Particle Physics Instrumentation

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Similar instrumentation is used for nuclear physics and nuclear medicine.

Detectors are often combinations of different specialized subdetectors

Here I discuss different subdetectors used in the LHC environment more specifically the ATLAS detector

Outline

LHC and its detectors

ATLAS and its subdetectors

Future Accelerators

The Large Hadron Collider

27km circumference double ring collider

13 TeV (6.5+6.5) – 0.999999991 times c, i.e. 3m/s less than c

4 interaction points with detectors – ATLAS, CMS, LHC-B and ALICE

1600 superconducting magnets (up to 9T) to bend and focus the beams

10^{34} protons/cm^2/sec focused into 16 μ beams that collide in the interaction points

Bunches with about 10^{11} protons each collide every 25 ns

~ 20 non-elastic collisions per bunch crossing

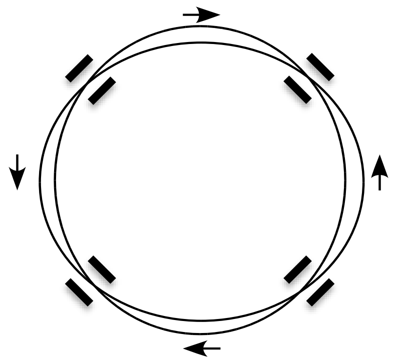
The total beam energy is 562 MJ – melts 2 ton cupper

Start of operations 2010 (2008)

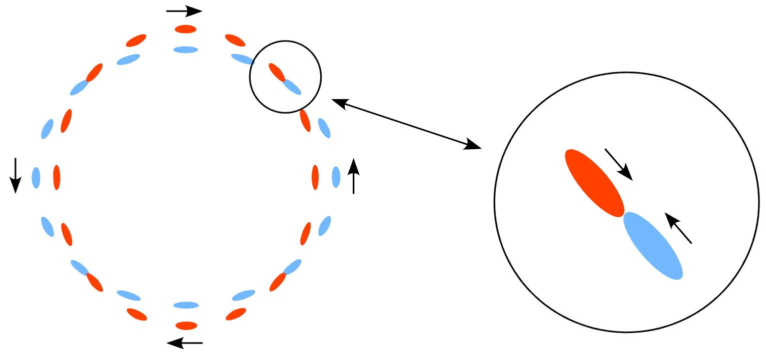
LHC

The Large Hadron Collider consist of two counterrotating 27 km circumference accelerator rings that intersect at 4 points where the proton beams collide.

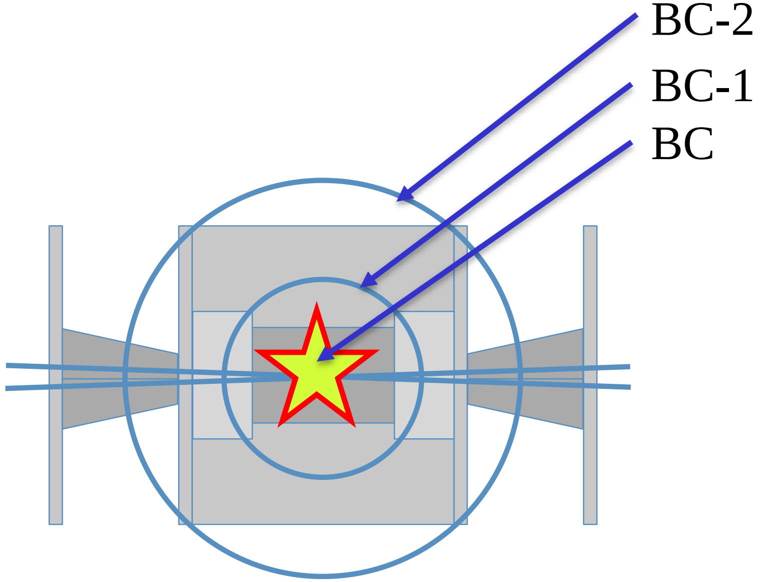
4 detectors are built around these interaction points to analyze the debris.



Most protons will pass through and continue to recirculate, but some would collide (also with rest gas)
Eventually all protons will be lost, but before that they will pass each other many times
A better solutions is to group the protons in **bunches** and let the bunches collide
Bunch length: 30cm
Bunch distance: 7.5m
Collide every 25ns



Local time reference

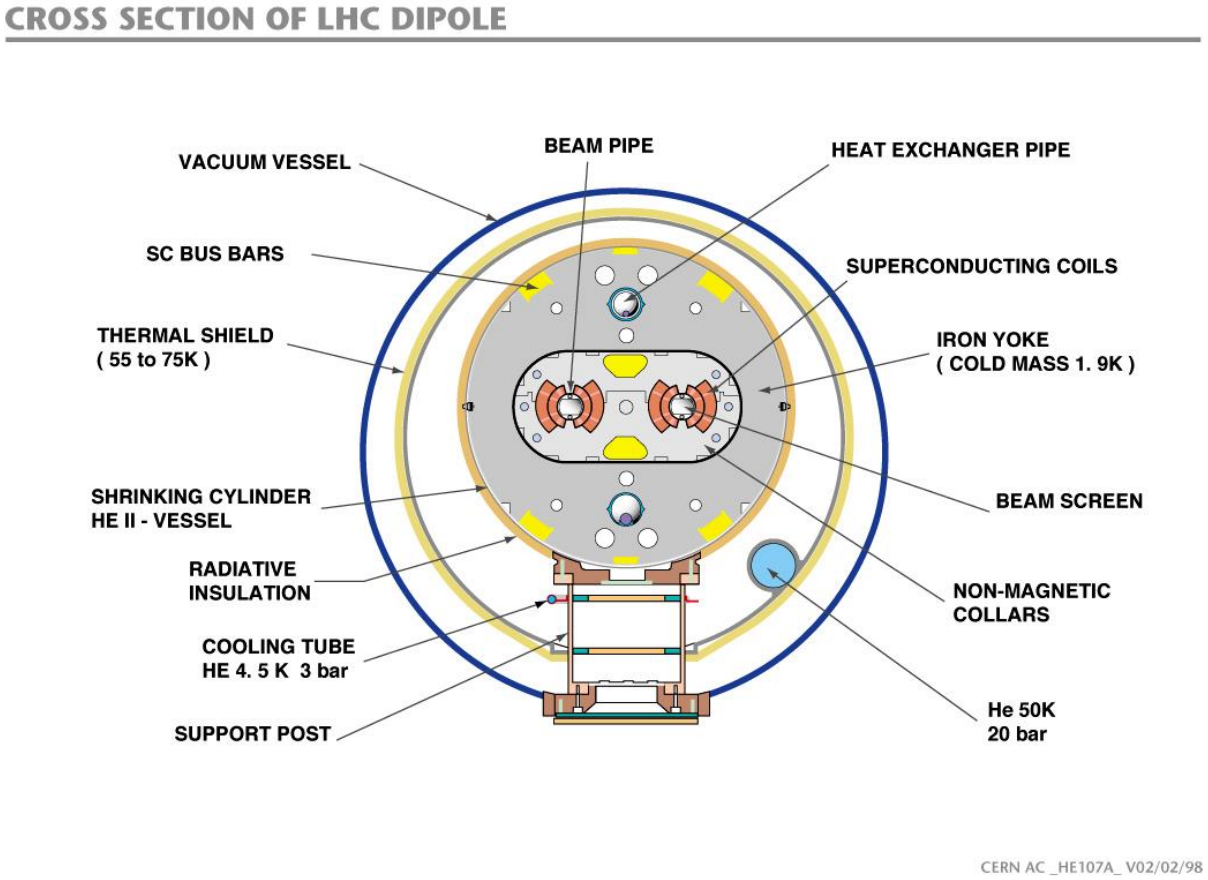


The bunch spacing is so close that when the particles formed in a bunch crossing move away (close to c) from the interaction point new bunch crossings occur (at the interaction point).
Local time reference for all detector elements are delayed so that they relate to correct Bunch Crossing number (BC)

The Large Hadron Collider

Insulation vacuum at 10^{-6} mBar in a volume of $15000 m^3$

Beam pipe vacuum 10^{-10} mBar (as on the moon)



The CERN Accelerator Systems

A hierarchical system of accelerators

Linac 2 → PS Booster → PS → SPS → LHC

50 MeV 1.4 GeV 25GeV 450GeV 6.5 (7) TeV

One or two injections into LHC per day

450 GeV injected protons accelerate to 6.5 TeV in 20 minutes

Aim for 7 TeV 2022

CERN Accelerator chronology

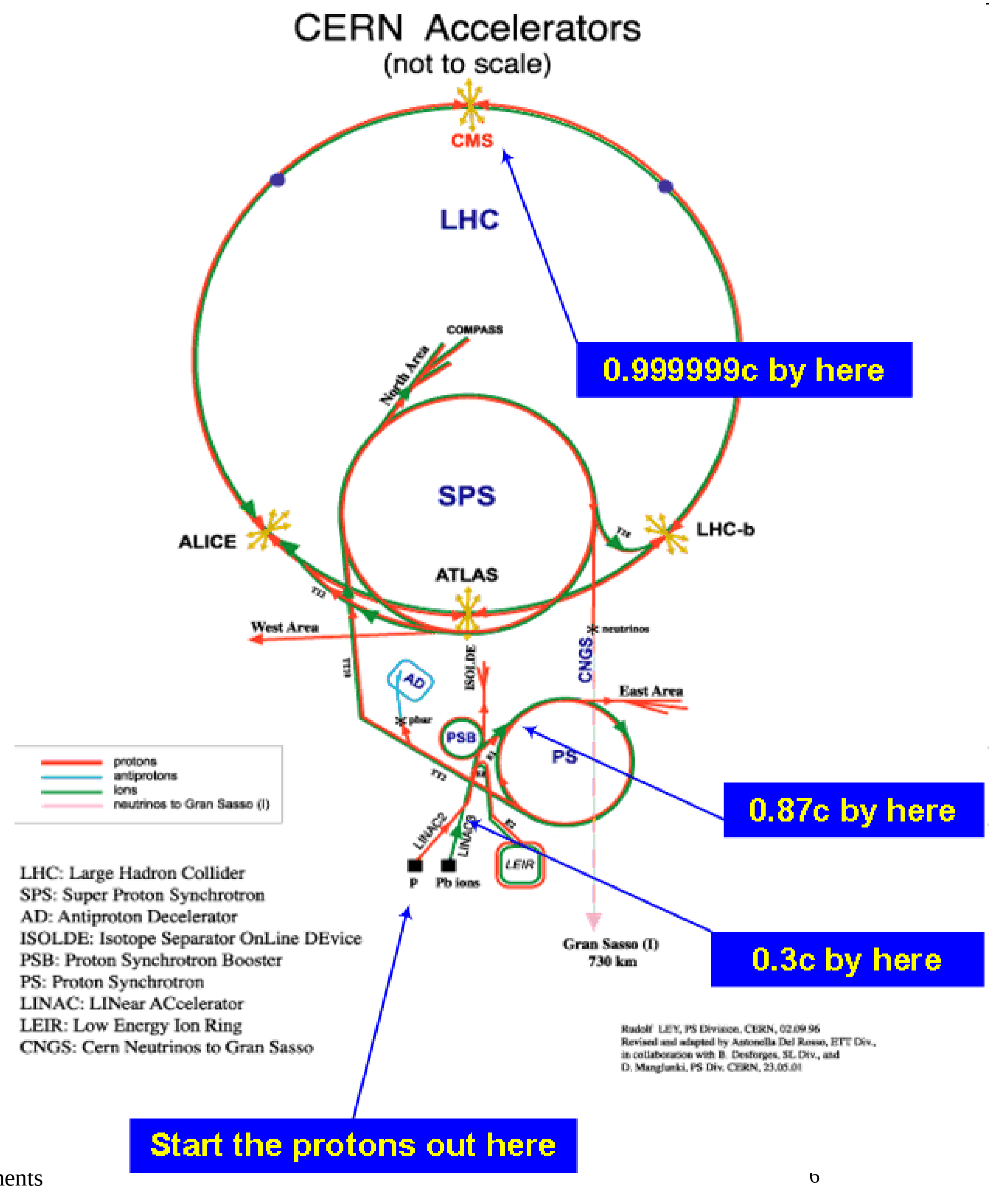
Linac 1 and PS started 1959

PS Booster started in 1972

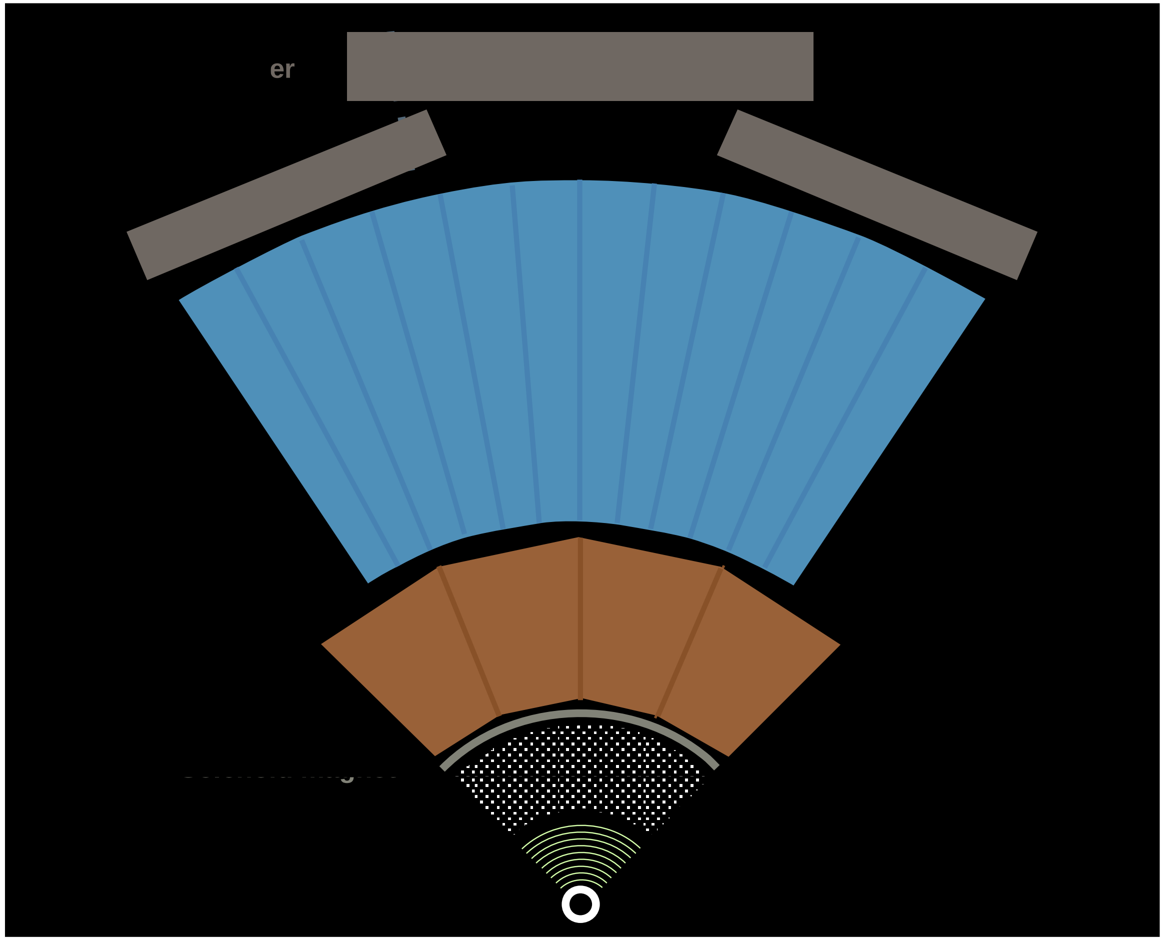
SPS started in 1976

Linac 2 started in 1978

LEP started in 1989 reached 104+104 GeV



Detector and Subdetectors



LHC detectors are often onion-like with multiple subdetector.

Long-lived particles, such as e-, e+, γ, hadrons (p, n..., jets), μ+, μ-, ν, enter the detector from the beam pipe..

Short-lived particles decay before leaving the beam-pipe

The **inner detector** (tracker) with Pixel, SCT and TRT find charged particle tracks

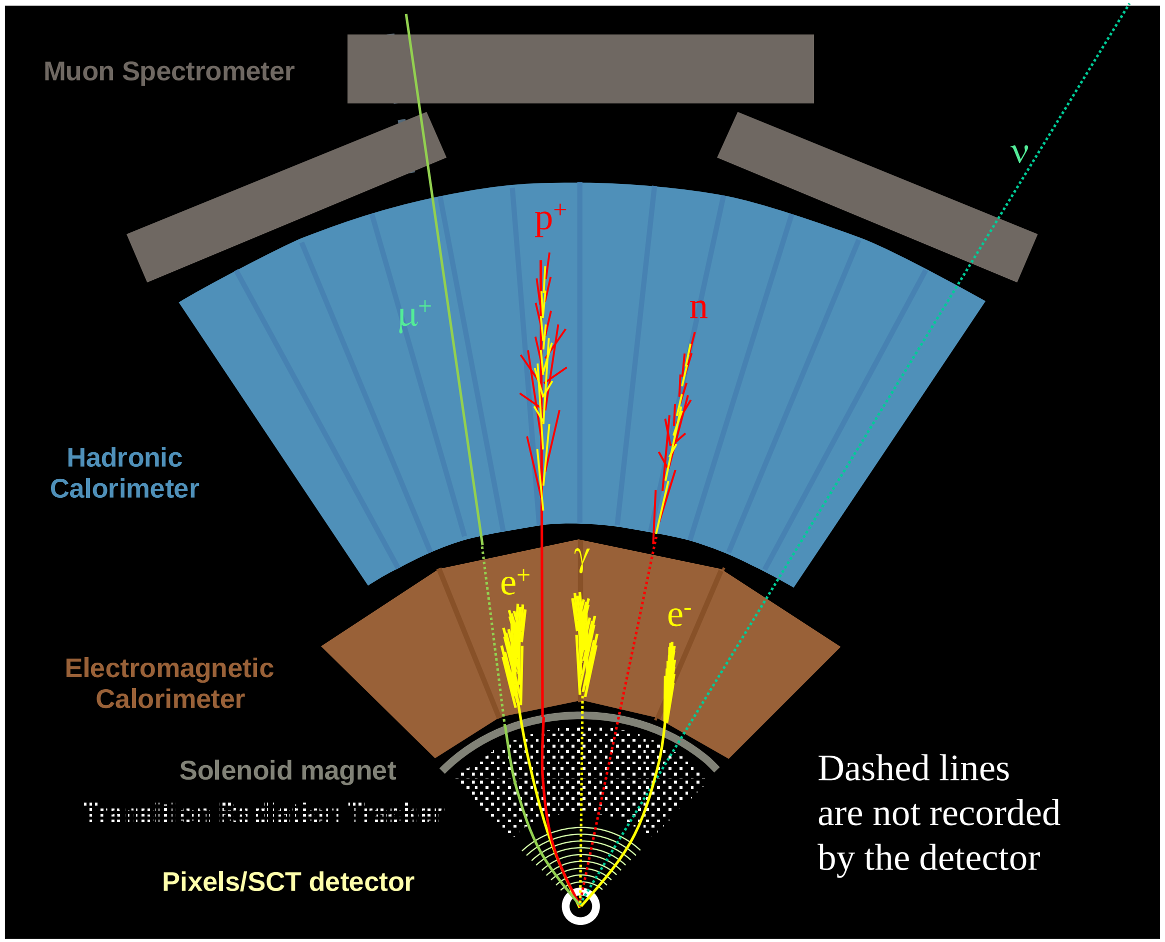
The **solenoid magnet** bend the tracks so that charge and momentum can be determined

The **electromagnetic calorimeter** is used to measure e/m tracks and energy

The **hadron calorimeter** to measure hadron and jet tracks and energy

The **muon detector** to detect muon tracks and momentum

Identifying the collision event



An **electron (e^-)** leaves a track in the inner detector with negative (here counter clockwise) curvature and showers and is absorbed in the electromagnetic calorimeter

An **high energy positron (e^+)** leaves a positive smaller curvature

A **photon (γ)** leaves no track in the inner detector

A **positive muon (μ^+)** leaves a positive curvature track in the inner detector, a weak track in the hadron calorimeter and a signal in the muon spectrometer

A **proton (p)** leaves a positive curvature track in the inner detector, a track in the e/m calorimeter and a track in the hadron calorimeter

A **neutron (n)** leaves no track in the inner detector o the e/m calorimeter and but a track in the hadron calorimeter

A **neutrino (ν)** does not leave any tracks at all

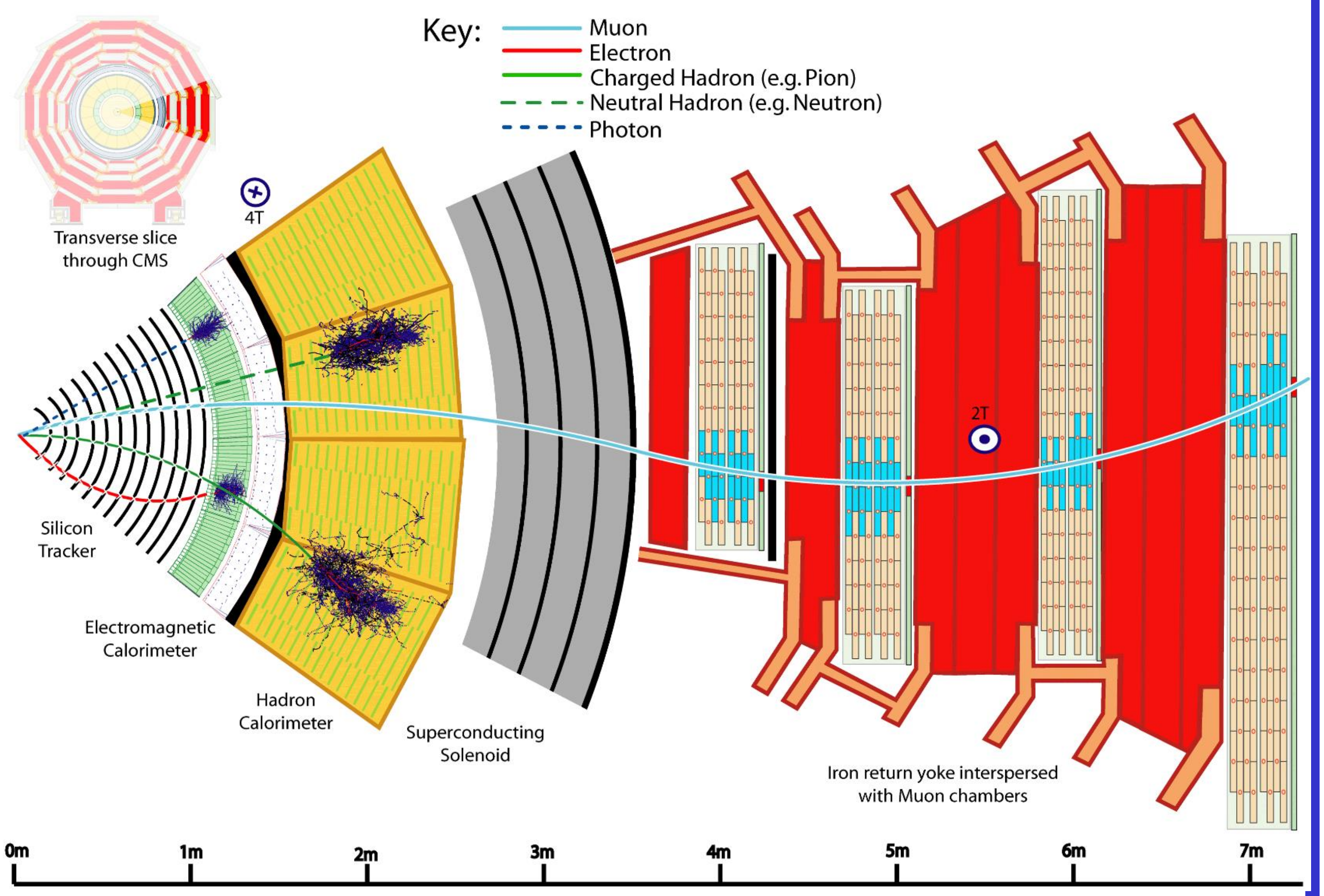
Identifying the collision event

Group particles from the same interaction point – could be outside beam pipe
Deduce source particle:

$e^+ + e^- \rightarrow Z$

$\mu^+ + \mu^- \rightarrow Z$

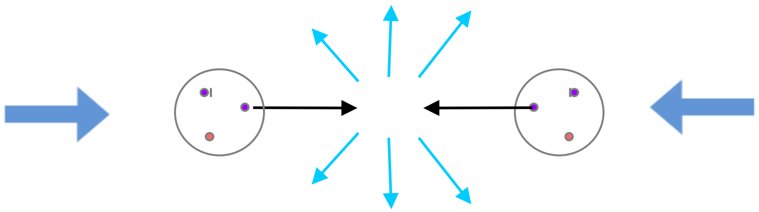
$2Z \rightarrow H$



Introduction

New physics can be explored by **colliding high energy particles**
The new particles can then be produced in these collisions if the energy is **sufficiently high**.

If we collide single protons the probability (cross section) for producing new particles is extremely small.
You need **many collisions** – for this you need **high luminosity** and **many repetitions**
To release a large amount of energy the collision must be head on.
The protons contain three quarks, so not only must the protons collide head-on but also their constituents.



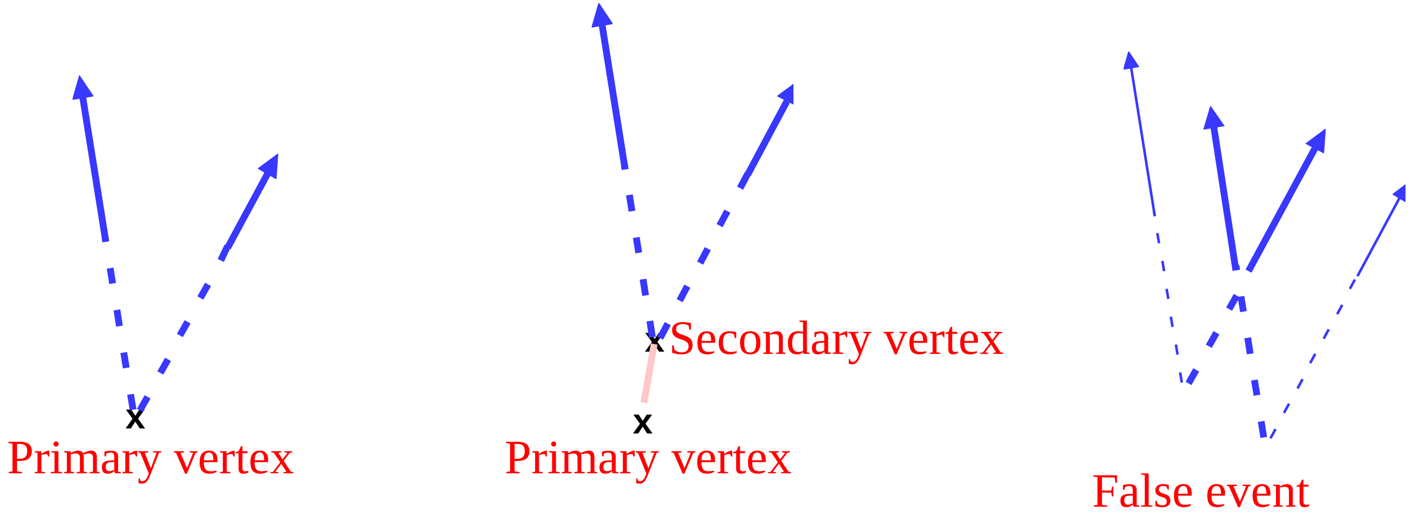
After many repetitions, we look for unusual interesting events.
One such event is not sufficient, we want **many** such events to believe the results.

Thus,

- **We must collide a large number of protons each time – use high luminosity proton beams**
- **We must repeat collisions many times – use high collision rates**

Short lived particles

You have to infer the existence of short lived (< 10^{-10} sec) particles by recording the disintegration products



But this opens for mistakes:

If A → B, C and you record B and C it is not **certain** they came from the same A. They might have come from **different** processes

Need to know the direction with high precision, to be able to identify if it is a secondary vertex

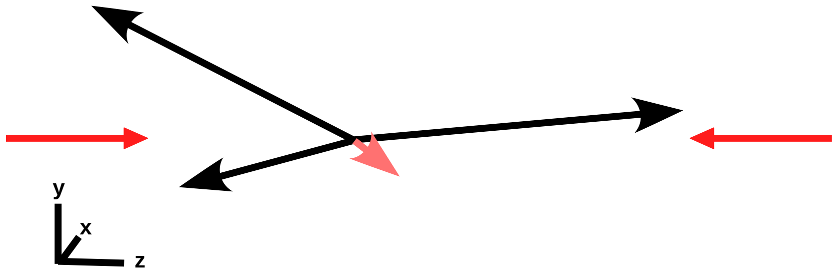
Missing Transverse Momenta (Energy)

The Center Of Gravity of all particles created in an explosion stay at the collision center

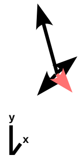
The vector sum of all momenta in the COG system is 0

Same thing can be seen in the transverse projection

If one particle is not detected there will be a **missing transverse momenta**



3D



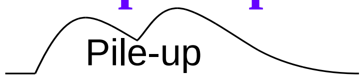
Transverse projection

Missing transverse momenta can be due to:

- Particles that cannot be detected (e.g. neutrinos)
- The detector contains holes (failing detector elements) that allow particles to escape, i.e. it is not hat we call **hermetic**

Desirable detector properties

- High precision inner detector position information to identify **secondary vertices**, but amplitude information is not needed here – many layers and many channels
- Inner detector should be a **light construction** that does not compromise calorimeter resolution
- Good energy information in calorimeters and muon detector to **determine missing momentum** accurately
- All detectable particles should be detected – **hermeticity**
- Detector signals are often long, many bunch crossings, but must be associated with correct bunch crossing, if not, causing false missing momentum – **pile-up** is also a problem at high count rates

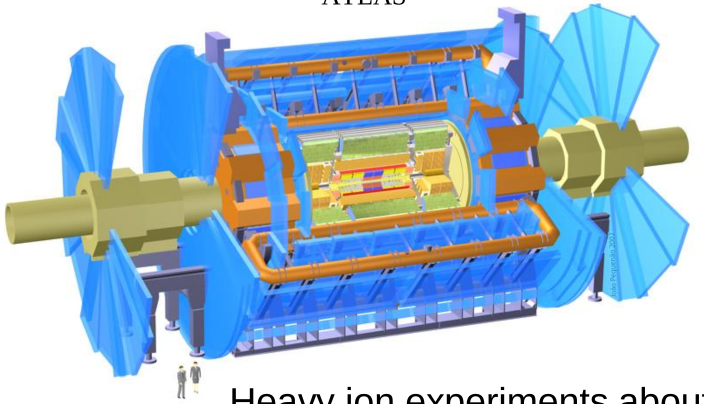


- E/M calorimeter should be **deep enough** to contain electrons and γ
- Hadron calorimeter should be **deep enough** to contain hadrons
- Higher energies → larger calorimeter structures
- **Radiation exposure** determine choice of detectors and electronics

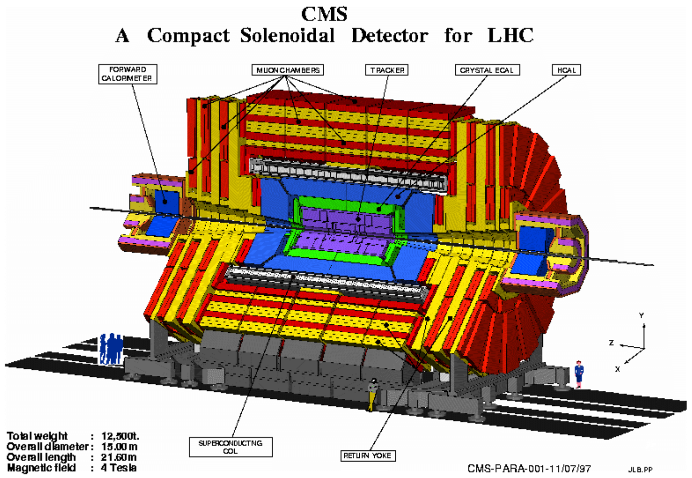
Design compromises necessary for economical reasons

LHC Detectors

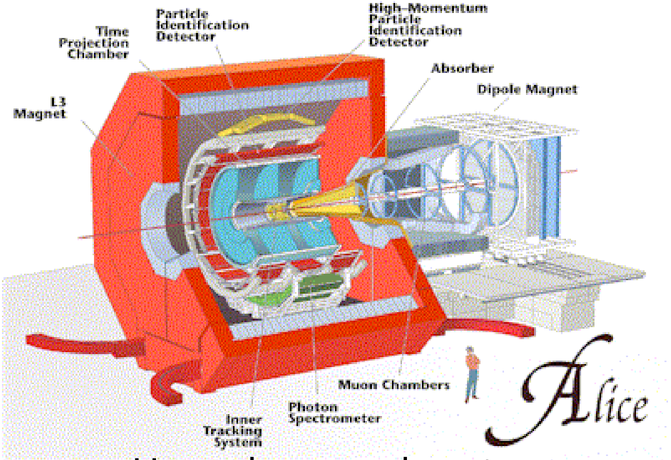
ATLAS



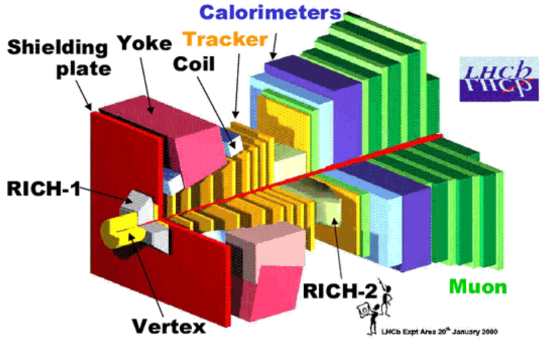
Heavy ion experiments about 2 weeks/year



ATLAS -CMS
Similar but different – magnet system, detector solutions, TDAQ system
Competition – Collaboration



Heavy ion experiments,
Pb – Pb or Au – Au



B physics at lower luminosities

Different sizes:
ATLAS 46x25 m
CMS 21x15 m
Alice 26x16 m
LHCB 21x10x13 m

LHC results and cost

RESULTS so far

Verified the Standard Model

Higgs particle discovered 2012 July 4th (Nobel prize 2013)

No strong indications for BSM physics (Beyond Standard Model) yet

No SUSY (SuperSymmetry) yet

COSTS

LHC material costs ~3.1 G€

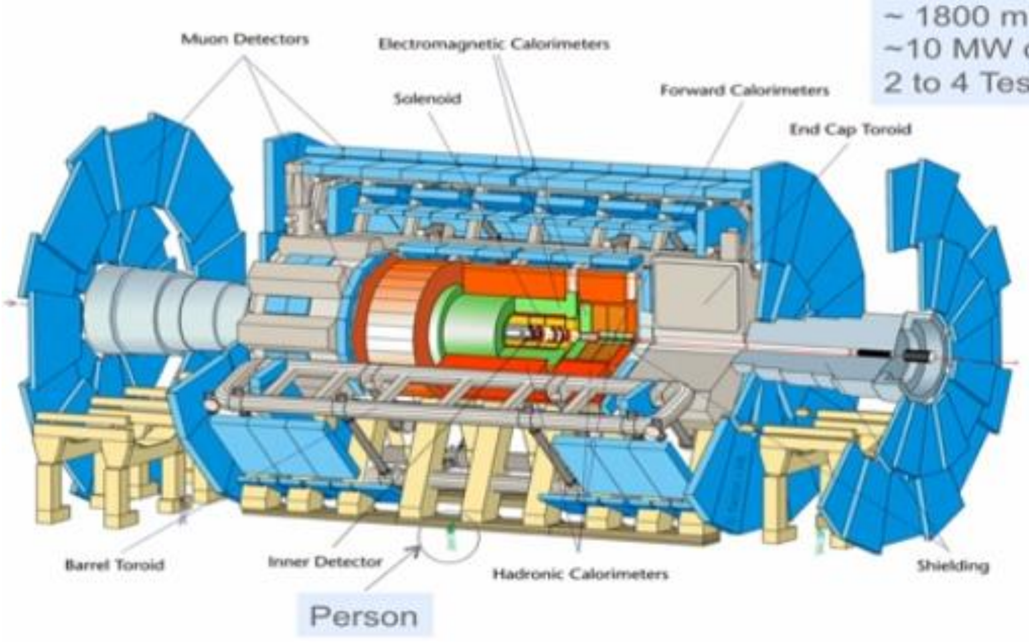
ATLAS material costs ~.3 G€

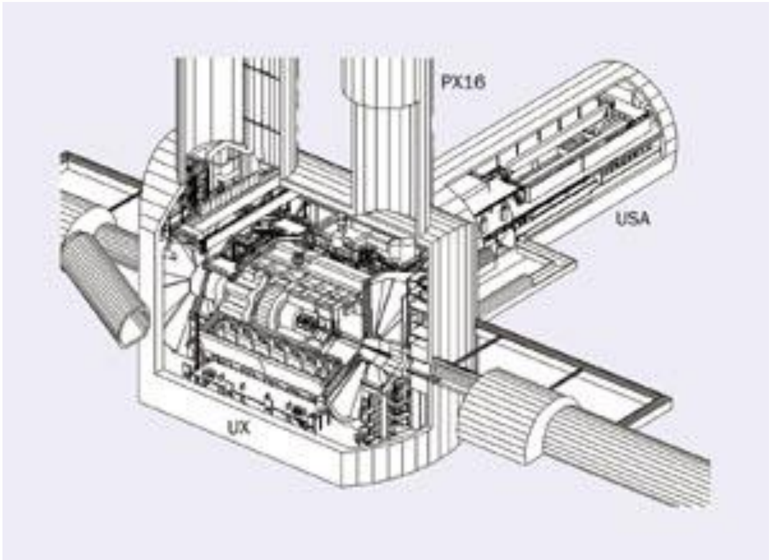
A ToroidaL ApparatuS - ATLAS

46 meters

~ 1800 miles of cables
~10 MW of electric power
2 to 4 Tesla mag. field

25 meters





USA = Underground Storage Area
100m below surface
Access shafts 12 – 22 m diam.

Inner detector 1 bit? - ~86 Mch

E/M calorimeter 16 bit - ~300 kch

Hadron calorimeter 16 bit ~10kch

Muon detector x bit ~100 kch

Weight 7000 tons

3000 physicists + x engineers

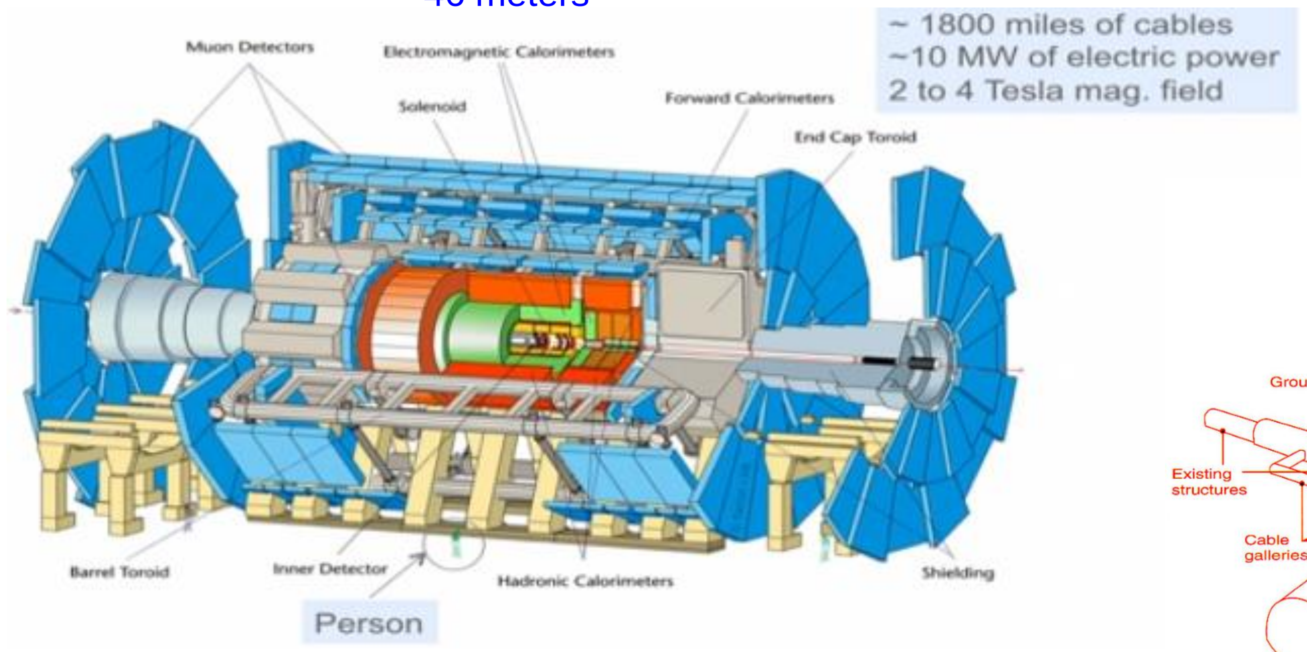
181 institutes from

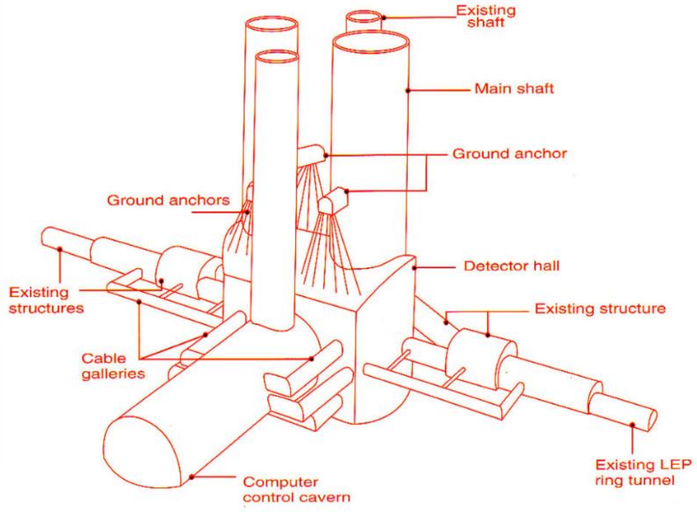
38 countries

A ToroidaL ApparatuS - ATLAS

46 meters

25 meters





Inner detector 1 bit? - ~86 Mch
E/M calorimeter 16 bit - ~300 kch
Hadron calorimeter 16 bit ~10kch
Muon detector x bit ~100 kch
Dipole magnet 2T 2.4m diam
Toriod magnets
Barrel 4T 20.1 m diam
Endcap 4T 10.7 m diam

Weight 7000 tons
3000 physicists + x engineers
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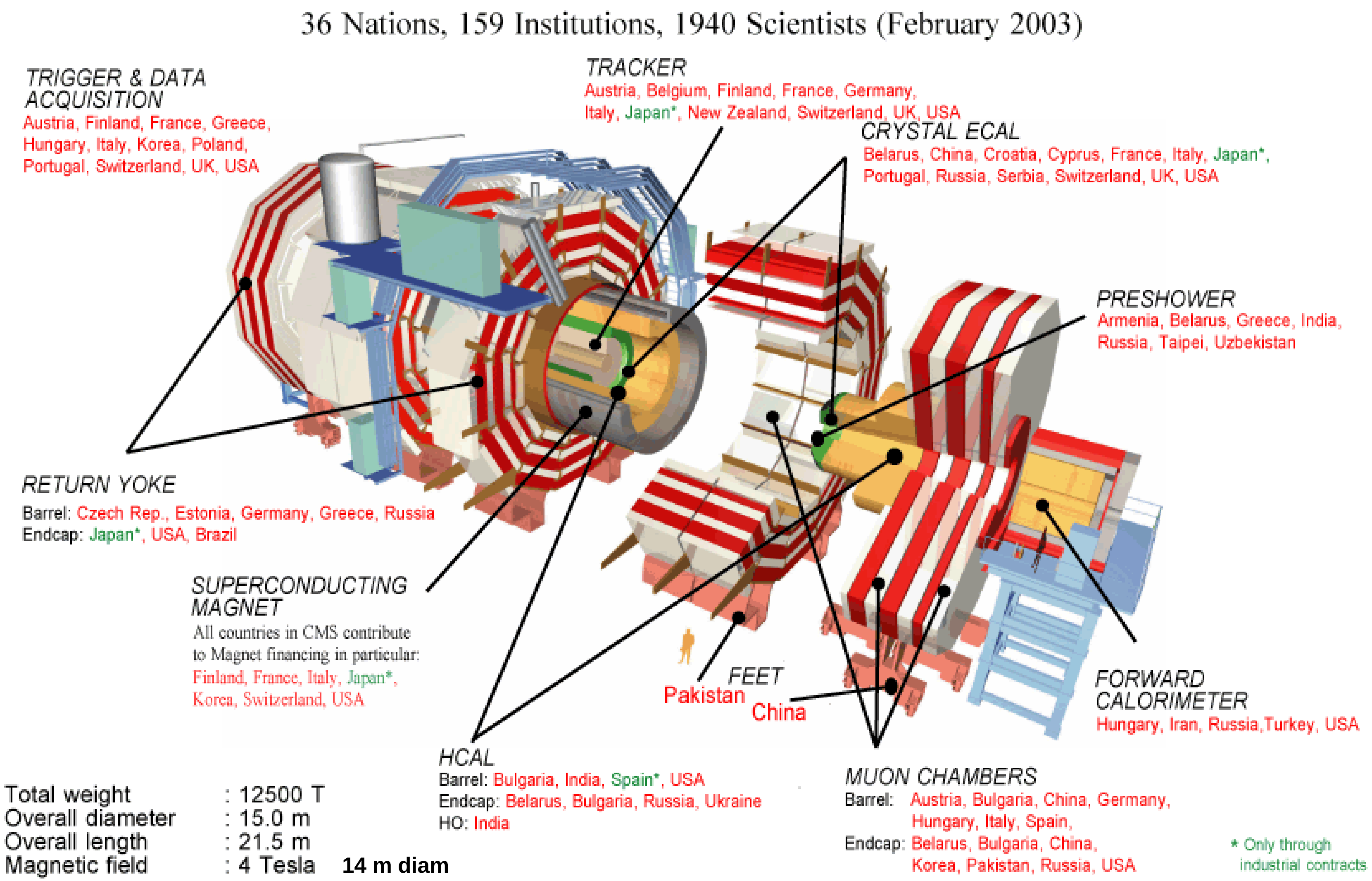
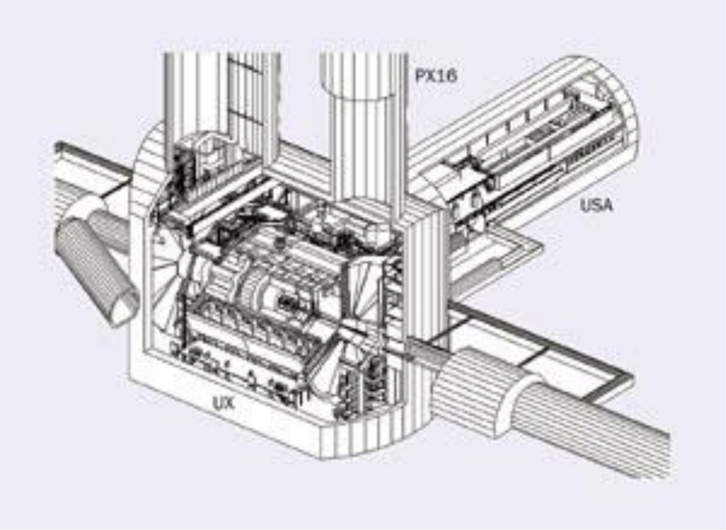
100m below surface
Access shafts 12 – 22 m diam.

CMS – Compact Muon Solenoid



14 m diam

ATLAS installation



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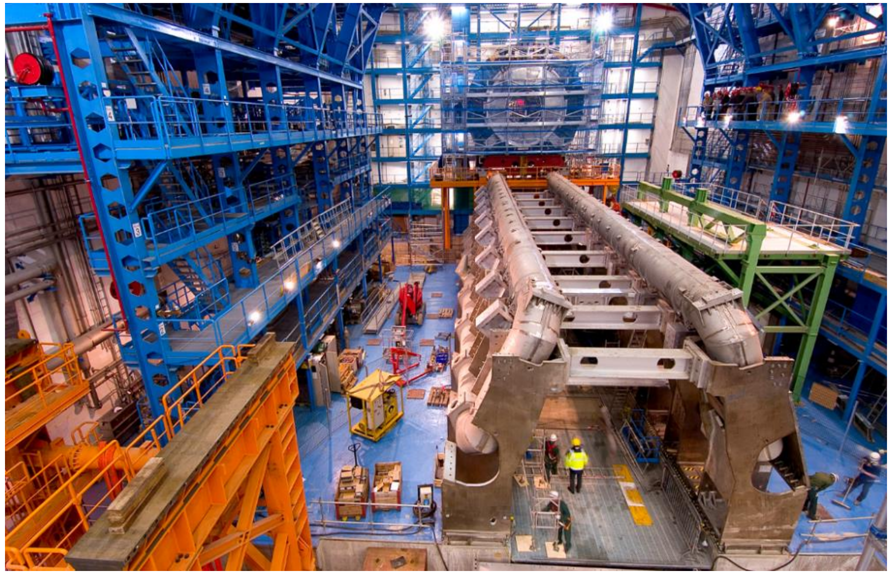


Radiation Detectors

All the subdetectors use radiation detectors or radiation detection principles to produce data signals.

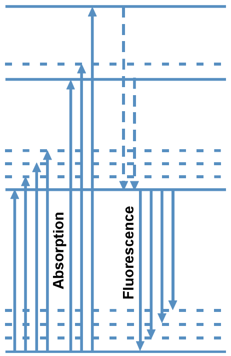
In radiation detectors particles are converted into electrical signals, sometimes via light

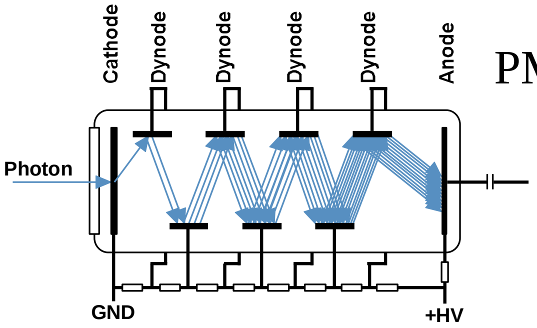
A large class of radiation detectors are based on **scintillation** where the ionizing radiation excites the inorganic or organic scintillator material. When the scintillator de-excites it emits light of characteristic wavelengths

The light can be collected by **photo multipliers (PMTs), APDs** (avalange photo diodes) or **SiPMs** (arrays of small GM detectors).

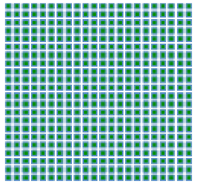
In another class of radiation detectors the radiation **ionizes the media** and an electric field separates the electrons and the ions. The media can be gaseous or liquid. Different media and different voltage gives different performance.

In semiconductor detectors the radiation creates **electron-hole pairs** that are separated by the field over a p-n junction

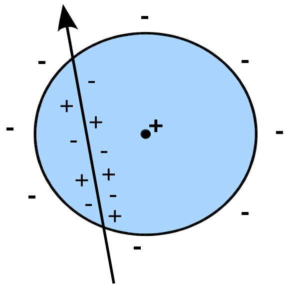


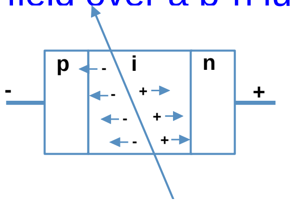


PMT

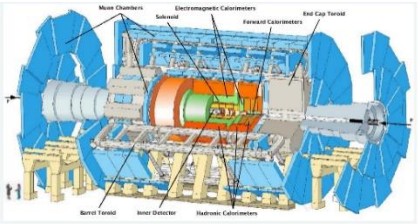


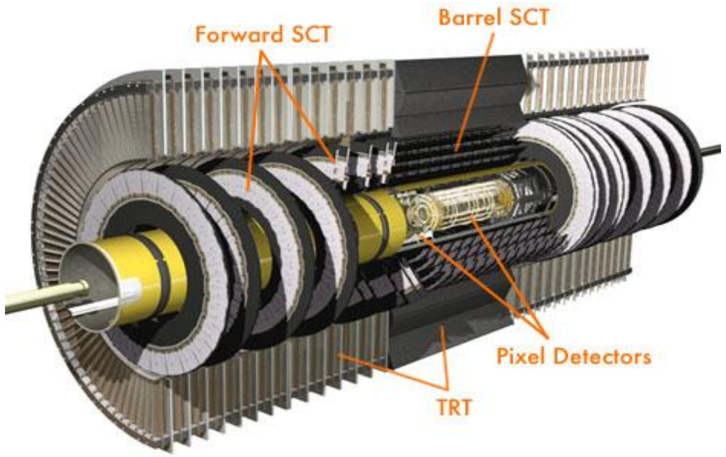
SiPM

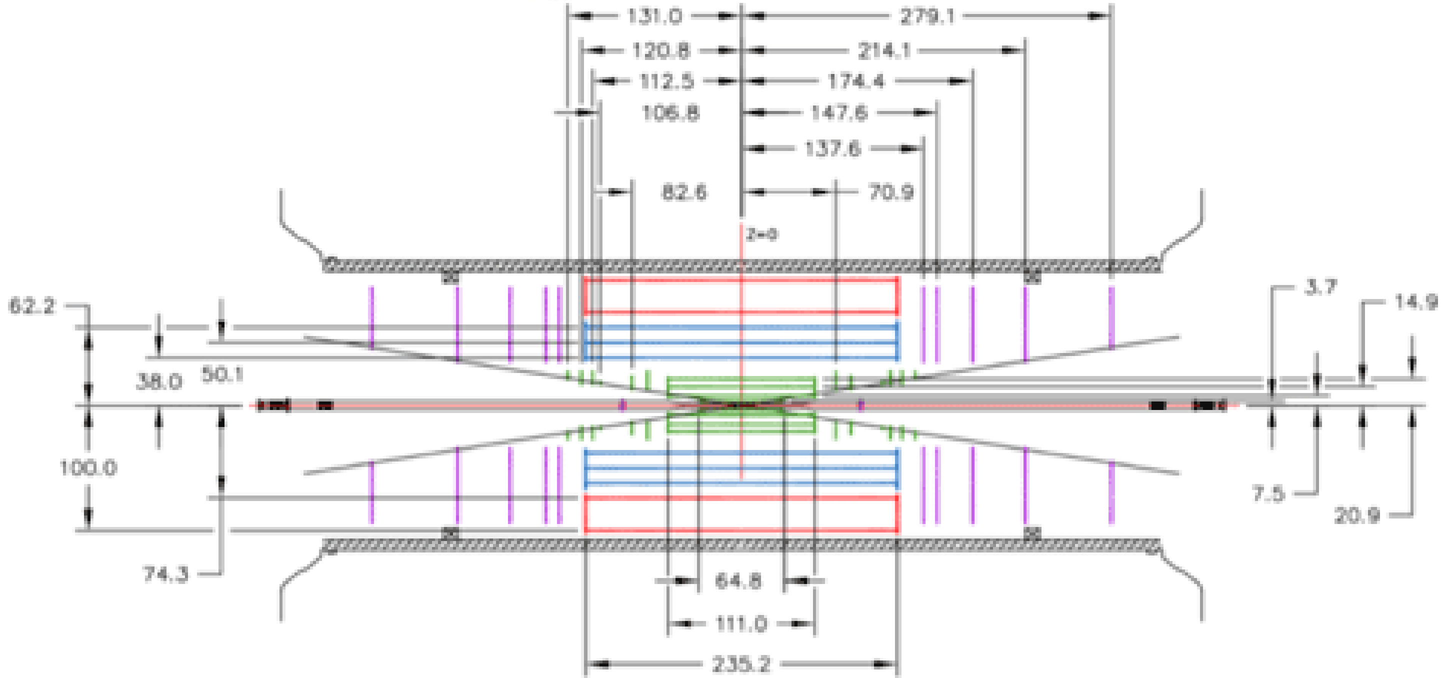




ATLAS inner detector







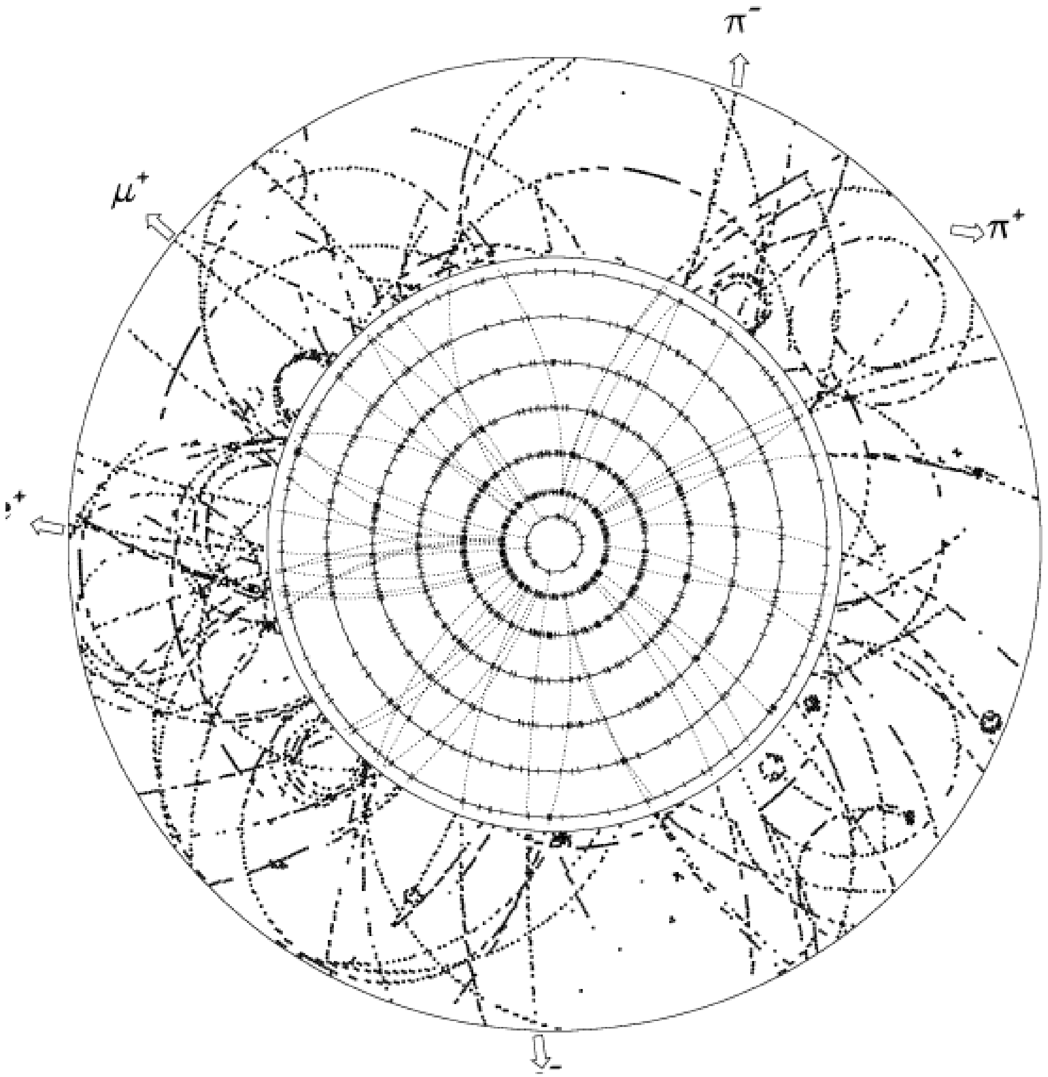
Magnetic field 2T
3 different detector types

Pixel detector 80 Mch
Silicon pad detector 2D resolution 12 μx110μ

Semiconducor Tracker (SCT) 6 Mch
Silicon strip detector (1D)
Double layers Resolution 23 μ x800μ

Transition Radiation Tracker (TRT) 300kch
Gas detector – straw tubes
Electron identification

ATLAS inner detector



About 1000 particles

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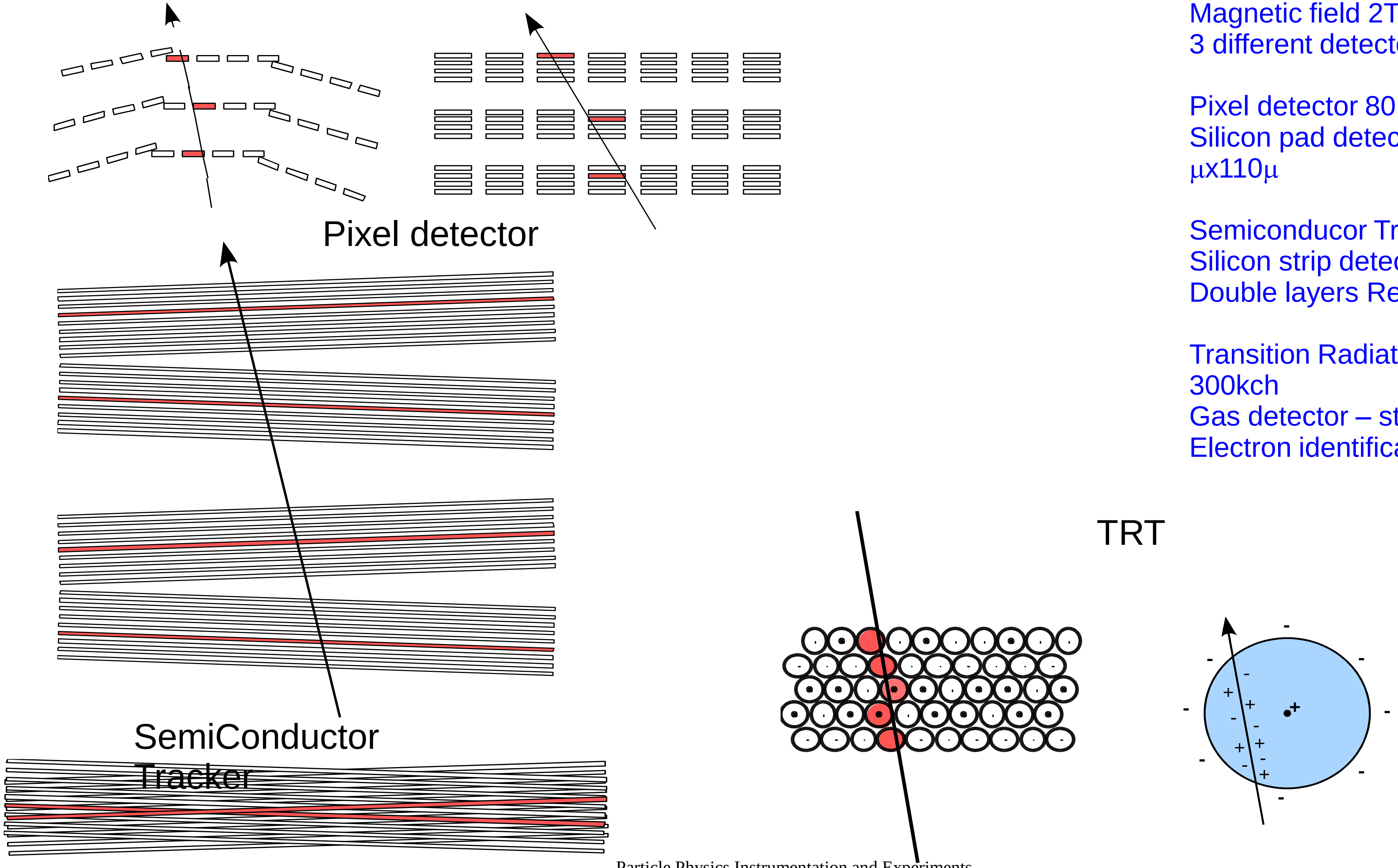
Electron identification

Pixel detector 3 sample points
Strip detector 4 sample points
TRT 36 sample points

ATLAS inner detector



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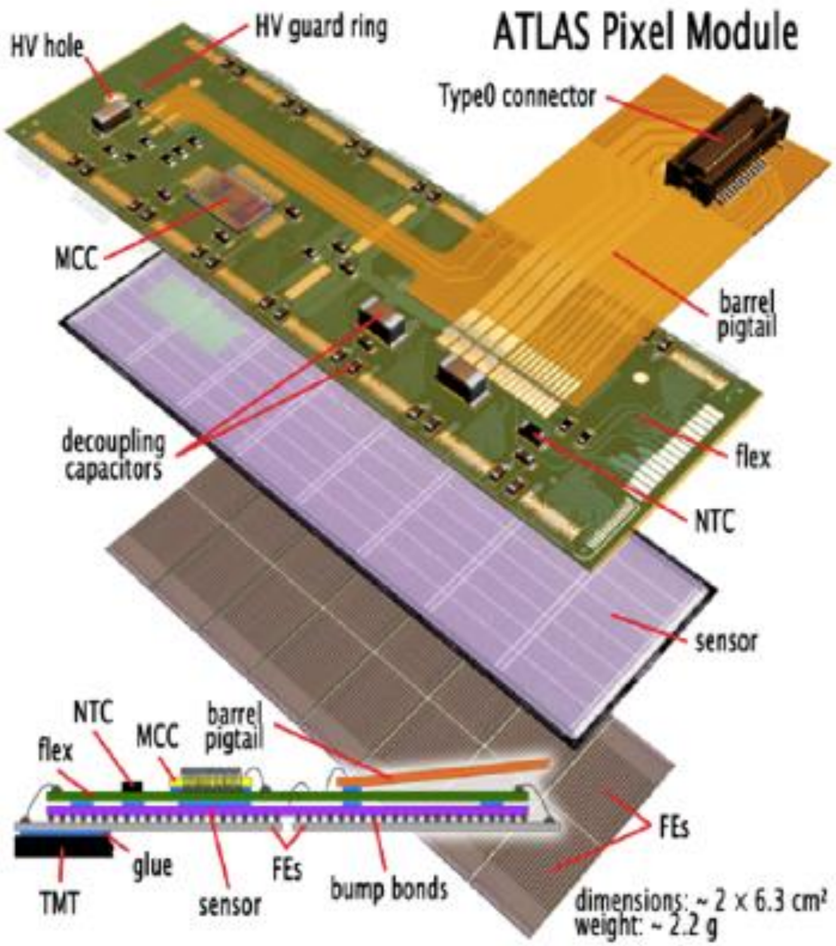
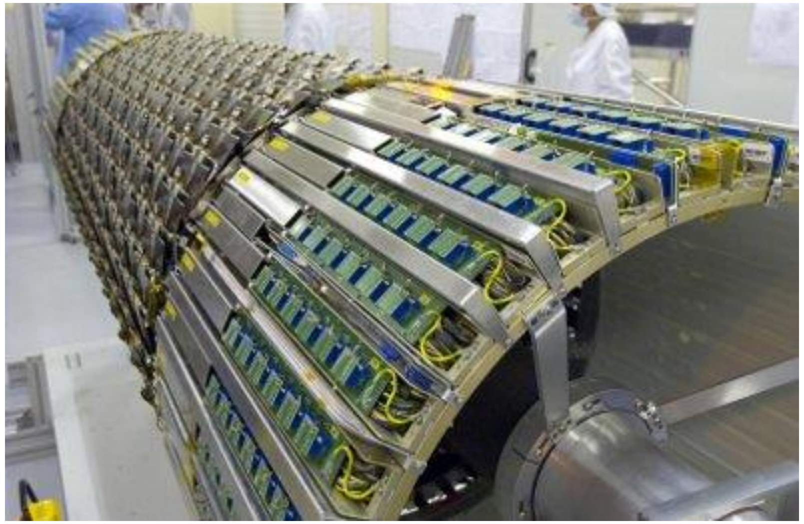
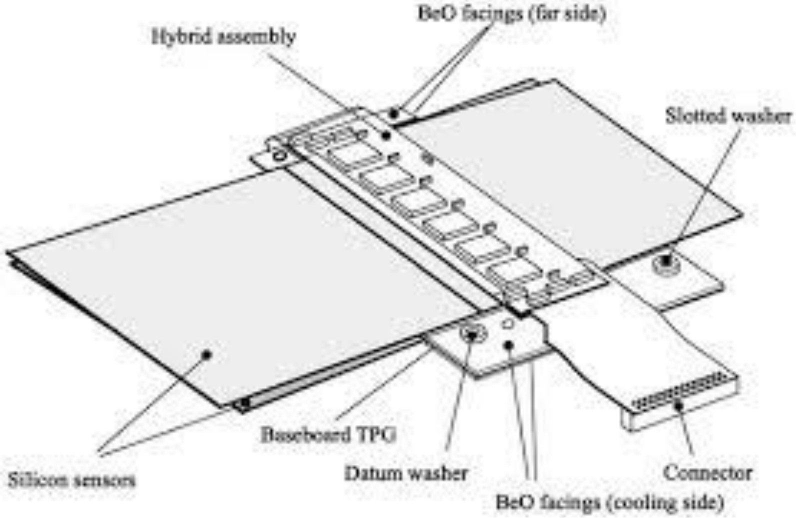
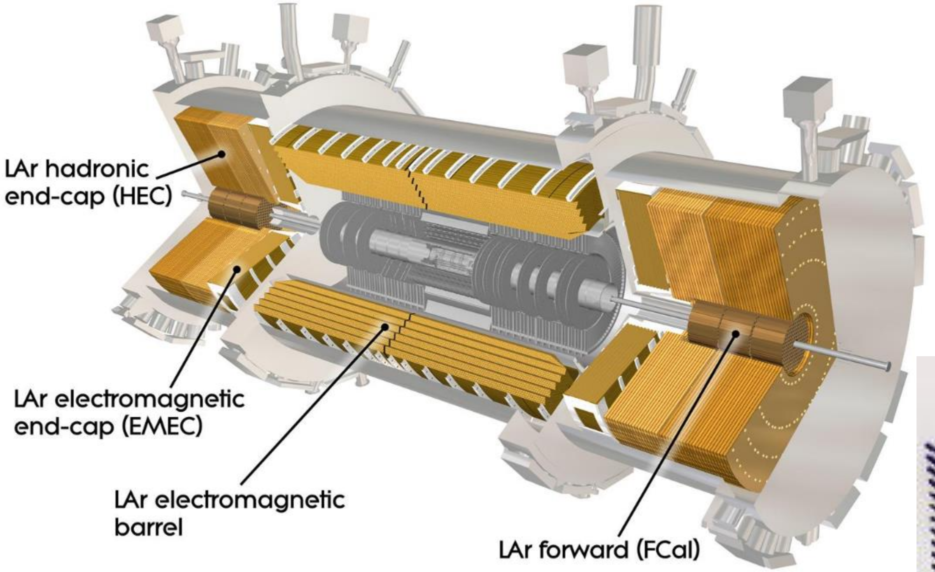






Radiation tolerance, power and cooling problematic

Liquid Argon e-m calorimeter

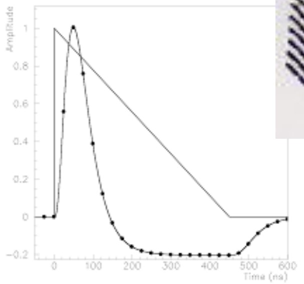


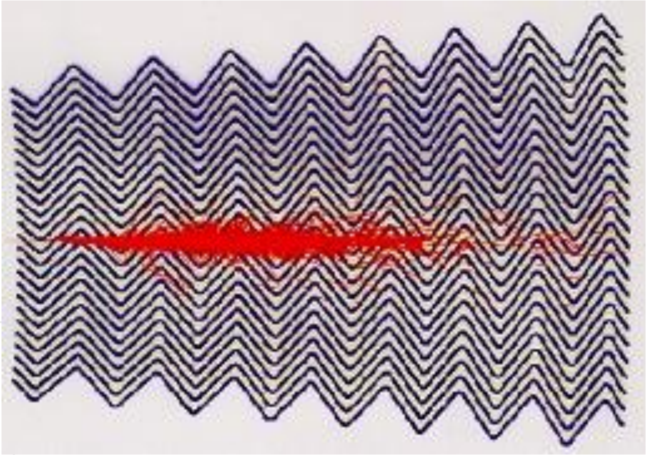
Liquid Argon-Lead/stainless steel calorimeter (87^oK)

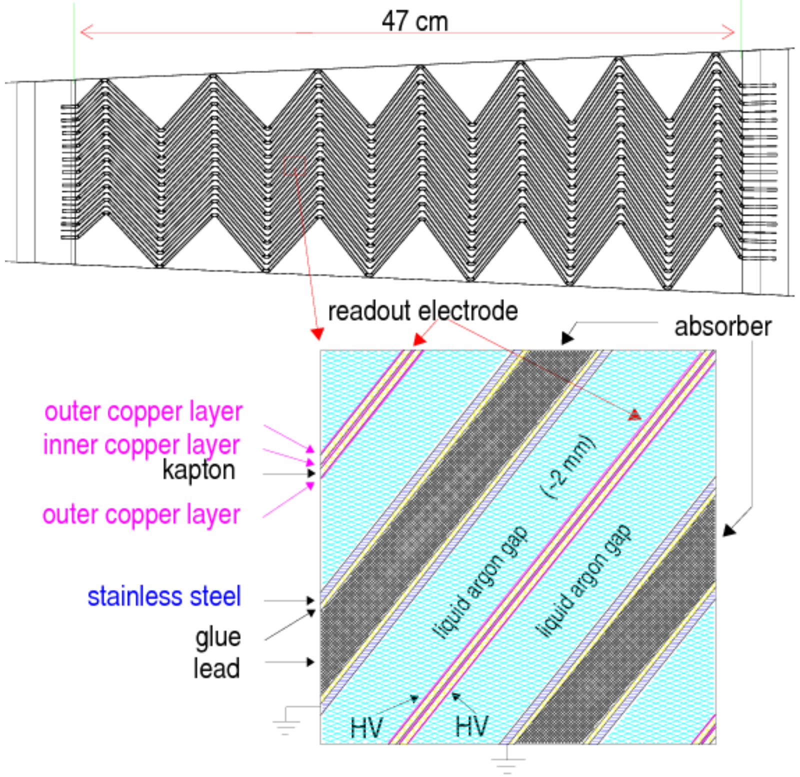
16-bit dynamic range

Cooled preamplifiers

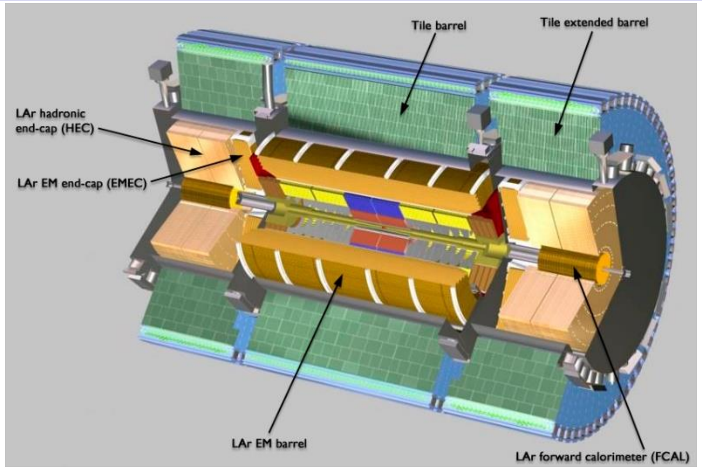
4 layers + presampler







TileCal hadron calorimeter

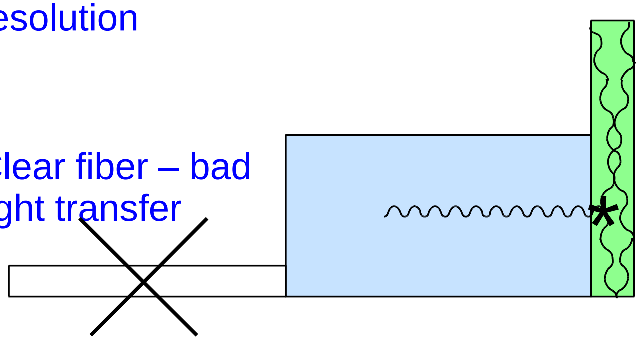


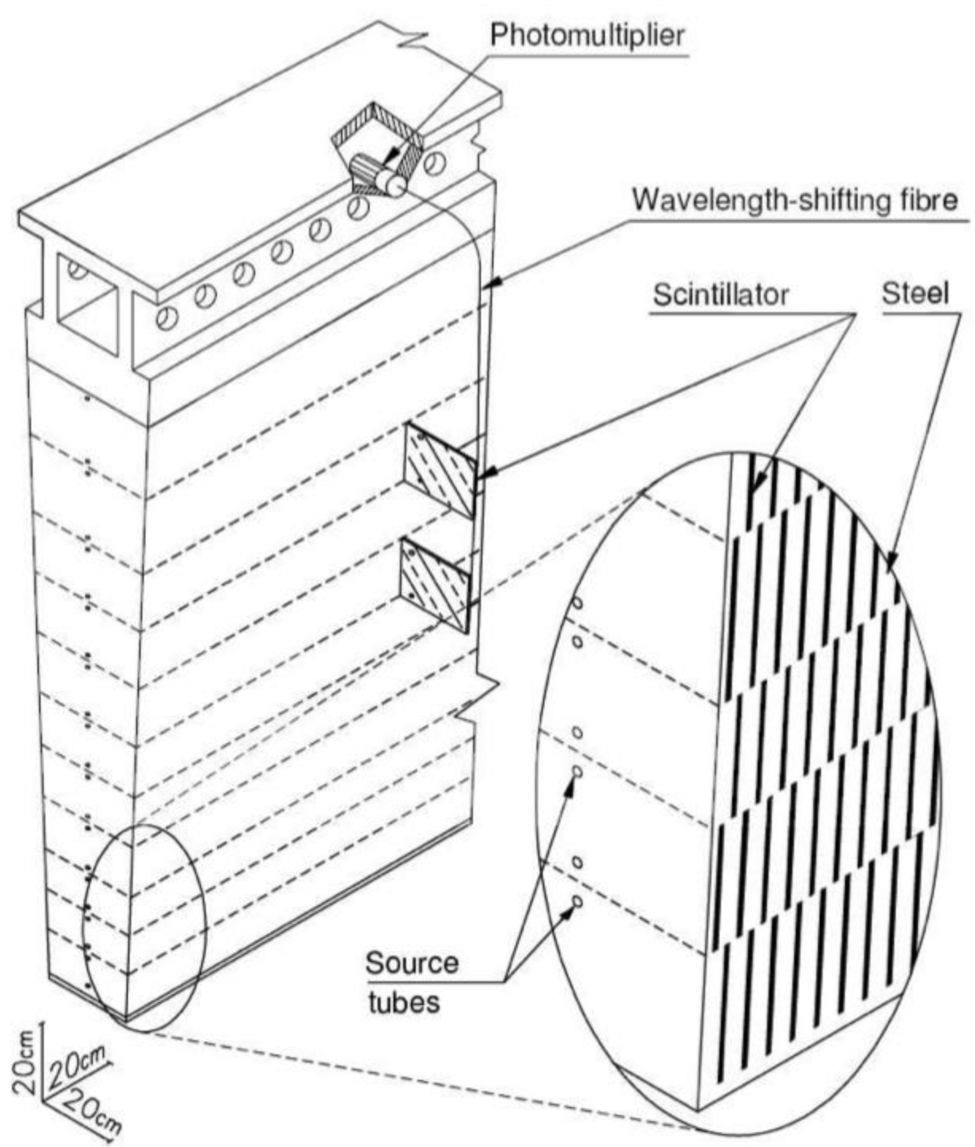
Interleaved wedge shaped modules with steel and scintillator tiles

256 modules, each weighing 10 tons

4 depth layers

Coarse spatial but good amplitude resolution





The Muon Spectrometer

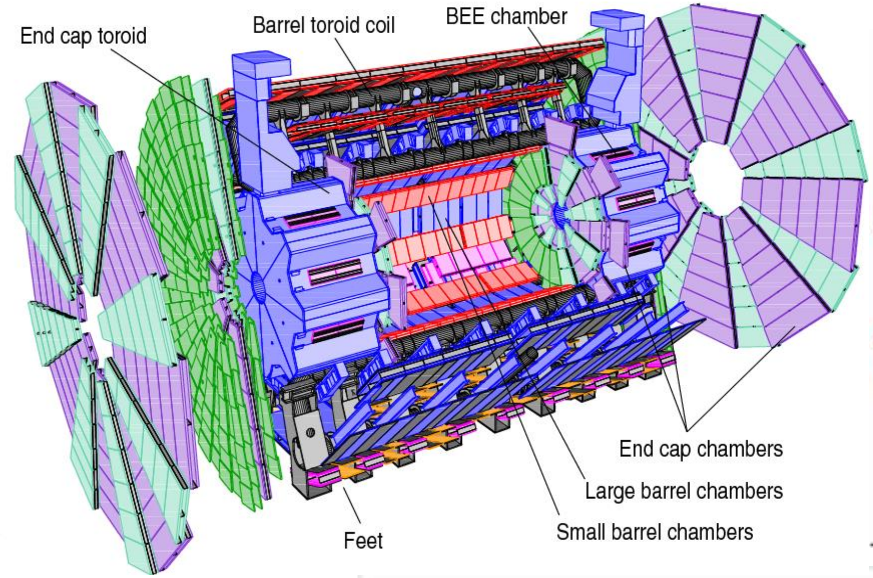
Geometrical alignment precision 30 μm

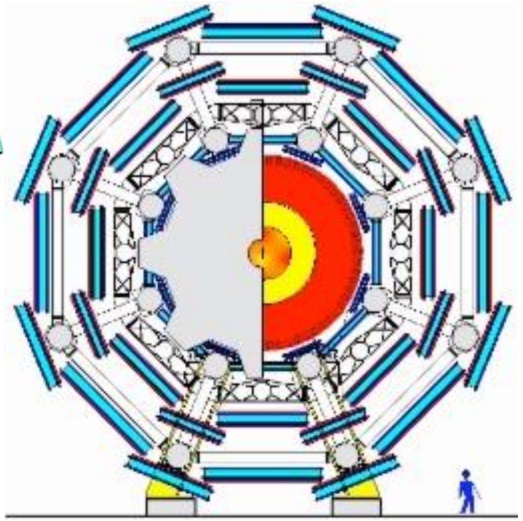
Alignment can change due to temperature change or deformations when the magnet field is changed

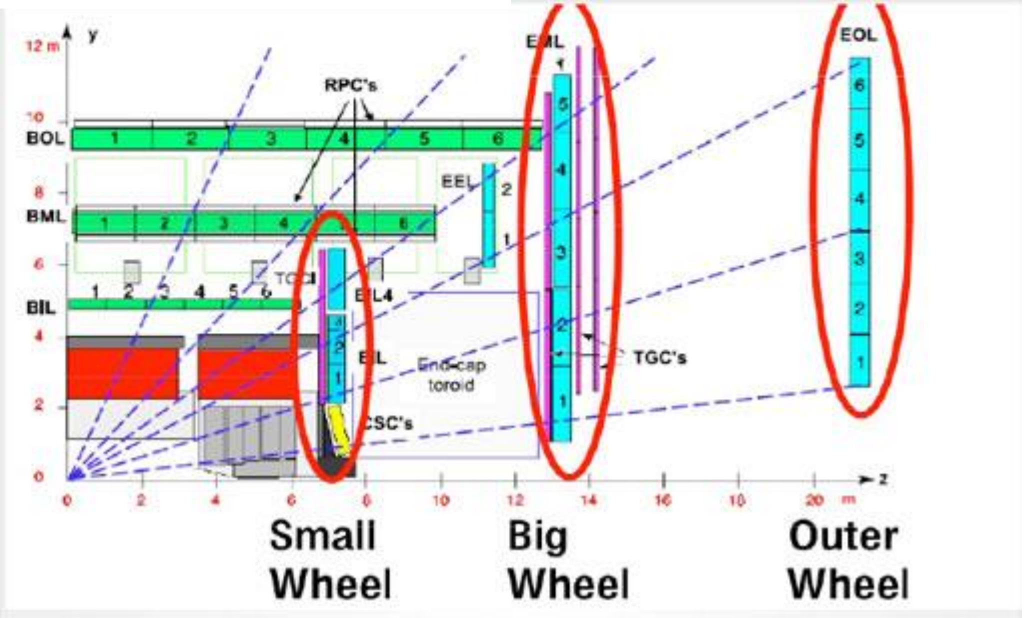
Cost → Use gas detectors, different types for precision and trigger and different types for normal and high intensity regions, close to beam pipe

MDT(Monitored Drift Tubes) and CSC (Cathode Strip Chambers) for high precision. CSC for high intensity forward regions

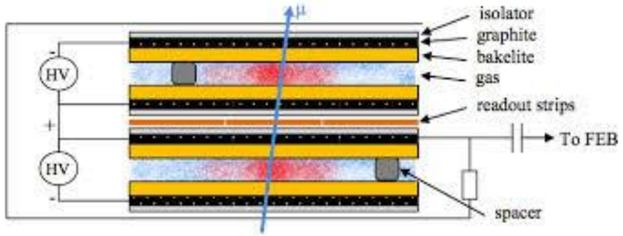
RPC (Resistive Plate Chambers) and TGC (Thin Gap Chambers) for trigger. TGC for high intensity regions.



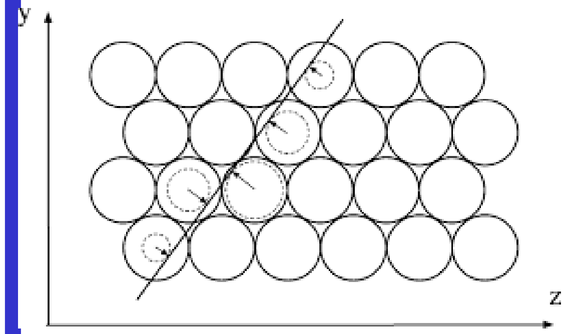


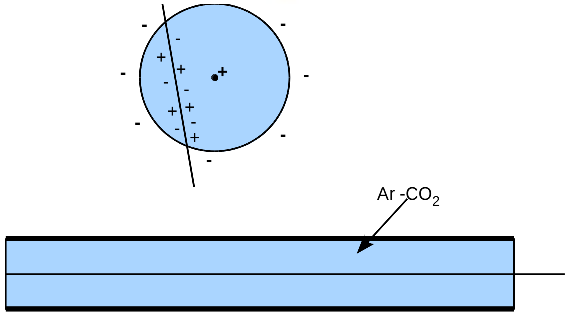


The Muon Spectrometer

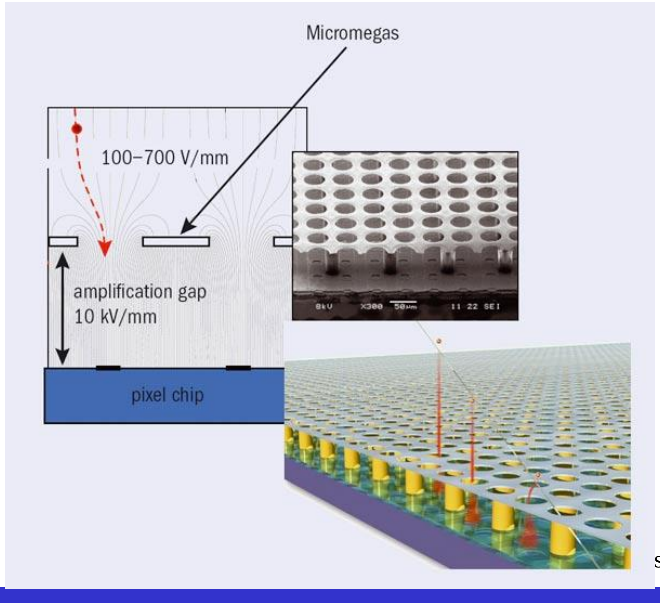


RPC – Resistive Plate Chamber



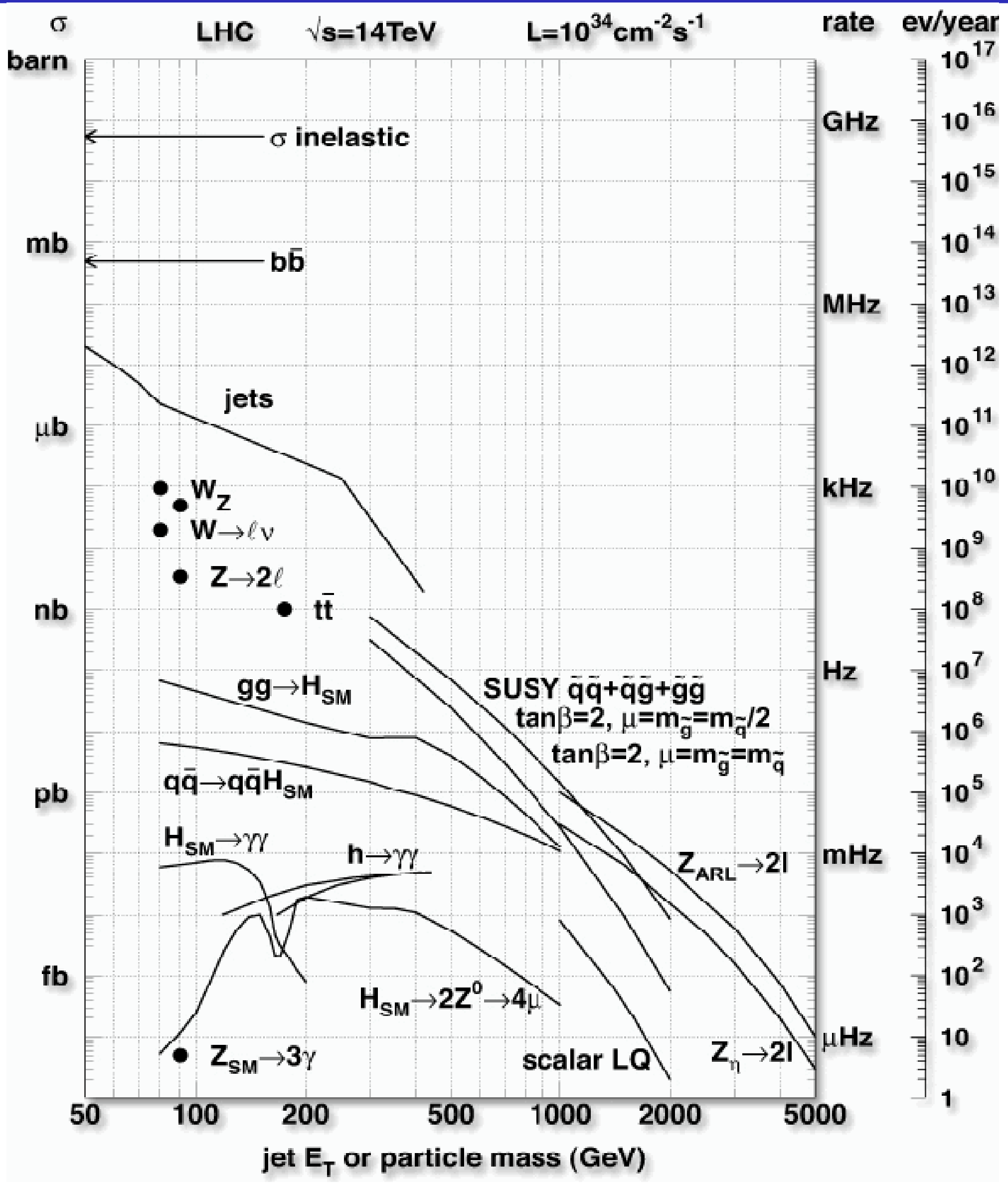


MDT – Monitored Drift Tubes



Micromegas for muon detector upgrade

Trigger and Data Acquistion (TDAQ)

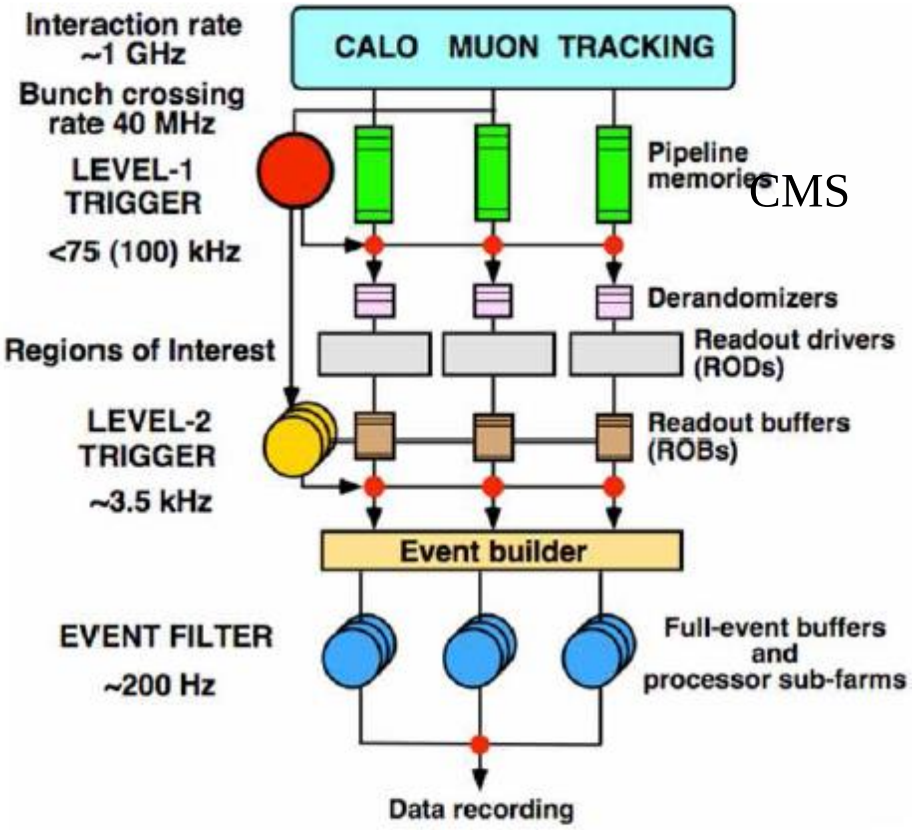


20 event per BC at nominal Luminosity
But SUSY not discovered yet

Trigger and Data Acquistion (TDAQ)

Reading out all data, every bunch crossing, was completely impossible 2008 – due to data transfer limitations

Solution -> use multilevel trigger – but introduce data storage limitations due to radiation tolerance problems



CMS

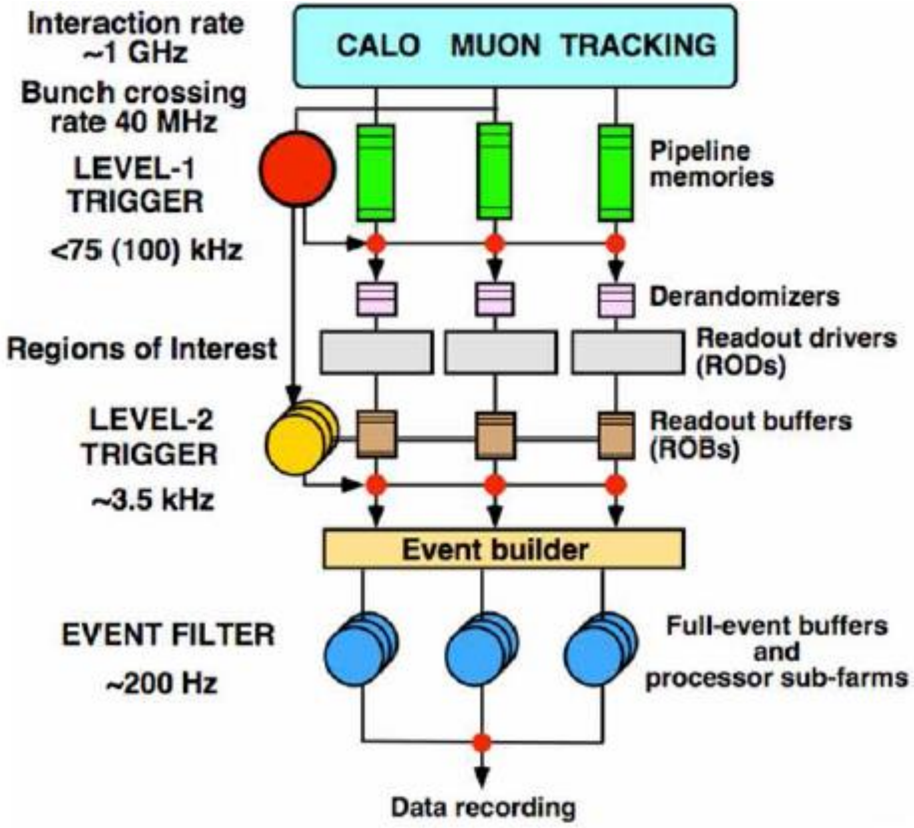
Trigger and Data Acquistion (TDAQ)

First level trigger – pipe-lined processing (in FPGAs) of merged calorimeter and muon data with reduced spatial and amplitude information - delivers Regions Of Interest

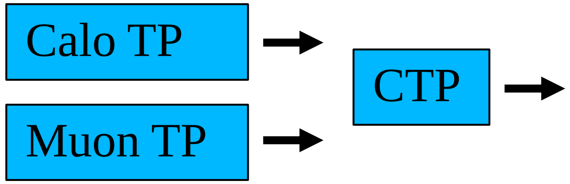
Second level trigger – PC based software processing full resolution data from all subdetectors but only from RIOs

Third level trigger – Event Builder – PC farm to on-line analyze all data at highest precision

A first selection criteria is to require large transverse energy components to guarantee a head-on collision



First level trigger



The Calorimeter trigger processor and the Muon trigger processor reports to the **Central Trigger Processor** (CTP)

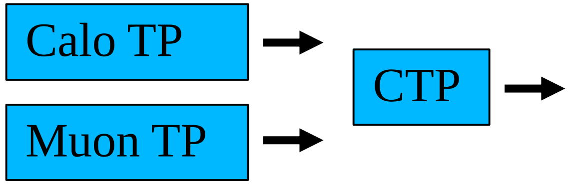
CTP looks for characteristic signatures in the data that indicates that the data contains an interesting event e.g.

- 4 isolated electrons or
- 4 muons or
- 2 high energy electrons over a certain threshold and 2 jets
- etc.

The search criteria are defined in the **Trigger Menu** data base

The current Trigger Menu selection is defined at the start of a run

First level trigger



All data can be stored on the detector for maximum 2.5 μs – the **latency** of the first level trigger

Before this, a decision must made on saving or not saving that data

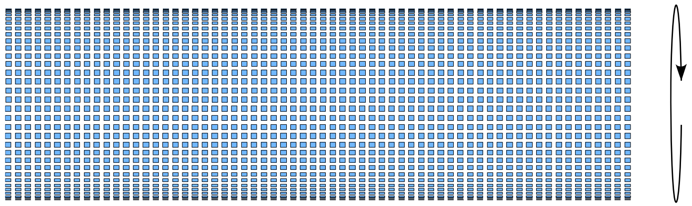
The specified data latency allows for sending the data from the detector to the trigger processor in USA-15 (Underground Storage Area), process it and send the result back to the detector for possible transmission of the entire data set.

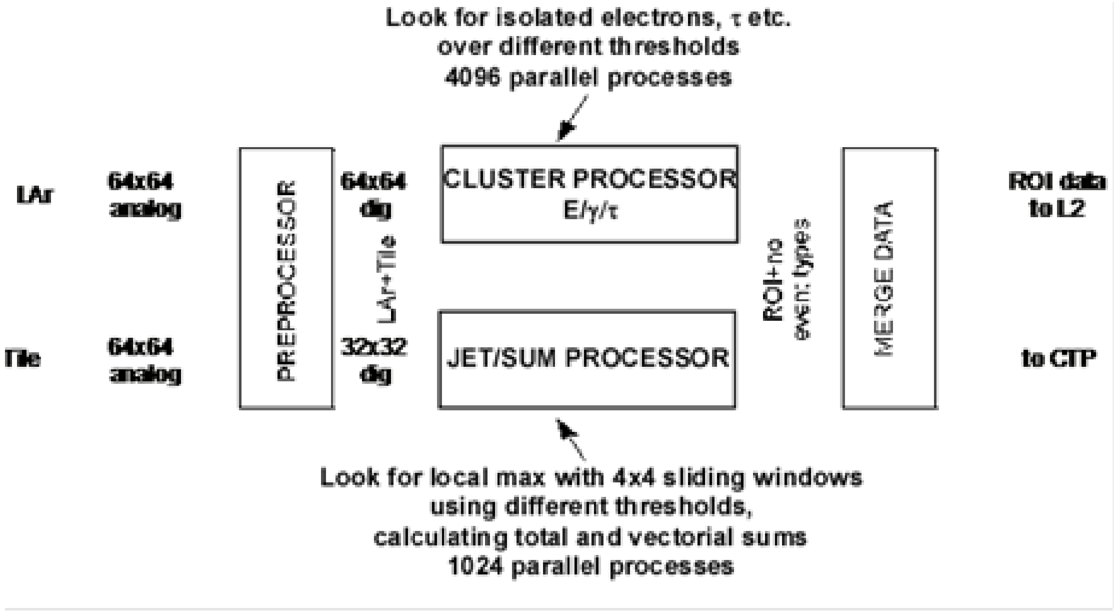
First level trigger

Each bunch crossing, i.e. each 25ns

4096 trigger data values arrive from LAr and Tile

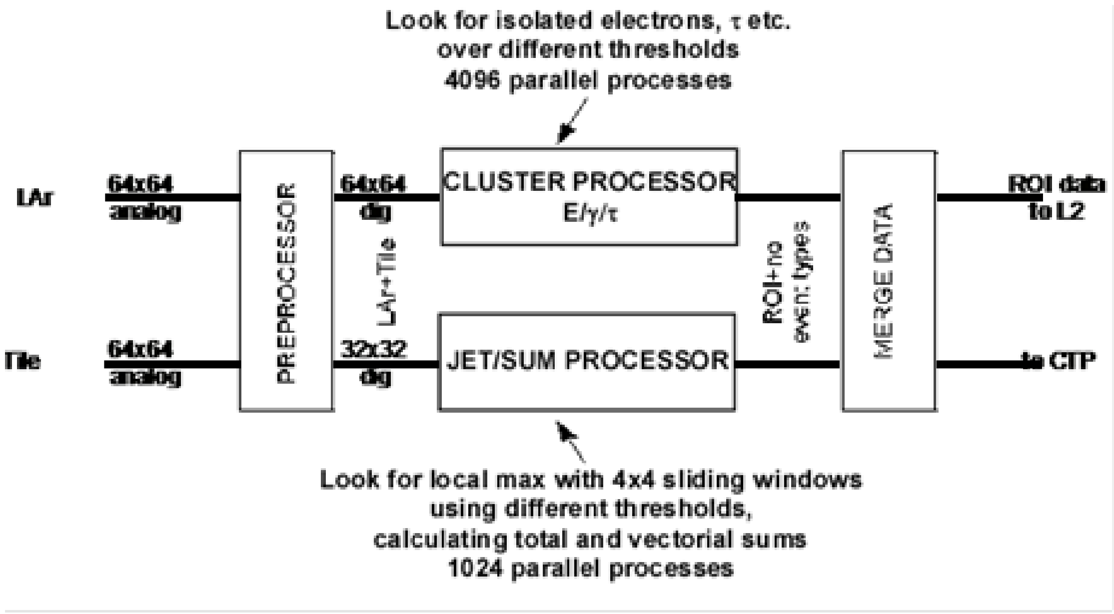
64 cell rows around the calorimeter cylinder and 64 cells in each row along the detector



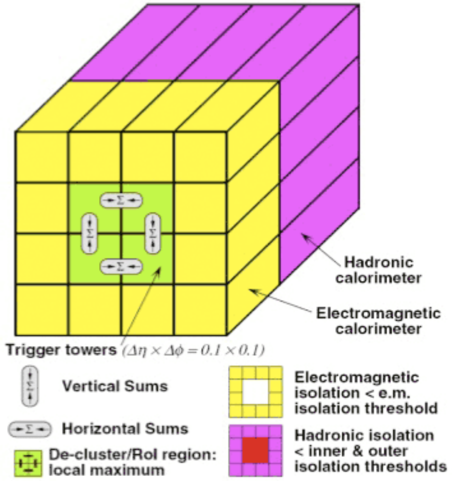


For each corresponding trigger cell one must study if it contained an interesting event
4096 parallel processes start every 25ns and should be completed within 1 μs
FPGAs widely used together with pipelined processing

First level trigger



CLUSTER FINDING e/γ ALGORITHM



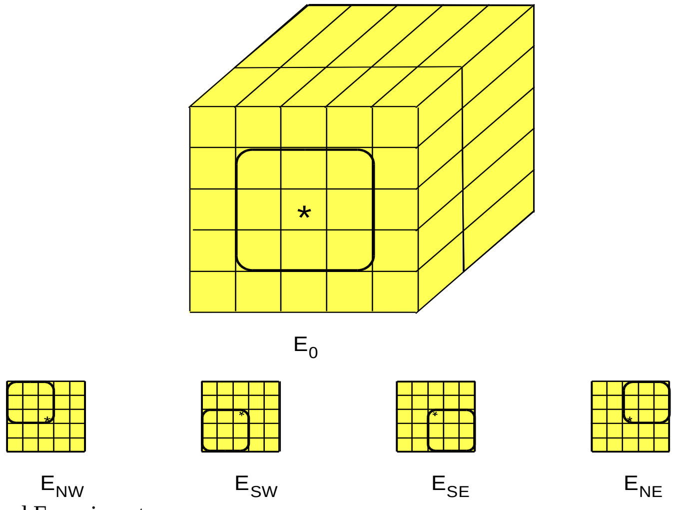
For each cell anf each set of thresh.

Vert. SUM or Hor. SUM > thresh.

Em isolation SUM< thresh.

Had isolation SUM < thresh.

JET MAX ALGORITHM



Condition for jet maximum: $E_{NW}, E_{SW}, E_{SE}, E_{NE} < E_0$

Synchronization

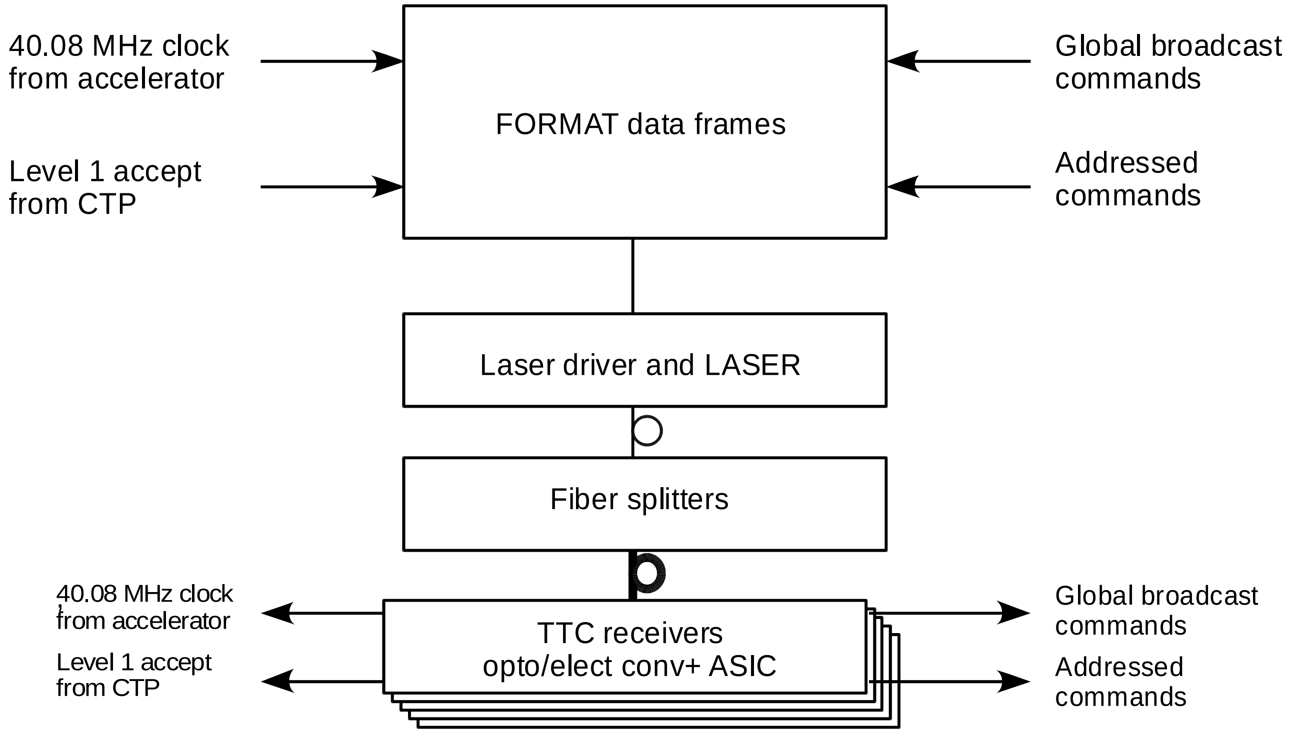
The Timing, Trigger and Control (TTC) system is responsible for synchronization

The accelerator clock 40.08 MHz distributed to all Front-End units with local phase control

L1A distributed to all FE-boards with programmable delay to maintain sync.

Addressed commands to configure local FE-boards

Maintains Bunch Crossing Identifier BCID to label events



Detector Control - DCS

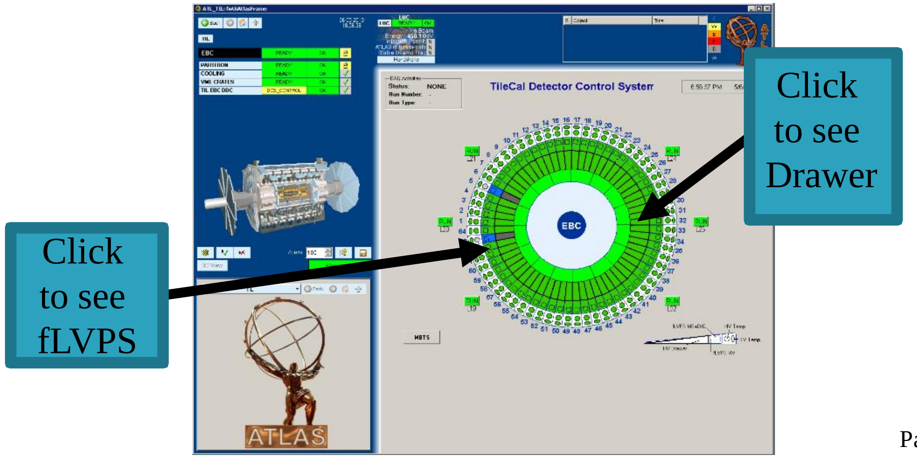
The Detector Control System or Slow Control, as it was called before, is responsible for initializing and monitoring of all system components including configuring programmable logic (FPGAs).

It will monitor parameters like temperatures, fan operation, pressures, voltages, currents, humilities, error conditions etc..

It is also responsible for safety functions and alarms

It records error conditions and archives monitored parameters

When supervising DCS it is important to have efficient and intuitive GUIs



ATLAS control room

ATLAS upgrades

LHC has yearly stops for minor repairs (End of YEar Stops, EYES)
and regular stops for longer maintenance and upgrade, LS 1-

Run 1 LS 1 Run 2 LS 2 Run 3 LS 3 Run 4 HL-LHC

2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2037?

-

End of operation 2037?

Initial operation - Run 1
Reduced energy 6.5 TeV
Luminosity:

ATLAS upgrades

LHC has yearly stops for minor repairs (End of YEar Stops, EYES)
and regular stops for longer maintenance and upgrade, LS 1-

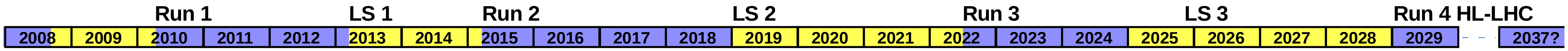
		Run 1			LS 1		Run 2				LS 2			Run 3				LS 3			Run 4 HL-LHC		
2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	- - -	2037?

End of operation 2037?

Upgrade phase 0 (LS 1) – 2008-2010
Prepare for almost full energy 13 TeV
Insertable B-layer (3.3 cm from beam center) – replaced the inner pixel layer

ATLAS upgrades

LHC has yearly stops for minor repairs (End of YEar Stops, EYES)
and regular stops for longer maintenance and upgrade, LS 1-

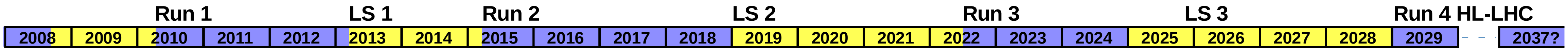


End of operation 2037?

Upgrade phase 1 (LS 2) – 2019-2022
3 times higher luminosity, need better algorithms and more processing power
Full energy 14 TeV
New Small Wheels
Topological trigger – not only count event but also consider their geometrical relationship
LAr fully digital trigger
New trigger architecture

ATLAS upgrades

LHC has yearly stops for minor repairs (End of YEar Stops, EYES)
and regular stops for longer maintenance and upgrade, LS 1-



End of operation 2037?

Upgrade phase 2 (LS 3) – 2025-27
Prepare for HL-LHC (High Luminosity LHC)
5 times nominal instantaneous luminosity, need still better algorithms
10 times total luminosity – luminosity leveling
New Trigger system – level 0 (L0a: 1MHz, Latency: 6μs) (level1 (L1a:<400kHz,Latency: <30μs))?
New inner detector – no TRT, track trigger (introducing track data into Level 1)?
New TileCal electronics – read out all data to USA-15 – fully digital trigger
New trigger architecture L0/L1?, higher rates, longer latencies
200 non-elastic collisions per bunch crossing

Different electronic design strategies

When designing the first (present) version of the ATLAS electronics then:

Special rad hard (tolerant) electronics was available (close to end of cold war)

High speed data transmission (optical or electrical) expensive→

Send reduced trigger data to external L1 trigger processor. Keep data on detector until L1 accepted –> reduced data flow

Now:

standard electronics reasonably radiation tolerant – SingleEveventError problems

High speed transmission available →

Remove all data from detector as soon as possible

Then:

FPGAs unsafe

Now:

SEE mitigation techniques exist making on-detector FPGAs feasible

Mistakes

We learn from mistakes but some times we forget what we learned'
Connector problems
Power supply problems
Radiation sensitivity problems
Problems with new untested techniques

Future

General trends

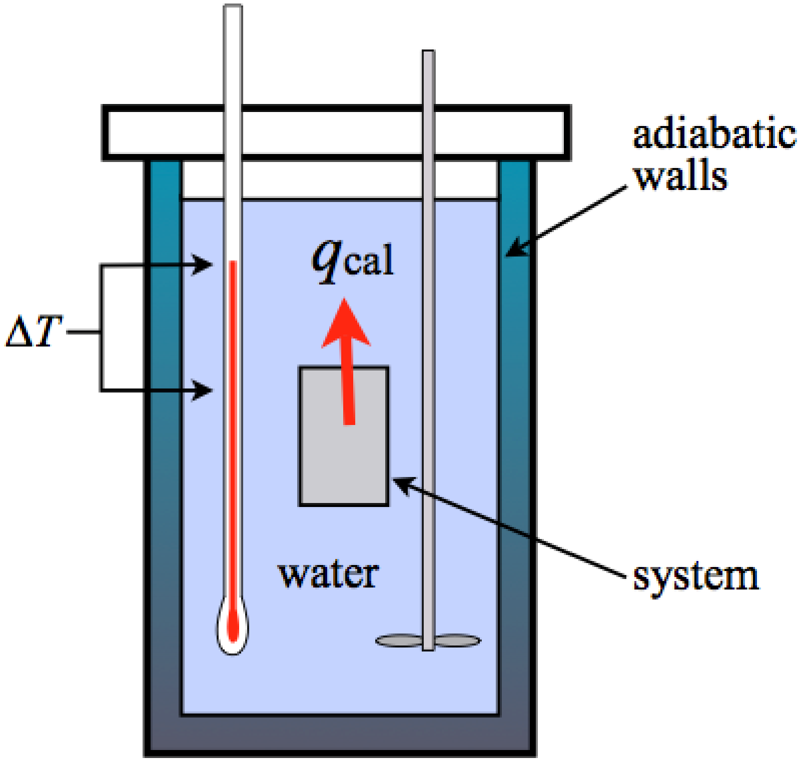
Higher energies
Higher luminosity
Higher granularity in all detector sub-systems
More complicated events to process early in the triggers
More on-detector FPGAs – new FPGAs more radiation tolerant to hard but not soft errors – develop correction strategies for soft errors
More high speed data transmission – 40 Gb/s or more
Early digitization – less analog, more digital

After 2037: FCC

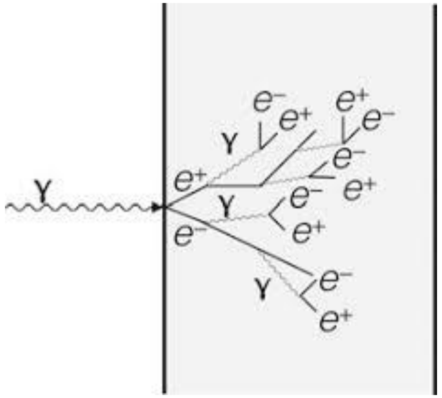
Future Circular Collider
FCC
50+50TeV
>10^{35} protons/cm^2/sec
First e^+ - e^- later p – e and p - p
100 km circumference
Assumes new magnet technologies
16TeV Nb_3Tn magnets
Conceptual Design Report 2019

Calorimeters

This is a classical calorimeter used by chemists
Its task is to measure all the heat dissipated by the system under study



Calorimeters



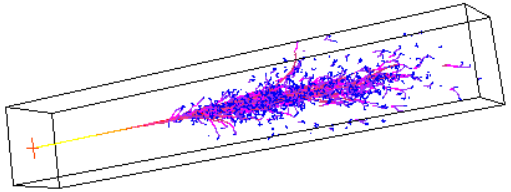
A particle physics calorimeter is supposed to contain all radiation of a certain type and estimate its energy and preferably also its trajectory

A calorimeter can be composed of a crystal or a combination of absorber and scintillator

If the incoming particle with the energy E is showered into n particles with similar energy, the total energy should be proportional to n and its standard deviation σ_E proportional to sqrt(E), i.e.

$$\sigma_E /E \text{ proportional to } E^{-1/2}$$

This assumes that the resolution is only dependent on statistics



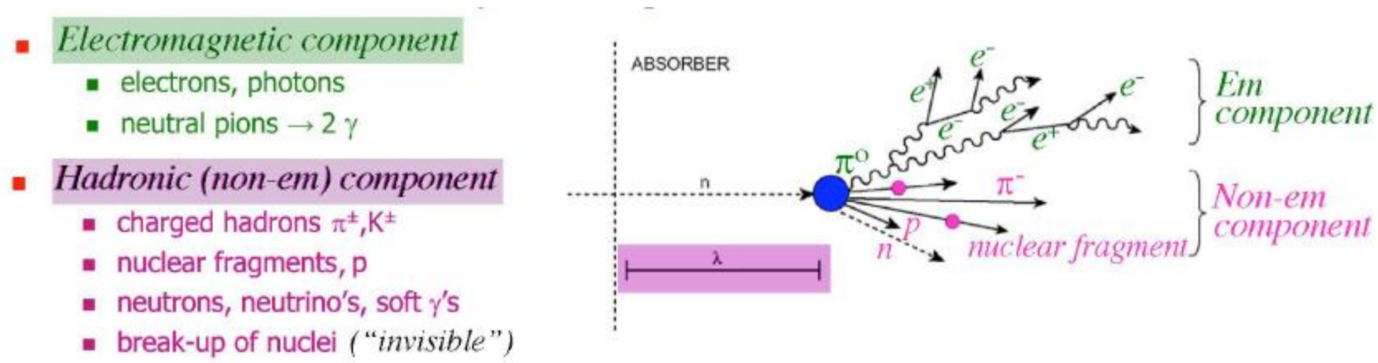
A simulated shower

Calorimeters

EM calorimeters and hadron calorimeters are optimized differently

Fluctuations in a hadron calorimeter deviates from $E^{-1/2}$

A hadronic shower consist of two parts, e and h



The "break-up of nuclei" contribution is lost to the signal

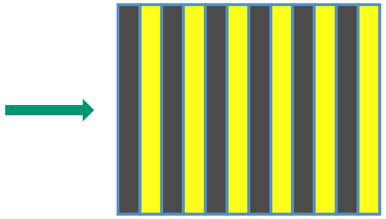
A hadron calorimeter can be characterized by the e/h ratio

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus c/E$$

a stochastic term number of shower Particles	b constant term and inhomogenities non-linearities	c noise term electronic noise

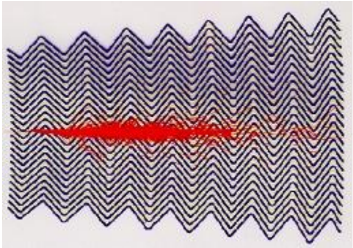
Calorimeters

Two main types of calorimeters
Homogeneous
Crystal or liquid
Sampling
Interleaved absorbers and scintillators

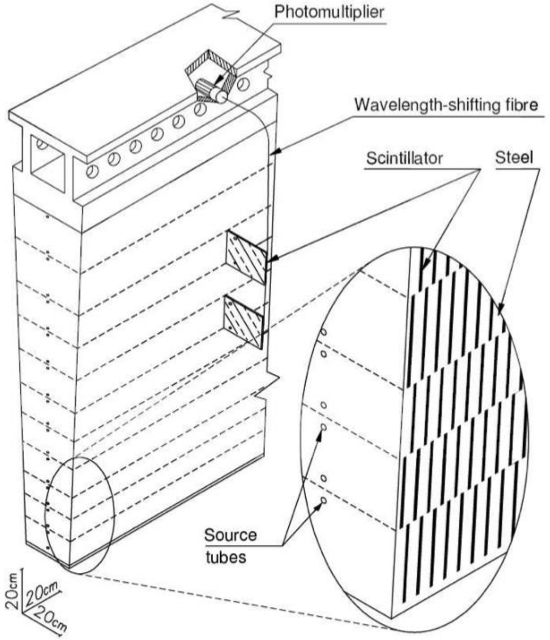


Hight Z values good for EM using U and W have been used
CMS ECAL is homogeneous and CMS HCAL sampling
ATLAS Lar (E/M) and TileCal (Hadron) are both sampling

To understand the calorimeter response require
multiple test beam campaignes



Lar: Ar (liq)+Pb



TileCal: Steel+plastic scintillator

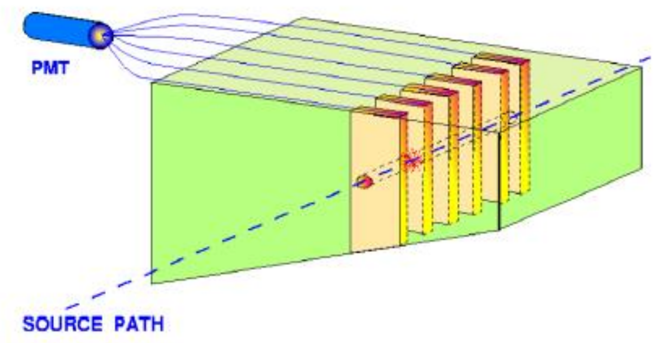
Calibration - problem for TileCal

Scintillators and fibers age due to radiation

PMTs age when exposed to light

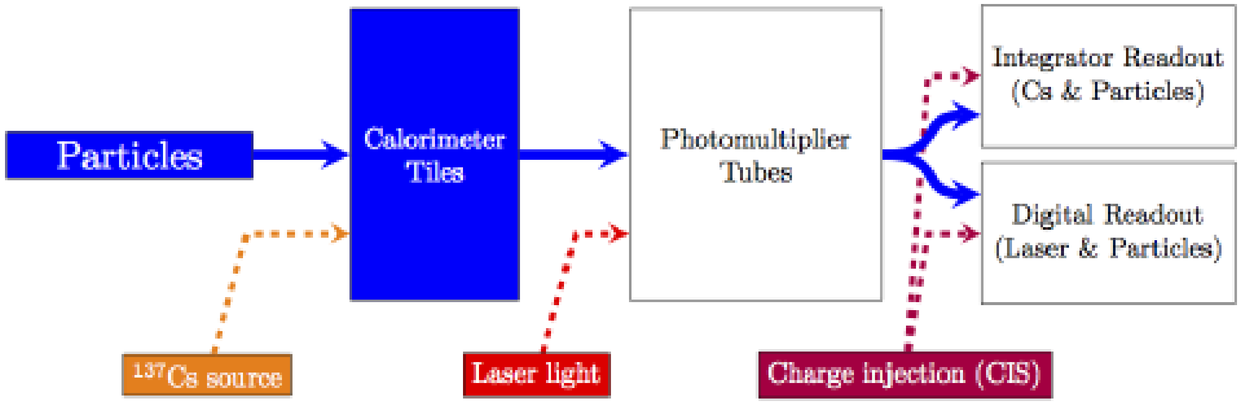
Three calibration methods:

- Cesium calibration – with circulating sources
- Laser calibration – with clear fibers
- Charge injection – in FEB



Performed often sometimes in gaps during measurements

Ref:
Richard Wigmans

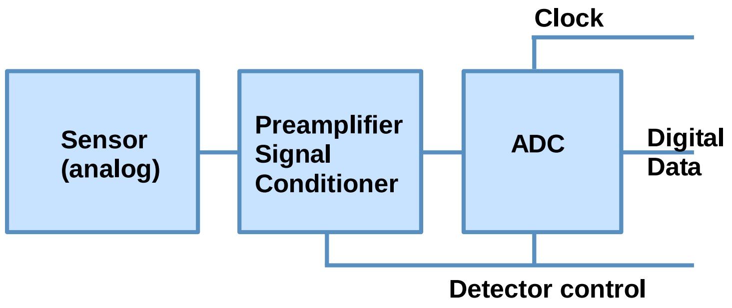


Trigger and Data Acquisition

TDAQ tasks:

- Read out data from the detectors (Readout)
- Collect complete events (Event Building)
- Keep some typical uninteresting events for further analysis
- Stores event data (Data logging)
- Provides control, configuration and monitoring facilities (Detector Control System, DCS)

Front-End modules



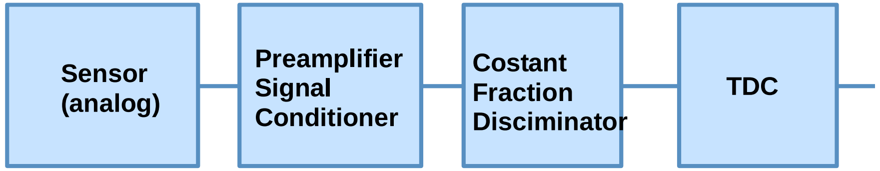
Most detector systems perform the digitization inside the front-end unit

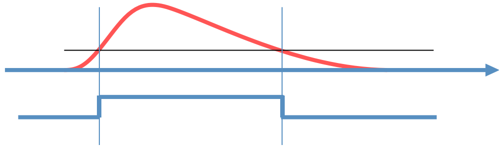
Preamplifiers are needed to amplify weak sensor signals
A signal conditioner will shape the signal to improve signal/noise ratio
A low pass filter will reduce high frequency noise
If a large dynamic range is desired the signal can be duplicated with different amplifications

The ADC will sample the signal at a suitable rate depending on the frequency range of the signal.
Nyquist sampling rate

Detector control is needed to program and calibrate the front end modules

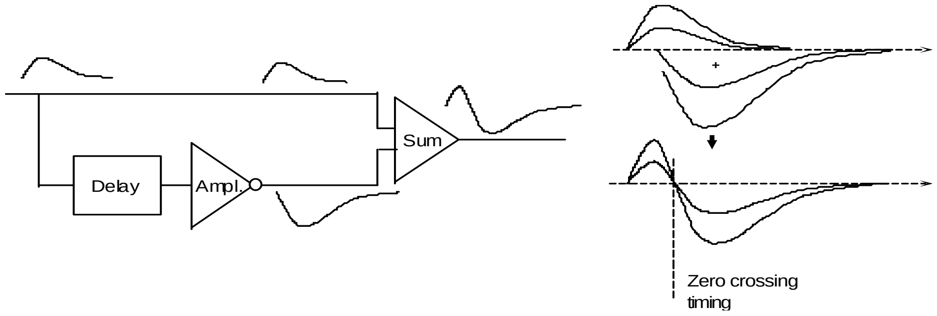
Front-End modules



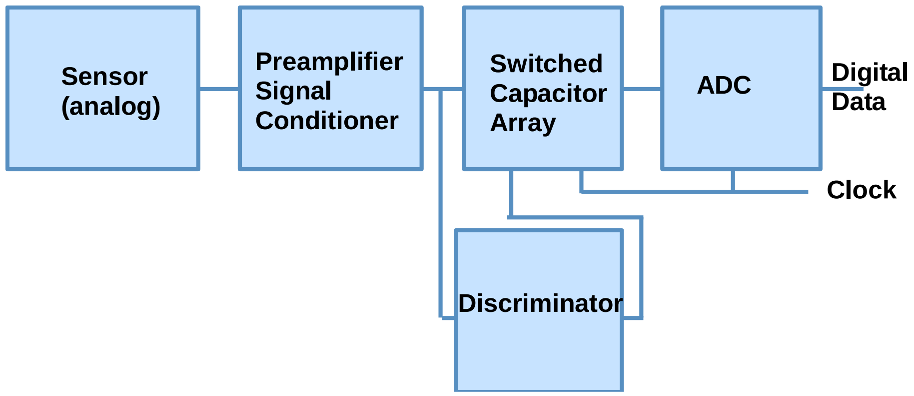


Instead of ADC a TOT, Time Over Threshold circuit can be used with a TDC, Time to Digital Converter to measure the pulse length
There is a non-linear relation between TOT and the amplitude.

This solution is suitable to use in combination with integrated circuits, i.e. ASICs or FPGAs



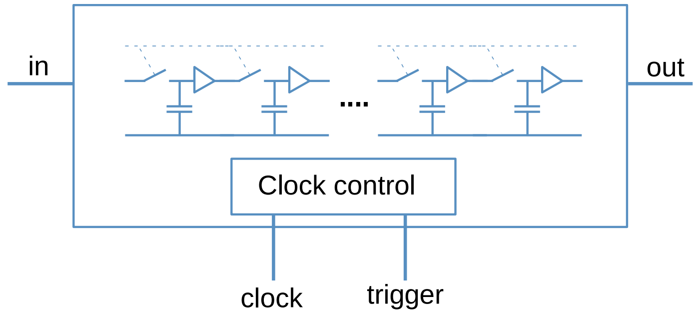
Front-End modules



A wave form sampler can be used in the front-end were analog samples are stored in a switched capacitor array - capable of multi Gbps sample rates

A trigger signal reduces the internal clock rate so that the samples can be read out in a standard ADC

Also called transient recorder



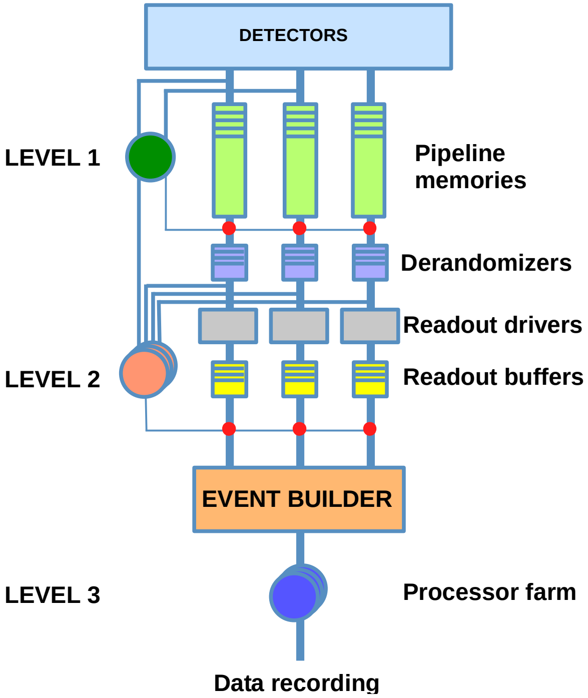
Trigger

Problem: How to extract meaning full information from ~10^8 channels and store it without exceeding the storage capacity

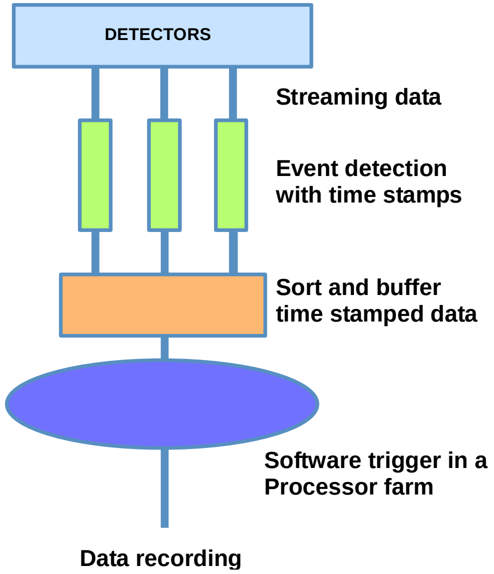
How to reduce data without loosing important data

Data Reduction – two different strategies

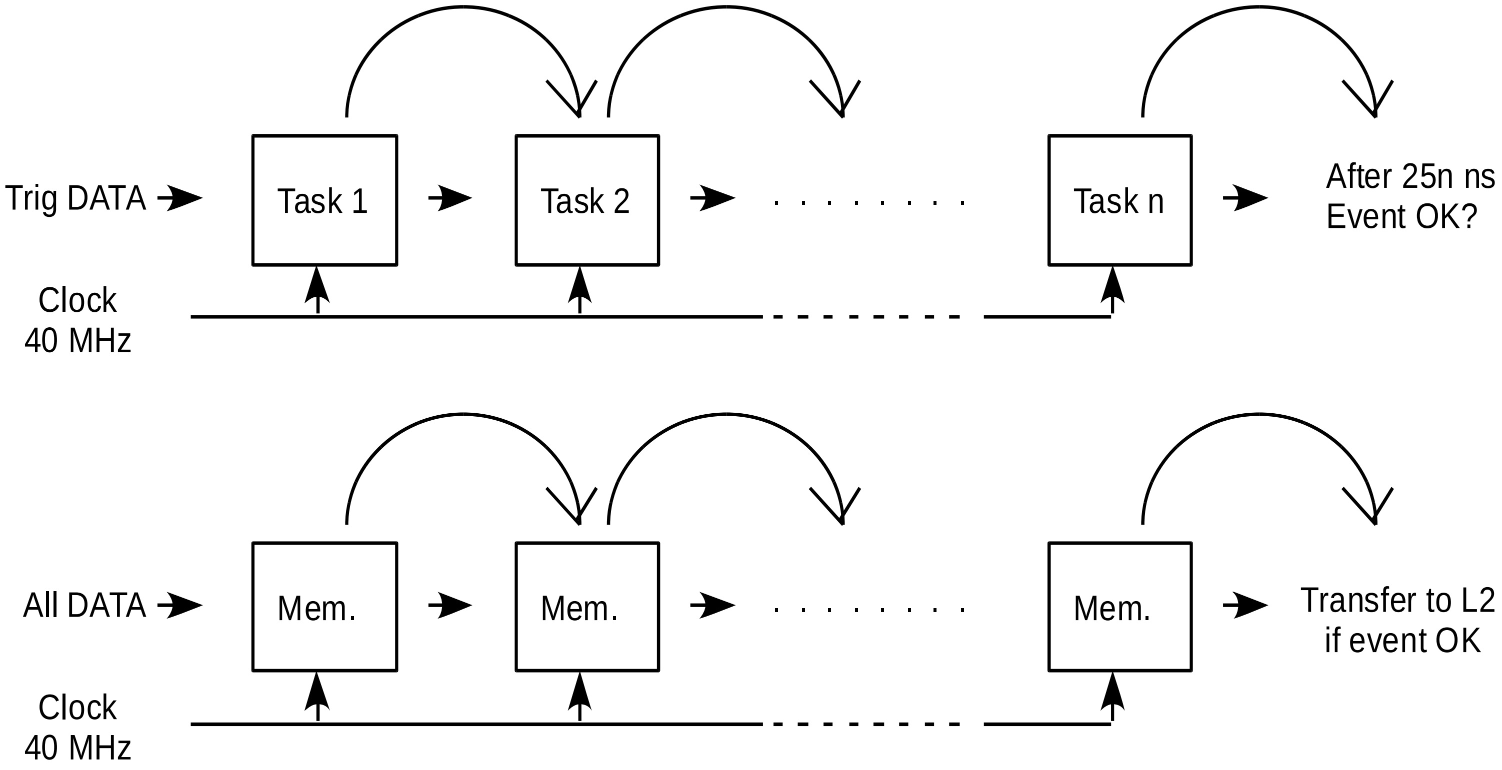
Traditional DAQ



Self triggered DAQ

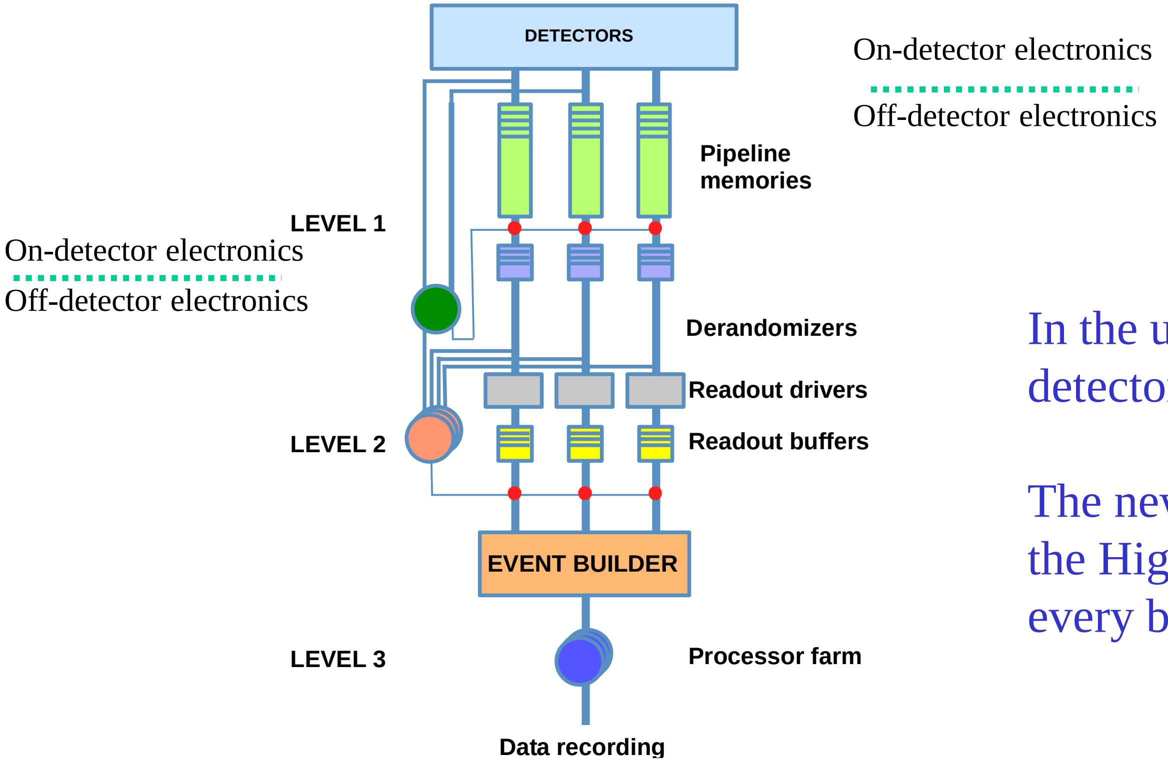


Pipelined Processing



On/off-detector Processing

In the original ATLAS electronics high band width communication was expensive -> Send reduced (amplitude and granularity data) trigger data to off detector LEVEL 1 Trigger processor. The decision is sent back to the detector.

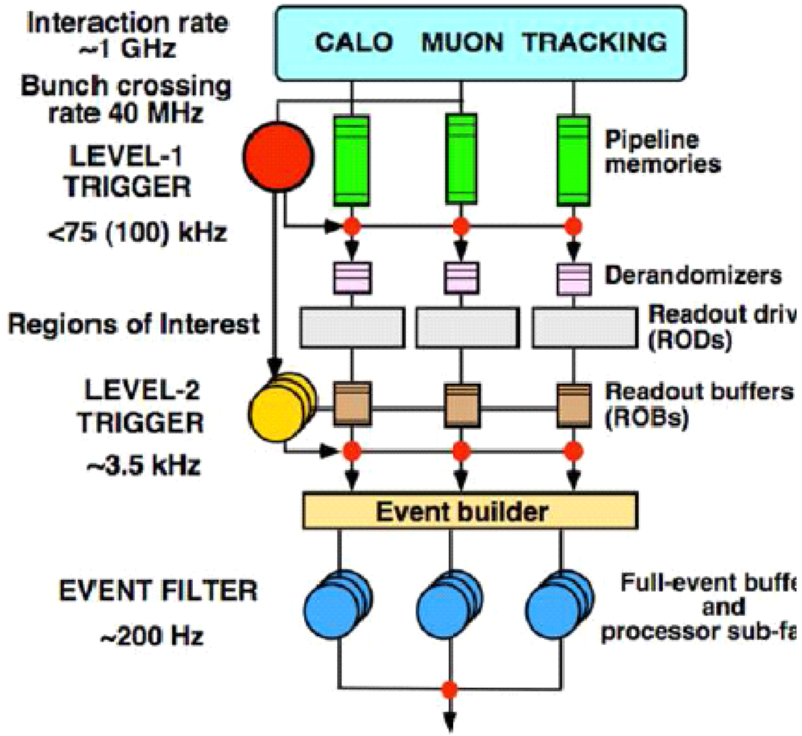


In the upgraded system digitized data is sent off detector without delay.

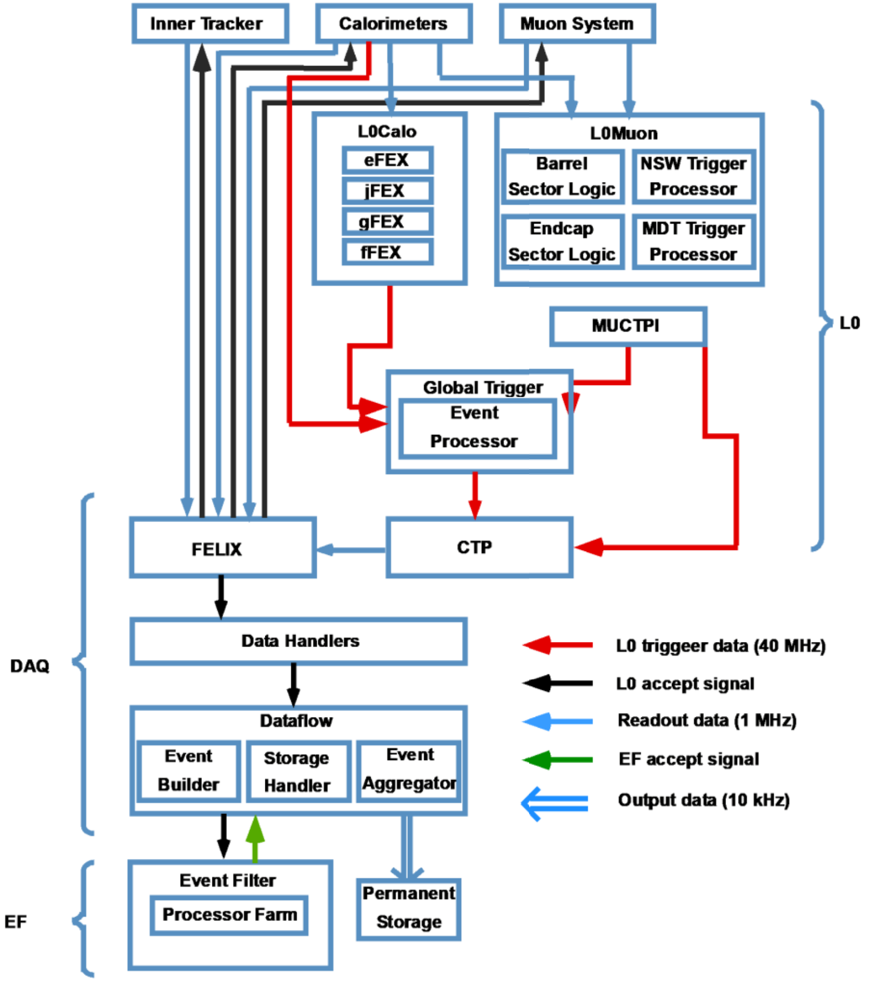
The new strategy is necessary to cope with the needs of the High-luminosity LHC and its 200 collision event at every bunch crossing.

ATLAS Phase-II TDAQ

Present system



Phase II system



Radiation tolerance

The on-detector electronics need to be sufficiently radiation tolerant
Verified by radiation testing
Expose system to different types of radiation – photon, electron, proton…
Different types of errors:

- TID – Total Ionizing Dose
  - The total energy absorbed by matter.
- NIEL – Non-Ionizing Energy Loss
  - elastic and non-elastic nuclear interactions,
  - displacement damage
- SEE – Single Event Effect
  - Single energetic particles cause bit flips

Simulate to estimate radiation levels
Apply correction factors
Test component samples and system parts to verify functionality at different
Radiation tolerance can vary

- From fabrication process to process
- From manufacturer to manufacturer
- From foundry to foundry
- From lot to lot

Mitigation
Rad-hard (rad-tolerant) electronics
Redundant
Partitions to limit error consequences
TMR – tripple mode redundancy

Future Detector R/D projects

EGFA Detector R&D Roadmap

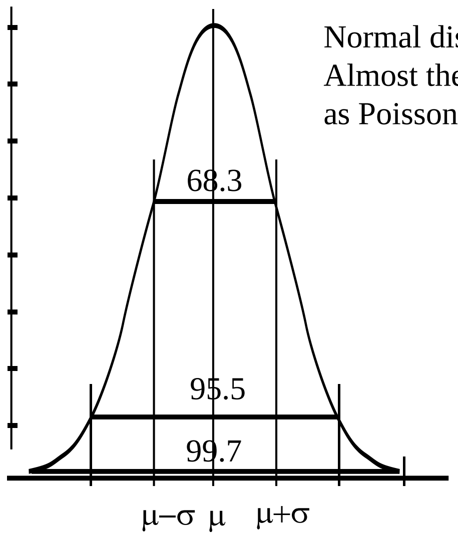
Future Circular Collider Conceptual Design Report

NuPECC Roadmap for Construction of Nuclear Physics - Research Infrastructures in Europe

Thank you for your attention

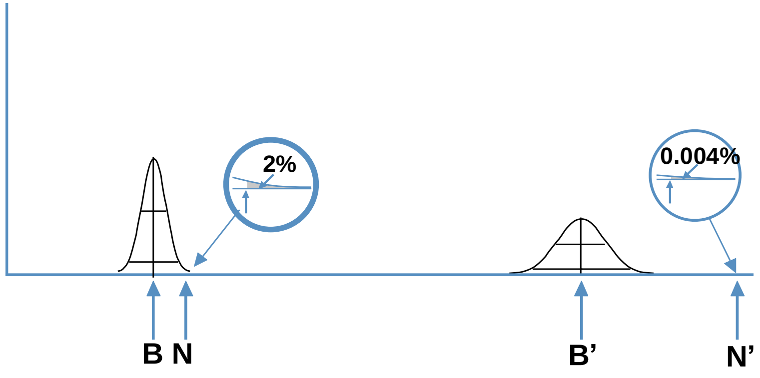
Why we need to record many events

To determine if **N** observed events include a new type of events that would constitute a discovery we must determine if the data could be produced by combinations of well-understood events. The probability for such events is the background **B** and its standard deviation σ(**B**)=sqrt(B) (Poisson statistics)



For **N** to be a discovery, **N** must be significantly larger than **B**
For example if **N** is 80 and **B** is 64 then σ(**B**) is 8
N is 2σ above i.e. 2% probability that N is just random noise

If we measure 4 times as long **N´** will be at 320 and **B´** 256 making σ(**B´**) 16, i.e. the difference is about 4σ(**B´**) corresponding to 0.004% that the measurement is just random noise. This is a much smaller probability but it is not enough to claim a discovery.

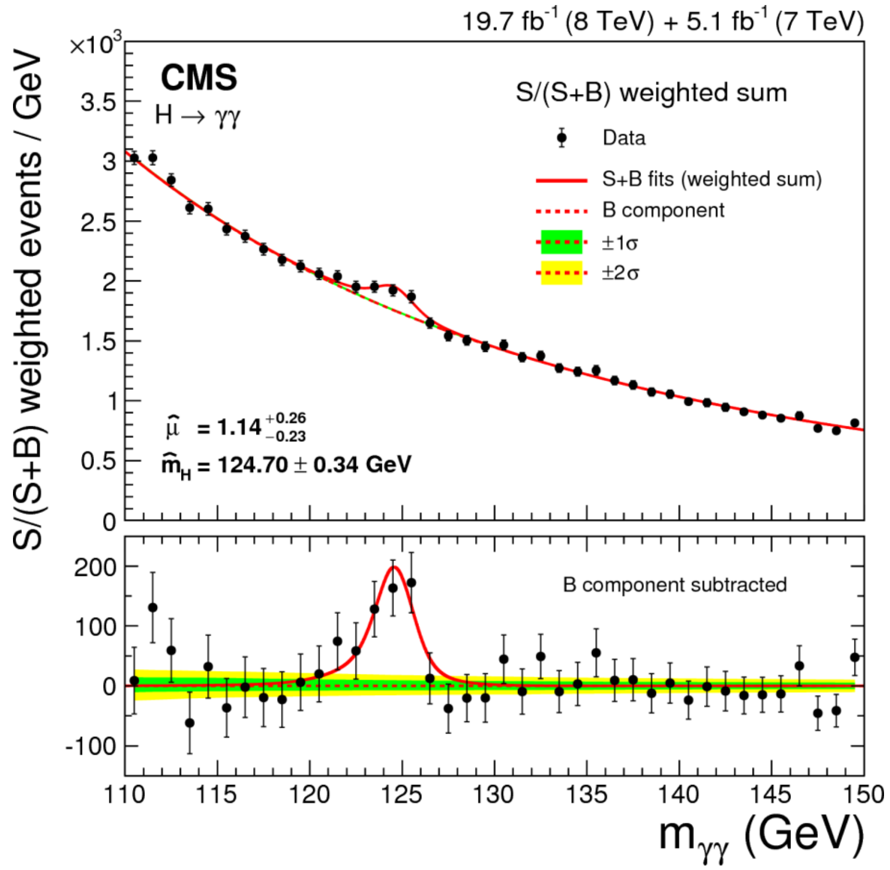


5σ (0.00002% it is random noise) is often required for discovery.

Why we need to record many events

The significance of N will grow after more measurements if it is a real effect, but the significance could also decrease or even disappear if it is not.

There are many 3σ effects that have disappeared, but a 5σ must have been a 3σ at some point (750GeV diphoton excess)



Beyond the Standard Model

We have a theory, the **Standard Model,** to explain much of the particle physics we have observed, but not all.
The task is to explore **Beyond Standard Model (BSM)** physics

One way is to find new **observational results t**hat cannot be explained by the Standard Model
Better precision (higher luminosity and longer measuring time) increases the probability for finding deviations

Another way is to **propose theories** that agrees with existing experimental results but also predicts new results that can be tested with experiments

Some potential BSM theories predict super symmetric partners to all normal particles **– none of which have been seen so far**

To progress we need to know where the Standard Model fails

We need more data and/or higher energies

Detectable Standard Model particles

u	c	t	γ
d	s	b	g
ν_e	ν_μ	ν_τ	Z
e	μ	τ	W

The **Standard Model,** explains most of the particle physics we have observed (but not all).
The most basic constituents are:
Leptons, quarks and bosons

These can be created in collisions in high energy physics experiments at accelerators, but short lived particles decay before they reach the active parts of the detector. They can only be deduced from their decay products.

We can detect **electrons,** (positive) **muons** and their anti-particles **(positrons** and **negative muons)**

The only boson we can detect directly is the **photon.**

We can detect composite particles (charged and uncharged) formed by quarks, called **hadrons** but have problems identifying them.

The hadrons can be **mesons** and **baryons** such as **protons** and **neutrons**

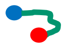
Jets

u	c	t	γ
d	s	b	g
ν_e	ν_μ	ν_τ	Z
e	μ	τ	W

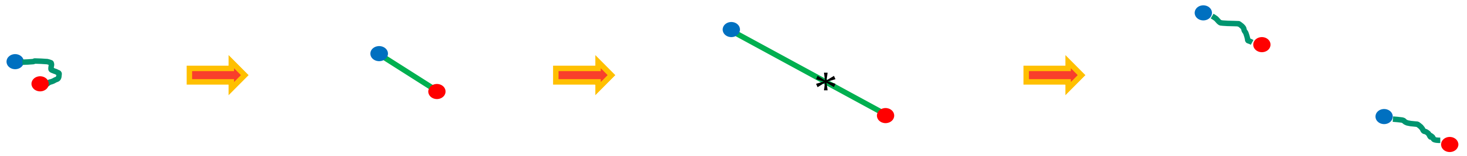
In the standard model there are **6 types of quarks and 6 types of antiquarks**.

Free quarks are never seen. You only see combinations of them, hadrons.
They can combine into **baryons** (3 quarks) or **mesons** (a quark-antiquark pair).

One way to **illustrate** the quark behavior is to see them as **string ends**.

A mesons will then be modelled as:  and a baryon (e.g. a proton) as:  or 

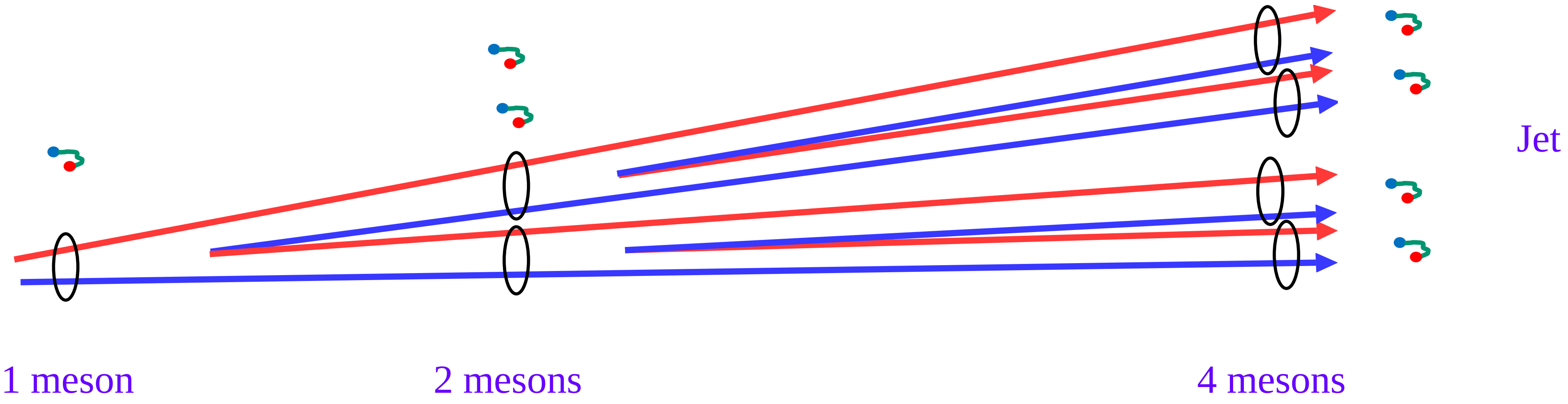
If you stretch a meson, i.e. trying to move the quark and antiquark away from each other, the string breaks.



Forming two strings with two new string ends, a new quark-antiquark par, and thus two mesons

Jets

If the quarks in a meson separate with a high kinetic energy there will be multiple string ruptures a **jet** of hadrons is produced



Jet fragmentation

Whenever a quark tries to escape a jet is formed