# Gaseous Detectors

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# Outline

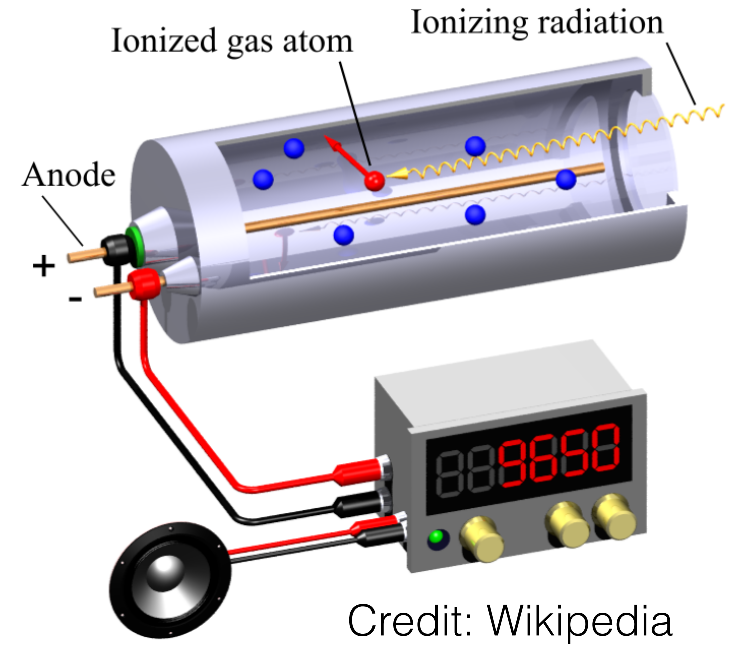
- Past developments
- Modern gaseous detector technologies
- Current R&D directions for future facilities

# The first gaseous detector

- Gas-filled detectors have a long and fruitful history in high-energy and nuclear physics experiments and radiation detection

- In 1908, H. Geiger devised a counter for alpha particles in the form of cylindrical single-wire counters working in a saturated discharge mode (Geiger mode)

  - Gaseous detectors evolved to a large number of specialized configurations, adapted to detect all forms of radiation with energy above 4 eV




Credit: Wikipedia

# Highlights of this technology

- Economic coverage of large areas and volumes
- Flexible geometries
- Low density
- Very good time (~10 ns) and position resolution (better than 100 μm in the direction along the wire)

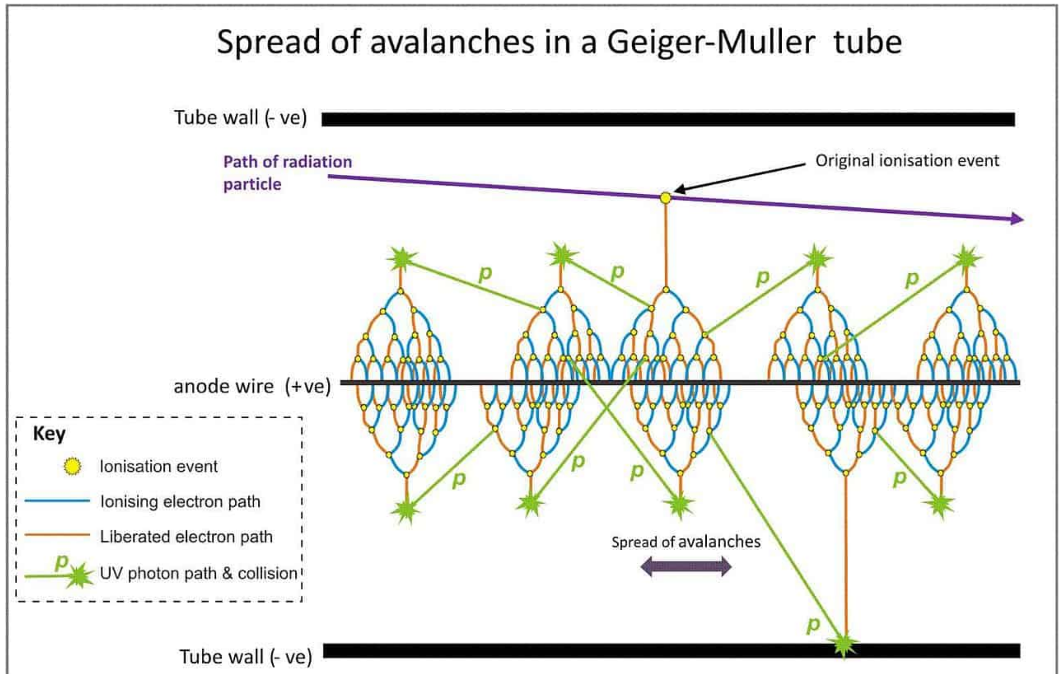
# Its basic operation

- Based on Townsend avalanche, triggered by the primary ionization created by the impinging radiation and developing in specialized “amplification regions”, where a large electric field is applied

- In some cases the avalanche is followed by subsequent discharge regimes, which provide further charge amplification

- The electric impulse thus developed is collected on patterned electrodes that provide position information and recorded by electronic means

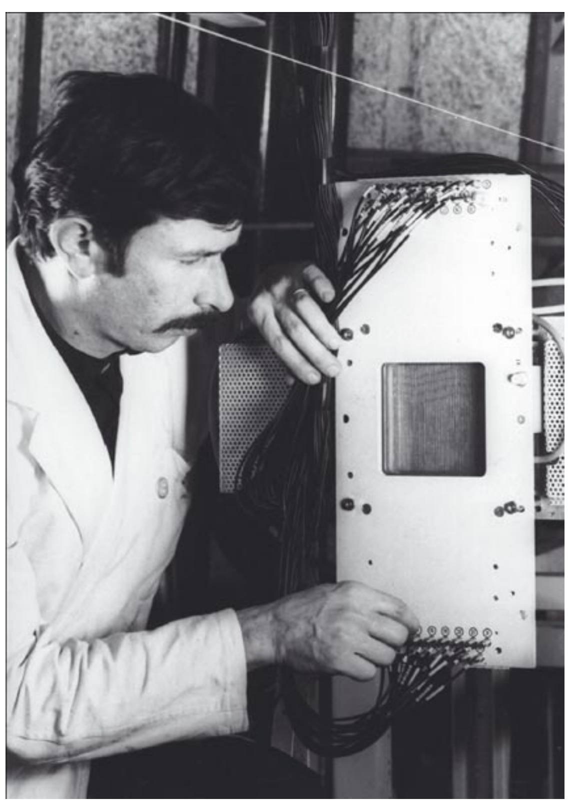
- In some applications it is advantageous to detect also the gaseous scintillation light emitted by the avalanches

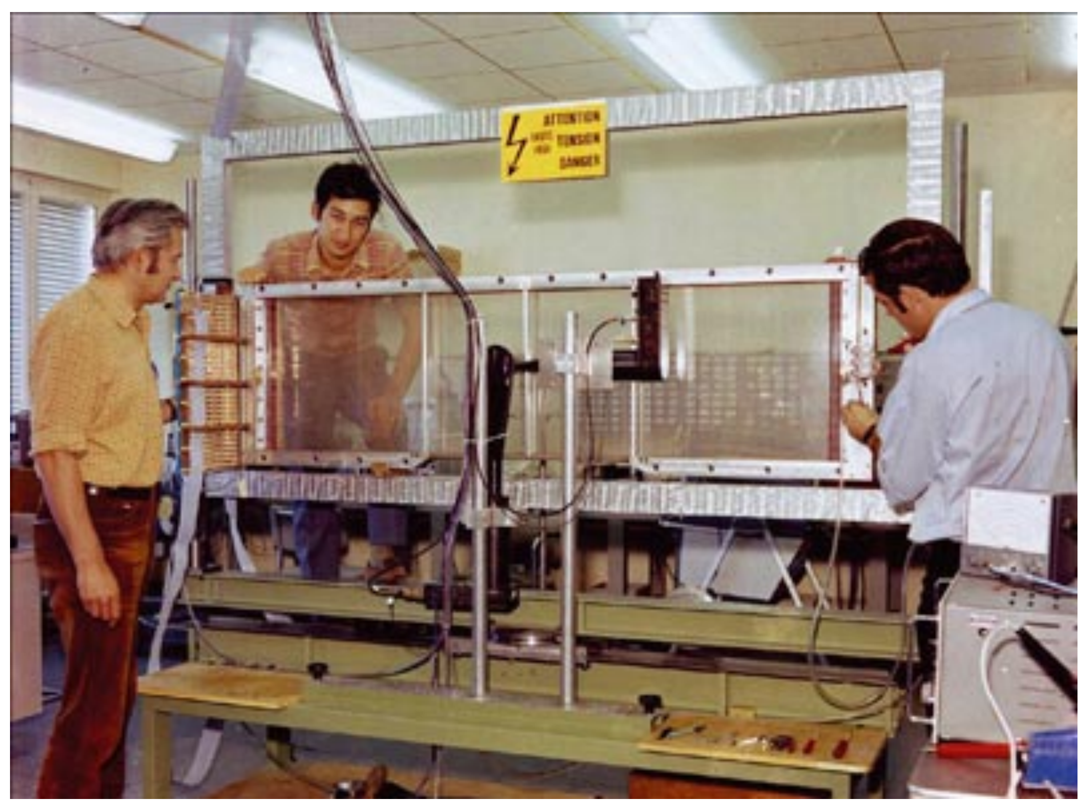


Credit: Wikipedia

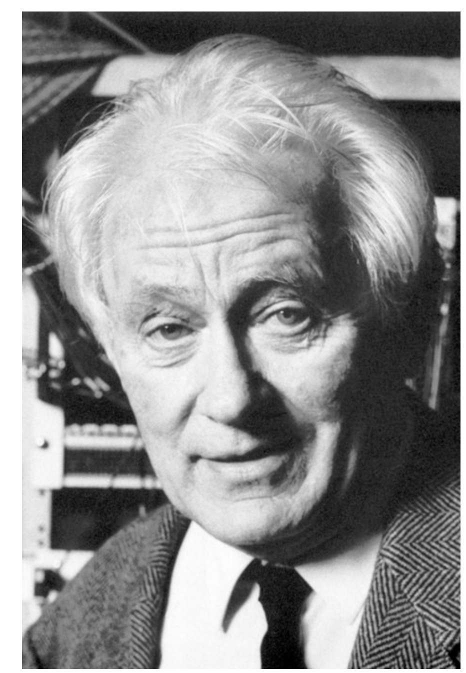
# MWPC

- Multiwire Proportional Chamber (MWPC) was **the first modern electronically-readout gaseous detector** developed by G. Charpak in 1968
- Moved us from the optically-readout era (bubble and cloud chambers) to the electronic era



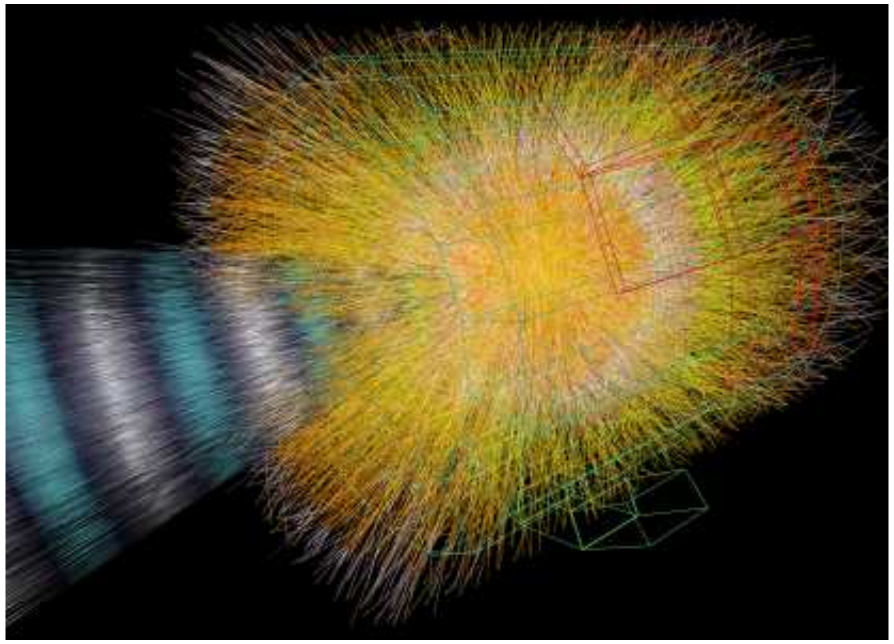



Credit: CERN Courier

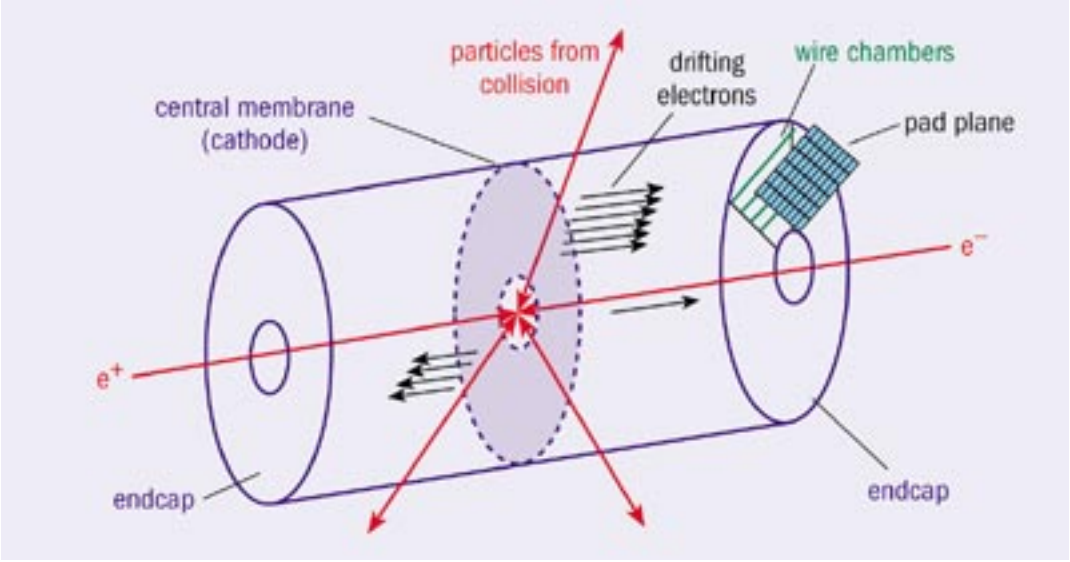


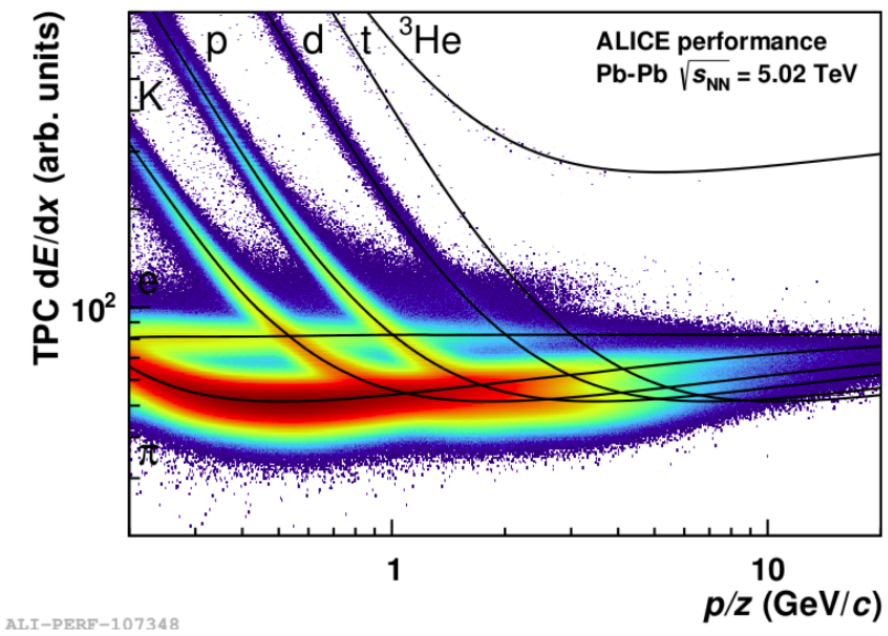
Georges Charpak
The Nobel Prize in Physics
1992

# TPC



- Time Projection Chamber (TPC) combines a measurement of drift time and charge induction on the endplates to achieve excellent pattern recognition for high multiplicity environments and moderate rates
- TPC provides **3D precision tracking**; the gaseous detector volume gives an extremely low material budget (x-y from wires and segmented cathode of MWPC; z from drift time)
- The high density of space points enables PID through ionization loss measurement



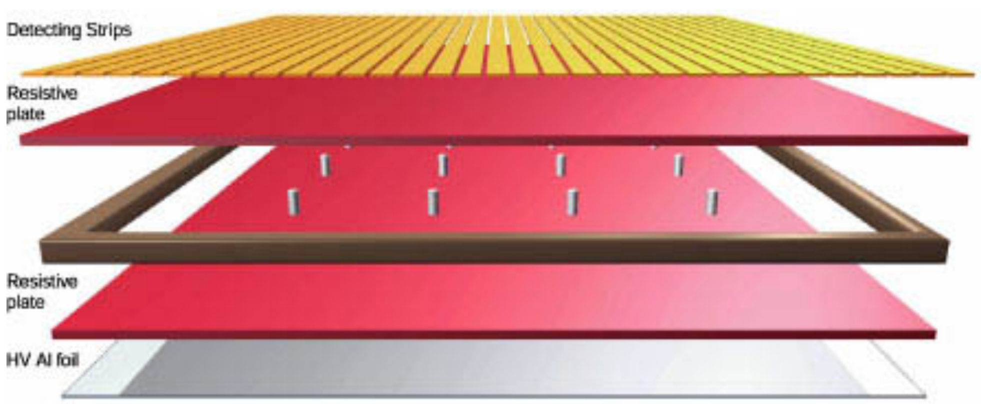



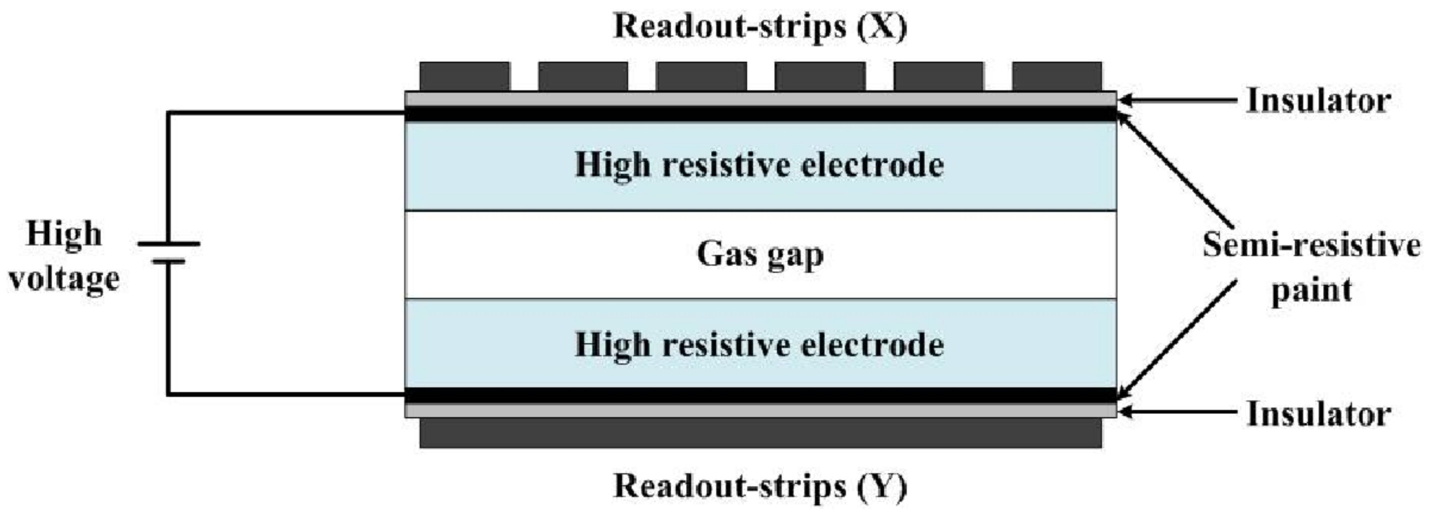
# RPC

- Another type of classic gas-filled detectors

**No wires!**

- Resistive Plate Chambers (RPC) are gaseous parallel-plate detectors that combine good spatial resolution with a time resolution of just ~1 ns comparable to that of scintillators
- Suitable for fast space-time particle tracking
- RPCs consist of two parallel plates, a positively-charged anode and a negatively-charged cathode, both made of a very high resistivity plastic material and separated by a gas volume



- Cons for “classical” gaseous detectors
  - Slow ion motion → fast gain drop at high fluxes
    - Space charge accumulation, distortion of electric field…
  - Limited multi-track separation：minimum wire distance ~1mm
  - Aging

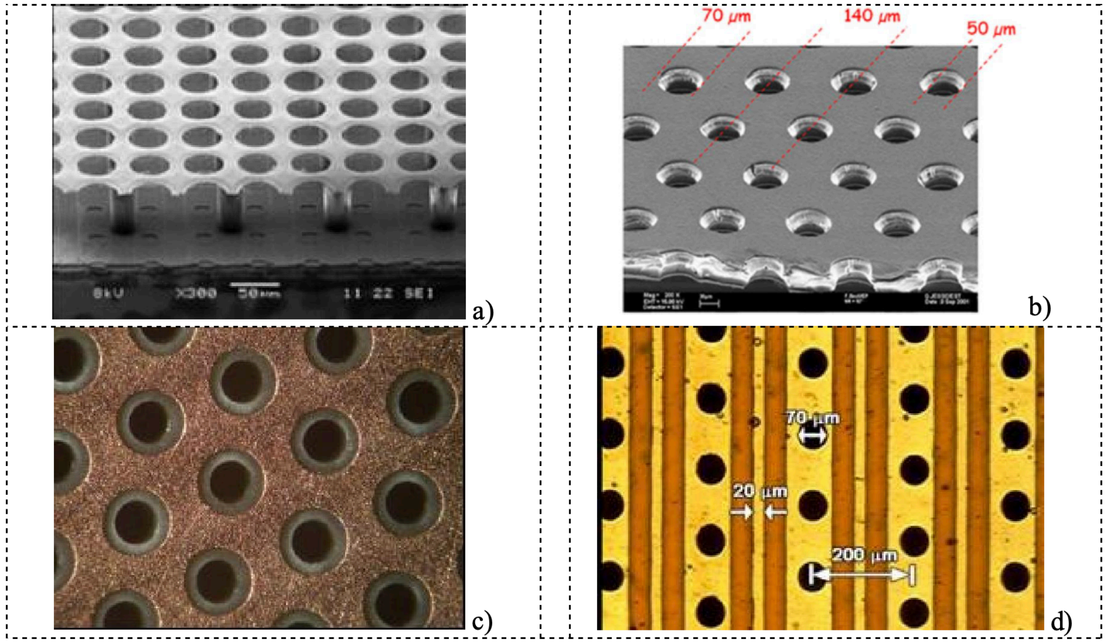
# Modern detector technologies

# Micropattern detectors (1/2)

- Very small amplification regions (sometimes below 50 µm) finely distributed on a surface and manufactured by modern microelectronics and etching technology
- Very good, isotropic, 2-D position resolution in digital readout mode over a finely segmented readout electrode
- Good time resolution and counting rate capability

**InGRID MICRO MEsh GAS chamber (MICROMEGAS)**
Pixel size: 50x50 µm
Avalanches timing & other measurements

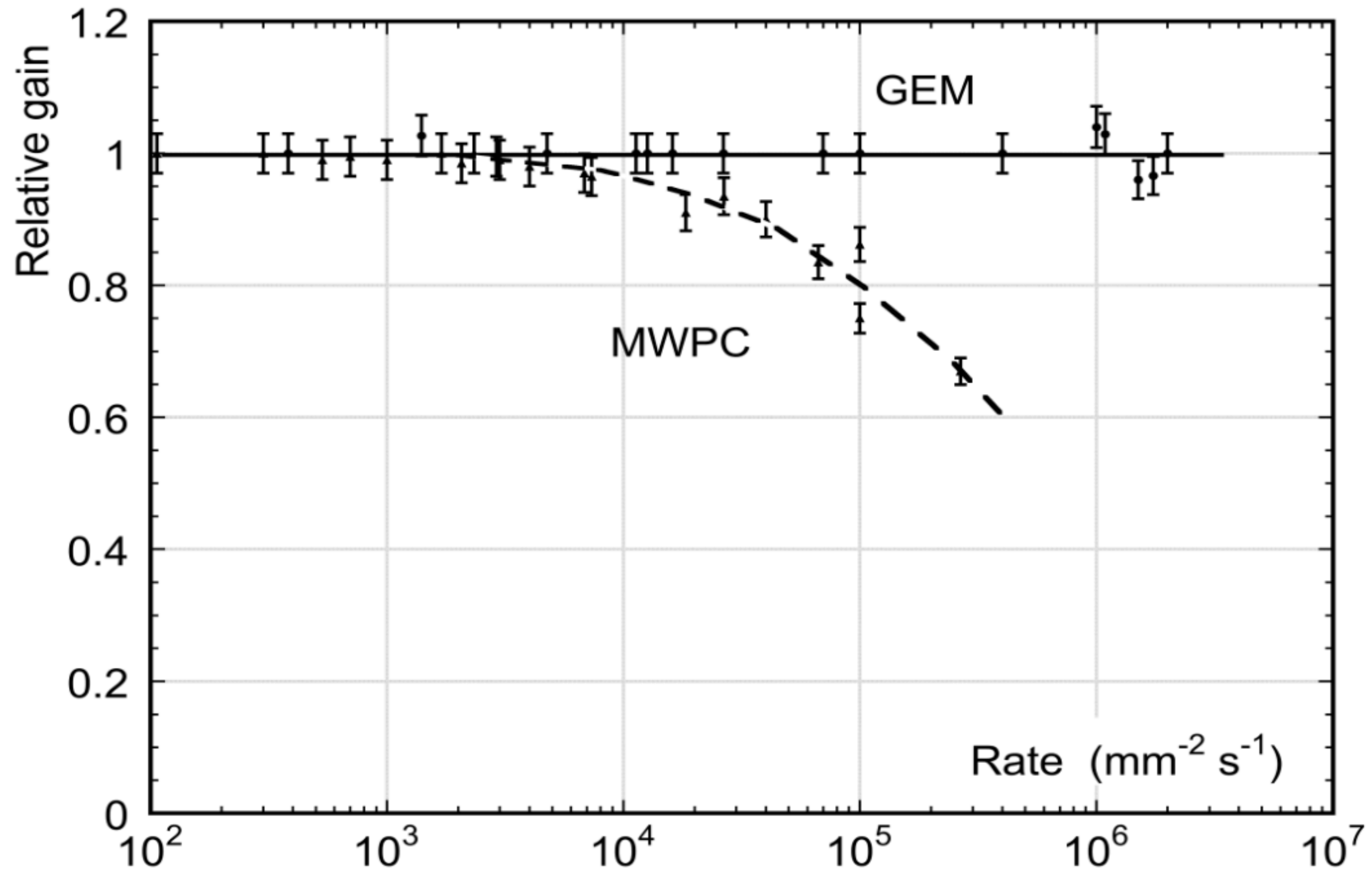
**Thick GEM**
Operates at 10x higher gain
Withstand even powerful spark discharges




**Gaseous Electron Multiplier (GEM)**
Similar to MICROMEGAS
But avalanches are strictly confined inside the holes

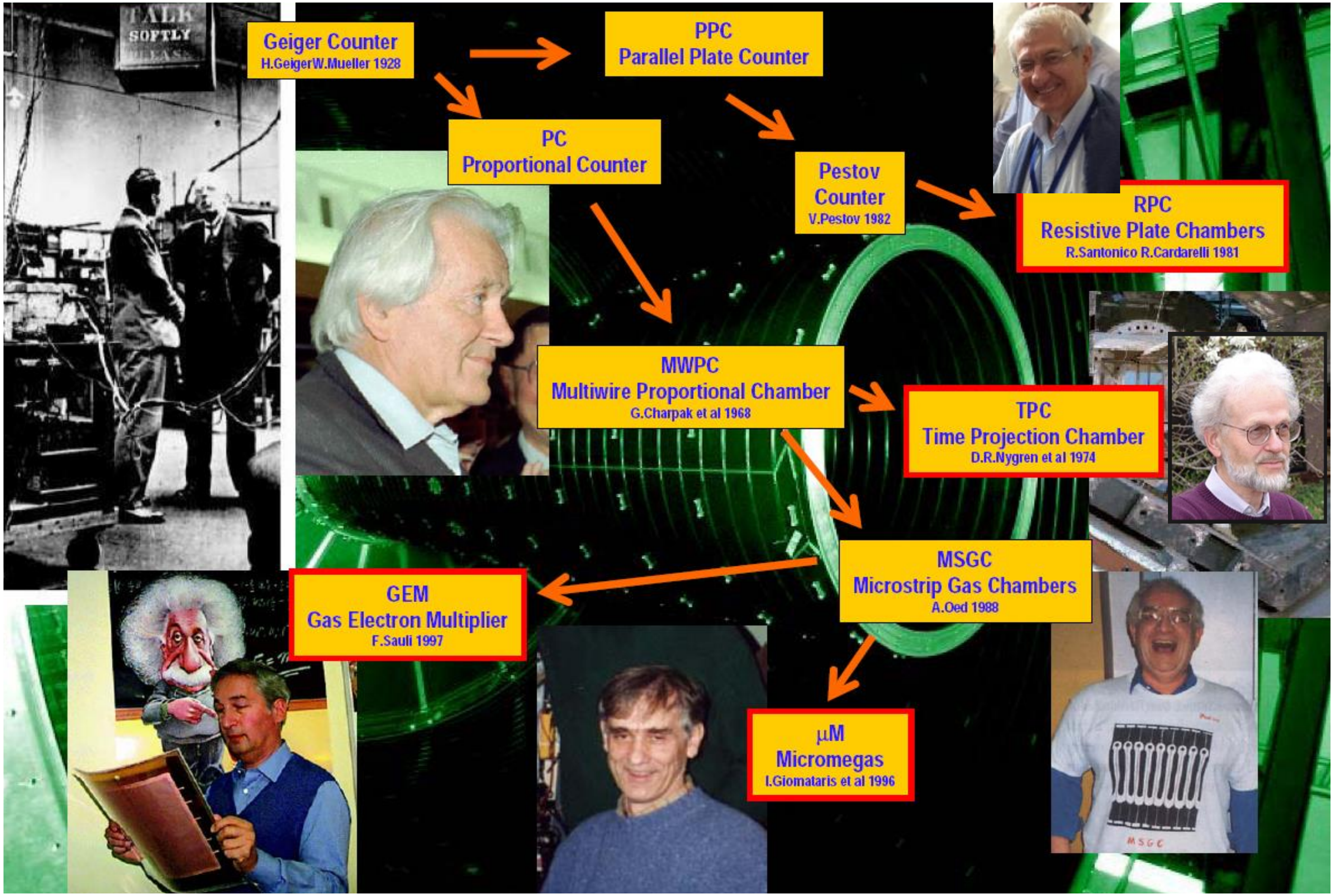
**Micro Hole Strip Plate (MHSP)**
Allows to combine preamplication in holes with the subsequent multiplication around fine strips

# Micropattern detectors (2/2)



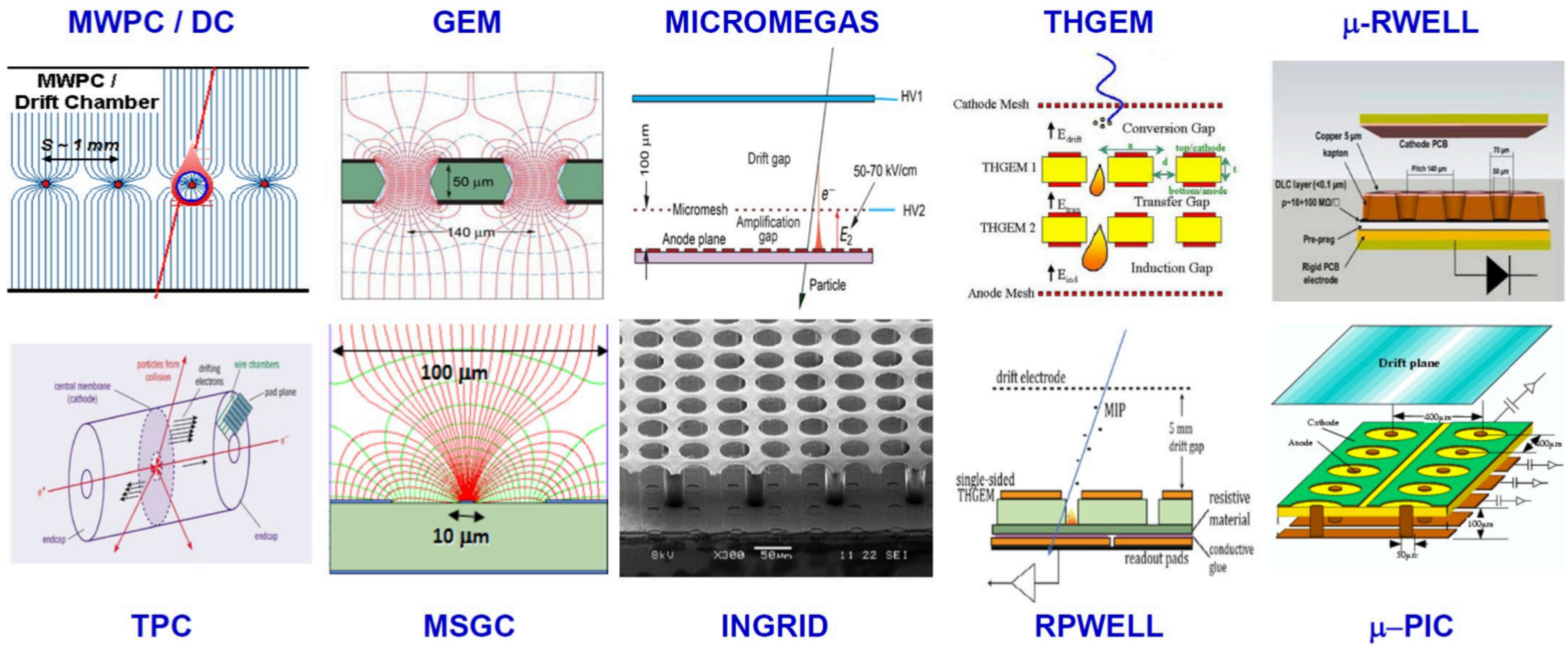

- Fine structure of the micropattern detectors electrodes renders them fragile and they (except for the thick GEM) can be easily destroyed by occasional sparks, almost unavoidable during high-gain or long-term operation
- Latest development：the implementation of resistive electrodes
  - Does not increase the maximum achievable gain but makes them spark-protected
- In addition, single-mask & self-stretching GEM techniques, which enable production of large-size foils and significantly reduce detector assembly time

# Evolution of gaseous detectors




Credit: Archana Sharma (CERN)

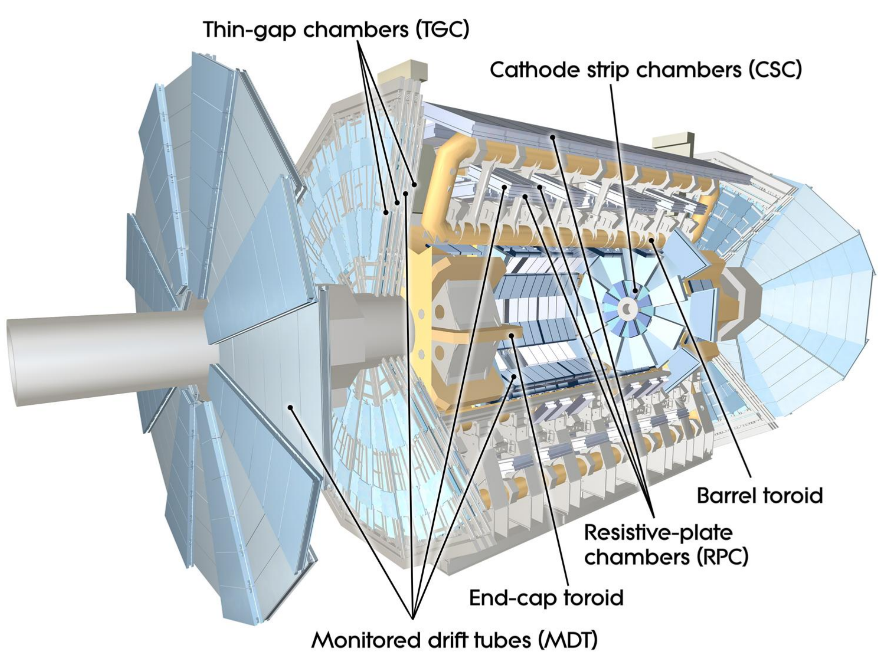
# Gaseous Detectors Family



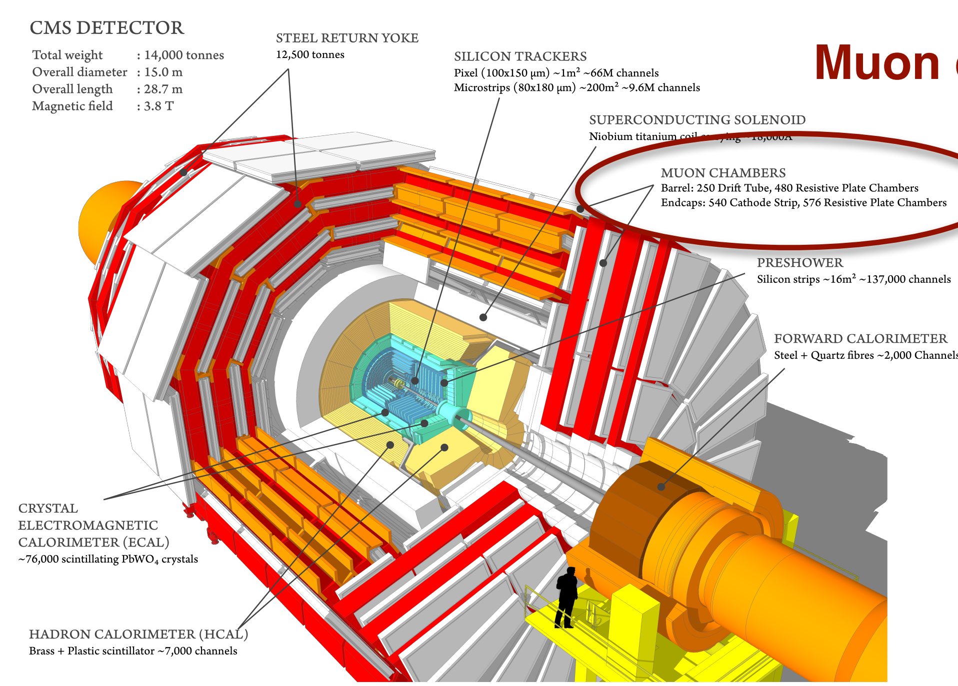

JINST 15 C10023 (2020) by Maxim Titov (Saclay)

# Gaseous detectors employed for CERN experiments (1/2)

- At LHC, the gaseous detectors are employed by ATLAS and CMS for the huge outer detector layers, covering thousands of square meters
  - A remarkable exception is ATLAS's Transition Radiation Tracker (TRT)

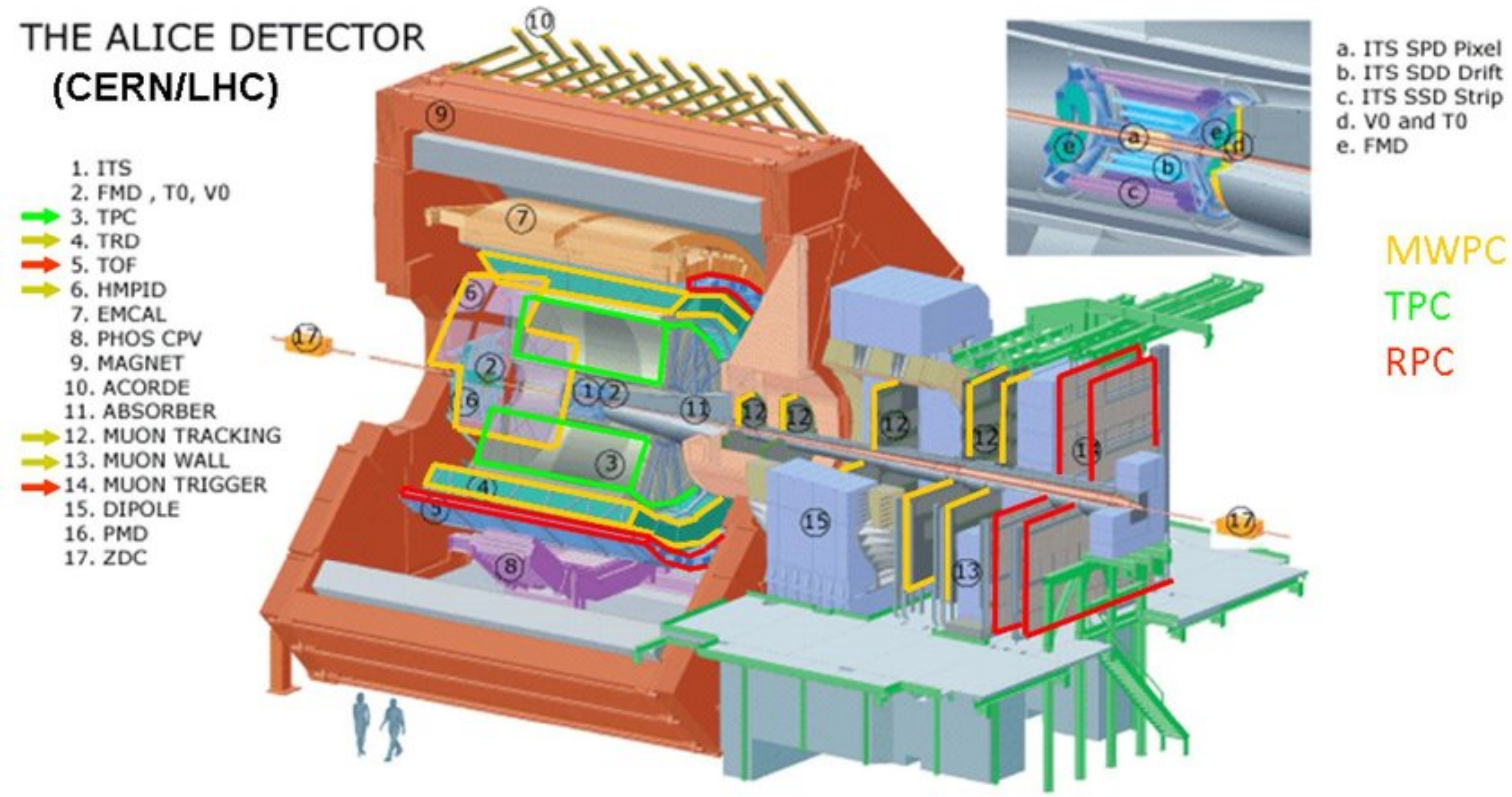



Muon spectrometer




Muon chambers

# Gaseous detectors employed for CERN experiments (2/2)

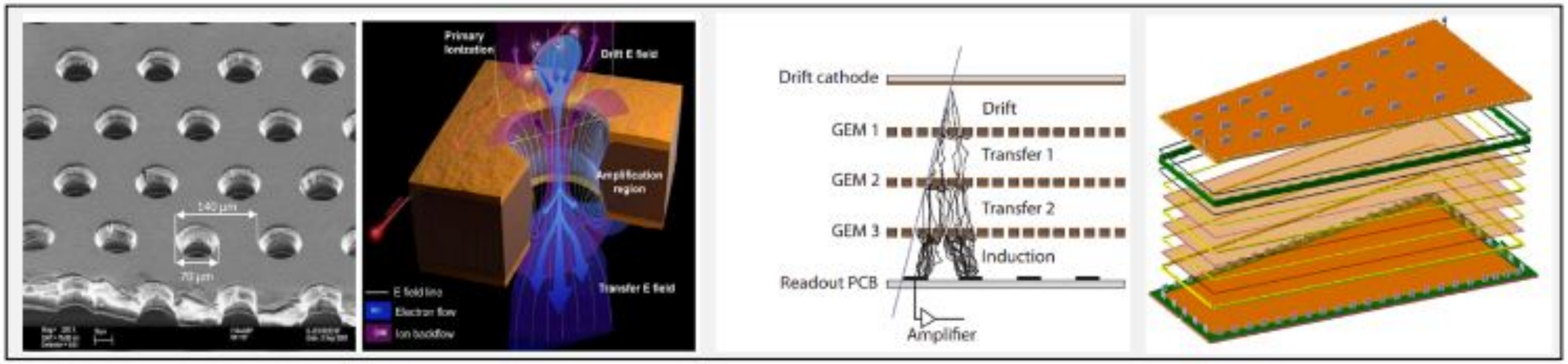


# MPGDs in the LHC experiments

| Experiment / Timescale | Application Domain | MPGD Technology | Total detector size / Single module size | Operation Characteristics / Performance | Special Requirements / Remarks |
|---|---|---|---|---|---|
| COMPASS TRACKING<br>> 2002 | Fixed Target Experiment (Tracking) | 3-GEM<br>Micromegas w/ GEM preampl. | Total area: 2.6 $m^2$<br>Single unit detect: 0.31x0.31 $m^2$<br>Total area: ~ 2 $m^2$<br>Single unit detect: 0.4x0.4 $m^2$ | **Max.rate**: ~100kHz/$mm^2$<br>**Spatial res.:** ~70-100μm (strip), ~120μm (pixel)<br>**Time res.:** ~ 8 ns<br>**Rad. Hard.:** 2500 mC/$cm^2$ | Required beam tracking (pixelized central / beam area) |
| TOTEM TRACKING:<br>> 2009 | Hadron Collider / Forward Physics (5.3≤\|η\| ≤ 6.5) | 3-GEM (semicircular shape) | Total area: ~ 4 $m^2$<br>Single unit detect: up to 0.03$m^2$ | **Max.rate**:20 kHz/$cm^2$<br>**Spatial res.:** ~120μm<br>**Time res.:** ~ 12 ns<br>**Rad. Hard.:** ~ mC/$cm^2$ | Operation in pp, pA and AA collisions. |
| LHCb MUON DETECTOR<br>> 2010 | Hadron Collider / B-physics (triggering) | 3-GEM | Total area: ~ 0.6 $m^2$<br>Single unit detect: 20-24 $cm^2$ | **Max.rate**:500 kHz/$cm^2$<br>**Spatial res.:** ~ cm<br>**Time res.:** ~ 3 ns<br>**Rad. Hard.:** ~ C/$cm^2$ | Redundant triggering |
| COMPASS RICH UPGRADE<br>> 2016 | Fixed Target Experiment (RICH - detection of single VUV photons) | Hybrid (THGEM + CsI and MM) | Total area: ~ 1.4 $m^2$<br>Single unit detect: ~ 0.6 x 0.6 $m^2$ | **Max.rate**:100 Hz/$cm^2$<br>**Spatial res.:** <~ 2.5 mm<br>**Time res.:** ~ 10 ns | Production of large area THGEM of sufficient quality |
| ATLAS MUON UPGRADE<br>CERN LS2 | Hadron Collider (Tracking/Triggering) | Resistive Micromegas | Total area: 1200 $m^2$<br>Single unit detect: (2.2x1.4$m^2$ ) ~ 2-3 $m^2$ | **Max. rate**:15 kHz/$cm^2$<br>**Spatial res.:** <100μm<br>**Time res.:** ~ 10 ns<br>**Rad. Hard.:** ~ 0.5C/$cm^2$ | Redundant tracking and triggering; Challenging constr. in mechanical precision |
| CMS MUON UPGRADE<br>CERN LS2 | Hadron Collider (Tracking/Triggering) | 3-GEM | Total area: ~ 143 $m^2$<br>Single unit detect: 0.3-0.4$m^2$ | **Max. rate**:10 kHz/$cm^2$<br>**Spatial res.:** ~100μm<br>**Time res.:** ~ 5-7 ns<br>**Rad. Hard.:** ~ 0.5 C/$cm^2$ | Redundant tracking and triggering |
| ALICE TPC UPGRADE<br>CERN LS2 | Heavy-Ion Physics (Tracking + dE/dx) | 4-GEM / TPC | Total area: ~ 32 $m^2$<br>Single unit detect: up to 0.3$m^2$ | **Max.rate**:100 kHz/$cm^2$<br>**Spatial res.:** ~300μm<br>**Time res.:** ~ 100 ns<br>**dE/dx:** 11 %<br>**Rad. Hard.:** 50 mC/$cm^2$ | - 50 kHz Pb-Pb rate;<br>- Continues TPC readout<br>- Low IBF and good energy resolution |

- The integration of MPGDs in large experiments was not rapid
- The recent choice of MPGDs for relevant upgrades of CERN experiments indicates the degree of maturity of given detector technologies

# The GEMs of CMS



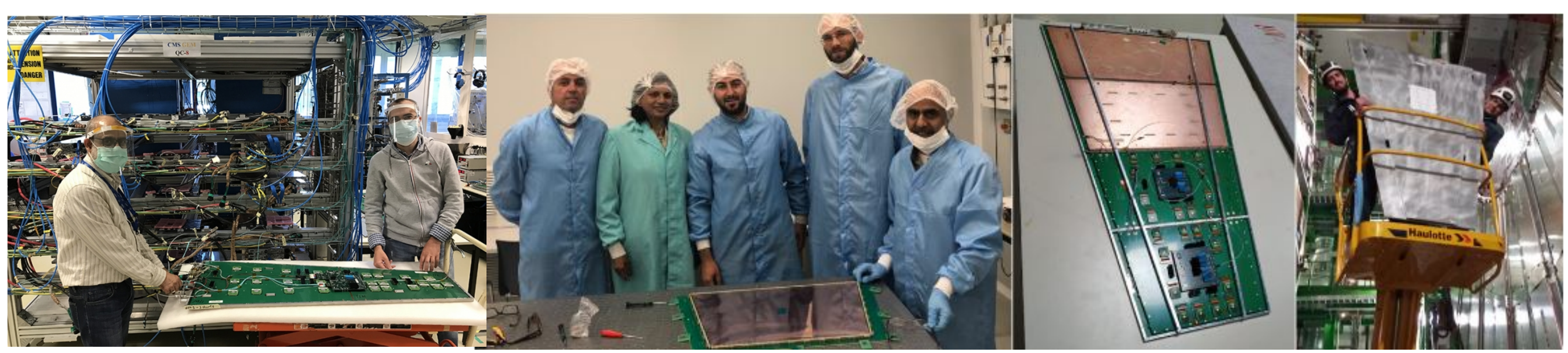

**GEM foil is made of a metal-clad polymer**

**Schematic view of the electric field lines**

**Principle of operation of a generic triple-GEM chamber**

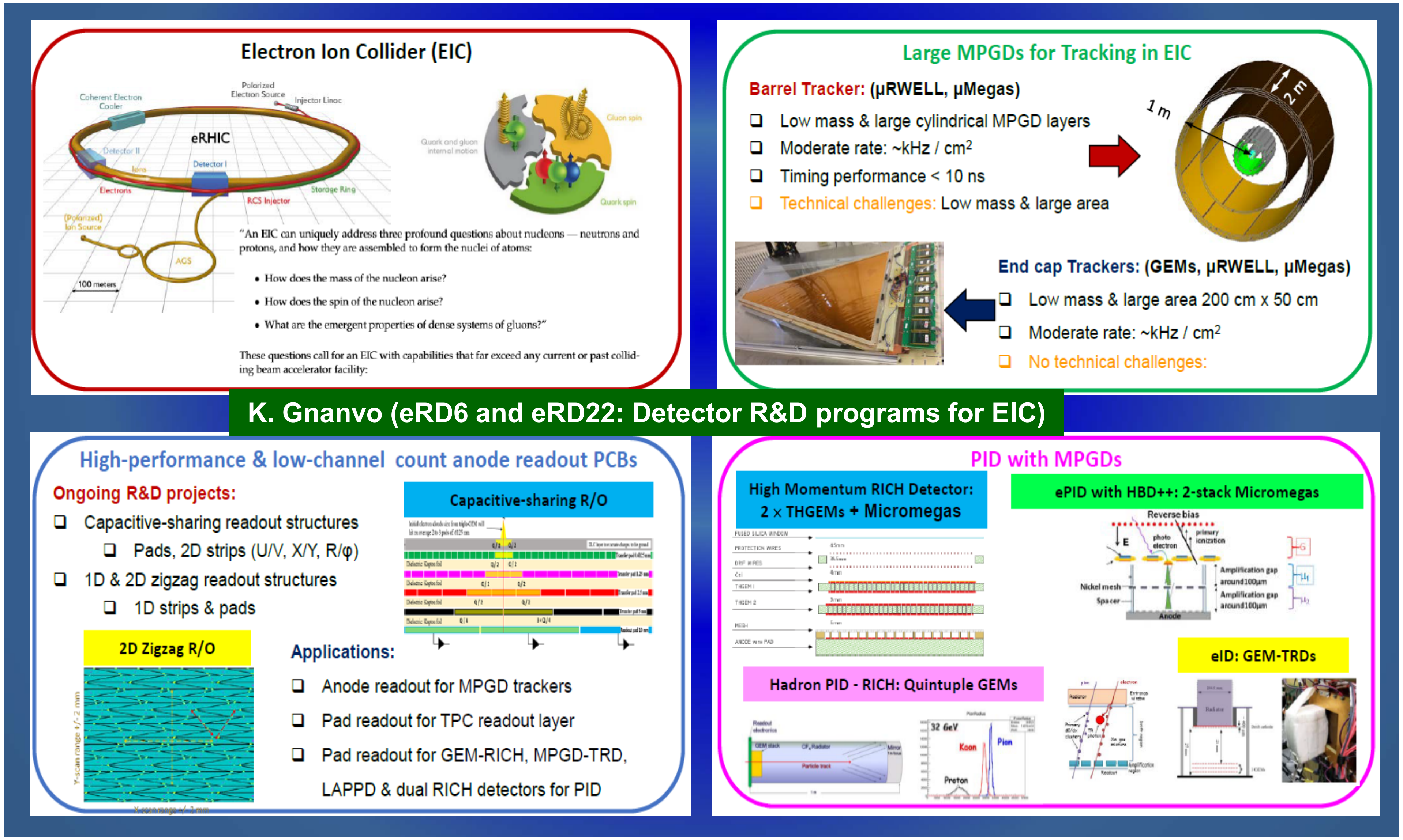
**Stack of 3 foils arranged in tandem for sharing maximum operational gain within the drift and readout electrodes separated by mechanical frames**

- A 5-year R&D program resulted in five generations of prototype detectors between 2010 and 2014
- An innovative technique of stretching foils to build detectors without glue was elaborated



# Gaseous detectors for future facilities (1/6)

- MPGDs are currently being implemented in a variety of heavy ion experiments and also foreseen for future facilities (e.g. ILC, CEPC, FCC, EIC…)




- All proposed EIC concepts feature a form of large MPGD detectors: Tracking (GEM, MICROMEGAS, μWELL), PID-RICH (THGEM+MM,GEM), TRD (GEM)

# Gaseous detectors for future facilities (2/6)

- Muon detectors in FCC experiments will cover an active area larger than 1000 $m^2$

- Large R&D efforts on TPCs are ongoing for the ALICE and MPD experiments, as well as for the future ILC and CEPC colliders

- At ILC, the beam bunch structure allows the implementation of the gating scheme for the ILD detector, based on large-aperture GEMs with honeycomb-shaped holes to minimize deteriorating influence of ion back flow on spatial resolution

# Gaseous detectors for future facilities (3/6)

- Three readout options are being developed for the TPC at ILC: GEM, MM and InGrid (an integrated readout of gaseous detectors using solid-state pixel chips)
- In contrary, under Z-pole operation mode at the CEPC (L ~$10^{36}$ $cm^{-2}s^{-1}$), there might be difficult to implement “open/close” gating mode scheme due to the lack of time
  - **MPGD associated to the silicon pixel technology** (e.g. “InGird” concept) is a promising option for the CEPC and ILC
  - This innovative technique provides the high granularity needed to resolve individual clusters which are separated by an average distance of a few hundred microns
  - dE/dx is determined by cluster counting technique, rather than by measuring the charge, with an ultimate precision of better than 3%
  - This also provides an unprecedented potential for pattern recognition in dense environments leading to superior double hit/track resolution and the possibility to discriminate against δ-rays

# Gaseous detectors for future facilities (4/6)

- **Hybrid approaches** combining different elements in a single devices, gaseous with non-gaseous detectors are also being studied

- MPGD hybridization, a strategy aiming to strengthen the detector performance, remains a valid asset for addressing future experimental challenges such as high granularity and precision timing

# Gaseous detectors for future facilities (5/6)

- All flavors of MPGDs are in high demand for future applications in high energy physics and heavy ion physics, including cryogenic LAr/LXe detectors for neutrino physics and dark matter searches
- Industrial manufacturing became mandatory and remains a central issue to be solved
- A clear direction for future developments is that of **resistive materials and related detector architectures**
  - to improve detector stability, making possible a higher gain in a single multiplication layer, a remarkable advantage for assembly mass production and cost
- Diamond-like carbon resistive layers are the key ingredients for increasing the rate capability of MPGDs
- Nowadays, many intensive R&D activities and their diversified applications are pursued within the world-wide CERN-RD51 collaboration
  - fundamental science, medical imaging, industrial applications …

# Gaseous detectors for future facilities (6/6)

- Contributions to the detector concepts are required for several domains
  - resistive materials, solid-state photon and neutron converters, innovative nanotechnology components
- **Material studies** can contribute to requirements related to low out-gassing, radiation hardness, radio-purity, inverter robustness and eco-friendly gases
- The development of the next generation of MPGDs can largely profit of emerging technologies as those related MicroElectroMechanical Systems (MEMS), sputtering, novel photoconverters, 3D printing of amplifying structures and cooling circuits, etc. ← **fabrication**

# Summary

- A century after the invention of the basic principle of gas amplification, gaseous detectors are still the first choice whenever the large-area coverage with low material budget is required
- Gaseous detectors will remain a key technology in particle physics experiments
- Advances in photo-lithography and microprocessing techniques during the past two decades triggered a major transition in the field from wire chambers to micropattern gas-amplification devices
- A lot of R&D activities are on-going for future particle physics facilities and industrial applications
    - Resistive materials and architectures; fast and precise timing; hybrid detectors; novel materials and fabrication techniques