Detektory do fizyki wysokich energii

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- Passage of particles through matter
- Photon detectors
- Scintillators
- Cherenkov light detectors, time-of-flight detectors
- Calorimeters
- Tracking detectors: silicon and gaseous detectors

Usual disclaimers:
Selective and biased introduction by a particle physicist
Many simplifications, avoid formalism
Slides of many colleagues used without proper references

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AGENCE ERASMUS+ FRANCE · EDUCATION & FORMATION

Bezmiechowa Górna, 11-20/07/2024

- Main **objectives**
  - **Reconstruction** of tracks and vertices
  - **Momentum measurement** for charged tracks in magnetic field
  - Particle identification using **dE/dx**

- Major **technologies**
  - **Gaseous detectors,** ionization in gas, gas amplification
  - Semiconductor detectors, electron-hole pairs in solid state material
  - Fiber trackers
  - Emulsions
  - …

Moving charge induces electric signal on metallic electrodes, that is read by dedicated electronics

Charge is internally multiplied to provide a measurable signal

Incoming particle creates sufficient charge

Gaseous detectors

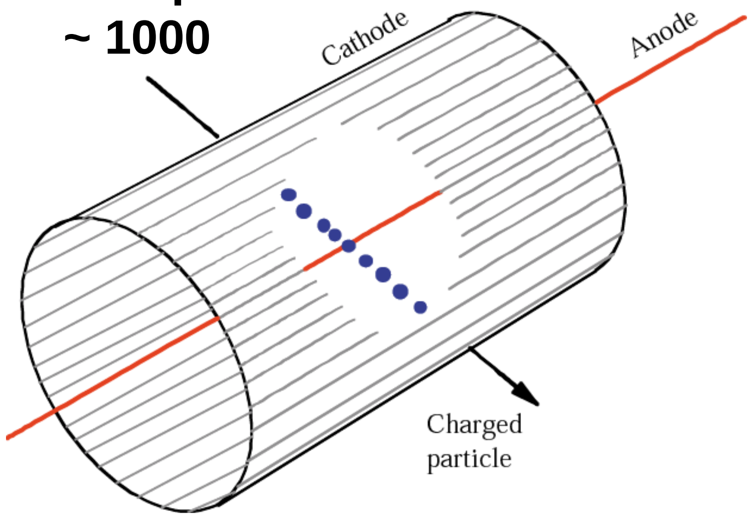
My first gaseous detector: Straw Tube

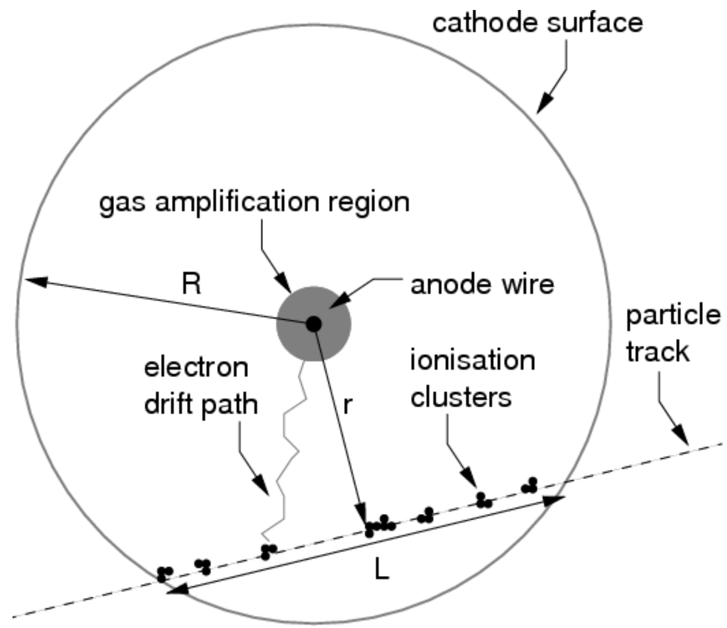
Cathode: A metallic cylinder of radius R

Anode: A gold plated tungsten wire of radius r_0

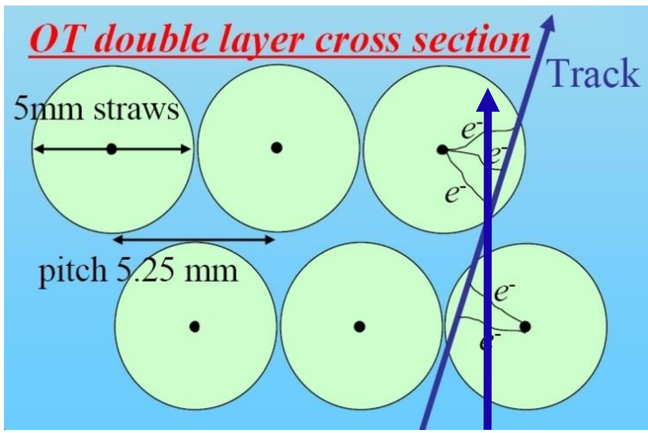
r_0 ~ 10 μm

R/r_0 ~ 1000



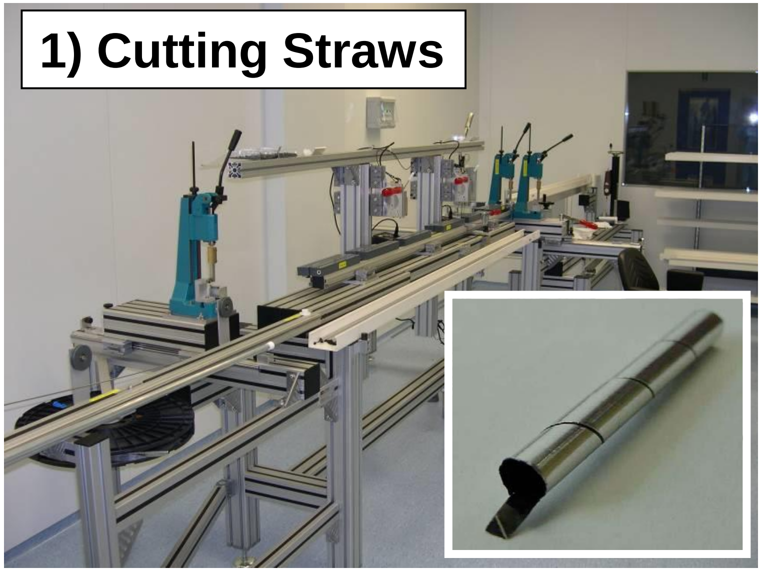


… and take MANY straws to have high efficiency.

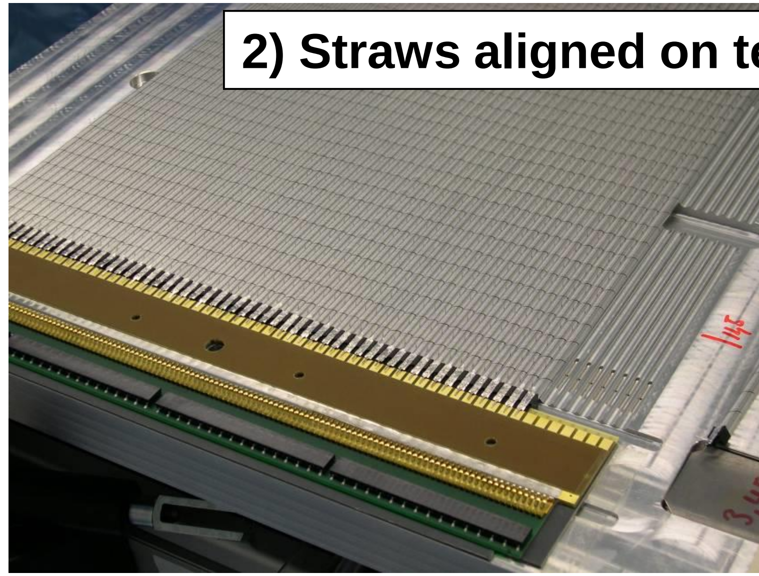


Q: How many space coordinates can you measure with a straw tube ? With which precision ?

Straw Tube : LHCb outer tracker (Runs 1, 2)

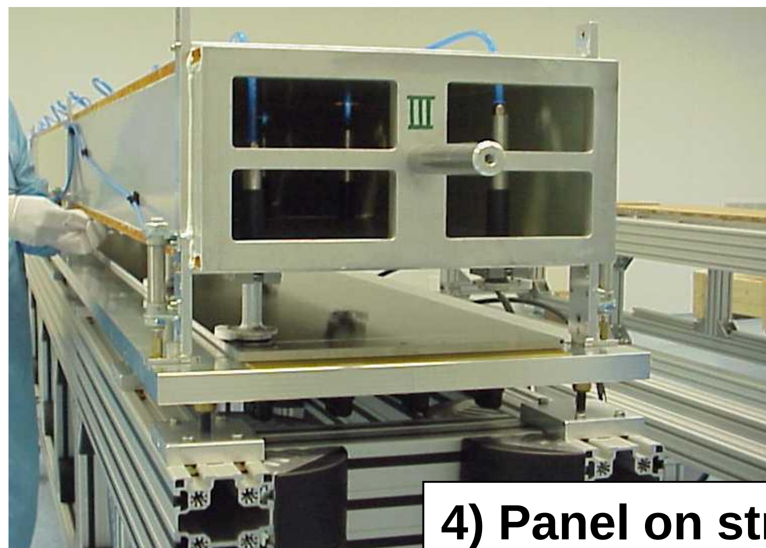


1) Cutting Straws

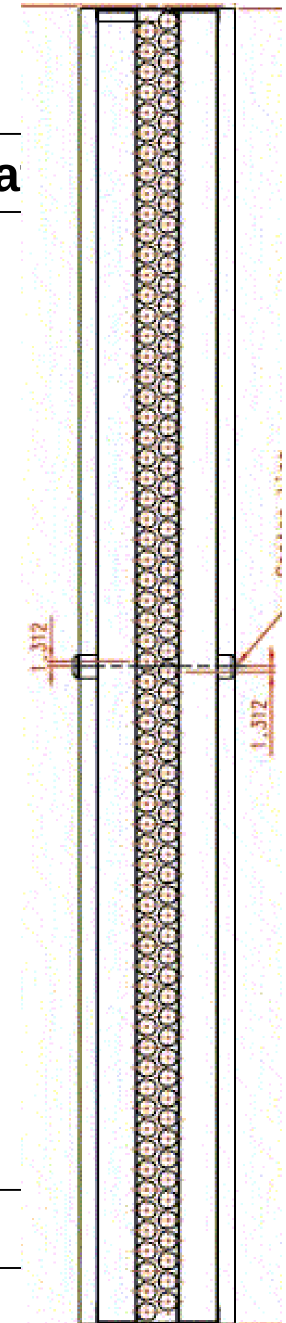


2) Straws aligned on templa

3) Glue on panel



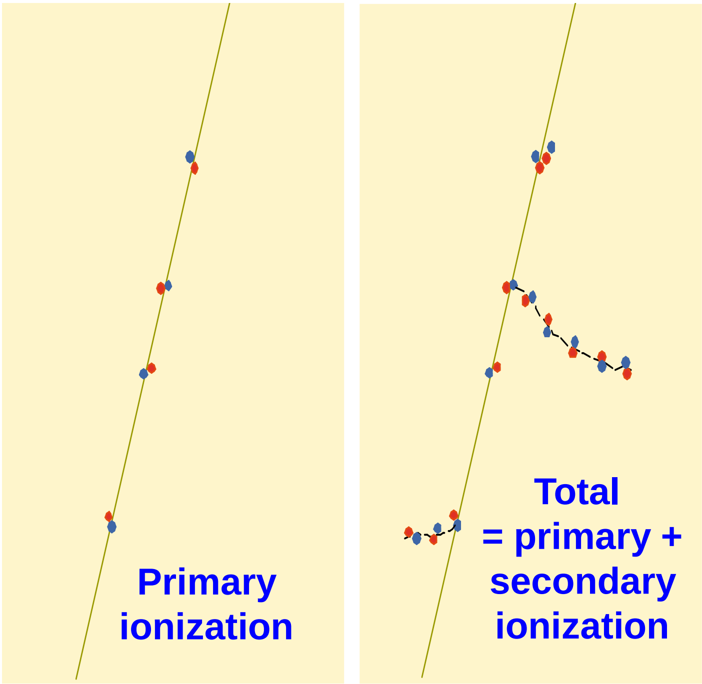
4) Panel on straws



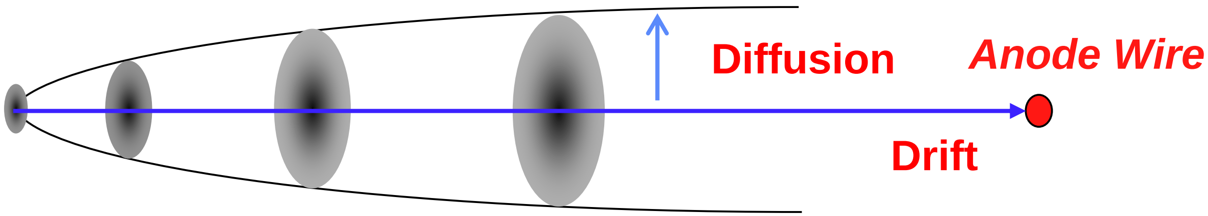
- Charged track passes through the gas in electric field
- **Primary ionization**: ~30 primary ionization clusters /cm in gas at 1 bar … *fluctuations !*
- **Secondary ionization**: clusters and delta-electrons, on average ~90 electrons / cm

$$n_{total} \sim 3 \times n_{primary}$$

- Numbers of pairs produced are Poisson distributed, for number of electrons long tail → limitation on dE/dx resolution



- Electrons and ions produced via ionization drift in the electric field, smeared by the diffusion
- Electrons drift faster



$$\frac{v_{electron}}{v_{ion}} \approx 10^3$$ **in CO_2 with E =10^4 V/cm**

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

Gas	Density (mg cm^{-3})	E_x (eV)	E_I (eV)	W_I (eV)	$dE/dx\|_{min}$ (keV cm^{-1})	N_P (cm^{-1})	N_T (cm^{-1})
He	0.179	19.8	24.6	41.3	0.32	3.5	8
Ne	0.839	16.7	21.6	37	1.45	13	40
Ar	1.66	11.6	15.7	26	2.53	25	97
Xe	5.495	8.4	12.1	22	6.87	41	312
CH_4	0.667	8.8	12.6	30	1.61	28	54
C_2H_6	1.26	8.2	11.5	26	2.91	48	112
iC_4H_{10}	2.49	6.5	10.6	26	5.67	90	220
CO_2	1.84	7.0	13.8	34	3.35	35	100
CF_4	3.78	10.0	16.0	54	6.38	63	120

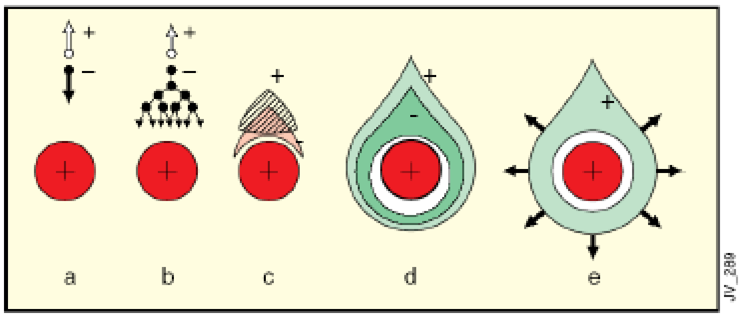
Total ionization (N_T)~ 3 times primary ionization (N_P)

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

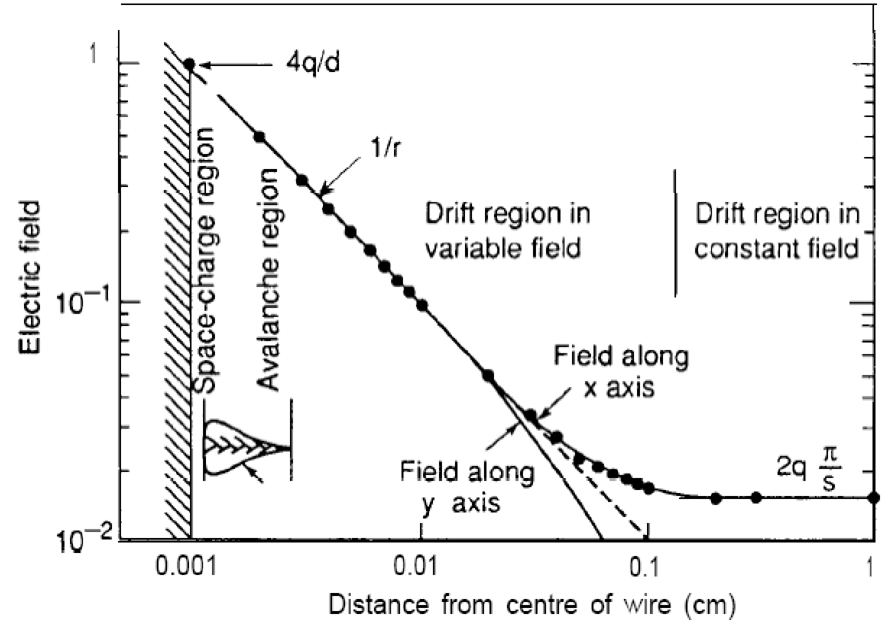
Avalanche development in high E field (~250 kV/cm) around a thin wire (multiplication region ~100 μm):

- Signal multiplication, Gain ~10^4

Gas amplification next to anode wire



GEORGES CHARPAK, **Nobel Lecture, December 8, 1992**



a) A **single primary electron** proceeds towards the wire anode

b) In the region of increasingly high field the electron experiences ionizing collisions (**avalanche multiplication**)

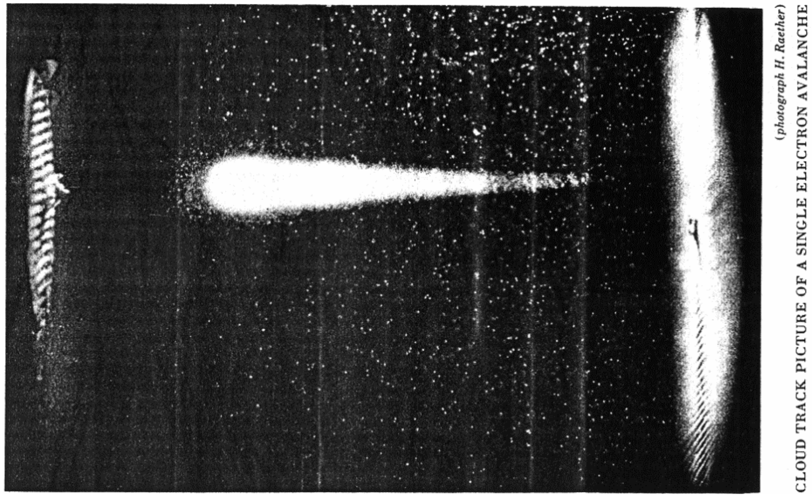
c) Electrons and ions are subject to **lateral diffusion**

d) A **drop-like avalanche** develops and surrounds the anode wire

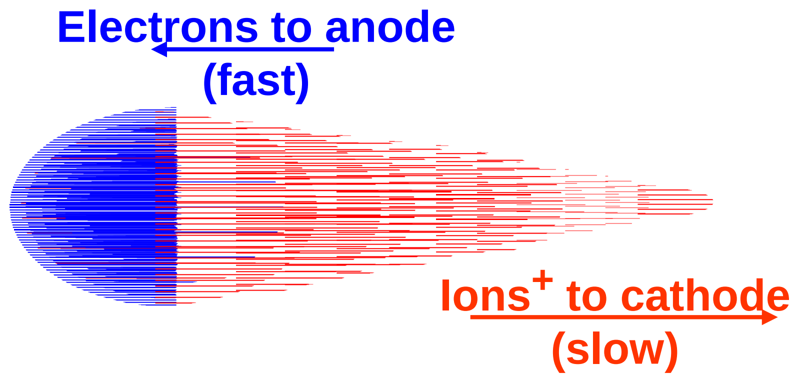
e) Electrons are quickly collected, while the ions begin drifting towards the cathode generating the signal at the electrodes

Q: Is it advantageous to multiplicate signal in a narrow region around the anode ?

Wire chambers: signal formation



Cloud track picture of a single electron avalanche



But: use induced charge…

F. Sauli, http://www.cern.ch/GDD

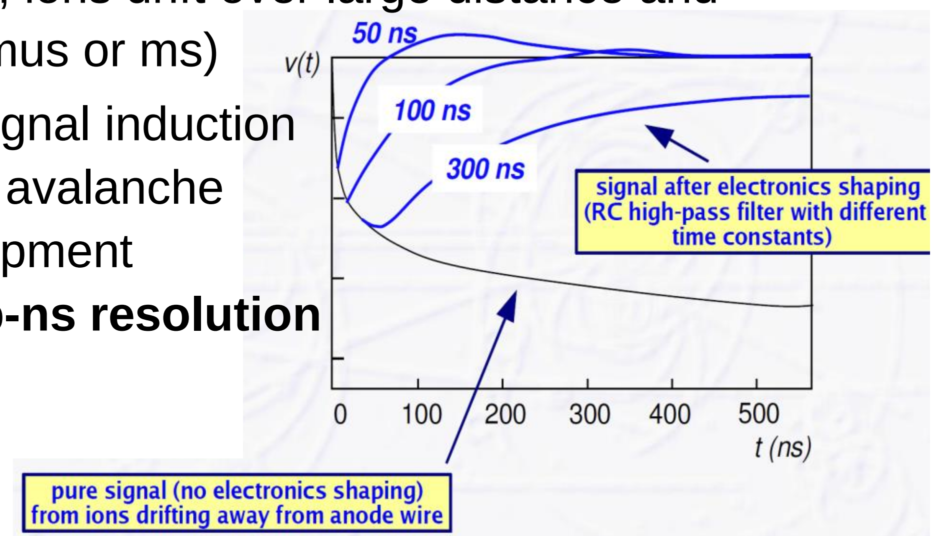
Signal amplitude

- Assuming that the total charge of the avalanche *Q* is produced at a (small) distance λ from the anode, the electron (q^-) and ion contributions (q^+) to the **total induced signal** ($q = q^- + q^+$) on anode is:

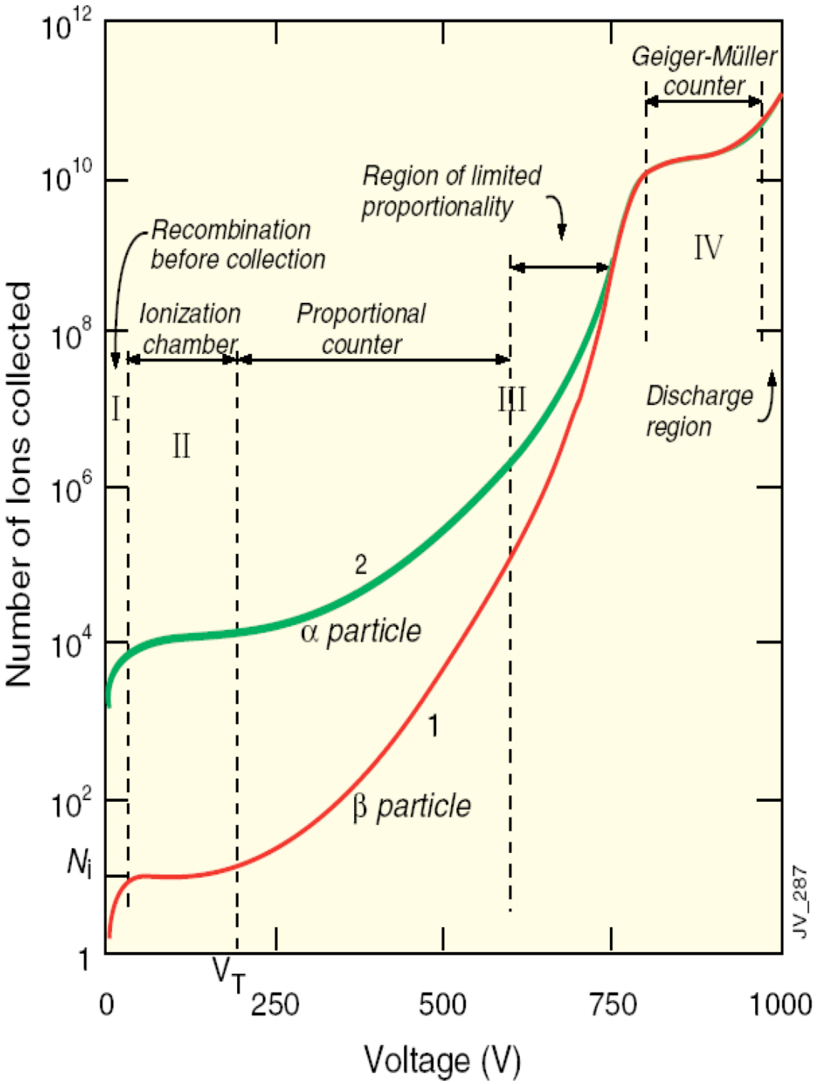
$$q^- = \frac{Q}{V_0}\int_a^{a+\lambda}\frac{dV}{dr}dr = -\frac{QC}{2\pi\varepsilon_0}\ln\frac{a+\lambda}{a} \ll q^+ = \frac{Q}{V_0}\int_{a+\lambda}^{b}\frac{dV}{dr}dr = -\frac{QC}{2\pi\varepsilon_0}\ln\frac{b}{a+\lambda}$$

Signal timing

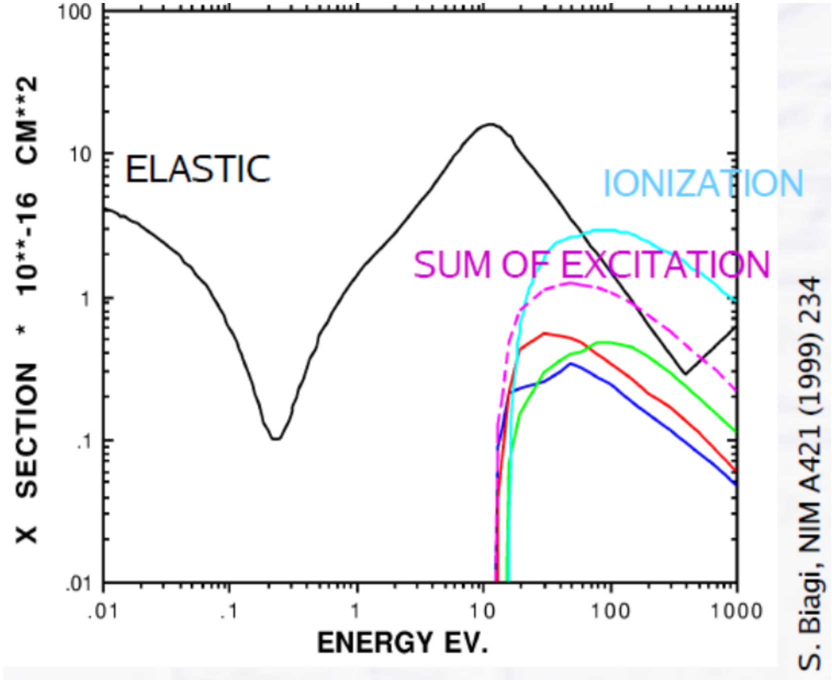
- Electrons from avalanche collected within a few ns, ions drift over large distance and time (mus or ms)
- Fast signal induction during avalanche development
  → **sub-ns resolution**



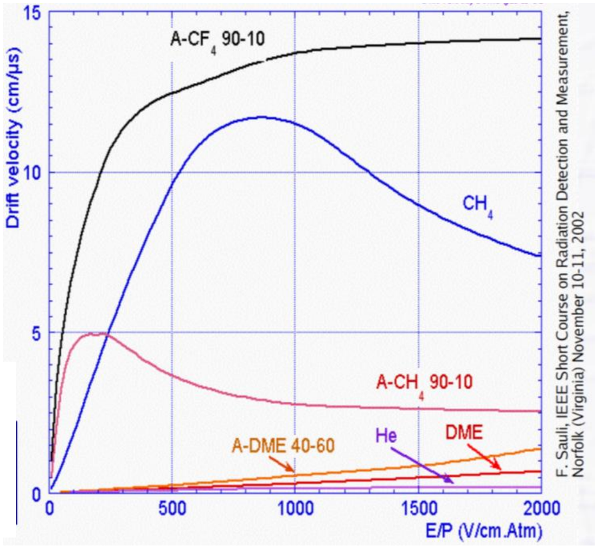
- Recombination before collection (I)
  - ions recombine before collected
- Ionization Mode (II)
  - full charge ionization charge;
  - no charge multiplication yet; gain ~ 1
- Proportional Mode (IIIa)
  - multiplication of ionization
  - signal proportional to ionization
  - measurement of dE/dx
  -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

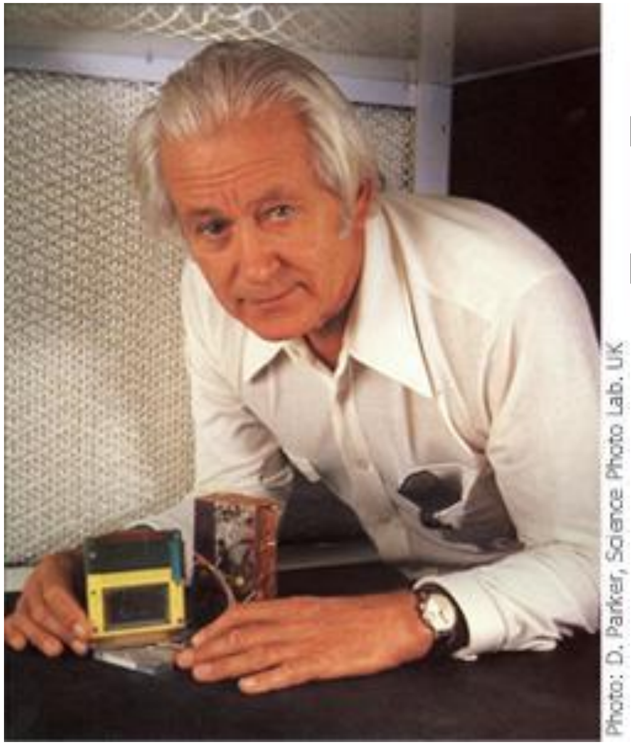


- **Quenching suppression**
- Argon atoms maybe ionized, but also can be excited with de-excitation via emission of UV photons (> 11.6 eV)
- UV photons hit surface of electrods and free new electrons → unstable operation
- Add gases with many vibrational and rotational energy levels: CO_2, CH_4 to absorb UV photons over a wide energy range, dissipation by collisions



- **Fast gas mixtures**
- Large range of velocities : 1 … 10 cm/μs
- Large drift velocities obtained by adding poly-atomic gas (CH_4, CO_2, CF_4) to Ar → e- cool due to energy transfer to rotational/vibrational modes of polyatomic gas
- Slow (CO_2 mixtures): 1-2 cm/μs, almost linear on E-field
- Fast (CF_4 mixtures): ~10 cm/μs or more
- Saturated (CH_4 mixtures): have maximum drift velocity at certain E-field, velocity less sensitive to field variations, almost const

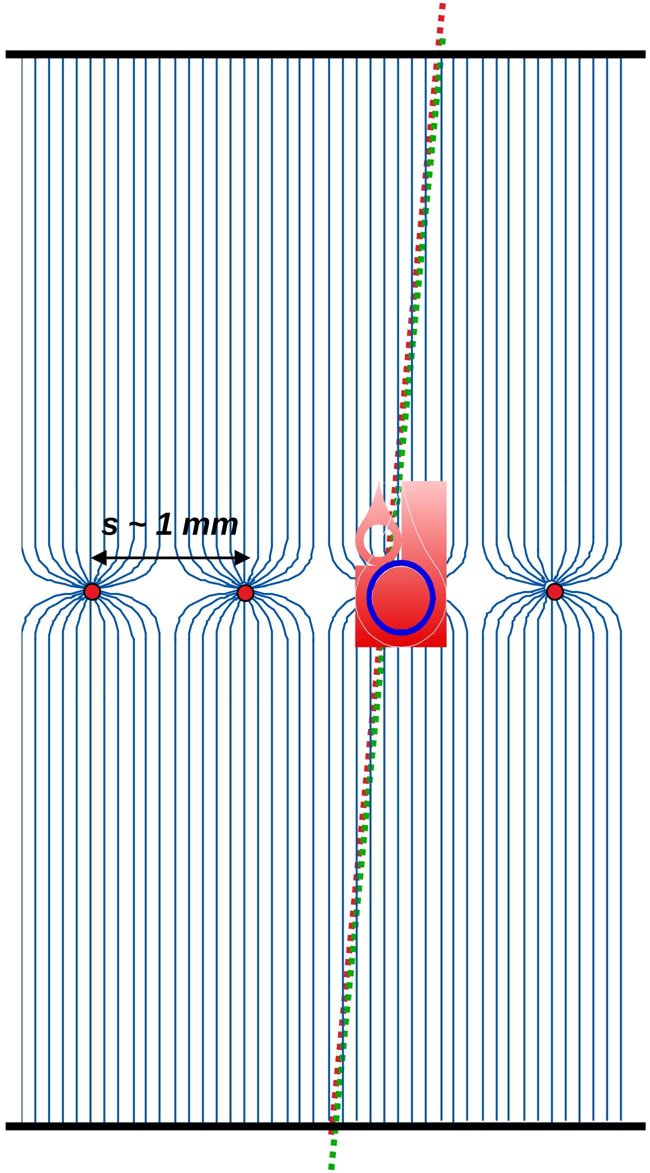




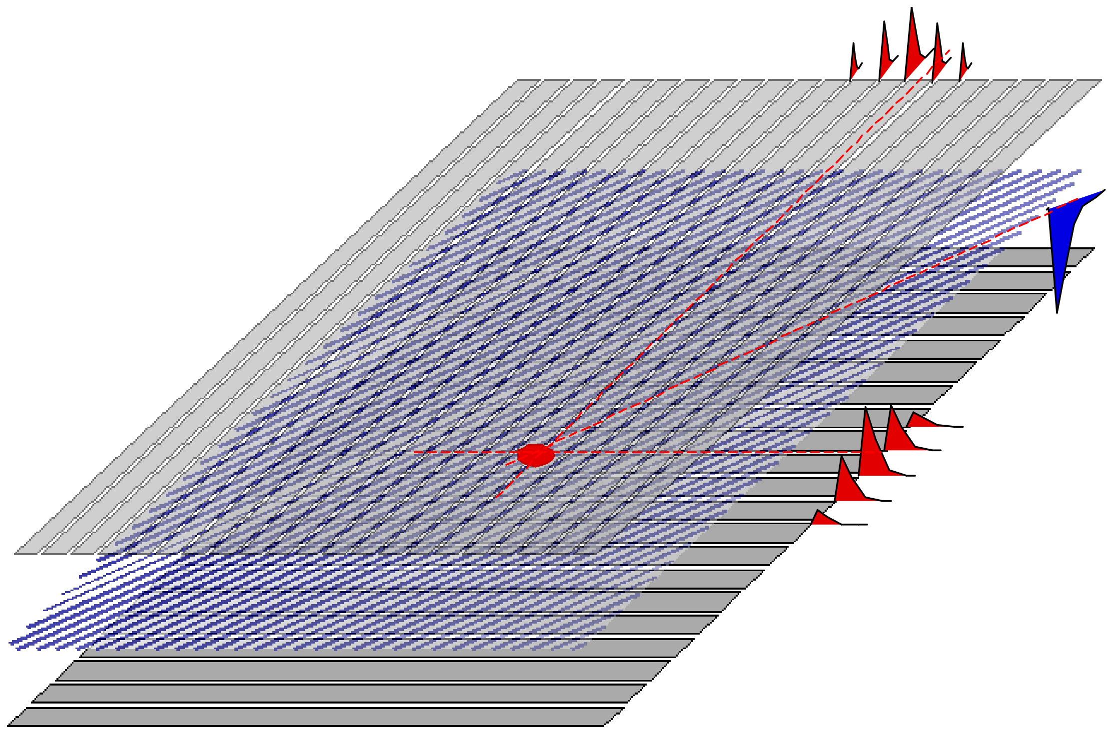
- Invented by Georges Charpak in 1968 … Nobel Prize in 1992
- Transformed in high precision Drift Chambers (DC), Time Projection Chamber (TPC) etc.

- Applications: X-ray and medical imaging, UV photon detection, neutron, and crystal diffraction and other material science studies, astronomy etc.

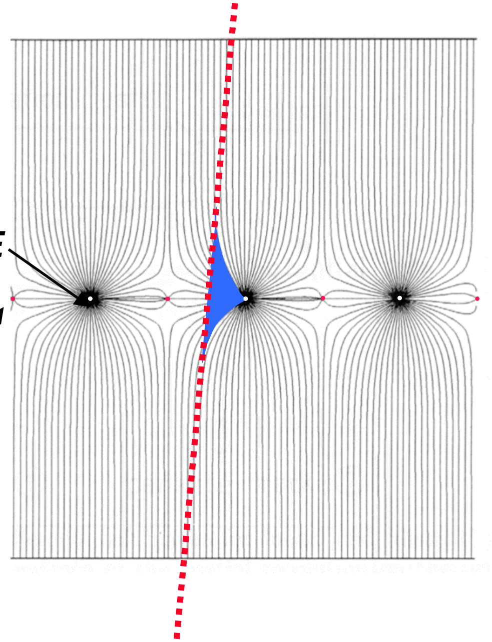
- Radiography of Charpak's hand made with a digital X-ray imaging apparatus based on the MWPC



- High-rate MWPC with digital readout
- Spatial resolution is limited to σ_x ~ s/sqrt(12) ~ 300 μm
- Two-dimensional MWPC readout cathode induced charge (Charpak and Sauli, 1973)

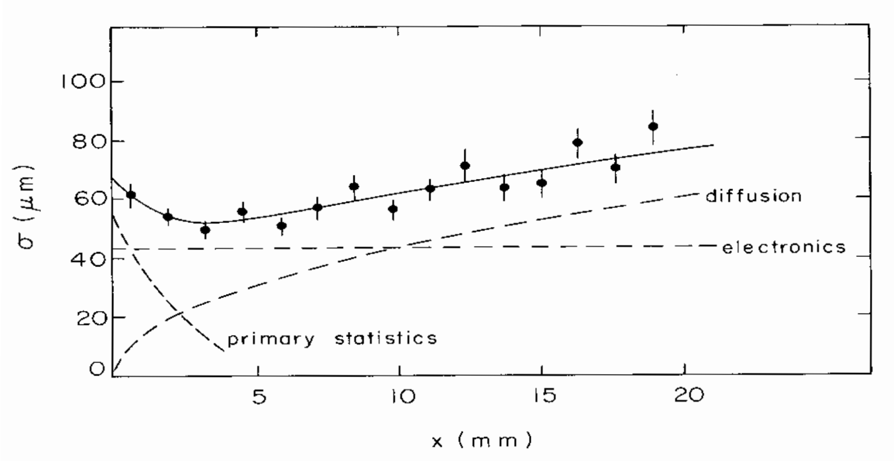


- Signal ~20000e, noise ~1000e
- Space resolution < 100 μm
- Resolution of MWPCs limited by wire spacing



- The electrons **drift time provides the distance** of the track from the anode → another way of measuring position
- **Spatial resolution** affected by distribution of primary ionization, diffusion, RO electronics, electric field (gas amplification), range of delta-electrons

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



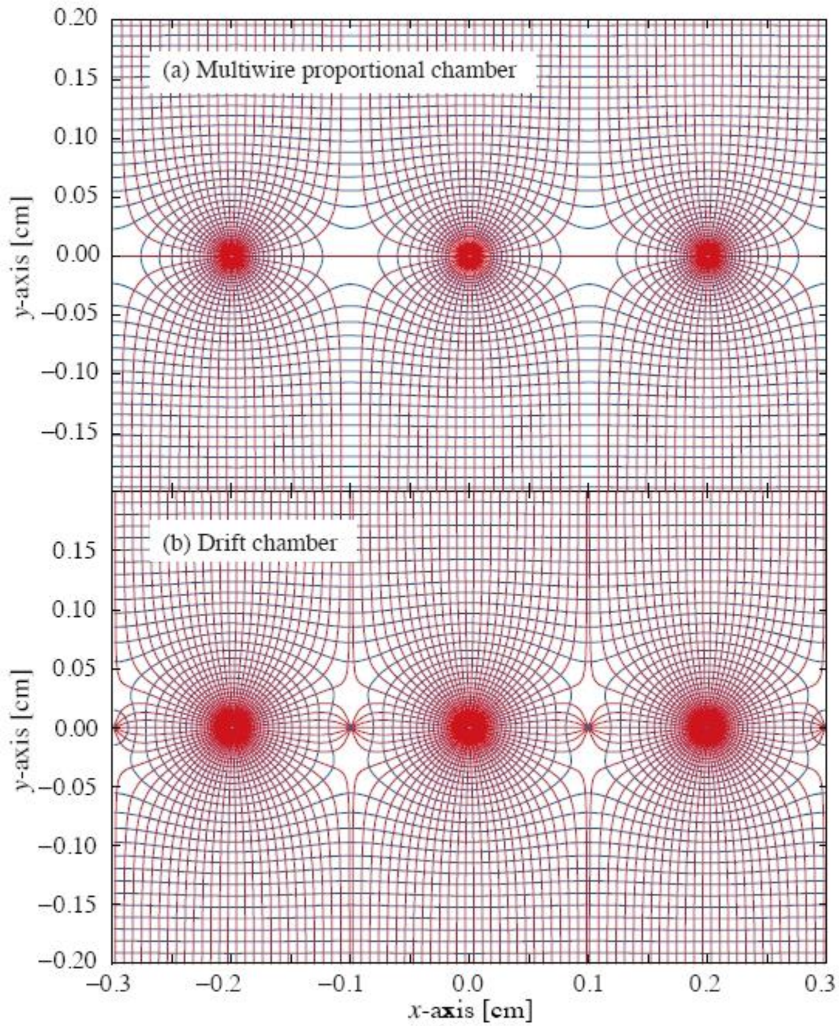


Figure 28.7: Electric field lines and equipotentials in (a) a multiwire proportional chamber and (b) a drift chamber.

Hexagonal drift cells formed by potential and sense wires (DC)

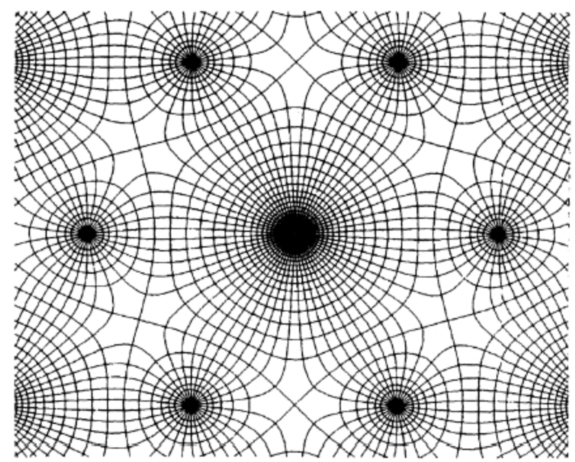
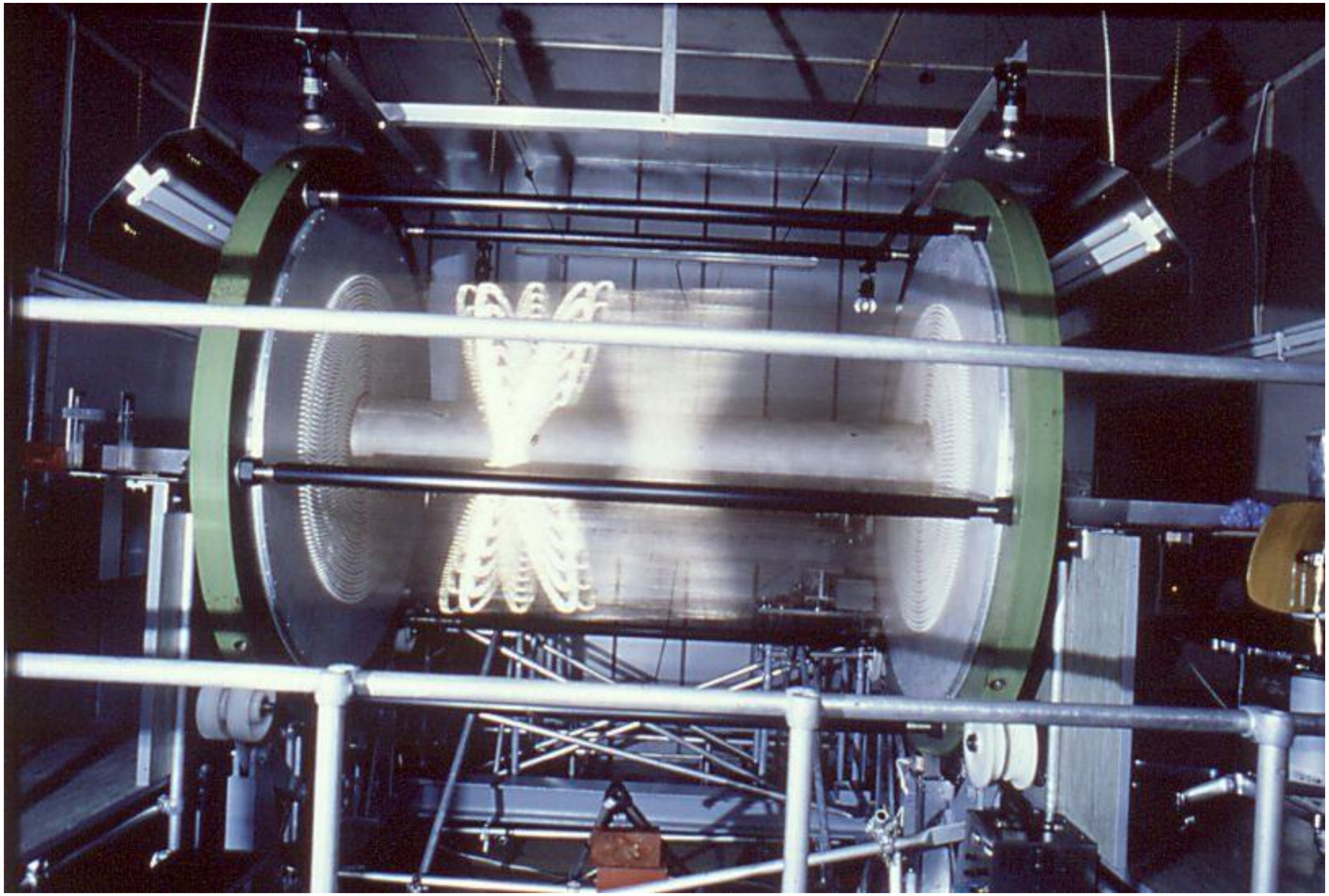


Figure 28.8: Electric field lines and equipotentials in a multiwire drift module. Each anode wire is surrounded by six cathode wires, and each cathode wire is surrounded by three anode wires.

ARGUS Drift Chamber



Hexagonal drift cells formed by potential and sense wires

Time Projection Chamber (TPC)

Large volume active detector.

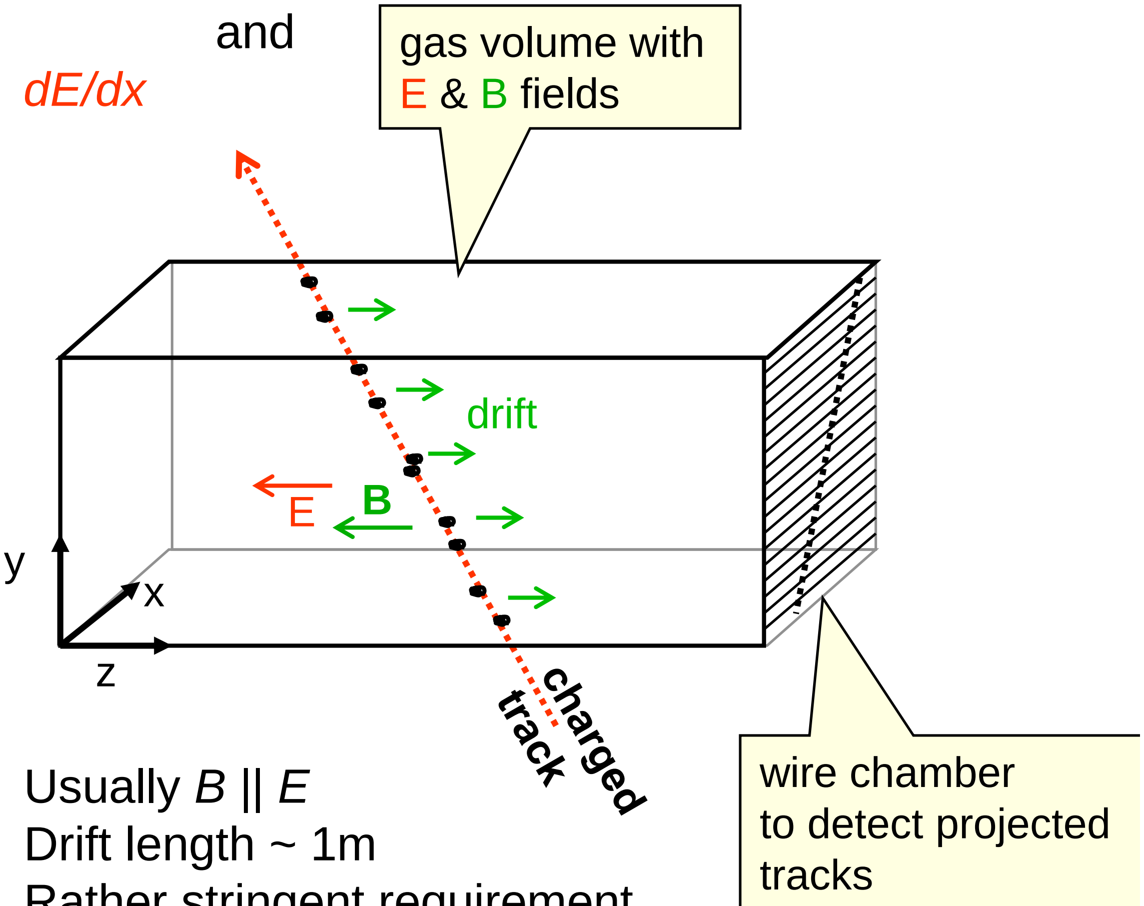
full 3-D track reconstruction

x-y from wires and segmented cathode

z from drift time

and

dE/dx



Usually *B* || *E*

Drift length ~ 1m

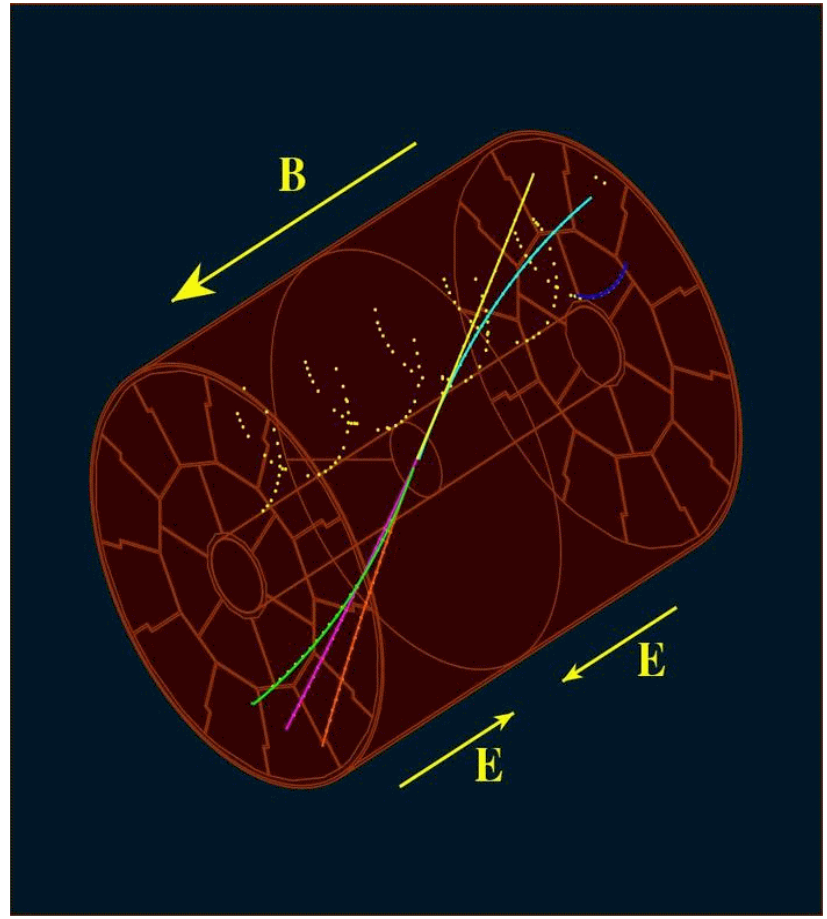
Rather stringent requirement on homogeneity of *E* and *B*

Space charge by ions

“Slow” detector $t_D \sim 10 .. 100$ μs

… or R-O from both sides :

- Smaller drift distance
- Faster signal collection, smaller diffusion
- Less requirements to the electric field
- Better efficiency



- Advantages
    - Complete track with one detector
    - Good particle ID with dE/dx
    - Drift parallel to B suppresses transverse diffusion by a factor 10 … 100
- Challenges
    - Long drift time, limited rate capability
    - Large volume (precision)
    - Large voltages (discharges)
    - Extremely large load at high luminosity, gating grid opened for triggered events only
- Typical resolution
    - z: mm; x: 150-300 μm; y: depends on read-out detector

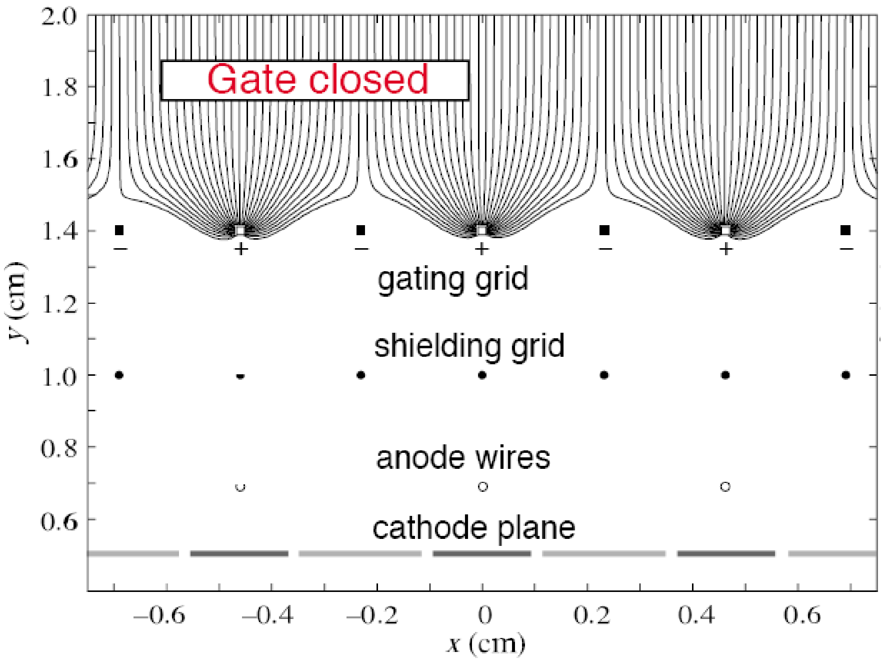
Difficulty: space charge effects due to slow moving ions change effective E-field in drift region ....

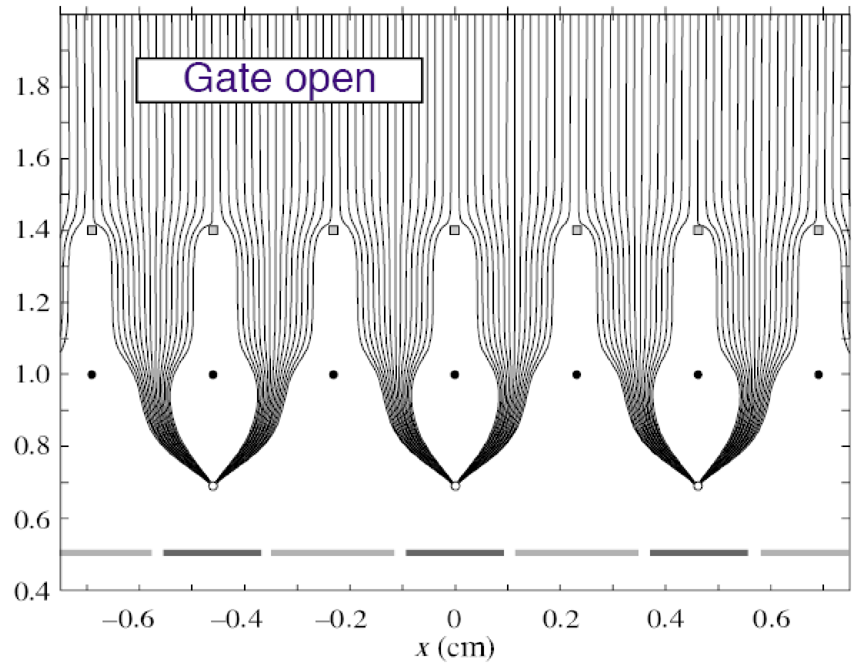
Important: most ions come from amplification region

Solution: Invention of gating grid; ions drift towards grid ...

[Also: shielding grid to avoid sense wire disturbance when switching]

Requires external trigger to switch gating grid ...

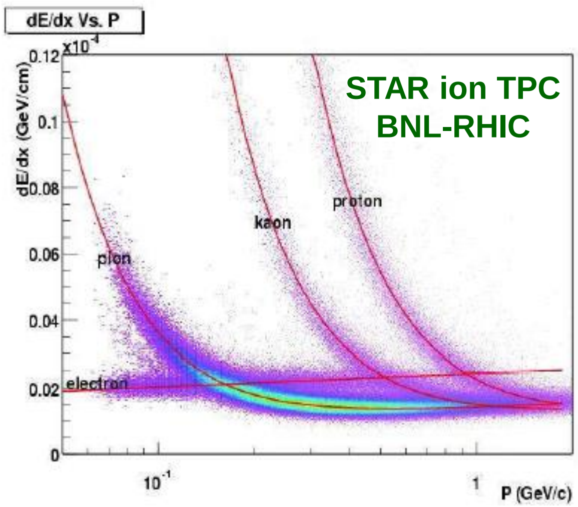




… more difficult for high multiplicities …

Relativistic Heavy Ion Collider
at Brookhaven

High particle multiplicities
Low beam intensities



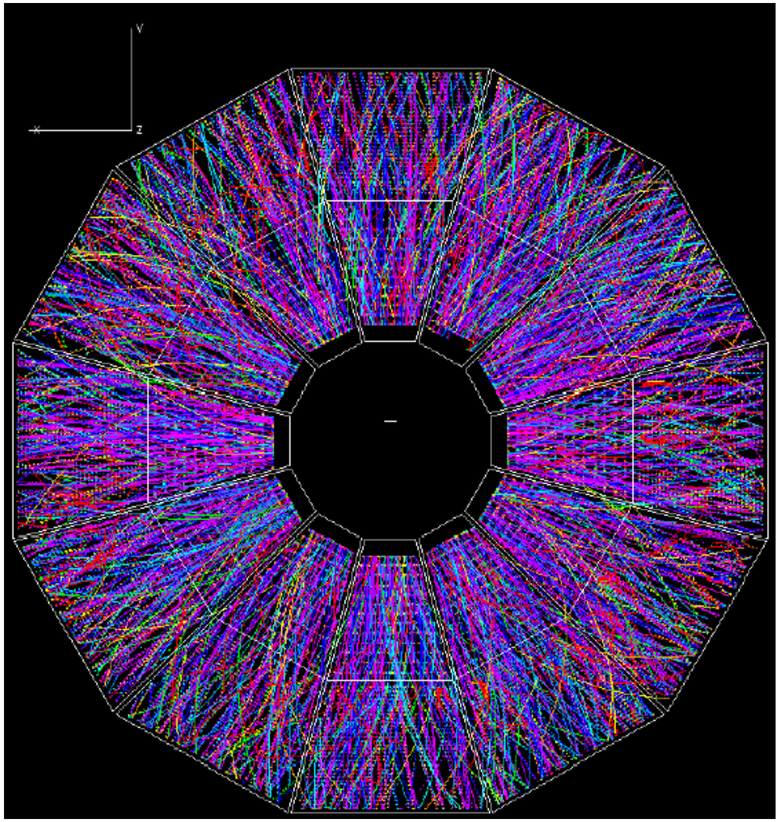
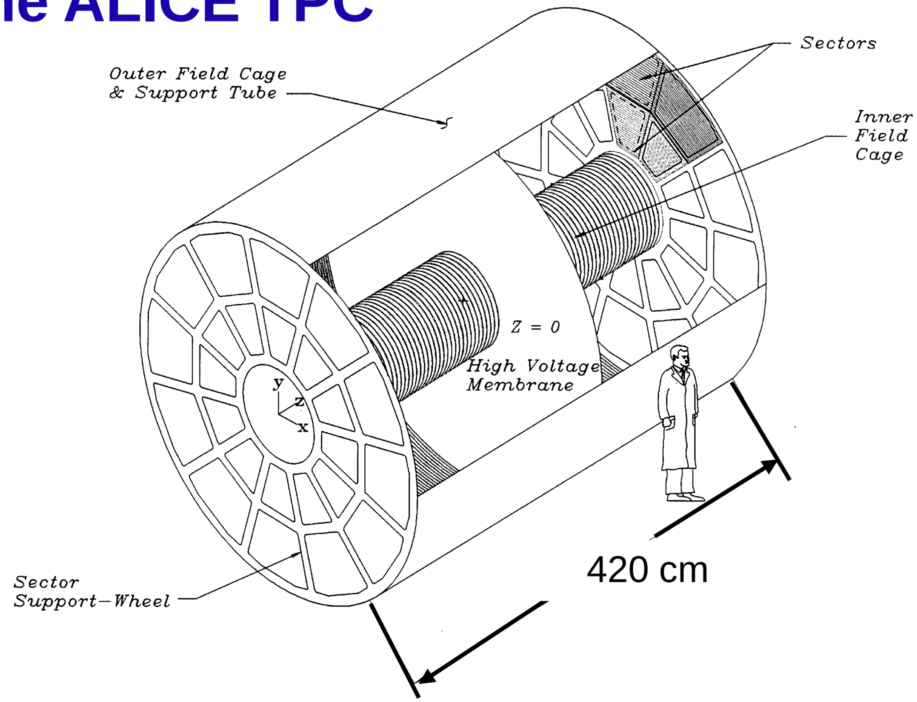
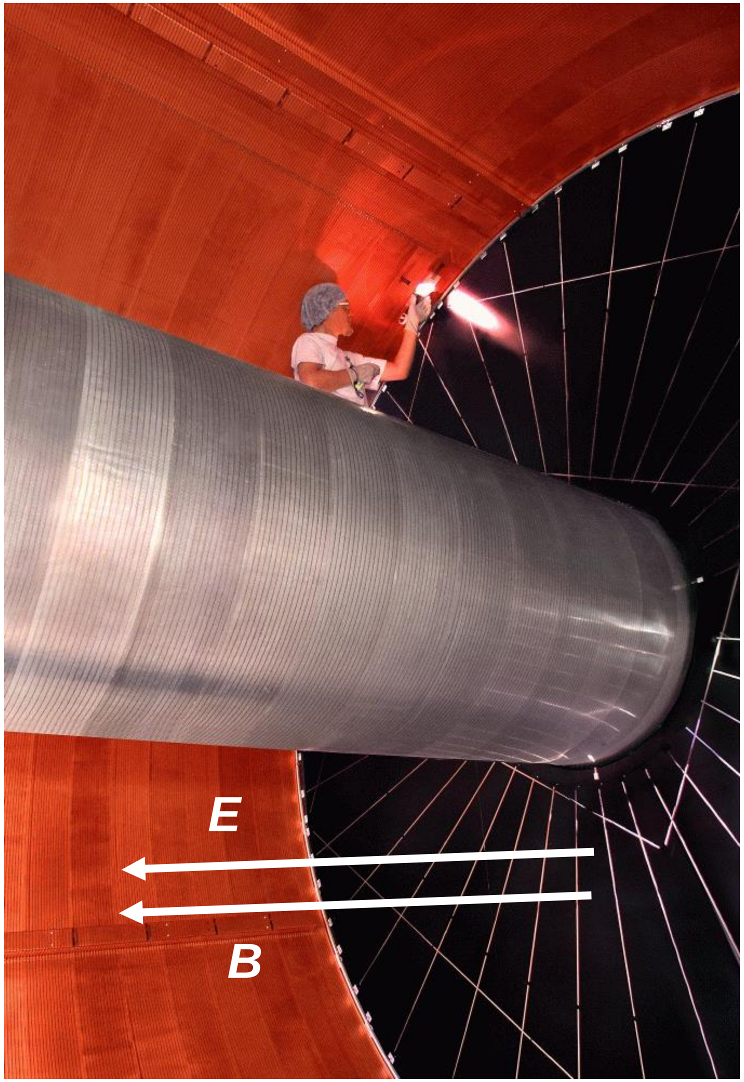


Image of Au-Au collision in STAR Time
Projection Chamber (TPC)

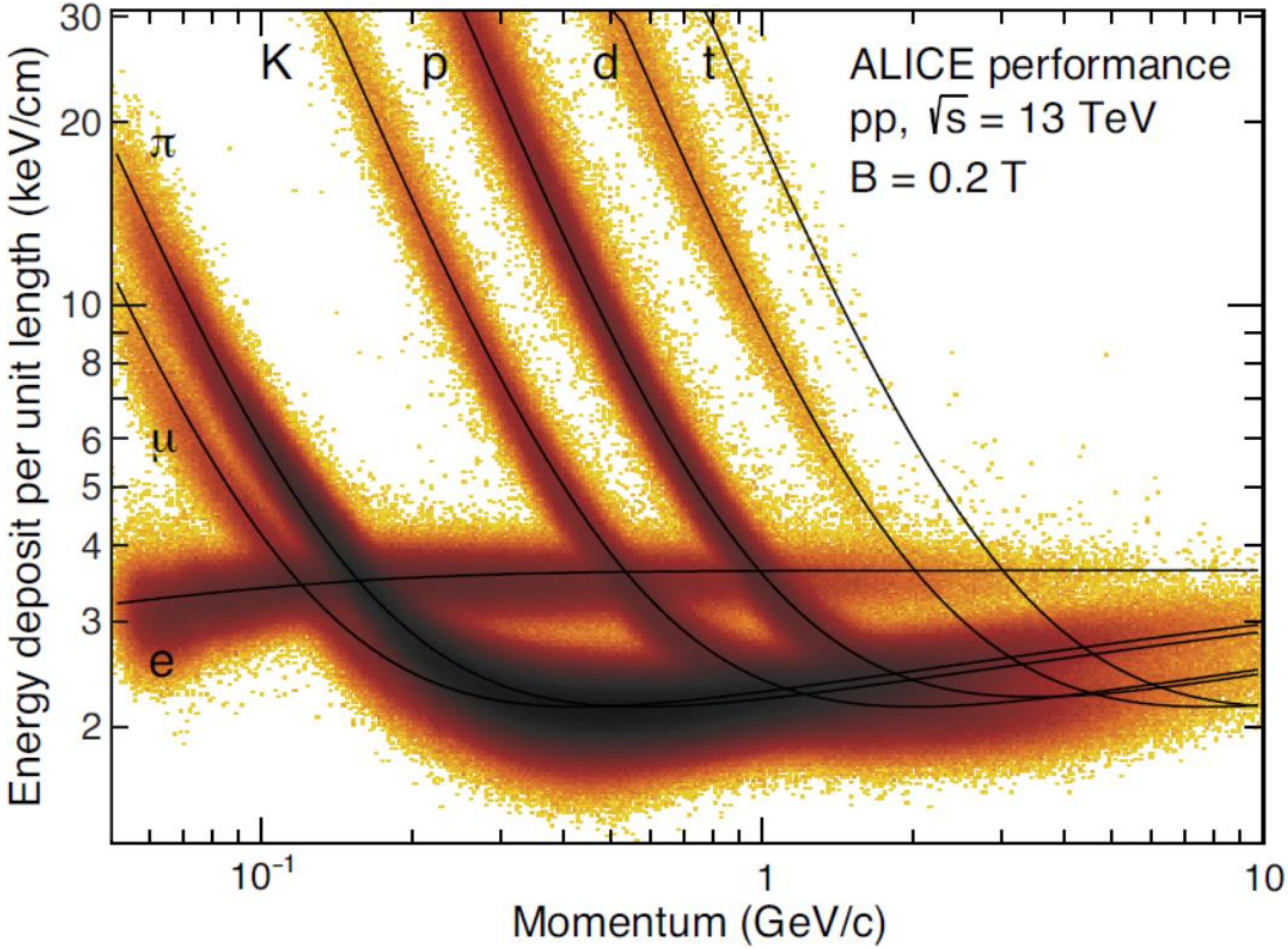
The ALICE TPC





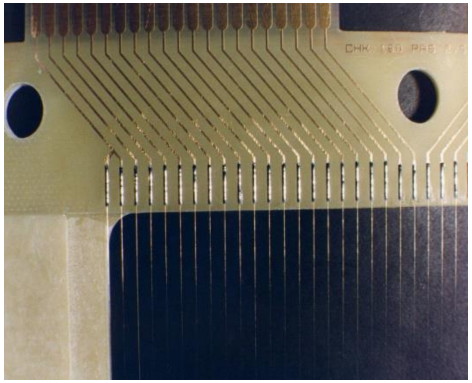
← ALICE TPC field cage

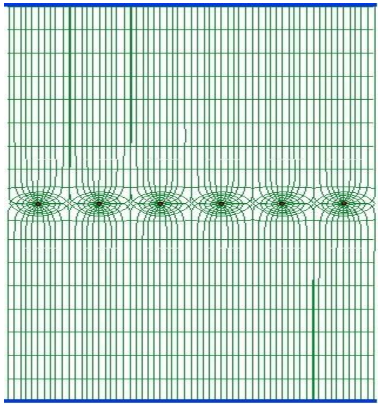
dE/dx with ALICE TPC



Micro-Strip Gas Chamber (MSGC): thin anode and cathode strips on insulating support

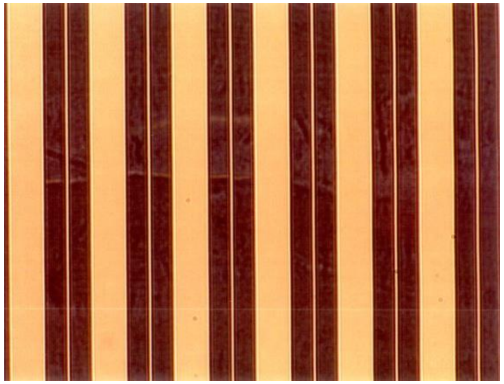
MWPC

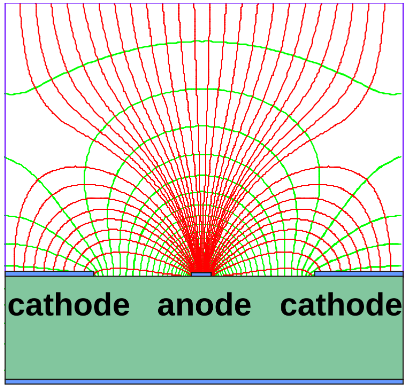




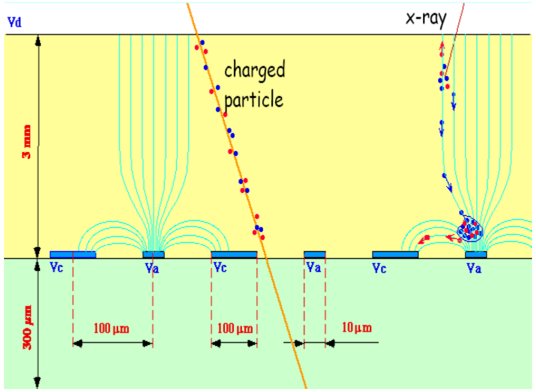
Typical distance between wires limited to 1 mm due to mechanical and electrostatic forces

MSGC

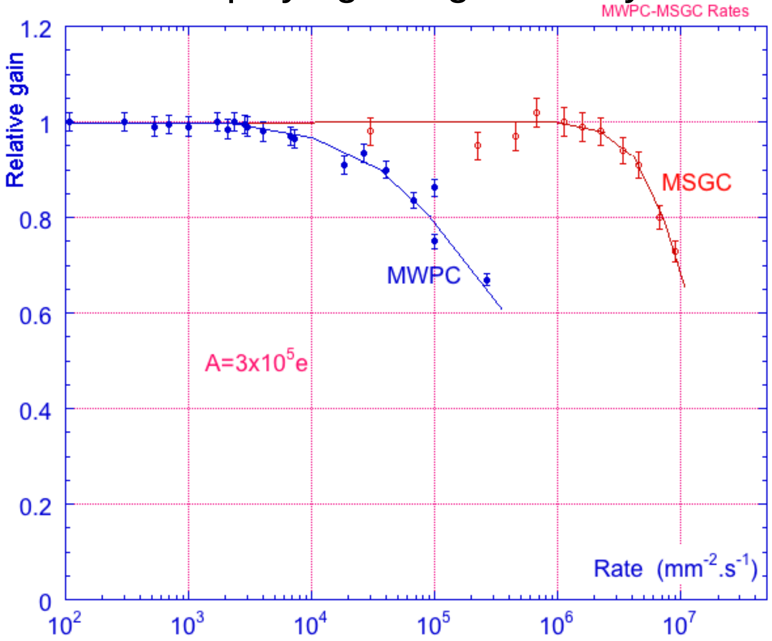




Typical distance between anodes 200 mum thanks to semiconductor etching technology



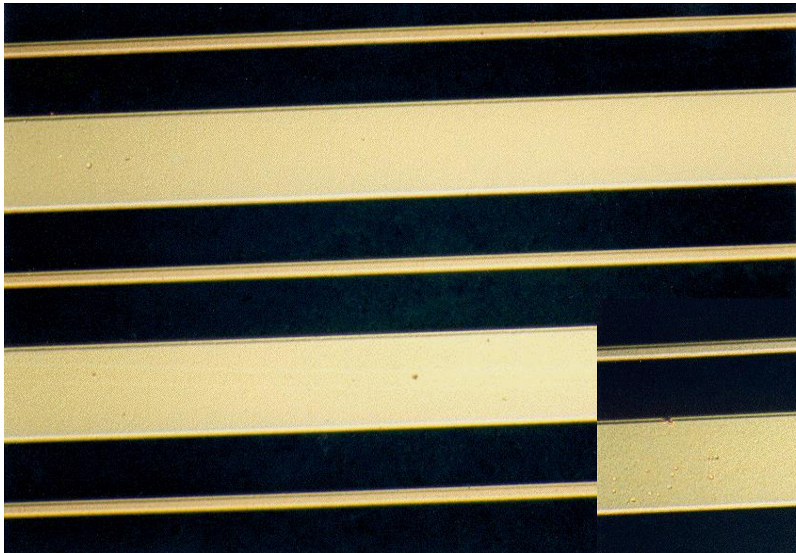
Rate capability limit due to space charge overcome by increased amplifying cell granularity



A. Oed, NIM A263 (1988) 351.

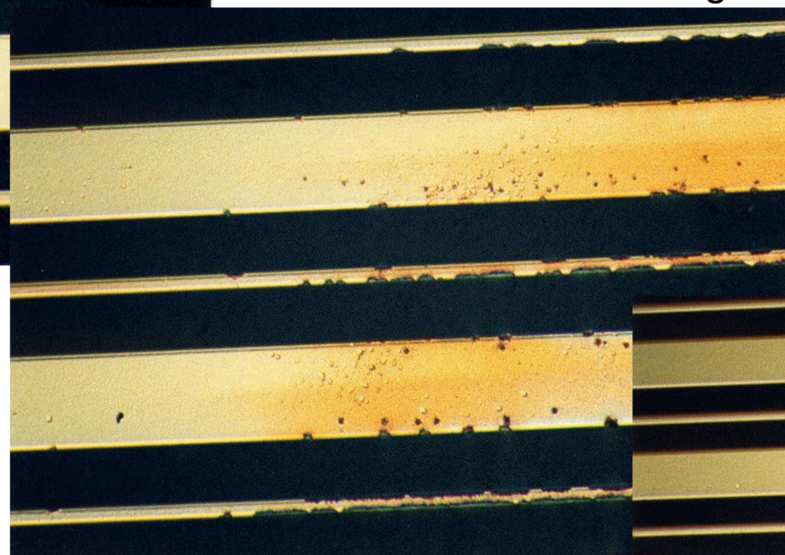
But discharges !

- Due to a small distance between anode and cathode the transition from proportional mode to streamer can be followed by spark, discharge, if the avalanche size exceeds ~10^7–10^8 electrons

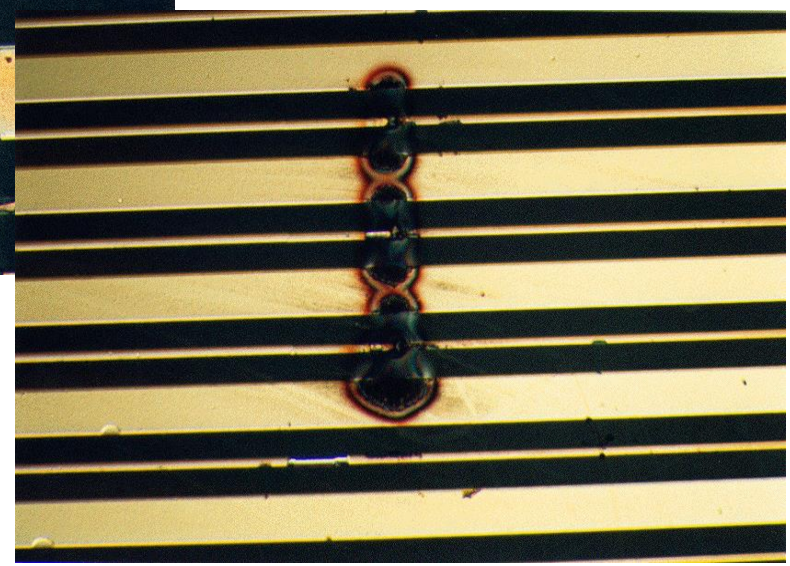


- Discharges are very fast (~ns), difficult to predict or prevent

microdischarges



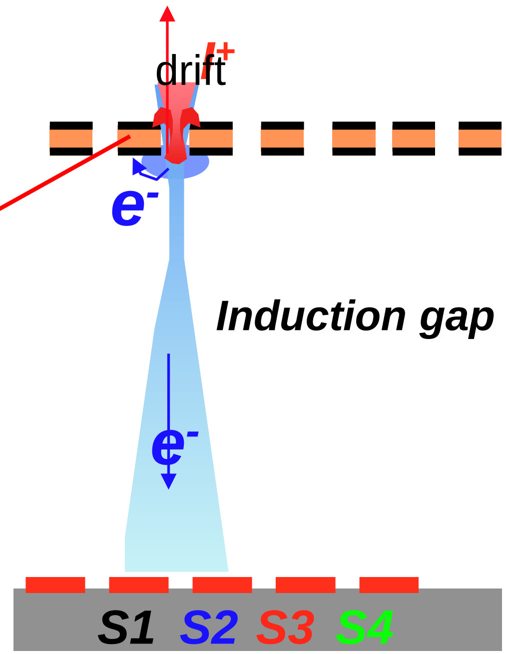
full breakdown

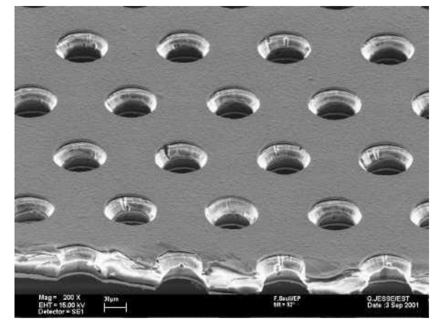


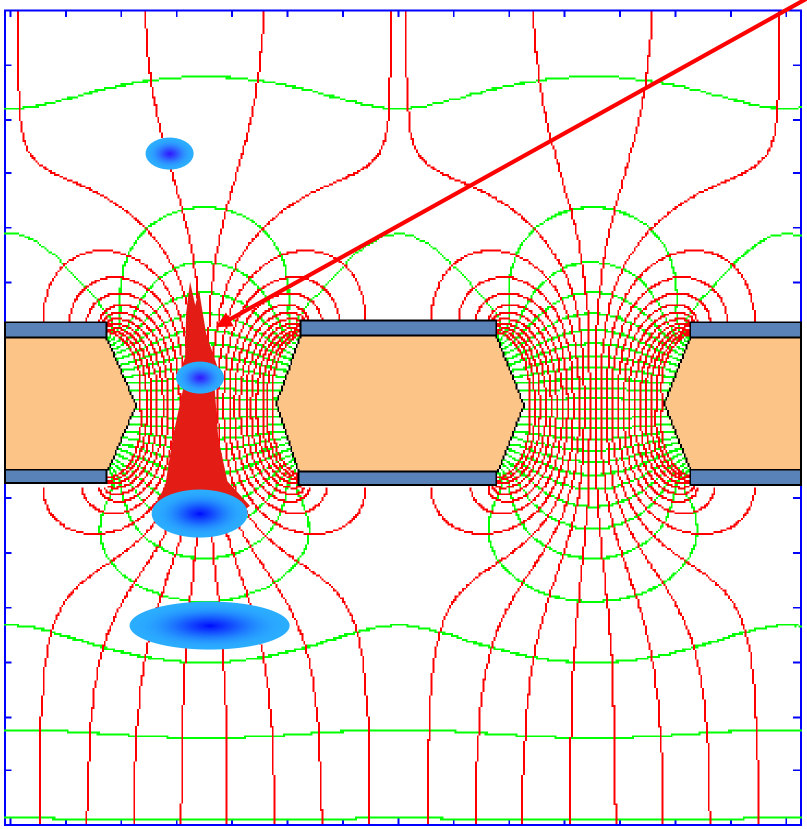
- Thin metal-coated polymer foil chemically pierced by a high density of holes

F. Sauli, 1995

- Thickness ~ 50 mum, hole diameter ~ 70 mum, pitch ~140 mum
- A difference of potentials between the two GEM electrodes ~ 500V
- Primary electrons released by ionizing particle, towards the holes, where high electric field triggers electron multiplication process.





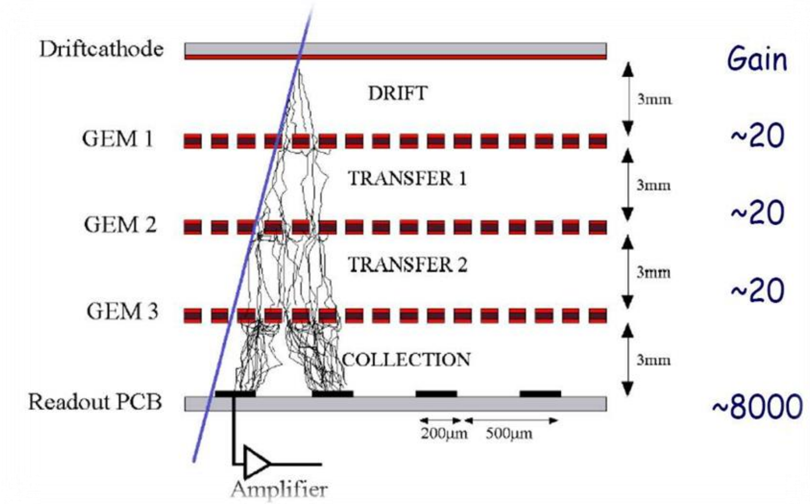


- Electrons collected on patterned readout board
- Fast signal can be detected on lower GEM electrode for trigger or energy discrimination
- All readout electrodes are at ground potential

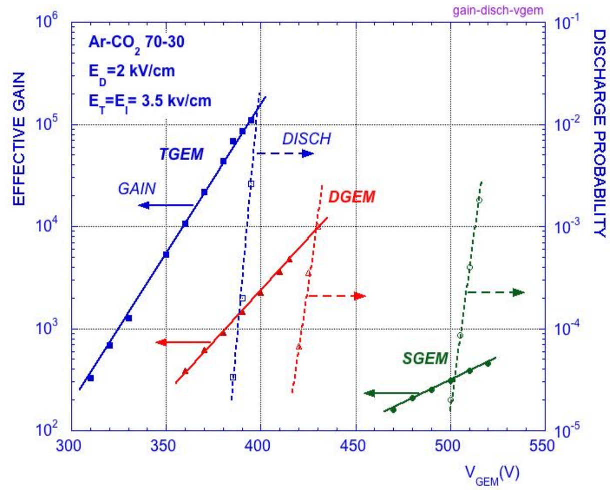
F. Sauli, NIM A386(1997)531
F. Sauli, http://www.cern.ch/GDD

Triple Gas Electron Multiplier (GEM)

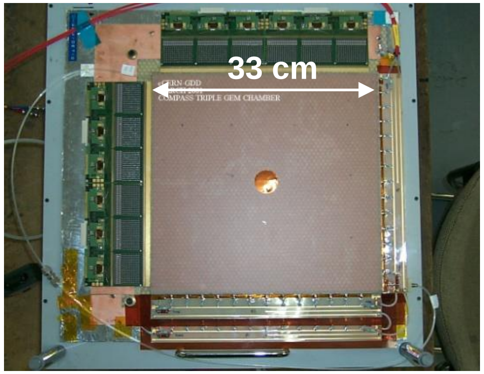
- Full decoupling of amplification stage (GEM) and readout stage (PCB, anode)



- For the same gain the discharge probability in a multi GEM configuration is much smaller.

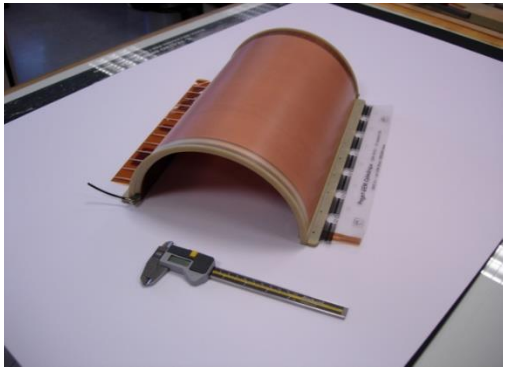


Amplification and readout structures can be optimized independently

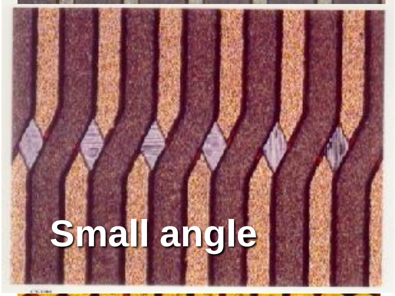


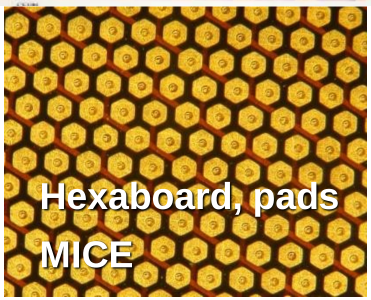
Compass

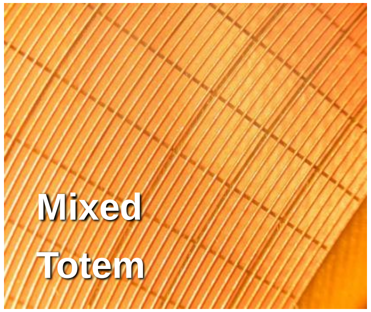
Totem



NA49-future





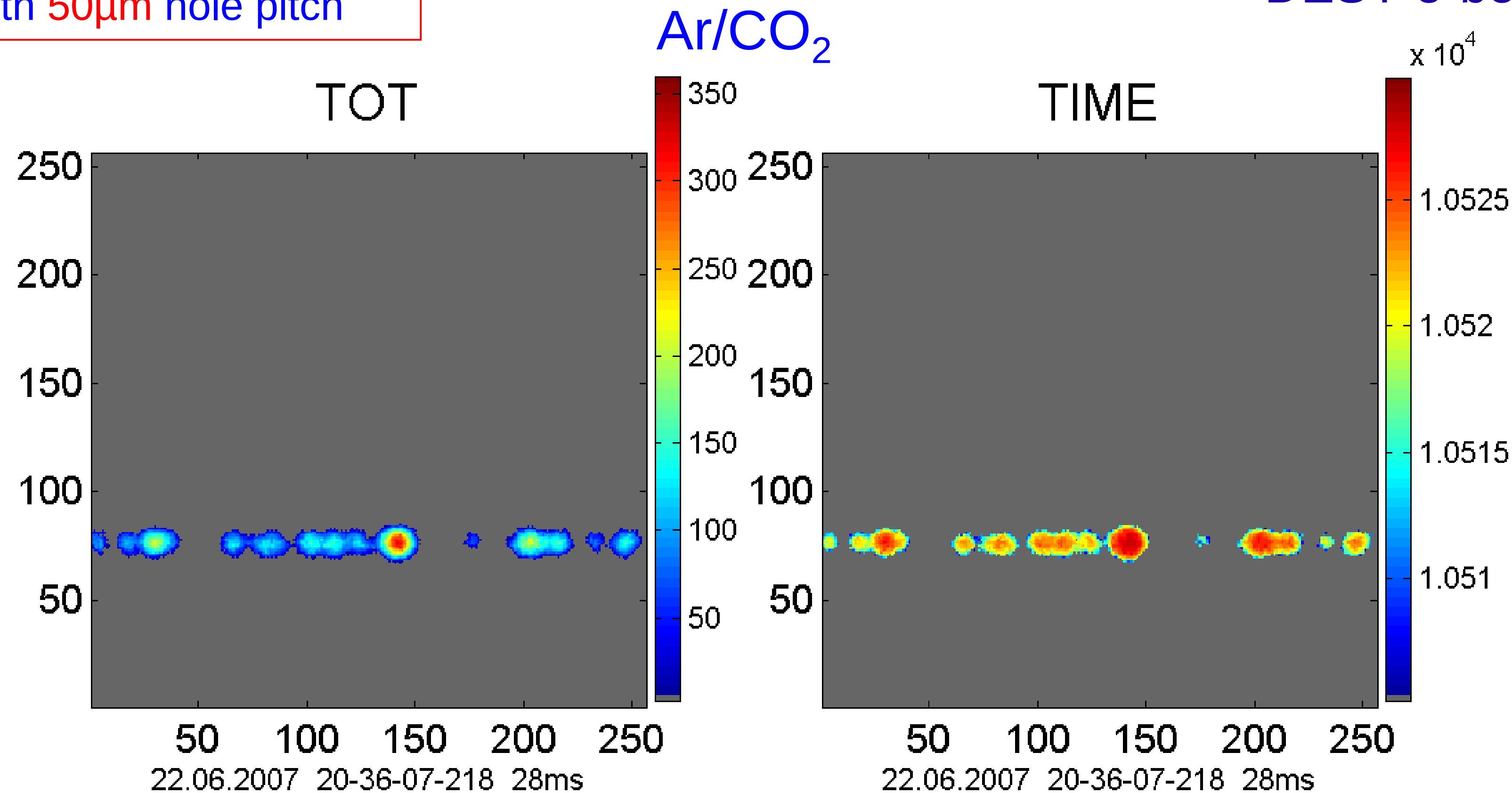


Electron tracks parallel to the cathode plane, passing between cathode and GEM1

RO with TIMEPIX

DESY e-beam

24x28mm^2 GEMs
with 50µm hole pitch



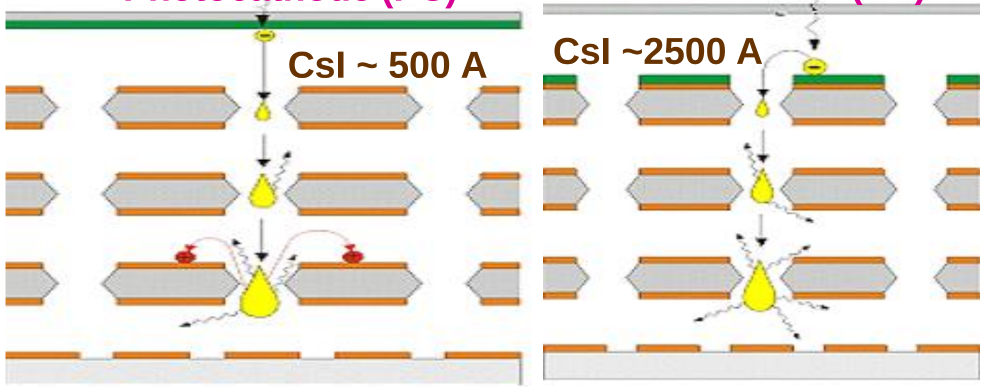
M. Titov

- ❑ Use time over threshold (TOT) information for clustering
- ❑ Gain with small pitched GEMs at $\Delta V_{GEM} \approx 346V$ comparable to $\Delta V_{GEM} \approx 403V$ with standard GEMs.

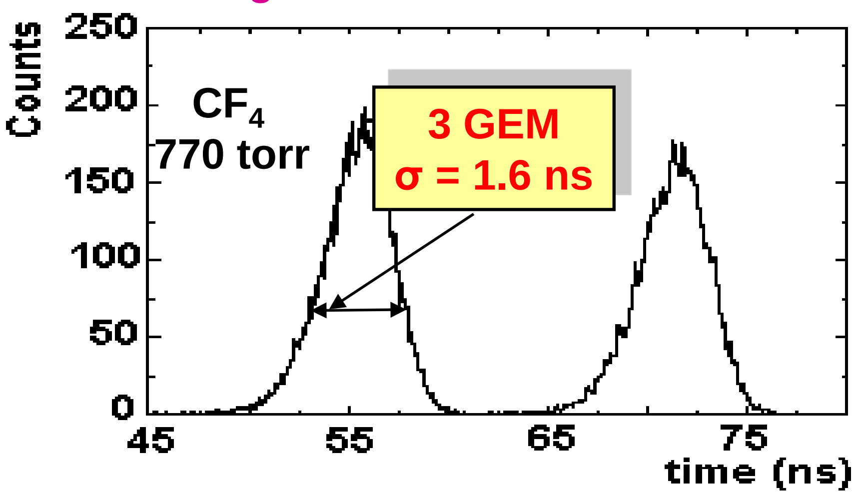
- **GEM Gaseous Photomultipliers** (GEM+CsI photocathode) to detect single photoelectrons: photoelectron initiates avalanche in a high field region (also MWPC, Micromegas, …)

Multi-GEM Gaseous Photomultipliers:

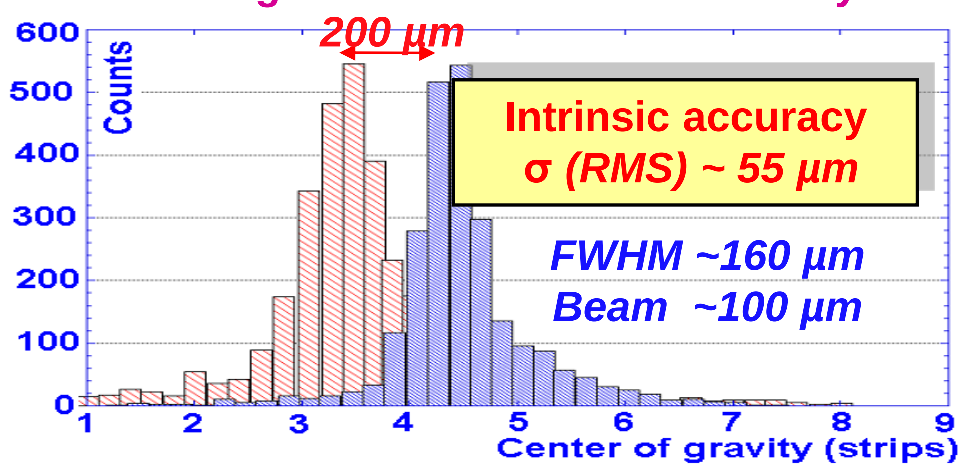
- Largely reduced photon feedback (can operate in pure noble gas & CF_4)
- Fast signals [ns] → good timing
- Excellent localization response
- Able to operate at cryogenic T



Single Photon Time Resolution:

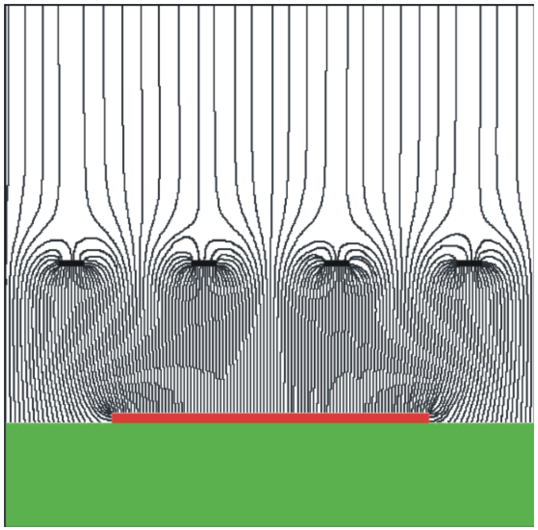


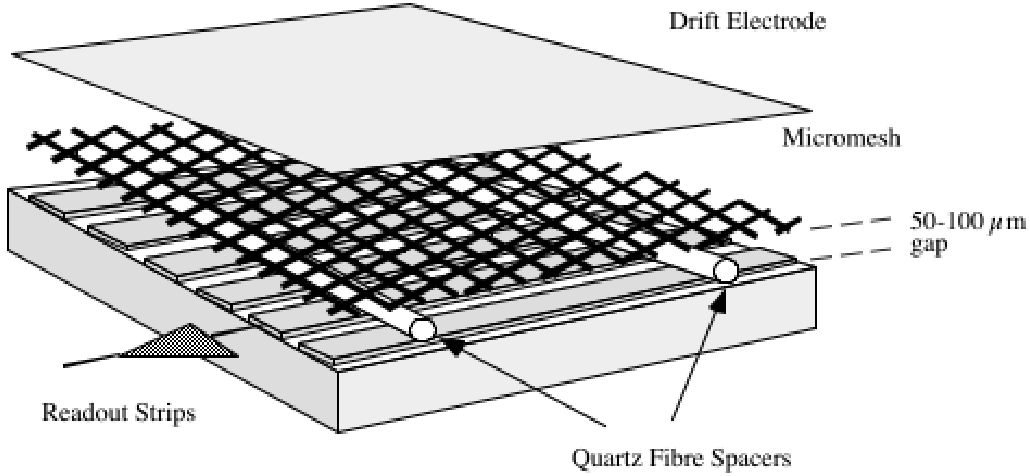
Single Photon Position Accuracy:



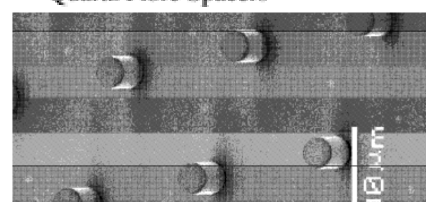
E.Nappi, NIMA471 (2001) 18; T. Meinschad et al, NIM A535 (2004) 324; D.Mormann et al., NIMA504 (2003) 93

- Parallel plate multiplication in thin gaps between a fine mesh and anode plate

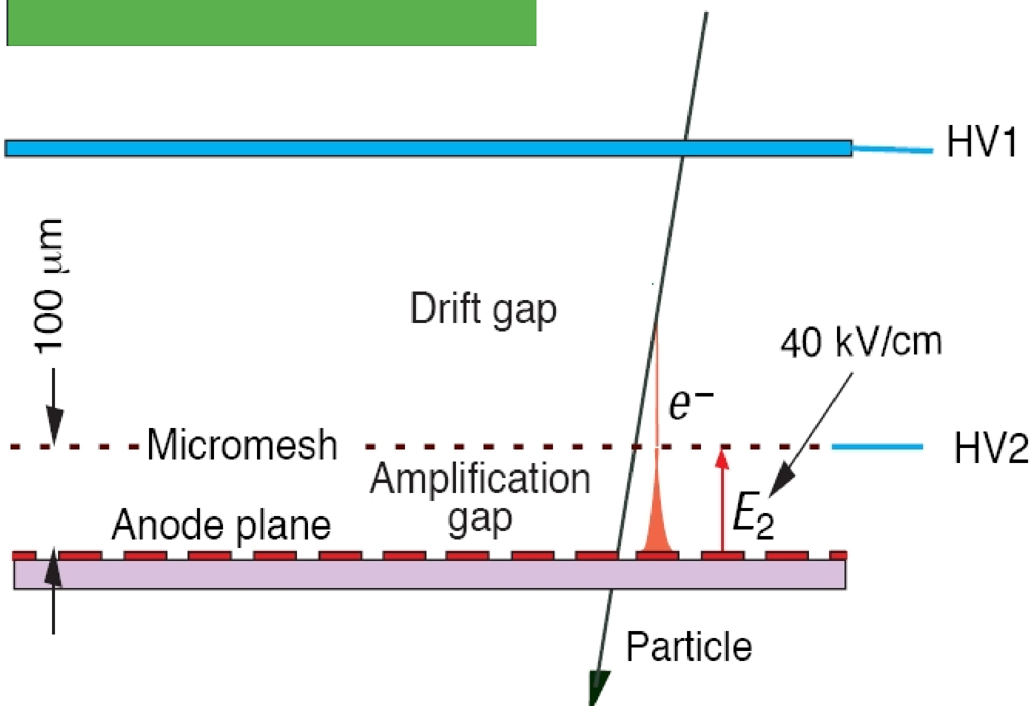


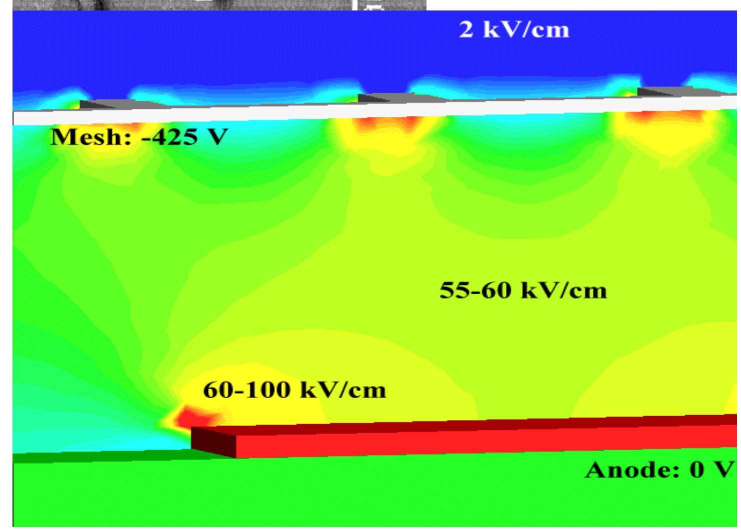


Giomataris, 1996



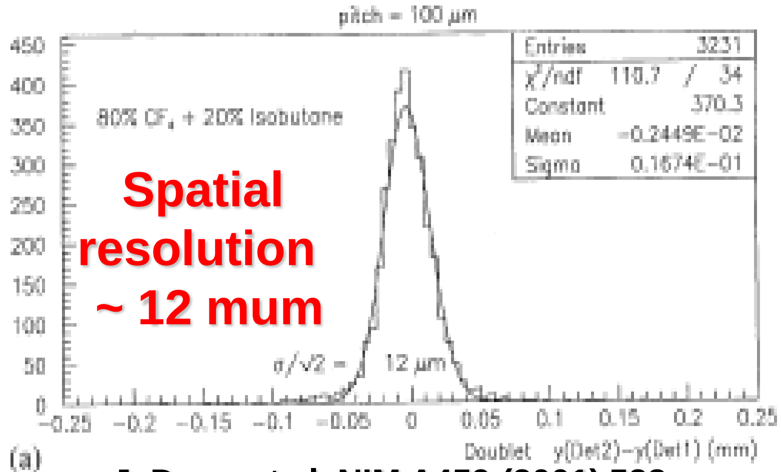
… or 50μm pillars





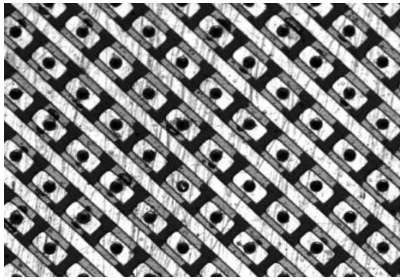
Y. Giomataris,
NIM A376(1996) 29

Small gap→ good energy resolution

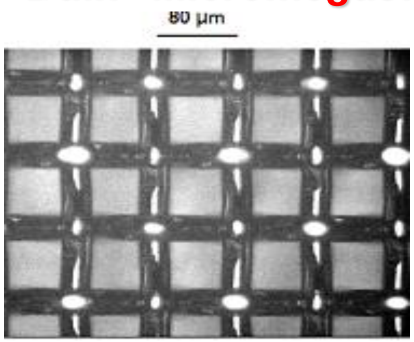


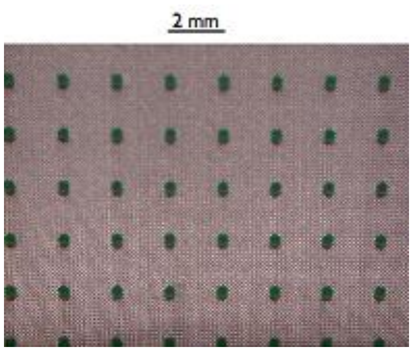
J. Derre et al, NIM A459 (2001) 523

CAST readout:

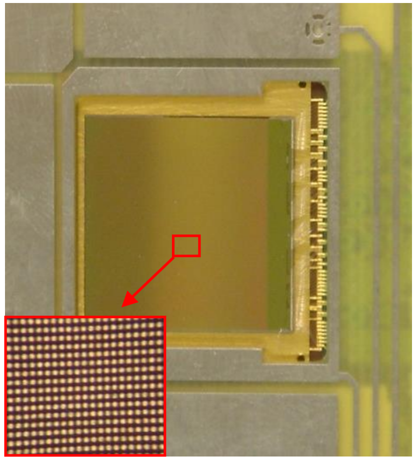


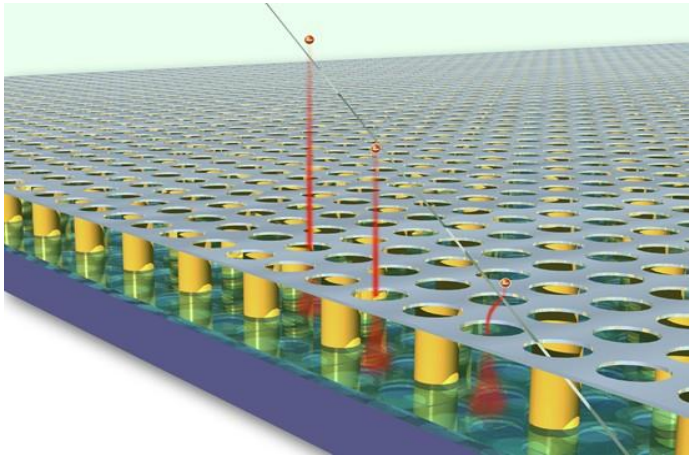
"Bulk" Micromegas:





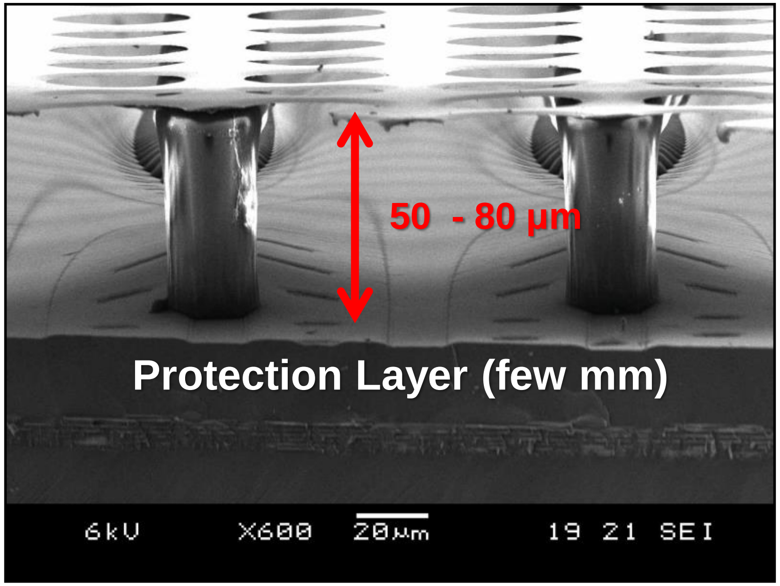
- **"InGrid" Concept**: By means of advanced wafer processing-technology INTEGRATE MICROMEGAS amplification grid directly (protection layer) on top of CMOS ("Timepix") ASIC
- **3D Gaseous Pixel Detector →** 2D (pixel dimensions) x 1D (drift time)

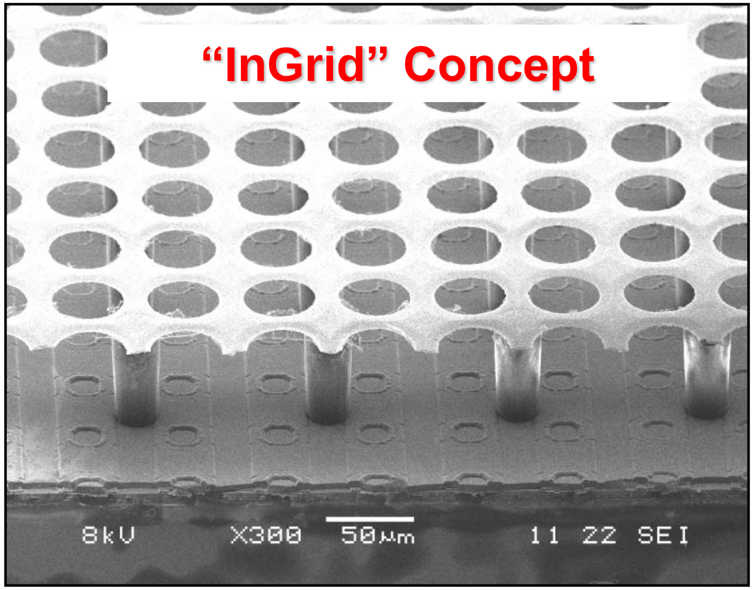




- Bump bond pads for Si-pixel
- Detectors - Timepix or Medipix2 (256 × 256 pixels of size 55 × 55 μm2) serve as charge collection pads.

- Each pixel can be set to:
  TOT ≈ integrated charge
  TIME = Time between hit and shutter end



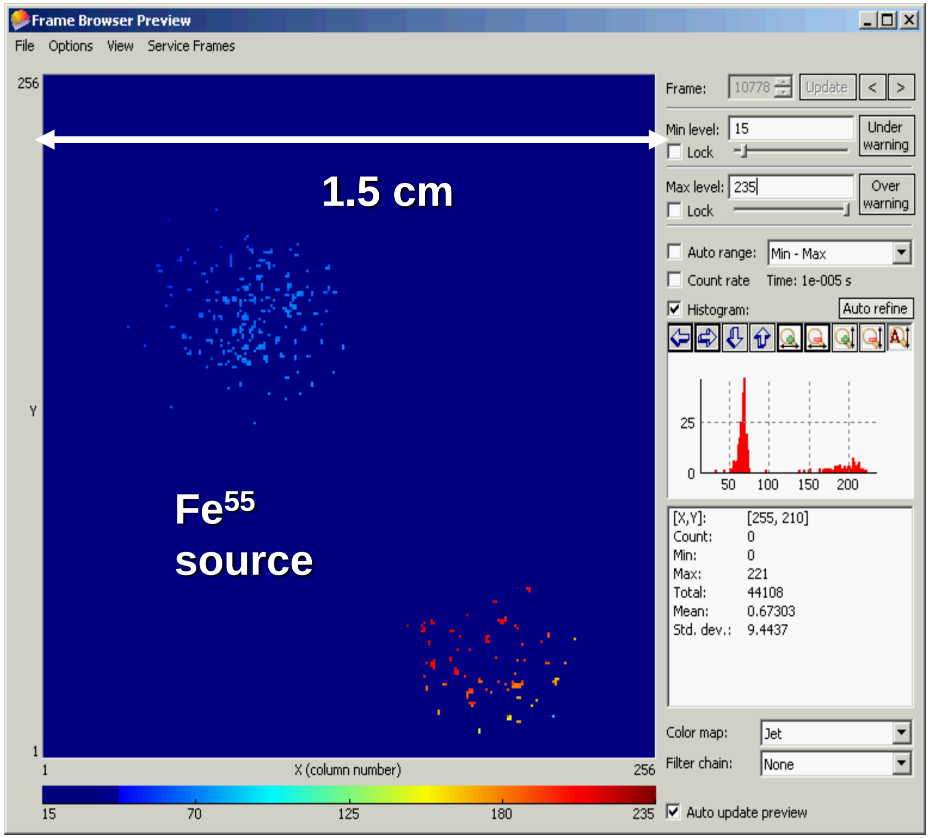


Observe electrons from an X-ray (5.9 keV) conversion one by one and count them in micro-TPC (6 cm drift)

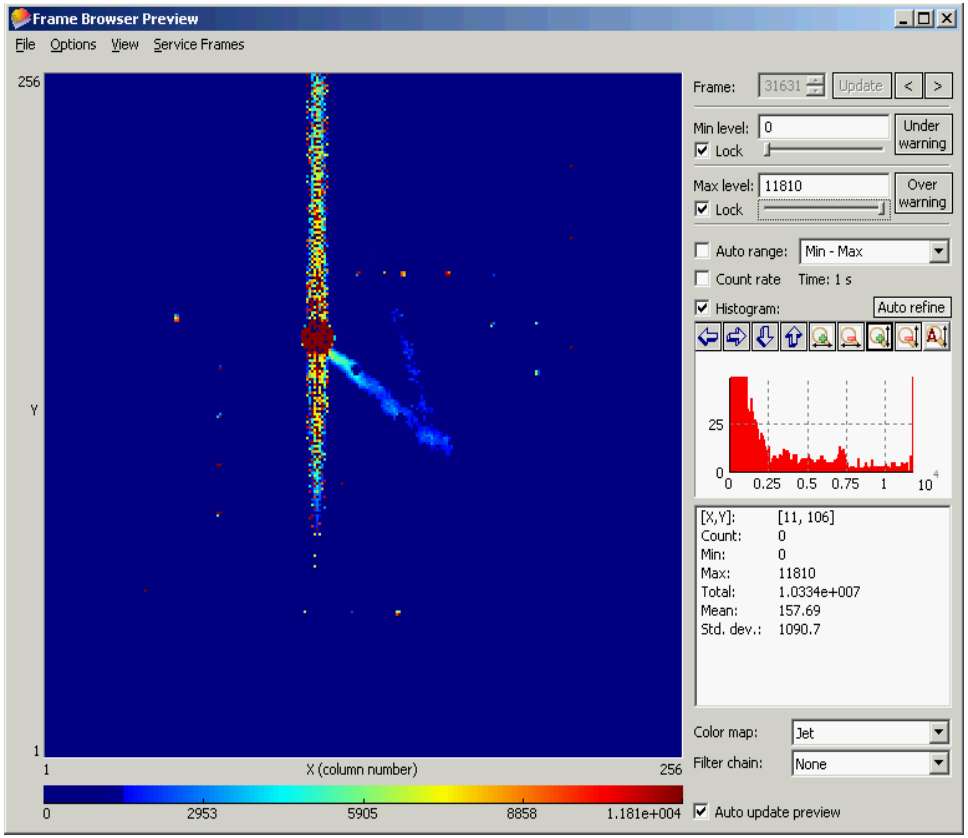
→ Study single electron response

Provoke discharges by introducing small amount of Thorium in the Ar gas - Thorium decays to Radon 222 which emits 2 alphas of 6.3 & 6.8 MeV

→ Round-shape images of discharges

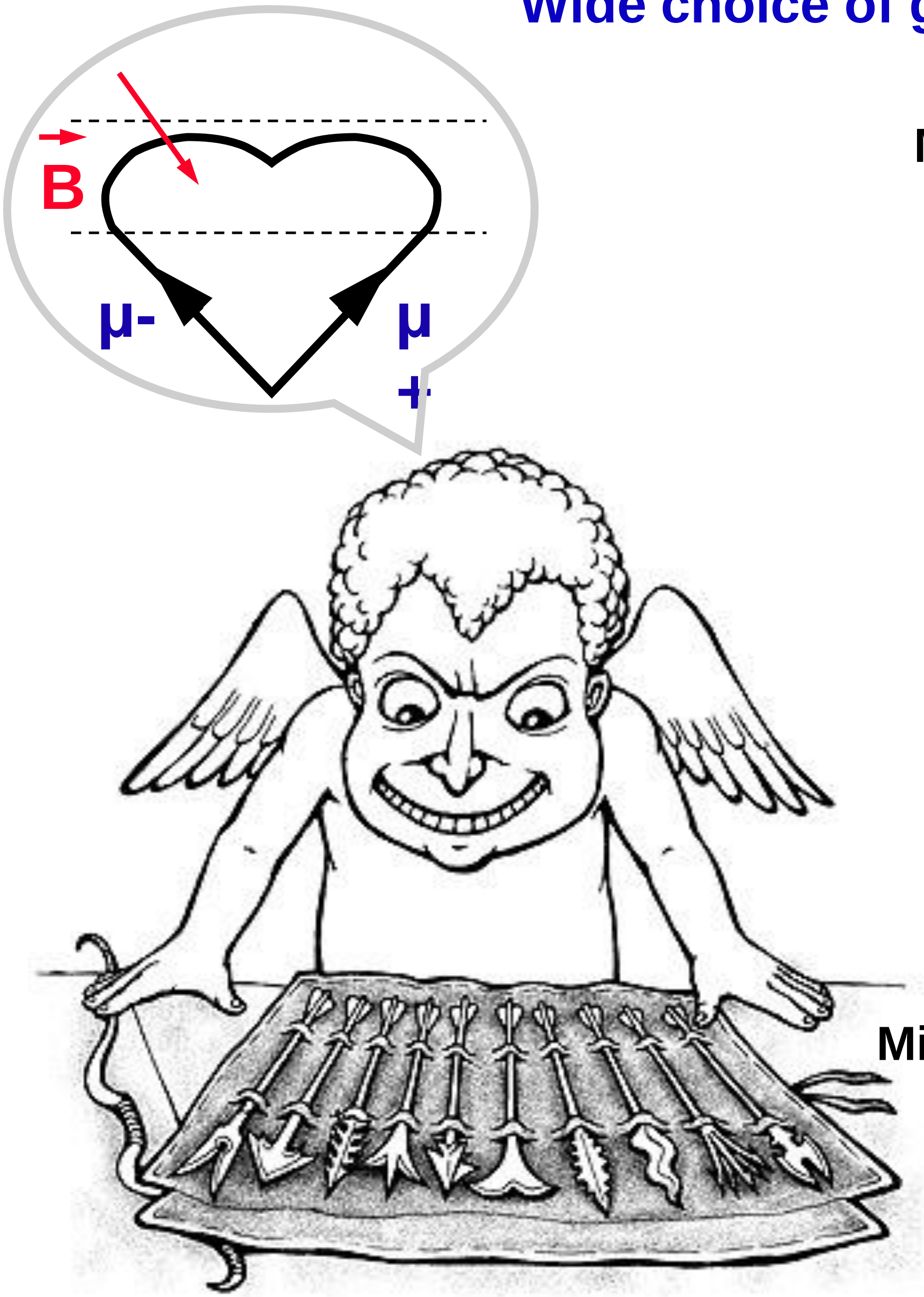


P. Colas, RD51 Collab. Meet., Jun.16-17, 2009, WG2 Meeting



M. Fransen, RD51 Collab. Meet., Oct.13-15, 2008, WG2 Meeting

Wide choice of gaseous detectors

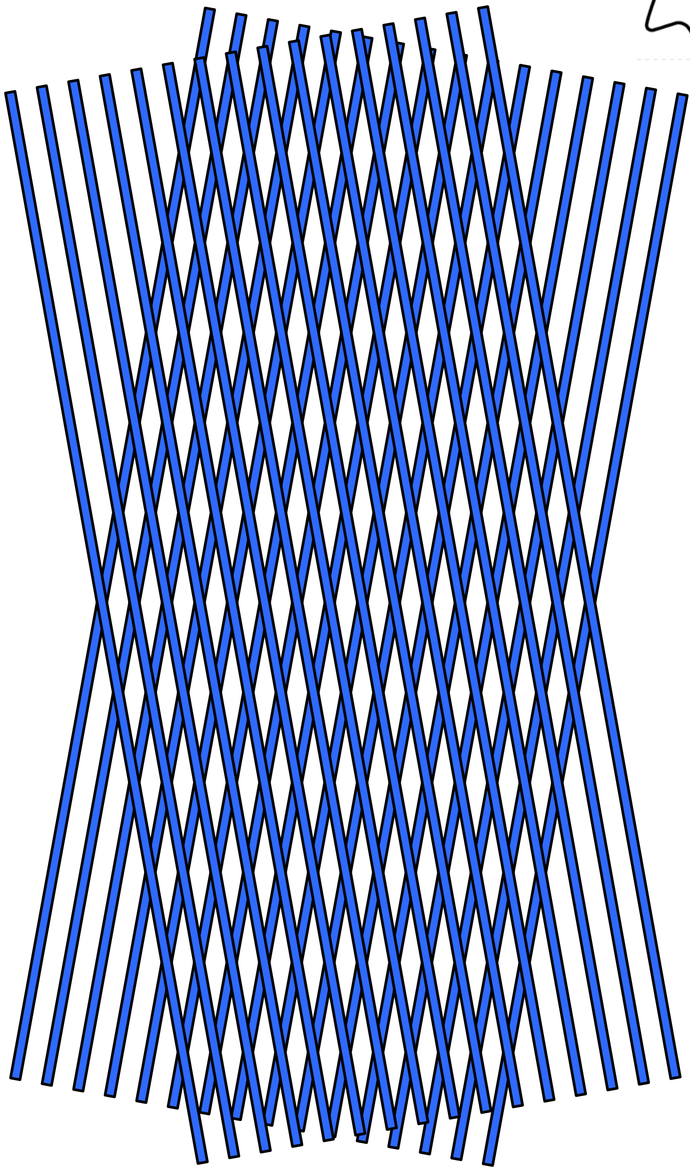


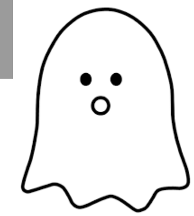
Multi Wire Proportional Chambers MWPC
Time Projection Chambers
Time Expansion Chambers
Proportional Chambers
Thin Gap Chambers
Drift Chambers
Jet Chambers
Straw Tubs
Micro Well Chambers
Cathode Strip Chambers
Resistive Plate Chambers
Micro Strip Gas Chambers
GEM - Gas Electron Multiplier
Micromegas – Micromesh Gaseous Structure

…

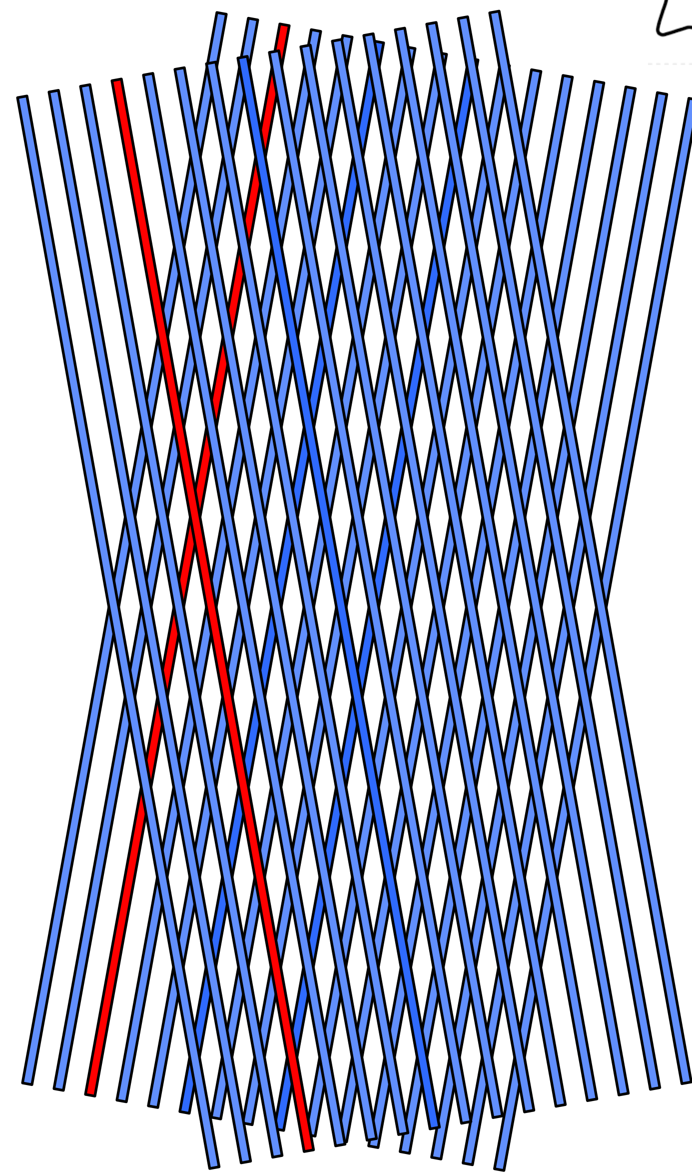
O. Ullaland

- Track reconstruction with straw-tube layers

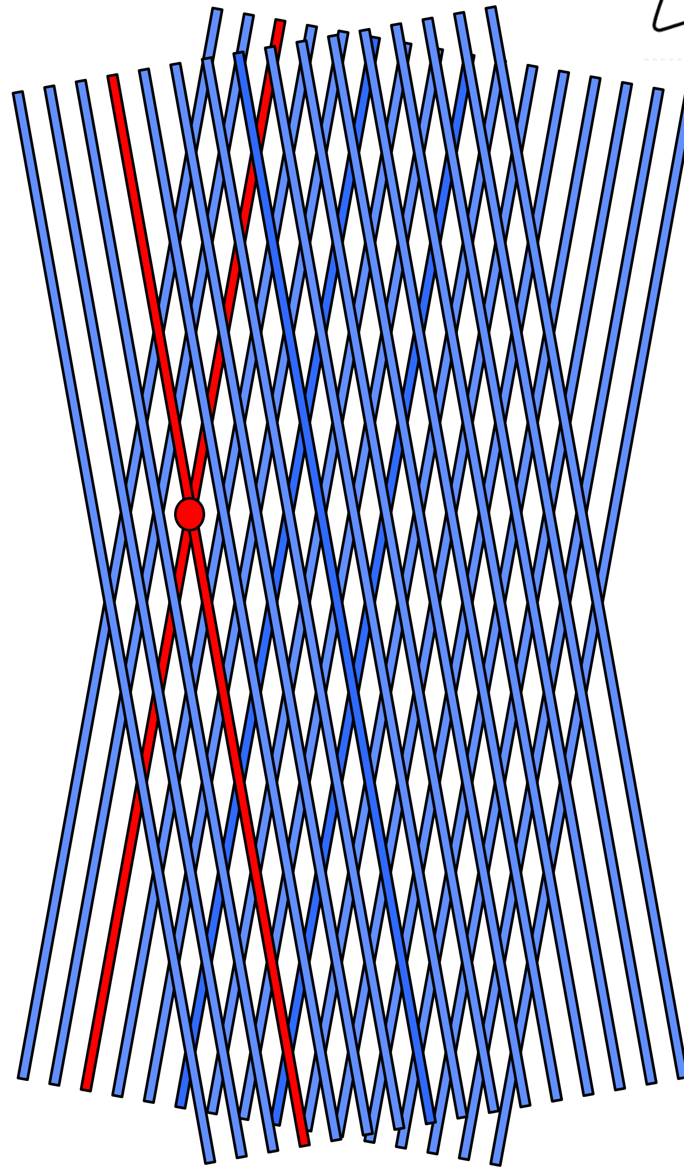




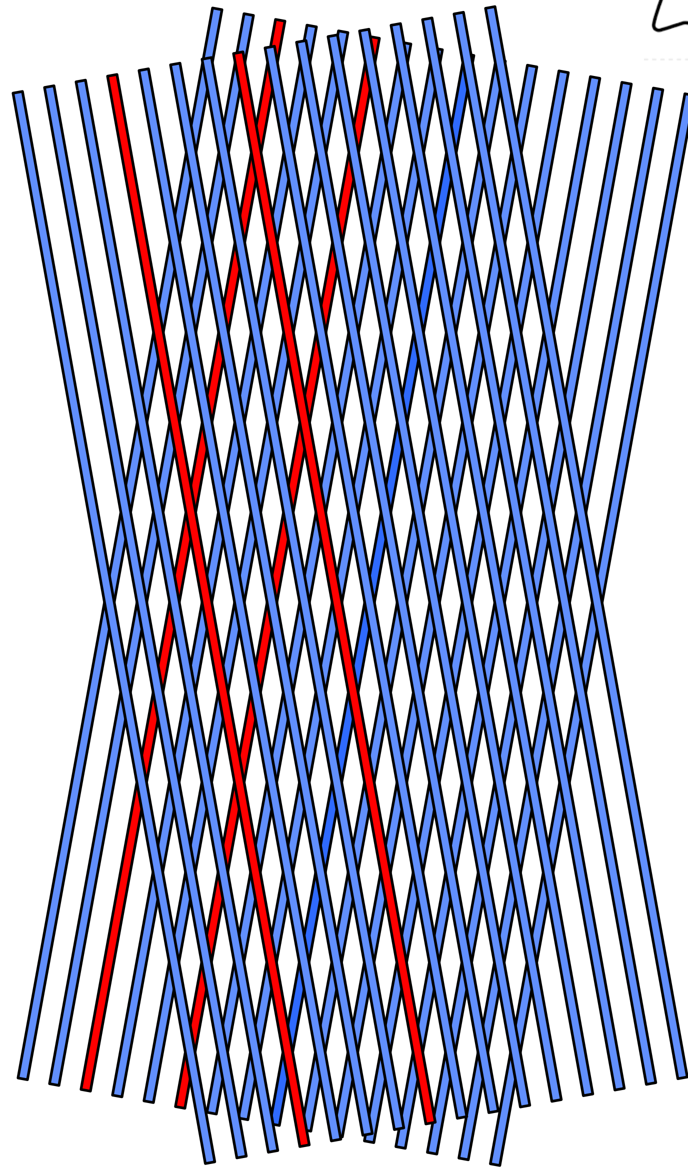
- Track reconstruction with straw-tube layers
- Two tubes fired



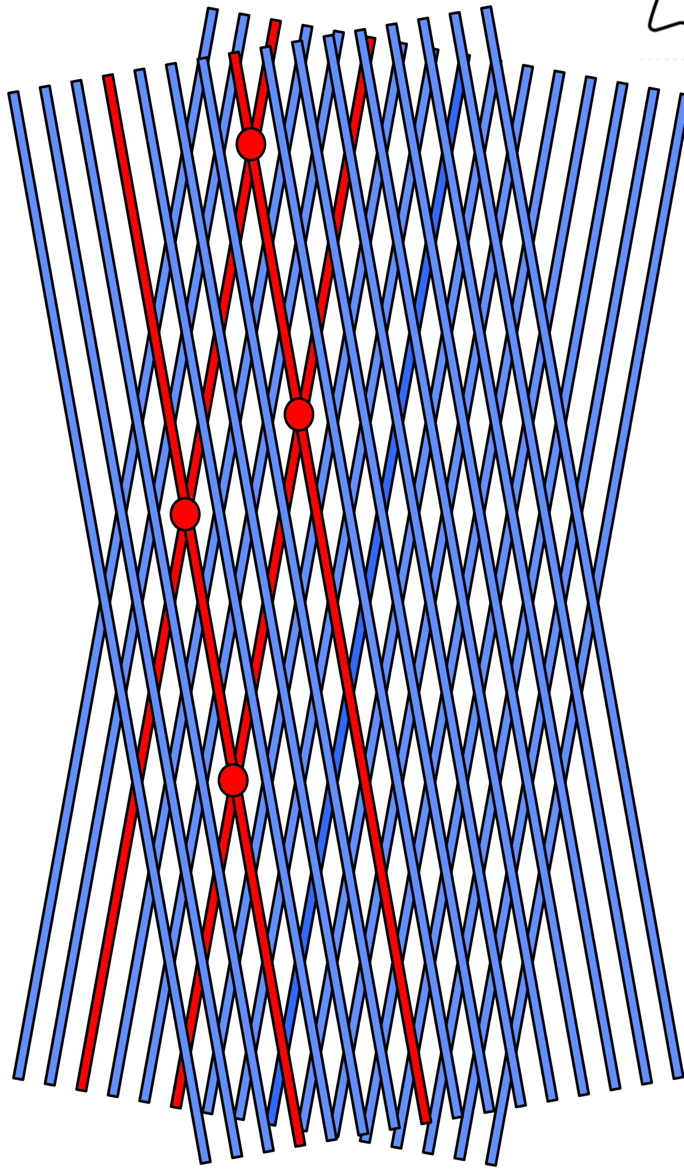
- Track reconstruction with straw-tube layers
- Two tubes fired
- How many tracks crossed the double layer ?



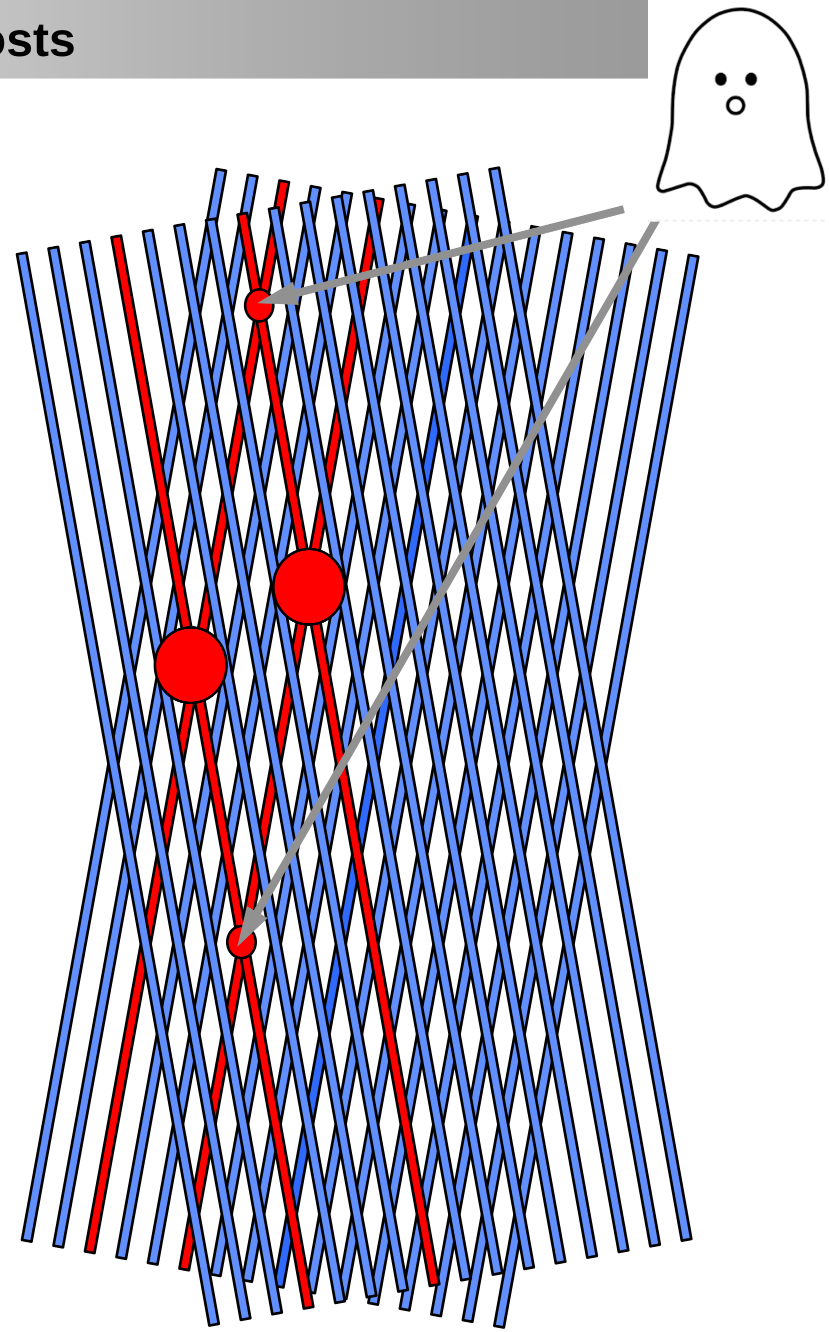
- Track reconstruction with straw-tube layers
- Four tubes fired

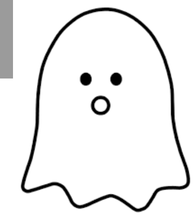


- Track reconstruction with straw-tube layers
- Four tubes fired
- How many tracks crossed the double layer ?

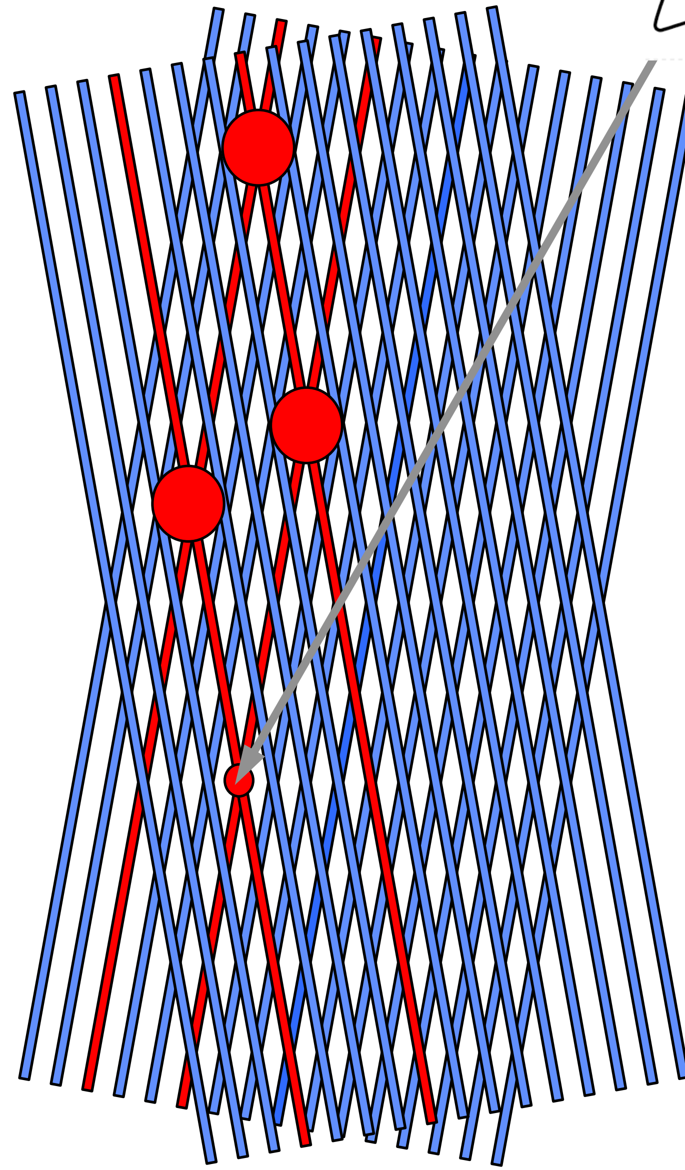


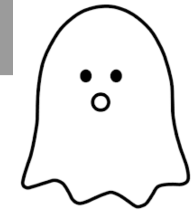
- Track reconstruction with straw-tube layers
- Four tubes fired
- How many tracks crossed the double layer ?
- 2 ?



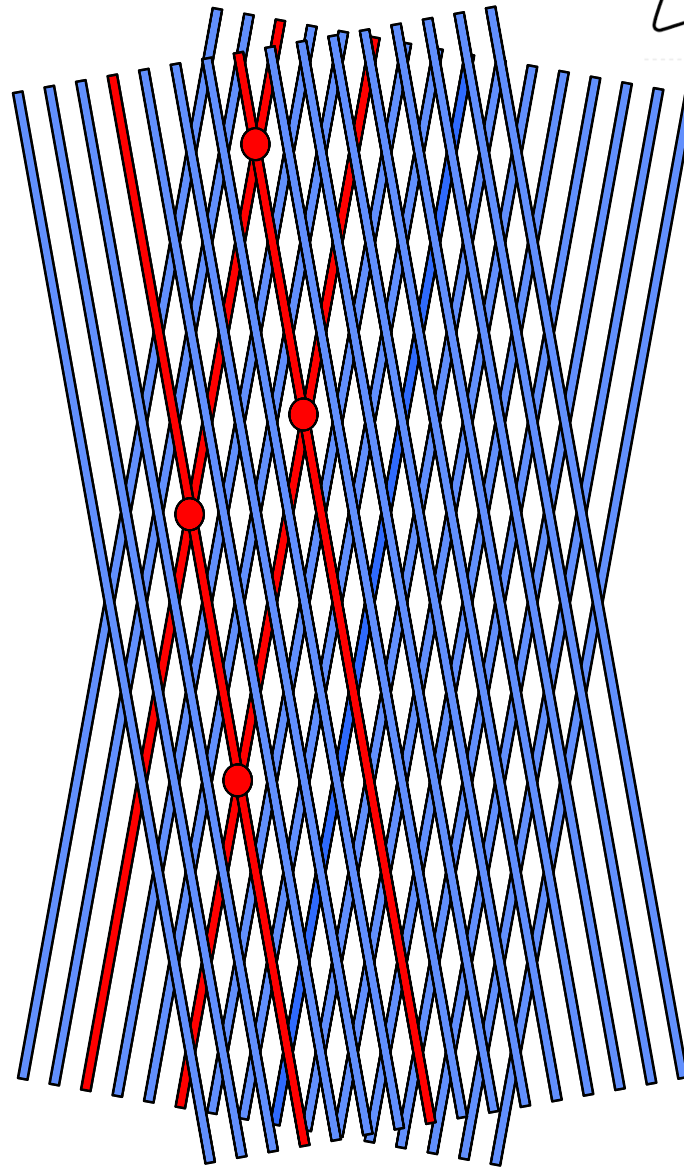


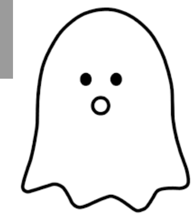
- Track reconstruction with straw-tube layers
- Four tubes fired
- How many tracks crossed the double layer ?
- 3 ?



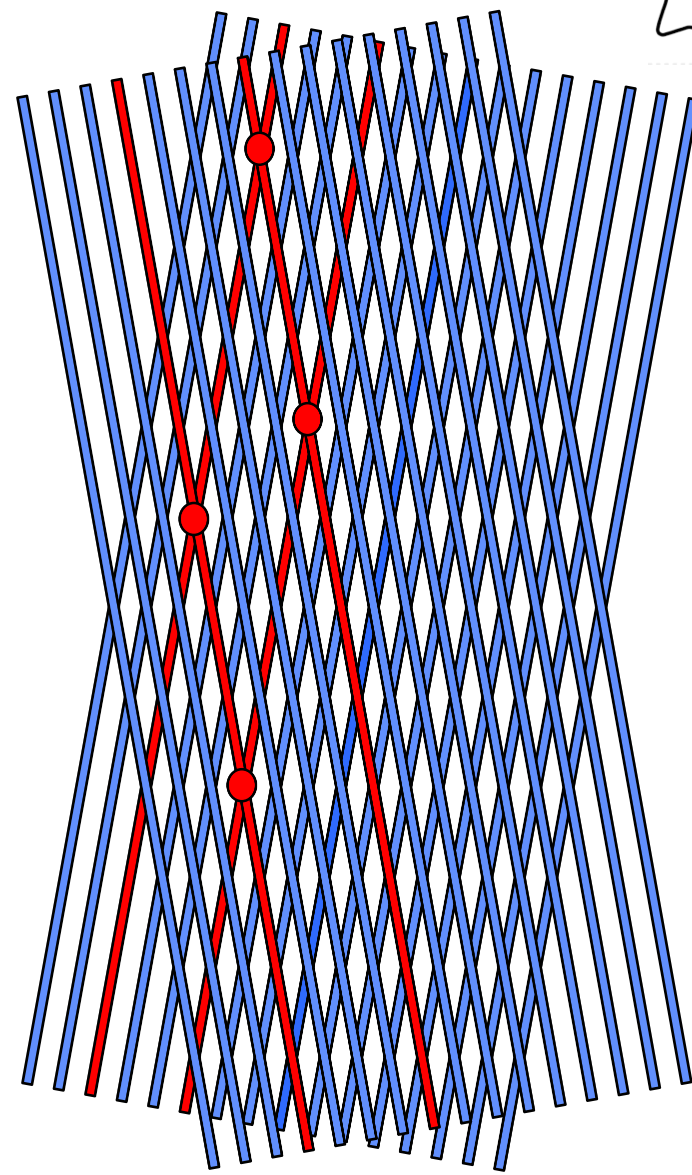


- Track reconstruction with straw-tube layers
- Four tubes fired
- How many tracks crossed the double layer ?
- More information needed !

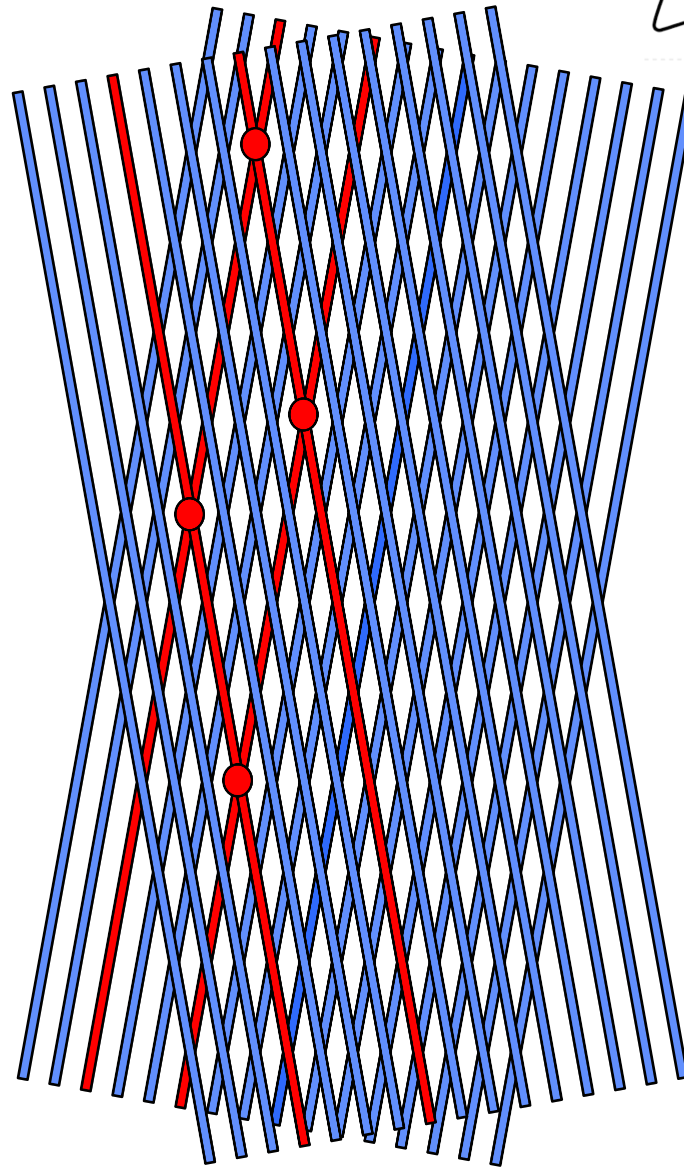


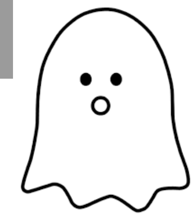


- Track reconstruction with straw-tube layers
- Four tubes fired
- How many tracks crossed the double layer ?
- More information needed
- Add another layer !

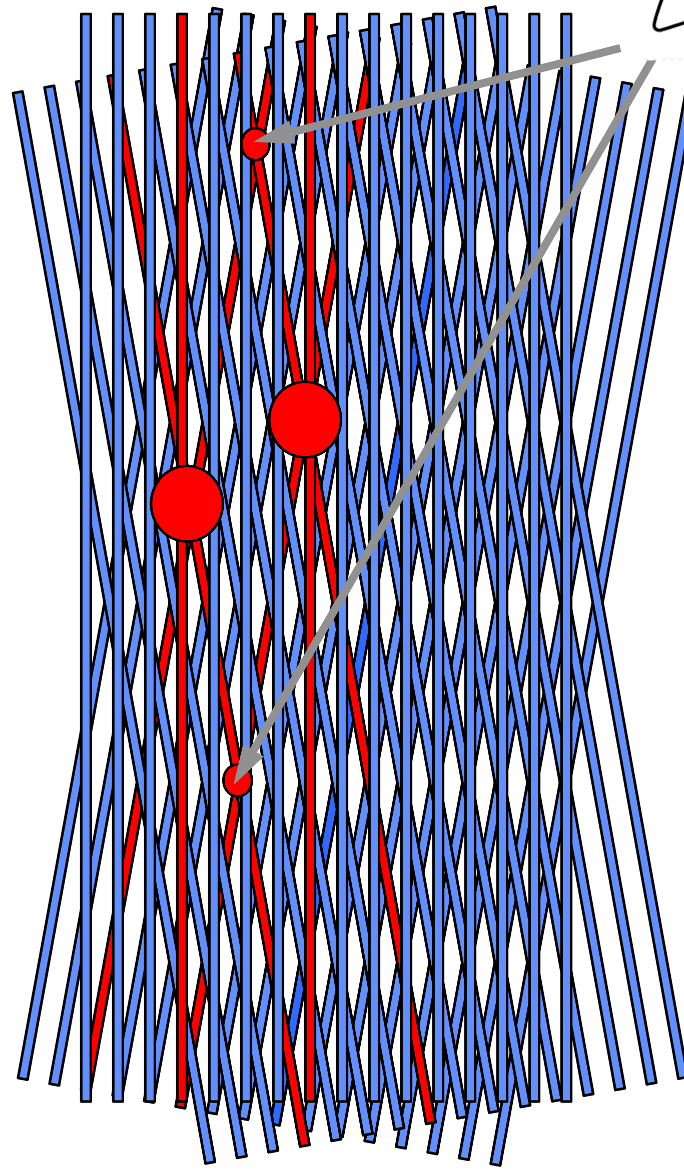


- ❑ **Track reconstruction with straw-tube layers**
- ❑ **Four tubes fired**
- ❑ **How many tracks crossed the double layer ?**
- ❑ **More information needed**
- ❑ **Add another layer**
- ❑ **How many tubes can be fired in the third layer ?**

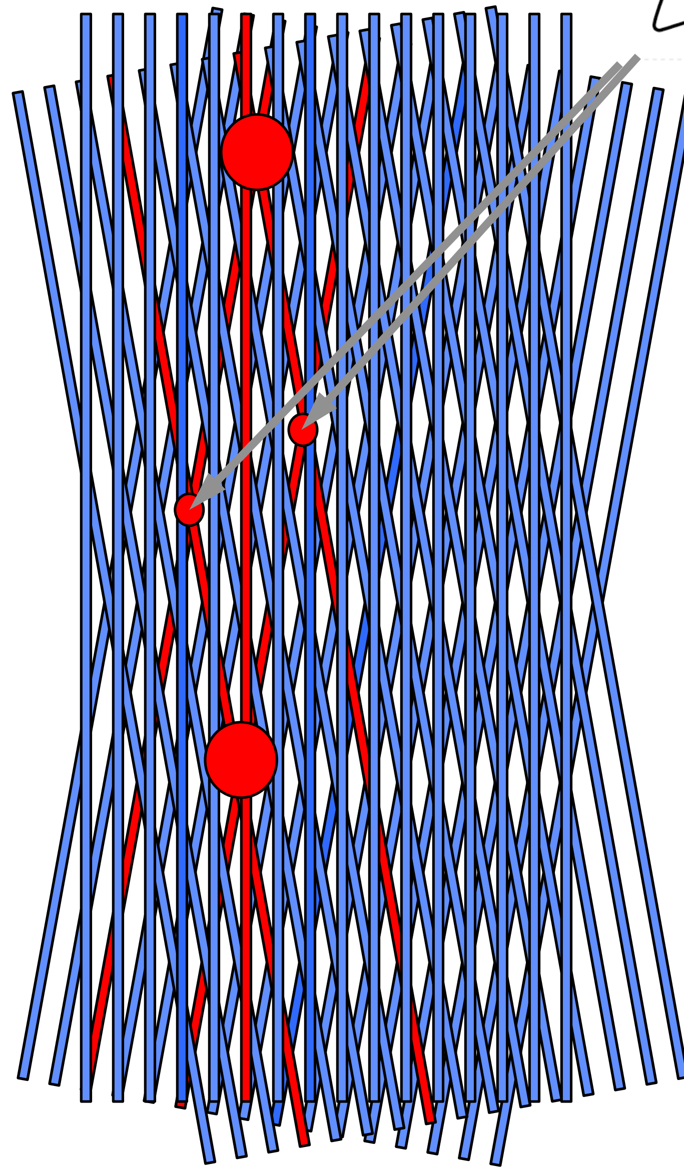


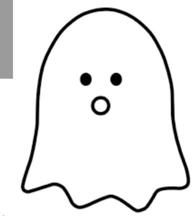


- Track reconstruction with straw-tube layers
- Four tubes fired
- How many tracks crossed the double layer ?
- More information needed
- Add another layer
- How many tubes can be fired in the third layer ?
- 2 ?

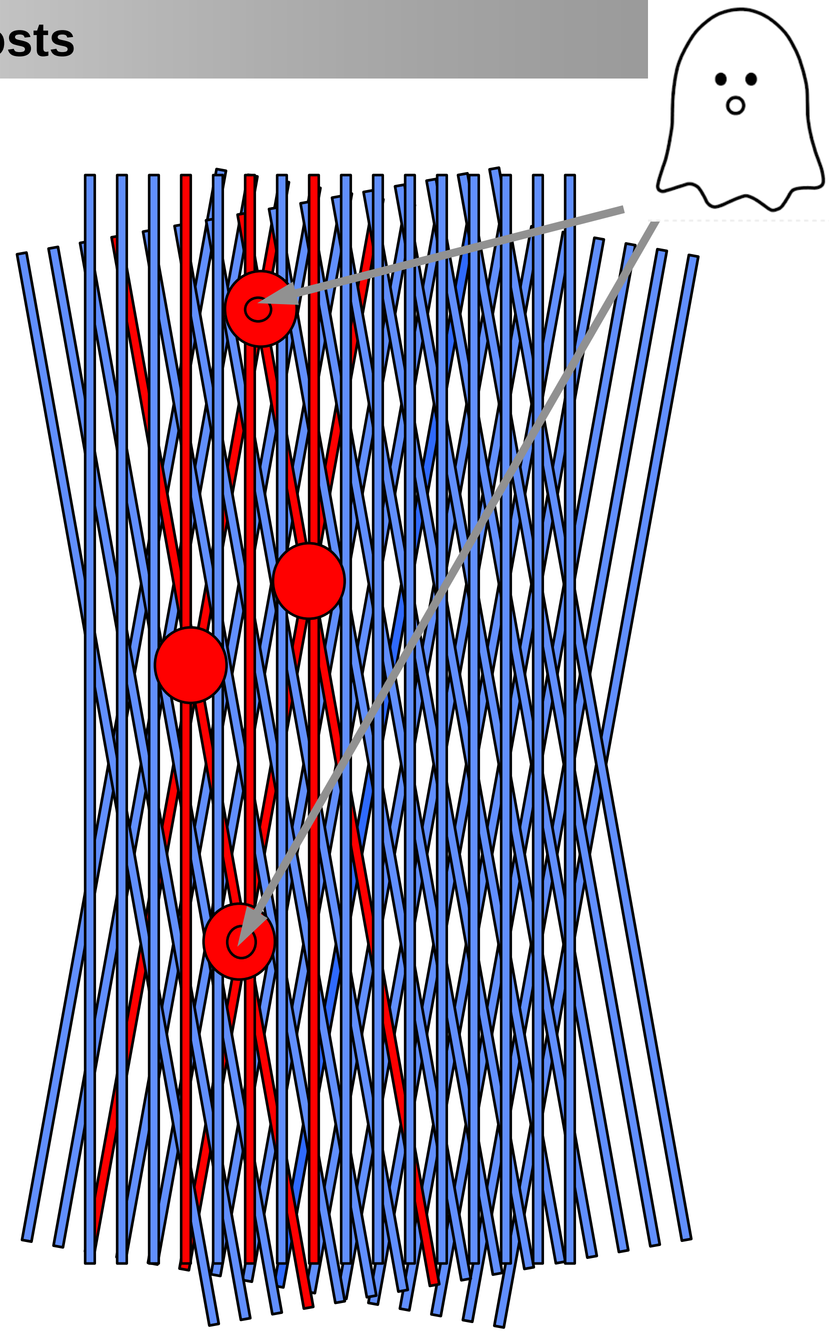


- Track reconstruction with straw-tube layers
- Four tubes fired
- How many tracks crossed the double layer ?
- More information needed
- Add another layer
- How many tubes can be fired in the third layer ?
- 1 ?

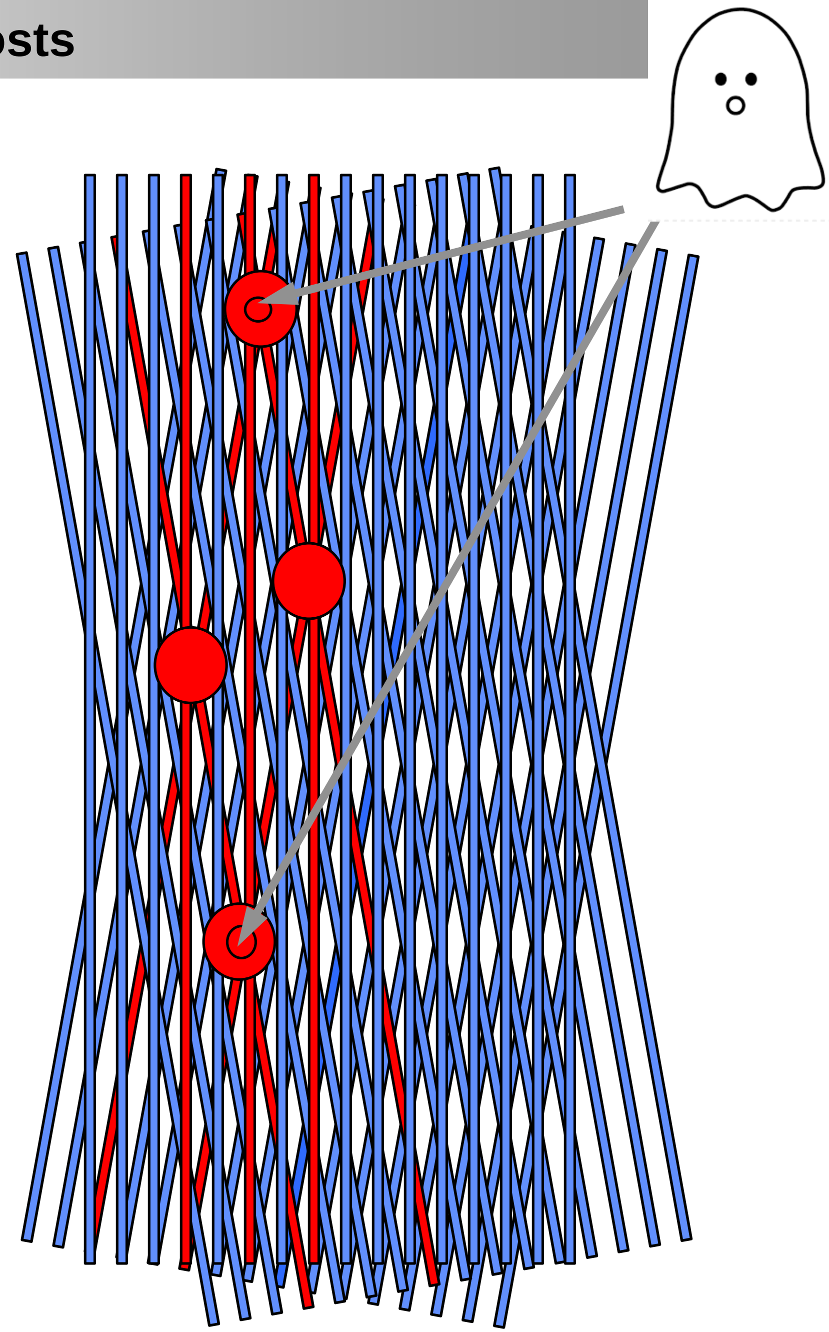




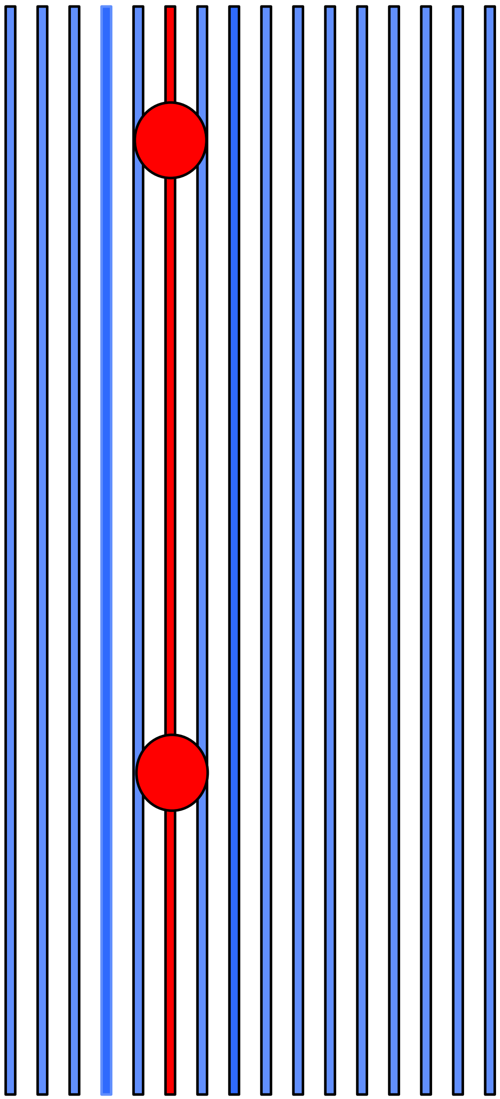
- ❑ **Track reconstruction with straw-tube layers**
- ❑ **Four tubes fired**
- ❑ **How many tracks crossed the double layer ?**
- ❑ **More information needed**
- ❑ **Add another layer**
- ❑ **How many tubes can be fired in the third layer ?**
- ❑ **3 ?**



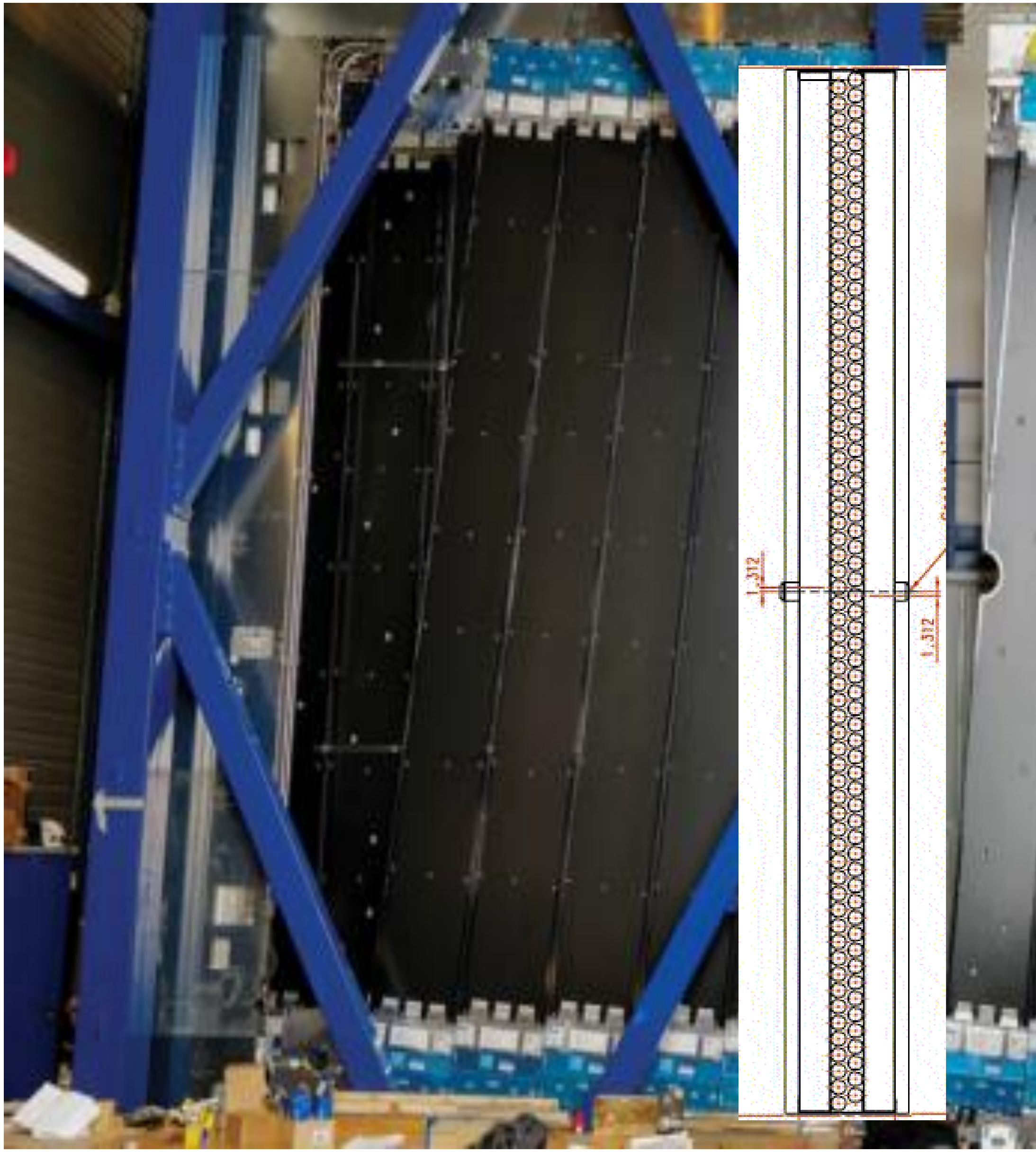
- **Homework:**
  - **Play the game with two stereo layers and six fired tubes**
  - **Add a “noisy” tube**



- **Homework:**
  - **And how about a single layer of tubes ?**



Q: how to choose between straw-tube and scintillating-fibers tracker ?



With that we are at **the end** of a (fast) lecture series on instrumentation.

You are supposed to retain from these lectures :

- Instrumentation by itself is a fascinating area
- However, instrumentation is a tool; it should be considered only in view of a targeted physics
- Conceptual comprehension of the instrumentation is essential, even for a theorist ☺
- There is a big variety of techniques for each method … the choice is often modulated by optimization of performance-background conditions-reliability-…-cost
- Complex detector is often designed for many physics tasks, detector choice is sometimes a compromise between their requirements

  → requires cross-detector optimization

  e.g. : tracking precision vs. material in front of calorimeter

  → requires often detailed simulation, and always understanding/experience of physics analysis and instrumentation techniques

  → requires simultaneous optimization of the whole chain : detector – front-end electronics – trigger/readout
- Despite increasing complexity of detector systems, you can still have a pleasure working on it, and there is still much room for bright original ideas

Selected reading

- C. Grupen, Particle Detectors, Cambridge University Press, 1996
- C. Grupen, I. Buvat, Handbook of Particle Detection and Imaging, Springer Verlag 2012
- G. Knoll, Radiation Detection and Measurement, 3rd ed. Wiley, 2000
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- Experimental techniques in high energy physics, T. Ferbel (editor), World Scientific, 1991.
- Instrumentation in High Energy Physics, F. Sauli (editor), World Scientific, 1992.