High School Teacher Programme 2016

https://indico.cern.ch/e/HST2016

• Particle Detectors •

Mar Capeans

CERN EP-DT

July 8th 2016

• Particle Detectors•

OUTLINE

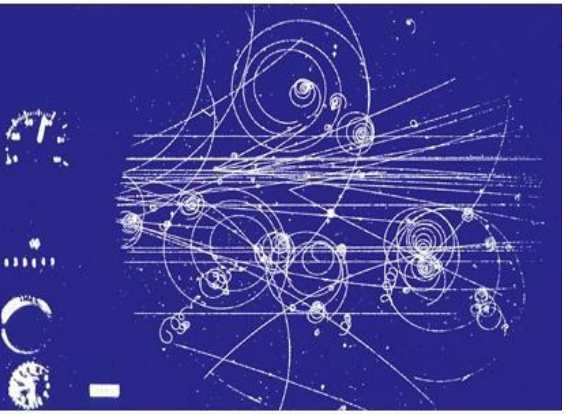
1. Particle Detector Challenges at LHC
2. Interactions of Particles with Matter
3. Detector Technologies
4. How HEP Experiments Work

Particle Physics Tools

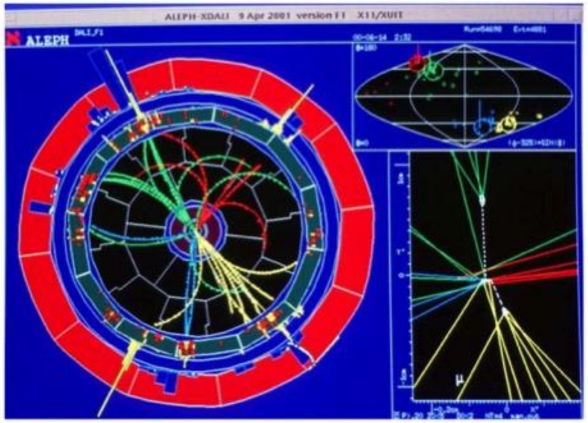
- **Accelerators**
  - Luminosity, energy…
- **Detectors**
  - Efficiency, granularity, resolution…
- **Trigger/DAQ (Online)**
  - Efficiency, filters, through-put…
- **Data Analysis (Offline)**
  - Large scale computing, physics results…

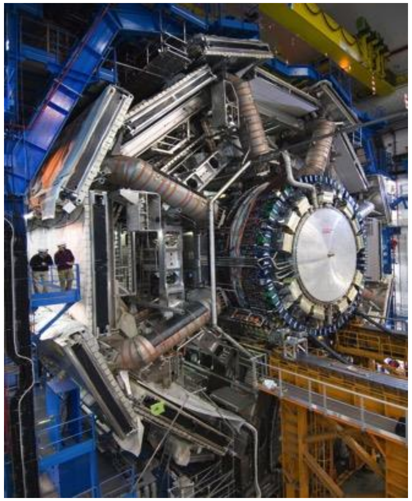
Imaging Events

50’s – 70’s

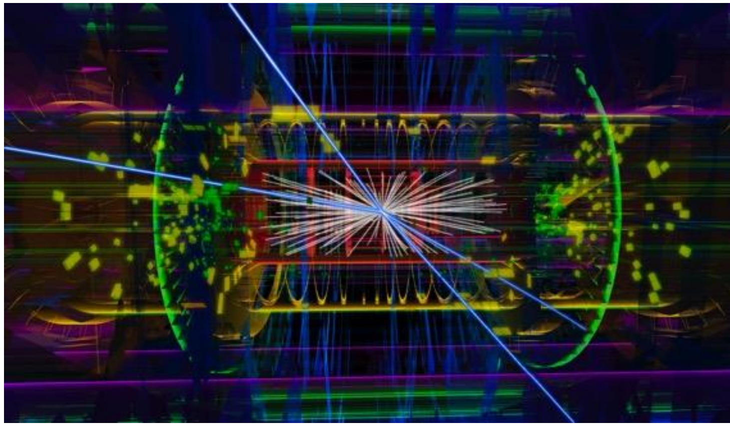


LEP: 88 - 2000



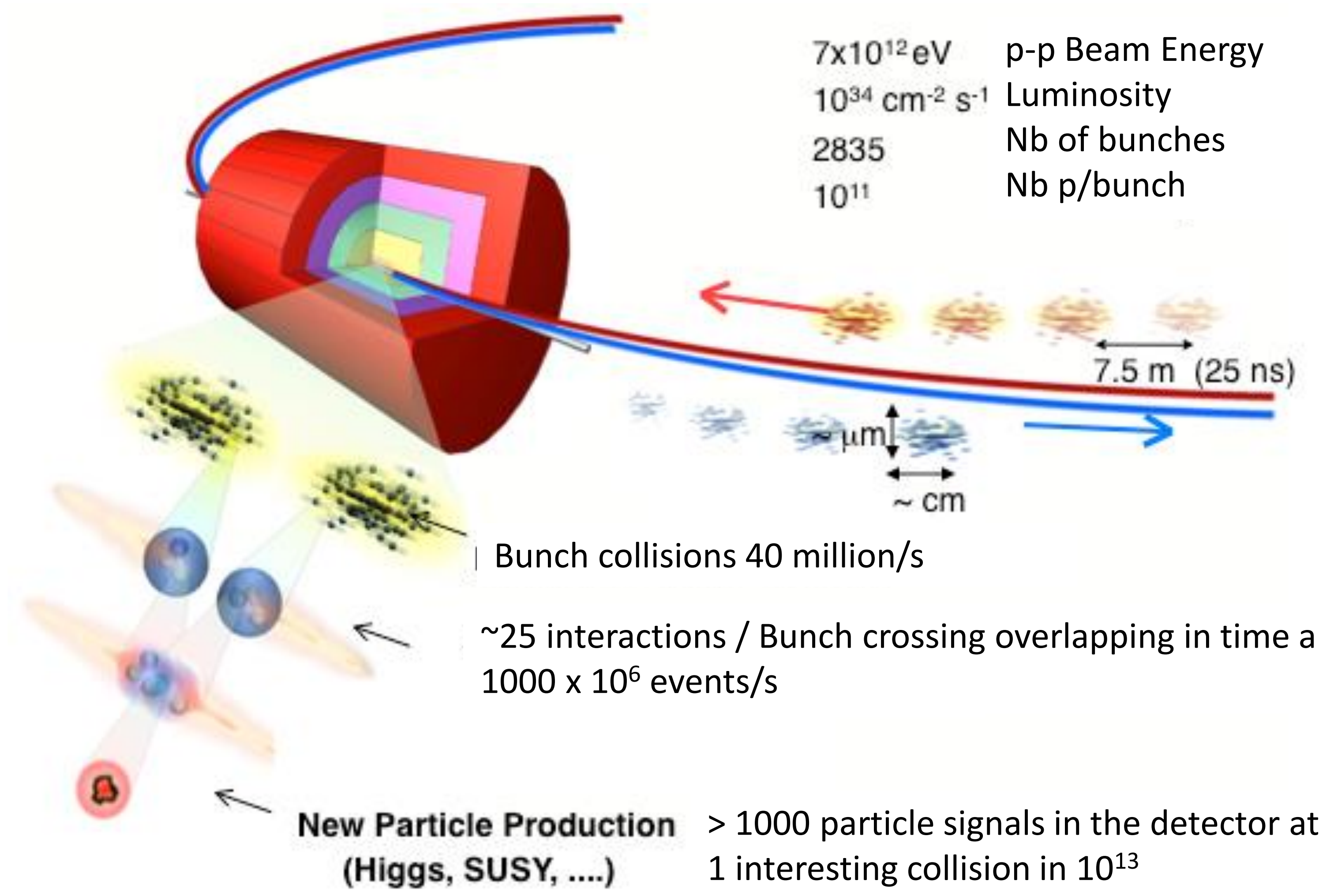


LHC



ATLAS Event

• LHC •



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

1000 x 10^6 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

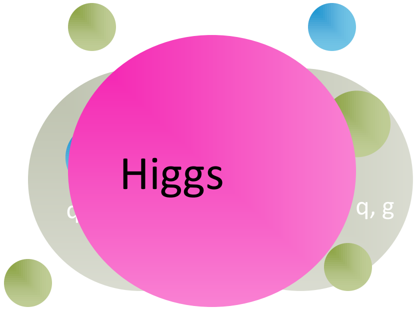
Very Difficult Environment

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)**

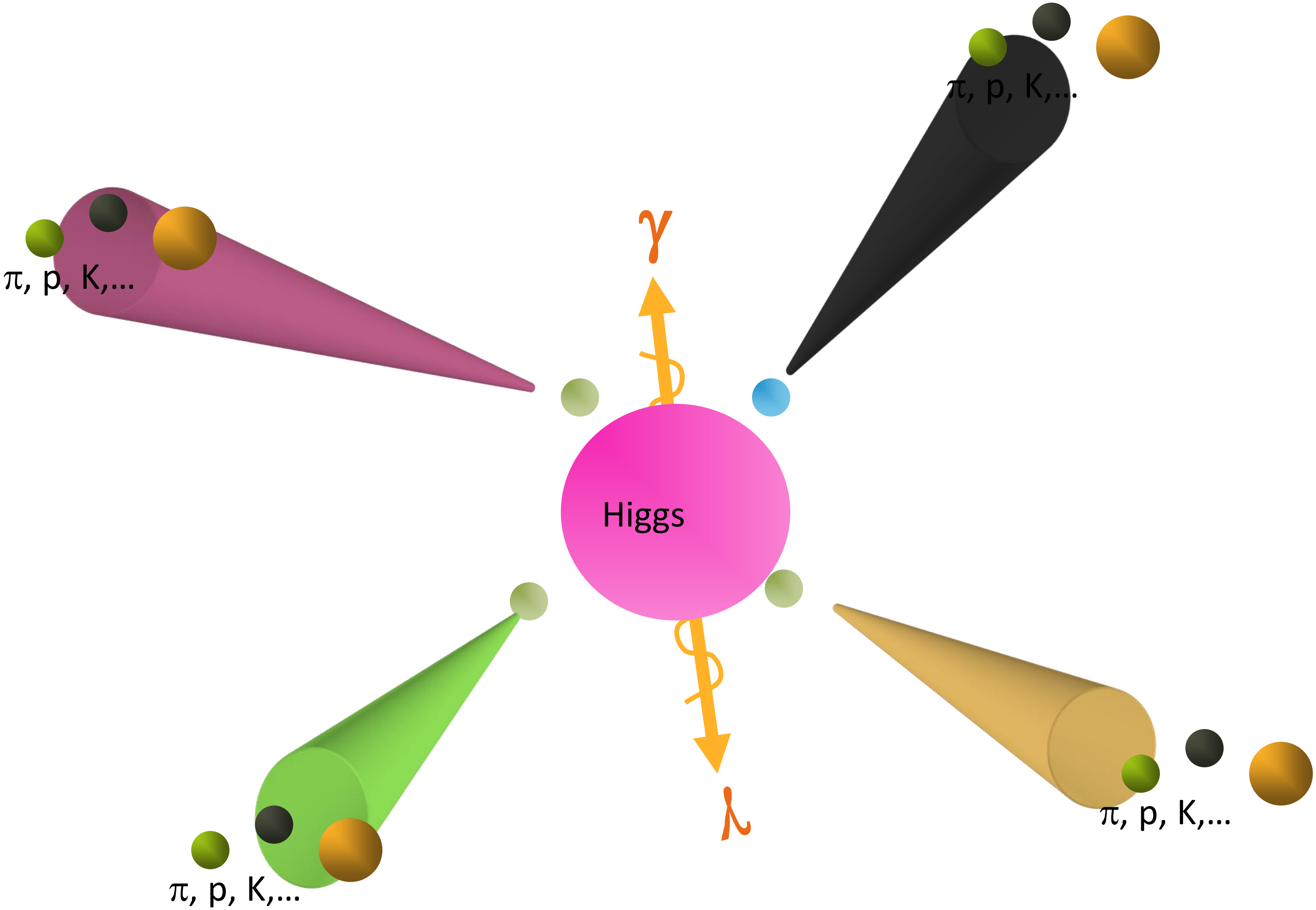
Large neutron fluxes, large photon fluxes capable of compromising the mechanical properties of materials and electronics components. Induced radioactivity in high Z materials (activation) which will add complexity to the **maintenance process**

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

Slide: W.Riegler, CEF

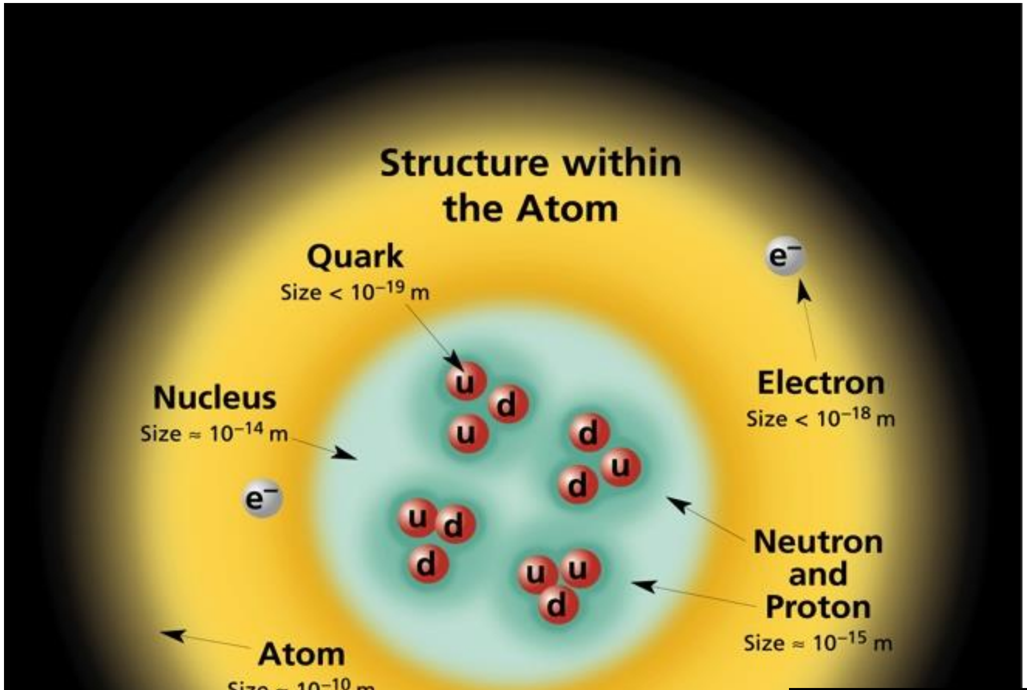
- **Only a few of the numerous known particles have lifetimes that are long enough to leave tracks in a detector**
- Most of the particles are measured through the decay products and their kinematic relations (invariant mass)
- Some short lived particles (b,c –particles) reach lifetimes in the laboratory system that are sufficient to leave short tracks before decaying → identification by measurement of short tracks
- Detectors are built to measure few charged and neutral particles (and their antiparticles) and photons: **$e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, K^{o}, $p^{\pm}$, n, ϒ**
- **Their difference in mass, charge and interaction is the key to their identification**

• Particle Detectors•

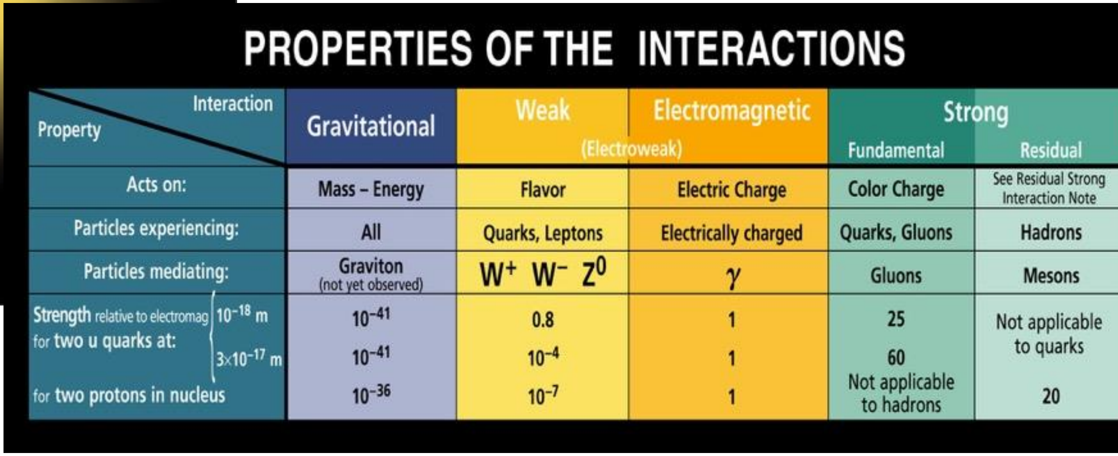
OUTLINE

1. Particle Detector Challenges at LHC
2. **Interactions of Particles with Matter**
3. Detector Technologies
4. How HEP Experiments Work

• Interactions•



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

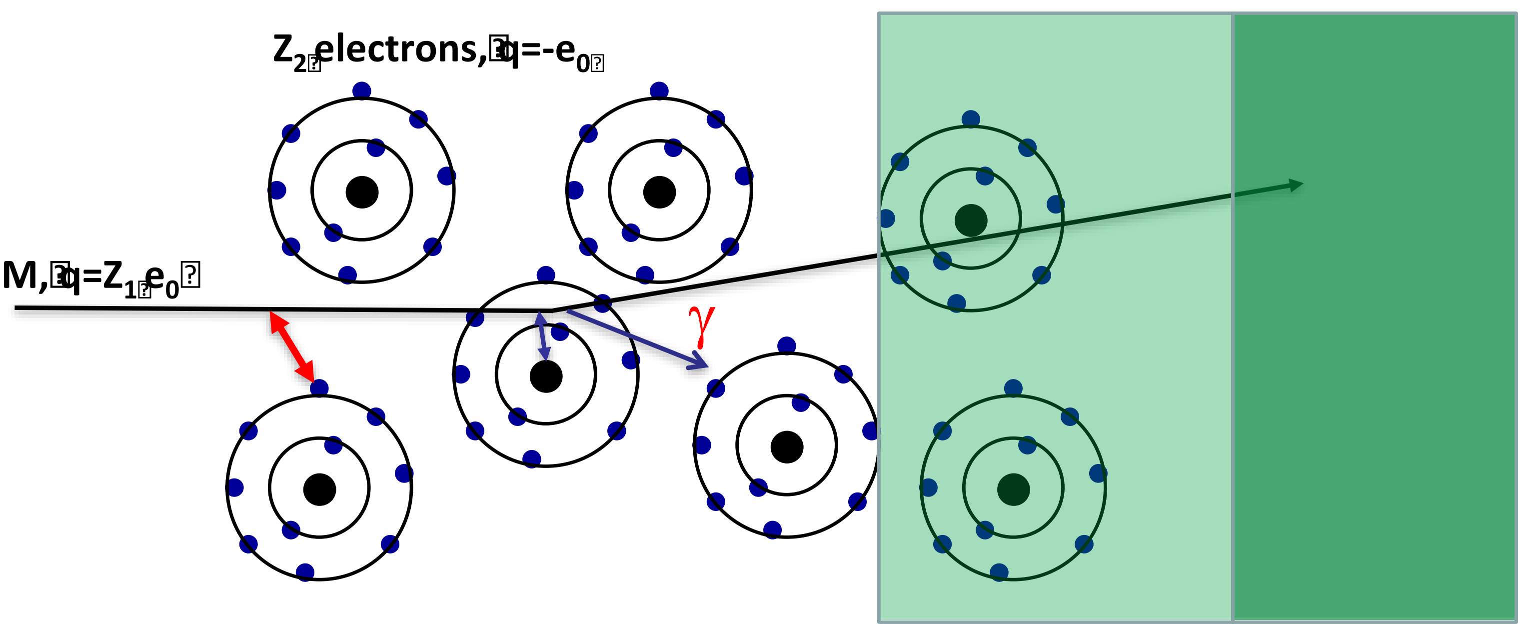


PROPERTIES OF THE INTERACTIONS

Interaction / Property	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	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

Slide: W.Riegler, CERN



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.

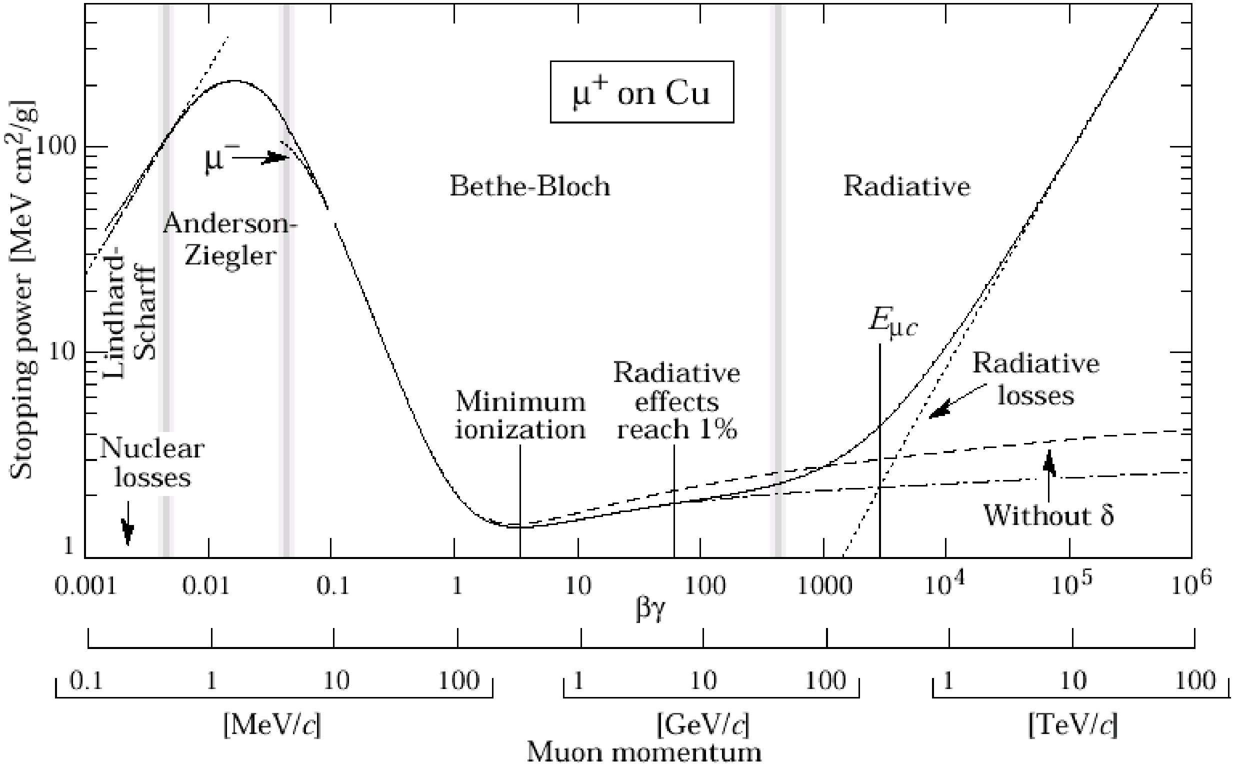
In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called Transition radiation.

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

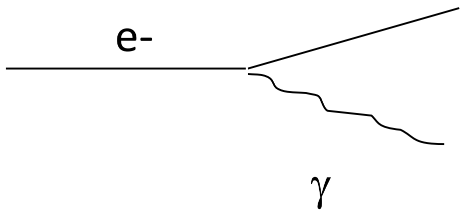
$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I^2} T^{\max} - \beta^2 - \frac{\delta}{2} \right]$$

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

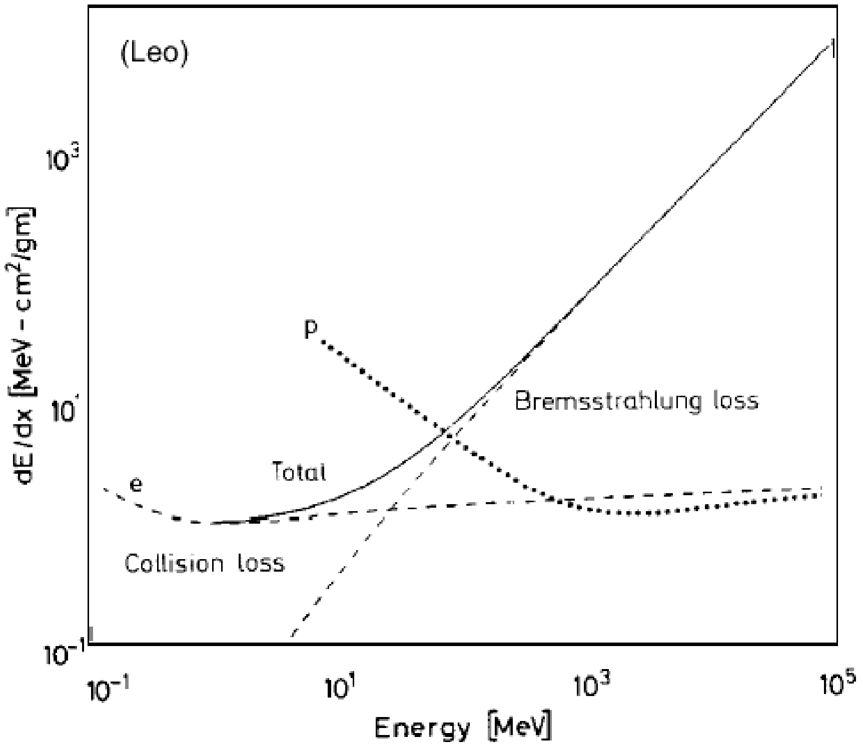


Electrons and Positrons

- Electrons/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 : □ goes as 1/m



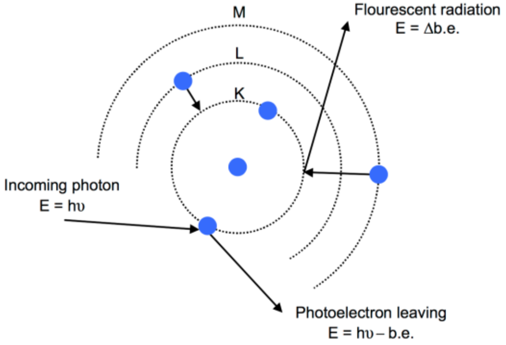
Deceleration of a charged particle when deflected by another charged particle, typically an electron by an atomic nucleus



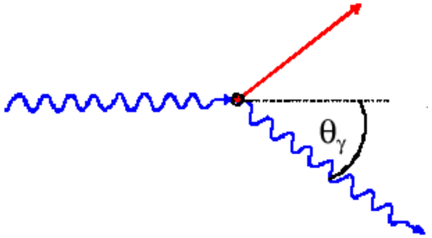
Neutral Particles

- **Photoelectric effect (Z^5)**; absorption of a photon by an atom ejecting an electron. The cross-section shows the typical shell structures in an atom.

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

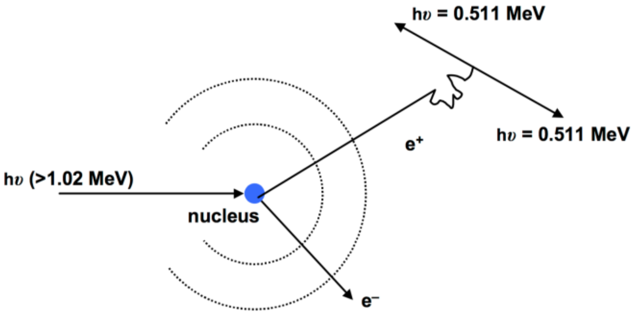


- **Compton scattering (Z)**; scattering of a photon against a free electron (Klein Nishina formula). This process has well defined kinematic constraints (giving the so called Compton Edge for the energy transfer to the electron etc) and for energies above a few MeV 90% of the energy is transferred (in most cases).



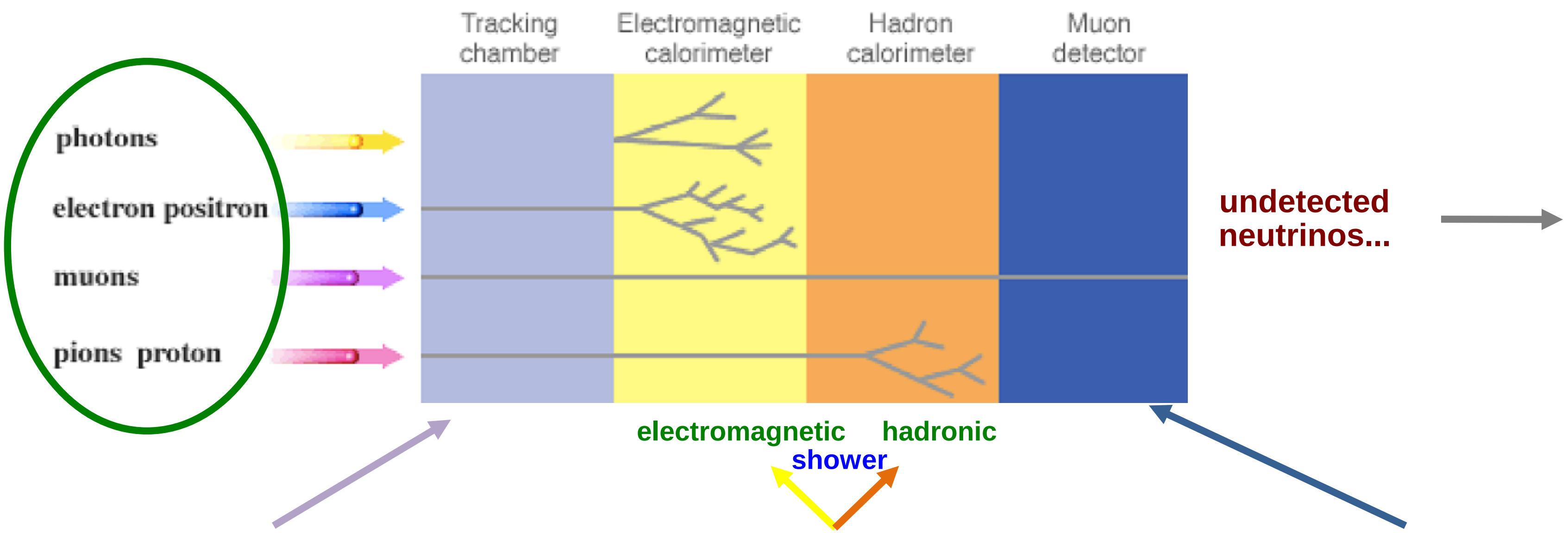
- **Pair-production (Z^2+Z)**; essentially bremsstrahlung; threshold at 2 m_e = 1.022 MeV. Dominates at a high energy.

  Most important in our field, Initiates EM shower in calorimeters



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)

Neutrinos

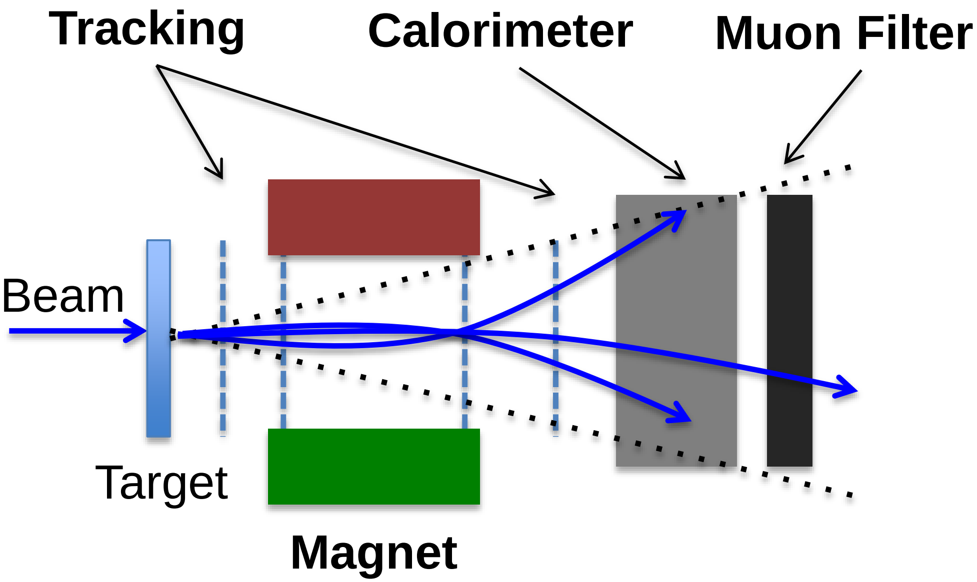
- Neutrinos interact only weakly, tiny cross-sections
- To detect neutrinos, we need first a charged particle (again)
  - Possible reactions:

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

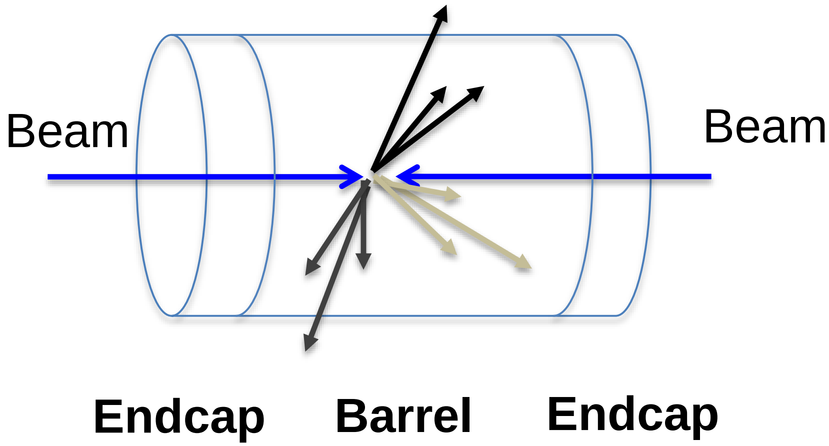
- The cross-section or the reaction $\boldsymbol{\nu_e + n \rightarrow e^- + p}$ is of the order 10^{-43} cm^2 (per nucleon, E_n ~ few MeV), therefore
  - Detection efficiency $\varepsilon_{det} = \sigma \times N^{surf} = \sigma \rho N_A d / A$
  - 1m Iron: $\varepsilon_{det} \sim 5 \times 10^{-17}$
- 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



• Particle Detectors •

OUTLINE

1. Particle Detector Challenges at LHC
2. Interactions of Particles with Matter
3. **Detector Technologies**
4. How HEP Experiments Work

• 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

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.

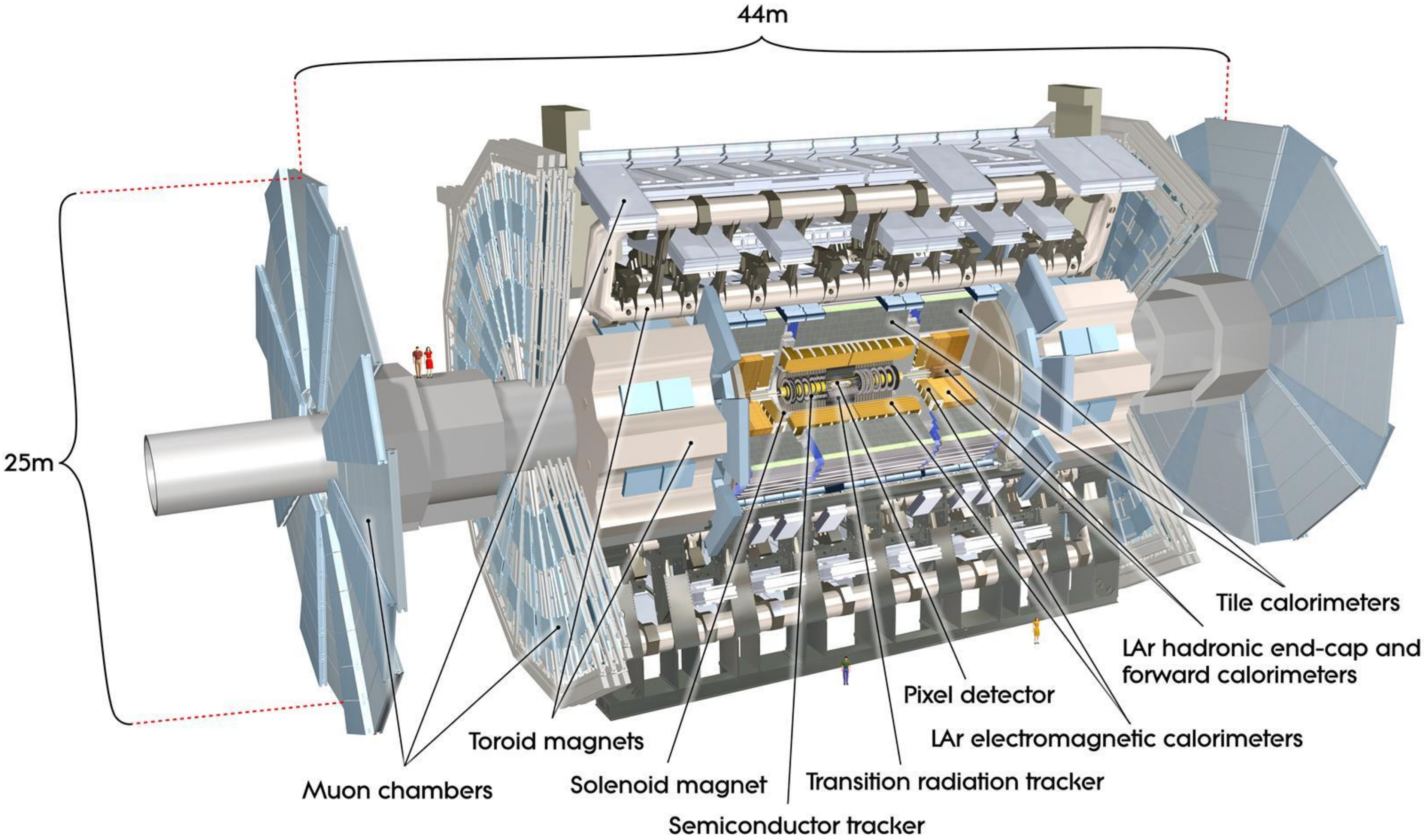
When a charged particle traverses Si, it produces ionizing and non-ionizing E Loss. The latter produces radiation damage, while ionization loss causes the creation of e-hole pairs which produces the signal.

Scintillators 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

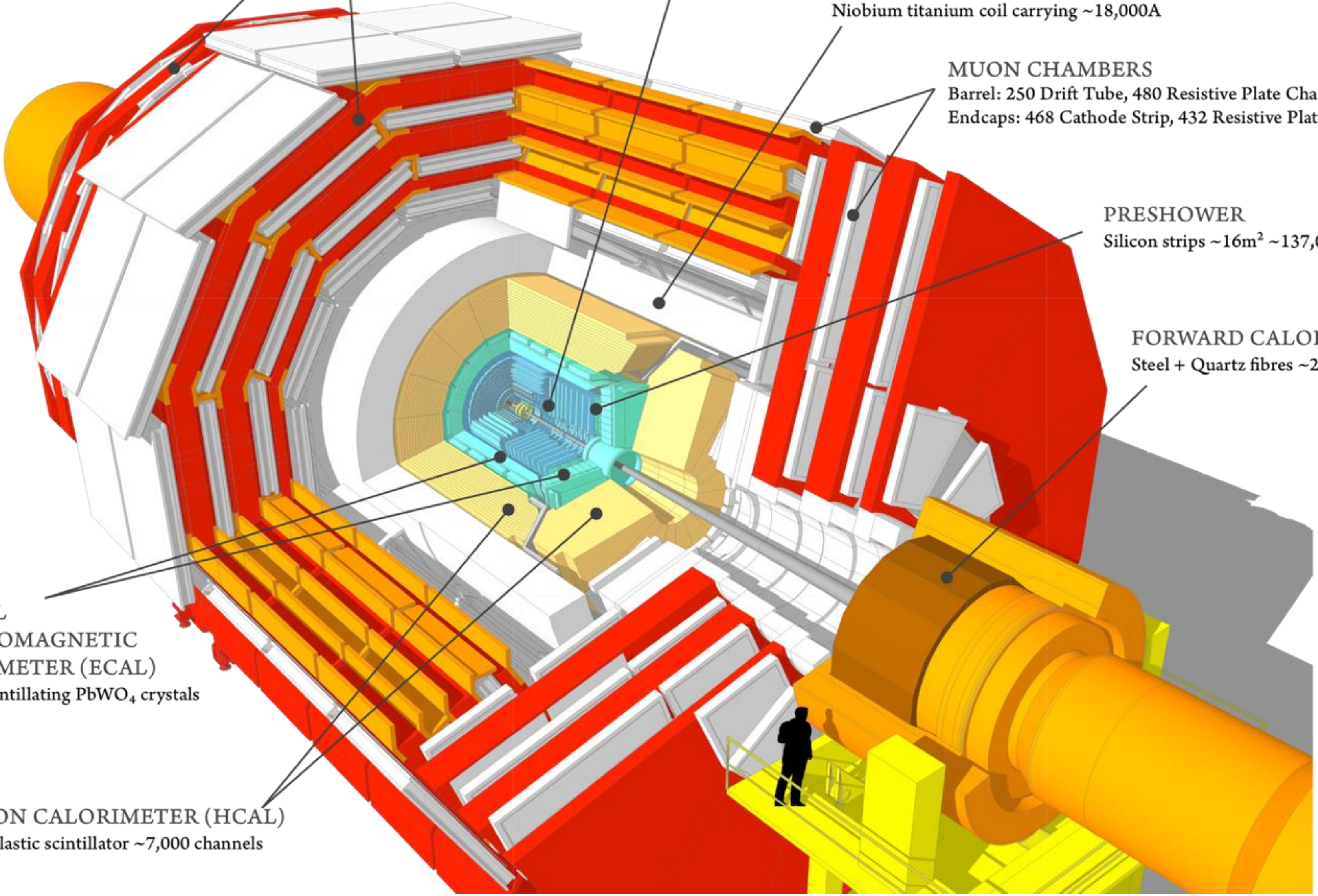
and from then on, it is all online (trigger, DAQ) and offline treatment and analysis ….

• 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) ~16m^2 ~66M channels
Microstrips (80x180 μm) ~200m^2 ~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 ~16m^2 ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

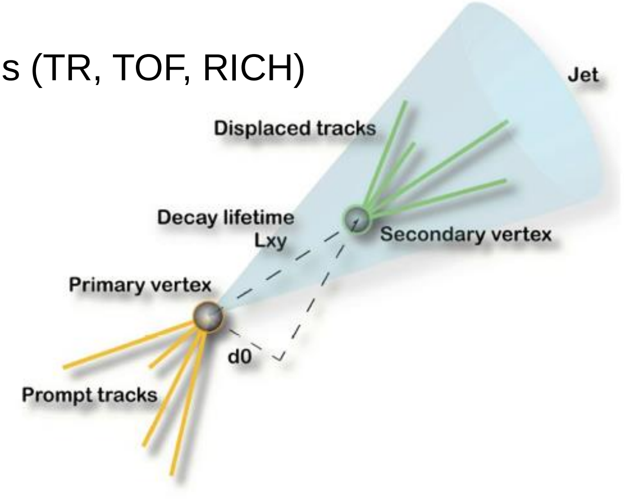
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

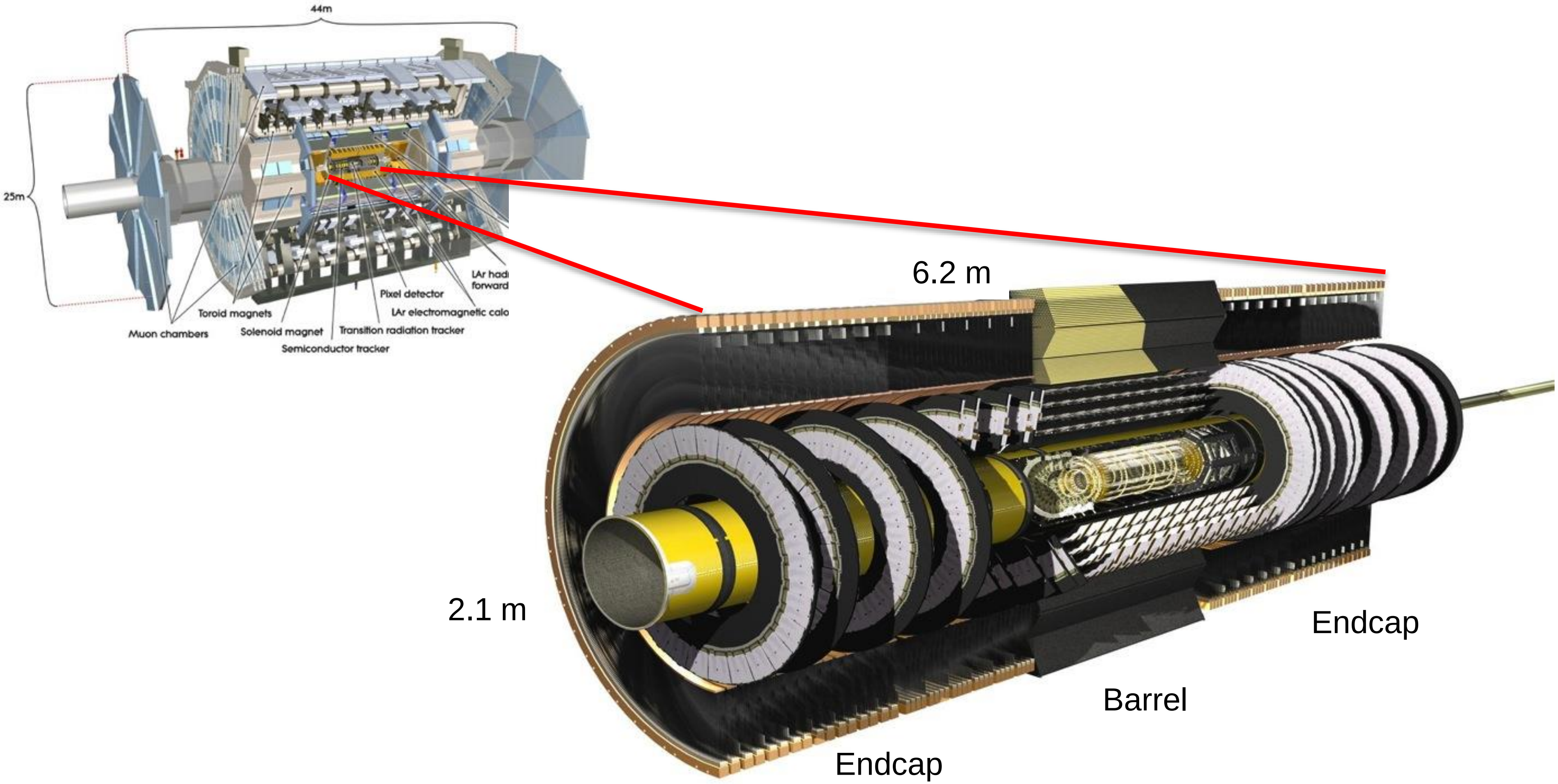
• Trackers•

- **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 (TR, 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

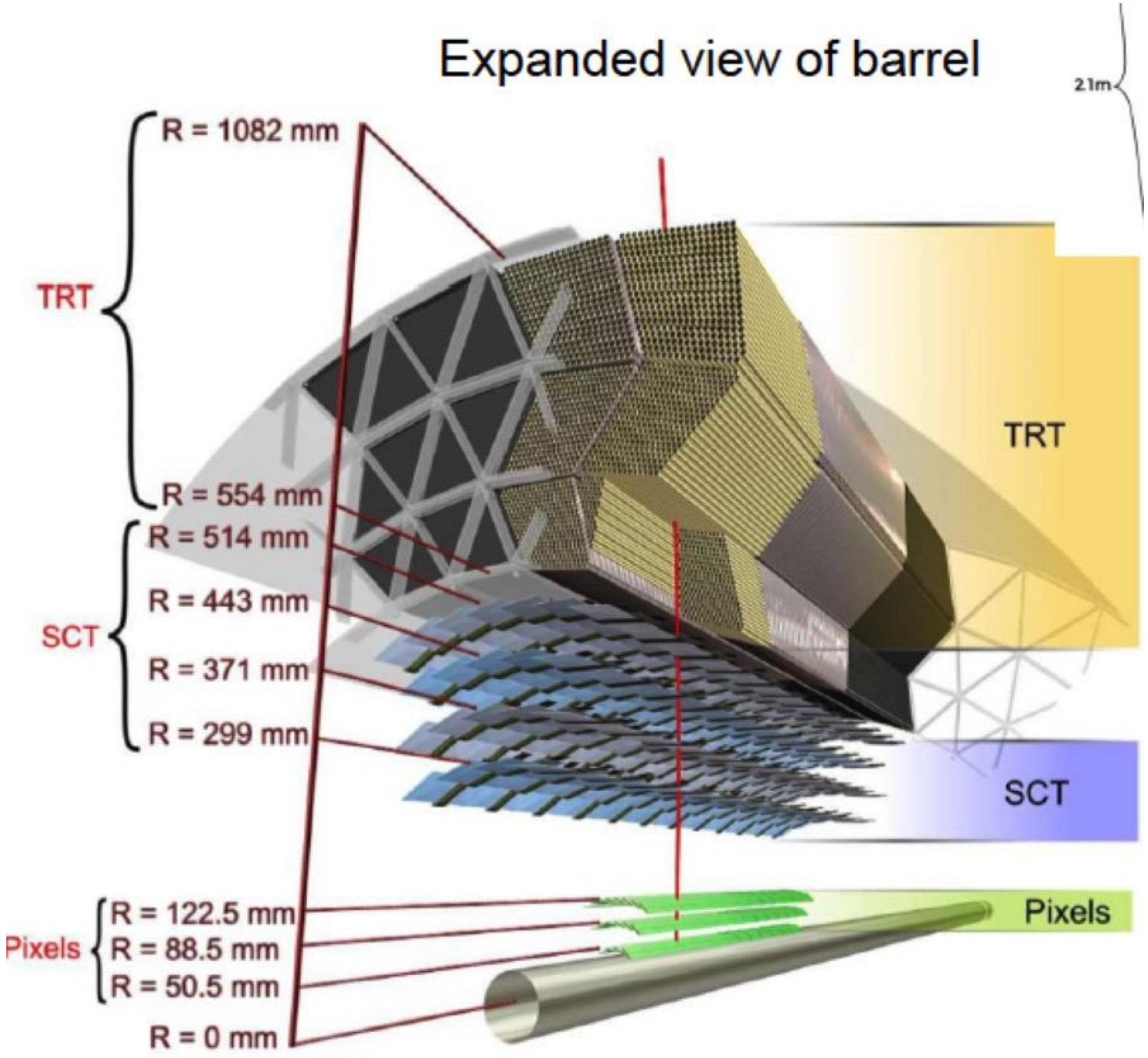


ATLAS Tracker

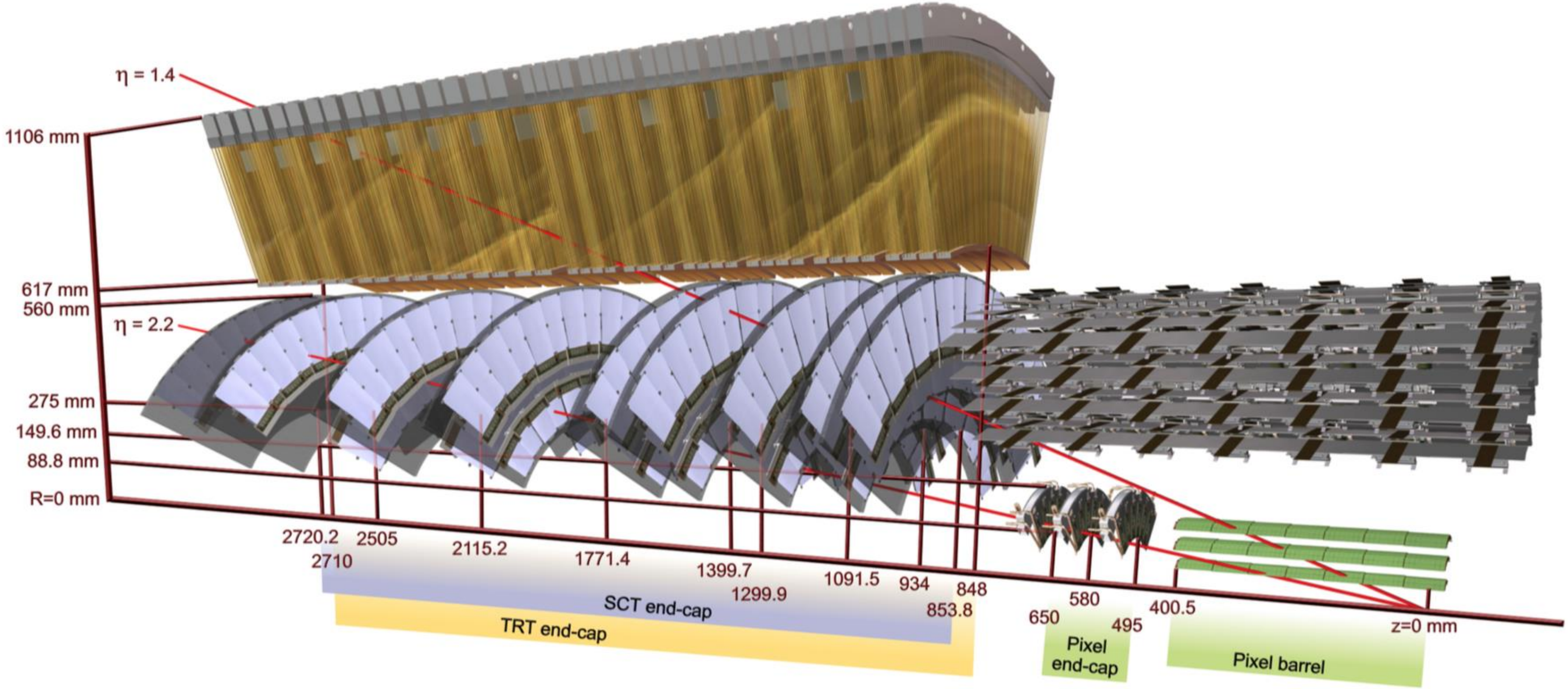
TRT (Straws-Gas)
350 kchannels
36 track points
σ ~130 µm

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

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



• Track Points •



ATLAS ID elements crossed by two charged particles of 10 GeV pT

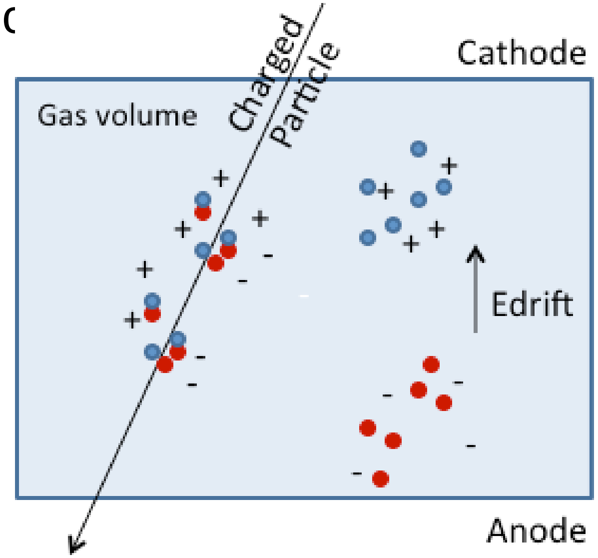
- A particle at |η| = 1.4 traverses the **beam-pipe**, **3 pixel** layers, **4 SCT disks** with double layers of sensors, and approximately **40 straws** in the TRT end-cap.
- A particle at |η| = 2.2 traverses the **beam-pipe**, only the **first pixel** layer, **2 end-cap pixel** disks and the last **4 disks of the SCT** end-cap.

Gaseous Detectors

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

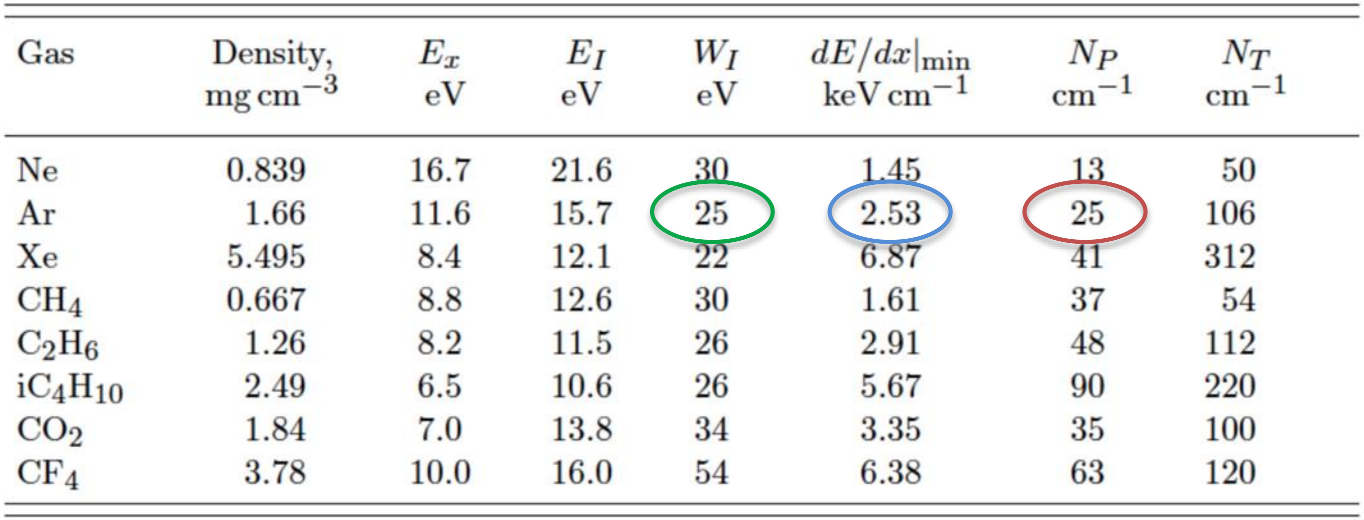
- **Excitation**, the particle passes a specific amount of energy to a gas atom
- **Ionization,** the particle knocks an electron off the gas atom, and leaves a positively charged ion

Resulting primary e^- will have enough kinetic ns of gas. The sum is called **Total Ionization**



• Ionization •

Energy Loss of Charged Particles in Gases



Gas	Density, mg cm^{-3}	E_x eV	E_I eV	W_I eV	$dE/dx\vert_{\mathrm{min}}$ keV cm^{-1}	N_P cm^{-1}	N_T cm^{-1}
Ne	0.839	16.7	21.6	30	1.45	13	50
Ar	1.66	11.6	15.7	25	2.53	25	106
Xe	5.495	8.4	12.1	22	6.87	41	312
CH_4	0.667	8.8	12.6	30	1.61	37	54
C_2H_6	1.26	8.2	11.5	26	2.91	48	112
iC_4H_{10}	2.49	6.5	10.6	26	5.67	90	220
CO_2	1.84	7.0	13.8	34	3.35	35	100
CF_4	3.78	10.0	16.0	54	6.38	63	120

n_p = *25 ion pairs/cm*

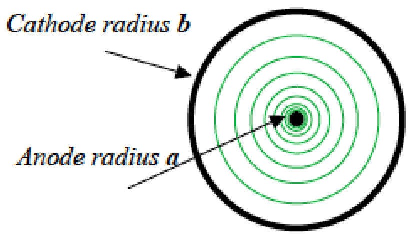
$n_T = \Delta E/W_i$ = *2.5 keV/cm* / *25 eV* = *100 ion pairs/cm*

- 100 pairs are not easy to detect, 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

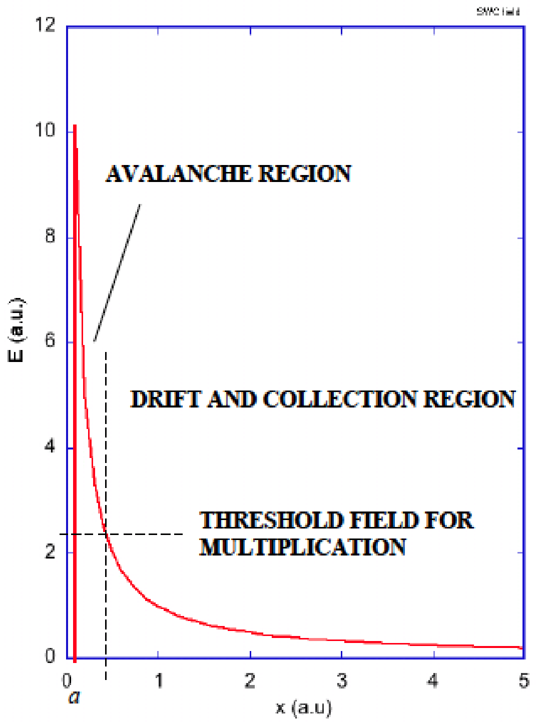


ELECTRIC FIELD AND POTENTIAL:

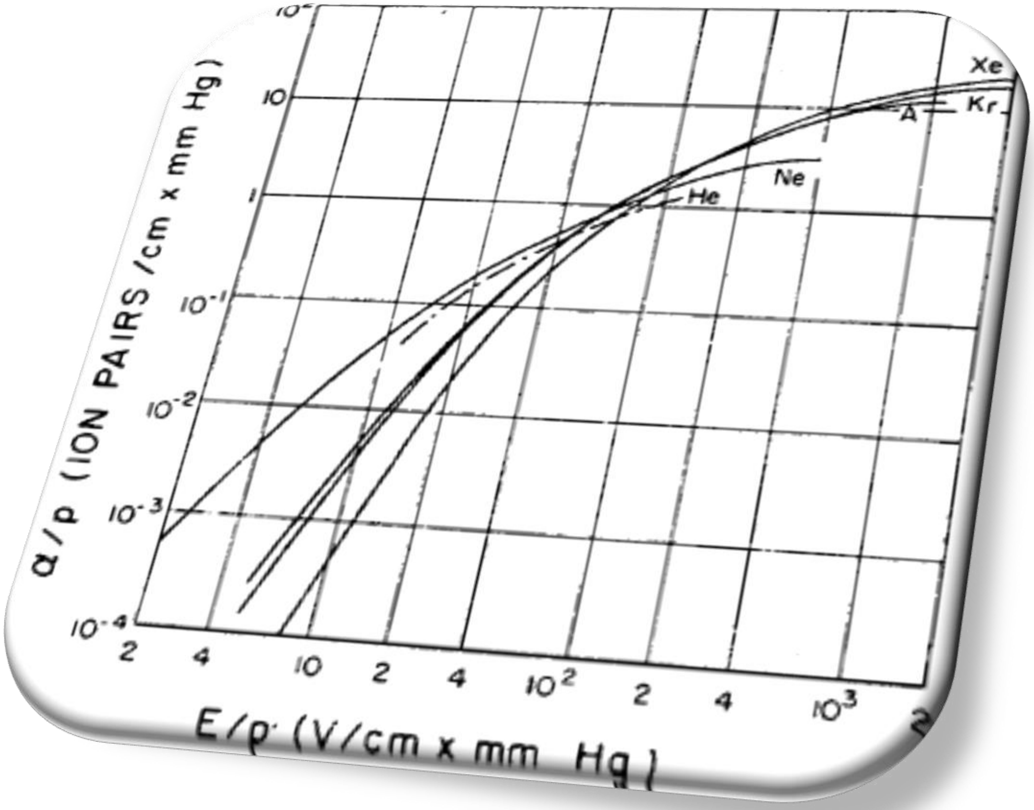
$$E(r) = \frac{CV_0}{2\pi\varepsilon_0}\frac{1}{r}$$

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

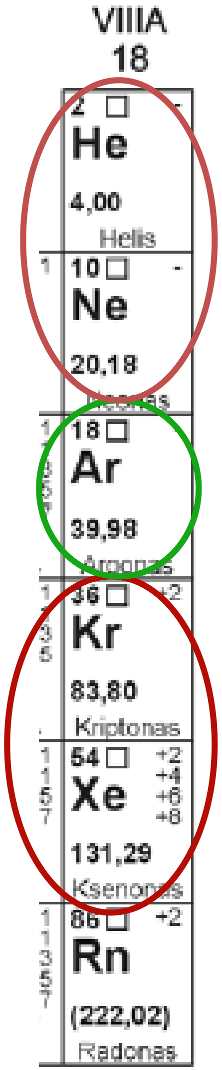
$$C = \frac{2\pi\varepsilon_0}{\ln(b/a)}$$ capacitance per unit length



• Noble Gases •



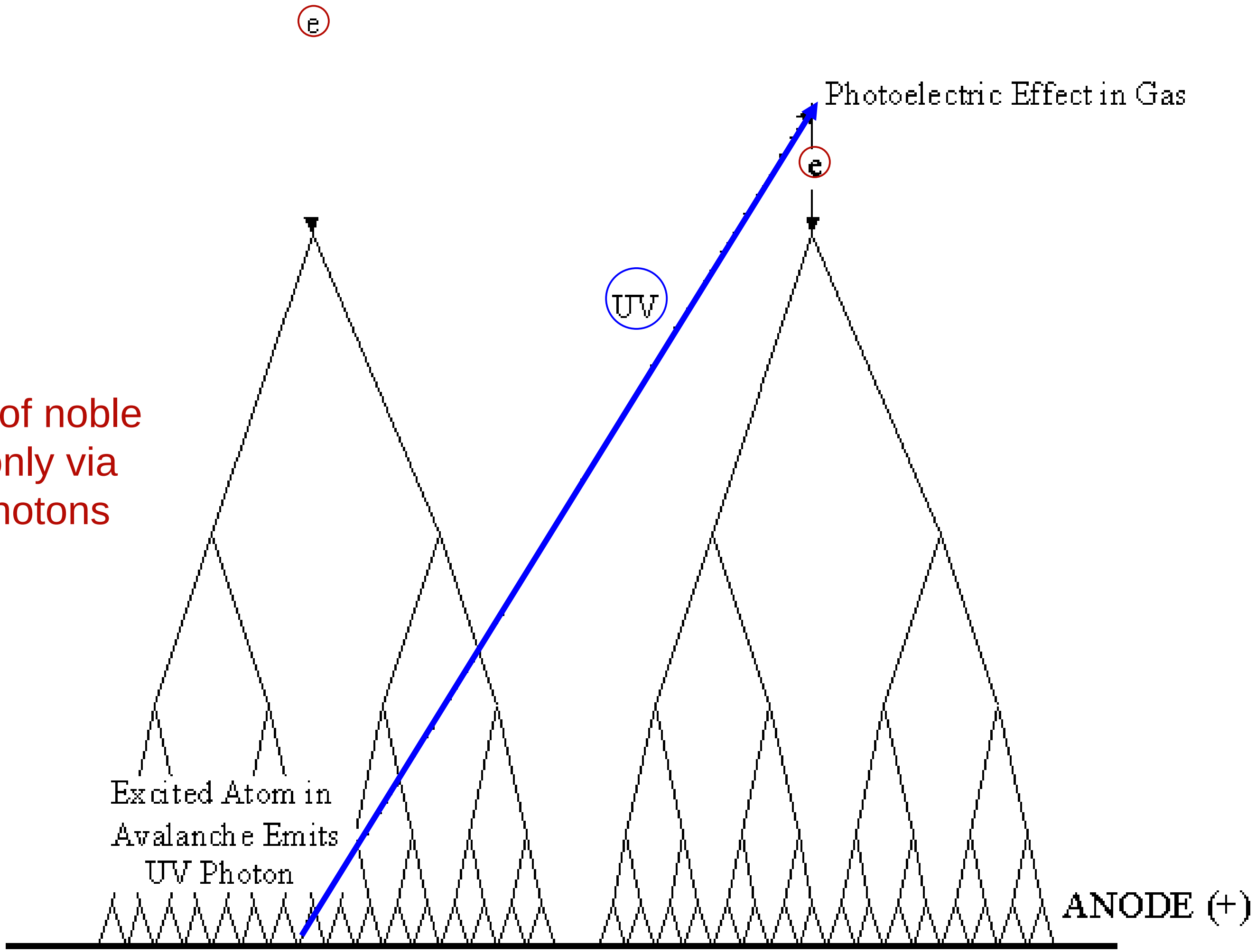
Noble gases require the lowest electric field for formation of avalanches



Light

Abundant
Inert
Cheap

Expensive



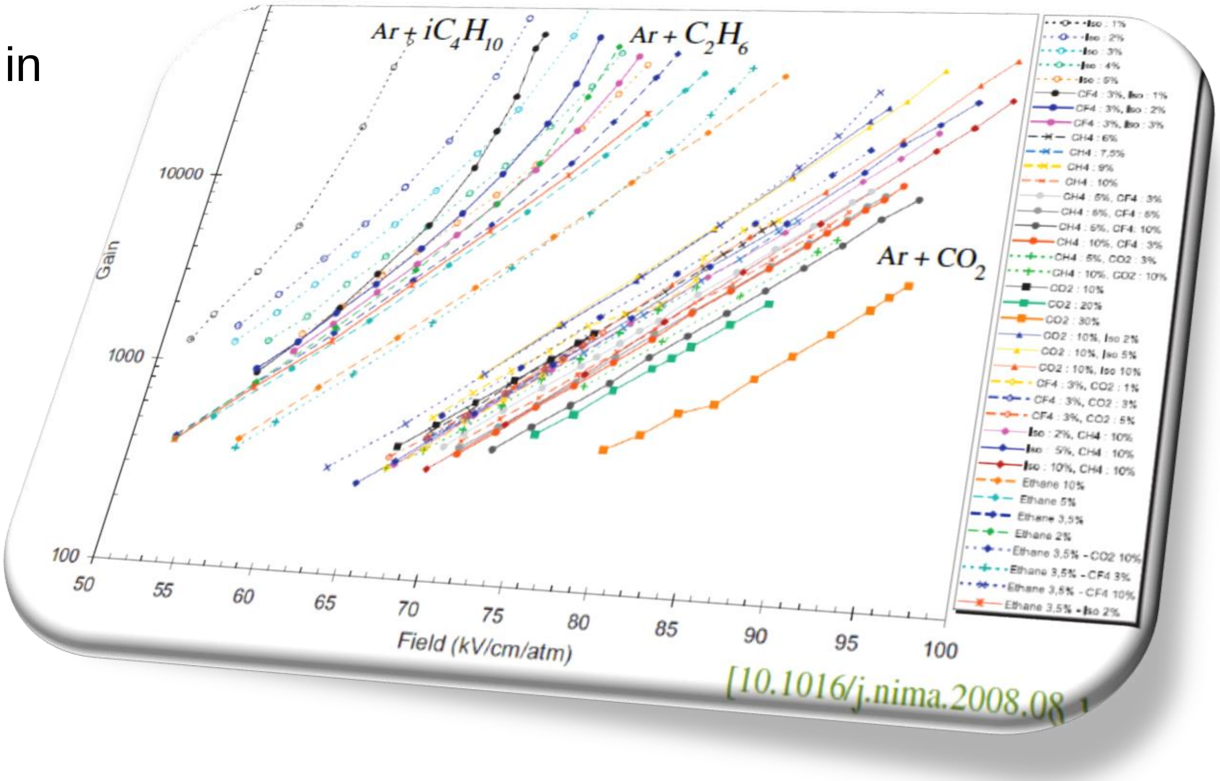
De-excitation of noble gases occur only via emission of photons

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

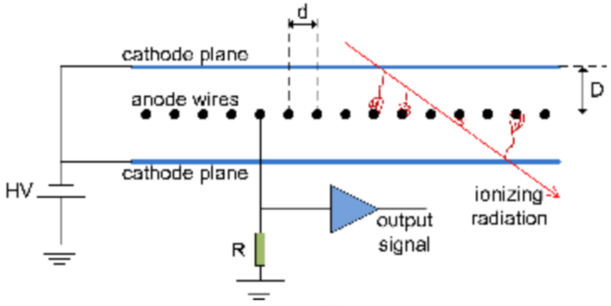


[10.1016/j.nima.2008.08

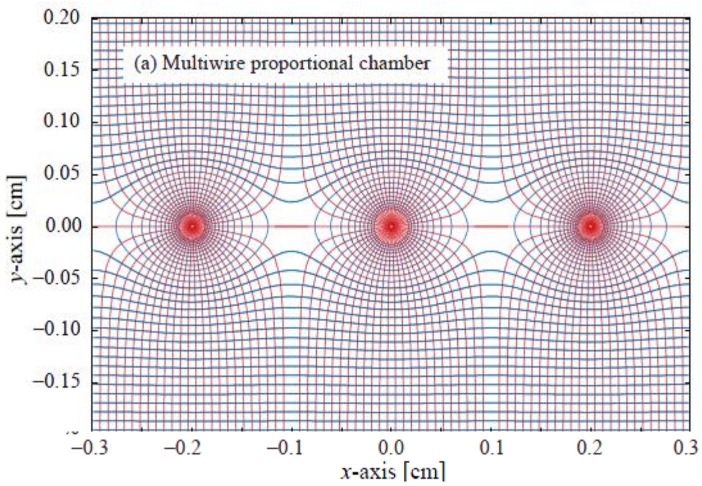
• Gas in LHC detectors •

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}

MWPC



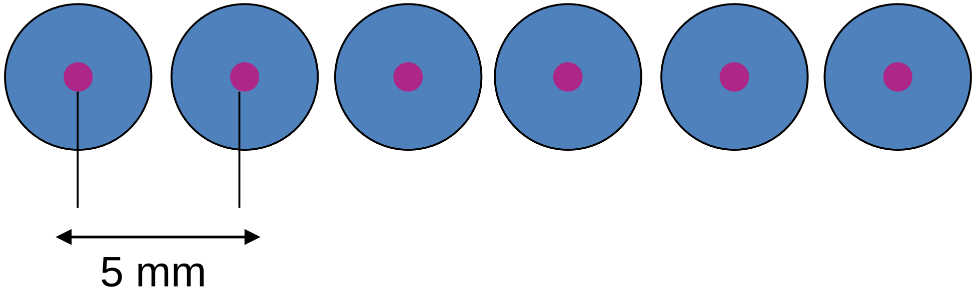
- Fast position-sensitive detectors (1968)
- Continuously active
- Efficient at particle fluxes up to several MHz/cm^2
- Sub-mm position accuracy
- **First electronic device allowing high statistics experiments !!**



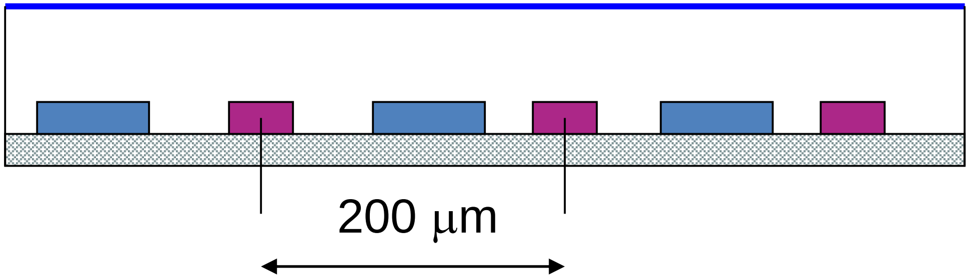
G.Charpak, Noble Prize in 1992

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

• Increasing Cell Granularity •



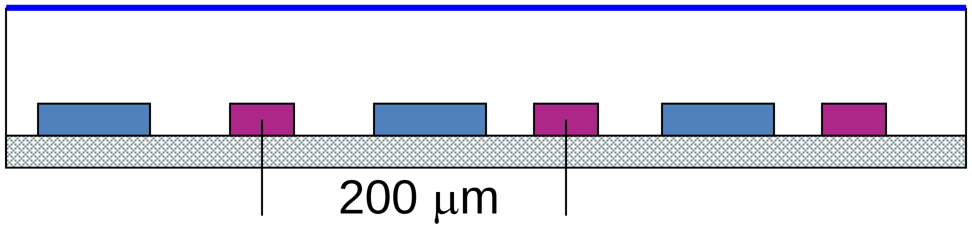
STRAW TUBES
Anode-cathode distance: 2 mm
Spatial resolution ~ 130-300 μm



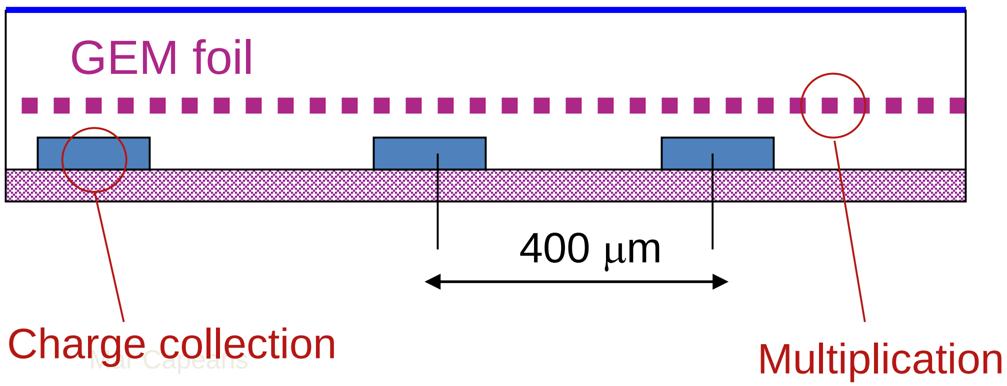
MICRO STRIP GAS CHAMBERS (MSGC - A.Oed,1988)
Semiconductor industry technologies
Anode-cathode distance: 40 μm
Spatial resolution ~ 40 μm

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

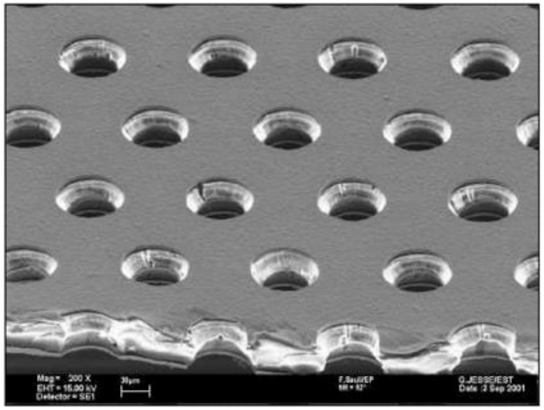
Decoupling Multiplication from Charge Collection



Micro Strip Gas Chamber



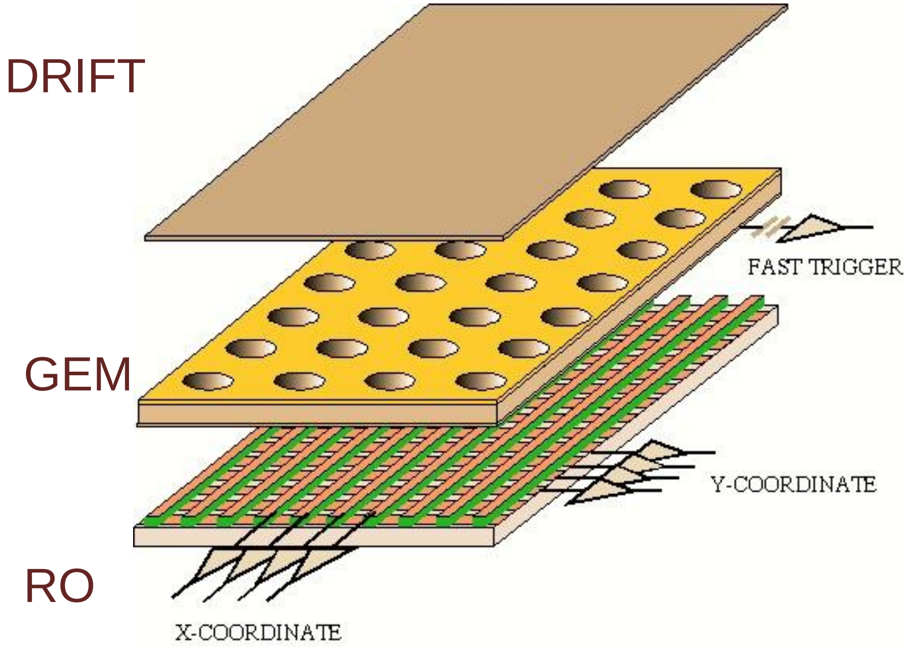
Gas Electron Multiplier
(GEM – F.Sauli, 1998)
Spatial resolution ~ 50 μm
Time resolution better than 10 ns

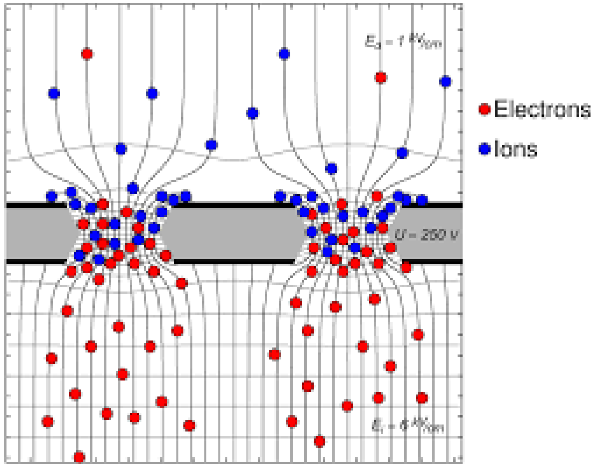


Thin metal-coated polymer foils
70 μm holes at 140 mm pitch

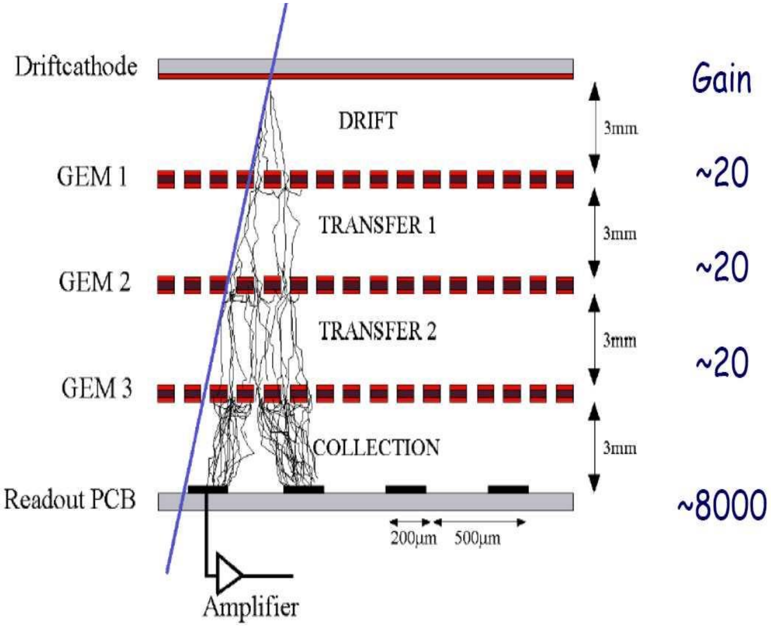
• GEM Detectors •

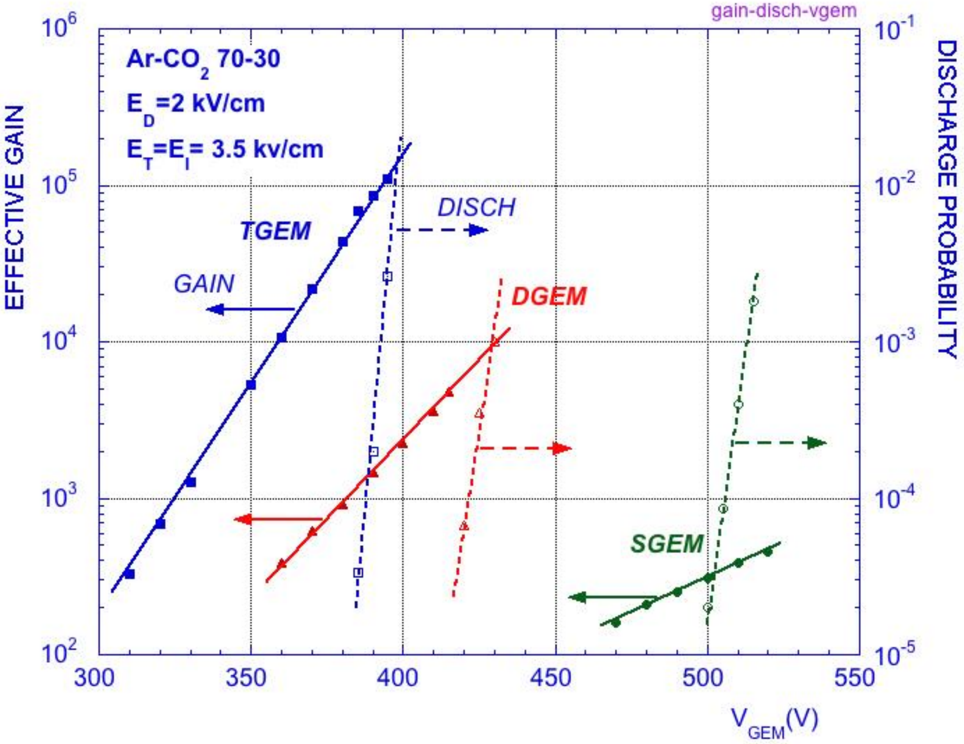
- Primary electrons are released by ionizing radiation in the gas (E-field between drift plane and GEM)
- By applying a suitable voltage difference between the two metal sides of the GEM, an electric field with an intensity as high as 100kV/cm is created inside the holes which act as multiplication channels
- Readout electrodes are at ground potential; electron charge is collected on strips or pads, ions are partially collected in the bottom of the GEM foil





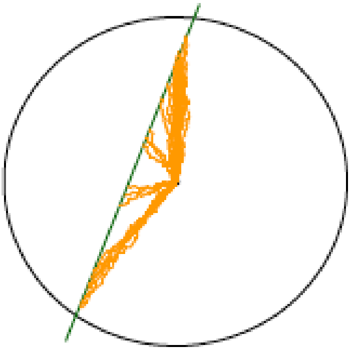
Multi-GEM detectors





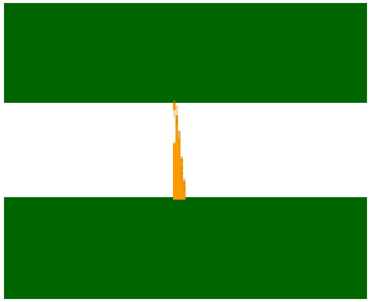
S. Bachmann et al Nucl. Instr. and Meth. A479(2002)294

Time Resolution



Cylindrical geometries have an important limitation:
Primary electrons have to drift close to the wire before the charge multiplication starts

Limit in the time resolution ~ 0.1μs



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)

• RPC •

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

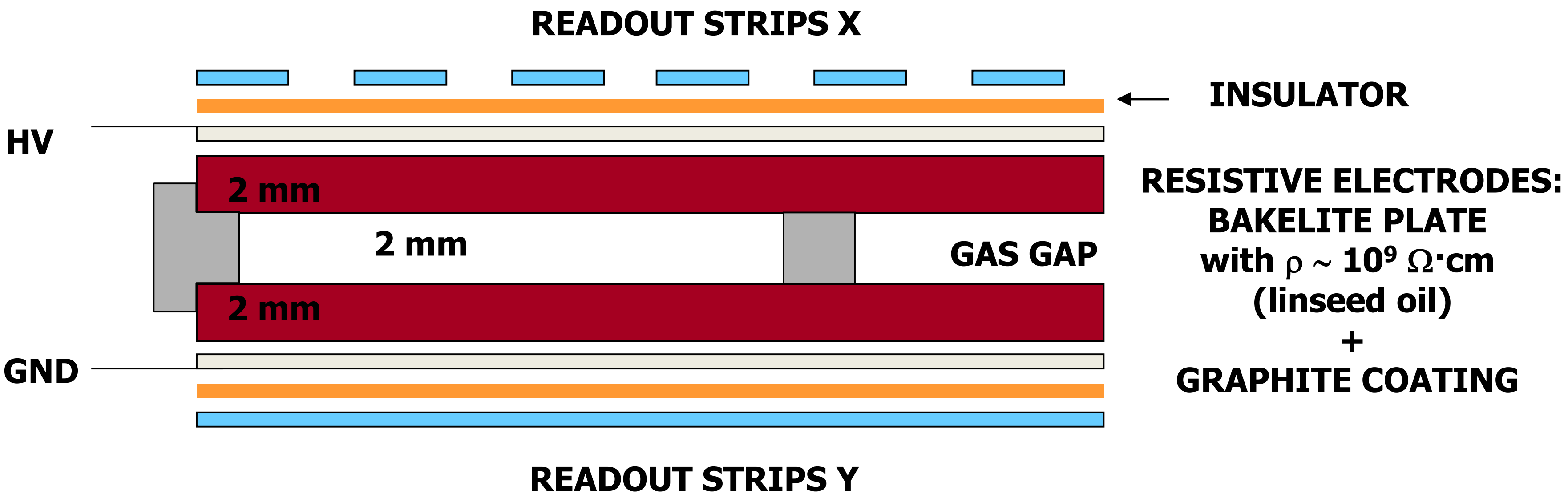
Fast timing: < 1 ns to ps for MRPC
Space resolution: ~mm
Rate capability: up to ~100 Hz/cm^2

RPC developments for LHC

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

Increased Rate Capability (~kHz/cm^2)

Large Background Radiation



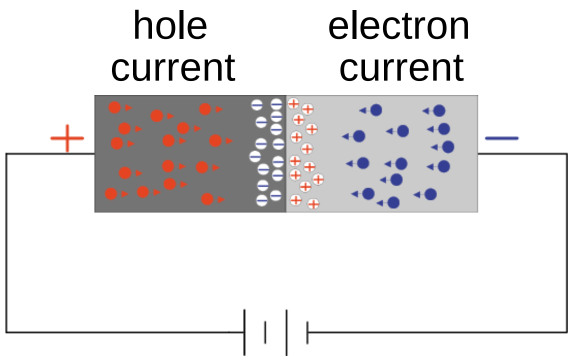
• Semiconductors •

- 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

- 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

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

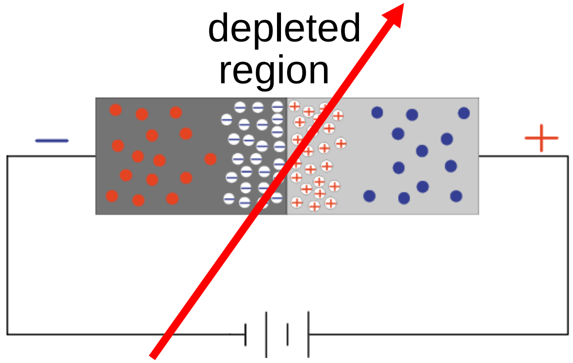


Current flow through diode if connects like this

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



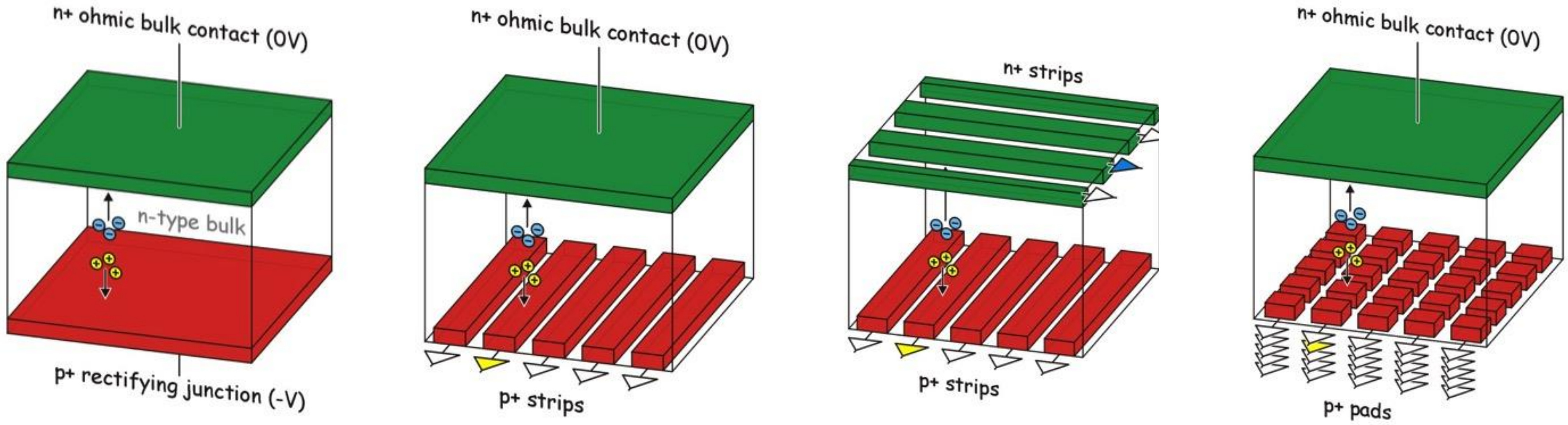
Charged particle can create new electron/hole pairs in depletion area sufficient to create a signal

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

• 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
    - <u>High primary ionization (larger signal), no amplification: </u>typical detector thickness (300 μm) result in 3.2 x10^4 e-/hole pairs
  - Si high density reduces the range of secondary e, thus **good spatial resolution**
    - 10 μm, the best ~1 μm
  - 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



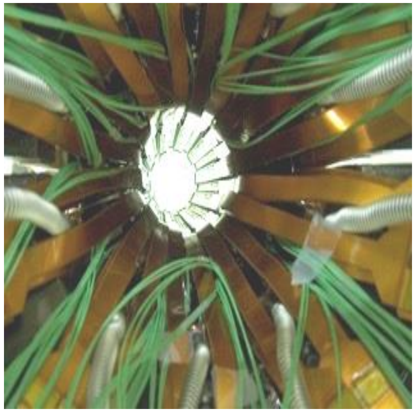
Strips

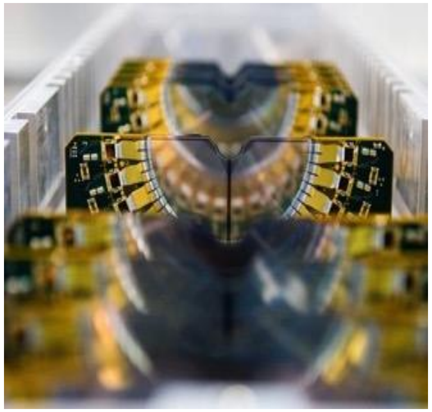
- Each strip is connected to one electronic readout channel
- First prototypes: ~ 1980
- Strip pitch: ~10-100 µm
- Position resolution: ~few µm due to charge sharing between neighbouring strips

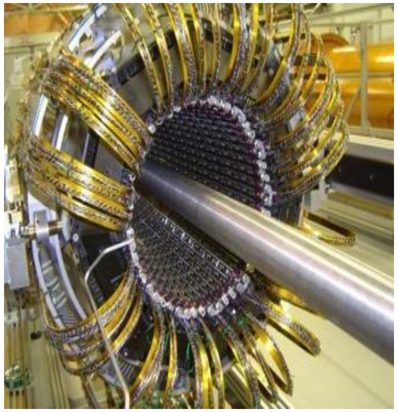
Pixels

- 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

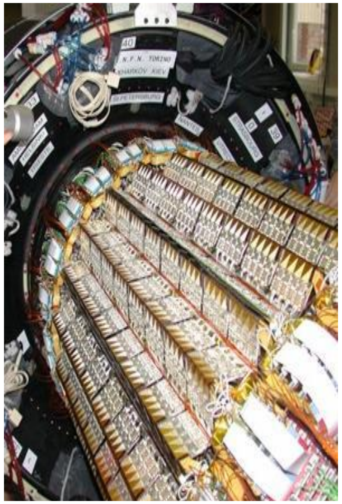
Silicon Detectors at LHC

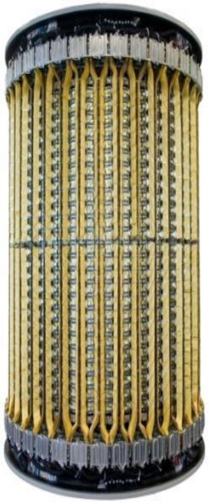

ALICE Pixel Detector

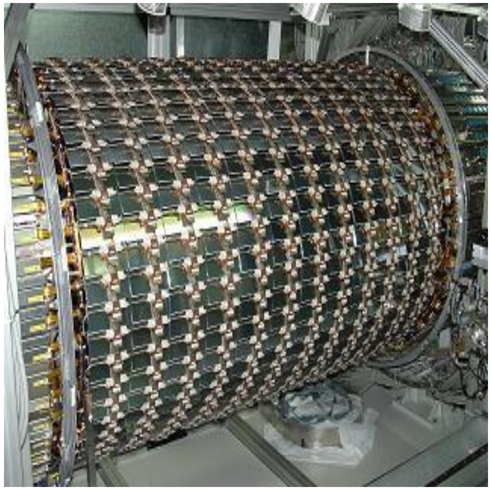

LHCb VELO

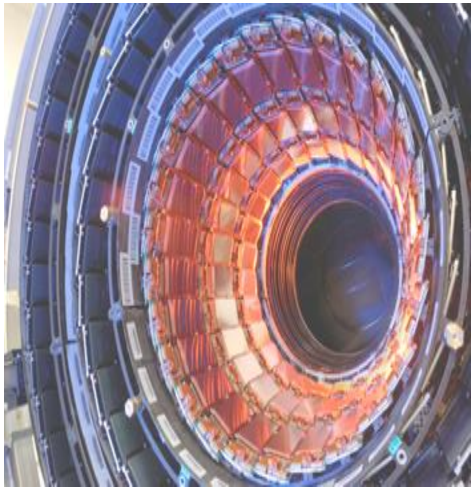

ATLAS Pixel Detector


CMS Pixel Detector


ALICE Drift Detector


ALICE Strip Detector


ATLAS SCT Barrel


CMS Strip Tracker IB

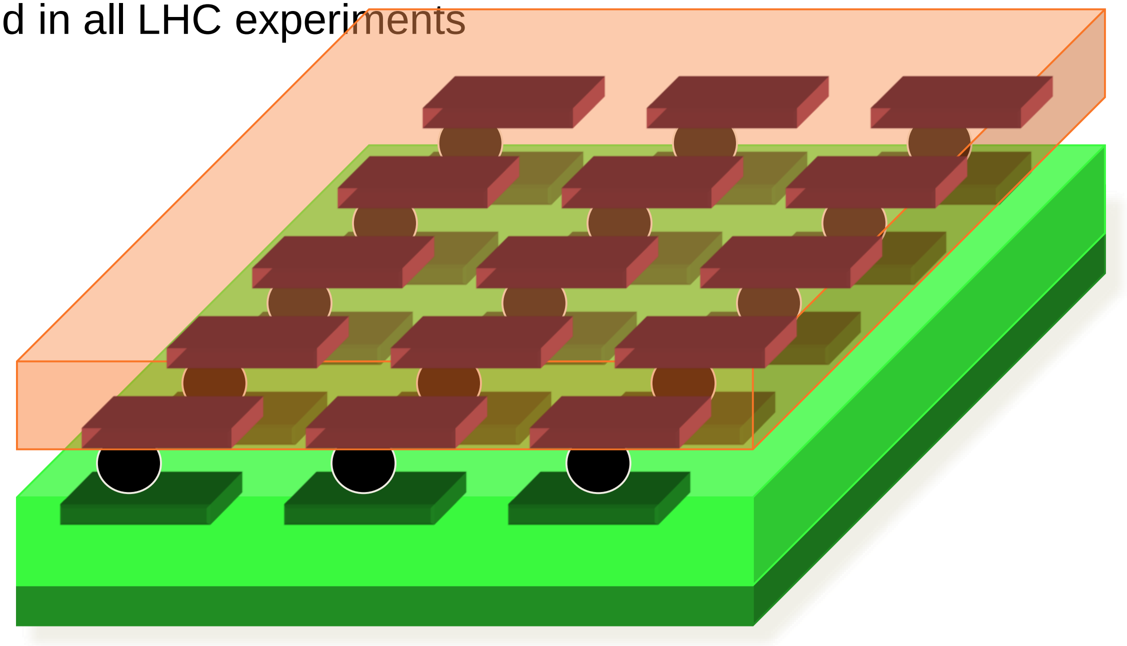
Slide: P. Riedler, CE

Hybrid Pixels

Development closely linked to progress in microelectrsnics and interconexión technologies (sensor & chip)

- Each pixel cell in the sensor is connected to a pixel cell in the readout chip via a bump bond
- Sensor and readout are optimized separately

- “Large” signal (sensor~200-300µm x 80 e-h pairs: 16000-24000 e-h)
- Thinning of readout wafers (~150µm at LHC)
- Mature technology employed in all LHC experiments



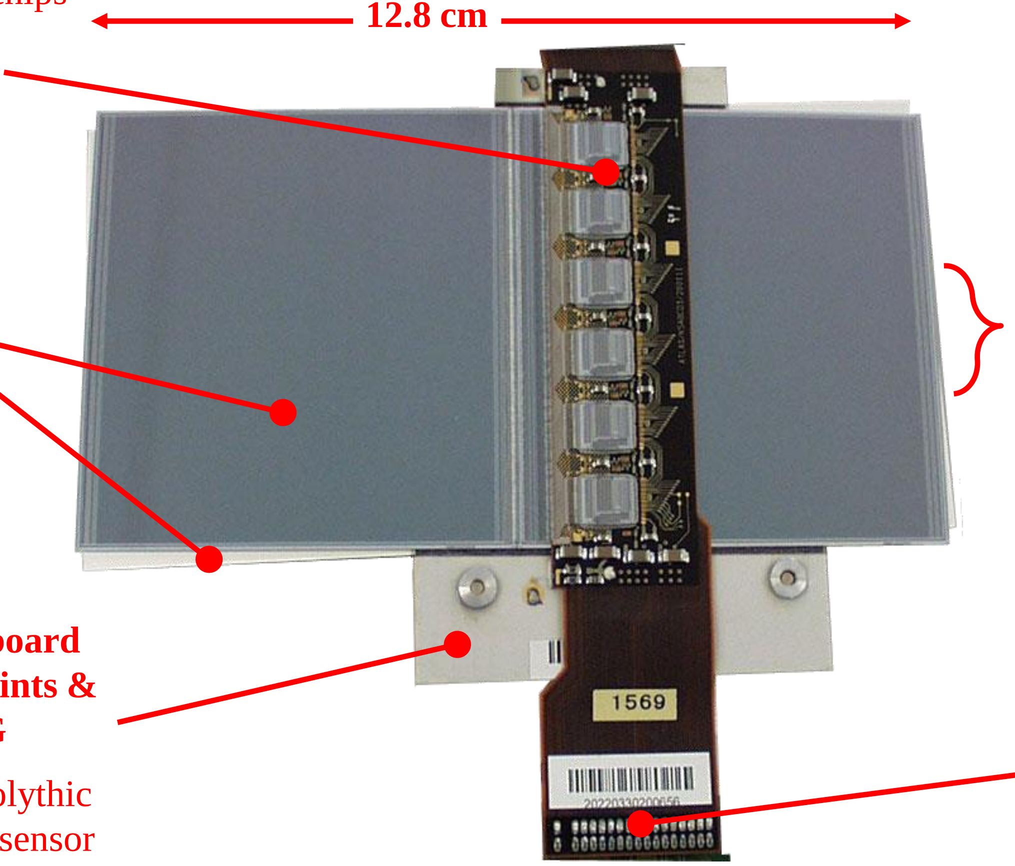
Readout Chip

Bump Bonds

Si Sensor

mar.capeans@cern.ch

ATLAS, Barrel SCT module



Hybrid assembly

with readout chips

4 Silicon sensors

280 μm thick

2.3° stereo angle

Overlap in ϕ & z to adjacent modules

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

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

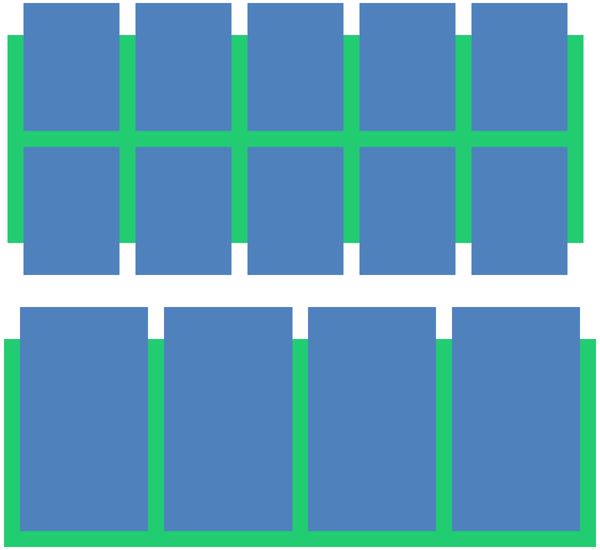
Power & data

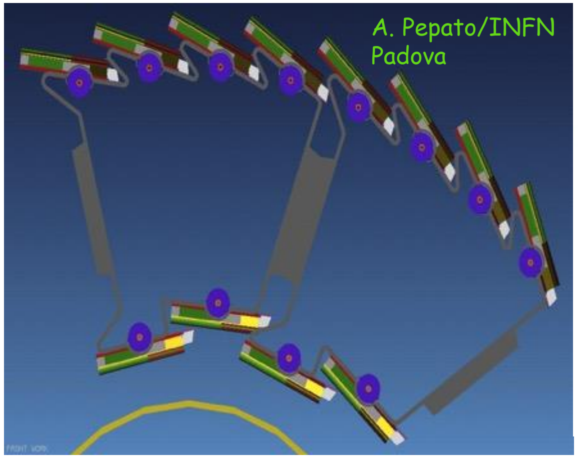
Fully equipped double sided electrical module with baseboard and readout hybrids

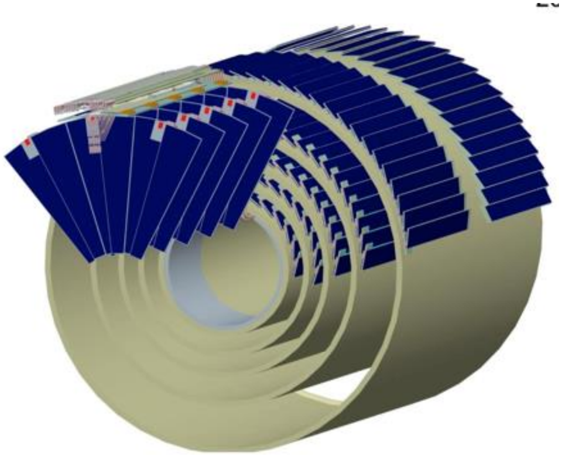
Slide: P. Riedler, CE

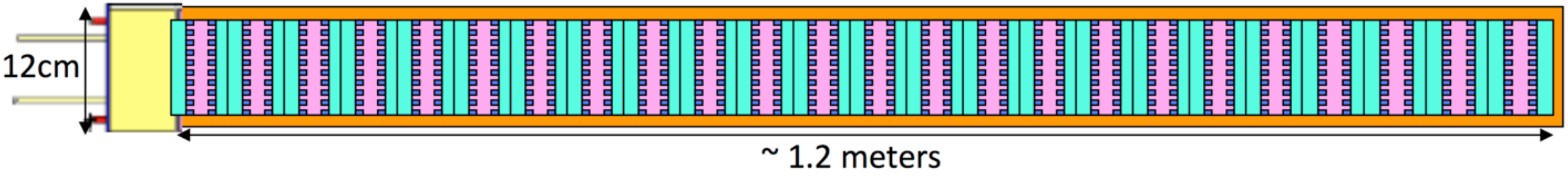
• Systems •

- **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

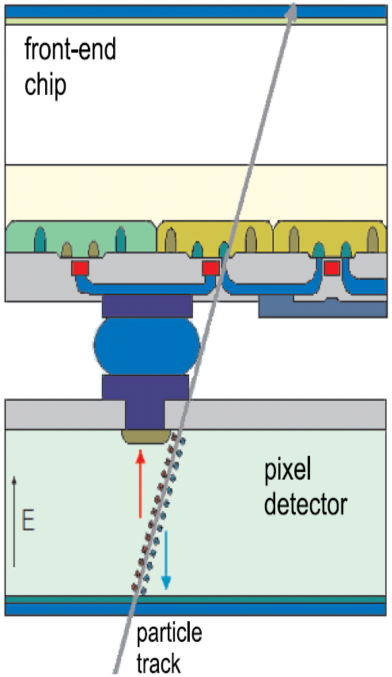
- Mechanical supports
- Cooling, thermal aspects
- Power supplies
- Services: cables, pipes, fiber links…
- Monitoring, sensors, alignment

mar.capeans@cern.ch

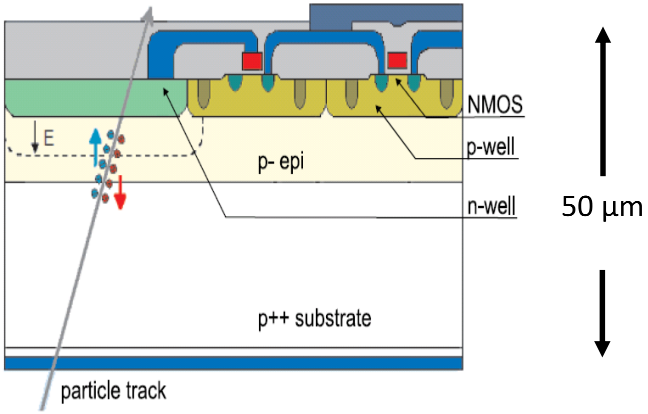
20/6/2016

Trends: Hybrid VS Monolithic

Hybrid Pixel Detector



Monolithic Pixel Detector (example)



Goal: get low mass, highly granular silicon pixel detectors without interconnection to a sensor.

⇒ Integrate charge generation volume into the readout chip.

“Disadvantages”

Signal ~ 80e-h/µm: <1000 e-h

Less radiation tolerant compared to hybrid pixel

New technology

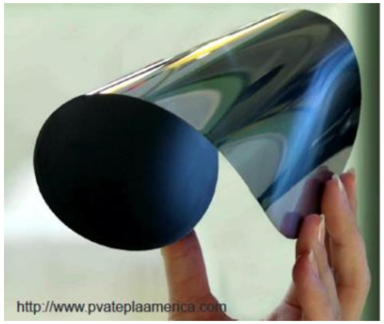
Slide: P. Riedler, CE

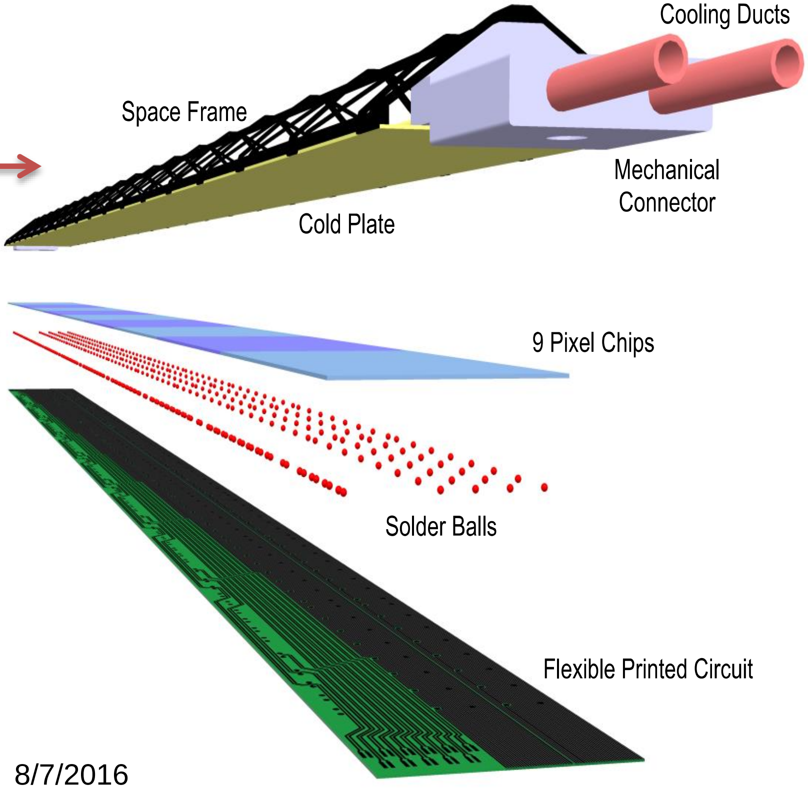
Silicon detectors, Trends

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

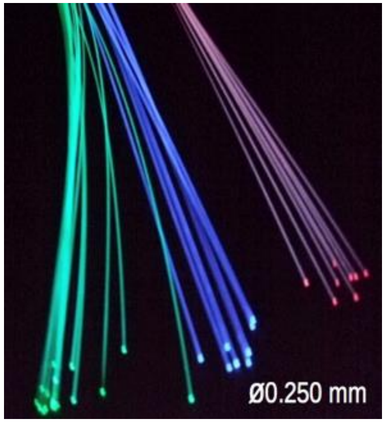

http://www.pvateplaamerica.com



Slide: A.Mapelli
CERN, PH-DT

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



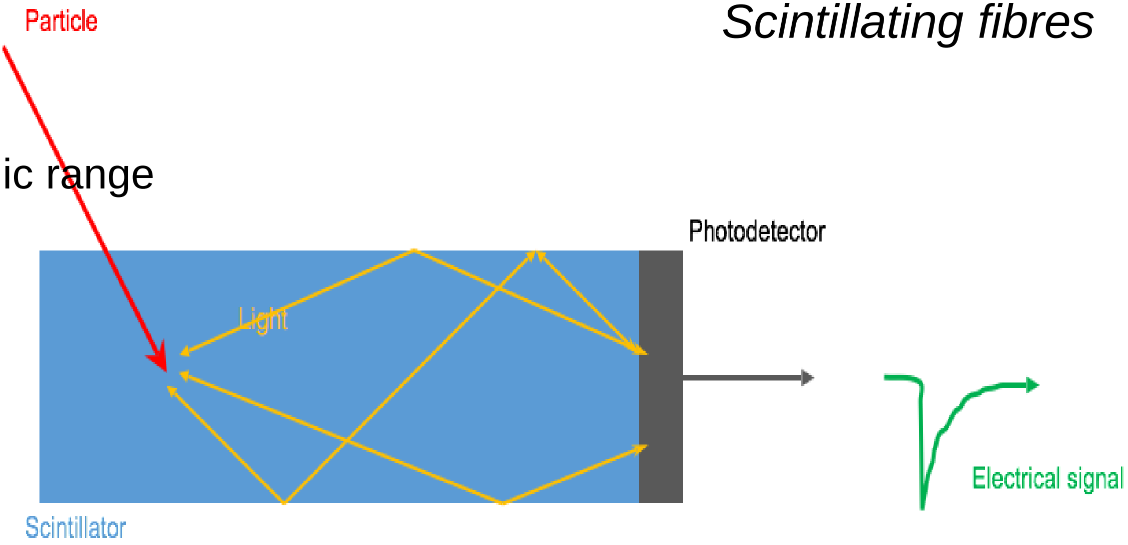
Scintillating fibres

Detector Principle

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

Main Features

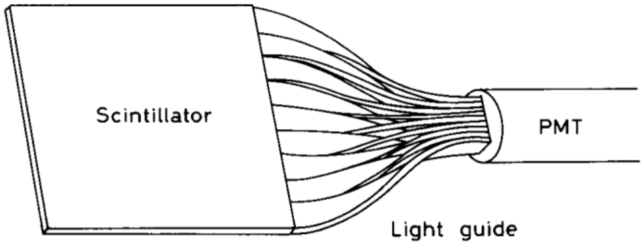
- Sensitivity to energy
- Good linearity over large dynamic range
- Fast time response
- Pulse shape discrimination



• 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

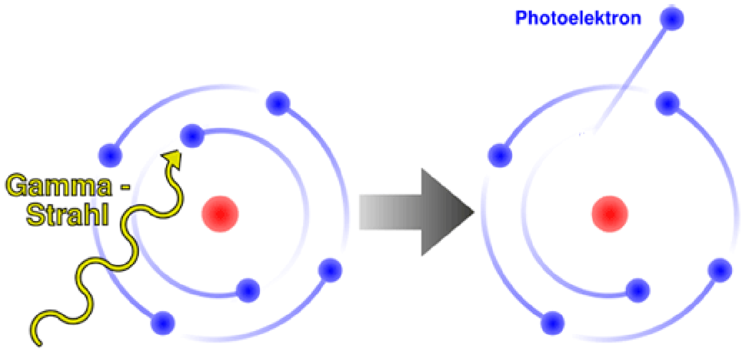
- The amount of light produced in the scintillator is very small. It must be amplified before it can be recorded as a pulse or in any other way.
- External wavelength shifters and light guides are used to aid light collection in complicated geometries; must be insensitive to ionising radiation and Cherenkov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

• Photo-detectors •

Slide: C.Joram, CERN

Purpose: Convert light into detectable electronic signal

Principle: Use photoelectric effect to ‘convert’ photons (γ) 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

Slide: C.Joram, CERN

Fibre mat

× 8

SciFi Module

× 12

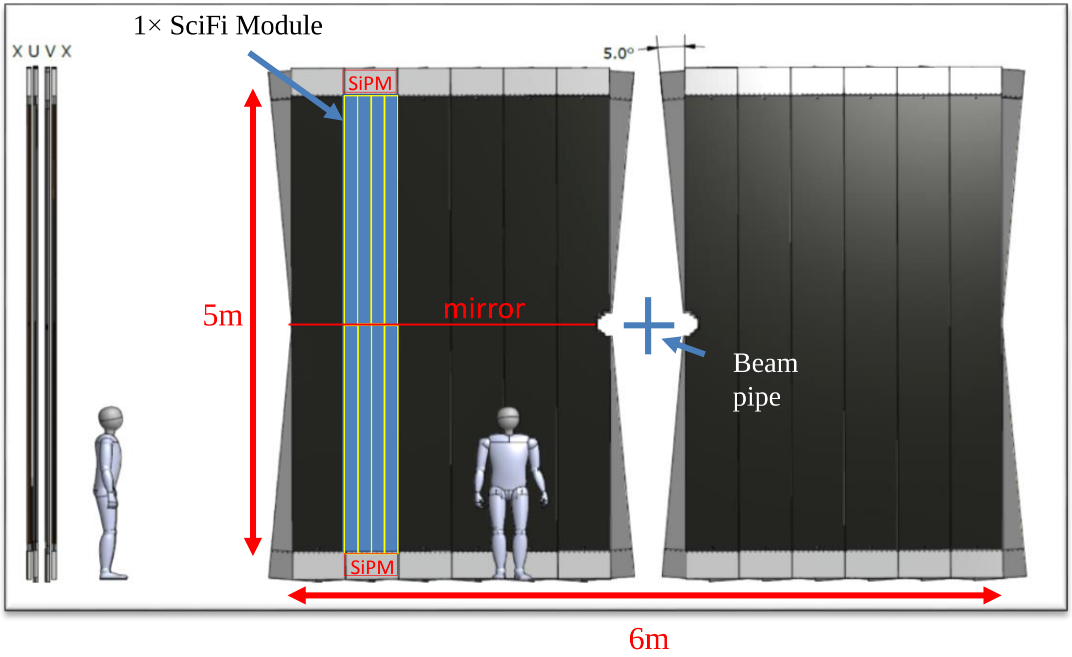
Detector Layer

× 4 (stereo angles 0°, +5°, -5°, 0°)

Tracking Station

× 3

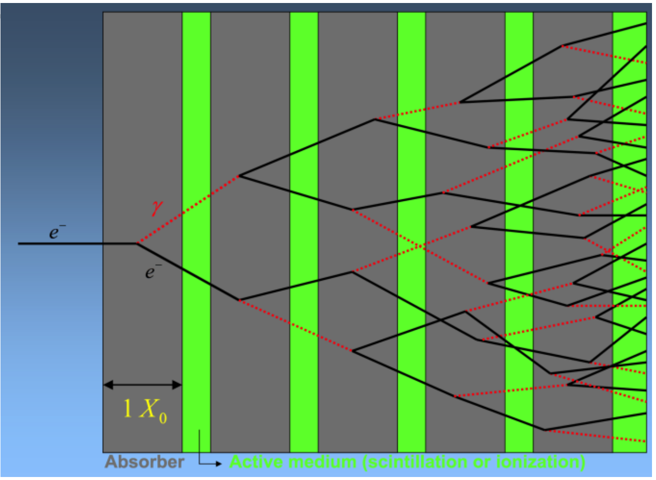
Scintillating Fibre Tracker



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

Calorimeters

- Goal is to measure energy of incoming particle
  - **Detect E of neutral or charged particles**. Stop particles (absorb all the energy), except muon (heavy) & neutrinos (weak interaction).
  - The interaction of the incident particle with the detector (through electromagnetic or strong processes) produces a shower of secondary particles with progressively degr
    - Measure the integral of energy loss per depth
    - Sample the energy loss at several points

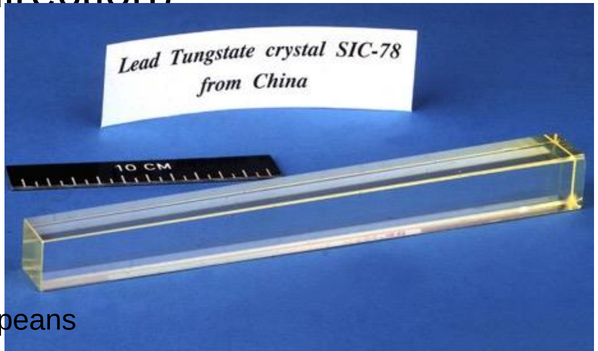


- Two types of calorimeters
  - Electromagnetic (photon and electron showers)
  - Hadron (pion, proton, neutron …)

Calorimeters

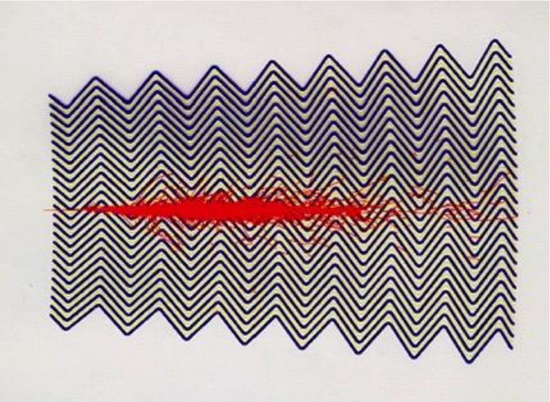
Homegeneous EM Calorimeter (CMS)

- Absorber = active detector
- Clear advantage: good energy resolution
  - 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)



Sampling EM Calorimeter (ATLAS)

- Absorber interleaved with detector
- Typical sampling calorimeters use iron or lead absorber material, variety of detectors in between possible: gas detectors (MWPCs), plastic scintillators, liquid noble gases (LAr, LKr)
- ATLAS is using LAr with “accordeon” shaped steel absorbers



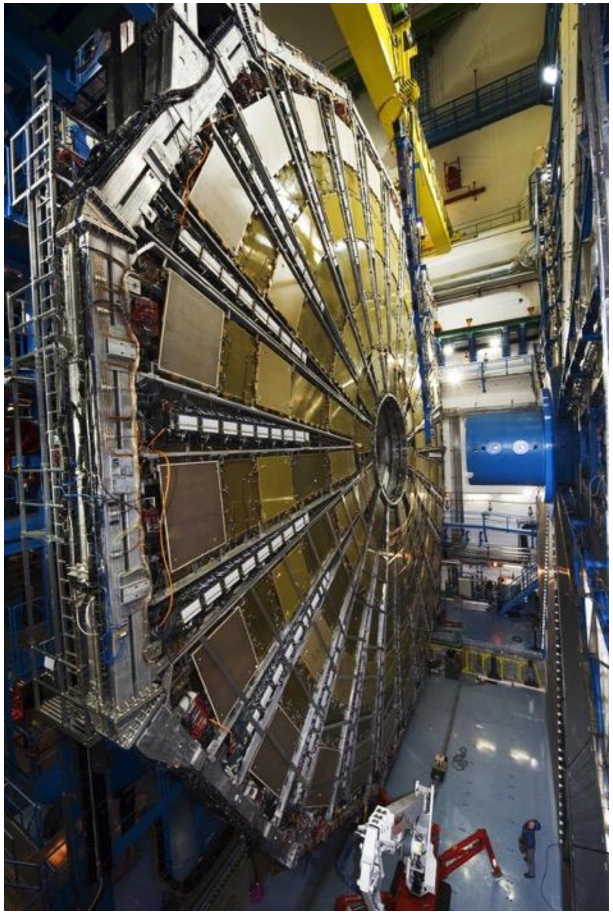
• Muon Systems •

- 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.

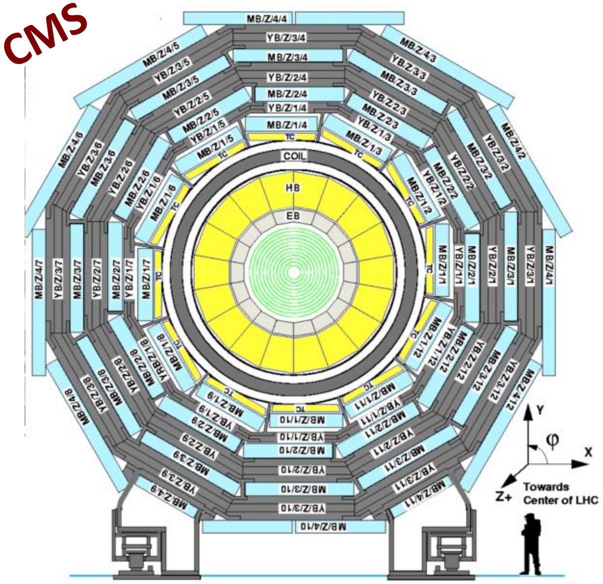
- They are fast detectors and are part of the Trigger system to select events

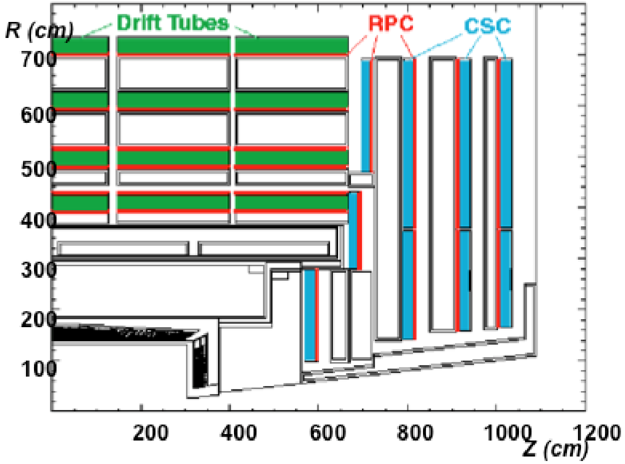


ATLAS,12 000 m^2, 1.1 Mchannels
Aligment precission <±30 mm

Muon Spectrometer

CMS





DRIFT TUBES (DT)

Central coverage

Tracking (100 μm) & 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)

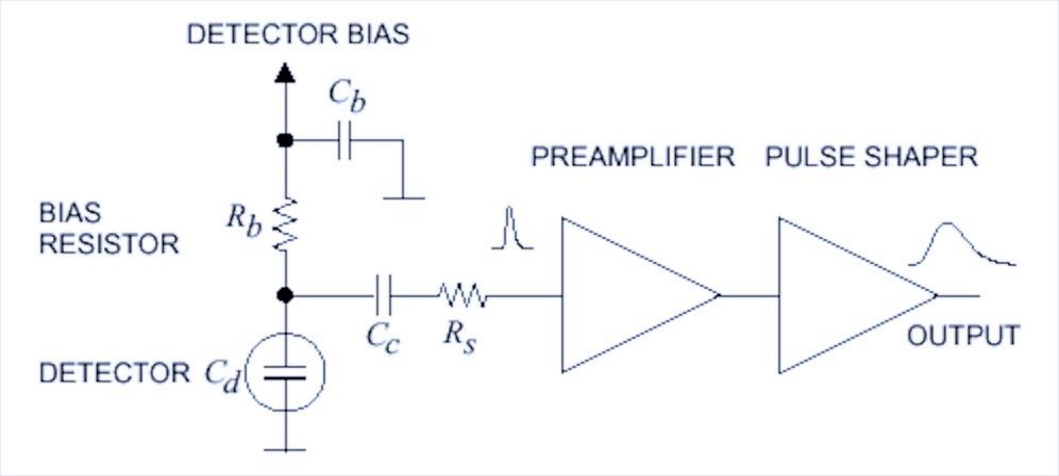
612 detectors

mar.capeans@cern.ch


AH

Signals

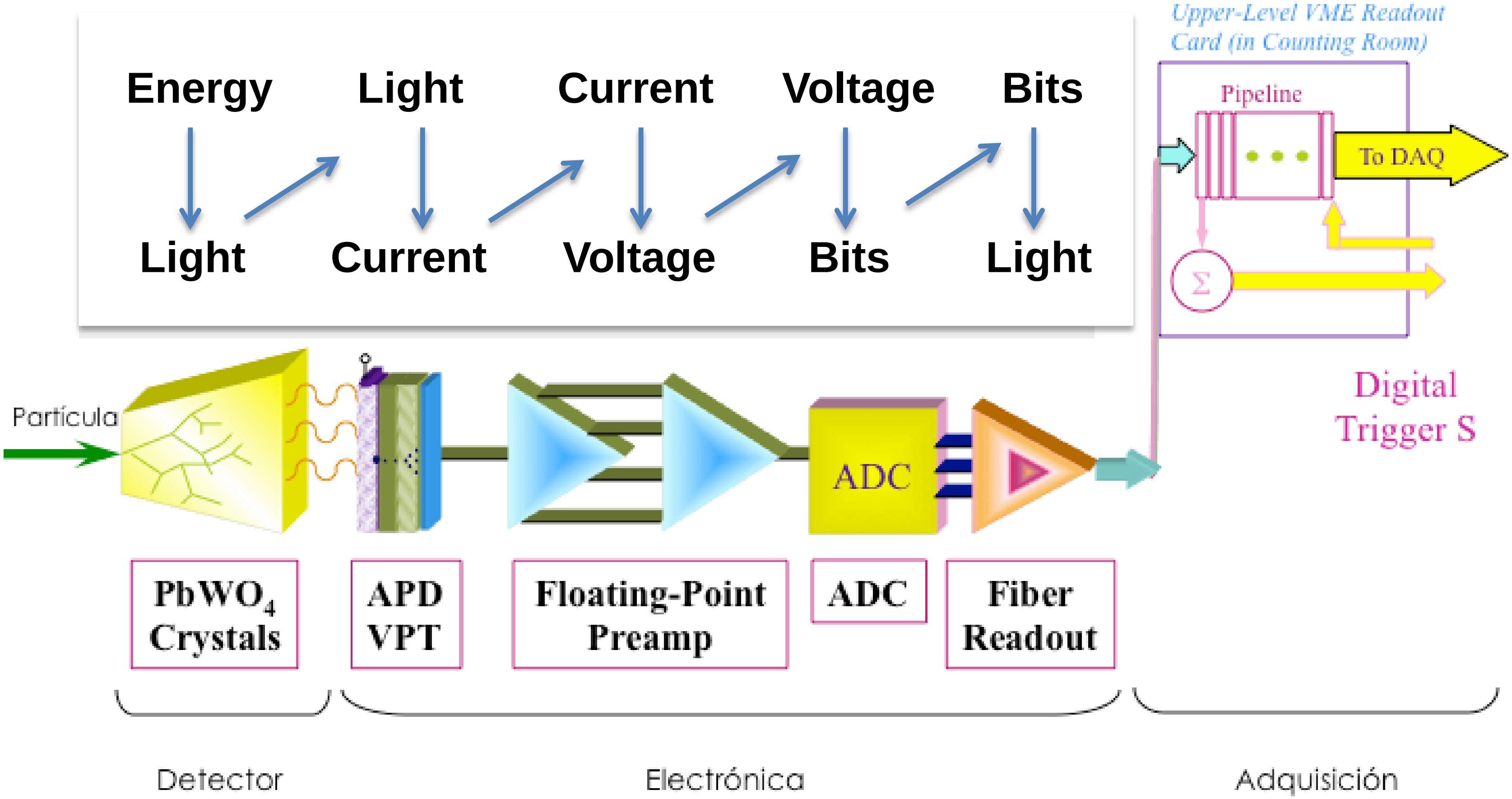
Most detectors rely critically on low noise electronics. A typical Front-End is shown below, where:



- Detector is represented by the capacitance C_d
- Bias voltage is applied through R_b
- Signal is coupled to the amplifier though a capacitance C_c
- R_s represents all the resistances in the input path

The preamplifier provides gain and feed a shaper which takes care of the frequency response and limits the duration of the signal.

Signals



Energy ↓ Light

Light ↓ Current

Current ↓ Voltage

Voltage ↓ Bits

Bits ↓ Light

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

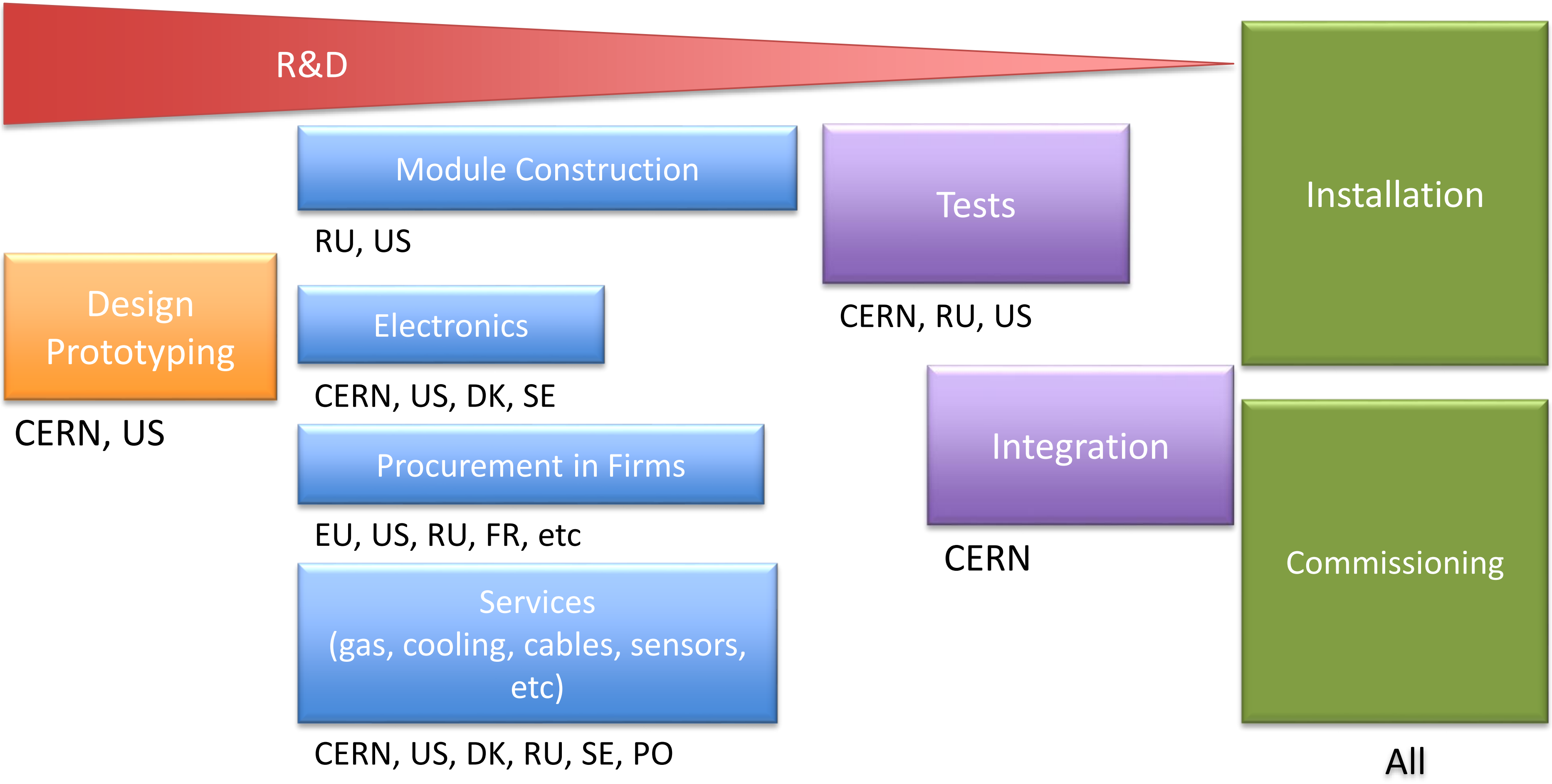
Last generation of HEP detectors are incredibly complex and state of the art pieces of technology

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

Experiment	Countries	Institutions	Scientists
ALICE	36	131	~1200
ATLAS	38	177	~ 3000
CMS	42	182	~ 3000
LHCb	16	65	~ 700

Distributed/Collaborative Projects

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



R&D

Design Prototyping

CERN, US

Module Construction

RU, US

Electronics

CERN, US, DK, SE

Procurement in Firms

EU, US, RU, FR, etc

Services
(gas, cooling, cables, sensors, etc)

CERN, US, DK, RU, SE, PO

Tests

CERN, RU, US

Integration

CERN

Installation

Commissioning

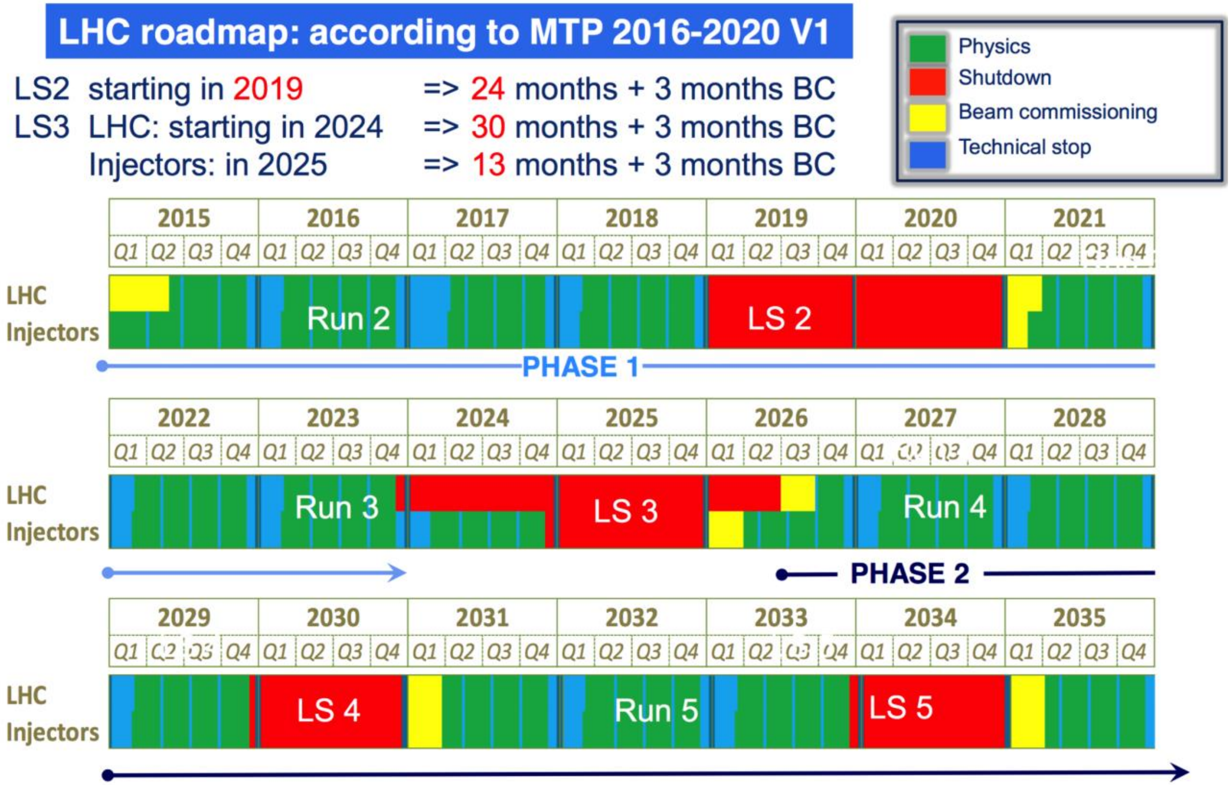
All

mar.capeans@cern.ch

• Future•

CERN’s priority is the explotation of the LHC to its maximum potential… 2035

- Run1: 2008 – 2013   7-8 TeV ~ 2000 Higgs
- Run2: 2015 – 2018   13-14 TeV
- Run3: 2021 – 2023   > Luminosity



LHC roadmap: according to MTP 2016-2020 V1

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC

🟩 Physics
🟥 Shutdown
🟨 Beam commissioning
🟦 Technical stop

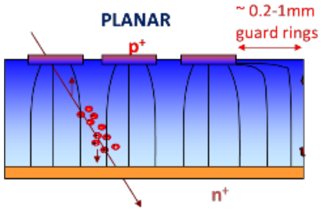
Further Detector Upgrades

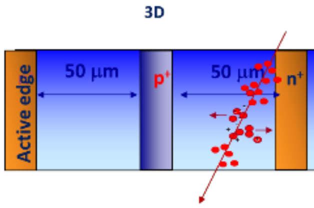
The discovery of the Higgs boson is the start of a major programme of work to measure this particle’s properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier

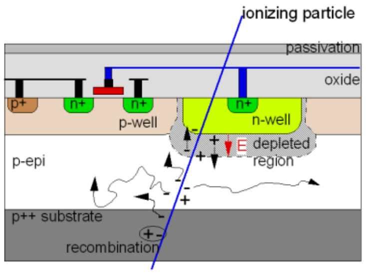
- **Must replace inoperable detector elements (rad damage)**
- **Must upgrade electronics to cope with increased rates**

Trackers R&D Efforts

- Improved radhard
- Optimization of sensor thickness (reduced leak current) and geometry (better overlap, less material)
- 3D sensors
- Combine sensor and electronics in one chip (MAPS on CMOS)
- On detector thermal management (CO_2)
- Scintillating Fiber Tracker (LHCb)







• 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 (≳10 Gbps)
- **Trigger/DAQ/Offline computing**
  - New trigger strategies, processing, networks, storage, CPU, CLOUD-computing…

Detector Trends

Sensors & FE

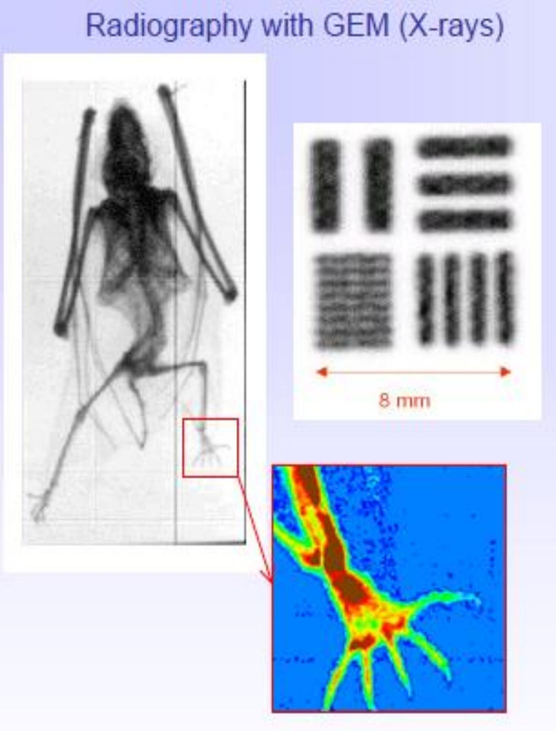
Increased position resolution (~μm level)
Increased timing accuracy (~ns)
Low mass
Increased radiation hardness
Integration sensors&electronics

Engineering

Interconnect technologies
Powering, Cooling
Services, Light-weight supports
New materials
Alignment, Stability…

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

• Other Fields of Application •



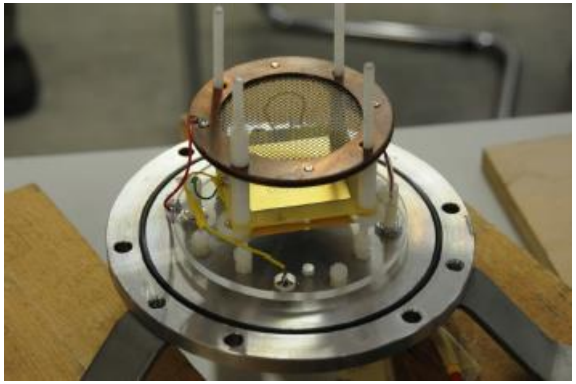
Fast and Therma Neutron Detection
Non-destructive diagnotic, Biology, Nuclear plants, …

Xray Low Energy
Radioactive waste…

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

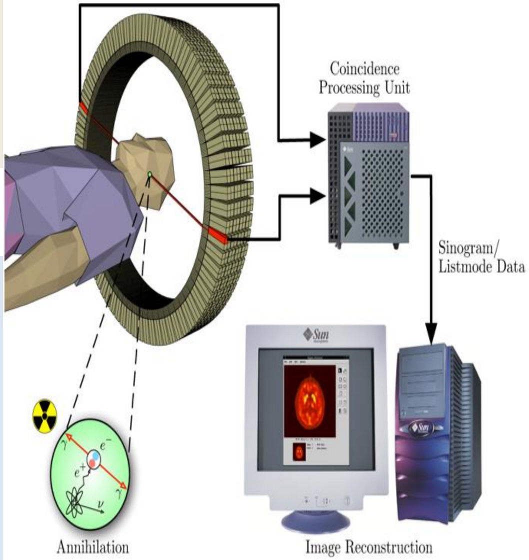
Gamma High Fluxes
Radiotherapy…

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



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

Thanks for your attention!

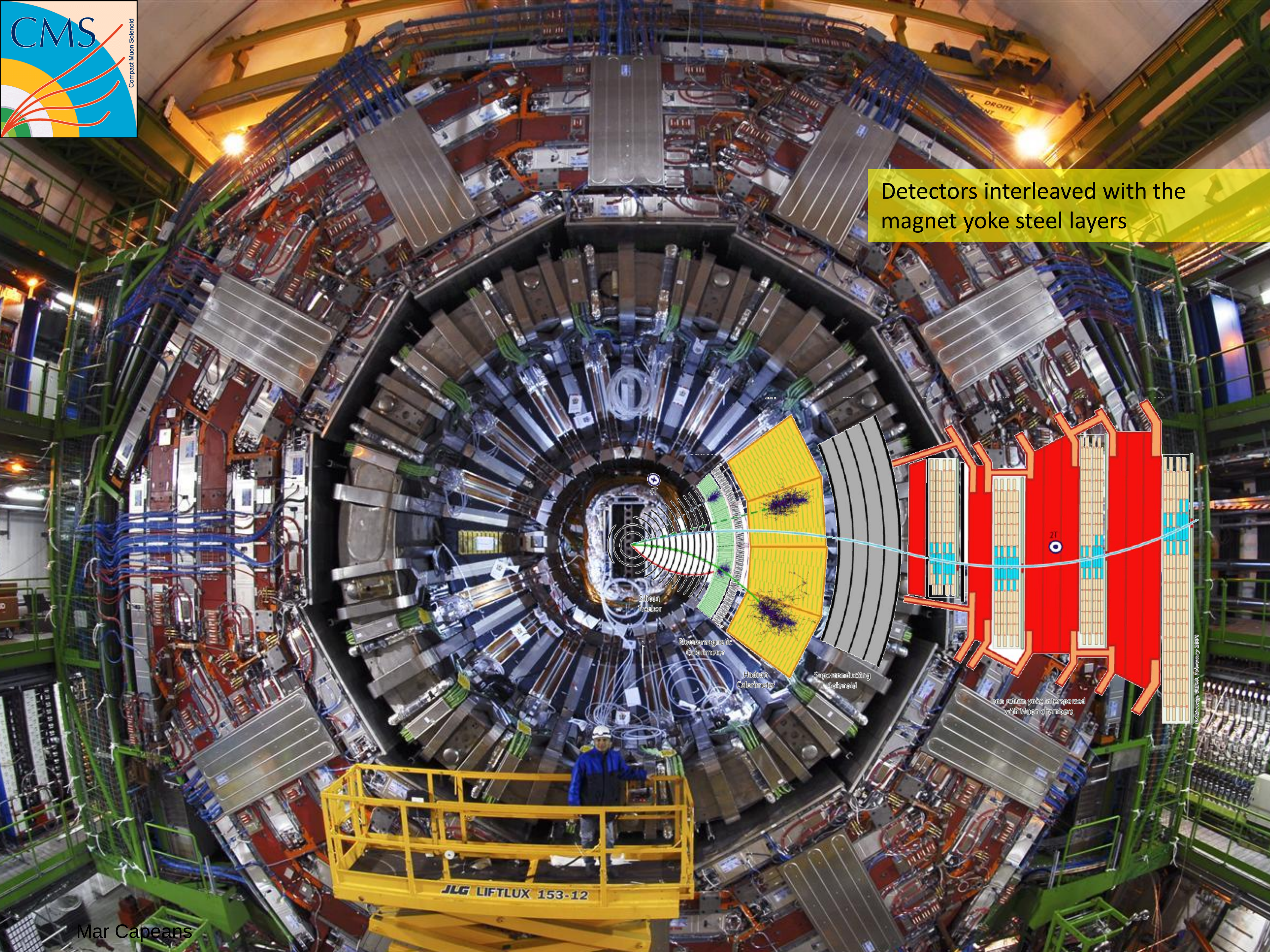
+

- *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

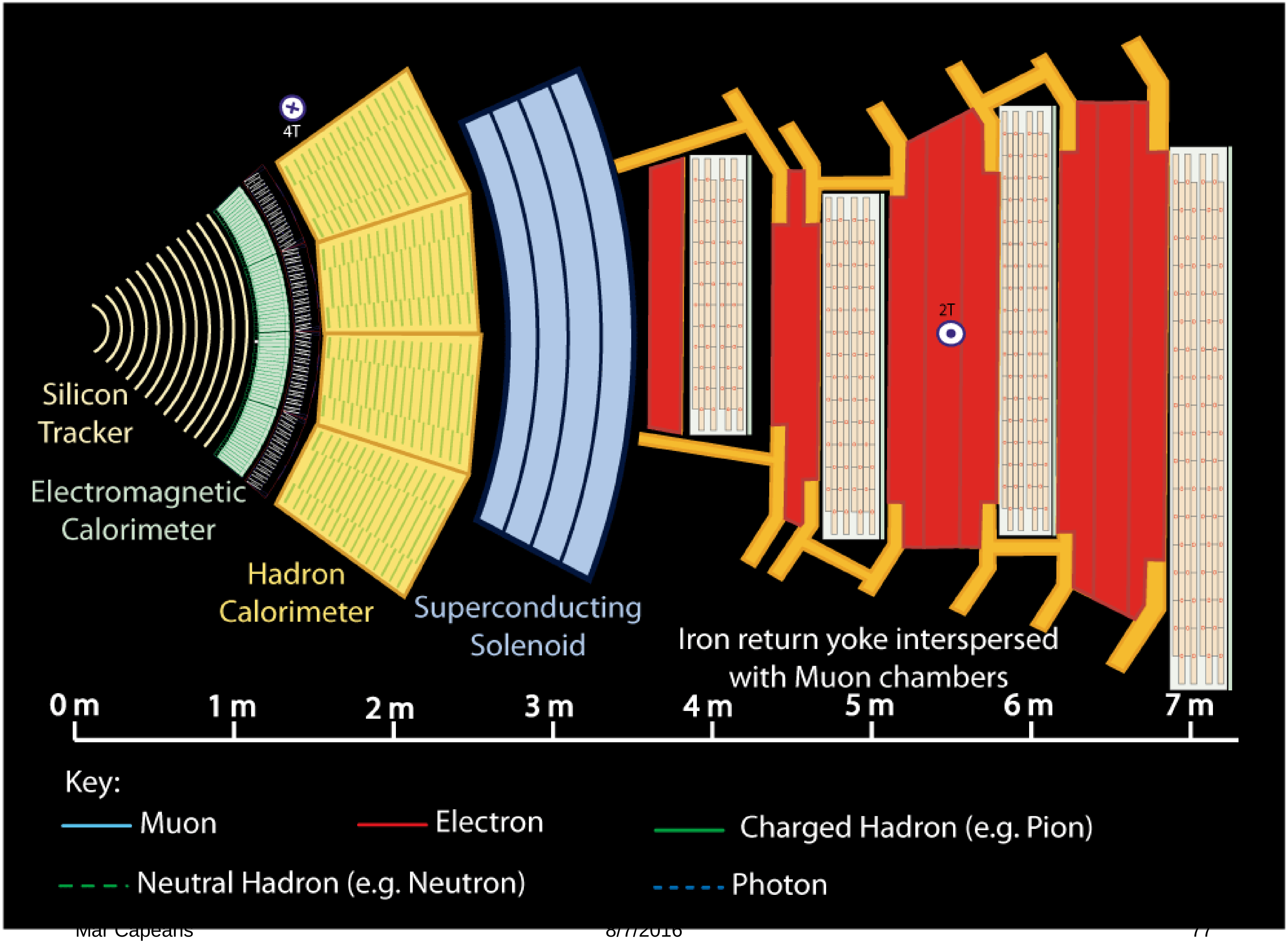
- **CERN Notes:**
- Fabjan & Fischer - Particle Detectors CERN-EP 80-27, Rep. Prog. Phys. **43** (1980) 1003
- F. Sauli - Principles of Operation of Multiwire Proportional and Drift Chambers, CERN 77-09

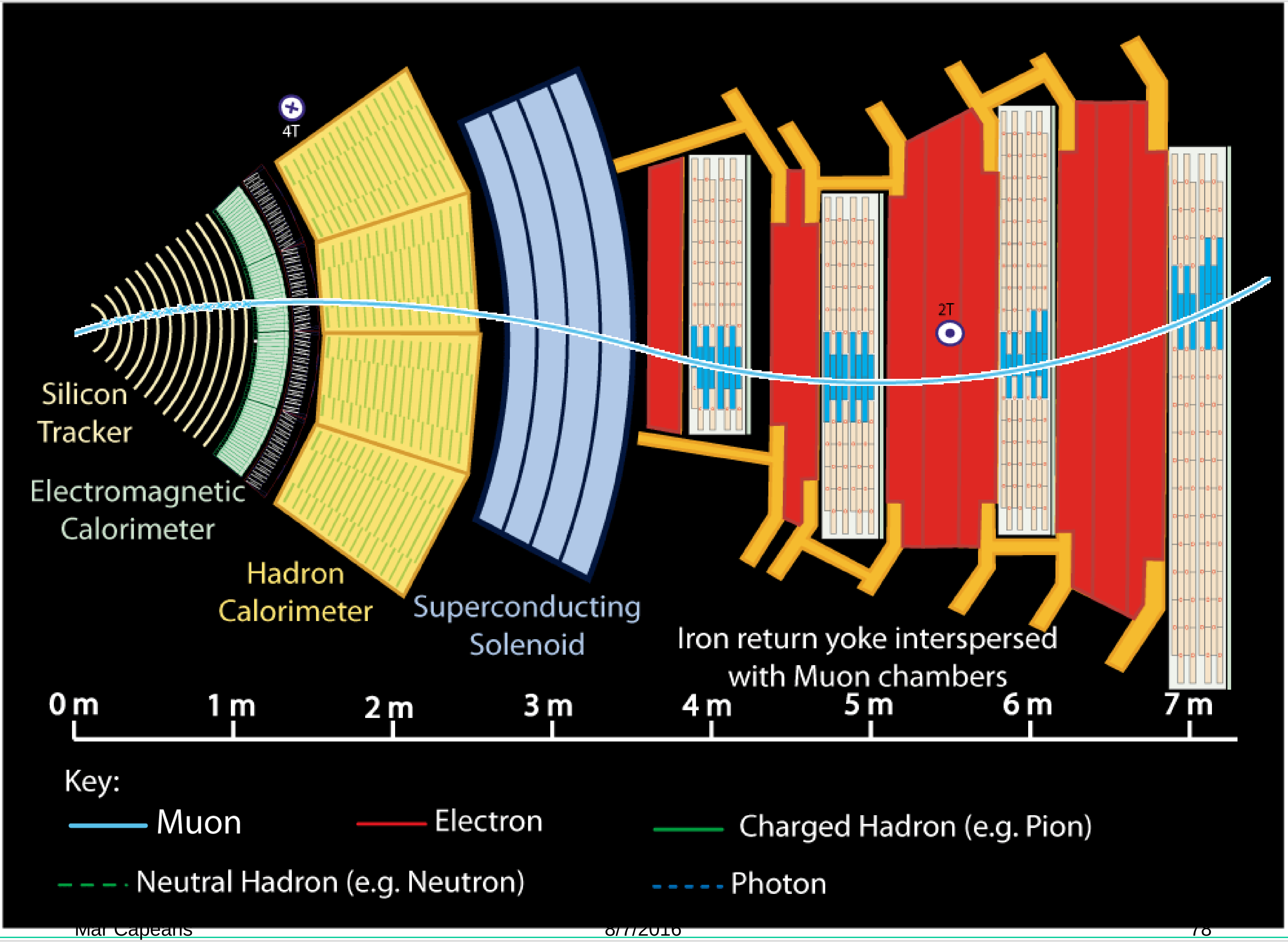
Spare Slides

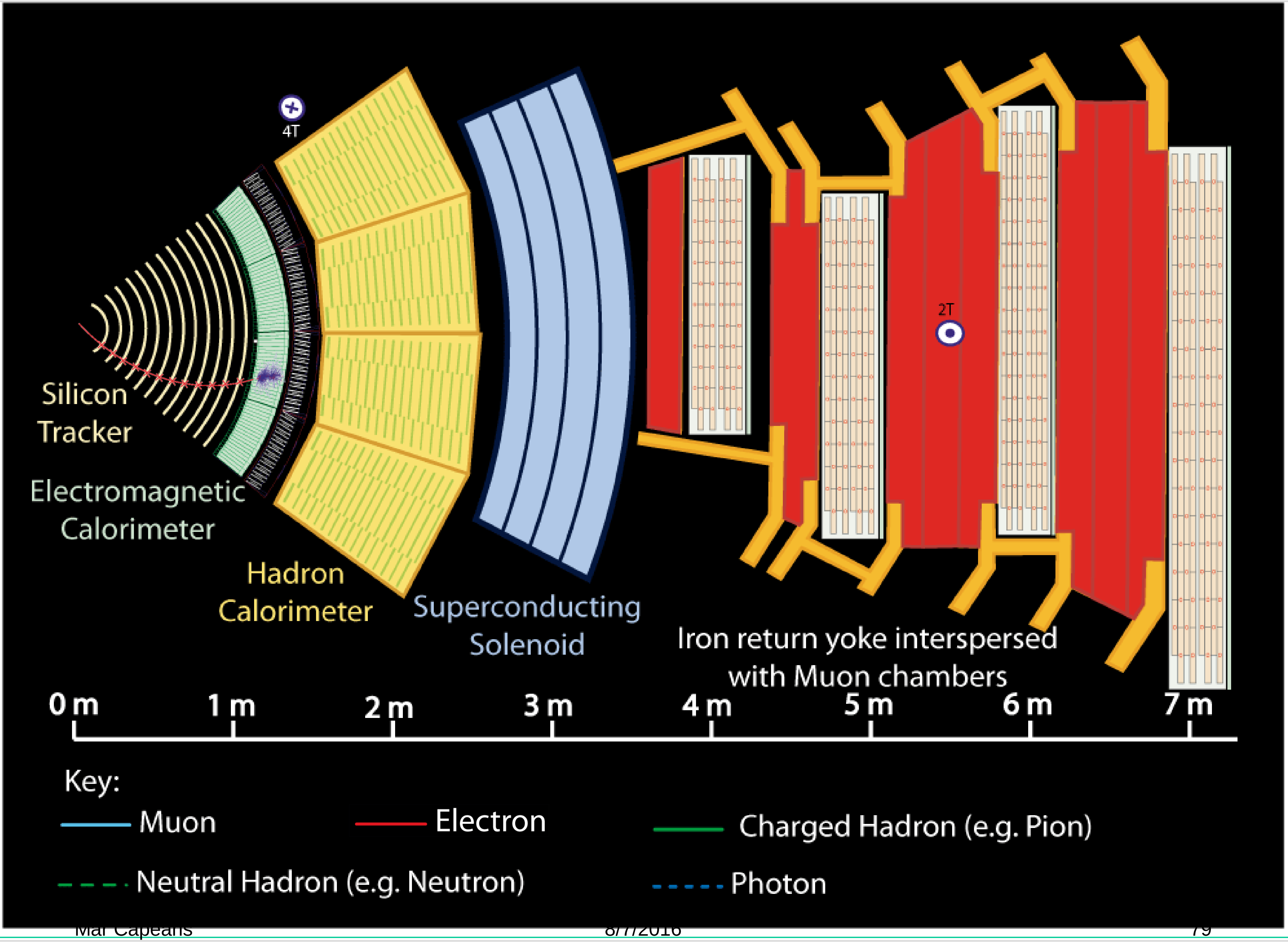


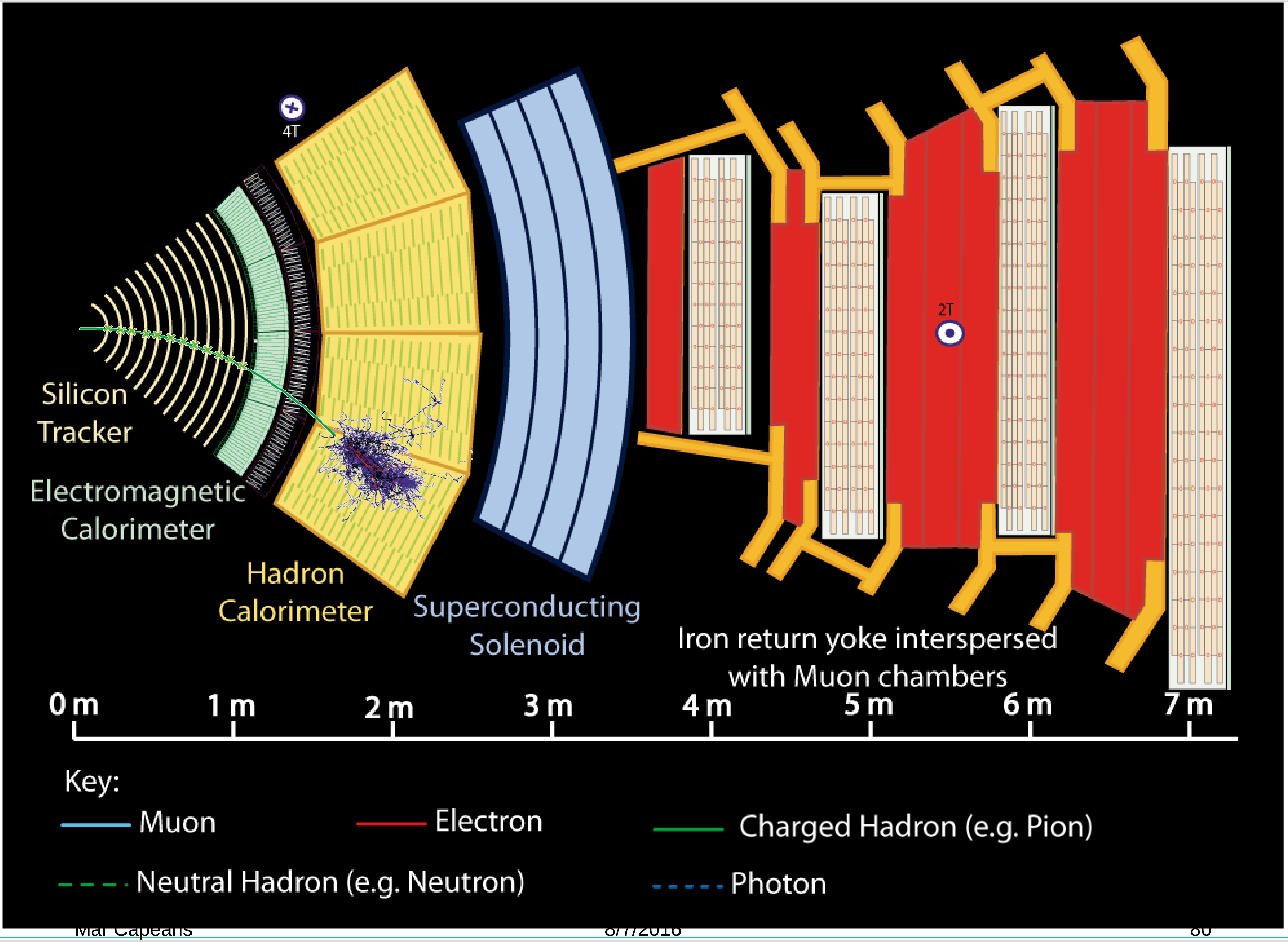
Detectors interleaved with the magnet yoke steel layers

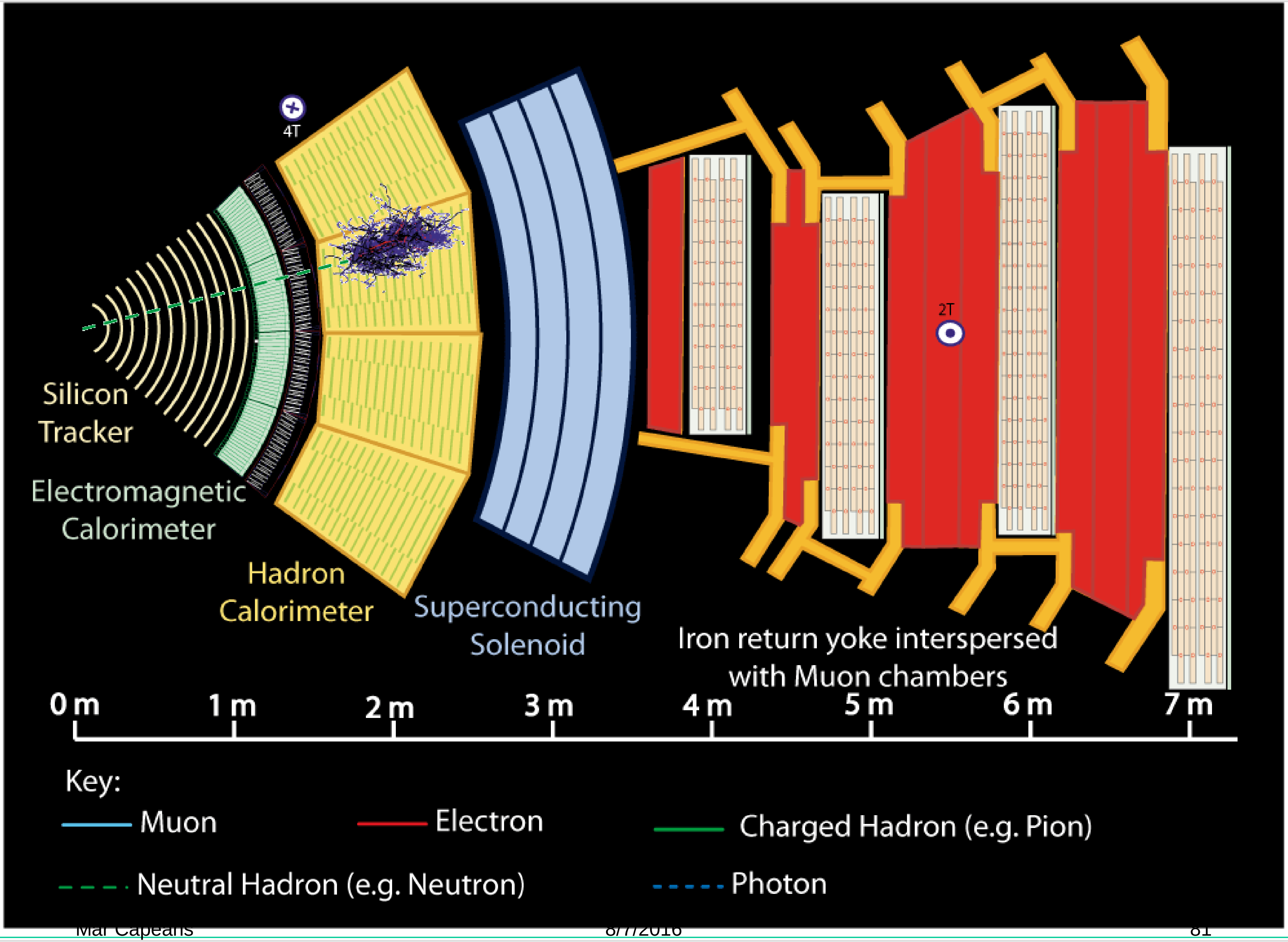
Mar Capeans

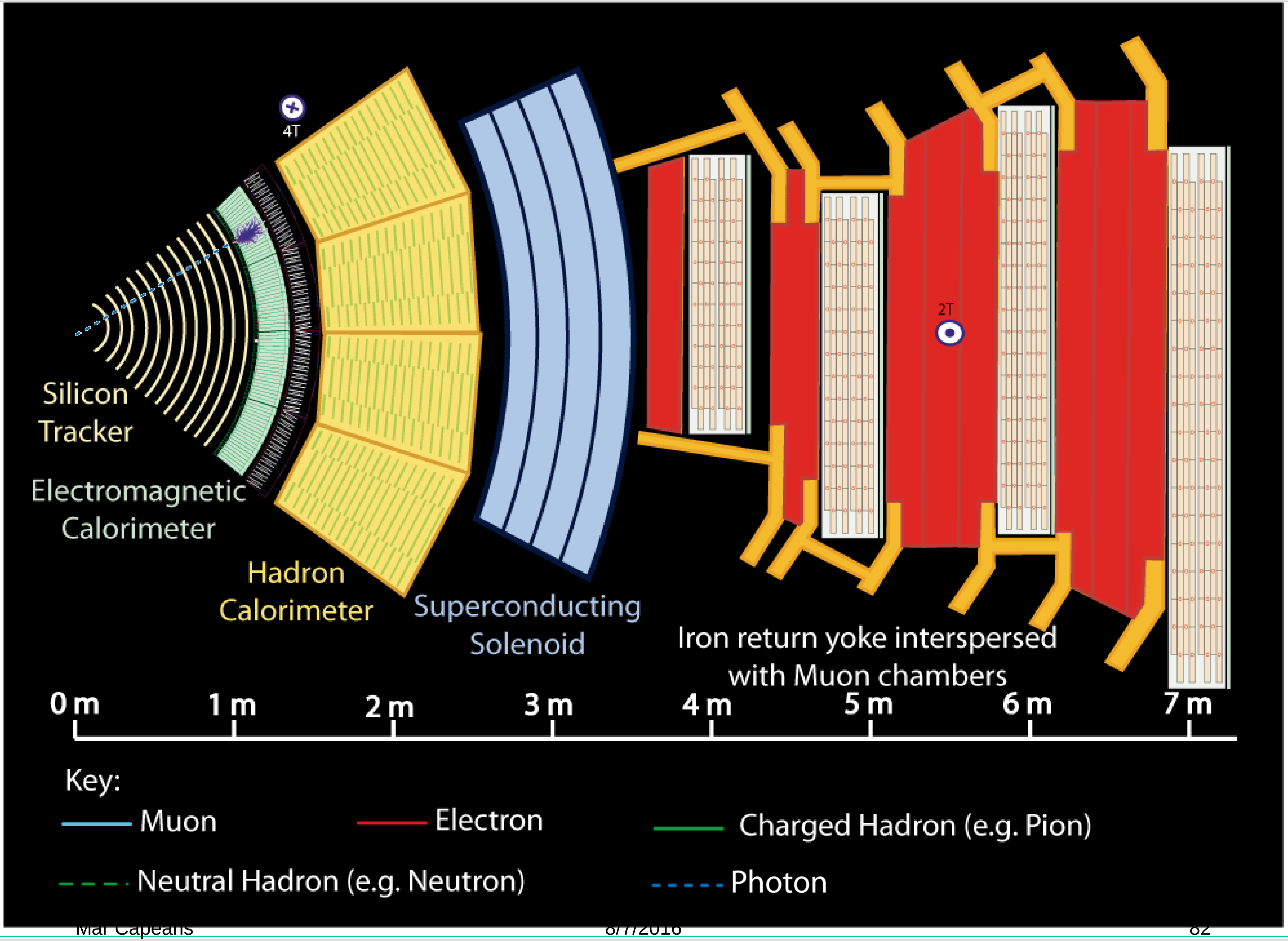

4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon


4T
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
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
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 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
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