High School Teacher Programme 2017

https://indico.cern.ch/e/HST2017

Introduction to Particle Detectors

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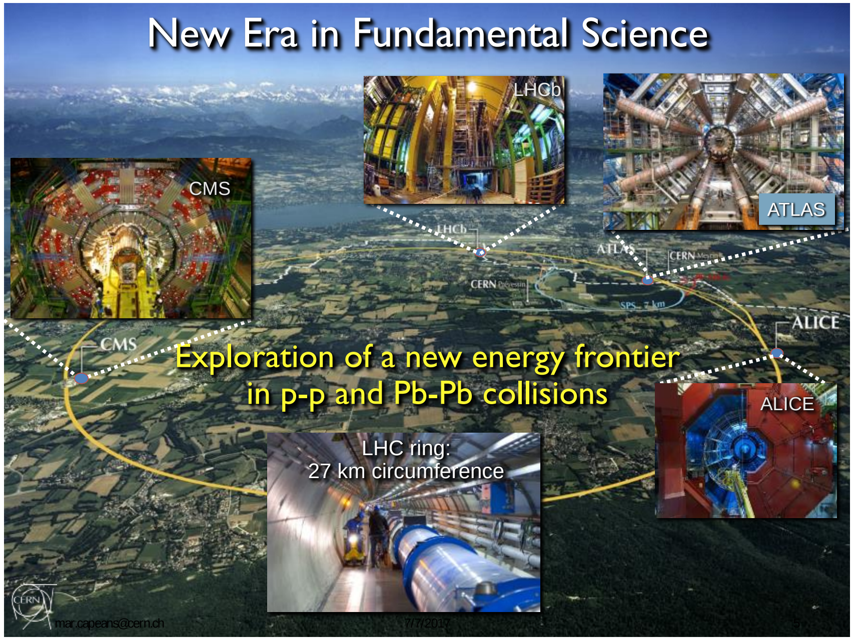
Outline

- **Detector Technologies**
- **How detectors are designed and used in HEP experiments, taking into account system aspects**
- **R&D trends, Future detectors**

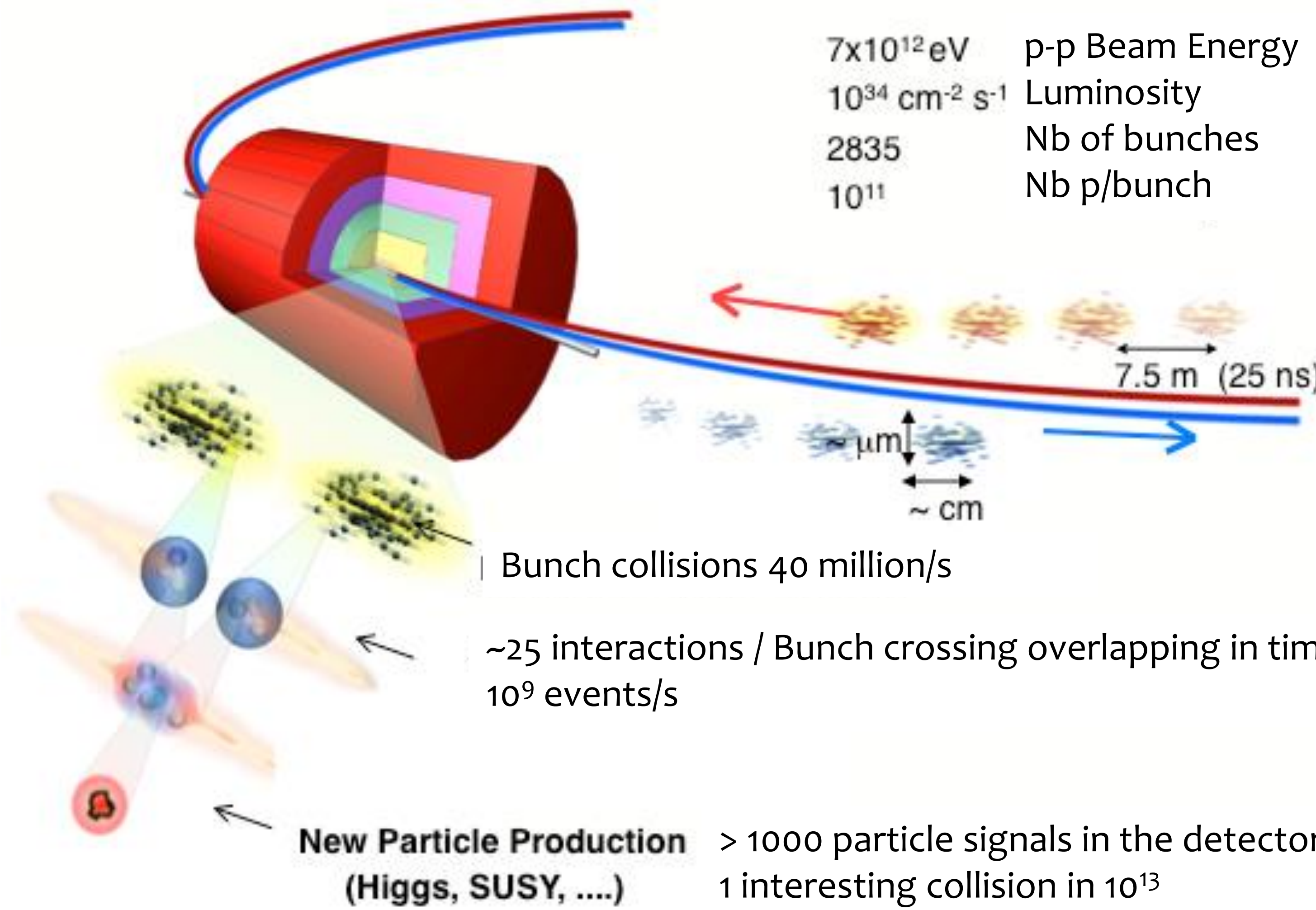
- For an in-depth, more academic exposure please see:
  - **CERN Summer students lectures** (5 h on detectors): https://indico.cern.ch/event/632096/
  - **Semiconductor Radiation Detectors** - Device Physics, G.Lutz, Springer
  - **Gaseous Radiation Detectors**, F.Sauli, Cambridge University Press, 2014
  - **Calorimetry**, R. Wigmans, Oxford Science Publications, 2000

Particle Physics Tools

- **Accelerators**
  - Luminosity, energy…
- **Detectors**
  - Efficiency, granularity, resolution…
- **Trigger/DAQ (Online)**
  - Efficiency, filters, through-put…
- **Data Analysis (Offline)**
  - Large scale computing, physics results…



LHC Detectors Context



7×10^{12} eV	p-p Beam Energy
10^{34} cm^{-2} s^{-1}	Luminosity
2835	Nb of bunches
10^{11}	Nb p/bunch

Bunch collisions 40 million/s

~25 interactions / Bunch crossing overlapping in time and space
10^9 events/s

> 1000 particle signals in the detector at 40MHz rate
1 interesting collision in 10^{13}

Past vs LHC

Dozens of particles/s		10^9 collisions/s
No event selection	**VS**	Registering $1/10^{12}$ events
‘Eye’ analysis		GRID computing

LHC … **Very Difficult Environment**

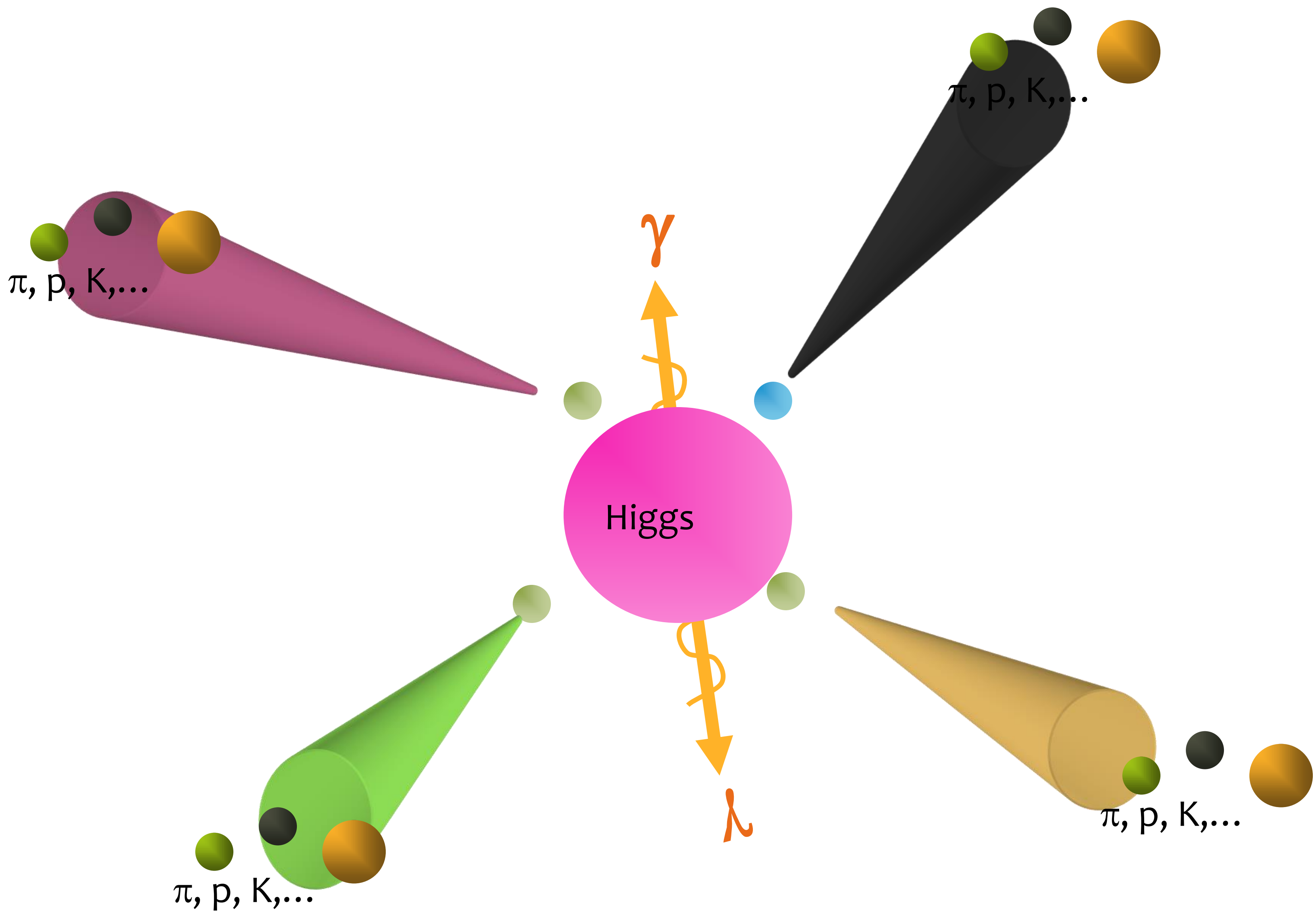
At each bunch crossing ~1000 individual particles to be identified every 25 ns …. High density of particles imply high granularity in the detection system … **Large quantity of readout services (100 M channels/active components)**

Large neutron fluxes, large photon fluxes capable of compromising the mechanical properties of materials and electronics components. Induced radioactivity in high Z materials (activation) which will add complexity to the **maintenance process**

Large Magnetic Fields in large volumes, which imply usage of **superconductivity (cryogenics)** and attention to **magnetic components** (electronics components, mechanical stress, ….)

Artistic Event

Artistic Event



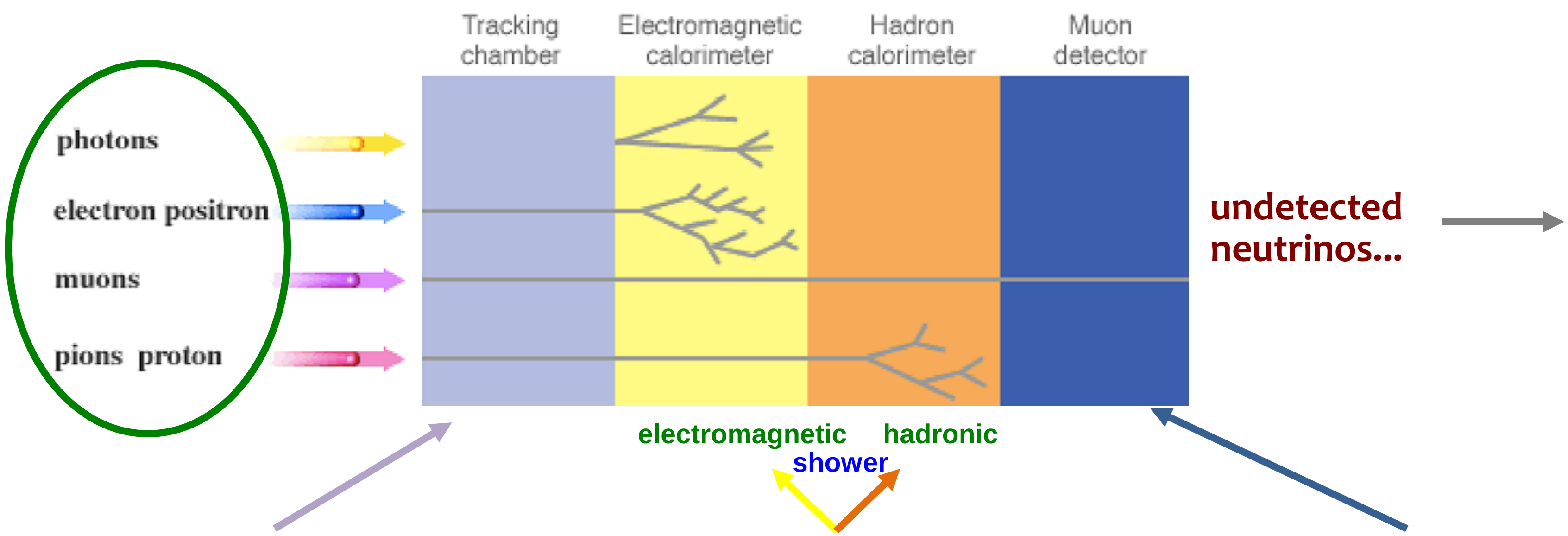
• Particle Detection •

- Usually we can not 'see' the reaction itself, but only the end products of the reaction
- In order to reconstruct the reaction mechanism and the properties of the involved particles, <u>we want the maximum information about the end products</u>
- **The ideal particle detector should provide…**
  - Coverage of full solid angle (no cracks, fine segmentation)
  - Measurement of momentum and/or energy
  - Detect, track and identify all particles (mass, charge)
  - Fast response, no dead time

  - Practical limitations: technology, space, budget

Interactions in the Detector

Low density → High density
High precision → Low precision
High granularity → Low granularity

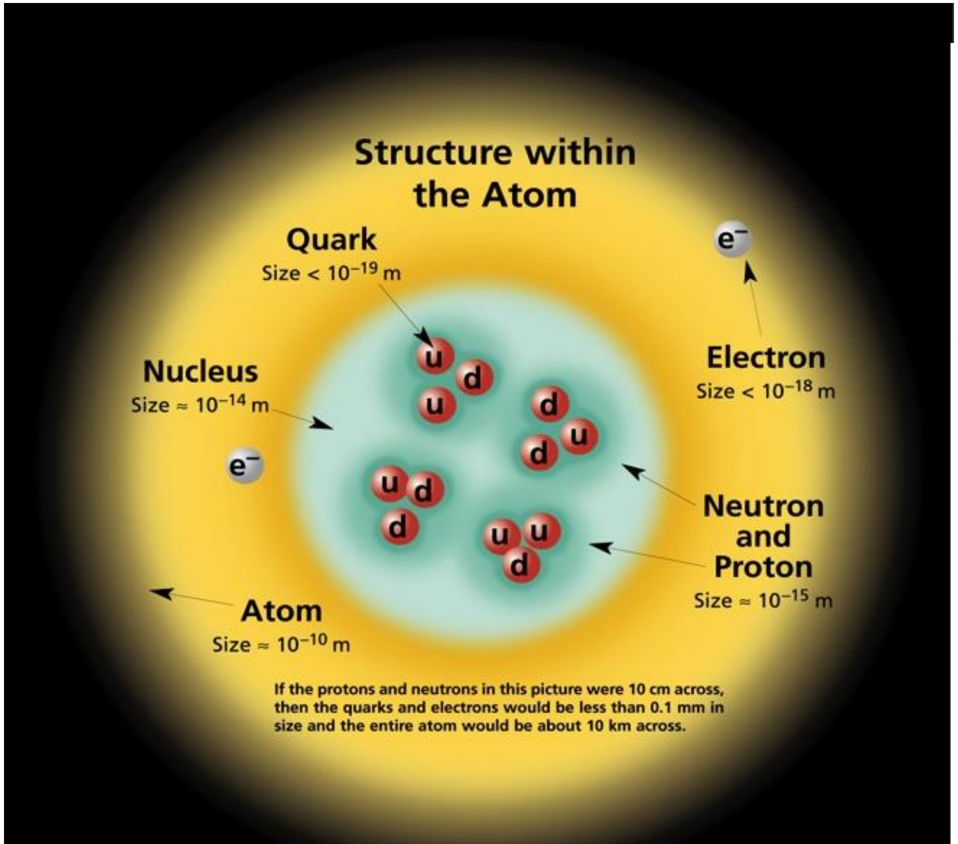


momentum measurement by curvature in magnetic field

energy measurement by creation and total absorption of showers

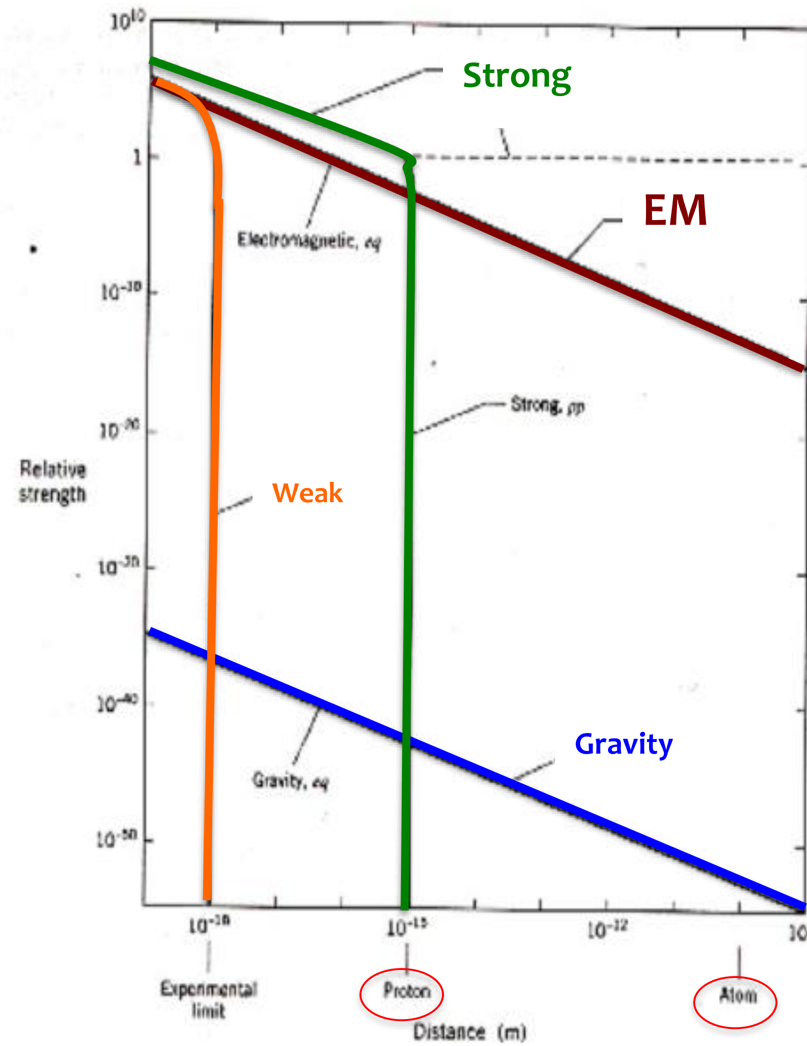
muon detection with improved momentum measurement (long lever arm)

Interactions



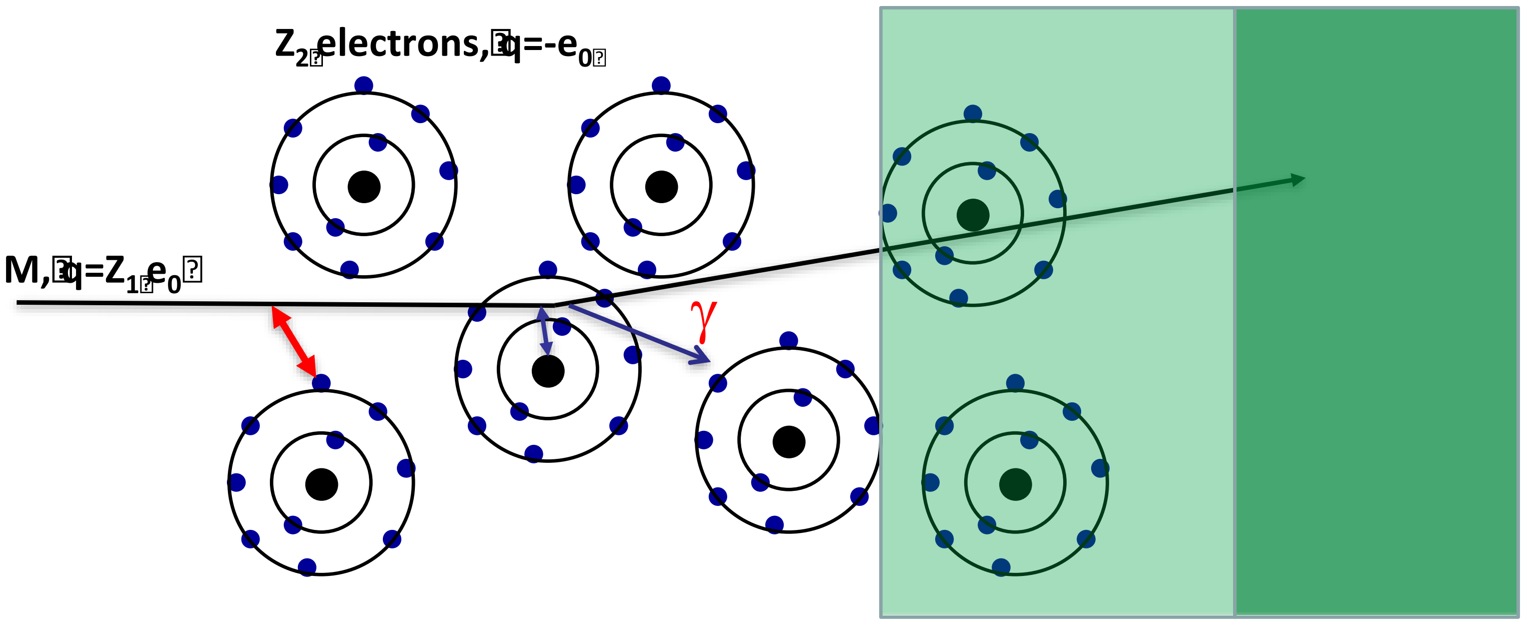
PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20



EM Interaction of Particles

Slide: W.Riegler, CERN



Interaction with the atomic electrons. The incoming particle loses energy and the atoms are <u>excited</u> or <u>ionized.</u>

Interaction with the atomic nucleus. The particle is deflected (scattered) causing <u>multiple scattering</u> of the particle in the material. During this scattering a <u>Bremsstrahlung</u> photon can be emitted.

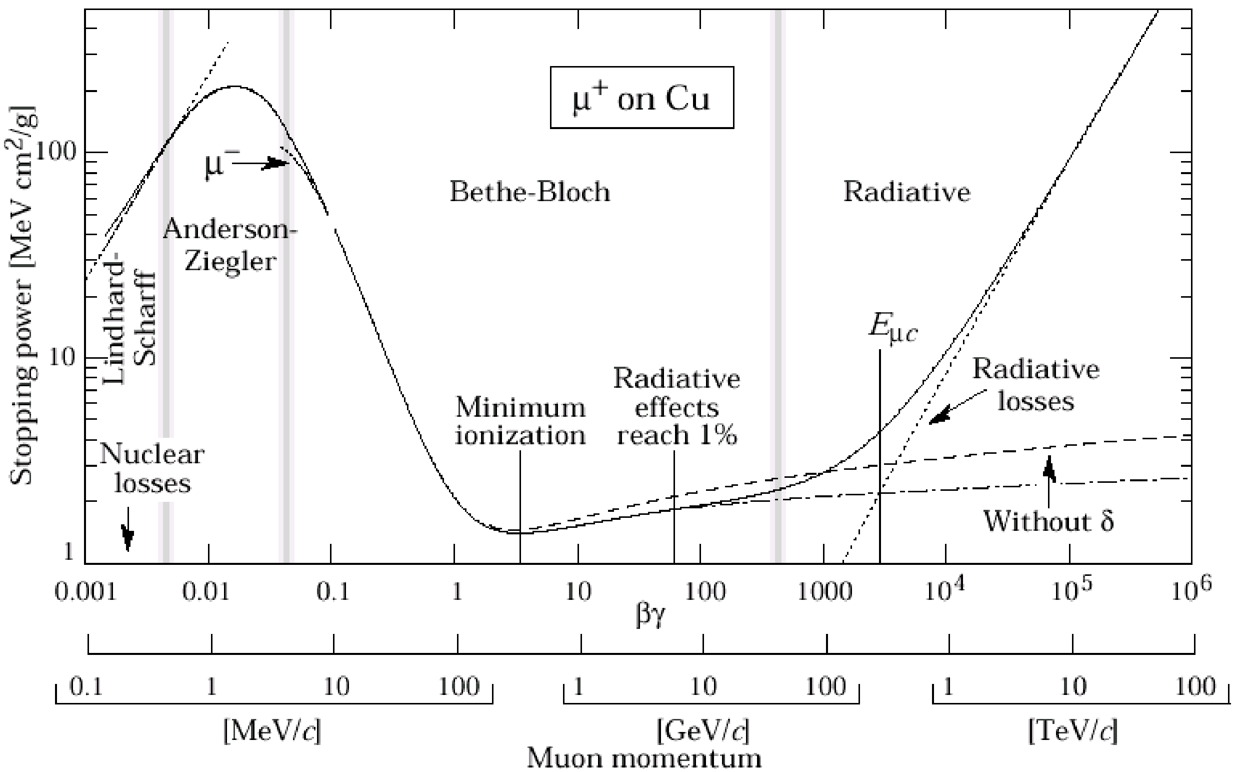
In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as <u>Cherenkov Radiation</u>. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called <u>Transition radiation</u>.

Heavy Charged Particles

Bethe-Bloch formula gives the mean rate of energy loss (stopping power) for a heavy charged particle ($m_0 >> m_e$), e.g. proton, k, π, μ

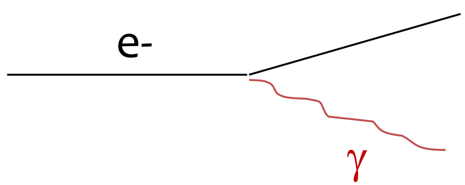
$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \gamma^2 \beta^2}{I^2} T^{max} - \beta^2 - \frac{\delta}{2} \right]$$

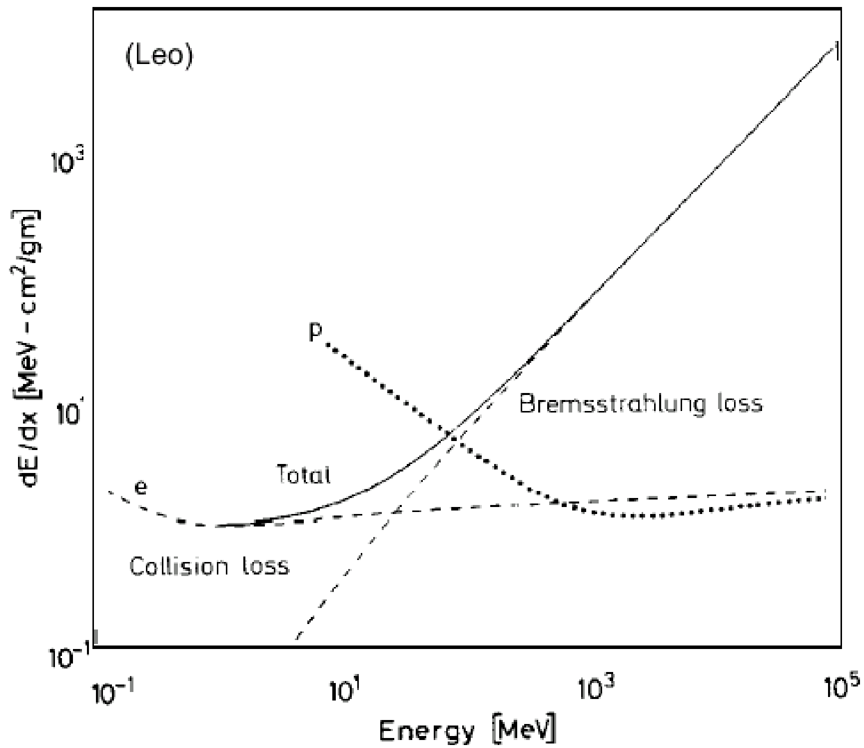
N: Avogadro's Nb
m_e: e- mass
Z, A: medium Atomic, Mass
I: effective ionization potenti
B: projectile velocity



Electrons and Positrons

- **Modify Bethe Bloch to take into account that incoming particle has same mass as the atomic electrons**
- Bremsstrahlung (**photon emission** by an electron accelerated in Coulomb field of nucleus) in the electrical field of a charge Z comes in addition : σ goes as $1/m^2$





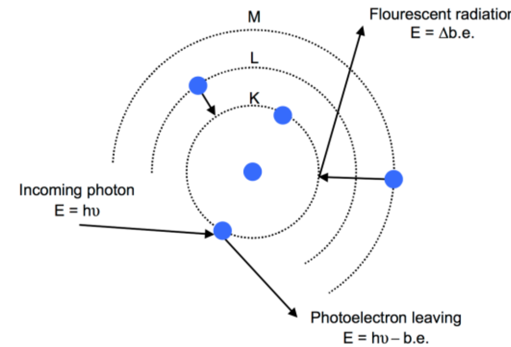
Neutral Particles

Contrary to charged particles that deposit energy continuously due to ionization, photons usually suffer one-off interactions producing charged particles

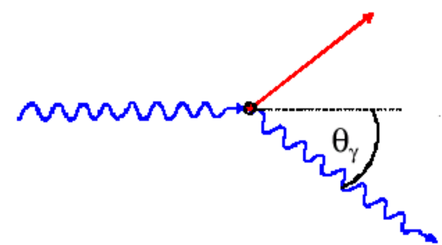
Energy (~KeV to MeV)

- **Photoelectric effect (Z^5)**; absorption of a photon by an atom **ejecting an electron.**

  Used in various detector technologies (very imp. In medical imaging)

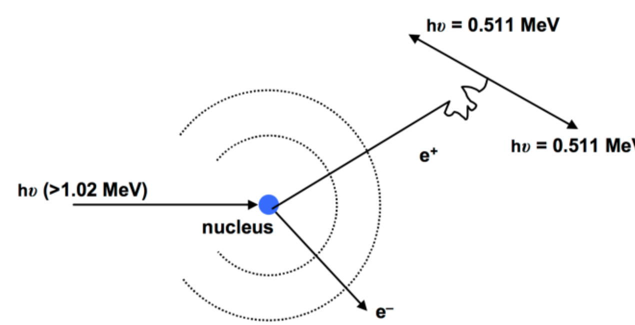


- **Compton scattering (Z)**; scattering of a photon against a free electron (Klein Nishina formula). It results **in a decrease in energy of the photon.** Part of the energy of the photon is transferred to the recoiling electron.



- **Pair-production (Z^2+Z)**; essentially bremsstrahlung, **photon creating an electron-positron pair near a nucleus.** Dominates at a high energy, threshold at 2 m_e = 1.022 MeV

  Most important in our field, Initiates EM shower in calorimeters



Neutrinos

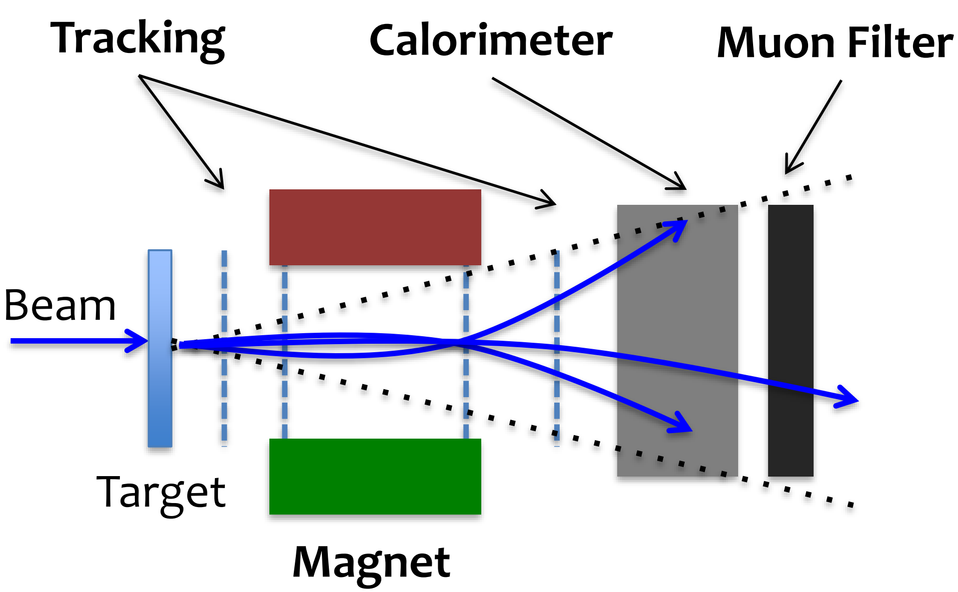
- Neutrinos interact only weakly, tiny cross-sections
- To detect neutrinos, we need first a charged particle (again)
  - Possible reactions:

$$\nu_\ell + n \to \ell^- + p \qquad \ell = e, \mu, \tau$$
$$\bar{\nu}_\ell + p \to \ell^+ + n \qquad \ell = e, \mu, \tau$$

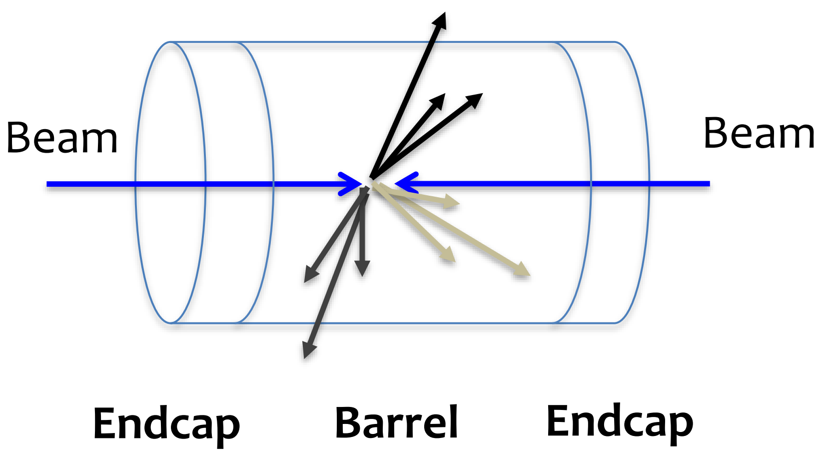
- The cross-section or the reaction $\mathbf{n_e + n \rightarrow e^- + p}$ is of the order 10^{-43} cm^2 (per nucleon, E_n ~ few MeV), therefore
  - Detection efficiency $e_{det} = s \times N^{surf} = s\ r\ N_A\ d\ /A$
  - 1m Iron: $e_{det} \sim 5 \times 10^{-17}$
- Neutrino detection requires big and massive detectors (kT) and high neutrino fluxes
- **In collider experiments, fully hermetic detector allow to detect neutrinos indirectly: we sum up all visible energy and momentum, and attribute missing energy and momentum to neutrino**

Detector Systems

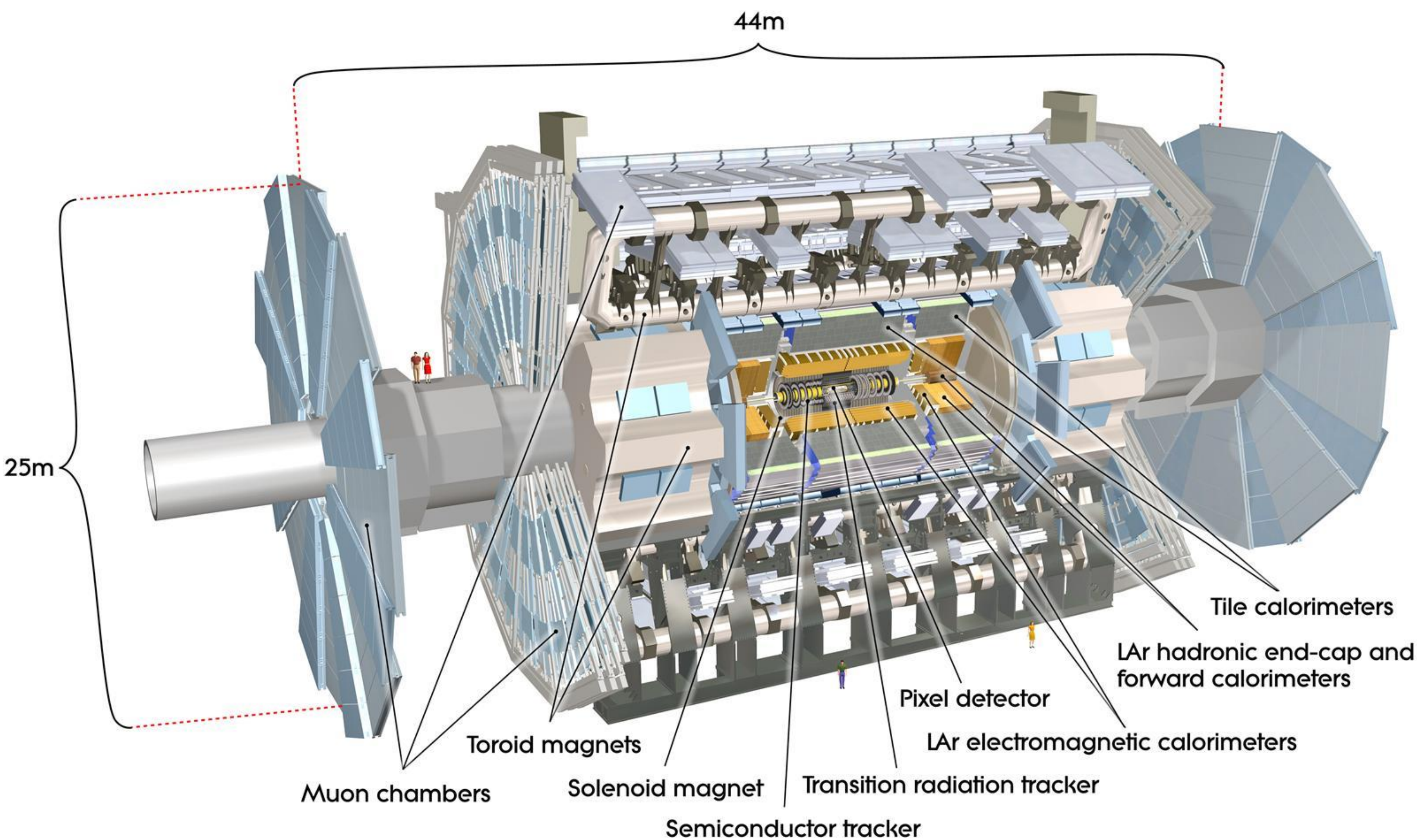
Fix Target Geometry

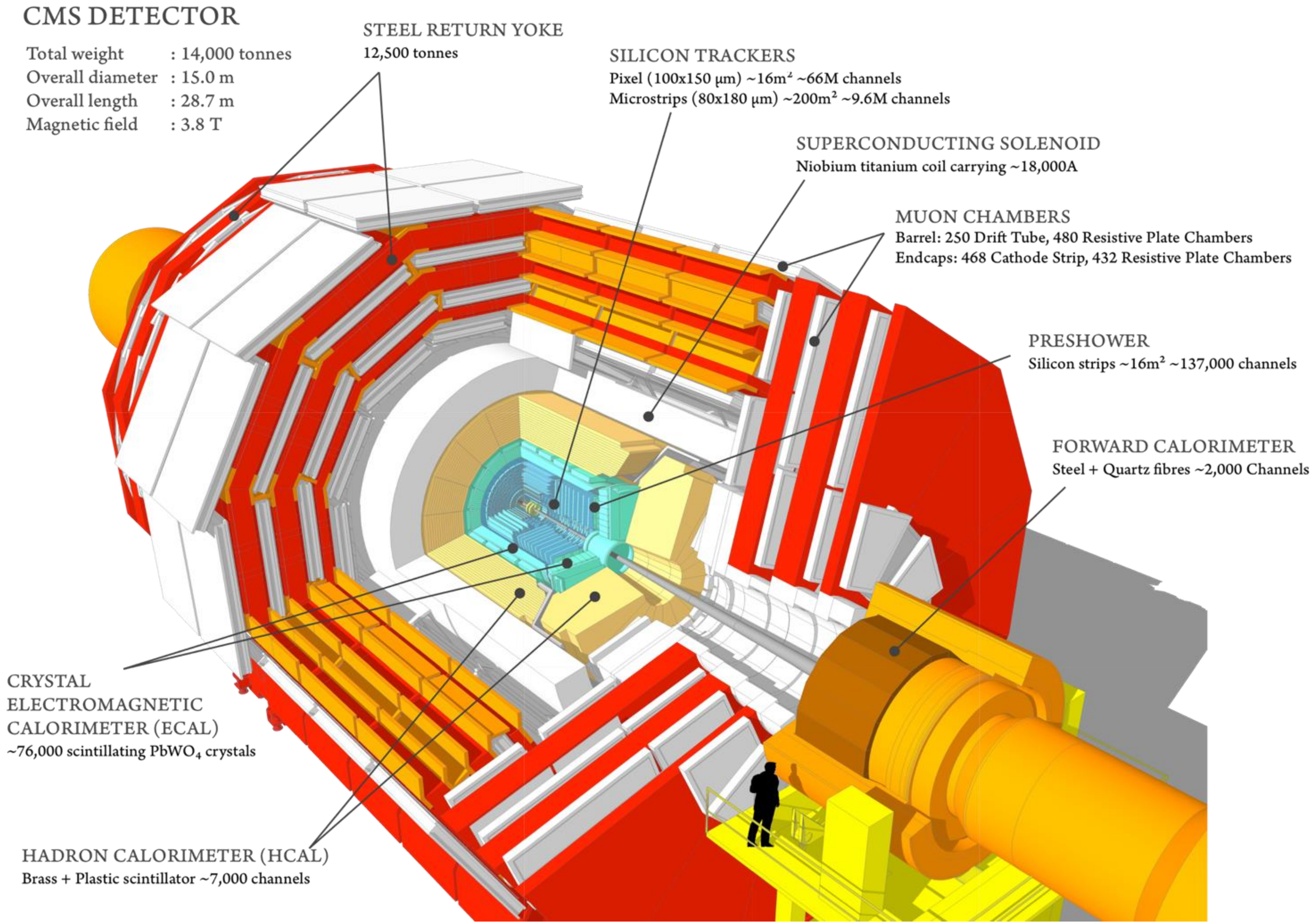


Collider Geometry



ATLAS Detector





CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

Detector Technologies

- How are reactions of the various particles with detectors turned into electrical signals. We would like to extract position and energy information channel by channel from our detectors.
- Three effects/**technologies** are usually used :

Ionisation detectors | Semiconductors | Scintillators

Ionisation detectors

If a particle has enough energy to ionize a gas atom or molecule, the resulting electrons and ions cause a current flow which can be measured.

Semiconductors

When a charged particle traverses Si, it produces ionizing and non-ionizing E Loss. The latter produces radiation damage, while ionization loss causes the creation of e-hole pairs which produces the signal.

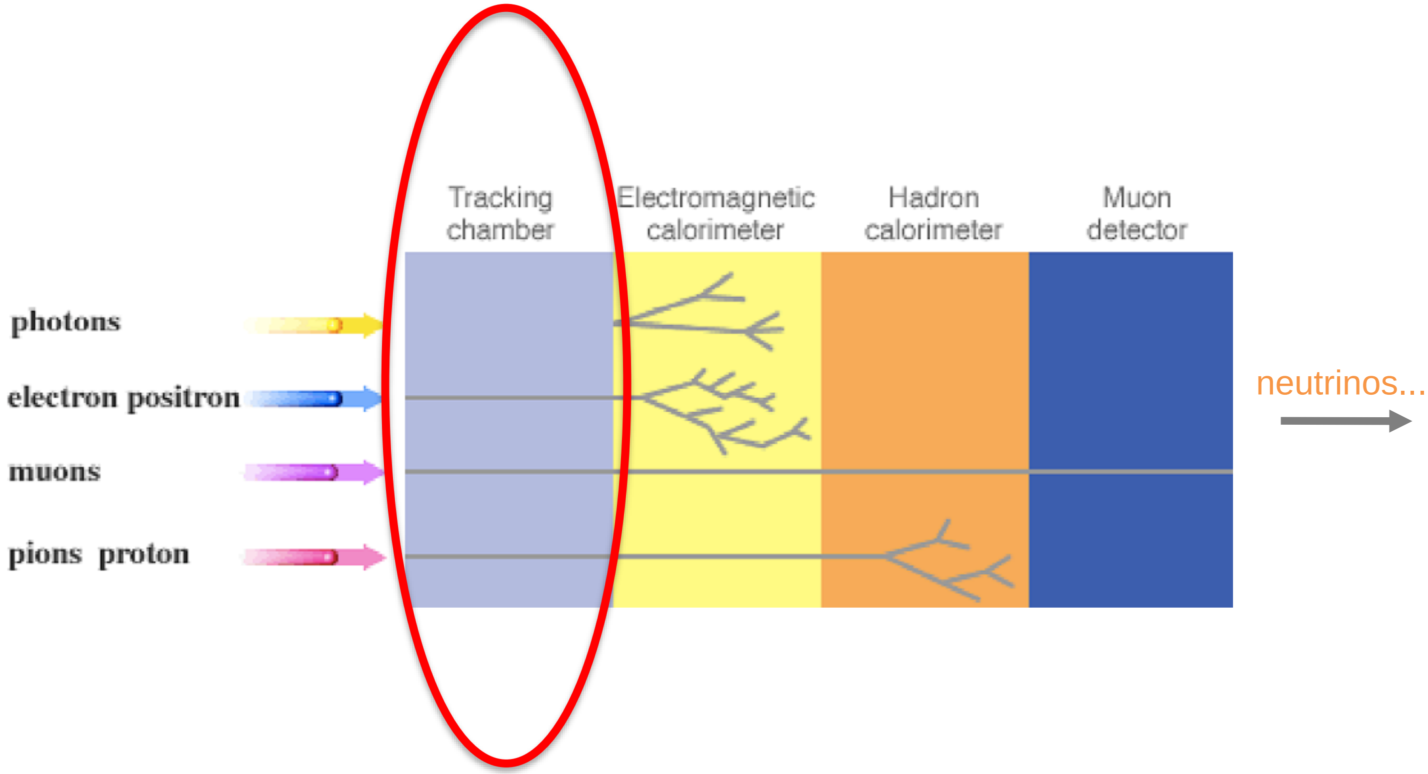
Scintillators

Scintillators are materials that produce sparks or scintillations of light when ionizing radiation passes through them. The charged particle excites atoms in the scintillator, e- returns to ground state by emitting a photon.

and these are used for different **functions**: tracking and/or triggering, energy measurements, photon detectors for Cherenkov or TRT, etc

and from then on, it is all online (trigger, DAQ) and offline treatment and analysis ….

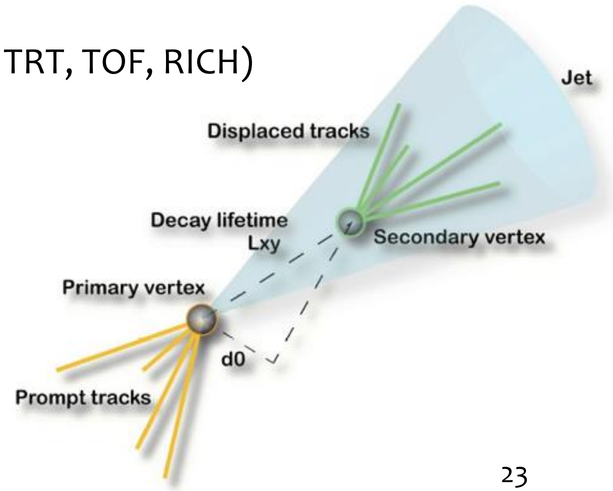
• Tracking•


Tracking chamber
Electromagnetic calorimeter
Hadron calorimeter
Muon detector
photons
electron positron
muons
pions proton
neutrinos...

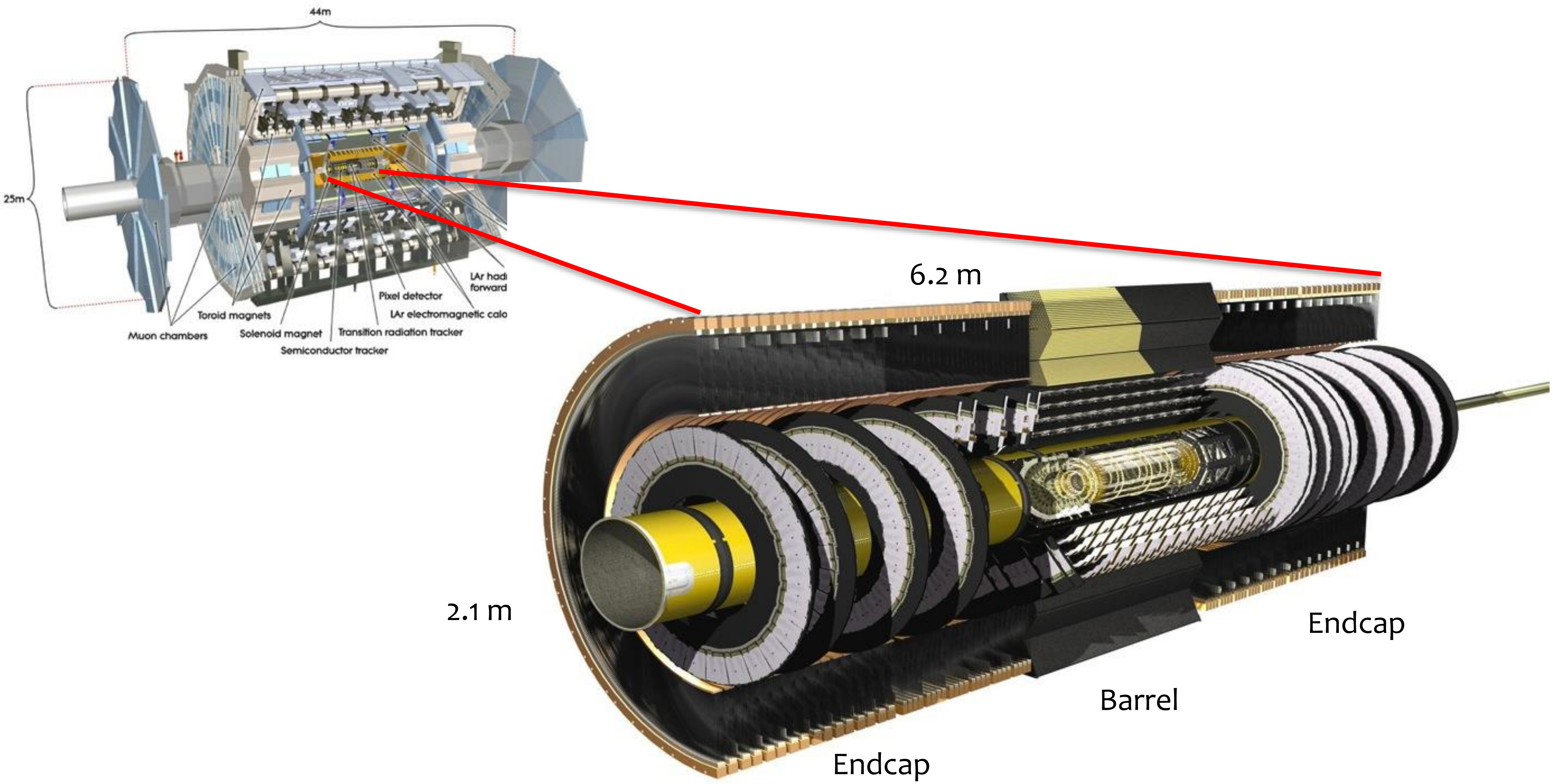
• Trackers •

- **Measure charged particles as they emerge from the interaction point, disturbing them as little as possible**
- Measure the trajectory of charged particles
  - Measure several points (hits) along the track and fit curves to the hits (helix, straight line)
- Determine their momentum
  - From their curvature in a magnetic field
- Extrapolate back to the point of origin
  - Reconstruct primary vertices
- Reconstruct secondary vertices
  - Long-lived particles have a measurable displacement between primary vertex and decay
- Match tracks with showers in the calorimeters or tracks in the muon systems
- Trackers also contribute to particle identification (PID)
  - Measuring rate of energy loss (dE/dx) in the tracker
  - Using dedicated detectors to distinguish different particle types TRT, TOF, RICH)

Want a compact detector, inside a magnetic field, to register as many hits as possible but light to minimise interactions of charged (and neutral) particles before they reach the calorimeter systems



ATLAS Tracker

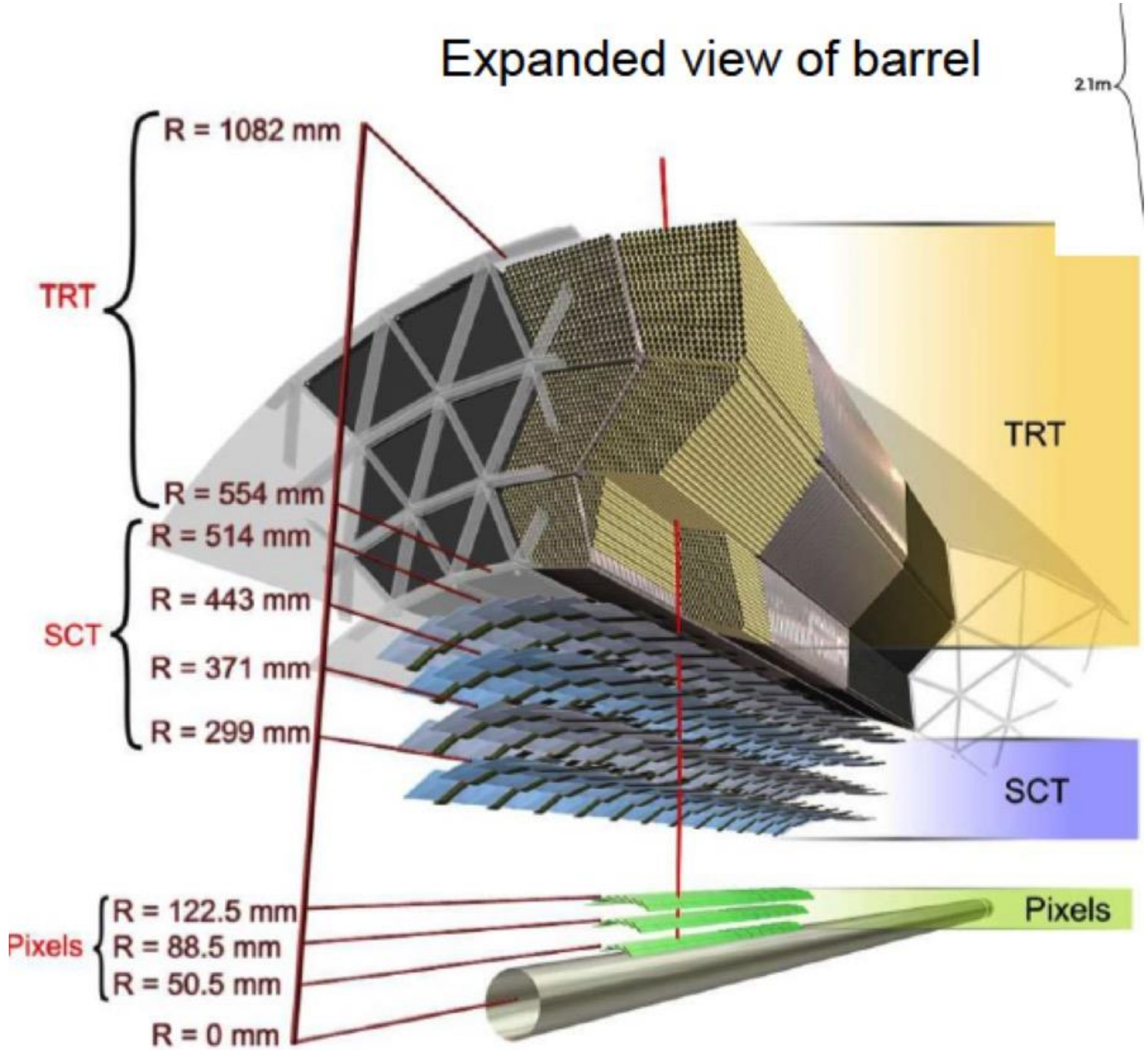


ATLAS Tracker

TRT (Straws-Gas)
350 kchannels
36 track points
σ ~130 µm

SCT (Silicon strips)
6.2 Mchannels
4 track points
σ ~16 µm

Pixel (Silicon pixels)
80 Mchannels
3 track points
σ ~10 µm

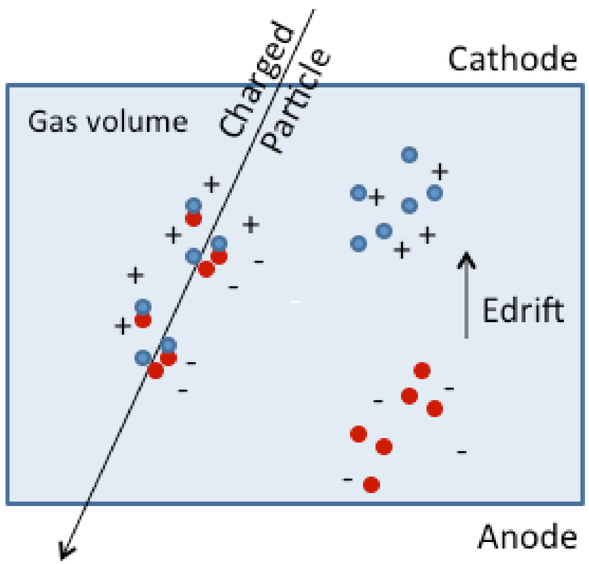


Gaseous Detectors

Any charged particle traversing a gas will loose energy due to interactions with the atoms of the gas. This results in:

- **Excitation,** the particle passes a specific amount of energy to a gas atom
- **Ionization,** the particle knocks an electron off the gas atom, and leaves a positively charged ion

Resulting primary e^- will have enough kinetic energy to ionize other atoms of gas. The sum is called **Total Ionization**

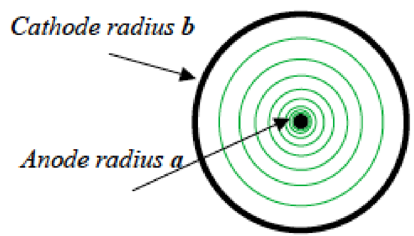


- Typically ~100 pairs/cm, and they are not easy to detect as the typical noise of an amplifier is ~1000 e^-
- **Need to MULTIPLY the electrons**

Amplification

- Multiplication requires fields where the e$^-$ energy occasionally is sufficient to ionise

THIN ANODE WIRE

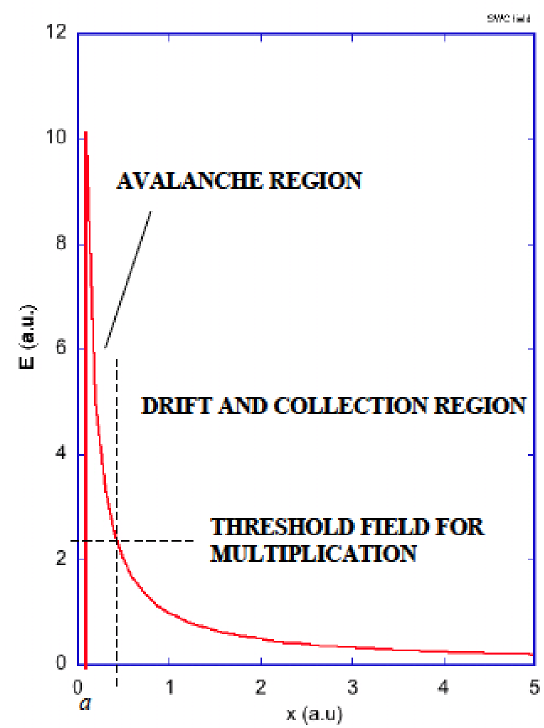


ELECTRIC FIELD AND POTENTIAL:

$$E(r) = \frac{CV_0}{2\pi\varepsilon_0}\frac{1}{r}$$

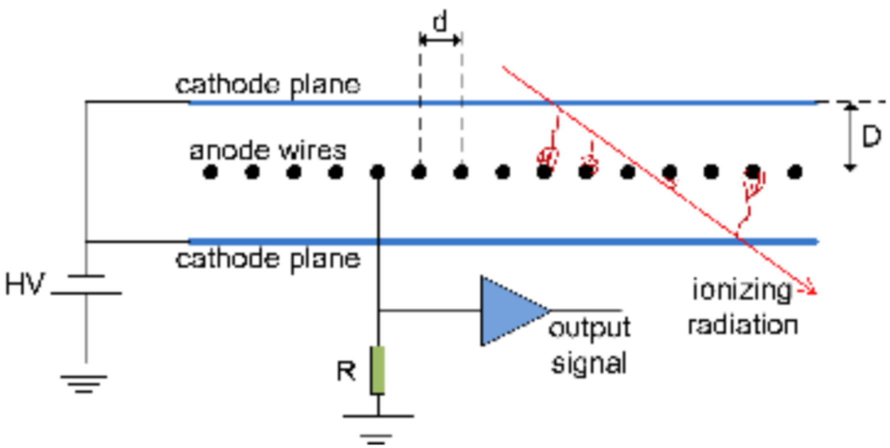
$$V(r) = \frac{CV_0}{2\pi\varepsilon_0}\ln\frac{r}{a}$$

$$C = \frac{2\pi\varepsilon_0}{\ln(b/a)}$$ capacitance per unit length



MWPC

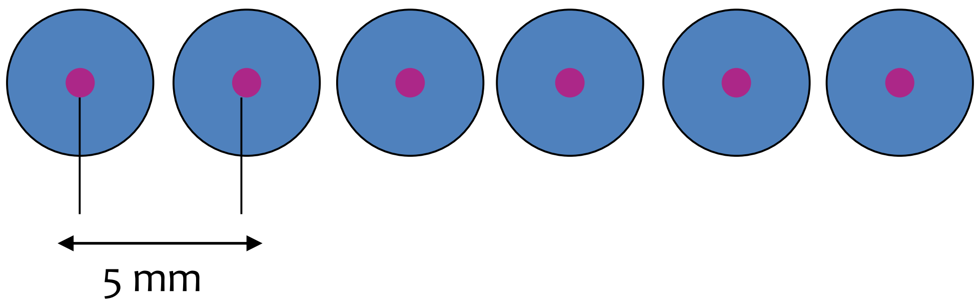
- Fast position-sensitive detectors (1968)
- Continuously active
- Efficient at particle fluxes up to several MHz/cm^2
- Sub-mm position accuracy
- **First electronic device allowing high statistics experiments !!**



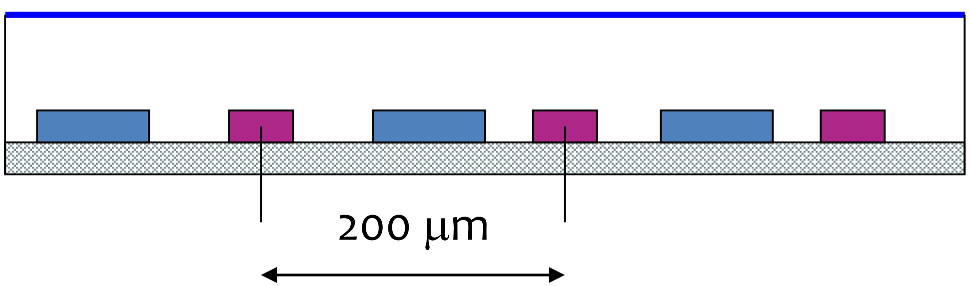
G.Charpak, Noble Prize in 1992

MWPC… Rate capability limited by space charge defined by the time of evacuation of positive ions

Increasing Cell Granularity



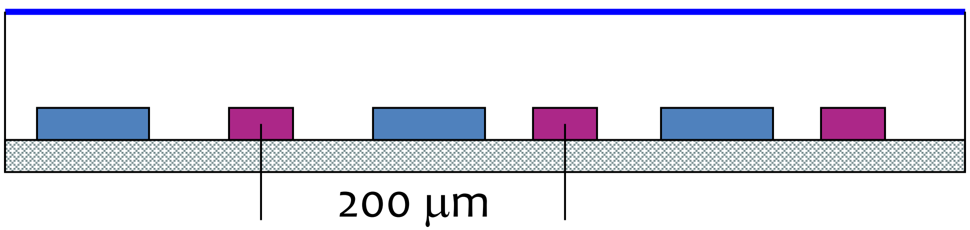
STRAW TUBES
Anode-cathode distance: 2 mm
Spatial resolution ~ 130-300 μm



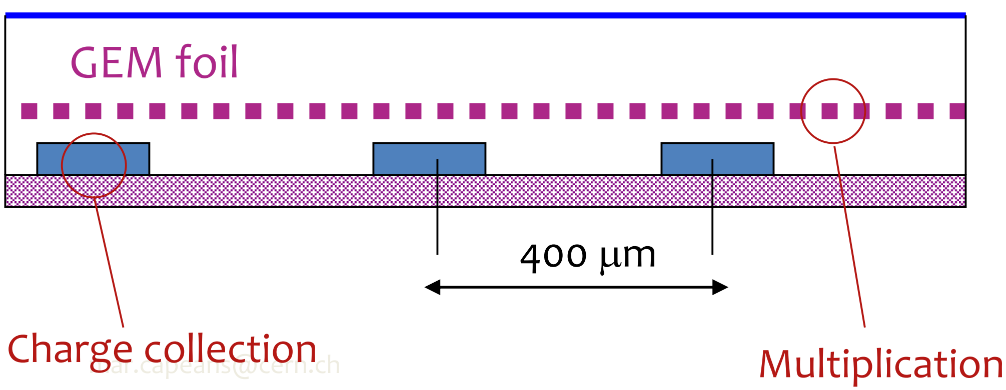
MICRO STRIP GAS CHAMBERS
(MSGC - A.Oed,1988)
Semiconductor industry technologies
Anode-cathode distance: 40 μm
Spatial resolution ~ 40 μm

MSGC… Very high rate capability due to small pitch and fast ion collection, but delicate structures with very high fields in electrodes edges…. sparks

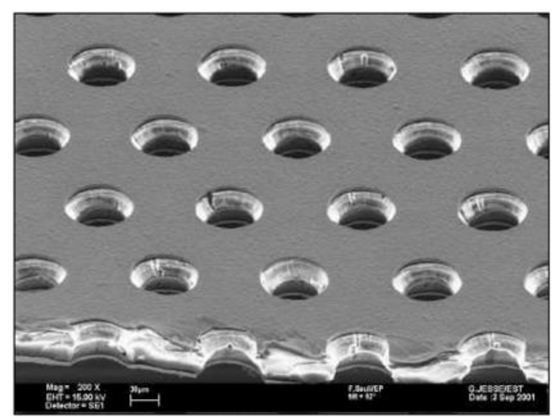
Decoupling Multiplication from Charge Collection



Micro Strip Gas Chamber



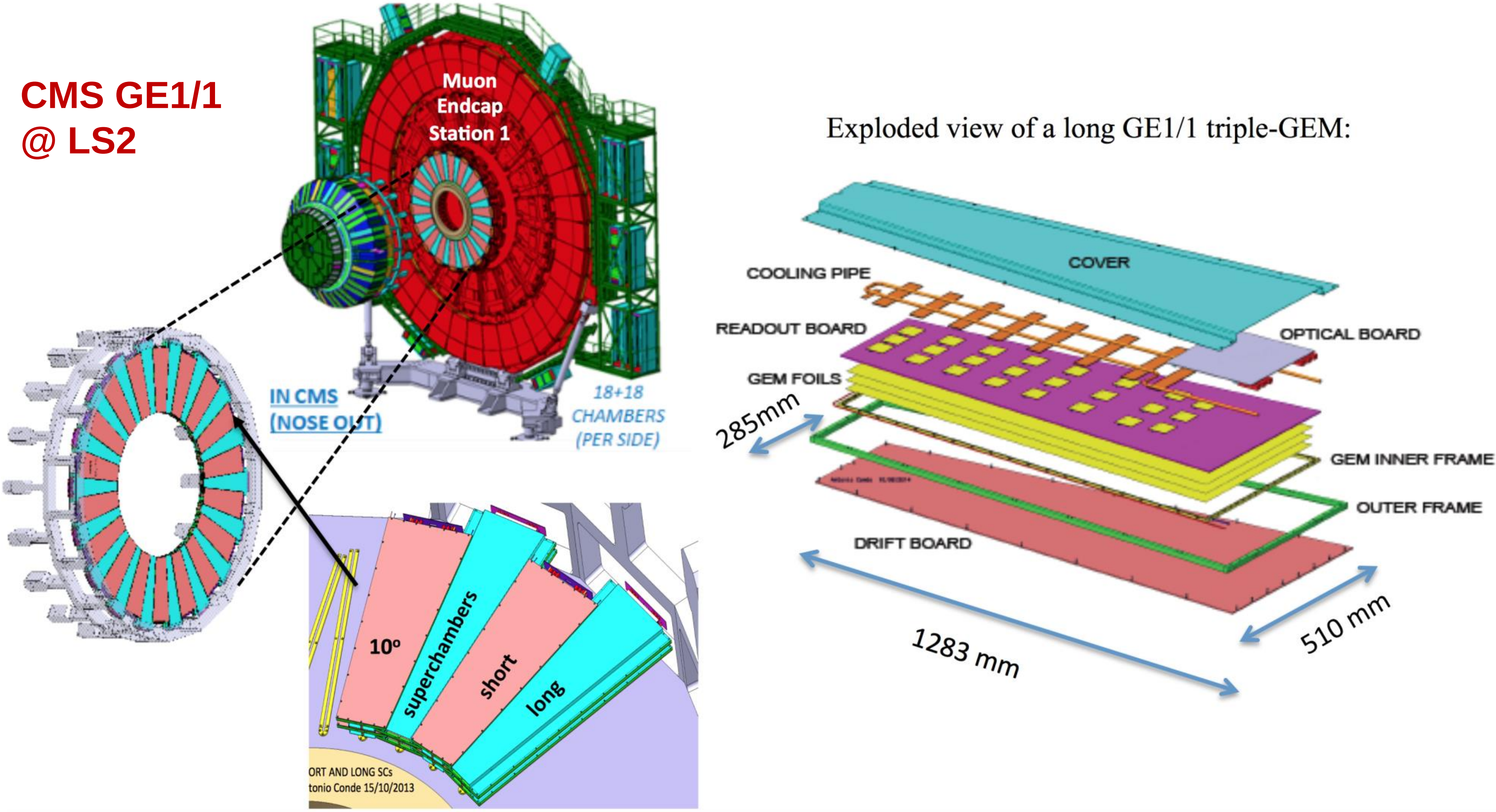
Gas Electron Multiplier
(GEM – F.Sauli, 1998)
Spatial resolution ~ 50 μm
Time resolution better than 10 ns



Thin metal-coated polymer foils
70 μm holes at 140 mm pitch

• New LHC Detectors with newest technologies (GEM) •

CMS GE1/1
@ LS2



Gas Detectors

- Good spatial resolution
- Good dE/dx
- Good Rate capability
- Fast & Large Signals
- Low radiation length
- Large area coverage
- Multiple configurations, flexible geometry

Gas detectors perform well where a precision of a few tens of microns is required

At very large radius, where large areas have to be covered, e.g. the muon chambers, it is unrealistic to use anything other than gas detectors.

In the intermediate region between about 20 cm and 2 m radius silicon and micropattern gas detectors meet as rivals, as both fulfill all the necessary requirements concerning precision, rate capability and radiation hardness.

• Semiconductors •

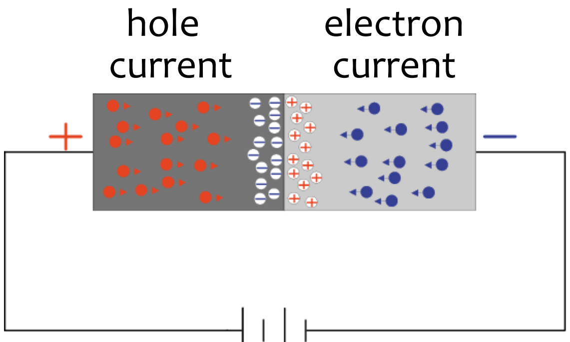
- Solid state ionization chamber, member of the large family of ionization detectors. A Si detector takes advantage of the special electronic structure of a semi-conductor.

  – Used in nuclear physics for Energy measurements since the 50ies
  – Appear in HEP in the 70ies
  – In the 80ies, planar technique of producing silicon radiation sensors, permitting segmentation of one side of the junction and the use of signals recorded on the segments to determine particle positions

Semiconductors

Basic element of a solid state (silicon) detector is… a **diode**
p-type (more holes) and n-type (more electrons) doped silicon material is put together

Please watch this fun video on transistors
https://www.youtube.com/watch?v=IcrBqCFLHIY

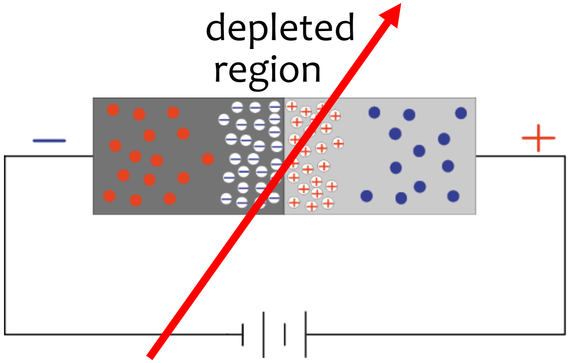


Current flow through diode if connects like this

For particle detectors: reverse bias the diode to create an active detection layer

Depletion layer: zone free of mobile charge carriers

- no free holes, no electrons so that we can observe the ionization charge
- thickness of depletion region depends on voltage, doping concentration



Typically 20000 - 30'000 electron/hole pairs in Si 300 μm
Compare to intrinsic Si: $4.5 \cdot 10^{8}$ per detector/cm^2

Charged particle can create new electron/hole pairs in depletion area sufficient to create a signal

• Semiconductors •

(more generally, solid state detectors)

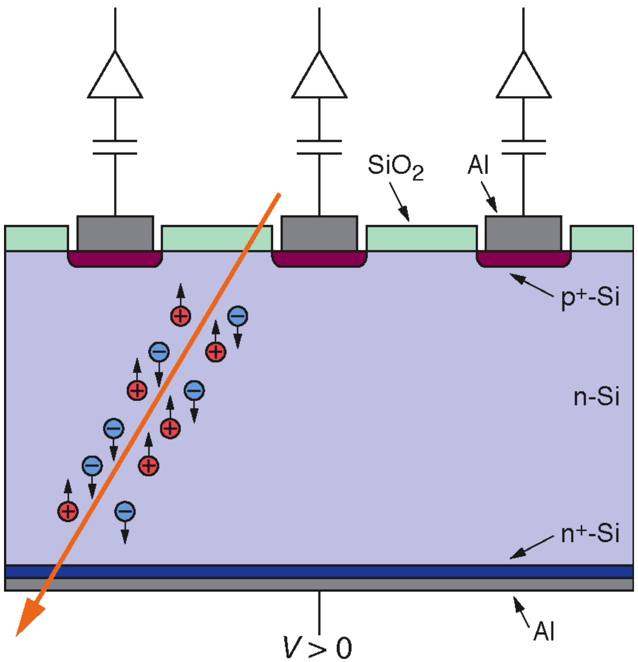
DC coupled strip detector

Through going charged particles create e^-h^+ pairs in the depletion zone (about ~25000 pairs in standard detector thickness).

These charges drift to the electrodes.

The drift (current) creates the signal which is amplified by an amplifier connected to each strip.

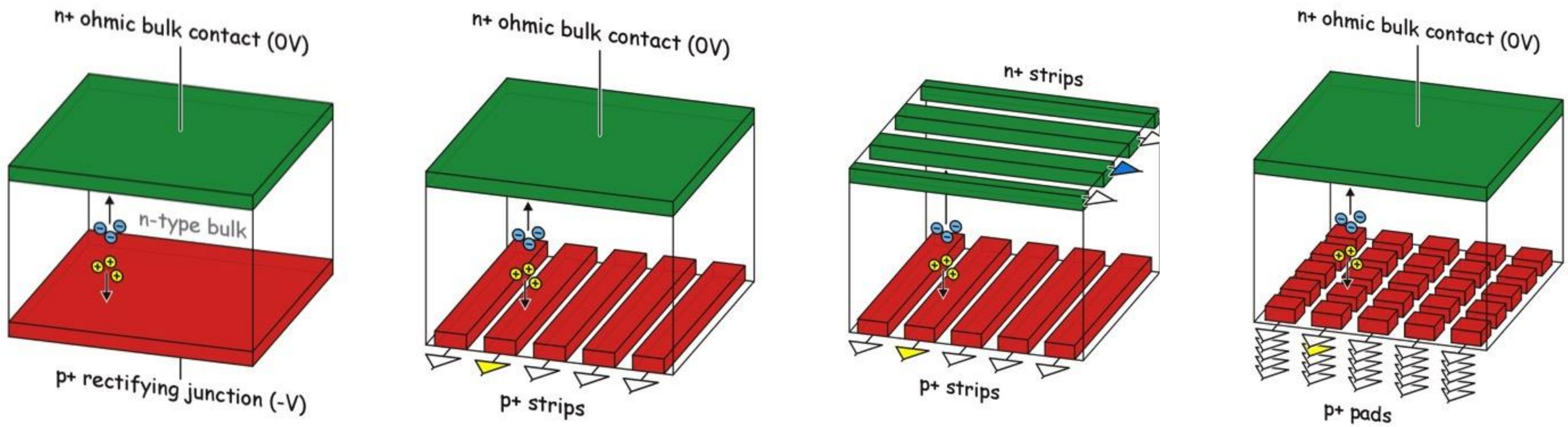
From the signals on the individual strips the position of the through going particle is deduced.



Semiconductors

- **Very attractive in HEP because of:**
  - Good intrinsic **energy resolution**
    - Silicon: 1 e-hole pair for every 3.6 eV released by a crossing particle. In Gas: 30 eV required to ionize a gas molecule
    - High primary ionization (larger signal), **no amplification:** typical detector thickness (300 mm) result in 3.2×10^4 e-/hole pairs
  - Si high density reduces the range of secondary e, thus **good spatial resolution**
    - 10 mm, the best ~1 mm
  - The **granularity** can also be very high
  - **Thin**, therefore can be positioned close to the interaction point
  - **Industrial process** (high yield, continuous development…)

Strips VS Pixels



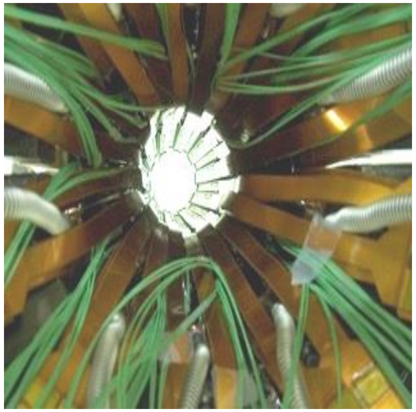
Strips

- Each strip is connected to one electronic readout channel
- First prototypes: ~ 1980
- Strip pitch: ~10-100 µm
- Position resolution: ~few µm due to charge sharing between neighbouring strips

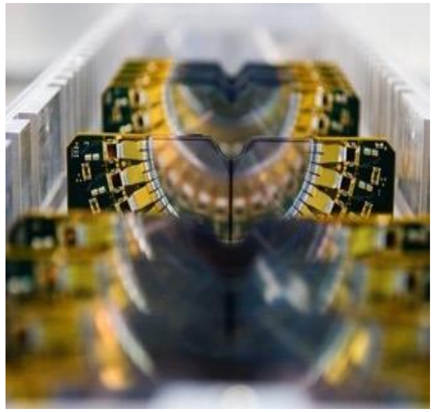
Pixels

- 2D resolution
- First prototypes ~1990
- Can be used for tracking or imaging:
  - particle tracking = detection of individual charged particles
  - imaging = count / integrate particles or photons

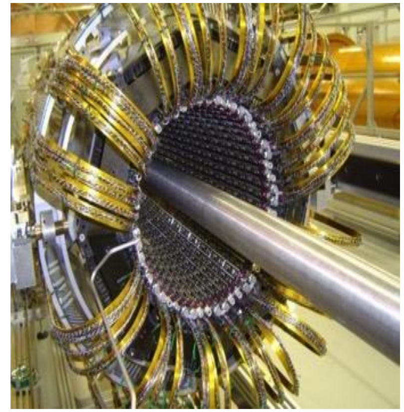
Silicon Detectors at LHC



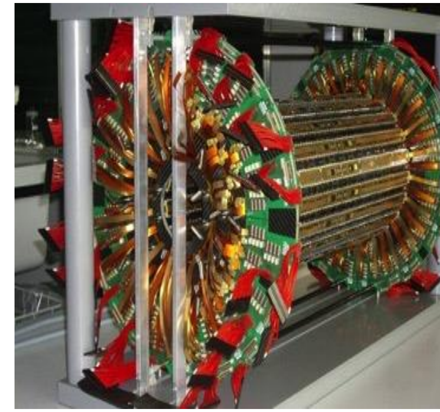
ALICE Pixel Detector



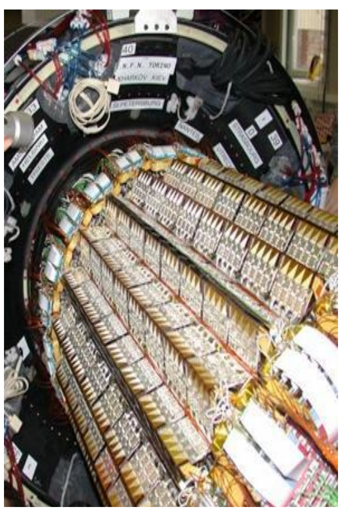
LHCb VELO



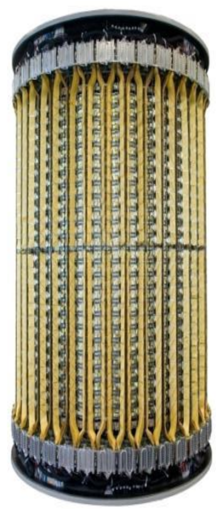
ATLAS Pixel Detector



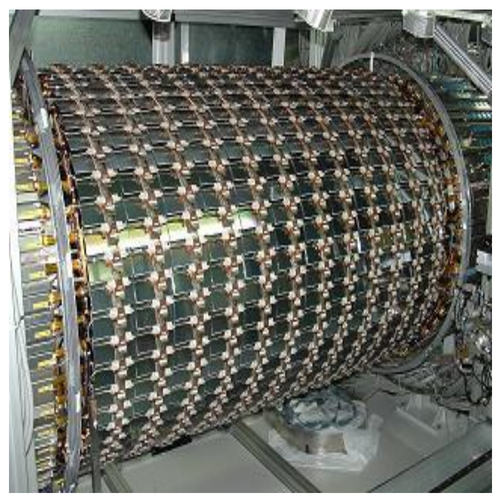
CMS Pixel Detector



ALICE Drift Detector



ALICE Strip Detector



ATLAS SCT Barrel

CMS Strip Tracker IB

ATLAS, Barrel SCT module

Hybrid assembly

with readout chips

12.8 cm

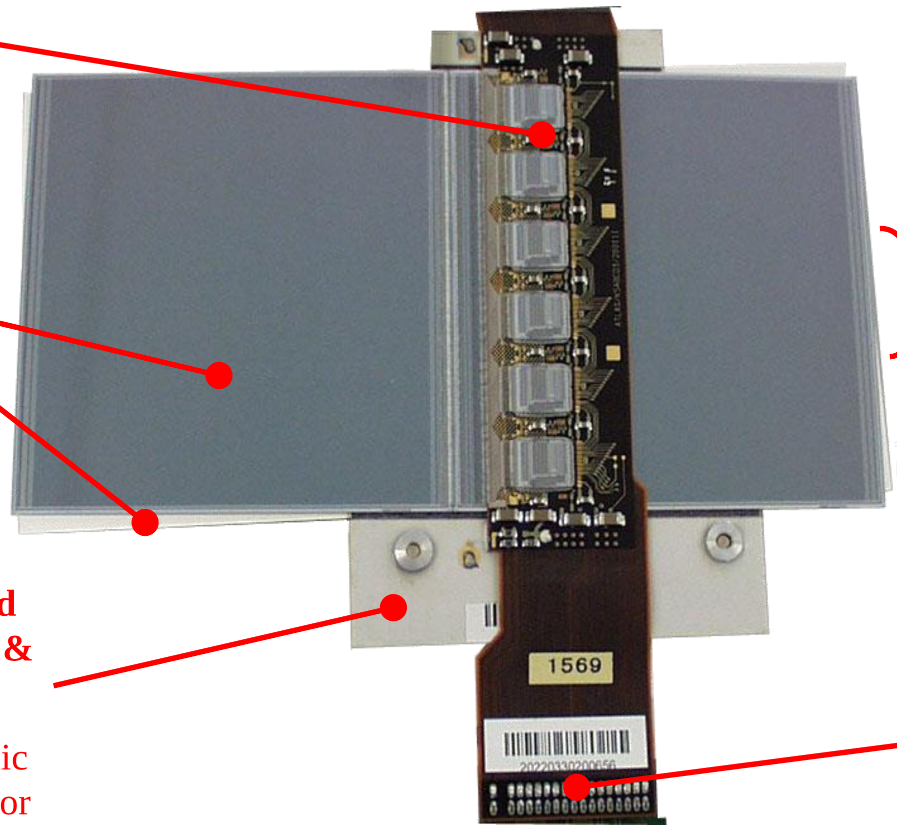
6 binary readout chips on either sensor side; sig:noise = 14:1

4 Silicon sensors

280 μm thick

2.3° stereo angle

Overlap in ϕ & z to adjacent modules



768 p^+ microstrips Cell size: 80 μm [ϕ pitch] × 13 cm [z]

Overall 6.3 10^6 channels

Be module baseboard with mounting points & central TPG

TPG (thermal pyrolythic graphite) plate for sensor cooling

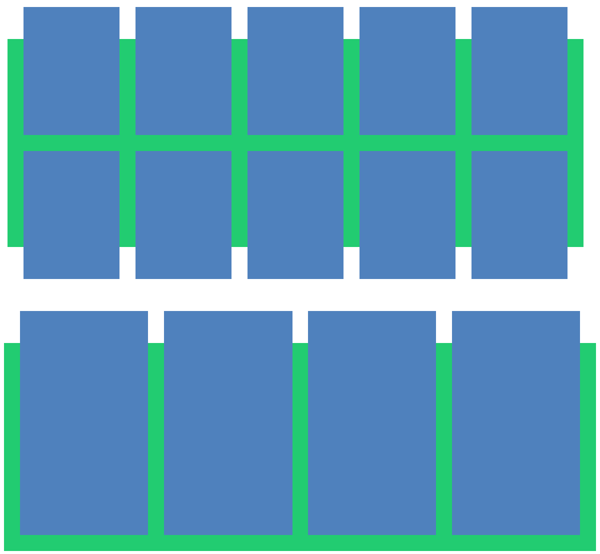
Connector

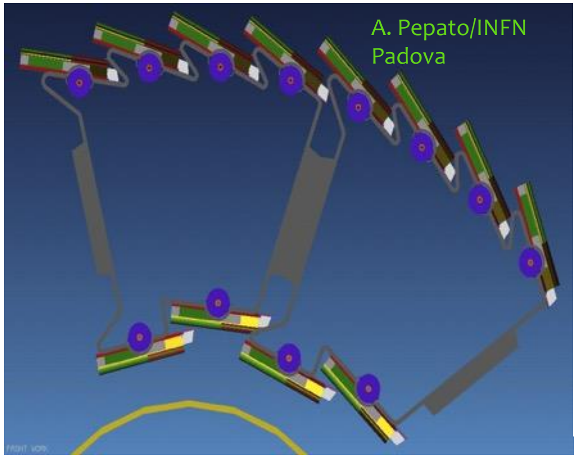
Power & data

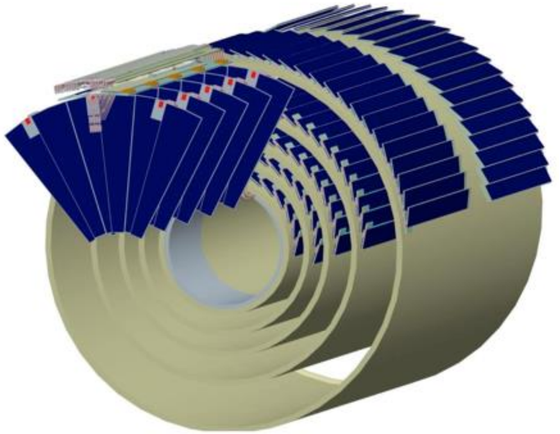
Fully equipped double sided electrical module with baseboard and readout hybrids

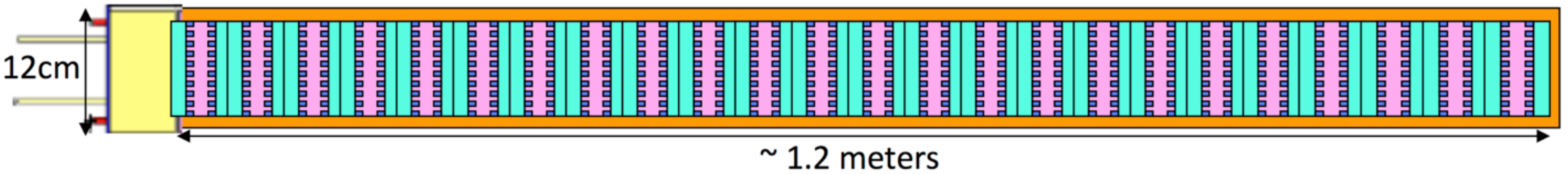
Systems

- **How to efficiently cover large surfaces? Ladders (modules)**
  - sensor size limited by wafer size and bump bonding requirements (flatness!), LHC experiments today: ~7cm x 2cm
  - chip size limited by process rules (larger chip means lower yield in production)









• Systems •

What is a system?

- Sensor
- Readout electronics
- Interconnection

- Mechanical supports
- Cooling, thermal aspects
- Power supplies
- Services: cables, pipes, fiber links…
- Monitoring, sensors, alignment

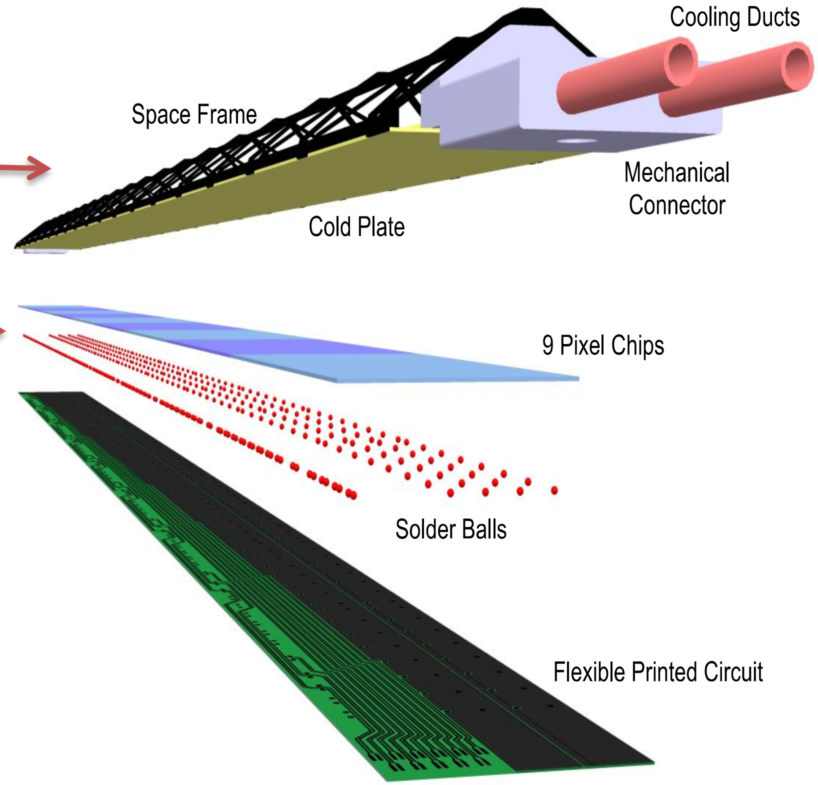
Slide: P. Riedler, CERN

• Silicon detectors, Trends •

ALICE ITS Upgrade: Inner Layer Stave

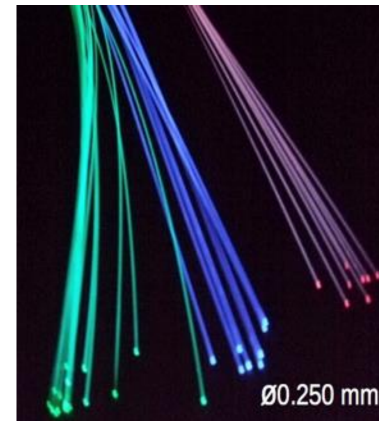
Light weight, compact modules to minimize material budget:

- Monolithic sensors: integrated sensor and electronics
- Integrated mechanical support and cooling
- 50 µm silicon sensors connected via solder points (direct on chip laser soldering) to a 2-layer Al(Cu)-polyimide flex cable
- Power and signal connections to each chip



• Scintillation Particle Detector •

Scintillators are materials that produce sparks or scintillations of light when ionizing radiation passes through them. The charged particle excites atoms in the scintillator, e- returns to ground state by emitting a photon



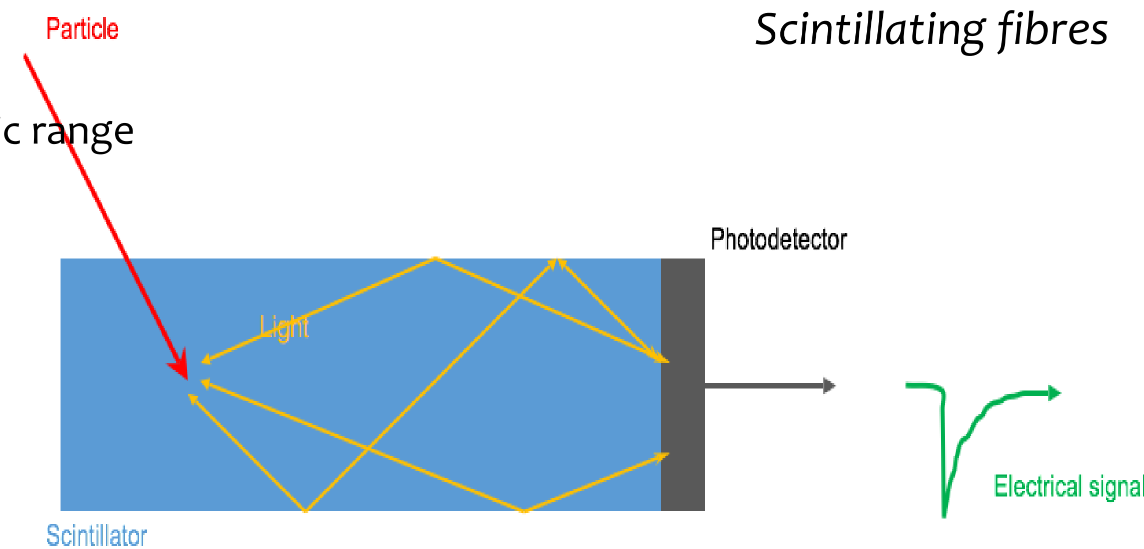
Scintillating fibres

Detector Principle

- dE/dx converted into visible light
- Detection via photosensor [e.g. photomultiplier, SiPM, human eye ...]

Main Features

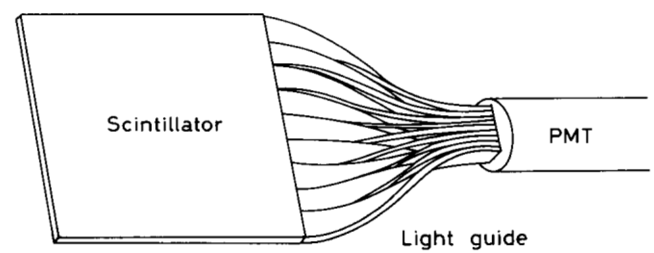
- Sensitivity to energy
- Good linearity over large dynamic range
- Fast time response
- Pulse shape discrimination



Scintillators

- Different types of scintillators
  - Inorganic crystalline scintillators (NaI, CsI, BaF_2...)
  - Nobel Gas (Ar)
  - Organic (Liquids or plastic scintillators)

- Many different geometries



Large plates of scintillators Coupled to single PMT

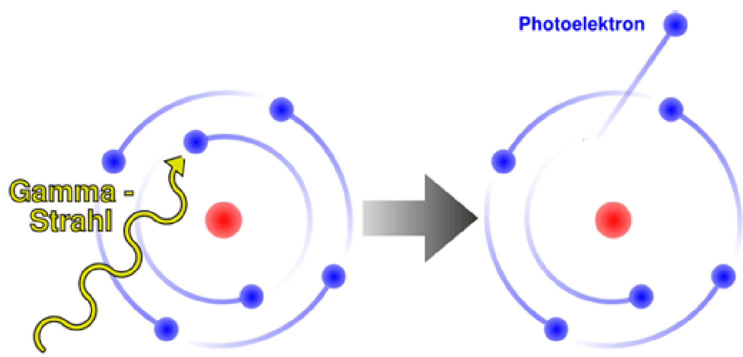
- The amount of light produced in the scintillator is very small. It must be amplified before it can be recorded as a pulse or in any other way.
- External wavelength shifters and light guides are used to aid light collection in complicated geometries; must be insensitive to ionising radiation and Cherenkov light

Photo-detectors

Slide: C.Joram, CERN

Purpose: Convert light into detectable electronic signal

Principle: Use photoelectric effect to ‘convert’ photons (**g**) to photoelectrons (pe)



Details depend on the type of the photosensitive material. Many photosensitive materials are semiconductors, but photoeffect can also be observed from gases and liquids.

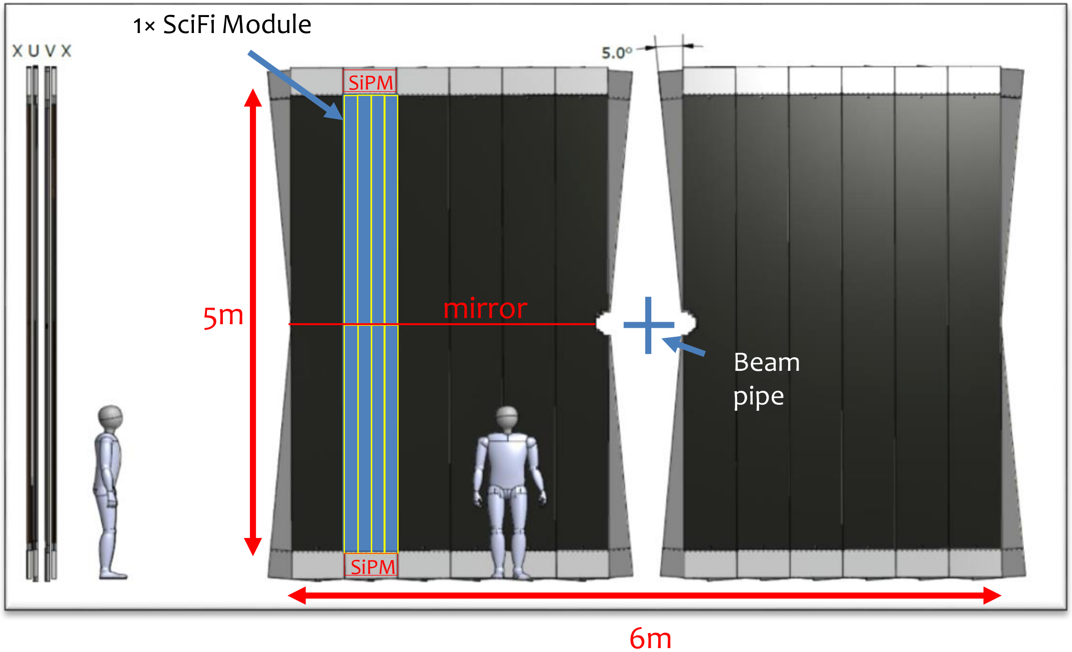
Photon detection involves often materials like K, Na, Rb, Cs (alkali metals) . They have the smallest electronegativity → highest tendency to release electrons.

SciFi in numbers

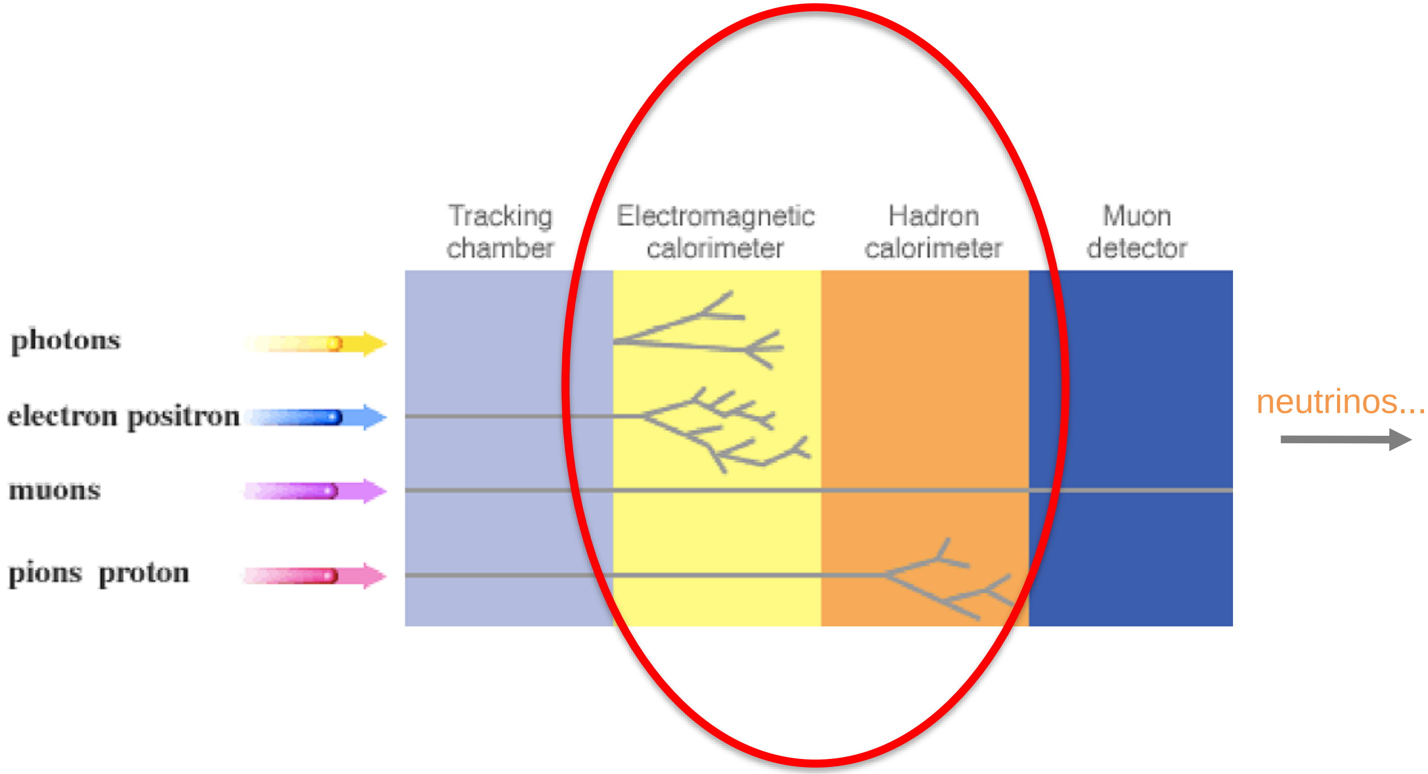
Fibre mat
× 8
SciFi Module
× 12
Detector Layer × 4 (stereo angles 0°, +5°, -5°, 0°)
Tracking Station × 3
Scintillating Fibre Tracker

- 250 micron diam fibers
- 1152 mats, 144 modules
- **360 m²** total area
- almost **11,000 km** of fibre
- **~590’000** SiPM channels

Fi-based downstream tracking stations
Single technology that can perform similarly to a silicon tracker, but cost-effective enough to cover the 30m2 of acceptance of each layer. The result is a light and uniform tracking detector without the need for cooling or signal cables entering into the detector acceptance.



Calorimetry



• Calorimeters •

- Experimental technique in nuclear and particle physics where the detection of a particle and the measurement of its properties is based **on total or partial absorption in the detector volume**

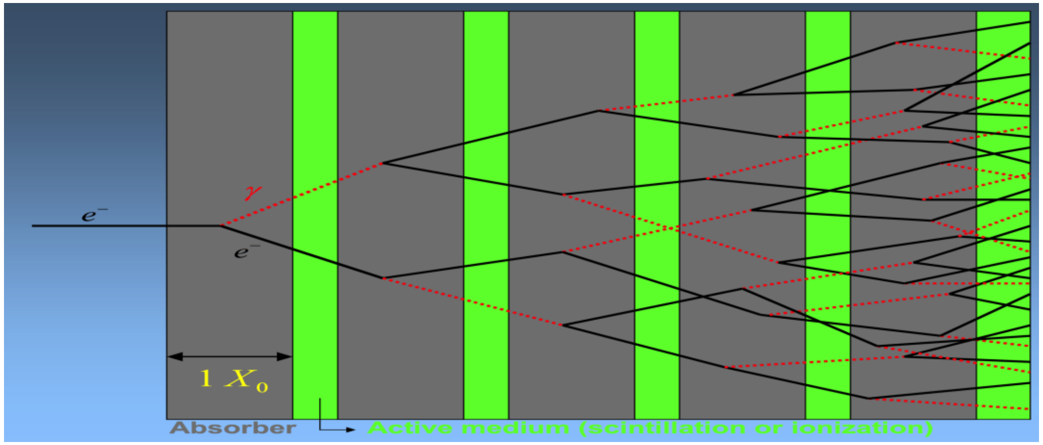
- It is a **destructive process**: particle's energy is converted in a detectable signal until the particle is absorbed (or leave the detector)

- First calorimeters in Particle Physics appeared in the '70s as need to measure energies of all particles, charged and neutrals, *except muon (heavy)* & *neutrinos (weak interaction)*

Calorimeters measure charged and neutral particles (g, e, jets (q,g), missing transverse energy i.e. neutrinos), performance improves with energy and is ~constant over 4p, high rate capabilities and fast making them suitable for trigger applications.

Calorimeters

1. An incident particle interacts with the calorimeter passive and active material
2. A cascade process is initiated: shower development depends on particle type and on detector material
3. Visible energy -heat, ionization, excitation of atoms, Cherenkov light- deposited in the active media of the calorimeter produces a detectable signal
4. Signal produced is proportional to the total energy deposited by the particle
5. **Calorimeter's calibration establishes a precise relationship between the 'visible energy' detected and the energy of the incoming particle**



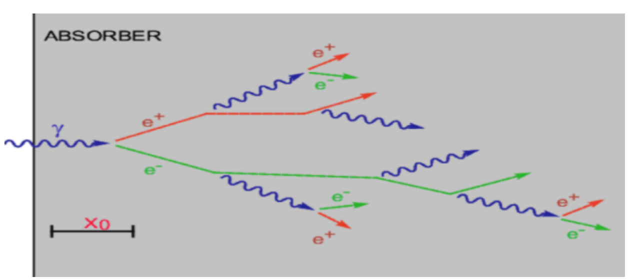
Calorimeter Types

By Particle Type	
Electromagnetic Calorimeter	**Hadronic Calorimeter**
Photons and electron showers (γ,e,π^o)	Charged and neutral hadrons, jets (π, p, n)

EM Shower

Energy losses result from different mechanisms, at high energy the most important processes:

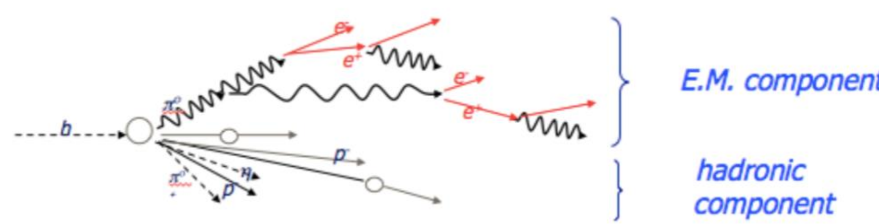
- Electron/Positrons: **Bremsstrahlung** $dE_{e\pm}/E_{e\pm} = - dx/Xo$
- Photons: **Pair productions** $dE_{\gamma}/E_{\gamma} = -(7/9)dx/Xo$



Hadronic Shower

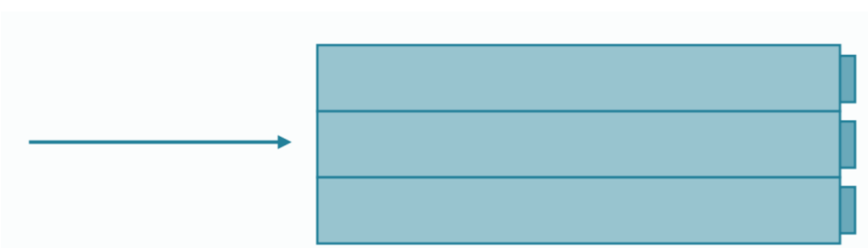
They develop as result of inelastic interaction with the media nuclei through a cascade process

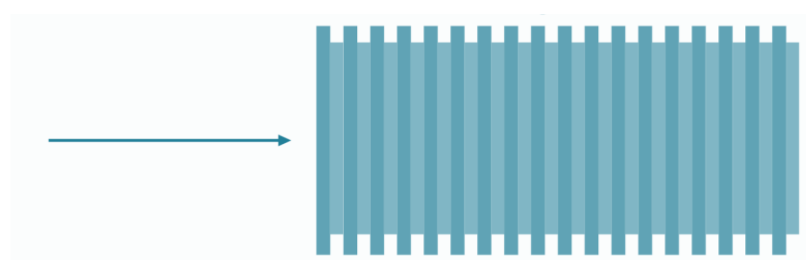
A multitude of effects are produced in the shower development which make the hadron calorimeters a more complicated detector to optimize and with a significantly worse intrinsic



Calorimeter Types

By Construction Type	
Homogenous Calorimeter	**Sampling Calorimeters**
Full absorption detectors, fully active medium for both energy degradation and signal generation	Alternating layers of absorber material to degrade the particle energy and active media to provide detectable signals
Scintillation Semiconductor Cherenkov Ionization (Common: LAr)	Common absorbers are Pb, Fe, Cu, U

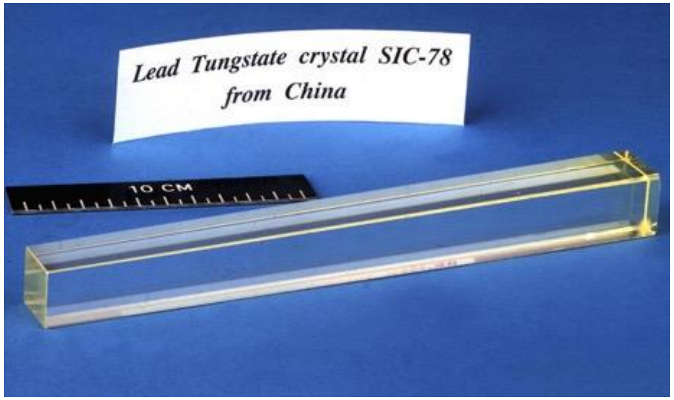




Calorimeters

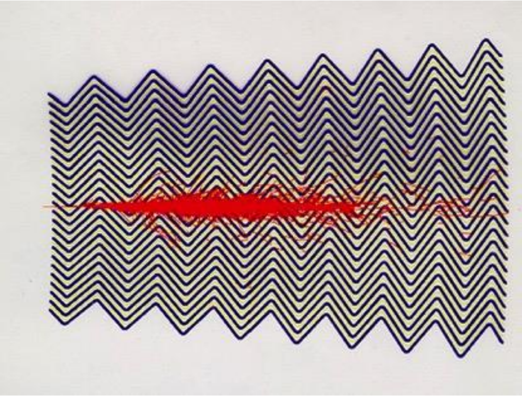
Homogeneous EM Calorimeter (CMS)

- Clear advantage: good energy resolution, good linearity
  - The entire shower is kept in active detector material (no shower particle is lost in passive absorber)
- Disadvantages: limited granularity
  - No information on shower shape in longitudinal direction (along particle flight direction)
  - Cost

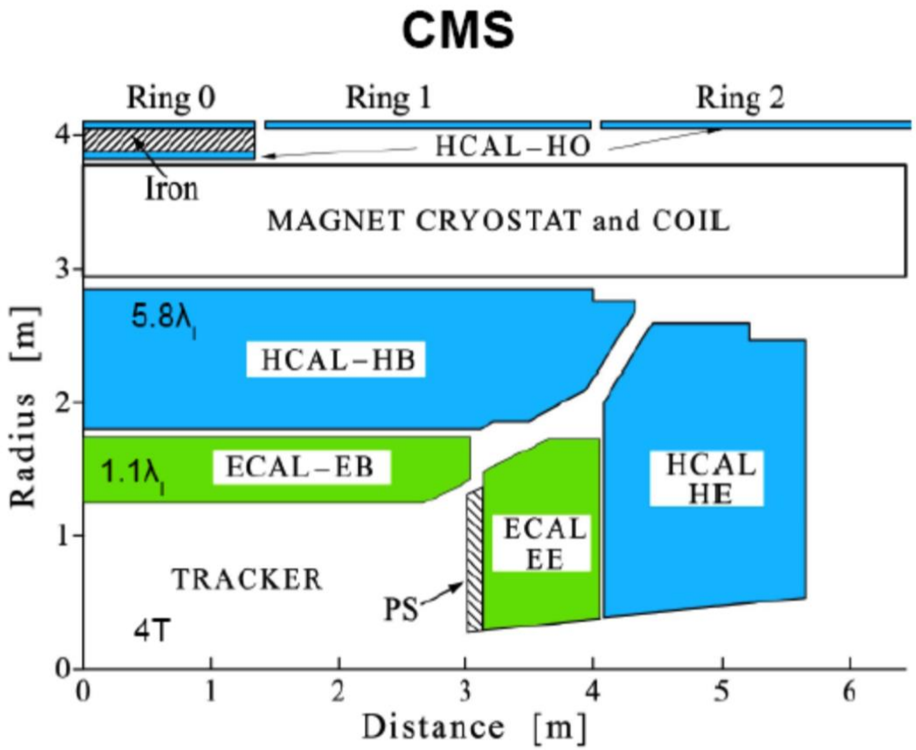


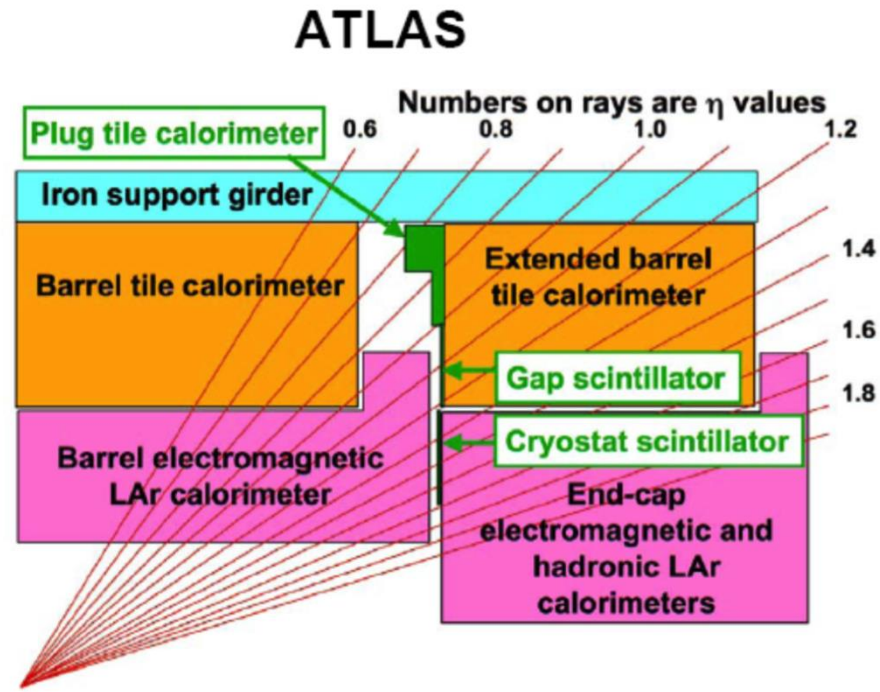
Sampling EM Calorimeter (ATLAS)

- Only a fraction of the energy deposited is detectable: less precision
- Typical sampling calorimeters use iron or lead absorber material, variety of detectors in between possible
- ATLAS is using LAr with "accordion" shaped steel absorbers (accordion geometry to provide better uniformity of response, less cabling, and fast signal extraction)



Calorimeter Systems

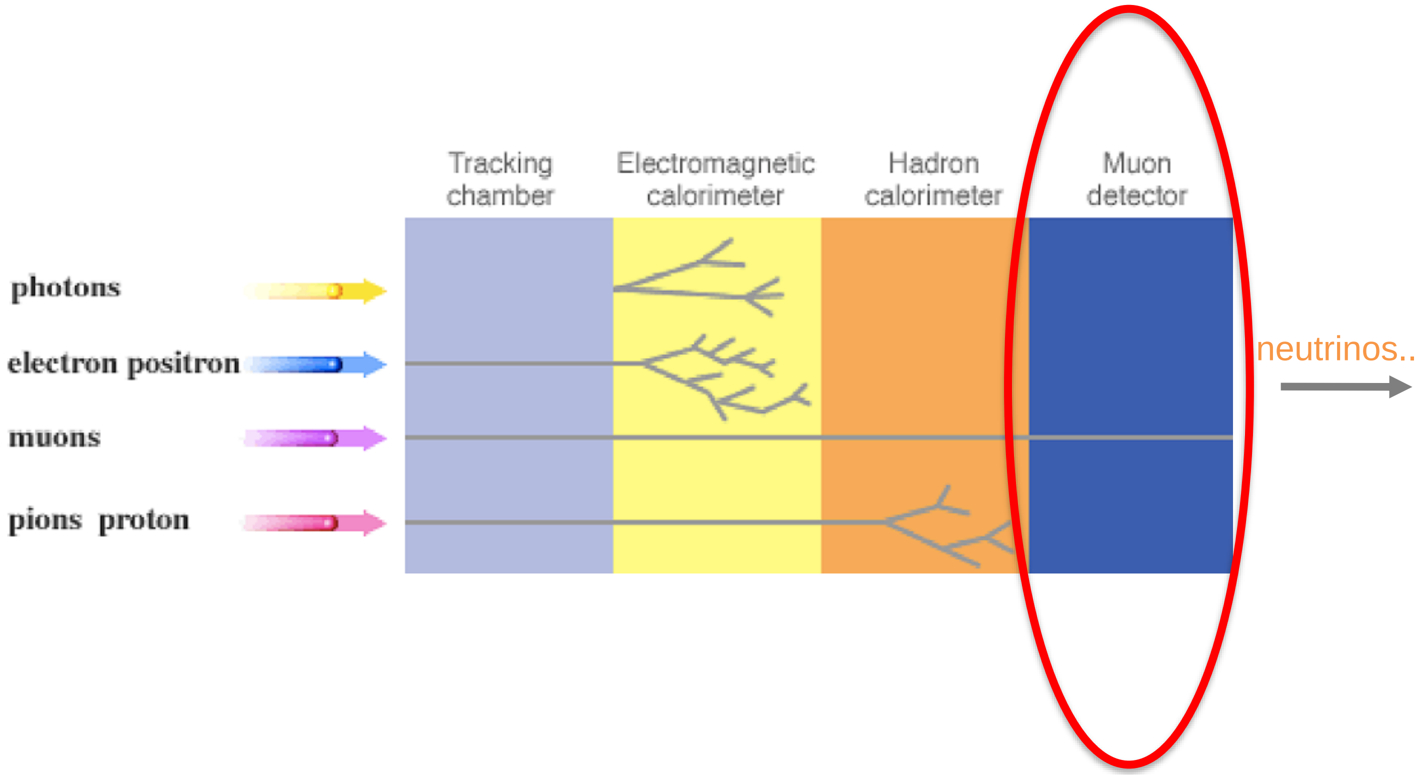




Homogenous ECAL based on scintillating Lead/Tungstate crystals.
HCAL: The hadron barrel (HB) and hadron endcap (HE) calorimeters are sampling calorimeters with 50 mm thick copper absorber plates interleaved with 4 mm thick scintillator sheets. Hadron Forward (HF) is a SS absorber and quartz fibers emitting Cherenkov light.

ECAL based on liquid argon sampling calorimeter; Lead absorber. In the forward regions (FCAL), used Cu rods.
HCAL is a sampling calorimeter using iron as absorber material and scintillating tiles as active material. The HEC (End-Cap calo) is an LAr sampling calorimeter with Cu plate absorbers.

Muon Systems



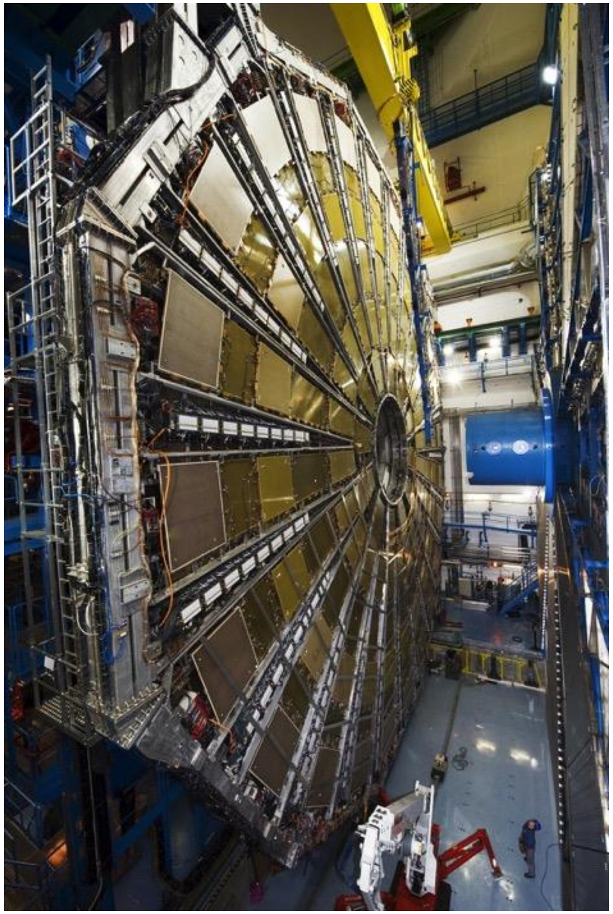
• Muon Systems •

- Function: muon detection; Muons are charged particles that are just like electrons and positrons, but 200 times heavier.

  Because muons can penetrate several metres of iron without interacting, unlike most particles they are not stopped by calorimeters. Therefore, chambers to detect muons are **placed at the very edge of the experiment** where they are the only particles likely to register a signal.

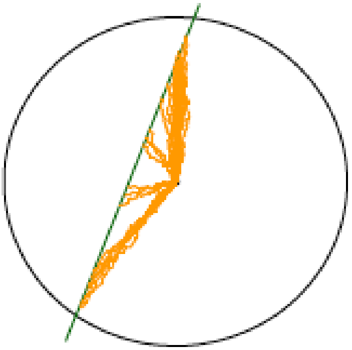
- Detection principle: Ionization detectors (gas), similar to precision trackers but usually of lower spatial resolution.

- **They are fast detectors and are part of the Trigger system to select events**

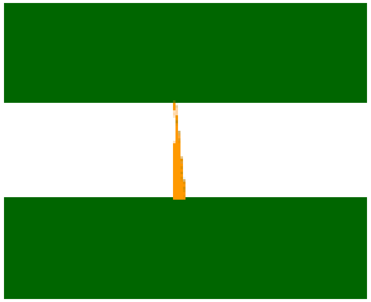


ATLAS,12 000 m², 1.1 Mchannels
Aligment precission <±30 mm

Time Resolution



Cylindrical geometries have an important limitation:
Primary electrons have to drift close to the wire before the charge multiplication starts
<u>Limit in the time resolution ~ 0.1μs</u>



In a parallel plate geometry the charge multiplication starts immediately because all the gas volume is active (uniform and very intense field). This results in much better time resolution (~ 1 ns)

Resistive Plate Chambers

Developed in the 80s as an **affordable, robust, large area detector** with:

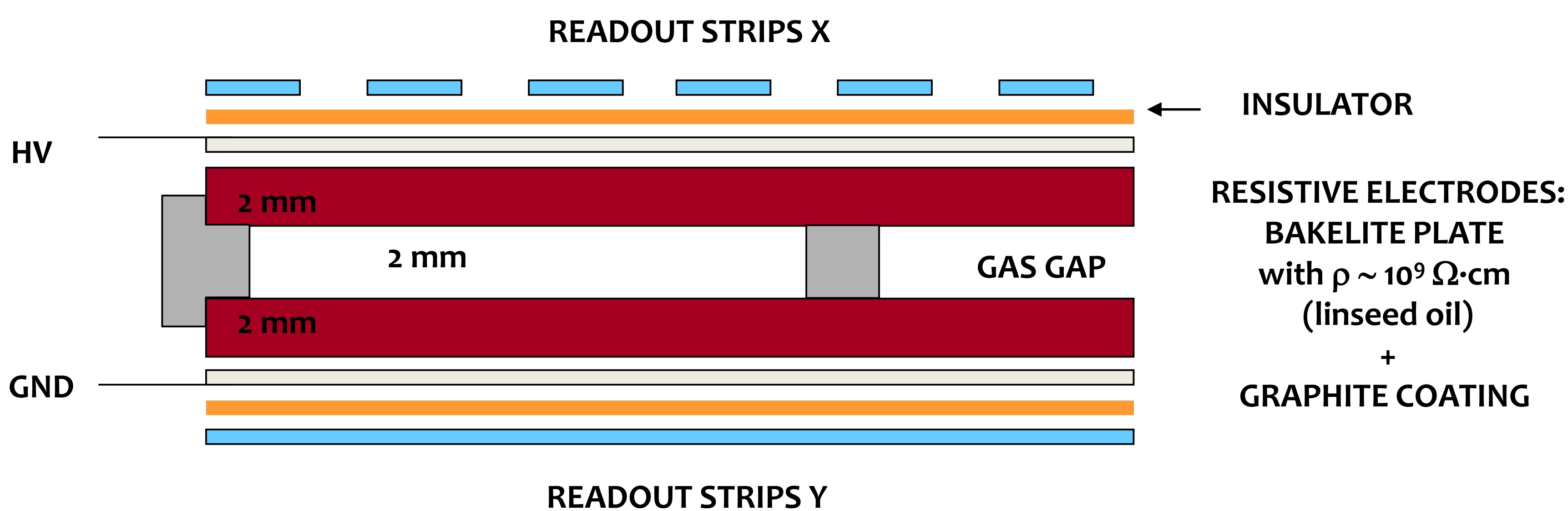
Fast timing: < 1 ns to ps for MRPC
Space resolution: ~mm
Rate capability: up to ~100 Hz/cm^2

RPC developments for LHC

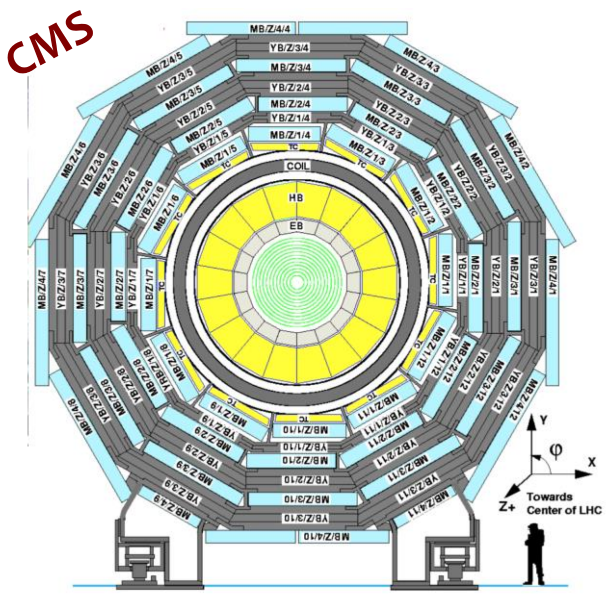
Large Area Coverage (> 5000 m^2) – Industrialization

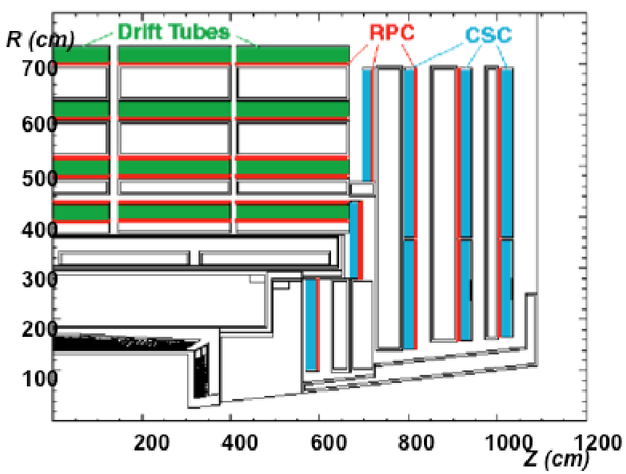
Increased Rate Capability (~kHz/cm^2)

Large Background Radiation



Muon Spectrometer





DRIFT TUBES (DT)
Central coverage
Tracking (100 mm) & trigger

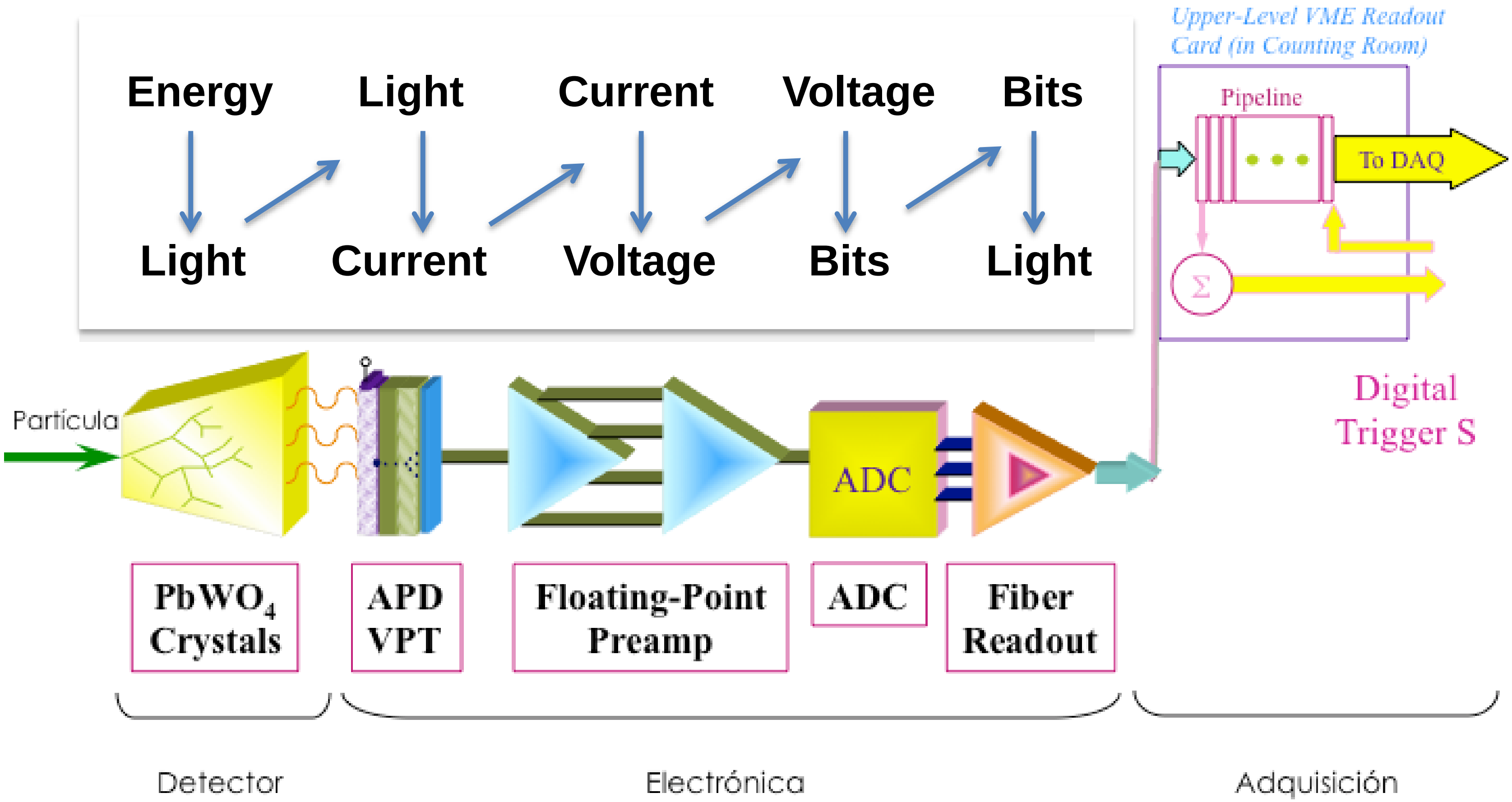
Traditional Technology

CATHODE STRIP CHAMBERS (CSC)
Forward coverage (6000 m2)
Tracking (1mm) & trigger
540 detectors, 0.5 MChannels

Designed to operate in intense magnetic field and neutron background ~1 kHz/cm^2

RESISTIVE PLATE CHAMBERS (RPC)
Central and forward coverage
Redundant Trigger (3 ns)
612 detectors

Signals


Energy
Light
Light
Current
Current
Voltage
Voltage
Bits
Bits
Light
Upper-Level VME Readout Card (in Counting Room)
Pipeline
To DAQ
Σ
Digital Trigger S
Partícula
ADC
PbWO4 Crystals
APD VPT
Floating-Point Preamp
ADC
Fiber Readout
Detector
Electrónica
Adquisición

Data Acquisition, Storage, Distribution and Processing is as complex as the detector itself

- Large data production (~PB/sec) versus storage capability (~GB/sec) forces huge online selection
- 3 levels of triggers (first level fully electronics based)
- Data distribution for offline processing using GRID system

Trigger	Método	Entrada Sucesos/s	Salida Sucesos/s	Factor de reducción
Nivel 1	HW (⌠, Calo)	$40\,000\ 10^3$	$100\ 10^3$	400
Nivel 2	SW (RoI, ID)	$100\ 10^3$	$3\ 10^3$	30
Nivel 3	SW	$3\ 10^3$	$0.2\ 10^3$	15

Tier O → **Worldwide LHC Computing Grid**

HEP Detectors

Last generation of HEP detectors are incredibly complex and state of the art pieces of technology

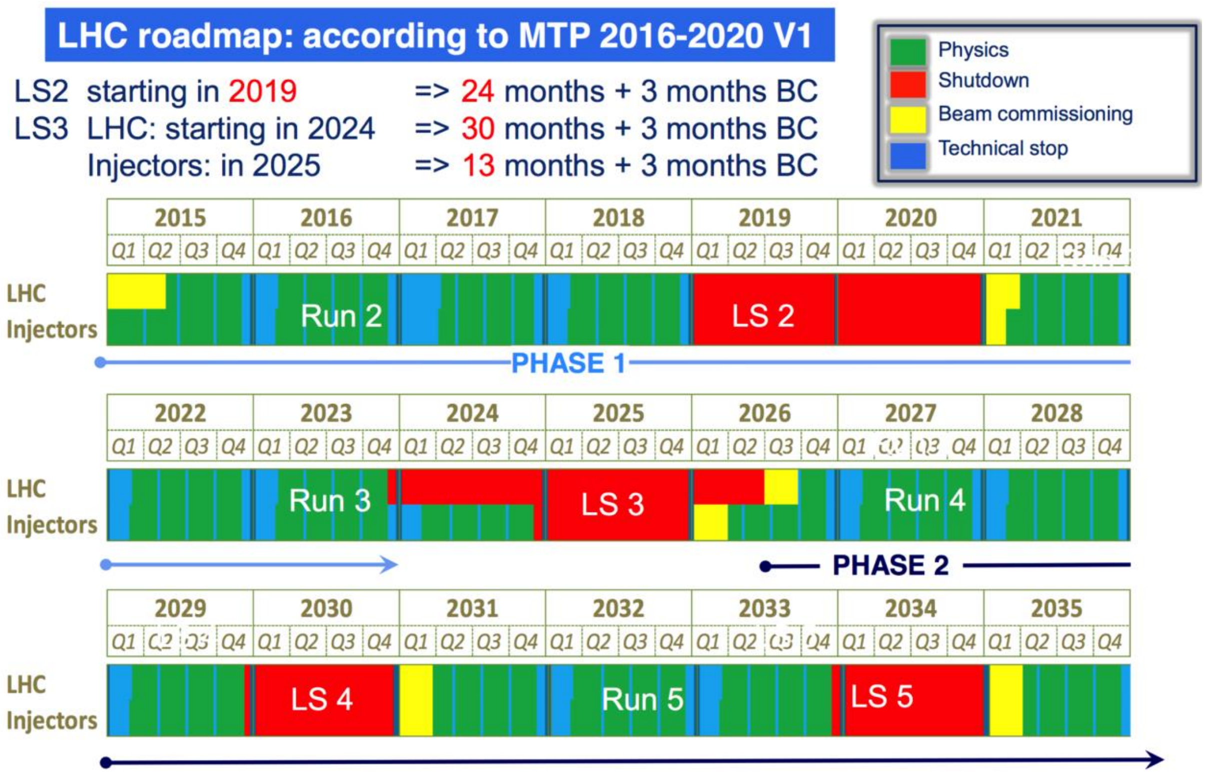
- Large use of (semiconductors/gas) radiation hard technology for trackers
- Calorimeters precise as never before
- Cryogenics for detectors and magnet systems
- Detector systems increased in size and complexity at least a factor 10
- The data flow and data processing is unprecedented
- Projects span over 3-4 decades, involving thousands of scientists

Experiment	Countries	Institutions	Scientists
ALICE	37	154	~1500
ATLAS	38	182	~ 3000
CMS	46	182	~ 3500
LHCb	16	69	~ 800

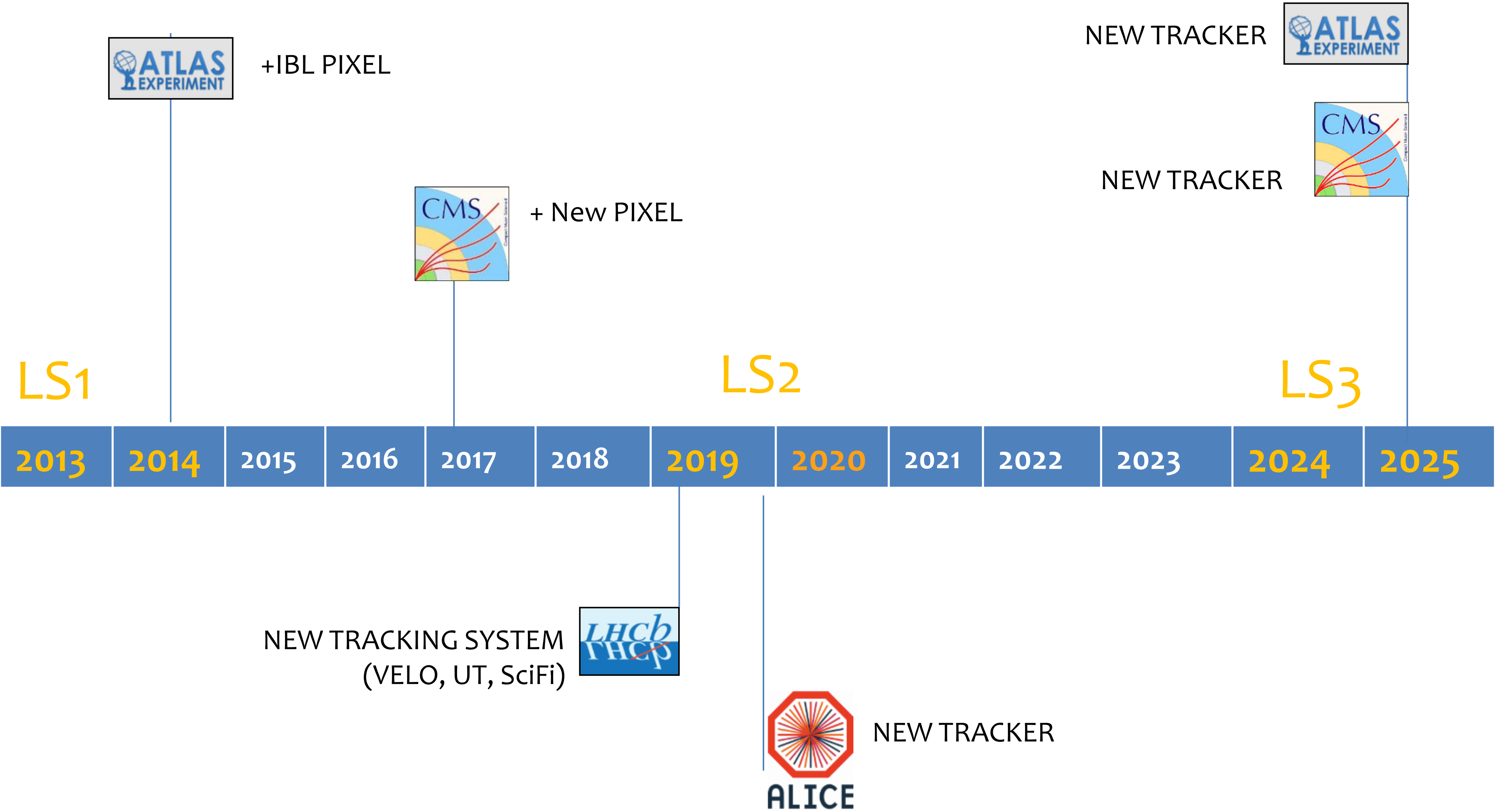
Future

The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier

- **Must replace inoperable detector elements (rad damage)**
- **Must upgrade electronics to cope with increased rates**



LHC Tracker Upgrades



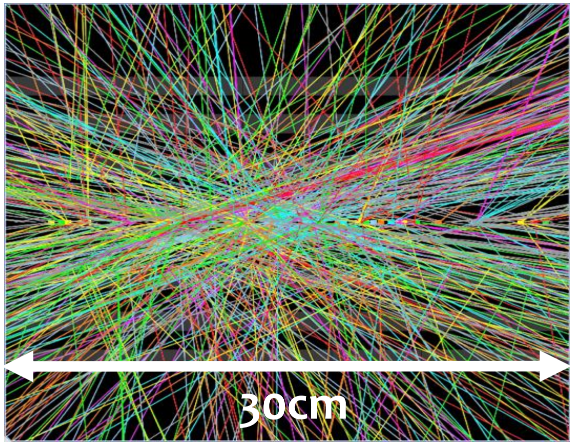
• Tracker Upgrades •

Challenges for HL-LHC

- Maximum leveled instantaneous luminosity of 7.5×10^{34} cm^{-2} s^{-1}. Currently ~1×10^{34} cm^{-2} s^{-1}
- 3,000 fb-1 Integrated luminosity to ATLAS/CMS over ten years of operation
- 200 (mean number of) proton-proton interactions per bunch crossing. Design was 23, recently extended capability to > 50 pp interactions per bunch crossing

- Higher particle fluences: **increased radiation tolerance**
- Higher occupancies: **finer segmentation**
- Larger Area (~200 m^2 for strips and 16 m^2 for pixels): **cheaper sensors, ease of construction, distributed production**
- Low noise and power

	Silicon Area (m^2)	MChannels
Pixel	8.2	638
Strip	193	74



• Detector Upgrades •

- **Calorimeters R&D Efforts**, towards rad tolerant systems
  - Rad-tolerant crystal scintillators (LYSO, YSO, Cerium Fluoride), WLS fibres in quartz capillaries, rad-tolerant photo-detectors (e.g. GaInP), change layout of tile calorimeter using WLS fibres within scintillator to shorten the light path length, High granularity Particle flow / Imaging Gas Calorimetry (CALICE)…
  - *Electronics upgrades:* On-detector front-end electronics with sufficient resolution and large dynamic range
- **Muon systems R&D Efforts**
  - Improved rate capability and timing, using novel detector technologies (e.g. MPGD)
- **Electronics**
  - Development of new front-end chips to cope with increased channel densities, develop high density interconnects, optiize power distribution, develop High speed links ($\gtrsim$10 Gbps)
- **Trigger/DAQ/Offline computing**
  - New trigger strategies, processing, networks, storage, CPU, CLOUD-computing…

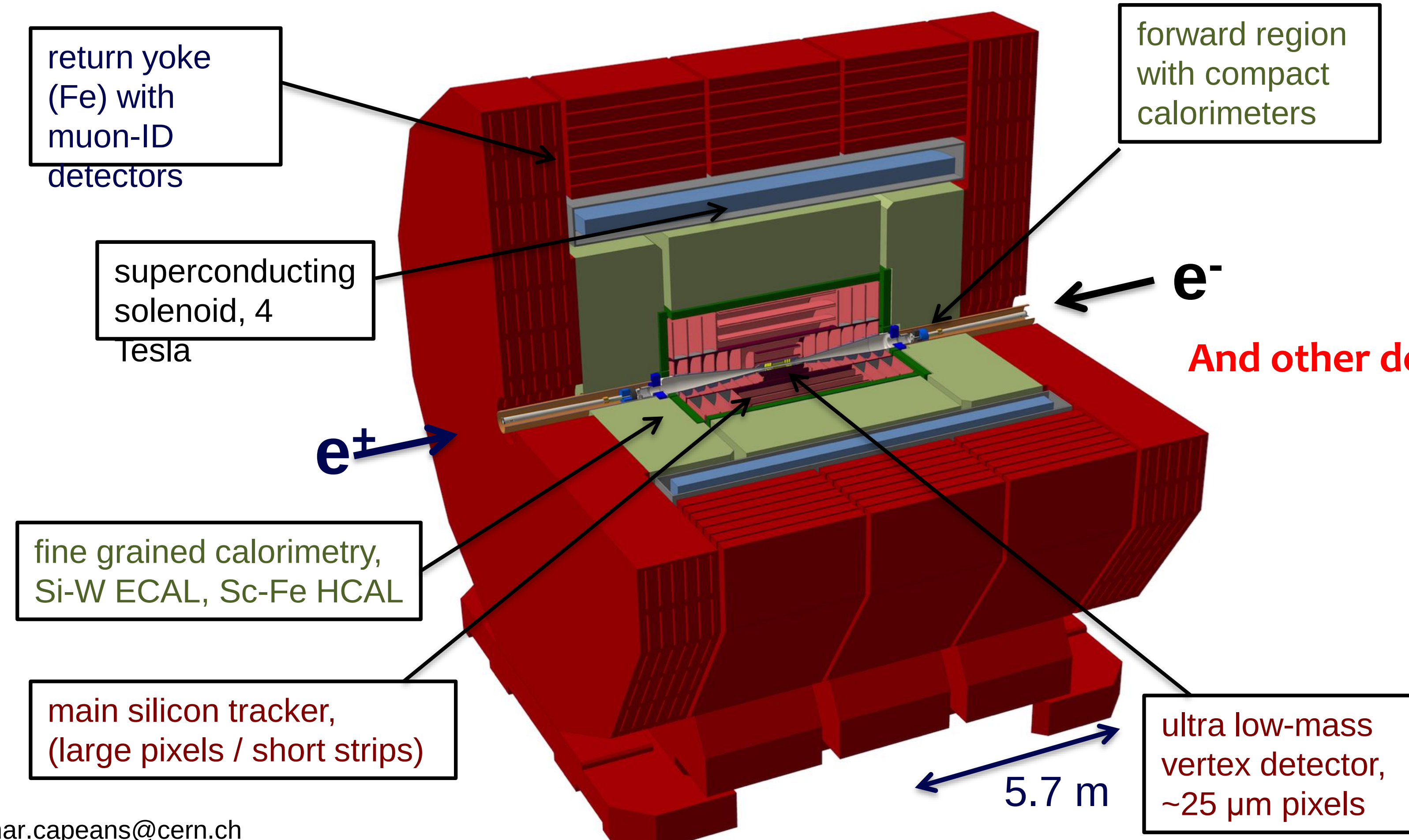
Diverse R&D

Driven by Study Projects

- **LCD**
  - The Linear Collider Detector focuses on physics and detector studies for a future e+e- collider at the TeV-scale
- **FCC**
  - The Future Circular Collider Study explores different designs of circular colliders (100 TeV) for the post-LHC era
- **Neutrino Platform**
  - Fundamental research in neutrino physics at particle accelerators worldwide

CLIC Detector

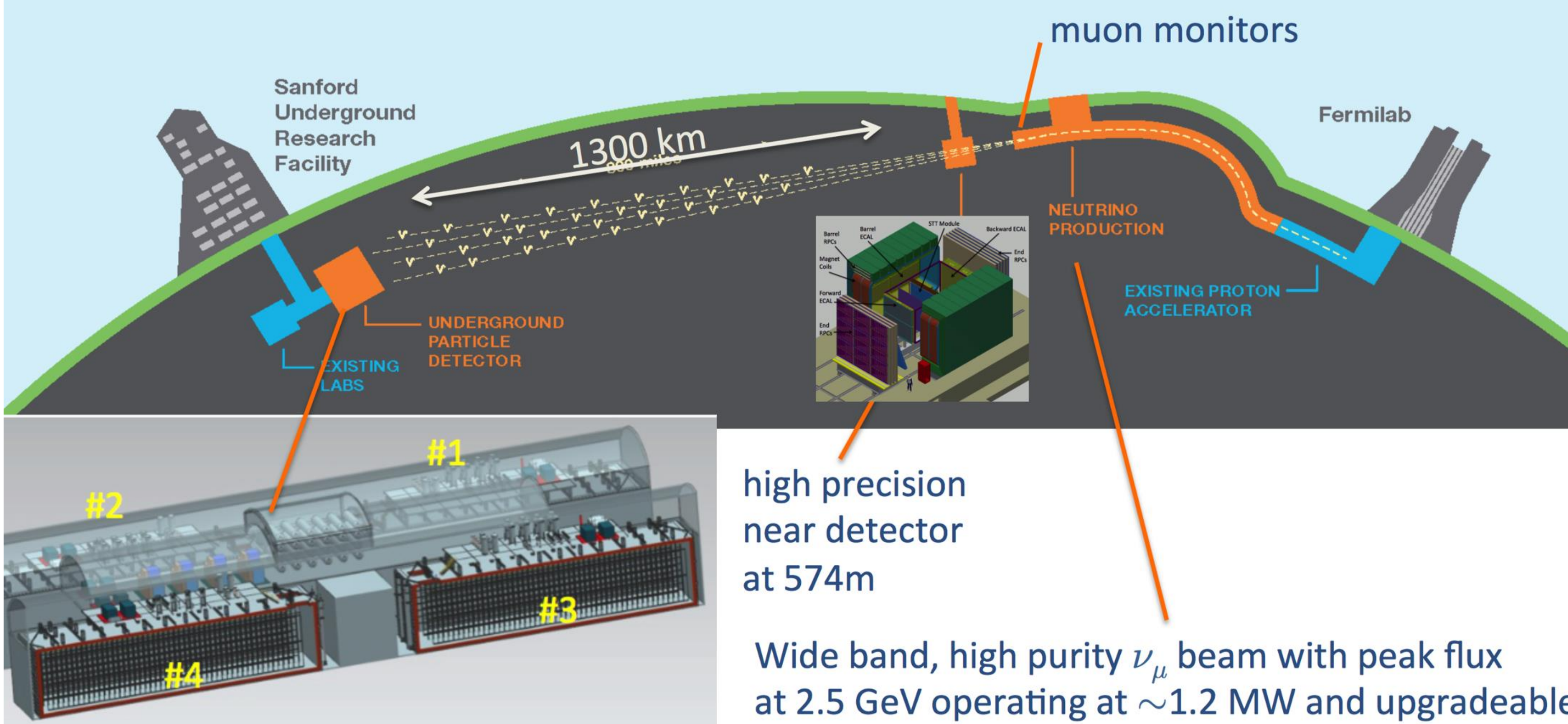
LHC: high rates of QCD backgrounds, need of complex triggers and high levels of radiation. **Linear colliders** imply collisions e+e- that are pointlike, with initial state well-defined and therefore with a clean experimental environment: possible trigger-less readout, and most important, low radiation levels. **Makes it easier to use new technologies.**



And other designs…

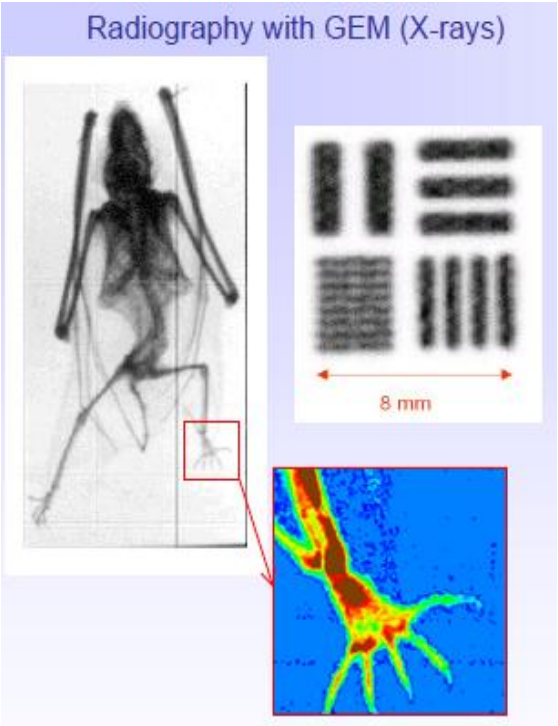
• Neutrino Detectors •

DUNE Overview



- four identical cryostats deep underground
- staged approach to four independent 10 kt LAr detector modules
- Single-phase and dual-phase readout under consideration

Other Fields of Application



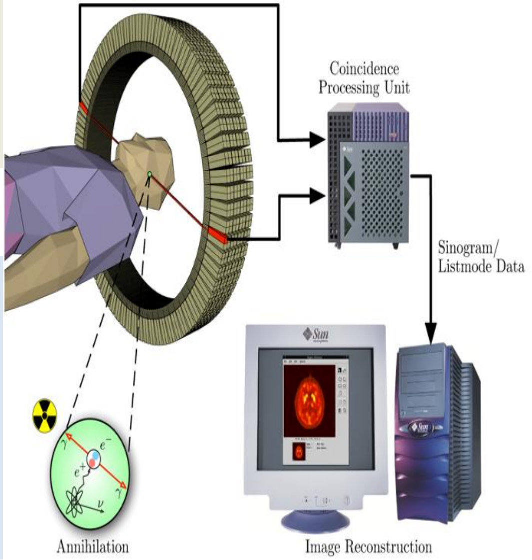
Fast and Therma Neutron Detection
Non-destructive diagnotic, Biology, Nuclear plants, …

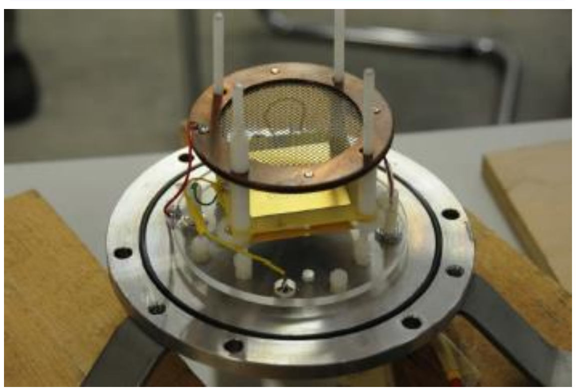
Xray Low Energy
Radioactive waste…

Pixelated GEMs
Microdosimetry, Direct measurements with real tissue, Radon monitors….

Gamma High Fluxes
Radiotherapy…

High Intensity Beam Monitors
Hadrontherapy, Ions beam monitoring…





Highly sensitive GEM-based UV flame and smoke detector

RETGEM-based detectors are able to reliably detect a 1.5 m^3 fire at a ~1 km distance

Ref. http://arxiv.org/pdf/0909.2480.pdf

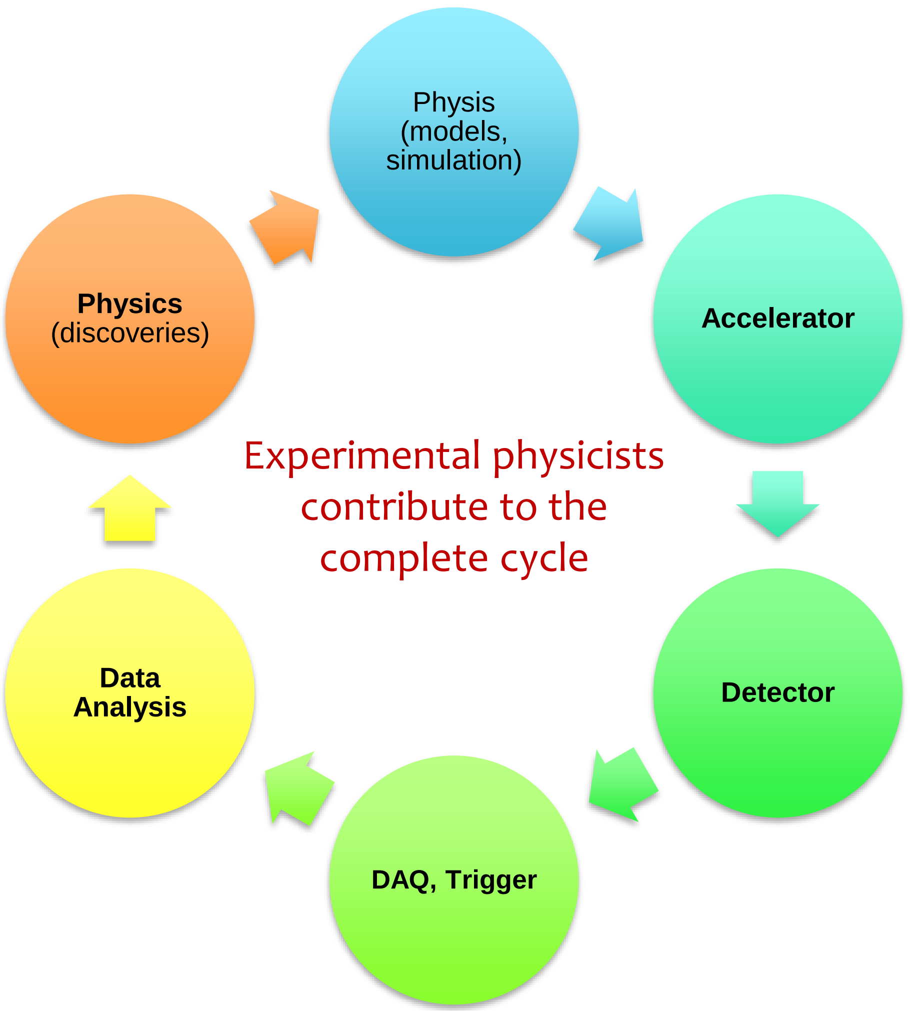
Message for your students

Experimental testing is the key to discover and advance knowledge.

New directions in science are launched by new improved tools much more often than by new concepts.

There is a very close relationship between physics discoveries and developments in instrumentation: Accelerators, Detectors, Electronics and Computing

Development of integrated designs is carried out in close collaboration with physicists, microelectronics experts, mechanical/thermal engineers, material/micro/nano technology scientists…



Thanks for your attention!

+

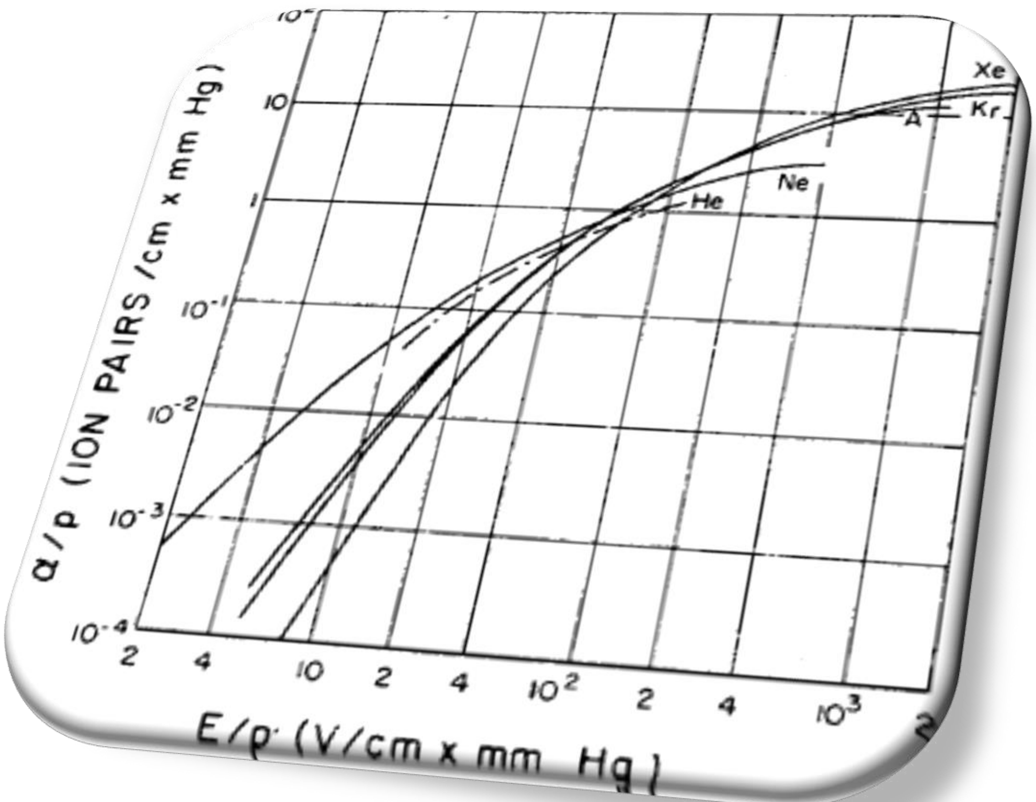
- *The Particle Detector BriefBook* http://www.cern.ch/Physics/ParticleDetector/BriefBook/
- CERN summer student lectures by W.Riegler: http://indico.cern.ch/conferenceDisplay.py?confId=134370
- ICFA Schools on Instrumentation
  - The last one: http://fisindico.uniandes.edu.co/indico/conferenceTimeTable.py?confId=61#20131125

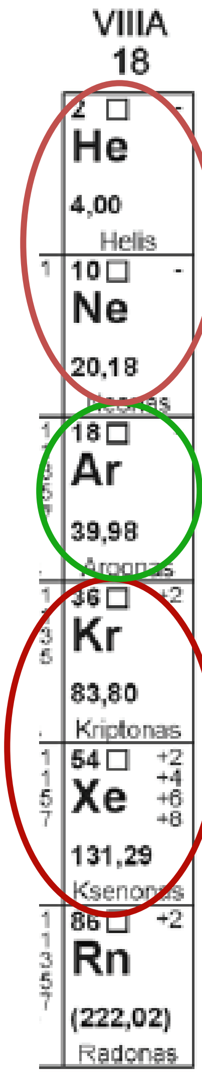
- **BOOKS:**
- K. Kleinknecht - Detectors for Particle Radiation, C.U.P. 1990
- R.K. Bock & A. Vasilescu - The Particle Detector BriefBook, Springer 1998
- R. Fernow - Introduction to Experimental Particle Physics, C.U.P. 1986
- **W.R. Leo - Techniques for Nuclear and Particle Physics Experiments, Springer-Verlag 1987**
- G.F. Knoll - Radiation Detection and Measurement, Wiley 1989

- **CERN Notes:**
- Fabjan & Fischer - Particle Detectors CERN-EP 80-27, Rep. Prog. Phys. **43** (1980) 1003
- F. Sauli - Principles of Operation of Multiwire Proportional and Drift Chambers, CERN 77-09

Spare Slides

Noble Gases





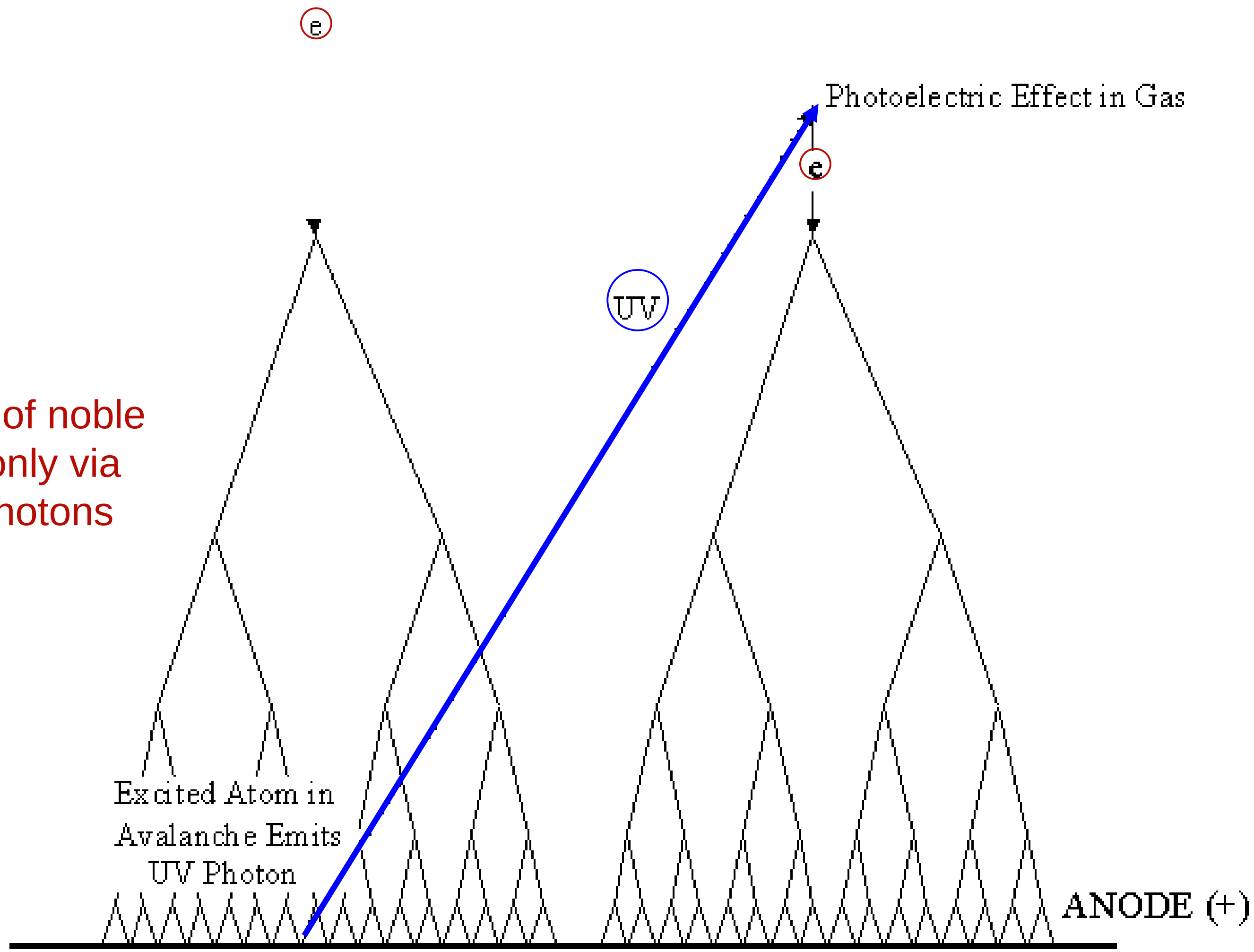
Light

Abundant
Inert
Cheap

Expensive

Noble gases require the lowest electric field for formation of avalanches

De-excitation of noble gases occur only via emission of photons

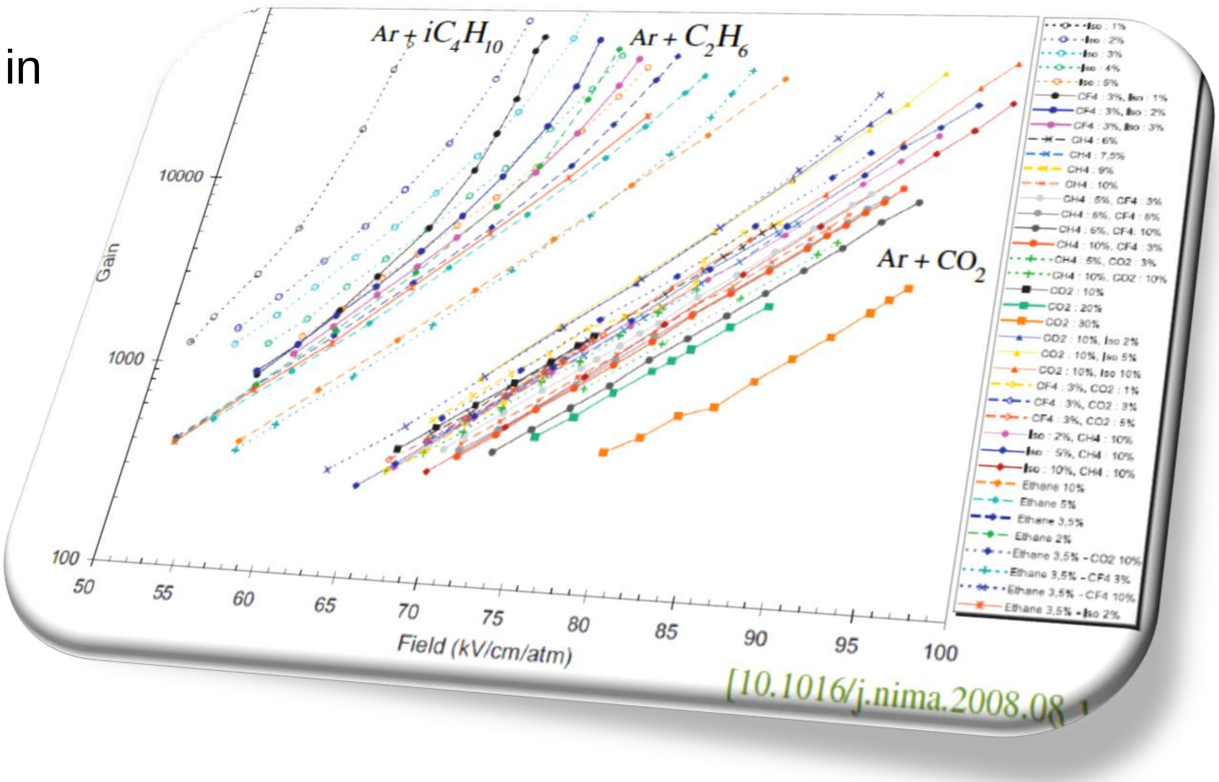


Primary avalanche **Secondary avalanche**

• Quencher Gases •

A polyatomic gas acts as a QUENCHER, i.e., absorbs photons in a large energy range due to the large amount of non-radiative excited states (rotational and vibrational)

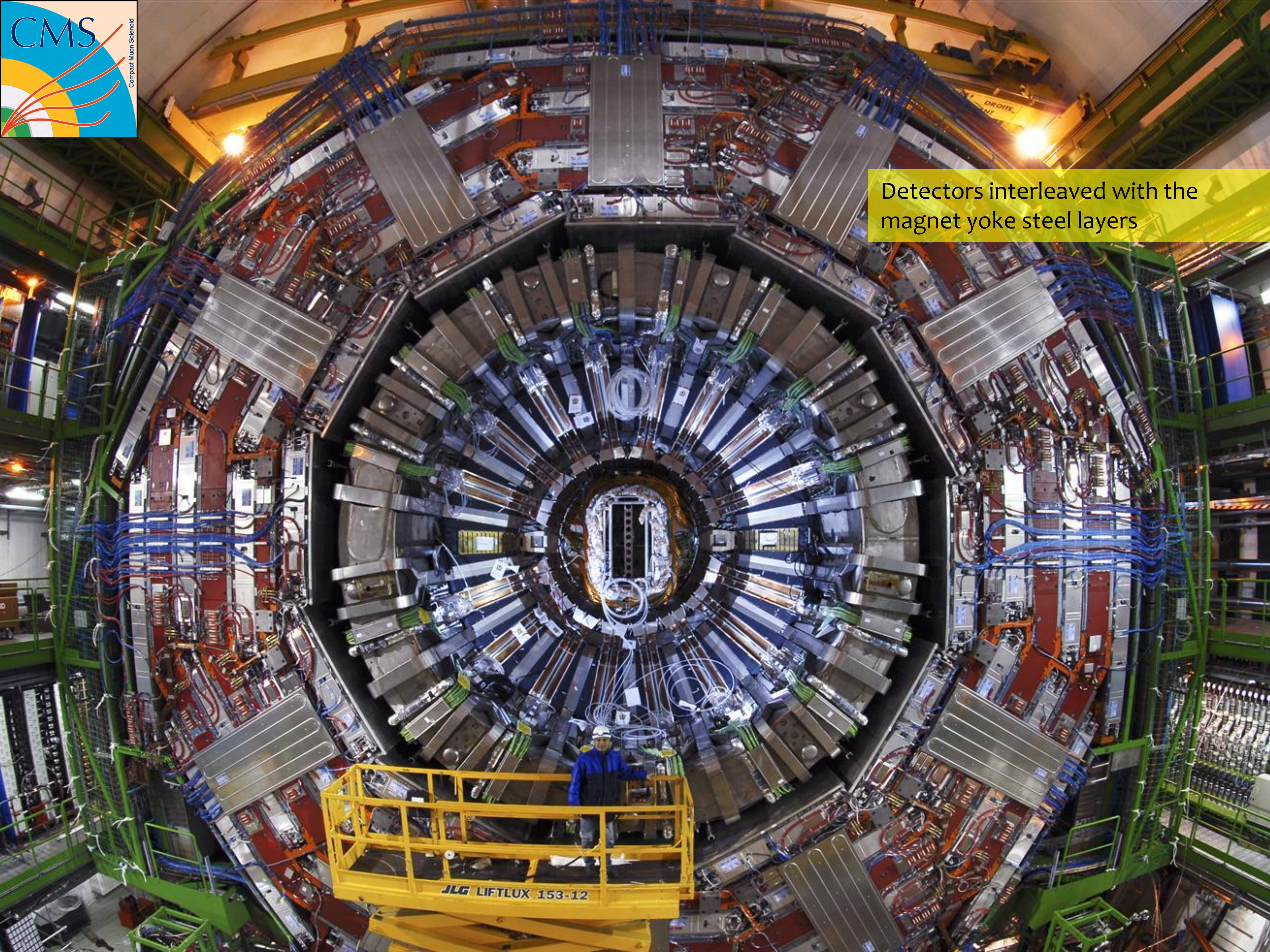
- Most organic compounds in the HC and -OH families. The quenching efficiency increases with the nb of atoms in the molecule
- Freons, BF_3
- CO_2: non flammable, non polymerizing, easily available



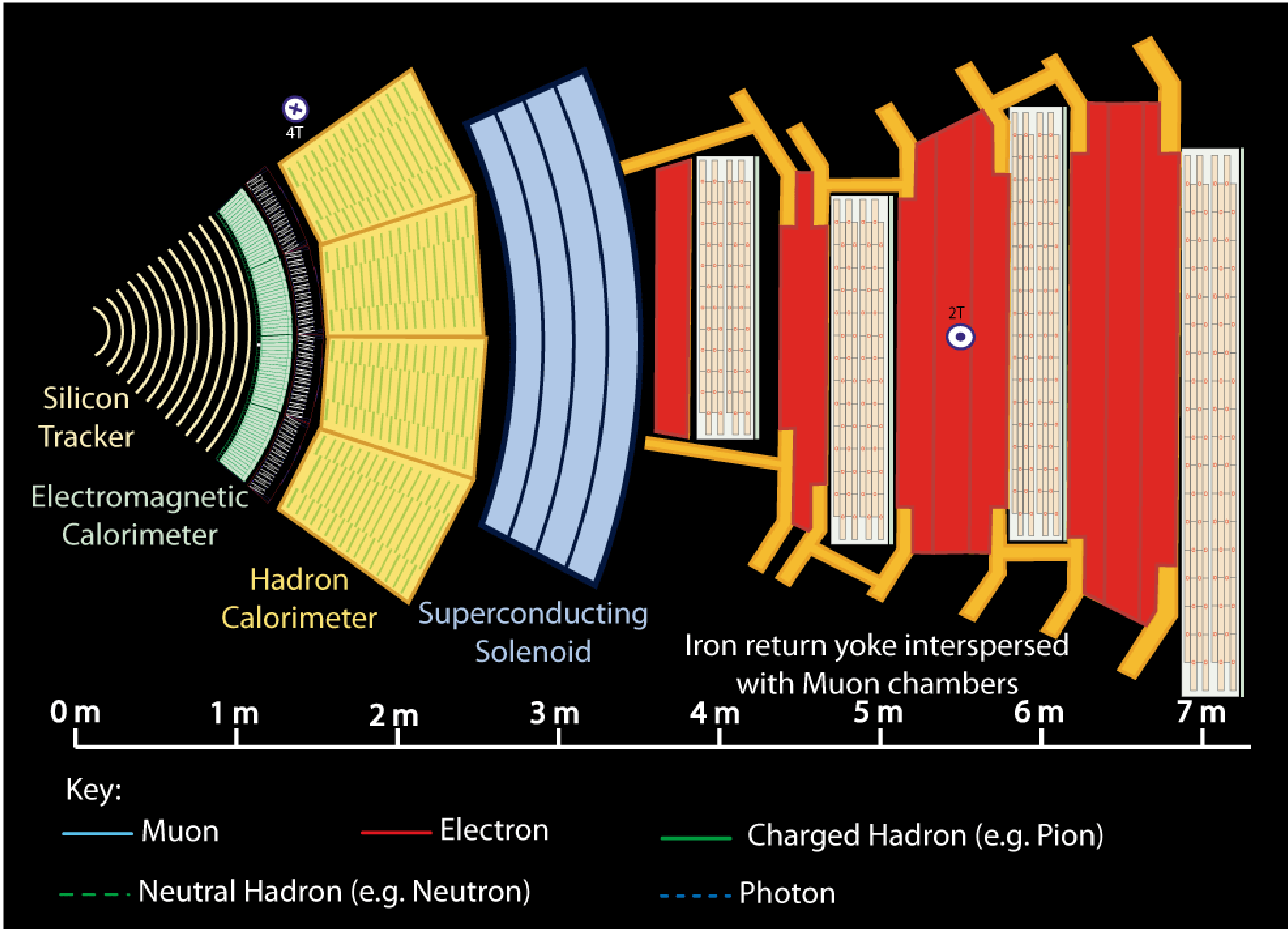
Gas in LHC detectors

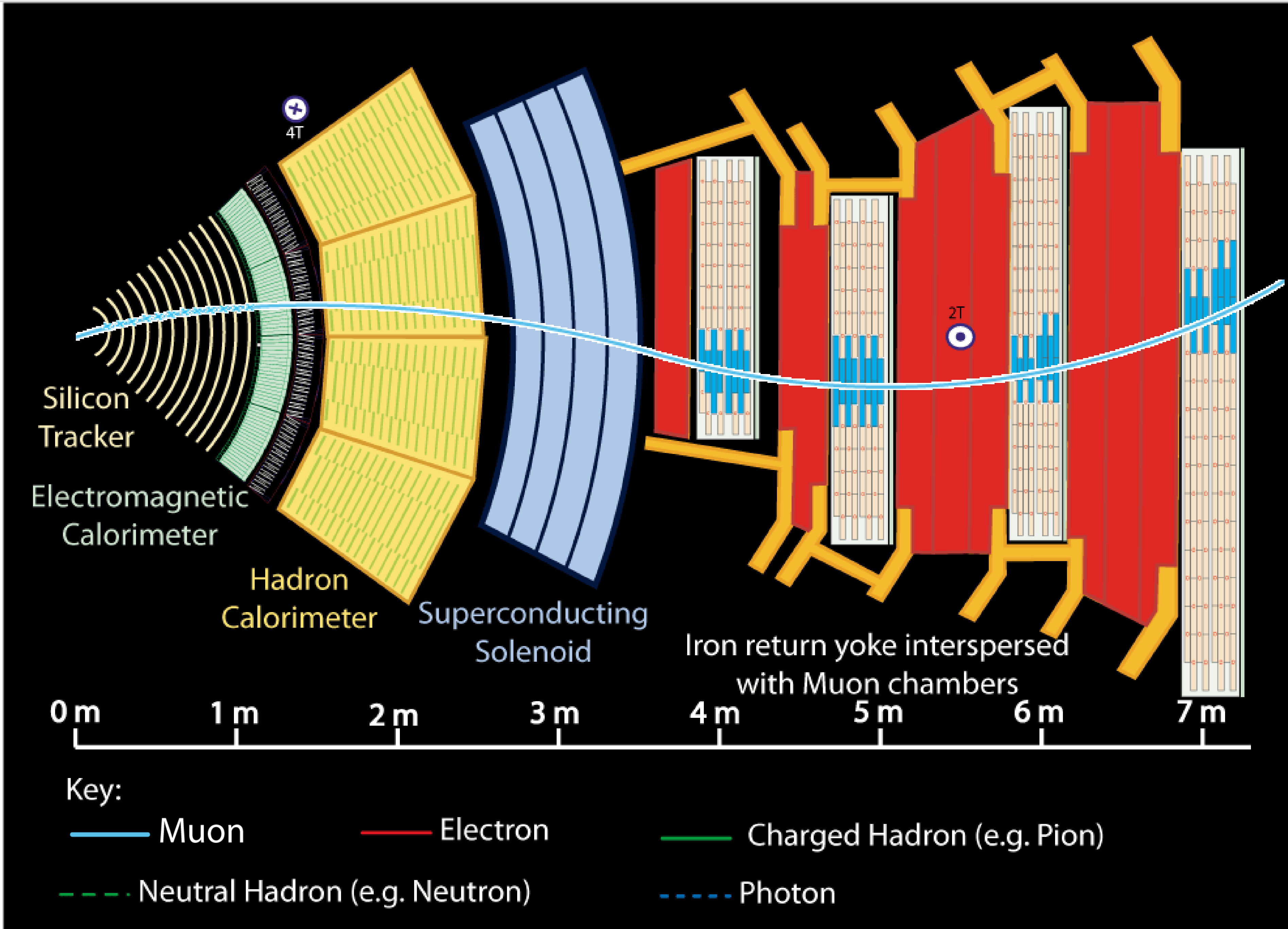
Experiment	Sub- Detector	Gas Mixture
ALICE	TPC, TRD, PMD	Noble Gas **+ CO_2**
ATLAS	CSC, MDT, TRT	
CMS	DT	
LHCb	OT straws	
TOTEM	GEM, CSC	
LHCb	MWPC, GEM	Ar **– CO_2 - CF_4**
CMS	CSC	
ATLAS, CMS, ALICE	RPC	$C_2H_2F_4$ - iC_4H_{10} - SF_6
ATLAS	TGC	CO_2 – n-pentane
LHCb	RICH	CF_4 or C_4F_{10}

CMS
Compact Muon Solenoid



Detectors interleaved with the magnet yoke steel layers


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon


4T
Silicon
Tracker
Electromagnetic
Calorimeter
Hadron
Calorimeter
Superconducting
Solenoid
2T
Iron return yoke interspersed
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0 m
1 m
2 m
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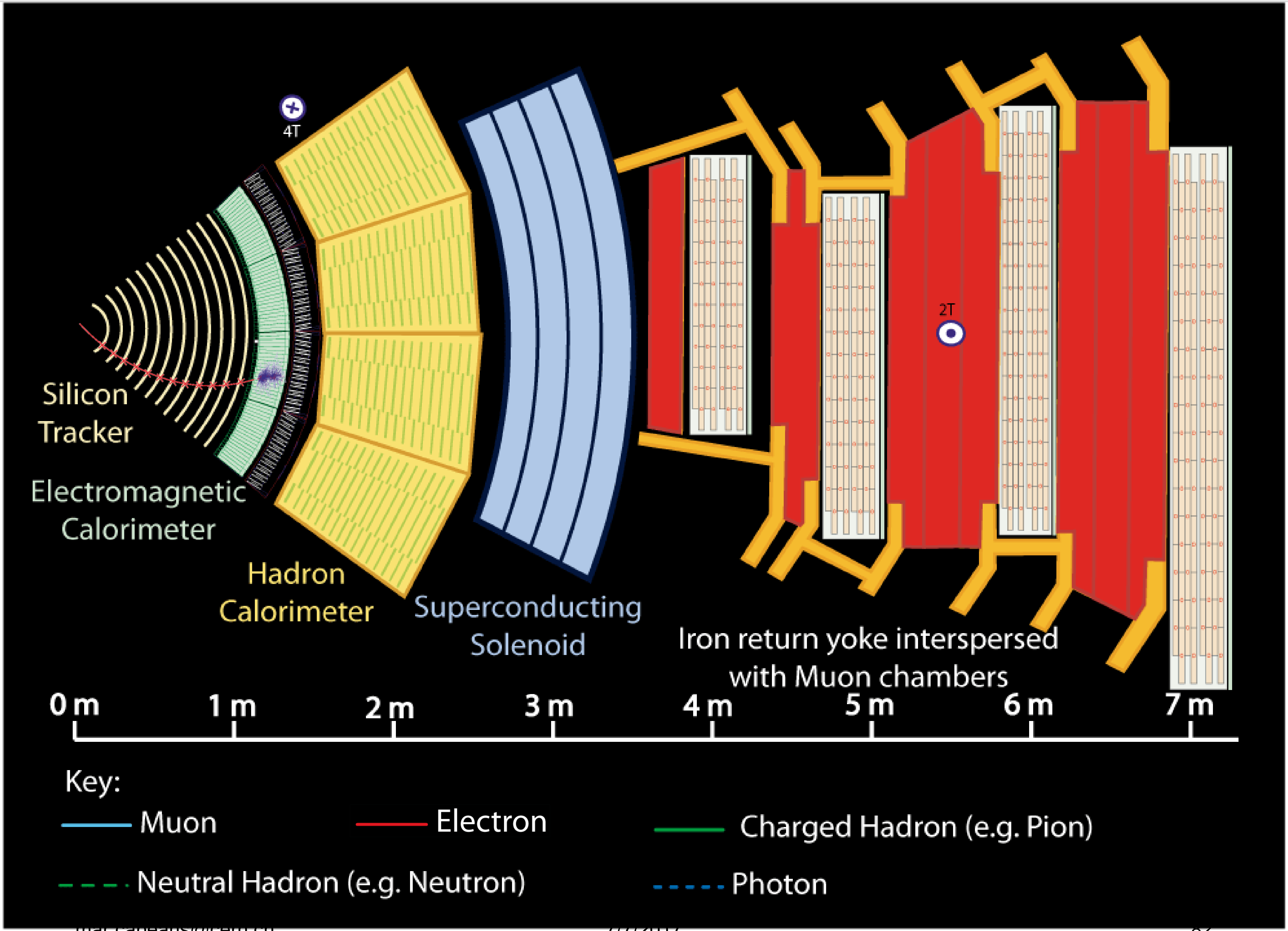
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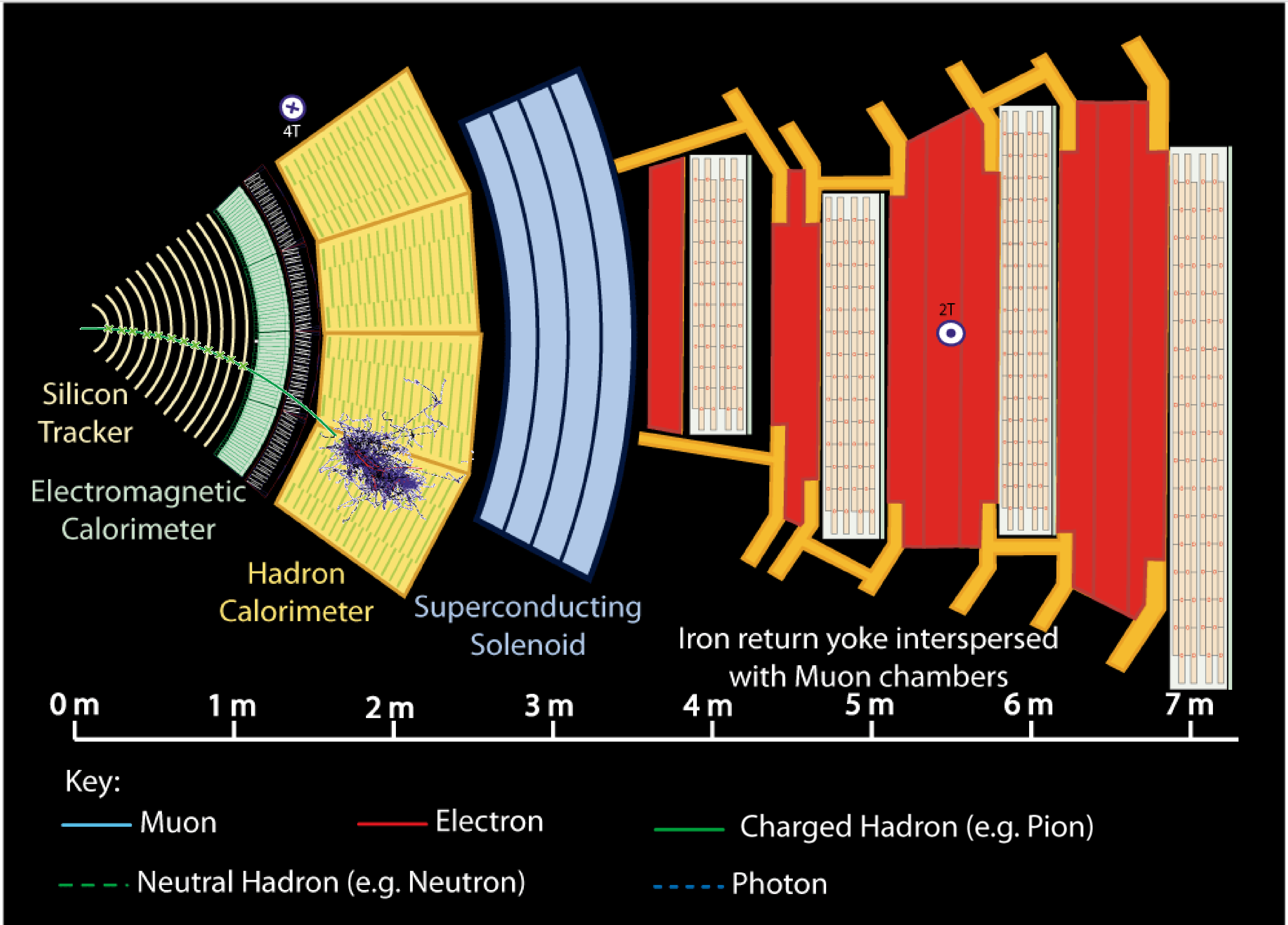
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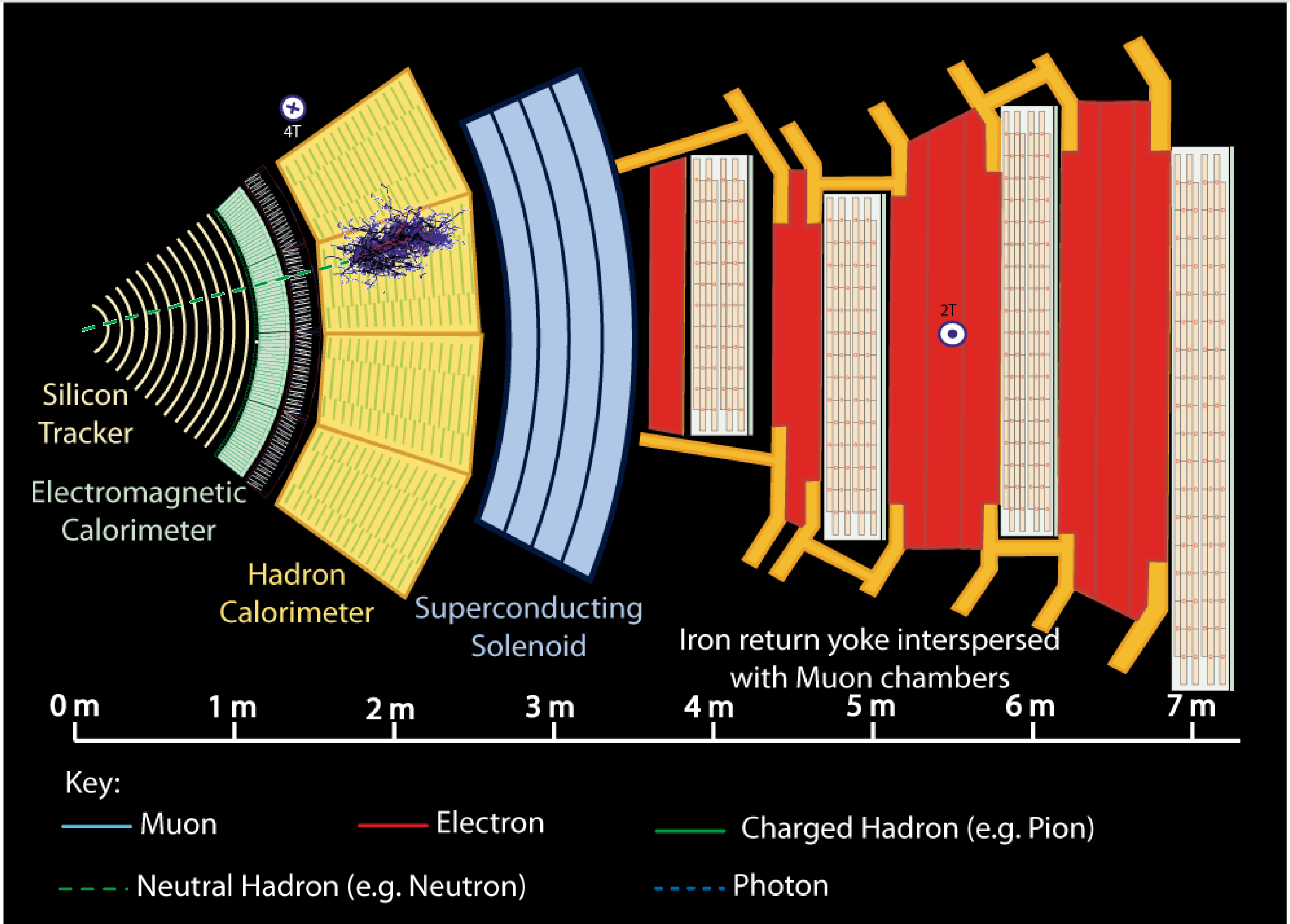
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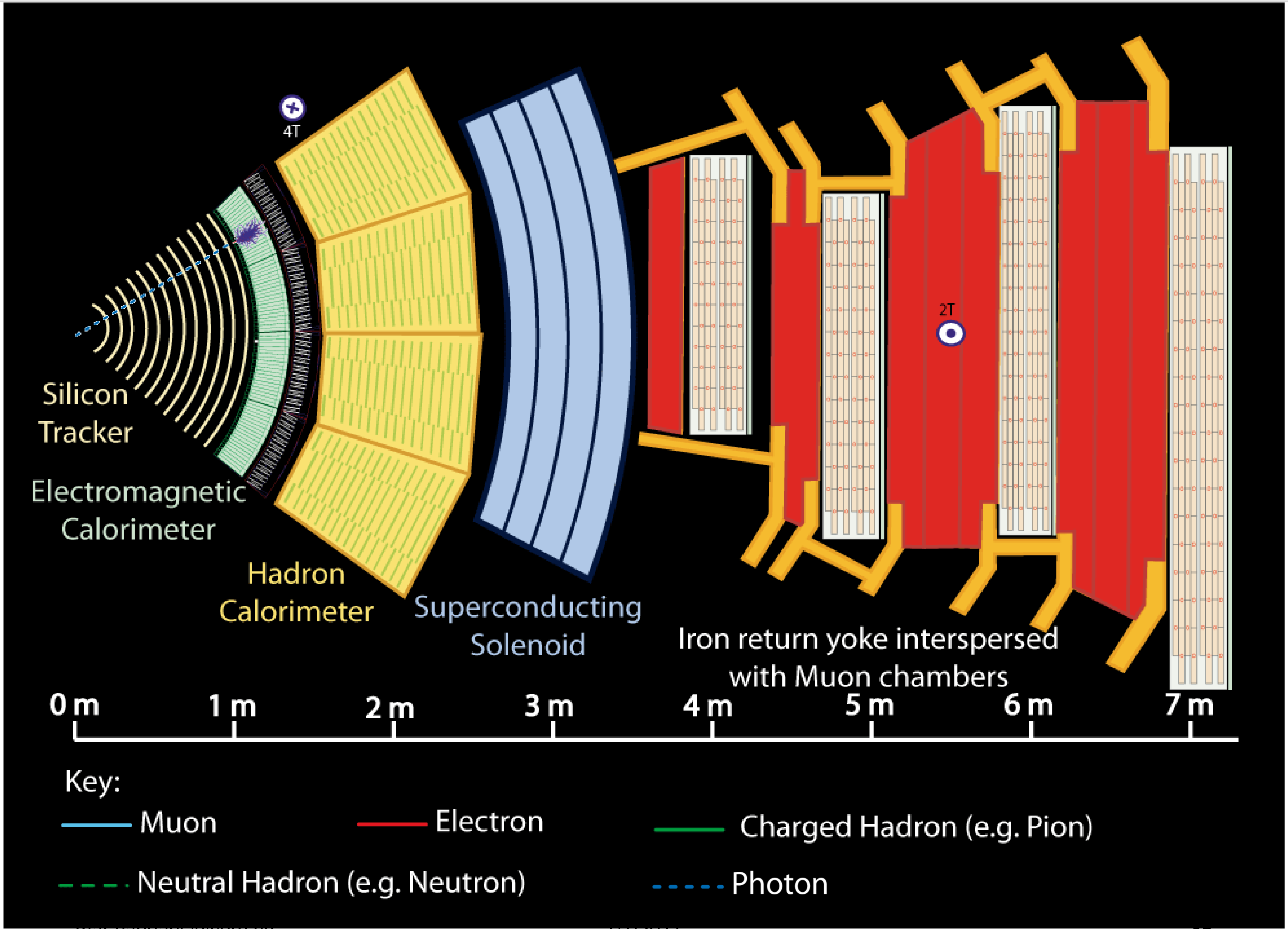
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Distributed/Collaborative Projects

Example, the ATLAS Transition Radiation Tracker *(non-exhaustive list!)*