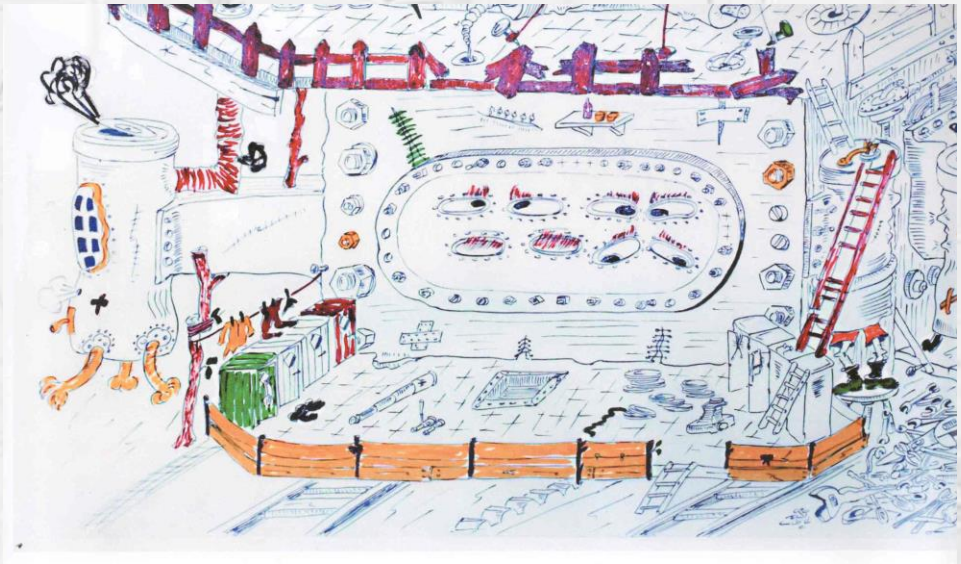
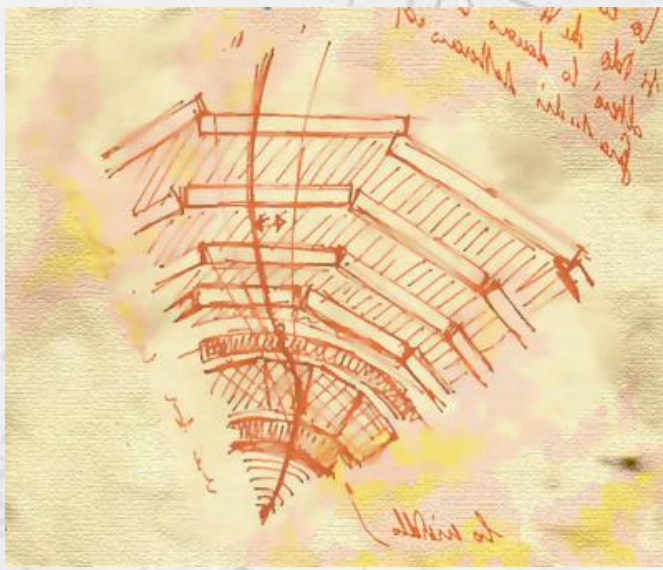
The Physics of Particle Detectors / Future Trends

Lecture I - Tracking Detectors (History, Gas/Si- Detectors)

Maxim Titov, CEA Saclay, France



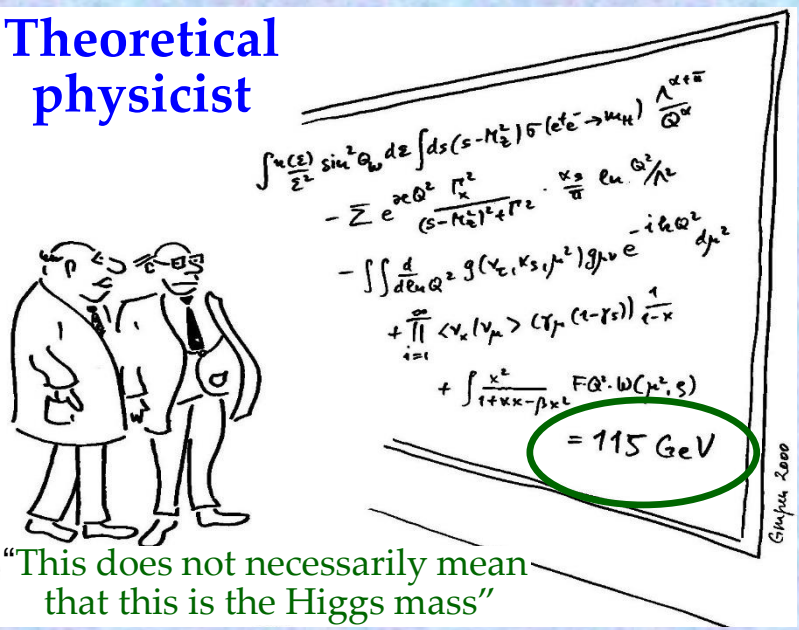
Artist's View of a Bubble chamber by a CERN physicist



Ukrainian Teacher Programme,
CERN, April 8-12, 2019

How (different) Physicists See the World ?

Theoretical physicist

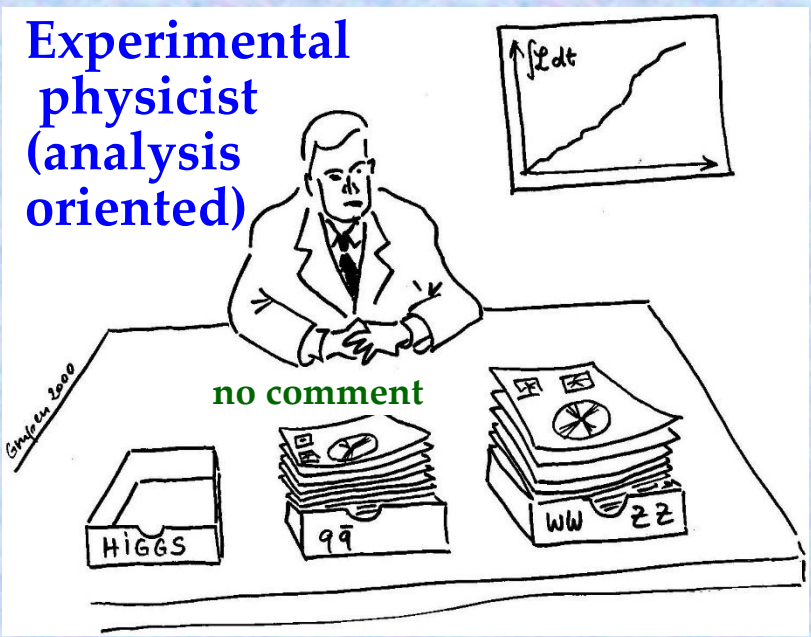


"This does not necessarily mean that this is the Higgs mass"

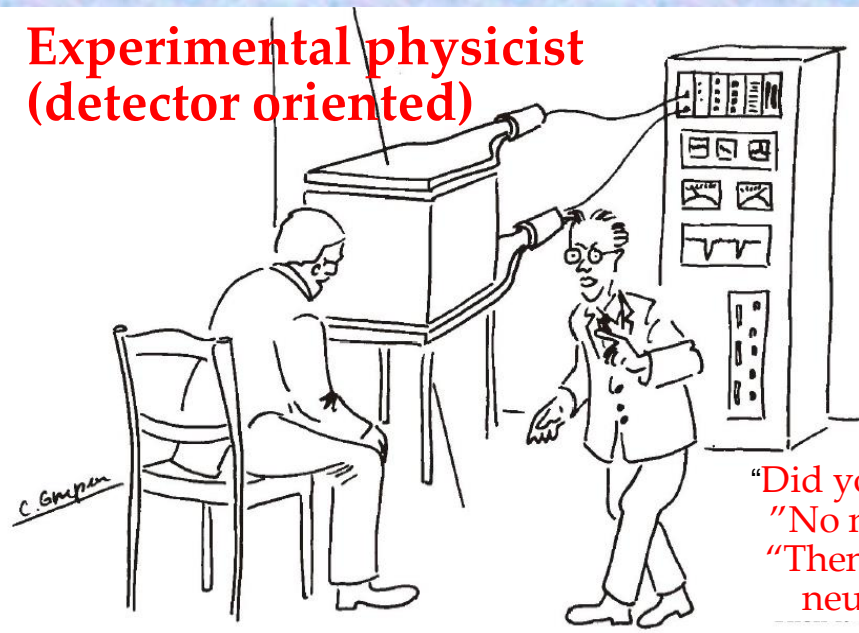
Accelerator physicist

"We have decided now to identify the particle species by a bar code!"

Experimental physicist (analysis oriented)



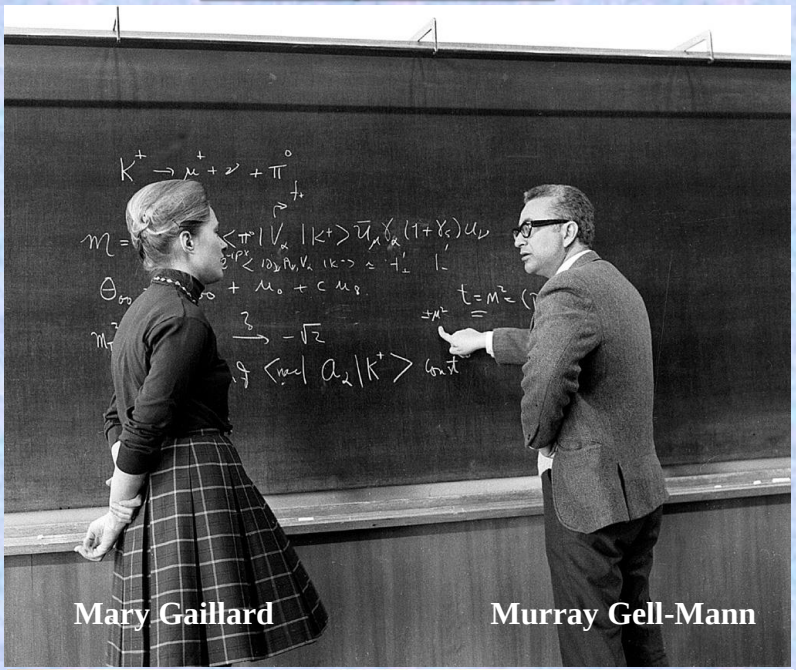
Experimental physicist (detector oriented)



"Did you see it?"
"No nothing."
"Then it was a neutrino!"

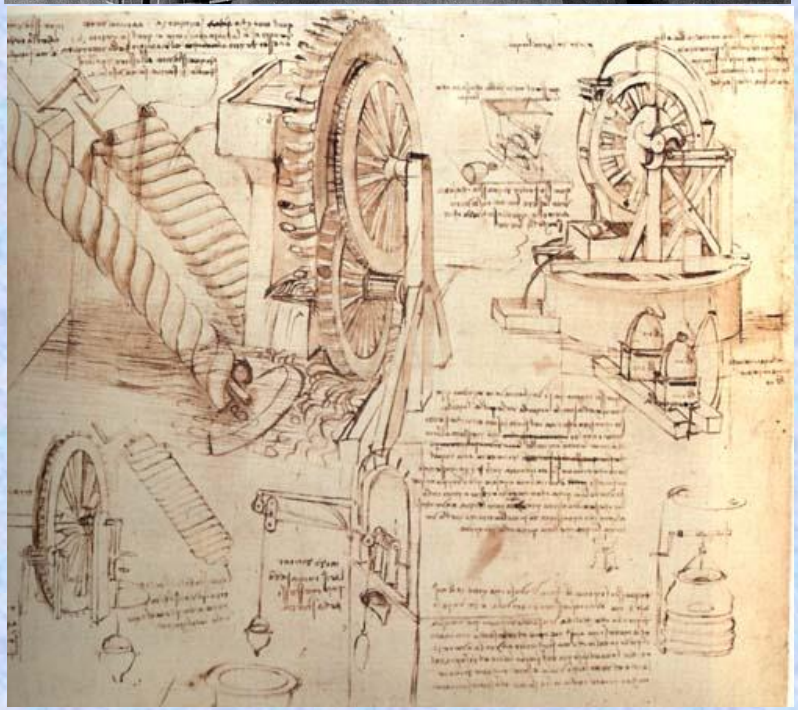
Cartoons by Claus Grupen

To do a HEP experiment, one needs:



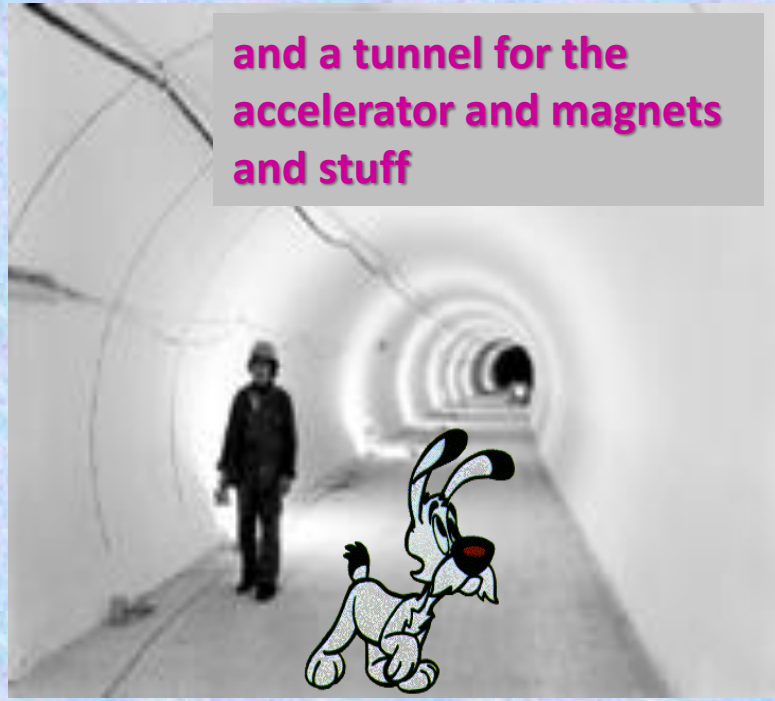
A theory:

and a cafeteria



Clear and easy understandable drawings

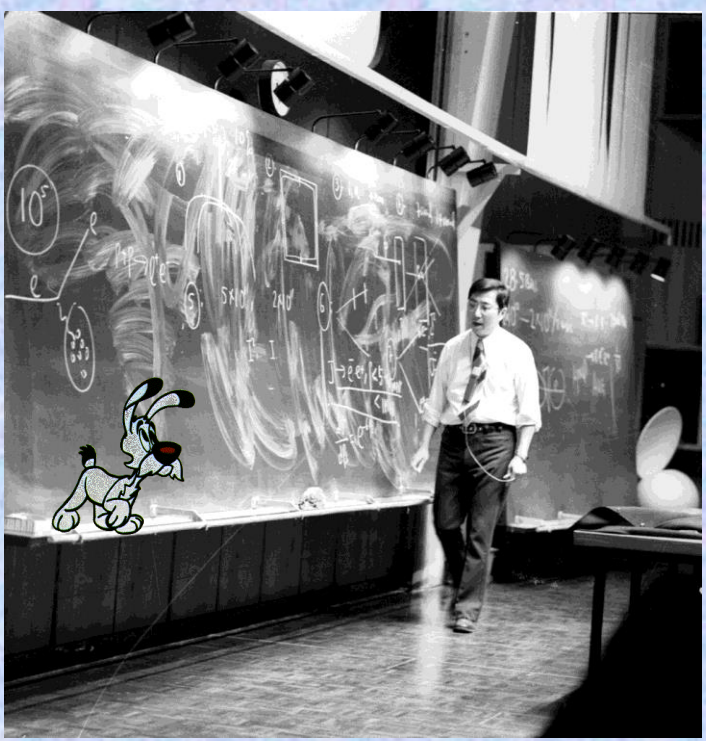
and a tunnel for the accelerator and magnets and stuff



O. Ullaland/2006

Easy access to the experiment

Physicists to operate detector/analyze data



and a Nobel prize

We will just concentrate on detectors

O. Ullaland/2006

The History of Instrumentation is VERY Entertaining

- A look at the history of instrumentation in particle physics

  → complementary view on the history of particle physics, which is traditionally told from a theoretical point of view

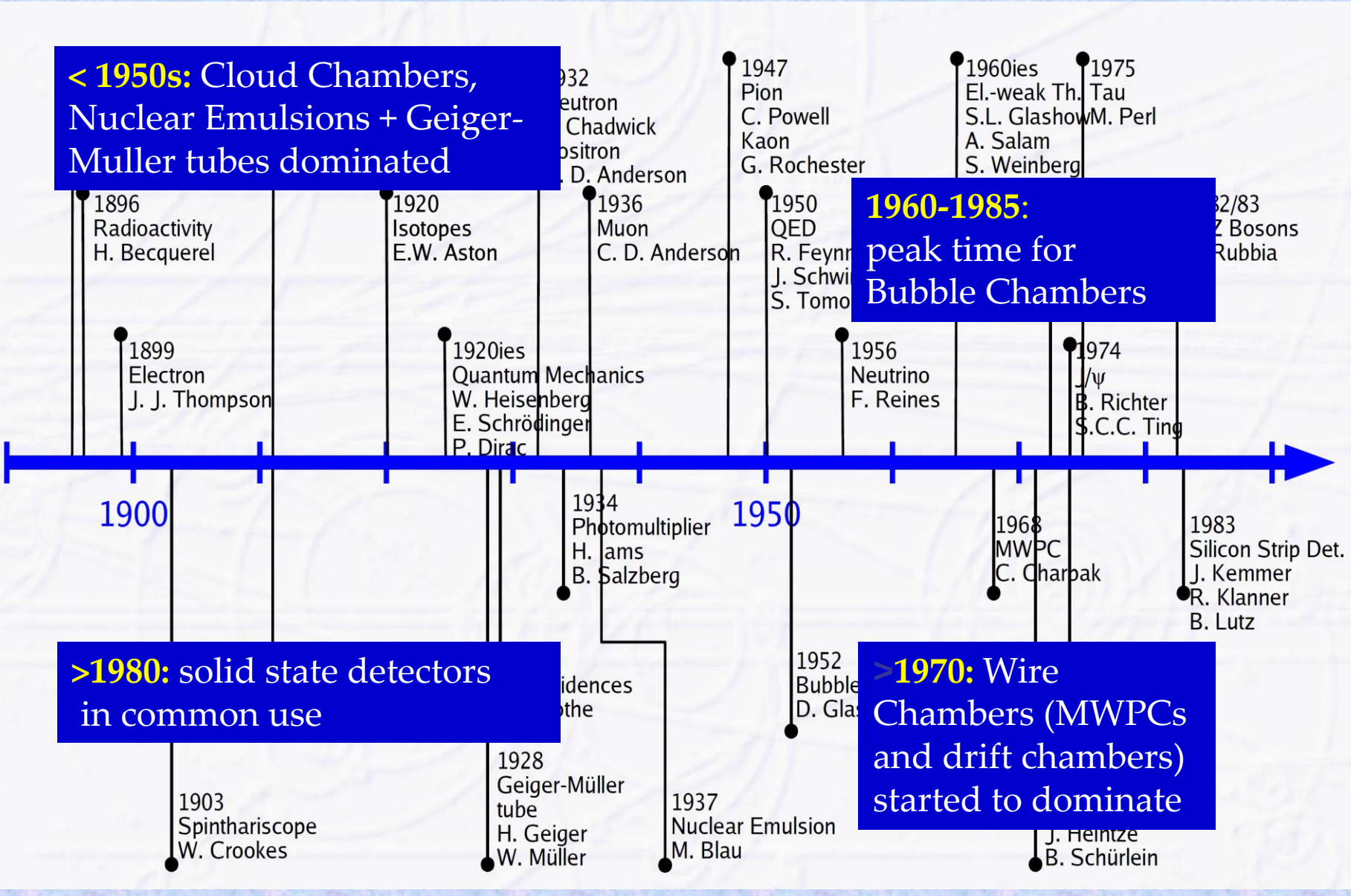
- The importance and recognition of inventions in the field of instrumentation is proven by the fact that

  → several Nobel Prices in physics were awarded mainly or exclusively for the development of detection technologies

Nobel Prizes in instrumentation ("tracking concepts"):

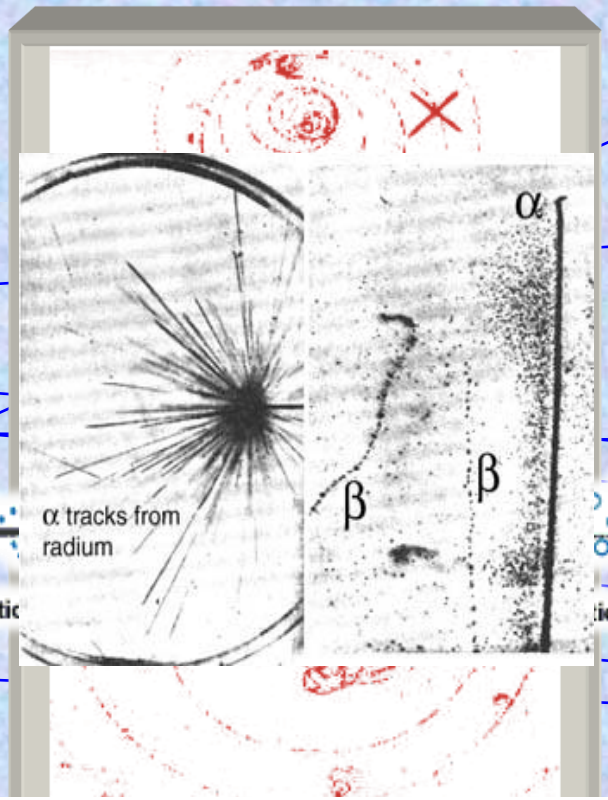
- 1927: C.T.R. Wilson, Cloud Chamber
- 1960: Donald Glaser, Bubble Chamber
- 1992: Georges Charpak, Multi-Wire Proportional Chamber

Timeline of Particle Physics and Instrumentation

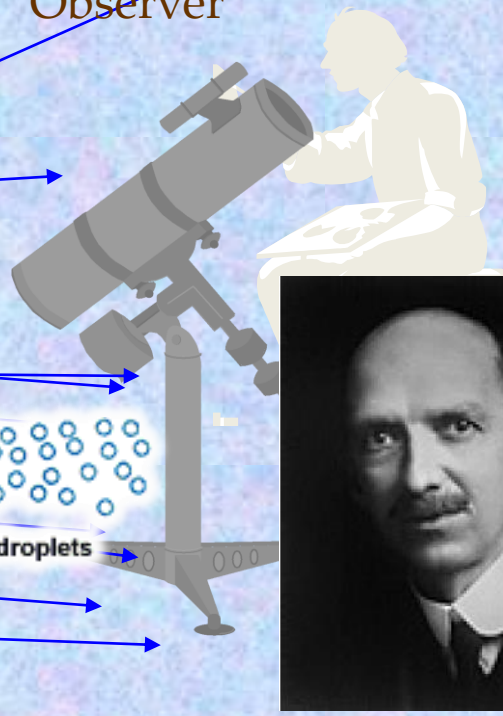


Classic Particle Tracking Detector: Cloud Chamber

Passage of charge particle would condense the vapor into tiny droplets, marking the particle's path → their number being proportional to dE/dx



Observer

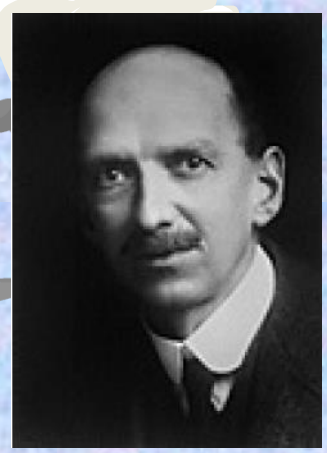


Flux of particles

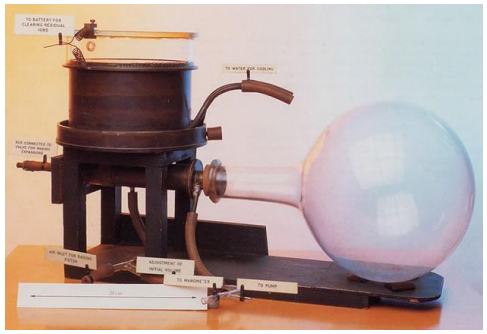
Charged partic

ion droplets

Cloud Chamber + Magnet



- **Cloud chamber (1911 by Charles T. R. Wilson, Noble Prize 1927)**
  - **chamber with over-saturated water vapour**
    - originally developed to study formation of rain clouds
  - **charged particles leave trails of ions**
    - water is condensing aound ions
  - **visible track as line of small water droplets**



Discovery of a Positron e+ from Cosmic Rays

1932 C.D. Anderson :

- Particle with positive curvature and minimum ionisation (droplets size)
- Track length is at least 10 times greater than the possible length of a proton path of this curvature
- Energy loss in a 6 mm of Pb: compatible with that of electron

Hypothesis (discovery !) :

- particle with mass ~m_e and charge +1, the positron

❖ *First anti-particle*

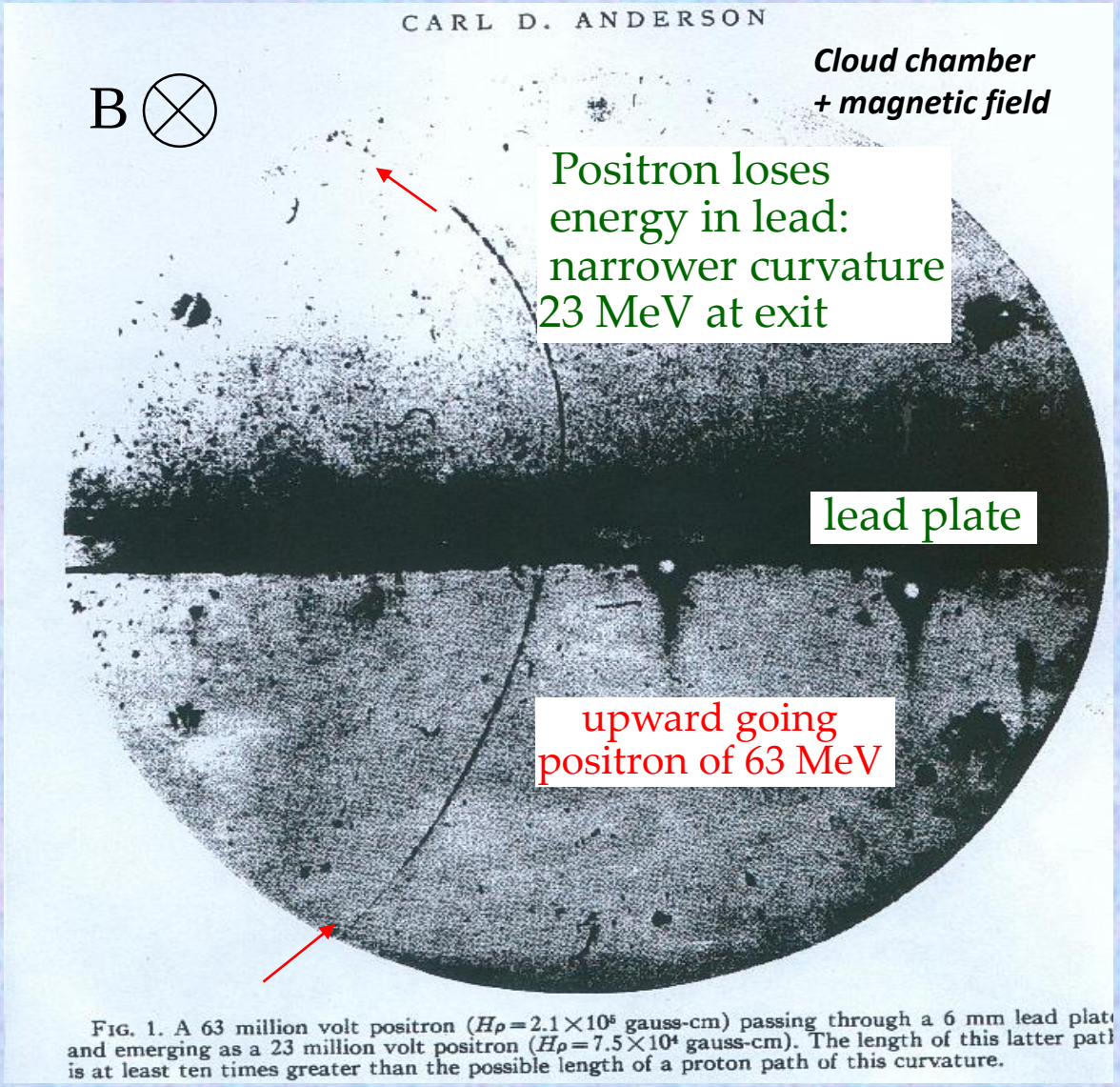


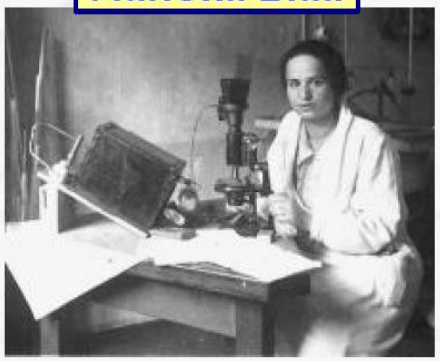
FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

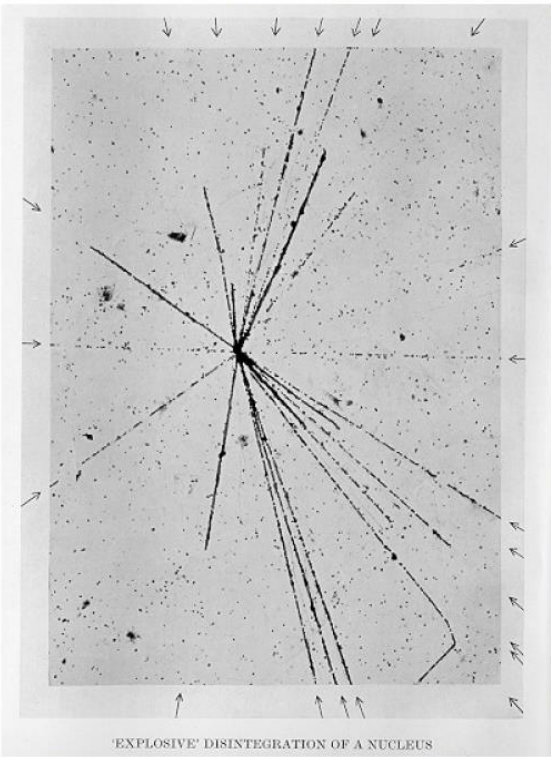
Discovery of the positron by Cloud Chamber
(1932 by Carl Anderson, Noble Prize 1936)

Nuclear Emulsion (I)

- **Pioneered by Marietta Blau between 1923 – 1938 (no Nobel Prize)**
  - photographic emulsion layer, 10 – 200 μm thick, uniform grains of 0.1 – 0.3 μm size
  - very high resolution for particle tracks
    - analysis of developed emulsion by microscope

Marietta Blau





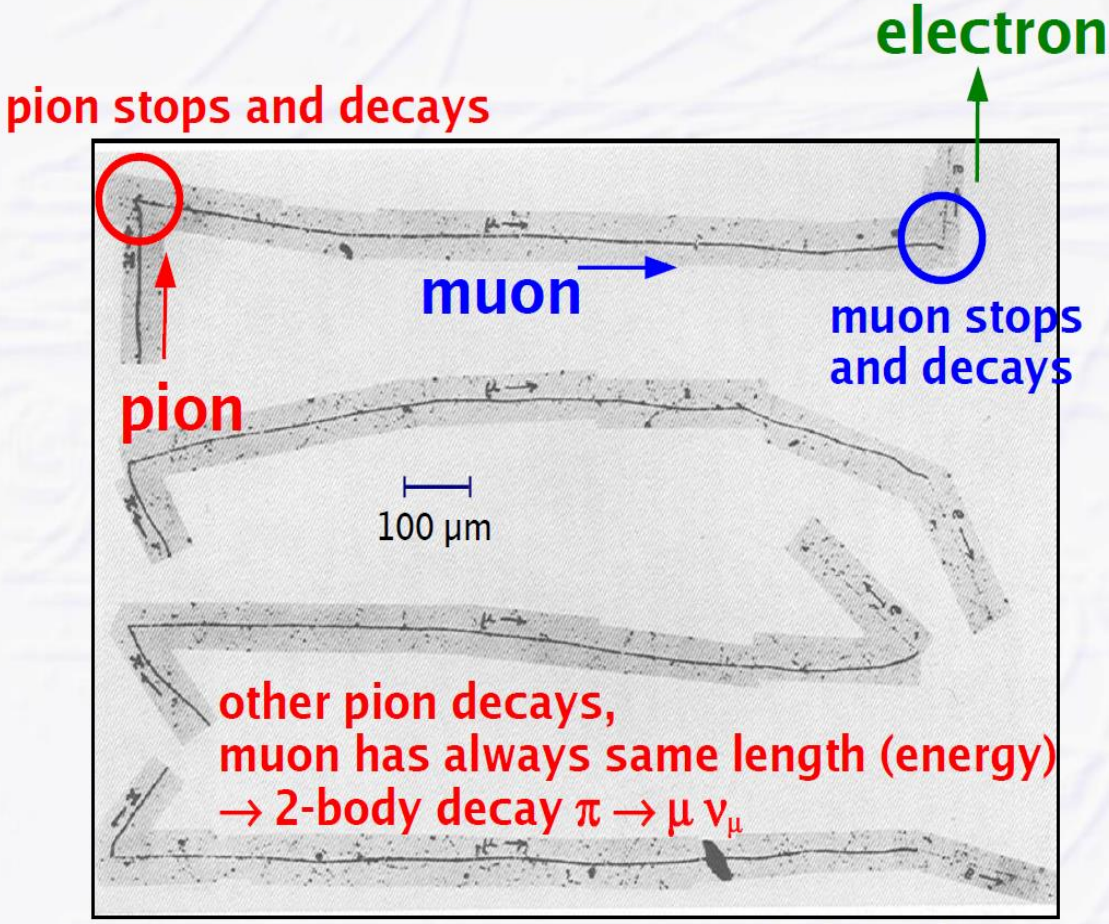
'EXPLOSIVE' DISINTEGRATION OF A NUCLEUS

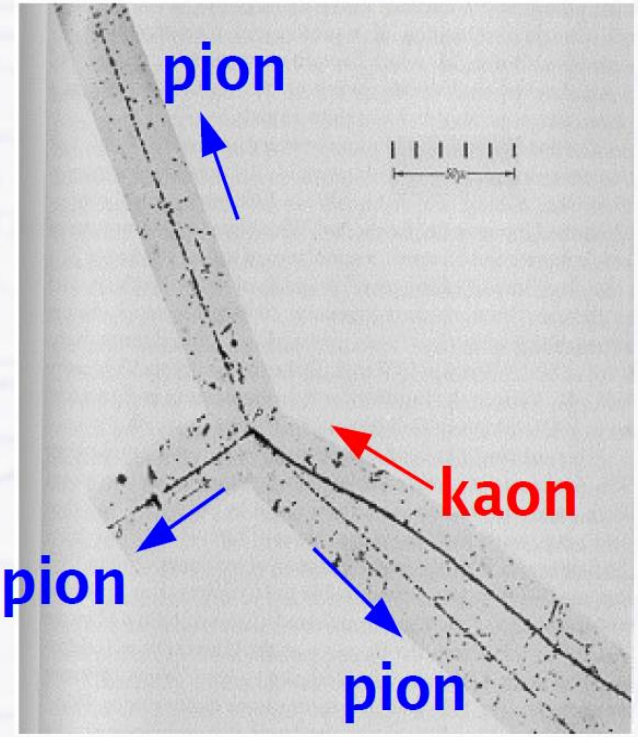
nuclear disintegration from cosmic rays, observed1937 for the first time

- **Since early 20th century**
  - important role of photography to study radioactivity
  - but capability to make individual tracks visible not seen until nuclear emulsion technique was developed

Nuclear Emulsion (II)

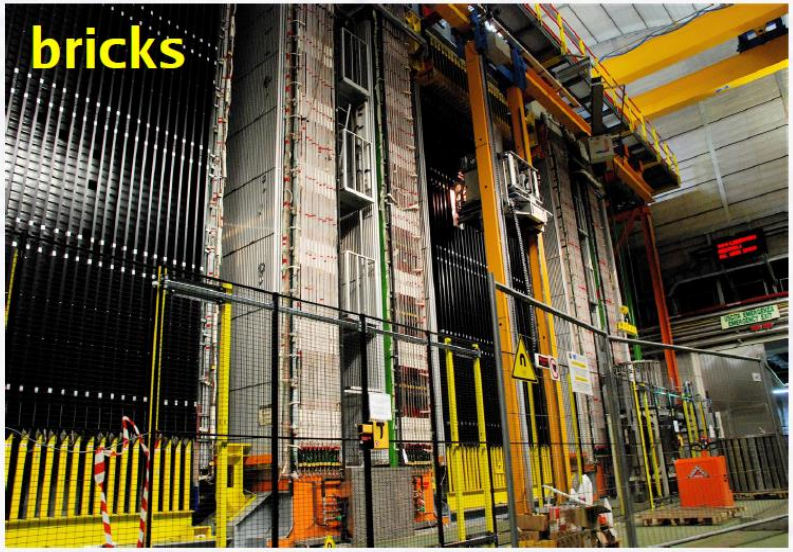
- Discovery of the pion in cosmic rays by Cecil Powell 1947 (Nobel Prize 1950)
- Discovery of the kaon 1949 (G. Rochester)



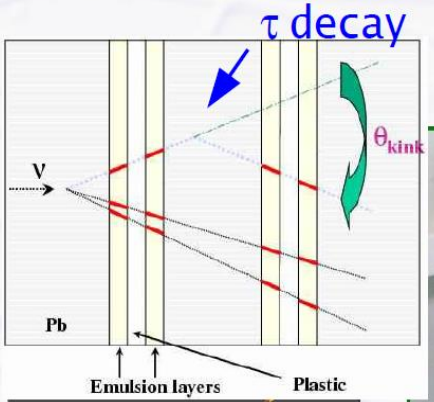


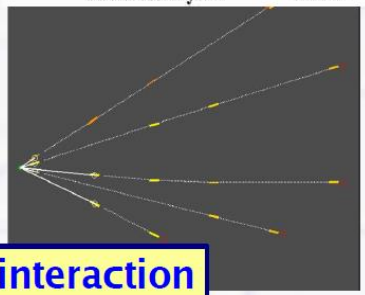
Nuclear Emulsion (III)

- **Still used in actual experiments with highest precision requirements over a large volume**
  - ν_μ beam sent from CERN to Gran Sasso Underground lab
  - OPERA experiment is searching for ν_τ appearance after neutrino oscill. $\nu_\mu \rightarrow \nu_\tau$
    - need to reconstruct τ decays ($\nu_\tau + N \rightarrow \tau^- + X$) (few ~100 μm track length)
    - 235'000 "bricks" (1.7 ktons) of lead + emulsion sheets

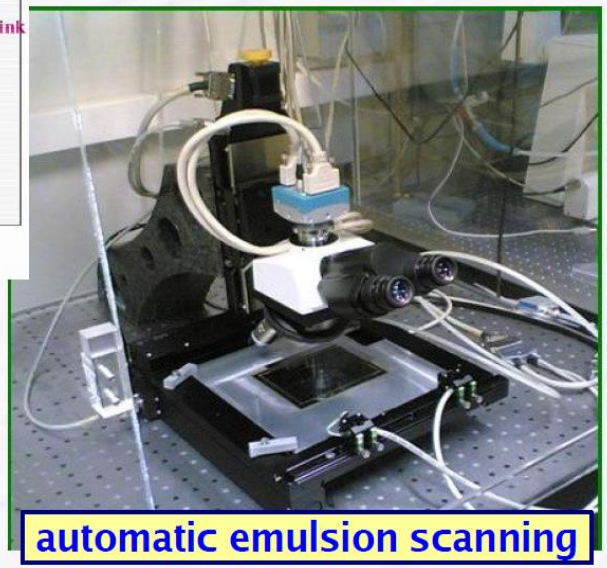


OPERA at Gran Sasso





ν_μ interaction



automatic emulsion scanning

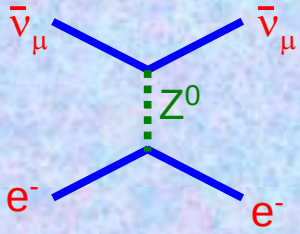
Bubble Chamber (I)

1952 by Donald Glaser, Noble Prize 1960

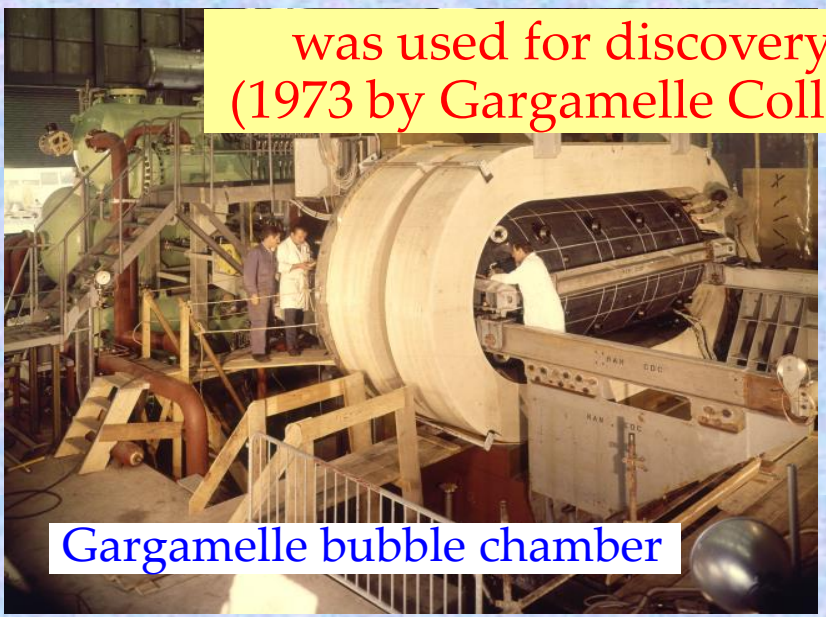
(4.8 x 1.85 m^2) chamber with liquid (H_2) at boiling point ("superheated")

Similar principle as cloud chamber:

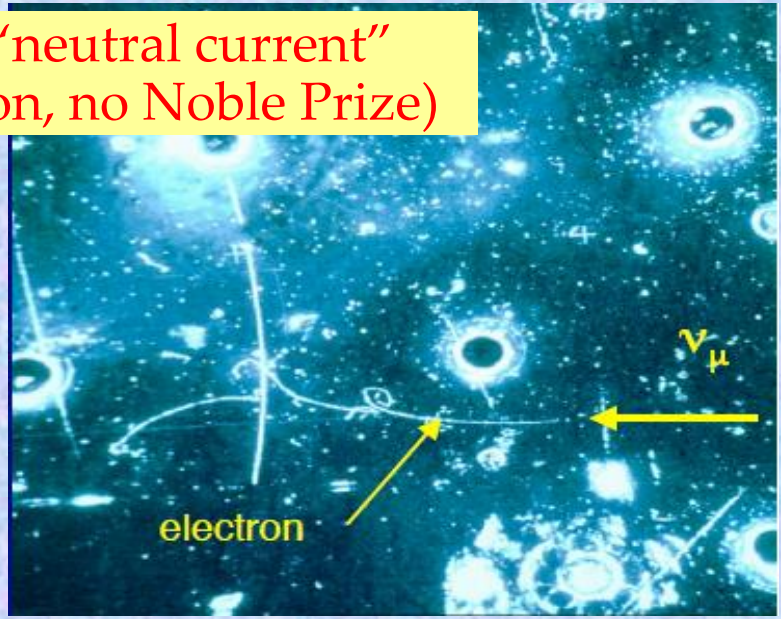
- Instead of supersaturating a gas with a vapor one would superheat the liquid.
- A particle leave a trail of ions along its path → make a liquid boil, and form gas bubbles around ions



was used for discovery of the "neutral current"
(1973 by Gargamelle Collaboration, no Noble Prize)

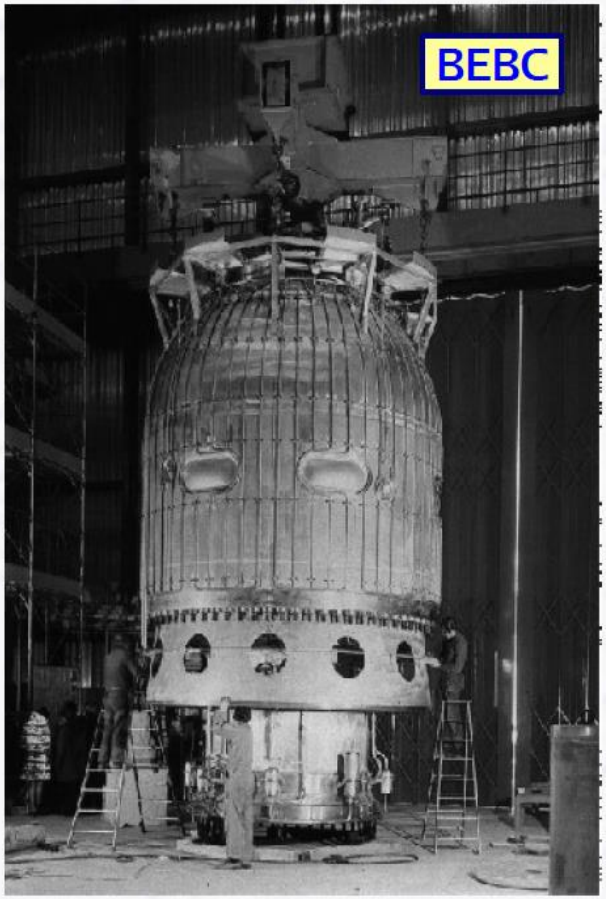

Gargamelle bubble chamber

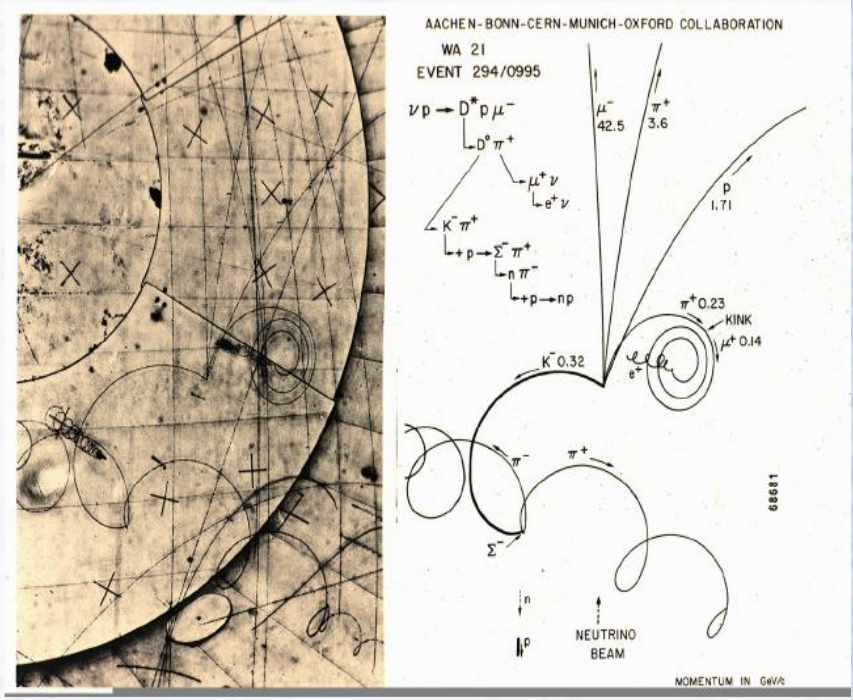
CERN



Bubble Chamber (II)

- **BEBC (Big European Bubble Chamber) at CERN, 1973 – 1984**
  - largest bubble chamber ever built (and the last big one...), ∅ 3.7 m
  - 6.3 million photographs taken, 3000 km of developed film
  - now displayed in permanent exhibition at CERN





production of D* meson
with long decay chain

Bubble Chamber

- Advantages:

liquid (hydrogen) is BOTH detector medium AND target

high precision (~ 5 μm)

- Disadvantages:

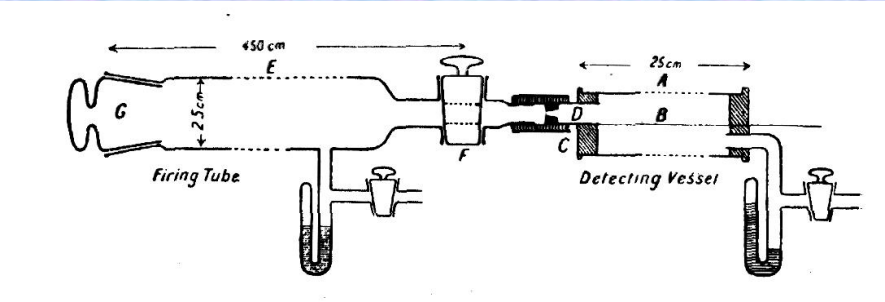
- NO TRIGGER -> has to be in superheated state when particle is entering

LOW RATE CAPABILITY
Need FASTER detector (electronics !)

In the Family of Gaseous Detectors with a glorious tradition

1st Revolution: The invention of the MWPC revolutionized particle detection and HEP, which passed from the manual (optical) to the electronic era.

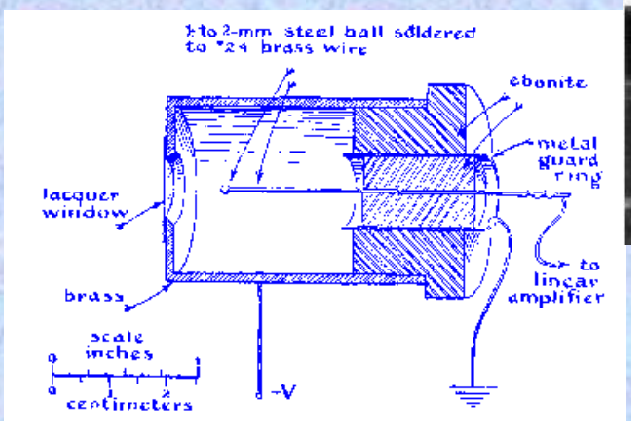
1908: FIRST WIRE COUNTER USED BY RUTHERFORD IN THE STUDY OF NATURAL RADIOACTIVITY



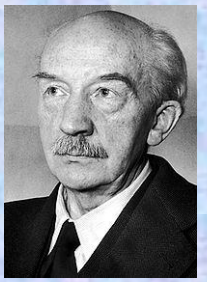
E. Rutherford and H. Geiger , Proc. Royal Soc. A81 (1908) 141

Nobel Prize in Chemistry in 1908

1928: GEIGER COUNTER SINGLE ELECTRON SENSITIVITY

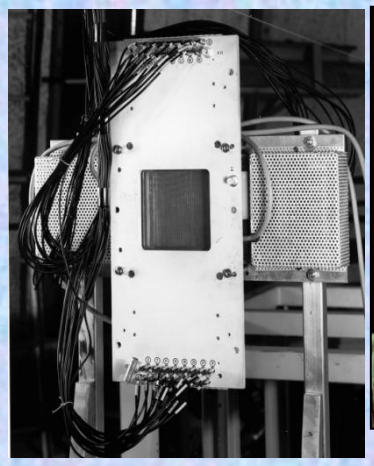


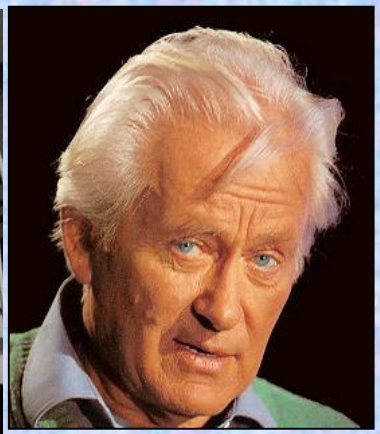
H. Geiger and W. Müller, Phys. Zeits. 29 (1928) 839



Walther Bothe Nobel Prize in 1954 for the "coincidence method"

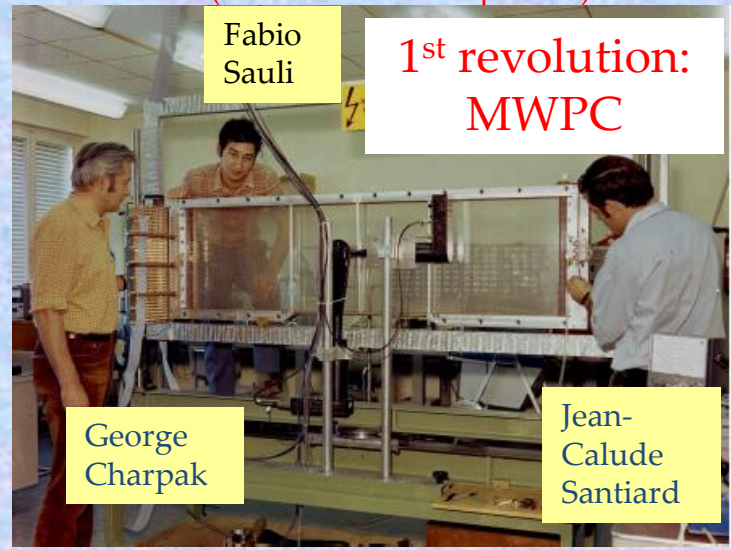
1968: MULTIWIRE PROPORTIONAL CHAMBER





Nobel Prize in 1992

G. Charpak, Proc. Int. Symp. Nuclear Electronics (Versailles 10-13 Sept 1968)



Gas Detector History

Geiger Counter
H.GeigerW.Mueller 1928

PPC
Parallel Plate Counter

PC
Proportional Counter

Pestov
Counter
V.Pestov 1982

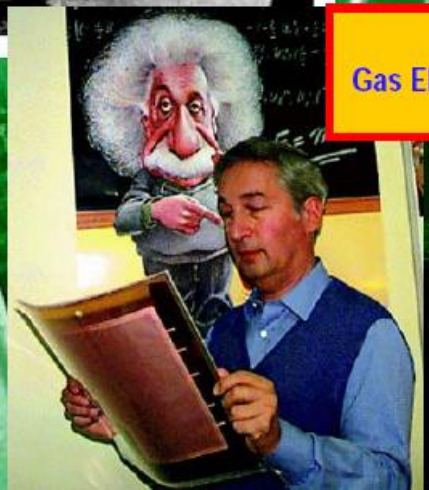
RPC
Resistive Plate Chambers
R.Santonico R.Cardarelli 1981

MWPC
Multiwire Proportional Chamber
G.Charpak et al 1968

TPC
Time Projection Chamber
D.R.Nygren et al 1974

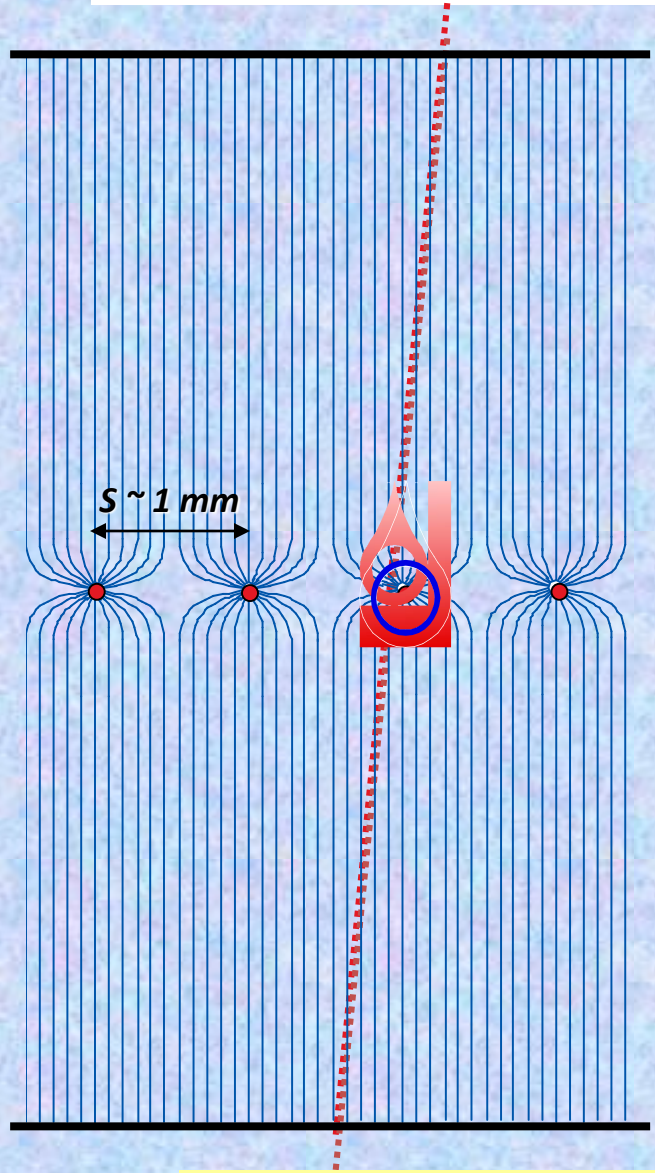
MSGC
Microstrip Gas Chambers
A.Oed 1988

GEM
Gas Electron Multiplier
F.Sauli 1997



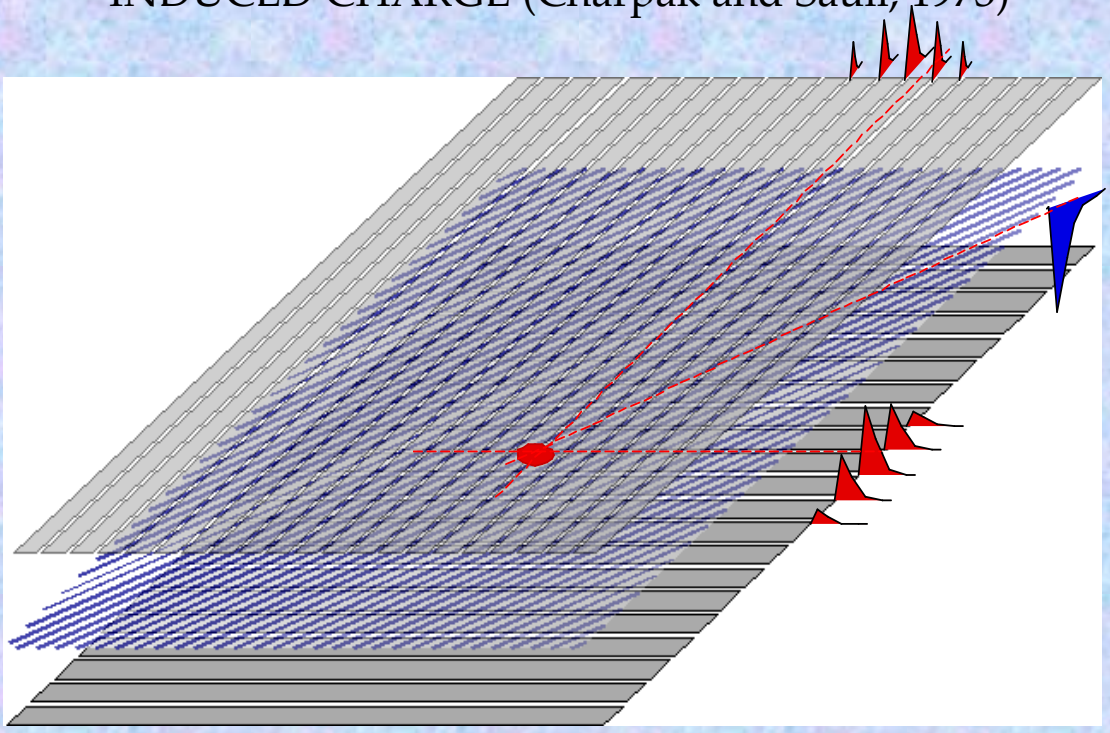
μM
Micromegas
I.Giomataris et al 1996

Multi-Wire Proportional Chamber (MWPC)



High-rate MWPC with digital readout:
Spatial resolution is limited to σ_x ~ s/sqrt(12) ~ 300 μm

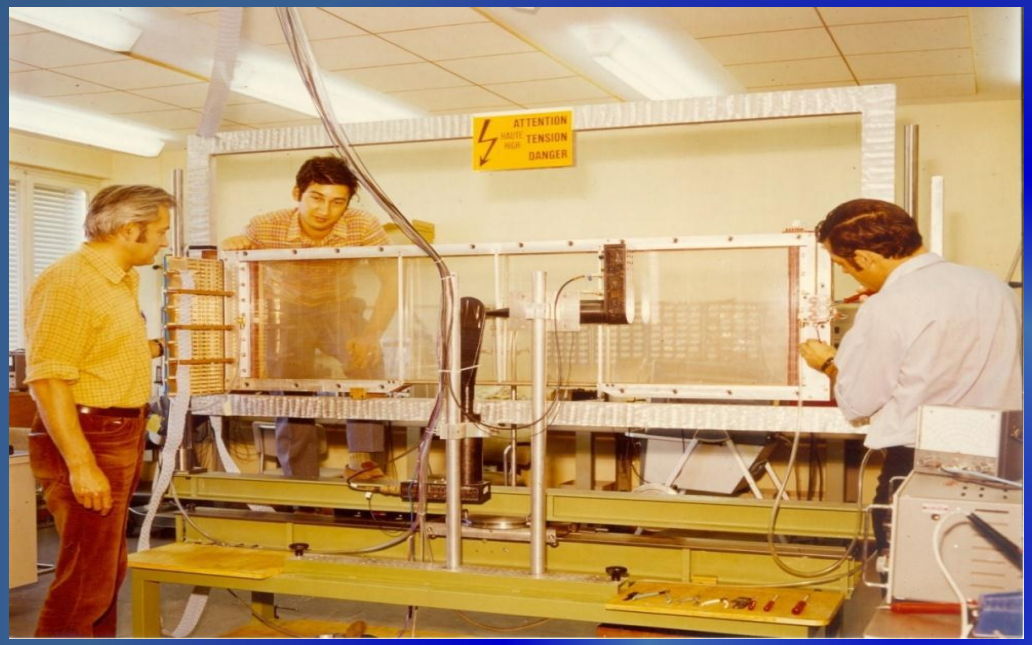
TWO-DIMENSIONAL MWPC READOUT CATHODE INDUCED CHARGE (Charpak and Sauli, 1973)



Spatial resolution determined by: Signal / Noise Ratio
Typical (i.e. 'very good') values: S ~ 20000 e: noise ~ 1000e
Space resolution < 100 μm

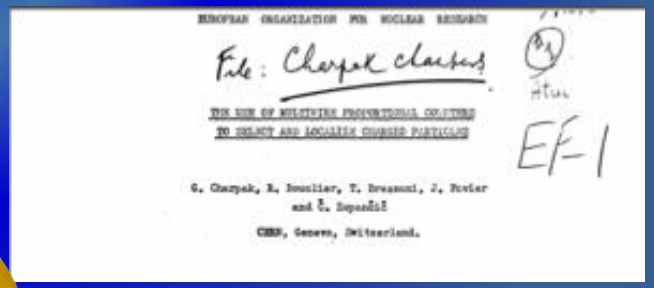
Resolution of MWPCs limited by wire spacing
better resolution → shorter wire spacing → more (and more) wires...

1968: MWPC – revolutionising the way particle physics is done



Detecting particles was a mainly a manual, tedious and labour intensive job – unsuited for rare particle decays

George Charpak developed the MultiWire Proportional Chamber, which revolutionized particle detection and High Energy Physics - which passed from the manual to the electronic era.


File: Charpak clusters

THE USE OF MULTIWIRE PROPORTIONAL COUNTERS TO SELECT AND LOCALIZE CHARGED PARTICLES

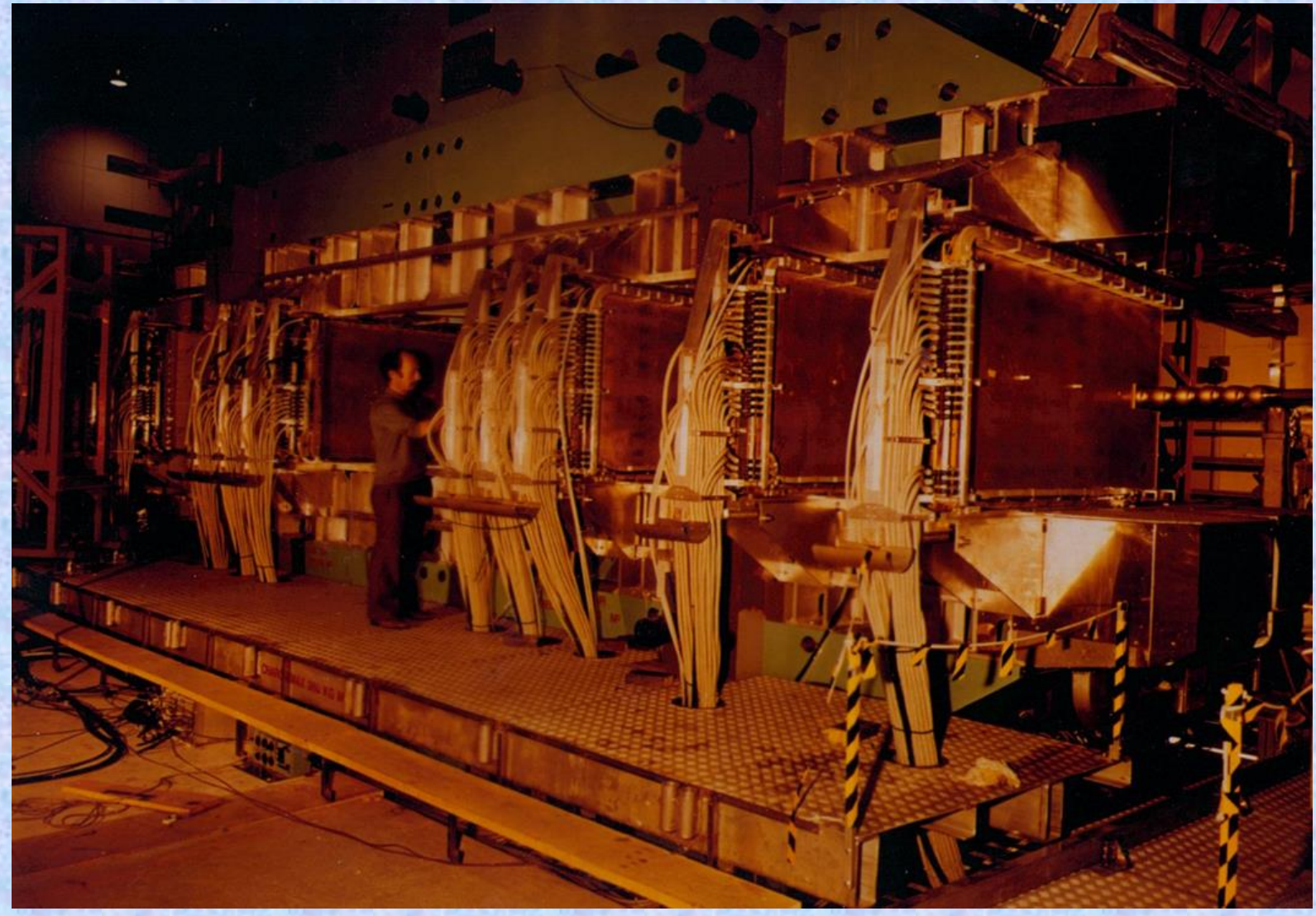
G. Charpak, R. Bouclier, T. Bressani, J. Favier and Č. Zupančič

CERN, Geneva, Switzerland.

EF-1

Electronic particle track detection is now standard in all particle detectors

First Large Experiment with MWPCs



1972-1983: SPLIT FIELD MAGNET DETECTOR

40 LARGE AREA MWPCs AT CERN ISR:

Nobel Prize: W, Z - Discovery at UA1/UA2 (1983)

UA1 used the largest imaging drift chamber of its day
(5.8 m long, 2.3 m in diameter)

It can now be seen in the CERN Microcosm Exhibition

Particle trajectories in the CERN-UA1
3D Wire Chamber
Discovery of W and Z bosons
C. Rubbia & S. Van der Meer Nobel 1984

Z → ee (white tracks)

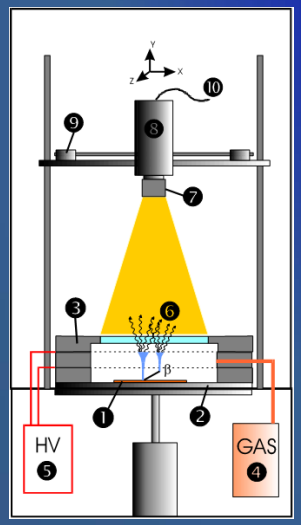
The 1970's Dream: Digital radiography with MWPC

1992:

Biospace: Company Founded In 1989 by Georges Charpak

~ 2000: LOW-DOSE 3D IMAGING (&à times less)

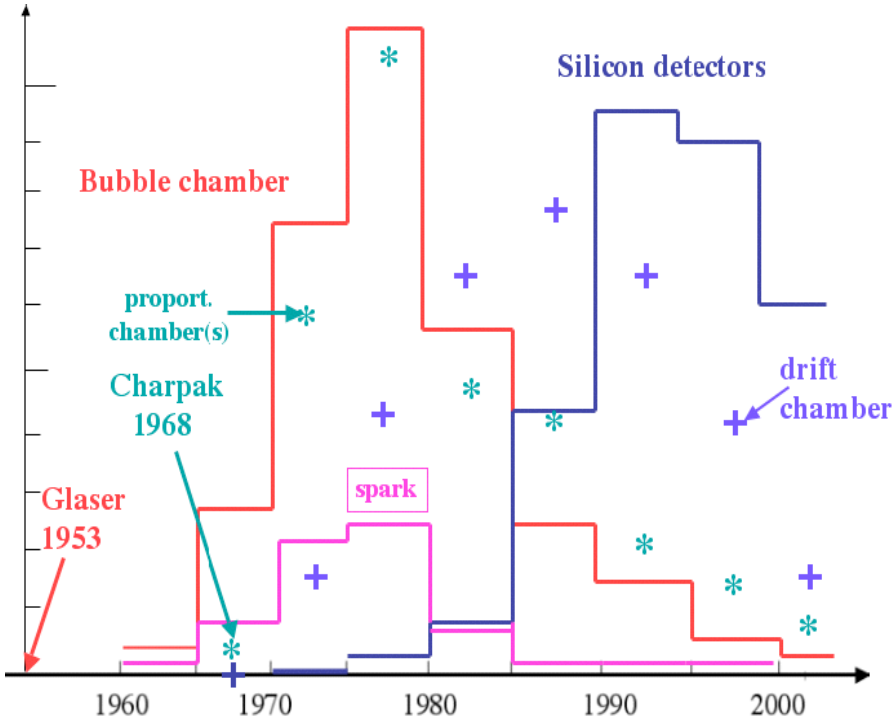
COMMERCIAL AUTORADIOGRAPHY SYSTEMS WITH GASEOUS DETECTORS



http://www.biospacelab.com

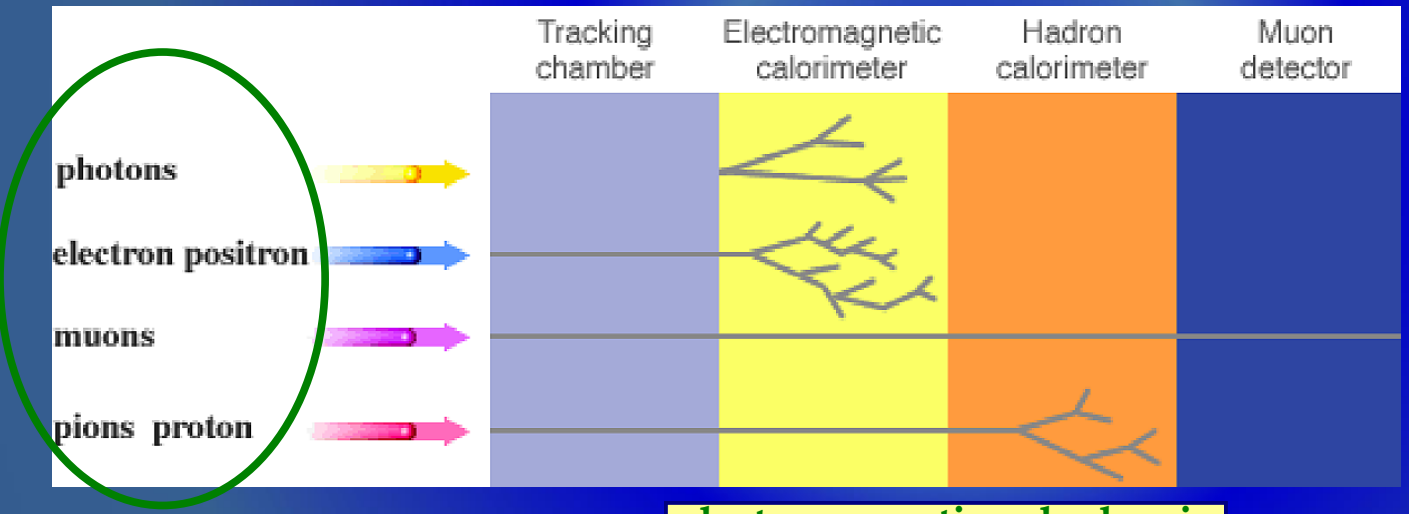
Tracking Detectors: History and Trends

- **Cloud Chambers, Nuclear Emulsions + Geiger-Müller tubes**
  → dominated until the early 1950s: Cloud Chambers now very popular in public exhibitions related to particle physics
- **Bubble Chambers had their peak time between 1960 and 1985**
  → last big bubble chamber was BEBC at CERN
- **Since 1970s: Wire Chambers (MWPCs and drift chambers) started to dominate**
- **Since late 1980s: Solid state detectors are in common use**
  → started as small sized vertex detectors (at LEP and SLC)
  → now ~200 m^2 Si-surface in CMS tracker
- **Most recent trend: hybrid detectors**
  → combining both gaseous and solid state technologies



Schematical View of a HEP Detector

- There is not one type of detector which provides all measurements we need -> "Onion" concept -> different systems taking care of certain measurement
- Detection of collision production within the detector volume
  - → resulting in signals due to electro-magnetic interaction
  - → exceptions: strong interactions in hadronic showers (hadron calorimeters)
  - → weak interactions at neutrino detection (not discussed here)



undetected neutrinos...

electromagnetic hadronic shower

momentum measurement by curvature in magnetic field

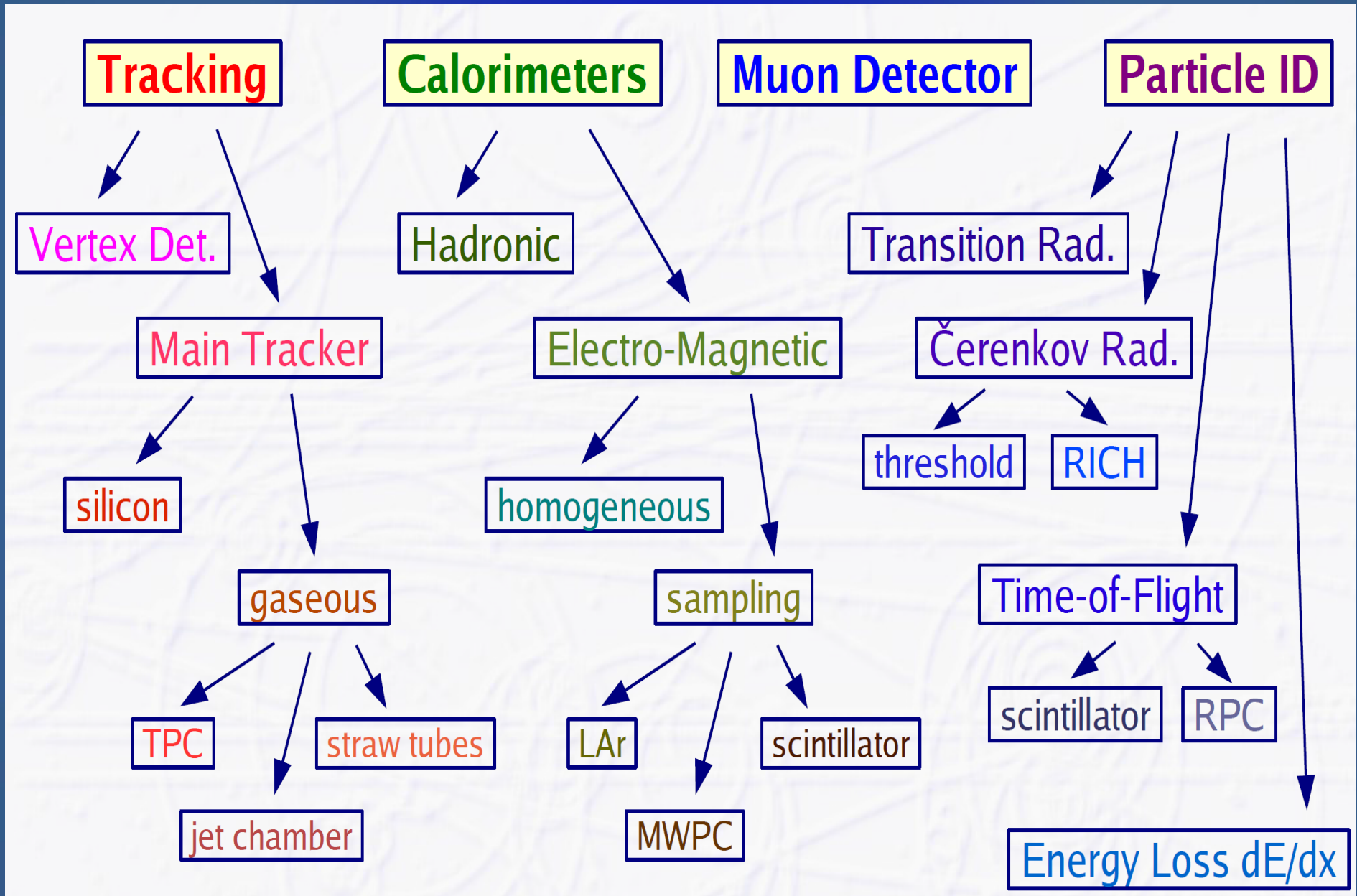
energy measurement by creation and total absorption of showers

muon detection with improved momentum measurement (long lever arm)

Particle Detectors: Physics Principles

- **Tracking Detector (or Tracker) = momentum measurement**
  - closest to interaction point: vertex detector (often silicon pixels)
    - measures primary interaction vertex and secondary vertices from decay particles
  - main or central tracking detector
    - measures momentum by curvature in magnetic field
    - two technologies: solid state detectors, Si strips or gaseous detectors
- **Calorimeters = energy measurement**
  - electro-magnetic calorimeters
    - measures energy of light EM particles (electrons, positrons, photons) based on electro-magnetic showers by bremsstrahlung and pair production
    - two concepts: homogeneous (CMS) or sampling (ATLAS)
  - hadron calorimeters
    - measures energy of heavy (hadronic) particles (pions, kaons, protons, neutrons) based on nuclear showers created by nuclear interactions
- **Muon Detectors = momentum measurement for muons (more precise)**
  - outermost detector layer, basically a tracking detector

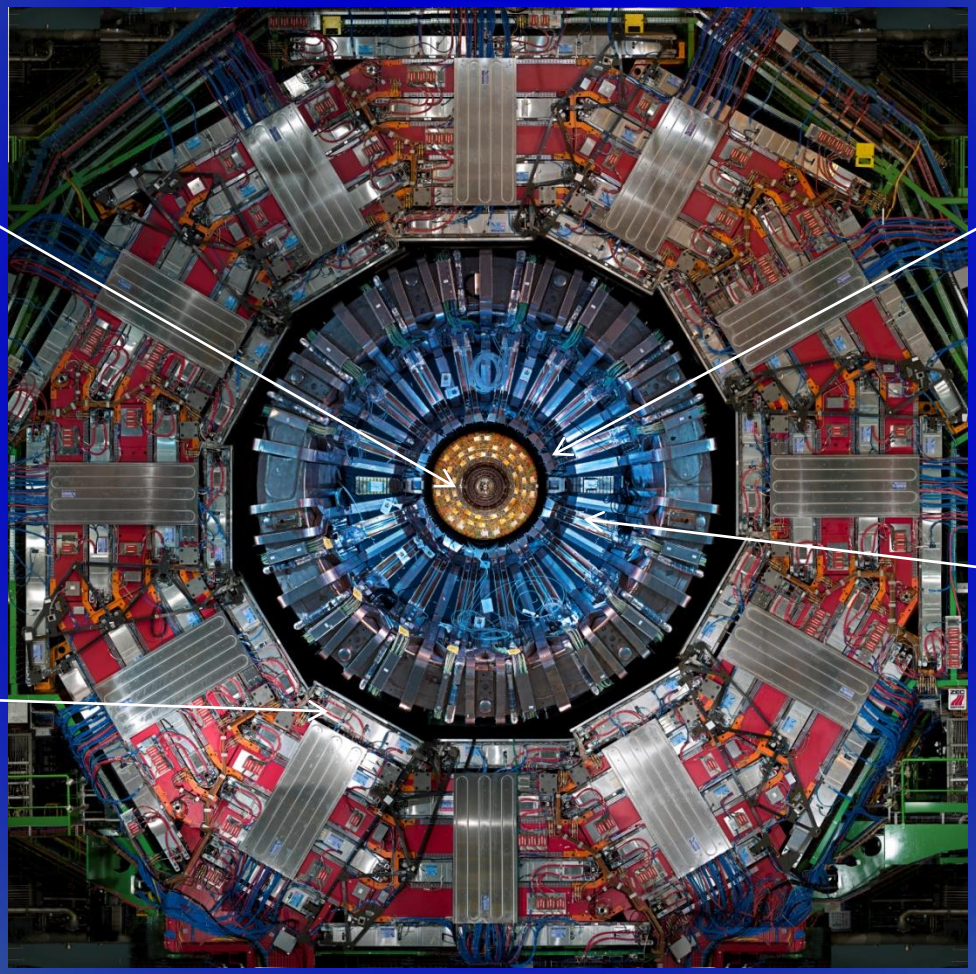
Particle Physics: Modern Detector Technologies



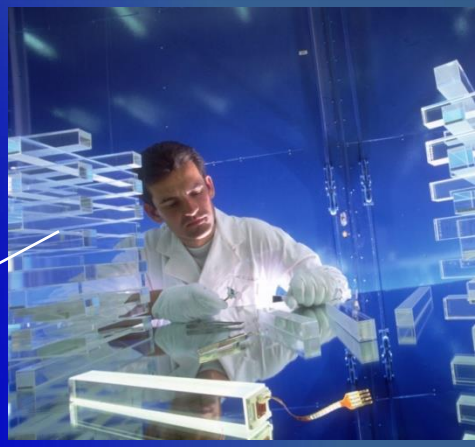
CMS Detector: Concept to Data Taking in 18 Years

3000 scientists from 40 countries
CMS Letter of Intent (Oct. 1992)

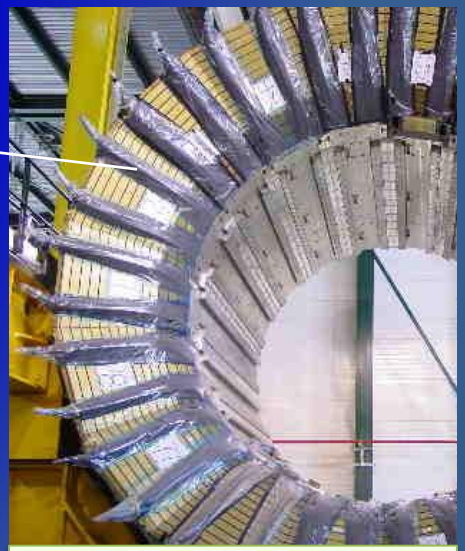
Silicon Tracker



Scintillating Crystals



Gaseous detectors

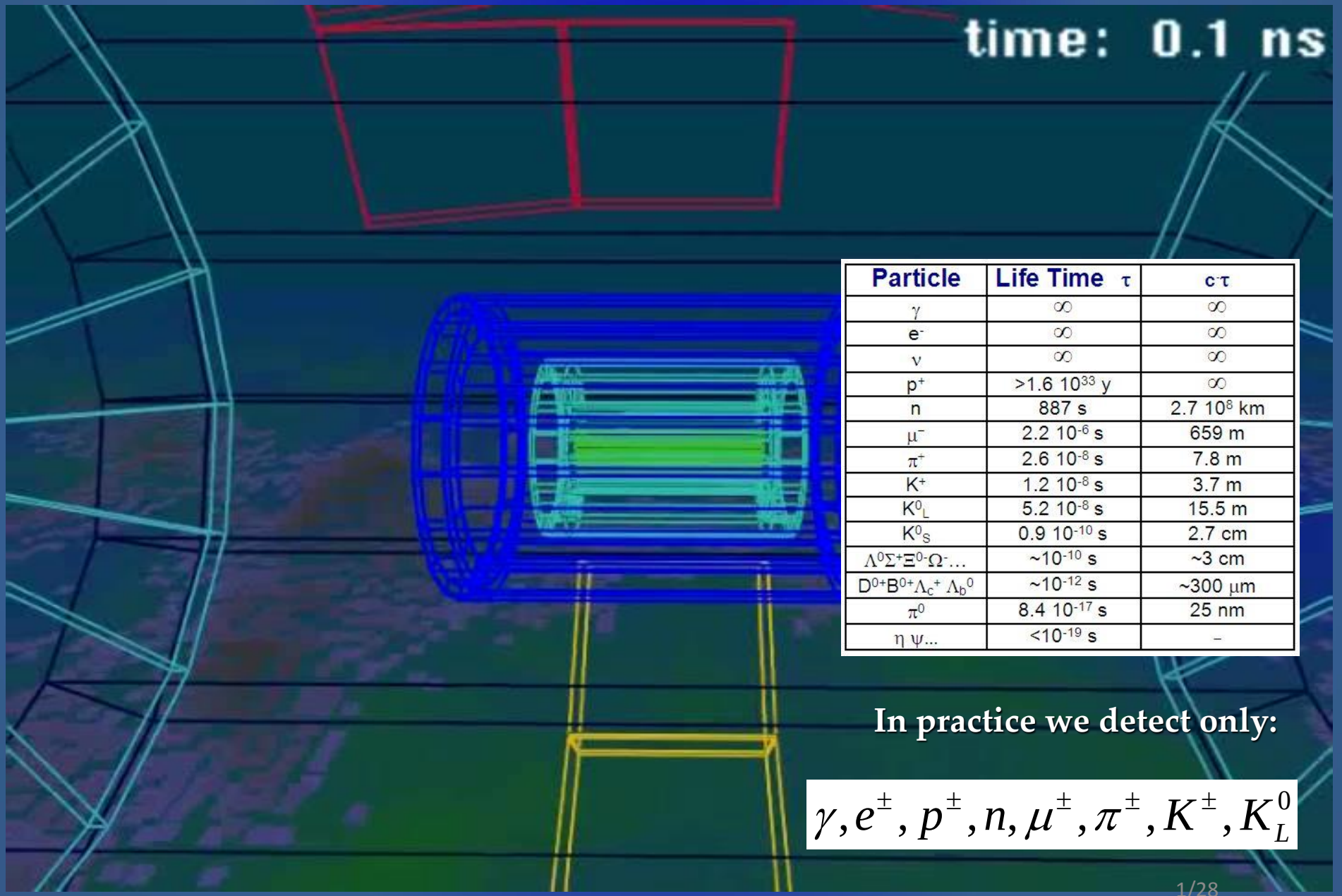


Brass plastic scintillator

The Largest and Most Complex Microscopes we've ever built

The "Gothic Cathedrals" of the 21st Century

Computer Simulated Event in ALICE



Particle	Life Time τ	$c\cdot\tau$
γ	∞	∞
e^-	∞	∞
ν	∞	∞
p^+	$>1.6\ 10^{33}$ y	∞
n	887 s	$2.7\ 10^{8}$ km
μ^-	$2.2\ 10^{-6}$ s	659 m
π^+	$2.6\ 10^{-8}$ s	7.8 m
K^+	$1.2\ 10^{-8}$ s	3.7 m
K^0_L	$5.2\ 10^{-8}$ s	15.5 m
K^0_S	$0.9\ 10^{-10}$ s	2.7 cm
$\Lambda^0\Sigma^+\Xi^0\text{-}\Omega^-\ldots$	$\sim 10^{-10}$ s	~3 cm
$D^{0+}B^{0+}\Lambda_c^+\ \Lambda_b^0$	$\sim 10^{-12}$ s	~300 μm
π^0	$8.4\ 10^{-17}$ s	25 nm
$\eta\ \psi\ldots$	$<10^{-19}$ s	-

In practice we detect only:

$$\gamma, e^{\pm}, p^{\pm}, n, \mu^{\pm}, \pi^{\pm}, K^{\pm}, K_L^0$$

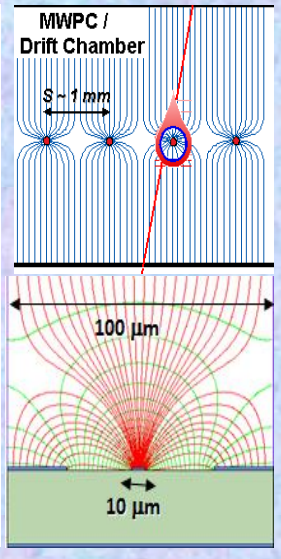
What do We See in Reality – The Challenge of Pileup

It is very important to determine with precision the particle trajectories to know their properties (momentum, position, direction etc) and to reconstruct the event

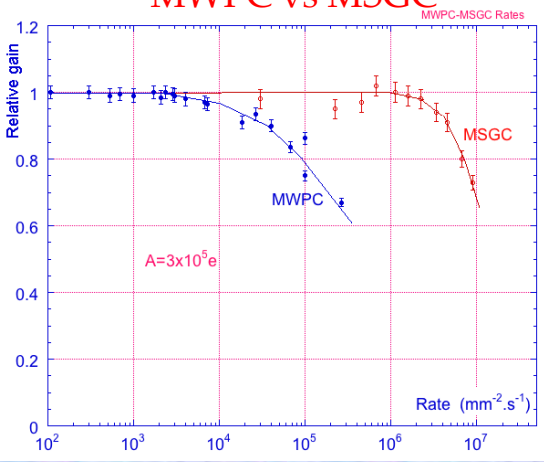
*real LHC pp event (~50 Vertices, 14 Jets, 2 TeV)

Micro-Pattern Gaseous Detector Technologies for Future Physics Projects

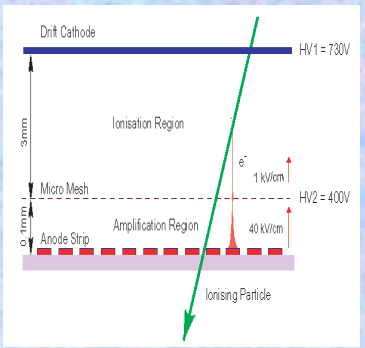
- Micromegas
- GEM
- Thick-GEM, Hole-Type and RETGEM
- MPDG with CMOS pixel ASICs ("InGrid")
- Micro-Pixel Chamber (µPIC)



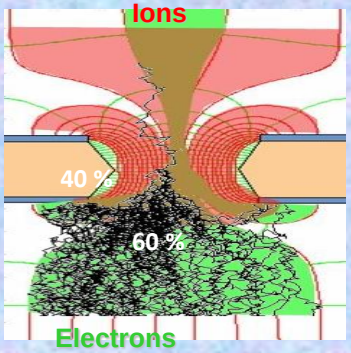
Rate Capability: MWPC vs MSGC



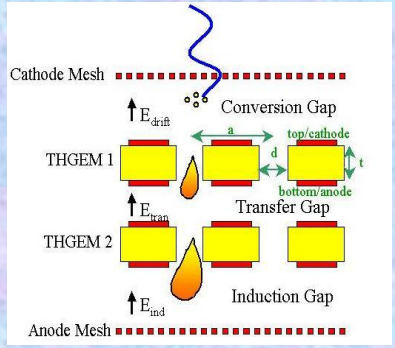
Micromegas



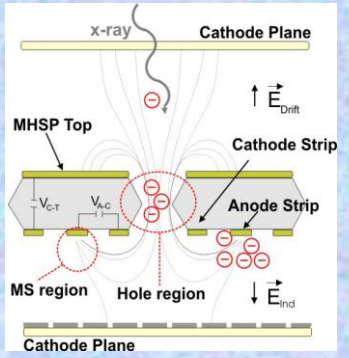
GEM



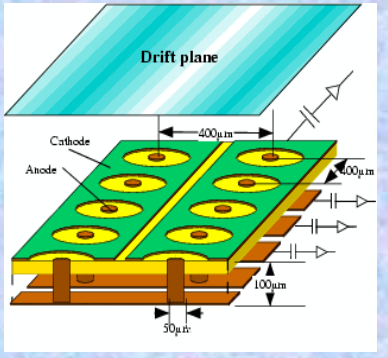
THGEM

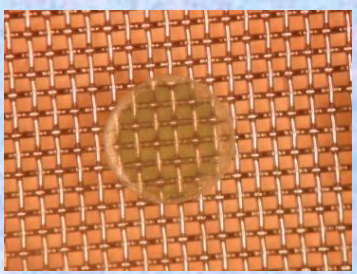


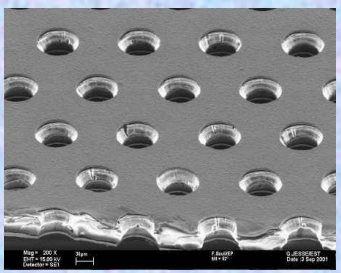
MHSP

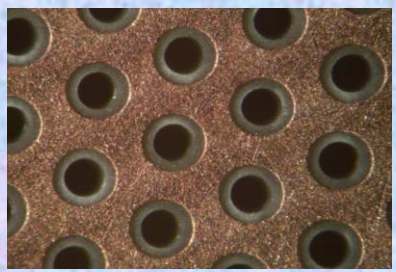


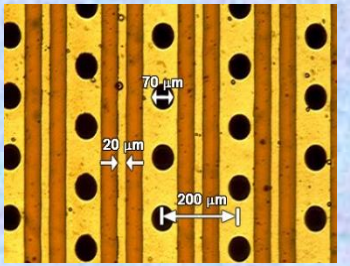
µPIC



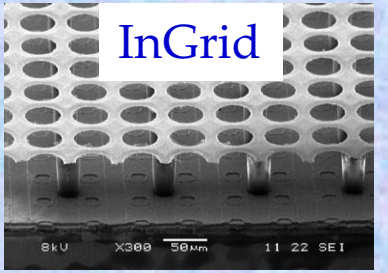








InGrid

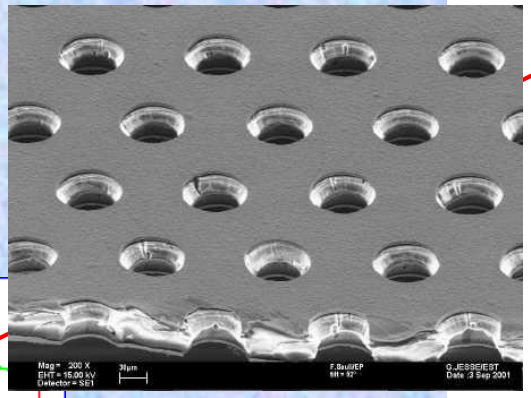


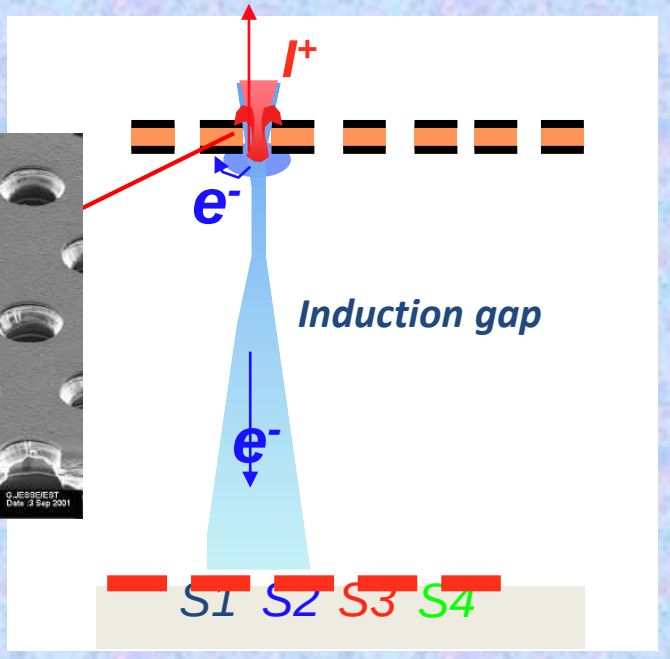
GEM (Gas Electron Multiplier)

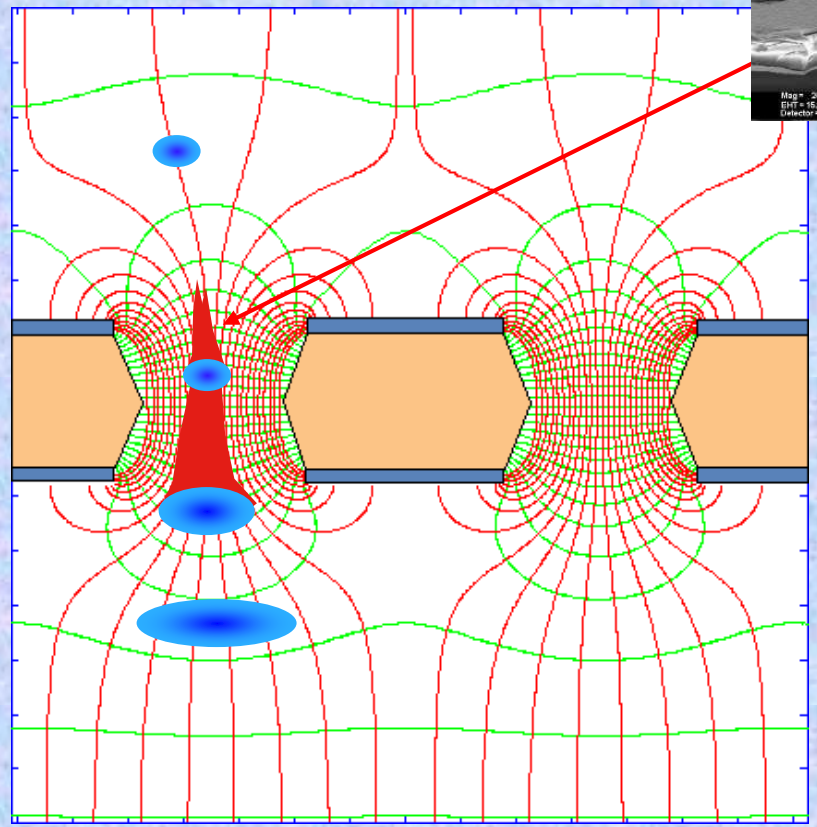
Thin metal-coated polymer foil chemically pierced by a high density of holes

A difference of potentials of ~ 500V is applied between the two GEM electrodes.

→the primary electrons released by the ionizing particle, drift towards the holes where the high electric field triggers the electron multiplication process.

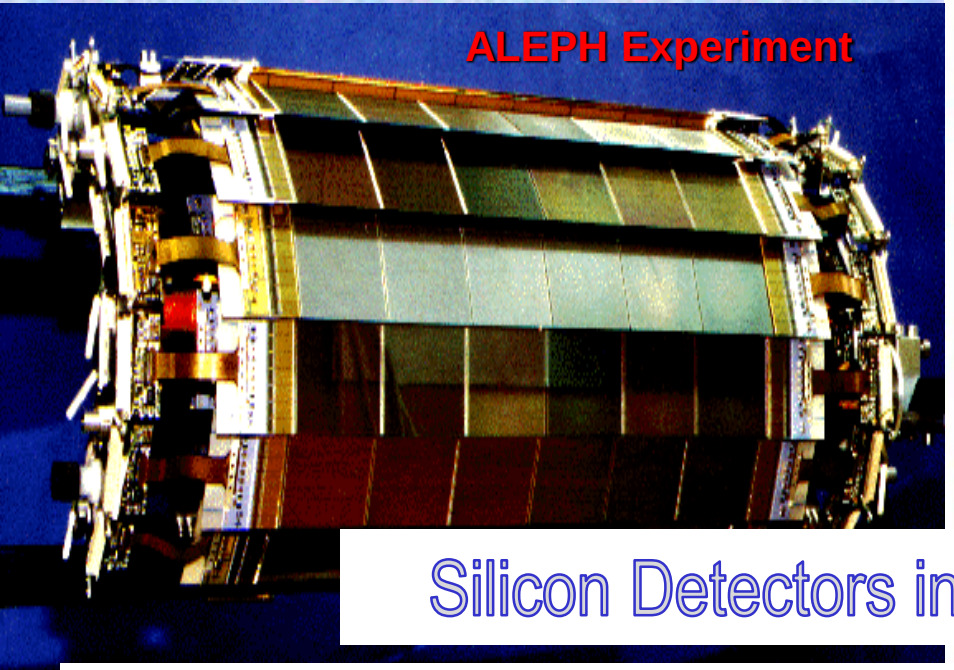


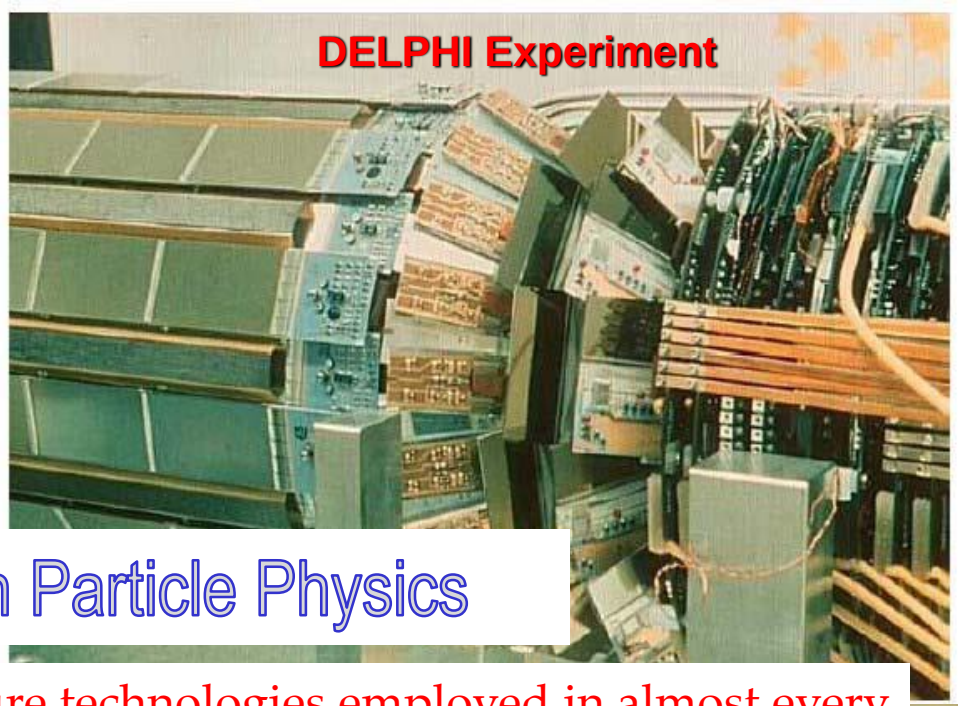




- Electrons are collected on patterned readout board.
- A fast signal can be detected on the lower GEM electrode for triggering or energy discrimination.
- All readout electrodes are at ground potential.

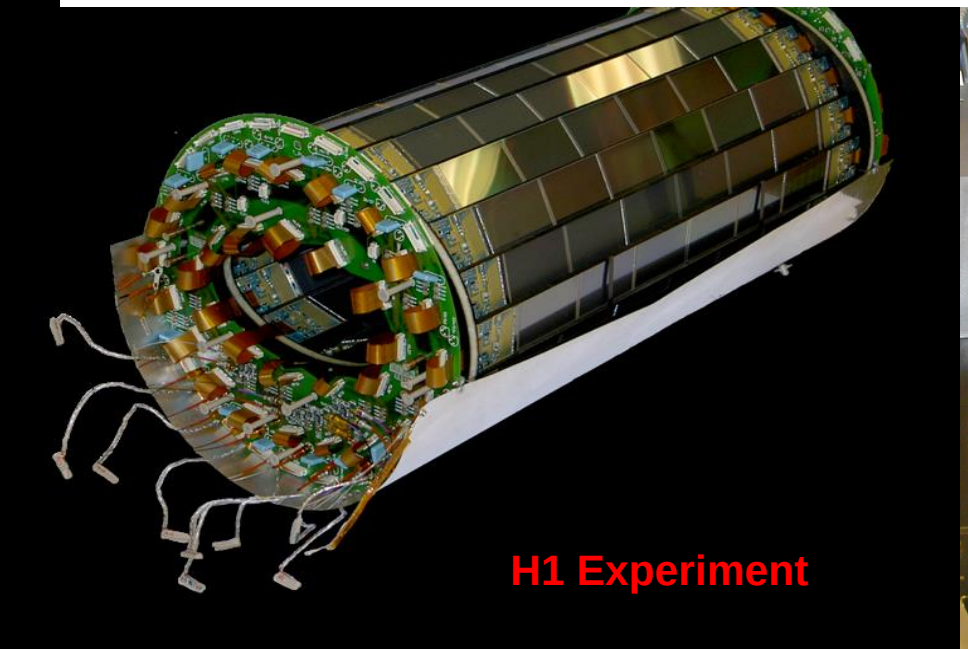
F. Sauli, Nucl. Instrum. Methods A386(1997)531
F. Sauli, http://www.cern.ch/GDD

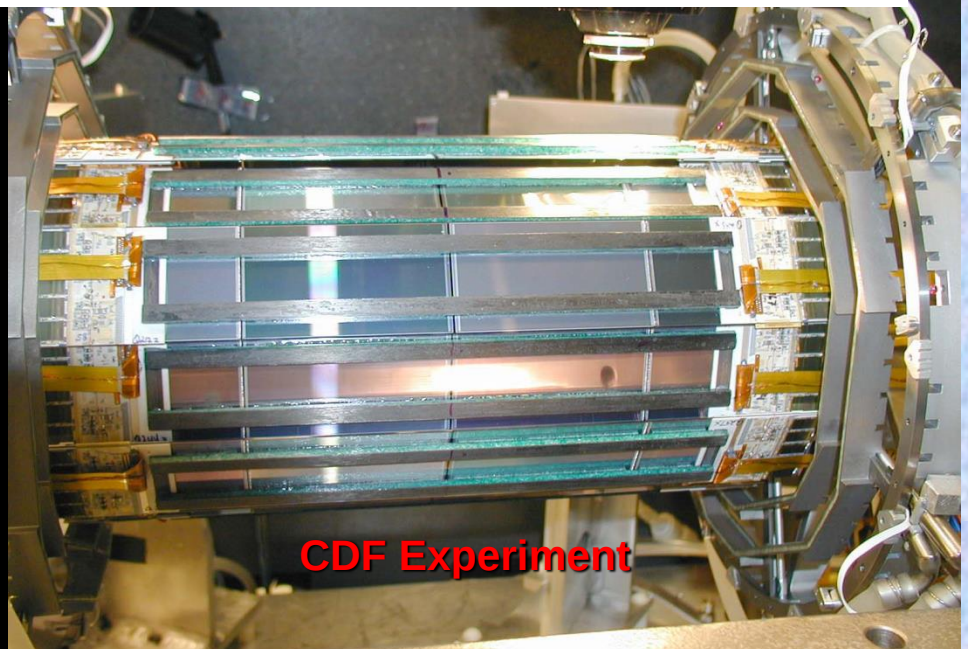




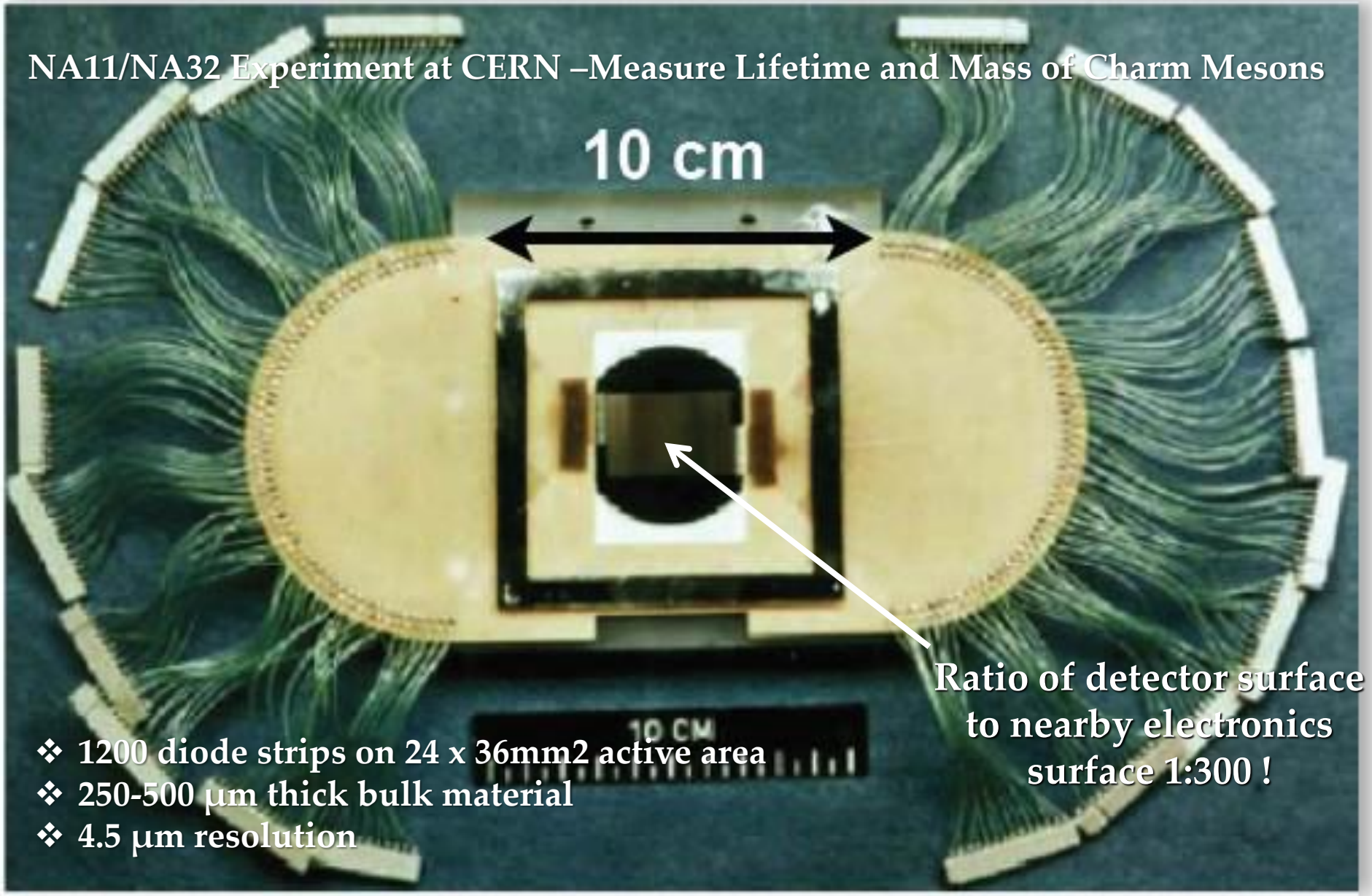
Silicon Detectors in Particle Physics

Strip and hybrid pixel detectors are mature technologies employed in almost every experiment in high energy physics.





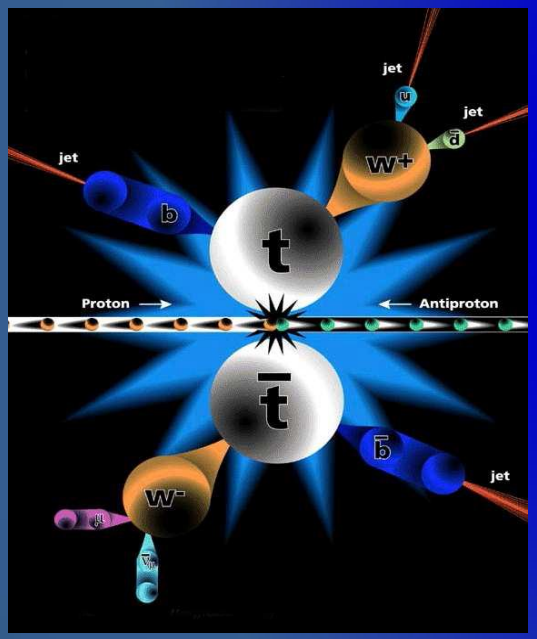
1983: First Silicon Strip Detector in HEP

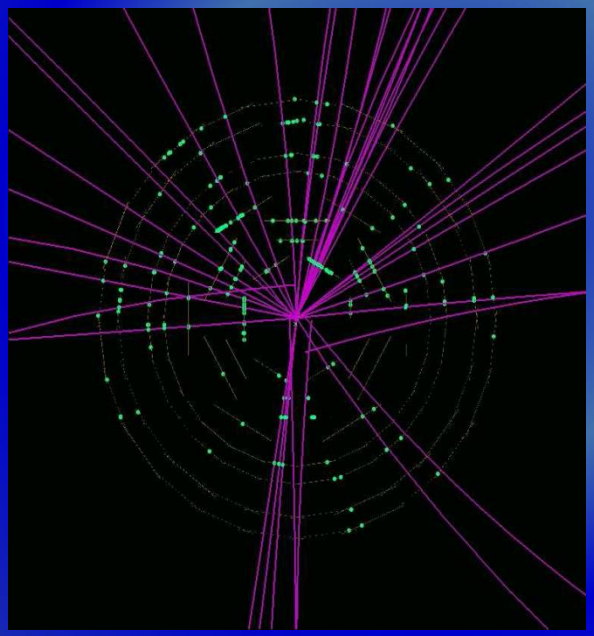


1995: Discovery of Top Quark at Tevatrion

1980's: The post era of the *Z and W discovery, after the observation of Jets at UA1 and* UA2 at CERN – "To proceed with high energy particle physics, one has to tag the flavour of the quarks!"

Top Quark Production at Tevatron
(t tbar → bW bbarW):





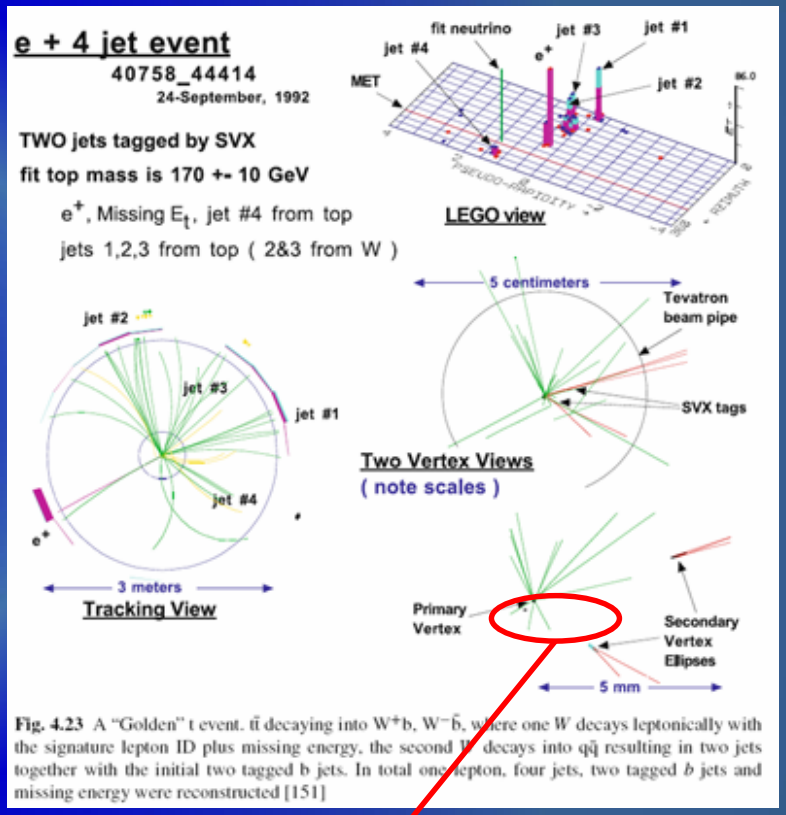
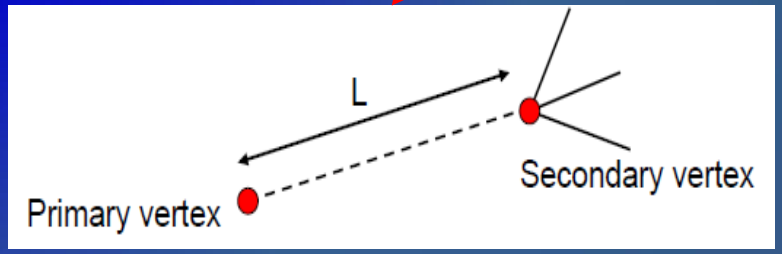


Fig. 4.23 A "Golden" t event. $t\bar{t}$ decaying into W^+b, $W^-\bar{b}$, where one W decays leptonically with the signature lepton ID plus missing energy, the second W decays into $q\bar{q}$ resulting in two jets together with the initial two tagged b jets. In total one lepton, four jets, two tagged b jets and missing energy were reconstructed [151]

b-jet identification is crucial, making use of 1.5 ps b lifetime:
→flight distance few 100 μm
→ need hit precision ~ 10 μm

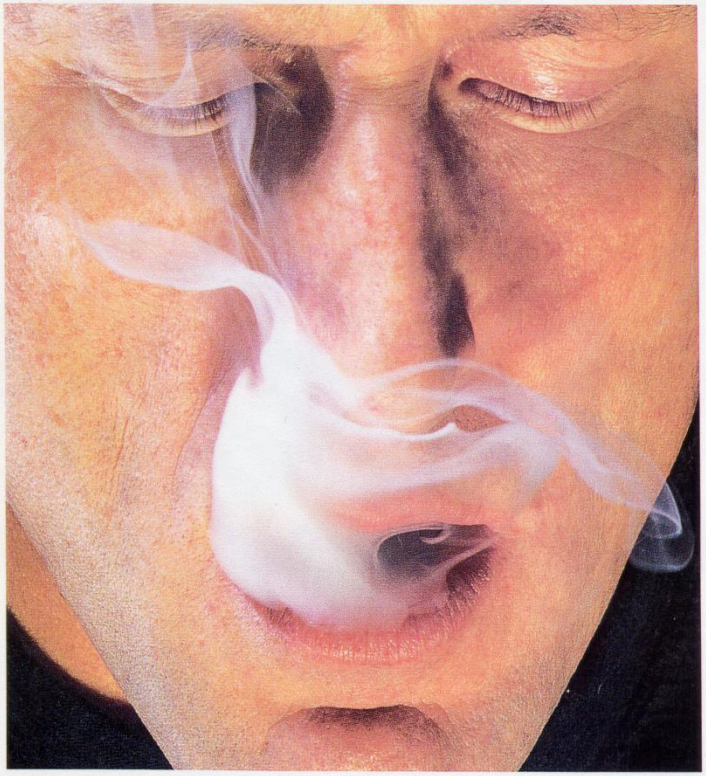


SCIENTIFIC AMERICAN

MAY 1995

$3.95
U.K. £2.75

What found the top quark.
Archaeology in peril.
The Niels Bohr mysteries.



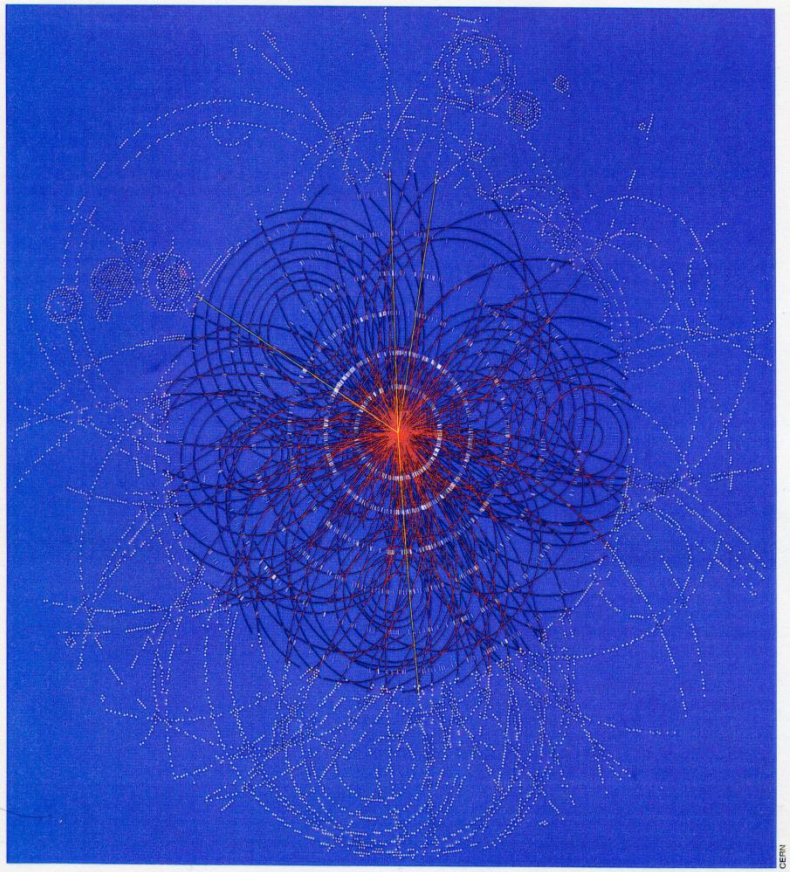
9 770036 873022 05>

***Clouds** of tobacco smoke continue their spread, despite warnings.*

The Silicon Microstrip Detector

Produced with the same tools used to create integrated circuits, these detectors recently helped to find the top quark and are central to other crucial experiments

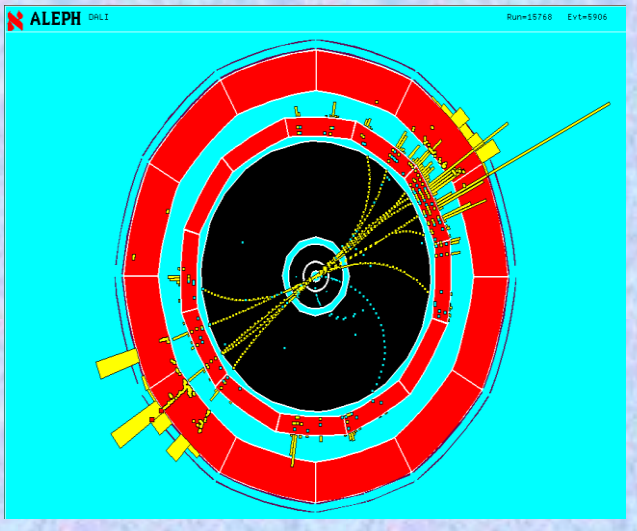
by Alan M. Litke and Andreas S. Schwarz



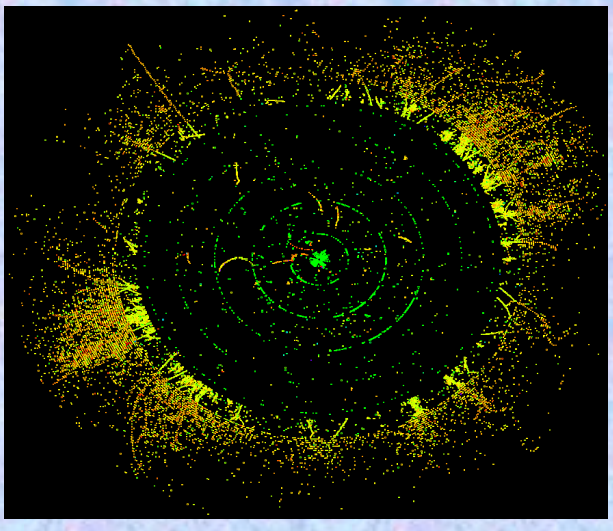
Silicon Detectors has transformed the way we look at particles

1950-1970: Pre-Silicon Era-
photo of ionization trails

1990: Si-vertex detector
& gaseous tracking (TPC)



2010s: SiD concept for ILC
- Si vertexing, Si tracking
- Si calorimetry



It might look like we are actually seeing less now,but we can see a lot more than in pre-silicon era !

From Microelectronics to Nanoelectronics:
Detectors are more and more based on semi-conductor technology
→ from vertex elements (20 um feature size)
→ to Si-calorimetry (ILC)

Silicon surface:

ATLAS and CMS need to exchange Si-trackers during LS3 (2022/23) due to radiation effects: **400 m^2**

CMS ECAL/HCAL Endcap: **600 m^2** ?

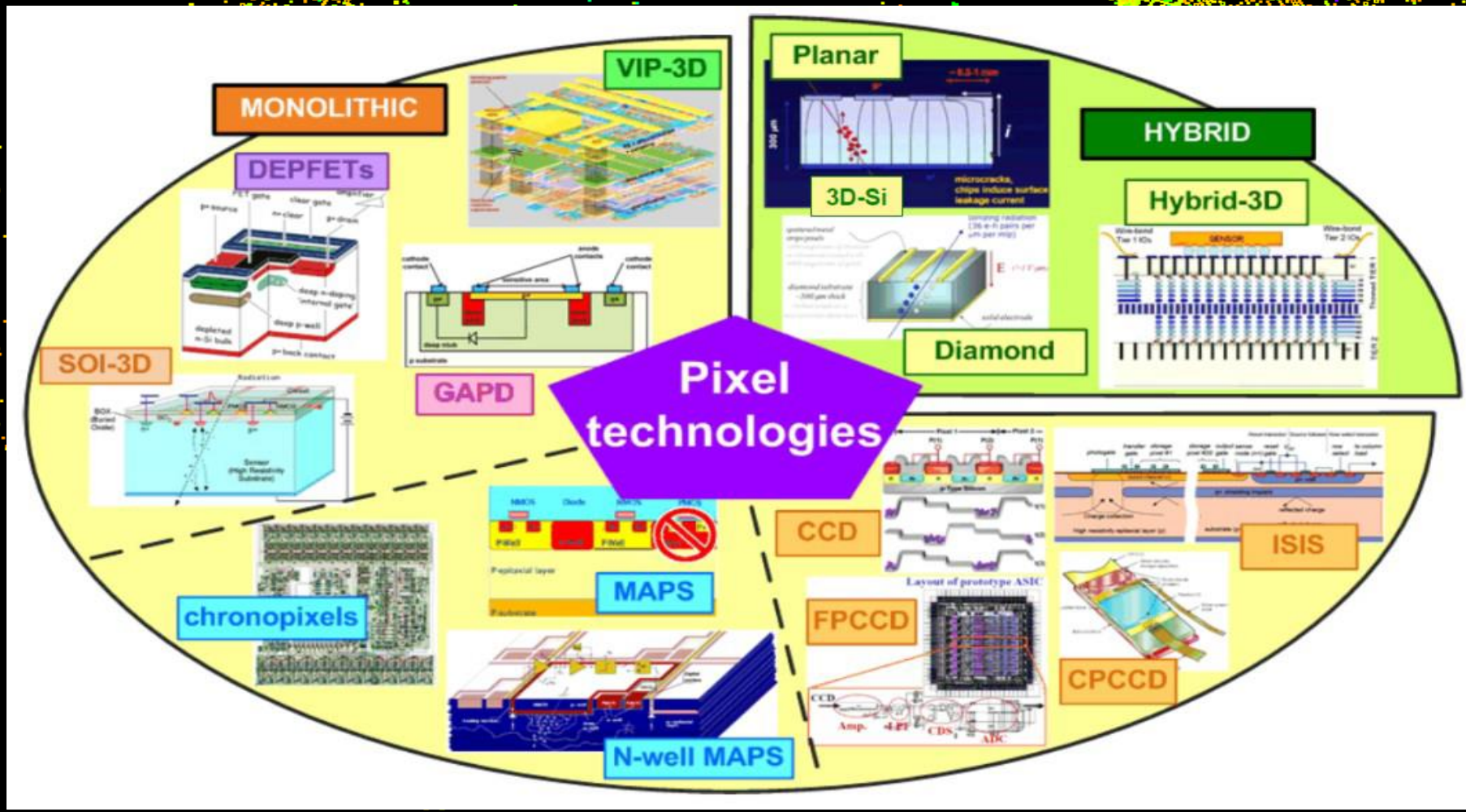
ILD/SiD ECAL: **2500 (1200) m^2**

Why are Silicon Detectors such a Success ?

Enormous benefit (compared to gaseous detectors):

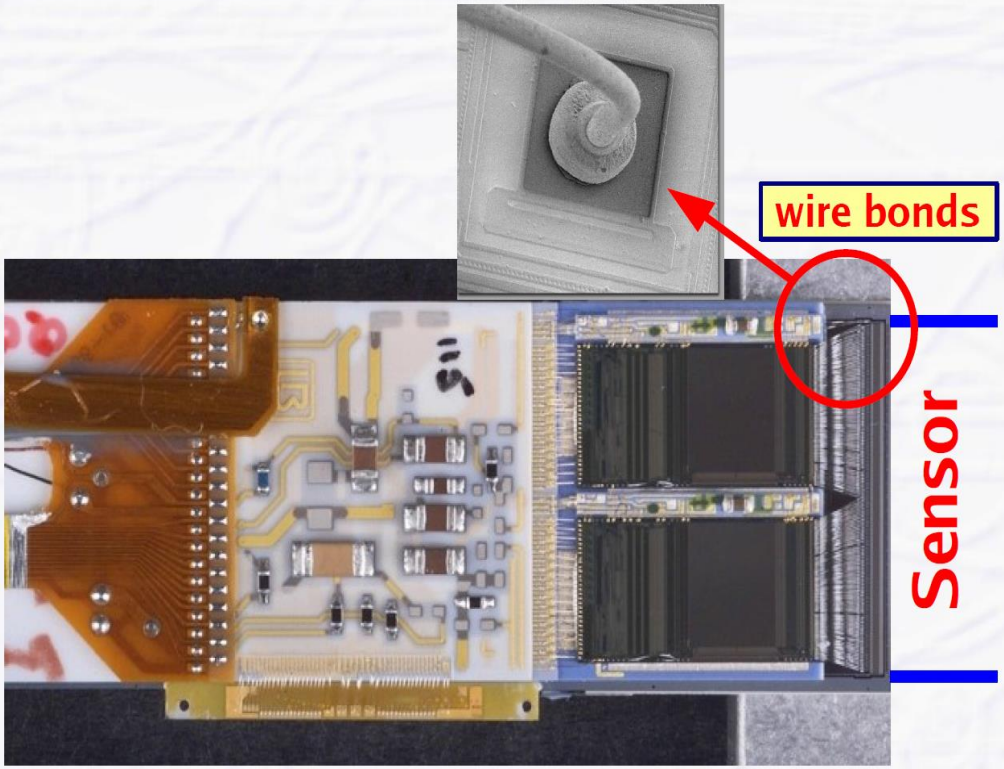
→ Huge technological advances of silicon technology in the IT industry

→ Pattern and structure are industry standard

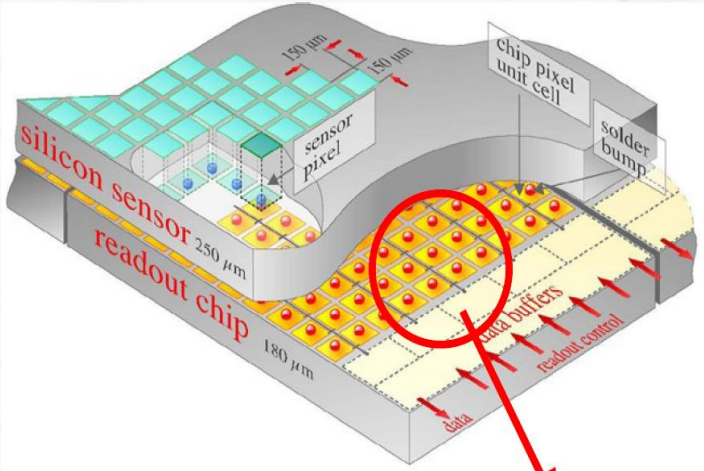


Si-Detector Electronics and Si-Pixels

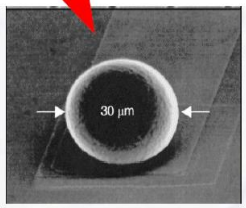
- **Silicon detectors have a laaaarge number of electronics channels, ~10^7 each for ATLAS and CMS Si trackers**
  - requires highly integrated chips for amplification, shaping, zero suppression (only information of strips with signals is read-out) and multiplexing (put all strip signals on a few cables only)
  - → **electronics is directly connected to the sensor (the "multi-diode") via wire bonds**



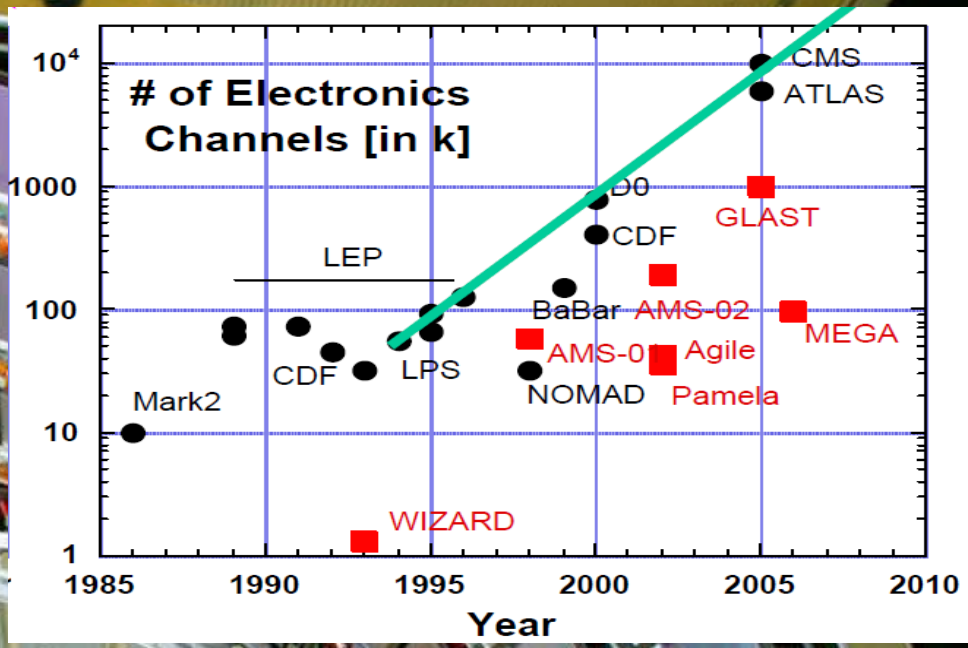
Si-strip detectors provide only 1 coordinate, Pixel detectors are 2D detectors

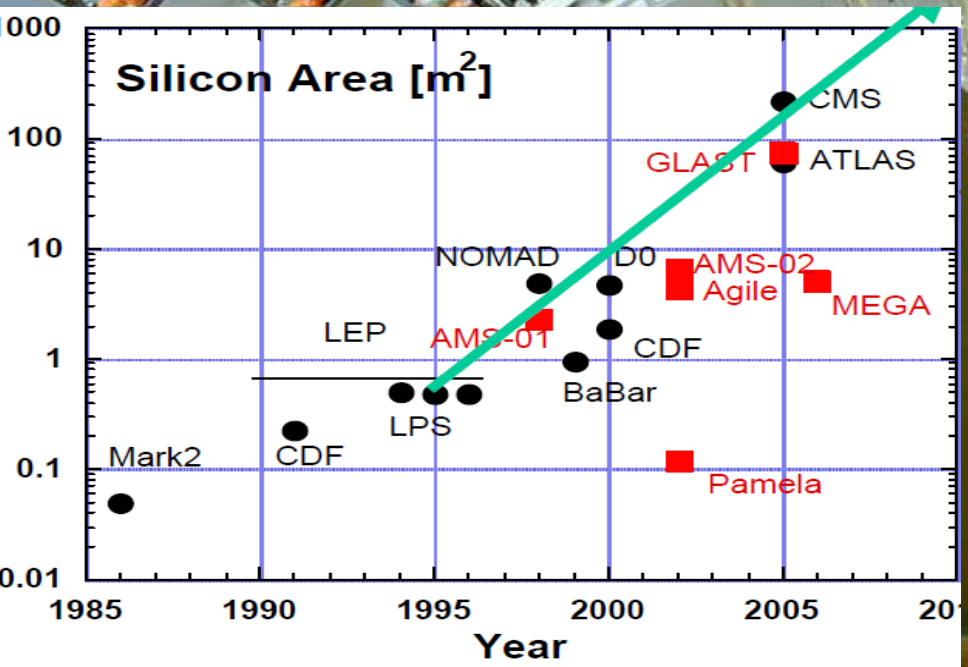


Pixel detector need "bump" bonding and have even more channels, ~10^8 - 10^9



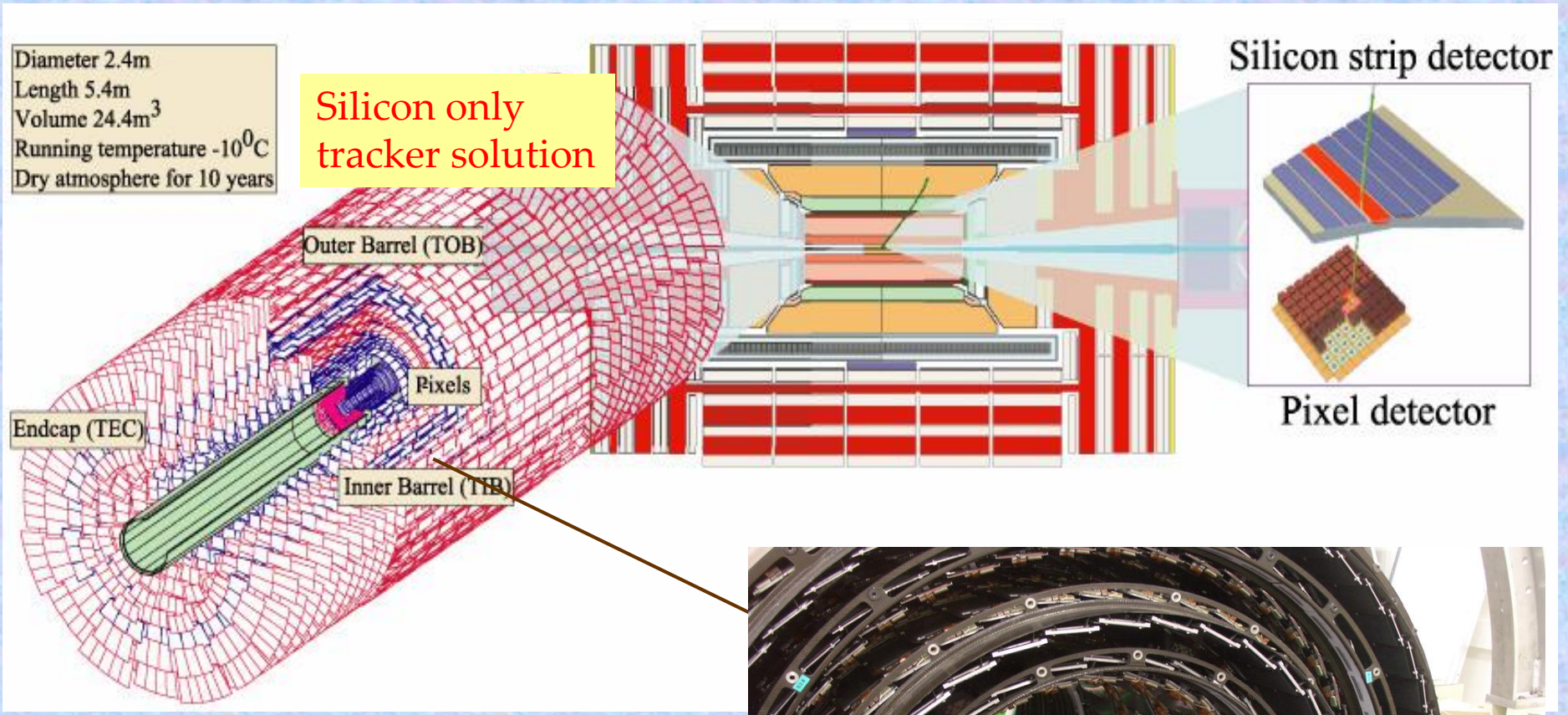
Silicon Detectors in Particle Physics: Evolution of Scale

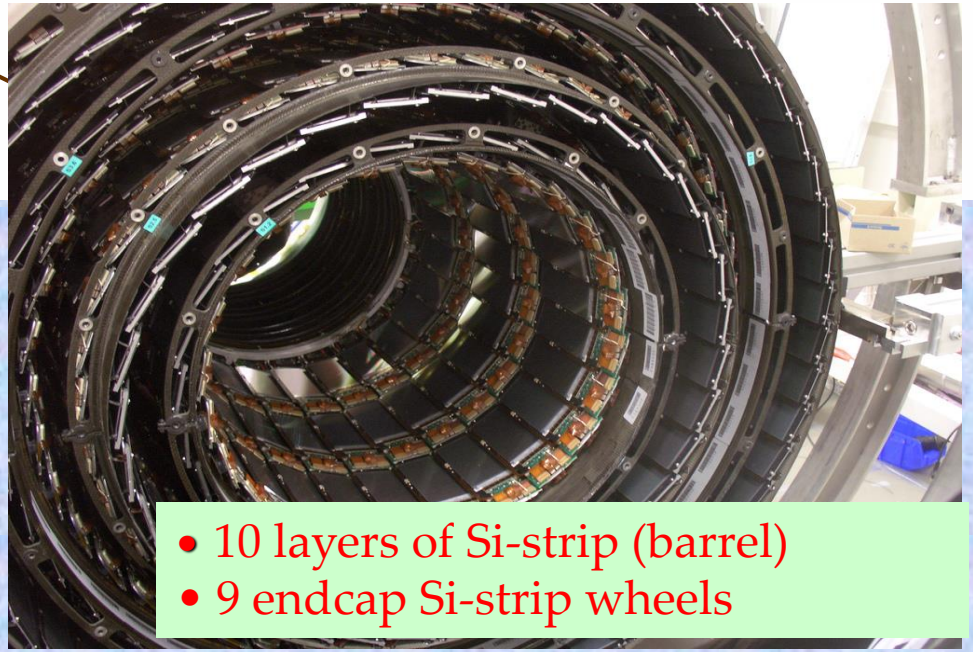




CMS: ~ 220 m^2 Silicon:
→ More than all other previous HEP experiments combined !

The CMS Tracker: Pixels and Strips





- 10 layers of Si-strip (barrel)
- 9 endcap Si-strip wheels

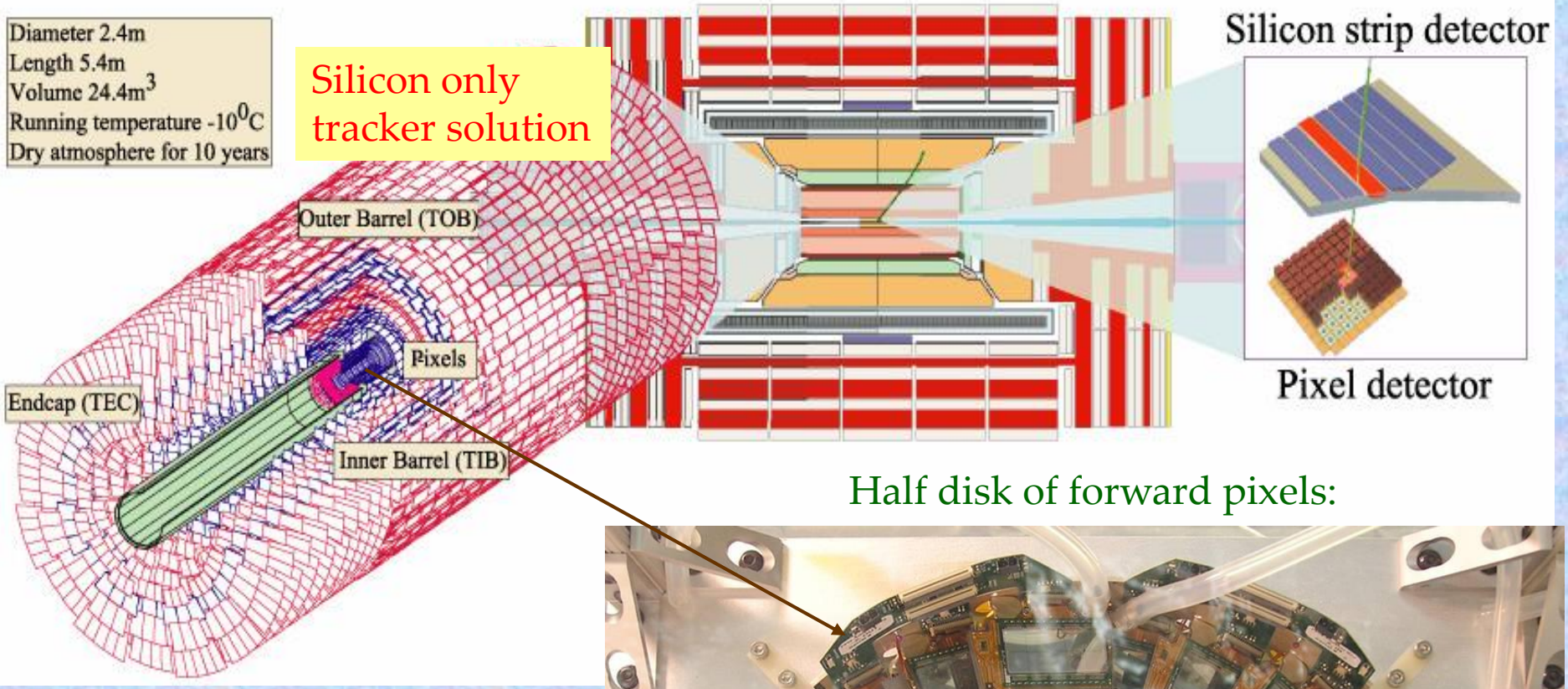
Silicon Strip Detectors: 220 m^2

- 25000 silicon sensors
- 10 M strips = electronic ch.
- 75376 readout chips
- 26.000.000 bonds
- 37.000 analog optical links

The CMS Tracker: Pixels and Strips

Diameter 2.4m
Length 5.4m
Volume 24.4m^3
Running temperature -10^{0}C
Dry atmosphere for 10 years

Silicon only tracker solution



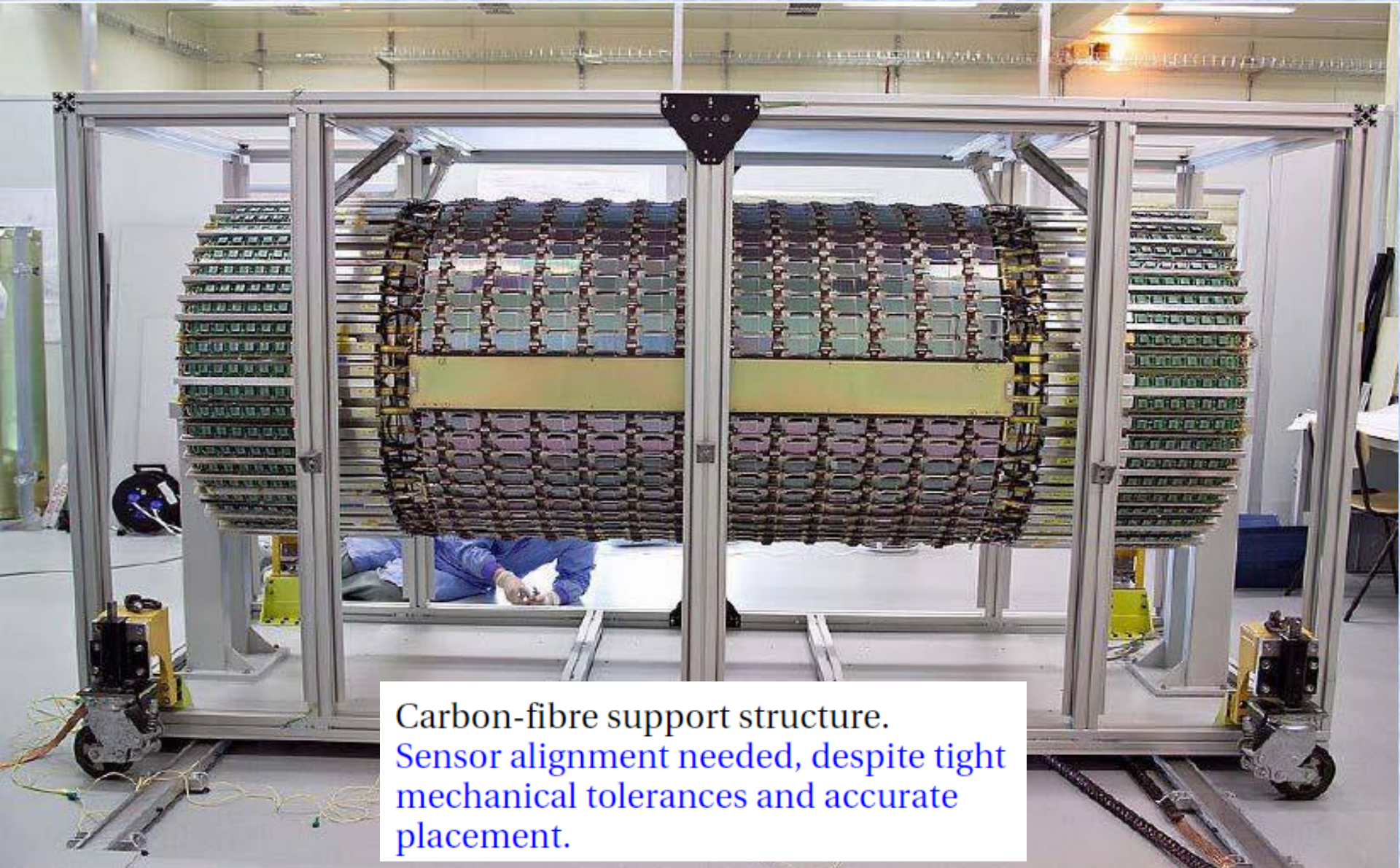
Half disk of forward pixels:

Pixel Detector: ~ m^2

- 3 layers of pixels
- 1440 pixel modules
- 66 M pixel = electronic channels

The ATLAS Inner Central Tracker (Barrel)

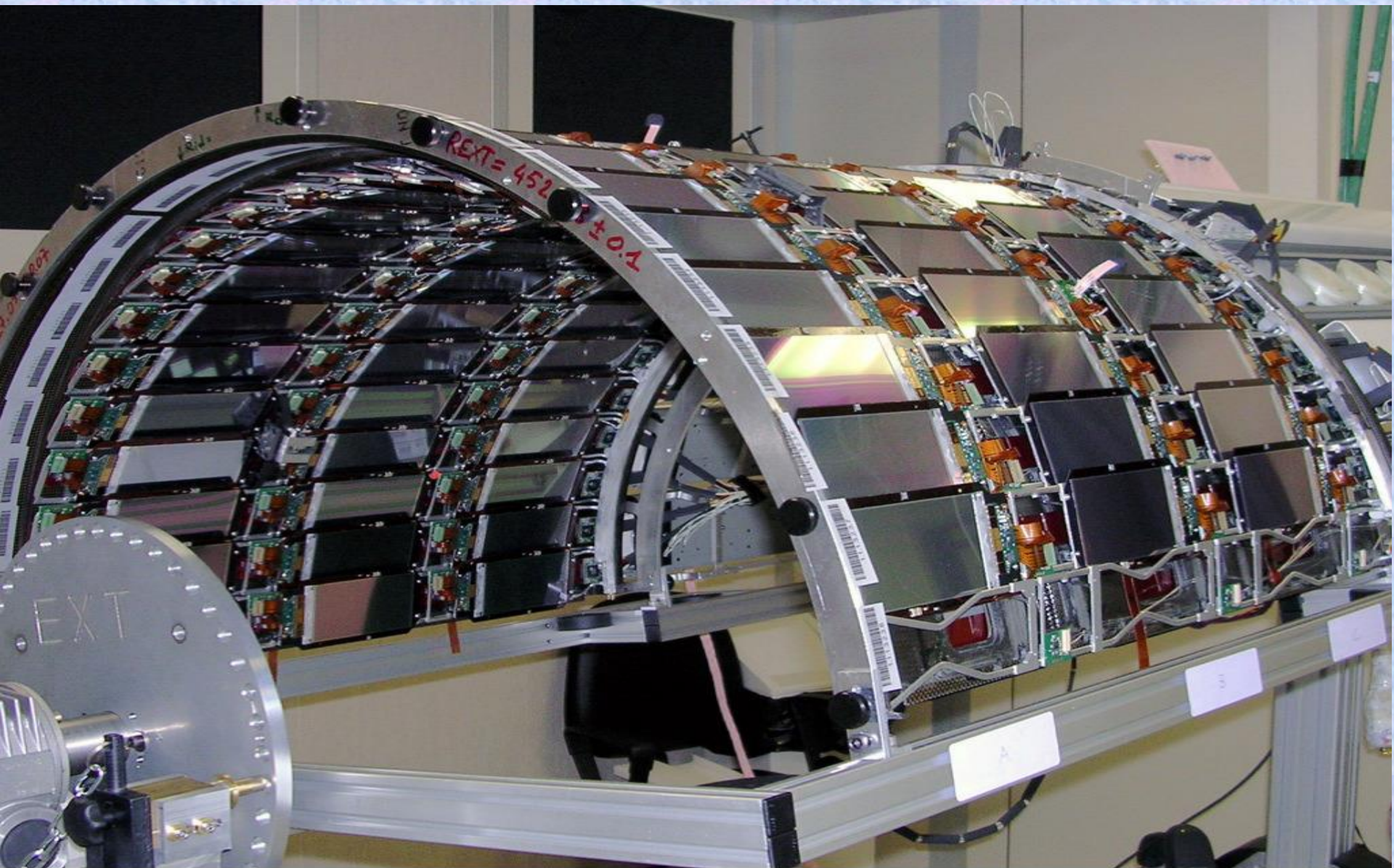
The most critical parts are the sensors, ASICs and system engineering (mechanics, power, cooling, assembly, etc) and integration



Carbon-fibre support structure.
Sensor alignment needed, despite tight mechanical tolerances and accurate placement.

The CMS Inner Central Detector (Barrel)

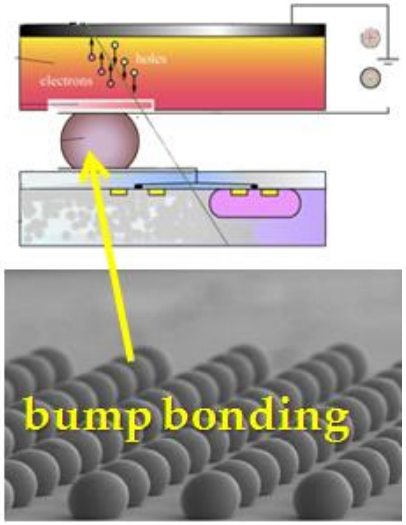
The most critical parts are the sensors, ASICs and system engineering (mechanics, power, cooling, assembly, etc) and integration



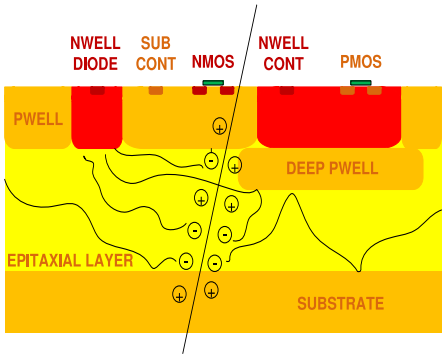
Solid State Tracking: Detector-Electronics Integration Trends

- Radiation hardness improvements demand newer technologies
- Improved functionality can only be achieved with higher integration
- Power dissipation and material budget must be reduced

TODAY: Pixels
50 – 100s μm

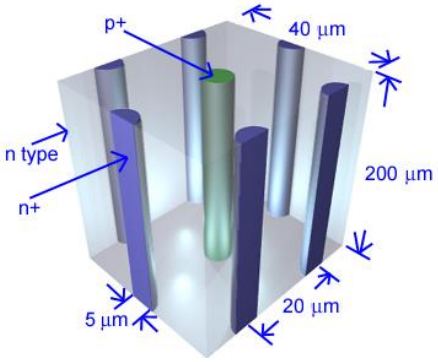


TODAY: Monolithic
25 – 50 μm (e.g. CMOS)



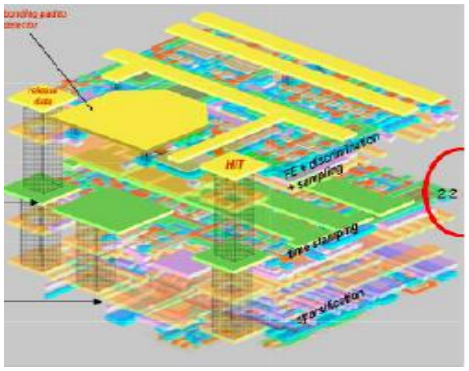
Integrated sensor & electronics: Less X0, no bonding, low noise

TOMORROW: 3D
Detectors (25–50 μm)



Lower V_{dep} (power)
Faster charge collection

Day After Tomorrow:
3D TSV (< 20 μm)



3D vertical Integration (TSV)

Motivation to develop new Pixel Detectors:

- Decrease fabrication cost
- Develop thinner pixel systems
- Easy fabrication of large area devices
- Integrate More (= denser) Intelligence

Trends and Perspectives:

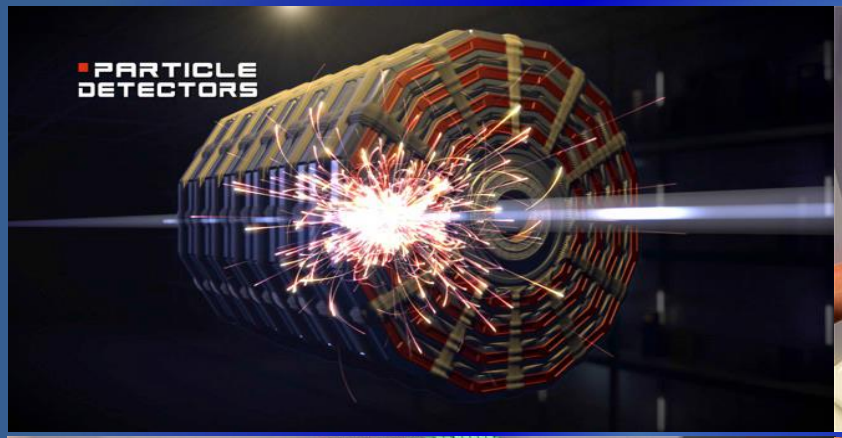
- Improve rad. hardness (p-type bulk)
- Reduce the thickness to 50 μm
- From 6″ to 8″ and 12″ wafers
- R&D on SLID/TSV interconnect.

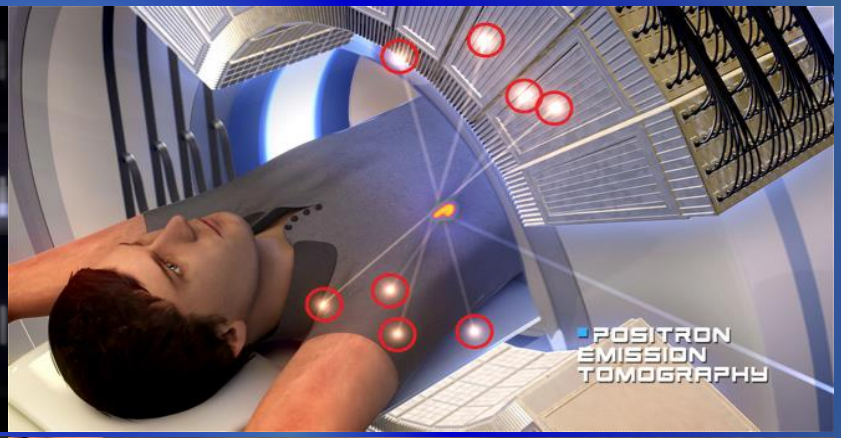
From LHC Particle Detectors to Medicine

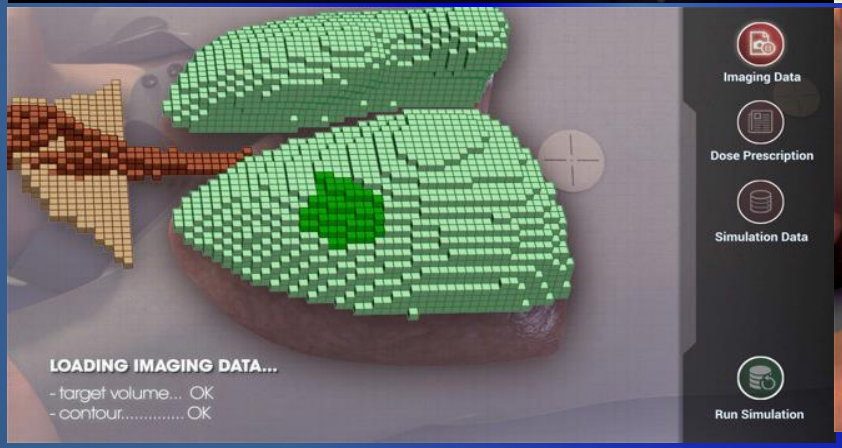
Silicon pixel detectors, and crystals of lead tangstate, used for calorimetry, have already found various applications, especially in medicine:

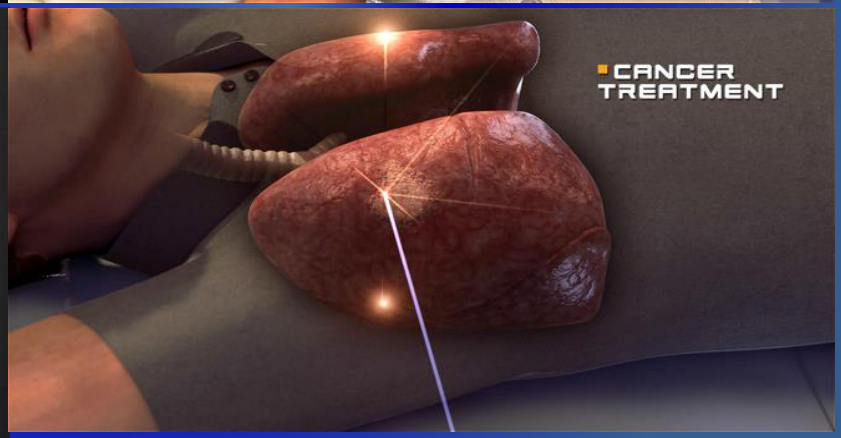
- Silicon pixels are deployed as Medipix, for medical imaging and diagnosis.

- CMS electronics to read out these crystals in a magnetic field opened the way to combined PET/MRI scanners.





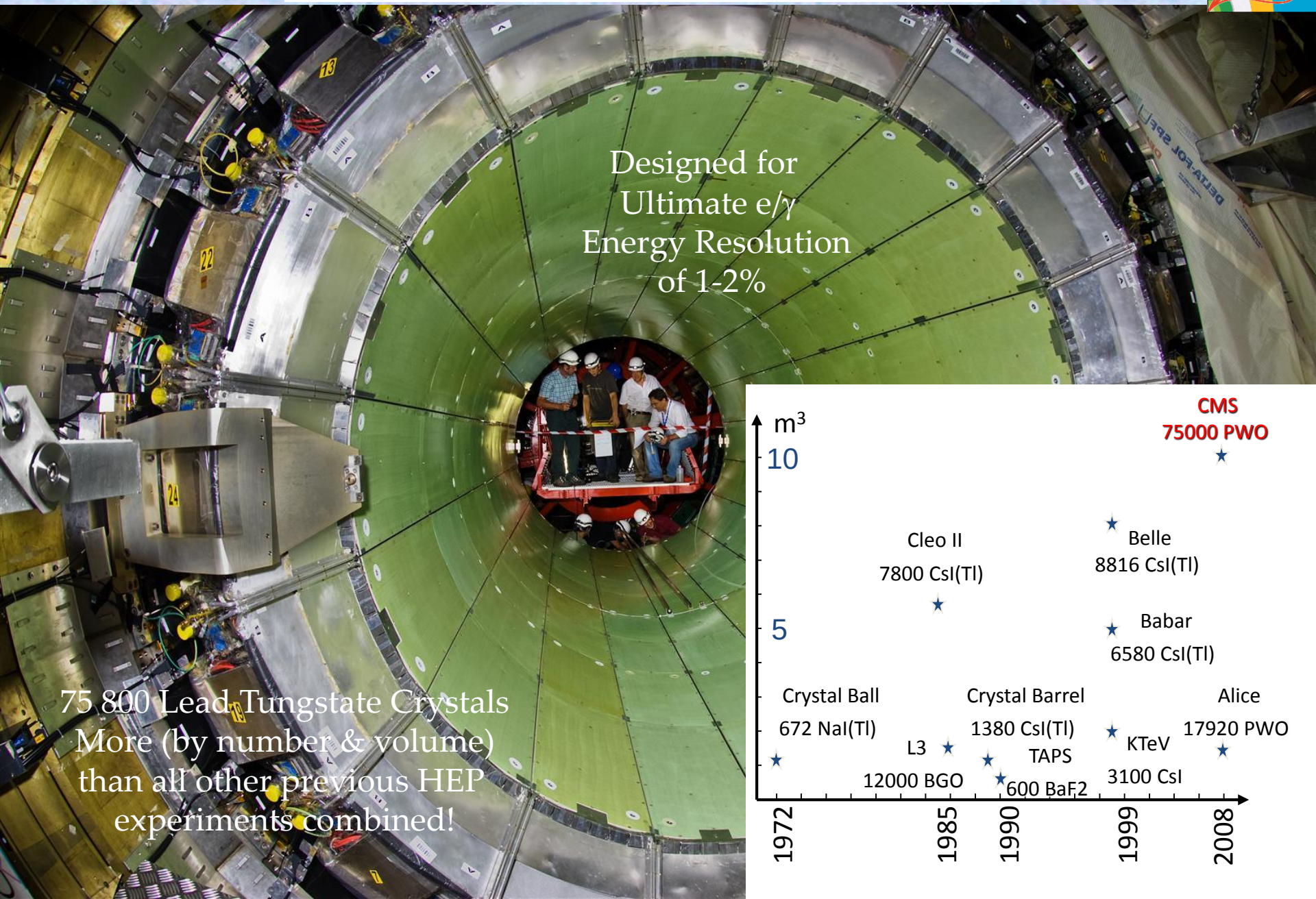




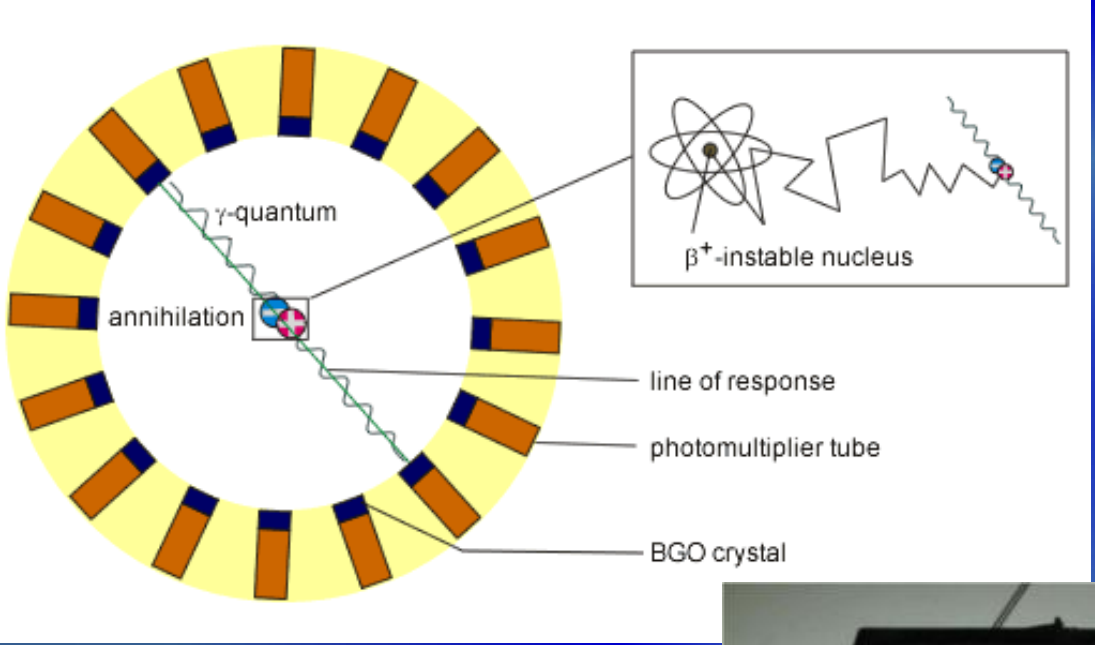
MEDIPIX: https://medipix.web.cern.ch/

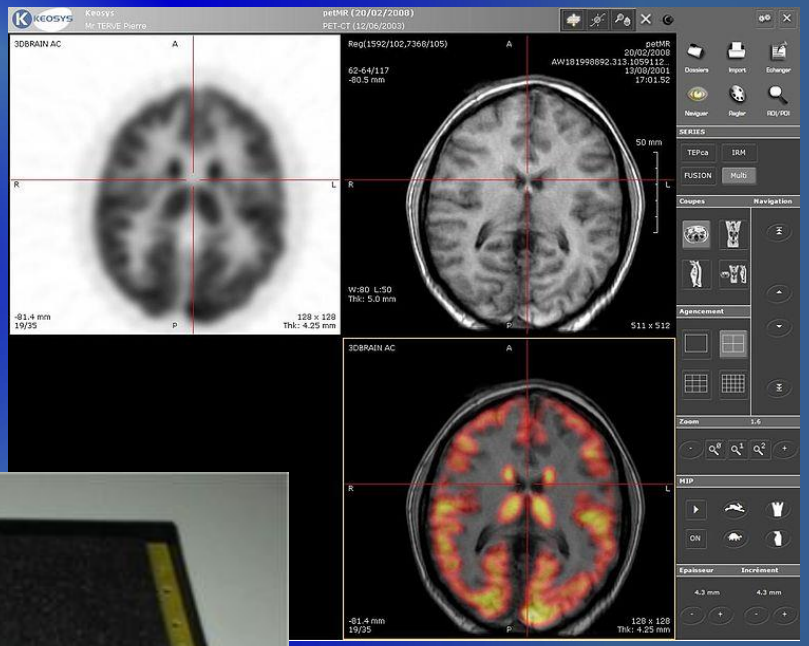
ClearPET: https://crystalclear.web.cern.ch/crystalclear/pet.html

CMS Electromagnetic Calorimeter



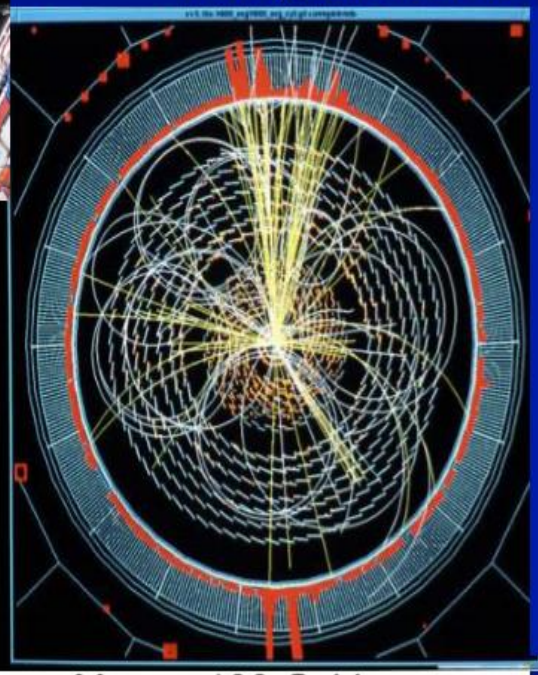
CERN to become established as an important facilitator of medical physics in Europe

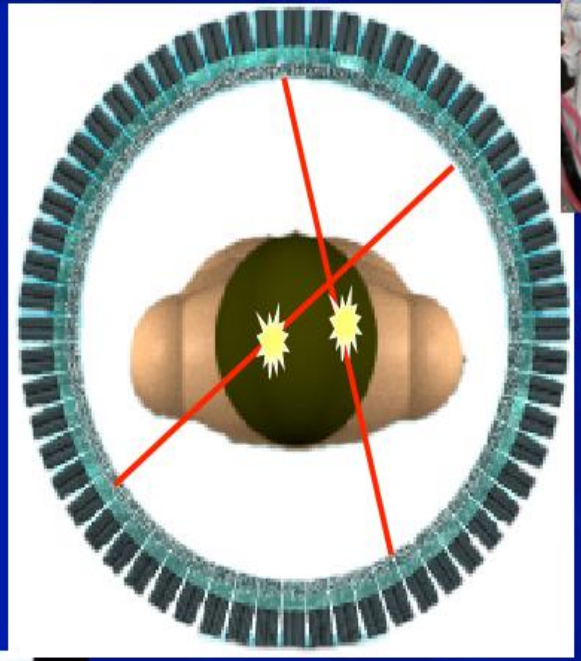




HEP & PET

Similarities and differences





Calorimeter

HEP

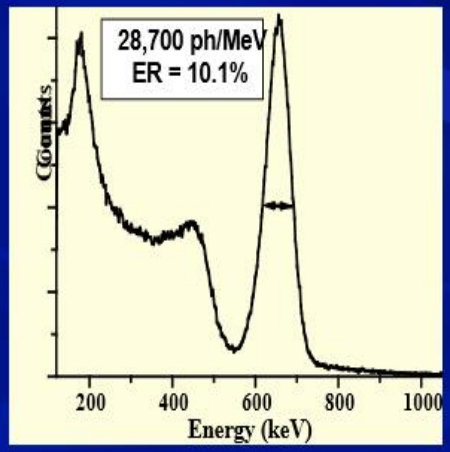
PET Camera

Biomedical Imaging

M_{Higgs} = 100 GeV

Similarities

Geometry and granularity
Detector (Crystals & scintillator)
Sensor (PMT,APD)
Digitizers: ADC,TDC,
Data volume (Gbytes)



Differences

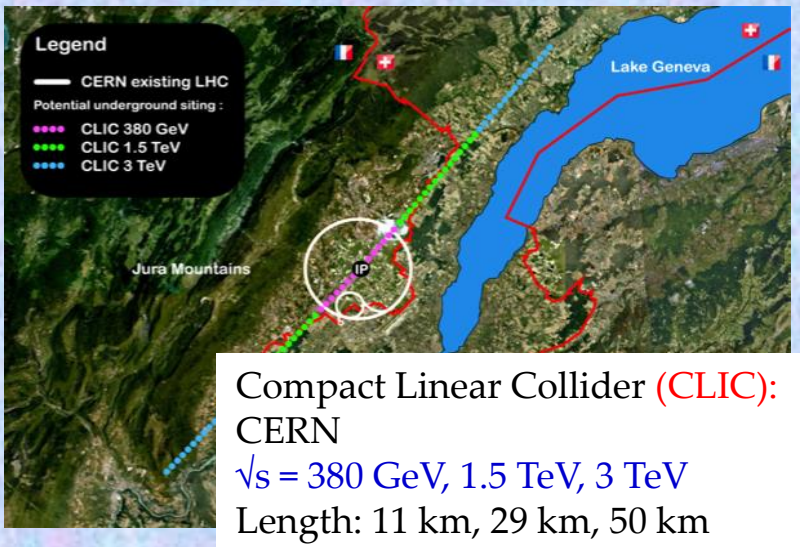
Energy range
(10GeV → -511keV)
Event Rate 40 → 10 MHz

No synchronization
Self triggered elrctronics
Multiple vertices

Future e+e- Colliders: "Higgs Factory" + possible Extension to Higher Energies

➢ Linear colliders: ILC, CLIC (extendable to higher energies)

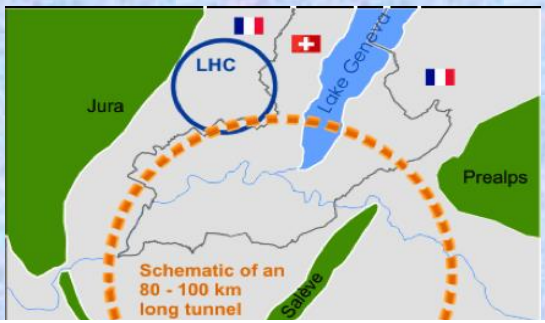
International Linear Collider (ILC):
Japan (Kitakami)
√s = 250 - 500 GeV (1 TeV)
Length: 21 km, 31 km (50 km)



Compact Linear Collider (CLIC):
CERN
√s = 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km, 50 km

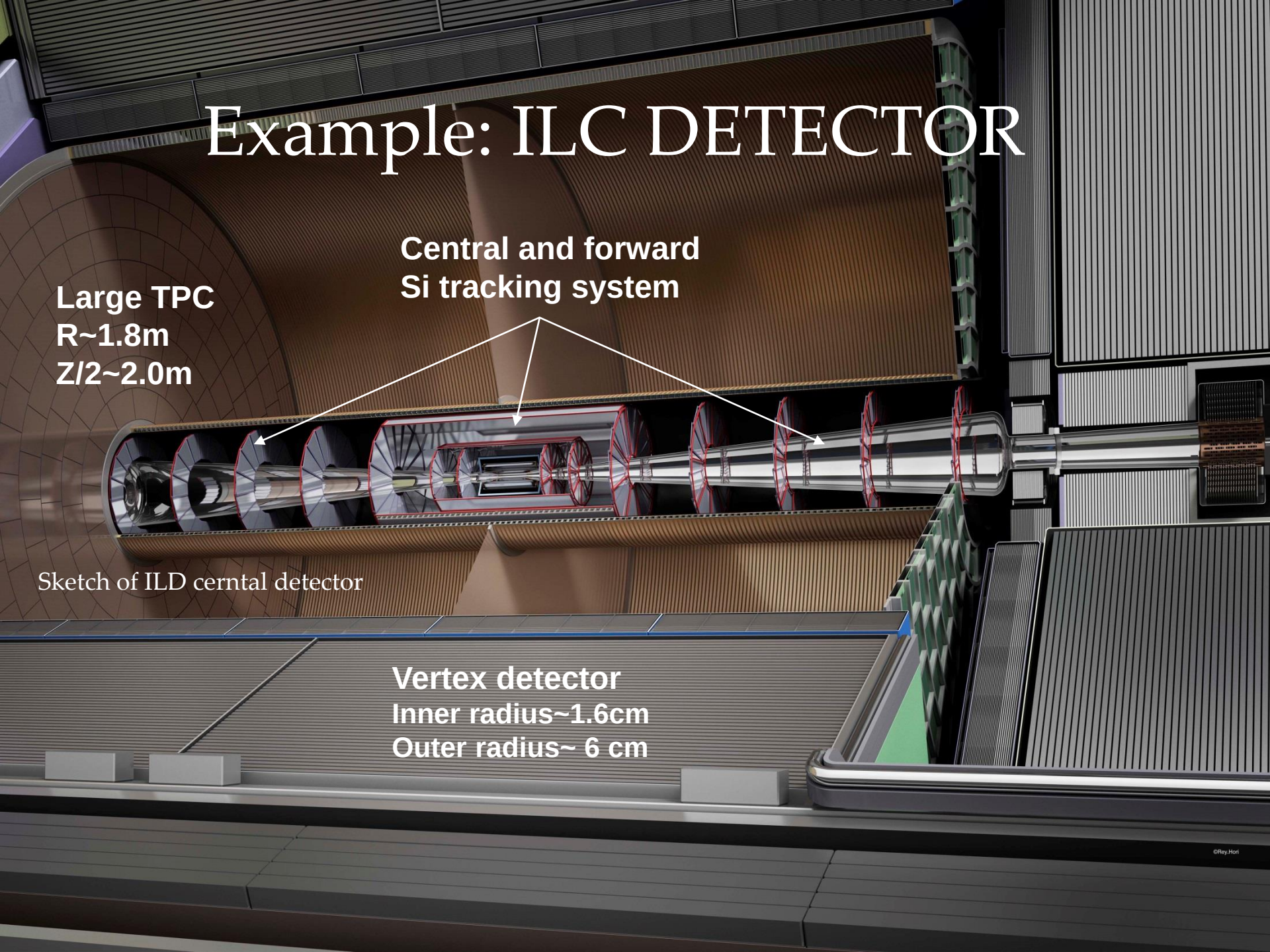
➢ Circular colliders: CEPC, FCC-ee

Circular Electron-Positron Collider (CEPC):
China
√s = 90 - 240 GeV (1 TeV)
Circumference: 100 km



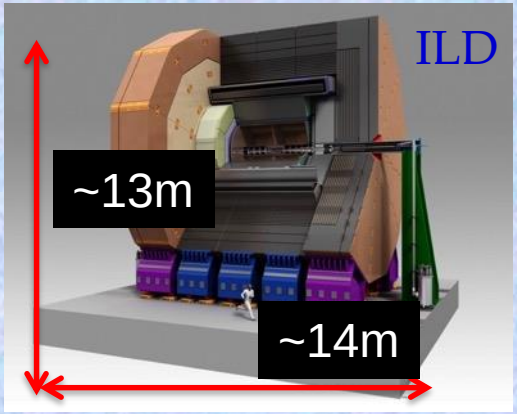
Future Circular Collider (FCC-ee):
CERN
√s = 90 - 350 GeV (1 TeV)
Circumference: ~100 km

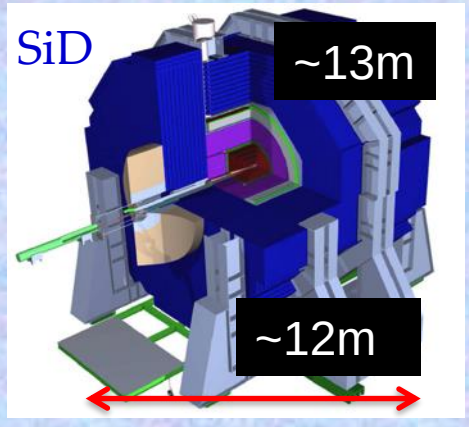
Example: ILC DETECTOR

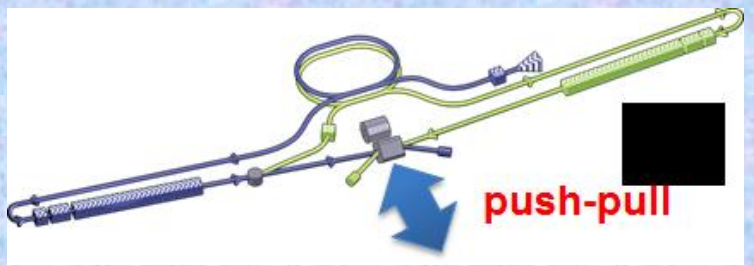


Sketch of ILD cerntal detector

Two Validated Detector Concepts: ILD and SiD







❖ **VERTEX**: flavour tag, IP resolution (H → bb, cc ττ)
~1/5 $r_{beampipe}$, 1/30 pixel size, ~1/10 resolution (ILC vs LHC)

$$\sigma_{IP} = 5 \oplus \frac{10}{p \sin^{3/2}\theta} (\mu m)$$

❖ **TRACKING**: recoil mass to Higgs (e+e- → ZH → llX)
~1/6 material, ~1/10 resolution (ILC vs LHC); B = 3.5 – 5T

$$\sigma(1/p) = 2 \times 10^{-5} (\mathrm{GeV}^{-1})$$

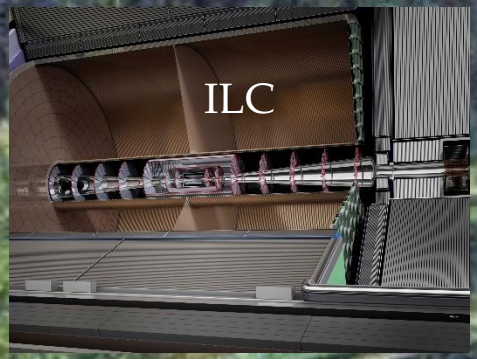
❖ **CALORIMETRY**: particle flow, di-jet mass resolution
1000x granularity, ~1/2 resolution (ILC vs LHC);
detector coverage down to very low angle

$$\sigma_E / E = 0.3 / \sqrt{E(\mathrm{GeV})}$$

ILD	SiD
Both optimized for PFA PFA Performance **~B·$R_{ECAL,inner}^2$** (two-track separation @ ECAL)	
B = 3.5 T	**B = 5 T**
$R_{ECAL,inner}$ = 1.8 m	**$R_{ECAL,inner}$ = 1.27 m**
Si + TPC tracking	**Tracking: Si only**
Share interaction point via push-pull	

ILC CMOS-based sensors for Science and Industry

CMOS sensors expected to provide an attractive trade-off between granularity, material budget, radiation tolerance, speed and power dissipation



Sub-atomic Physics:

- BT (EUDET, AIDA),
- Vertex det. (STAR, ALICE)

- X-Ray imaging lights sources equipment (SOLEIL)
- Industrial quality control (soldering, u-cracks)

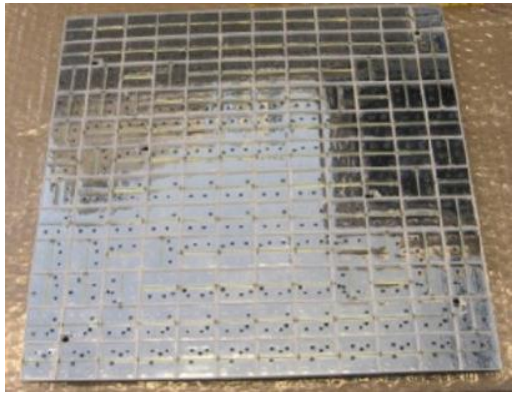
- X-Ray imagers molecular biology (nano-science)
- Mass spectroscopy (PIMMS)

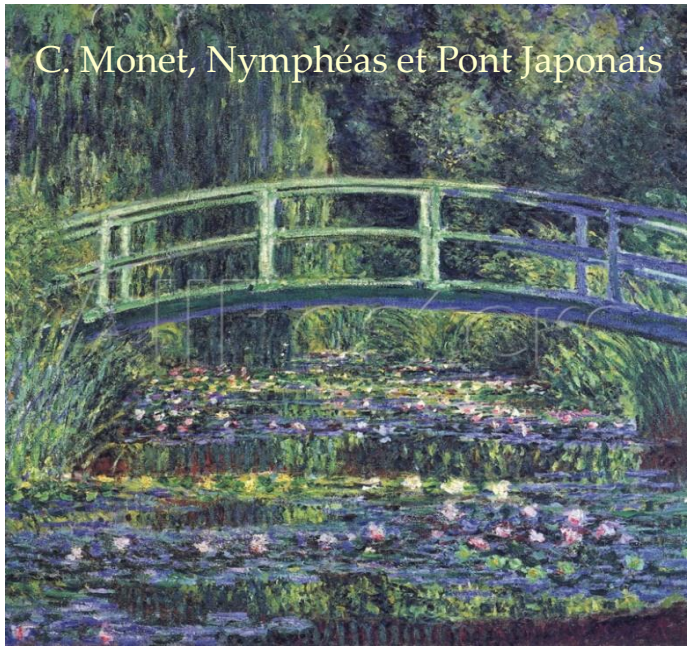
Art: C. Monet, Nymphéas et Pont Japonais

From SiPM-based ILC Calorimeter to Advanced PET-Systems

2006: ILC Calorimetry (8k ch.):

First large experience with SiPM operation (2006):



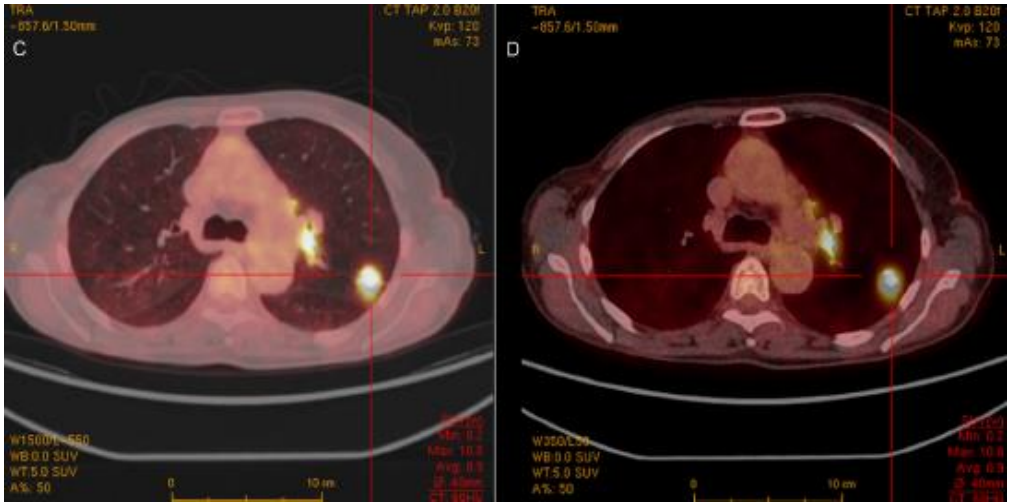


Today's PET imaging platforms using SiPMs:

- GE clinical PET/MR uses analog SiPM
- VEREOS Philips PET/CT uses digital SiPM

Multi-channels arrays of crystals + SIPM:

- minimum dead material between crystals
- SiPM packaging is crucial →up to 50% sensitivity improvement
- Monolithic arrays/high density of chan.

SiPMs represent today the future of Nuclear Medical Imaging → the only slowing down factor at the moment being the high associated cost.

A muli-modality approach (PET/CT,PET/MR) will be more and more requested in the clinical practice.