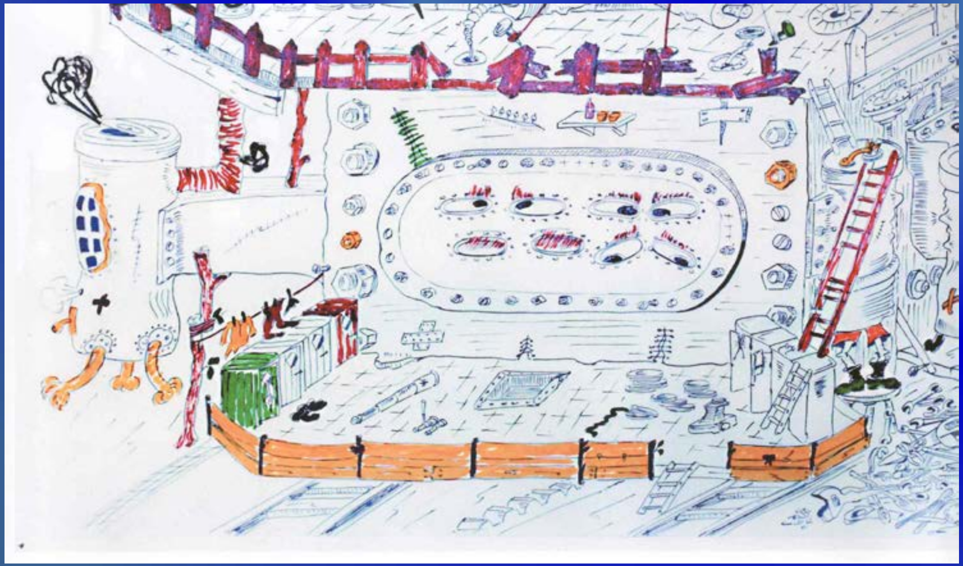
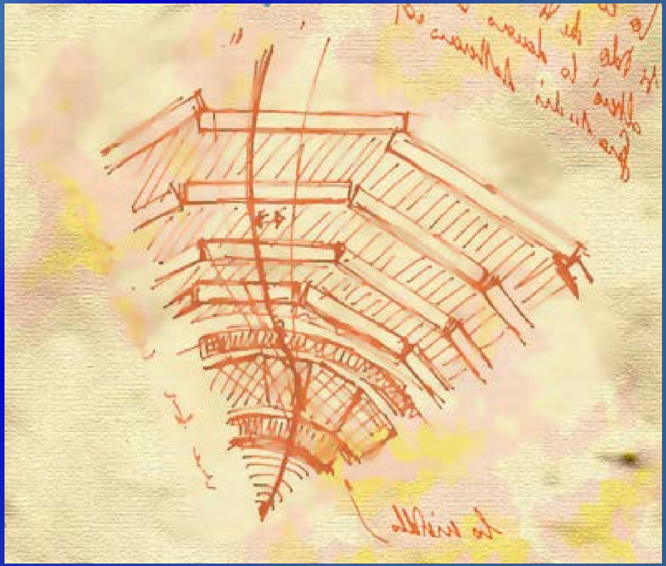
The Physics of Modern Particle Detectors: Gaseous Detectors

From (very) basic ideas to rather complex detector systems

Maxim Titov, CEA Saclay, France

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

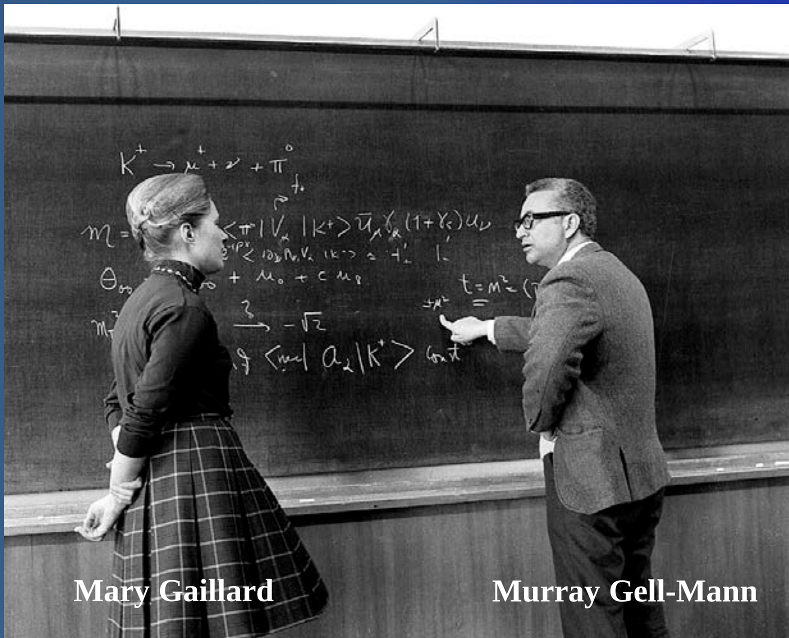




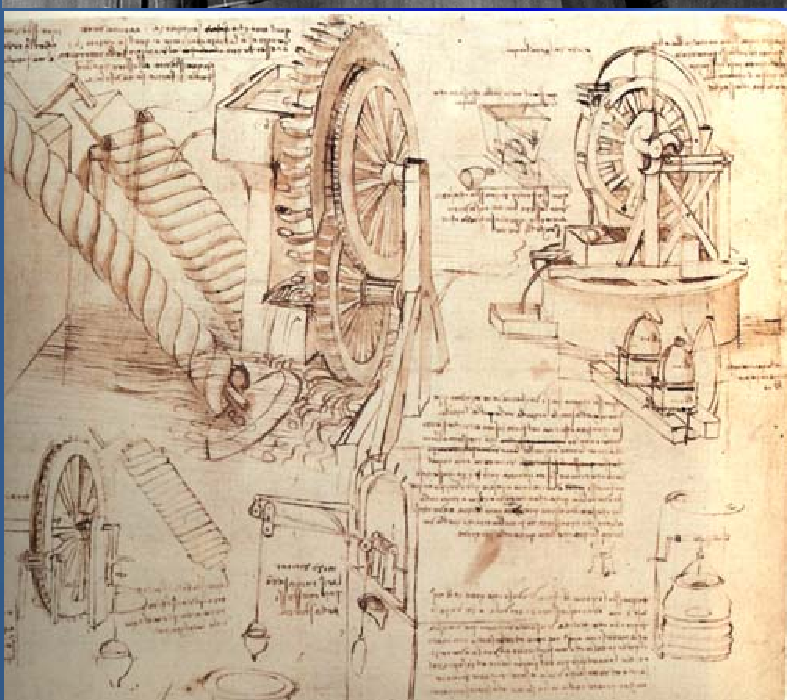
IEEE NPSS Workshop on Applications of Radiation Instrumentation,
Dakar, Senegal, December 3-5, 2020

To do a HEP experiment, one needs:

A theory:



and a cafeteria

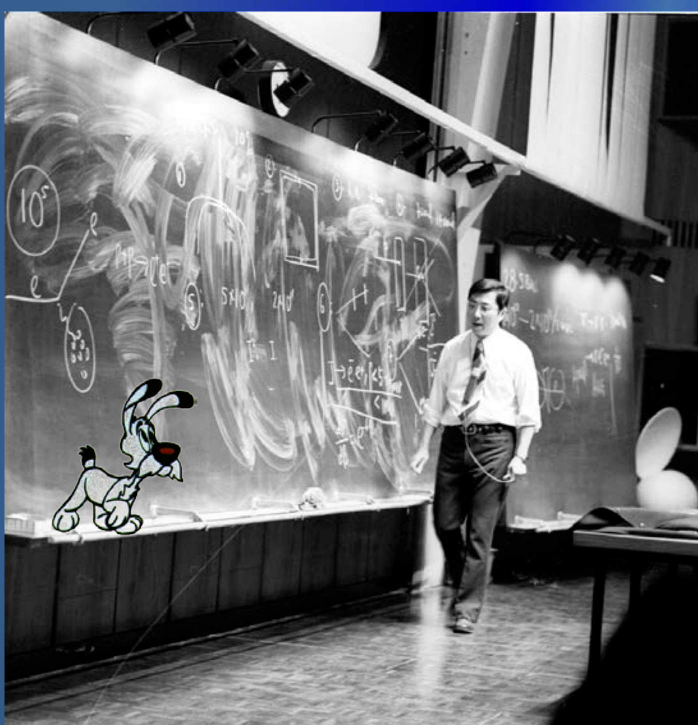


Clear and easy understandable drawings

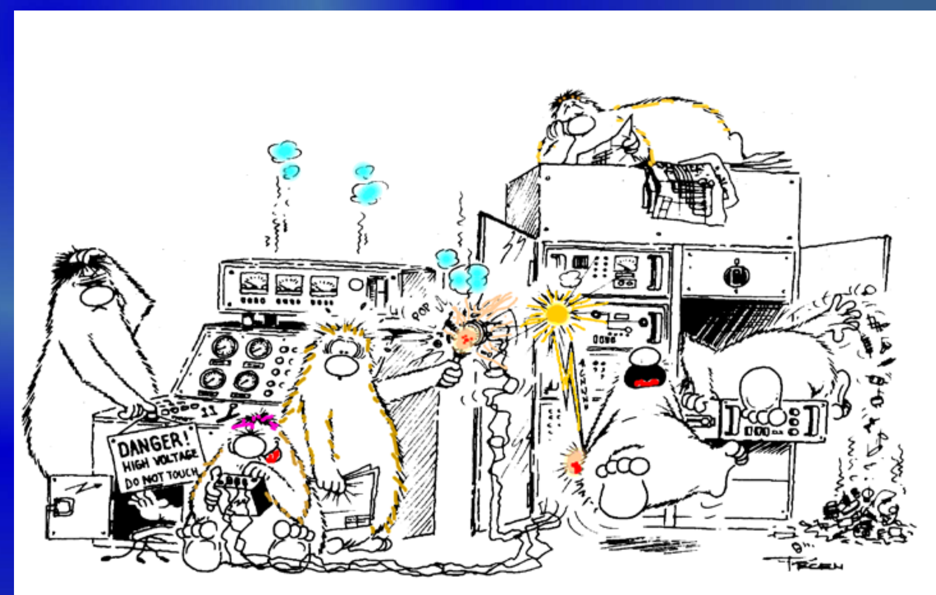
and a tunnel for the accelerator and magnets and stuff

Easy access to the experiment

Physicists to operate detector/analyze data



and a Nobel prize



We will just concentrate on particle detectors – "gaseous detectors"

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

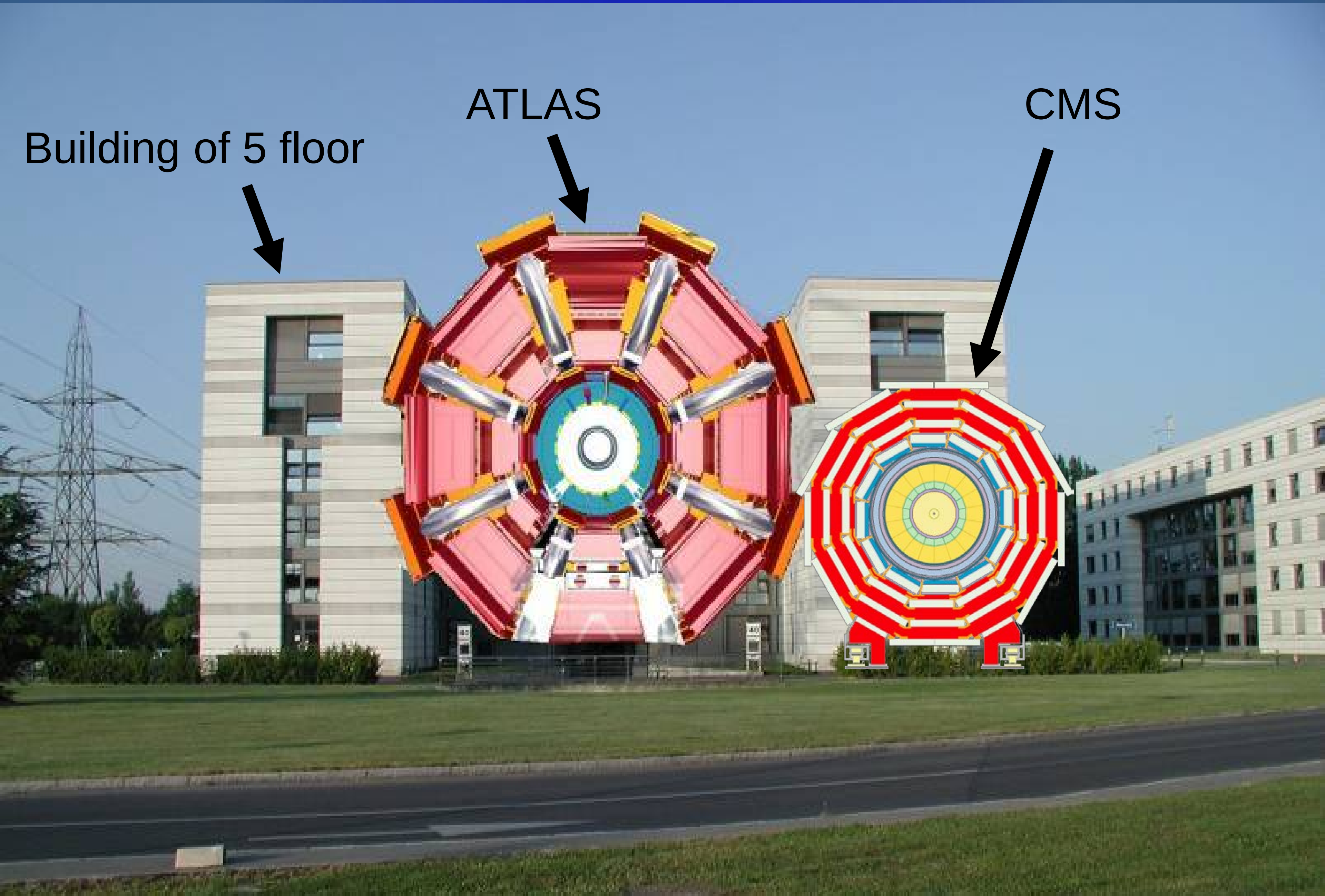
- ✓ The importance and recognition of inventions in the field of instrumentation is proven by the fact that

  → 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

ATLAS and CMS Detectors at CERN: Two Giants

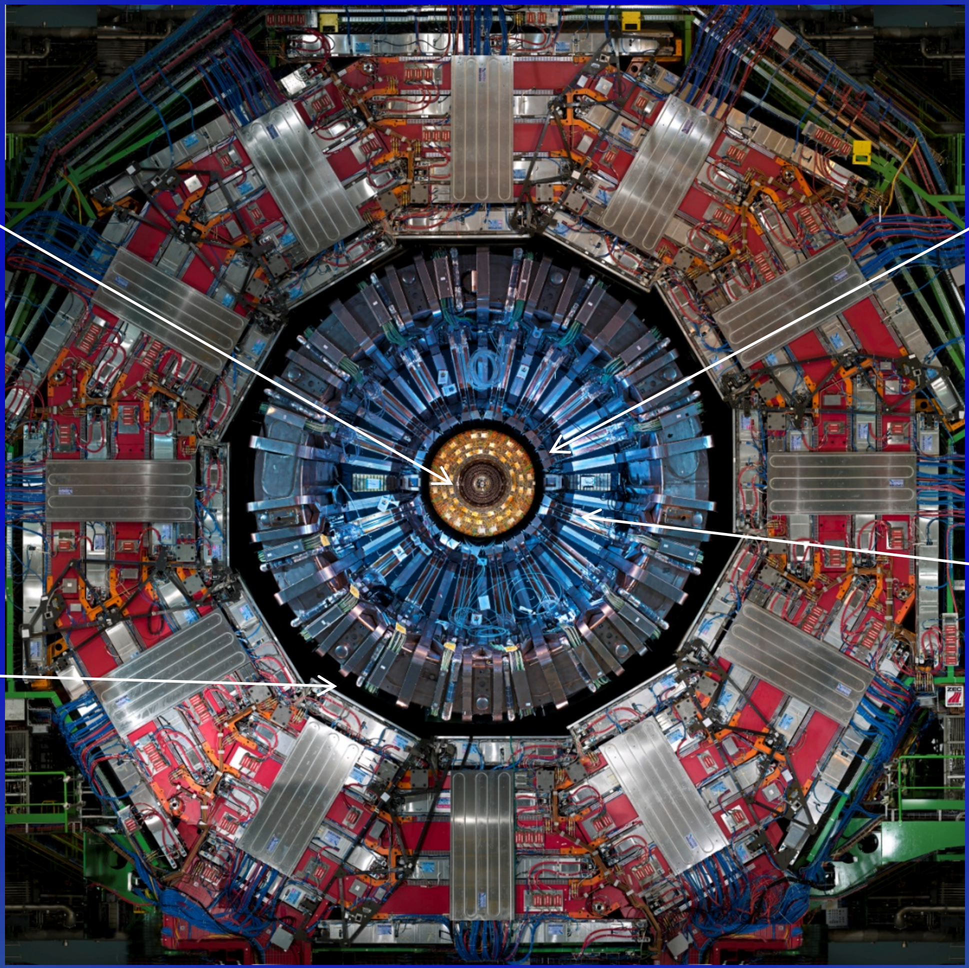


The CMS Detector: Concept to Data Taking – Took 18 Years

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

Silicon Tracker

Gaseous detectors

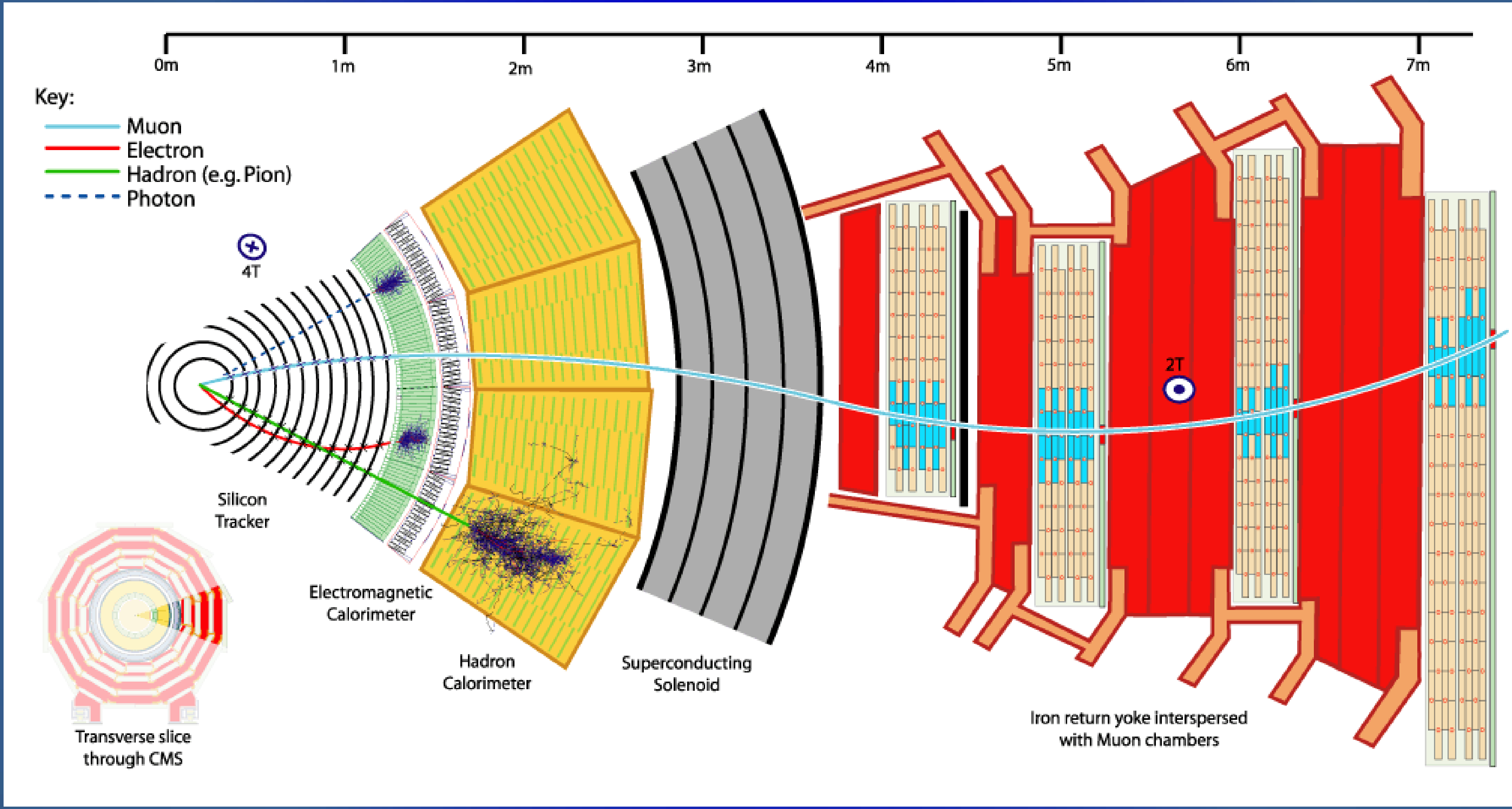


Scintillating Crystals

Brass plastic scintillator

A Typical Today's Particle Detector

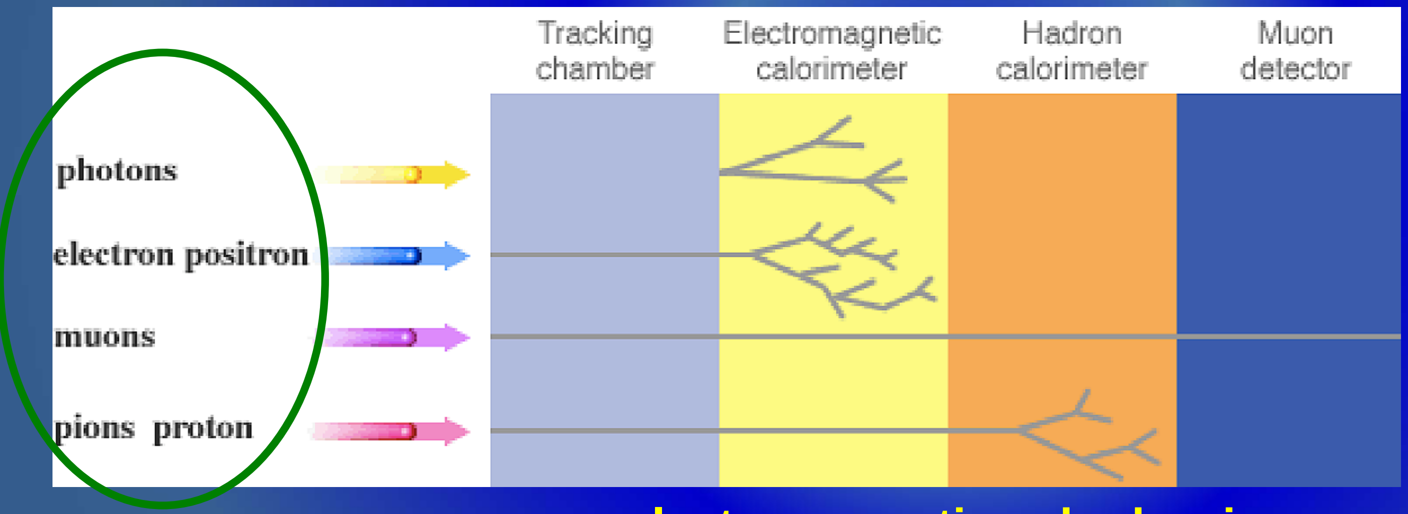
Cut-away view of CMS Experiment



Tracker Calorimeter Coil Muon Detector and iron return yoke

Schematic 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...

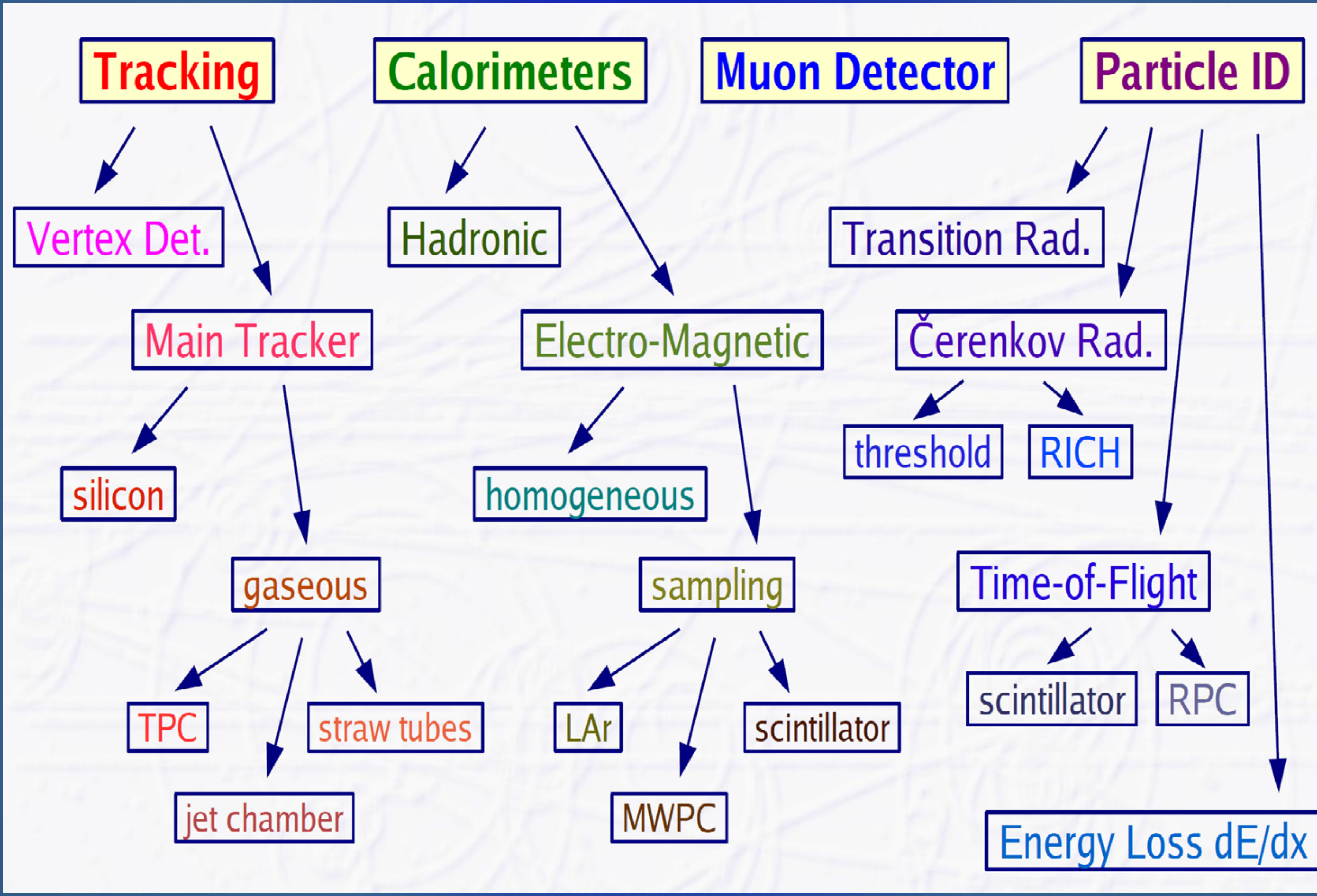
electromagnetic **hadronic**
shower

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)

Modern Detector Technologies in Particle Physics

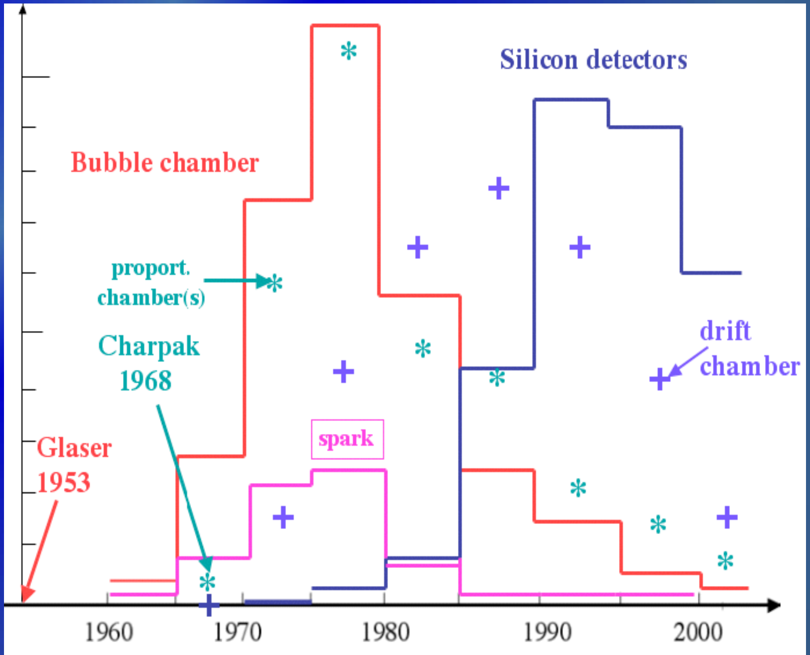


Particle Detectors: Physics Principles

- **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 (silicon) detectors 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**
  - outermost detector layer, basically a tracking detector

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; recently being replaced by Micro-Pattern Gas Detectors (MPGD)**
- **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: silicon hybrid detectors, 3D-sensors, Monolithic Active Pixel Sensors (MAPS)**
  → See Cinzia Da Via lecture



Today's Tracking Detector and Technologies

3 Major Technologies of Tracking Detectors

✓ **Gaseous detectors**
→ **ionization in gas**

typically ~100 e–/cm, not sufficient to create significant signal height above noise for standard amplifiers
→ requires gas amplication ~10^4 to get enough signal over noise

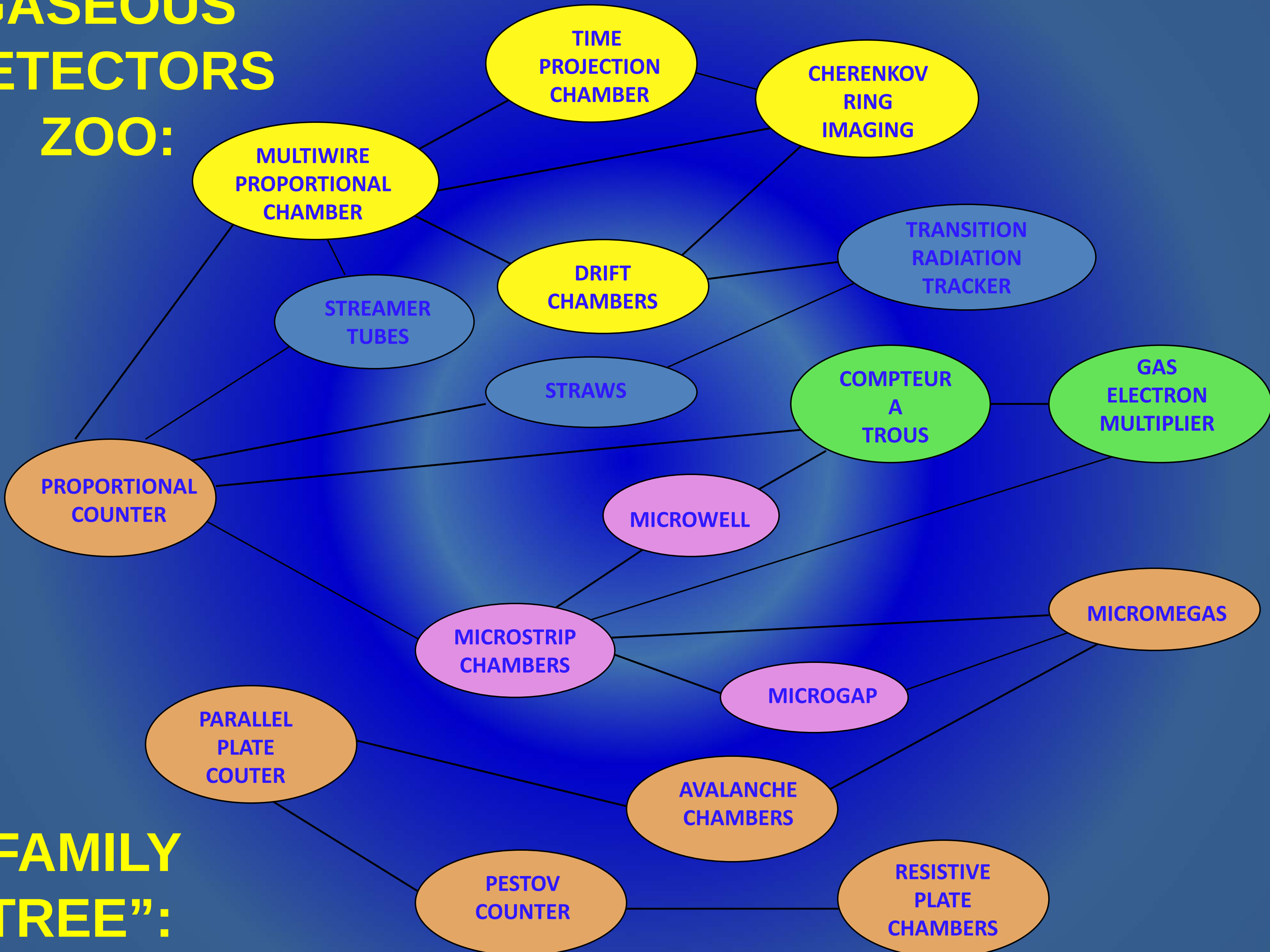
✓ **Silicon detectors**
→ **electron – hole pairs in solid state material**

typically ~100 e– - hole pairs/µm
300 µm thick detector creates high enough signal w/o gas amplification

✓ **Fiber trackers**
→ **scintillating fibers**

scintillation light detected with photon detectors (sensitive to single electrons)

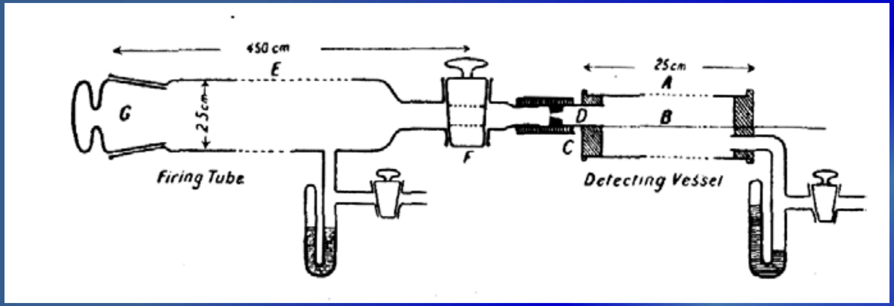
GASEOUS DETECTORS ZOO:



"FAMILY TREE":

In the Family of Gaseous Detectors with a Glorius Tradition

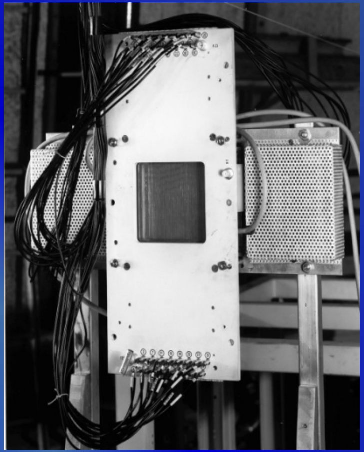
1908: FIRST WIRE COUNTER USED BY RUTHERFORD
IN THE STUDY OF NATURAL RADIOACTIVITY

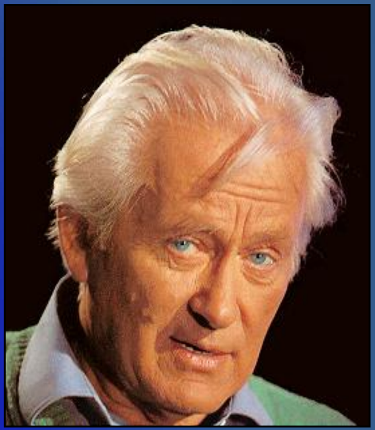


E. Rutherford and H. Geiger , Proc. Royal Soc. A81 (1908) 141

Nobel Prize in Chemistry in 1908

1968: MULTIWIRE PROPORTIONAL CHAMBER

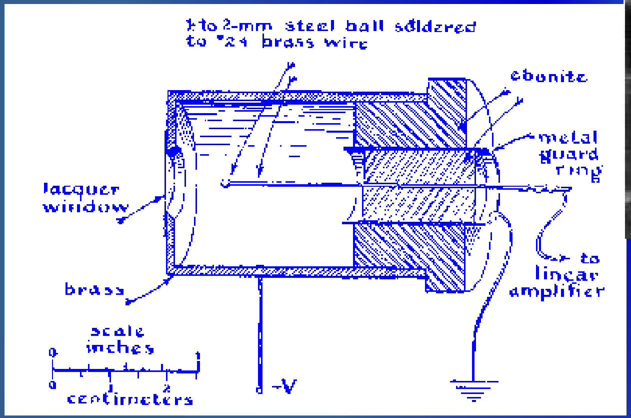




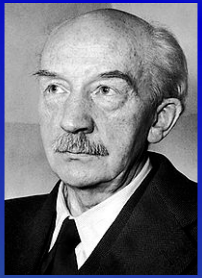
Nobel Prize in 1992

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

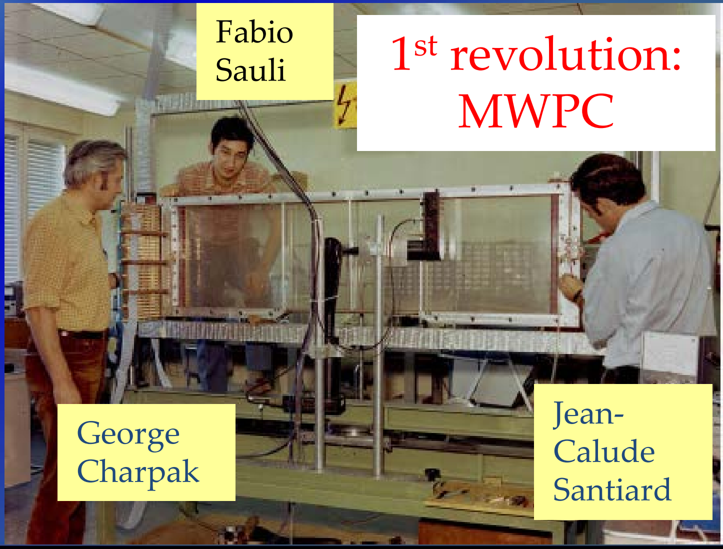
1928: GEIGER COUNTER
SINGLE ELECTRON SENSITIVITY



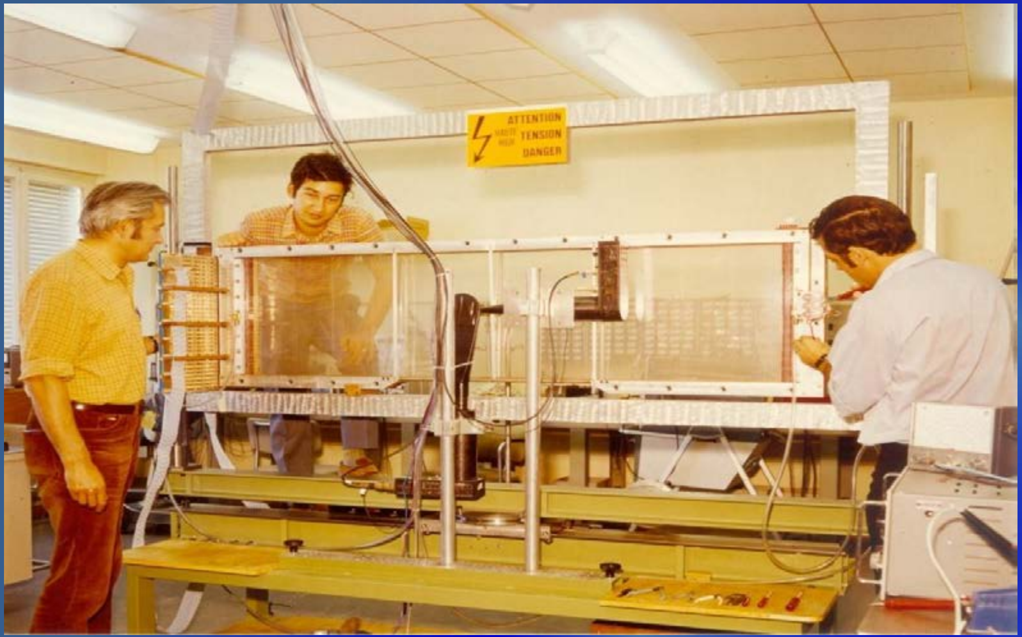
H. Geiger and W. Müller, Phys. Zeits. 29 (1928) 839



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

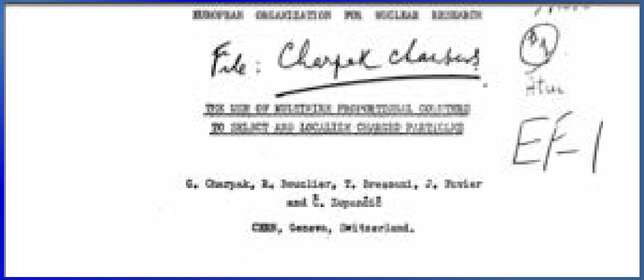


MWPC – Revolutionising the Way Particle Physics is Done



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

1968: George Charpak developed the MultiWire Proportional Chamber, which revolutionized particle detection and High Energy Physics - which passed from the manual to the electronic era.



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

File: Charpak chambers

EF-1

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.

Electronic particle track detection is now standard in all particle detectors

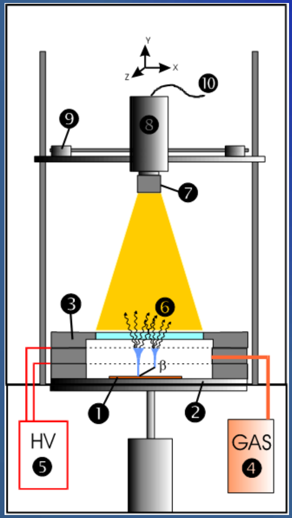
MWPC – Revolutionising the Way Particle Physics is Done

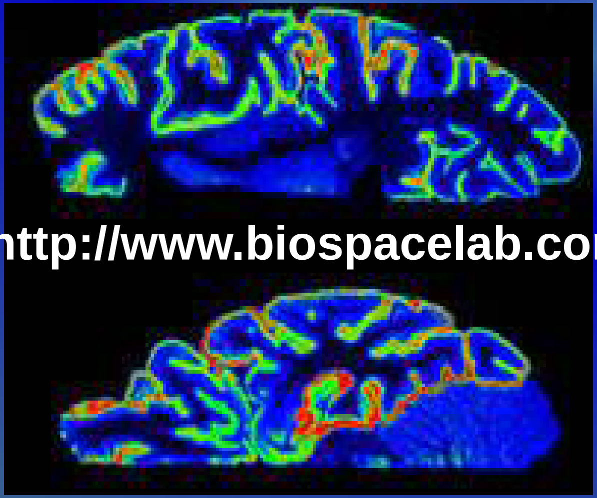
1992:

Biospace: Company Founded In 1989 by Georges Charpak

~ 2000: LOW-DOSE 3D IMAGING

COMMERCIAL AUTORADIOGRAPHY SYSTEMS WITH GASEOUS DETECTORS





http://www.biospacelab.com

Gaseous Detectors: Why do we use gas medium ?

Three states of matter:
Solid, Liquid, Gas – why use Gas as a medium for ionization ?

- **Effectively quite light in terms of gm/cm^2, requirement for reducing multiple scattering in particle physics**

- **Few other technologies can easily realize detectors with as large a sensitive area as gas-filled devices**

- **Gas-filled detectors are relatively cheap in terms of $ per unit area/volume**

- **There are optimized gas mixtures for charged particles detection (high energy and nuclear physics), X-rays (synchrotron physics, astronomy) and neutrons (neutron scattering, national security)**

- **Electron transport characteristics are favorable and well characterized**

- **Gas gain, *M* (electron multiplication factor), can be achieved, over many orders of magnitude (large dynamic range)**

- **Ionization collection or fluorescence emission can form the signal**

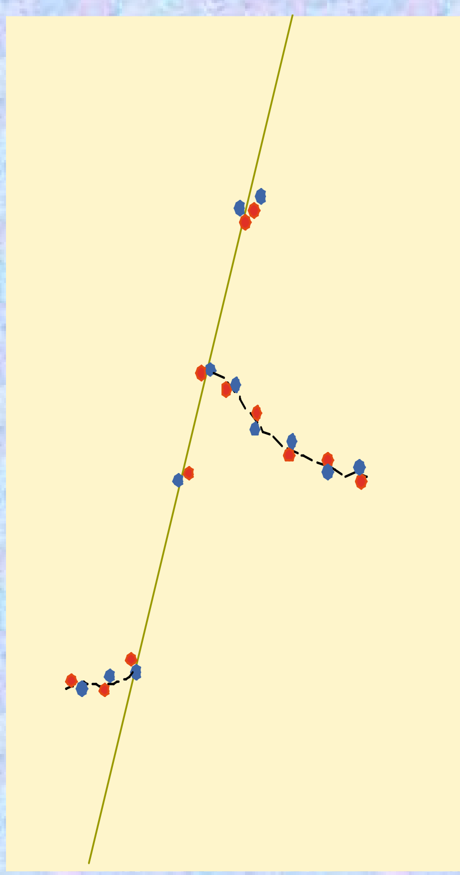
Schematic Principle of Gas Detectors

TOTAL IONIZATION:
- Primary electron-ion pairs
- Clusters
- Delta-electrons

Statistics of primary ionization:

Poisson: $P_k^n = \frac{n^k}{k!} e^{-n}$

***n**: average*
***k**: actual number*



Relevant Parameters
for gas detectors

Ionization energy	:	E_i
Average energy/ion pair	:	W_i
Average number of primary ion pairs [per cm]	:	n_p
Average number of ion pairs [per cm]	:	n_T

Differences due to δ-electrons

$$\langle n_T \rangle = \frac{L \cdot \langle \frac{dE}{dx} \rangle_i}{W_i}$$

[about 2-6 times n_p]
[L: layer thickness]

δ-electrons lead to secondary ionization and limit spatial resolution; typical length scale of secondary ionization: 10 μm. Example: kinetic energy: T_{kin} = 1 keV; gas: Isobutane → range: R = 20 μm ...
[using R [g/cm²] = 0.71 $(T_{kin})^{1.72}$ [MeV]; valid for T_{kin} < 100 keV]

Gas	<Z>	ρ [g/cm³]	E_i [eV]	W_i [eV]	dE/dx [keV/cm]	n_p [cm⁻¹]	n_T [cm⁻¹]
He	2	$1.66\cdot10^{-4}$	24.6	41	0.32	5.9	7.8
Ar	18	$1.66\cdot10^{-3}$	15.8	27	2.44	29.4	94
CH_4	19	$6.7\cdot10^{-4}$	13.1	28	1.48	18	53
C_4H_{10}	34	$2.42\cdot10^{-3}$	10.6	23	4.50	46	195

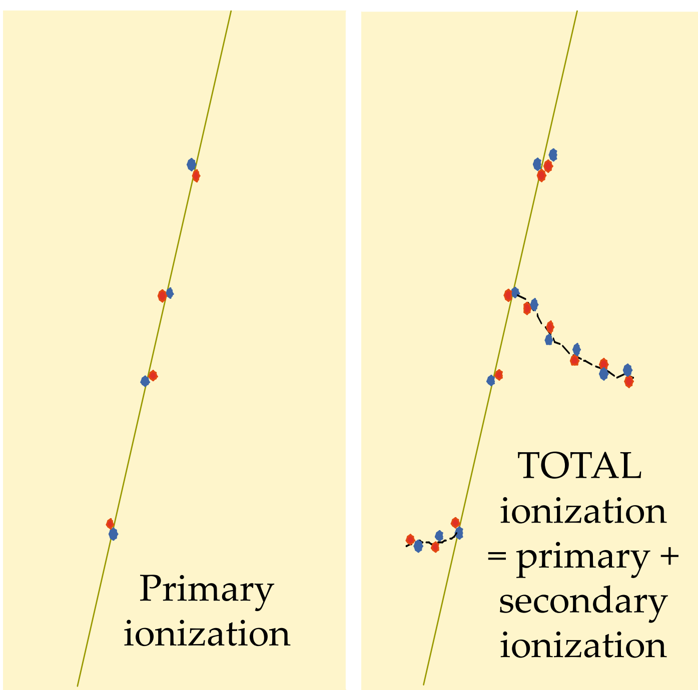
N_{TOTAL} ~ 100 e-ion pairs (typical number for 1 cm of gas) is impossible to detect → the typical noise of very modern pixel ASICs is ~ 100e-
Need to increase number of e-ion pairs → … but ☺ … how ???

Gaseous Detectors: Ionization Statistics

TOTAL IONIZATION:

- Primary electron-ion pairs
  → Coulomb interactions of charged particles with molecules
  → typically ~ 30 primary ionization clusters /cm in gas at 1 bar

- Secondary ionization: clusters and delta-electrons → on average 90 electrons/cm in gas at 1 bar



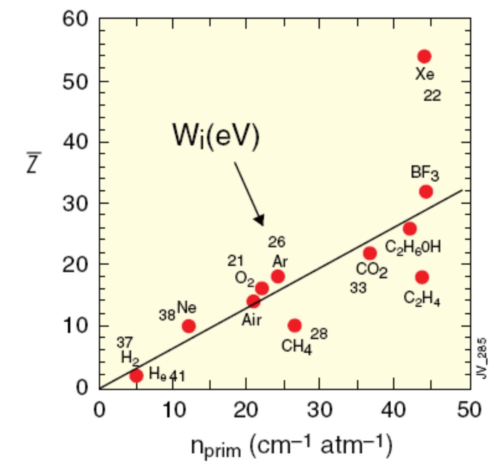
The actual number of primary electron/ion pairs (n_p) is Poisson distributed:

$$P(n_p, \langle n_p \rangle) = \frac{\langle n_p \rangle^{n_p} e^{-\langle n_p \rangle}}{n_p!}$$

σ_I : Ionization x-Section
n_e : Electron density
L : Thickness

$$\langle n_p \rangle = L/\lambda \qquad \lambda = 1/(n_e \sigma_I)$$

Number of primary electron/ion pairs in frequently used gases:



Detection efficiency of a perfect detector is limited to:

→ for thin (L) layers ε can be significantly lower than 1

$$\varepsilon = 1 - e^{-n_p}$$

$$\langle n_p \rangle = L/\lambda$$

GAS (STP)	thickness	ε (%)
Helium	1 mm	45
	2 mm	70
Argon	1 mm	91.8
	2 mm	99.3

Ionization Statistics: Table for most common gases

Properties of noble and molecular gases at normal temperature and pressure (NTP: 20° C, one atm). E_X, E_I: first excitation, ionization energy; W_I: average energy per ion pair; $dE/dx|_{min}$, N_P, N_T: differential energy loss, primary and total number of electron–ion pairs per cm, for unit-charge minimum-ionizing particles. Values often differ, depending on the source, and those in the table should be taken only as approximate (Sauli and Titov 2010)

Gas	Density (mg cm^{-3})	E_x (eV)	E_I (eV)	W_I (eV)	$dE/dx|_{min}$ (keV cm^{-1})	N_P (cm^{-1})	N_T (cm^{-1})
He	0.179	19.8	24.6	41.3	0.32	3.5	8
Ne	0.839	16.7	21.6	37	1.45	13	40
Ar	1.66	11.6	15.7	26	2.53	25	97
Xe	5.495	8.4	12.1	22	6.87	41	312
CH_4	0.667	8.8	12.6	30	1.61	28	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

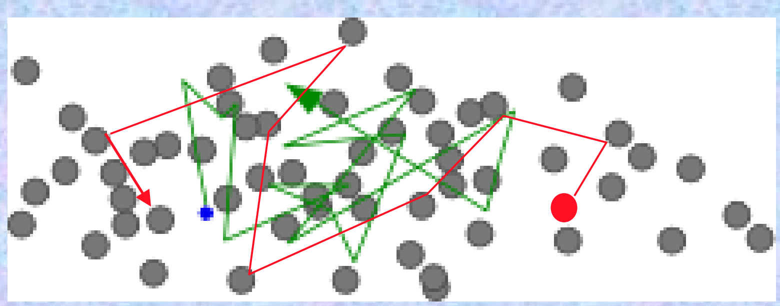
Total ionization (N_T)~ 3 times primary ionization (N_P)

N_T ~ 100 e-ion pairs during ionization process (typical number for 1 cm of gas) is not easy to detect → typical noise of modern pixel ASICs is ~ 100e- (ENC)

Need to increase number of e-ion pairs → … ☹ … how ??? – GAS AMPLIFICATION

Drift and Diffusion of Electrons / Ions in the Gas

ELECTRIC FIELD E = 0: THERMAL DIFFUSION



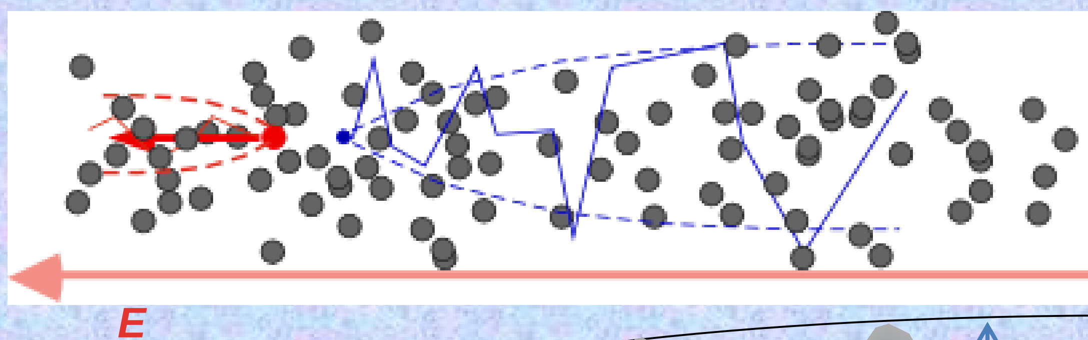
Maxwell energy distribution:

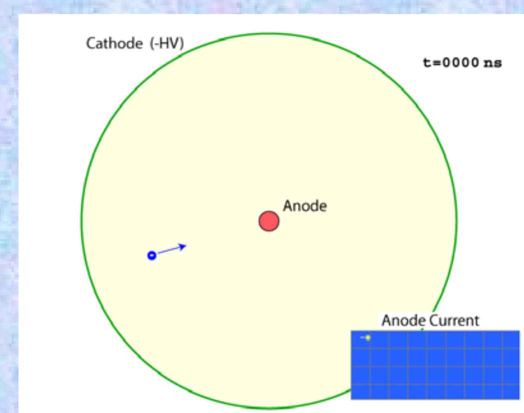
$$F(\varepsilon) = C\sqrt{\varepsilon}\, e^{-\frac{\varepsilon}{KT}}; \quad \langle\varepsilon\rangle \sim kT \sim 0.025\ \text{eV}$$

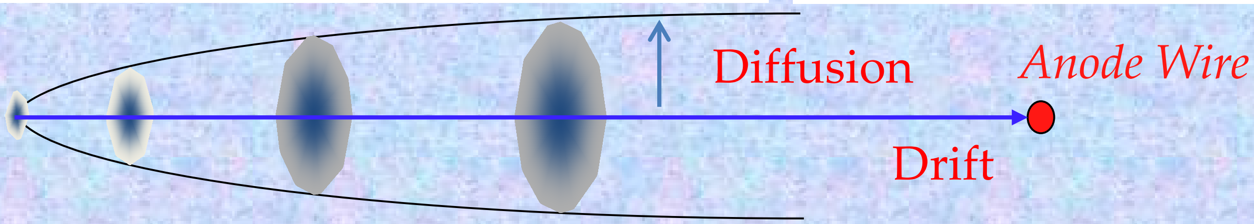
RMS of charge diffusion: $\sigma_x = \sqrt{2Dt}$

ELECTRIC FIELD E > 0: CHARGE TRANSPORT AND DIFFUSION

IONS ELECTRONS

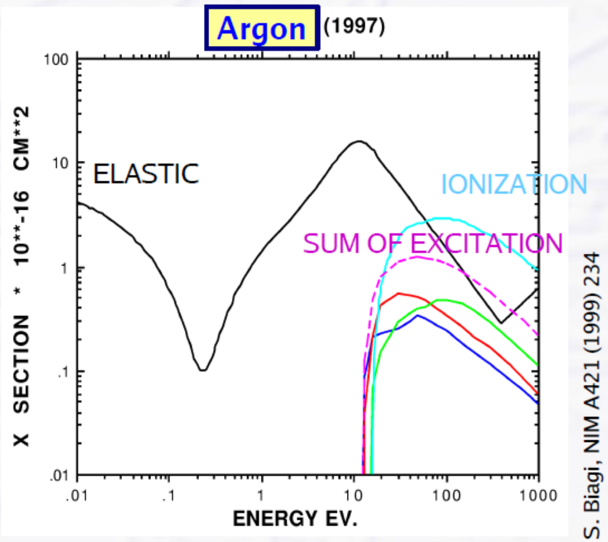




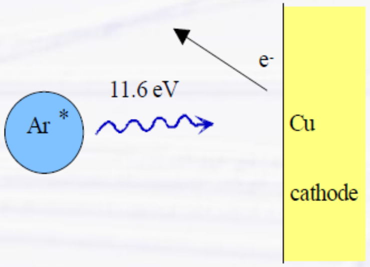


Selection of Gas Mixture: Quenching of Photons

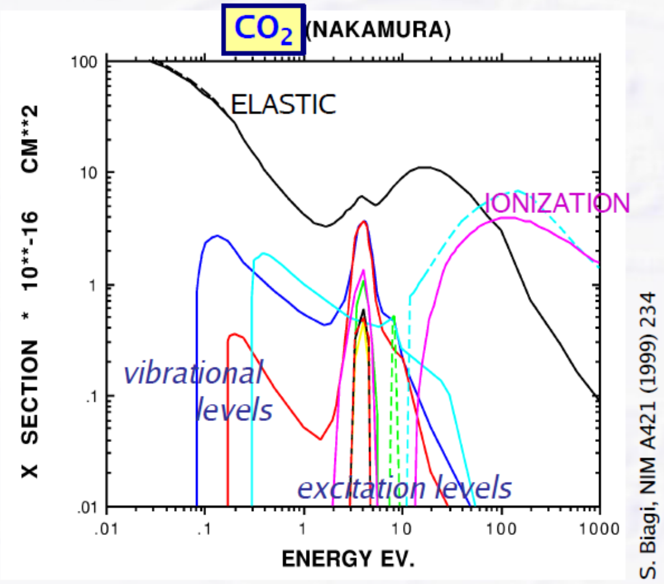
- Slight problem in gas avalance
  - Argon atoms can be ionized but also can be brought into excited states
  - Exited Argon atoms can only de-exite by emission of high-UV photons



consequence: UV photons (>11.6 eV) hit surface of metals (cathode) and free new electrons, ionization energy of Cu = 7.7 eV



VERY unstable operation

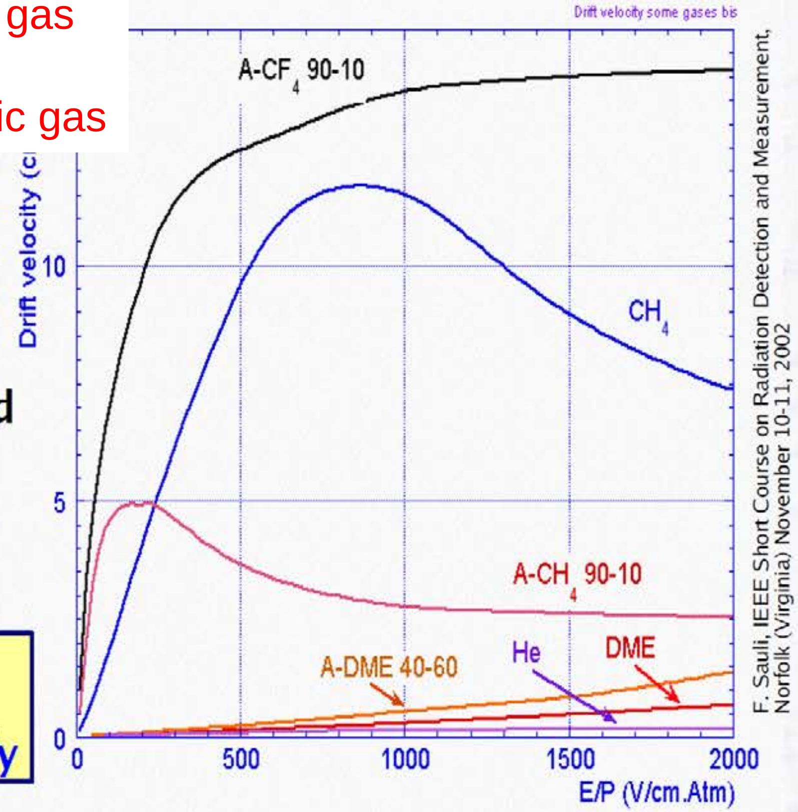


- Solution
  - Add gases with many vibrational and rotational energy levels: CO_2, CH_4
  - Absorption of UV photons over a wide energy range; dissipation by collisions

Selection of Gas Mixture: Drift Velocity

- **Large range of drift velocities in gases: 1 .... 10 cm/µs**

Large drift velocities are obtained by adding polyatomic gas (CH_4, CO_2, CF_4) to Ar → electrons cool due to energy transfer to rotational/ vibrational modes of the polyatomic gas



- **Typical categories**
  - "slow" gases, e.g. CO_2 mixtures
    - 1-2 cm/µs, almost linear dependence on E-field
  - "fast" gases, e.g. CF_4 mixtures
    - ~10 cm/µs or more

LHC detectors need fast gases = short drift time to collect all electrons until next bunch crossing (25 ns) or at least within a few bunch crossings only

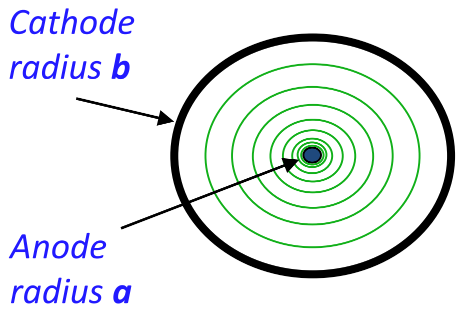
  - "saturated" gases, e.g. CH_4 mixtures
    - have maximum of drift velocity at certain E-field
    - widely used: Ar/CH_4 (90/10)

variety of gases allows multiple combinations: lots of *black magic!*

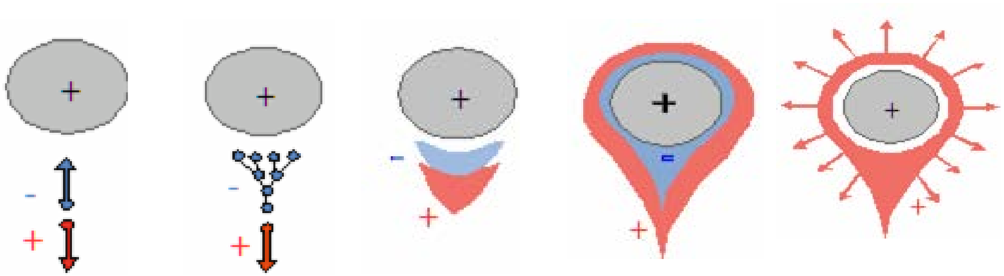
gases with drift velocity maximum are rather convienient: drift velocity less sensitive to E-field variations and almost constant

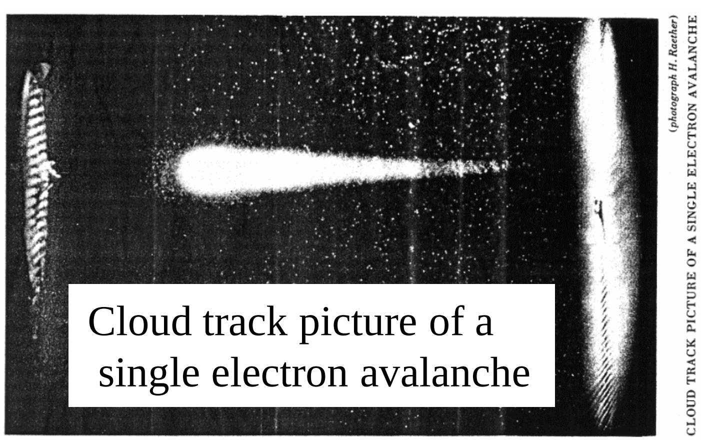
Single-Cell Wire Proportional Counter

Thin anode wire (~20–50um) coaxial with cathode:



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

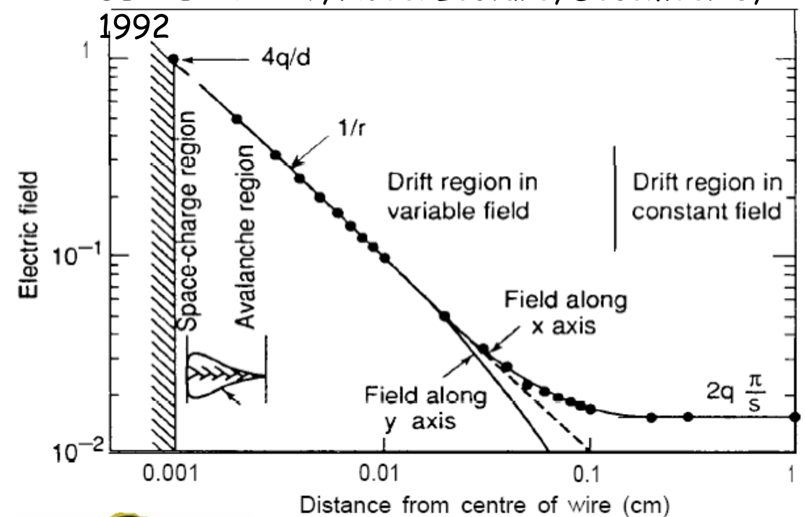


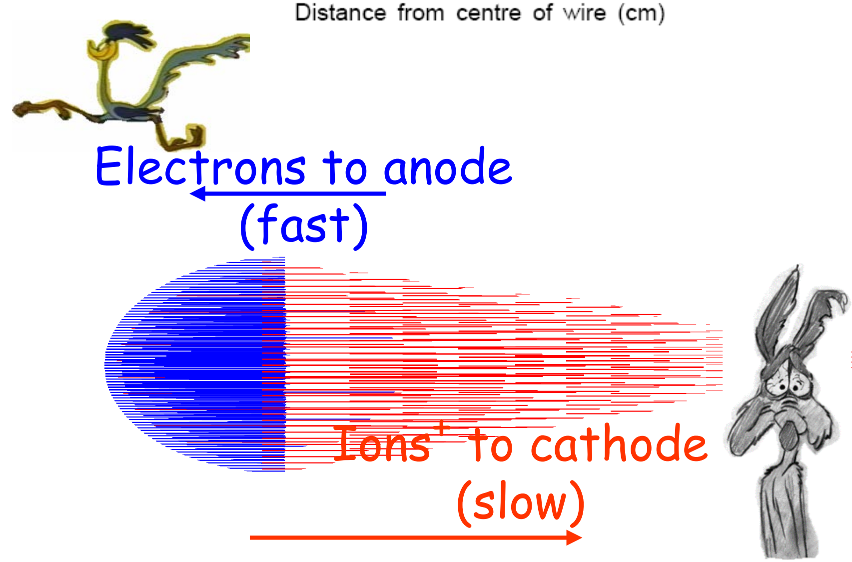


Cloud track picture of a single electron avalanche

Avalanche development in the high electric field (~ 250 kV/cm) around a thin wire (multiplication region ~ 100 um):

GEORGES CHARPAK, Nobel Lecture, December 8, 1992

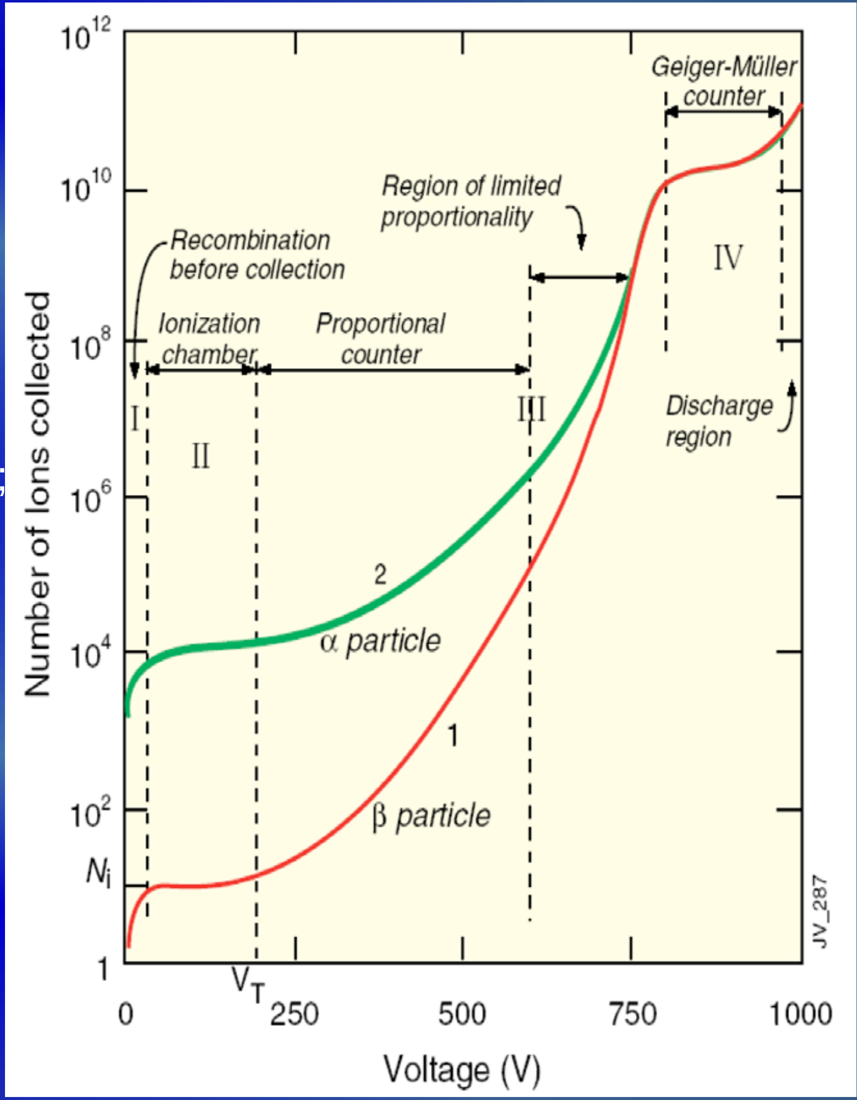




Operation Modes of Gaseous Detector

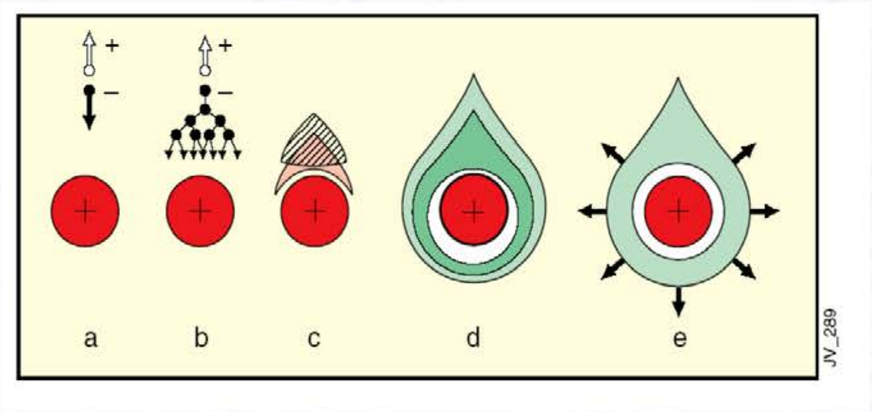
High Voltage

- Recombination before collection (I)
  - ions recombine before collected
- Ionization Mode (II)
  - full charge ionization charge;
  - no charge multiplication yet; gain ~ 1
- Proportional Mode (IIIa)
  - multiplication of ionization
  - signal proportional to ionization
  - measurement of dE/dx
  - secondary avalanches need quenching;
  - gain ≈ $10^4 – 10^5$
- Limited Proportional Mode (IIIb) (saturated, streamer)
  - secondary avalanches created by photoemission from primary ones;
  - signal no longer proportional to ionization → requires strong quenchers or pulsed HV; gain ~ 10^{10}
- Geiger Mode (IV)
  - massive photoemission; full length of the anode wire affected;
  - discharge stopped by HV cut



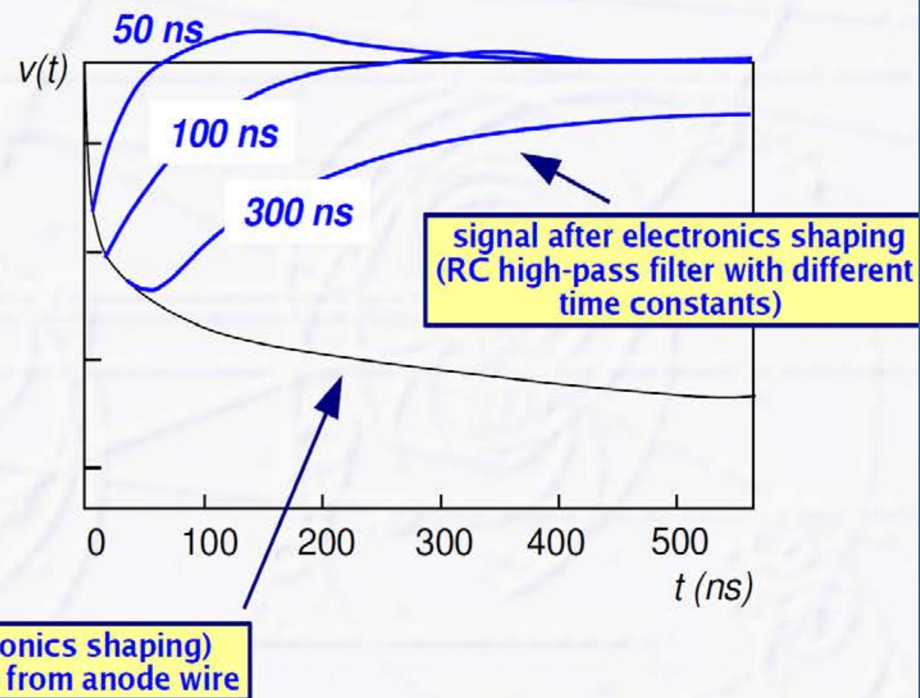
Wire Chamber – Signal Formation

- **Signal formation is DIFFERENT to what you may think of**



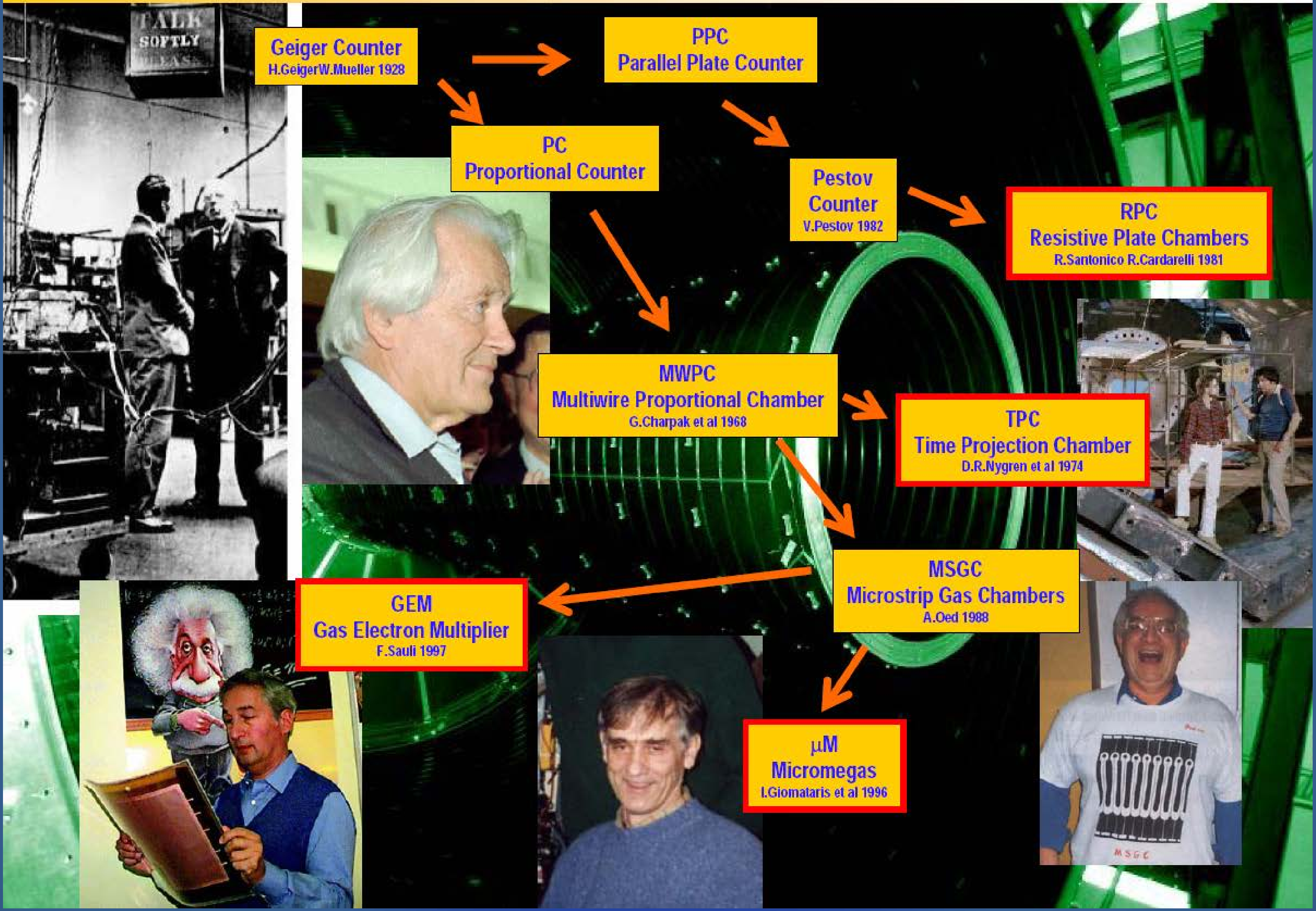
  - Electrons from avalance are collected within a very short time (few ns)
  - Contribution of electrons to wire signal is rather small (few % only)

- **Main part of the signal comes from the IONS**
  - Ions drift back to cathode over long distance (several mm or cm) and time (many µs or even ms)
  - Moving ion charge creates signal via influence (mirror charge in conductor)

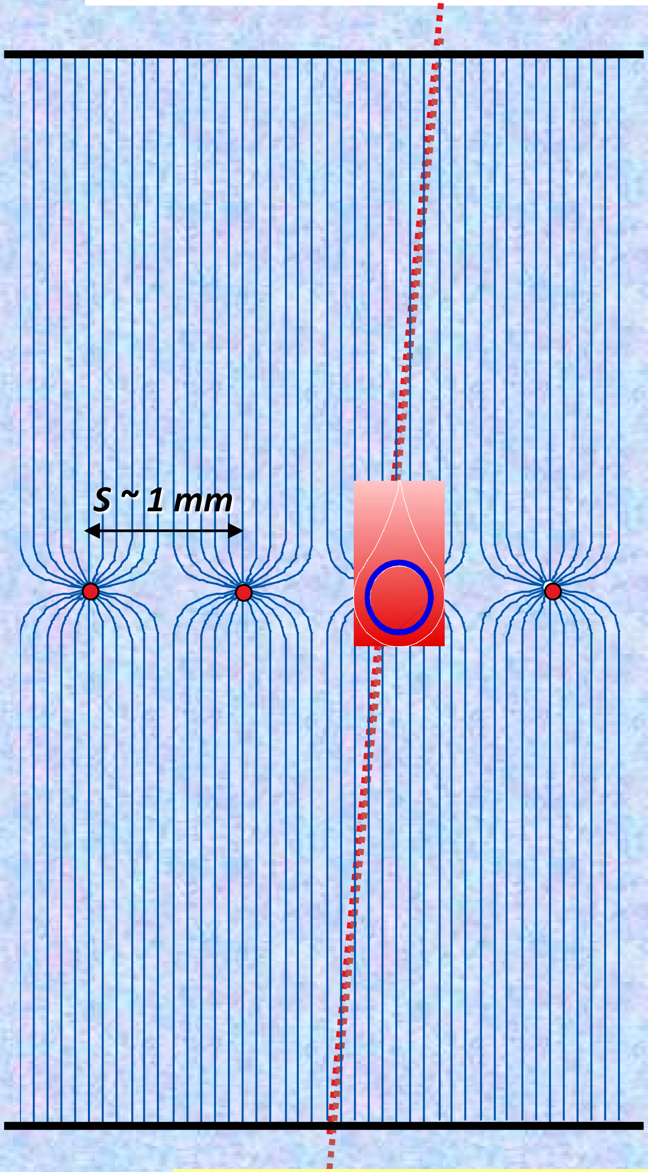


Advanced Concepts in Gaseous Detectors

Gas Detector History



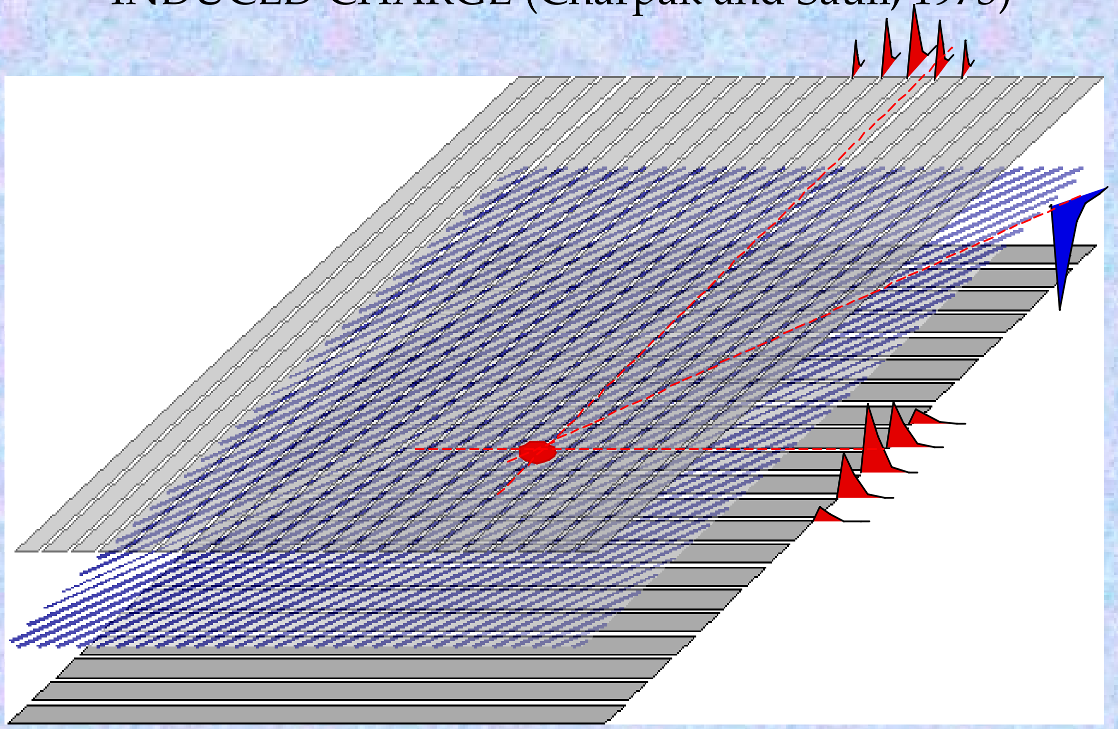
Multi-Wire Proportional Chamber (MWPC)



High-rate MWPC with digital readout:

Spatial resolution is limited to $\sigma_x \sim s/\mathrm{sqrt}(12) \sim 300\ \mu m$

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...

First Public Presentation of Multi-Wire Proportional Chamber

colloque
international
sur
l'électronique
nucléaire

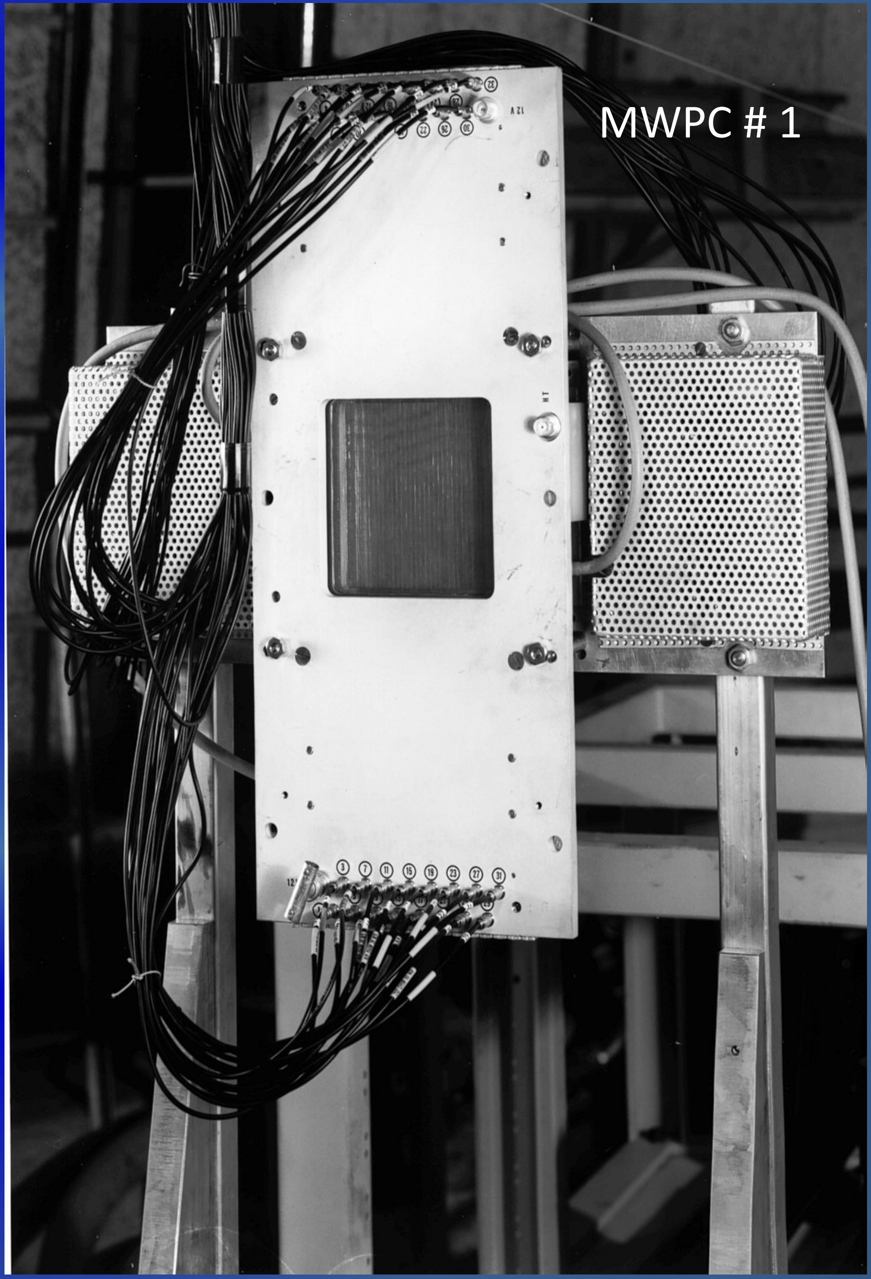
VERSAILLES,
10-13 September 1968

*

international
symposium
on
nuclear
electronics

Chambres à Etincelles
Spark chambers

Rapporteur Reporter	**M. CHARPAK** CERN - GENEVE (Suisse)
Secrétaire scientifique Scientific Secretary	**M. FEUVRAIS** Faculté des Sciences - Lyon (France)



1968: Multi – Wire Proportional Chamber (MWPC)

NUCLEAR INSTRUMENTS AND METHODS 62 (1968) 262–268; © NORTH-HOLLAND PUBLISHING CO.

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

Received 27 February 1968

Properties of chambers made of planes of independent wires placed between two plane electrodes have been investigated. A direct voltage is applied to the wires. It has been checked that each wire works as an independent proportional counter down to separations of 0.1 cm between wires.

Counting rates of 10^5/wire are easily reached; time resolutions of the order of 100 nsec have been obtained in some gases; it is possible to measure the position of the tracks between the wires using the time delay of the pulses; energy resolution comparable to the one obtained with the best cylindrical chambers is observed; the chambers operate in strong magnetic fields.

1. Introduction

Proportional counters with electrodes consisting of many parallel wires connected in parallel have been used for some years, for special applications. We have investigated the properties of chambers made up of a plane of independent wires placed between two plane electrodes. Our observations show that such chambers offer properties that can make them more advantageous than wire chambers or scintillation hodoscopes for many applications.

2. Construction

Wires of stainless steel, 4×10^{-3} cm in diameter, are stretched between two planes of stainless-steel mesh, made from wires of 5×10^{-3} cm diameter, 5×10^{-2} cm apart. The distance between the mesh and the wires is 0.75 cm. We studied the properties of chambers with wire separation $a = 0.1$, 0.2, 0.3 and 1.0 cm. A strip of metal placed at 0.1 cm from the wires, at the same potential (fig. 1), plays the same role as the guard rings in cylindrical proportional chambers. It protects the wires against breakdown along the dielectrics. It is

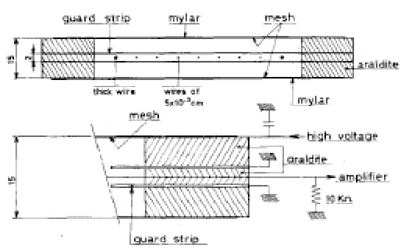


Fig. 1. Some details of the construction of the multiwire chambers.
A copper shield protects the wires at their output from the chamber and contains the solid state amplifiers.

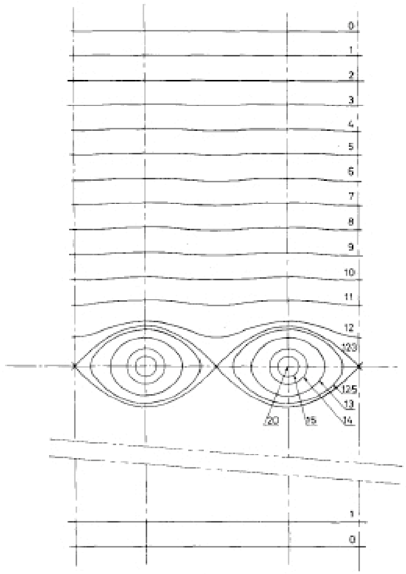
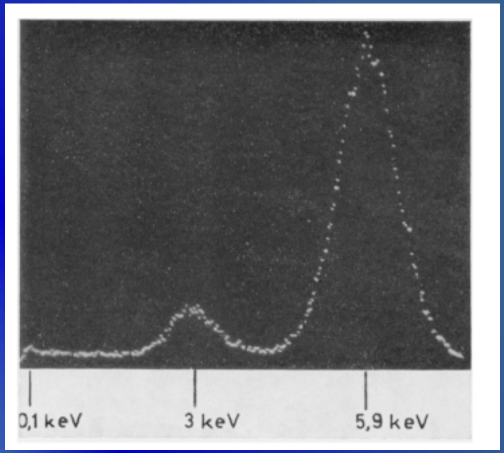
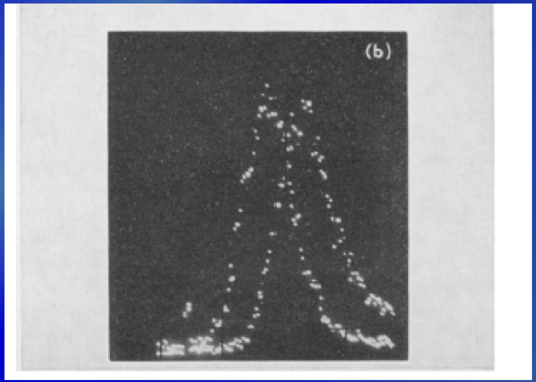


Fig. 2. Equipotentials in a chamber.
Wires of 4×10^{-3} cm diameter, 0.3 cm separation, and 1.5 cm total thickness. 20 V applied between the wires and the external mesh. Results from an analogic method.

ENERGY RESOLUTION ON 5.9 KeV:



DEPENDENCE OF COLLECTION TIME FROM TRACK'S DISTANCE:



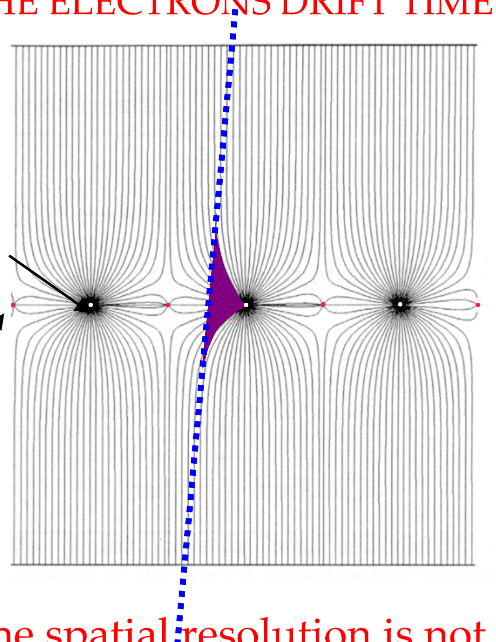
→ **DRIFT CHAMBERS**

G. Charpak,R. Bouclier, T. Bressan,J. Favier and C. Zupancic: The use of Multiwire Proportional Counters to select and localize Charged Particles, Nuc. Instr. and Meth. 62(1968)262

Drift Chambers

FIRST DRIFT CHAMBER OPERATION (H. WALENTA ~ 1971)
HIGH ACCURACY DRIFT CHAMBERS (Charpak-Breskin-Sauli ~ 1973-75)

THE ELECTRONS DRIFT TIME PROVIDES THE DISTANCE OF THE TRACK FROM THE ANODE:



Measure drift time t_D
[need to know t_0; fast scintillator, beam timing]

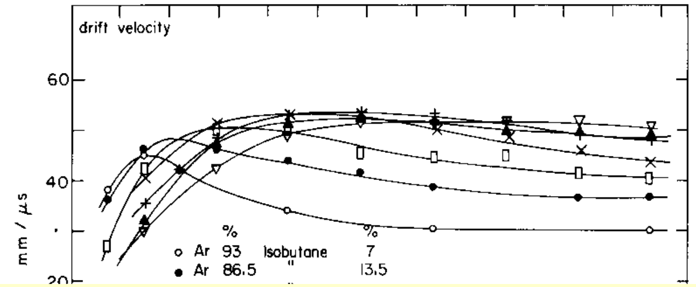
Determine location of original ionization:

$$x = x_0 \pm v_D \cdot t_D$$
$$y = y_0 \pm v_D \cdot t_D$$

If drift velocity changes along path:

$$x = \int_0^t$$

In any case:
Need well-defined drift field ...



Choose drift gases with little dependence $v_D(E) \rightarrow$ linear space - time relation r(t)

drift field [V/cm]

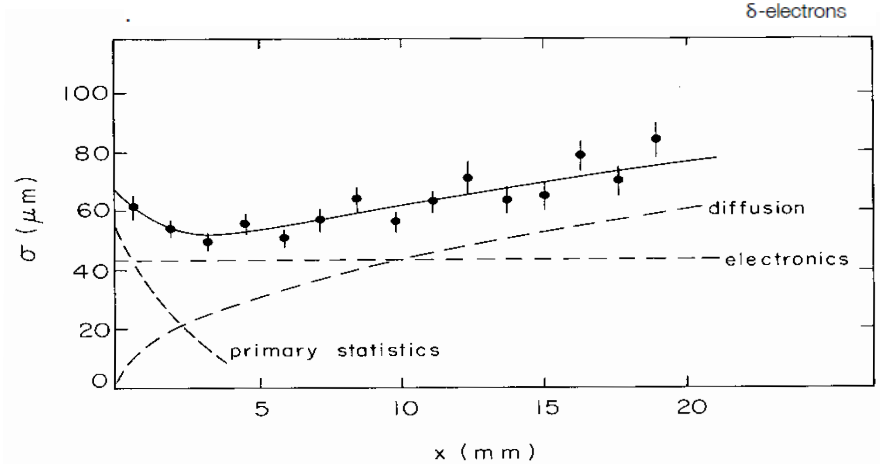
The spatial resolution is not limited to the cell size

$$\sigma_x^2 = \left(\frac{1}{64N^2}\right) \cdot \frac{1}{x^2} + \frac{2D}{v_d} \cdot x + \sigma^2_{const}$$

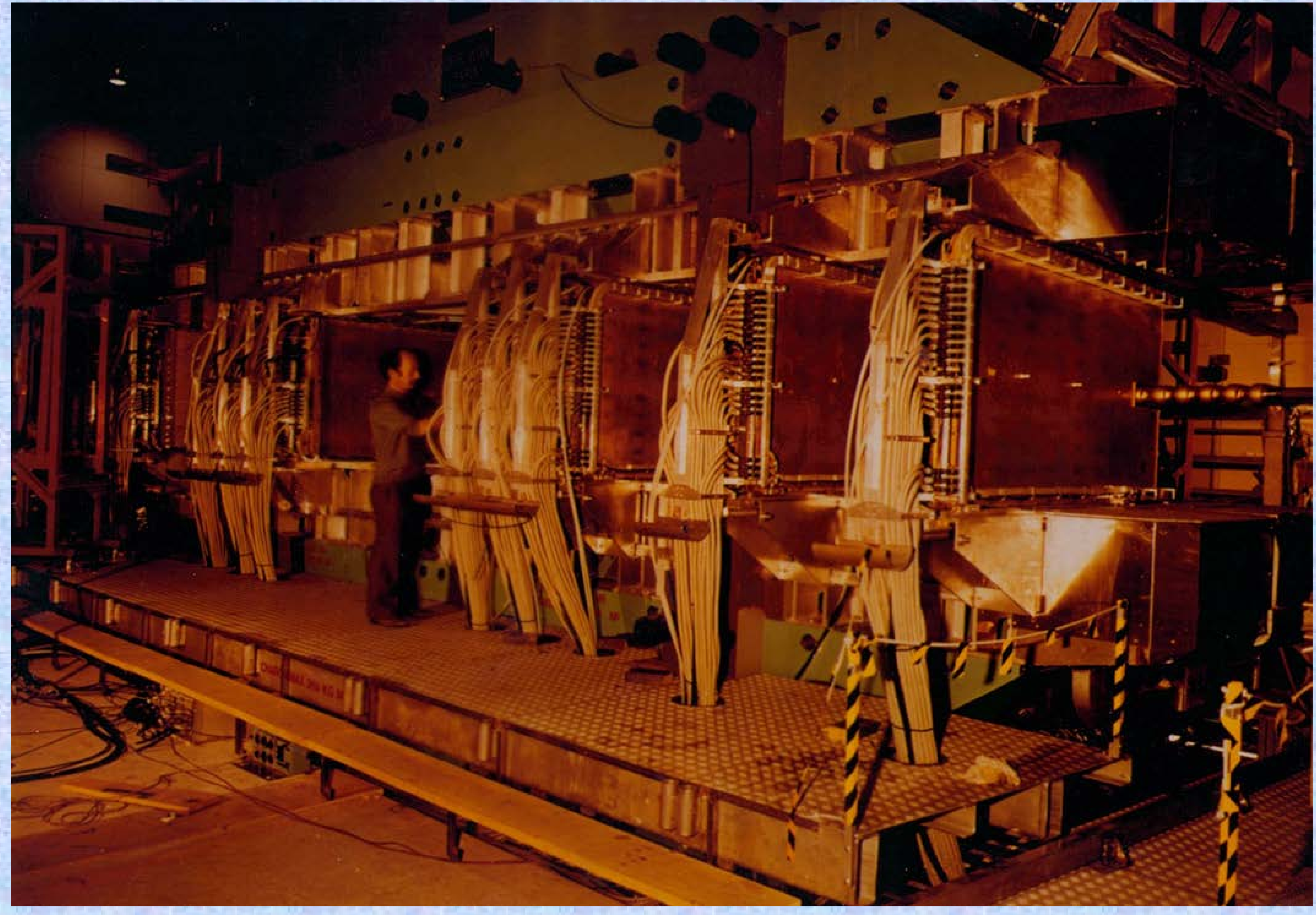
1st ionization statistics; diffusion; electronics δ-electrons

Factors affecting spatial resolution:

- Distribution of primary ionization
- Diffusion
- Readout electronics
- Electric field (gas amplification)
- Range of 'delta electrons'



First Large Experiment with MWPCs



1972-1983: SPLIT FIELD MAGNET DETECTOR

40 LARGE AREA MWPCs AT CERN ISR:

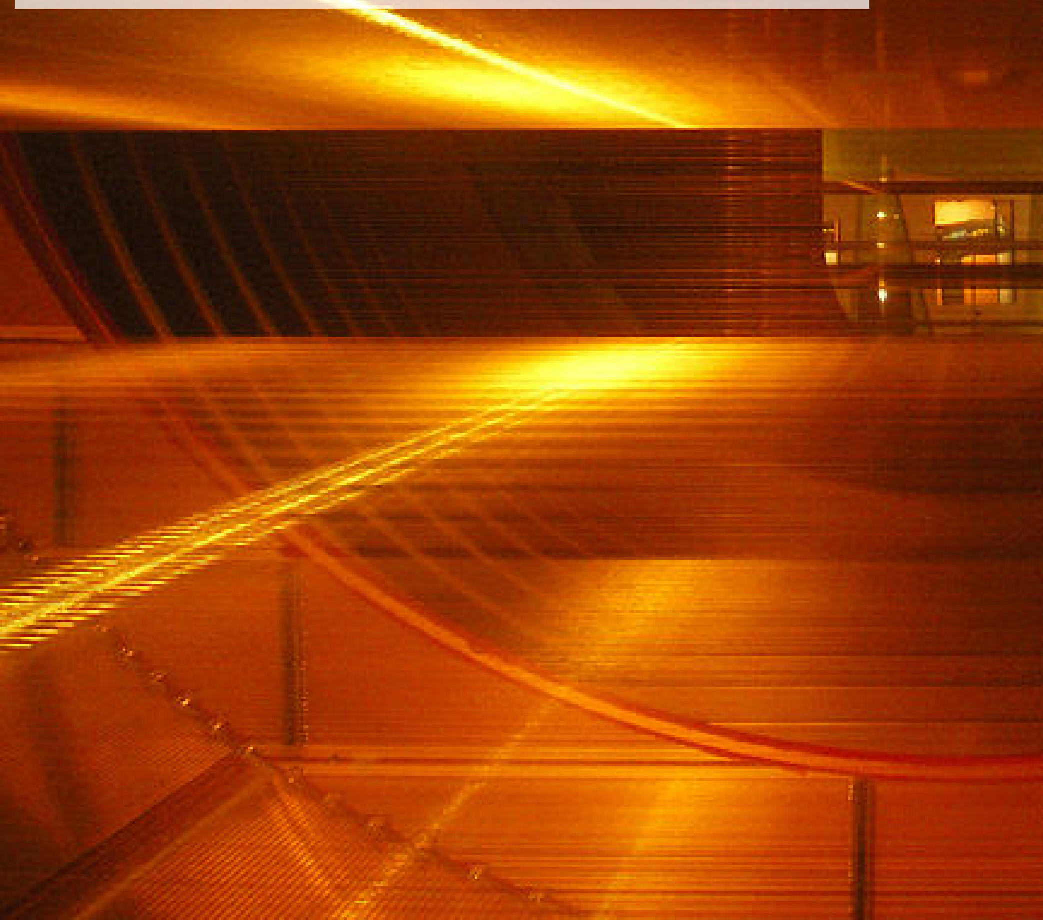
“Enormous Wire Chambers”: Wide-Spread Tool in HEP for > 40 Years

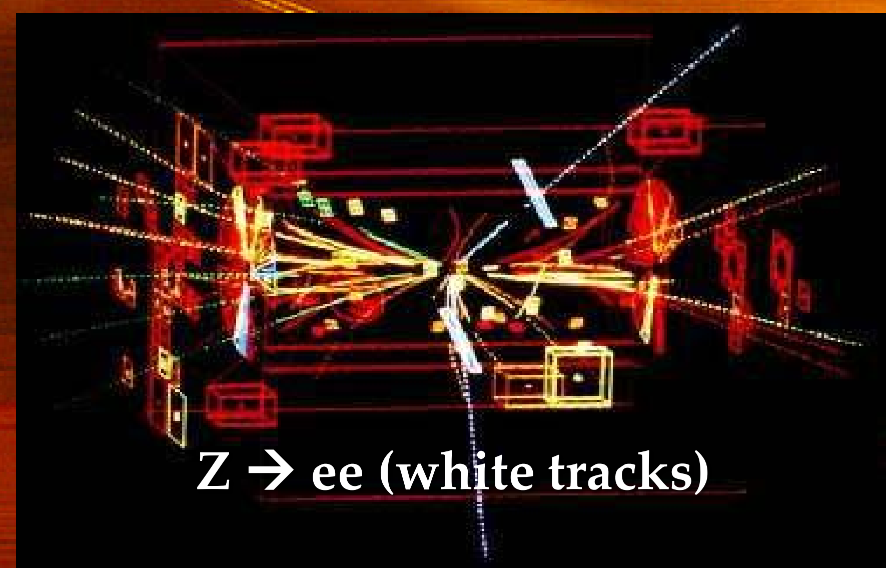
Nobel Prize: W, Z - Discovery at UA1/UA2 (1983)

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

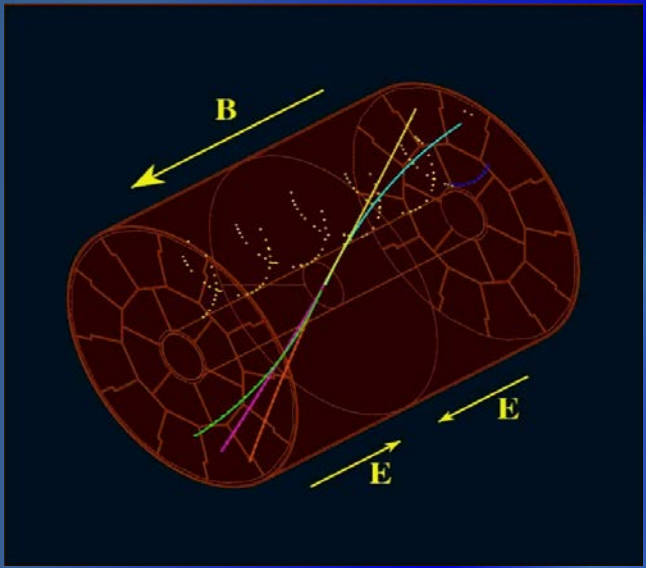




Z → ee (white tracks)

Time Projection Chamber (TPC)

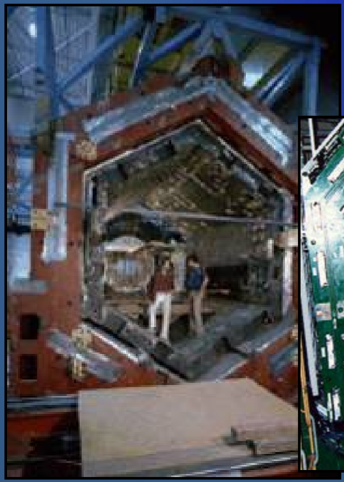
- ✓ Invented by David Nygren (Berkeley) in 1974
  → Proposed as a central tracking device for the PEP-4 detectors @ SLAC 1976

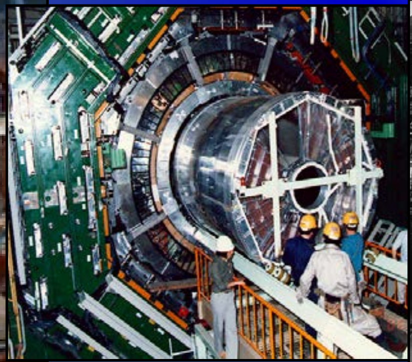


PEP4 (SLAC)

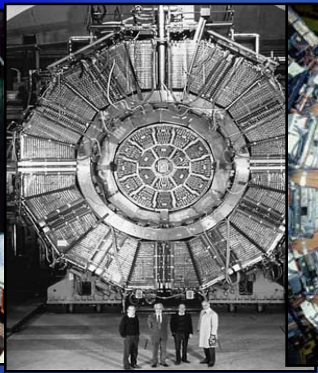
PARAMETER / EXPERIMENT	PEP4	TRIUMF	TOPAZ	ALEPH	DELPHI	STAR	ALICE [1]
1. OPERATION	1982 / 1984	1982 / 1983	1987	1989	1989	2000	2009
INNER / OUTER RADIUS [m]	0.2 / 1.0	~0.15 / 0.50	0.38 / 1.1	0.35 / 1.8	0.35 / 1.4	0.5 / 2.0	0.85 / 2.5
MAX. DRIFTLENGTH (L/2) [m]	1	0.34	1.1	2.2	1.34	2.1	2.5
MAGNETIC FIELD [T]	0.4 / 1.325	0.9	1	1.5	1.23	0.25 / 0.5	0.5
GAS :	Ar / CH4	Ar / CH4	Ar / CH4	Ar / CH4	Ar / CH4	Ar / CH4	Ne /CO2/ N2
Mixture	80 / 20	80 / 20	90 / 10	91 / 9	80 / 20	90 / 10	90/ 10/ 5
Pressure [atm]	8.5	1	3.5	1	1	1	1
DRIFT FIELD [KV / cm / atm]	0.088	0.25	0.1	0.11	0.15	0.14	0.4
ELECTRON DRIFT VELOCITY [cm/μsec]	5	7	5.3	5	6.69	5.45	2.7
$\omega\tau$ (see 2.2.1.3)	0.2 / 0.7	2	1.5	7	5	1.15 / 2.3	< 1
PADS: Size w•L [mm•mm]	7.5x7.5	(5.3-6.4)x19	(9-11)x12	6.2x30	~7x7	2.85x11.5	4x7.5
						6.2x19.5	6x10/15
Max. no. 3-D points	15 - straight	12	10 - linear	9+12 - circular	16 - circular	13+32 - straight	63+64+32
dE/dx: Max. no. samples/track	183	12	175	148+196	192	13+32	63+64+32
Sample size [mm atm]; w or p	4•8.5; wires	6.35; wires	4x3.5; wires	4 ; wires	4 ; wires	11.5 + 19.5;pads	7.5+10+15; pads
GAS AMPLIFICATION	1000	50 000		3000-5000	5000	3000/1100	20 000
GAP a-p; a-c; c-gate [2]	4; 4; 8	6	4; 4; 8	4; 4; 6	4; 4; 6	2; 2; 6 / 4; 4 ; 6	2; 2; 3 / 3; 3; 3
PITCH a-a; cathode; gate	4; 1; 1		4; 1; 1	4; 1; 2	4; 1; 1	4; 1; 1/ 4; 1; 1	2.5; 2.5; 1.5
PULSE SAMPLING [MHz/ no. samples]	10/455, CCD	only 1 digitiz., ADC	10/ 455, CCD	11/ 512, FADC	14/ 300, FADC	9.6 / 400	5-10/500-1000, ADC
GATING [3]	≥1984 o.on tr.	≥1983 o.on tr.	o. on tr.	synchr. cl.wo.tr	static	o.on tr.	o.on tr.
PADS, total number	15 000	7800	8200	41 000	20 000	137 000	560 000
PERFORMANCE							
Δx_T [μm]-best / typ.	130-200	200/	185/230	170/200-450	180/190-280	300-600	spec:800-1100
Δx_L [μm]-best / typ.	160-260	3000	335/900	500-1700	900	500-1200	spec:1100-1250
2-TRACK SEPARATION [mm], T / L	20		25	15	15	8 - 13 / 30	
$\partial p/p^2$ $[GeV/c]^{-1}$: TPC alone; high p	0.0065		0.015	0.0012	0.005	0.006	spec:0.005
dE/dx [%] SINGLE TRACKS/ IN JETS	2.7 / 4.0		4.4 /	4.4 /	5.7 / 7.4	7.4 / 7.6	spec:4.9 / 6.8
COMMENTS		a in single PCs	chevron pads	circular pad rows	circular pad rows	No field wires	No field wires
		strong ExB effect				> 3000 tracks	≤ 20 000 tracks

1) Expected performance
2) a = anode, p = pads, c = cathode grid
3) o. on tr.: gate opens on trigger; cl.wo.tr. : opens before collision and closes without trigger; static : closed for ions only (see text).

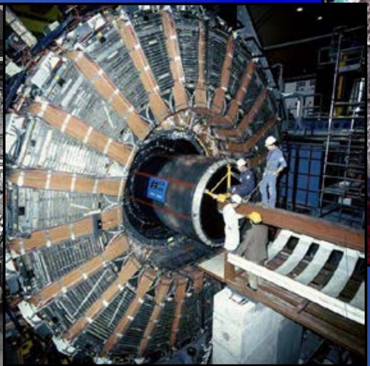




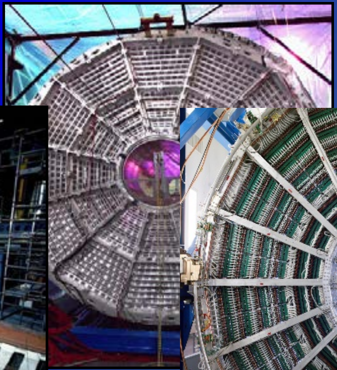
TOPAZ (KEK)



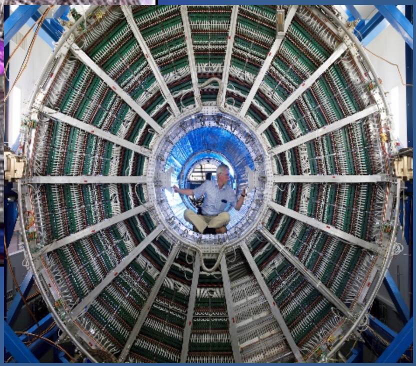
ALEPH (CERN)



DELPHI (CERN)



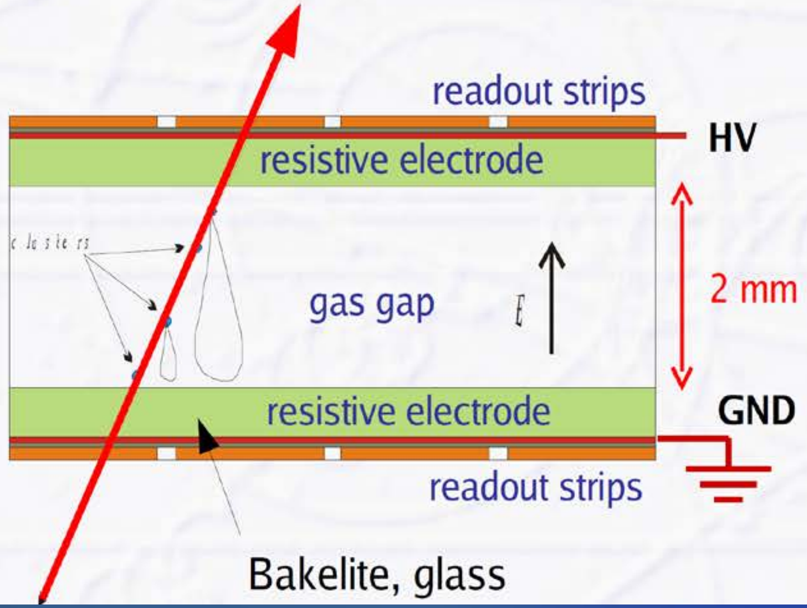
STAR (BNL)



ALICE (CERN)

Conceptual View of Resistive Plate Chambers (RPC)

- **There are also gaseous detectors without wires**
  - two resistive plates (~10^9 Ωcm) with a small gas gap (2 mm) and large high voltage (12 kV) on outside electrodes
  - strong E-field: operation in "streamer mode"
    - gas avalance already starting in gas gap (no wires involved)
    - developing of "streamers" (blob with lots of charge, almost like a spark)
    - signal on external read-out strips via influence (segmented for position resolution)
    - streamer/discharge is "self-quenching": stops when near-by resistive electrodes are locally discharged (E-field breaks down)



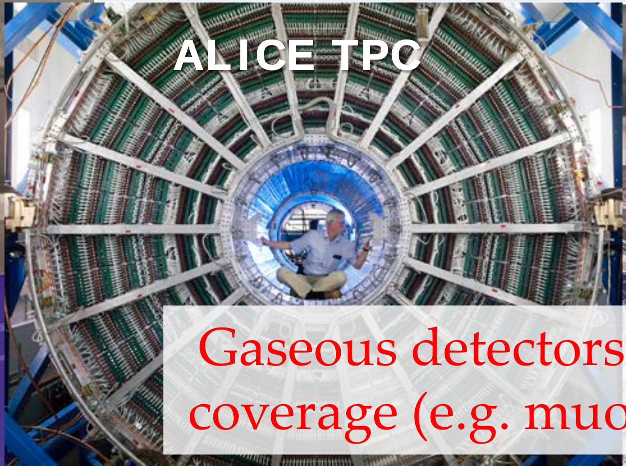
Advantages: simple device,
good to cover large areas,
VERY fast!!!

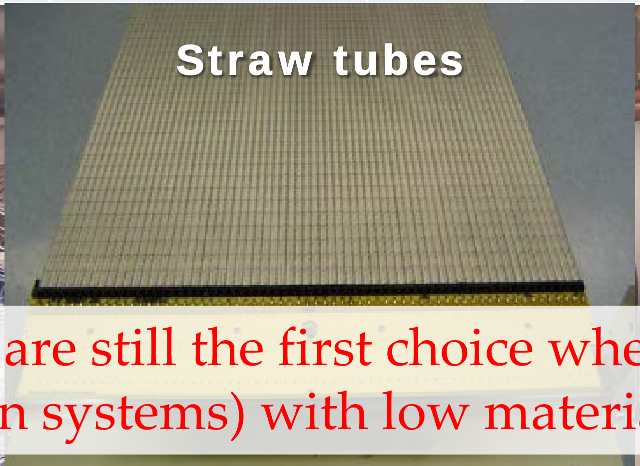
→ used as trigger devices in LHC experiments, time resolution ~ 50 – 100 ps

Disadvantages: Choice of resistive material + surface quality crucial, affects "dark" trigger rate

Gaseous Detectors in LHC Experiments

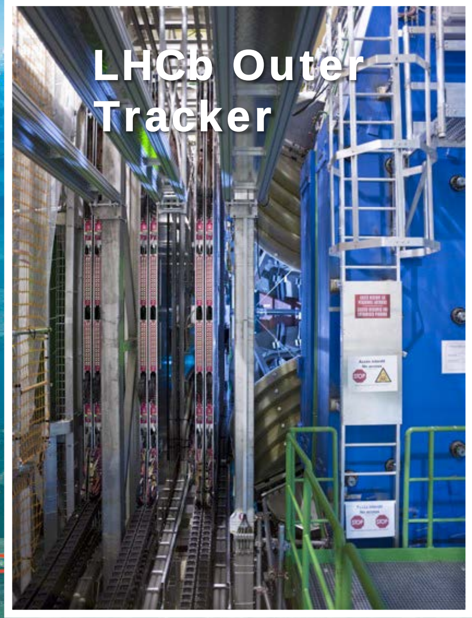
	Vertex	Inner Tracker	PID/ photo-det.	EM CALO	HAD CALO	MUON Track	MUON Trigger
ATLAS	-	TRD (straws)	-	-	-	MDT (drift tubes), CSC, Micromegas	RPC, TGC, Micromegas
CMS ----- TOTEM	-	-	-	-	-	Drift tubes, CSC, GEM ----- GEM	RPC, CSC GEM ----- GEM
LHCb	-	Straw Tubes	-	-	-	MWPC	MWPC, GEM
ALICE	-	TPC (MWPC replaced with MPGDs)	TOF(MRPC), PMD, HPMID (RICH-pad chamber), TRD (MWPC)	-	-	Muon pad chambers	RPC

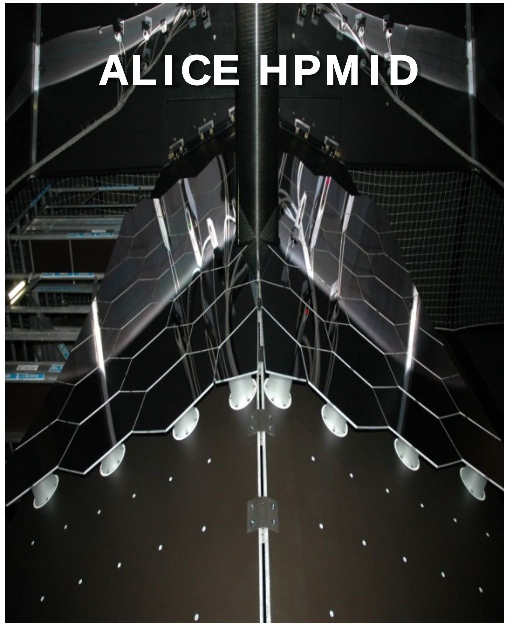


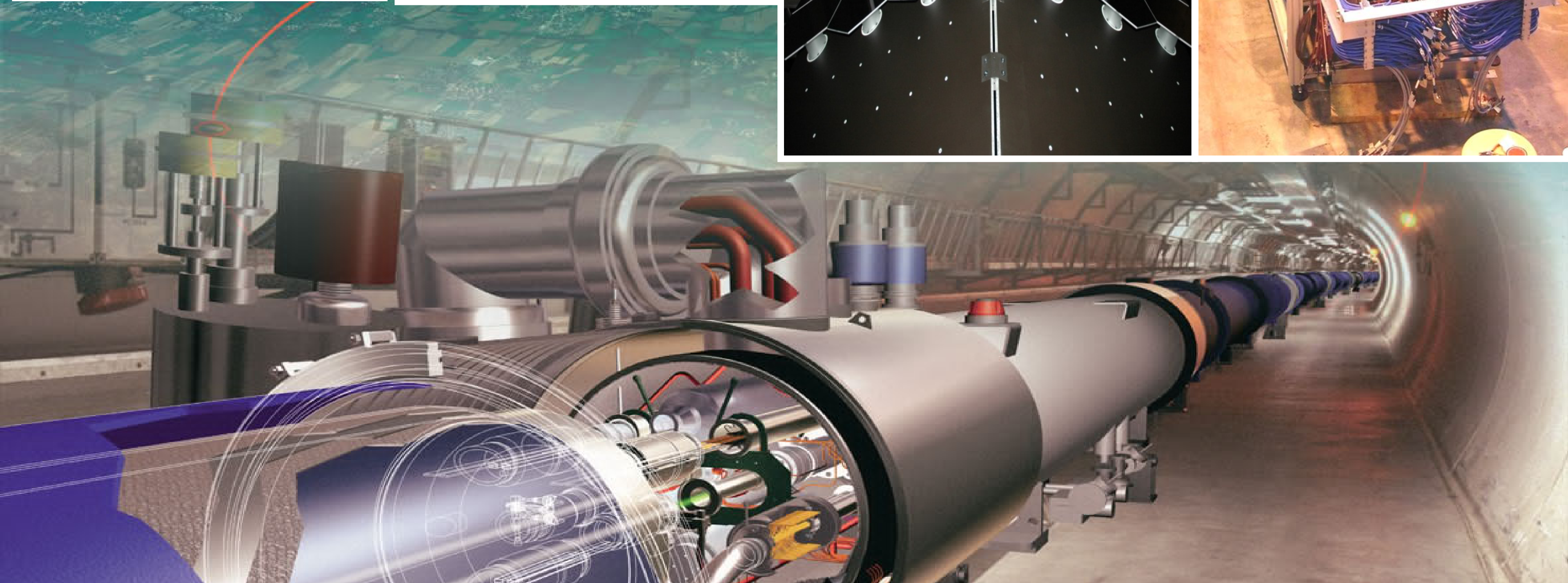


Gaseous detectors are still the first choice whenever the large-area coverage (e.g. muon systems) with low material budget is required

Gaseous Detectors in LHC Experiments

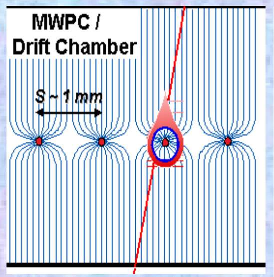


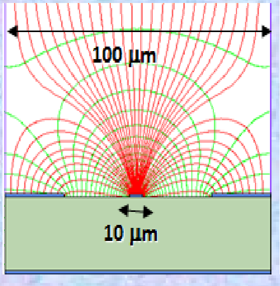




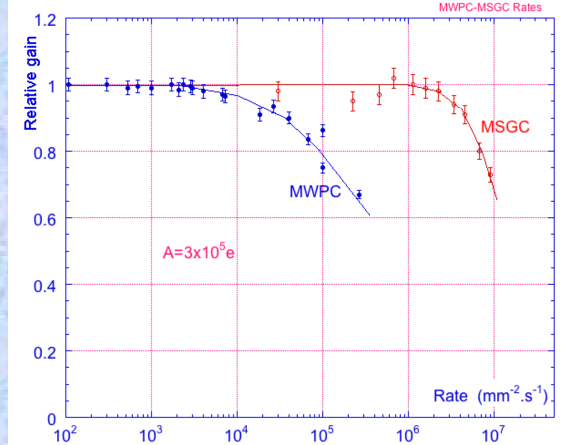
Micro-Pattern Gaseous Detector Technologies for Future Physics Projects

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

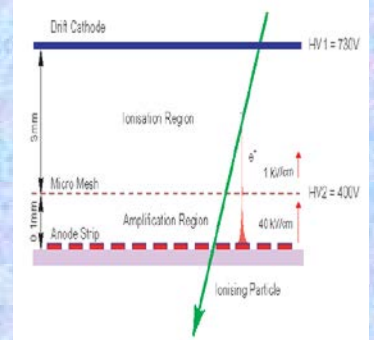


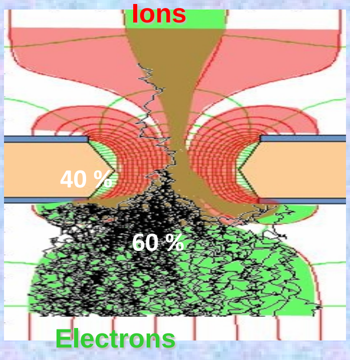


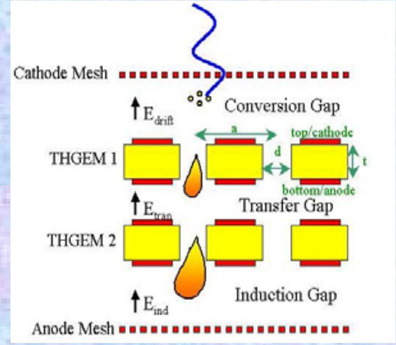
Rate Capability:
MWPC vs MSGC

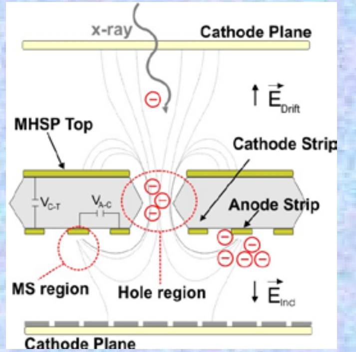


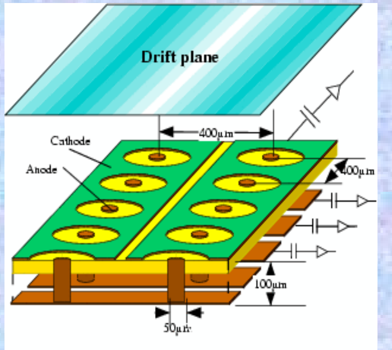
Micromegas | GEM | THGEM | MHSP | µPIC

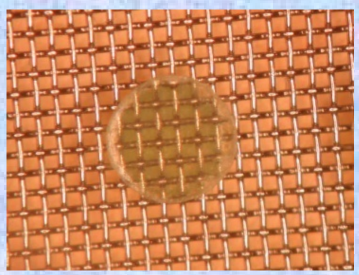


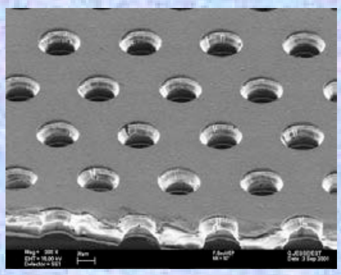


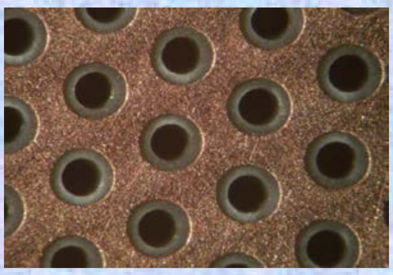


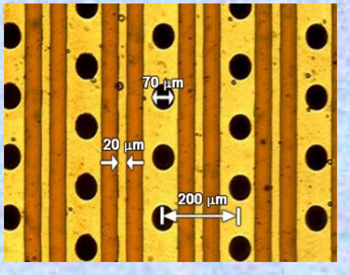


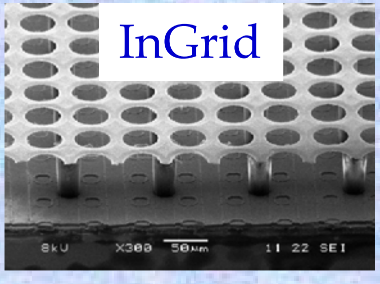








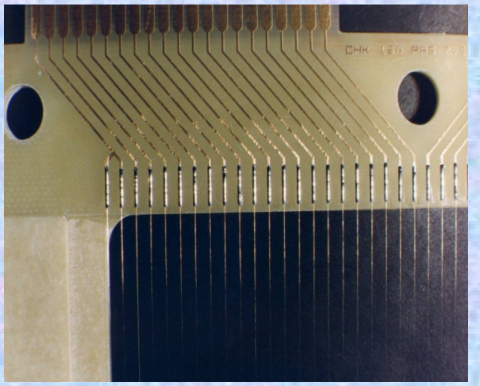


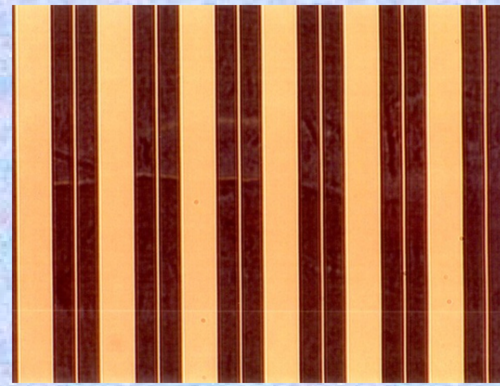


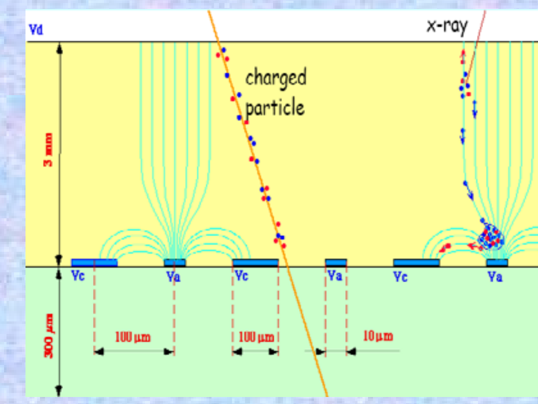
Micro-Strip Gas Chamber (MSGC)

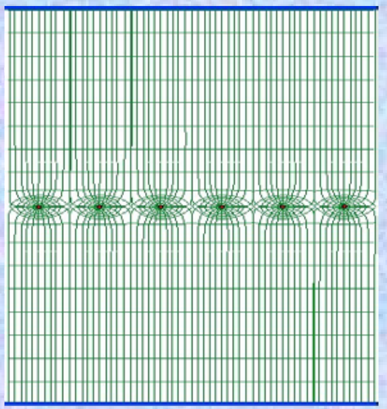
MWPC

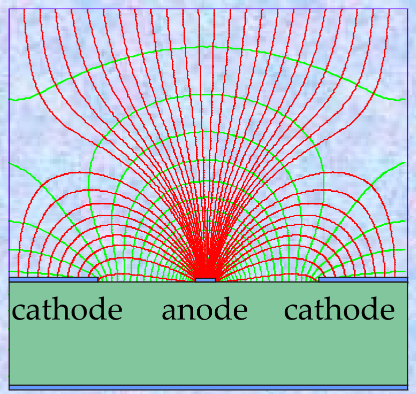
MSGC



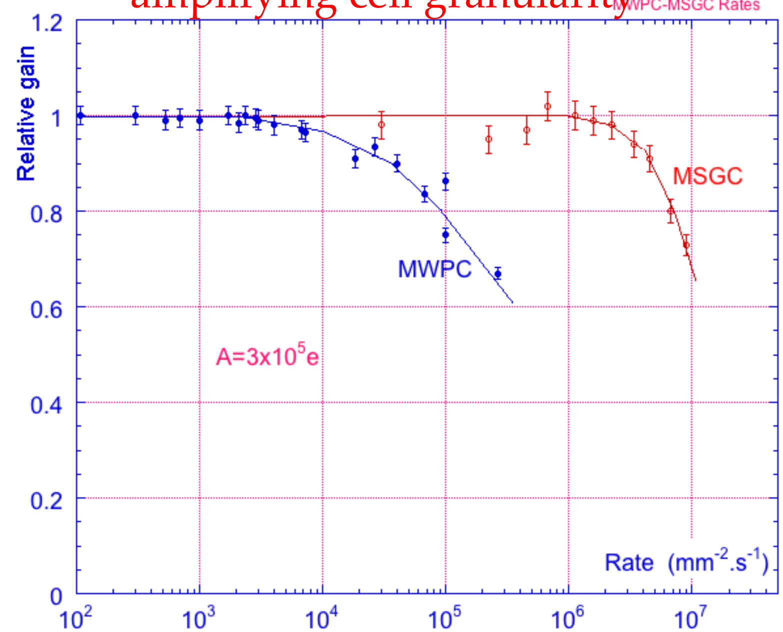








Rate capability limit due to space charge overcome by increased amplifying cell granularity



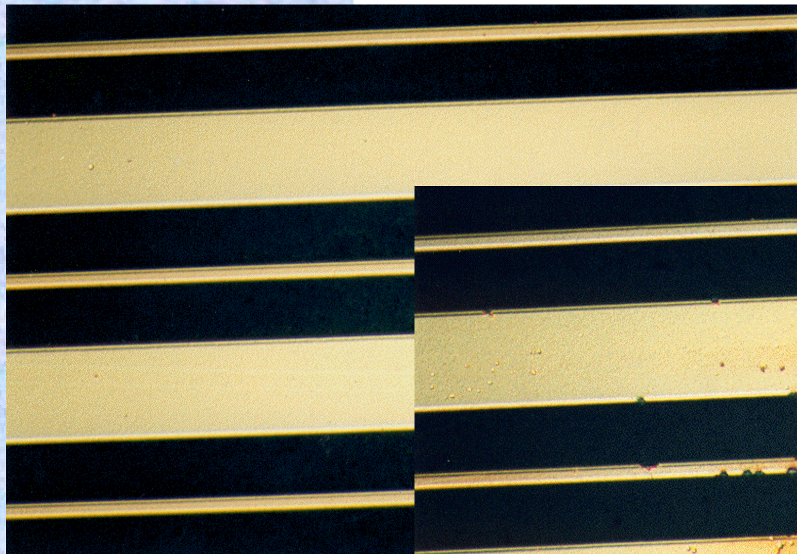
Typical distance between wires limited to 1 mm due to mechanical and electrostatic forces

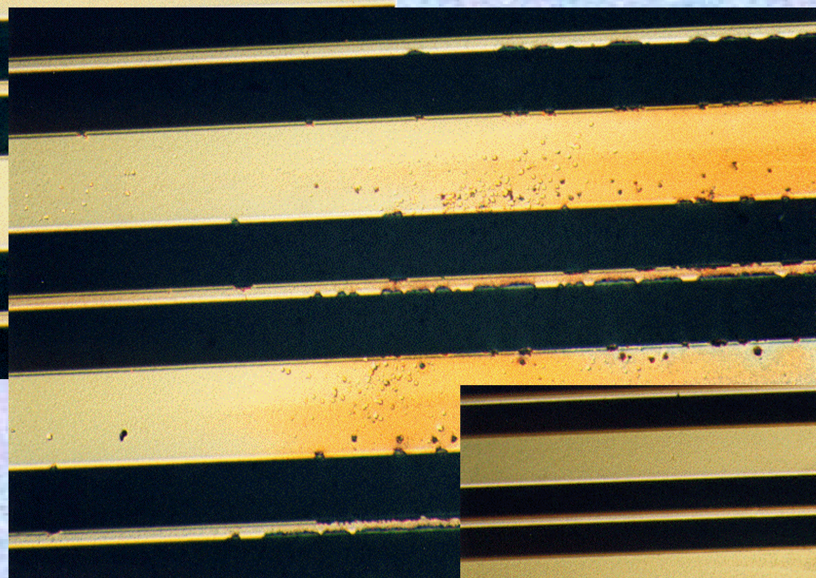
Typical distance between anodes 200 mm thanks to semiconductor etching technology

A. Oed, Nucl. Instr. and Meth. A263 (1988) 351.

MSGC Discharge Problems

Discharge is very fast (~ns)
Difficult to predict or prevent





MICRODISCHARGES

Owing to very small distance between anode and cathode the transition from proportional mode to streamer can be followed by spark, discharge, if the avalanche size exceeds
RAETHER'S LIMIT
$Q \sim 10^7 - 10^8$ electrons

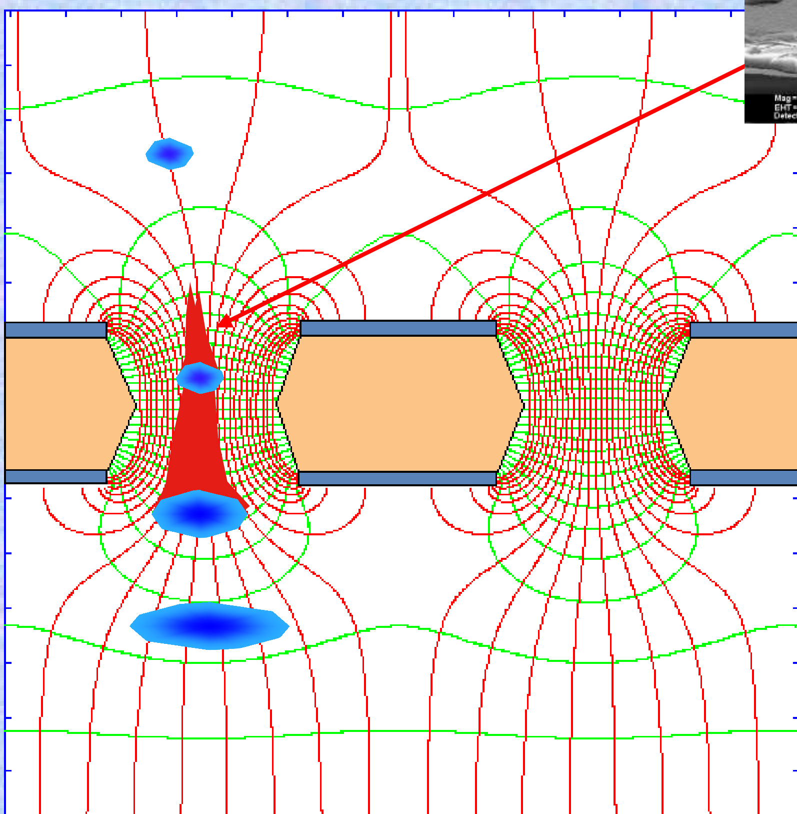
FULL BREAKDOWN

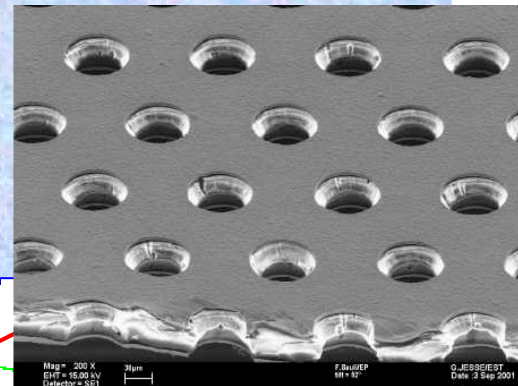
GEM (Gas Electron Multiplier)

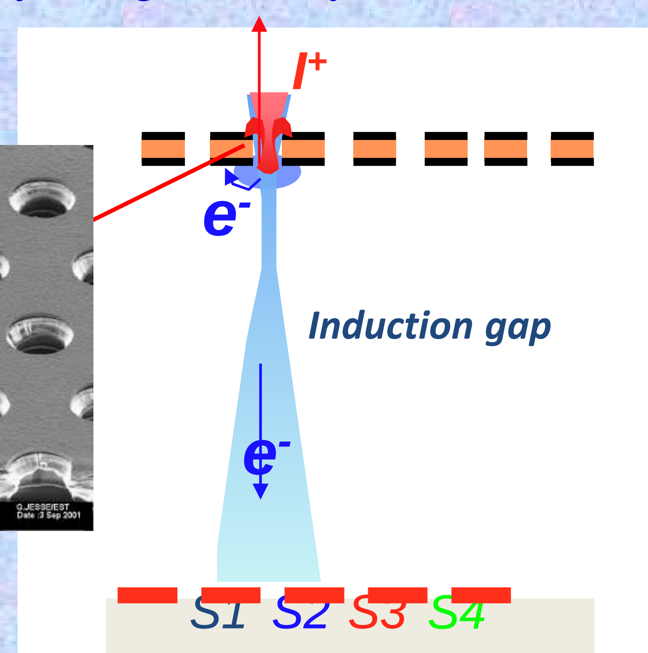
Thin metal-coated polymer foil chemically pierced by a high density of holes

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.







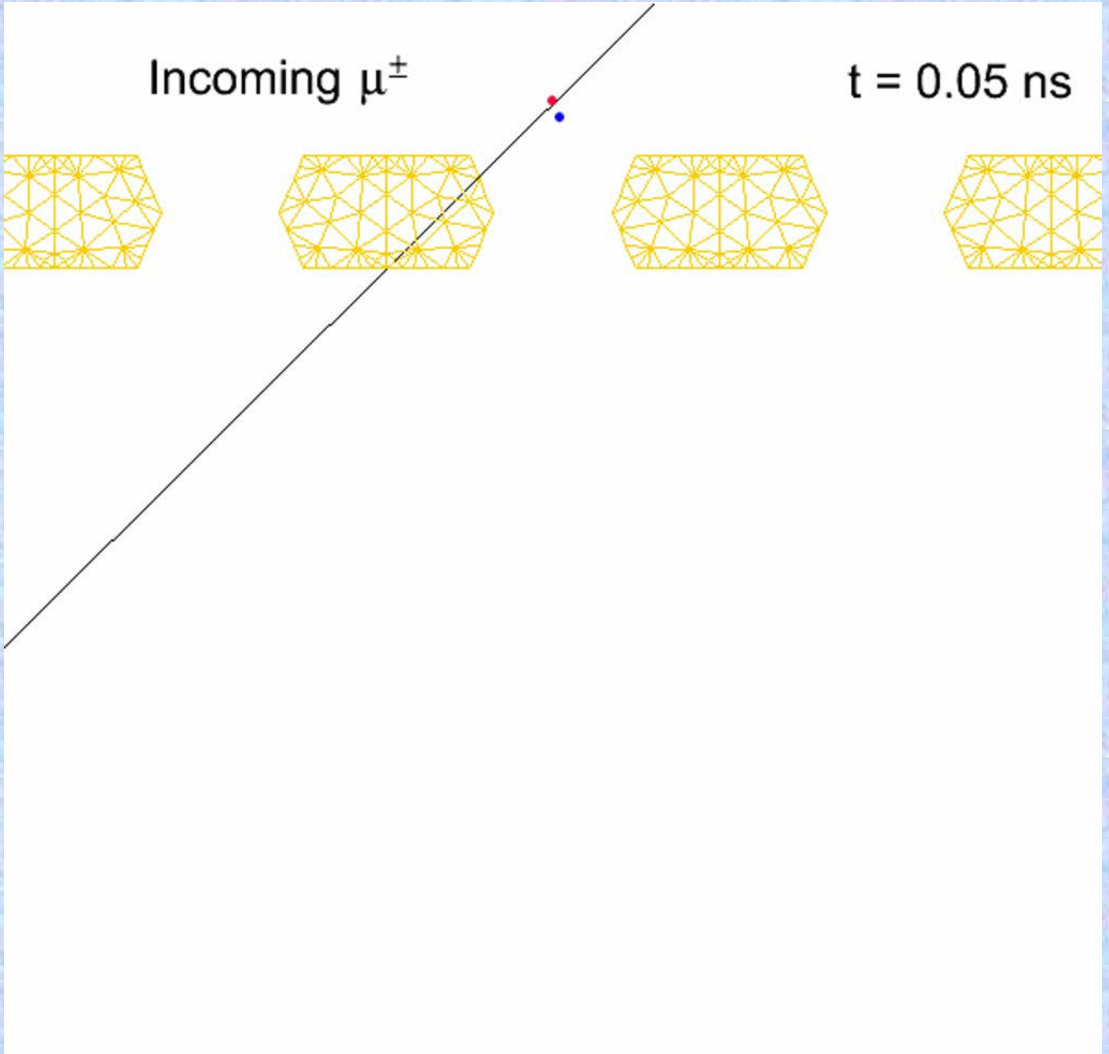
- Electrons are collected on patterned readout board.
- A fast signal can be detected on the lower GEM electrode for triggering or energy discrimination.
- All readout electrodes are at ground potential.

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

MPGD Simulation Tools (Avalanche Simulation in GEM)

Animation of the avalanche process (monitor in ns-time electron/ion drifting and multiplication in GEM):

electrons are blue, ions are red, the GEM mesh is orange

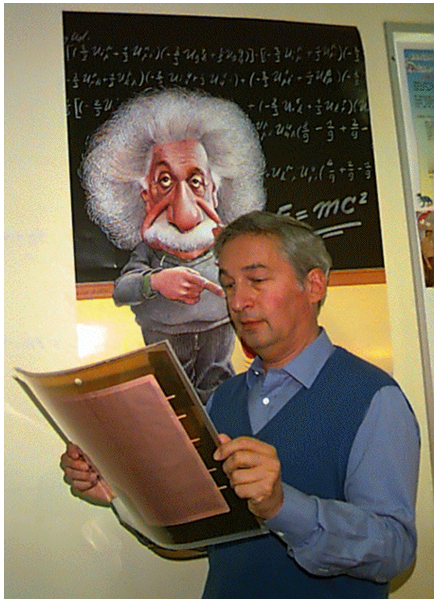


- ANSYS: field model
- Magboltz 8.9.6: relevant cross sections of electron-matter interactions
- Garfield++: simulate electron avalanches

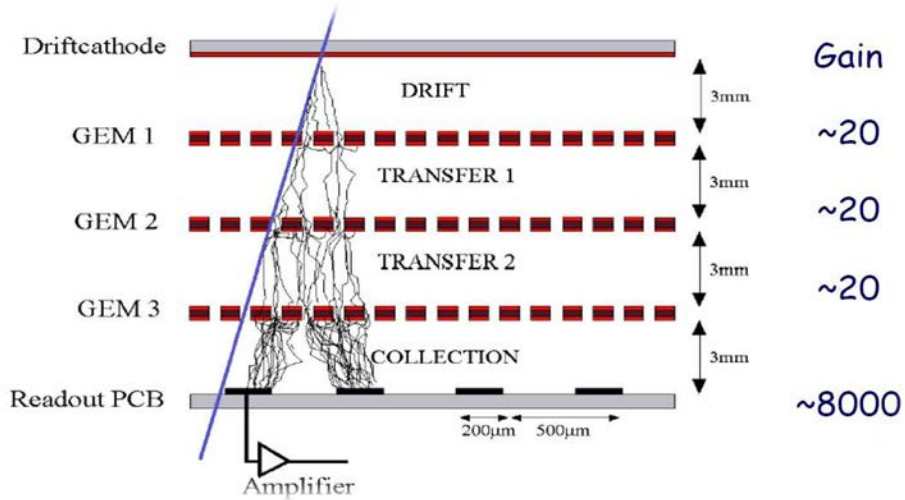
http://cern.ch/garfieldpp/examples/gemgain

Gas Electron Multiplier (GEM)

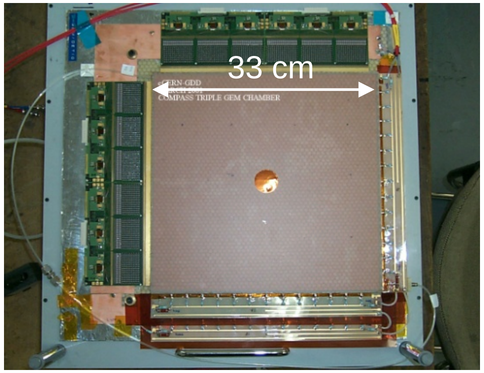
F. Sauli, NIM A386(1997) 531;
F. Sauli, http://www.cern.ch/GDD



Full decoupling of amplification stage (GEM) and readout stage (PCB, anode)

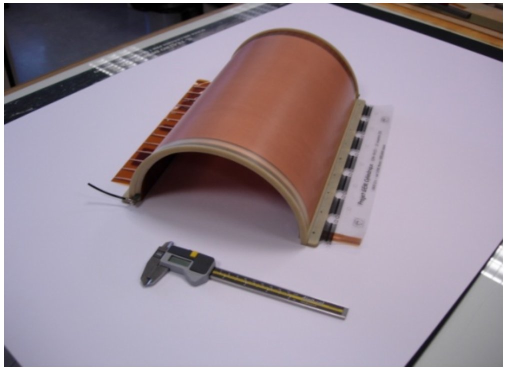


Amplification and readout structures can be optimized independently !

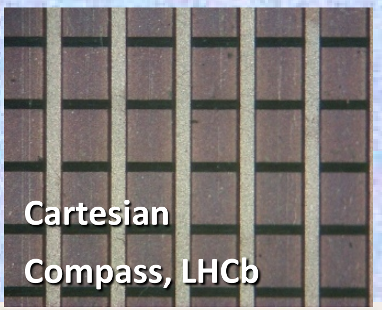


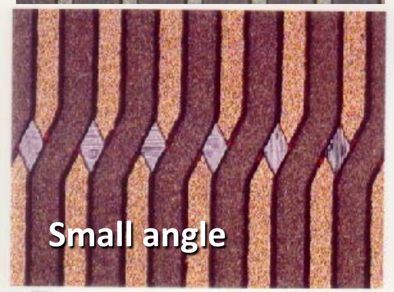
Compass

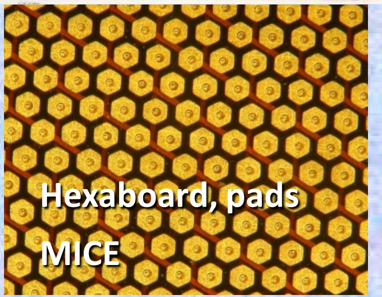
Totem



NA49-future





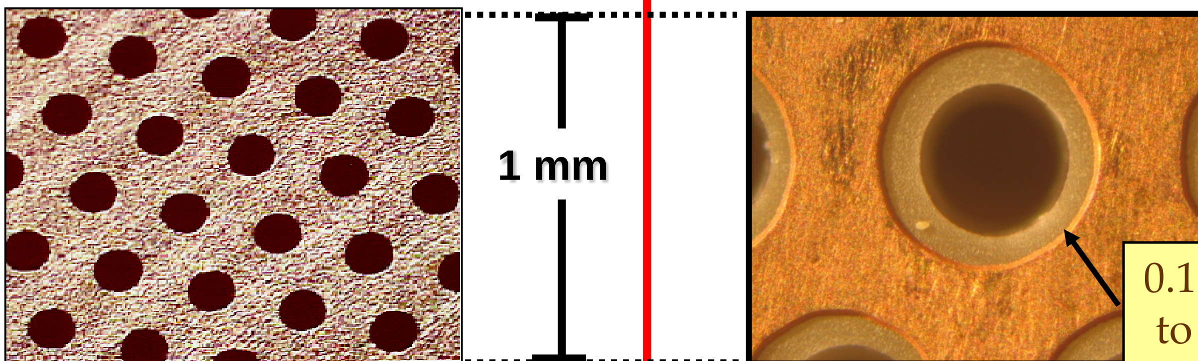


Thick-GEM Multipliers (THGEM)

Simple & Robust → Manufactured by standard PCB techniques of precise drilling in G-10 (and other materials) and Cu etching

STANDARD GEM
10^3 GAIN IN SINGLE GEM

THGEM
10^5 gain in single-THGEM



0.1 mm rim to prevent discharges

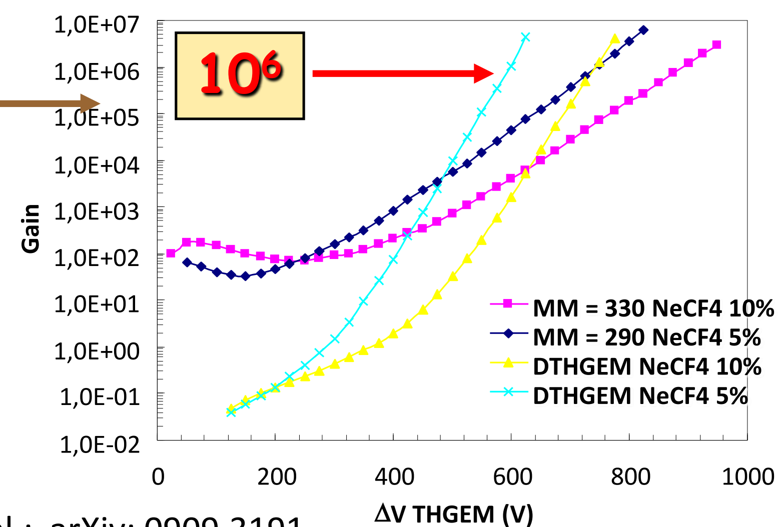
Other groups developed similar hole-multipliers:

- Optimized GEM: L. Periale et al., NIM A478 (2002) 377.

- LEM: P. Jeanneret,
- PhD thesis, 2001.

- Effective single-electron detection (high gas gain ~10^5 (>10^6) @ single (double) THGEM)
- Few-ns RMS time resolution
- Sub-mm position resolution
- MHz/mm^2 rate capability
- Cryogenic operation: OK
- Gas: molecular and noble gases
- Pressure: 1mbar - few bar

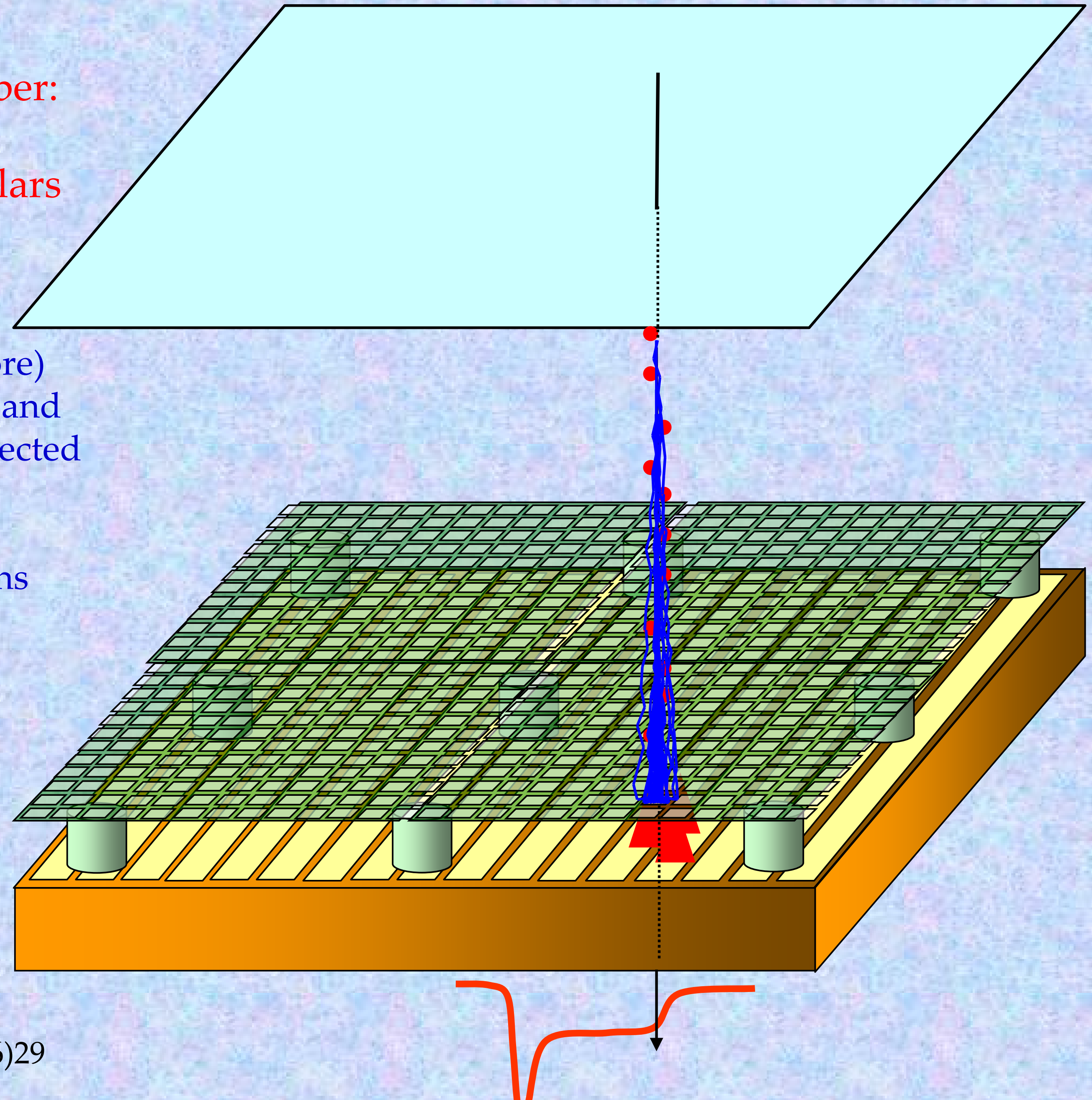
Double THGEM or THGEM/Micromegas



C. Azevedo et al.; arXiv: 0909.3191

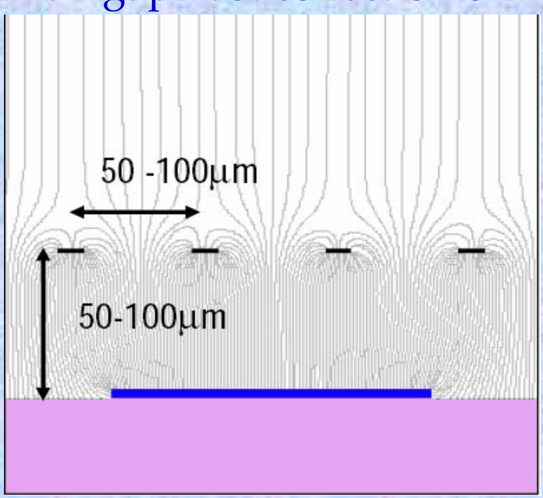
MICro MEsh GAseous Structure (MICROMEGAS)

Micromesh Gaseous Chamber:
micromesh supported
by 50-100 μm insulating pillars

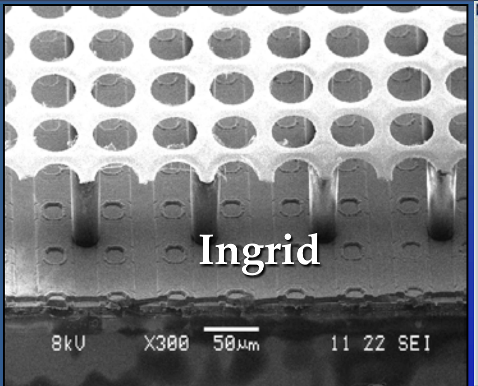


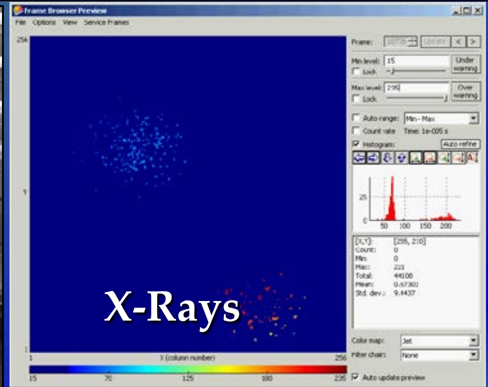
Multiplication (up to 10^5 or more) takes place between the anode and the mesh and the charge is collected on the anode (one stage)

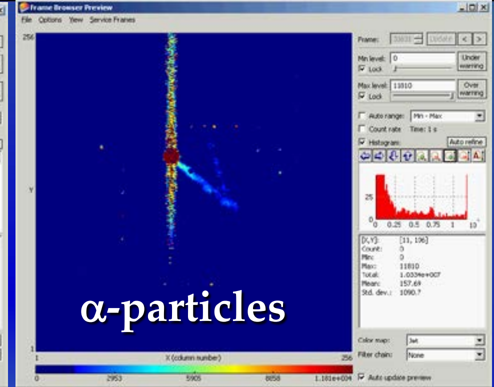
Small gap: fast collection of ions

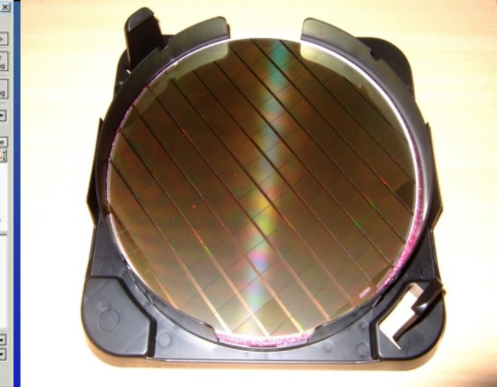


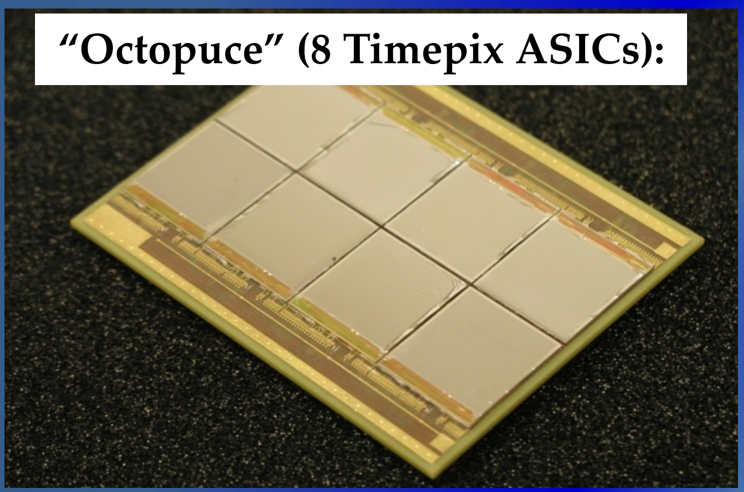
Y. Giomataris et al, NIM A376(1996)29





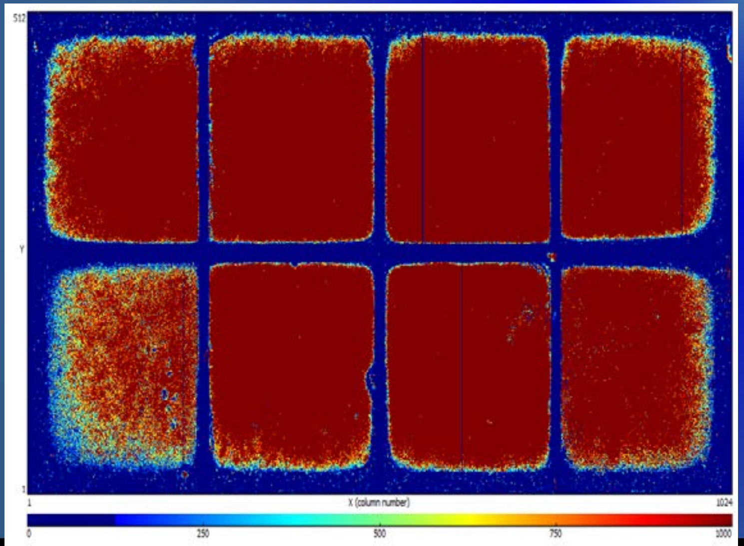


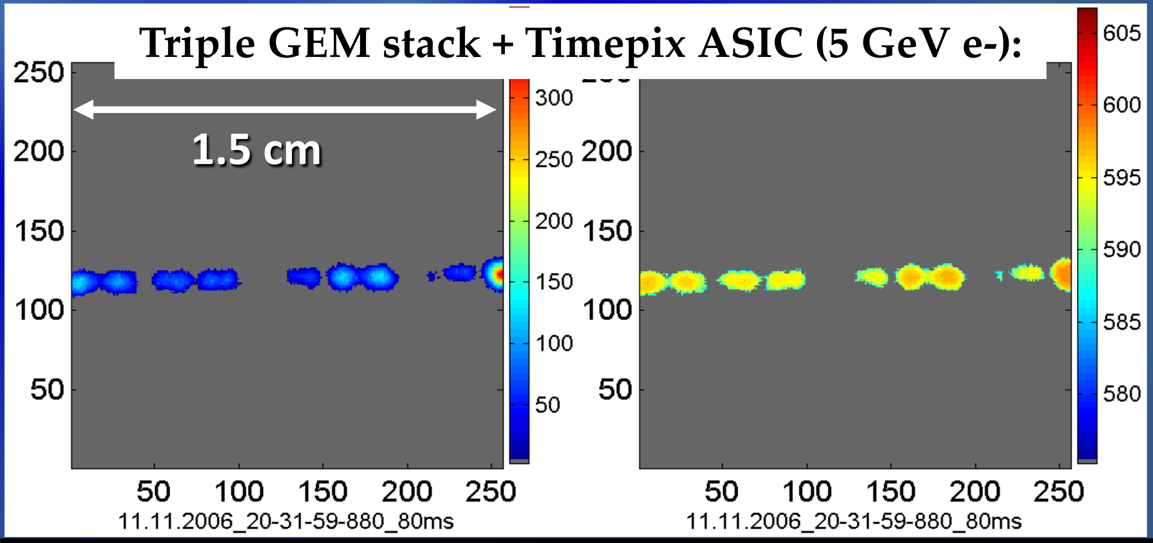




ULTIMATE INTEGRATION OF GASEOUS and SIICON DETECTORS –

PIXEL READOUT of MICRO-PATTERN GASEOUS DETECTORS

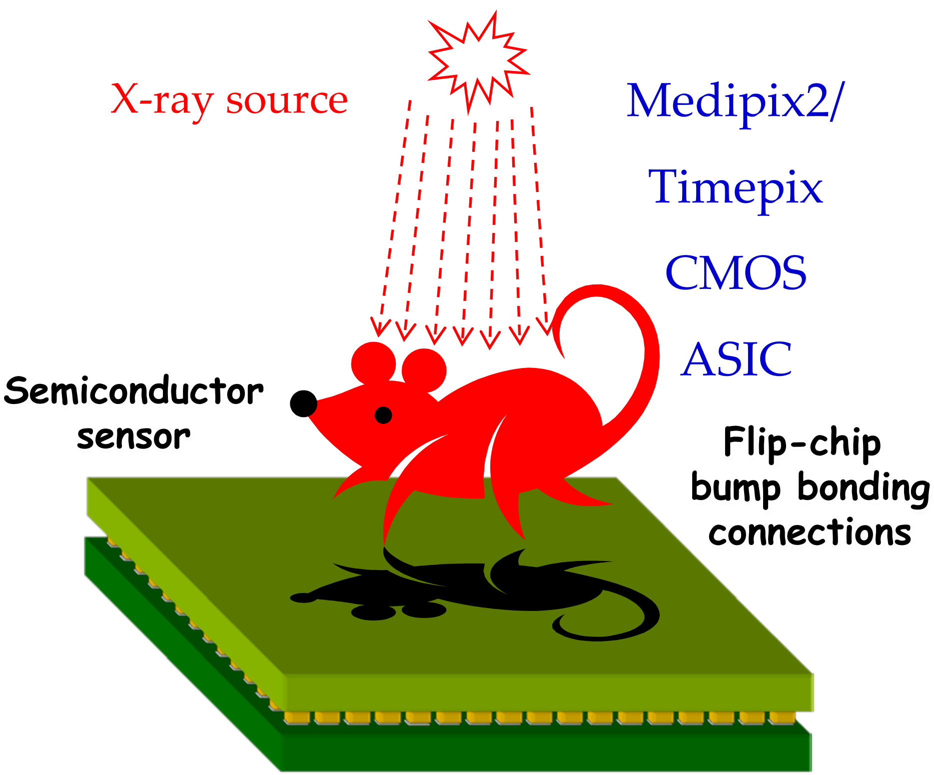




Pixel Readout of Micro-Pattern Gaseous Detectors

Use a CMOS Pixel ASIC (w/o Si sensor), assembled below MPGDs (GEM/Micromegas),as charge collecting anode and fully integrated readout electronics

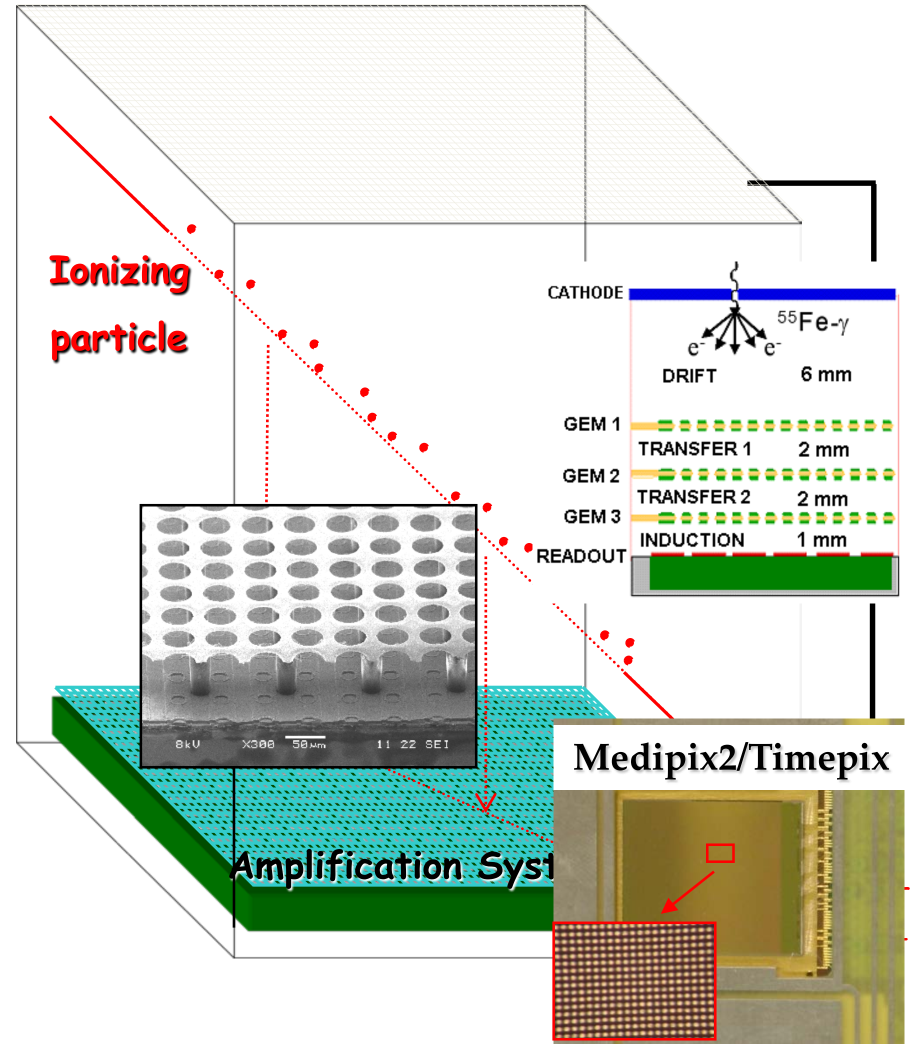
Solid state pixel detector



Medipix2 / Timepix ASIC (0.25 μm –IBM/CMOS)

- 256 × 256 pixels of 55 × 55 μm^2 size
- Medipix2: digital with 2 THR (low and high)
- Timepix: 2 modes (TOT ≈ integrated charge
  TIME = Time between hit and shutter end)

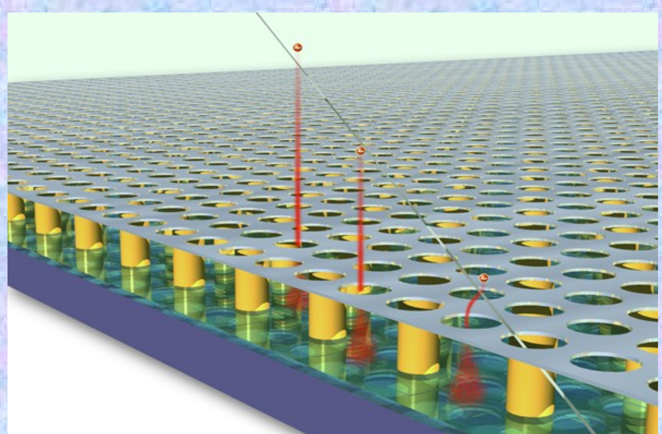
Gaseous detector

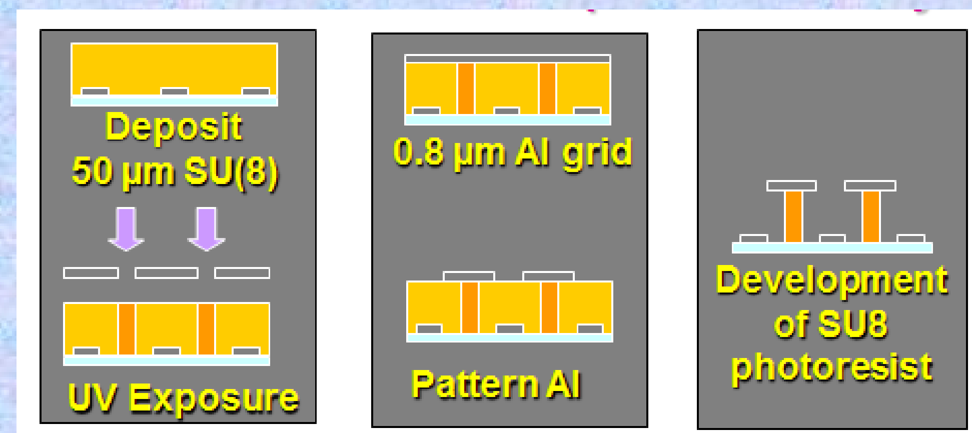


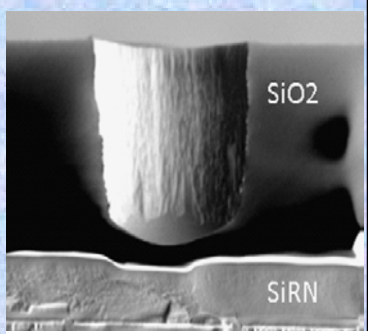
Pixel Readout of MPGDs: "InGrid" Concept

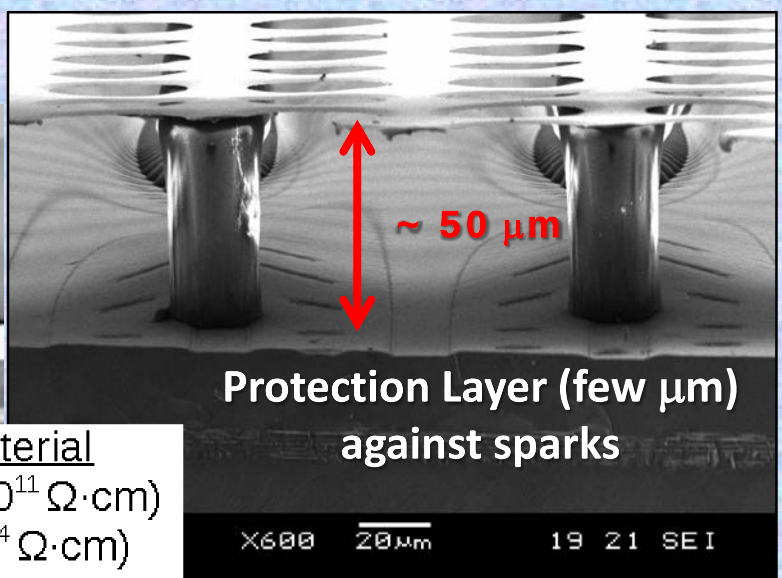
"InGrid" Concept: By means of advanced wafer processing-technology INTEGRATE MICROMEGAS amplification grid directly on top of CMOS ("Timepix") ASIC

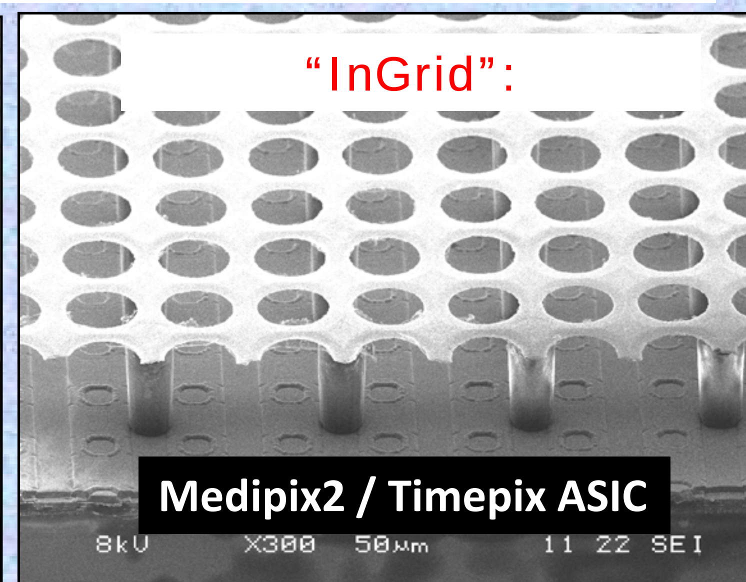
3D Gaseous Pixel Detector → 2D (pixel dimensions) x 1D (drift time)









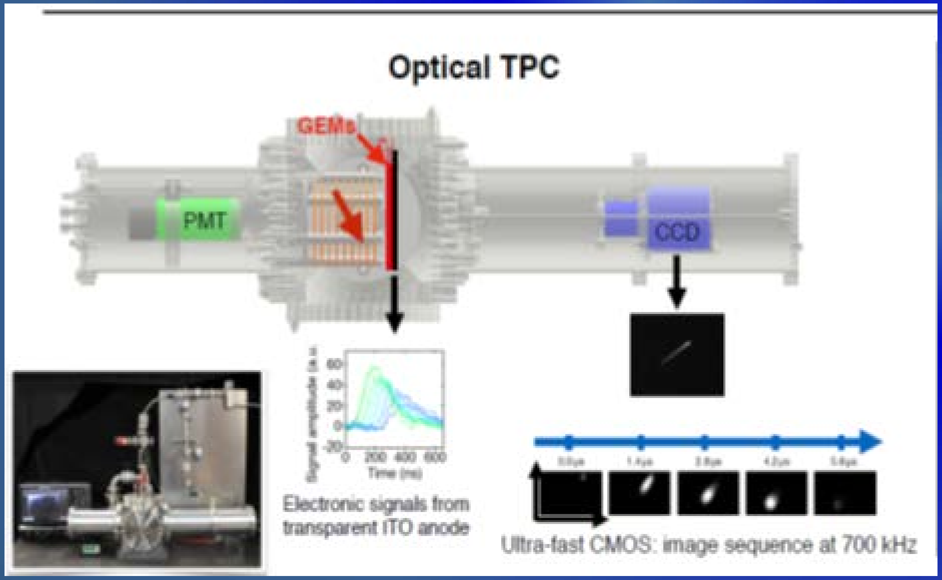


high resistive material
15 μm aSi:H (~10^{11} Ω·cm)
8 μm $Si_X N_Y$ (~10^{14} Ω·cm)

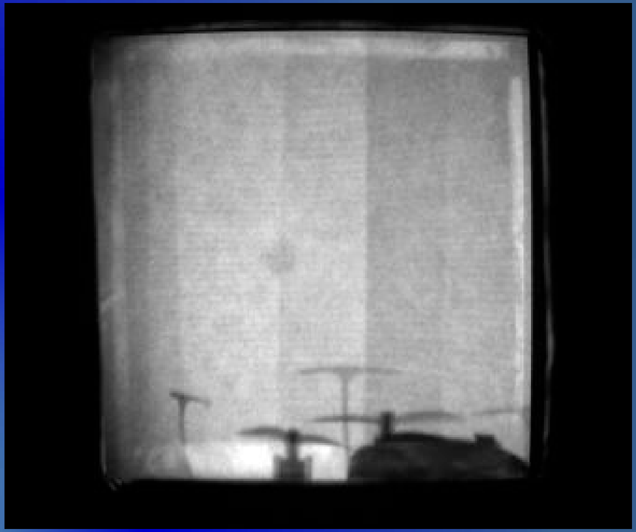
Optical Readout of MPGDs: Imaging Applications

Developments of scintillation light readout of MicroPattern Gaseous Detectors (MPGDs): GEMs, Micromegas, …

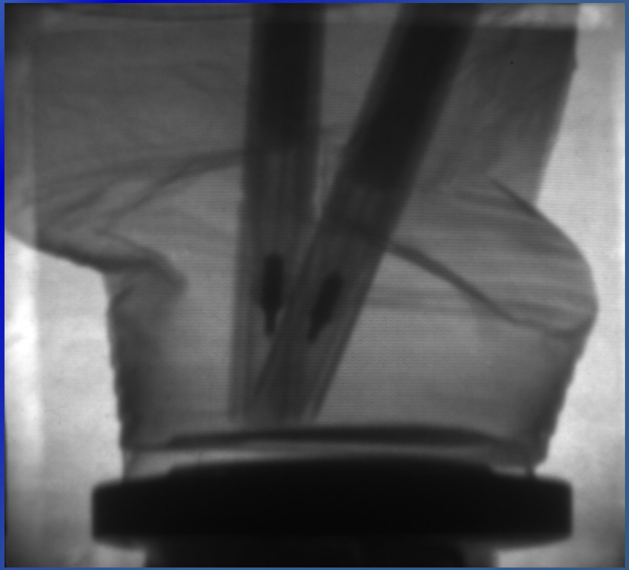
- ✓ Optical TPC (Combined electronic + optical readout)
- ✓ Ultra-fast optical readout (TPCs, beam monitor)
- ✓ Low-material budget, online beam monitoring
- ✓ Detector physics studies
- ✓ among other applications…



Fluoroscopy:

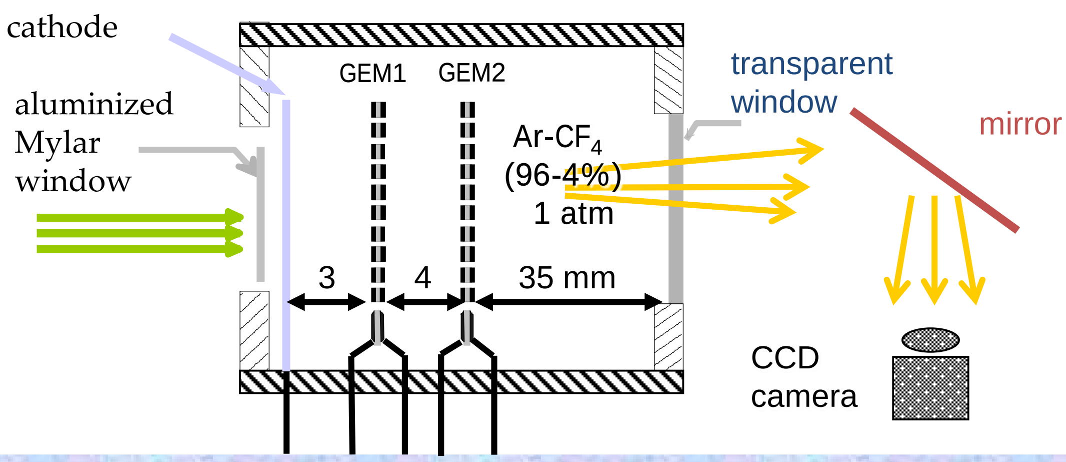


CT and 3 D Imaging:



A Scintillating GEM for Dose Imaging in Radiotherapy

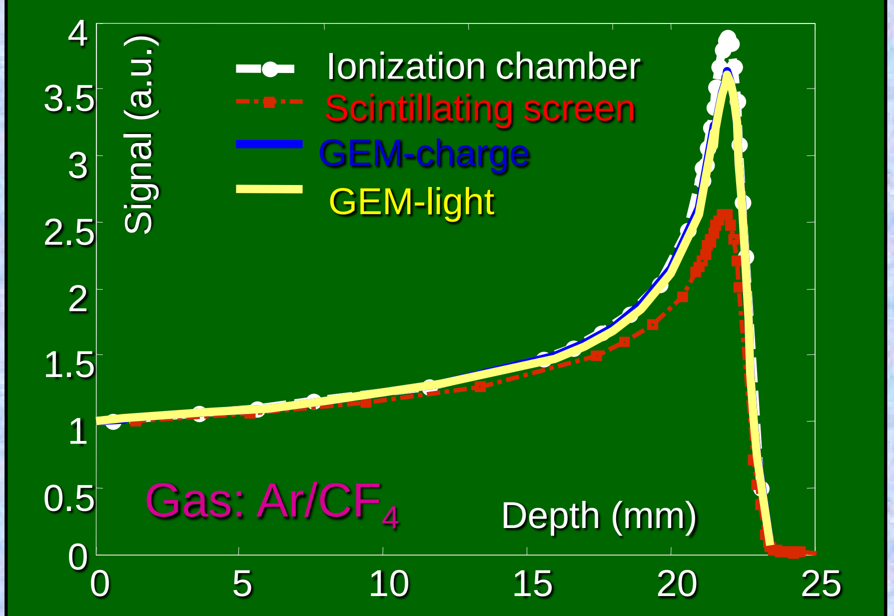
Scintillation light (optical) & charge Readout:



Light output for 138 MeV protons:

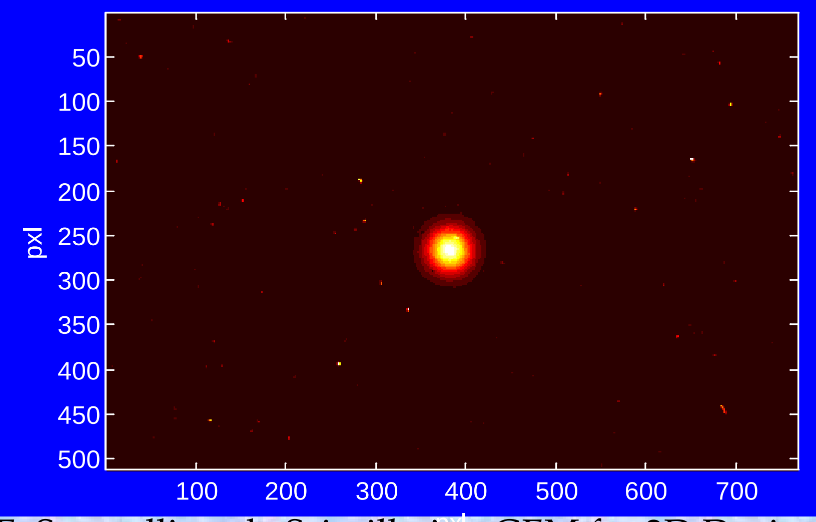
Scintillation type	Gas gain	Light signal (CCD) at 1Gy proton dose (ADU)
Screen (Gd_2O_2S:Tb)		2670
Ar/CO_2 (90:10)	3000	270
Ar/CF_4(90:10)	1400	2350
Ar/CF_4 (95:5)	1300	4000
Ar/CF_4 (97,5:2,5)	770	2000

Bragg curve with 360 MeV a-beam

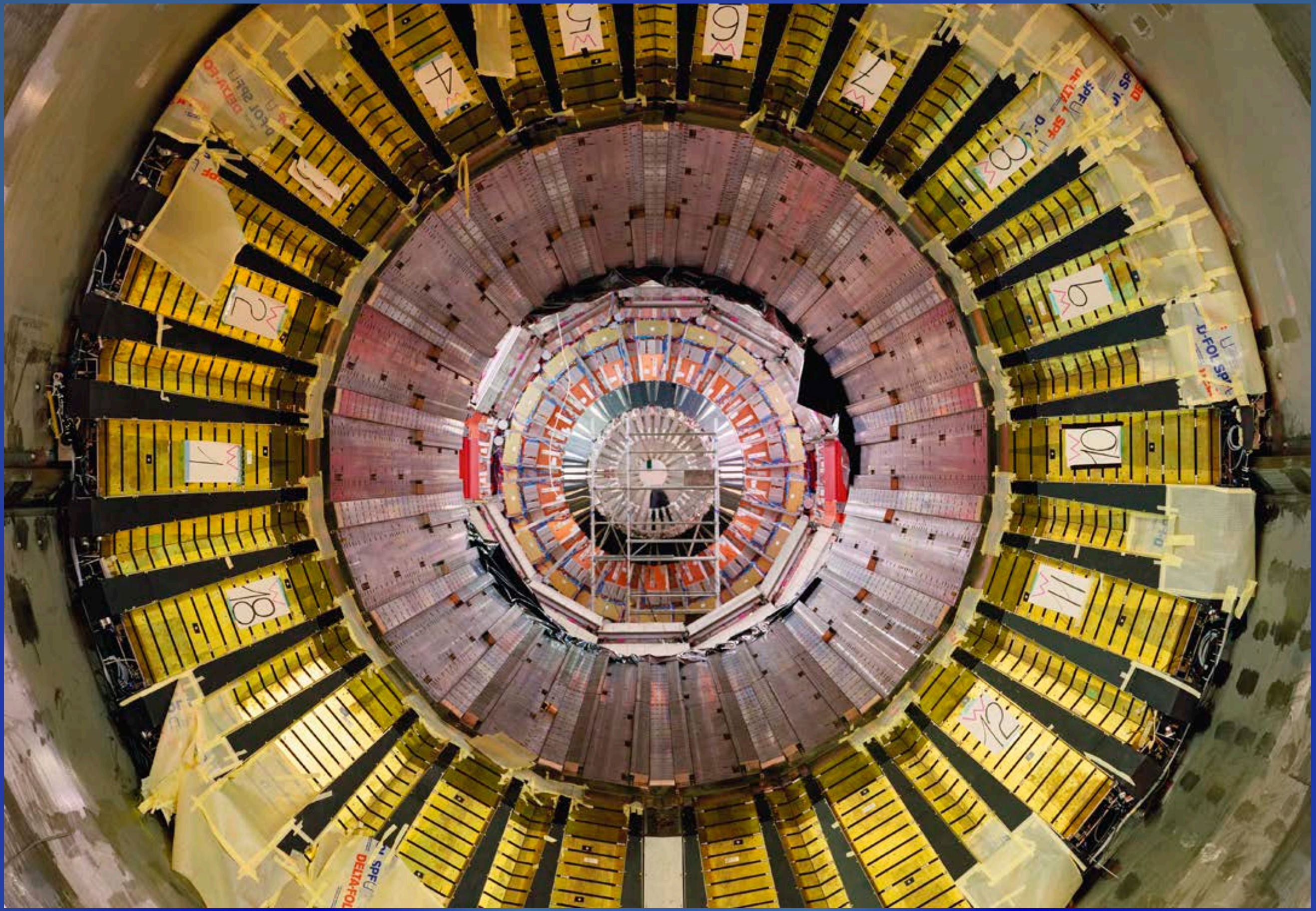


LIGHT SIGNAL FROM GEM:

(only 4% smaller than ionization chamber signal)



E. Sevaralli et al., Scintillating GEM for 2D Dosimetry in a-beam, submitted to IEEE TNS
S. Fetal et al., NIMA513 (2003) 42



Knowledge is limited. Whereas the Imagination embraces the entire world… Albert Einstein

Bridge the gap between science and society …

The Role of Big High Energy Physics Laboratories:
– innovate, discover, publish, share

… and bring the world together