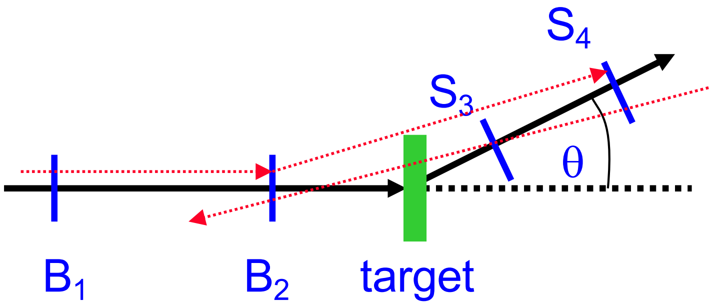
Trigger

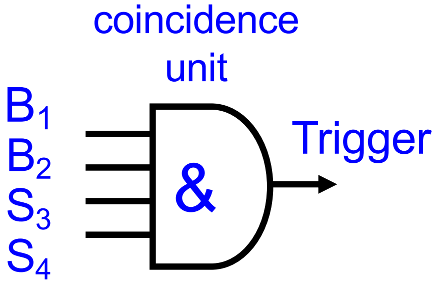
What is it ? A system defining conditions under which an event shall be recorded.

Why is it needed ?
- Selection of interesting events
- Suppression of “background” (= uninteresting events)
- Reduction of recorded data size

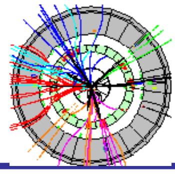
A very simple example of a trigger: A scattering experiment where only beam particles scattered from the target under the angle θ shall be recorded



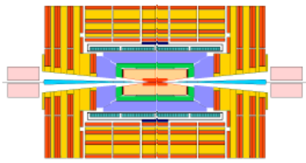
Condition for recording:
$T = B_1 \cap B_2 \cap S_3 \cap S_4$



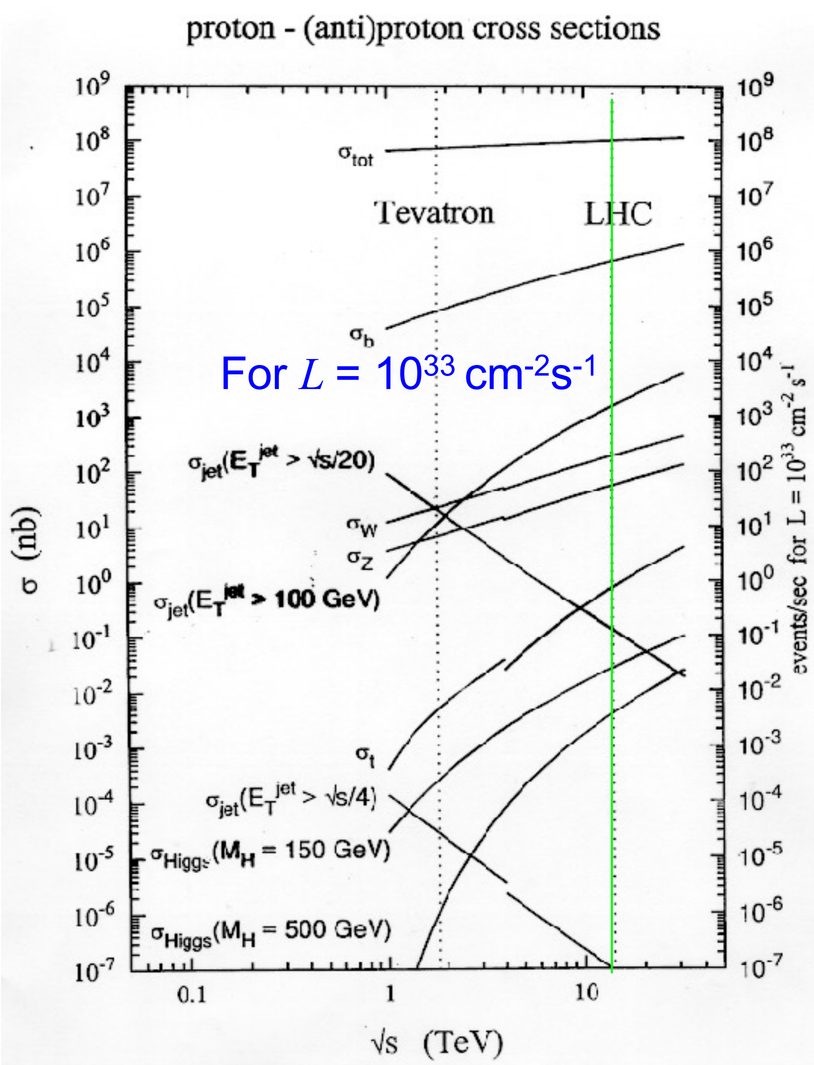
All other events $\dashrightarrow$ will be rejected.



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

Trigger = f ( **)**

event data · detector parameters · physics channels



LHC:

Interaction rate 2015-2018, 2022- ~ $4{\cdot}10^7$ bunch crossings (BX) / second

Experiments can only record ~ few kHz of BX (event size few MB)

$\Rightarrow$ necessary trigger rejection $\geq \sim 10^4$

“interesting” event rate (top, Higgs, susy): (very) rare (few Hz or even much less)

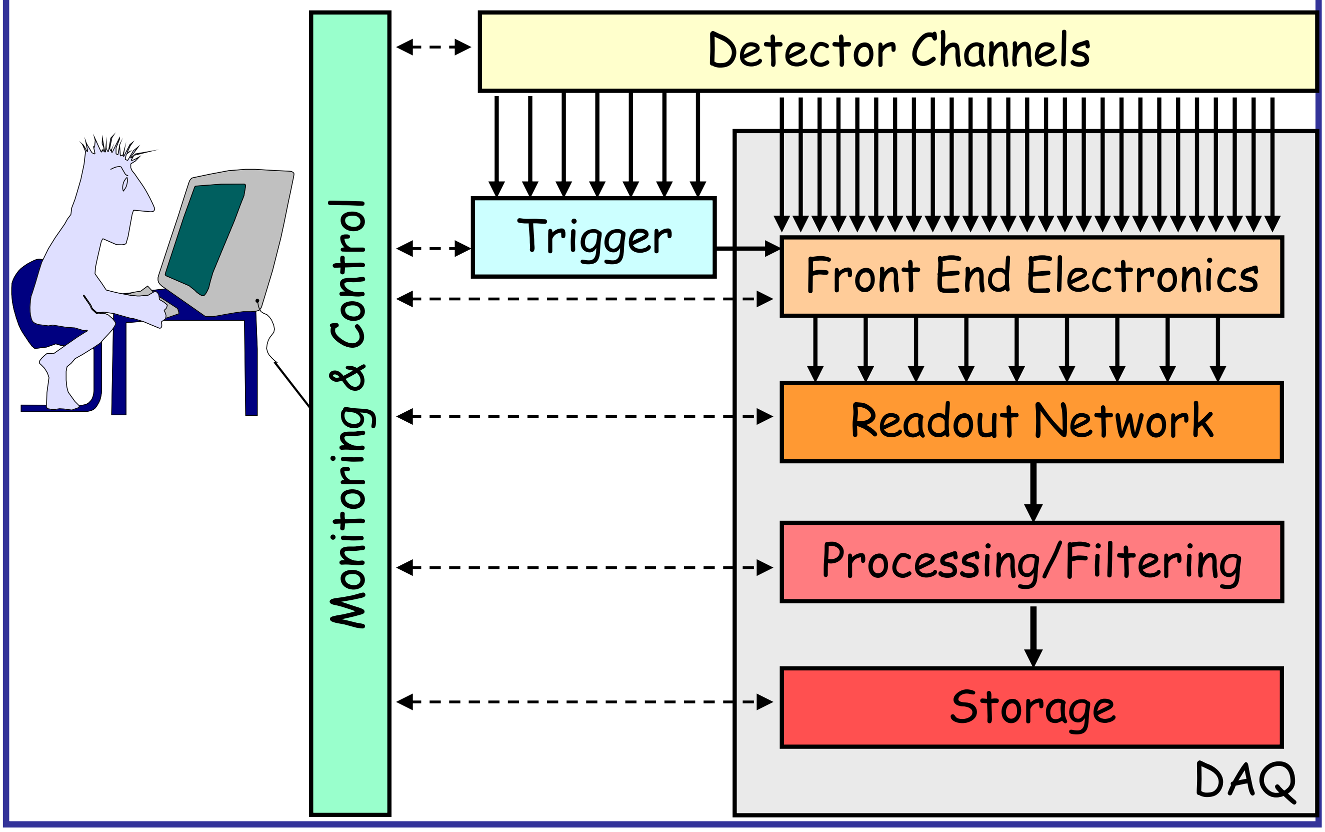
Event signitures mostly based on high p_T objects: → particles (e, γ, μ, jets) with large energies & large angles w.r.t. to beam direction.

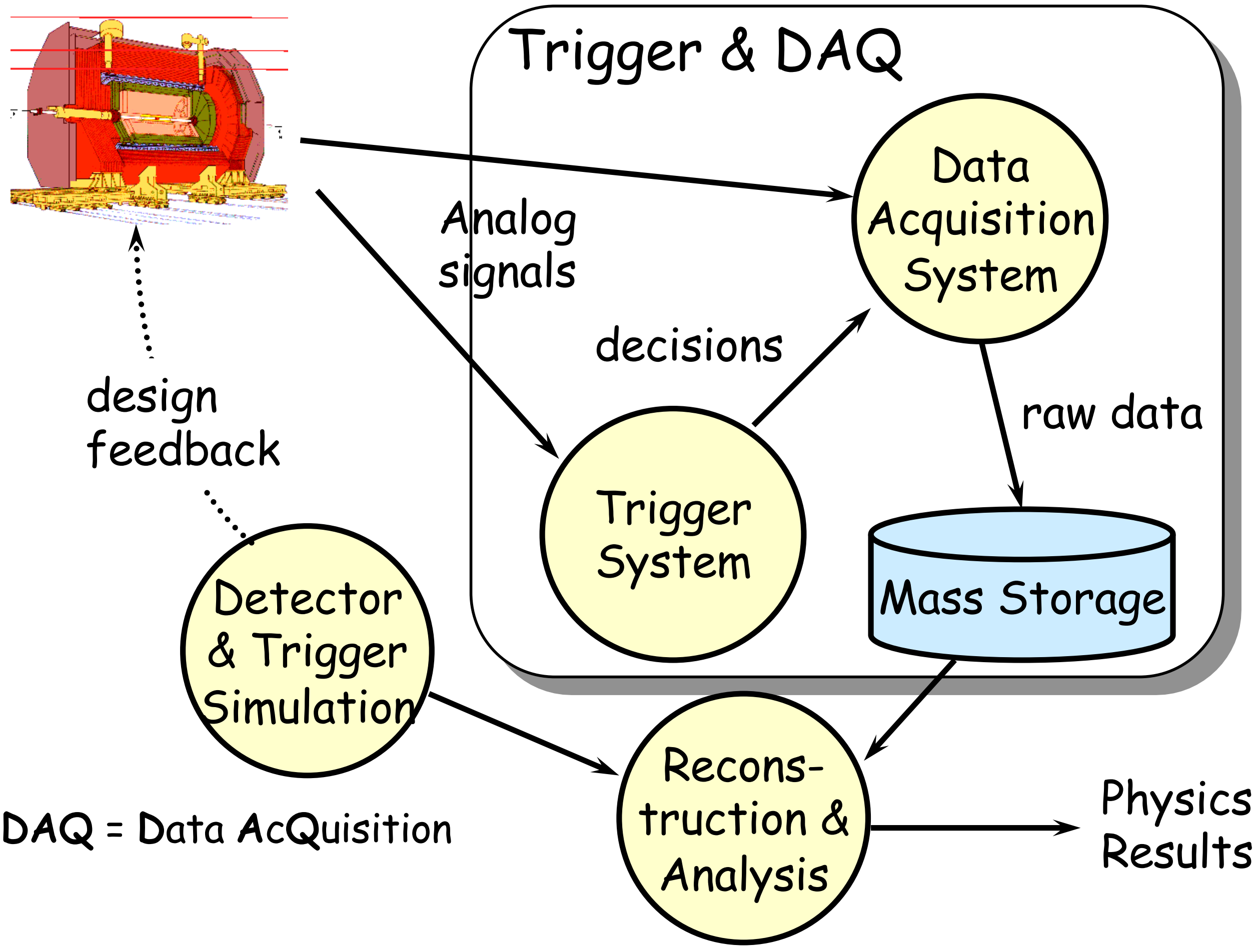
Trigger System:

- Selects in Real Time "interesting" events from the bulk of collisions. - Decides if YES or NO the event should be read out of the detector & stored

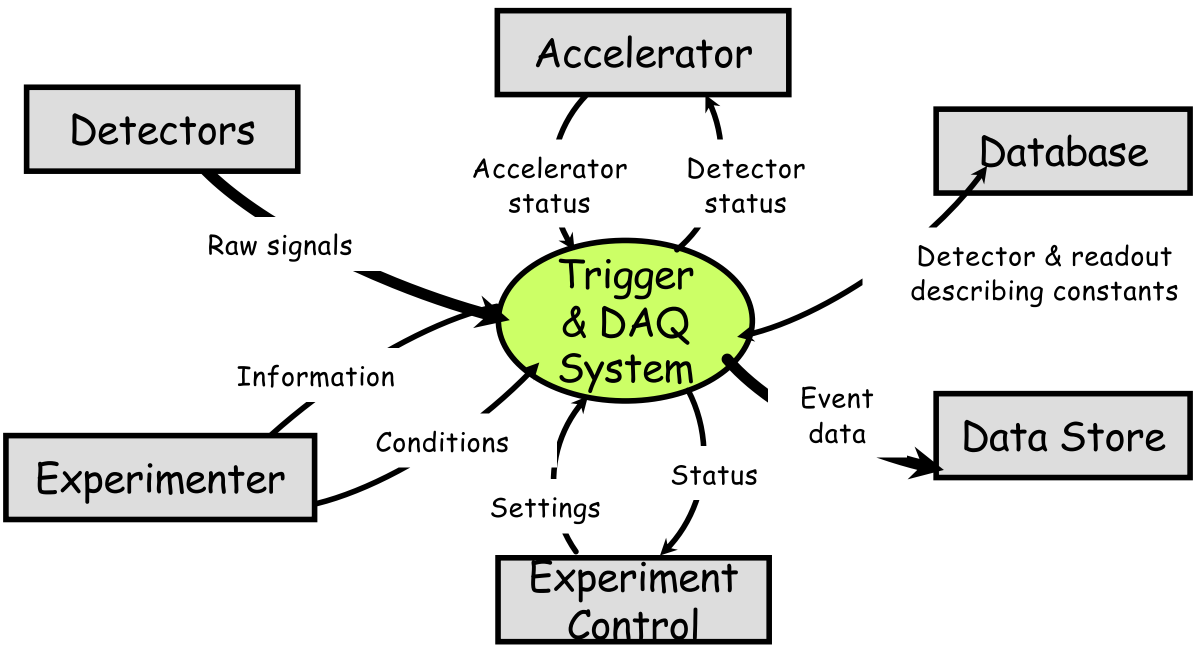
Data Acquisition System

- Gathers the data produced by the detector & stores it (for positive trigger decisions)
  - Front End Electronics:
    - Receive detector, trigger and timing signals & produce digitized information
  - Readout Network
    - Reads front end data & forms complete events (maybe in stages) - Event building
  - Central DAQ
    - Stores event data, can do data processing or filtering
    - Overall Configuration Control & Monitoring





Main role of Trigger & DAQ: select interesting events, process signals generated in experiment & write them onto storage but



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

Signal acquisition:
- signal amplitude, shape $\rightarrow$ energy deposit in detector
- signal time $\rightarrow$ time of particle passage

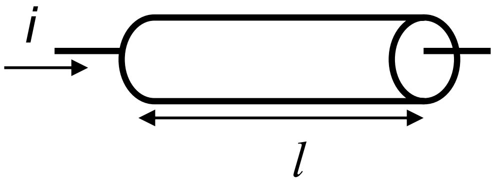
Signals usually
- small (order of pC $\approx 10^6$ e^-, PMT, wire chambers)
- very small (order of 1-10 fC $\approx 10^3$–10^4 e^-, silicon detectors)
- short (order of μs, thick detectors)
- very short (order of ns, thin detectors)

Signals need to be: amplified, shaped, discriminated, digitized, transferred

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

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

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

- $dv \rightarrow$ thermal noise (~ current noise)
- $dn \rightarrow$ shot noise (~ voltage noise), $1/f$ noise

Noise analysis in detectors

based on H.Spielers: ”Low-noise electronics” in PDG:s particle detector review

Equivalent noise charge (ENC)

$$\text{ENC} = F_i\, i_n\sqrt{\tau} \;\oplus\; F_v e_n C_i \frac{1}{\sqrt{\tau}} \;\oplus\; F_{vf} a_n C_i$$

$\boldsymbol{F_i}, \boldsymbol{F_v}$ and $\boldsymbol{F_{vf}}$ numerical factors (often O(1)) that depend on the circuit layout and its noise filtering capability.

$\tau\ [ns]$ peaking time of shaper or sampling time

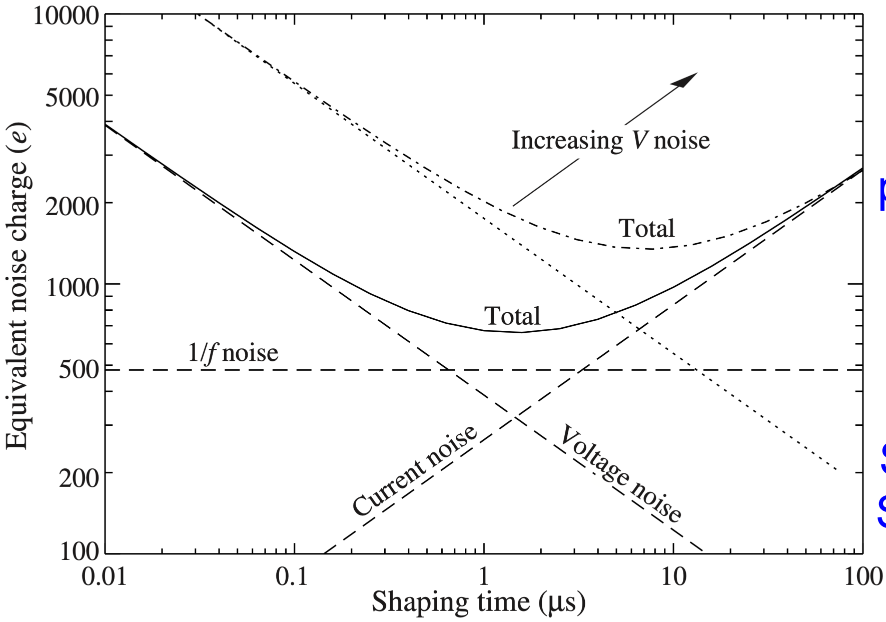
$\boldsymbol{C_i[pF]}$ total input capacitance (detector & amplifier)

$\boldsymbol{i_n\ [pF/\sqrt{Hz}]}$ current noise (incl. leakage current + bias & amplifier/shaper circuit currents) – “parallel” noise

$\boldsymbol{e_n\ [nV/\sqrt{Hz}]}$ voltage noise (incl. amplifier/shaper & electrode resistance + any input protection) – “series” noise

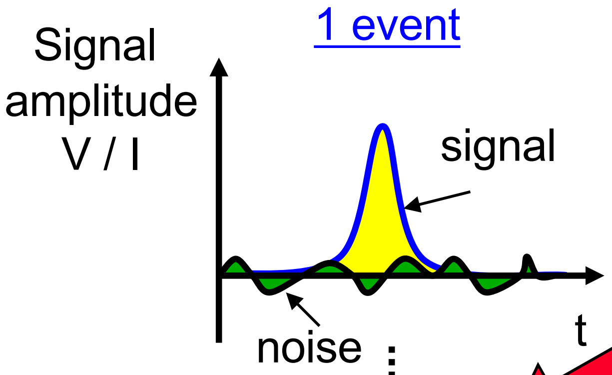
$\boldsymbol{a_n\ [pV/\sqrt{Hz}]}$ ***1/f*** noise due to (de)trapping in el. circuits

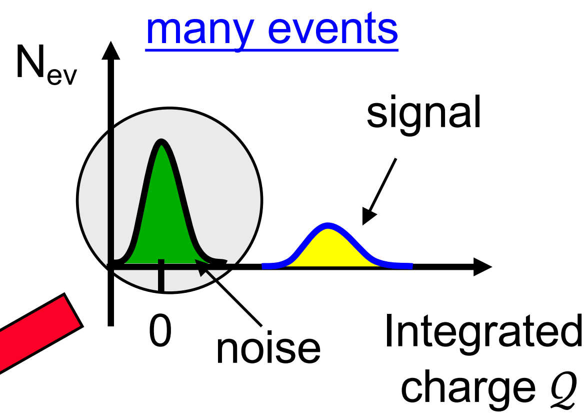
Example of ENC vs shaping time:



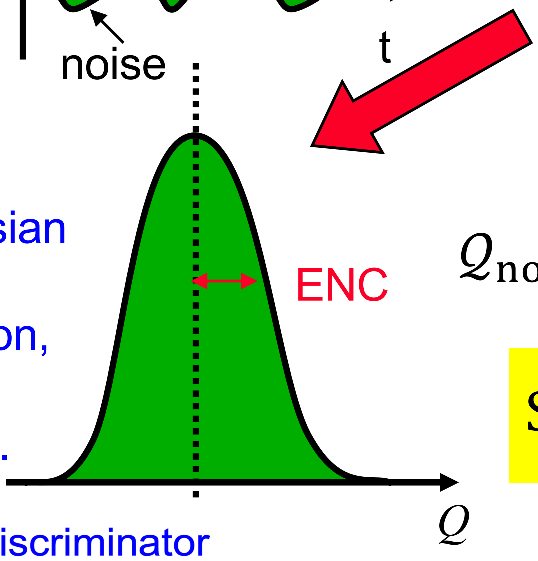
NB! very device & amplifier circuit dependent. In practice noise levels range from a few ENC (for CCDs) to 10^4 ENC (in high-C_i LAr calorimeters).
Si strip sensor ~ 10^3
Si pixel sensor ~ 10^2

How things should look like for single and multiple events:





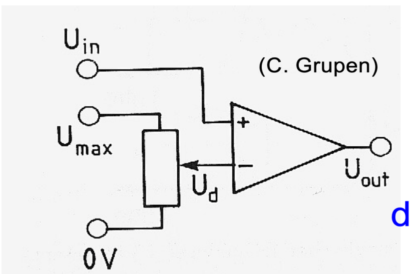
Noise is random → Gaussian charge distribution, centred around 0.



$$Q_{\text{noise}} \propto e^{-Q^2/\text{ENC}^2}$$

$$\boxed{S/N = Q_{\text{signal}}/\text{ENC}}$$

- Discriminator



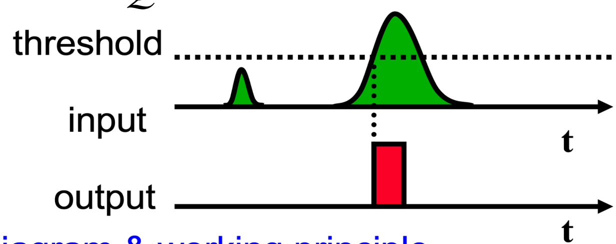
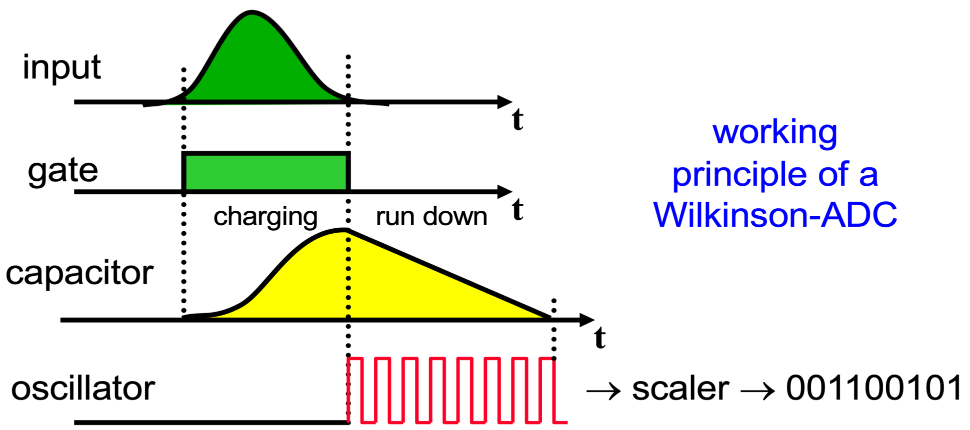


diagram & working principle of a discriminator

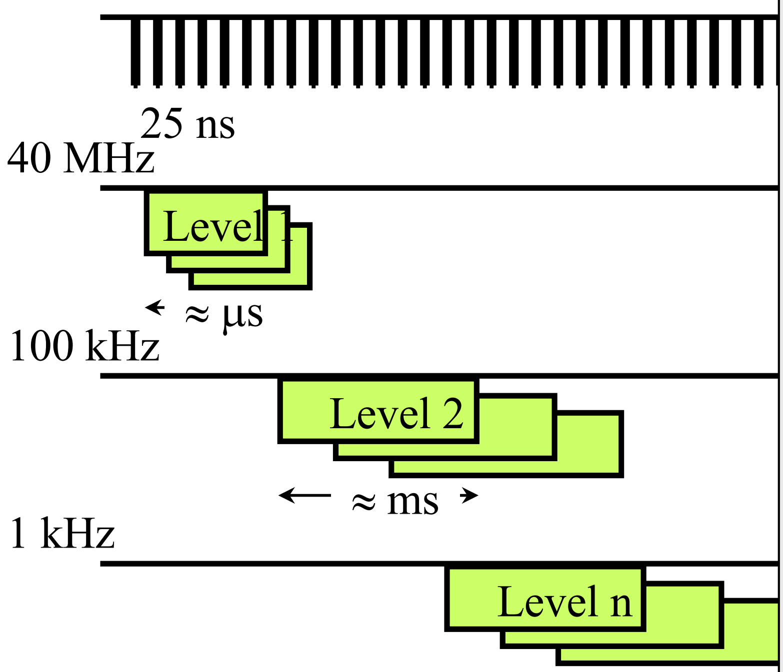
- Analog-to-Digital Converter (ADC)



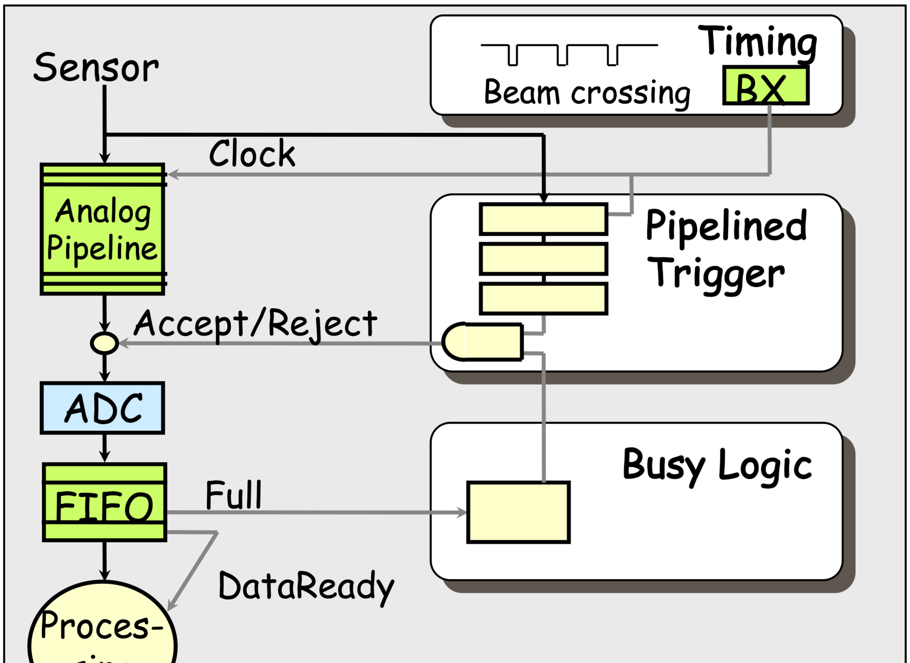
working principle of a Wilkinson-ADC

for example LHC timing

p p crossing rate 40 MHz



- Level 1 trigger time exceeds bunch interval
- Event overlap & signal pileup (signal from several bunch crossing in data since shaping/ charge collection time > 25 ns)
- Very high number of channels



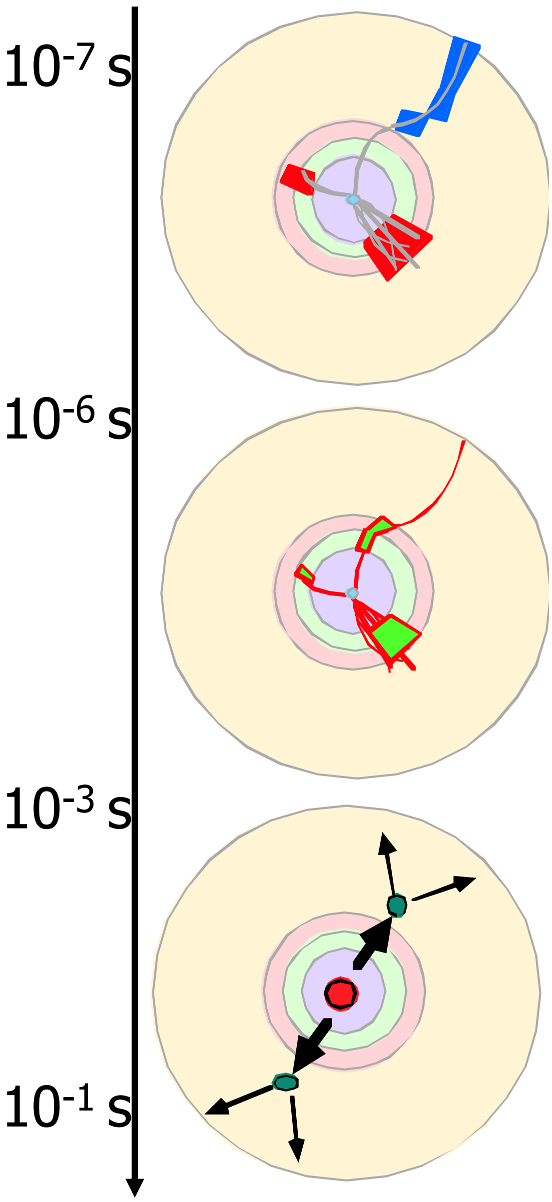
- **Front-end Pipelines:** Storage of detector data while waiting for trigger decision since decision time > time btwn bunch crossings

Trigger and DAQ

Trigger decision taken on several levels with increasing complexity & selectivity ('divide et impera'). Start with coarse information & refine as you go along. Employ parallelism as much as possible in search of relevant info.

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

Level "0": Event rate: $4 \cdot 10^7$ Hz. Detector channels: 10^7 - 10^8 DAQ running constantly at 40 MHz. Data flow ≈ 10^{14} B/s

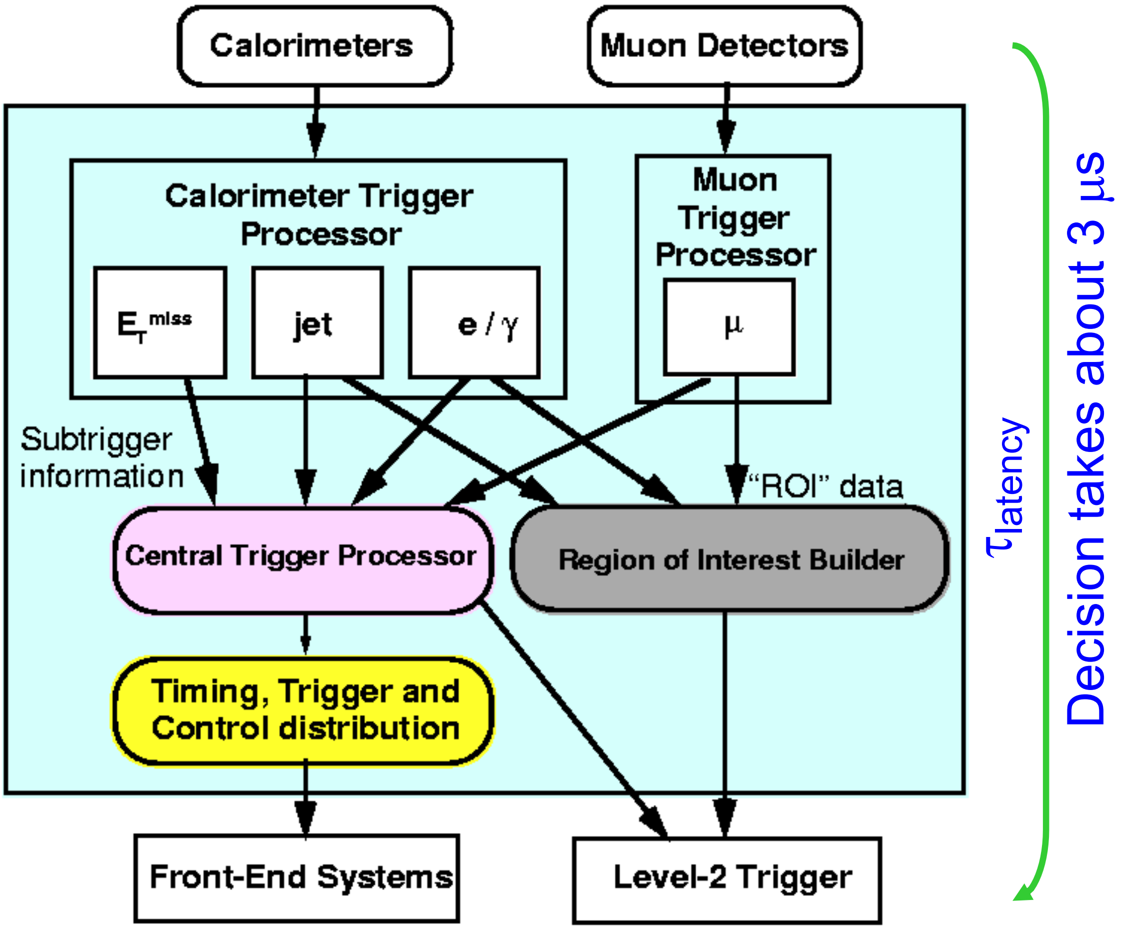


Level-1 trigger: coarse selection of interesting candidate events within a few μs. L1-trigger output rate ≈ 100 kHz. Implementation: specific hardware (ASICS, FPGA, DSP)

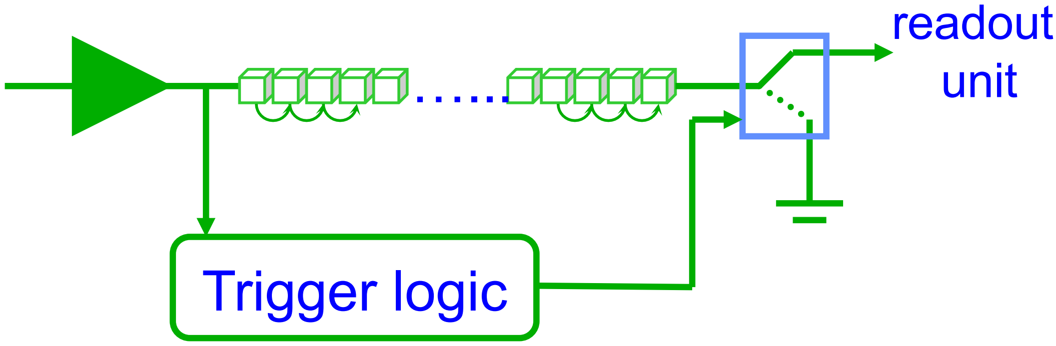
Level-2 or High Level Trigger (HLT): partial identification of physics process. Writing data to storage medium. Output rate: a few kHz. Total event size: few MB. Implementation: fast processor farms.

New paradigm: Triggerless readout implemented by LHCb. Possible due to zero suppression on detectors & comparatively small total event size (~100 kB).

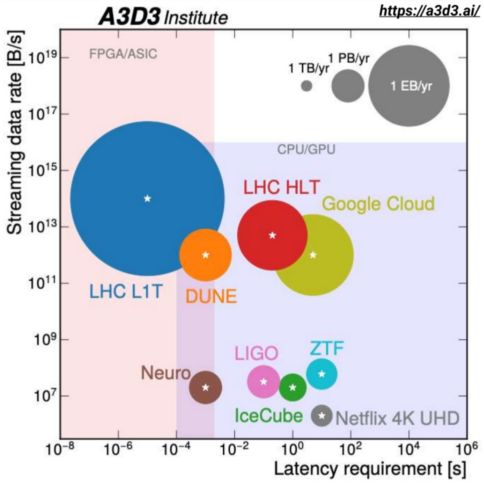
Example: ATLAS level-1 trigger



The L1 trigger 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.

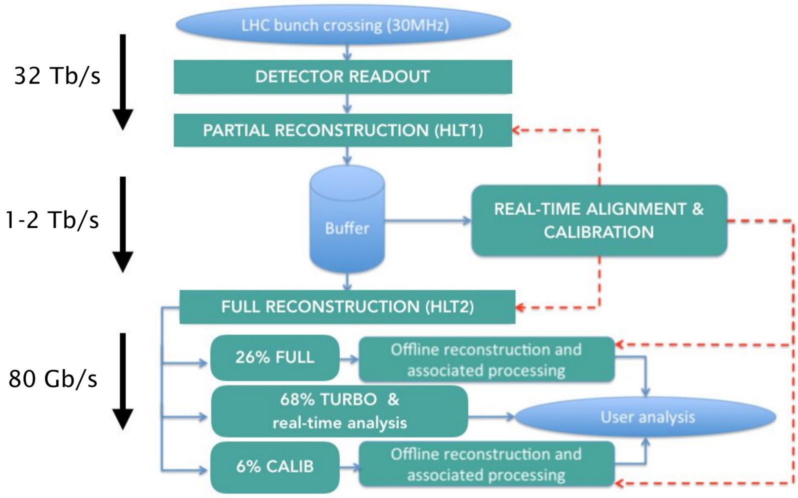


- Limiting factor is bandwidth = maximimal output data rate.
- Employ machine learning techniques to make trigger selection more "efficient"

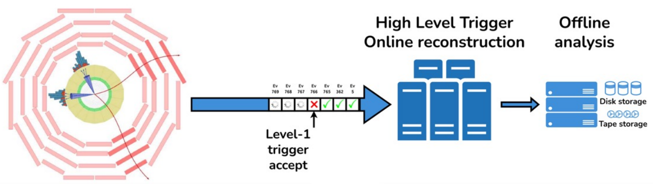


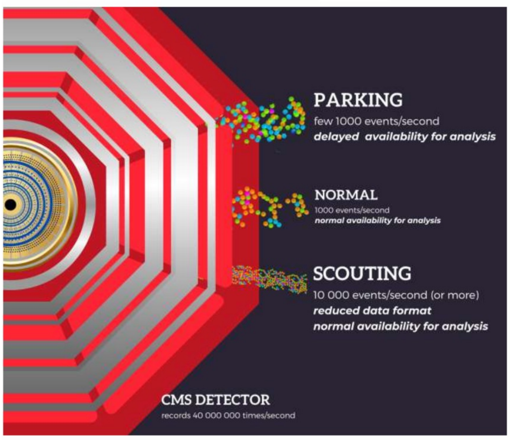
LHCb triggerless readout

- Two stages of software filtering:
  1) "HLT1" on GPGPUs
  2) "HLT2" on CPUs
- Large storage buffer to decouple the two
- Calibration and alignment are performed "semi-live", while the data are buffered

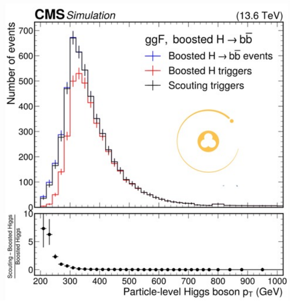


CMS HLT data streams





- In the second step, CMS software trigger, **High Level Trigger** (HLT), reconstructs the events selected by L1T
  - Capacity increased by 20% in 2024
  - GPU-accelerated reconstruction in O(100 ms) per event
  - Increasingly ML-based object identification
- **Record-high rates of events stored in 2024:**



- **~2 kHz** for prompt reconstruction (twice the design value)
- **~5 kHz** for opportunistic reconstruction ("**parking**")
- **~27 kHz** for **HLT Scouting** i.e. analysis with HLT-reconstructed events and objects

Detector Systems

Remember: we want to have info on...

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

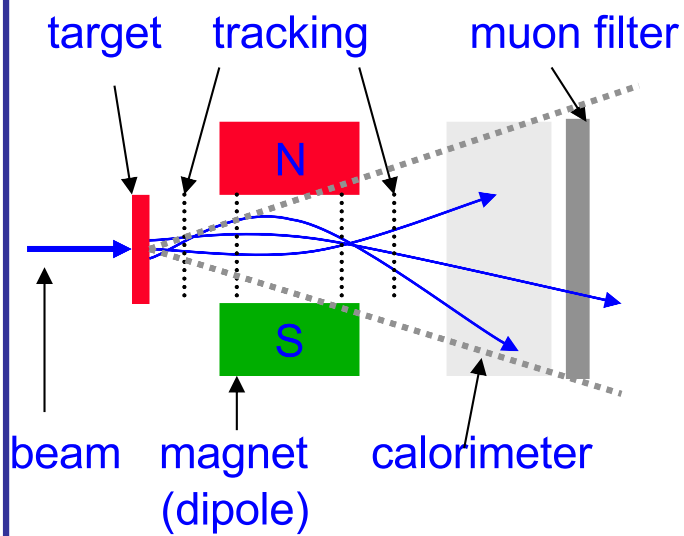
Can't be achieved with a single detector !

$\Rightarrow$ integrate detectors to detector systems

Geometrical concepts

Fix target geometry

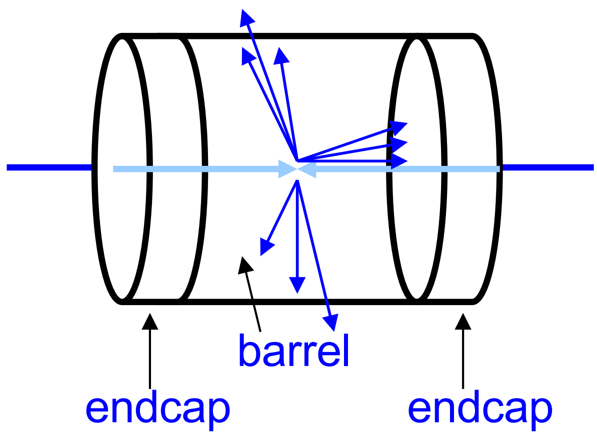
"Magnet spectrometer"



- limited solid angle dΩ coverage
- relatively easy access (cables, maintenance)

Collider Geometry

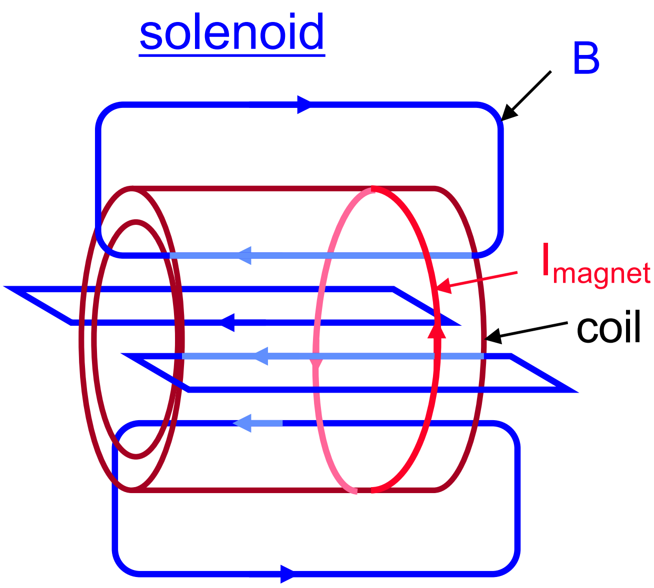
"4π Multi purpose detector"

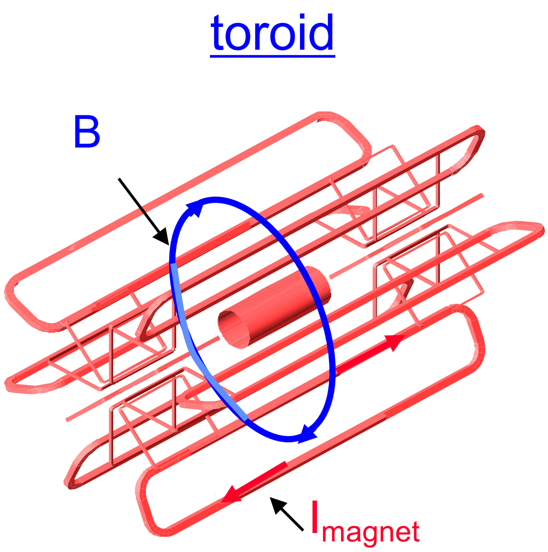


- "full" dΩ coverage
- very restricted access

Collider geometry continued

Magnetic field configurations:





solenoid

+ large homogenous field inside coil
- weak opposite field in return yoke
- size limited (due to cost)
- relatively high material budget (outside solenoid)

Examples:

- CMS (superconducting solenoid, 3.8 T)

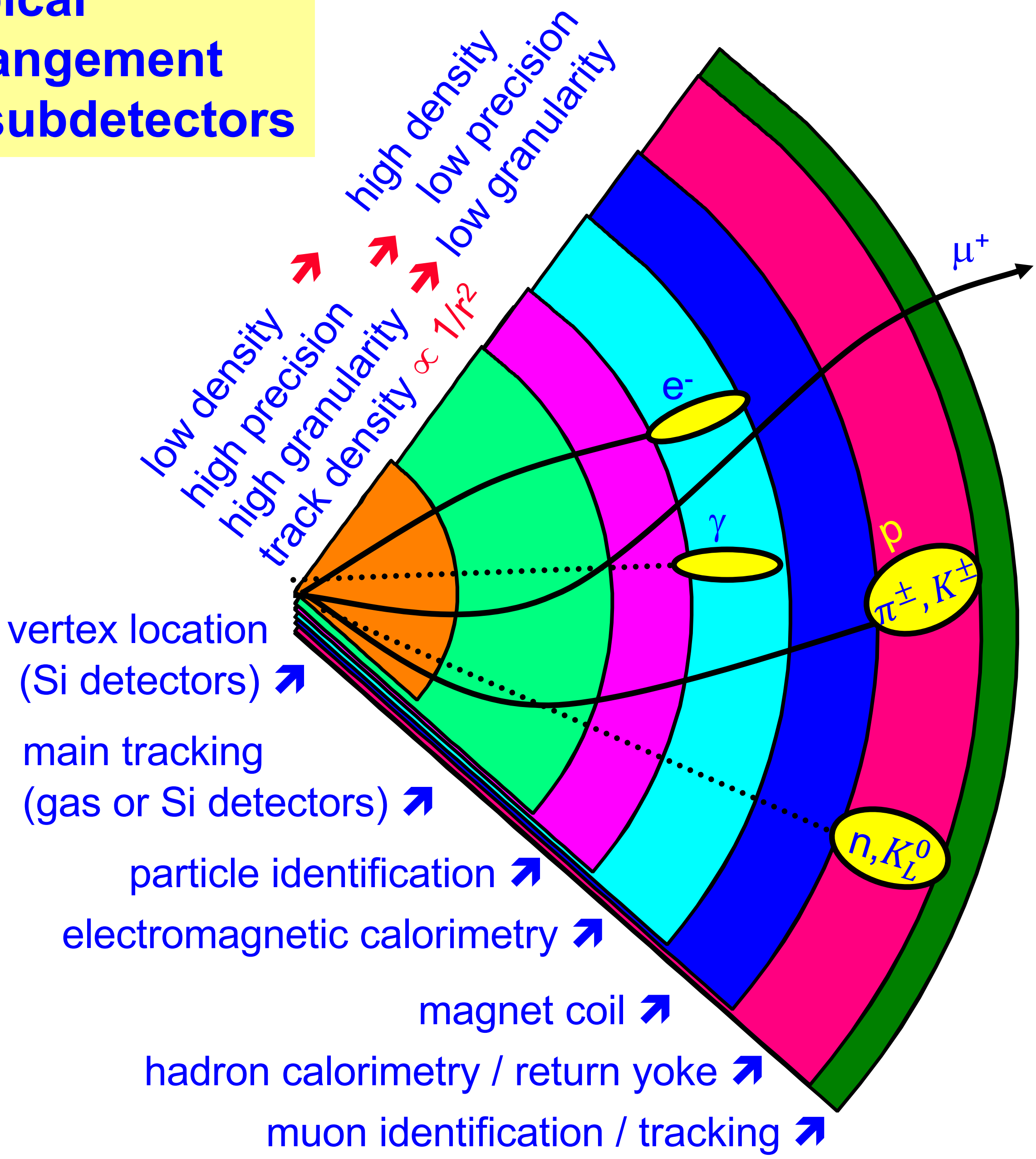
toroid

+ relatively large fields over large volume
+ relatively low material budget
- non-uniform field
- complex structure

Example:

- ATLAS (barrel air toroid, superconducting, 0.7 T)

Typical arrangement of subdetectors



General purpose experiments at hadron colliders require high precision tracking also for high energetic muons ➔ large muon systems with high spatial resolution placed behind the calorimeters and magnetic coil.

Some practical considerations before building a detector

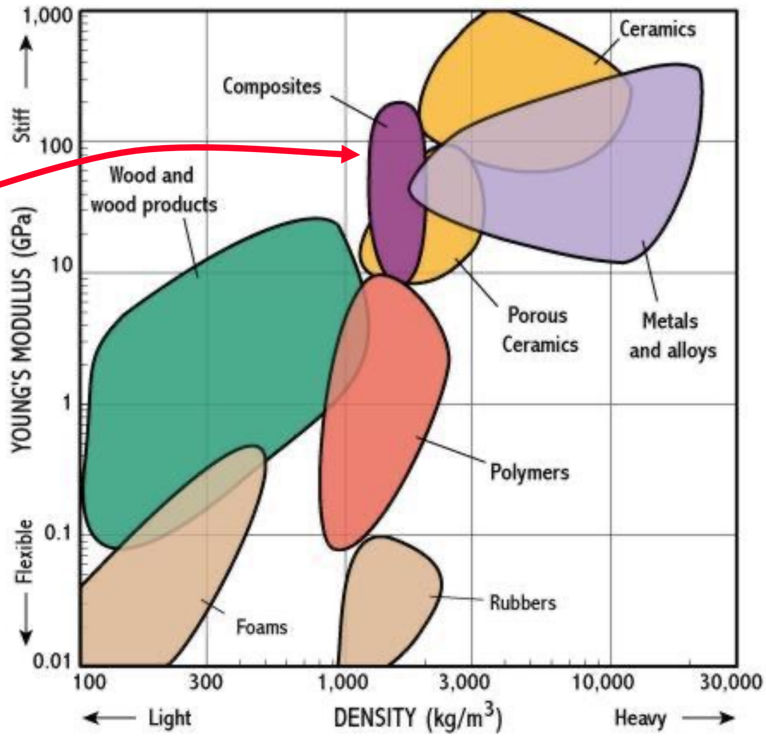
Find compromises & clever solutions …

- Mechanical stability, precision ⇔ distortion of resolution (due multiple scattering), electron radiation, photon conversion
- Hermeticity ⇔ routing of signal cables and gas 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, e.g. glass or carbon fiber reinforced epoxy materials, are interesting alternatives to use for the support structures due to their low density (resulting in less multiple scattering) & good stability.



Constraints on trackers

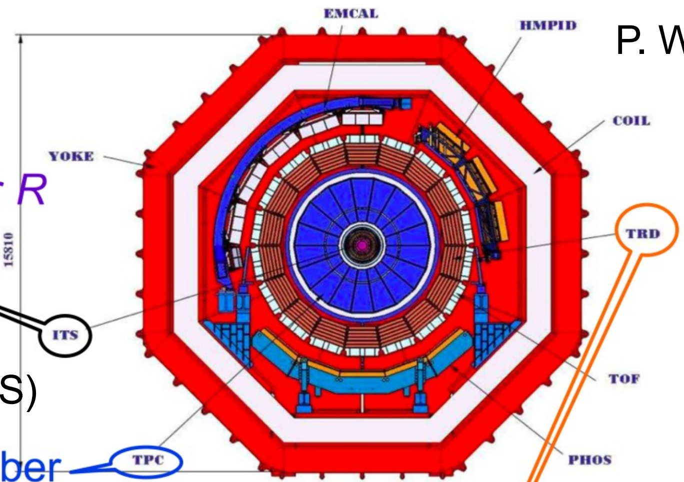
P. Wells

- High occupancy, high radiation dose and high data rate
  - At full design luminosity,> 50 interactions per pp bunch crossing
    → 1000 charged particles in tracker, every 25ns.
  - Even higher multiplicity in central (head-on) Pb-Pb collisions (ALICE speciality) with >10000 charged particles in trackers
  - Design for 10^{15} neq (neutron equivalent) for innermost layers (10 year lifetime)
- Minimise material for most precise measurements & to minimise interactions before the calorimeter
  - Increasing sensor granularity to reduce occupancy
    → increase number of electronics channels and heat load
    → more material
- Technology choice
  - Silicon detectors, usually pixels for vertexing, and strips for tracking
    → good spatial resolution, high granularity, fast signal response, & thin detector gives a large signal.
  - Usually complemented by gas detectors further away from vertex

Overall design choices

P. Wells

- ATLAS and CMS General Purpose Detectors (GPDs)
  - Central tracker covers $|\eta|<2.5$.
    Polar angle expressed as pseudorapidity: $\eta = -\ln \tan(\theta/2)$
- ALICE – optimised for heavy ions, high occupancy
  - Tracker restricted to $|\eta|<0.9$, plus forward muons
- All three are symmetric about the interaction point
  - Solenoid magnet providing uniform magnetic field parallel to the beam direction
- LHCb – beauty-hadron production in forward direction
  - Despite the different geometry, design is driven by the same principles to give optimal performance
  - Tracker is not in a magnetic field. Tracks are measured before and after a dipole magnet

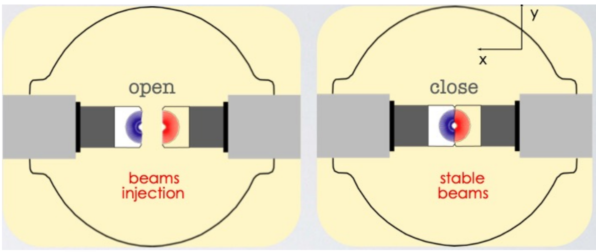


P. Wells

ALICE

- Lower B (0.5 T), larger R
- Upgraded ITS
  - 7 layers of Monolithic Active Pixel Sensors (MAPS)
- Time Projection Chamber
  - Large volume gas detector with central electrode
  - GEM chambers with anode pad readout in end plates
  - Very good two-track resolution
  - Very low material in active region
- Transition Radiation Detector
  - Electron ID, and improves momentum resolution
  - Outer radius 3.7m

VELO: closes around beam



P. Wells

LHCb tracking

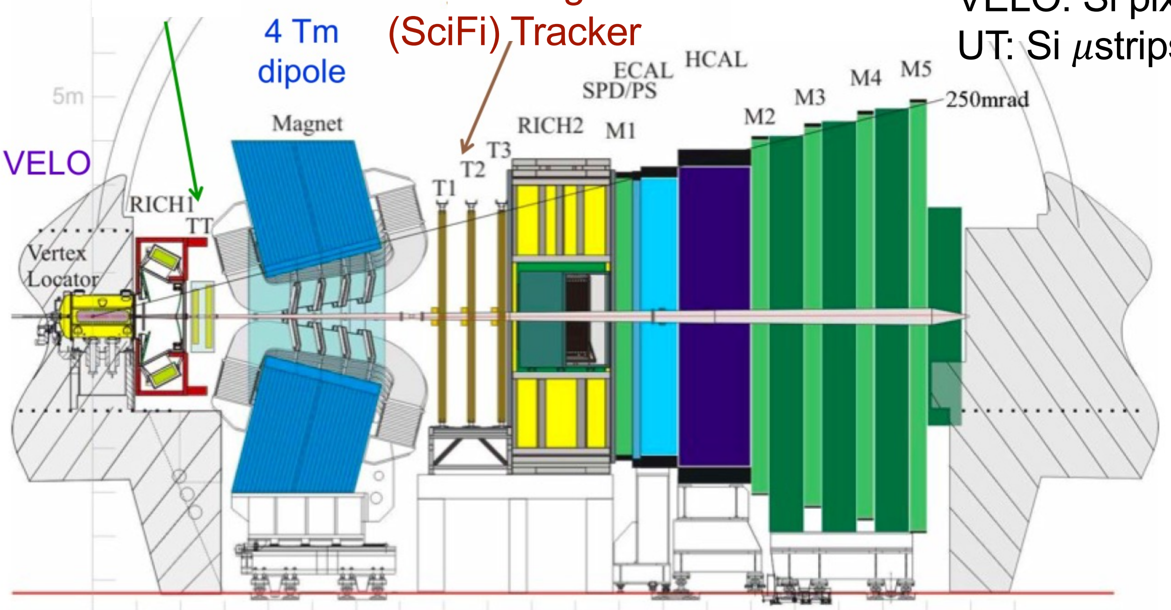
Upstream Tracker (UT)

4 Tm dipole

Scintillating Fibre (SciFi) Tracker

VELO: Si pixel
UT: Si μstrips

VELO

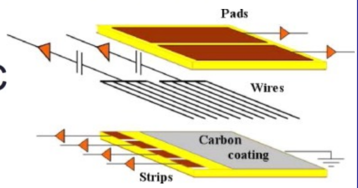


Overall Design Choices (Multipurpose Detectors)

ATLAS and CMS: multipurpose experiments, need to detect muons over a large p_T range 3 GeV < p_T <3 TeV, muon systems are stand-alone trackers

K. Hoeffner

- ATLAS
  - Air core toroid → no multiple scattering, good resolution
  - Toroidal B-field of 0.7 T → next slide for B-field
  - Three stations (min. number needed), very large area to be covered
  - Punch through from calorimeters to be treated
  - Technology choices: pressured DT, RPC, CSC, TGC



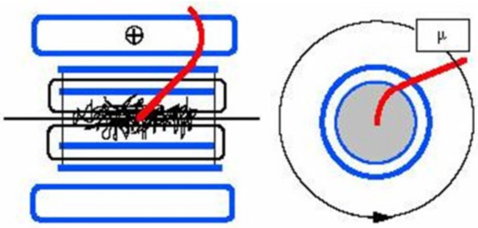
- CMS
  - Iron return yoke → resolution limited by multiple scattering
  - Less problems with punch through
  - Complementary technologies, high redundancy
  - 4 stations on muon track
  - Technology choice: DT, RPC, CSC

TGC = Thin Gap Chambers

Impact of Magnet Design

K. Hoeffner

ATLAS A Toroidal LHC ApparatuS



Main magnet = Toroid, B = 0.7 T

Bending in (r,z)

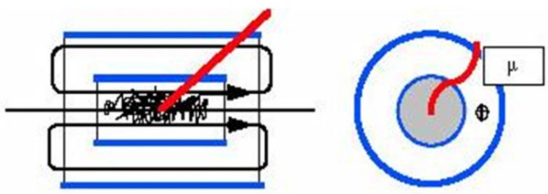
Straight track in (r,ϕ) → Extrapolation to z-coord. of the beam (~cm)

In tracker additional solenoid, B = 2 T, here bending in transversal plane (r,ϕ)

No iron in muon system

Homogeneous B-field

CMS Compact Muon Solenoid



Just one magnet, Solenoid B = 3.8 T

Bending in transversal plane (r,ϕ)

In (r,z) straight track → Extrapolation to beam (focused dimension) → Trigger on impact parameter

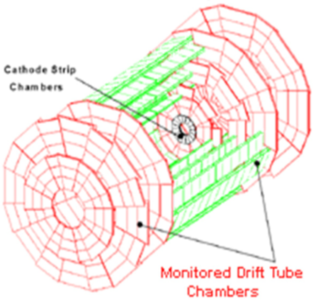
Requires return yoke in muon system

Inhomogeneous field at large η

Momentum Resolution

ATLAS

B = 0.7 T
L ~ 5 m
N = 3 Stations * 8 Points



s = 750 μm for 1 TeV Track
10% → σ = 75 μm

Δp/p ~ 6%

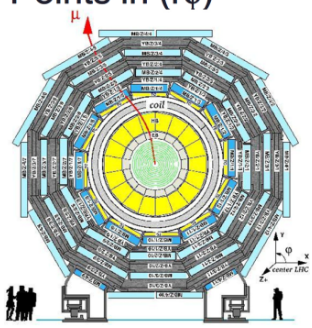
$$s = \frac{0.3 \cdot B[T] \cdot L[m]^2}{8 \cdot p[GeV]}$$

$$\frac{\Delta p_T}{p_T} \propto \frac{1}{s} \cdot \delta_{spatial} \cdot \sqrt{\frac{720}{N_{Stat}}}$$

CMS

K. Hoeffner

B ~ 2 T (B-Field in Fe)
L ~ 3.5 m
N = 4 Stations * 8 Points in (rφ)



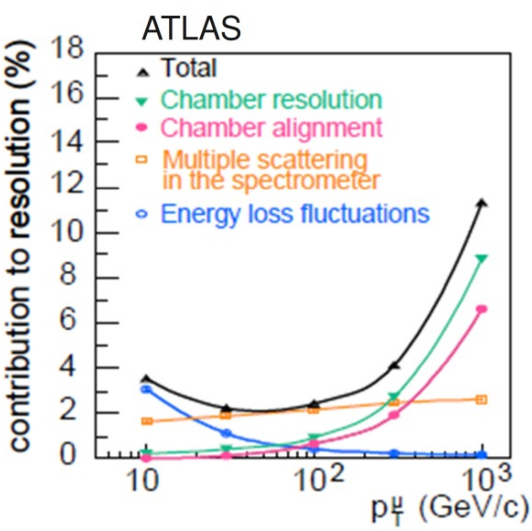
s = 900 μm for 1 TeV Track
10% → σ = 90 μm

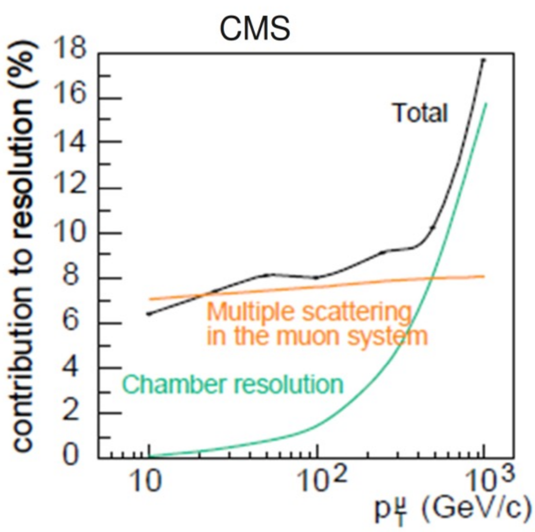
Δp/p ~ 12 % (Multiple scattering in Fe ~100 μm)

Combine with Tracker Δp/p ~ 2 %

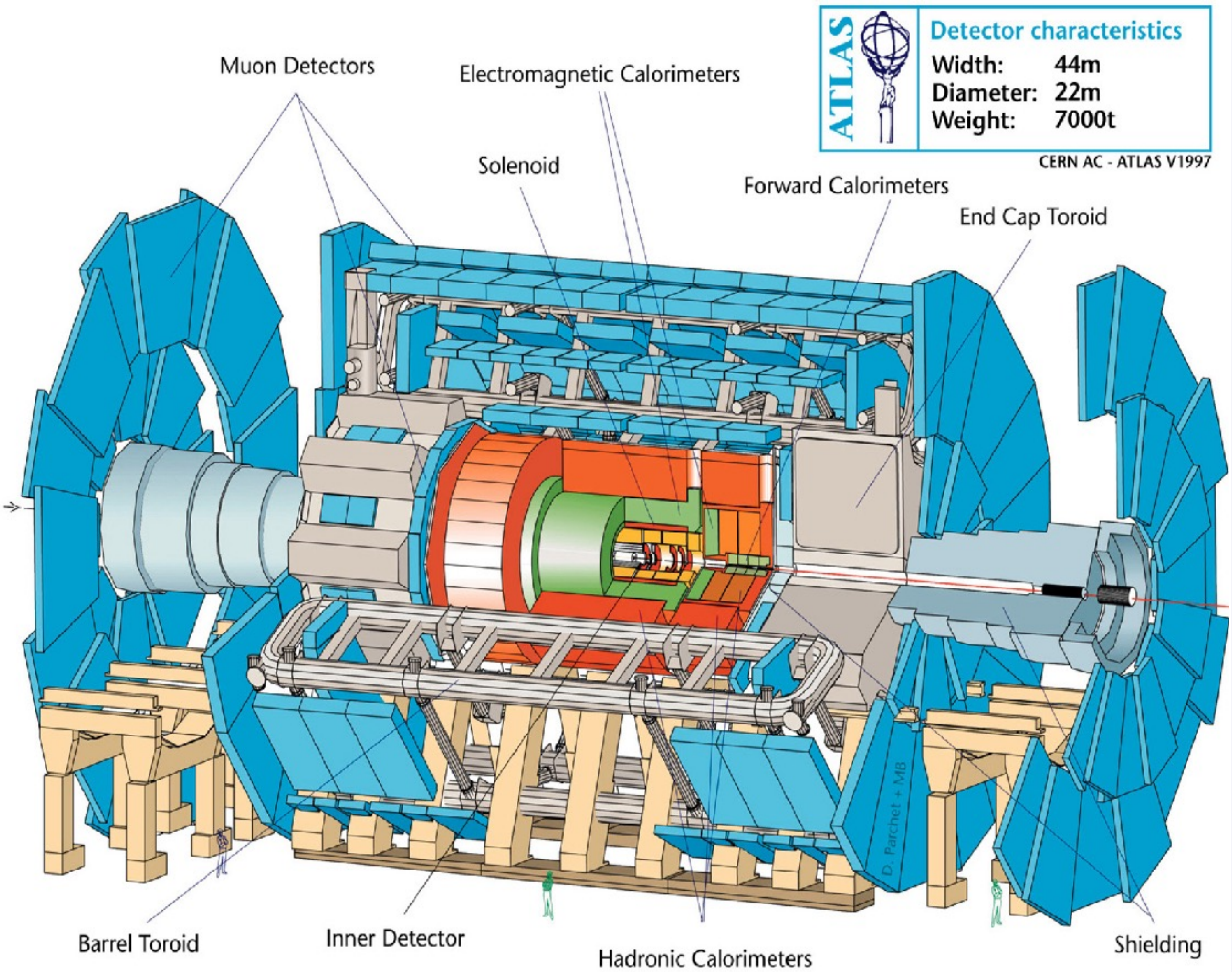
Combined Resolution

K. Hoeffner





ATLAS experiment at LHC



- Tracking ($|\eta| < 2.5$ inside a 2T s.c. solenoid)

-- Si micro strips and pixels

-- Transition Radiation Tracker (e/π separation)

- Calorimetry ($|\eta| < 5$)

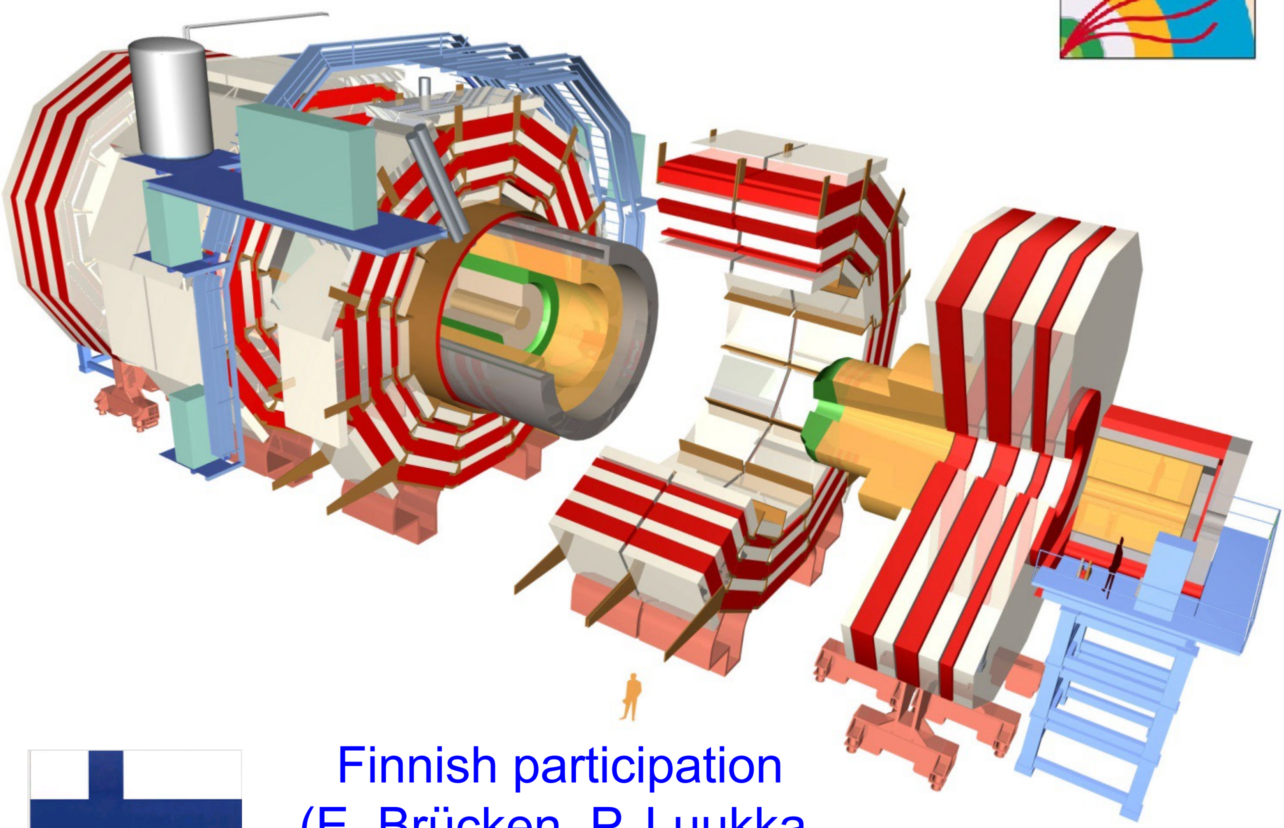
-- Electromagnetic: Pb – LAr (central+forward)

-- Hadronic: Fe/scint. (central), Cu/W-LAr (forward)

- Muon spectrometer ($|\eta| < 2.7$)

-- Air-core toroids (0.7 T) with muon chambers

CMS experiment at LHC



Finnish participation
(E. Brücken, P. Luukka,
M. Voutilainen and K.
Österberg et al.)

Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t

- Tracking ($|\eta| < 2.5$)

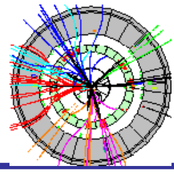
-- Si micro strips and pixels

- Calorimetry ($|\eta| < 5$)

-- Electromagnetic: $PbWO_4$ crystals (central+endcap)

-- Hadronic: brass/scintillator (central+endcap),
Fe/scintillator (forward)

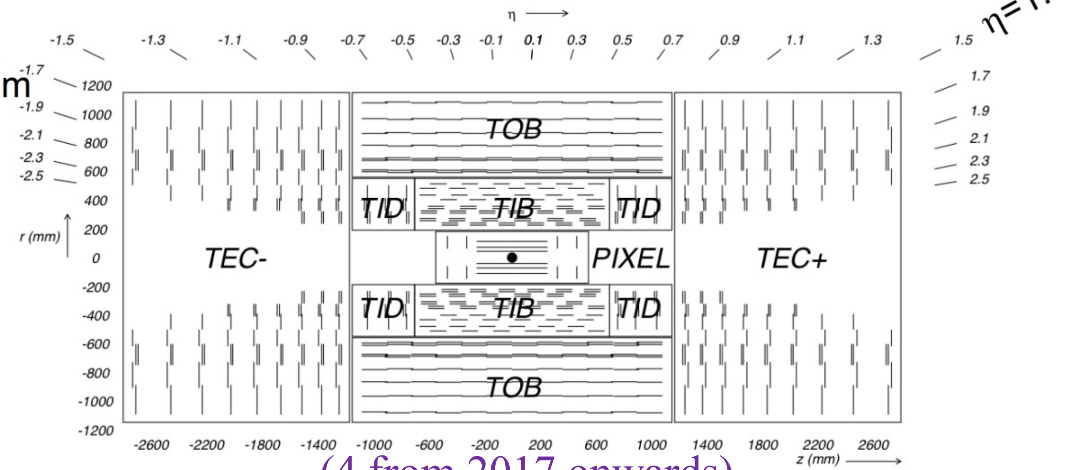
- All above inside a 3.8 T superconducting solenoid
Instrumented iron return yoke for muon detection



CMS tracker layout

P. Wells

- Silicon Barrels and Disks (including End-Cap disks)

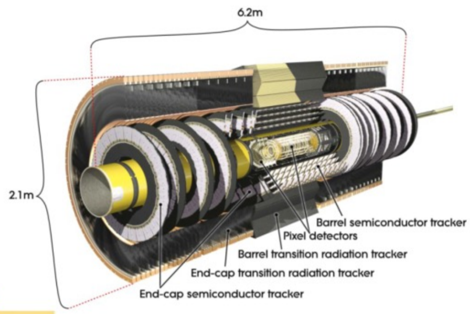


(4 from 2017 onwards)

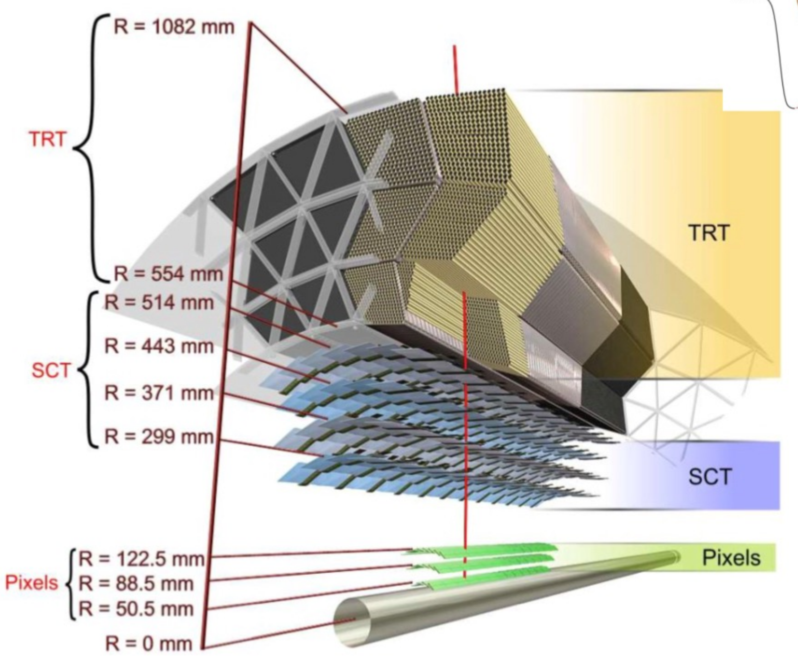
- Barrels have 3 pixel layers and 10 microstrip layers
  - Inner strips 10cm x 80 to 120 μm (320 μm thick)
  - Outer strips 25cm x 180 to 120 μm (500 μm thick for S/N)
  - 4 strip layers have additional stereo module for z coordinate

P. Wells

ATLAS ID



Expanded view of barrel



Barrel track passes:
~36 TRT 4mm straws (Transition Radiation Tracker – gas detector)

4x2 Si strips on stereo modules12cm x 80 μm, 285μm thick

3 pixel layers, 250μm thick   4 since 2015