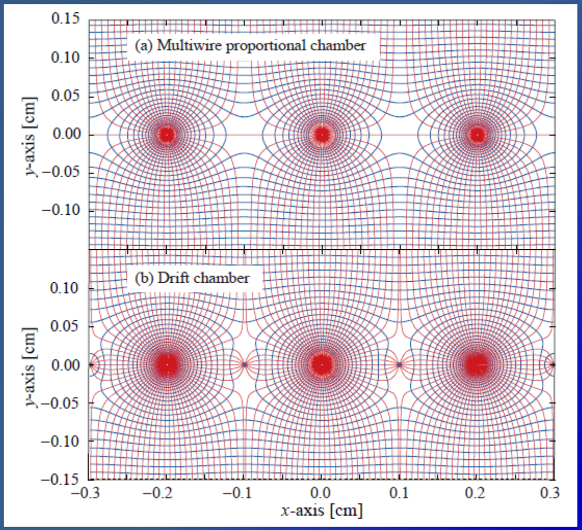
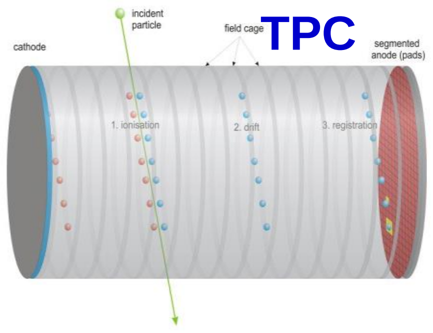
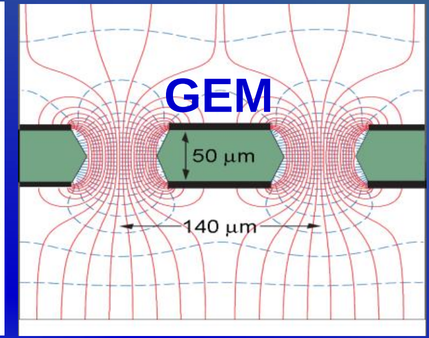
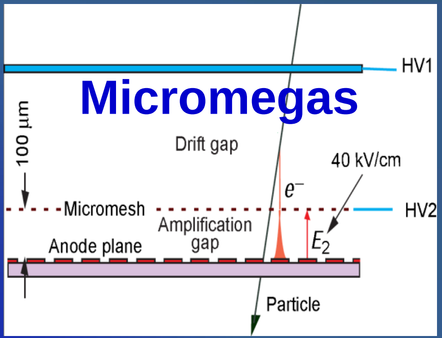


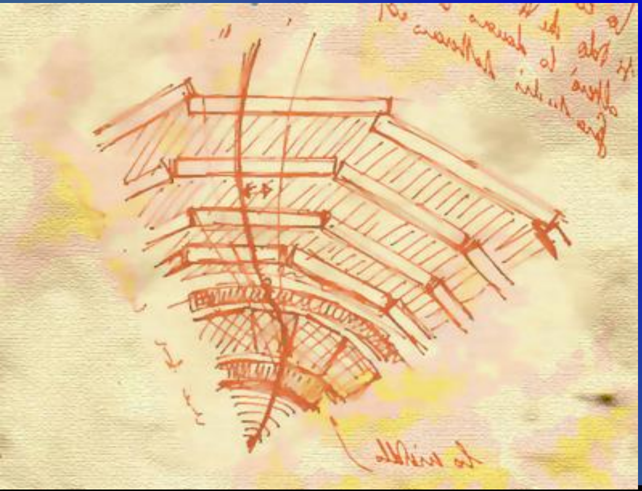


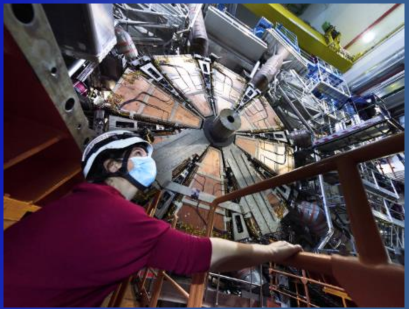


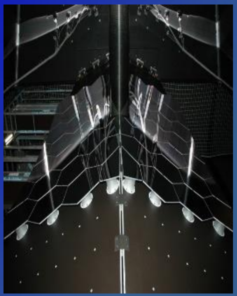


From (very) Basic Ideas to Rather Complex Gaseous Detector Systems

Maxim Titov, CEA Saclay, Irfu, France

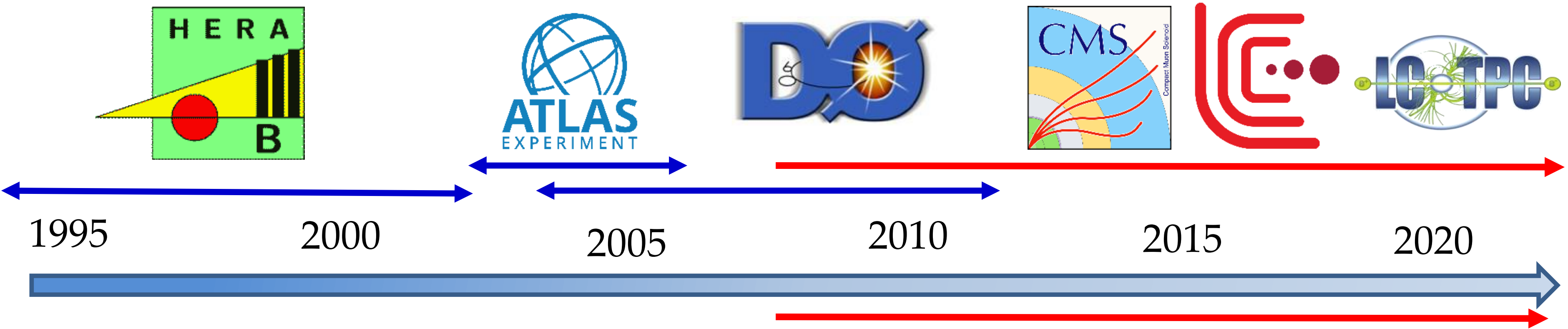


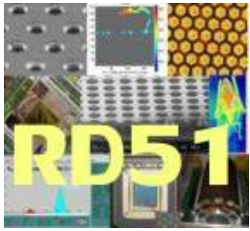


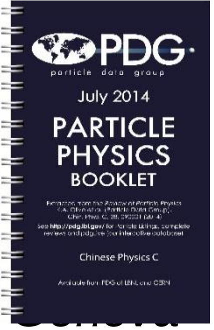


IEEE NPSS Educom International Summer School (REISS)
Faculté des Science, University Mohamed V of Rabat,
Morocco, July 1-10, 2024

Professional Experience: International Collaborations






PDG
particle data group
July 2014
PARTICLE PHYSICS BOOKLET
Chinese Physics C

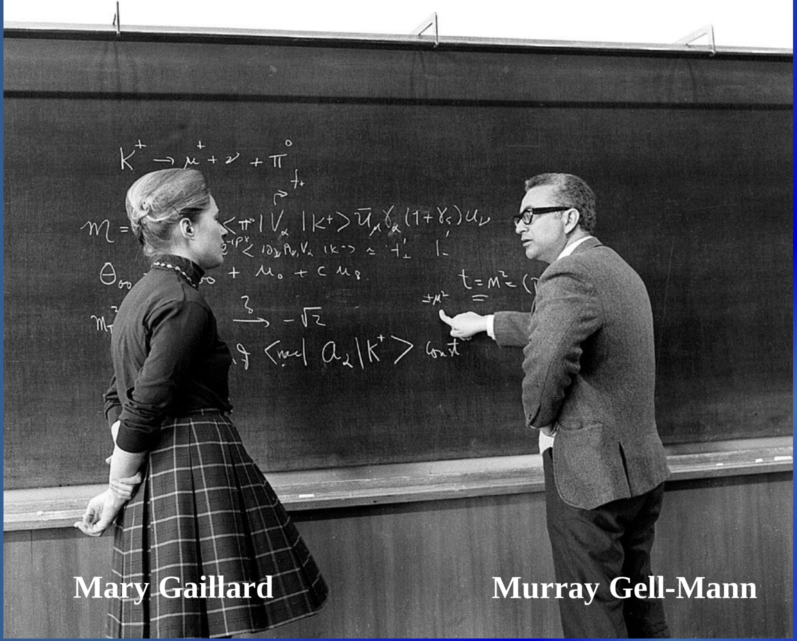
1993 – 2003: HERA-B Experiment at DESY / HERA, Hamburg
2003 – 2006: ATLAS Experiment at CERN / LHC, Geneva
2004 – 2011: DZero Experiment at Fermilab / Tevatron, Chicago

2008 – 2023: RD51 Collaboration (“Micro-Pattern Gas. Detectors”) at CERN, Geneva
2023, 2008 - 2015 Spokesperson of the RD51 Collaboration
2024 – present: DRD1 Collaboration (“Gaseous Detectors”) at CERN, Geneva
2024 - 2025 Spokesperson of the DRD1 Collaboration

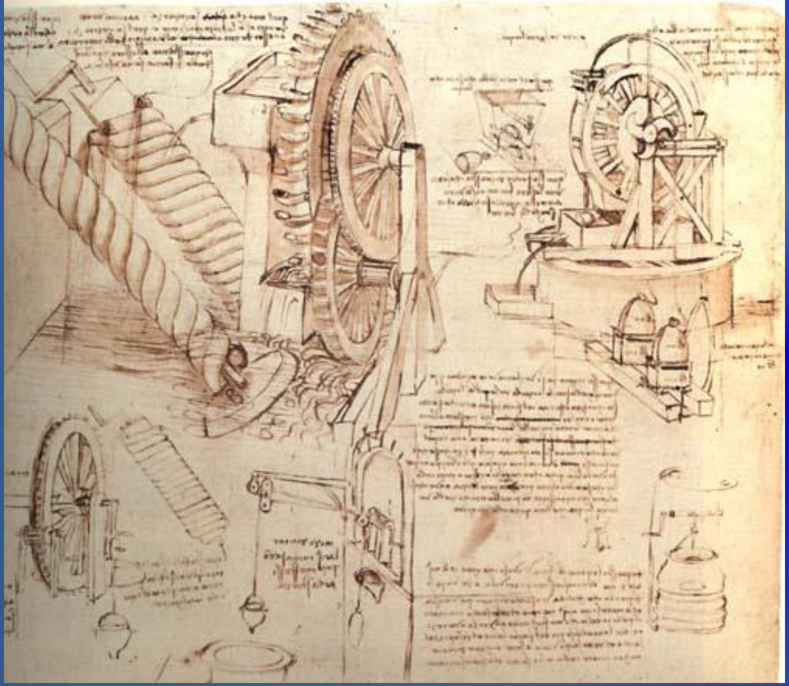
2007 – present: CMS Experiment at CERN / LHC, Geneva
2007 – present: International Linear Collider Project in Japan *(ILC)*
2007 – present: Particle Data Group *(PDG)* Collaboration
2024 – present: Chair of the European Laboratory Directors Working Group
“Sustainability Assessment of Future Accelerators”

To make a collider experiment, one needs:

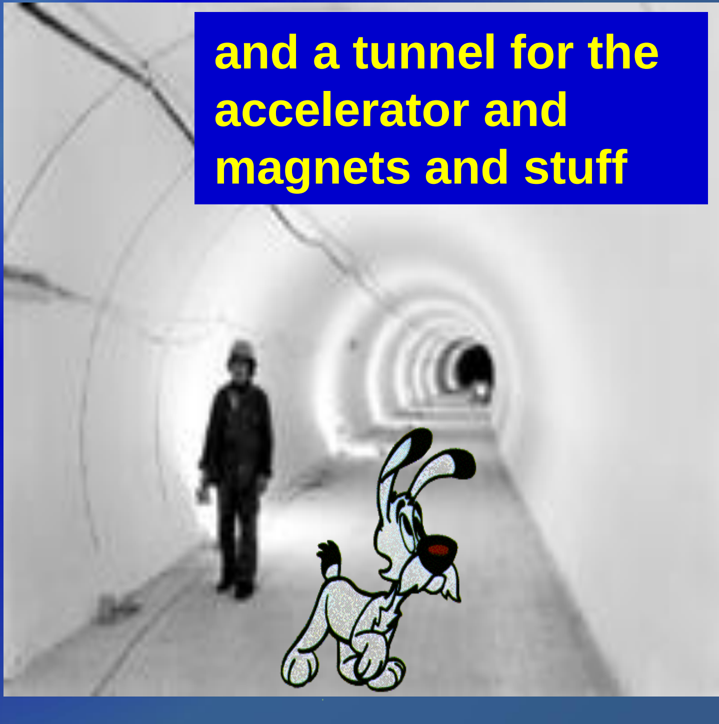
A theory:



and a cafeteria



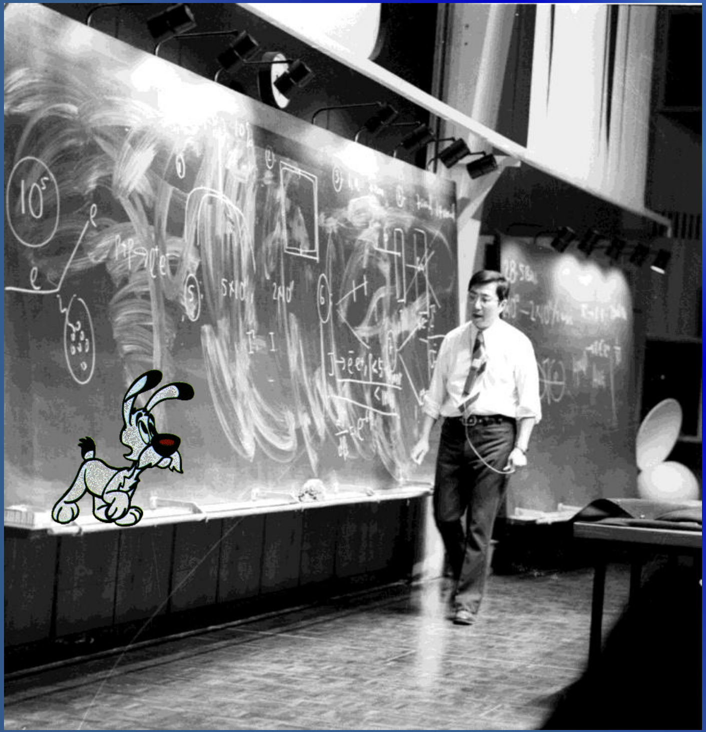
Clear and easy understandable drawings



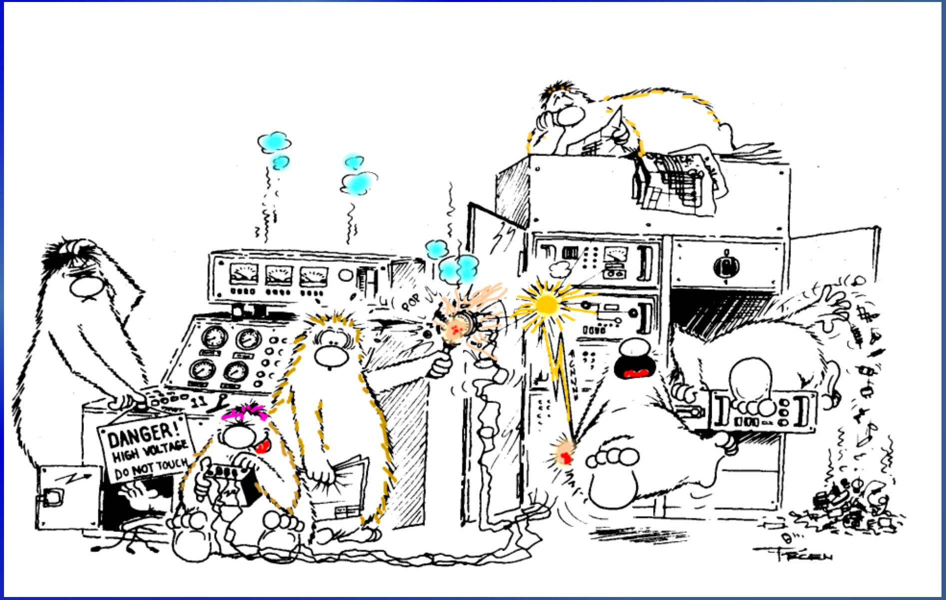
and a tunnel for the accelerator and magnets and stuff

Easy access to the experiment

Physicists to operate detector/analyze data



and a Nobel prize



We will just concentrate on 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

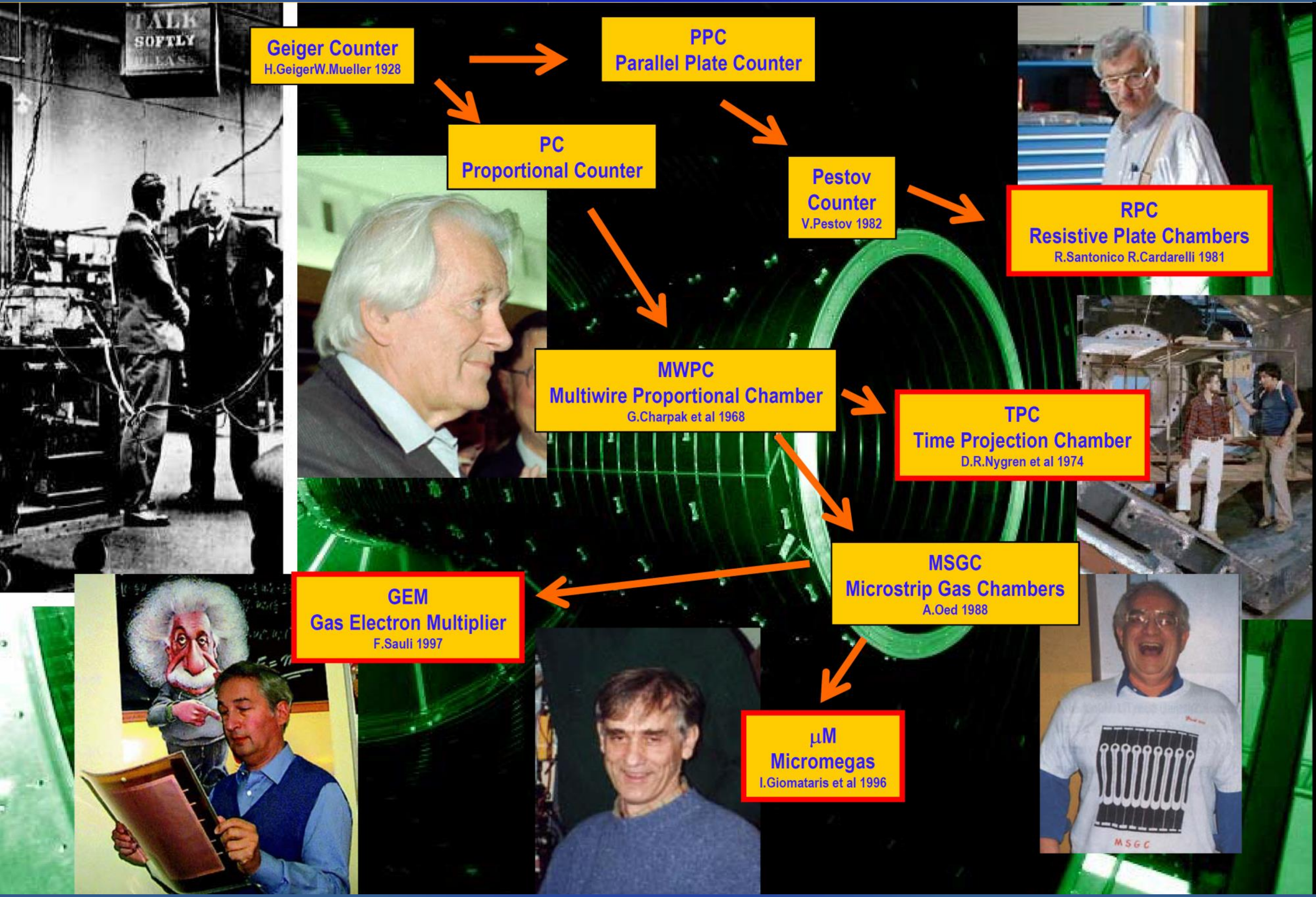
- ✓ The importance and recognition of inventions in the field of instrumentation is proven by the fact that

  → 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

Gas-Based Detectors: A Brief 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

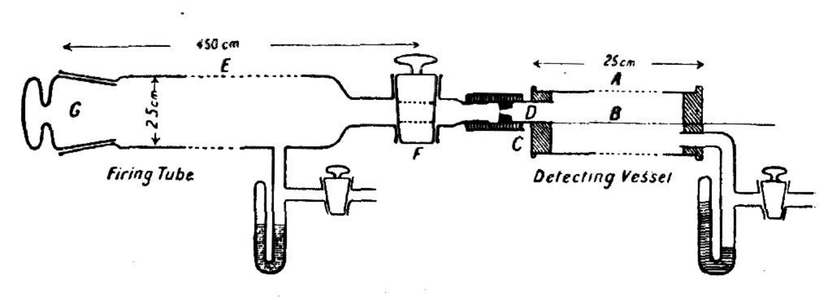
MSGC
Microstrip Gas Chambers
A.Oed 1988

GEM
Gas Electron Multiplier
F.Sauli 1997

μM
Micromegas
I.Giomataris et al 1996

Family of Gaseous Detectors with a Glorious Tradition

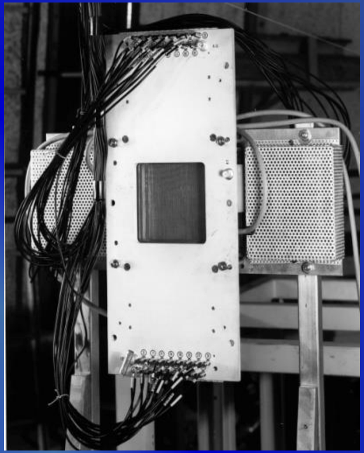
1908: FIRST WIRE COUNTER USED BY RUTHERFORD IN THE STUDY OF NATURAL RADIOACTIVITY

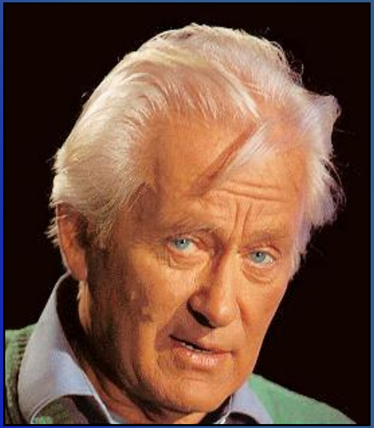


E. Rutherford and H. Geiger , Proc. Royal Soc. A81 (1908) 141

Nobel Prize in Chemistry in 1908

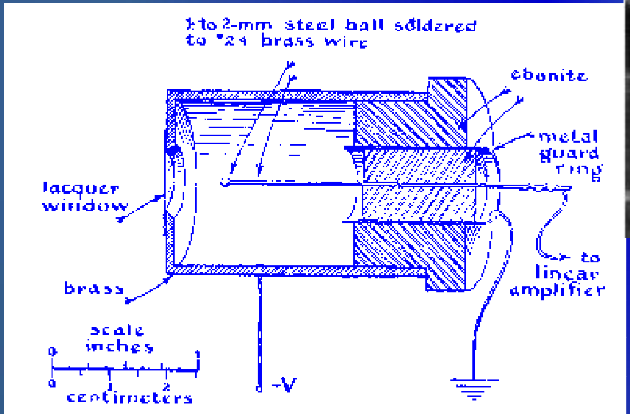
1968: MULTIWIRE PROPORTIONAL CHAMBER



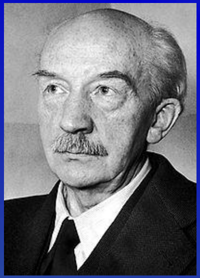


Nobel Prize in Physics 1992

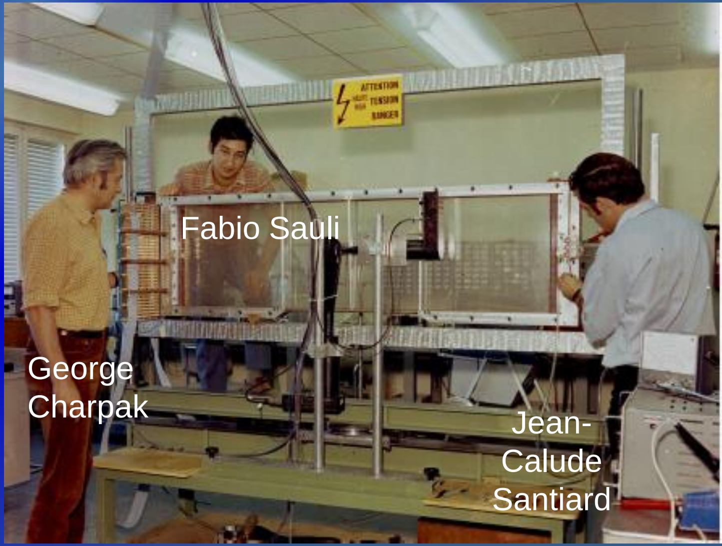
1928: GEIGER COUNTER SINGLE ELECTRON SENSITIVITY



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



Walther Bothe Nobel Prize in Physics 1954 for the “coincidence method”



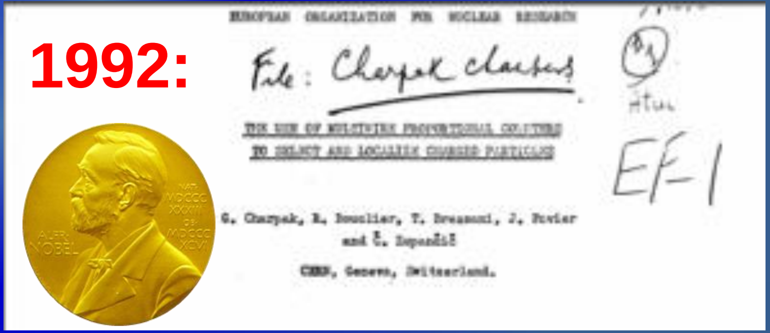
G. Charpak, Proc. Int. Symp. Nuclear Electronics (Versailles 10-13 Sept 1968)

1968: MWPC – Revolutionising the Way Particle Physics is Done

G. Charpak, F. Sauli and J.C. Santiard

Before MWPC: 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, (MWPC), which revolutionized particle detection & HEP, ***and marked transition from Manual to Electronics era***



1992:

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.

“Image” & “Logic (electronics)” tradition combined into the “Electronics Image” detectors during the 1970ies

Multi-Wire Proportional Chambers – Particle Physics Spin-Off

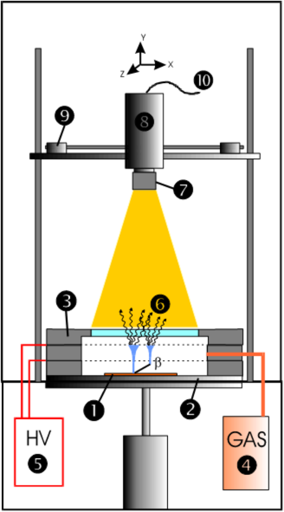
Biospace: Company Founded In 1989 by Georges Charpak

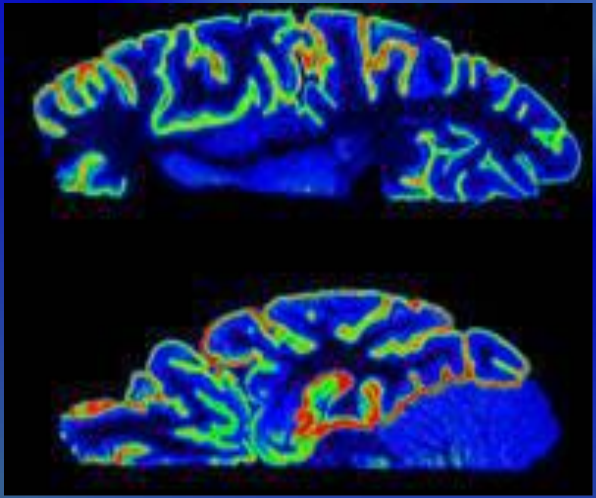
http://www.biospacelab.com:

Our digital autoradiography system leverages the gas detection technology invented by our founder Georges Charpak:
Nobel Prize in Physics in 1992.

~ 2000: LOW-DOSE 3D IMAGING

COMMERCIAL AUTORADIOGRAPHY SYSTEMS WITH GASEOUS DETECTORS





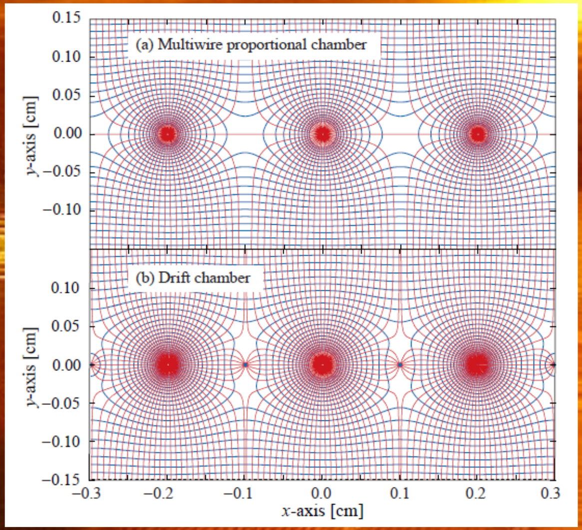
1983/1984: Discovery of W and Z Bosons at UA1/UA2

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

It can be seen in the CERN Microcosm Exhibition

Discovery of W and Z bosons
C. Rubbia & S. Van der Meer,

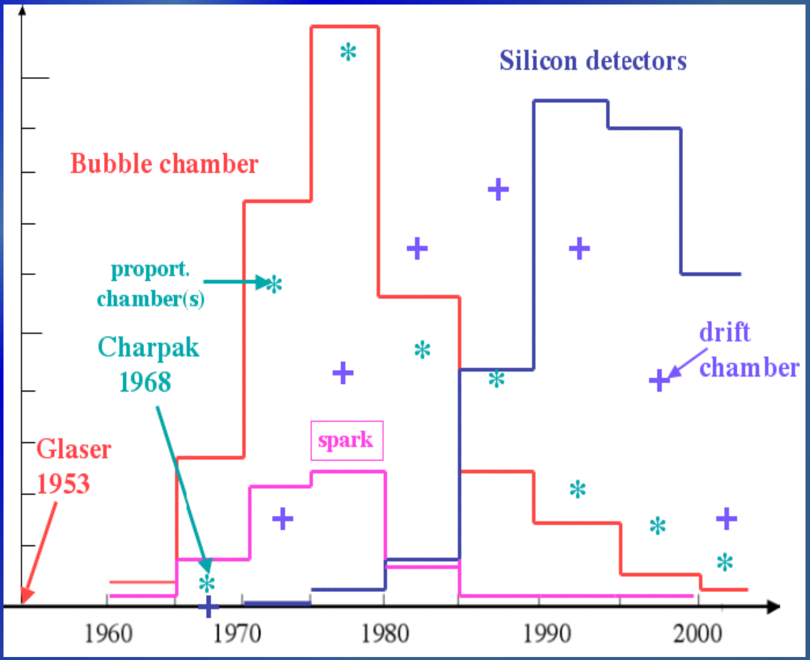
1984:

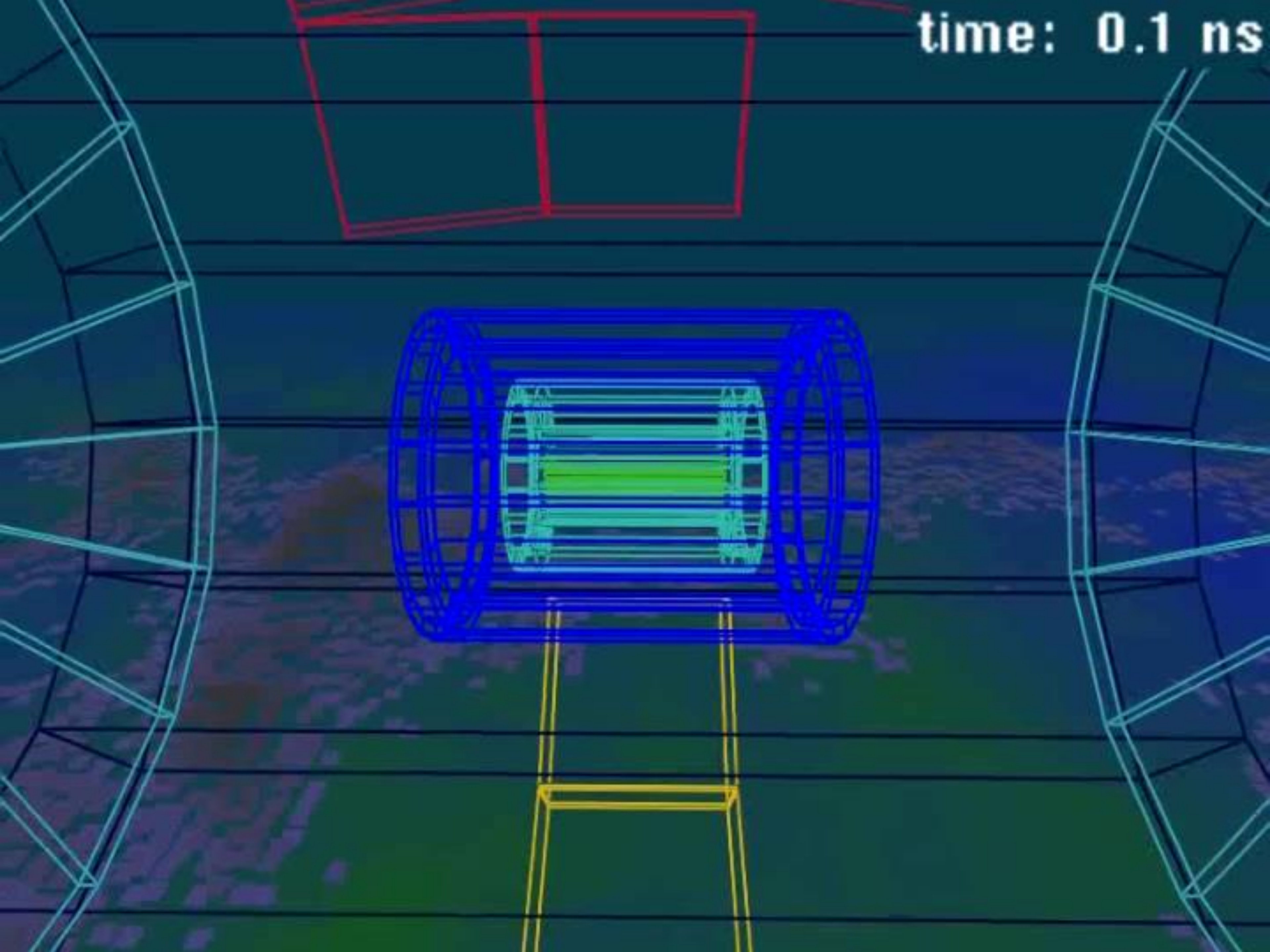


Z → *ee* (white tracks) at UA1/CERN

“Classic Detectors”: Some 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 strips & hybrid detectors, 3D-sensors, CMOS Monolithic Active Pixel Sensors (MAPS)**

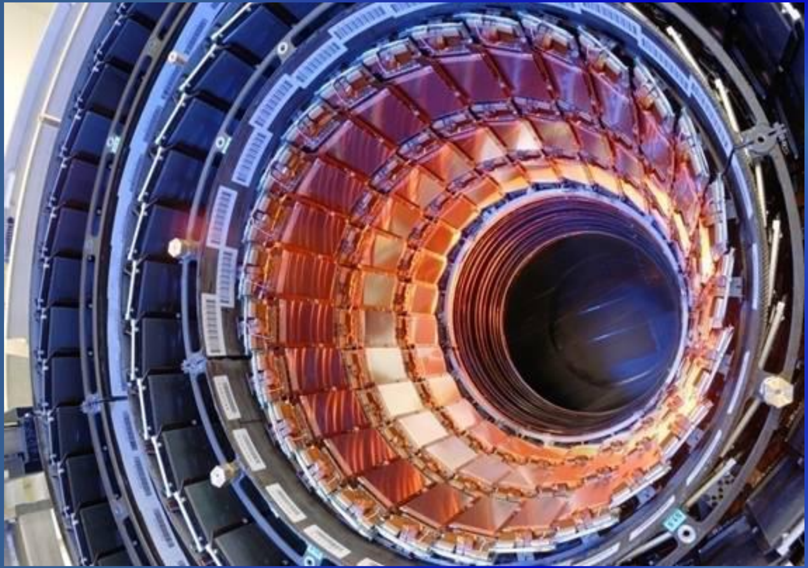



time: 0.1 ns

State-of-the-Art in Tracking and Vertex Detectors

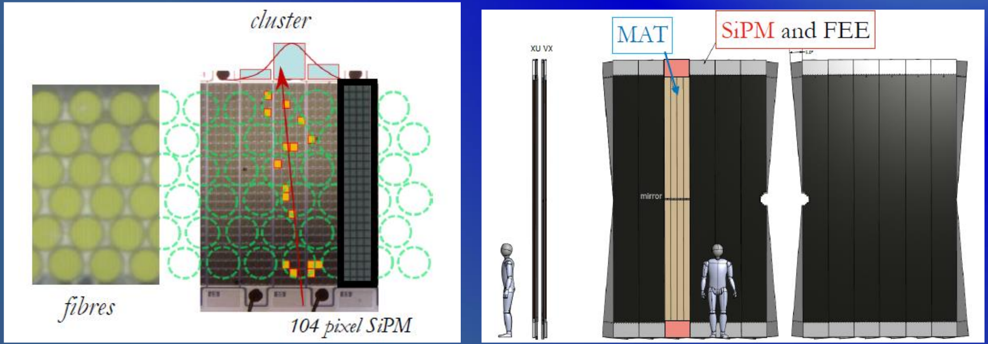
Today’s 3 major technologies of Tracking Detectors:

Silicon (strips, pixels, 3D, CMOS, monolithic):
→ electron – hole pairs in solid state material

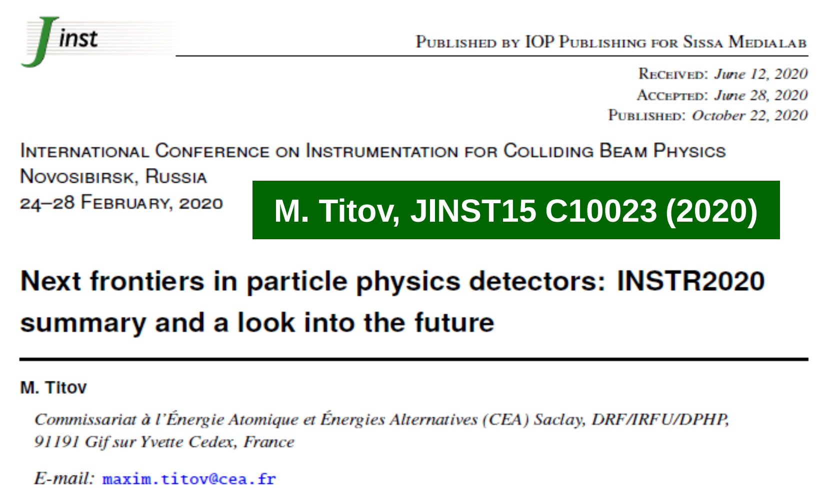


Gaseous (MWPC, TPC, RPC, MPGDs):
→ ionization in gas

Fiber Trackers: → scintillation light detected with photon detectors (sensitive to single electrons)



LHCb Tracker Upgrade (Sci-fibers with SiPM readout):



Jinst
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Accepted: June 28, 2020
Published: October 22, 2020

International Conference on Instrumentation for Colliding Beam Physics
Novosibirsk, Russia
24–28 February, 2020

M. Titov, JINST15 C10023 (2020)

Next frontiers in particle physics detectors: INSTR2020 summary and a look into the future

M. Titov

Commissariat à l’Énergie Atomique et Énergies Alternatives (CEA) Saclay, DRF/IRFU/DPHP, 91191 Gif sur Yvette Cedex, France

E-mail: `maxim.titov@cea.fr`

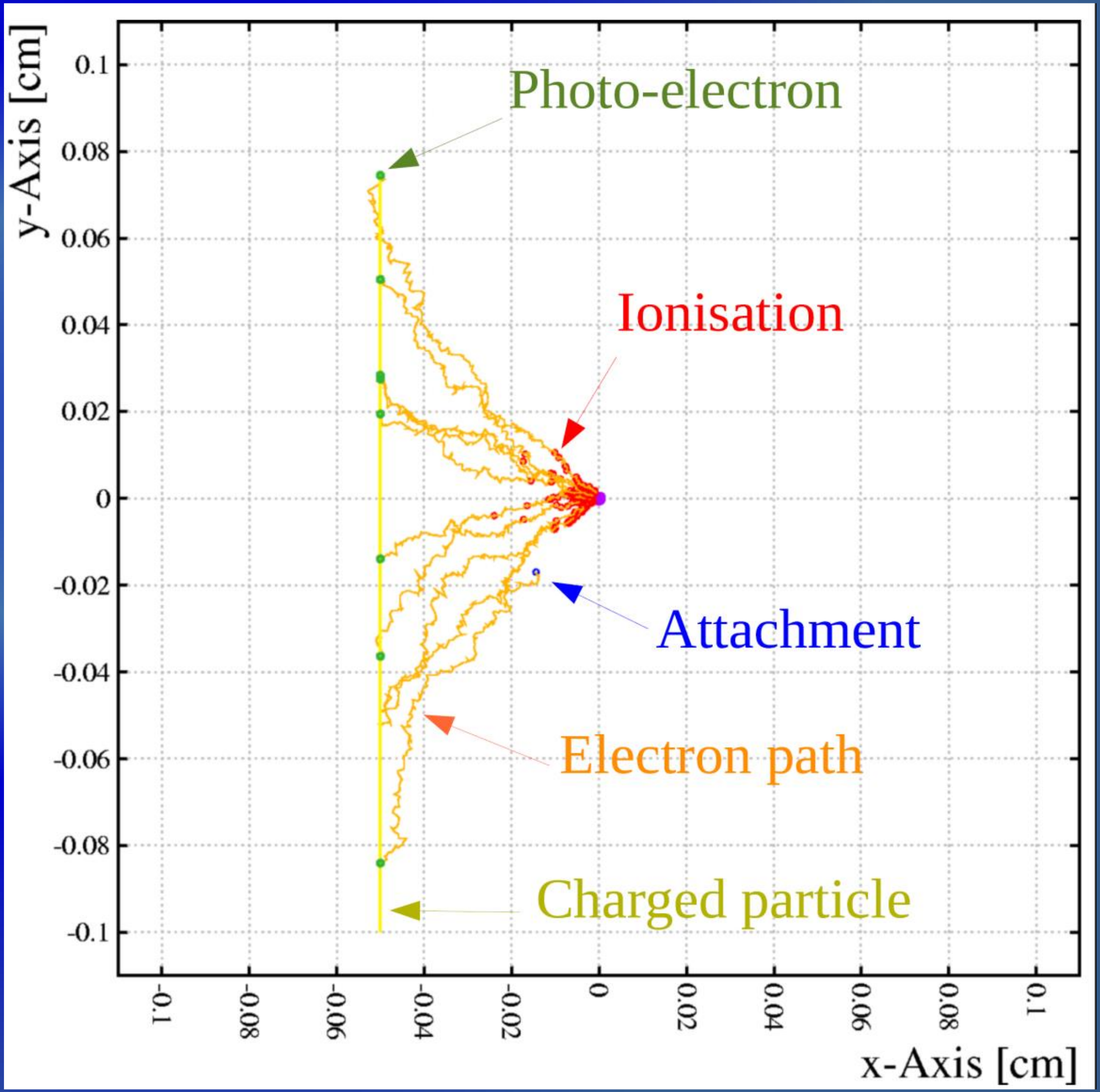
Gaseous Detectors: Working Principle

- ✓ a charged particle passing through the gas ionizes a few gas molecules;
- ✓ the electric field in the gas volume transports the ionisation electrons and provokes multiplication;
- ✓ the movement of electrons and ions leads to induced currents in electrodes;
- ✓ the signals are processed and recorded.

Example:

- 10 GeV muon crossing
- Gas mixture: Ar/CO2 (80:20) %
- Electron are shown every 100 collisions, but have been tracked rigorously.
- Ions are not shown.

At the 100 µm – 1 mm scale:

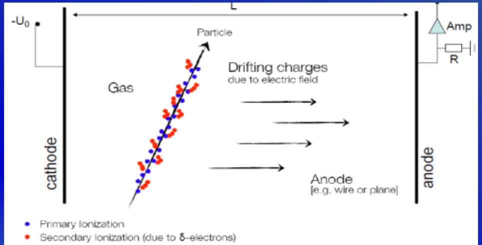


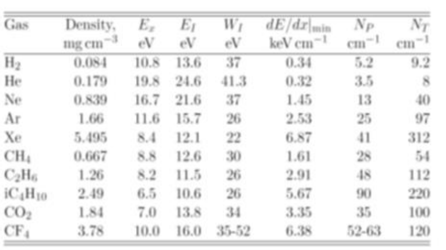
Gas Detectors: Why Use Gas as a Medium for Ionization ?

- ✓ **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**

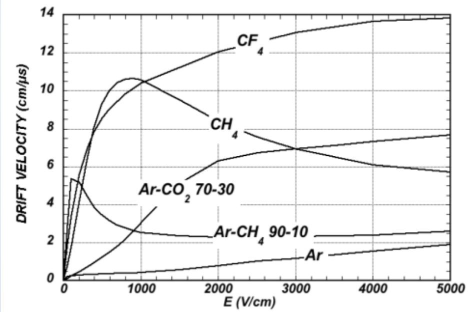
Gaseous Detectors: Signal Generation

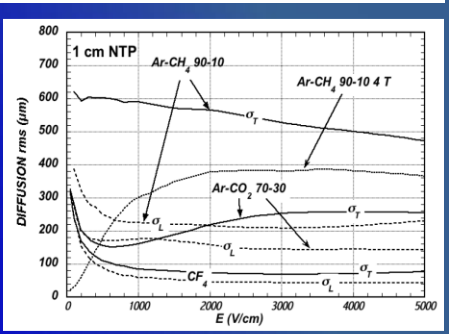
- ✓ **Ionization statistics in gas**
- ✓ **Charge transport in gas**
  - a) Diffusion
  - b) Electron and ion mobility
  - c) Drift velocity
- ✓ **Loss of Electrons / Attachment**
- ✓ **Charge multiplication / Gas Amplification**

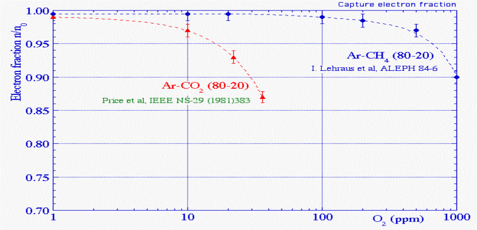


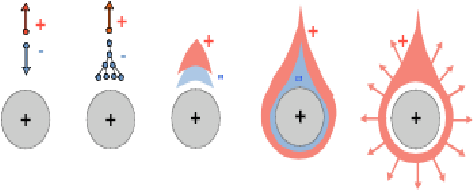


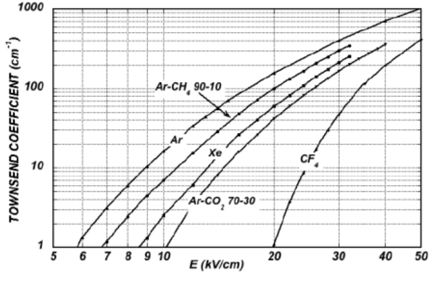
Gas	Density, mg cm^{-3}	E_x eV	E_I eV	W_I eV	$dE/dx\|_{min}$ keV cm^{-1}	N_P cm^{-1}	N_T cm^{-1}
H_2	0.084	10.8	13.6	37	0.34	5.2	9.2
He	0.179	19.8	24.6	41.3	0.32	3.5	8
Ne	0.839	16.7	21.6	37	1.45	13	40
Ar	1.66	11.6	15.7	26	2.53	25	97
Xe	5.495	8.4	12.1	22	6.87	41	312
CH_4	0.667	8.8	12.6	30	1.61	28	54
C_2H_6	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	35-52	6.38	52-63	120









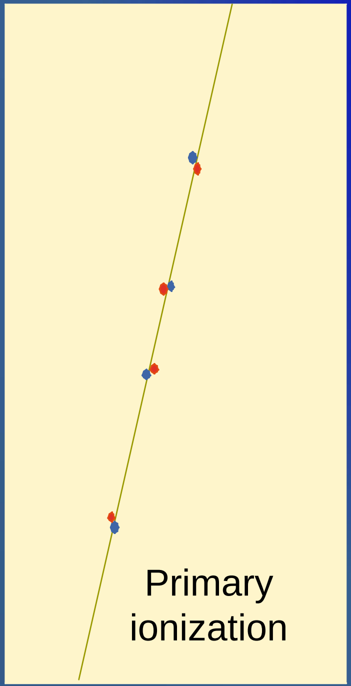


Efficient Gaseous Detector development *(energy deposit, electric fields, drift velocity & diffusion, attachment and amplification)* is today possible with *existing precise and reliable simulation tools*

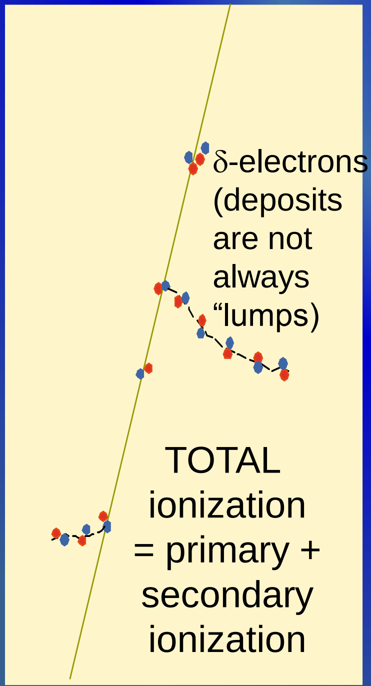
Gaseous Detectors: Ionization Statistics (I)

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



Primary ionization



δ-electrons (deposits are not always "lumps")

TOTAL ionization = primary + secondary ionization

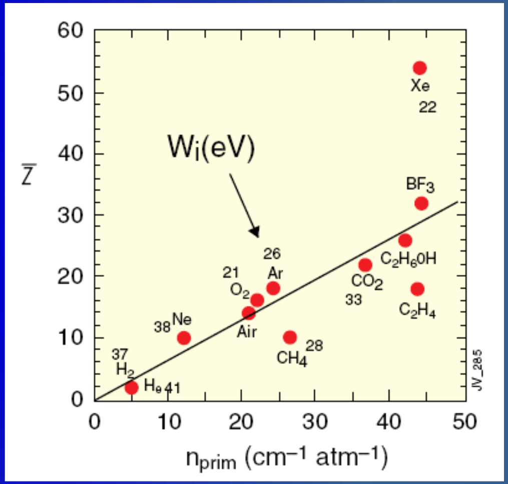
The actual number of primary electron/ion pairs (n_p) is Poisson distributed:

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

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

Review of Particle Physics, Particle Data Group (2024)

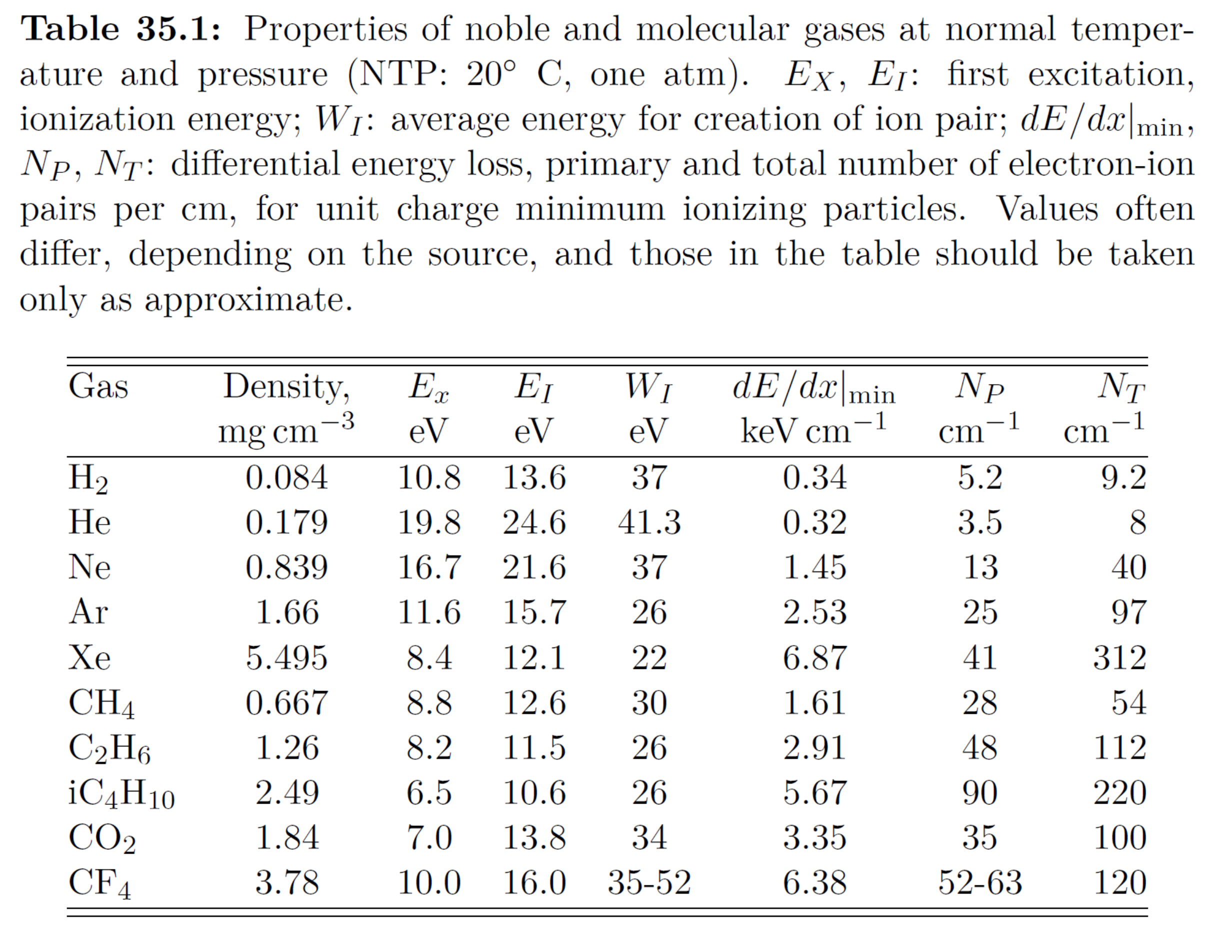


Table 35.1: Properties of noble and molecular gases at normal temperature and pressure (NTP: 20° C, one atm). E_X, E_I: first excitation, ionization energy; W_I: average energy for creation of ion pair; $dE/dx|_{\min}$, N_P, N_T: differential energy loss, primary and total number of electron-ion pairs 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.

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}
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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	35-52	6.38	52-63	120

Ar/CO$_2$ (70/30):

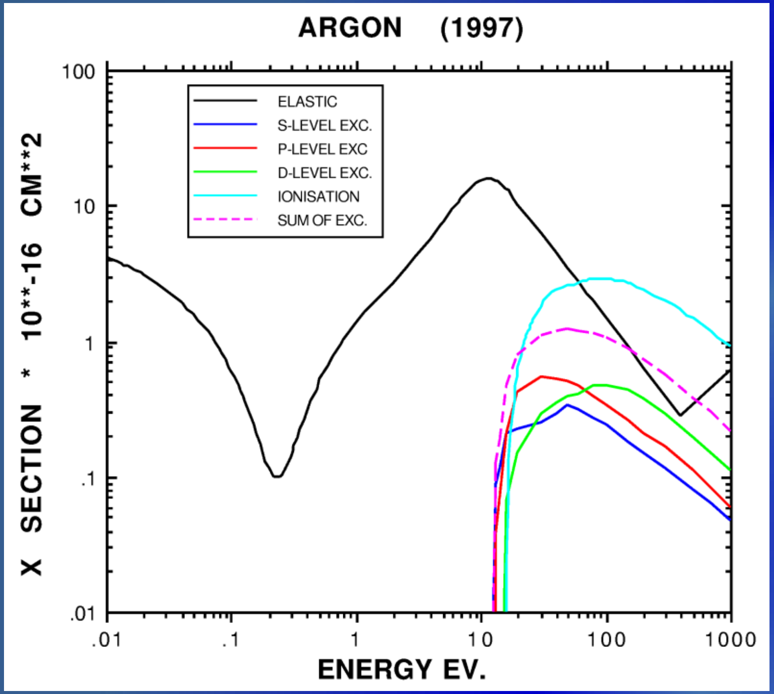
$$N_P = 25 \cdot 0.7 + 35 \cdot 0.3 = 28 \frac{\text{pairs}}{\text{cm}}; \qquad N_T = \frac{2530}{26} \cdot 0.7 + \frac{3350}{35} \cdot 0.3 \approx 97 \frac{\text{pairs}}{\text{cm}}.$$

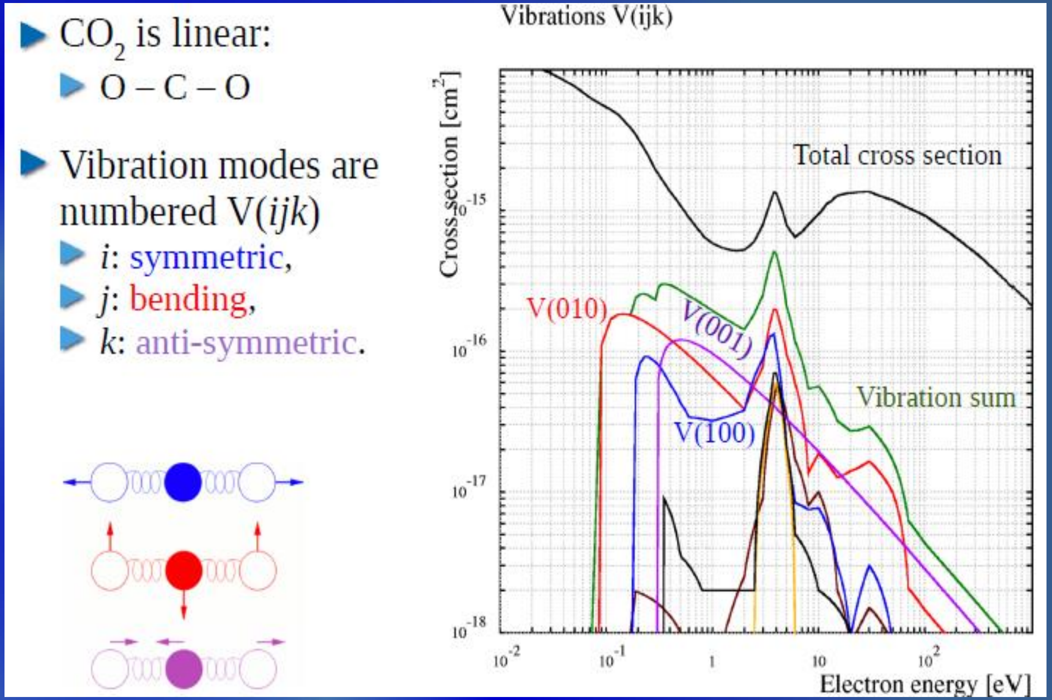
N_T ~ 100 e-ion pairs during ionization process (typical number for 1 cm of gas) is not easy to detect → typical noise of modern pixel ASICs is ~ 100e- (ENC)

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

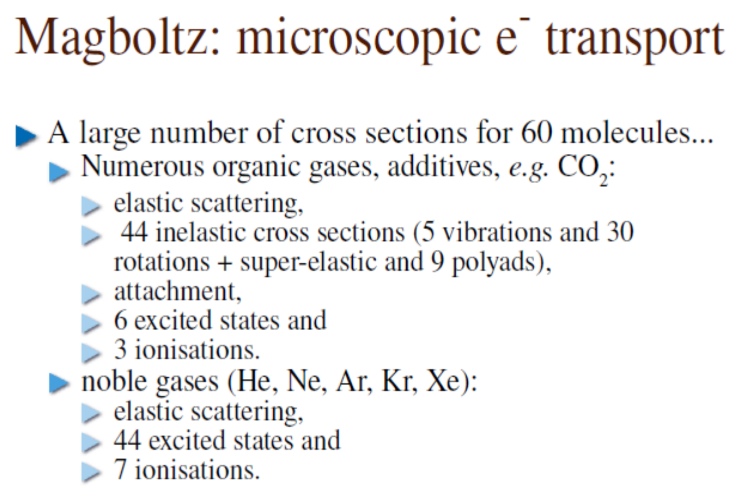
Transport of Electrons in Gases: Drift Velocity

CHARGE TRANSPORT DETERMINED BY ELECTRON-MOLECULE CROSS SECTION:



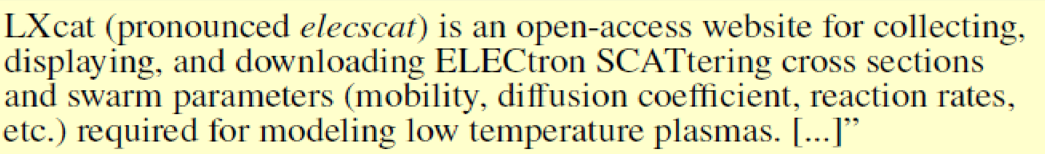


- CO_2 is linear:
  - O – C – O
- Vibration modes are numbered V(*ijk*)
  - *i*: symmetric,
  - *j*: bending,
  - *k*: anti-symmetric.



Magboltz: microscopic e$^-$ transport

- A large number of cross sections for 60 molecules...
  - Numerous organic gases, additives, *e.g.* CO_2:
    - elastic scattering,
    - 44 inelastic cross sections (5 vibrations and 30 rotations + super-elastic and 9 polyads),
    - attachment,
    - 6 excited states and
    - 3 ionisations.
  - noble gases (He, Ne, Ar, Kr, Xe):
    - elastic scattering,
    - 44 excited states and
    - 7 ionisations.



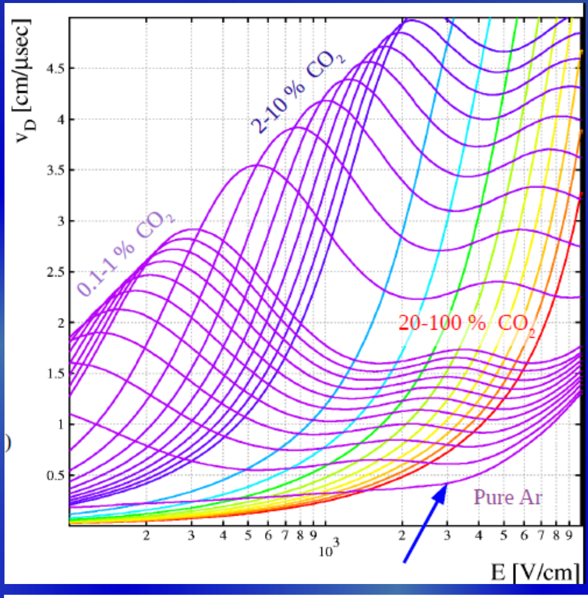
LXcat (pronounced *elecscat*) is an open-access website for collecting, displaying, and downloading ELECtron SCATtering cross sections and swarm parameters (mobility, diffusion coefficient, reaction rates, etc.) required for modeling low temperature plasmas. [...]"

Lxcat:
http://www.lxcat.laplace.univ-tlse.fr/]

Magboltz:
S. Biagi, Nucl. Instr. and Meth. A421 (1999) 234
http://magboltz.web.cern.ch/magboltz/

Transport of Electrons in Gases: Drift Velocity

Large drift velocities are achieved by adding polyatomic gases (usually hydrocarbons, CO2, CF4) having large inelastic component at moderate energies of a few eV → electron ”cooling” into the energy range of the Ramsauer-Townsend minimum (at ~0.5 eV) of the elastic cross-section.

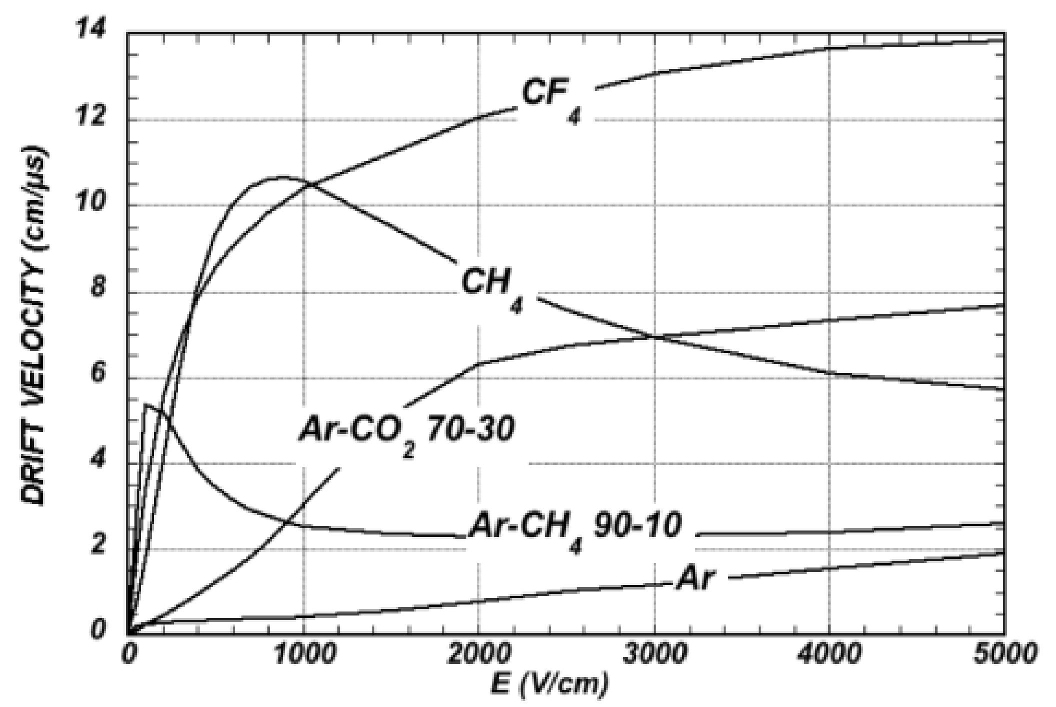


Even small addition of CO2 to Ar makes gas dramatically fster

Additives like CO2 & hydrocarbons are called “quenchers” or “admixtures”

Large range of drift velocities in gases: 1 .... 10 cm/µs; typical categories:

- ✓ “slow” gases, e.g. Ar/CO2 mixtures 1-2 cm/µs, almost linear dependence on E-field
- ✓ “fast” gases, e.g. Ar/CF4 mixtures ~10-15 cm/µs
- ✓ “saturated” gases, e.g. Ar/CH4; - e.g. Ar/CH4 (90/10) – drift velocity less sensitive to E-field variations and nearly constant (useful for drift chamber operation)

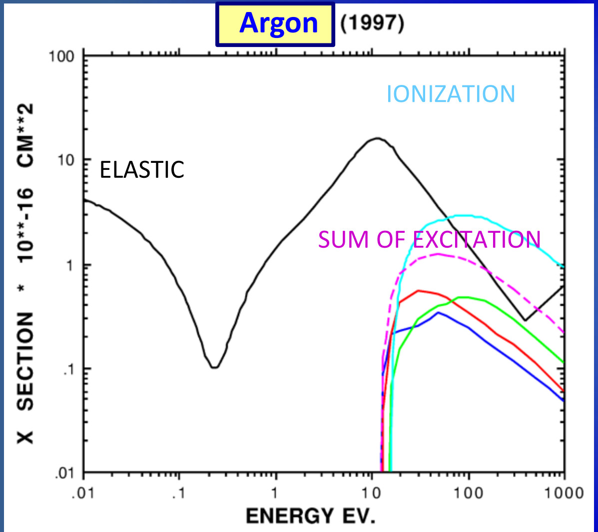


Selection of Gas Mixture: Quenching of Photons

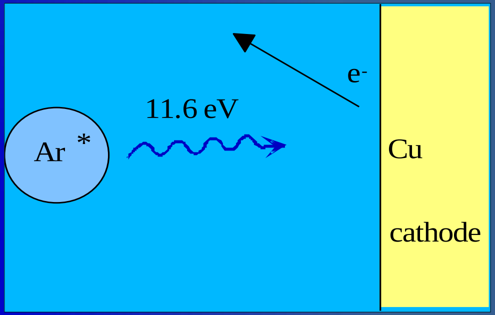
- **Slight problem in gas avalance**

→ 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

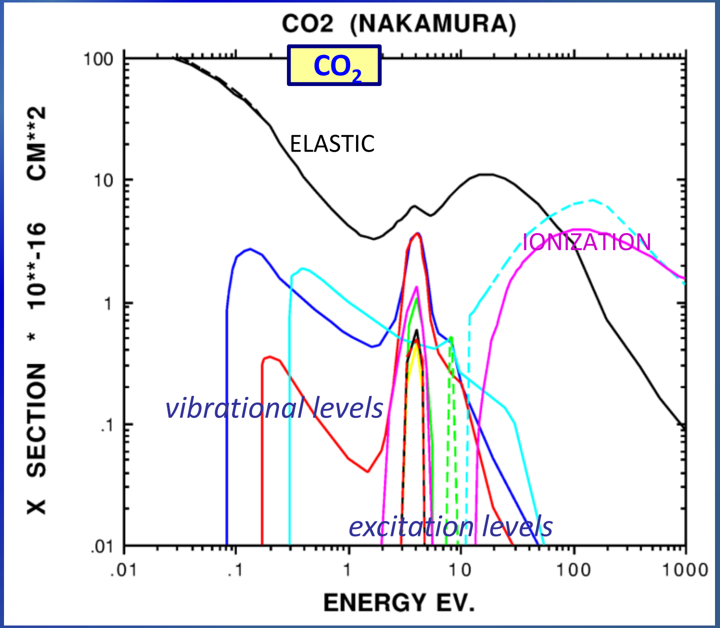


VERY unstable operation

- **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 or dissociation into smaller molecules (see aging effects)



Transport of Electrons in Gases: Diffusion

An initially point like cloud of electrons will ‘diffuse’ because of multiple collisions and assume a Gaussian shape. The diffusion depends on the average energy of the electrons. The variance σ^2 of the distribution grows linearly with time. In case of an applied electric field it grows linearly with the distance.

$$n(x) = \left(\frac{1}{\sqrt{4\pi Dt}}\right)^3 e^{\frac{-(x-v_D t)^2}{4Dt}}$$

$$v_D = \frac{\Delta s}{\Delta t} \qquad \sigma_x = \sqrt{2Dt} = \sqrt{2D\frac{s}{v_D}}$$

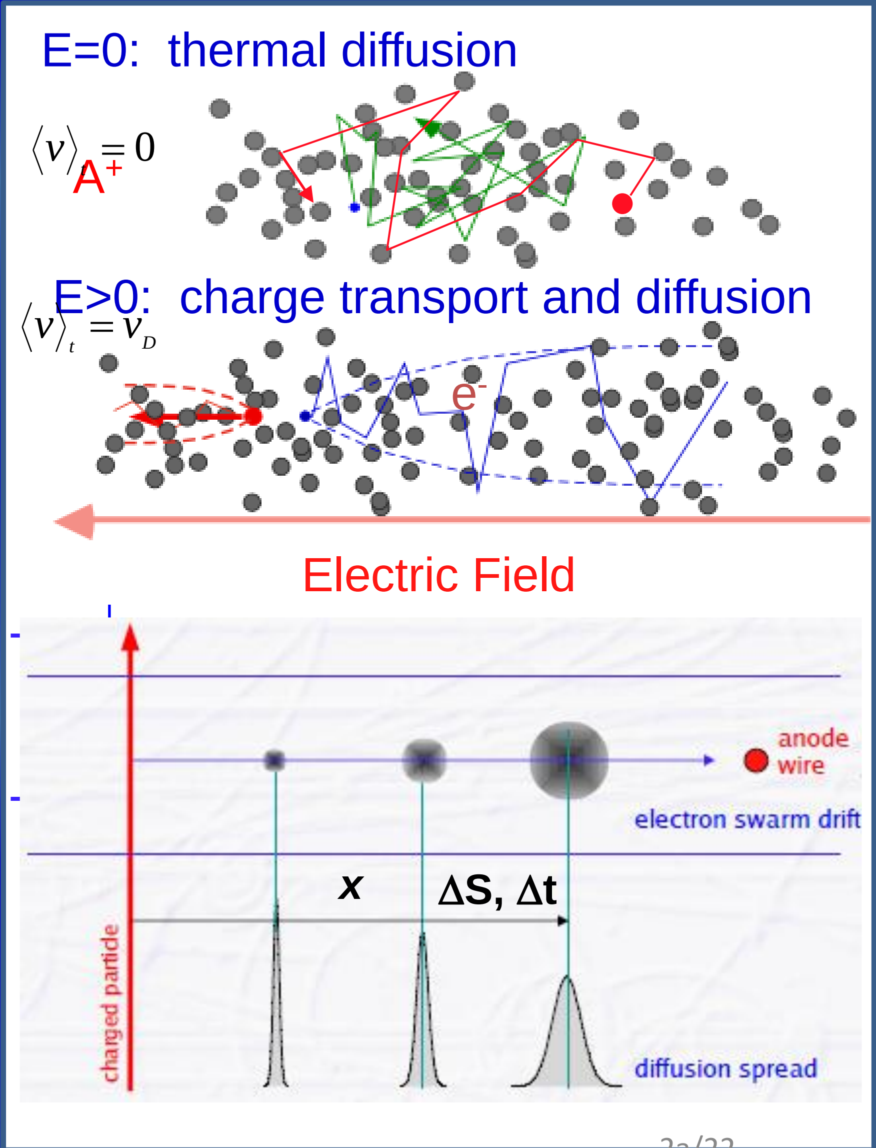
Solution of the diffusion equation (l=drift distance)

$$D = \frac{2}{3}\frac{v}{eE}\epsilon \qquad \sigma_x = \sqrt{\frac{4}{3}\frac{l}{eE}\epsilon}$$

‘Cold’ gases are close to the thermodynamic limit i.e. gases where the average microscopic energy ε=1/2mu2 is close to the thermal energy 3/2kT.

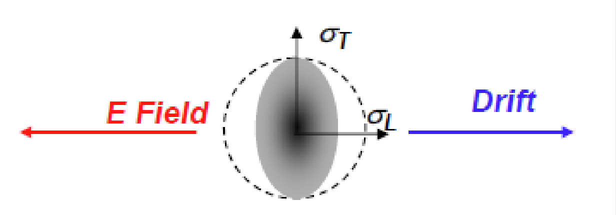
CH$_4$ has very large fractional energy loss
→ low ε → low diffusion.

Argon has small fractional energy loss/collision → large ε → large diffusion.



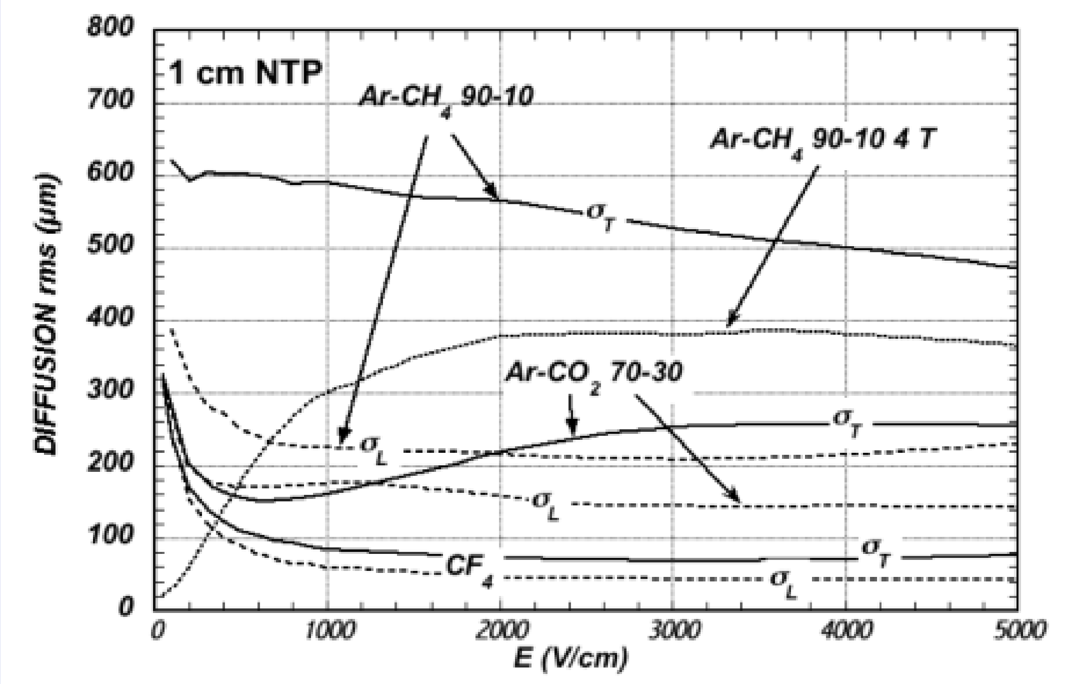
Transport of Electrons in Gases: Diffusion

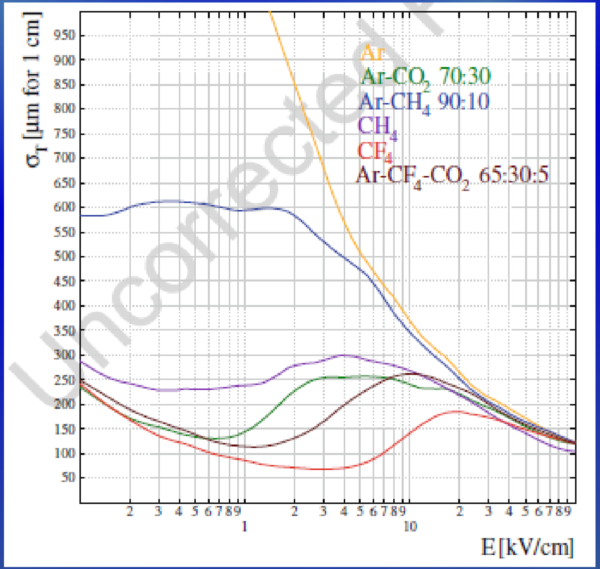
Electric field alters the diffusion so that it is necessary to introduce two diffusion coefficients:
longitudinal diffusion (σ_L) and transverse diffusion (σ_T)

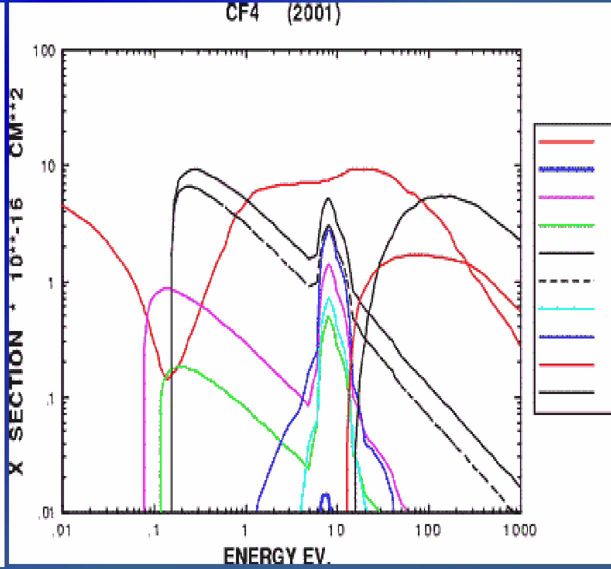


- ✓ CO_2 is much cooler gas than CH_4 at low electric fields → allows to optimize separately diffusion properties in the drift and multiplication regions (but, CH4 is much better quencher than CO2)

- ✓ CF4 has the largest drift velocity
- ✓ & lowest electron diffusion among known gases due to the sizeable Ramsauer-Townsend dip in the elastic cross-section which coincides with a very large vibrational modes (but, CF4 has a small quenching cross-section of excited Ar states and emits light from the far UV to the visible light)

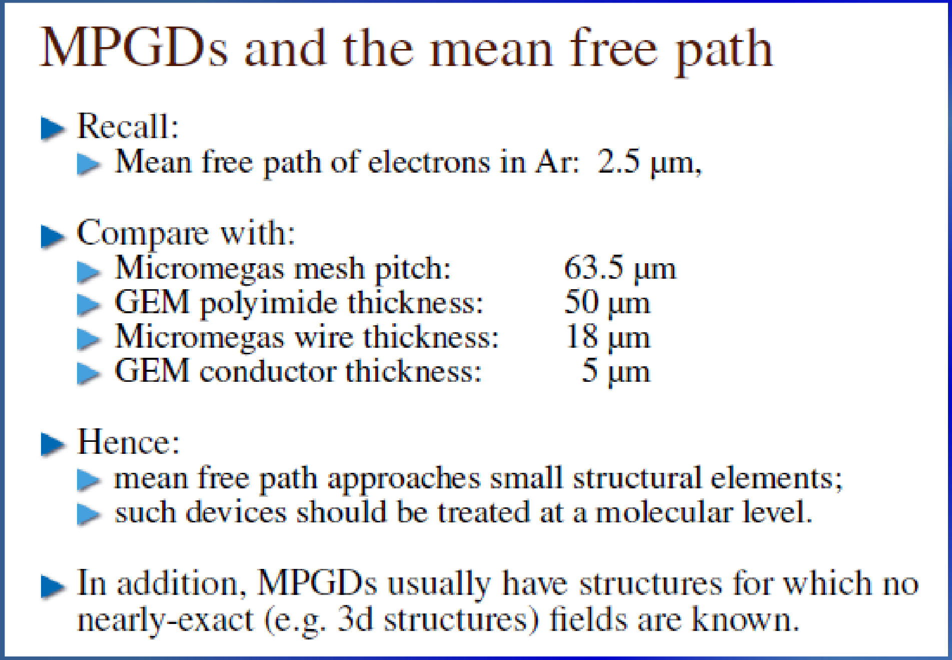






Gaseous Detectors: Software and Simulation Tools

Garfield, together with HEED, Degrad, Magboltz, SRIM, ANSYS, COMSOL, and neBEM software packages represent the core simulation tools for microscopic modelling of gaseous detector response.



MPGDs and the mean free path

- Recall:
  - Mean free path of electrons in Ar: 2.5 µm,
- Compare with:
  - Micromegas mesh pitch: 63.5 µm
  - GEM polyimide thickness: 50 µm
  - Micromegas wire thickness: 18 µm
  - GEM conductor thickness: 5 µm
- Hence:
  - mean free path approaches small structural elements;
  - such devices should be treated at a molecular level.
- In addition, MPGDs usually have structures for which no nearly-exact (e.g. 3d structures) fields are known.

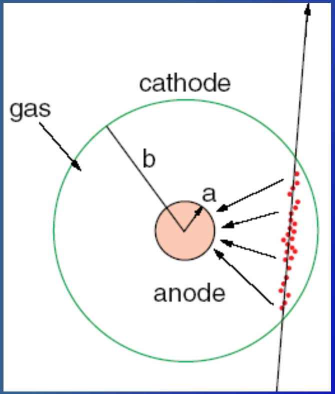
- ✓ ***HEED – energy loss, a photo-absorption and ionization model***
- ✓ ***DEGRAD – electron transport, cluster size distribution***
- ✓ ***Magboltz – electron transport properties: drift, diffusion, multiplication, attachment***
- ✓ ***ANSYS, COMSOL, neBEM – electric field maps in 2D / 3D***
- ✓ ***Garfield – fiedls, drift properties, signals (interfaced to above)***

Some recent highlights:

- ***Garfield++ et al. (new development and maintenance of codes, documentation, examples)*** **https://gitlab.cern.ch/garfield/garfieldpp**
- ***Garfield++ and delayed weighting fields in the calculation of the induced signal (resistive electrodes)***
- ***Greenhouse gases***
- ***Improving accuracy of the modelling and the detector physics understanding: Penning transfer, Non equilibrium effect in gaseous detectors, Ions and cluster ions***

Single Wire Proportional Counter: Avalanche Development

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



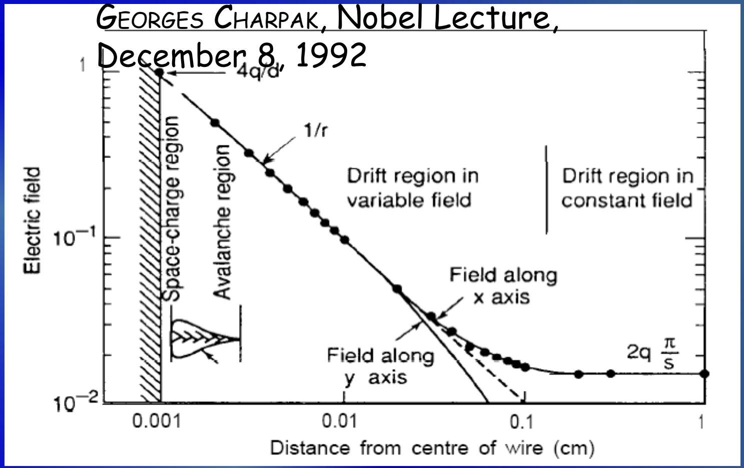
Electric field:

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

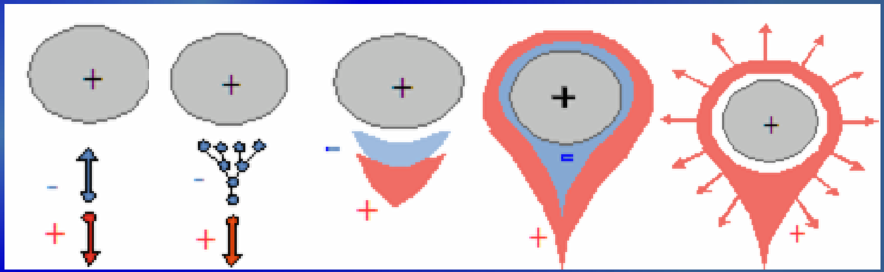
$$C=\frac{2\pi\varepsilon_0}{\ln(b/a)}$$

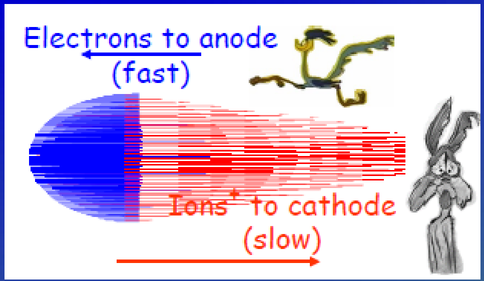
- *Strong increase of E-field close to the wire*
  - → ***electron gains more and more energy***
- *Above some threshold (>10 kV/cm)*
  - → *electron energy high enough to ionize other gas molecules*
  - → *newly created electrons also start ionizing*
- *Avalanche effect: exponential increase of electrons (and ions)*
- *Measurable signal on wire*
  - → *organic substances responsible for “quenching” (stopping) the discharge*

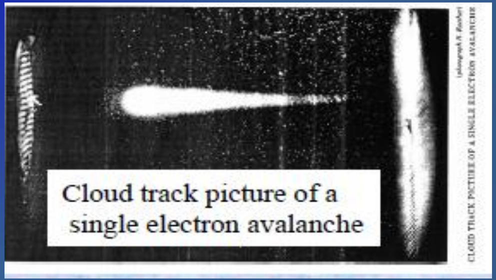
Avalanche development in the high electric field around a thin wire (multiplication region ~< 50 um):


Georges Charpak, Nobel Lecture, December 8, 1992

Different stages in the gas amplification process next to the anode wire.

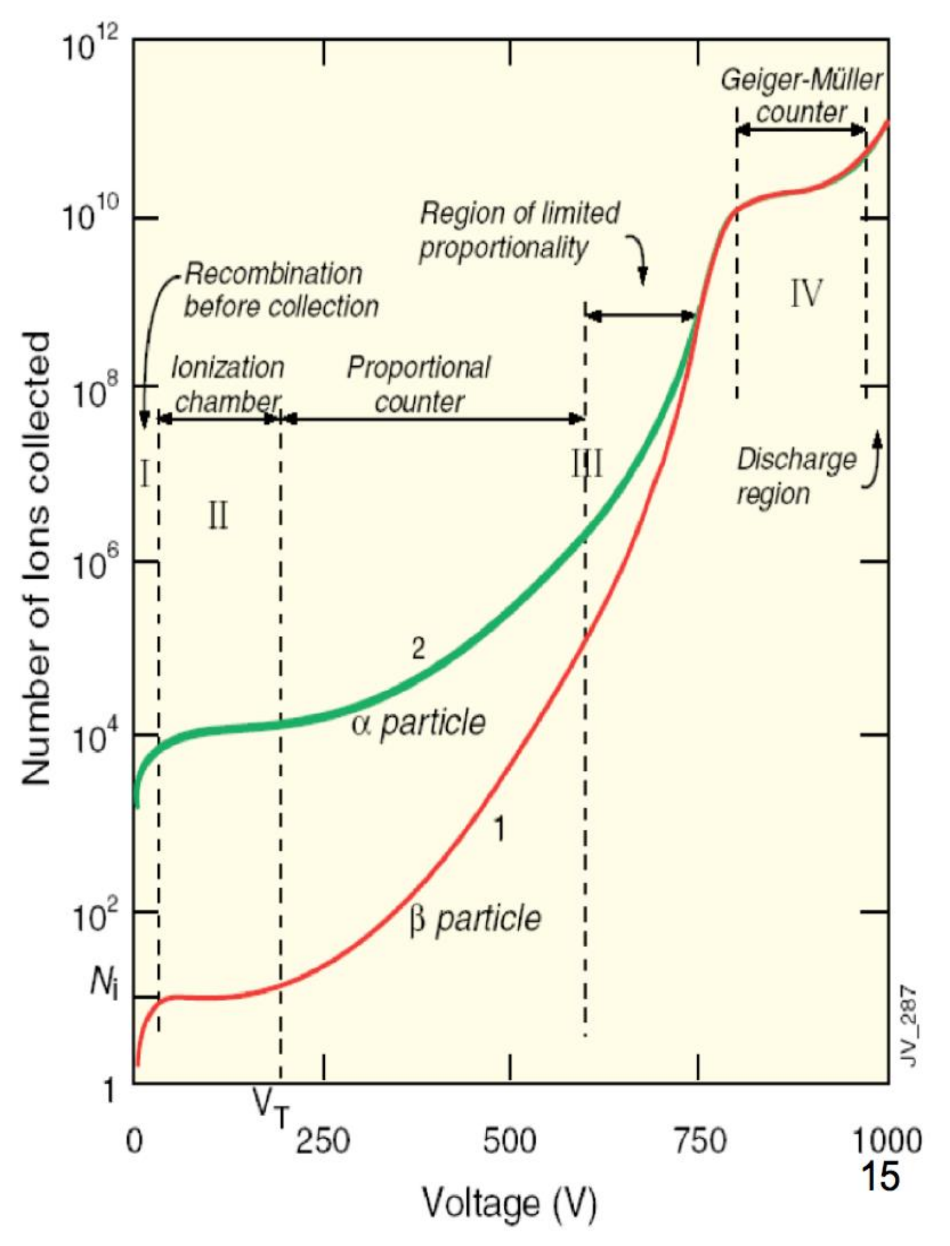





Cloud track picture of a single electron avalanche

Operation Modes of Gas Detector: Gain-Voltage Characteristics

- ✓ ***Ionization mode (II):***
  - *→ full charge collection, but no multiplication – gain = 1*
- ✓ ***Proportional mode (IIIA):***
  - *→ Multiplication of ionization starts; detected signal proportional to original ionization → possible energy measurement (dE/dx)*
  - *→ proportional region (gain ~ 10^3 – 10^4)*
  - *→ semi-proportional region (gain ~ 10^4 – 10^5), space charge effects*
  - *→ secondary avalanches need quenching*
- ✓ ***Limited proportional mode (saturated, streamer) (IIIB):***
  - *→ saturation (gain > 10^6), independent of number of primary electrons*
  - *→ streamer (gain > 10^7), avalanche along the particle track*
- ✓ ***Geiger mode (IV):***
  - *→ Limited Geiger region: avalanche propogated by UV photons;*
  - *→ Geiger region (gain > 10^9), avalanche along the entire wire*



Wire Proportional Counter: Signal Development

Incremental charge induced by Q moving through dV:

$$dQ = \frac{Q}{V_0} dV = \frac{Q}{V_0} \frac{dV}{dr} dr$$

Assuming that the total charge of the avalanche Q is produced at a (small) distance l from the anode, the electron and ion contributions to the induced charge are:

$$q^- = \frac{Q}{V_0} \int_a^{a+\lambda} \frac{dV}{dr} dr = -\frac{QC}{2\pi\varepsilon_0} \ln\frac{a+\lambda}{a}$$

and

$$q^+ = \frac{Q}{V_0} \int_{a+\lambda}^{b} \frac{dV}{dr} dr = -\frac{QC}{2\pi\varepsilon_0} \ln\frac{b}{a+\lambda}$$

The total induced signal is $q = q^- + q^+ = -\frac{QC}{2\pi\varepsilon_0} \ln\frac{b}{a} = -Q$ *on the anode* *(* $+Q$ *on the cathode)*

The ratio of electron and ion contributions:

$$\frac{q^-}{q^+} = \frac{\ln(a+\lambda) - \ln a}{\ln b - \ln(a+\lambda)}$$

For a counter with a=10μm, b=10 m: q^-/q^+ ~1%

The electron-induced signal is negligible

Neglecting electrons, and assuming all ions leave from the wire surface:

$$q(t) = q^+(t) = -\int_0^t dq = -\frac{QC}{2\pi\varepsilon_0} \ln\frac{r(t)}{a}$$

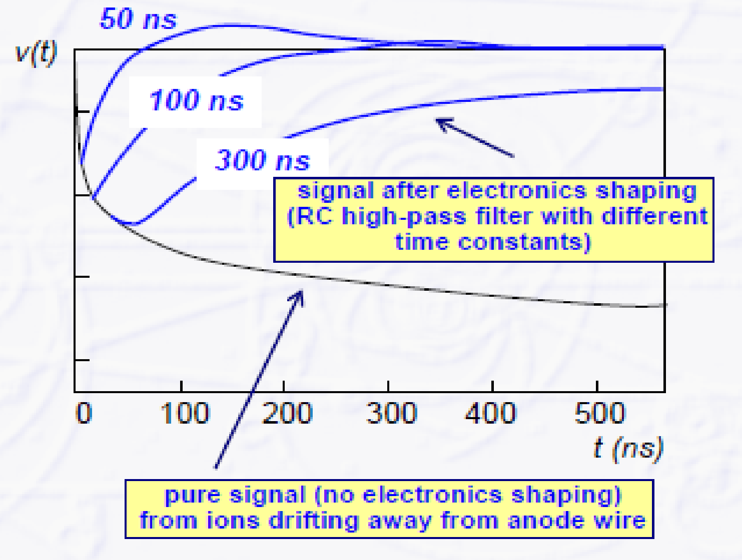
$$\frac{dr}{dt} = \mu^+ E = \frac{\mu^+ C V_0}{2\pi\varepsilon_0} \frac{1}{r}$$

$$q(t) = -\frac{QC}{2\pi\varepsilon_0} \ln\left(1 + \frac{\mu^+ C V_0}{2\pi\varepsilon_0 a^2} t\right) = -\frac{QC}{2\pi\varepsilon_0} \ln\left(1 + \frac{t}{t_0}\right)$$

$$i(t) = -\frac{QC}{2\pi\varepsilon_0} \frac{1}{t_0 + t}$$

Total ions drift time:

$$T^+ = \frac{\pi\varepsilon_0 (b^2 - a^2)}{\mu^+ C V_0} \qquad q(T^+) = -Q$$

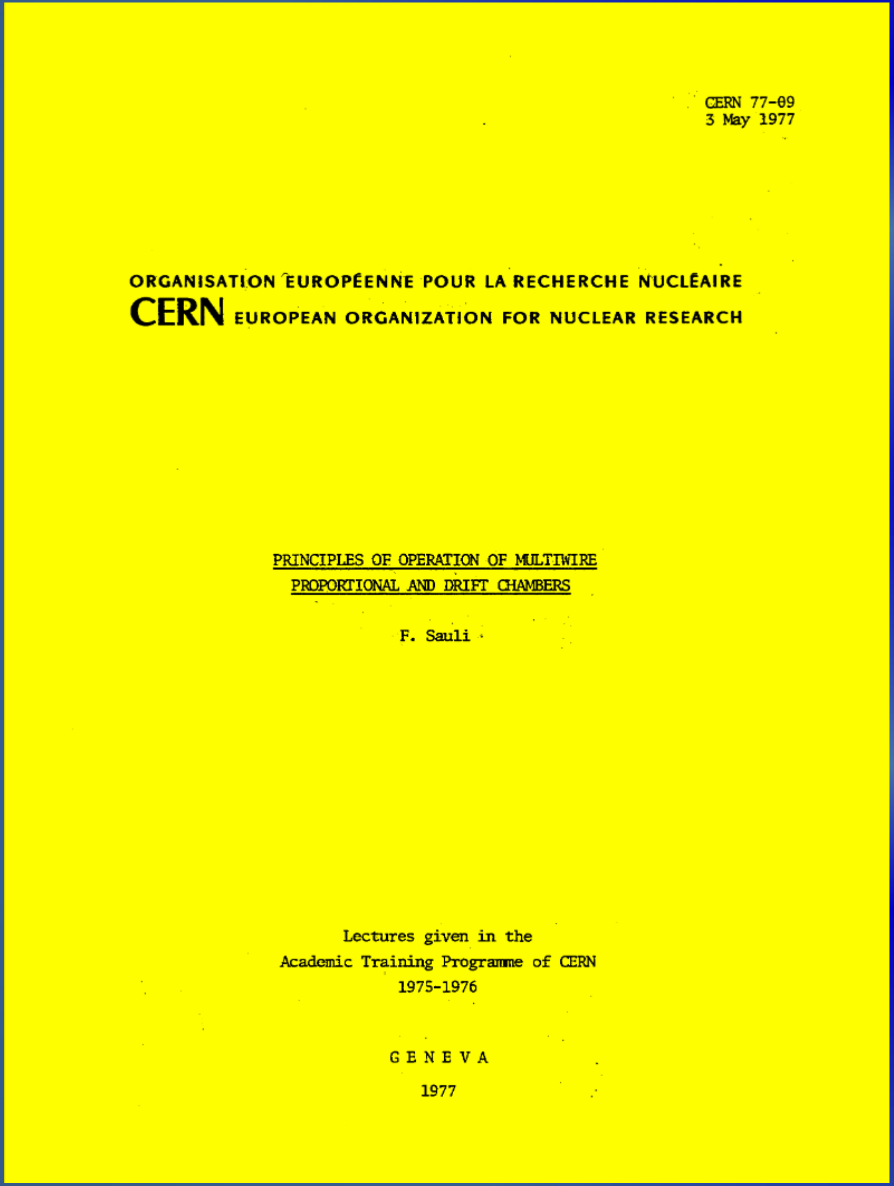


signal after electronics shaping (RC high-pass filter with different time constants)

pure signal (no electronics shaping) from ions drifting away from anode wire

Useful Write-Ups on Gaseous Detectors

Wire & Drift Chamber Basics



CERN 77-09
3 May 1977

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

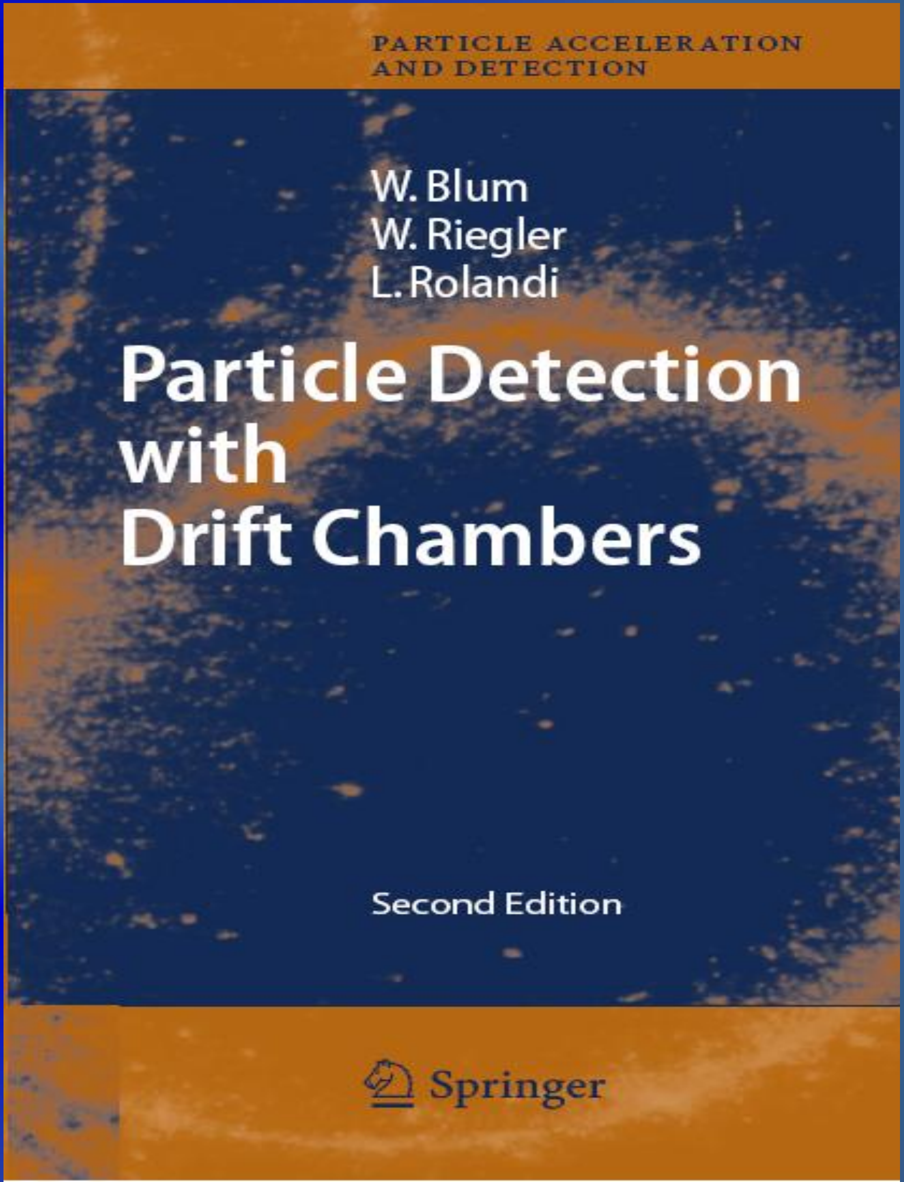
PRINCIPLES OF OPERATION OF MULTIWIRE
PROPORTIONAL AND DRIFT CHAMBERS

F. Sauli

Lectures given in the
Academic Training Programme of CERN
1975-1976

GENEVA
1977

More on signal theorems, readout electronics etc. can be found in:



PARTICLE ACCELERATION
AND DETECTION

W. Blum
W. Riegler
L. Rolandi

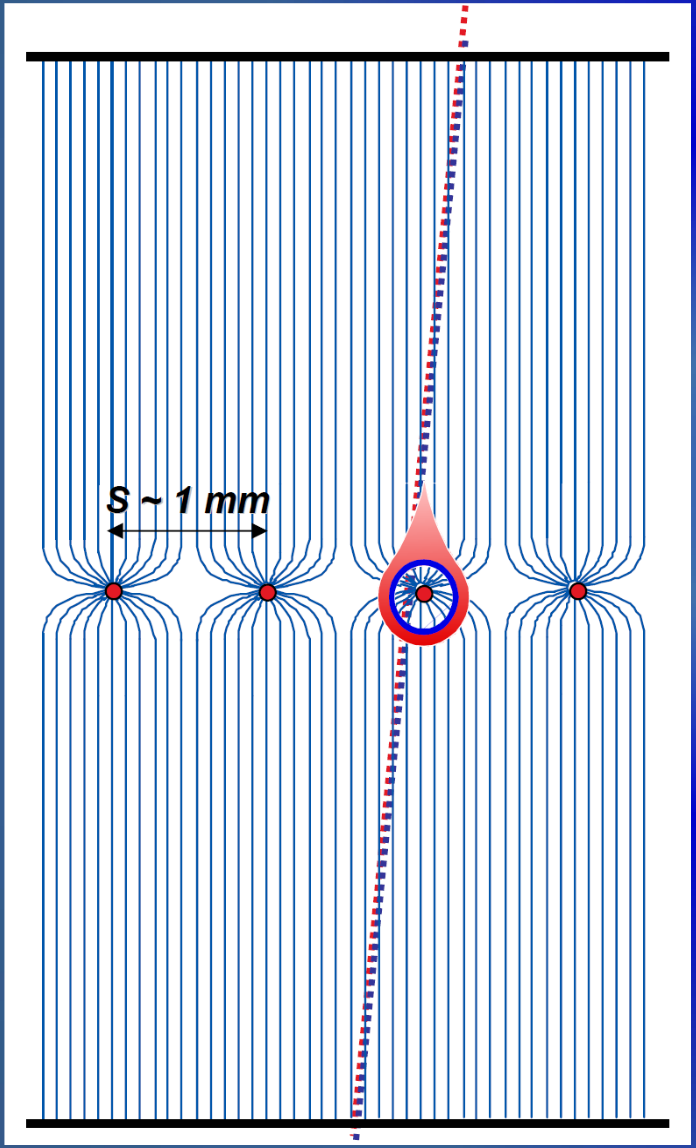
Particle Detection
with
Drift Chambers

Second Edition

Springer

Multi-Wire Proportional Chamber (MWPC)

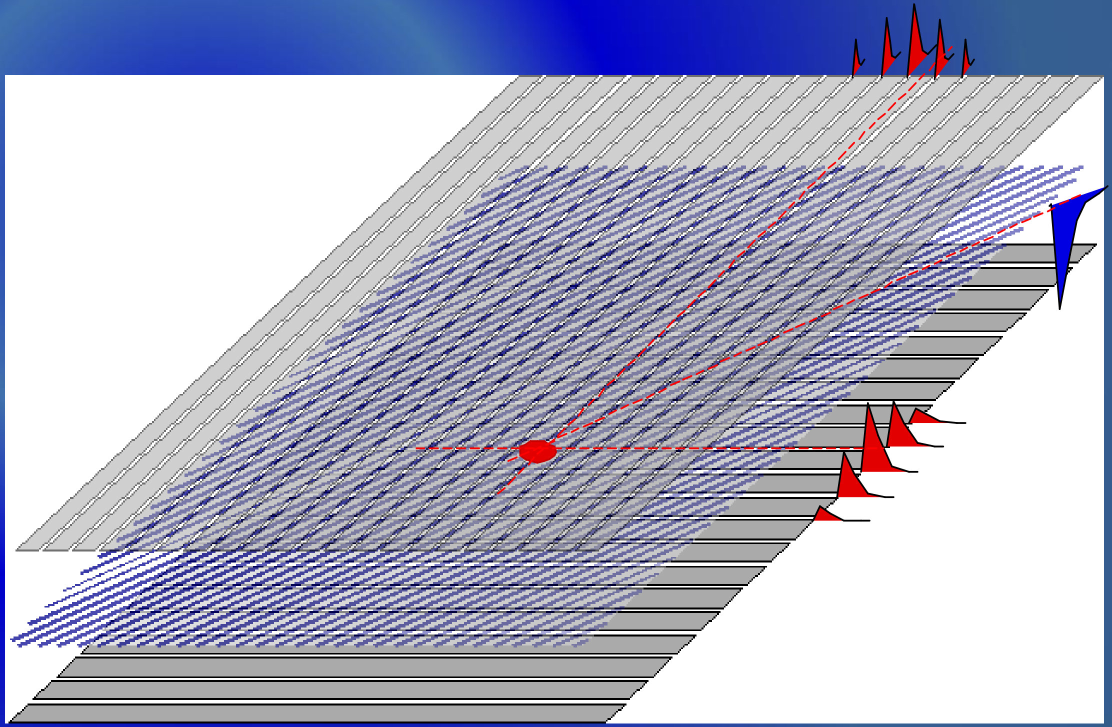
Simple idea to multiply SWPC cell → First electronic device allowing high statistics experiments !!



High-rate MWPC with digital readout:

Spatial resolution is limited to s_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

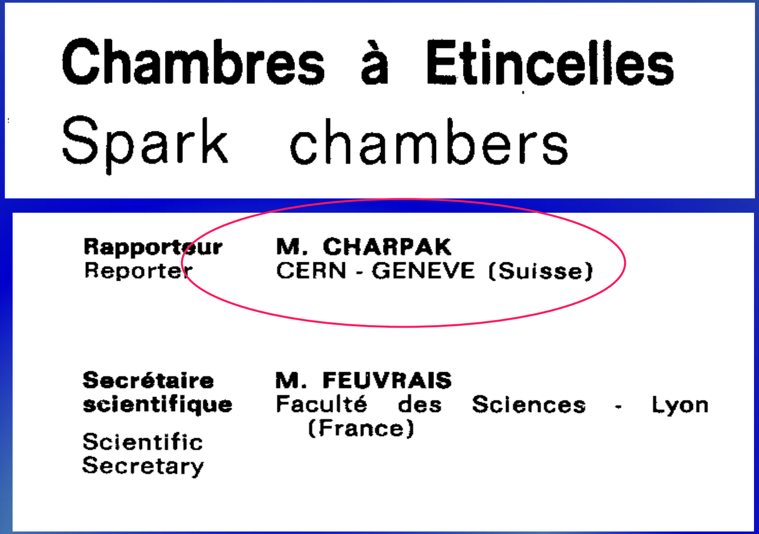
Space resolution < 100 μm

MWPC: First Presentation and First Large Experiment

colloque
international
sur
l'électronique
nucléaire
*
international
symposium
on
nuclear
electronics

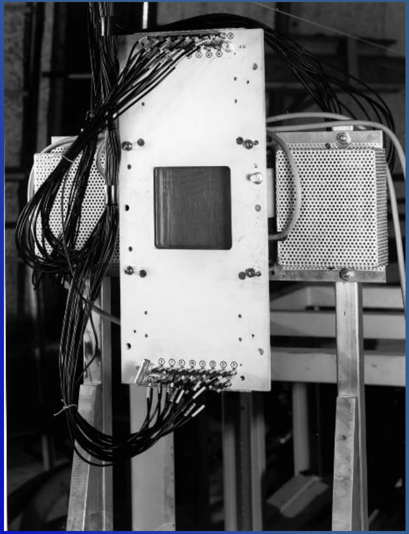
First presentation:

VERSAILLES,
10-13 September 1968



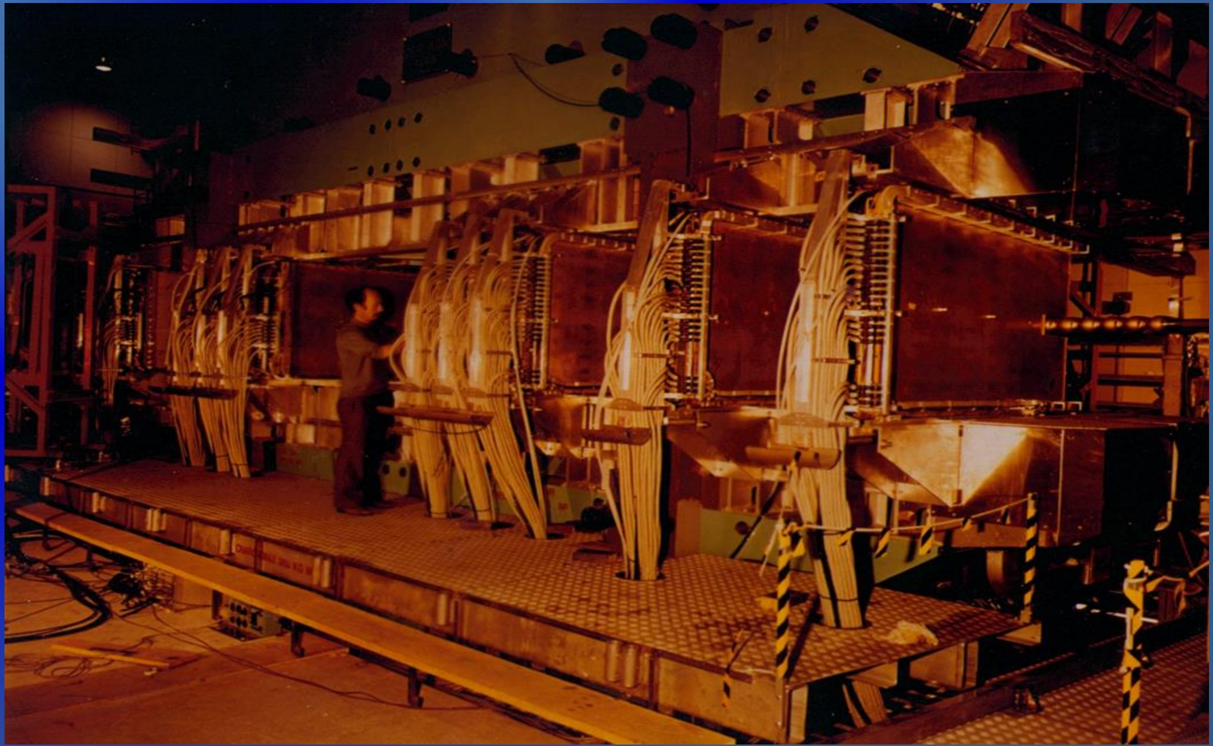
Chambres à Etincelles
Spark chambers

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

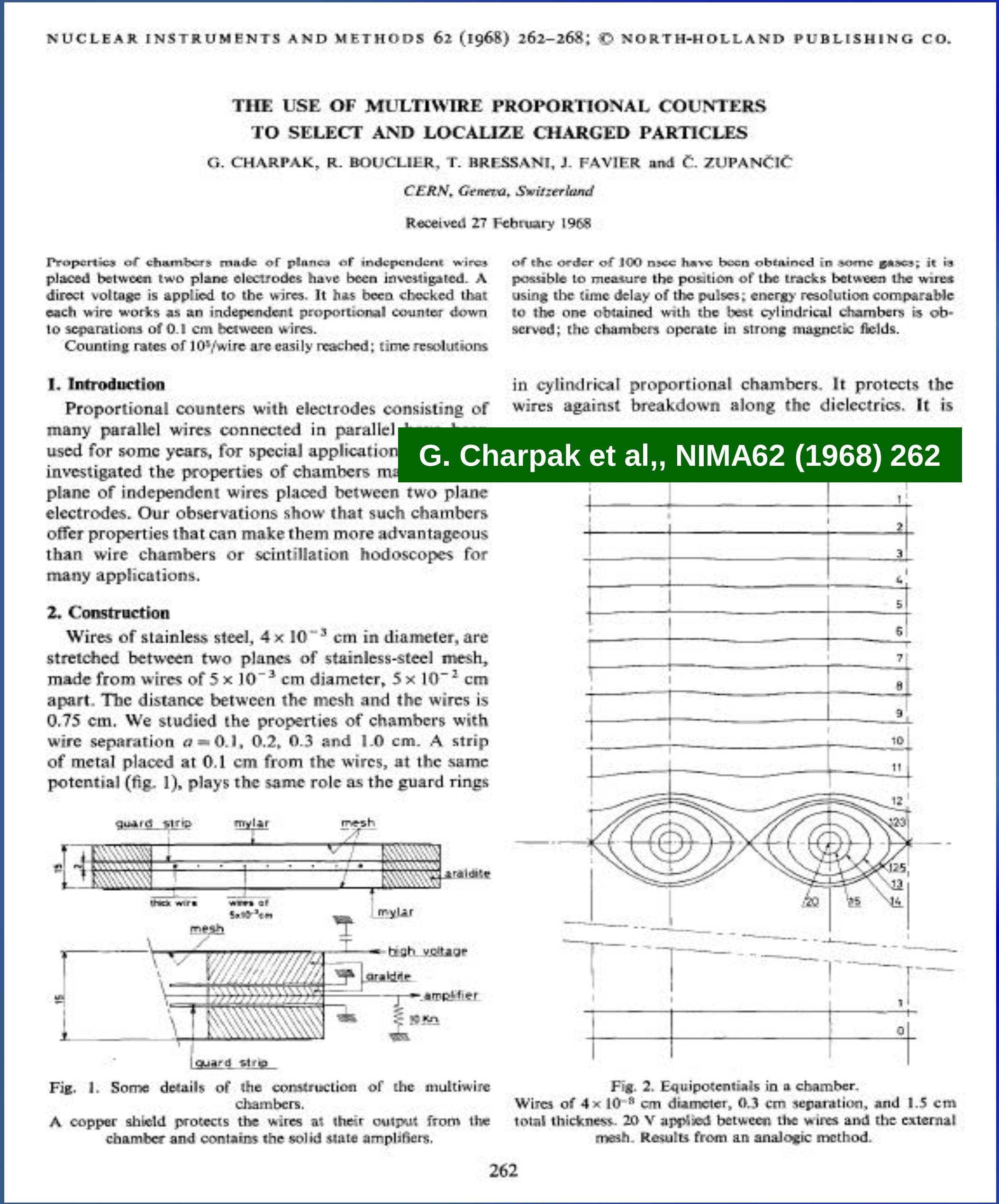


First Large Experiiment:

1972-1983:
SPLIT FIELD MAGNET DETECTOR: ~ 40 LARGE AREA MWPCs @ CERN ISR



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

used for some years, for special application

investigated the properties of chambers ma

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.

G. Charpak et al,, NIMA62 (1968) 262

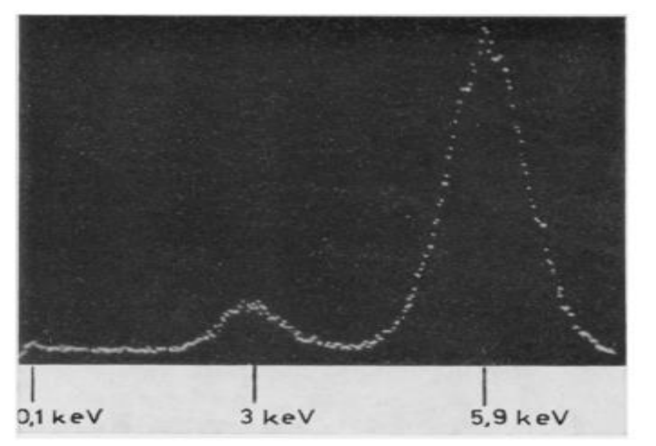
2. Construction

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

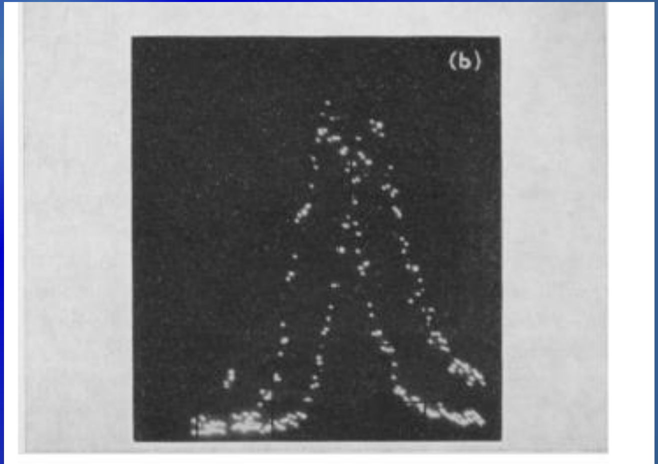
Fig. 1. Some details of the construction of the multiwire chambers.
A copper shield protects the wires at their output from the chamber and contains the solid state amplifiers.

Fig. 2. Equipotentials in a chamber.
Wires of 4×10^{-8} 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:

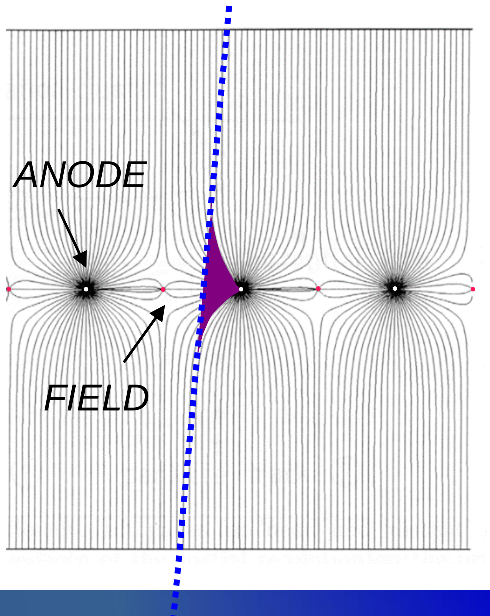


→ **DRIFT CHAMBERS**

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:



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

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

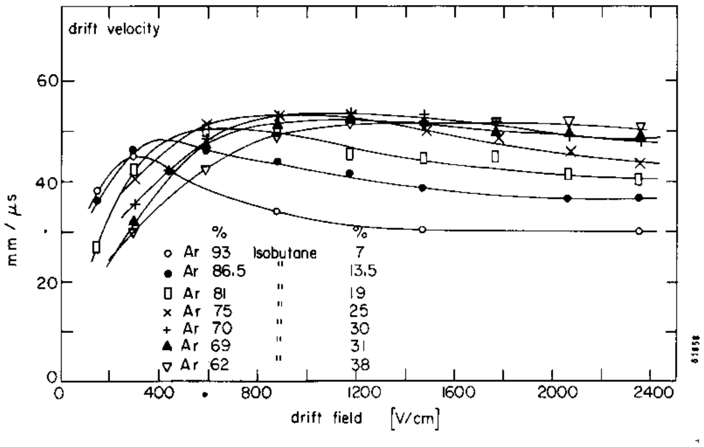
Determine location of original ionization:

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

If drift velocity changes along path:

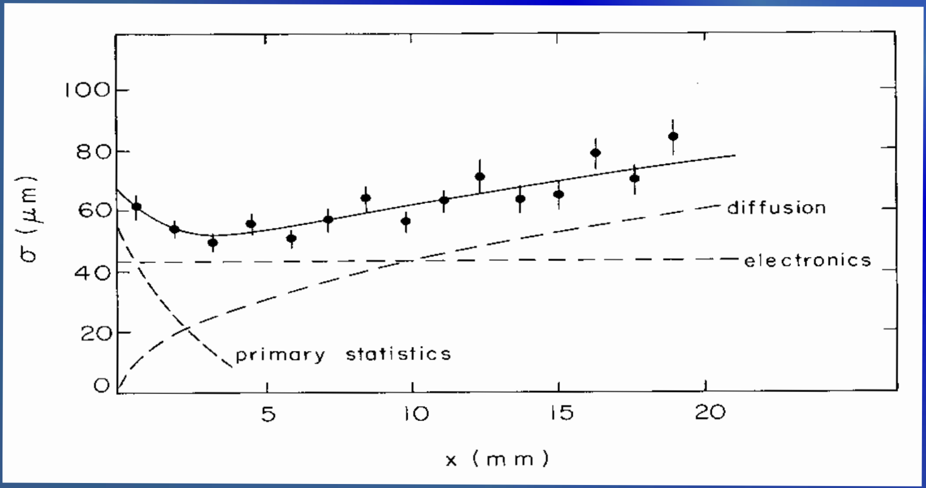
$$x = \int_0^{t_D} v_D \, dt$$

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



The spatial resolution is not limited to the cell size :

$$\sigma_x^2 = \underbrace{\left(\frac{1}{64N^2}\right)\cdot\frac{1}{x^2}}_{1^{st}\text{ ionization statistics}} + \underbrace{\frac{2D}{v_d}\cdot x}_{\text{diffusion}} + \underbrace{\sigma^2_{\text{const}}}_{\text{electronics, }\delta\text{-electrons}}$$



Typical single point resolutions of drift chambers:
50...150 µm depends on length of the drift path

- ✓ *primary ionization statistics: how many ion pairs, ionization fluctuations dominates close to the wire*
- ✓ *diffusion of electrons in gas: dominates for large drift length*
- ✓ *electronics: noise, shaping characteristics constant contribution (drift length independent)*

Multi-Wire Proportional Chamber (MWPC): Wire Displacements

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

- ✓ **Small wire displacements reduce field quality**

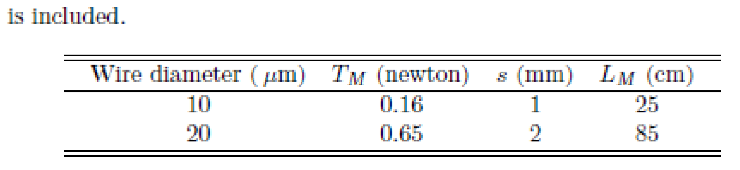
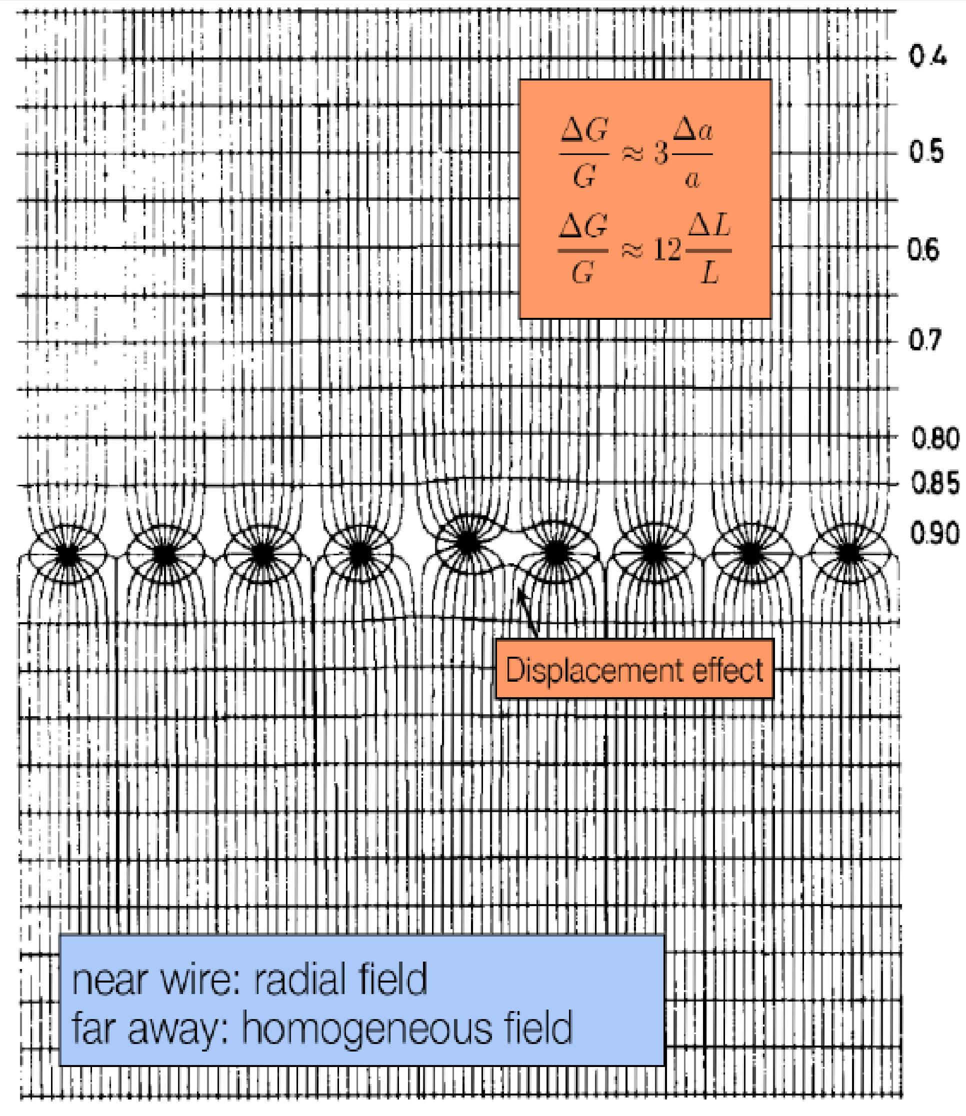


Table 35.1: Maximum tension T_M and stable unsupported length L_M for tungsten wires with spacing s, operated at $V_0 = 5$ kV. No safety factor is included.

Wire diameter (μm)	T_M (newton)	s (mm)	L_M (cm)
10	0.16	1	25
20	0.65	2	85

- ✓ **Need high mechanical precision both for geometry and wire tension ... (electrostatic and gravitation, wire sag …)**
- ✓ Several simplifying assumptions are made in analytical calculations: electrostatic force acting on the wire does not change during wire movements, or varies linearly with the displacement, the wire shape is parabolic; only one wire moves at a time.
- ✓ The advantage of numerical integrations using Garfield++ program is to simulate the collective movement of all wires, which are difficult analytically, and to consider all forces acting on a wire: forces between anode wire and other electrodes (wires, cathode) & gravitational force



$$\frac{\Delta G}{G} \approx 3\frac{\Delta a}{a}$$

$$\frac{\Delta G}{G} \approx 12\frac{\Delta L}{L}$$

Displacement effect

near wire: radial field
far away: homogeneous field

Wire & Drift Chambers: Wide-Spread Tool in HEP for > 40 Years

Interior of OPAL drift chamber
Length: 4 m; R = 185 cm; 159 measurements per track
[$\sigma_{r\phi}$ = 135 μm, σ_z = 60 mm]

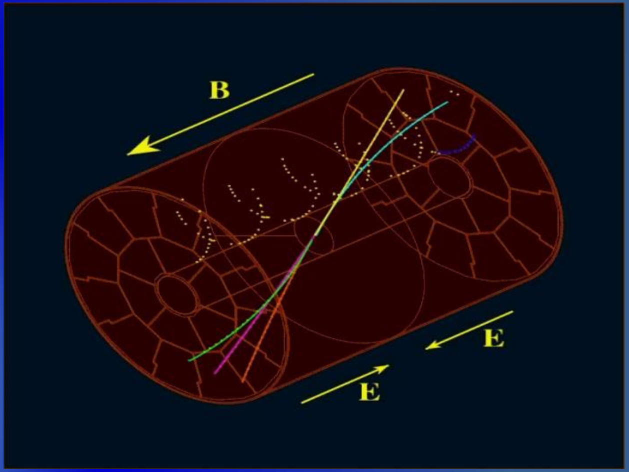
Time Projection Chamber (TPC) in Particle and Ion Physics

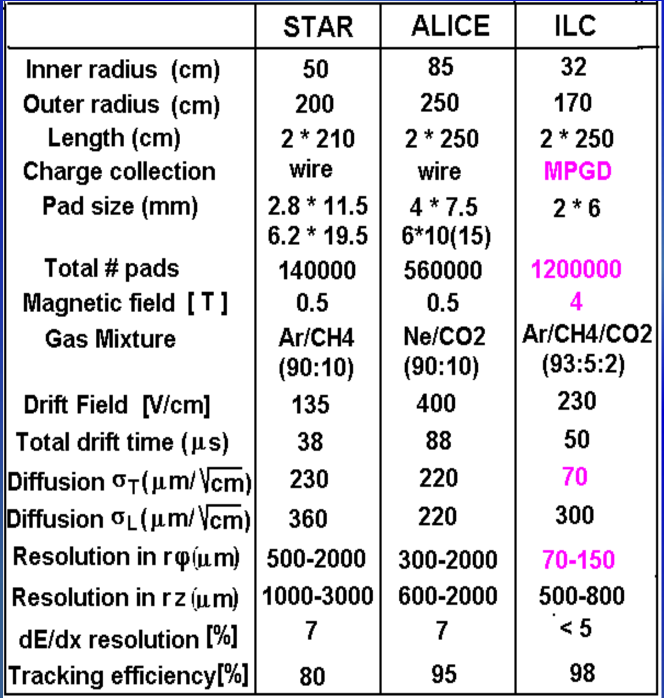
PEP4 (SLAC)

ALEPH (CERN)

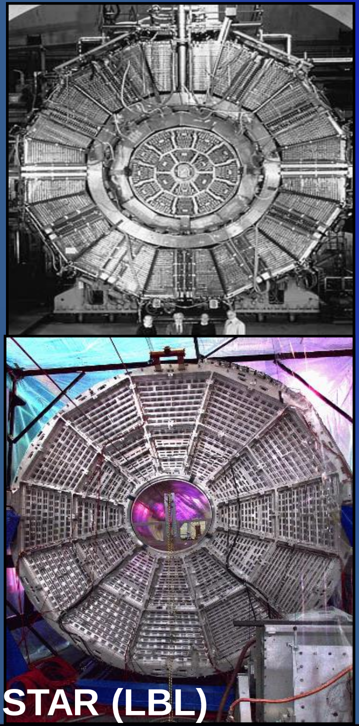
- ✓ **Invented by David Nygren (Berkeley) in 1974**
- ✓ **Proposed as a central tracking device for the PEP-4 detector @ SLAC in 1976**
- ✓ **More (and even larger) were built, based on <u>MWPC readout</u>, serving as a powerful tool for:**
  - **Lepton Colliders (LEP, Higgs Factories)**
  - **Modern heavy ion collisions (RHIC, EIC)**
  - **Liquid and high pressure TPCs for neutrino and dark matter searches**

An ultimate drift chamber design is TPC concept - 3D precision tracking with low material budget & PID through differential energy loss dE/dx measurement and/or cluster counting dN_{cl}/dx tech.





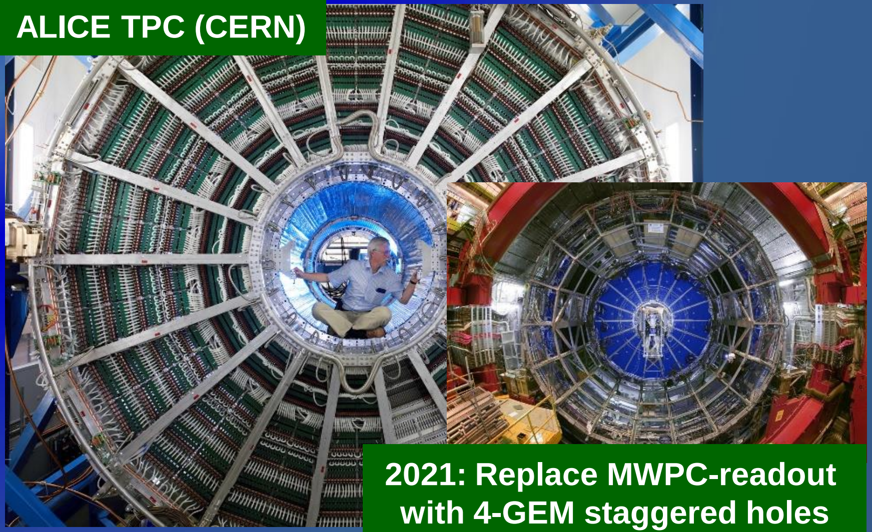
	STAR	ALICE	ILC
Inner radius (cm)	50	85	32
Outer radius (cm)	200	250	170
Length (cm)	2 * 210	2 * 250	2 * 250
Charge collection	wire	wire	MPGD
Pad size (mm)	2.8 * 11.5 6.2 * 19.5	4 * 7.5 6*10(15)	2 * 6
Total # pads	140000	560000	1200000
Magnetic field [T]	0.5	0.5	4
Gas Mixture	Ar/CH4 (90:10)	Ne/CO2 (90:10)	Ar/CH4/CO2 (93:5:2)
Drift Field [V/cm]	135	400	230
Total drift time (μs)	38	88	50
Diffusion σ_T ($\mu m/\sqrt{cm}$)	230	220	70
Diffusion σ_L ($\mu m/\sqrt{cm}$)	360	220	300
Resolution in $r\varphi$ (μm)	500-2000	300-2000	70-150
Resolution in rz (μm)	1000-3000	600-2000	500-800
dE/dx resolution [%]	7	7	< 5
Tracking efficiency[%]	80	95	98



STAR (LBL)

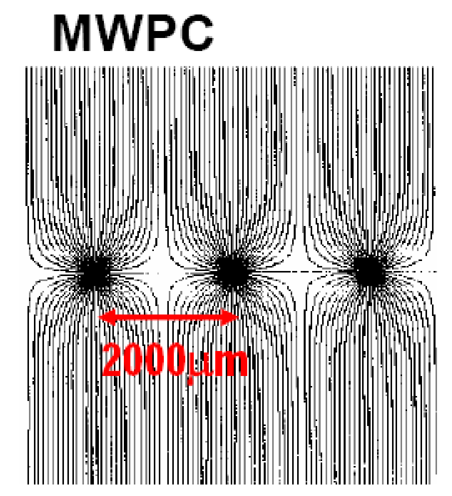
<u>New generation of TPCs use MPGD-based readout:</u> e.g. ALICE Upgrade, T2K, ILC, CepC

ALICE TPC (CERN)



2021: Replace MWPC-readout with 4-GEM staggered holes

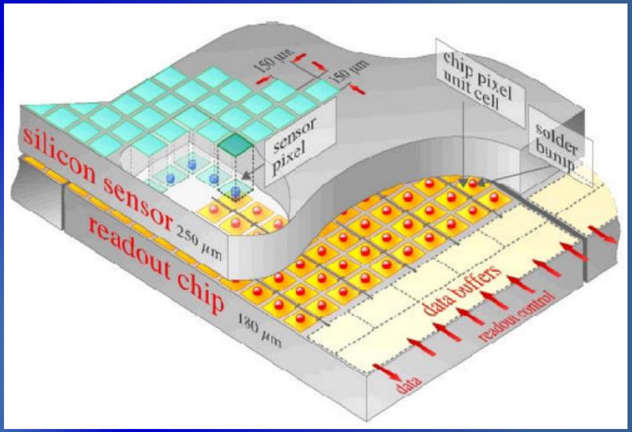
Micro-Pattern Gaseous Detectors:
Bridging the Gap for Tracking between Wire Chambers and Silicon-based Devices

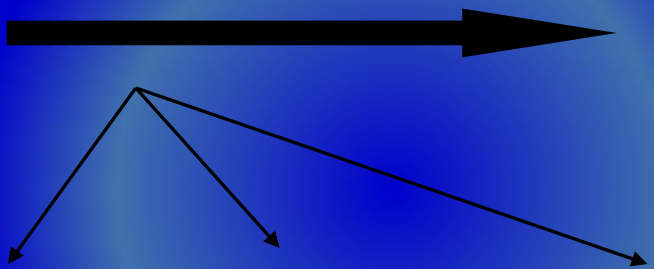


$\sigma \sim 100\ \mu m$

$\sigma < 10\ \mu m$

Pixel System:





Advantages of gas detectors:
- *low radiation length*
- *large areas at low price*
- *flexible geometry*
- *spatial, energy resolution …*

Problem:

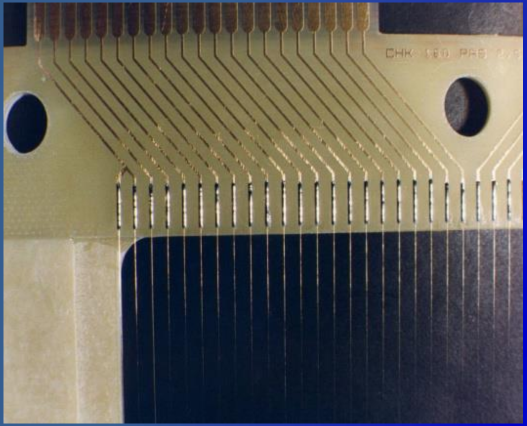
✓ *rate capability limited by space charge defined by the time of evacuation of positive ions*

Solution:

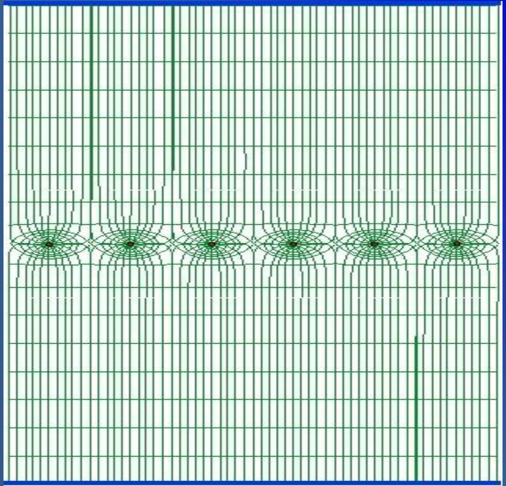
✓ ***reduction of the size** of the detecting cell (limitation of the length of the ion path) **using chemical etching and photo-lithographique techniques** developed for microelectronics and keeping at same time similar field shape.*

Micro-Strip Gas Chamber (MSGC): An Early MPGD

Multi-Wire Proportional Chamber (MWPC)

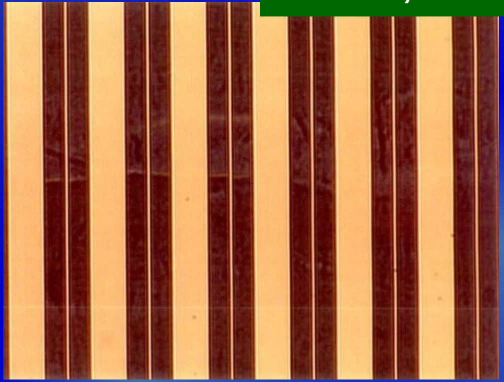


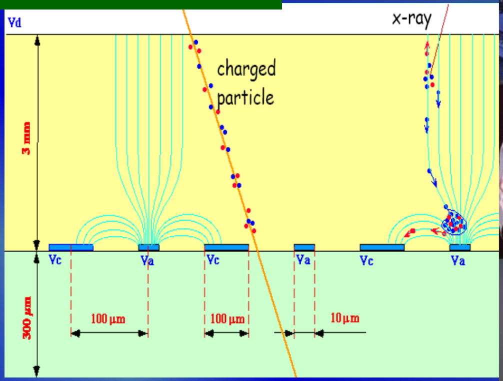
Typical distance between wires limited to ~1 mm due to mechanical and electrostatic forces

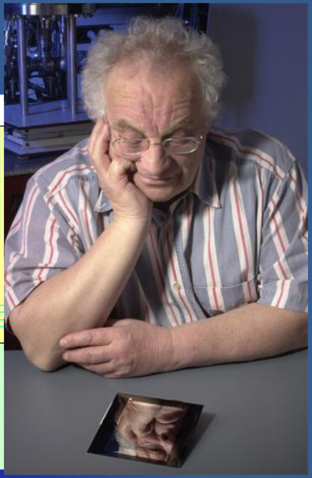


Micro-Strip Gas Chamber (MSGC)

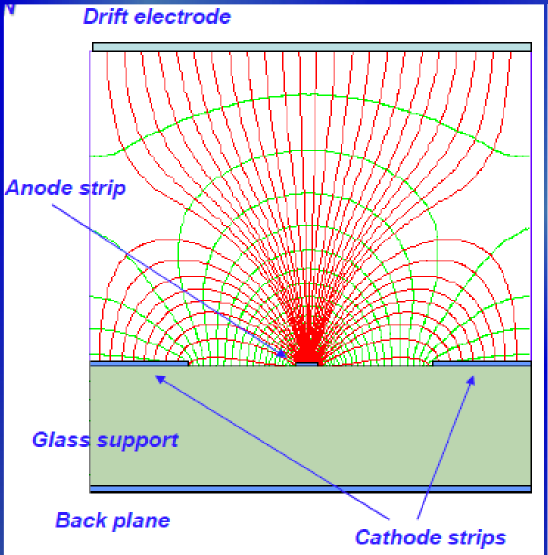
A. Oed, NIMA263 (1988) 351





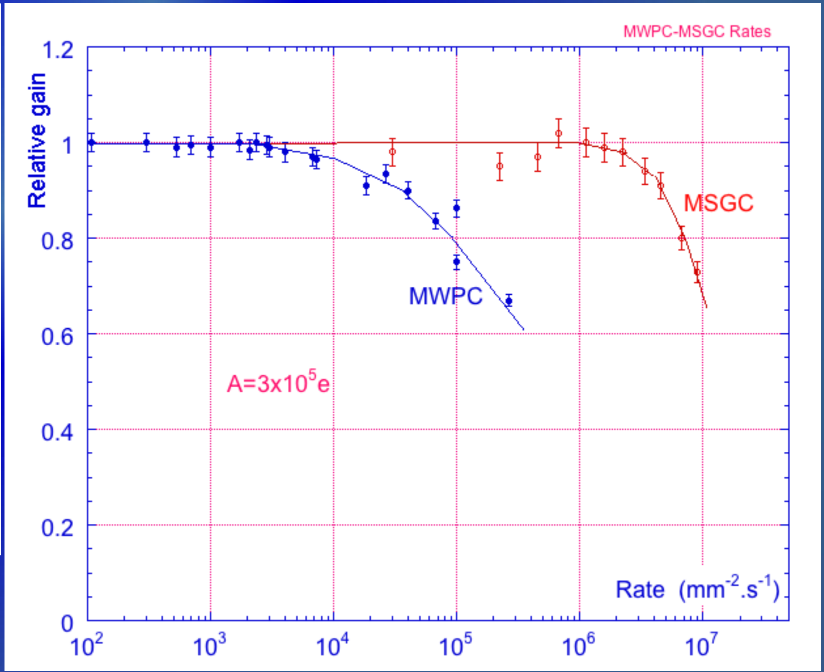


Excellent spatial resolution



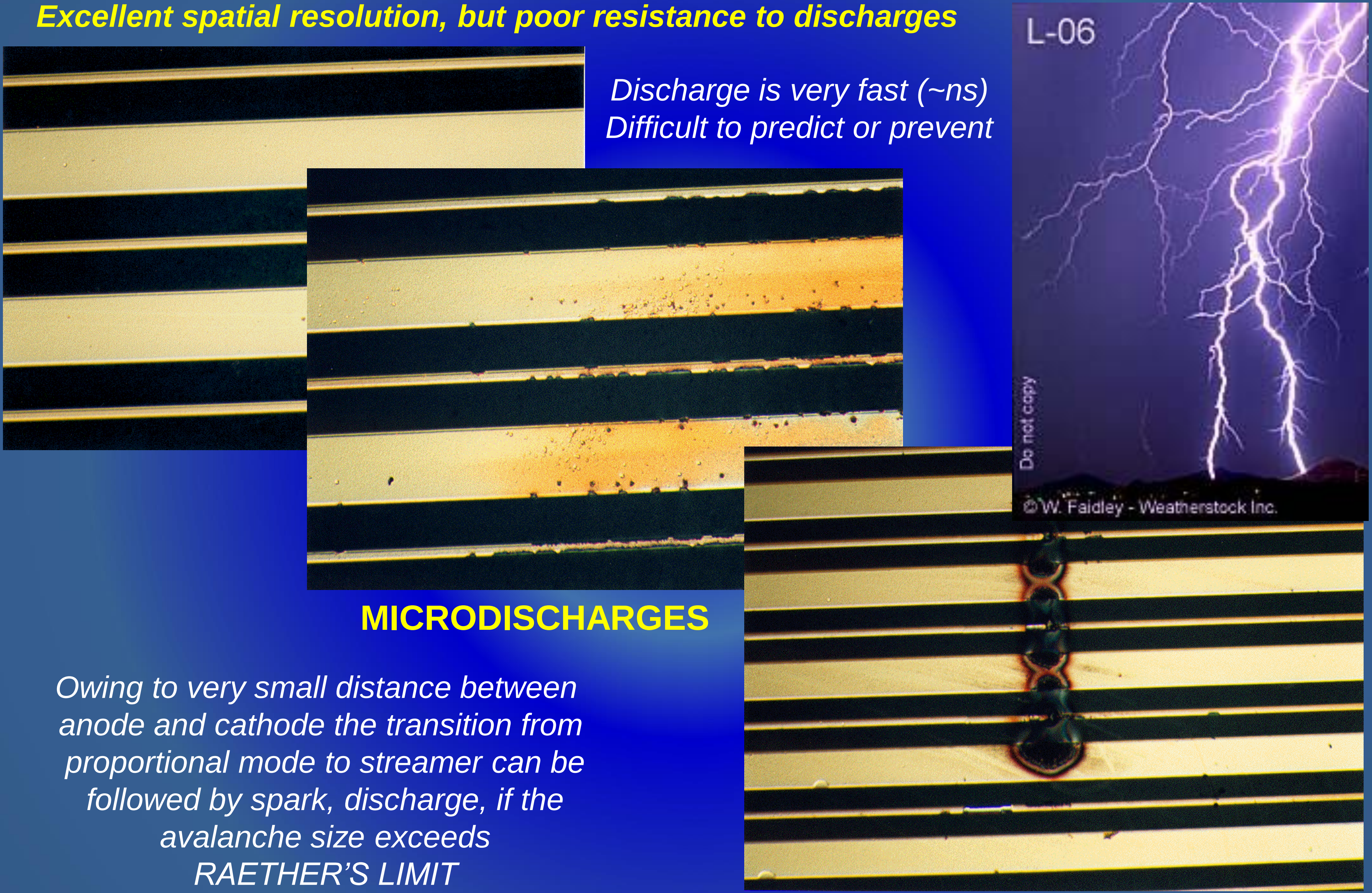
Typical distance between electrodes ~100 μm

MSGC significantly improves rate capability due to fast removal of positive ions



MSGC Discharge Problems

Excellent spatial resolution, but poor resistance to discharges



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

MICRODISCHARGES

FULL BREAKDOWN

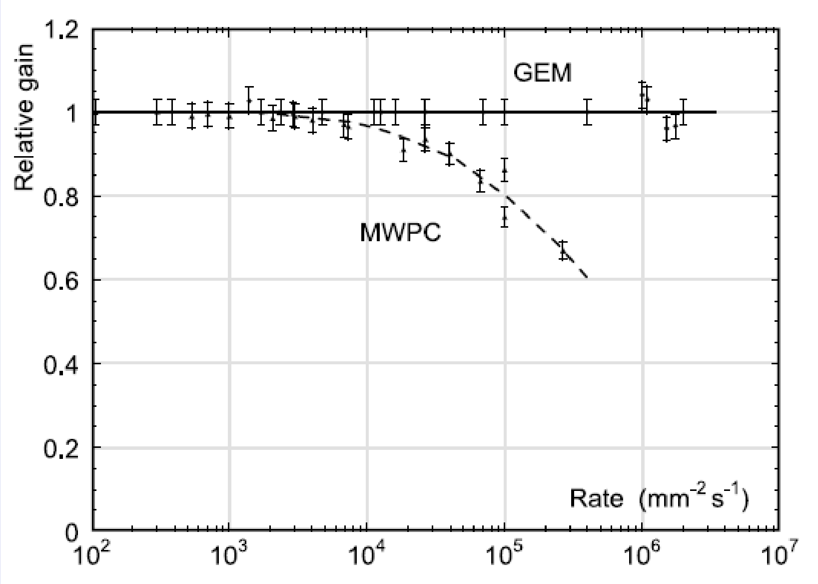
Owing to very small distance between anode and cathode the transition from proportional mode to streamer can be followed by spark, discharge, if the avalanche size exceeds
RAETHER'S LIMIT
$Q \sim 10^7 – 10^8$ electrons

Micro-Pattern Gaseous Detector Technologies (MPGD)

- ✓ *Micromegas*
- ✓ *Gas Electron Multiplier (GEM)*
- ✓ *Thick-GEM (LEM), Hole-Type & RETGEM*
- ✓ *MPDG with CMOS pixel ASICs ("GridPix")*

- ✓ *Micro-Pixel Chamber (μ–PIC)*
- ✓ *μ–Resistive WELL (μ-RWELL)*
- ✓ *Resistive-Plate WELL (RPWELL)*

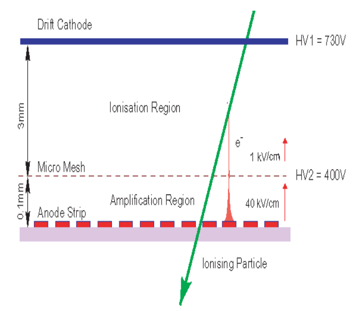
Rate Capability: MWPC vs GEM:

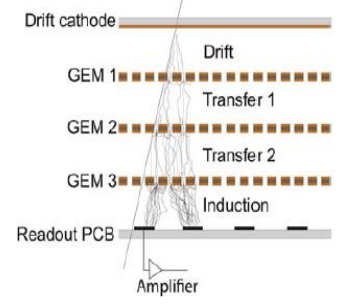


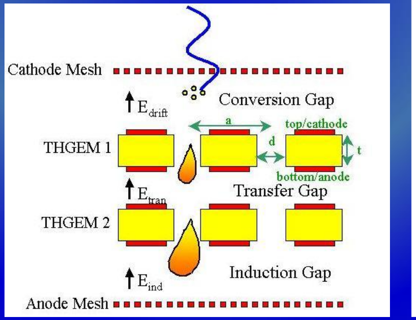
Micromegas

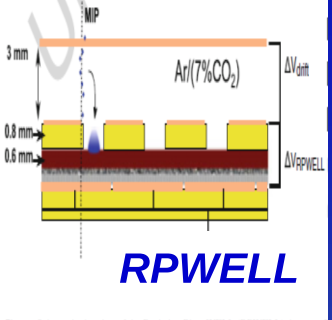
GEM

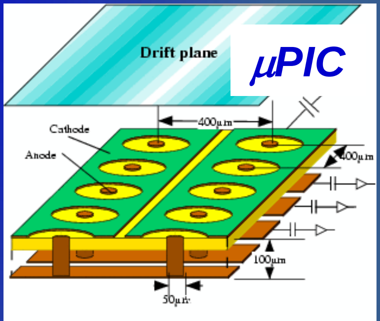
THGEM

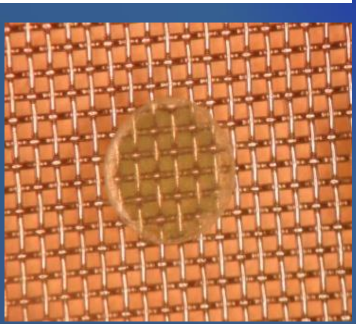


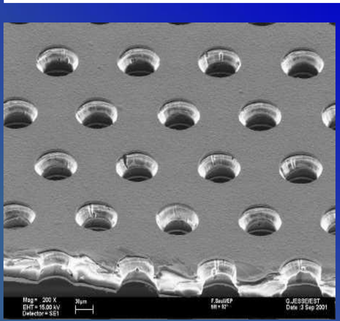


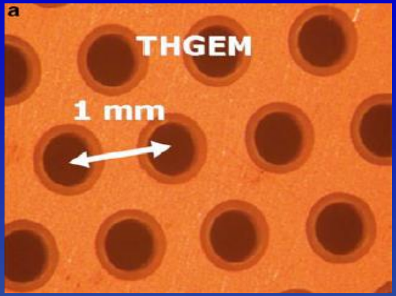


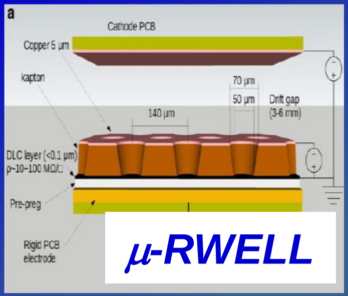


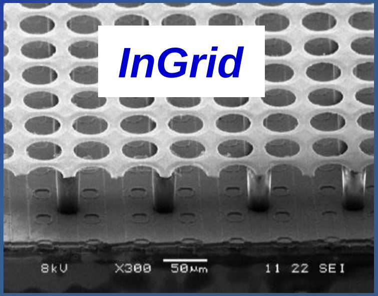










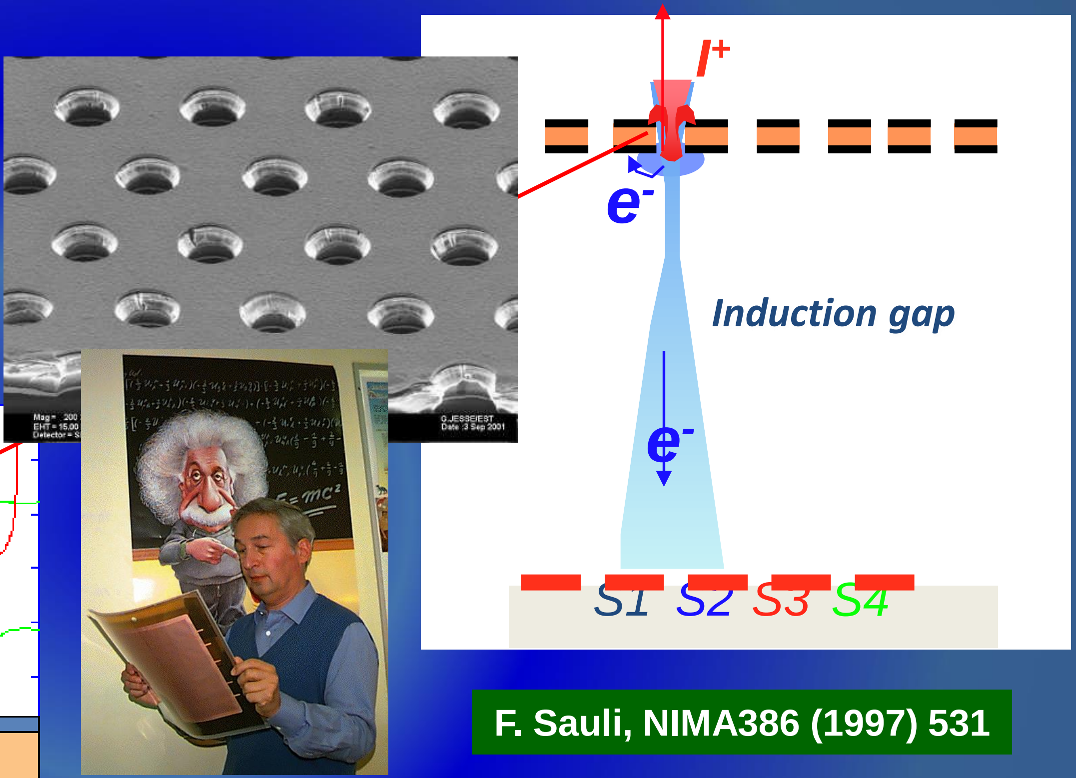


Gas Electron Multiplier (GEM)

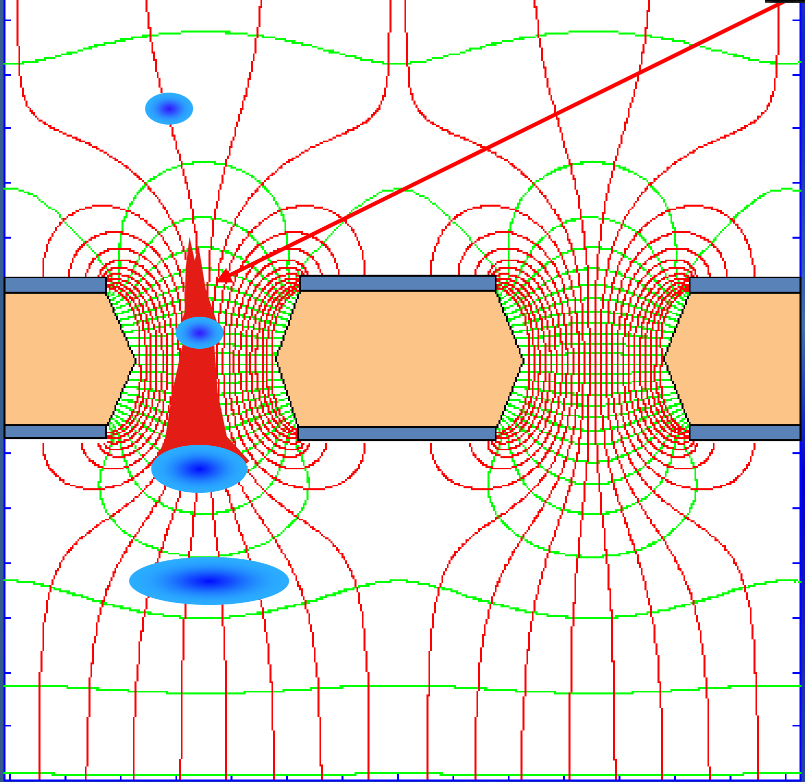
Thin metal-coated polymer foil chemically pierced by a high density of holes

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.



F. Sauli, NIMA386 (1997) 531

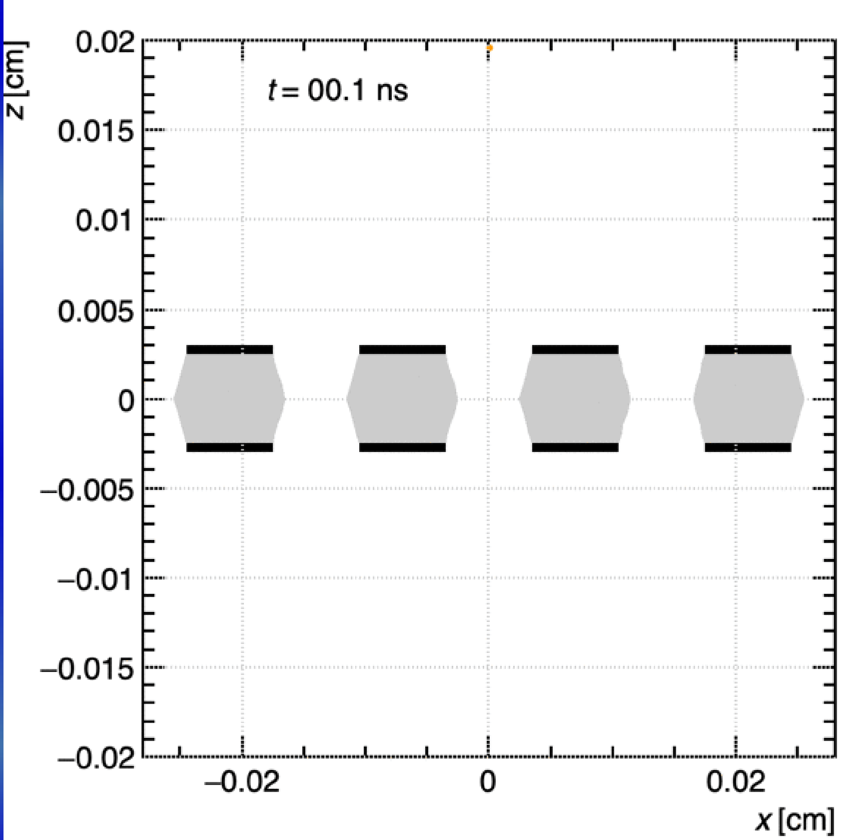


- ✓ Electrons are collected on patterned readout board.
- ✓ A fast signal can be detected on the lower GEM electrode for triggering or energy discrimination.
- ✓ All readout electrodes are at ground potential.
- ✓ Positive ions partially collected on GEM electrodes

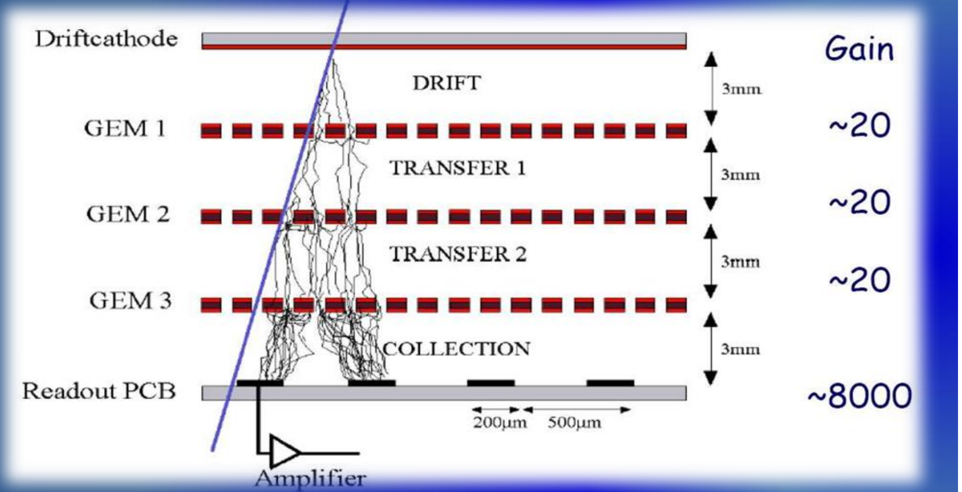
Avalanche Simulation in GEM & Triple-GEM Structures

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

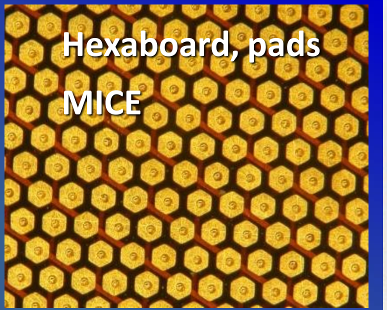
http://cern.ch/garfieldpp/examples/gemgain

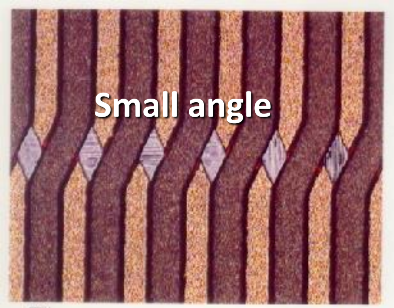


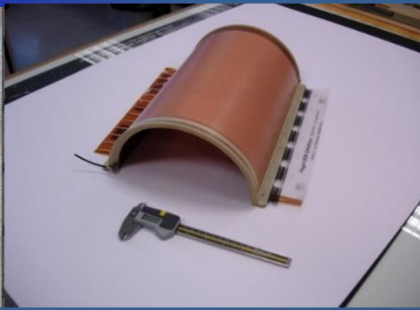
Full decoupling of amplification stage (GEM) and readout stage (PCB, anode)



Amplification and readout structures can be optimized independently !



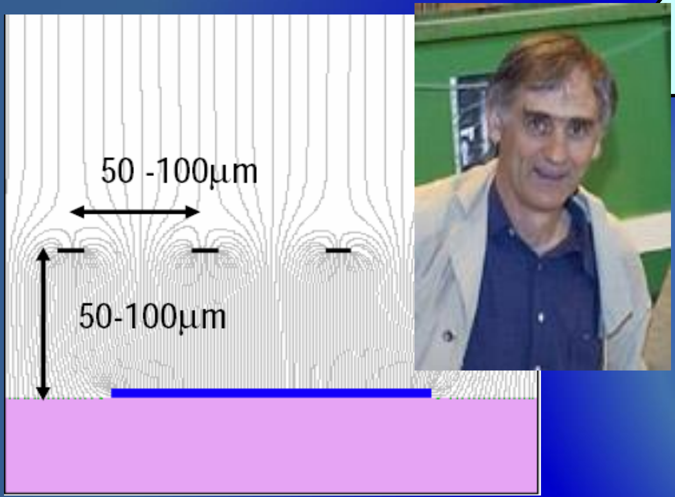


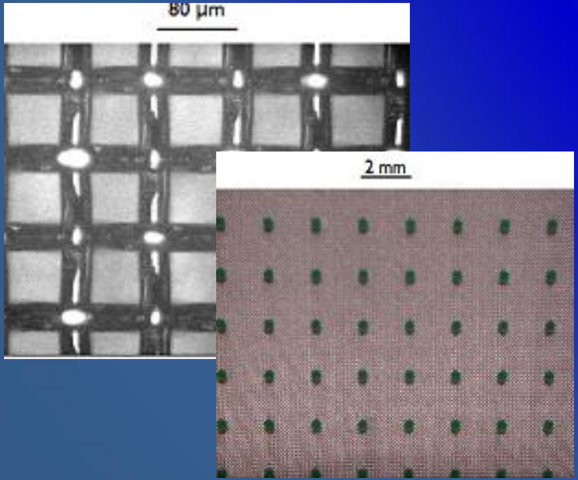


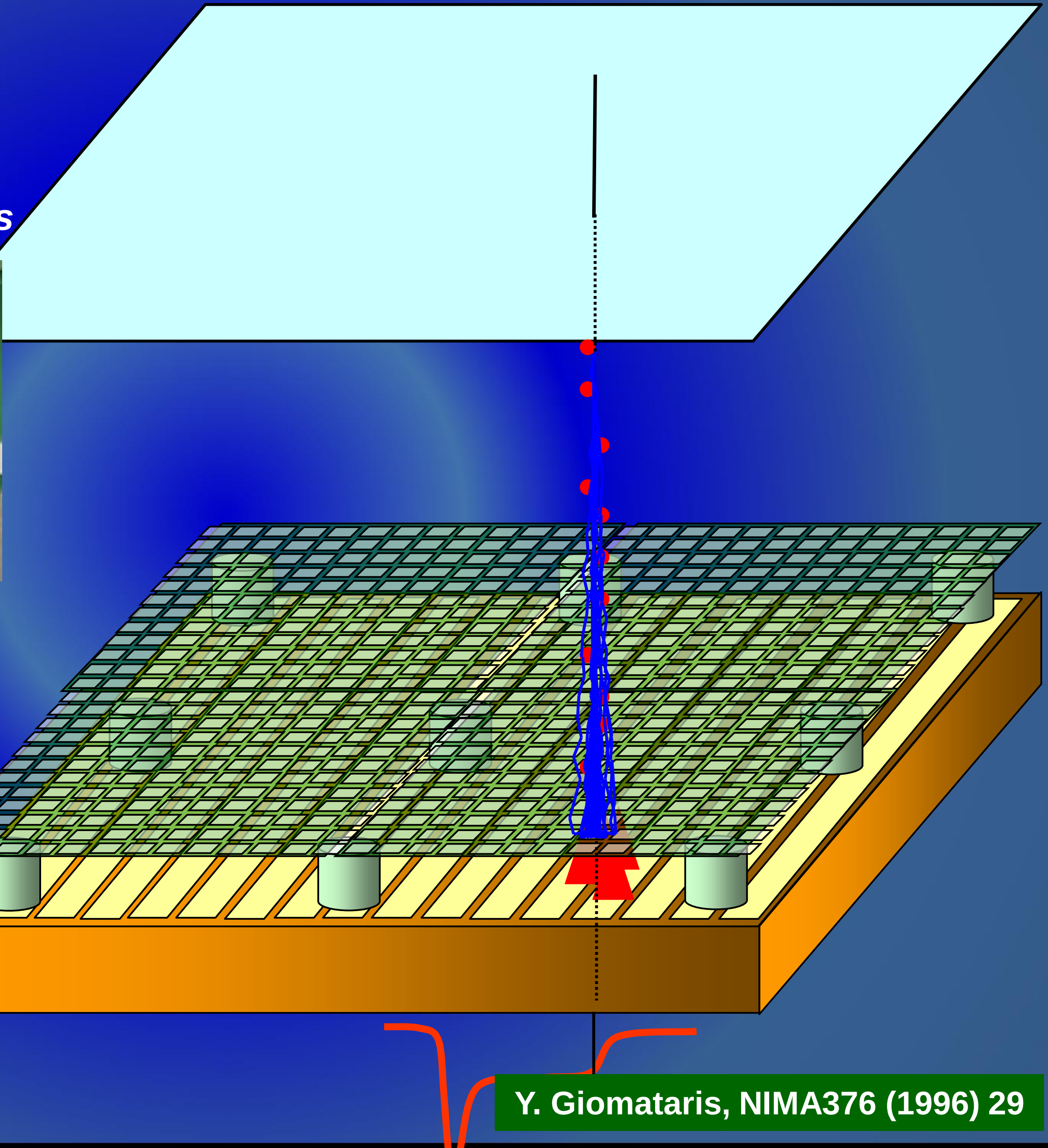
Micro Mesh Gaseous Structure (MICROMEGAS)

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

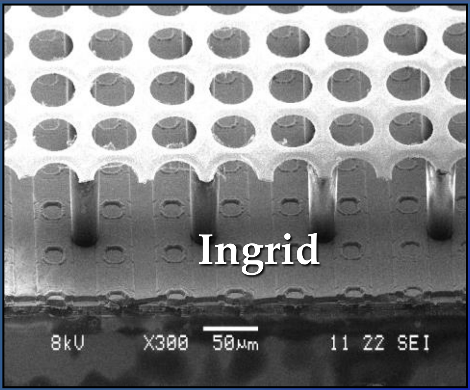
Small gap: fast collection of ions

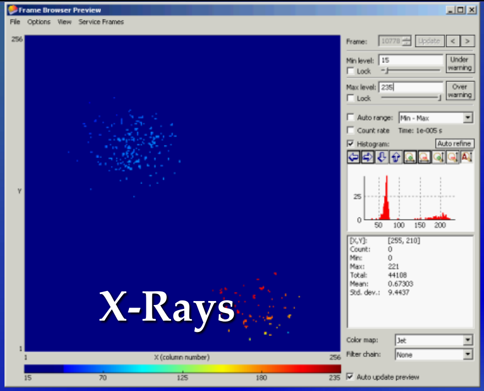




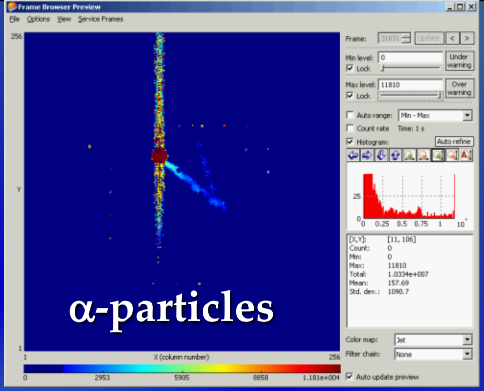


Y. Giomataris, NIMA376 (1996) 29



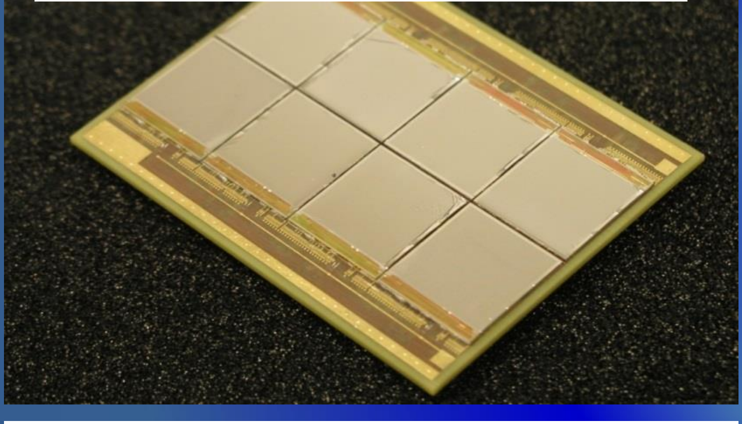


Frame: 10778
Min level: 15
☐ Lock
Max level: 235
☐ Lock
☐ Auto range: Min - Max
☐ Count rate Time: 1e-005 s
☑ Histogram:
[X,Y]: [255, 210]
Count: 0
Min: 0
Max: 221
Total: 44108
Mean: 0.67303
Std. dev.: 9.4437
Color map: Jet
Filter chain: None
☑ Auto update preview



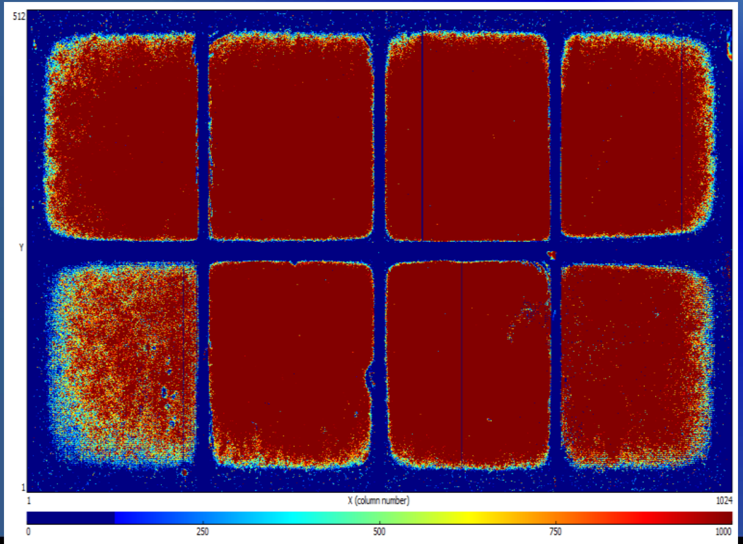
Frame: 31631
Min level: 0
☑ Lock
Max level: 11810
☑ Lock
☐ Auto range: Min - Max
☐ Count rate Time: 1 s
☑ Histogram:
[X,Y]: [11, 106]
Count: 0
Min: 0
Max: 11810
Total: 1.0334e+007
Mean: 157.69
Std. dev.: 1090.7
Color map: Jet
Filter chain: None
☑ Auto update preview

“Octopuce” (8 Timepix ASICs):

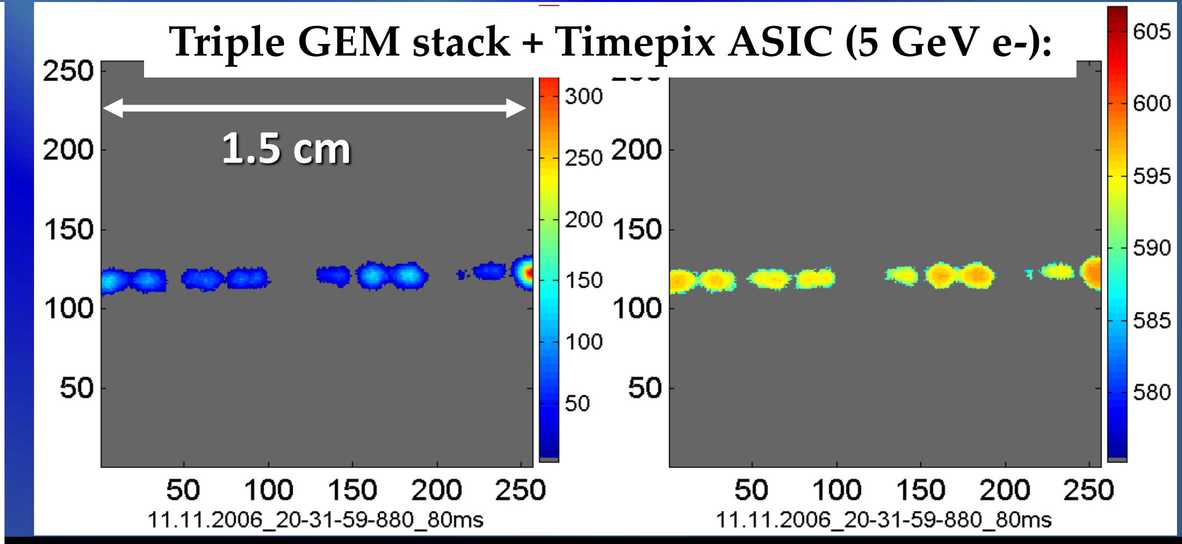


ULTIMATE INTEGRATION OF GASEOUS and SIICON DETECTORS –

PIXEL READOUT of MICRO-PATTERN GASEOUS DETECTORS



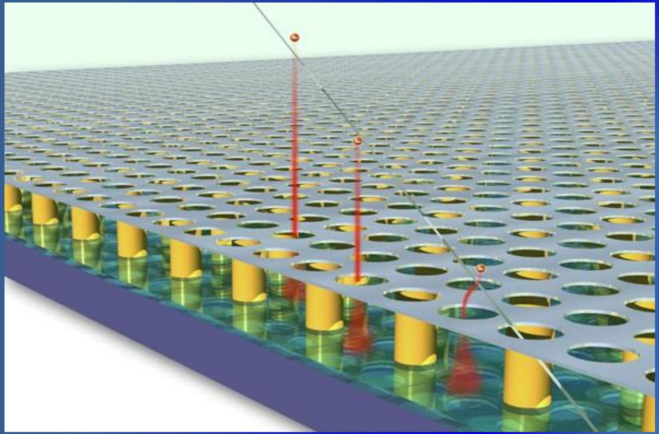
Triple GEM stack + Timepix ASIC (5 GeV e-):

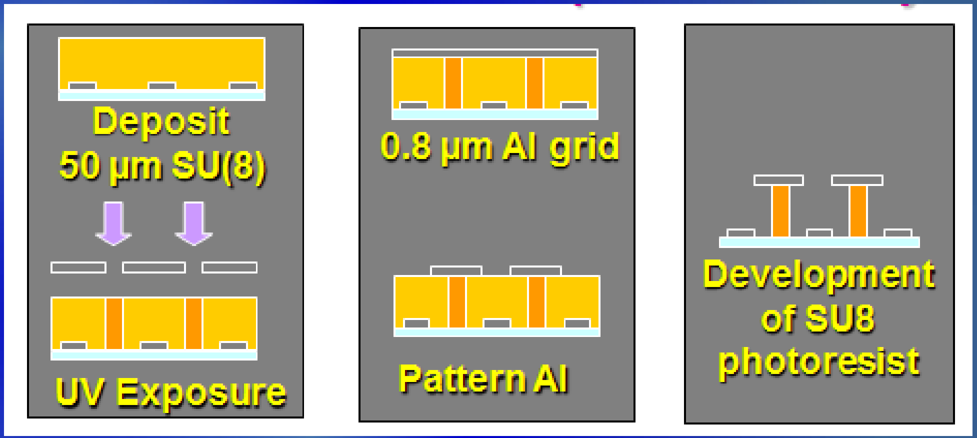


Pixel Readout of MPGDs: "GridPix" Concept

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

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





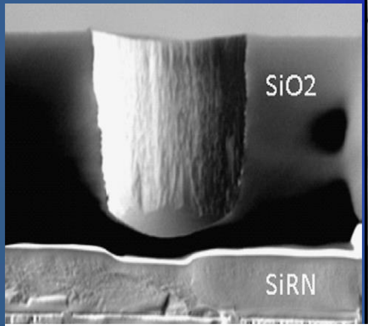
Deposit 50 μm SU(8)

UV Exposure

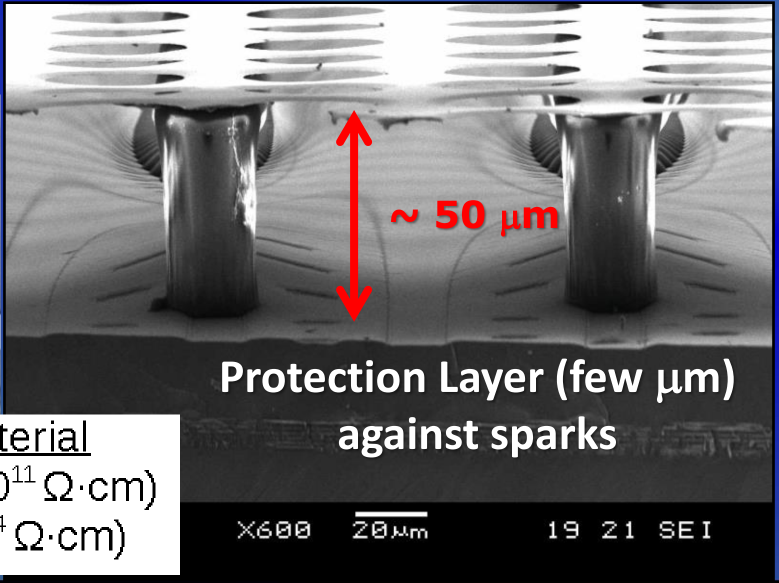
0.8 μm Al grid

Pattern Al

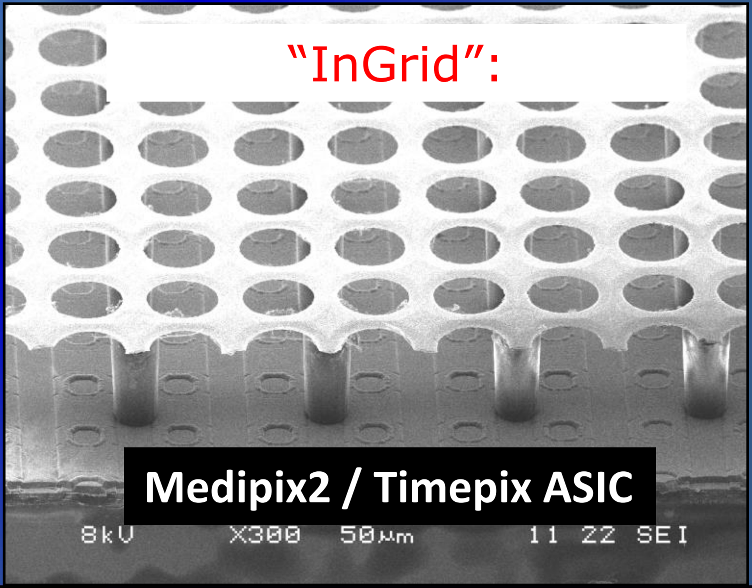
Development of SU8 photoresist



<u>high resistive material</u>
15 μm aSi:H (~10^{11} Ω·cm)
8 μm Si_XN_Y (~10^{14} Ω·cm)



Protection Layer (few μm) against sparks



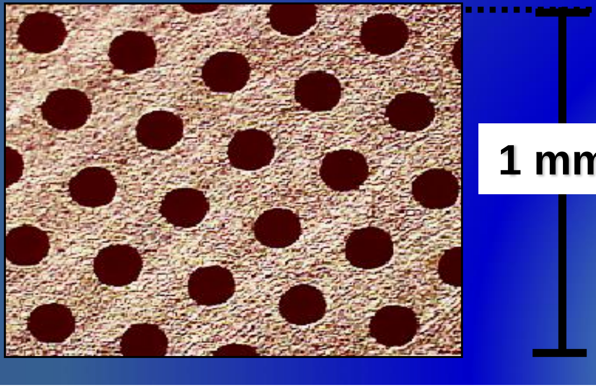
"InGrid":

Medipix2 / Timepix ASIC

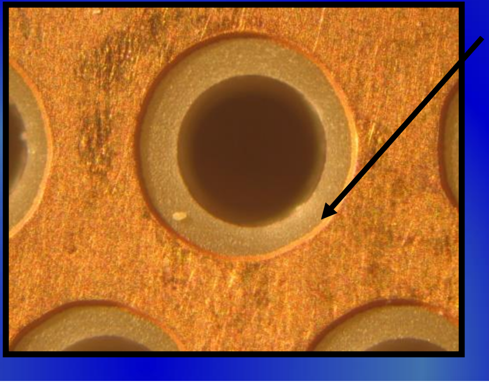
Other MPGDs Concepts: THGEM, μRWELL, RPWELL

THGEM Manufactured by standard PCB techniques of precise drilling in G-10 (and other materials) and Cu etching

STANDARD GEM

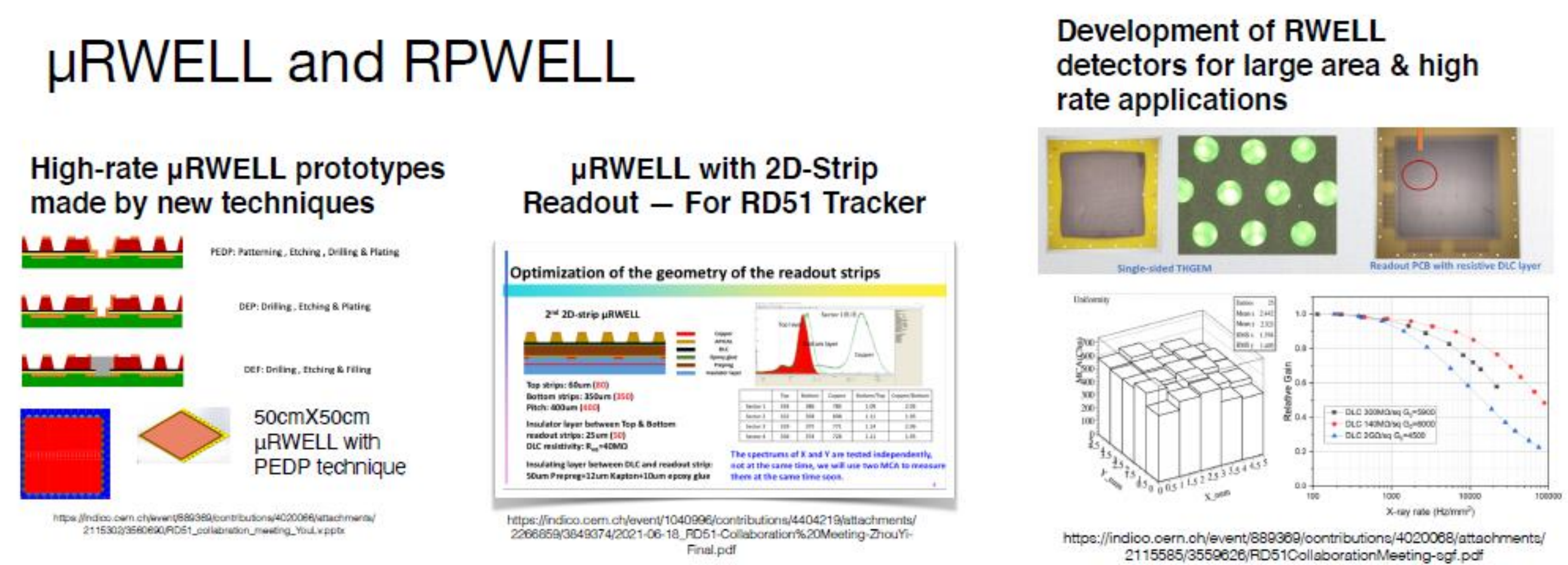


THGEM



0.1 mm rim to prevent discharges

L. Periale, NIMA478 (2002) 377
LEM!: P. Jeanneret, PhD thesis, 2001



μRWELL and RPWELL

High-rate μRWELL prototypes made by new techniques

PEDP: Patterning , Etching , Drilling & Plating

DEP: Drilling , Etching & Plating

DEF: Drilling , Etching & Filling

50cmX50cm μRWELL with PEDP technique

https://indico.cern.ch/event/889369/contributions/4020066/attachments/2115302/3560690/RD51_collabration_meeting_YouLv.pptx

μRWELL with 2D-Strip Readout — For RD51 Tracker

Optimization of the geometry of the readout strips

2nd 2D-strip μRWELL

Top strips: 60um (80)
Bottom strips: 350um (350)
Pitch: 400um (400)

Insulator layer between Top & Bottom readout strips: 25um (50)
DLC resistivity: R_{sq}=40MΩ

Insulating layer between DLC and readout strip: 50um Prepreg=12um Kapton+10um epoxy glue

The spectrums of X and Y are tested independently, not at the same time, we will use two MCA to measure them at the same time soon.

https://indico.cern.ch/event/1040996/contributions/4404219/attachments/2266859/3849374/2021-06-18_RD51-Collaboration%20Meeting-ZhouYi-Final.pdf

Development of RWELL detectors for large area & high rate applications

Single-sided THGEM

Readout PCB with resistive DLC layer

https://indico.cern.ch/event/889369/contributions/4020068/attachments/2115585/3559626/RD51CollaborationMeeting-sgf.pdf

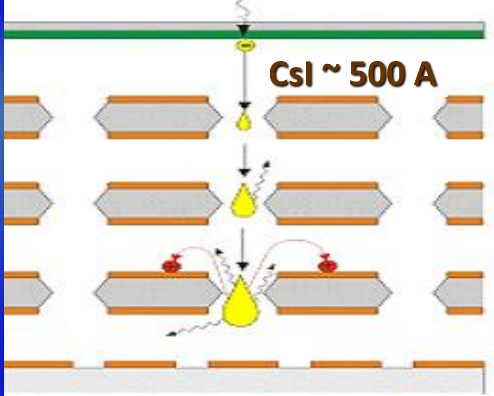
MPGD-Based Gaseous Photomultipliers

GEM or THGEM Gaseous Photomultipliers (CsI -PC) to detect single photoelectrons

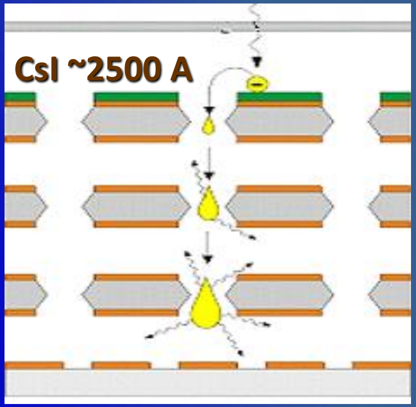
Multi-GEM (THGEM) Gaseous Photomultipliers:

- ✓ *Largely reduced photon feedback (can operate in pure noble gas & CF_4)*
- ✓ *Fast signals [ns] → good timing*
- ✓ *Excellent localization response*
- ✓ *Able to operate at cryogenic T*

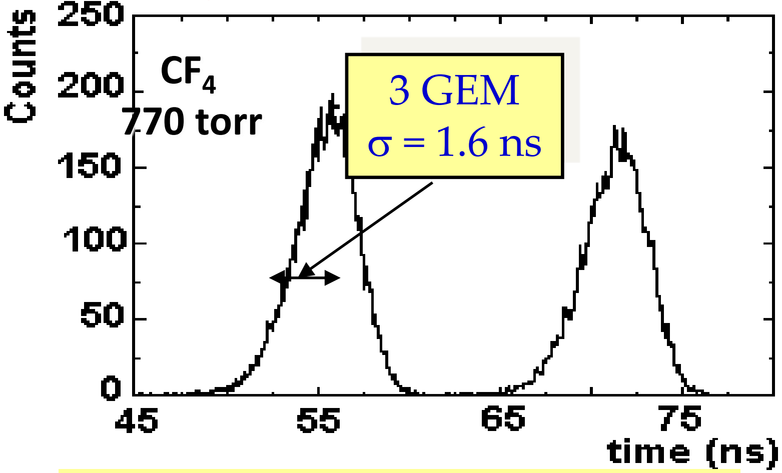
Semitransparent Photocathode (PC)



Reflective Photocathode (PC)

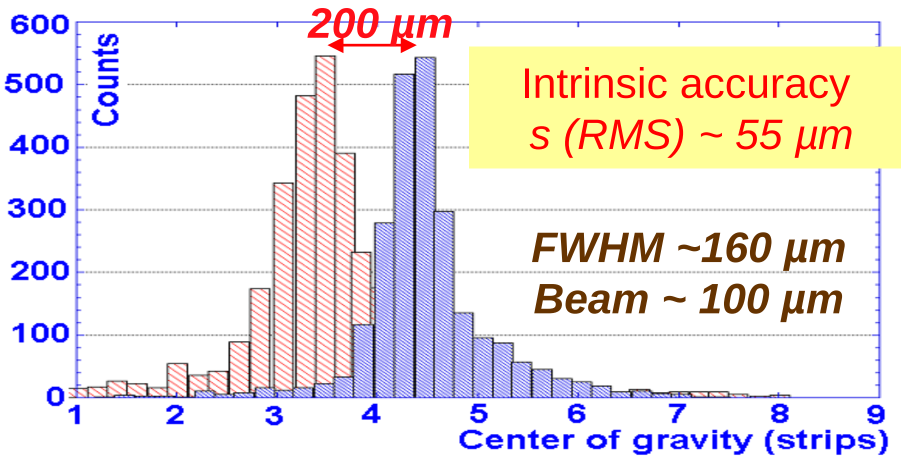


Single Photon Time Resolution:



Micromegas: s ~ 0.7 ns with MIPs

Single Photon Position Accuracy:



Intrinsic accuracy
s (RMS) ~ 55 μm

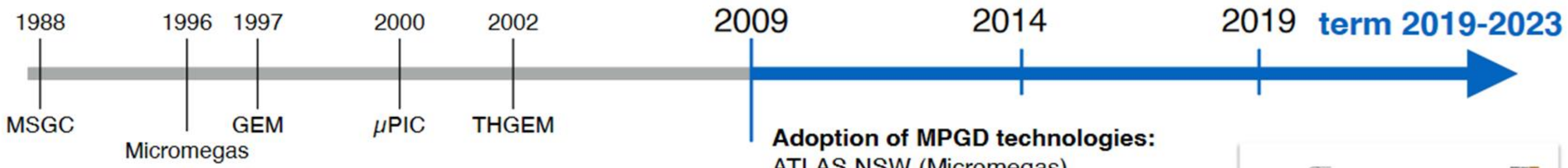
FWHM ~160 μm
Beam ~ 100 μm

E.Nappi, NIMA471 (2001) 18; T. Meinschad et al, NIM A535 (2004) 324; D.Mormann et al., NIMA504 (2003) 93

Legacy of the CERN-RD51 Collaboration: 2008-2023

***RD51* CERN-based *"TECHNOLOGY - DRIVEN R&D COLLABORATION"* was established to advance MPGD concepts and associated electronics readout systems**

RD51 community: ~ 90 institutes, 500 members



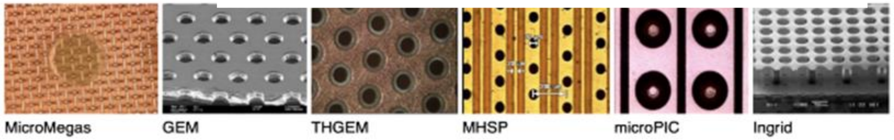
2008:


CERN-LHCC-2008-011 (LHCC-P-001)
RD51 2008-001
28 July 2008

R & D Proposal

Development of Micro-Pattern Gas Detectors Technologies

Editors: Matteo Alfonsi (CERN), Alain Bellerive (Carleton University), Amos Breskin (Weizmann Institute), Erik Van der Bij (CERN), Michael Campbell (CERN), Mar Capeans (CERN), Paul Colas (CEA Saclay), Silvia Dalla Torre (INFN Trieste), Klaus Desch (Bonn University), Ioannis Giomataris (CEA Saclay), Harry van der Graaf (NIKHEF), Lucie Linssen (CERN), Rui de Oliveira (CERN), Vladimir Peskov (St Etienne), Werner Riegler (CERN), Leszek Ropelewski (CERN), Fabio Sauli (TERA Foundation), Frank Simon (MPI Munchen), Hans Taureg (CERN), Maxim Titov (CEA Saclay), Andy White (University of Texas), Rob Veenhof (CERN)



Adoption of MPGD technologies:
ATLAS NSW (Micromegas)
CMS forward tracking update (GEM)
COMPASS RICH upgrade (hybrid MPGD)
ALICE TPC upgrade (GEM)
KLOE2 & BESIII (GEM)
LBNO-DEMO (THGEM)
T2K/ND280 TPC (Micromegas)
n-detection at ESS (GEM)
Muon radiography (Micromegas)

RD51 Spokespersons:
L. Ropelewski (2008-2022)
M. Titov (2008-2015, 2023)
S. Dalla Torre (2016-2022)
E. Oliveri (2023)

2018:


May 2018

R&D PROPOSAL
RD51 EXTENSION BEYOND 2018

EDITORS:
S. Dalla Torre (INFN Trieste), E. Oliveri (CERN),
L. Ropelewski (CERN), M. Titov (CEA Saclay)

Abstract

arXiv:1806.09955v1 [physics.ins-det] 26 Jun 2018

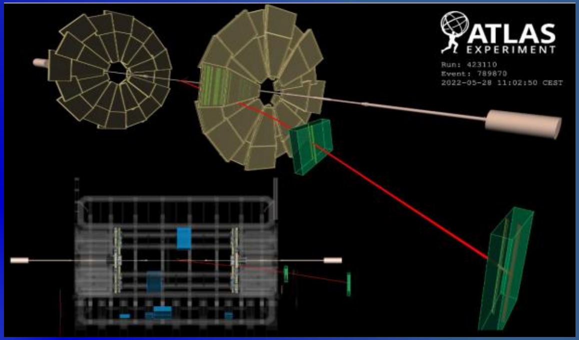
arXiv:1806.09955

- ✓ ***Many of the MPGD Technologies were introduced before the RD51 was founded***
- ✓ ***With more techniques becoming available, new detection concepts were introduced and the existing ones were substantially improved during the RD51 period (2008-2023)***
- ✓ ***Beyond 2023, RD51 served as a nuclei for the new DRD1 ("all gas detectors") collaboration, anchored at CERN, as part of the ECFA Detector R&D Roadmap***

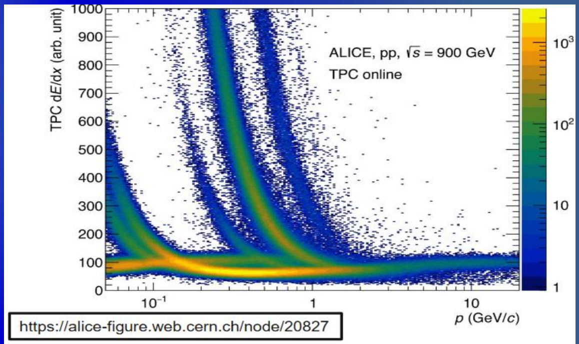
CERN Detector Seminars in 2022: LS2 Upgrades

Major MPGDs developments for ATLAS, CMS, ALICE upgrades, towards establishing technology goals and technical requirements, and addressing engineering and integration challenges … and first results from Run 3 !!!

"The New Small Wheel project of ATLAS"
by Theodoros Vafeiadis (17 Jun 2022)
https://indico.cern.ch/event/1168778/

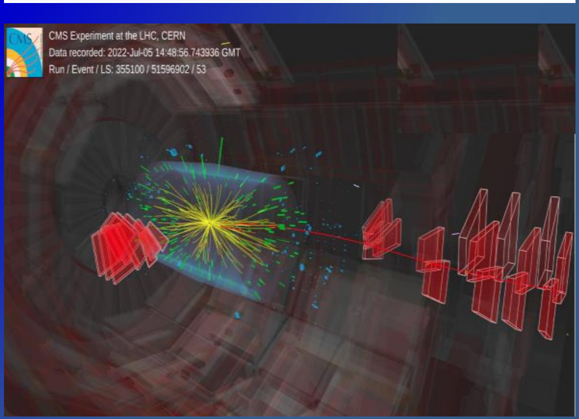


"Continuous data taking with the upgraded ALICE GEM-TPC"
by Robert Helmut Munzer (24 Jun 2022),
https://indico.cern.ch/event/1172978/



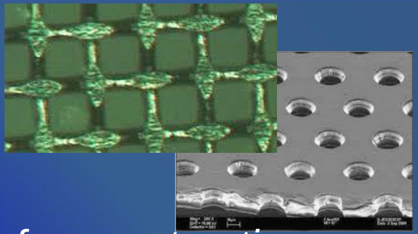
https://alice-figure.web.cern.ch/node/20827

"The GEM detectors within the CMS Experiment"
Michele Bianco (08 Jul 2022)
https://indico.cern.ch/event/1175363/



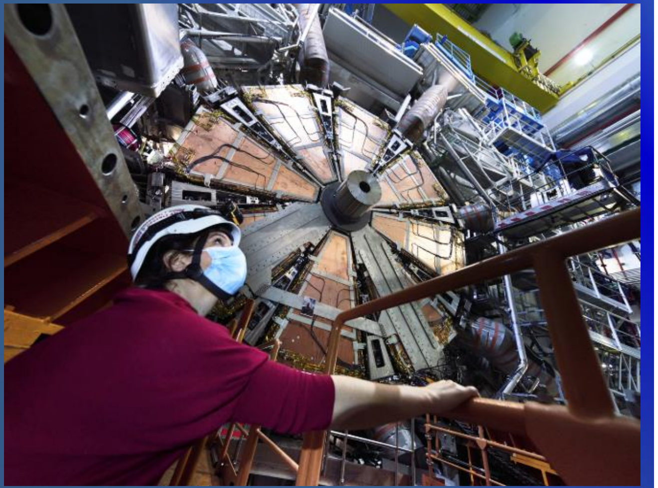
All three major LHC upgrades, incorporating MPGDs, started their R&D in close contact with RD51, using dedicated setups at GDD-RD51 Laboratory

2022: MPGDs for High Luminosity LHC Upgrades



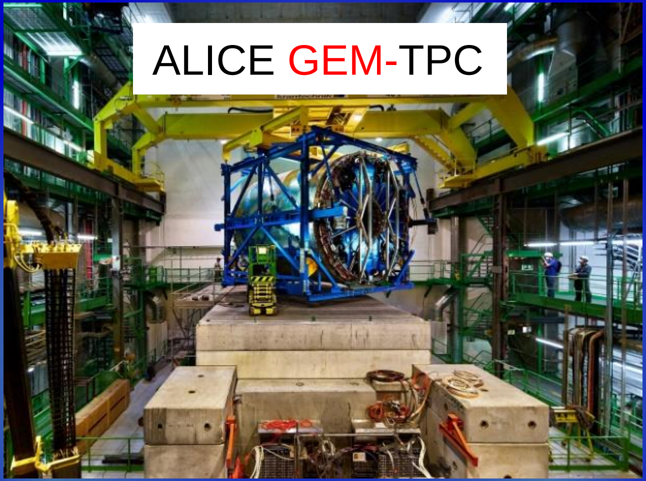
The <u>successful implementation of MPGDs for relevant upgrades of CERN</u> experiments indicates the degree of maturity of given detector technologies for constructing large-size detectors, the level of dissemination within the HEP community and their reliability

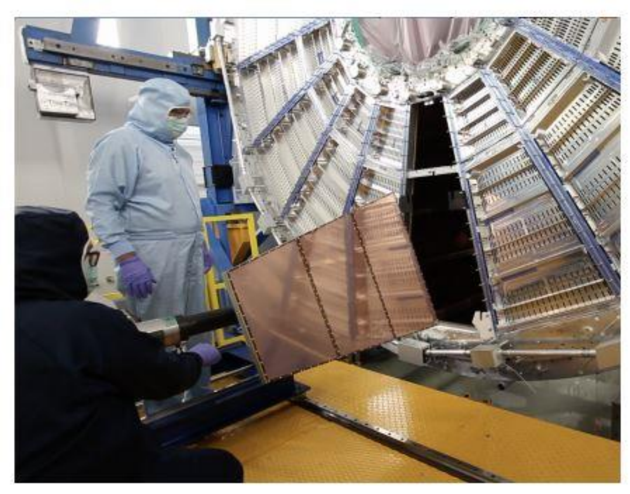
ATLAS NSW MicroMegas



https://ep-news.web.cern.ch/content/atlas-new-small-wheel-upgrade-advances-0

ALICE GEM-TPC





https://ep-news.web.cern.ch/upgraded-alice-tpc

CMS GEM muon endcaps

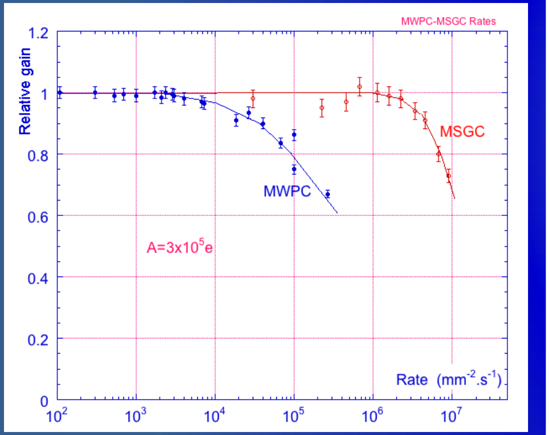
https://ep-news.web.cern.ch/content/demonstrating-capabilities-new-gem

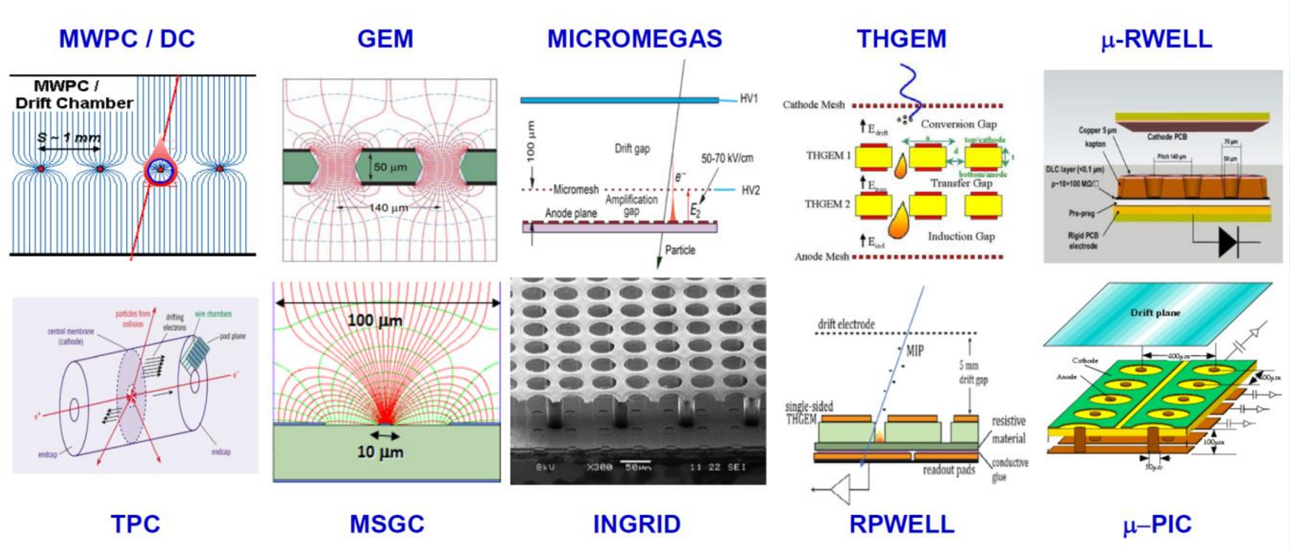
Gaseous Detectors: From Wire/Drift Chamber → Time Projection Chamber (TPC) → Micro-Pattern Gas Detectors

Primary choice for large-area coverage with low material-budget (+ dE/dx measurement)

1990's: Industrial advances in photolithography has favoured the invention of novel micro-structured gas amplification devices (MSGC, GEM, Micromegas, …)

Rate Capability:
MWPC vs MSGC



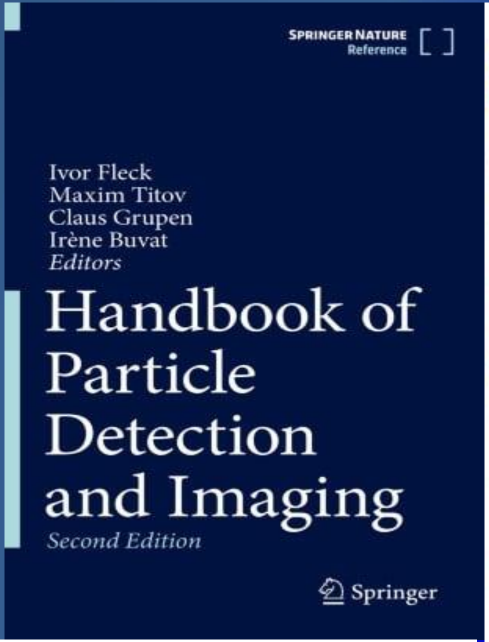


Examples of Gaseous Detectors for Future Colliders:

HL-LHC Upgrades: Tracking (ALICE TPC/MPGD); Muon Systems: RPC, CSC, MDT, TGC, GEM, Micromegas;
Future Hadron Colliders: FCC-hh Muon System (MPGD - OK, rates are comparable with HL-LHC)
Future Lepton Colliders: Tracking (FCC-ee / CepC - Drift Chambers; ILC / CePC - TPC with MPGD readout)
Calorimetry (ILC, CepC – RPC or MPGD), Muon Systems (OK)

Future Election-Ion Collider: Tracking (GEM, μWELL; TPC/MPGD), RICH (THGEM), TRD (GEM)

Dissemination of MPGD Applications in HEP & Other Fields



SPRINGER NATURE
Reference

Ivor Fleck
Maxim Titov
Claus Grupen
Irène Buvat
Editors

Handbook of Particle Detection and Imaging

Second Edition

Springer

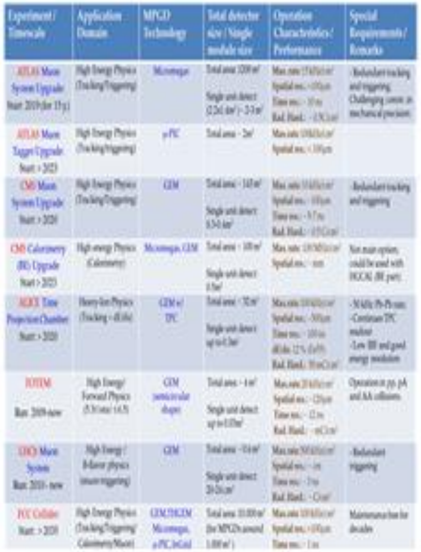
Gaseous Detectors

Maxim Titov

Contents

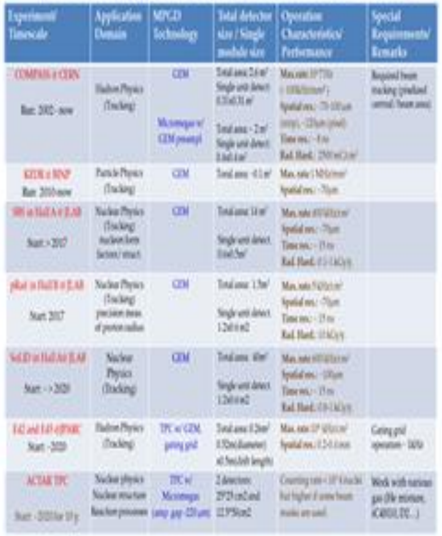
Abstract

Over the course of the last 50 years, the advances and breakthrough in instrumentation, leading to the development of new, cutting-edge technologies, drove the progress in experimental particle physics. A true innovation in detector concepts came in 1968, with the development of a fully parallel readout for a large array of sensing elements – the Multi-Wire Proportional Chamber (MWPC), which earned Georges Charpak a Nobel Prize in Physics in 1992. This invention revolutionized particle detection, which moved from optical-readout devices (cloud chamber, emulsion or bubble chambers) to the electronics era. Since then, radiation detection and imaging with gaseous detectors, capable of economically covering large detection volume with low mass budget, have been playing an important role in many fields of science. Over the past three decades, advances in photo-lithography, microelectronics, and printed-circuit board (PCB) techniques



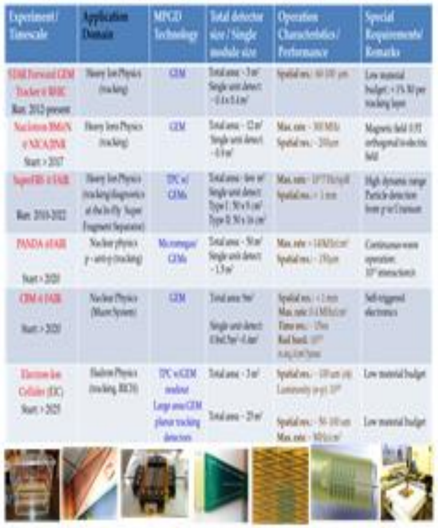
MPGD Technologies for the International Linear Collider

MPGD Tracking Concepts for Hadron / Nuclear Physics

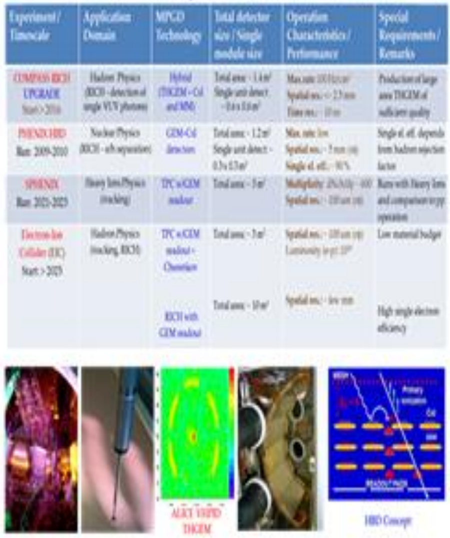


Cylindrical MPGDs as Inner Trackers for Particle / Nuclear Physics

MPGD Tracking for Heavy Ion / Nuclear Physics



MPGD Technologies for Photon Detection



https://indico.cern.ch/event/581417/contributions/2558346/attachments/1465881/2266161/2017_05_Philadelphia_MPGD2017-ConferenceSummary_25052017_MS.pdf

Towards Large Area in Fast Timing GASEOUS DETECTORS

Multi-Gap Resistive Plate Chambers (MRPC):

- ✓ ALICE TOF detector (160m^2) achieved time res. ~ 60 ps
- ✓ New studies with MRPC with 20 gas gaps using a low-resistivity 400 µm-thick glass → down to 20 ps time resolution

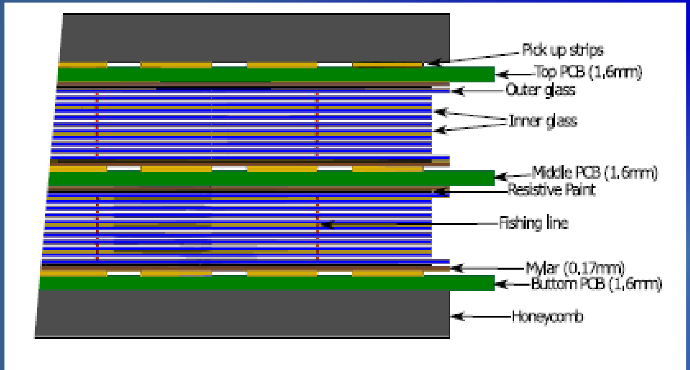
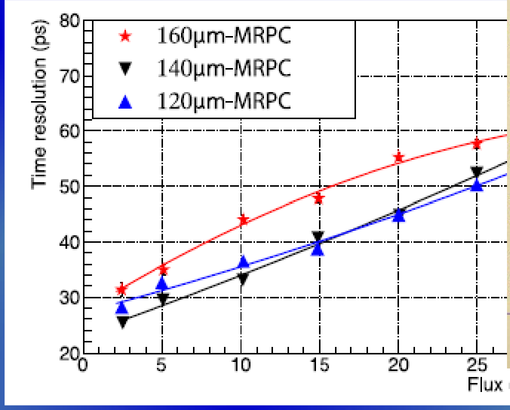
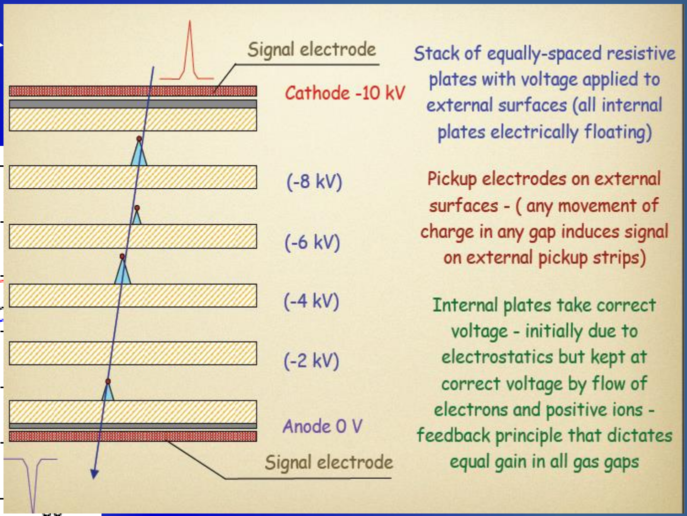


Fig. 1. Cross section of the double stack 20-gap MRPC.





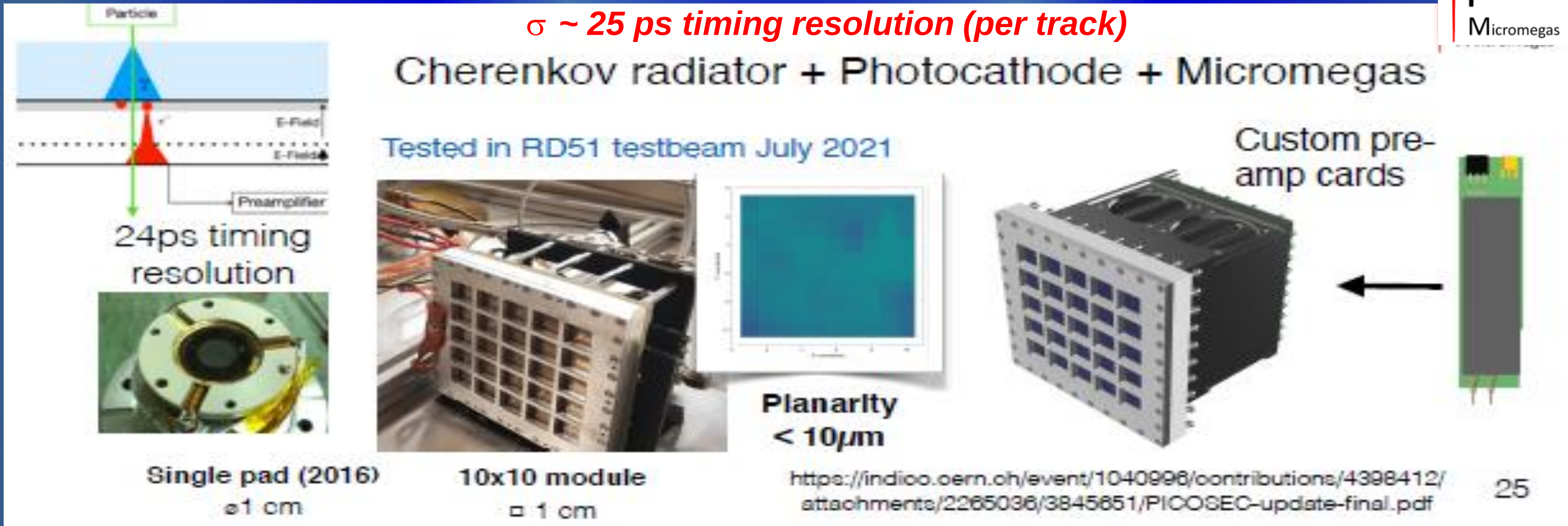
Stack of equally-spaced resistive plates with voltage applied to external surfaces (all internal plates electrically floating)

Pickup electrodes on external surfaces - (any movement of charge in any gap induces signal on external pickup strips)

Internal plates take correct voltage - initially due to electrostatics but kept at correct voltage by flow of electrons and positive ions - feedback principle that dictates equal gain in all gas gaps

Gaseous Detectors: Micromegas with Timing (RD51 Picosec Collaboration)

PICOSEC Micromegas



σ ~ 25 ps timing resolution (per track)

Cherenkov radiator + Photocathode + Micromegas

Tested in RD51 testbeam July 2021

Custom pre-amp cards

24ps timing resolution

Planarity < 10µm

Single pad (2016)
⌀1 cm

10x10 module
□ 1 cm

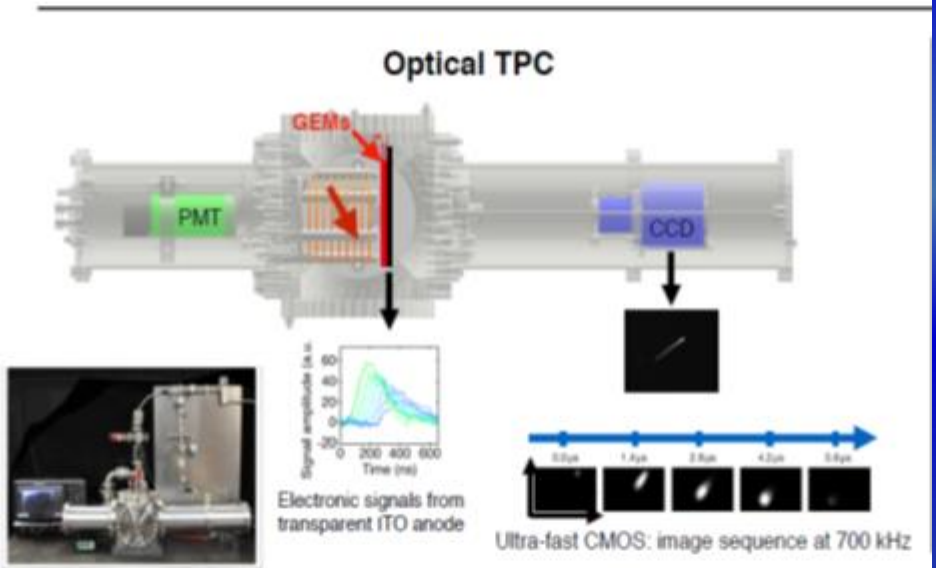
https://indico.cern.ch/event/1040996/contributions/4398412/attachments/2265036/3845651/PICOSEC-update-final.pdf

25

Optical Readout of MPGDs: Imaging Applications

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

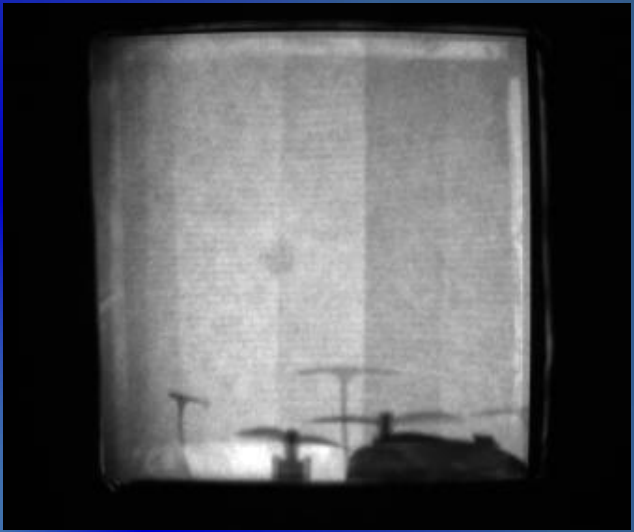
- ✓ Optical TPC (Combined electronic + optical readout)
- ✓ Ultra-fast optical readout (TPCs, beam monitor)
- ✓ Low-material budget, online beam monitoring
- ✓ Detector physics studies
- ✓ among other applications…



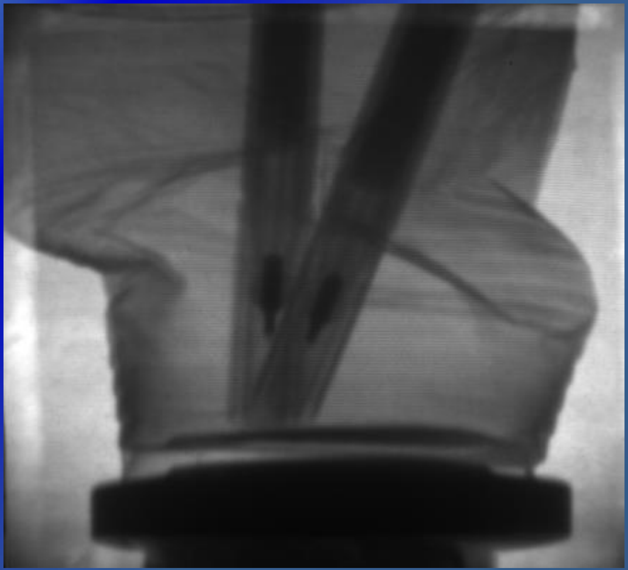
Electronic signals from transparent ITO anode

Ultra-fast CMOS: image sequence at 700 kHz

Fluoroscopy:



CT and 3 D Imaging:



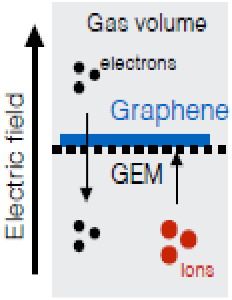
Graphene-based Functional Structures and Nanostructures for novel MPGD Concepts

Graphene layers for: ion-backflow suppression,
protection of photocathodes, solid conversion layers

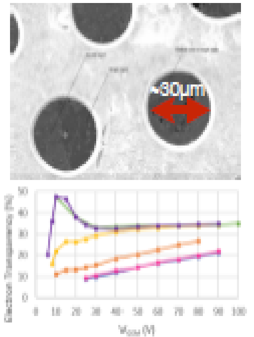
PhD project of Giorgio Orlandini (FAU Erlangen-Nürnberg) in EP-DT-DD Gaseous Detector Development lab

The unique properties of two-dimensional materials such as graphene as well as carbon-based nanostructures offer new perspectives for novel gaseous radiation detectors. This may include performance improvements for detectors for HEP experiments as well as new application fields combining wideband sensitivity of advanced materials with high gain factors and granularity offered by Micro Pattern Gaseous Detectors.

Application 1:
Suspended graphene for ion back-flow suppression and gas separation



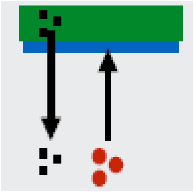
Previous work

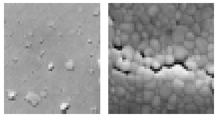


https://doi.org/10.1016/j.nima.2015.11.077

Suppressing ion back flow can significantly **improve high-rate capabilities** and **reduced electric field distortions** in Time Projection Chambers.

Application 2:
Protection of photocathodes with graphene layers

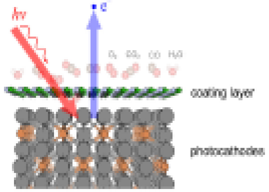




Damage of CsI

https://doi.org/10.1016/j.nima.2009.05.179

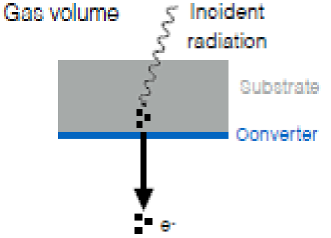
Protection and decrease of work function by coating layer



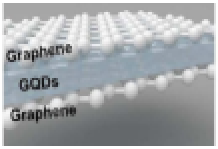
https://www.nature.com/articles/s41699-018-0062-6

Atomically thin coating layers could **protect sensitive photocathodes** such as CsI against environmental factors and ion bombardment, which is important for preserving specifications of precise timing detector in harsh ion-back flow conditions. Additionally, **modifications of the work functions**of converter layers can be used to increase QE.

Application 3:
Graphene and nanostructures for photoconversion and as solid converters



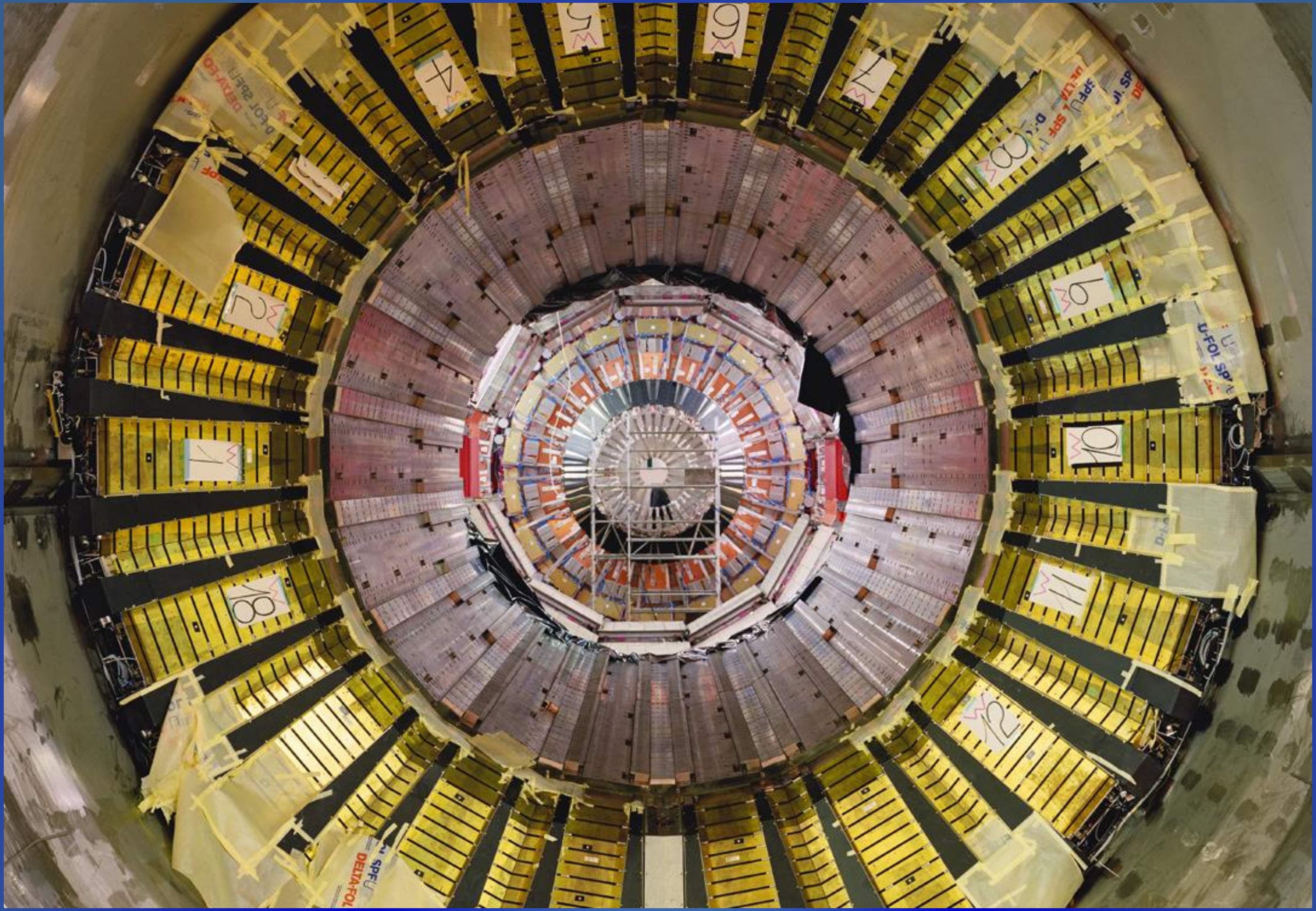
Possible system with UV-to-NIR response



https://www.nature.com/articles/srep05603.pdf

Graphene quantum dots (GQD), carbon nanotubes and graphene have been shown to exhibit **broadband sensitivity** and could be used as versatile **conversion layers**. Utilising solid conversion layers enables high **detection efficiencies** and can be used for **precise timing** with gaseous radiation detectors.

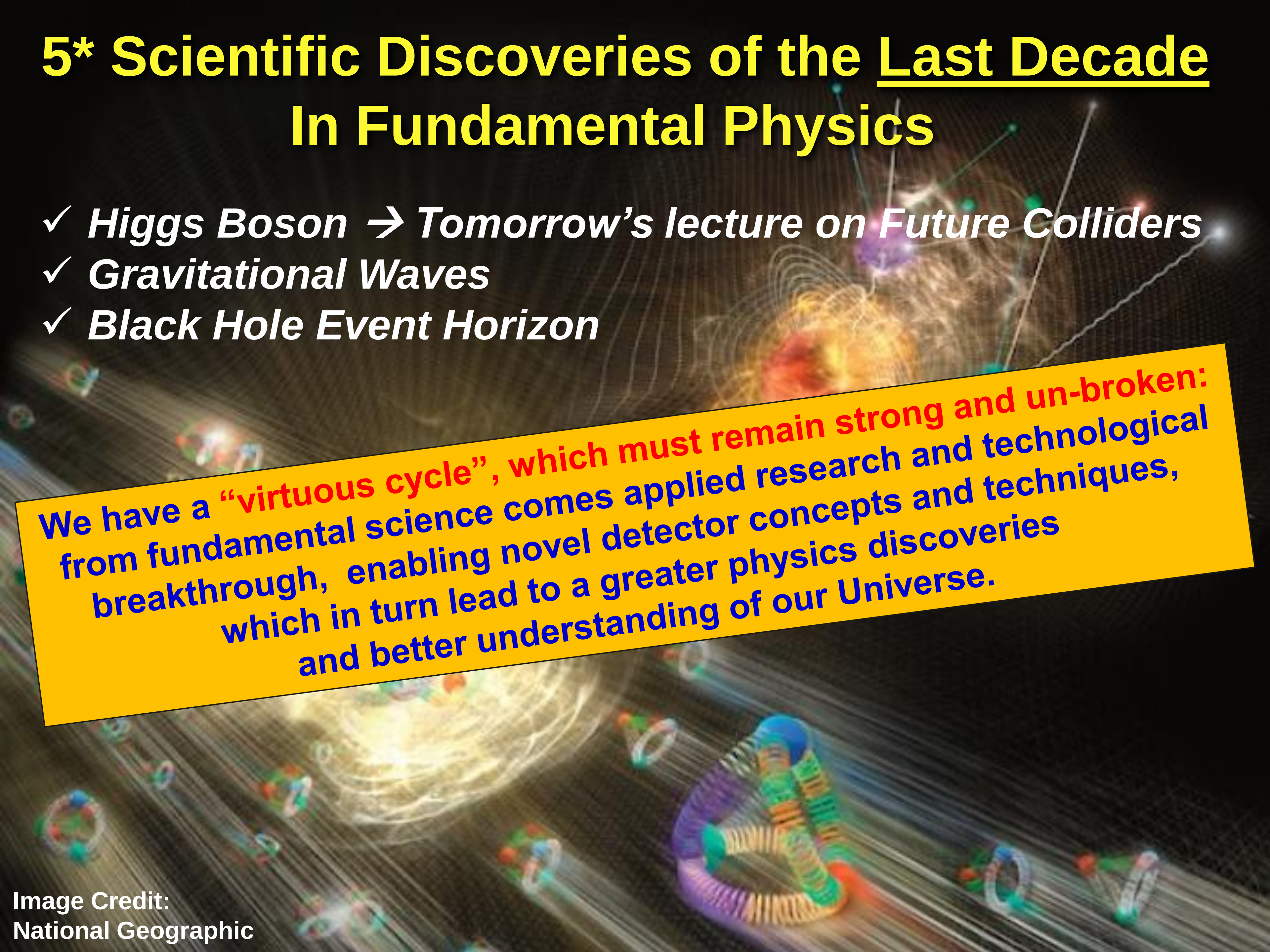
First work on GEM & graphene layers: NIMA824 (2016) 571



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

Bridge the gap between science and society …

5* Scientific Discoveries of the Last Decade In Fundamental Physics



- ✓ *Higgs Boson → Tomorrow's lecture on Future Colliders*
- ✓ *Gravitational Waves*
- ✓ *Black Hole Event Horizon*

We have a "virtuous cycle", which must remain strong and un-broken: from fundamental science comes applied research and technological breakthrough, enabling novel detector concepts and techniques, which in turn lead to a greater physics discoveries and better understanding of our Universe.

Image Credit:
National Geographic