Introduction to Particle Detectors

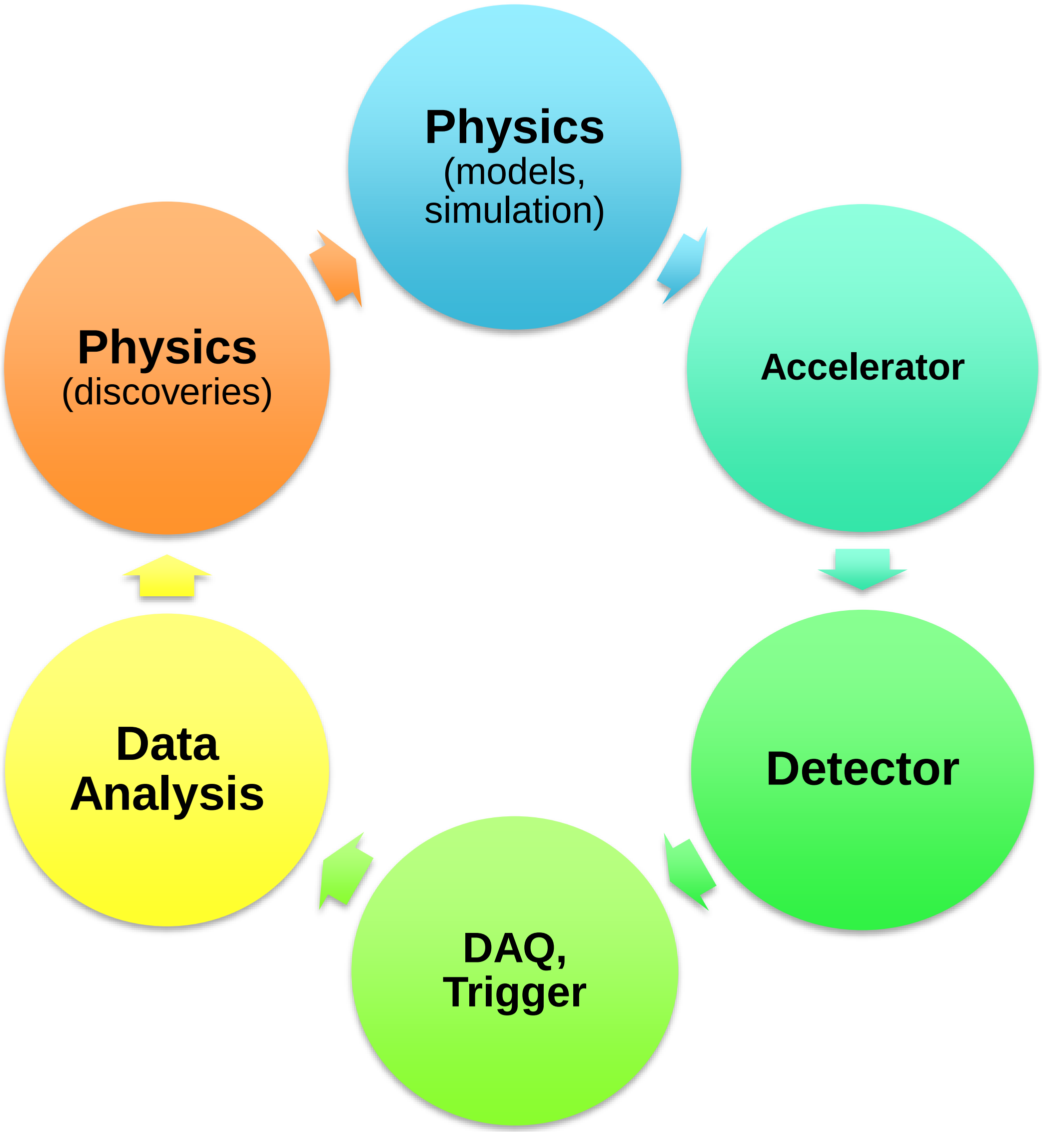
HSSIP-Spain

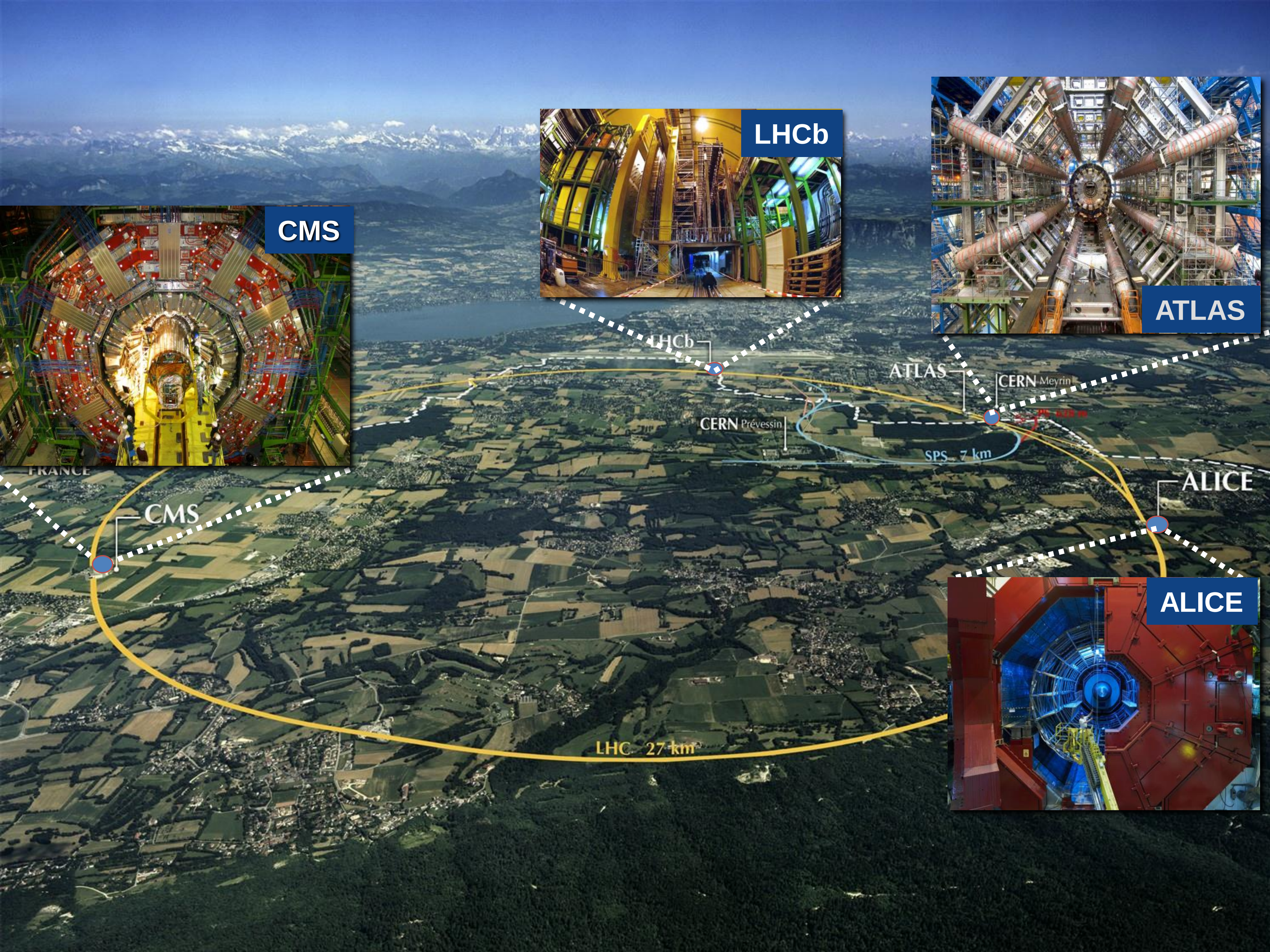
https://indico.cern.ch/e/ESHSSIP19

Mar Capeans

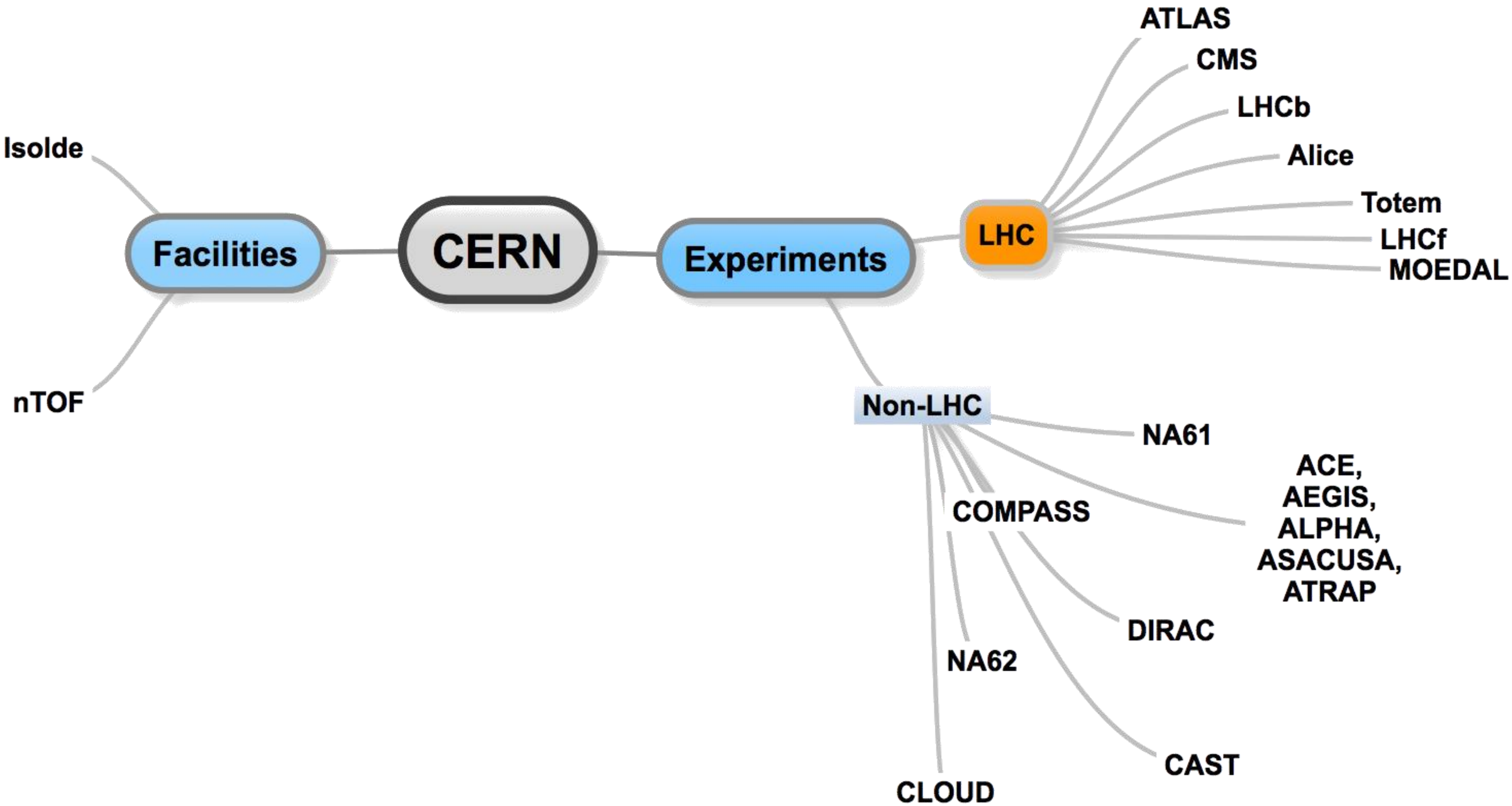
CERN October 1st 2019

Particle Physics Tools

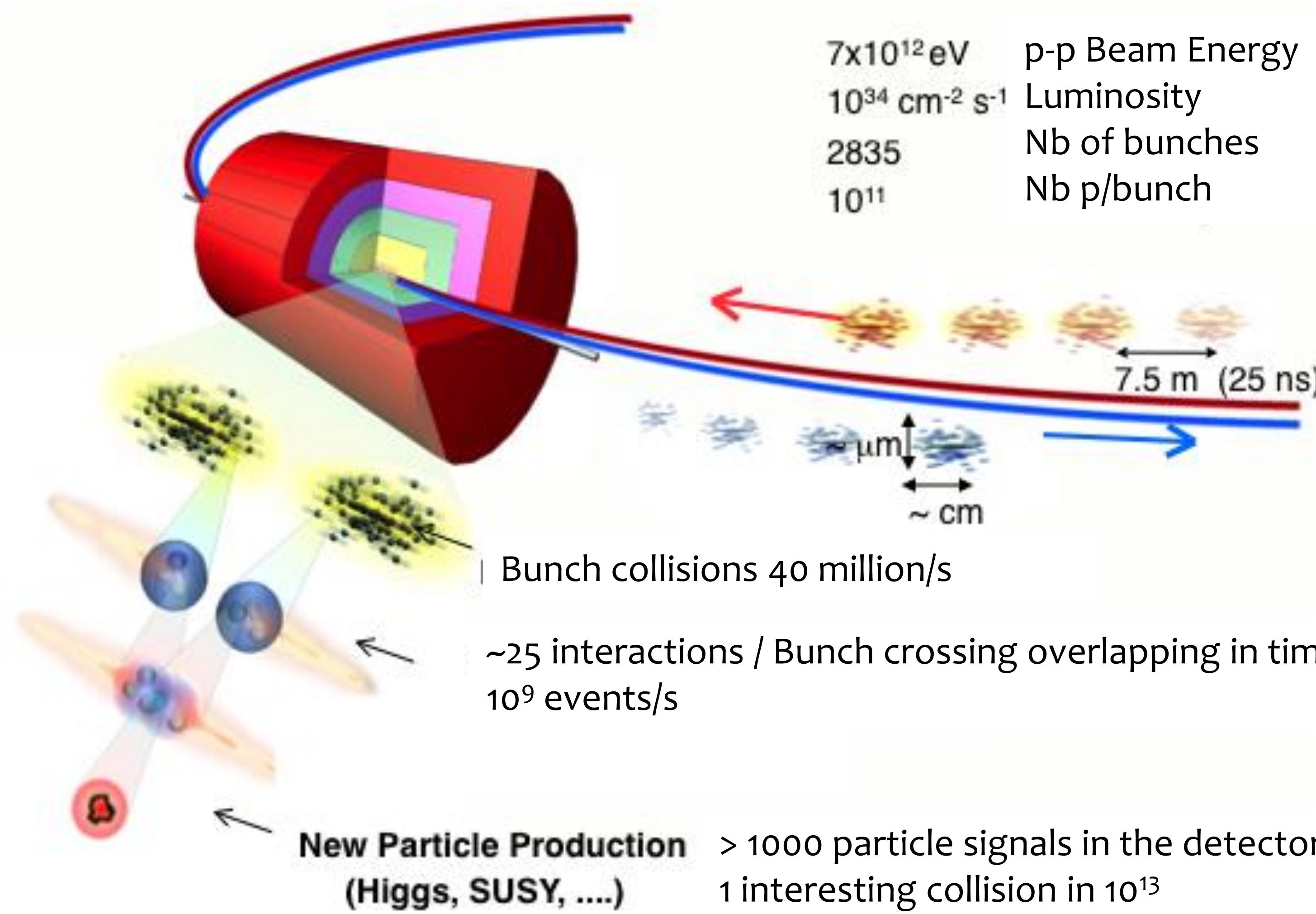



LHCb
CMS
ATLAS
ALICE
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
ALICE
CMS
LHC 27 km

Scientific Strategy



• LHC Detectors Context •



p-p Beam Energy
Luminosity
Nb of bunches
Nb p/bunch

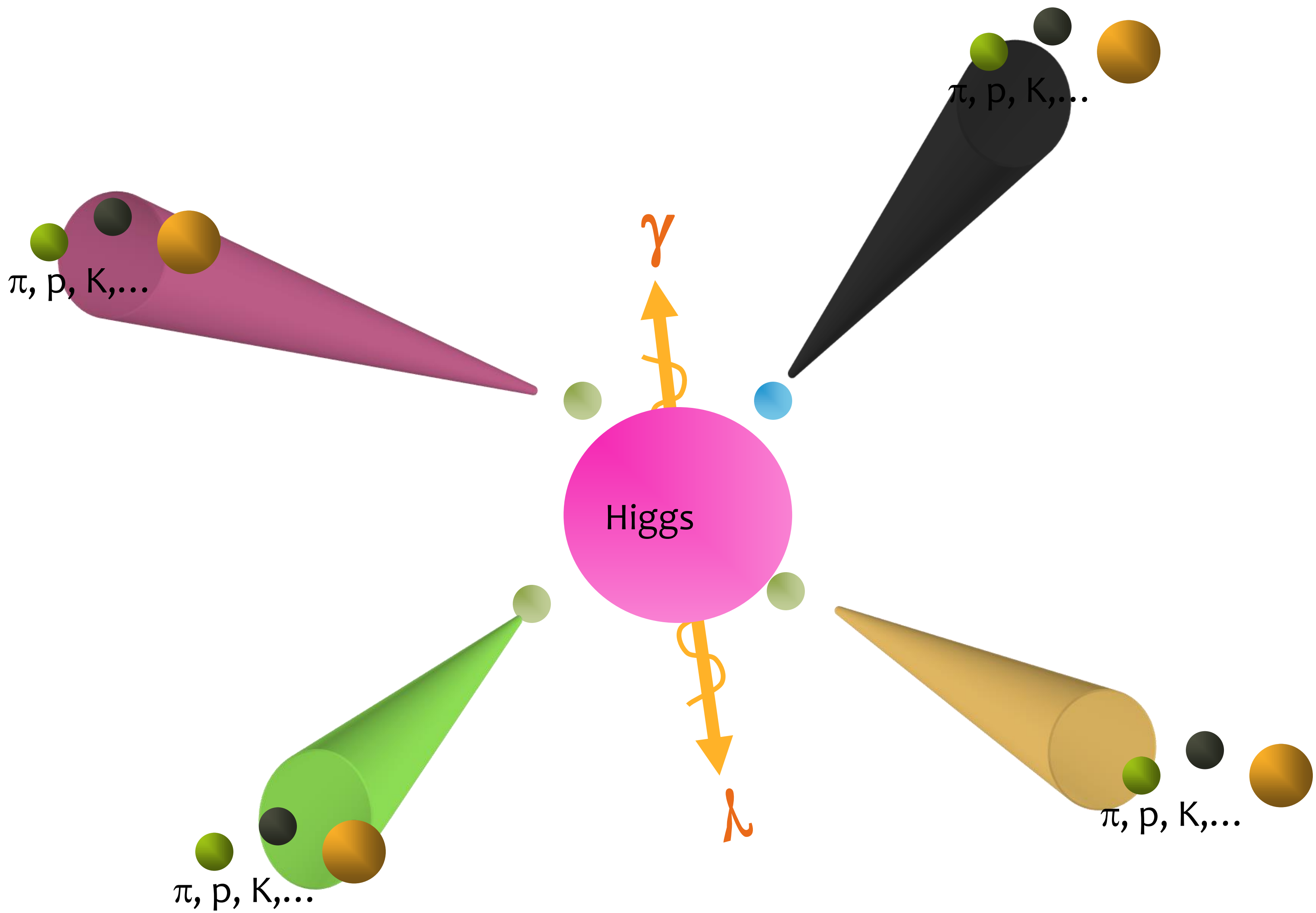
Bunch collisions 40 million/s

~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}

Artistic Event

Artistic Event



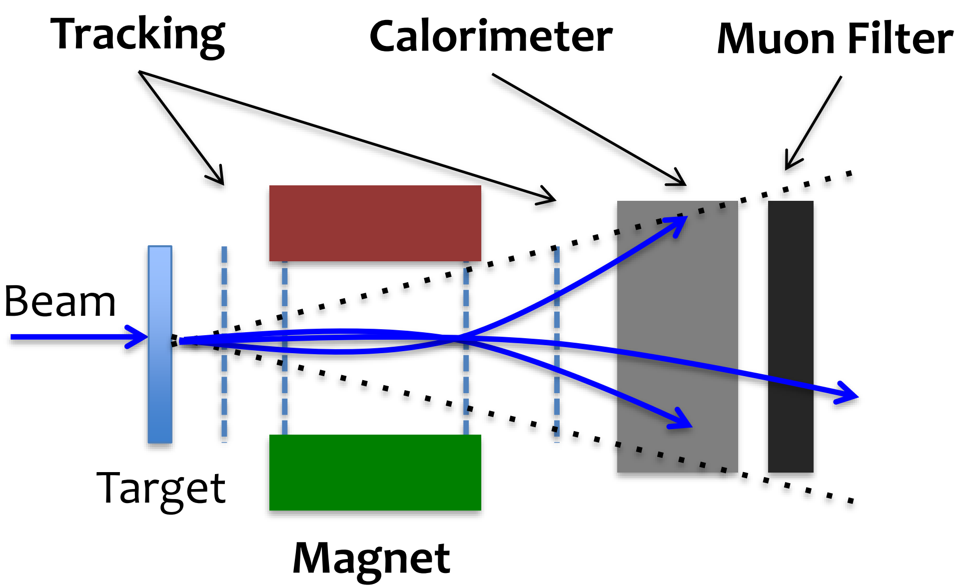
Particle Detection

- 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, **we want the maximum information about the end products**
- **The ideal particle detector should provide…**
  - Coverage of full solid angle (no cracks, fine segmentation)
  - Detect, track and identify all particles (mass, charge)
  - Measurement of momentum and energy
  - Fast response, no dead time

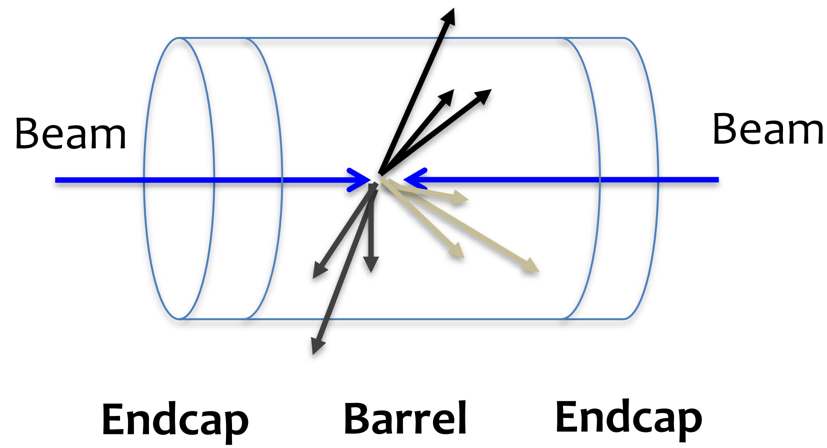
  - Practical limitations: technology, space, budget…

• Detector Systems •

Fix Target Geometry

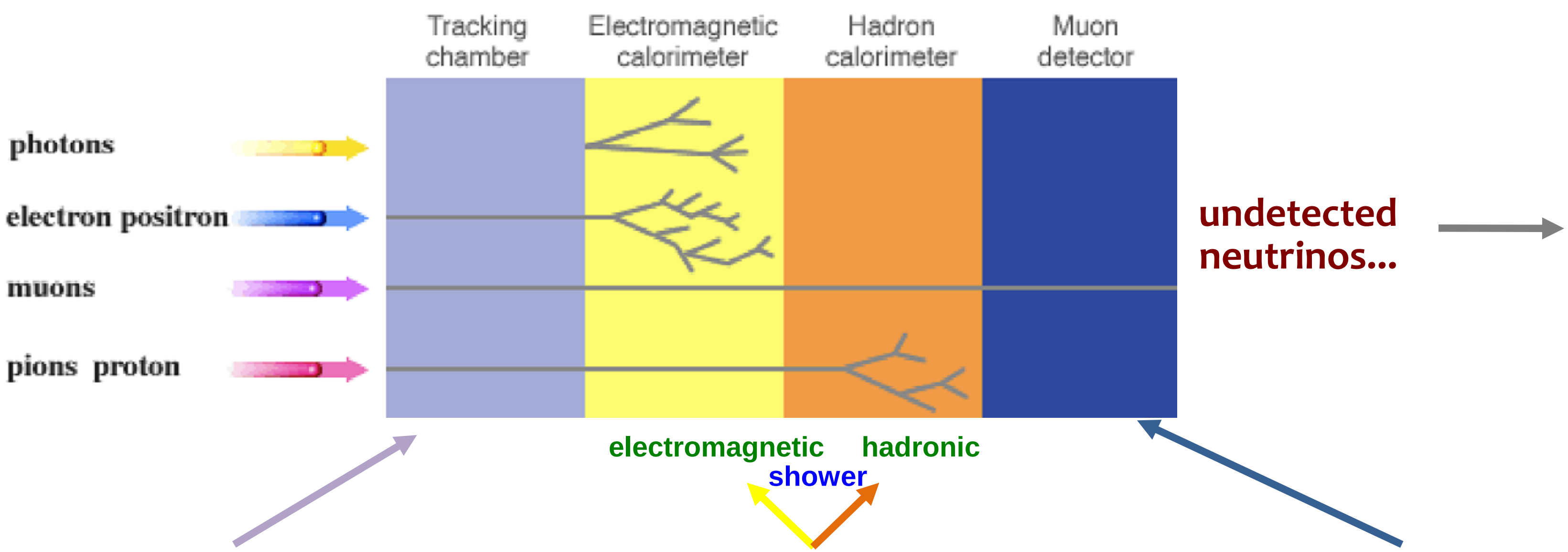


Collider Geometry



Interactions in the Detector

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

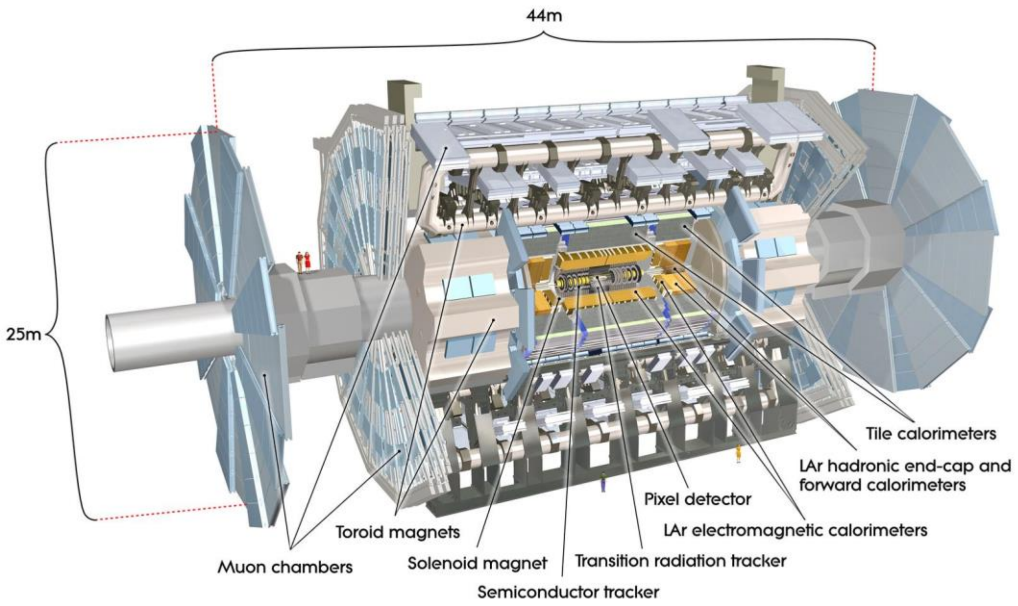


momentum measurement by curvature in magnetic field

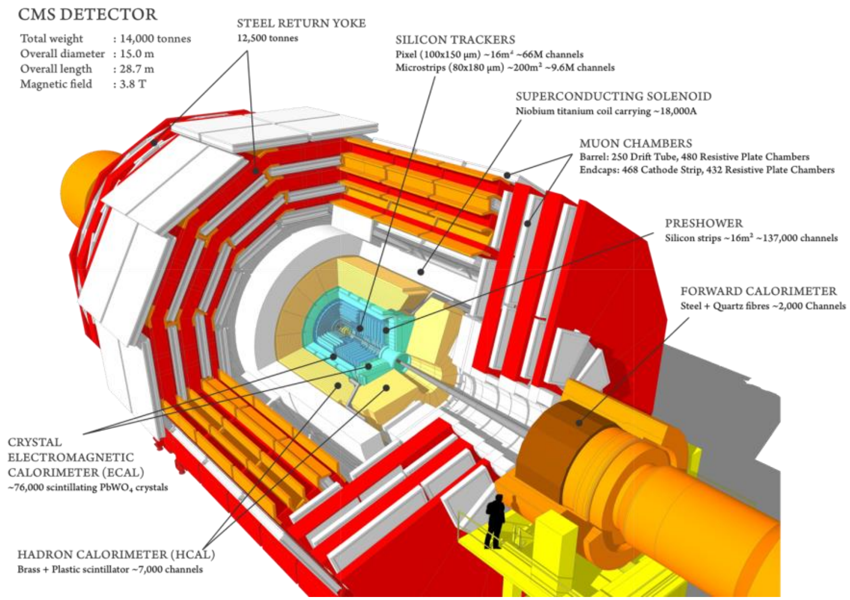
energy measurement by creation and total absorption of showers

muon detection with improved momentum measurement (long lever arm)

ATLAS & CMS



44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker



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 $PbWO_4$ 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.**
- Three effects/**technologies** are usually used :

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**.

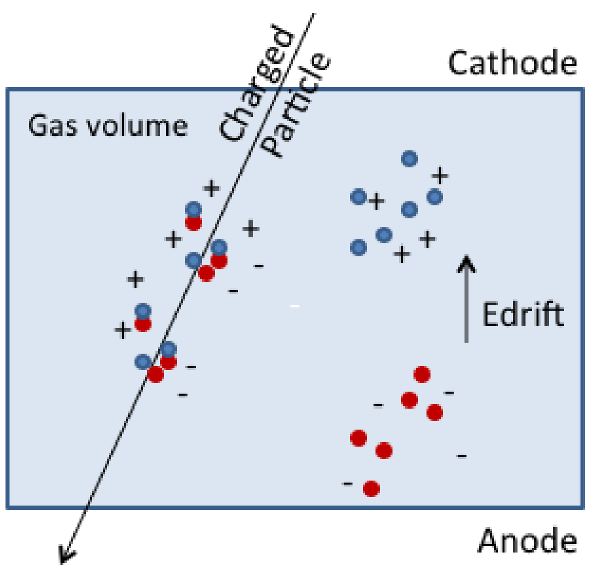
and these are used for different **functions**: tracking and/or triggering, energy measurements, photon detectors for Cherenkov or TRT, etc

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**

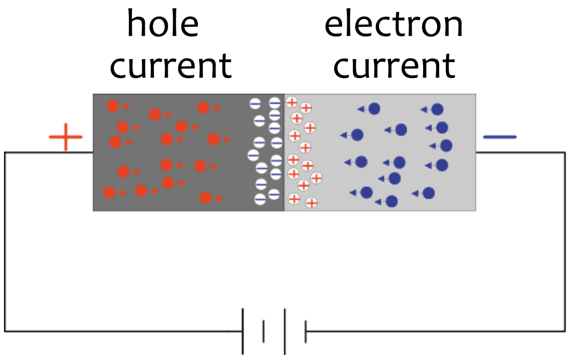


- Typically ~100 pairs/cm, and they are not easy to detect as the typical noise of an amplifier is ~1000 e^-
- **Need to MULTIPLY the electrons**

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

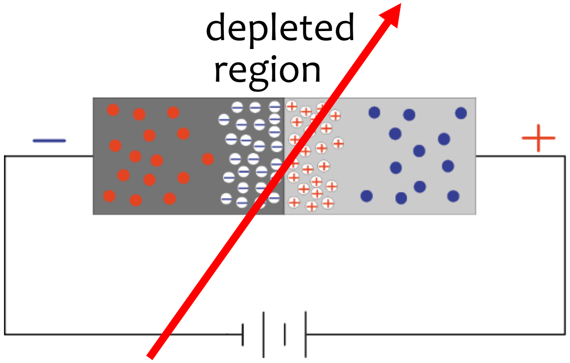


Current flow through diode if connects like this

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



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

Slide: A.Mapelli
CERN, PH-DT

Scintillation Particle Detector

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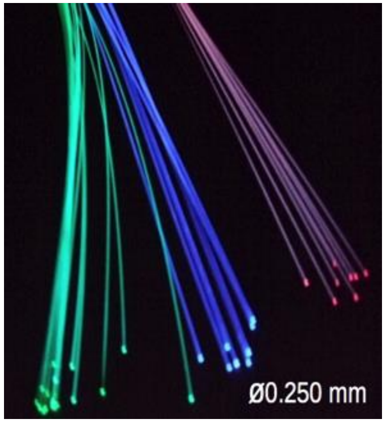


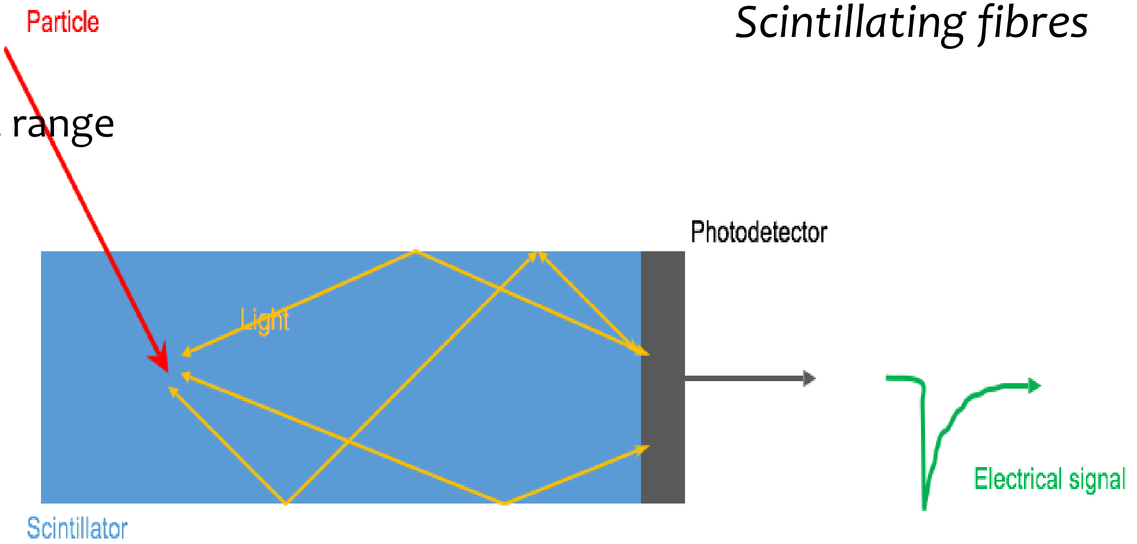
Scintillating fibres

Detector Principle

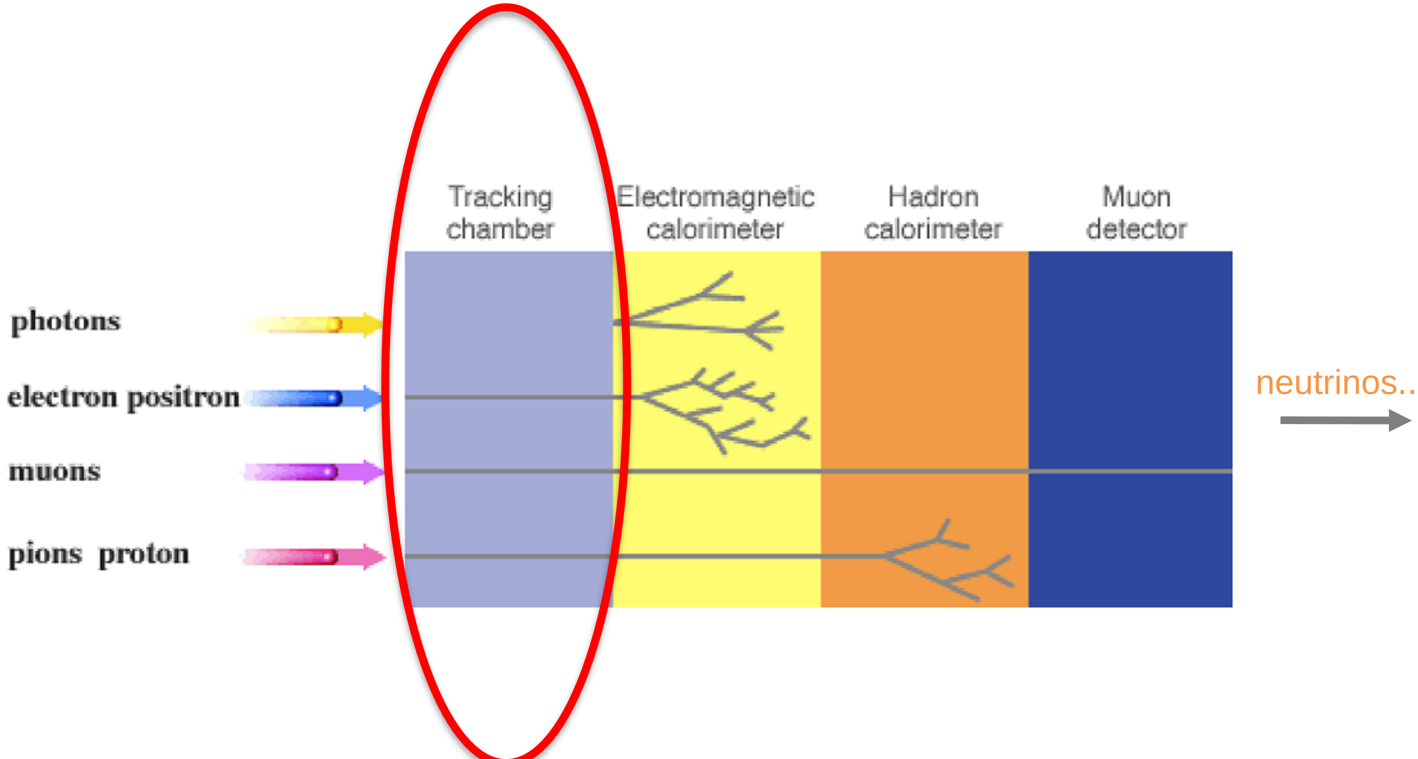
- dE/dx converted into visible light
- Detection via photosensor [e.g. photomultiplier, SiPM…]

Main Features

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

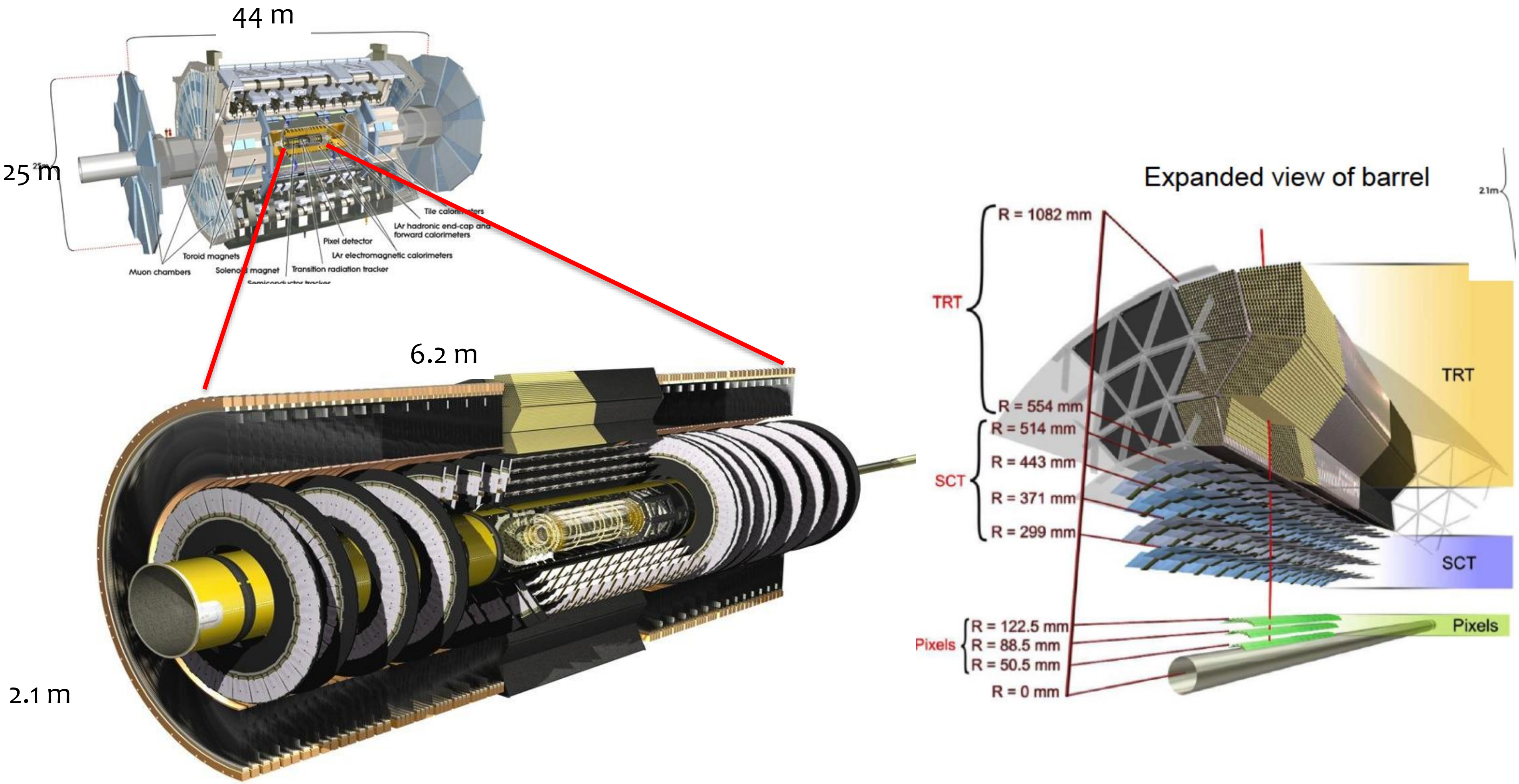


Tracking



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

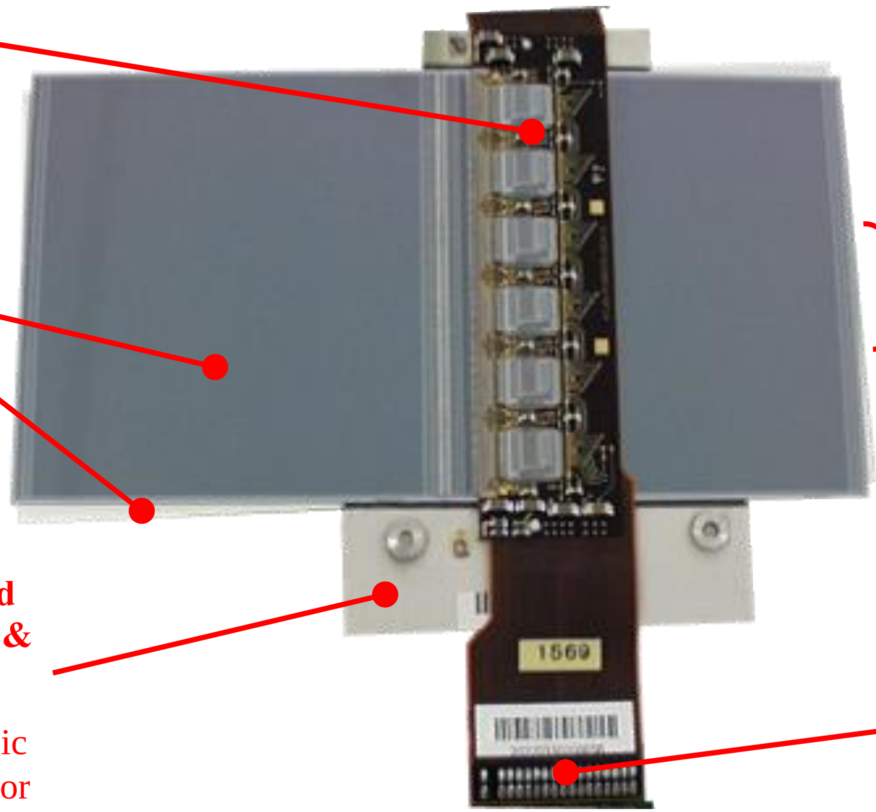


ATLAS, Barrel SCT module

Hybrid assembly
with readout chips

12.8 cm

4 Silicon sensors
280 ∝m thick
2.3°   stereo angle
Overlap in ƒ & *z* to adjacent modules



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

768 p^+ microstrips Cell size: 80 ∝m [ƒ 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

What is a system?

- Sensor
- Readout electronics
- Interconnection

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

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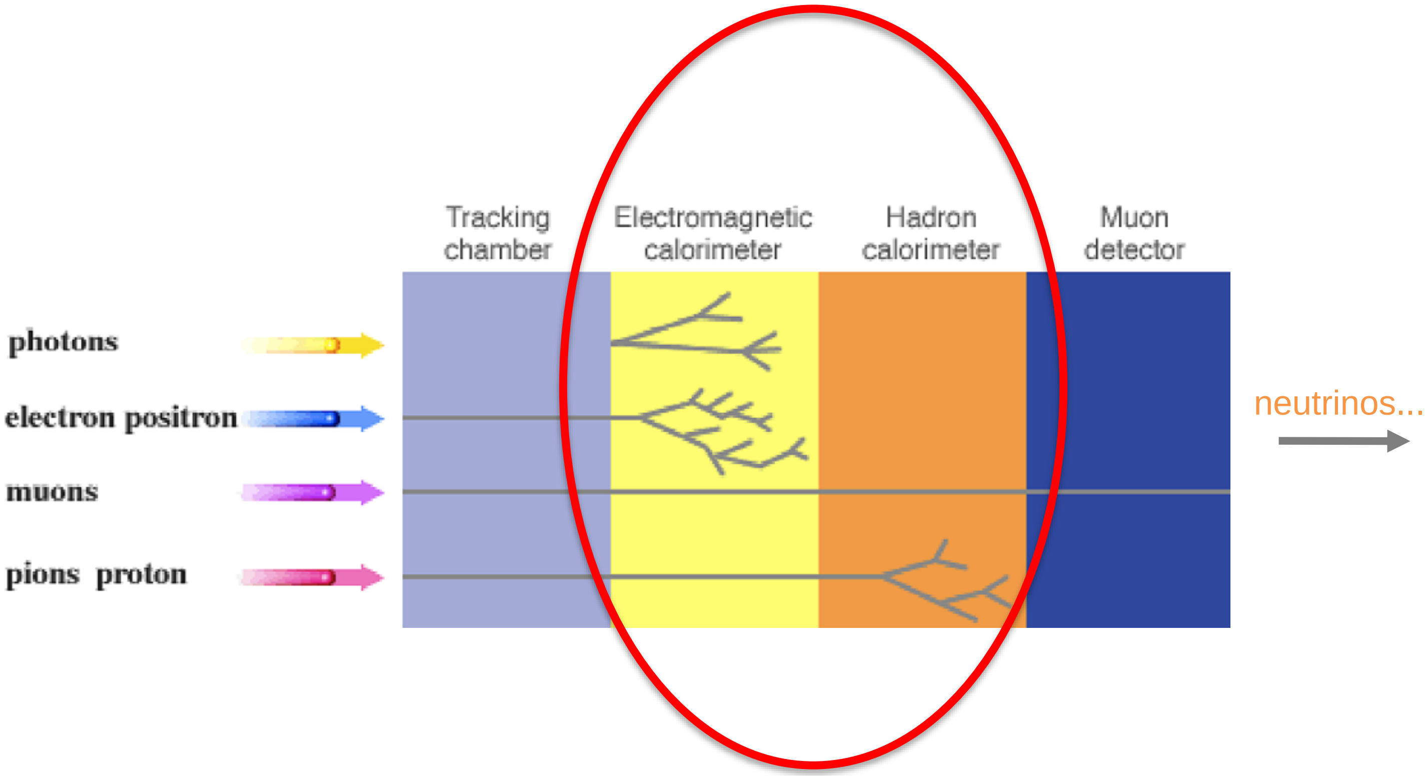
• Calorimetry •

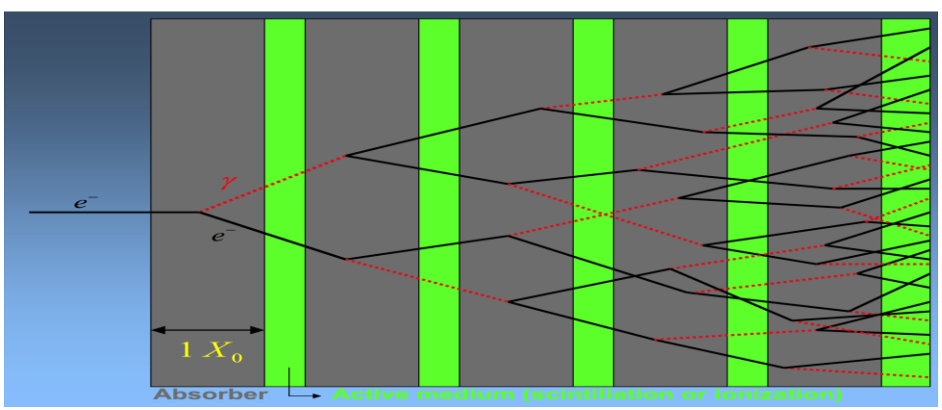


Calorimeters measure charged and neutral particles, performance improves with energy and is ~constant over 4p, high rate capabilities and fast, making them suitable for trigger applications.

• Calorimeters •

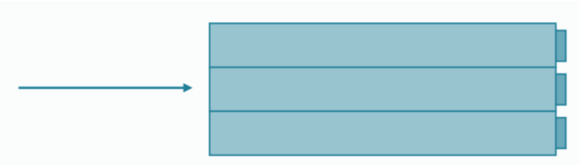
Electromagnetic Calorimeter	Hadronic Calorimeter
Photons and electron showers (γ,e,π^o)	Charged and neutral hadrons, jets (π, p, n)

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



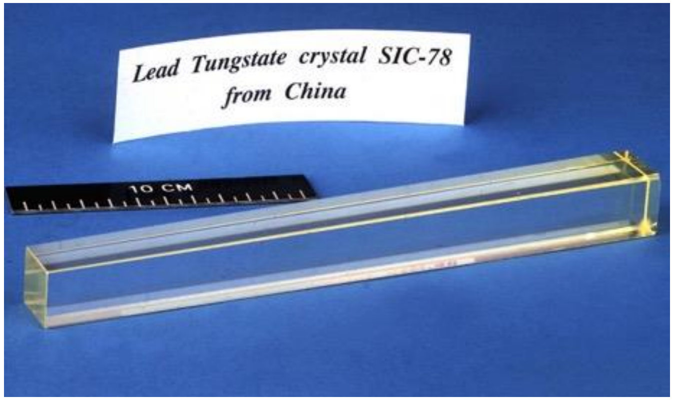
Calorimeter's calibration establishes a precise relationship between the 'visible energy' detected and the energy of the incoming particle

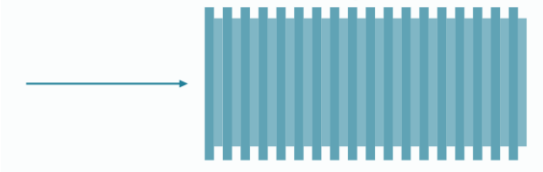
Calorimeters



Homogeneous EM Calorimeter (CMS)

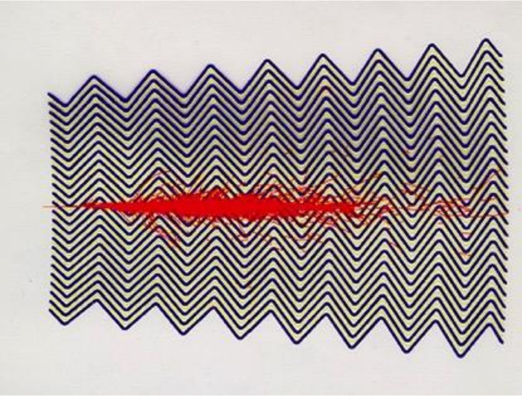
- Clear advantage: good energy resolution, good linearity
  - The entire shower is kept in active detector material (no shower particle is lost in passive absorber)
- Disadvantages: limited granularity
  - No information on shower shape in longitudinal direction (along particle flight direction)
  -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



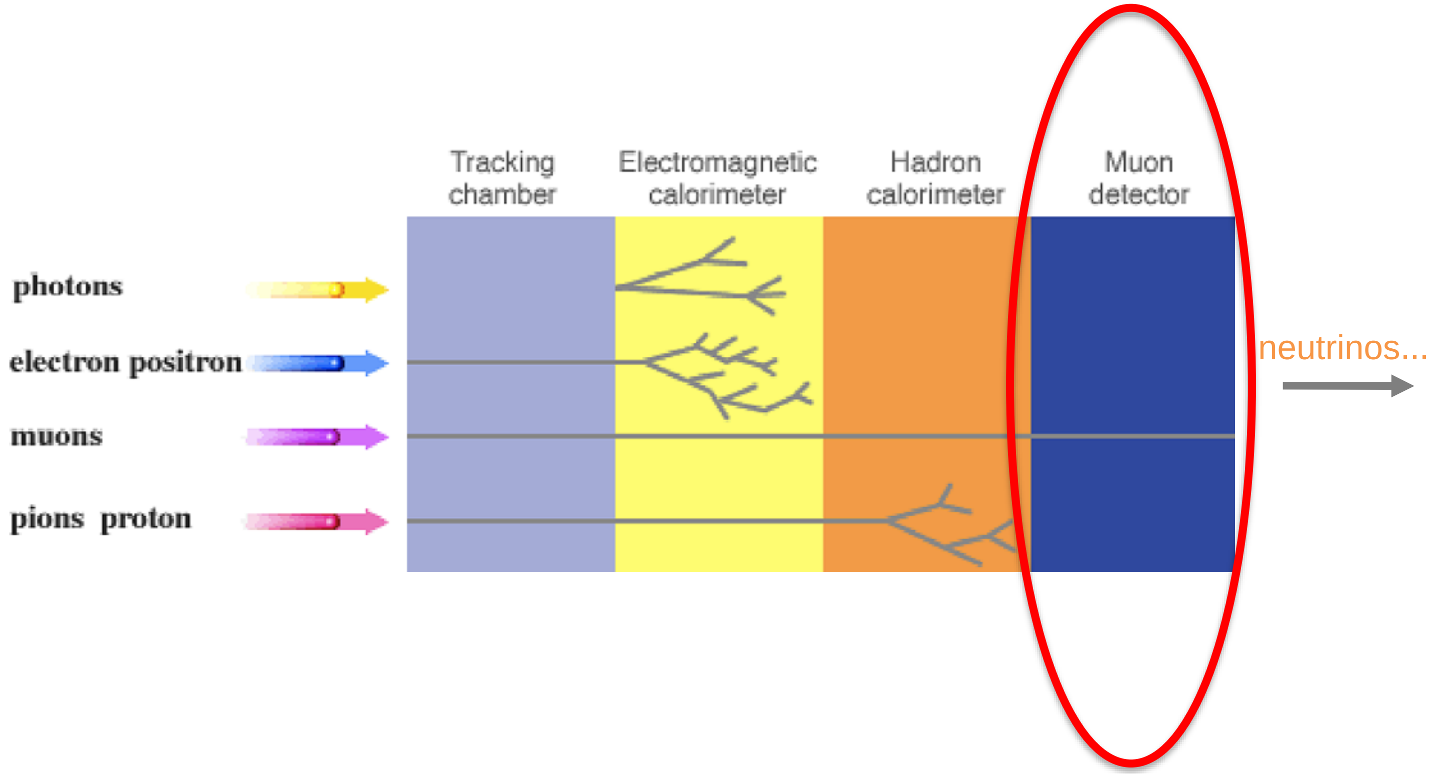


Sampling EM Calorimeter (ATLAS)

- 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)



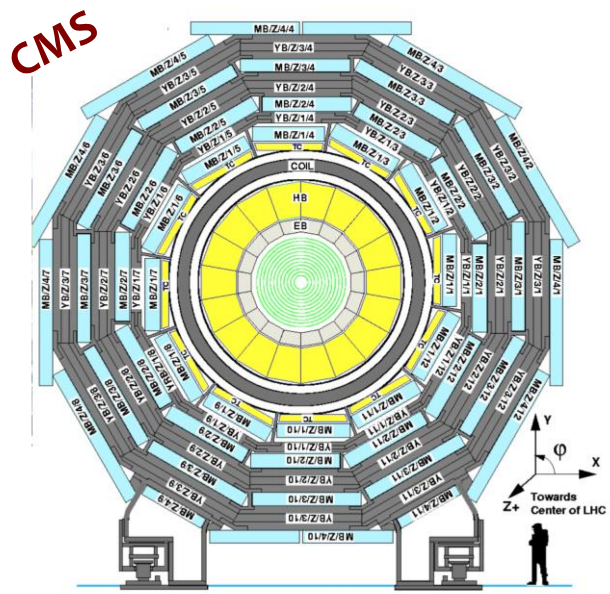
Muon Systems

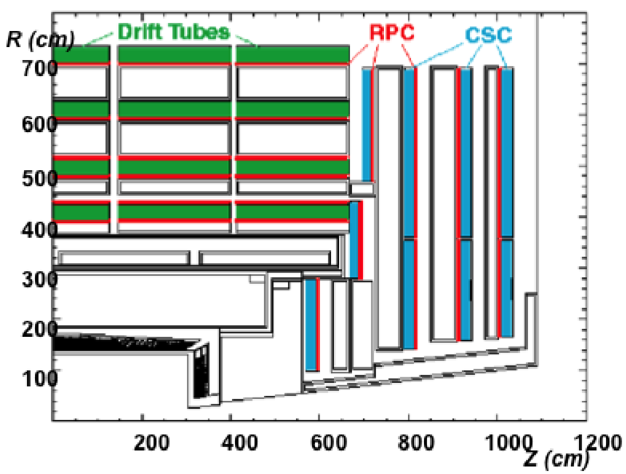


Muons are charged particles just like electrons and positrons, but 200 times heavier. Because muons can penetrate several metres of iron without interacting, they are not stopped by calorimeters. Therefore, muon chambers are placed at the very edge of the experiment where the only particles likely to register a signal are.

Muon Systems

• Muon Spectrometer •





Traditional Technology

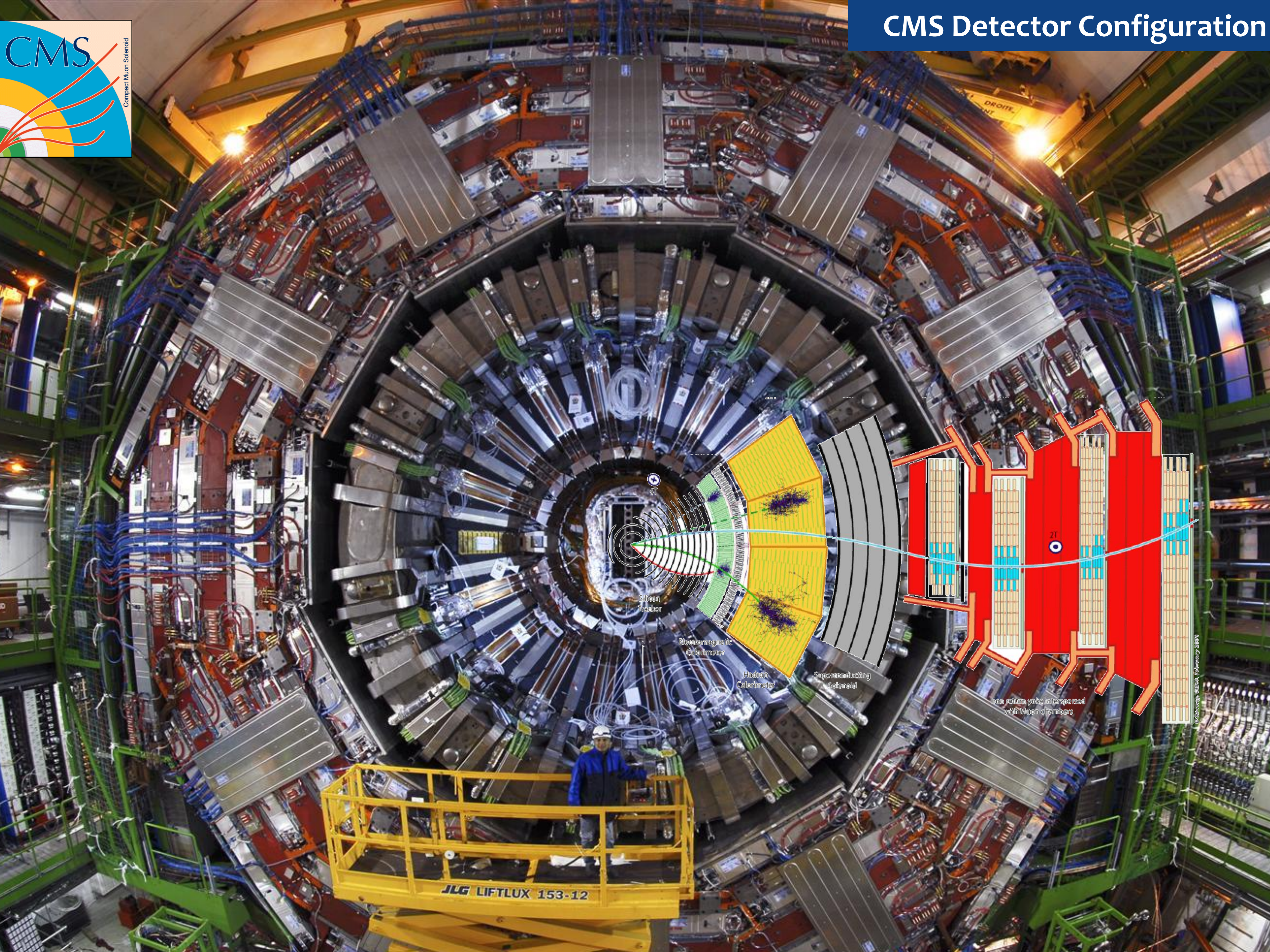
DRIFT TUBES (DT)
Central coverage
Tracking (100 mm) & trigger

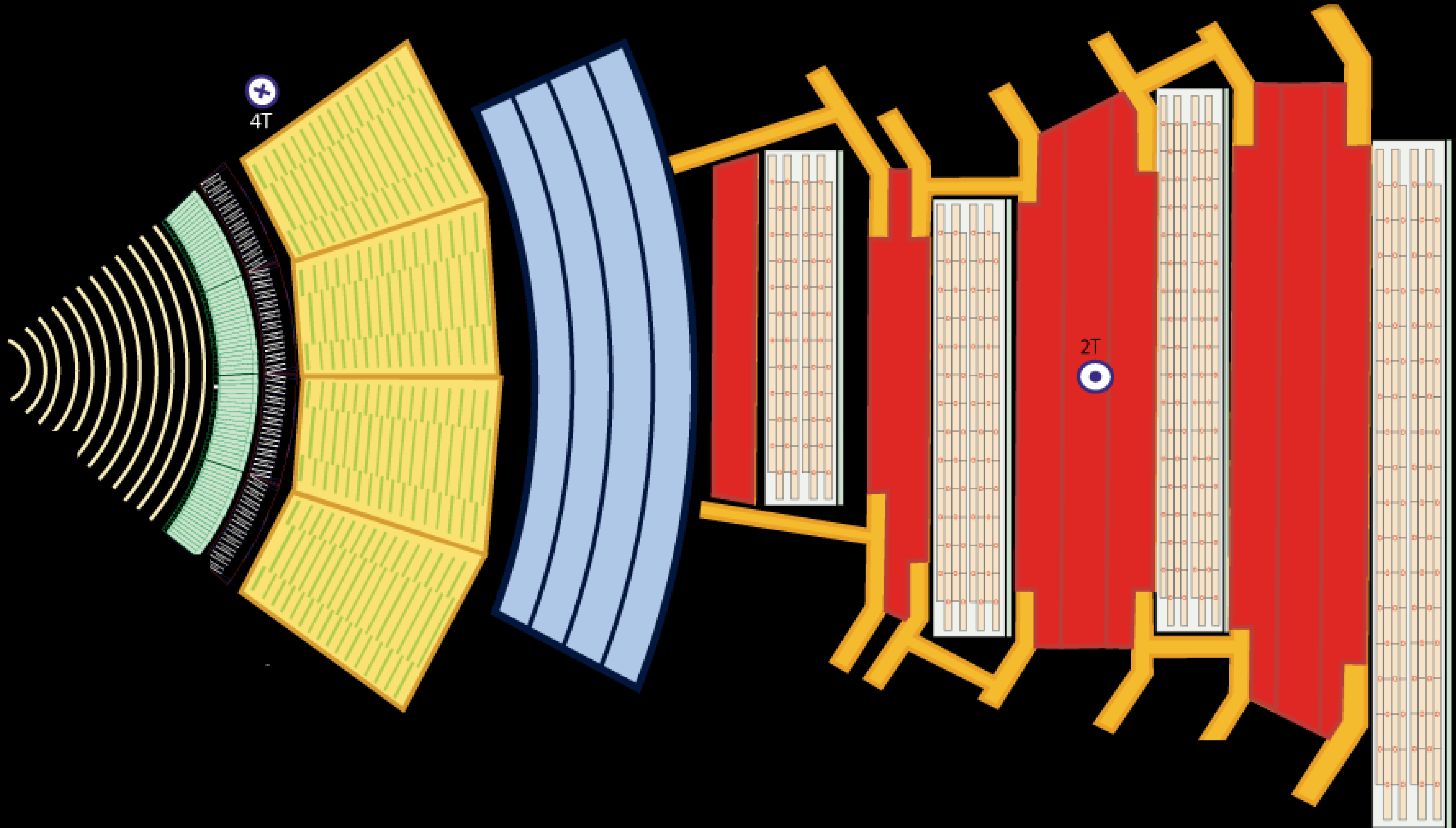
CATHODE STRIP CHAMBERS (CSC)
Forward coverage (6000 m2)
Tracking (1mm) & trigger
540 detectors, 0.5 MChannels

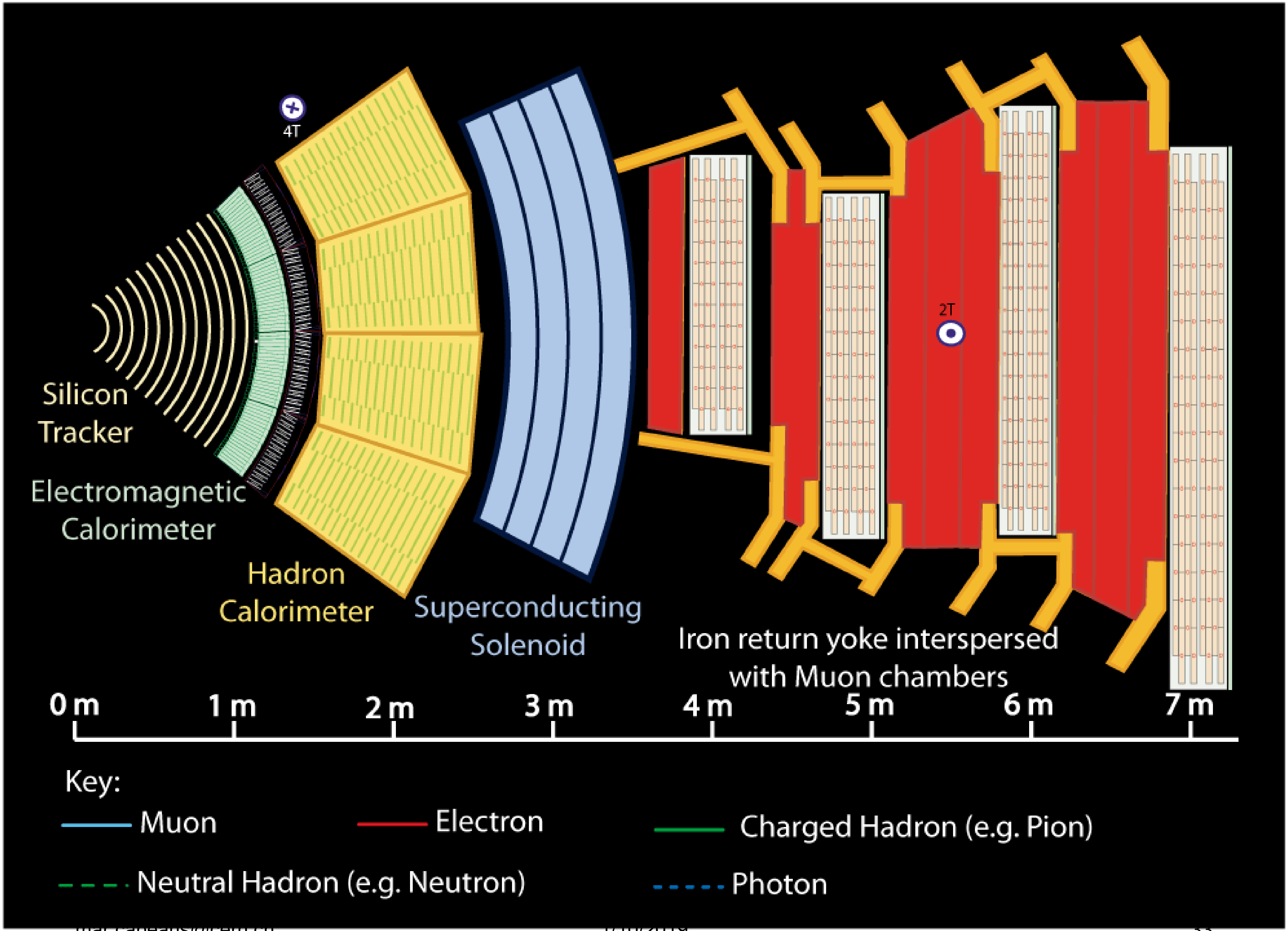
Designed to operate in intense magnetic field and neutron background ~1 kHz/cm^2

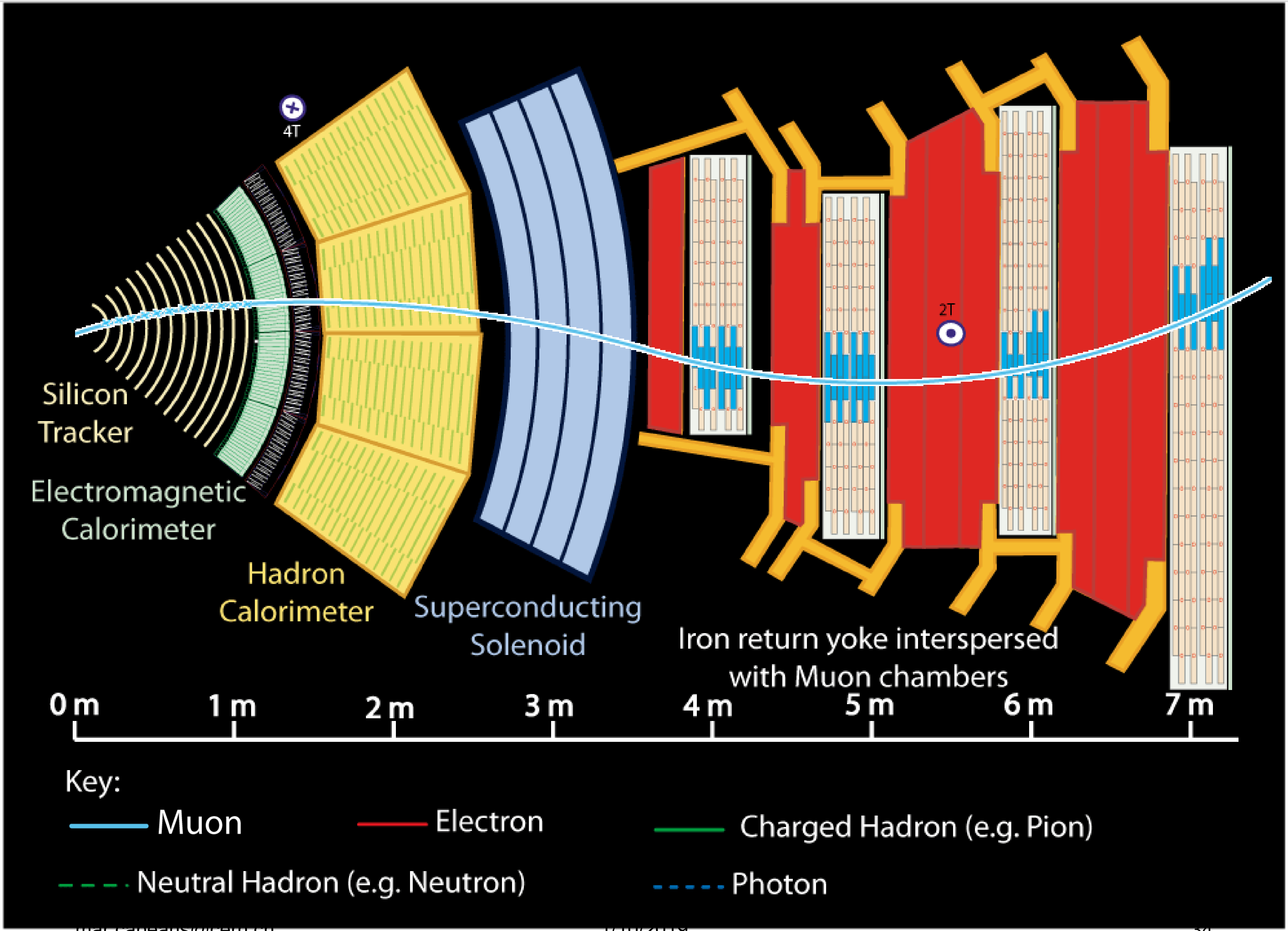
RESISTIVE PLATE CHAMBERS (RPC)
Central and forward coverage
Redundant Trigger (3 ns)
612 detectors

CMS Detector Configuration




4T
2T


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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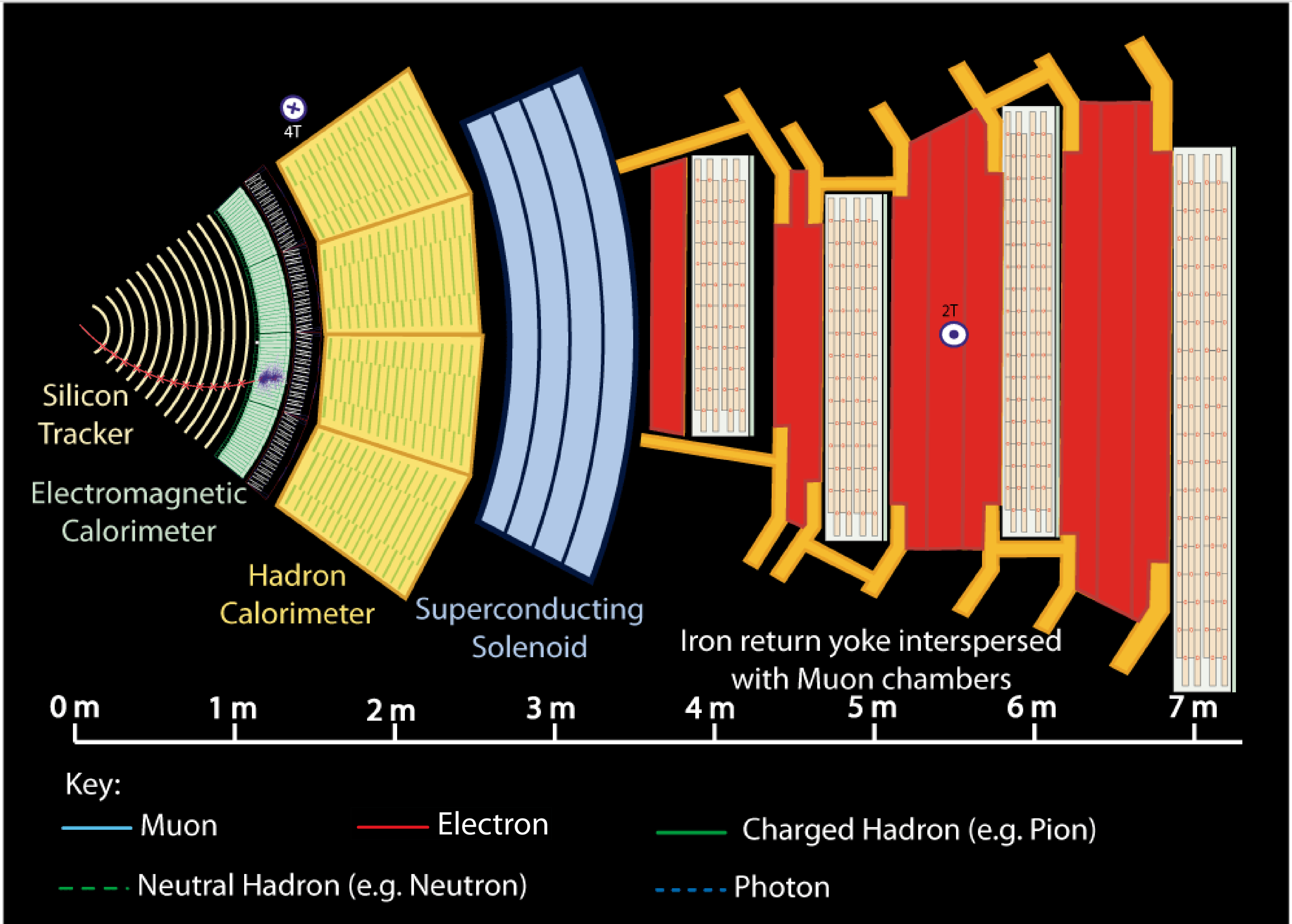
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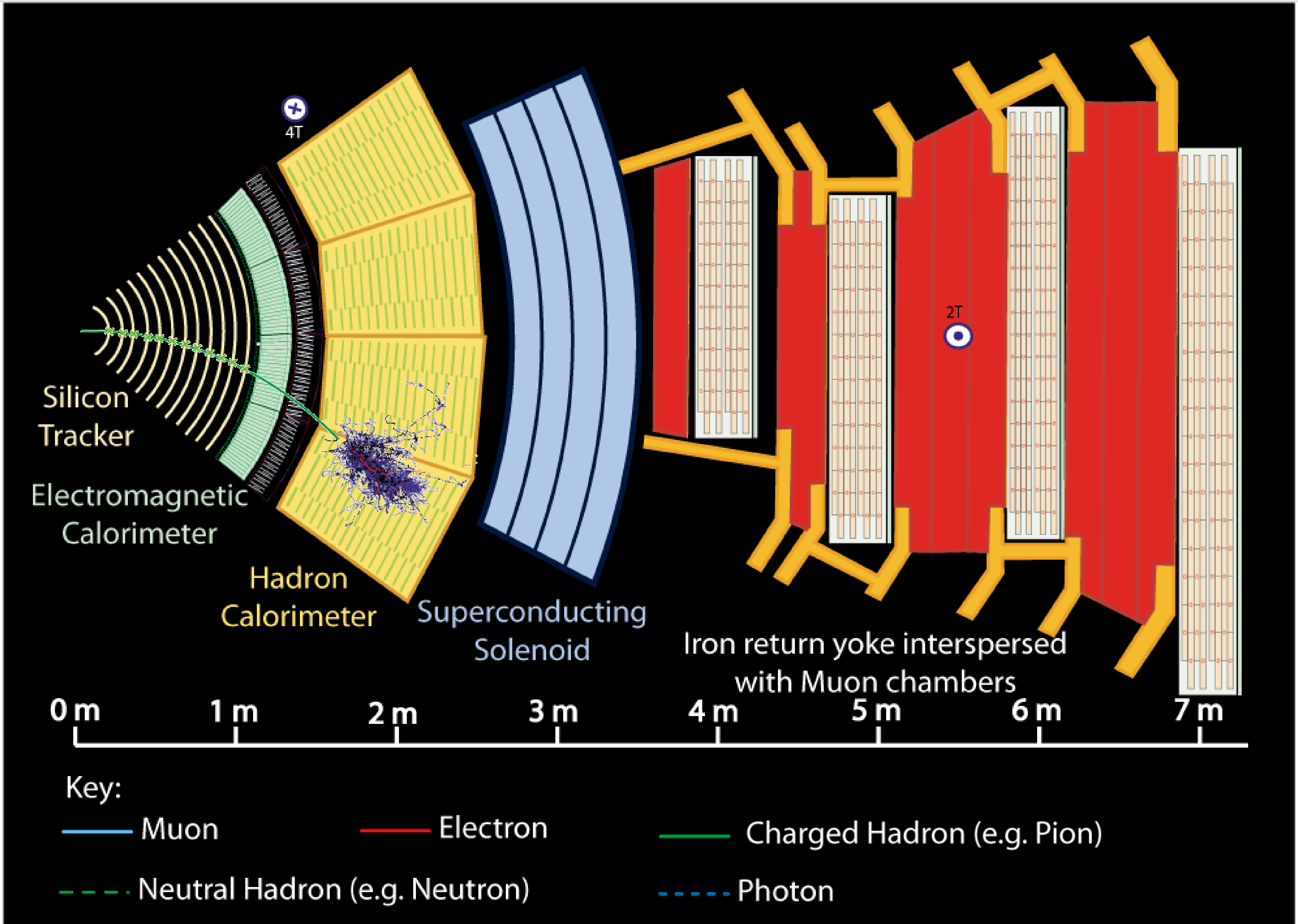
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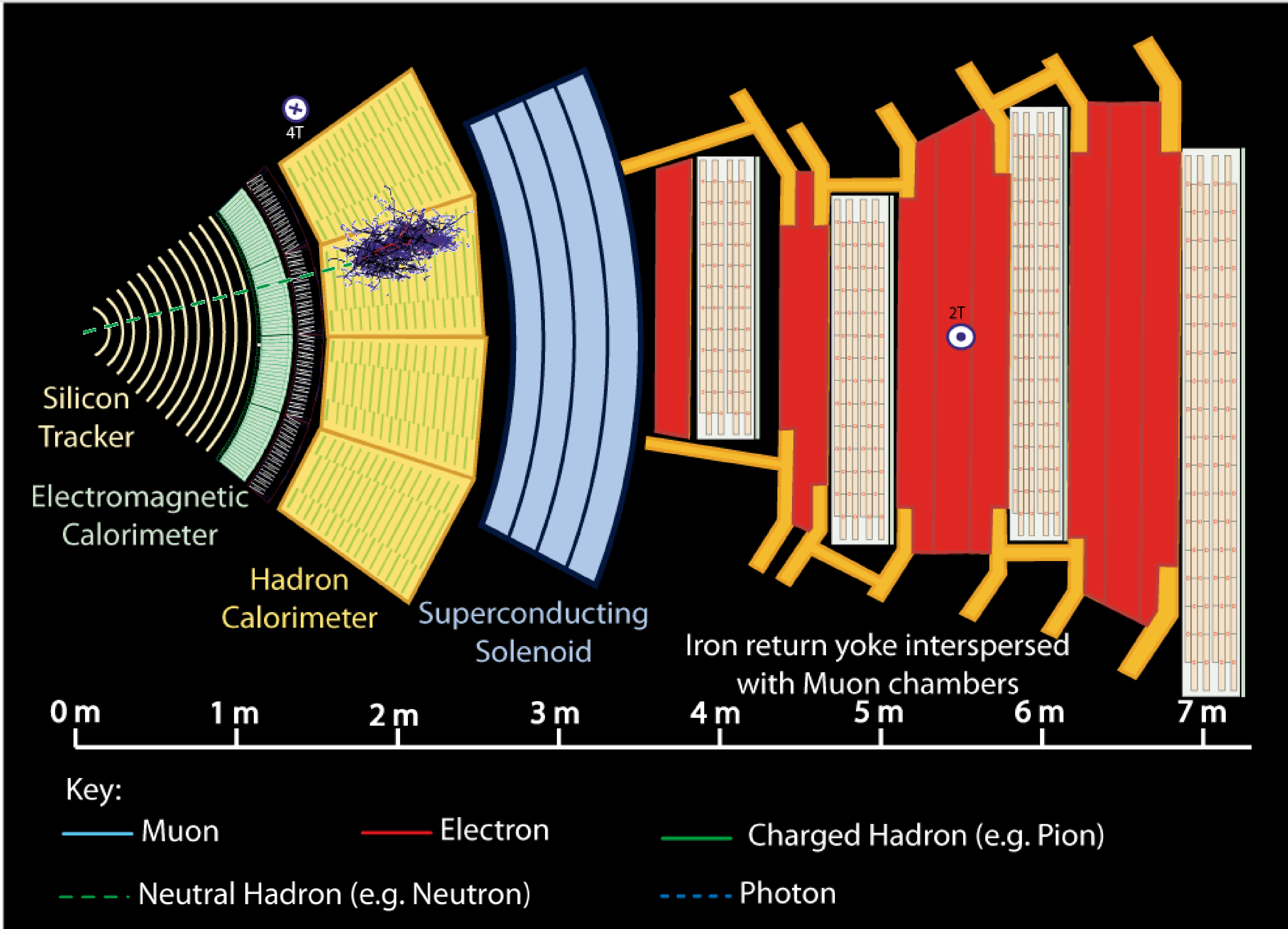
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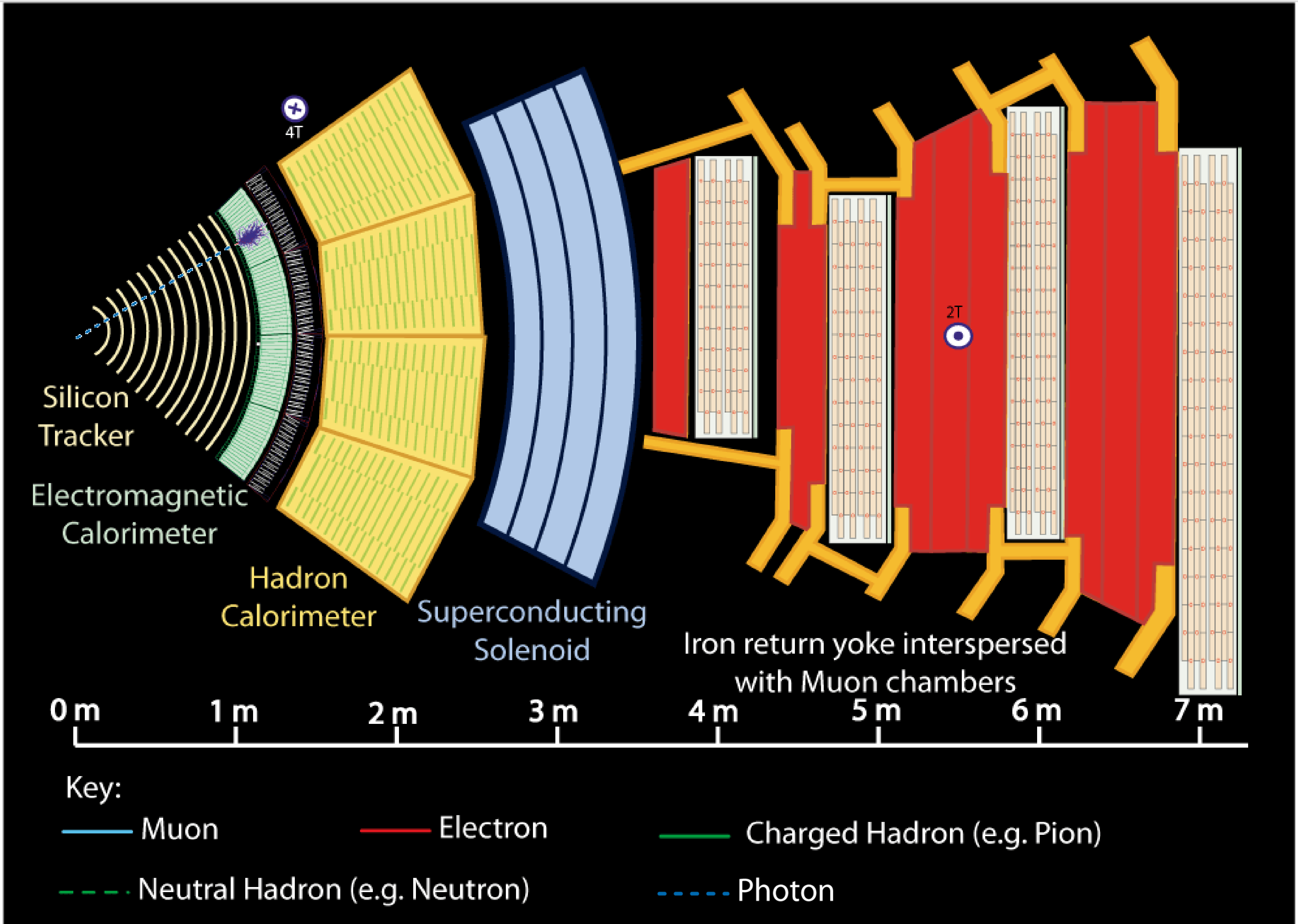
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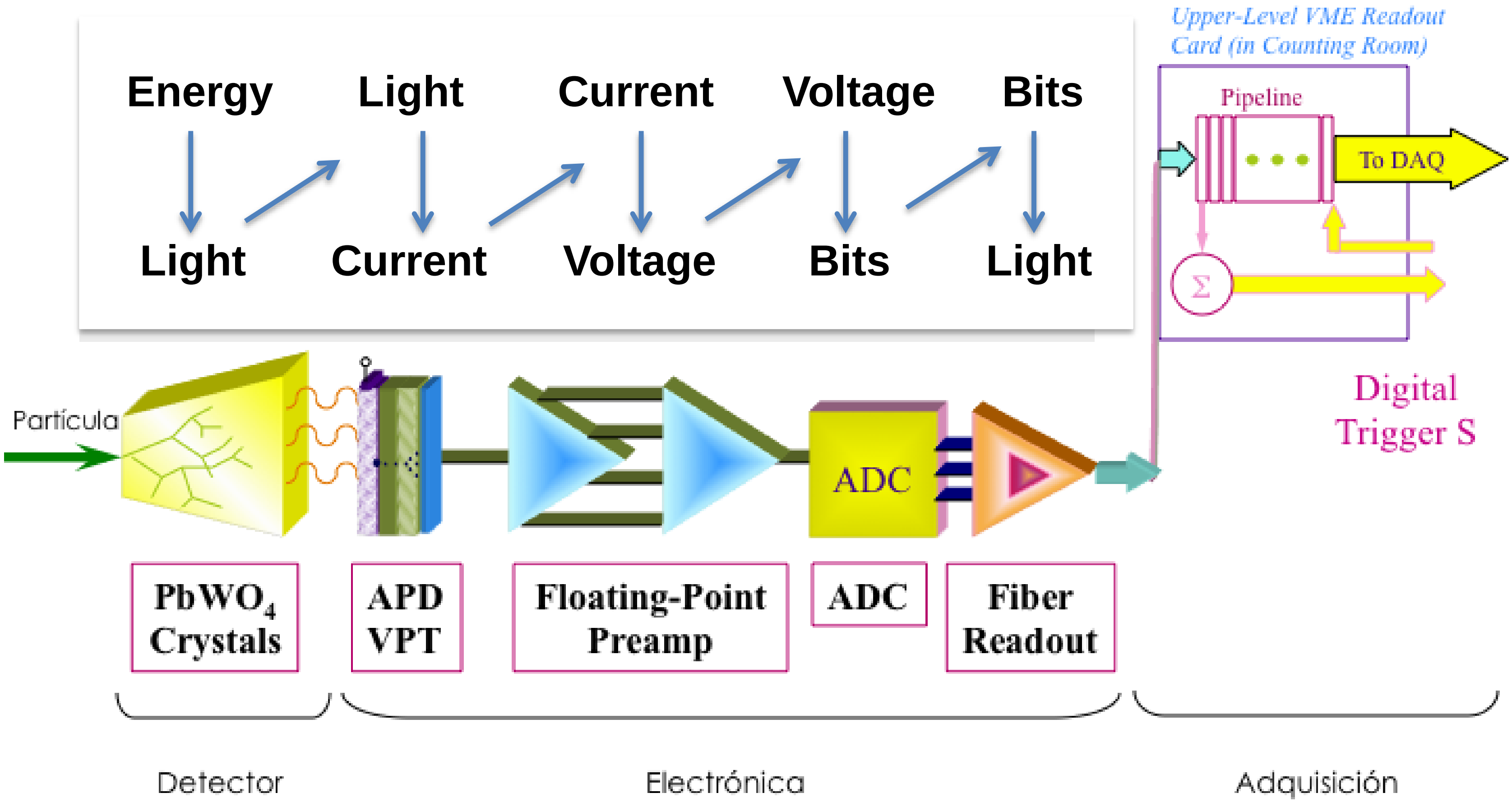
• Signals •



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
$PbWO_4$ 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

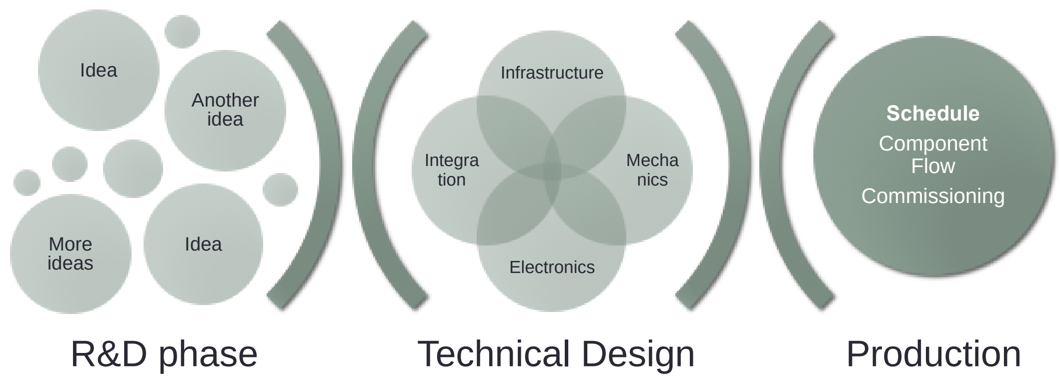
Tier O → **Worldwide LHC Computing Grid**

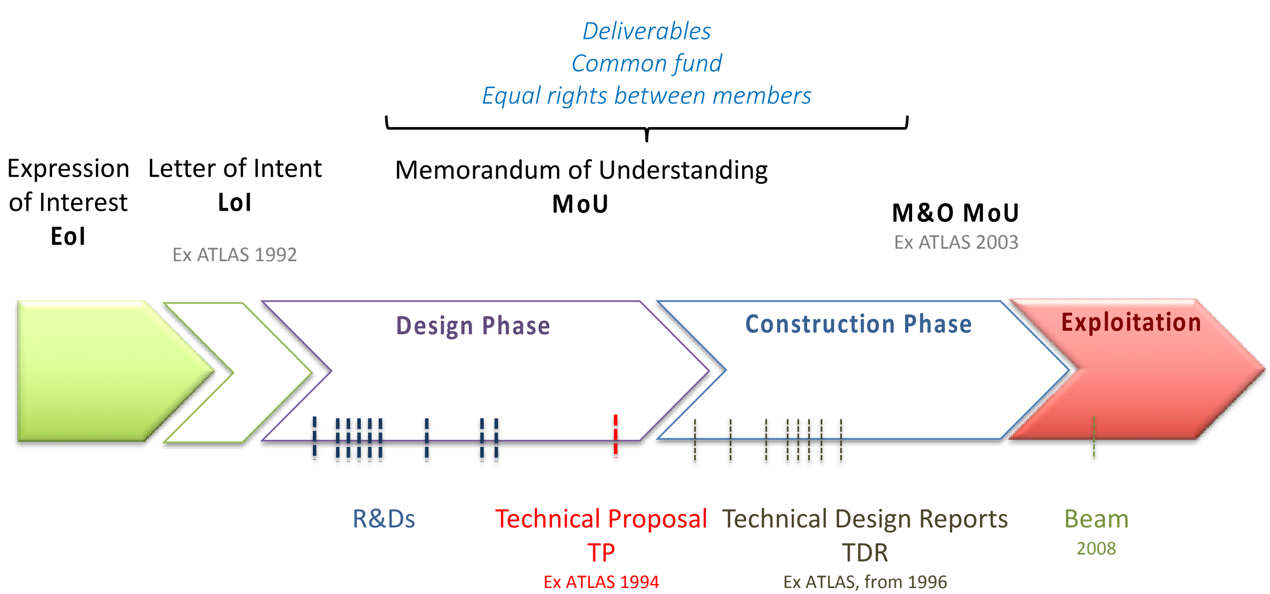
HEP Detectors

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

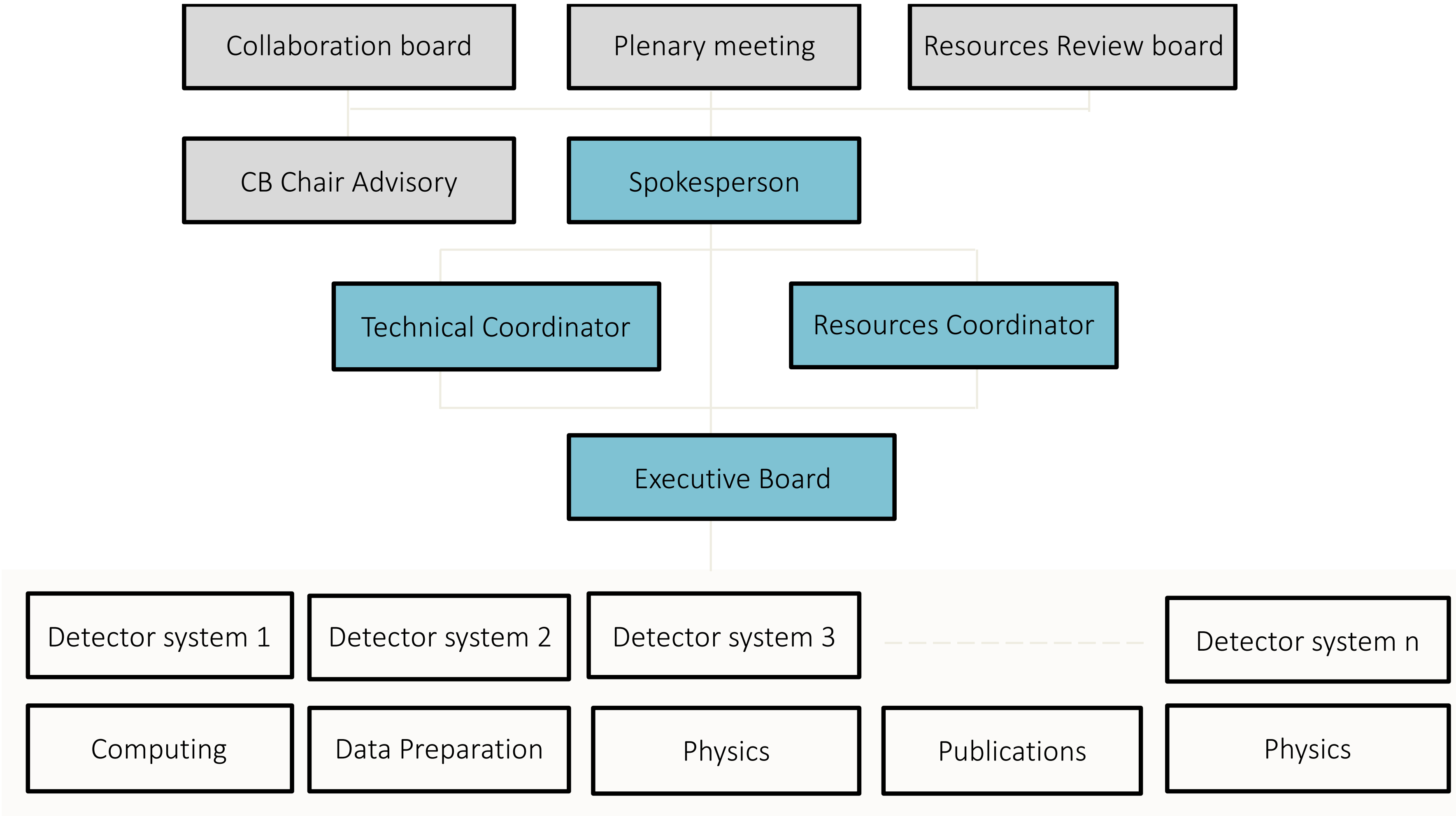
Experiment	Countries	Institutions	Scientists
ALICE	37	154	~1500
ATLAS	38	182	~ 3000
CMS	46	182	~ 3500
LHCb	16	69	~ 800

Experiment's Cycle





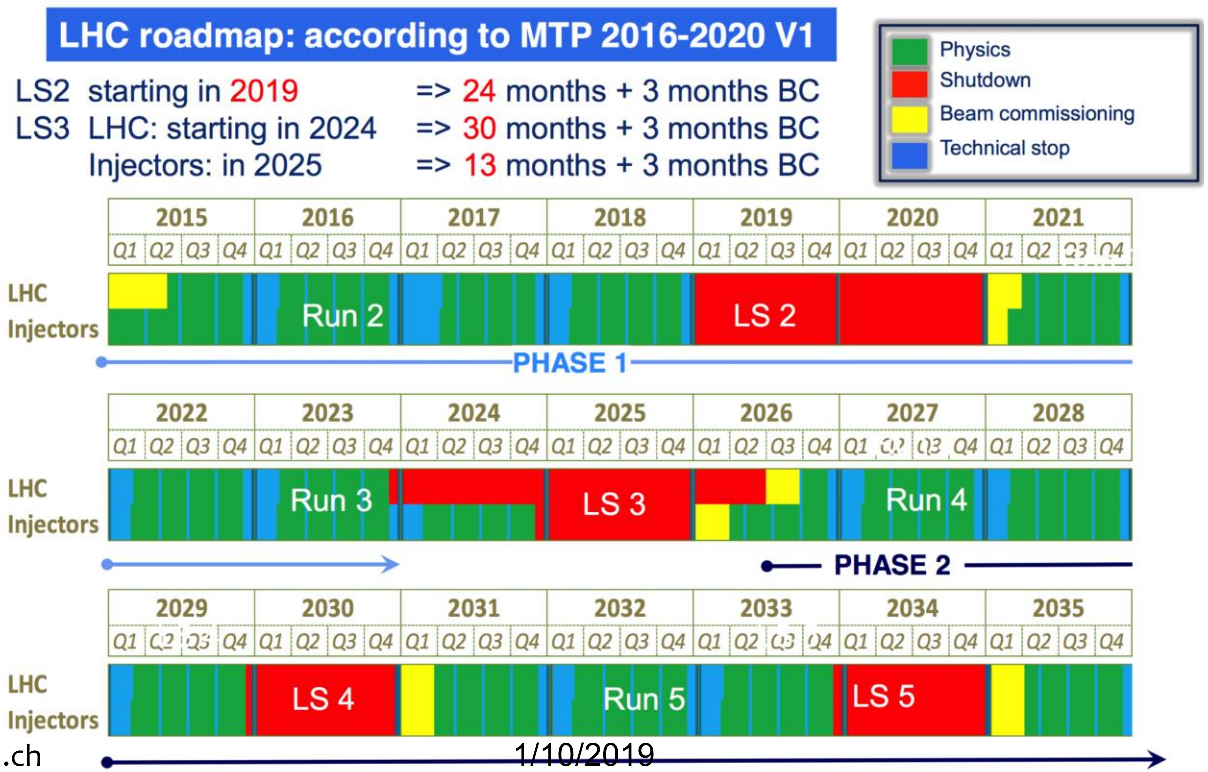
Experiment's Org



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**

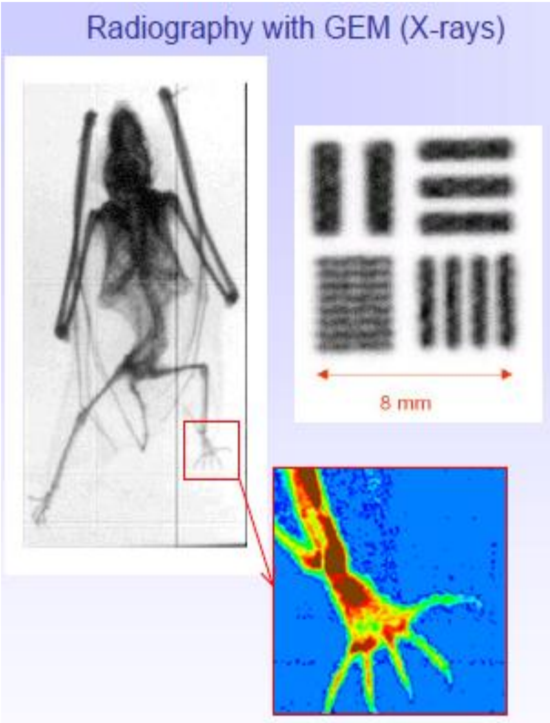


• Diverse R&D •

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

• Other Fields of Application •



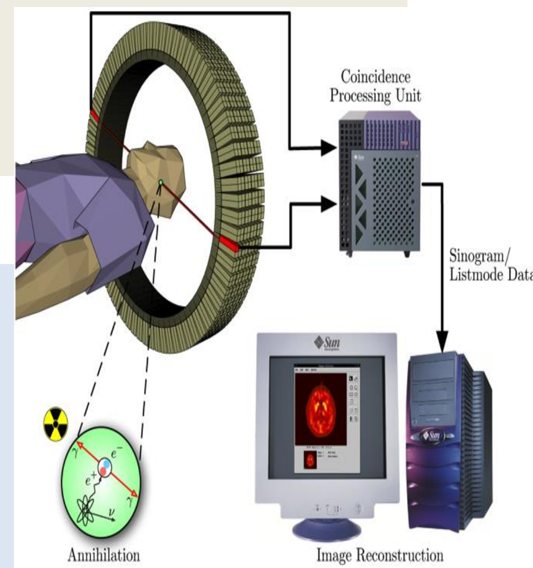
Fast and Therma Neutron Detection
Non-destructive diagnotic, Biology, Nuclear plants, …

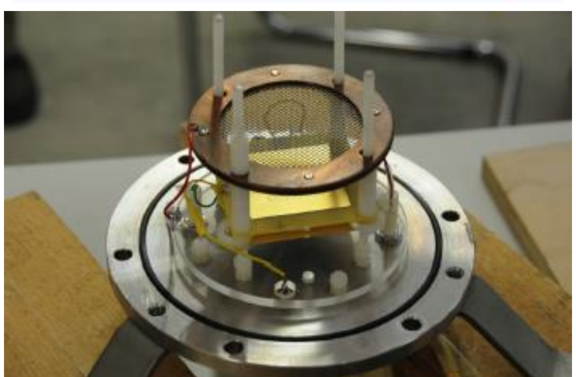
Xray Low Energy
Radioactive waste…

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 m³ fire at a ~1 km distance

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

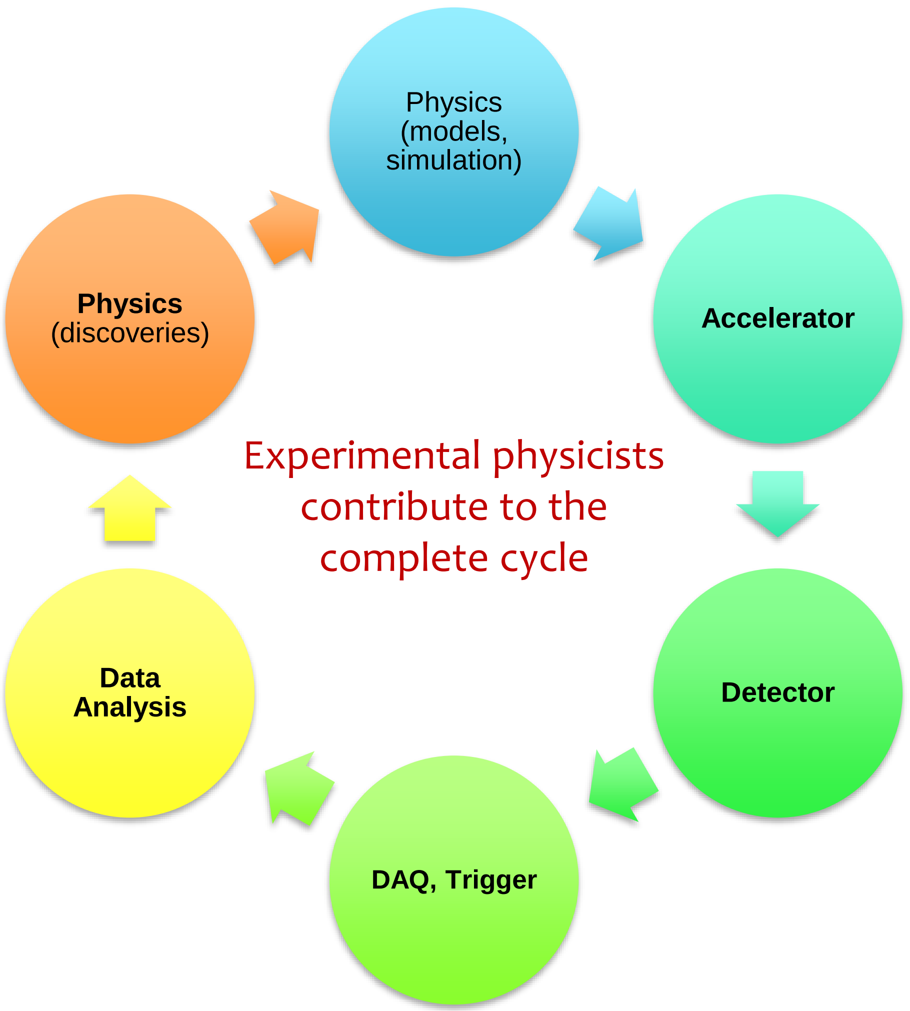
• Experimental Physicists •

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!

+

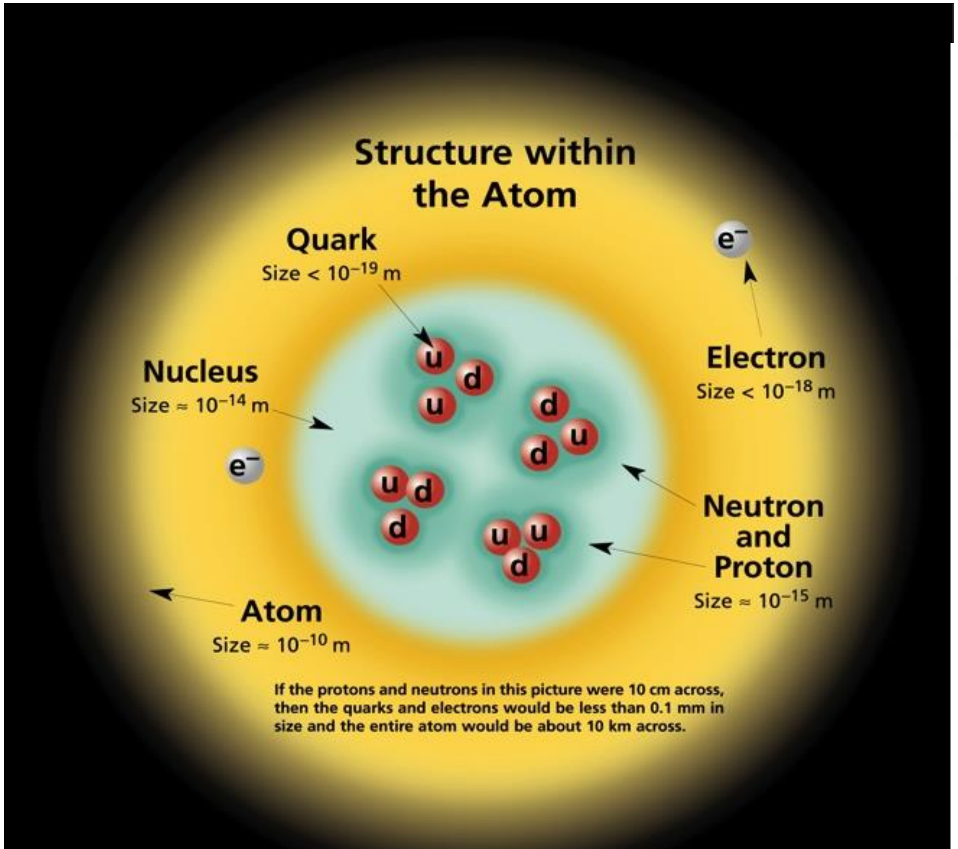
- *The Particle Detector BriefBook* http://www.cern.ch/Physics/ParticleDetector/BriefBook/
- CERN summer student lectures by W.Riegler: http://indico.cern.ch/conferenceDisplay.py?confId=134370
- ICFA Schools on Instrumentation
  - http://fisindico.uniandes.edu.co/indico/conferenceTimeTable.py?confId=61#20131125

- **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

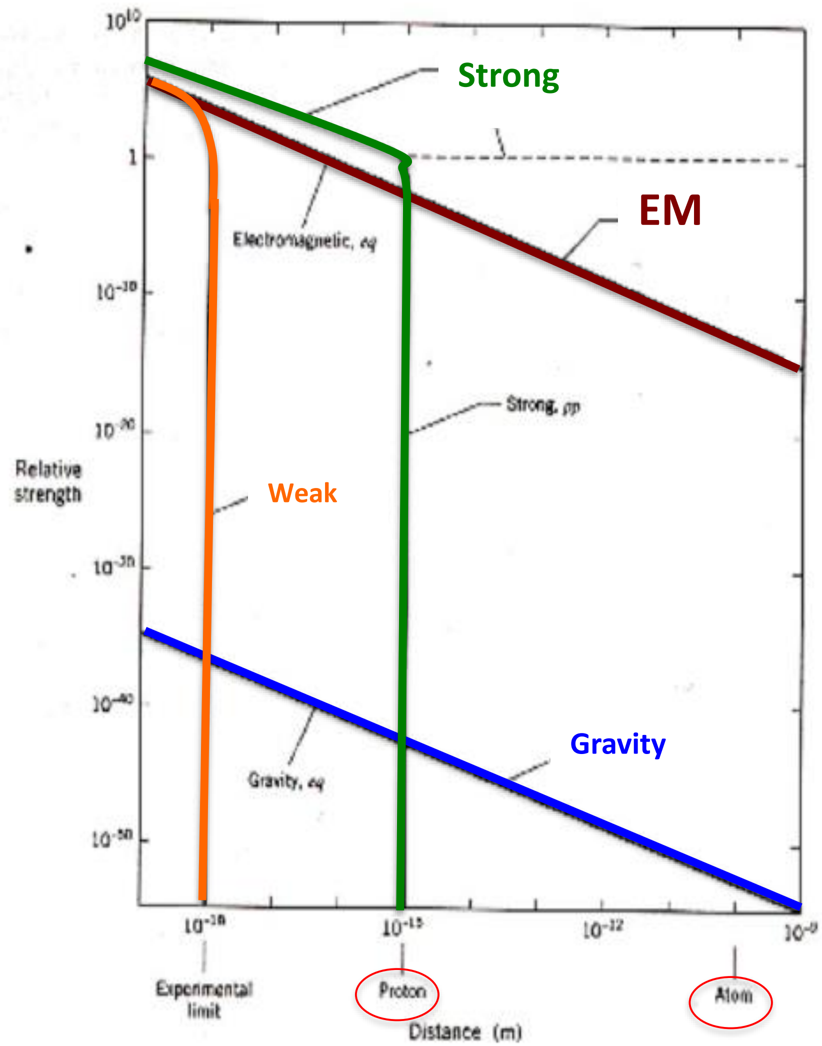
Spare Slides

Interactions



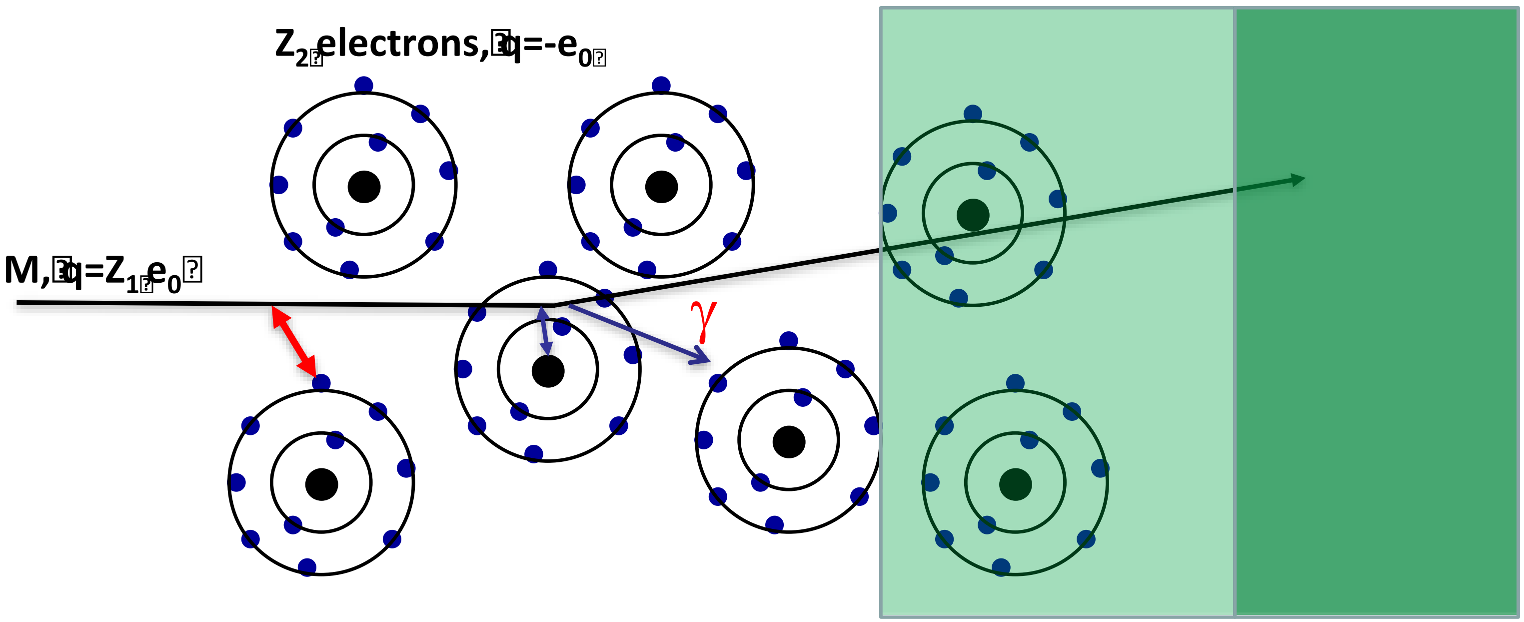
PROPERTIES OF THE INTERACTIONS

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
Strength relative to electromag for two u quarks at: 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

RN



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

Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung 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 Cherenkov Radiation. 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 Transition radiation.

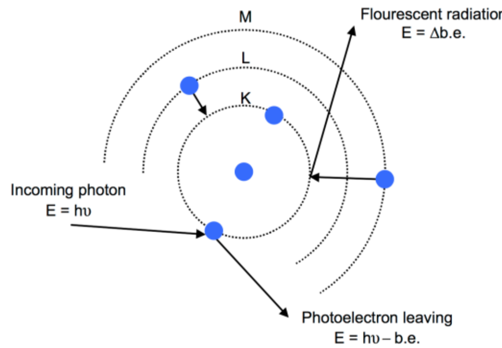
• Neutral Particles •

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

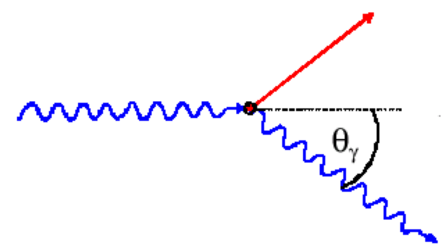
Energy (~KeV to MeV)

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

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

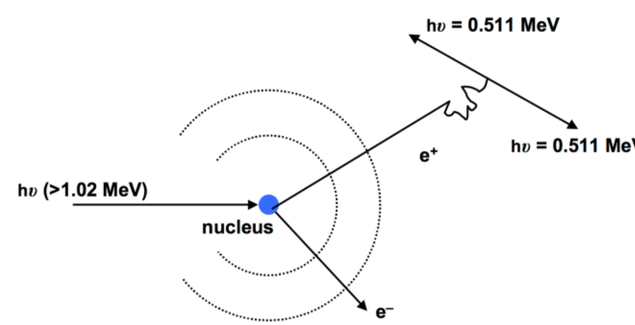


- **Compton scattering (Z)**; scattering of a photon against a free electron (Klein Nishina formula). It results **in a decrease in energy of the photon.** Part of the energy of the photon is transferred to the recoiling electron.



- **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

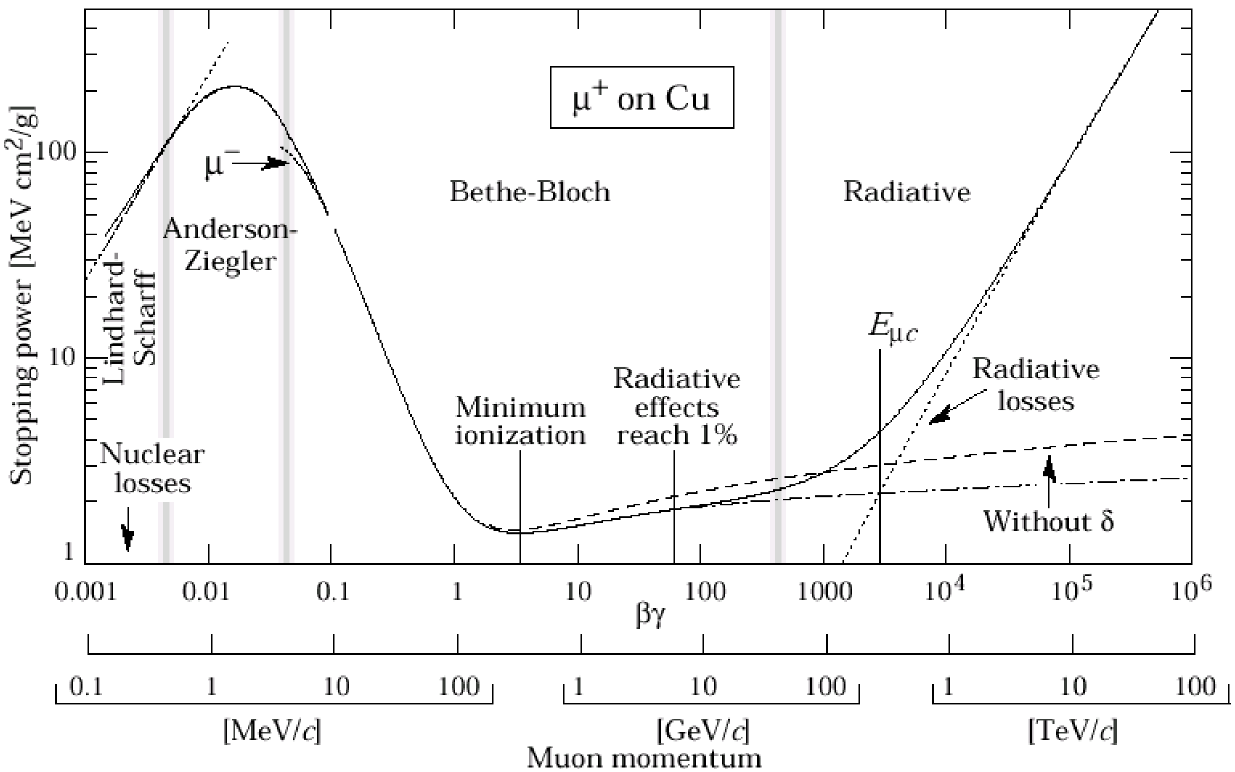


Heavy Charged Particles

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

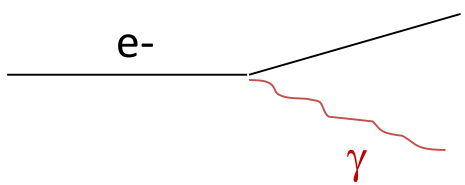
$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I^2} T^{max} - \beta^2 - \frac{\delta}{2} \right]$$

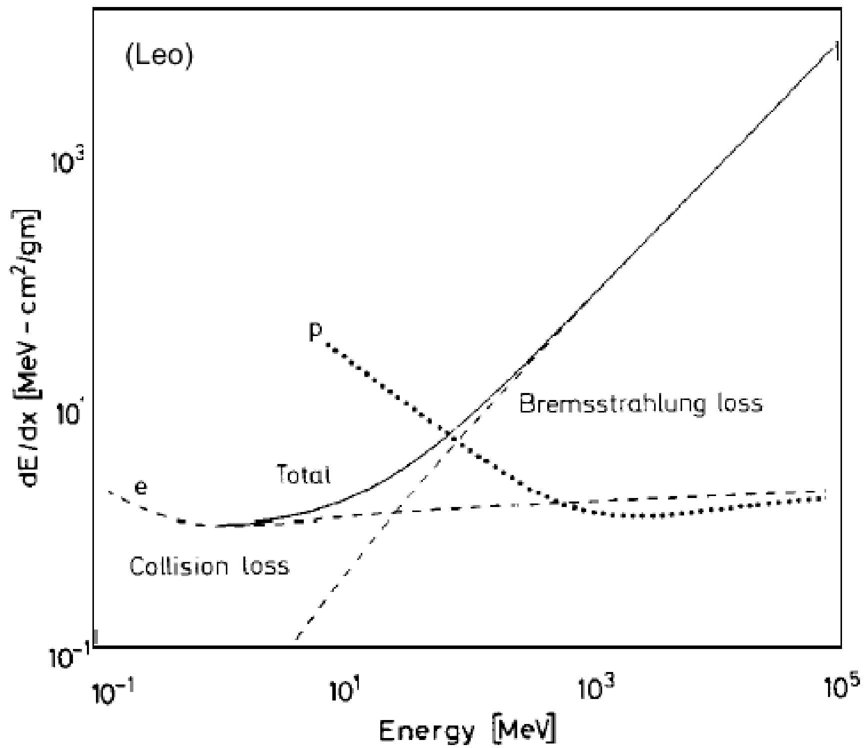
N: Avogadro's Nb
m_e: e- mass
Z, A: medium Atomic, Mass
I: effective ionization potenti
B: projectile velocity



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 $1/m^2$





• Neutrinos •

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

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

- 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**

Gas Detectors

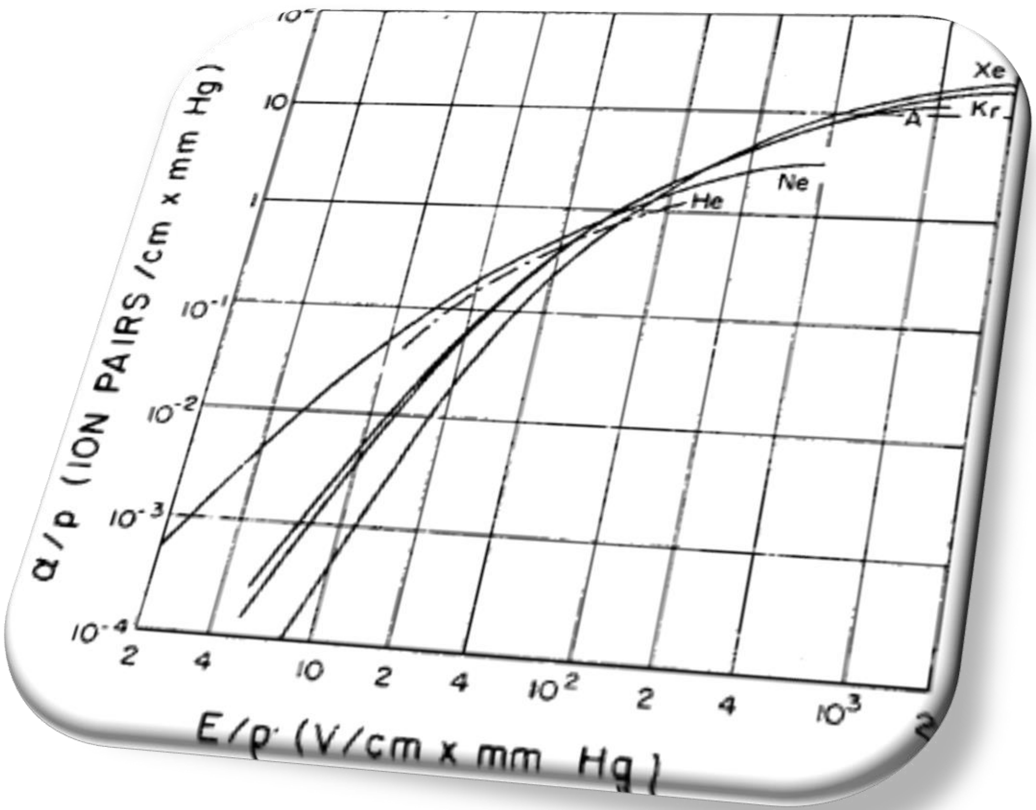
- Good spatial resolution
- Good dE/dx
- Good Rate capability
- Fast & Large Signals
- Low radiation length
- Large area coverage
- Multiple configurations, flexible geometry

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

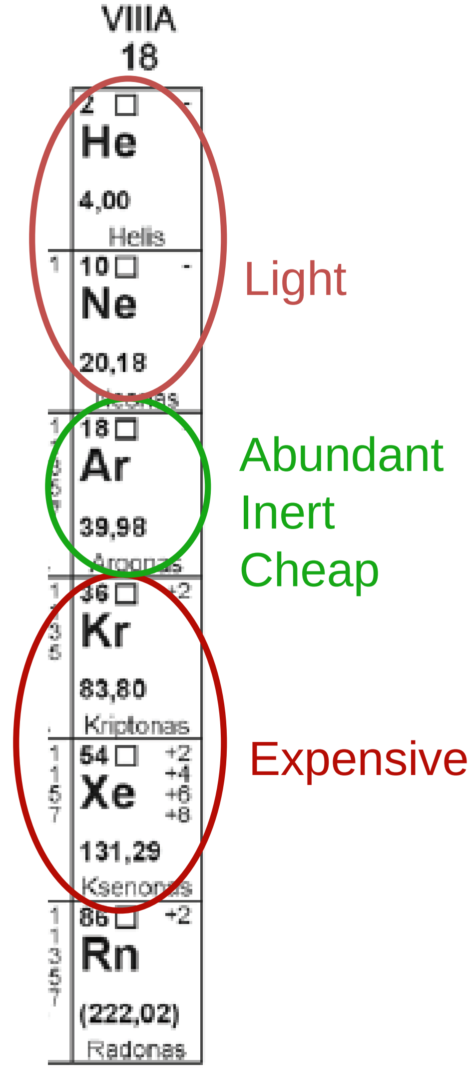
At very large radius, where large areas have to be covered, e.g. the muon chambers, it is unrealistic to use anything other than gas detectors.

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.

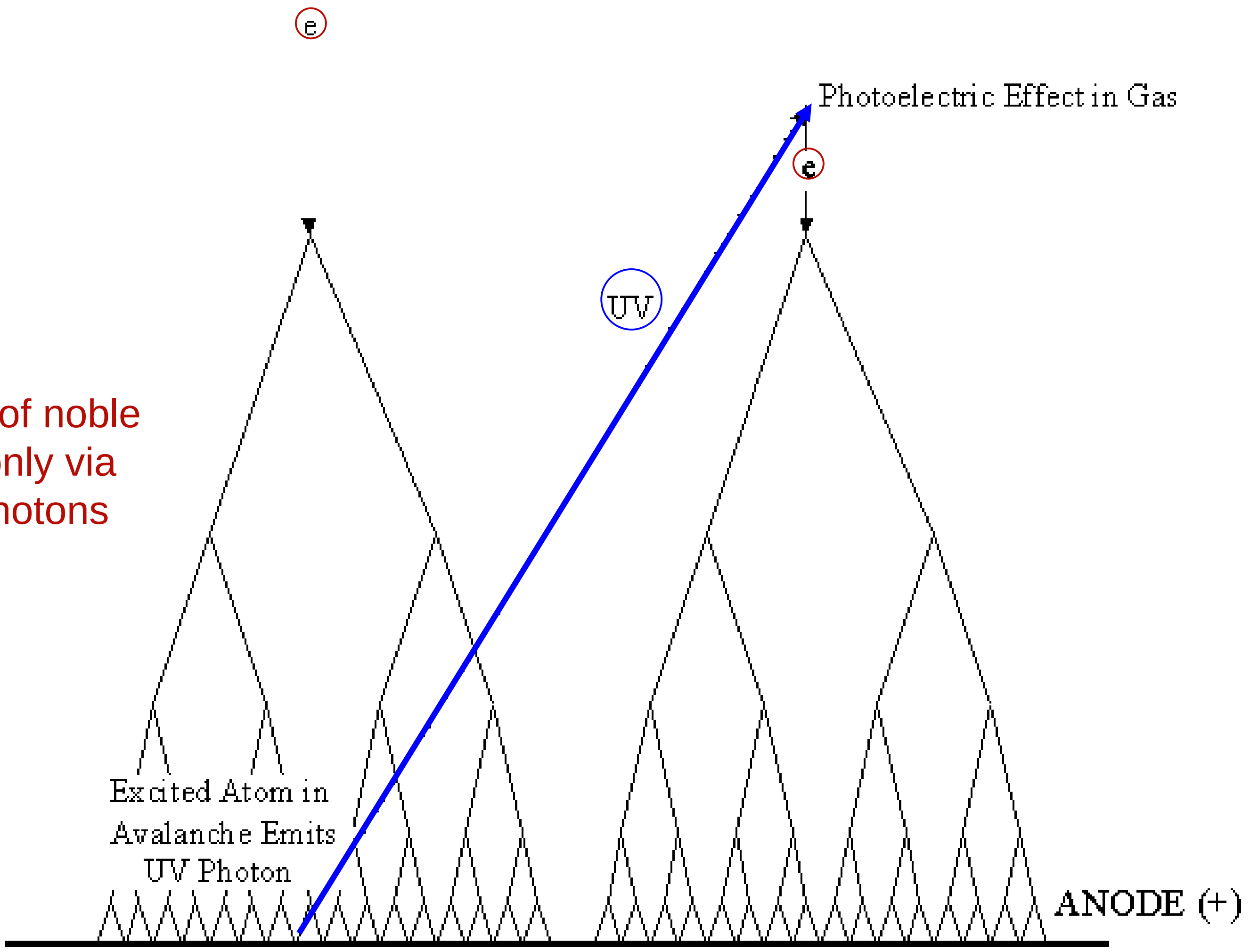
• Noble Gases •



Noble gases require the lowest electric field for formation of avalanches



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

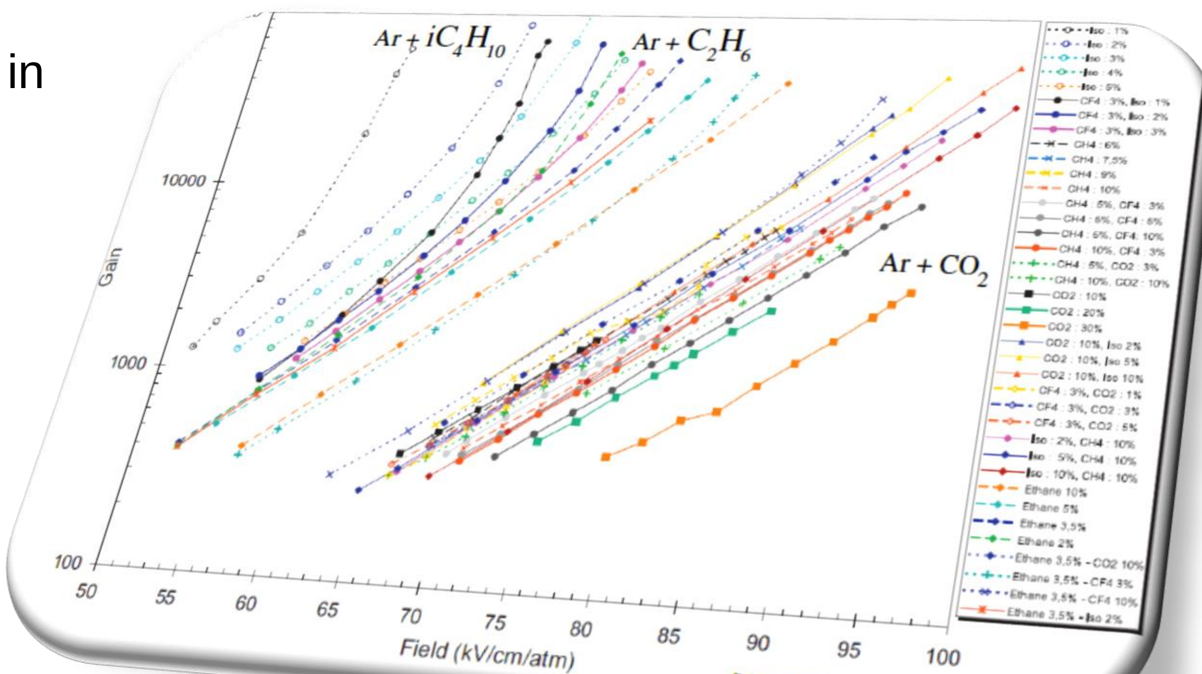


Primary avalanche **Secondary avalanche**

• 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



[10.1016/j.nima.2008.08.1

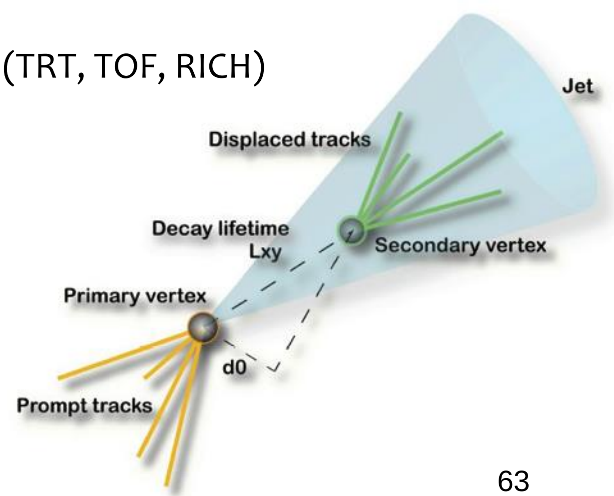
Gas in LHC detectors

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}

Trackers

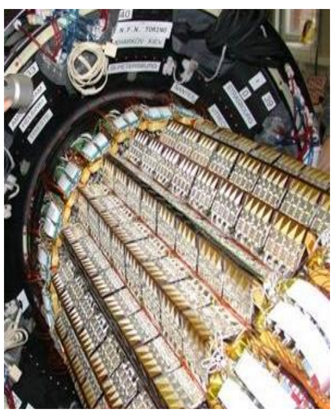
- **Measure charged particles as they emerge from the interaction point, disturbing them as little as possible**
- Measure the trajectory of charged particles
  - Measure several points (hits) along the track and fit curves to the hits (helix, straight line)
- Determine their momentum
  - From their curvature in a magnetic field
- Extrapolate back to the point of origin
- Match tracks with showers in the calorimeters or tracks in the muon systems
  - Reconstruct primary vertices
- Reconstruct secondary vertices
  - Long-lived particles have a measurable displacement between primary vertex and decay
- 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

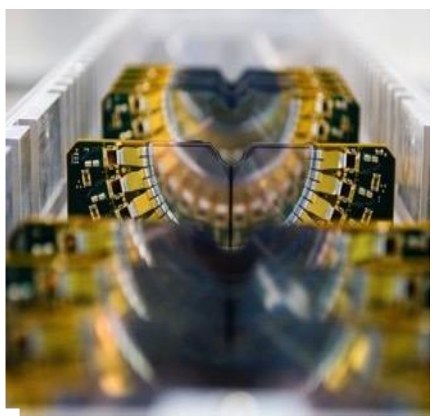


Semiconductors

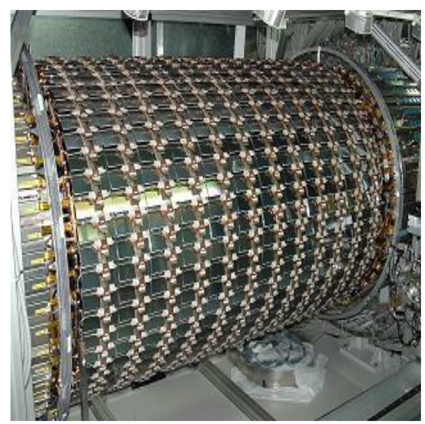
- **Very attractive in HEP because of:**
  - Good intrinsic **energy resolution**
    - Silicon: 1 e-hole pair for every 3.6 eV released by a crossing particle. In Gas: 30 eV required to ionize a gas molecule
    - High primary ionization (larger signal), **no amplification**: typical detector thickness (300 mm) result in 3.2 x10^4 e-/hole pairs
  - Si high density reduces the range of secondary e, thus **good spatial resolution**
  - The **granularity** can also be very high
  - **Thin**, therefore can be positioned close to the interaction point
  - **Industrial process** (high yield, continuous development…)



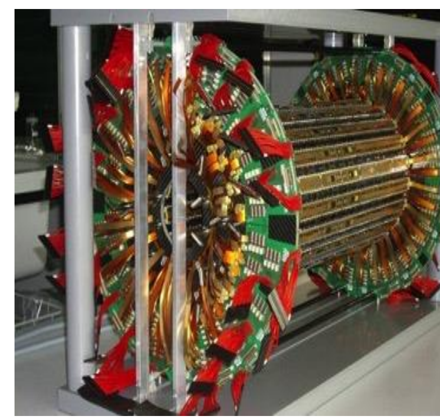
ALICE Drift Detector



LHCb VELO



ATLAS SCT Barrel

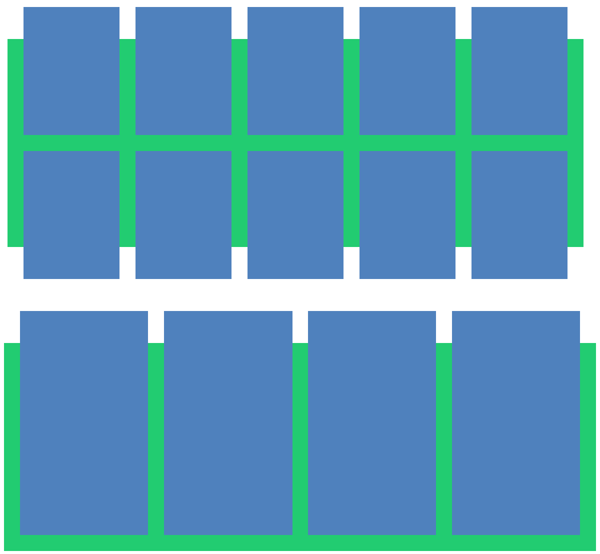


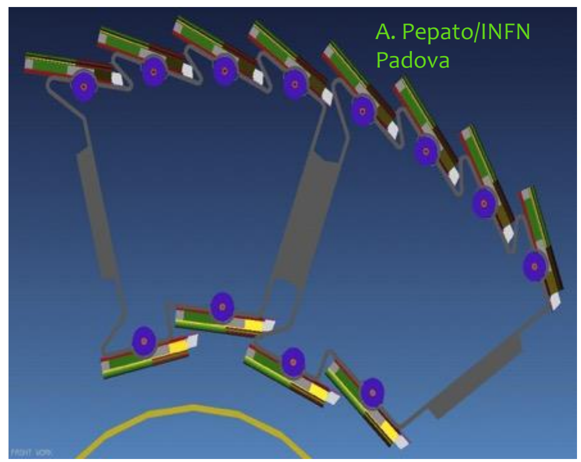
CMS Pixel Detector

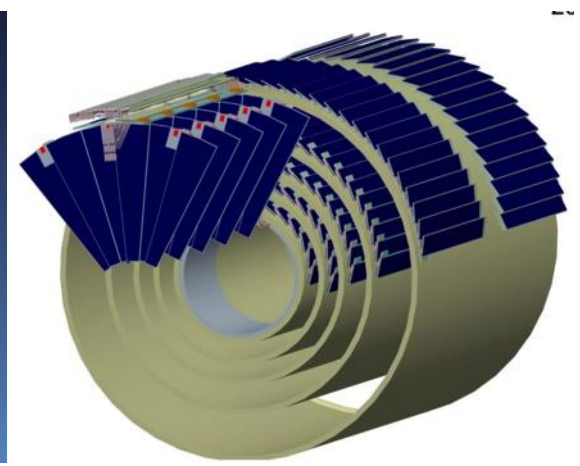
Slide: P. Riedler, CERN

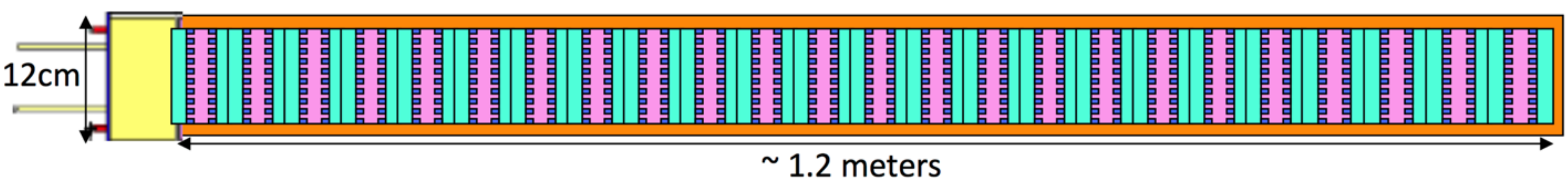
• Systems •

- **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)







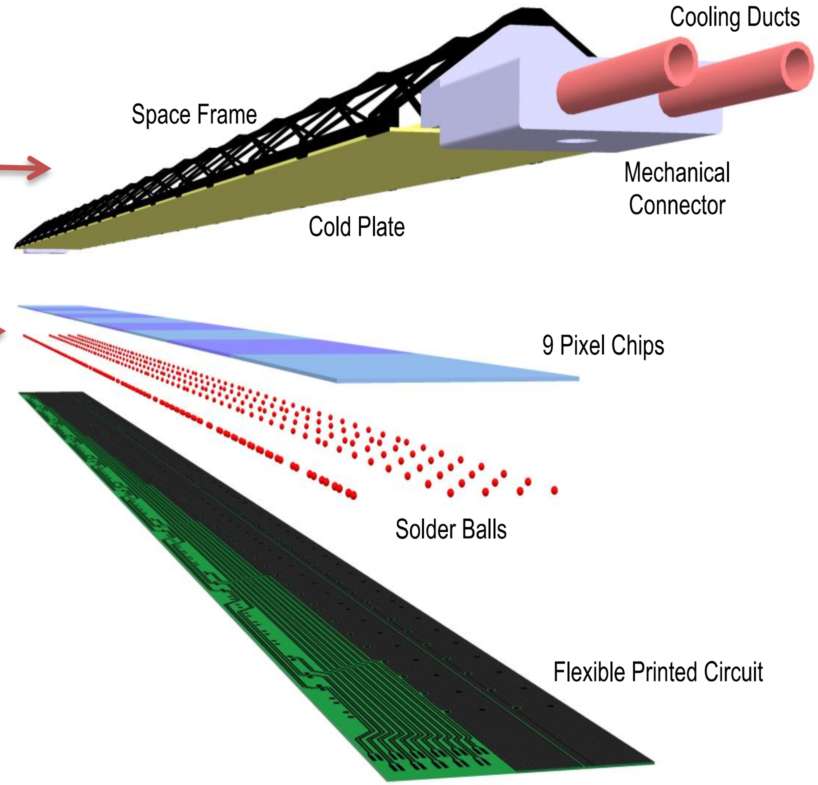


Silicon detectors, Trends

ALICE ITS Upgrade: Inner Layer Stave

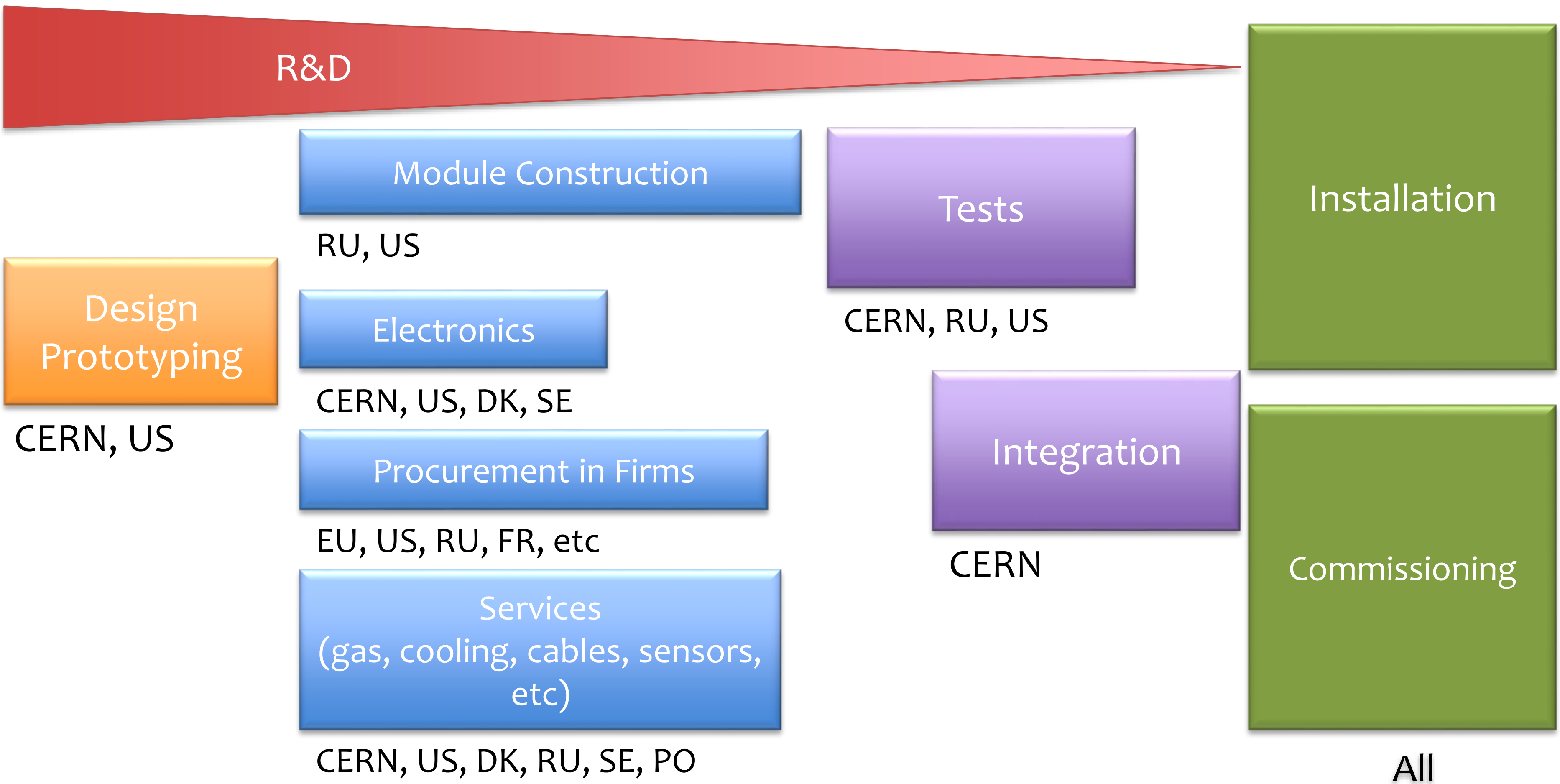
Light weight, compact modules to minimize material budget:

- 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



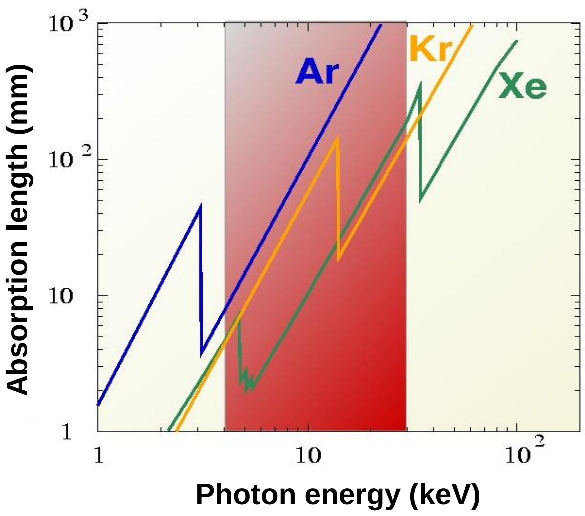
Distributed/Collaborative Projects

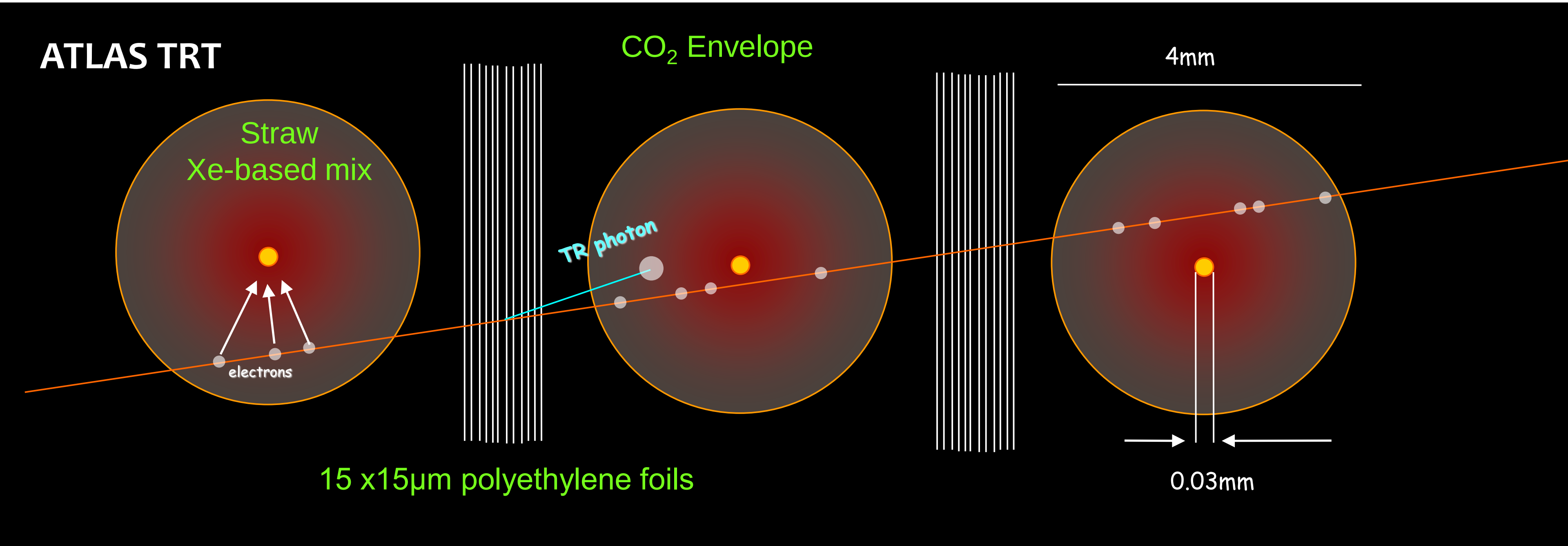
Example, the ATLAS Transition Radiation Tracker *(non-exhaustive list!)*



Transition Radiation

- TR: **photon emitted** by a charged particle when traversing the boundary between materials with different dielectric constants
- This effect depends on the relativistic factor γ = *E*/*m* and is strongest for electrons, which means it can be used for particle identification
- Typical TR photon energy depositions in the TRT are 5-15 keV, while mips, such as pions, deposit ~2 keV. The parameter used in electron identification is the number of local energy depositions on the track above a given threshold (300 eV VS 6 keV) .





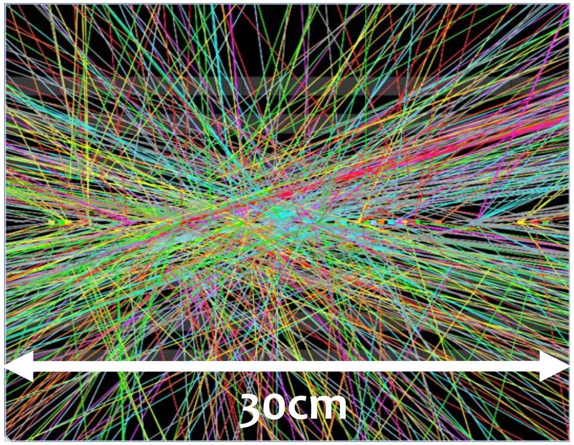
• Tracker Upgrades •

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

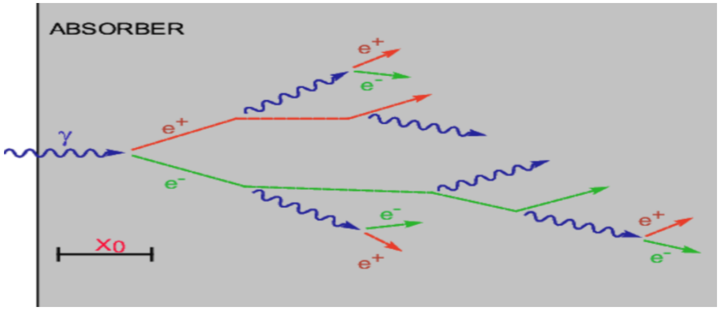


Calorimeter Types

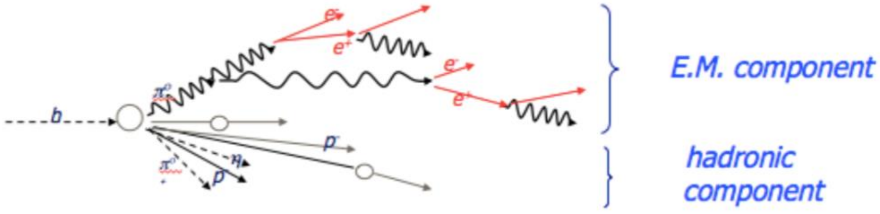
By Particle Type	
Electromagnetic Calorimeter	**Hadronic Calorimeter**
Photons and electron showers (γ,e,π^o)	Charged and neutral hadrons, jets (π, p, n)

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

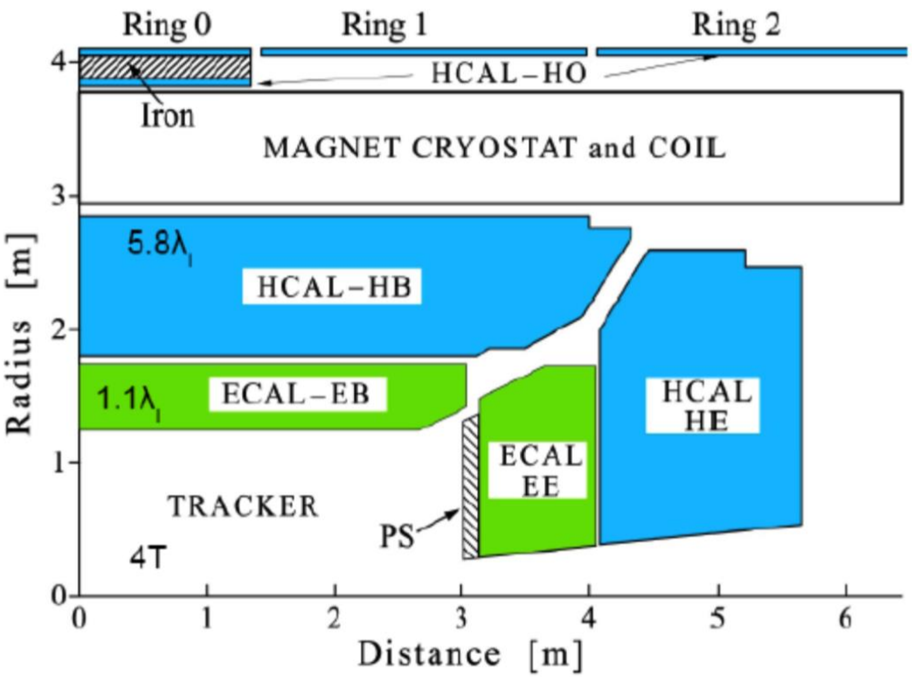
- Electron/Positrons: **Bremsstrahlung** $dE_{e\pm}/E_{e\pm} = - dx/Xo$
- Photons: **Pair productions** $dE_{\gamma}/E_{\gamma} = -(7/9)dx/Xo$

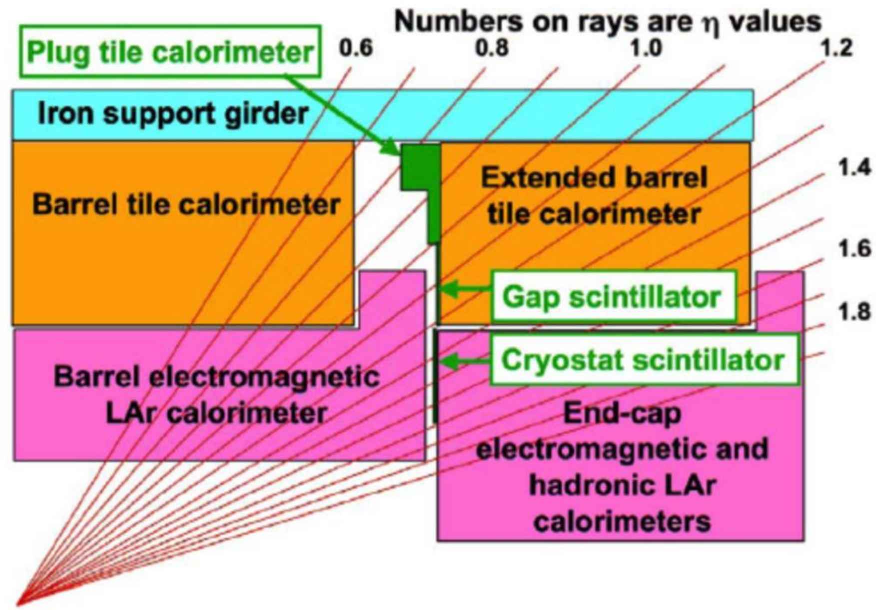


Hadronic Shower
They develop as result of inelastic interaction with the media nuclei through a cascade process
A multitude of effects are produced in the shower development which make the hadron calorimeters a more complicated detector to optimize and with a significantly worse intrinsic resolution



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.

• 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…