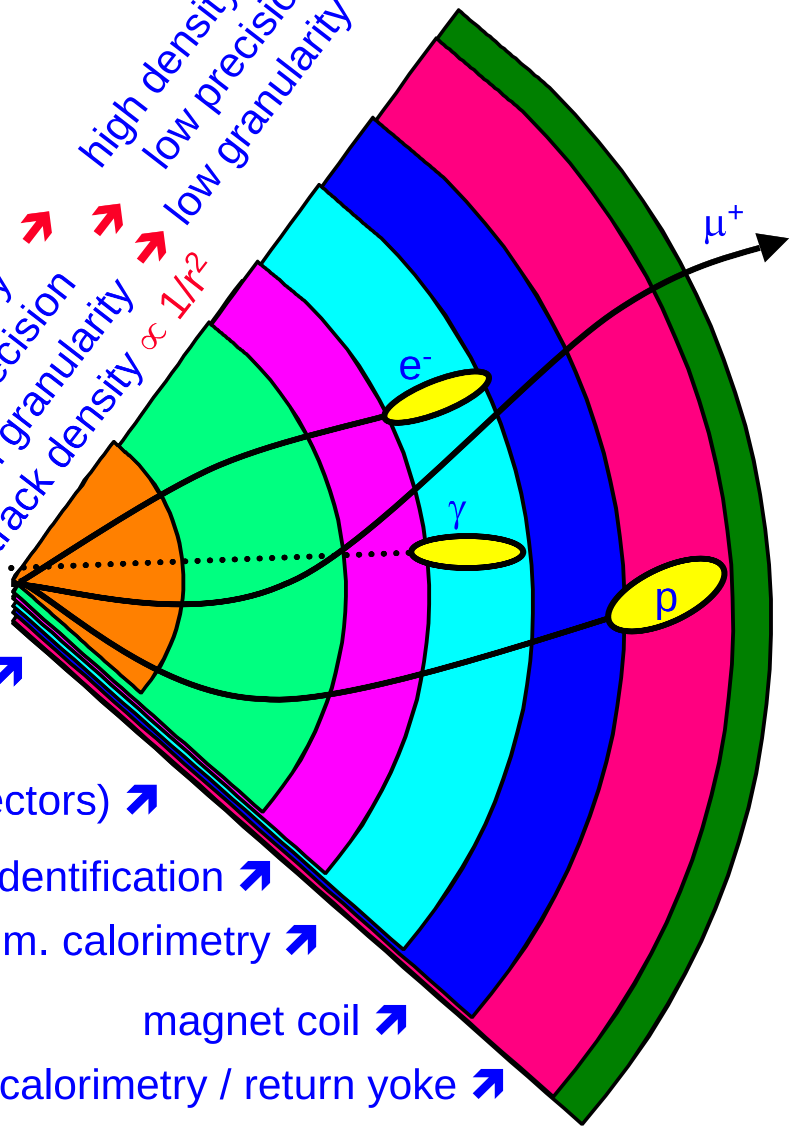
- DELPHI (SC, 1.2T)
- L3 (NC, 0.5T)
- CMS (SC, 4T)

- \+ Rel. large fields over large volume
- \+ Rel. low material budget
- \- non-uniform field
- \- complex structure

Example:

- ATLAS (Barrel air toroid, SC, 0.6T)

Typical arrangement of subdetectors



Low density
high precision
high granularity
track density $\propto 1/r^2$

↗ ↗ ↗

high density
low precision
low granularity

vertex location
(Si detectors) ↗

main tracking
(gas or Si detectors) ↗

particle identification ↗

e.m. calorimetry ↗

magnet coil ↗

hadron calorimetry / return yoke ↗

muon identification / tracking ↗

ATLAS and CMS require high precision tracking also for high energetic muons ➔ large muon systems with high spatial resolution behind calorimeters.

Some practical considerations before building a detector

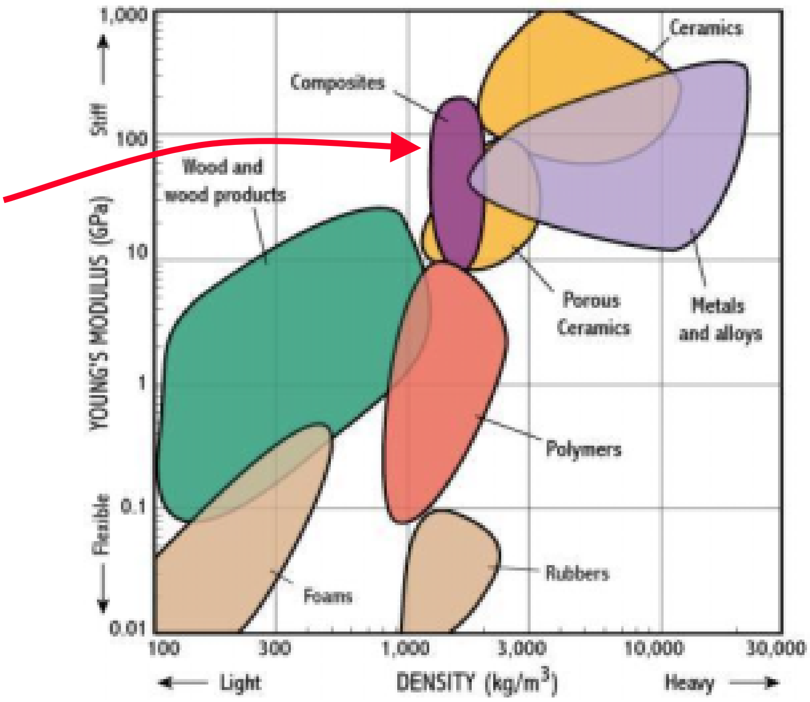
Find compromises and clever solutions …

- Mechanical stability, precision ⇔ distortion of resolution (due multiple scattering, conversion of gammas)
- Hermeticity ⇔ routing of cables and pipes
- Hermeticity ⇔ thermal stability
- Hermeticity ⇔ accessibility, maintainability
- Compatibility with radiation

… and always keep an eye on cost

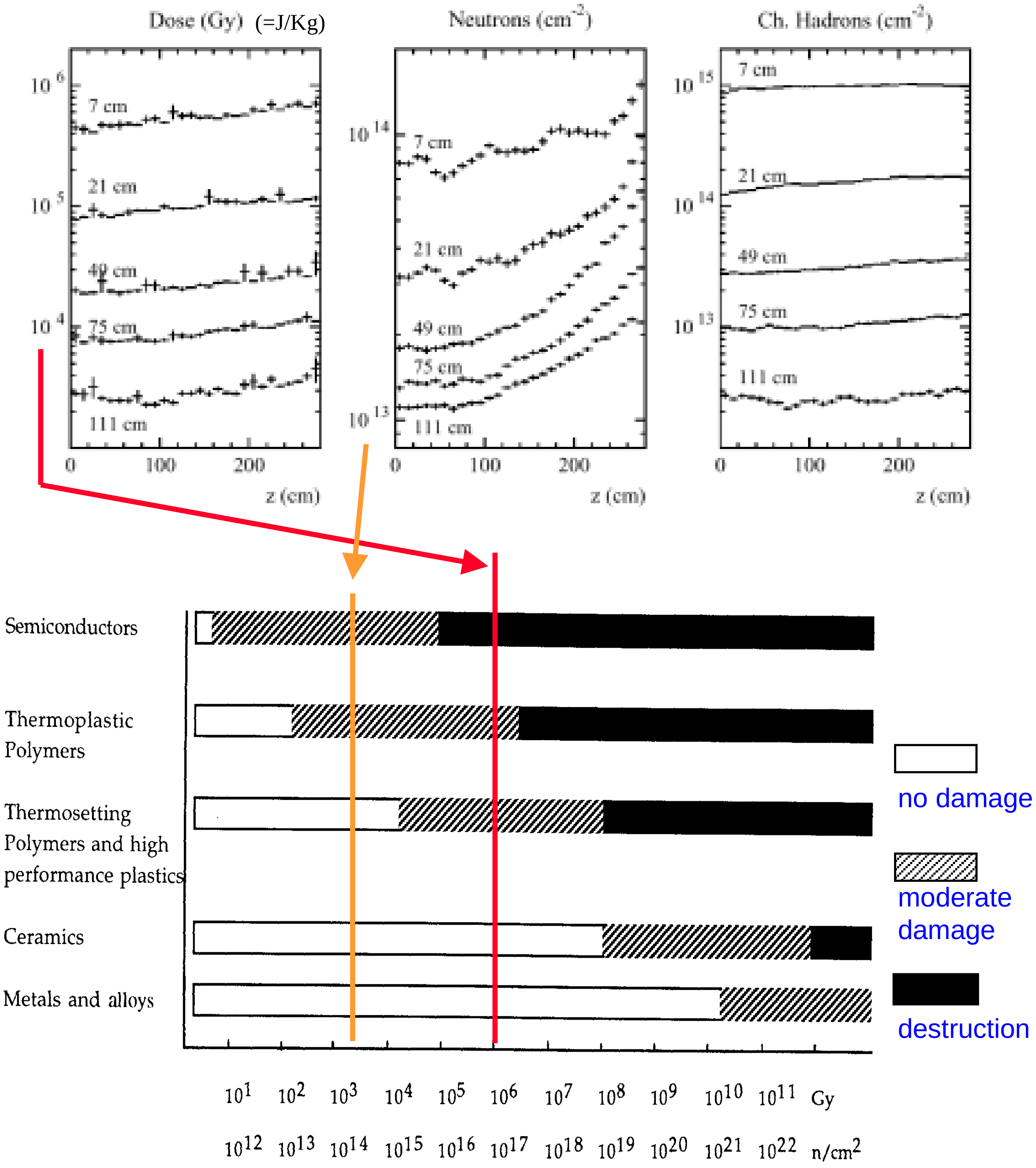
$$E[\mathrm{N/m^2}] = \frac{F/A}{\Delta L/L} \qquad \left(\text{Young's modulus} = \frac{\text{stress}}{\text{strain}}\right)$$

Composites are very interesting candidates, e.g. glass or carbon fiber reinforced epoxy materials.



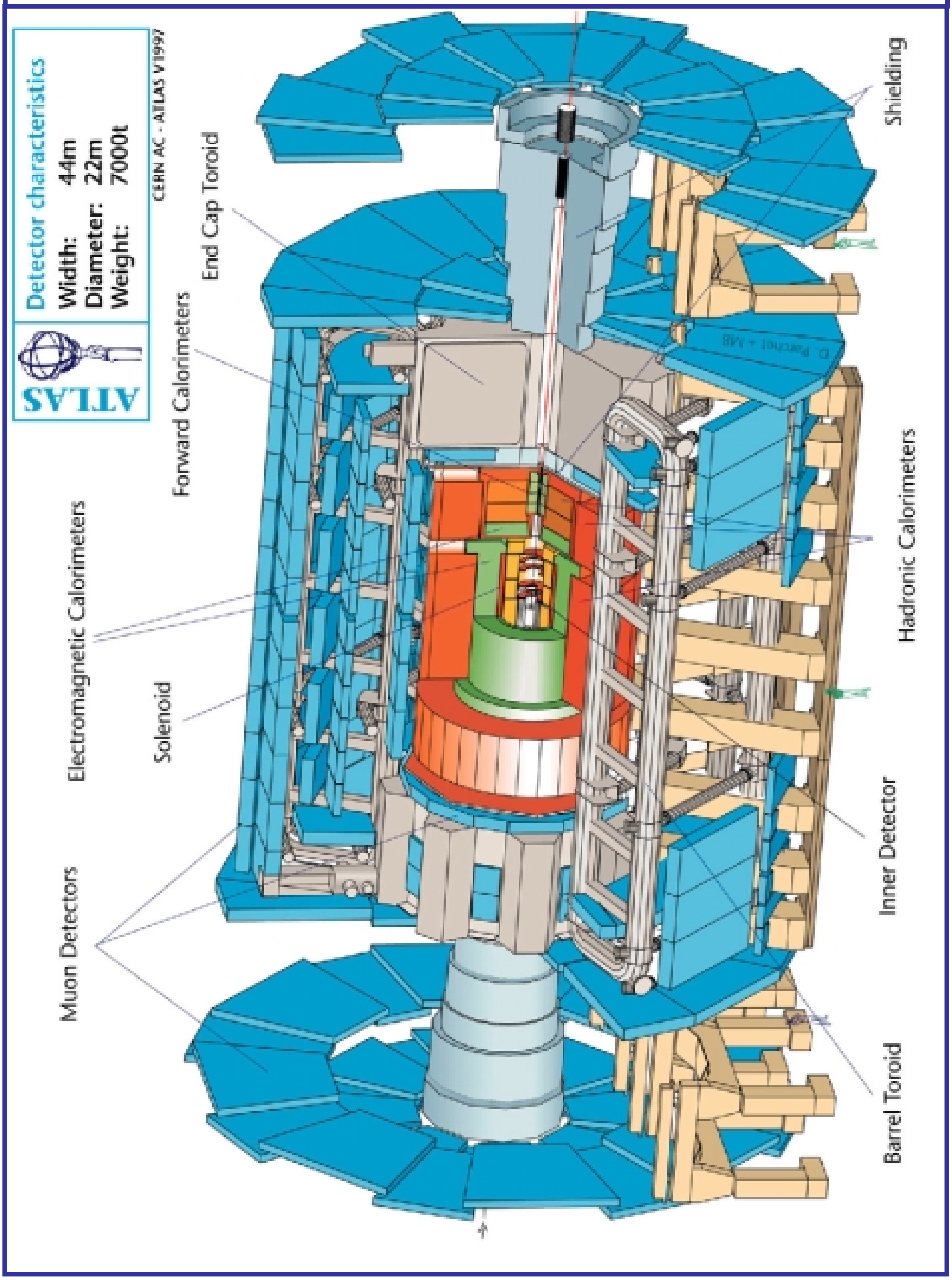
Radiation damage to materials

Radiation levels in CMS Inner Tracker (0 < z < 280 cm)

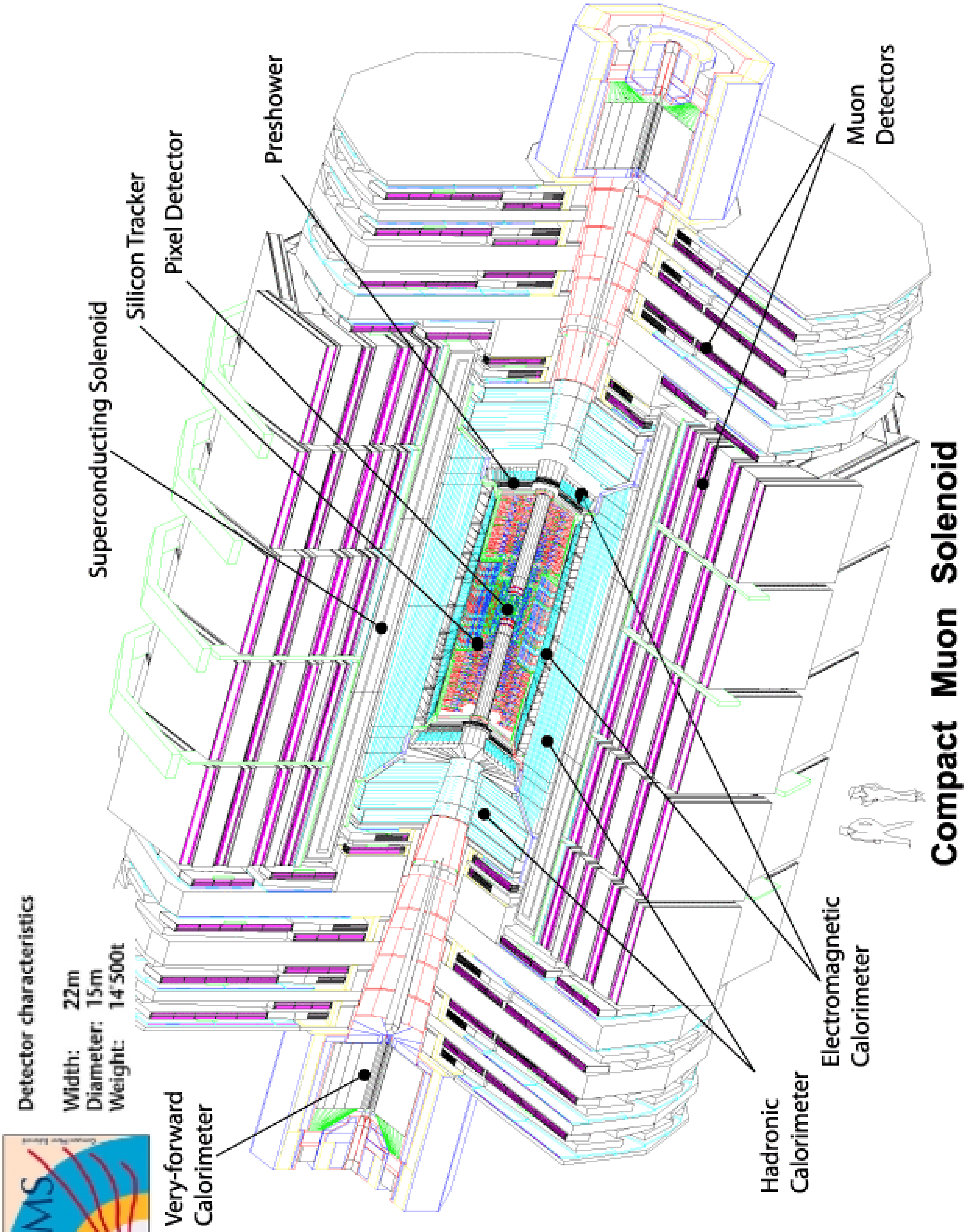


H. Schönbacher, M. Tavlet, CERN 94-07

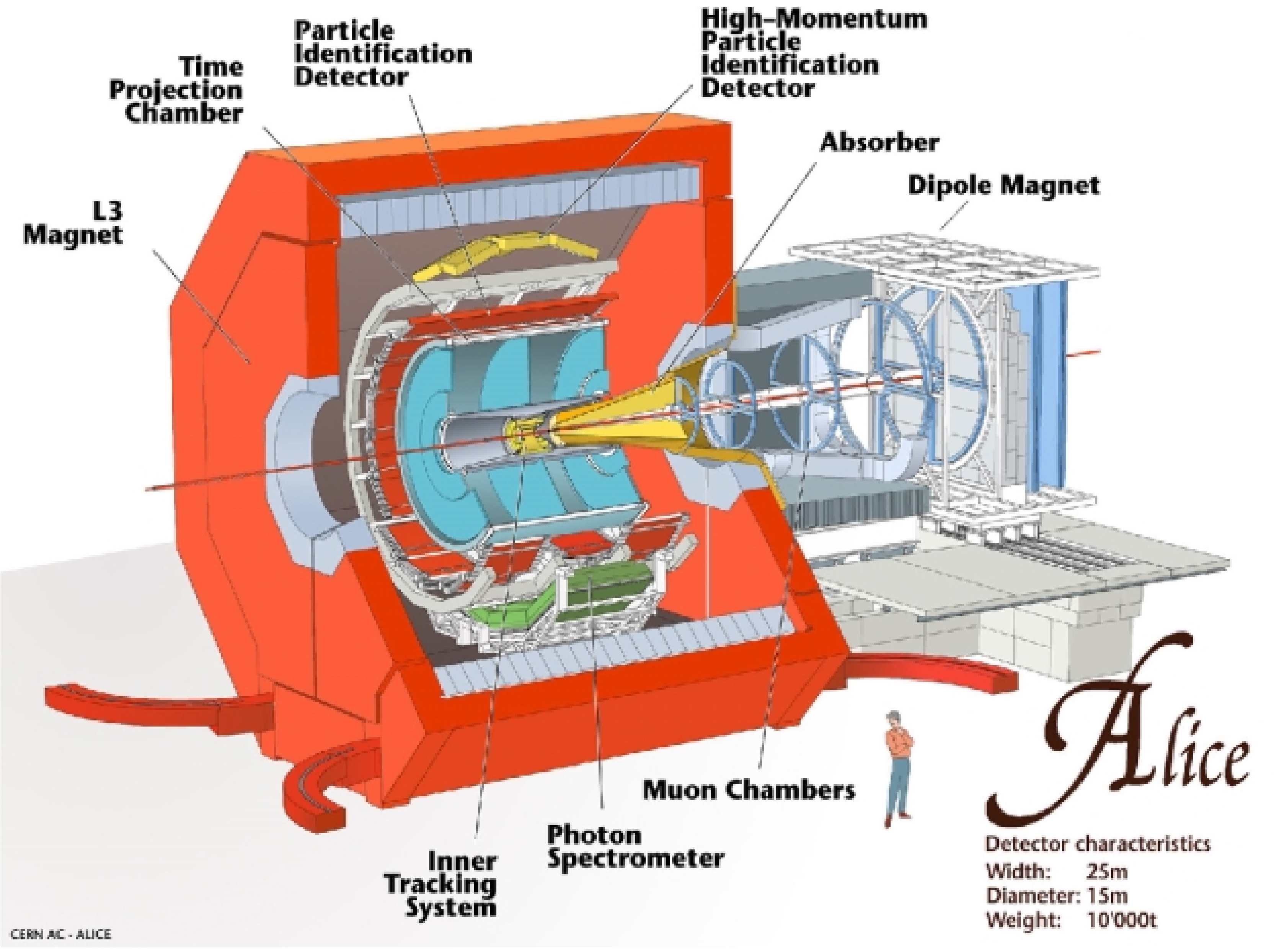
Detector Systems



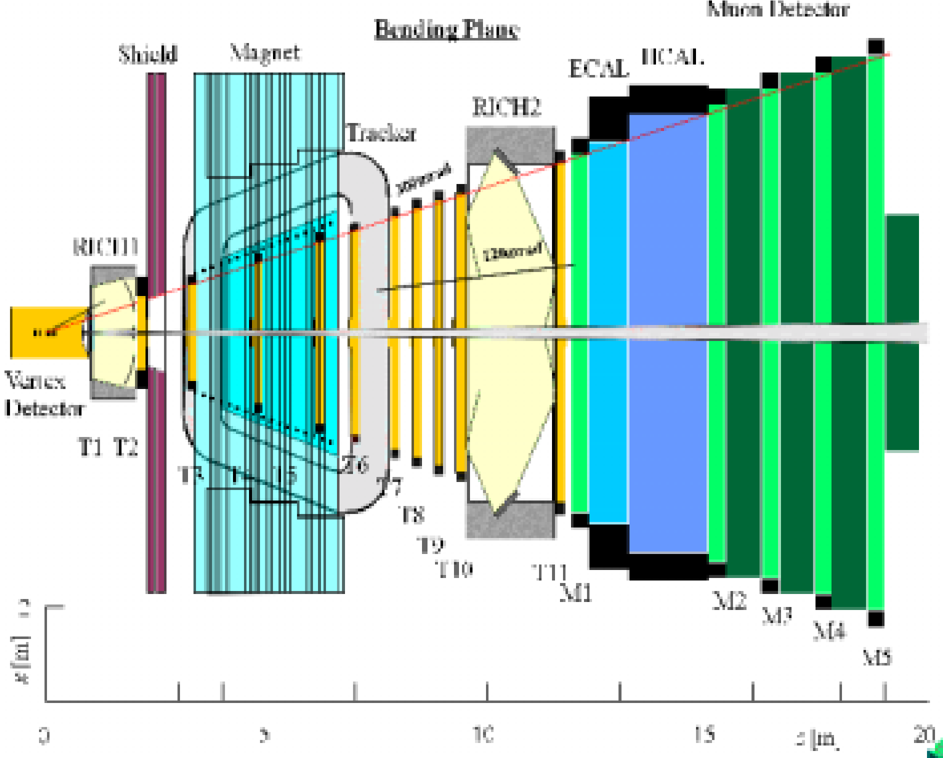
Detector Systems

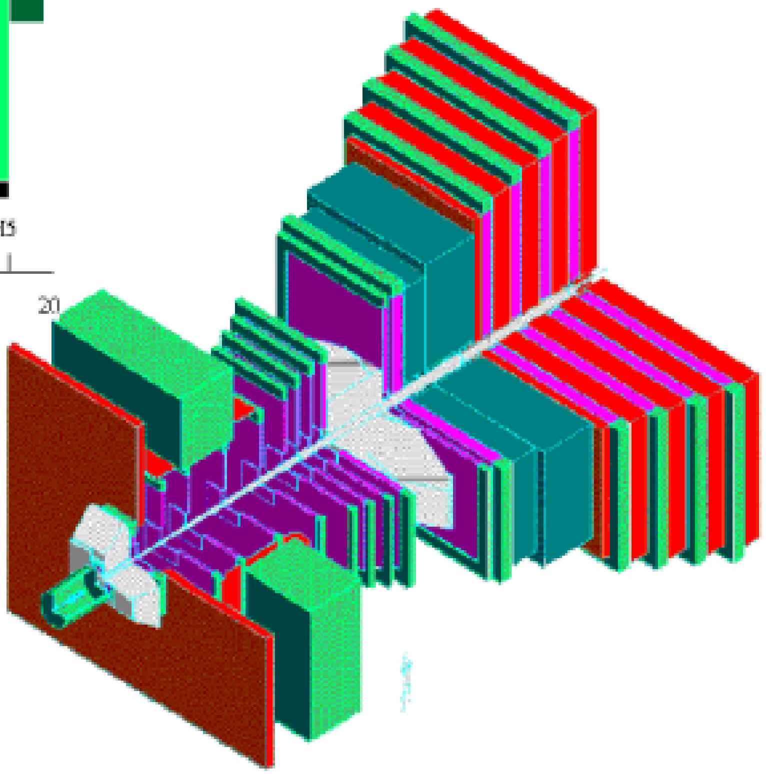


Detector Systems



Detector Systems





Detector Characteristics

Length:	20 m
Width:	12 m
Height:	12 m
Weight:	2'000 tons

Detector Exhibition

more or less confirmed…

- GEM, Compass geometry, Bernhard Ketzer
- NA49 (G. Fischer, absent until beginning of July)
- HARP TPC, Lucie Linssen
- ALICE RICH, Paolo Martinengo
- ALICE TPC, Tom Meyer
- LHCb Velo, Paula Collins
- HPD (Christian Hansen)
- RPC (C. Williams)
- LHCb RICH Aerogel (Marco Musy)
- ATLAS TRT (Hans Danielson)
- CMS inner tracker mechanics (Hans Danielson)
- MEDIPIX (Bettina Mikulec)
- Paul trap (Christian Regenfuss)

Wishlist

- ATLAS ECAL (P. Fassnacht)
- ATLAS muon, MDT (G. Mikenberg)
- CMS ECAL (PbWO4 -> Ph. Bloch, P. Lecoq.)
- CMS HCAL (scint. Tile -> D. Greem, A. Ferrando)