TRACKING DETECTORS

Lecture 1

Basics: propagation of particles in media and measurements

Lecture 2

Main tracking detector concepts and examples of their use

Lecture 3

Overview of muons systems at collider experiments

Main design considerations

spatial resolution

two-track spatial resolution

time resolution

response time

dead time (two-track time resolution)

enhanced charged particle id capabilities

radiation hardness

COST

Tracking detector concepts

Gaseous wire chambers
- PC, MWPC, DT, MWDC, CSC, adding 2nd coordinate

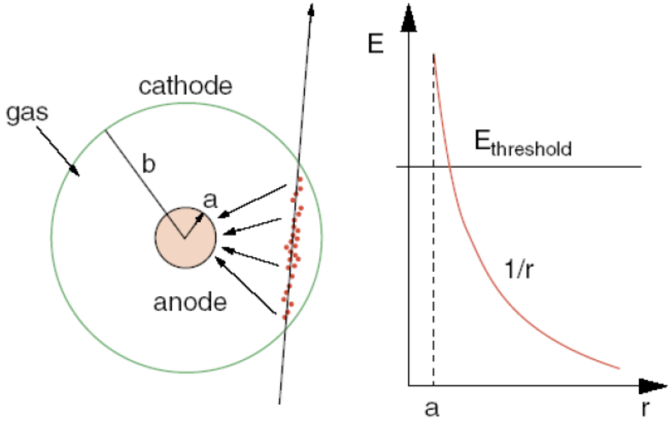
Gaseous wireless chambers:
- RPC, GEM, MSGC, …

Solid state detectors:
- scintillators, semiconductors

Wire chambers: proportional tube and gas multiplication

Recall: 100 e/cm – too few to detect directly

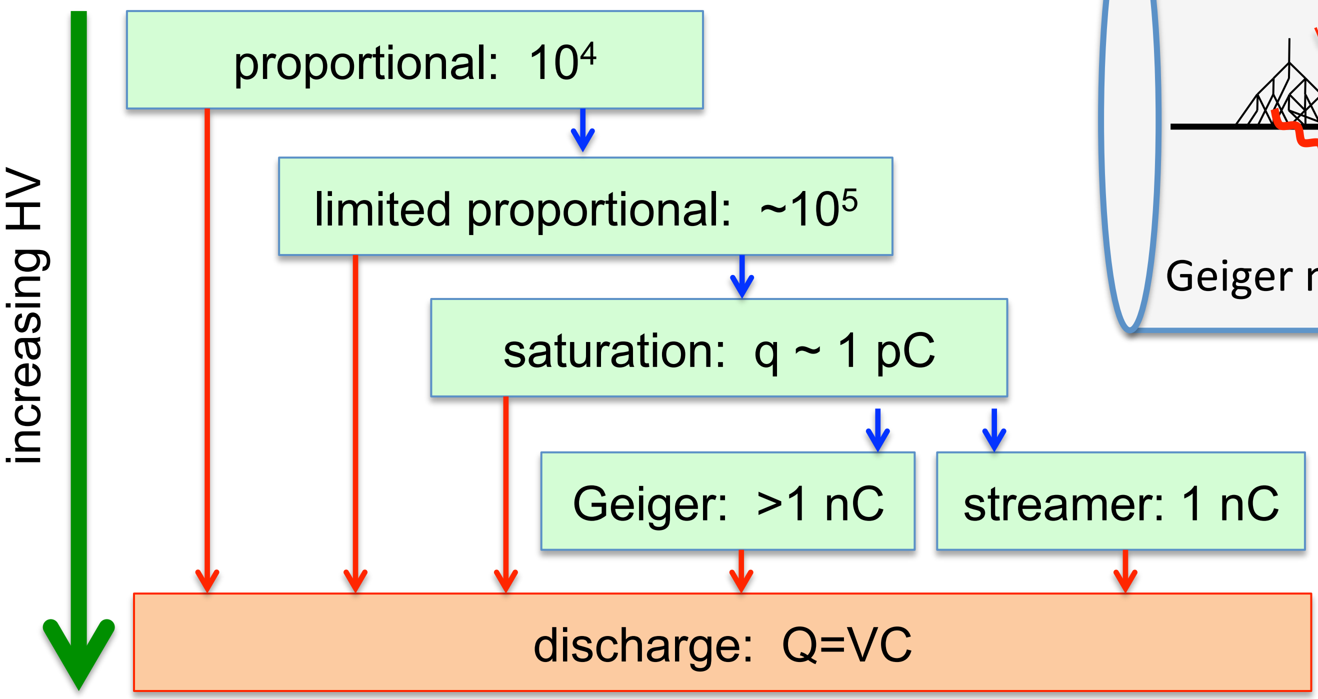
Solution (invented by Rutherford)**:**
introduce thin wires (typically, 20-100 μm) at positive high potential (typically, a few kV) for gas multiplication

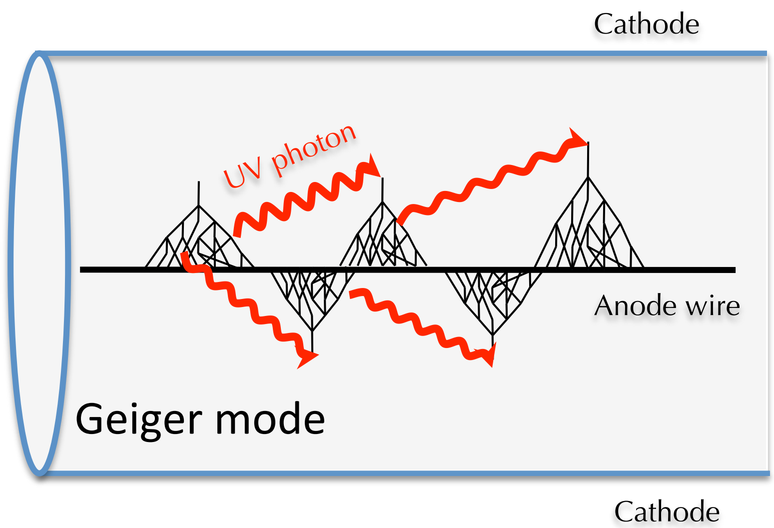


- Electric field E ~ 1/r
- In vicinity of the wire, electrons get sufficient energy between collisions to ionize gas
- Avalanche develops with the overall multiplication (gas gain) controllable by tuning high voltage

Wire chambers: gas gain

Gas gain regimes





Maximal gas gain before onset of a discharge depends on amount of quenching gas.
Gas efficient in absorption of UV is called quenching gas (e.g. organic molecules).

Wire chambers: role of avalanche ions

Avalanche starts and ends in 2-3 ns

Amplifier gets only 1-2% of a signal over this time

The bulk of electrons sit on the anode wire held there by the cloud of positive ions.

Ions with total charge Q slowly drift away from a wire.

Correspondingly electrons migrate from the wire to the cathode via the power supply and amplifier. The amplifier sees current

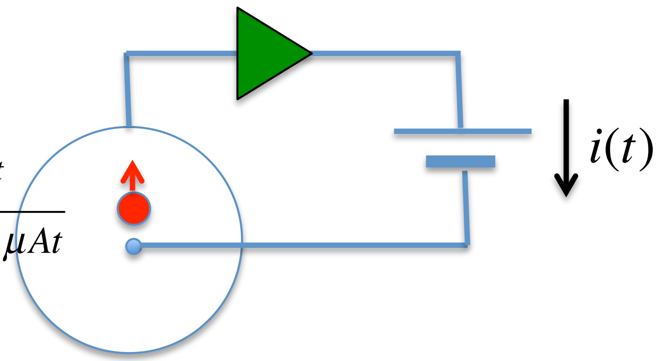
$$i(t) = \frac{i_0}{1 + t/\tau_0}$$

$$v = \mu E$$

$$\frac{dr}{dt} = \mu \frac{A}{r}$$

$$r \cdot dr = \mu A \cdot dt$$

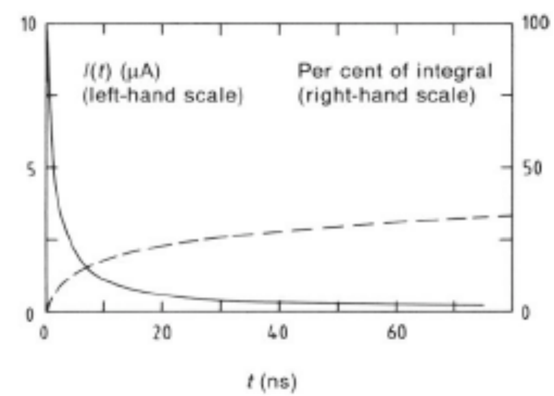
$$r(t) = \sqrt{r_0^2 + 2\mu A t}$$



$$\Delta U = QE(r) \cdot dr = Q\frac{A}{r} \cdot \mu \frac{A}{r} dt = Q\frac{A^2}{r_0^2 + 2\mu A t} dt$$

$$\Delta U = V \cdot dq = Vi \cdot dt$$

$$i(t) = Q\frac{A^2}{2V} \cdot \frac{1}{r_0^2 + 2\mu A t}$$



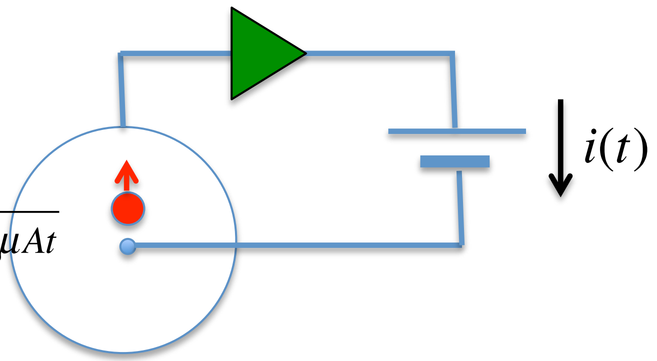
Wire chambers: role of avalanche ions

$$v = \mu E$$

$$\frac{dr}{dt} = \mu \frac{A}{r}$$

$$r \cdot dr = \mu A \cdot dt$$

$$r(t) = \sqrt{r_0^2 + 2\mu A t}$$



Avalanche starts and ends in 2-3 ns

Amplifier gets only 1-2% of a signal over this time

The bulk of electrons sit on the anode wire held there by the cloud of positive ions.

Ions with total charge Q slowly drift away from a wire.

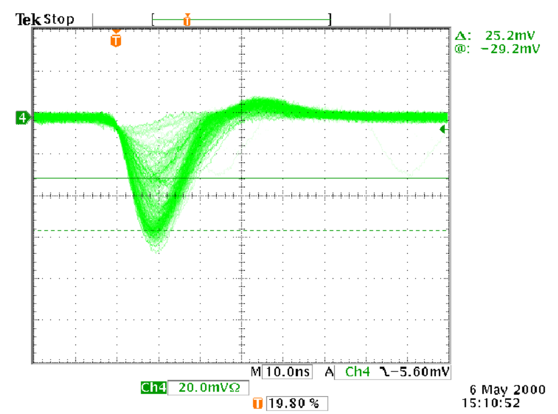
$$\Delta U = QE(r) \cdot dr = Q\frac{A}{r} \cdot \mu \frac{A}{r} dt = Q\frac{A^2}{r_0^2 + 2\mu A t} dt$$

$$\Delta U = V \cdot dq = Vi \cdot dt$$

$$i(t) = Q\frac{A^2}{2V} \cdot \frac{1}{r_0^2 + 2\mu A t}$$

Correspondingly electrons migrate from the wire to the cathode via the power supply and amplifier. The amplifier sees current

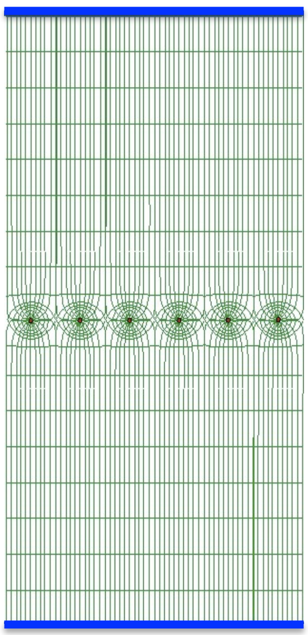
$$i(t) = \frac{i_0}{1 + t/\tau_0}$$



To suppress a very long tail (~ms!), amplifiers are used with proper RC-filter with RC>100 ns (quiz: why not much shorter?)

Wire chambers:
Multi-Wire Proportional Chambers (MWPC)

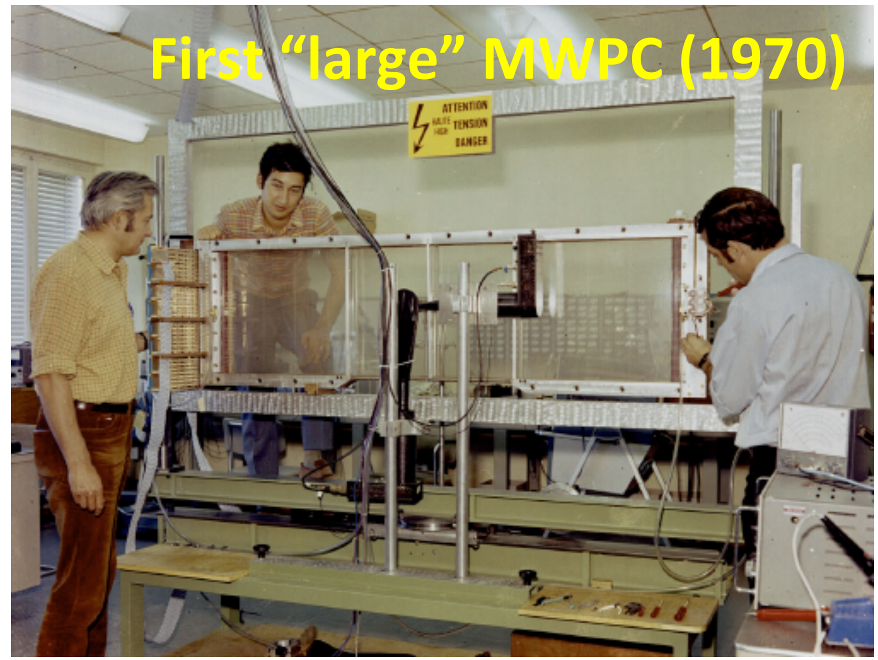
Multi-wire proportional chamber (invented by Charpak, Nobel Prize in 1992)



plane of thick cathode wires

plane of anode wires

plane of thick cathode wires

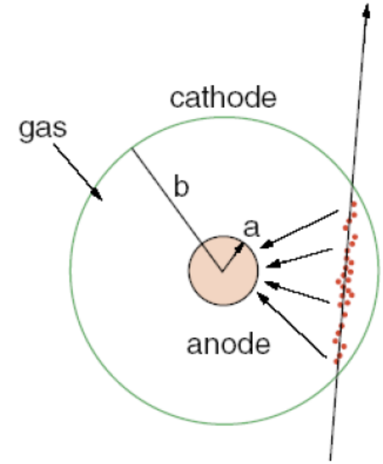


Typical geometry: anode-cathode gap is 5 mm
20 μm anode wires, 1-2 mm pitch
Yes/No readout: 1-2 mm / sqrt(12) = 300-600 μm

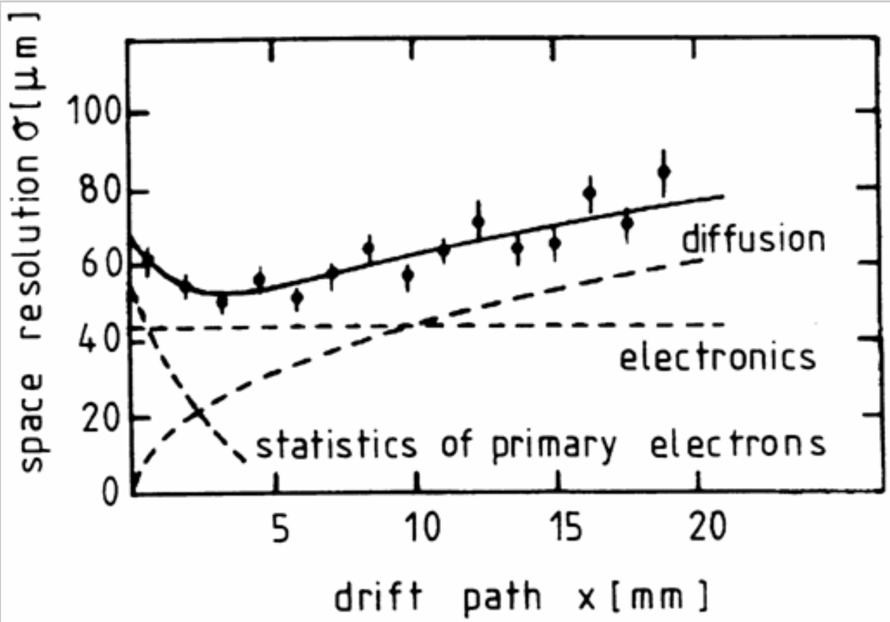
Wire chambers:
Simple Drift Tubes

Concept:

- know when particles go through detector (t_0):
- measure drift time: $\Delta t = t_{signal} - t_0$
- drift distance: $x = f(\Delta t)$
- with saturated drift velocity (independent of E), calibration of $x = f(\Delta t)$ is much easier



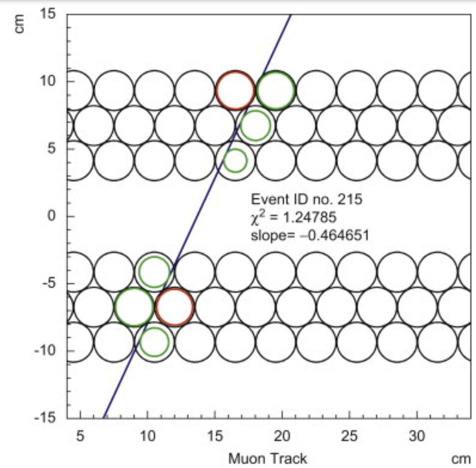
- Typical resolution of **100-200 μm**
- Some gases are better than others
- Increasing pressure helps, but makes maintenance more difficult

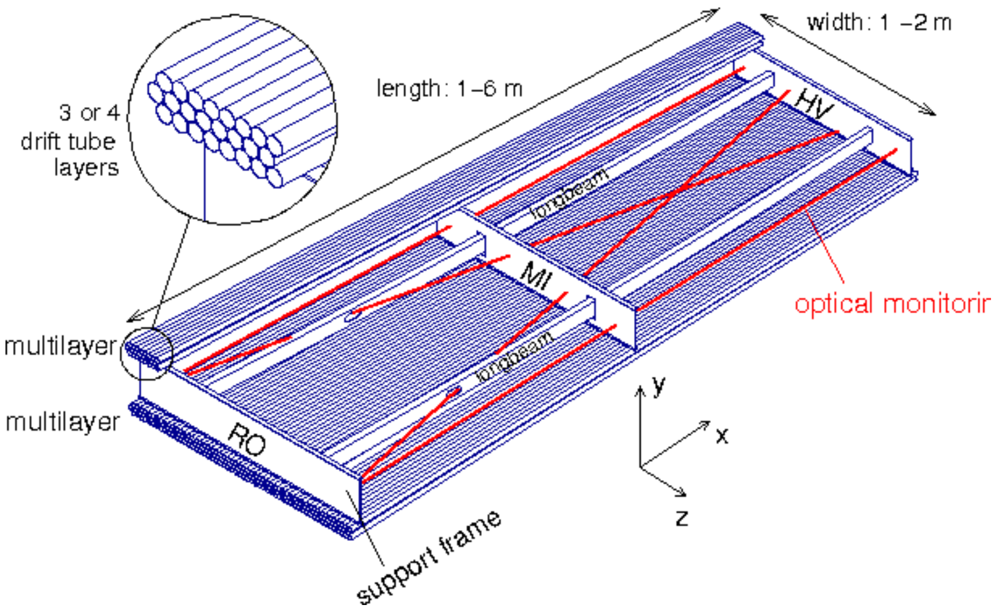


Wire chambers: Simple Drift Tubes

ATLAS muon chambers:

- 350K tubes
- gas volume 700 m^3
- pressure 3 bar (Ar+CO_2=93%+7%)
- spatial resolution 80 μm

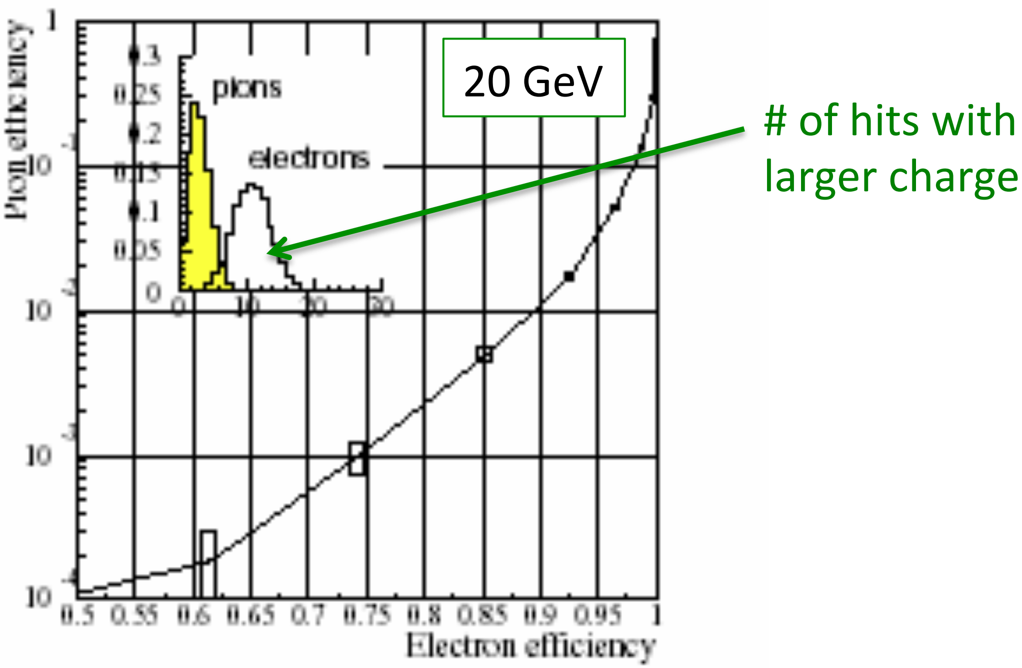


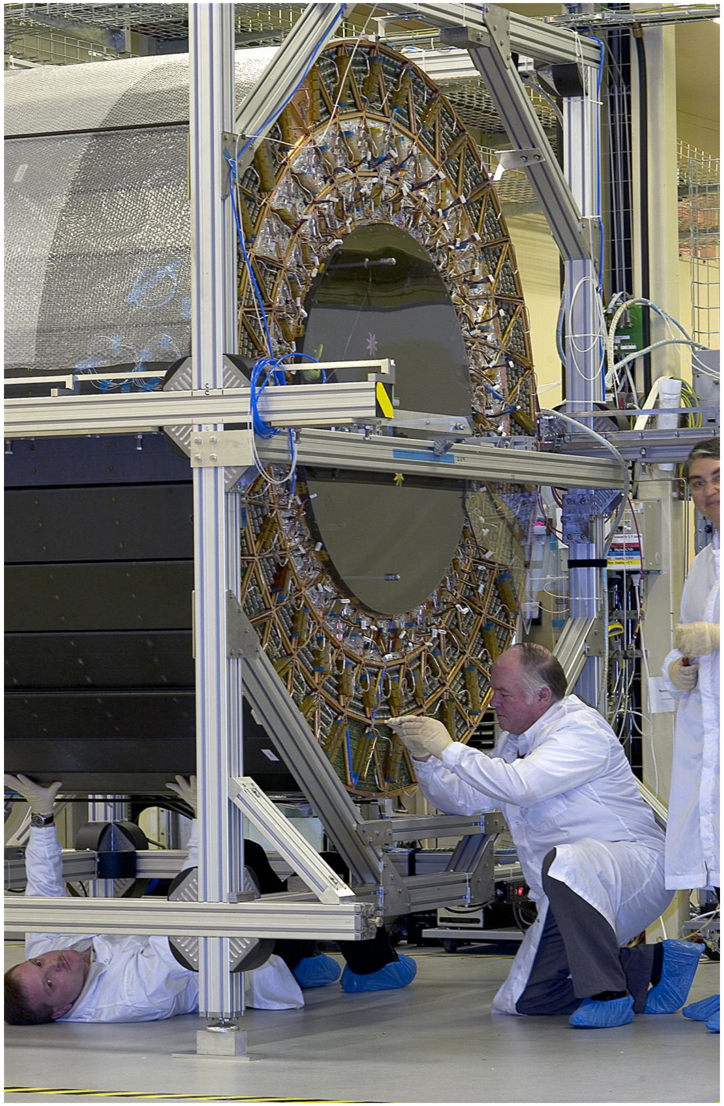


Wire chambers: Simple Drift Tubes with TRD capabilities

ATLAS Transition Radiation Tracker

- "straws": multilayer tubes, 4 mm in diameter
- 40 ns drift time
- spatial resolution 130 μm
- 36 straws per track
- Gas: $Xe+CO_2$

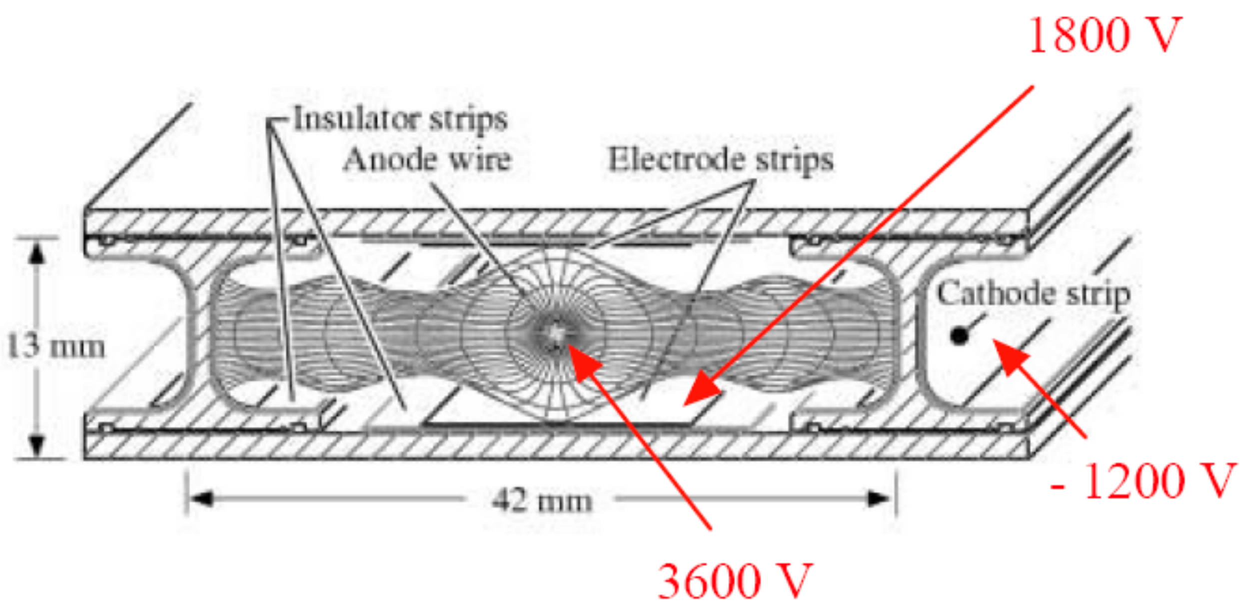




Wire chambers:
Drift Tubes with field shaping electrodes

Example: CMS barrel muon chambers

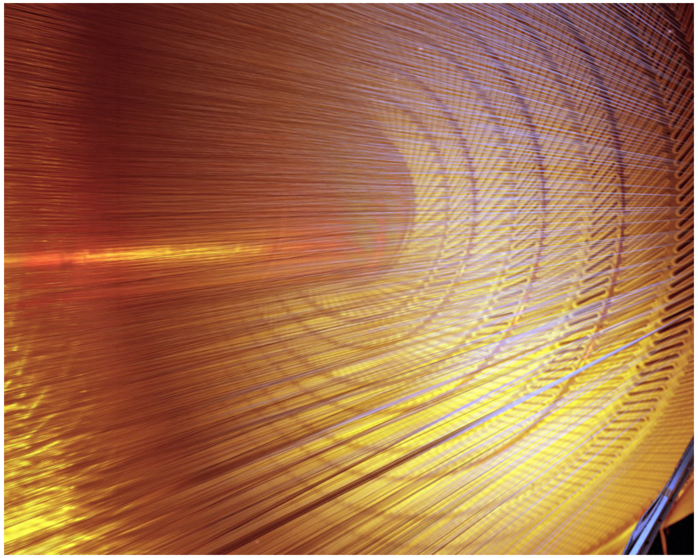
- 2 cm drift
- 250 μm spatial resolution

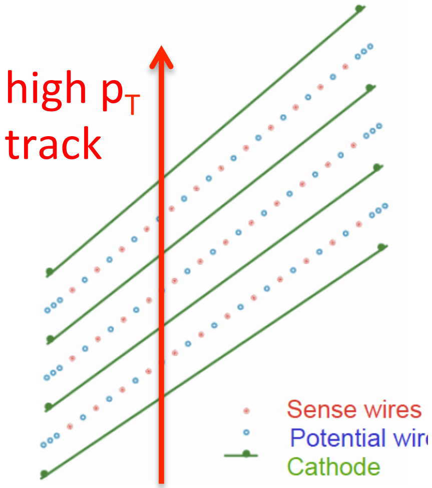


Wire chambers: Multi-Wire Drift Chambers

CDF Central Tracker

Figure 4. The COT during "stringing" of the wire planes and field sheets. The carbon composite inner cylinder, aluminum end plate (east) and aluminum outer cylinder are visible. Superlayers 1-5 have been strung and superlayer 6 is about half done. A wire plane is being inserted at 10:00 and a field plane at 4:00. Pre-tension fixtures are seen in superlayers 6 – 8.



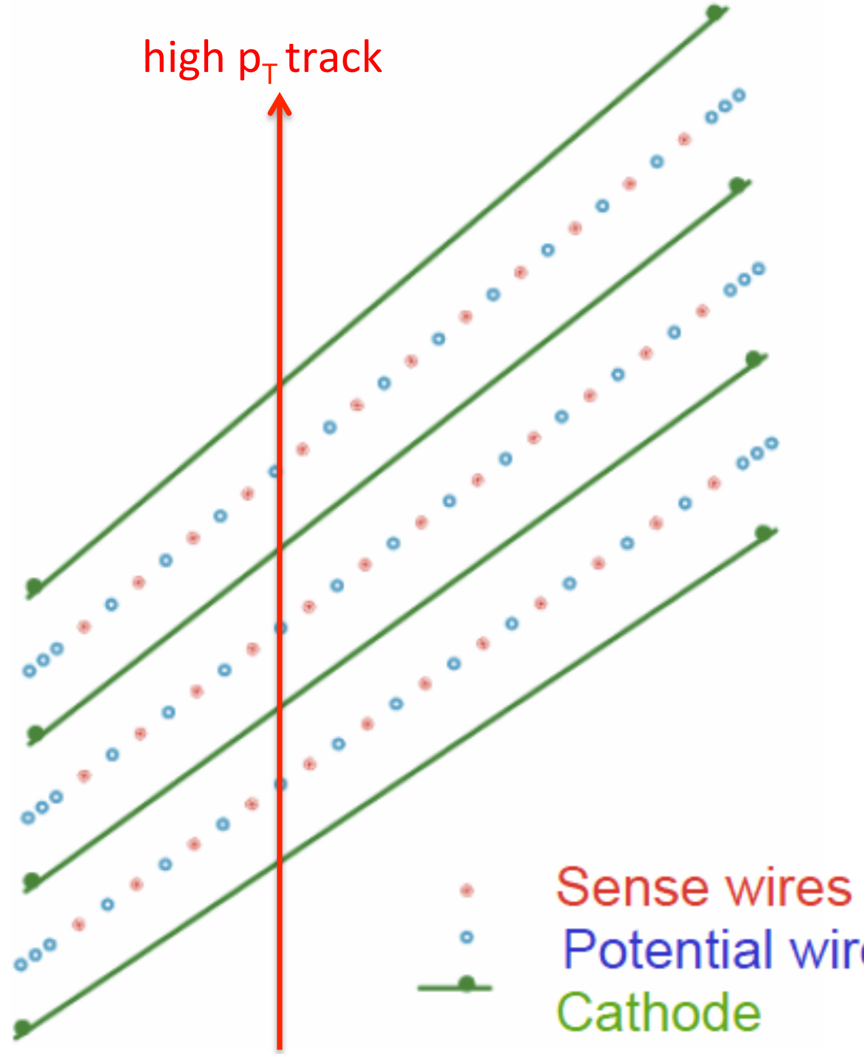


Wire chambers: Multi-Wire Drift Chambers

CDF Central Tracker

Quiz:

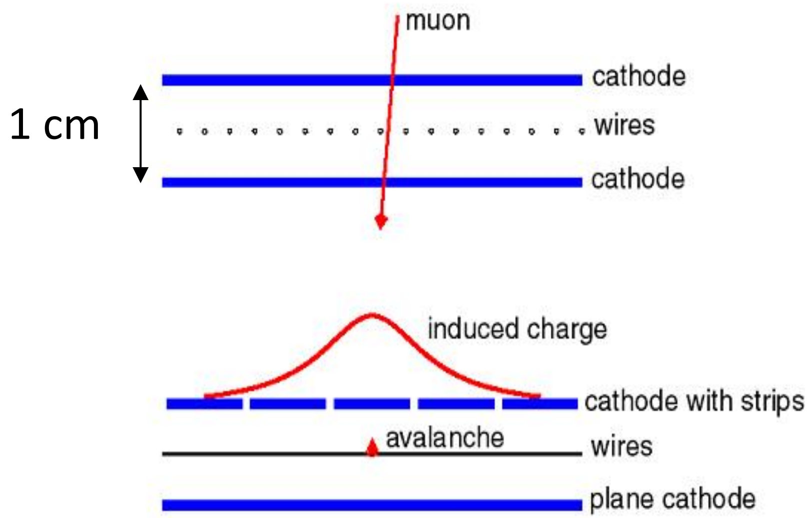
- why tilted?
- why extra potential wires?

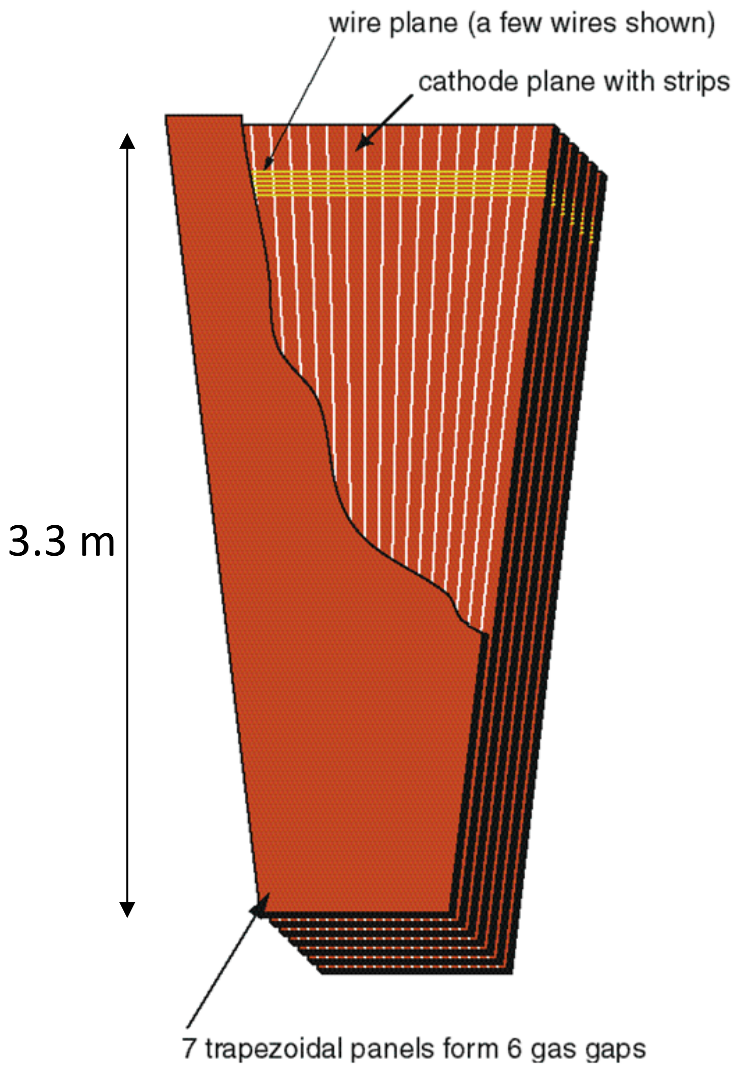


Wire chambers: Cathode Strip Chambers

CMS endcap muon system

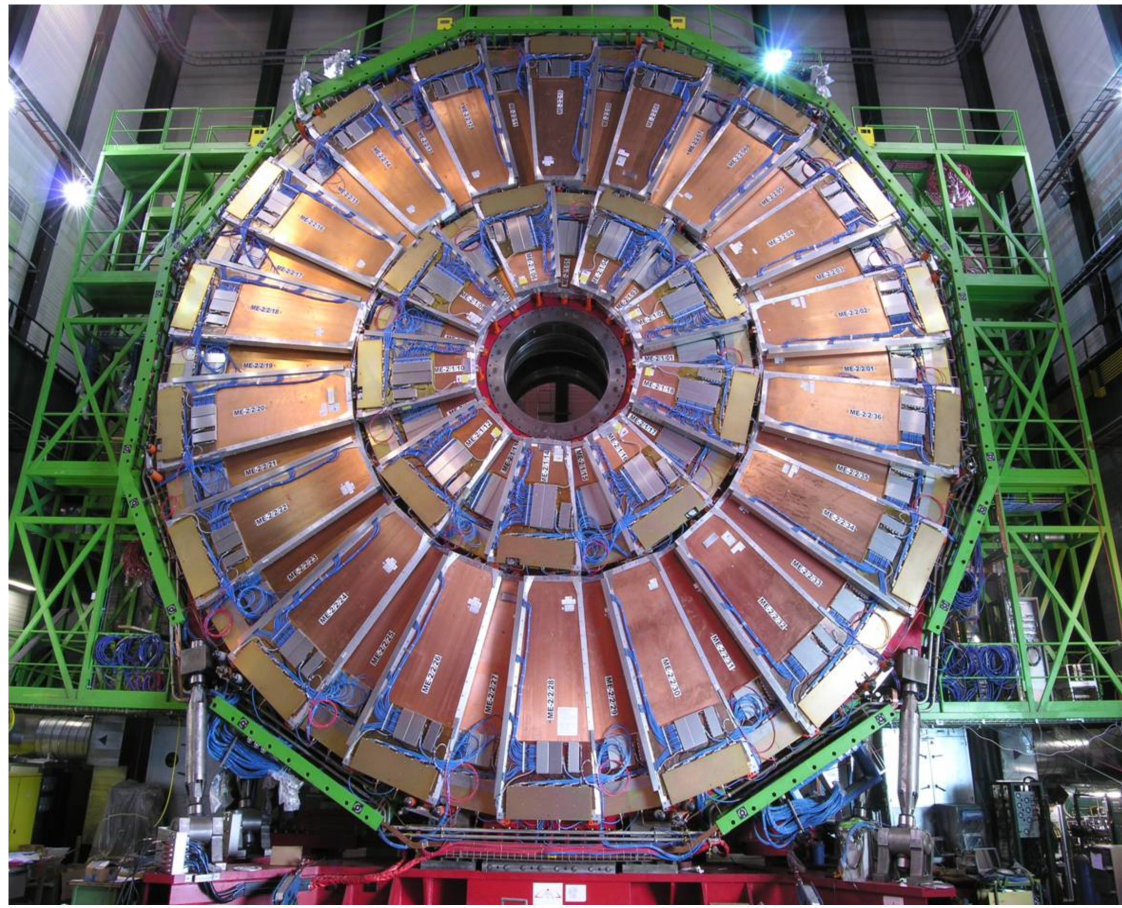
- 1 cm gas gap
- 0.5-1.5 cm strips (trapezoidal!)
- 100-300 µm spatial resolution





Wire chambers: Cathode Strip Chambers

CMS endcap muon system



Wire chambers: How can we get the second coordinate?

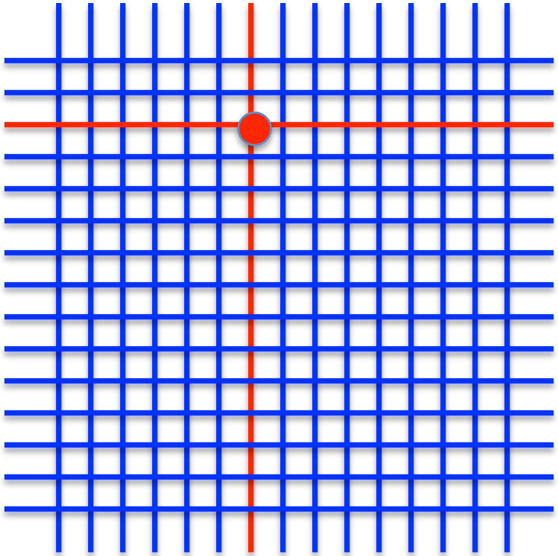
Options

- add more planes (or readout wires and cathode strips)
- two-sided drift time readout (time of flight along the tube)
- two-sided charge readout from resistive anode wire
- “chevron” strip readout

Wire chambers: How can we get the second coordinate?

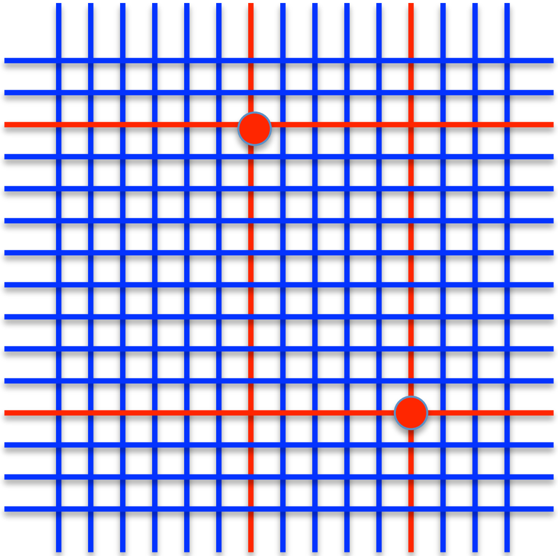
Options

- add more planes (or readout wires and cathode strips)



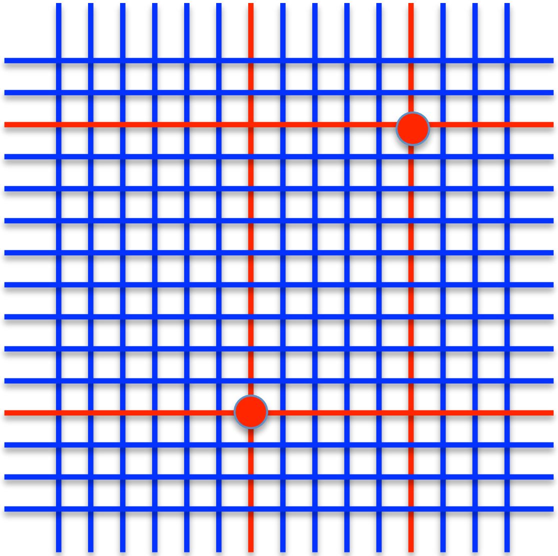
Wire chambers:
How can we get the second coordinate?

Combinatorial confusion for more than one particle:

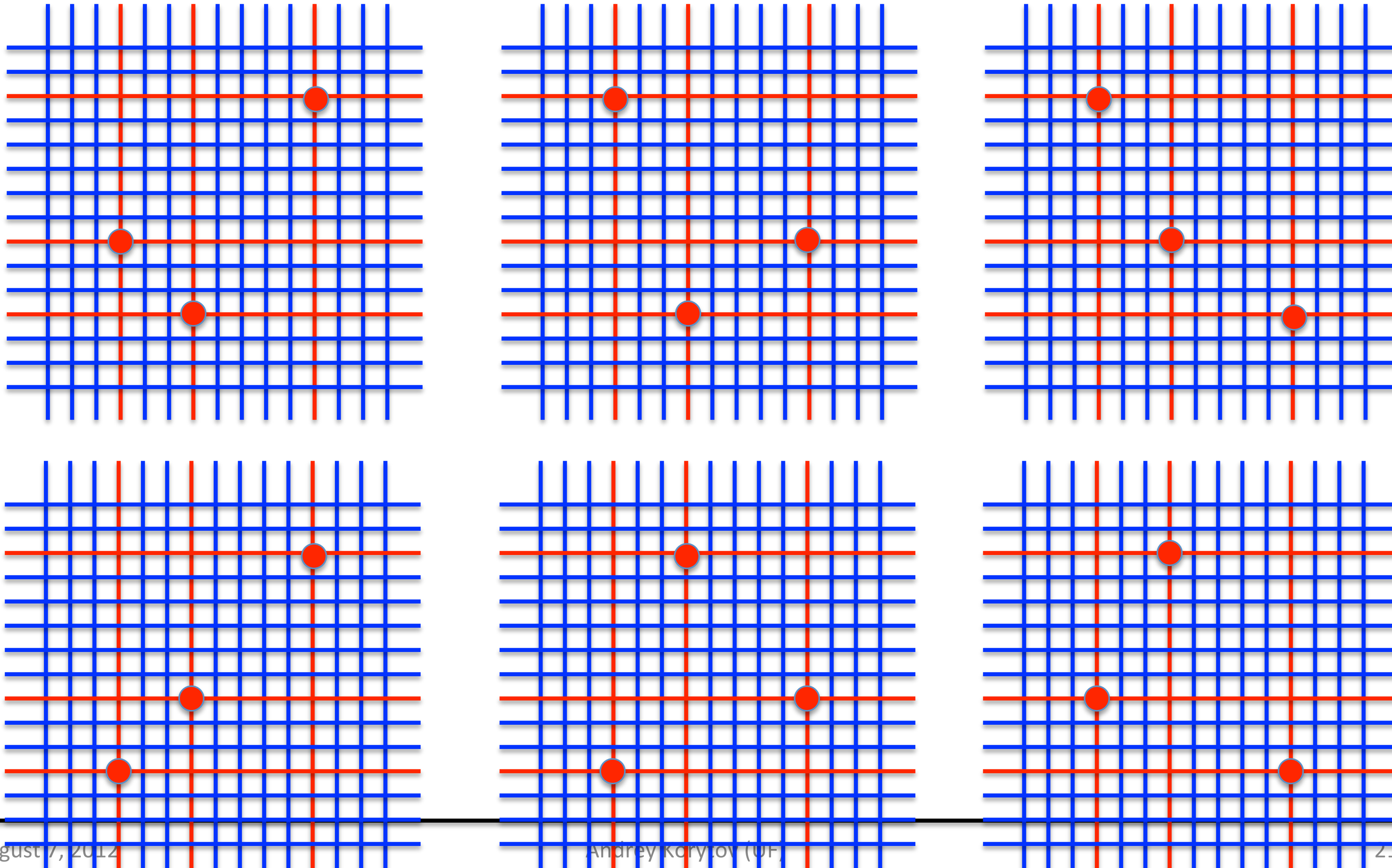


Wire chambers:
How can we get the second coordinate?

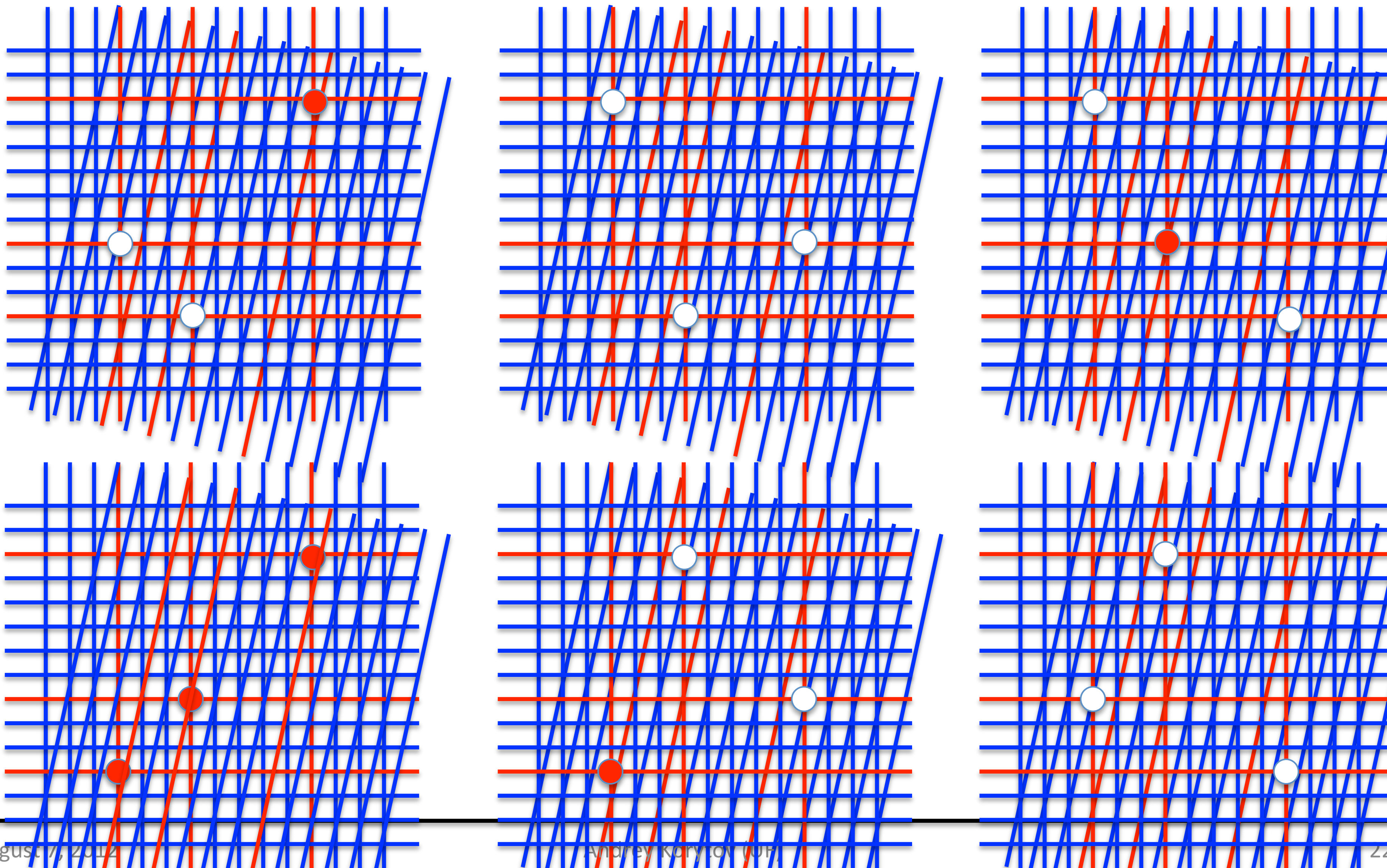
Combinatorial confusion for more than one particle:



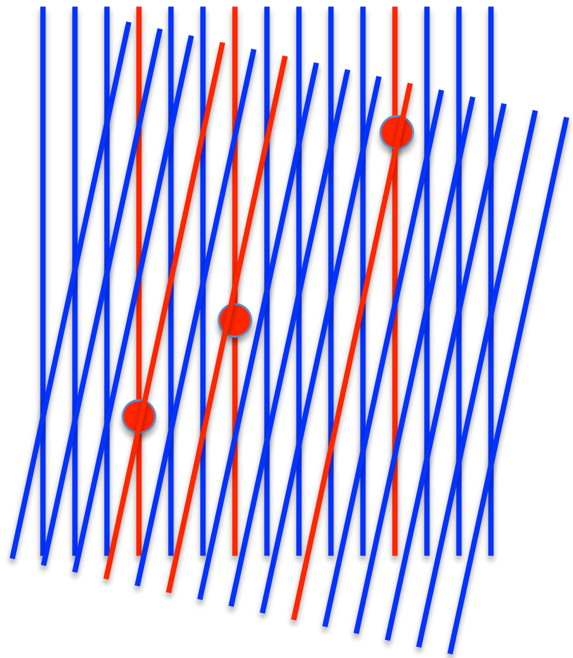
Wire chambers: Proliferation of options for multiple tracks



Wire chambers: Add third layer?



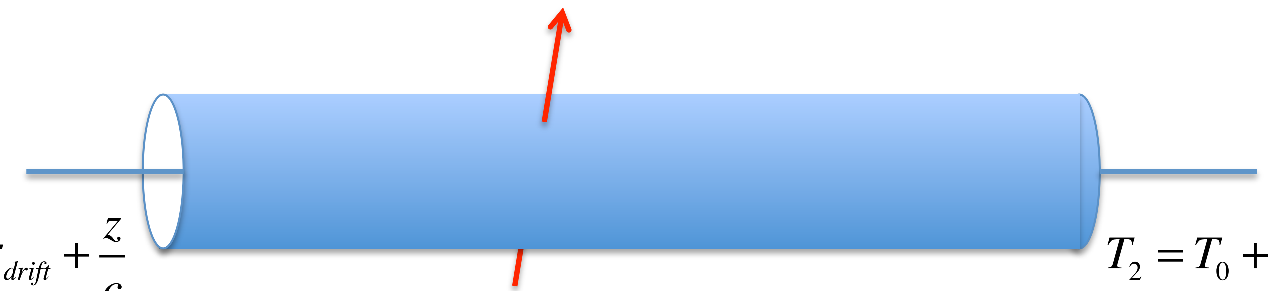
Wire chambers:
Use small-angle "stereo" layers…



Wire chambers:
How can we get the second coordinate?

Options

– two-sided drift time readout (time of flight along the tube)



$$T_1 = T_0 + \tau_{drift} + \frac{z}{c}$$

$$T_2 = T_0 + \tau_{drift} + \frac{(L - z)}{c}$$

$$z = \frac{L}{2} + \frac{\Delta T}{2} c$$

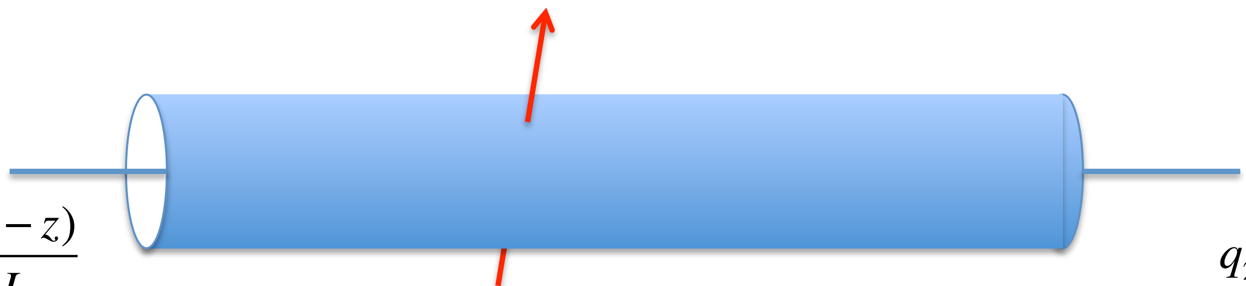
$$\tau_{drift} = \frac{T_1 + T_2}{2} - T_0 - \frac{L}{c}$$

Wire chambers: How can we get the second coordinate?

Options

– two-sided charge readout from resistive anode wire

$$q_1 = Q\frac{(L-z)}{L}$$



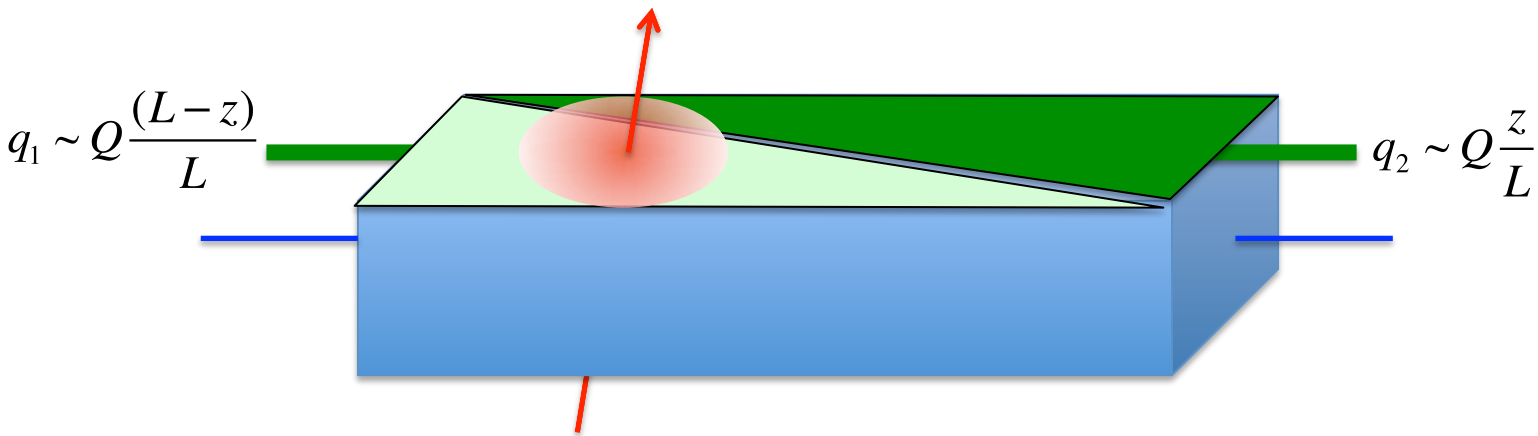
$$q_2 = Q\frac{z}{L}$$

$$z = \frac{q_2}{q_1 + q_2}L$$

Wire chambers: How can we get the second coordinate?

Options

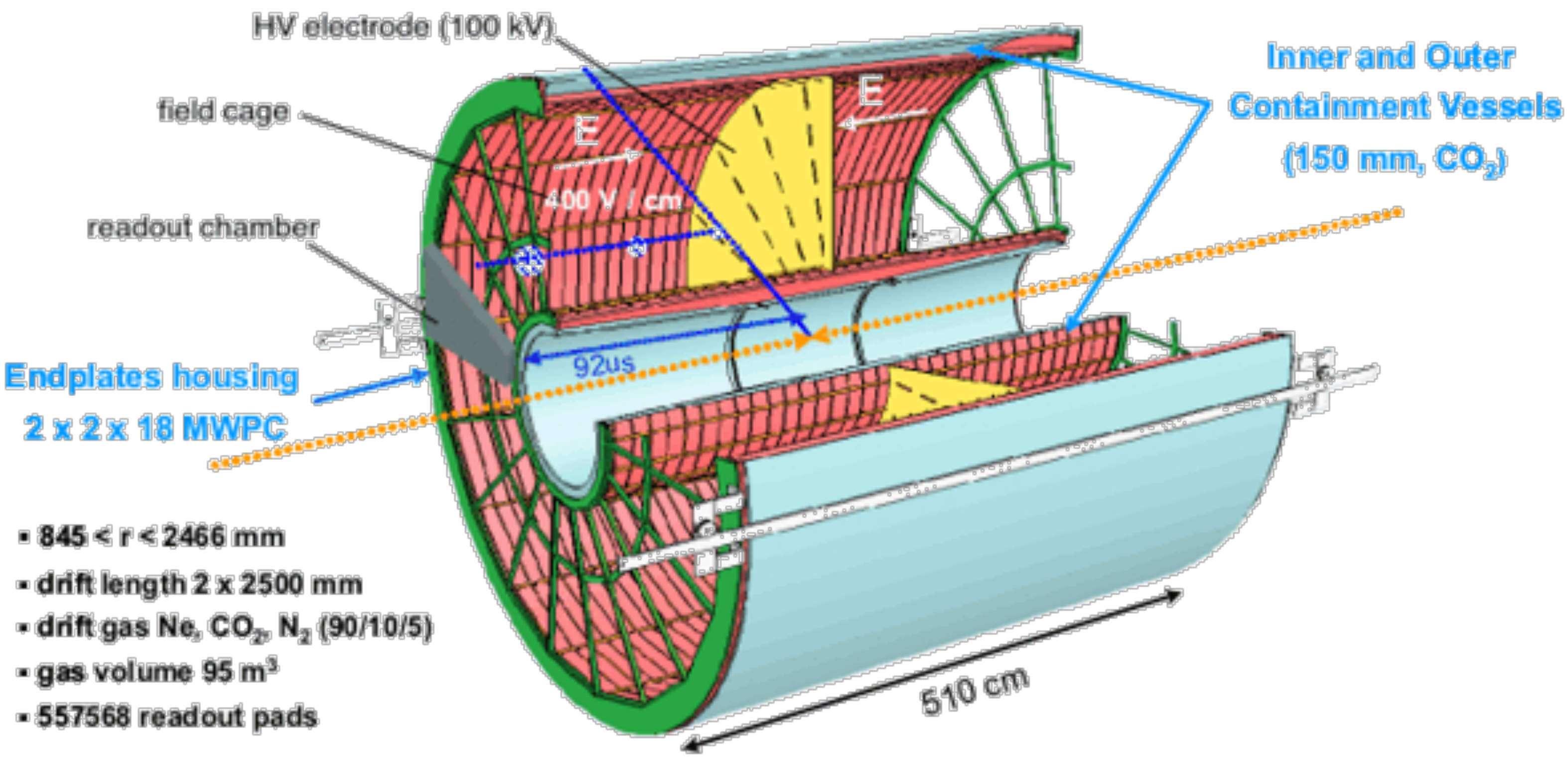
- "chevron" strip readout



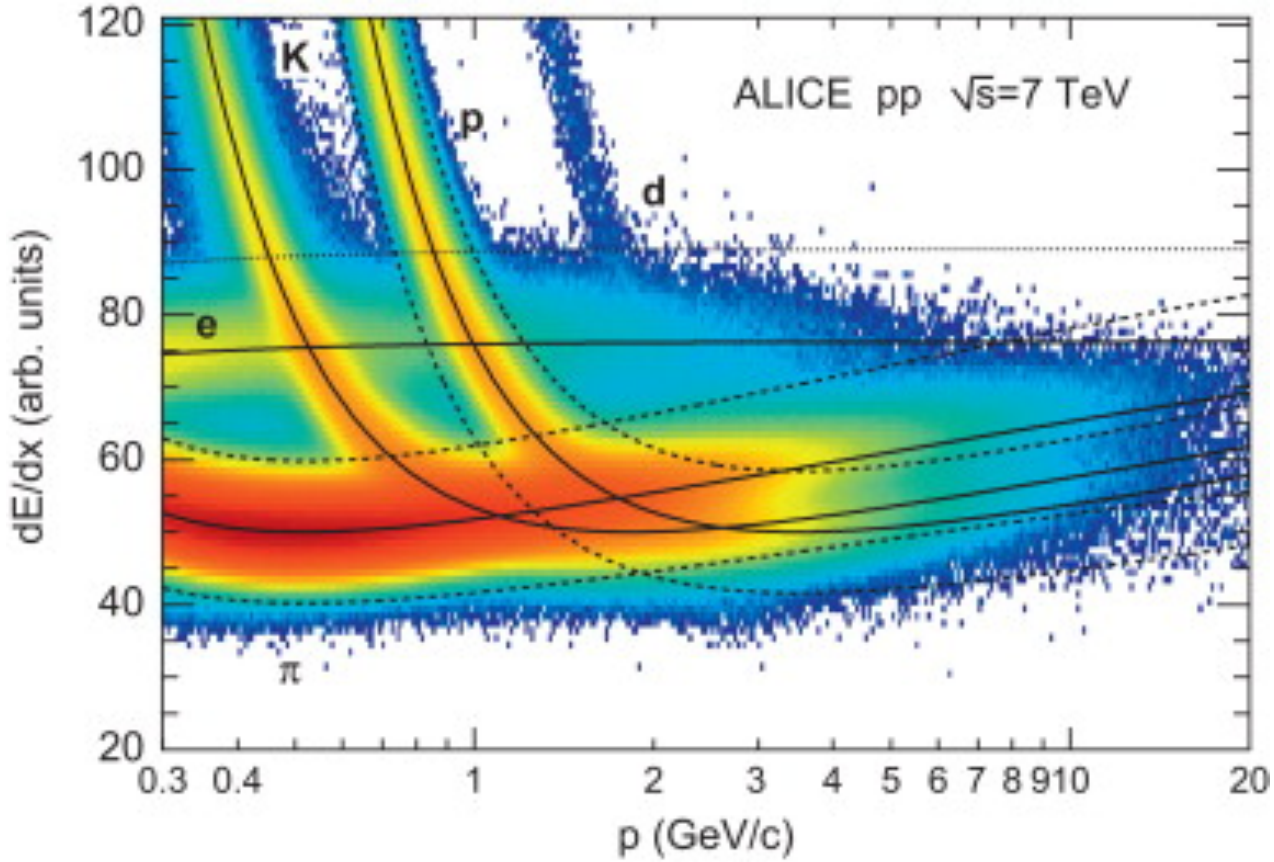
$$z \sim \frac{q_2}{q_1+q_2}L$$

Wire chambers:
HUGE Volume Drift Chambers

ALICE
Time Projection Chamber (TPC)



Average ionization



Simultaneous measurement of momentum and dE/dx can help resolve **π/K/p**

(e and μ are identified with help of dedicated detector subsystems: calorimeters and muon system)

Tracking detector concepts

Gaseous wire chambers

– PC, MWPC, DT, MWDC, CSC, adding 2^{nd} coordinate

Gaseous wireless chambers:

– RPC, MSGC, GEM…

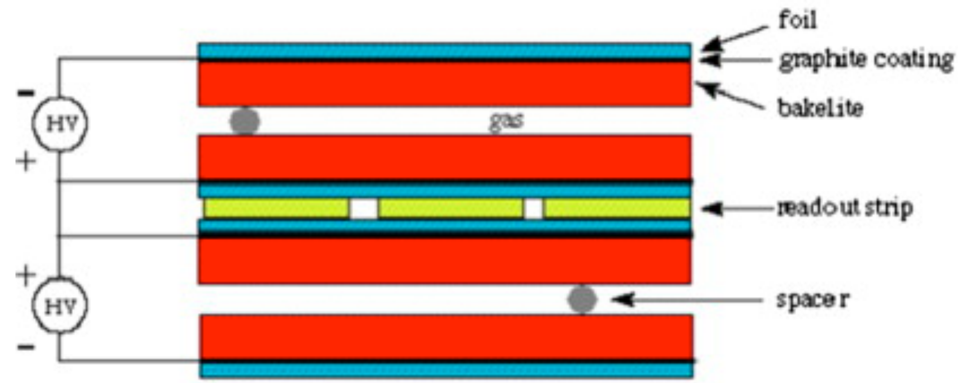
Solid state detectors:

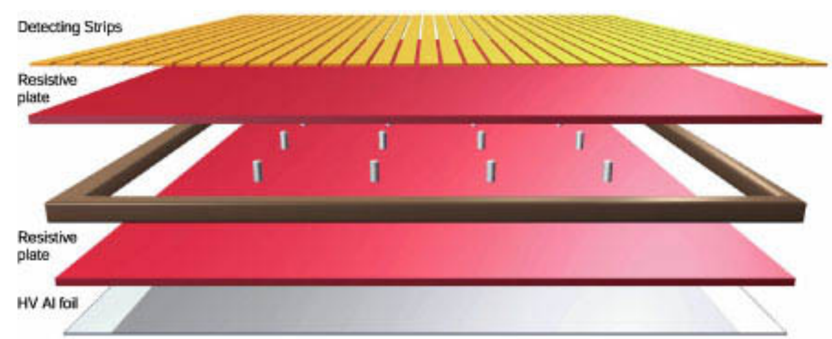
– scintillators, semiconductors

Gaseous wireless chambers: Resistive Plate Chambers

Concept:

- two plates of high resistivity material (not too high, though)
- gas gap in between
- conductive strips or pads outside
- as avalanche develops, high resistivity does not allow for fast replenishing of stored charge on resistive electrodes
- hence, discharge terminates
- signal is read from strips
- the local place where the discharge took place remains dead until the charge gets restored with time (τ=RC)



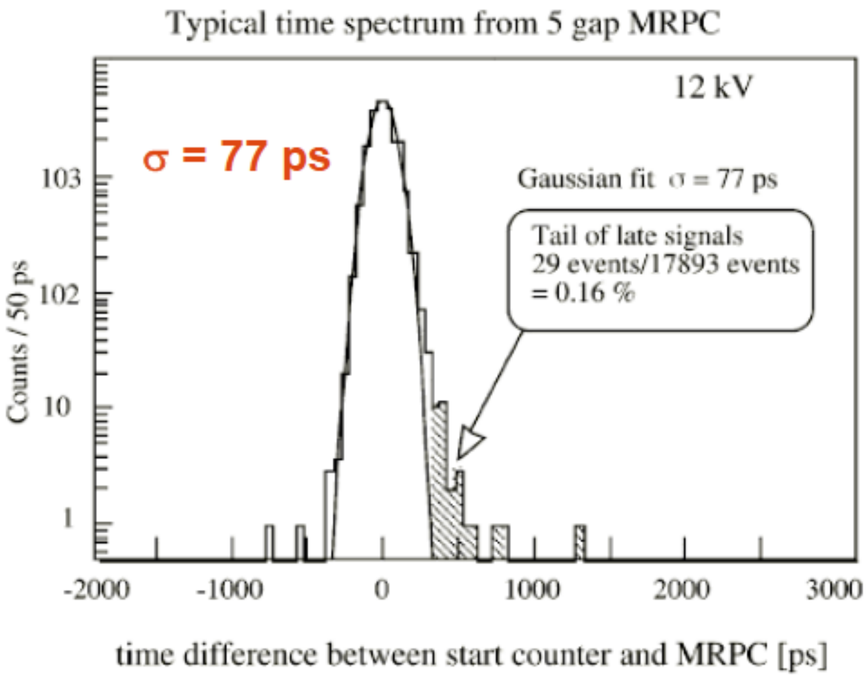


Performance:

- timing < 1 ns
- intrinsic resolution < 1 mm
- rate capabilities < 1 kHz/cm^2
- have rather high spurious noise

Gaseous wireless chambers: Resistive Plate Chambers

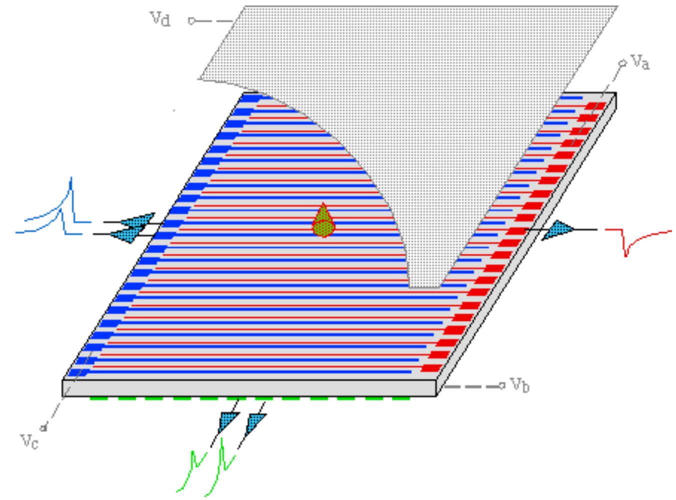
Very fast!

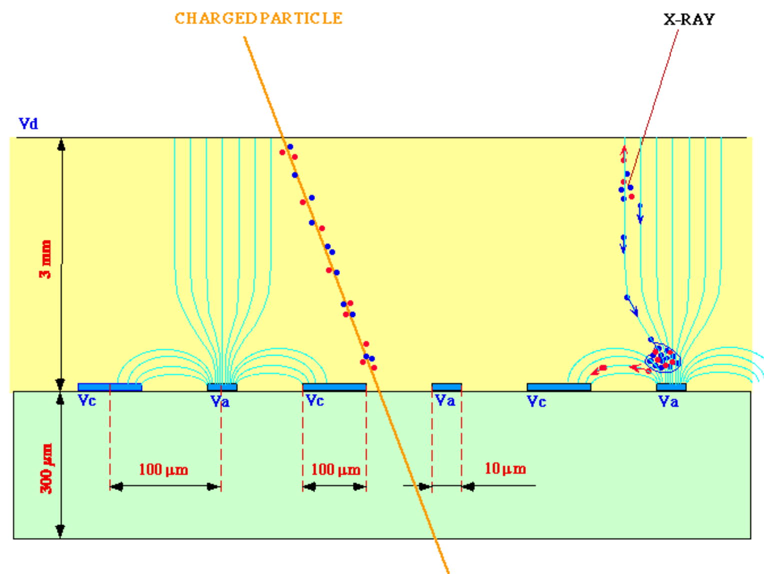


Gaseous wireless chambers: Micro-Strip Gas Chambers

Fairly recent development (1988 by Oed):

– A pattern of thin (10 μm) anode and thicker cathode strips on a insulating substrate with a pitch of a few hundred μm.
– Anode strips work as anode wires and provide moderate gas gain (x100) before transitioning into a discharge mode.
– Spatial resolution: <50 μm
– Size: ~30x30 cm^2



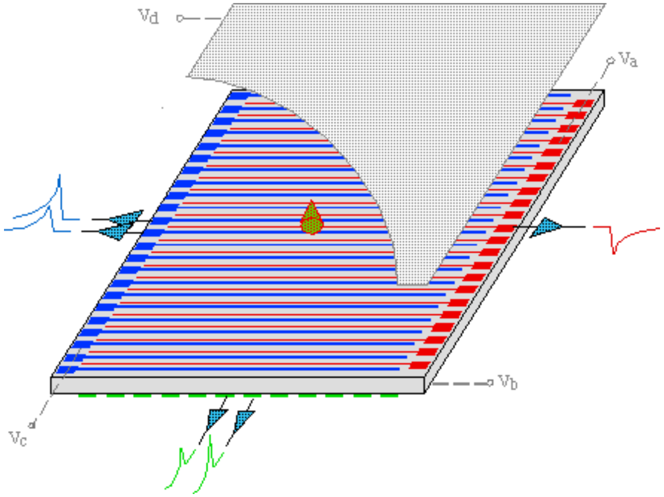


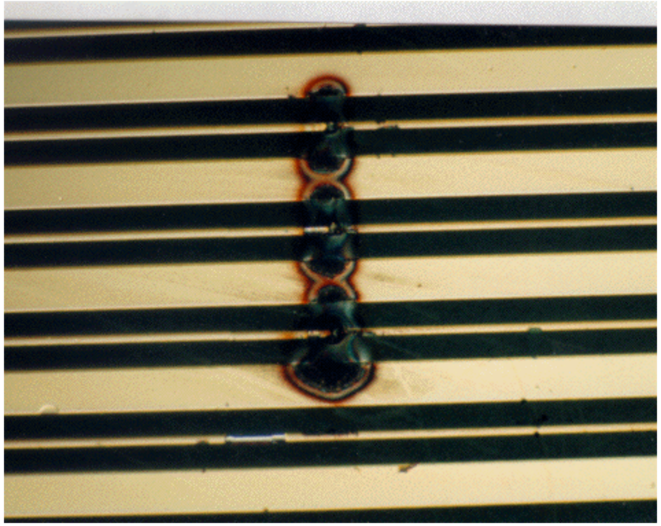
Gaseous wireless chambers: Micro-Strip Gas Chambers

Fairly recent development (1988 by Oed):

- A pattern of thin (10 μm) anode and thicker cathode strips on a insulating substrate with a pitch of a few hundred μm.
- Anode strips work as anode wires and provide moderate gas gain (x100) before transitioning into a discharge mode.
- Spatial resolution: <50 μm
- Size: ~30x30 cm^2

- Unlike for wires, discharge in MSGC may cause serious permanent damage to strips. MSGC with damaged strips is not operable.
- Highly ionizing slow particles are notoriously problematic

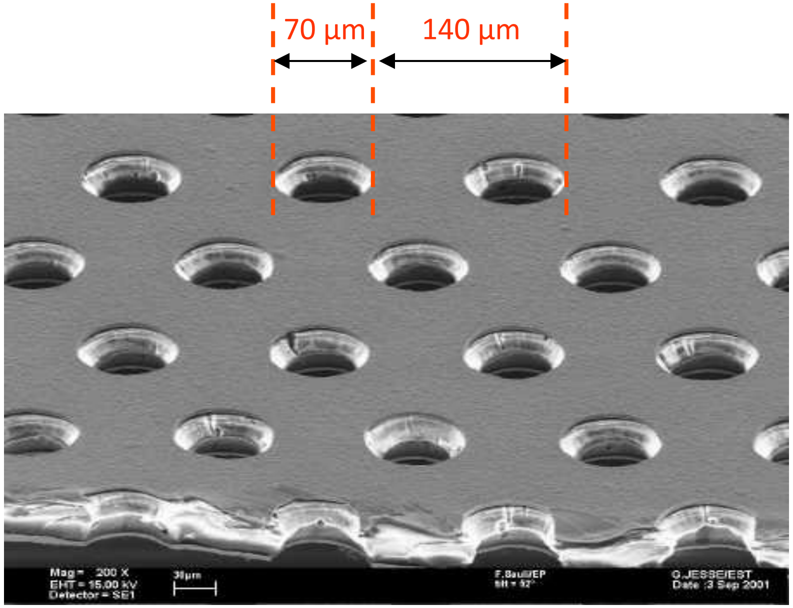




Gaseous wireless chambers: Gas Electron Multiplier (GEM)

Fairly recent development (invented in 1997 by Sauli):

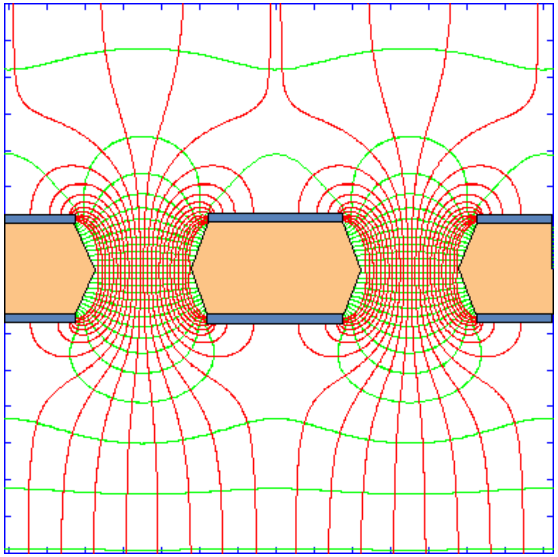
- At thin (50 μm) insulating Kapton film metalized on both sides is punctured with a pattern of pinholes. Can be manufactured using standard printed circuit wet etching techniques.

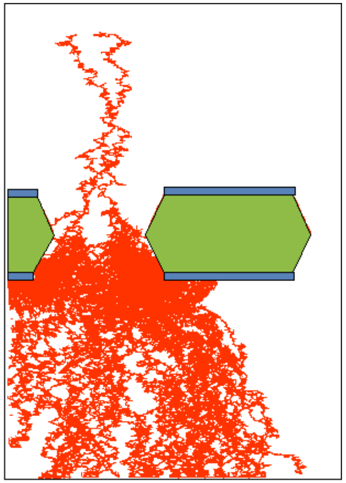


Gaseous wireless chambers: Gas Electron Multiplier (GEM)

Fairly recent development (invented in 1997 by Sauli):

- At thin (50 μm) insulating Kapton film metalized on both sides is punctured with a pattern of pinholes. Can be manufactured using standard printed circuit wet etching techniques.
- HV is applied across the film
- High electric field going through holes allows for a fair gas gas gain (>100/GEM, 10^7 for triple GEM).

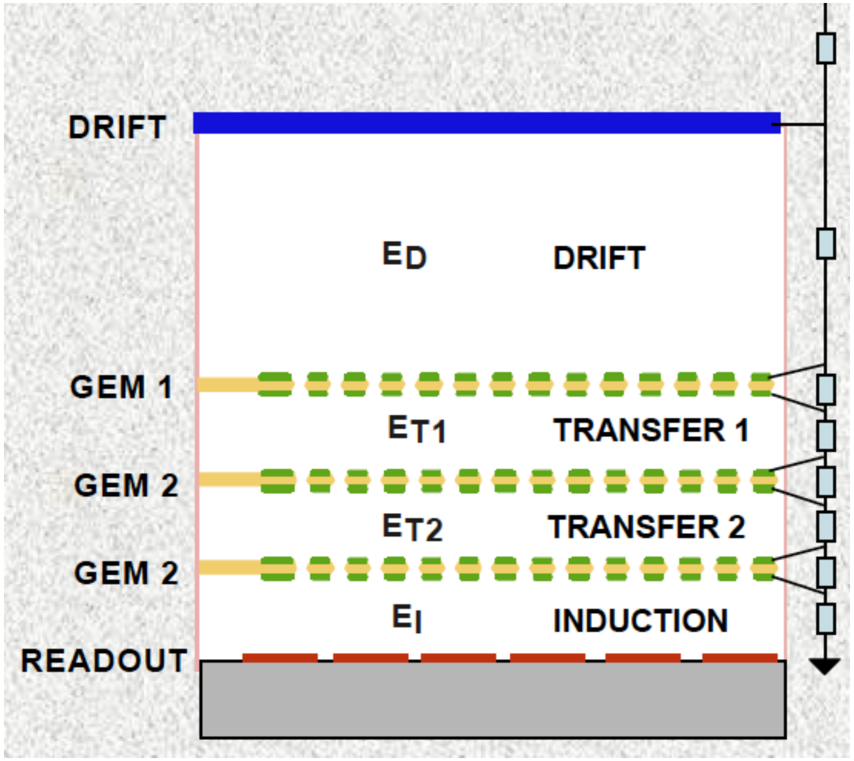




Gaseous wireless chambers: Gas Electron Multiplier (GEM)

Fairly recent development (invented in 1997 by Sauli):

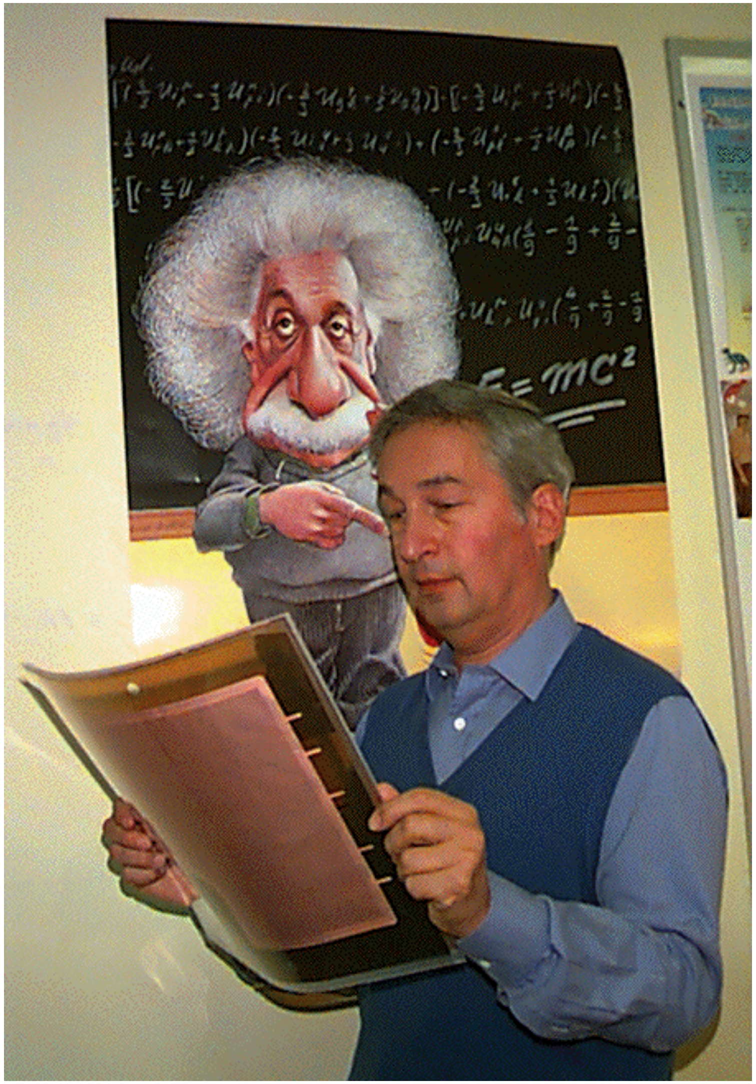
- At thin (50 μm) insulating Kapton film metalized on both sides is punctured with a pattern of pinholes. Can be manufactured using standard printed circuit wet etching techniques.
- HV is applied across the film
- High electric field going through holes allows for a fair gas gas gain (>100/GEM, 10^7 for triple GEM).
- Ionization is collected from the drift volume
- Induced signal is read out from pickup strips
- High rate capabilities: >10^6 Hz/mm^2
- Spatial resolution: ~50 μm
- Size: up to 30x30 cm^2



Gaseous wireless chambers: Gas Electron Multiplier (GEM)

Fairly recent development (invented in 1997 by Sauli):

- At thin (50 µm) insulating Kapton film metalized on both sides is punctured with a pattern of pinholes. Can be manufactured using standard printed circuit wet etching techniques.
- HV is applied across the film
- High electric field going through holes allows for a fair gas gas gain (>100/GEM, 10^7 for triple GEM).
- Ionization is collected from the drift volume
- Induced signal is read out from pickup strips
- High rate capabilities: $>10^6$ Hz/mm^2
- Spatial resolution: ~50 µm
- Size: up to 30x30 cm^2
- Already used in LHCb (muon trigger). Proposed for the very forward muon system upgrade in CMS



Tracking detector concepts

Gaseous wire chambers

– PC, MWPC, DT, MWDC, CSC, adding 2nd coordinate

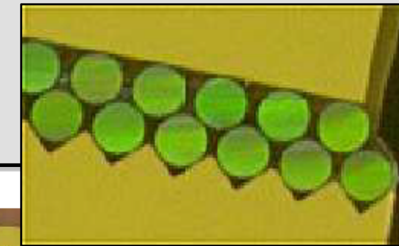
Gaseous wireless chambers:

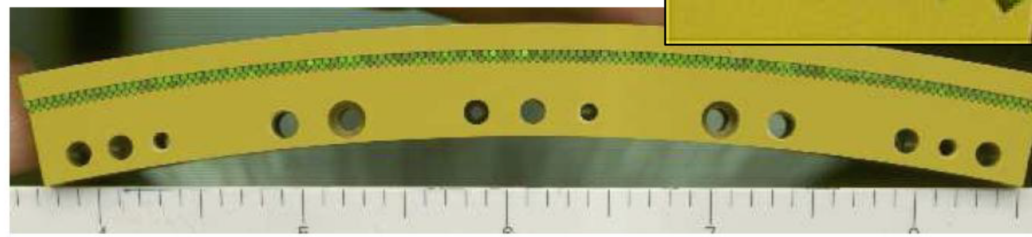
– RPC, GEM, MSGC, …

Solid state detectors:

– scintillators, semiconductors

Solid state detectors: Scintillators





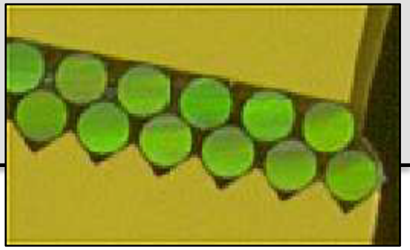
D0 Tracker example:

- Very little room for gaseous tracker: $R_{max} - R_{min}$ = 52 – 20 cm

- Double-layers of scintillating fibers
  - 835 μm in diameter
  - up to 2 m length

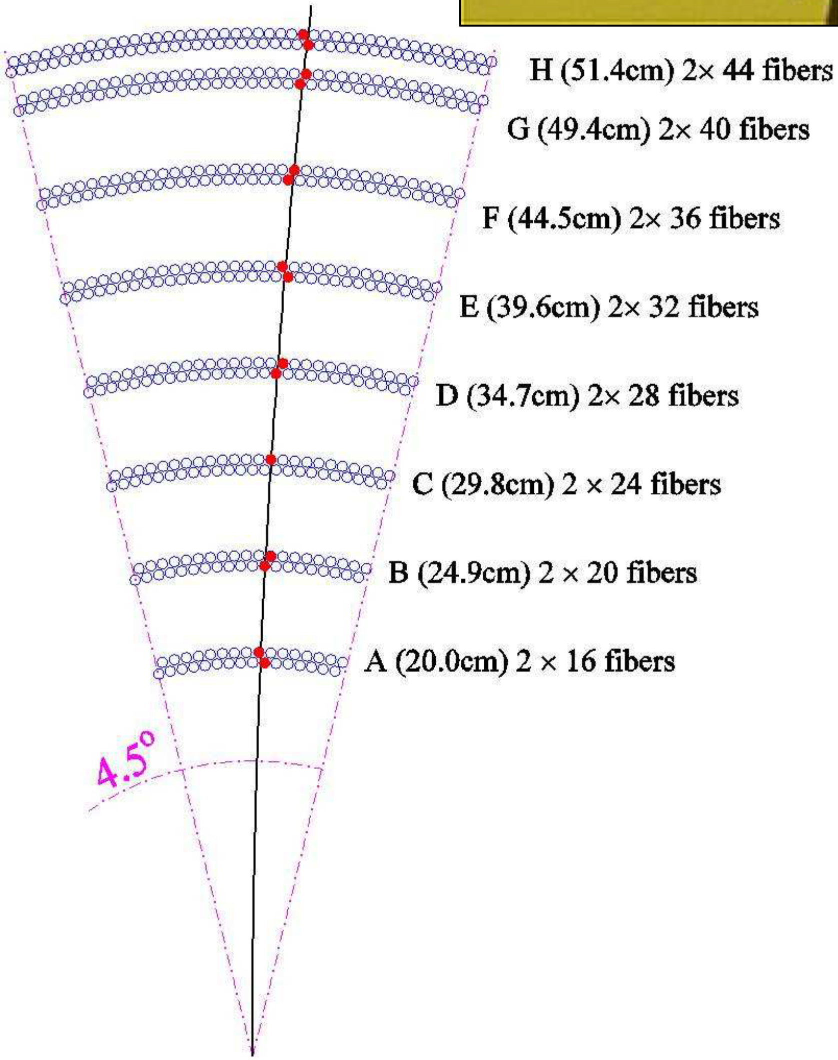
- 8 axial doublets
- 4+4 stereo-angle doublets: ±3°

Solid state detectors: Scintillators



D0 Tracker example:

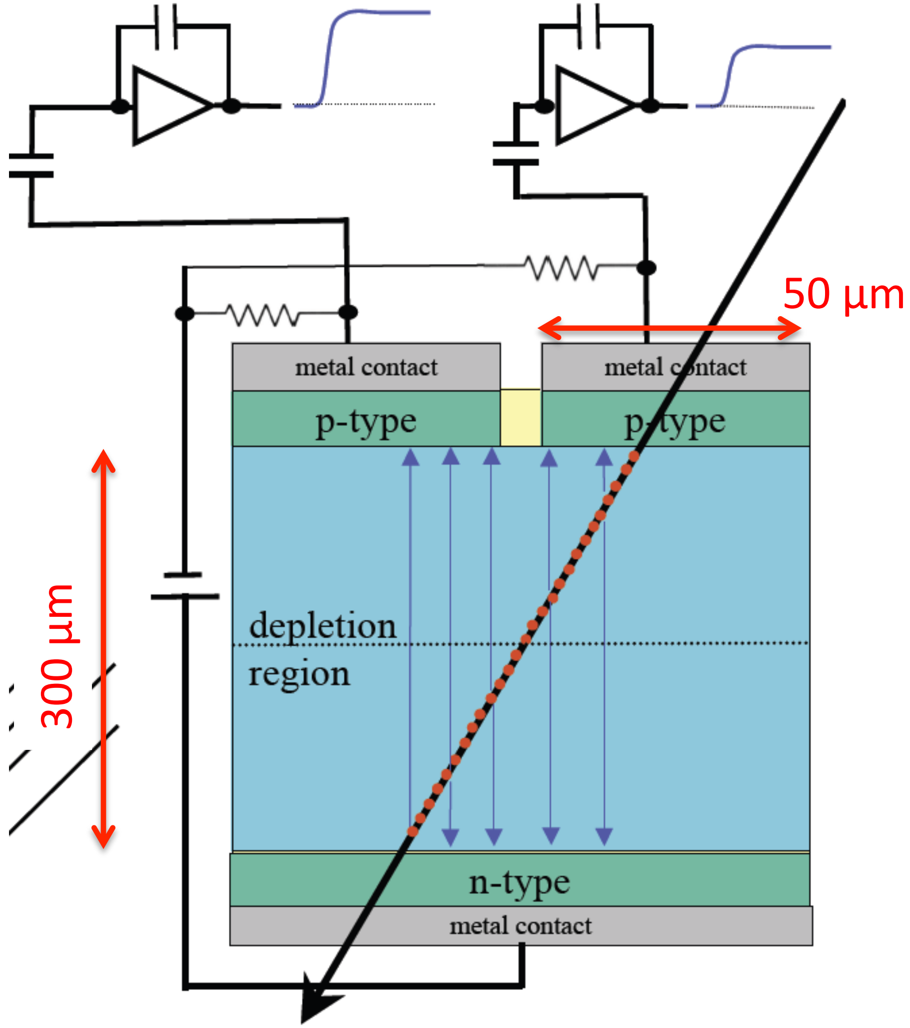
- Very little room for gaseous tracker: $R_{max} - R_{min}$ = 52 – 20 cm
- Double-layers of scintillating fibers
  - 835 μm in diameter
  - up to 2 m length
- 8 axial doublets
- 4+4 stereo-angle doublets: ±3°
- Spatial resolution: 100 μm/doublet
- Fast readout (good for trigger!)



Solid state detectors: Semiconductors

Concept:

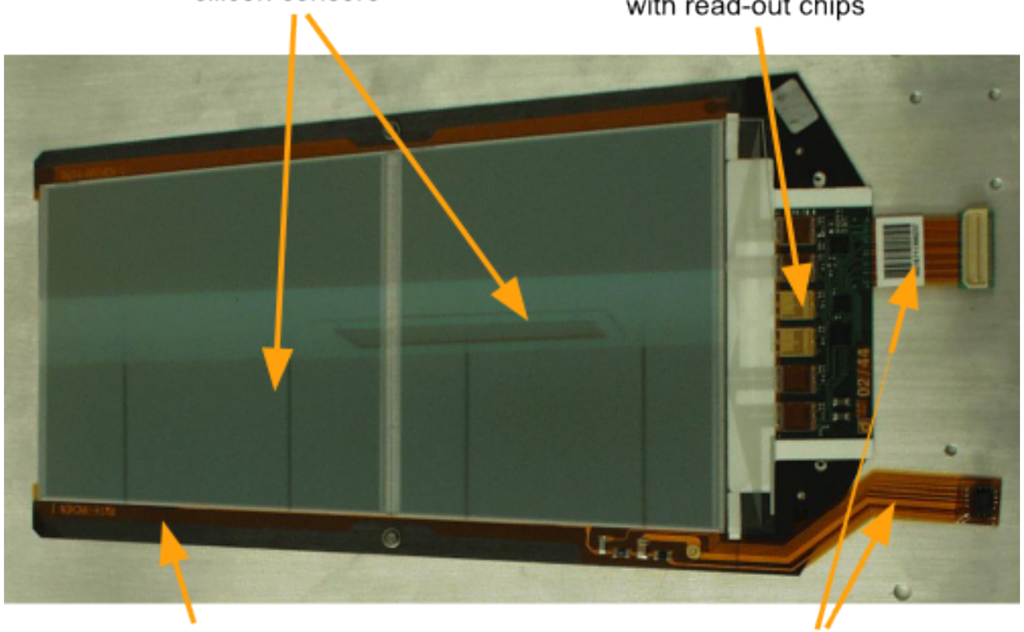
- Inverse potential applied to p-n junction in Si creates a large volume depleted of charge carriers.
- Semiconductor behaves as an insulator with no current flowing.
- Ionization releases electron-hole pairs that drift apart and can be collected on either side by etched strips or pixels.

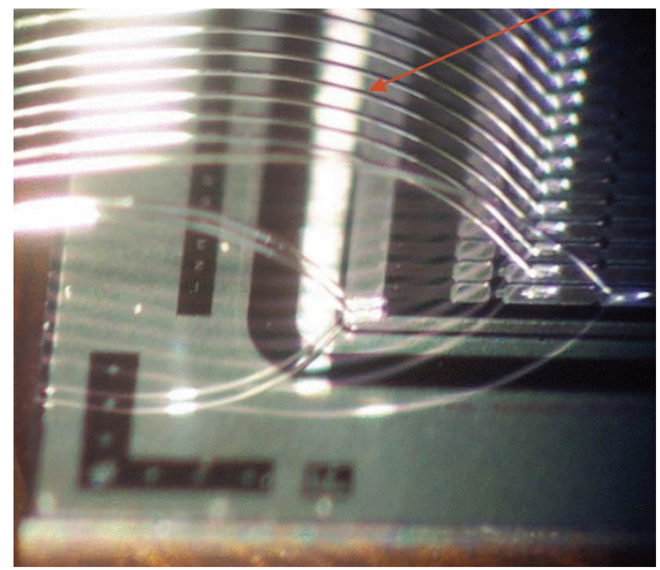


Solid state detectors: Semiconductors

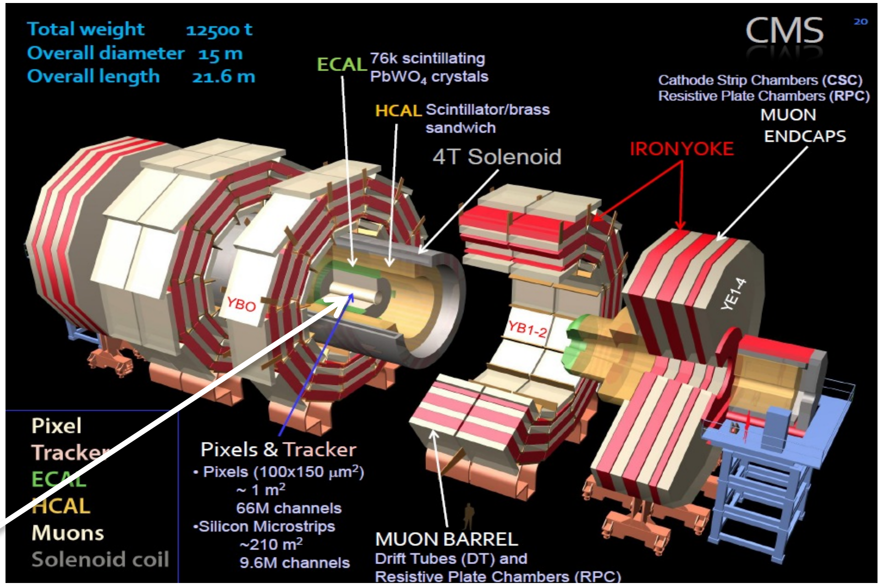
Challenges

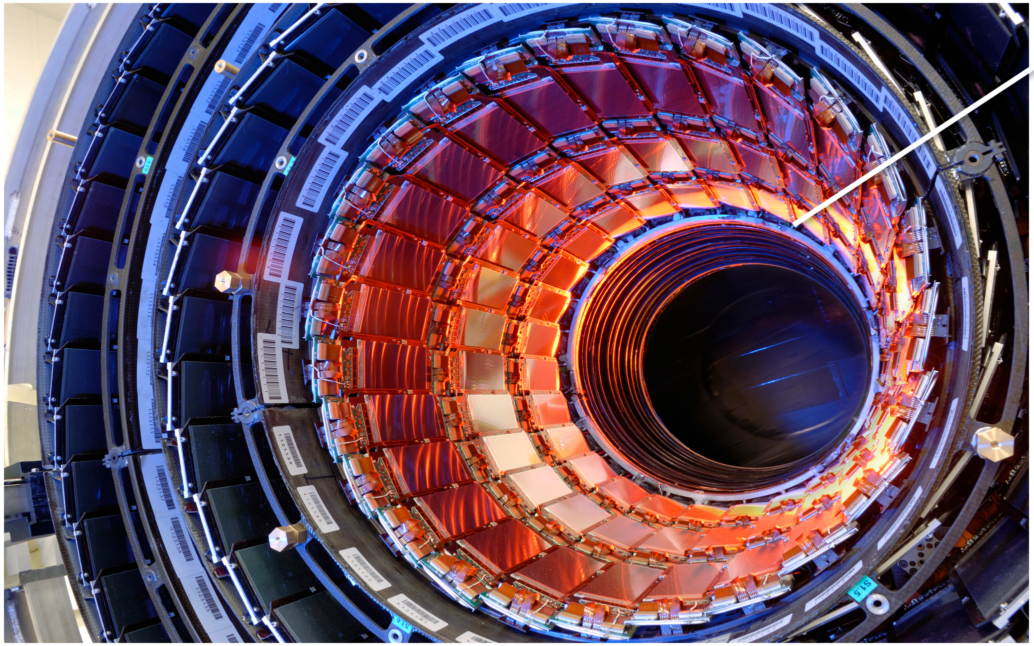
- Connection to readout electronics
- Sheer number of readout channels
- Cooling
- Radiation hardness in long run





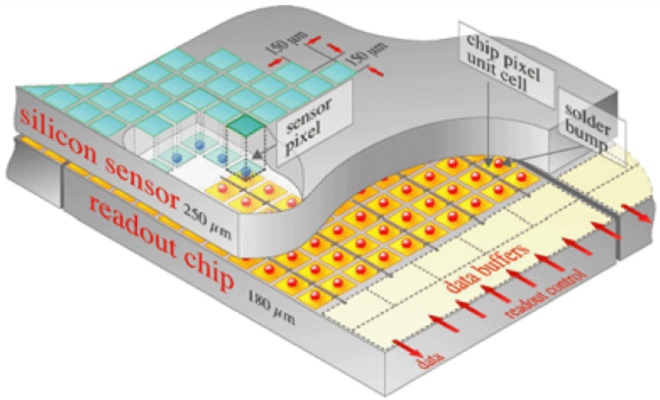
Solid state detectors:
Semiconductors pixel detectors

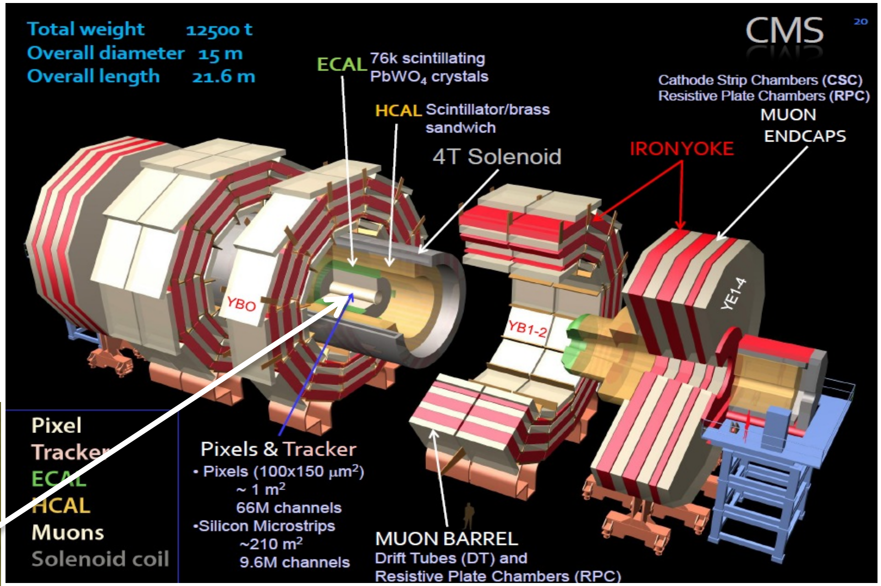




200 m^2 of sensitive area
(half of basketball court)
10 M channels
80 – 200 μm strips
Spatial resolution: **15-40 μm**

Solid state detectors: CMS Si pixel detector





1 m^2 of sensitive area
66 M channels
100x150 µm^2 pixels
Spatial resolution: **13 µm**

Summary

Large variety of tracking detectors allows one to meet a broad spectrum of requirements:

- overall event reconstruction and measuring momenta
- vertexing
- muon identification
- ever growing demand to include more tracking information in the trigger

Development of tracking detectors continues

Aging Effects in Wire Chambers