Detector Physics
at Hadron Colliders (Part II)

Sebastian Grinstein (ICREA/IFAE)

- Introduction to tracking detectors
- Gaseous tracking detectors
- Semiconductor tracking detectors

With material from:
- *G. Eigen*
- *N. Wermes*
- *N. Pauly*
- *C. Gruppen & B. Shwartz*

HASCO Summer School, Göttingen, 21-26 July 2019

GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

IFAE
Institut de Física
d'Altes Energies

EXCELENCIA
SEVERO
OCHOA

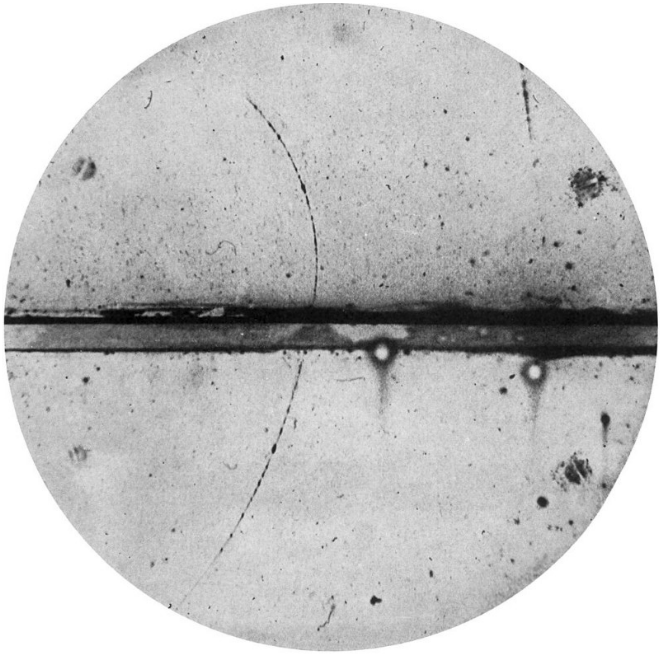
BIST Barcelona Institute of Science and Technology

BIST
Barcelona Institute of
Science and Technology

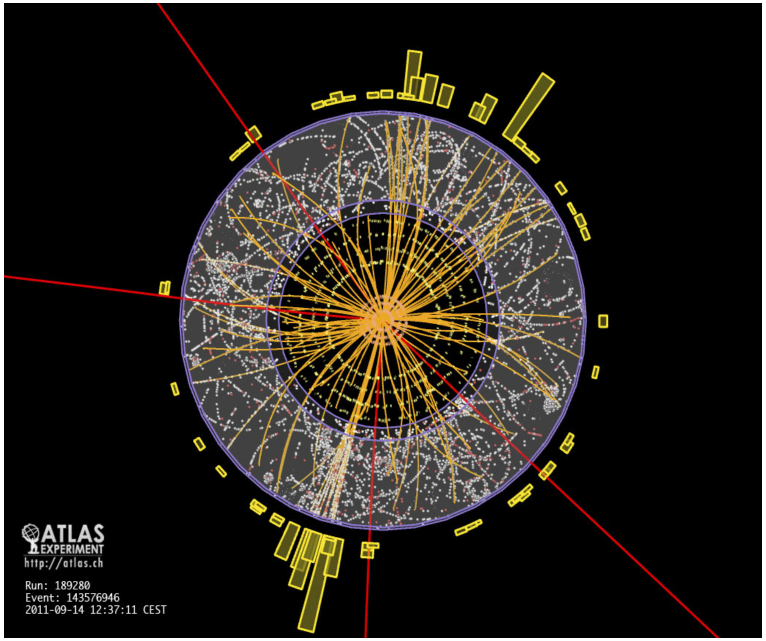
ICREA

Tracking Detectors

- Tracking: reconstruction of trajectory (or track) of electrically charged particles in a detector (tracker), from patterns of measured hits
  - Important for: measurement of particle properties (momentum & charge – with B field), heavy flavor identification (via identification of primary and secondary vertices) and aid in jet reconstruction (track separation inside jets). *[also: dE/dX in low momentum tracks]*



Cloud chamber
(positron discovery 1932)

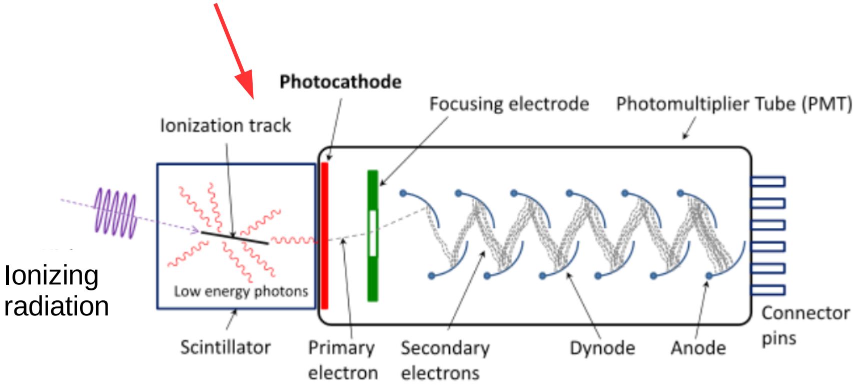


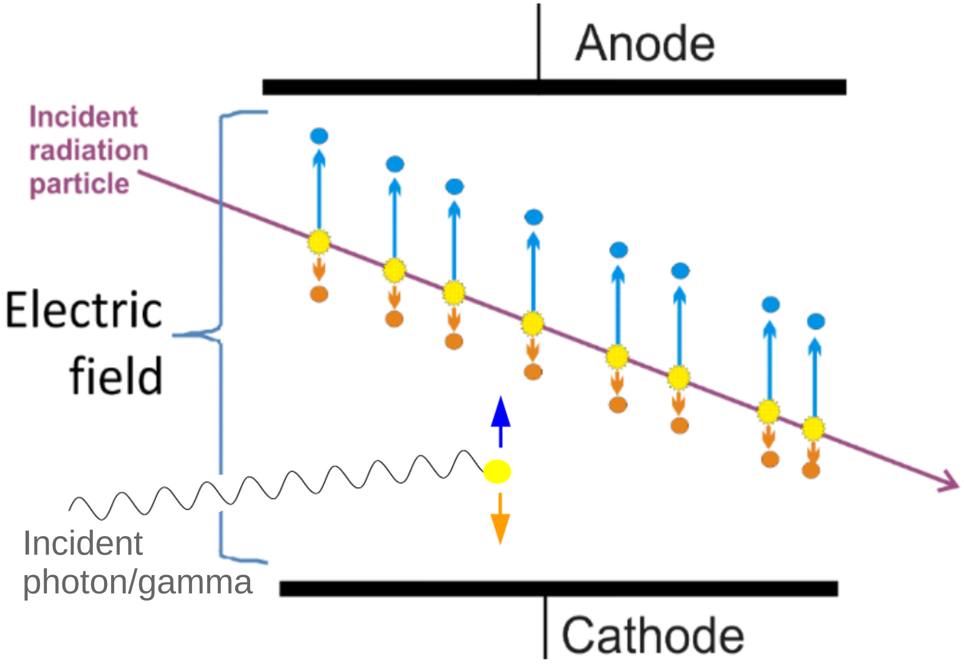
ATLAS 4 muon event
(Run 1 - 2011)

Tracking Detectors

Two basic detector types:

- **Gaseous** (liquid) detectors
  - Ionization, proportional or Geiger mode operation
- **Solid-state** detector
  - Semiconductor-based
  - Scintillators





Ionization detectors

Ideal detector:

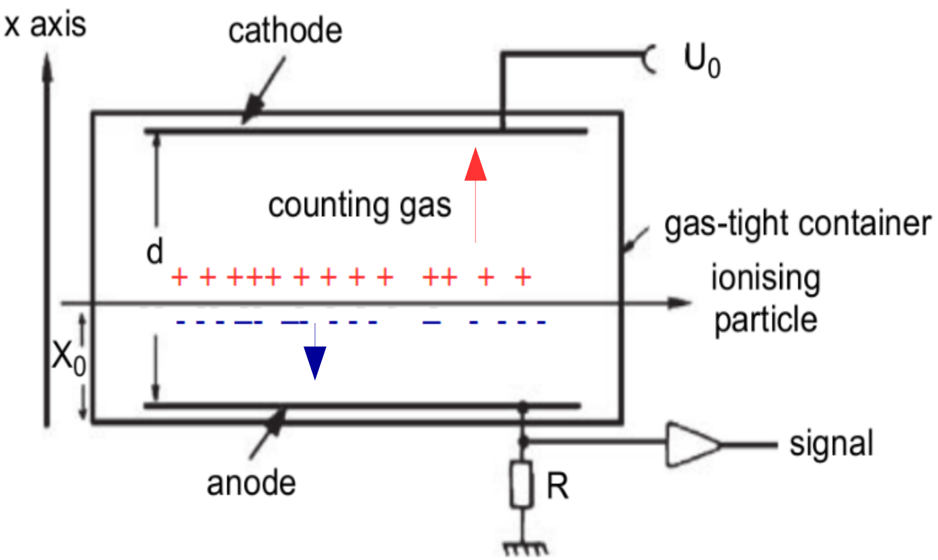
- High/good: efficiency and position resolution
- Low: fake rate, material budget, operational requirements and cost

Gaseous Tracking Detectors

ALICE TPC – CERN

Gaseous Detectors

“Simplest” detector:



Ionization counter

- Measures the amount of (primary) ionization produced by charged particle

Collected charge:

- Parallel plate capacitor: Q = N e → V = N e / C (C: capacitance of detector)
- Typical signal (for a ~few cm size detector)
  - 5 MeV α-particle in Ar (e-ion energy W=26 eV) with C = 10 pF → V=3 mV
  - But: MIP in 4cm or Ar → V=7 µV (too small! → will need to address this)

Signal formation:

- How does the signal look like?

Signal Formation

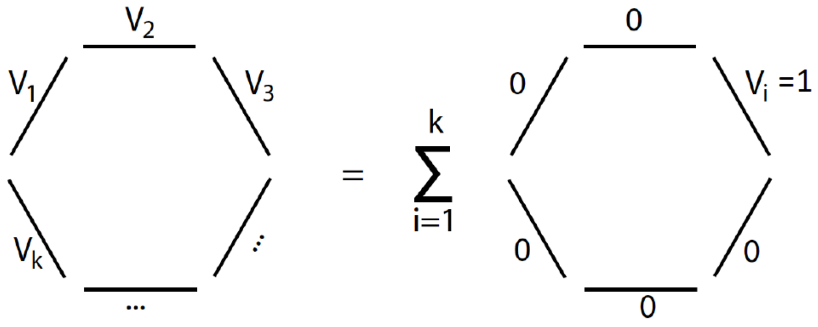
Shockley-Ramo theorem

- Given n electrodes in the detector, one wants to know the current i_k (k = 1, 2, …, n) injected in one of these electrodes by the motion of a charge q somewhere between the electrodes
- The theorem says that current injected in this electrode is $$i_k = \frac{dQ_k}{dt} = q\vec{u}_q\vec{E}_k$$
- Where Q_k is the induced charge on the electrode k, u_q is the velocity of the charge q and E_k is the electric field at the point occupied by charge q when the electrode k is at 1 V potential and all other electrodes are set at zero potential (weighting field)
- Parallel plate capacitor:

$$\vec{E} = -\frac{V_0}{d}\vec{e}_x \ , \qquad C = \frac{\epsilon\epsilon_0 A}{d}$$

$E_k = 1/d$, and for low E fields: $v = \mu E$

- *mobility μ*
- *constant E field, ~constant drift velocity*
- *at high E filed, v saturates v=constant*



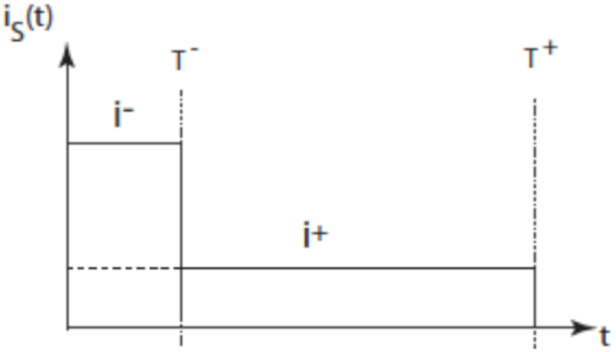
Signal Formation

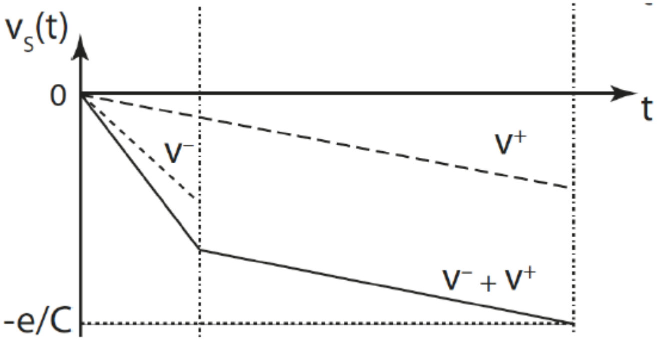
- Using Shockley-Ramo for parallel plate capacitor (with E_a weighting field and u charge velocities)

$$i_- = -e\vec{u}_-\vec{E}_a = e\frac{u_-}{d}$$

$$i_+ = e\vec{u}_+\vec{E}_a = e\frac{u_+}{d}$$

- Electron drift velocity >> ion drift velocity (different mobilities)





$$Q^{tot} = Q^- + Q^+ = -\frac{-Ne}{d}\left(\int_0^{T^-} u_-\,dt + \int_0^{T^+} u_+\,dt\right) = -\frac{-Ne}{d}u_-\left(\frac{d - x_0}{u_-}\right) - \frac{-Ne}{d}u_+\left(\frac{x_0}{u_+}\right) = -Ne$$

As expected, Q=Ne
(note that both electrons and ions contribute to signal)

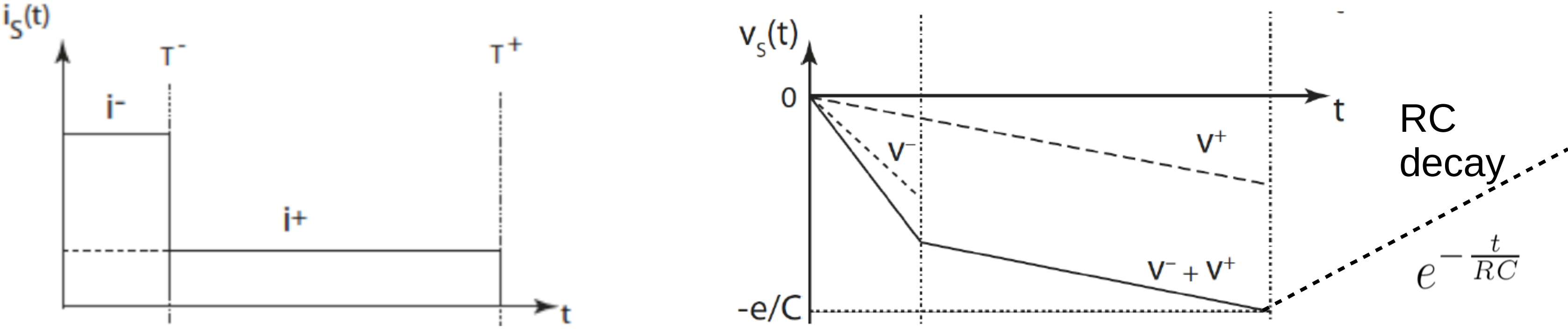
Signal Formation

- Using Shockley-Ramo for parallel plate capacitor (with E_a weighting field and u charge velocities)

$$i_- = -e\vec{u}_-\vec{E}_a = e\frac{u_-}{d}$$

$$i_+ = e\vec{u}_+\vec{E}_a = e\frac{u_+}{d}$$

- Electron drift velocity >> ion drift velocity

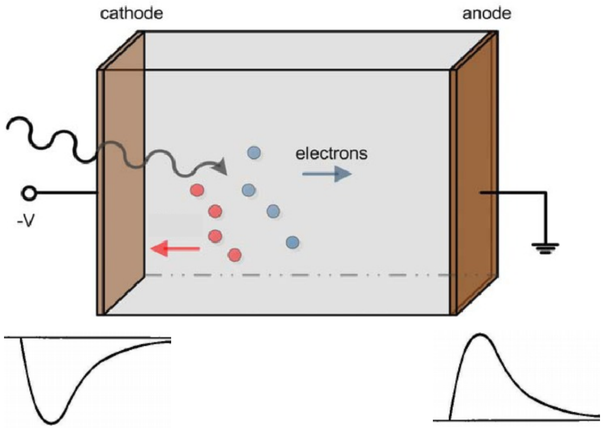


$$Q^{tot} = Q^- + Q^+ = -\frac{-Ne}{d}\left(\int_0^{T^-} u_-\,dt + \int_0^{T^+} u_+\,dt\right) = -\frac{-Ne}{d}$$

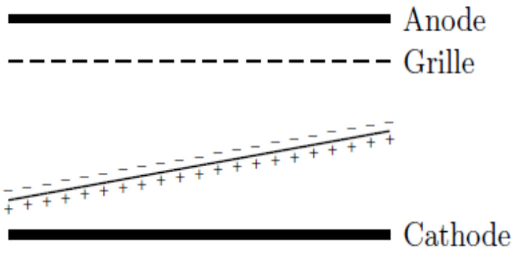
Typical:
E = 500V/cm
u_- = 5 cm/μs, u_+= 5 cm/ms, d~10cm
T^- = 2 μs, while T^+ = 2 ms

Signal Formation

- Movement of both electron and ion charge create signals on both electrodes
- On each electrode a total charge of Q=Ne is induced

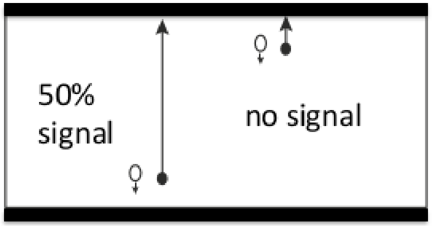


- If the produced charges have very different mobilities then part of the signal is lost (or comes too late) and the signal becomes dependent on where the charge was deposited!



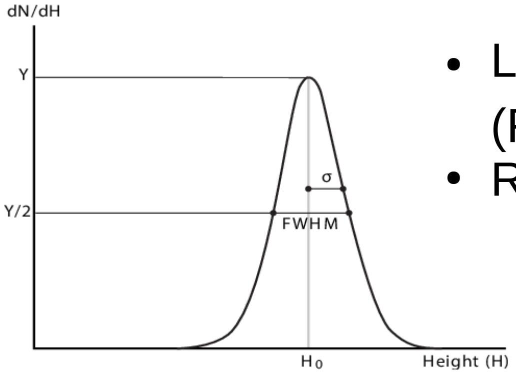
- In gases, ion mobility << electron mobility => one solution would be to add a grid to define a new charge collection region (Fricsh grid)

- Another example is CdTe (high Z material for X-ray detectors)



Energy Resolution (Fano Factor)

- The production of pairs of charge carriers for a given energy loss is a statistical process. If, on average, N charge-carrier pairs are produced one would expect this number to fluctuate according to Poisson √N
- The fluctuation around the average value is smaller by a factor F depending on the material, since for a given energy deposit, the number of produced charge carriers is limited by energy conservation
- Fano factor: F = (observed variance in N)/(Poisson predicted variance) < 1
  - Material specific (Ar ~ 0.17, Xe ~ 0.17; Si ~ 0.12, Ge ~ 0.13)



- Limiting resolution: (FWHM)/H_0 (FWHM = 2 √(2 ln(2)) σ = 2.35 σ)
- Resolution:

$$\sigma^2_{N_i} = F N_i$$

$$\left(\frac{\sigma_{N_i}}{N_i}\right)^2 = \frac{F}{N_i}$$

Example:

- α particle with E= 5.5 MeV completely stopped in Ar gas with W ~ 30 eV

$$N_i = \frac{E_{abs}}{W} = \frac{5.5 \times 10^6}{30} = 1.83 \times 10^5 \text{pairs} \qquad R = 2.35\sqrt{\frac{F}{N_i}} = 0.213\%$$

Corresponding to a width of R x 5500 keV = 11.7 keV

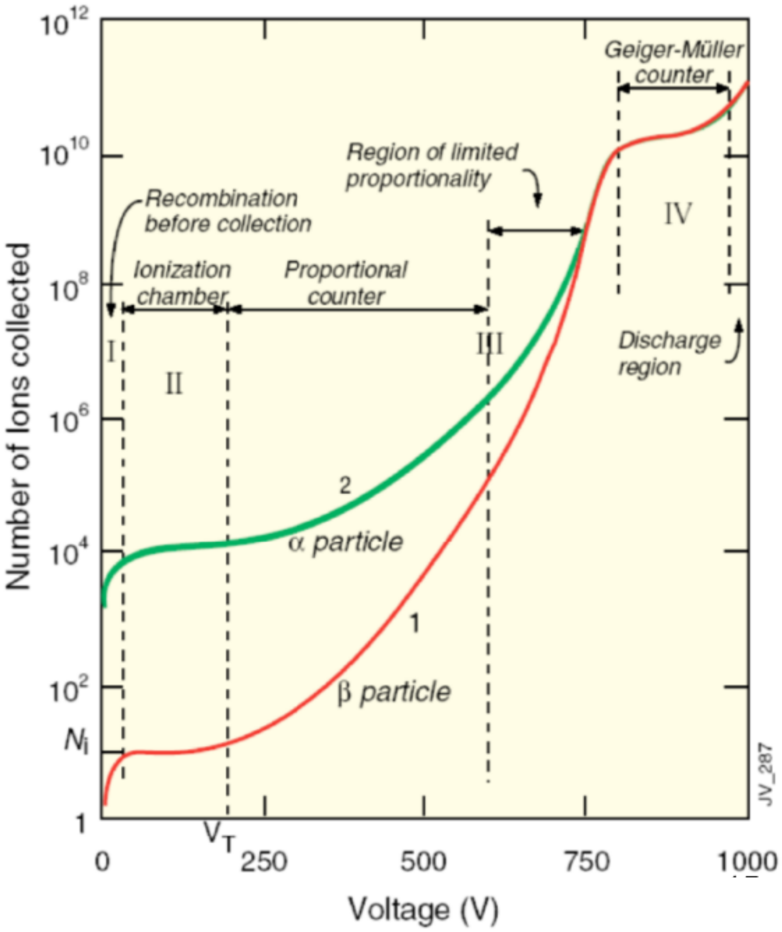
Gaseous Detectors

- Ionization chambers do not yield enough signal for mip detection
- How to improve?
    - Reduce capacitance or, better, get more charge! (V = Q / C)
    - **Increase HV to obtain signal gain**

If field strength in some region of the counter volume is high, an electron can gain enough energy between two collisions to ionize another atom.

Increase HV

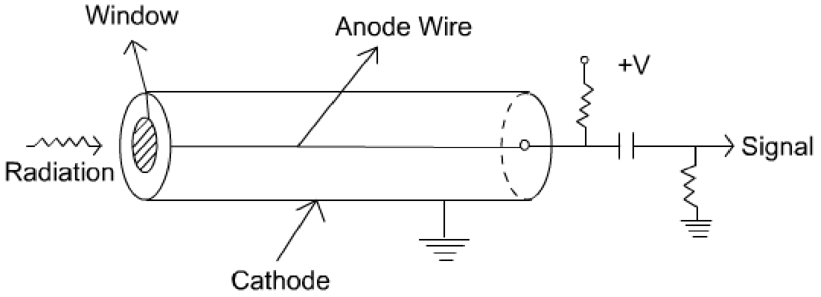
- Recombination before collection
- Ionization range
    - Collect ionization
- Proportional regime
    - Signal is amplified
    - Signal is proportional to primary ionization
- Geiger-Müller region
    - Photo-electron production dominates, loss of proportionality



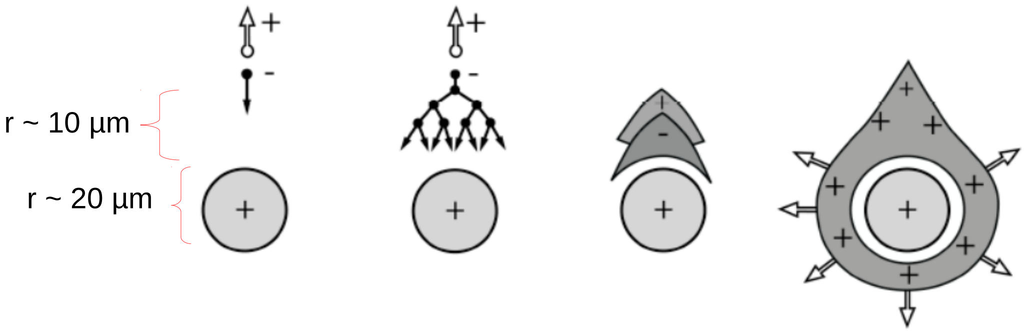
Gas Choice

- Gas should **not** contain any electronegative component since electronegative molecule tends to form negative ions → no charge multiplication
- Since oxygen is electronegative → no air
- Noble gases are a good choice: not electronegative, easily purified and single atoms → no rotation or vibration states that can absorb electron energy → avalanche occurs at a lower voltage than in other gases
- Argon is the least expensive → very frequent use
  - However:
    - De-excitation by photon emission (UV) → possibility of UV absorption and e-emission → avalanche repeat
    - Ions that reach the cathode may liberate new electrons → avalanche repeat
    - Solution: add “quenching” gas, typically polyatomic gas: isobutane (C_4H_{10}), methane (CH_4),… which have many degrees of freedom of rotation and vibration to disperse energy

Proportional Counters



- Wire surrounded by a tube with gas
- Electric field strong in vicinity of wire (E~1/r)
- Further ionizations generated close to wire
  - Drift time to wire proximity introduces “delay” in the signal
- Secondary ionizations proportional to the number of primary ionizations



$$\mathrm{d}N(x) = \alpha N(x)\,\mathrm{d}x$$

$$N(x)/N_0 = e^{\alpha x} = A$$ (Gain)

$$\alpha = \sigma_{ion}\, n = \frac{1}{\lambda_{ion}}$$

1st Townsend coefficient

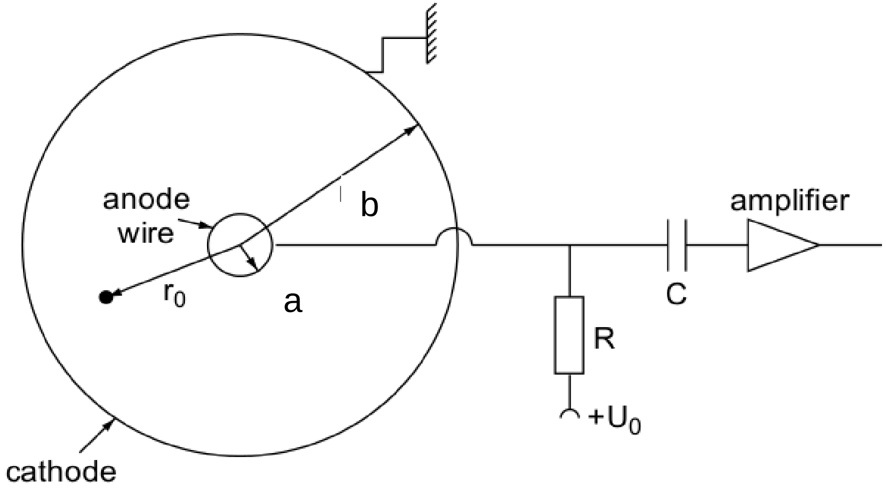
- α depends on free path, ionization energy, electric field, pressure...
- Note that ionization caused by electrons (not ions)
- In proportional regime, A = constant ~ $10^4 - 10^6$
  - A can be easily measured, example:
  - X ray of energy E in gas with W energy for ionization: $N_0 = E/W$ and $Q = e\,N_0\,A$

Gain key for mip detection:
can do tracking

Proportional Counters

- To obtain the signal formation one can apply Shockley-Ramo
- The ratio of electron and ion charge:

$$\left(\frac{Q_S^-}{Q_S^+}\right)_{r_0} = \frac{\ln r_0/a}{\ln b/r_0}$$

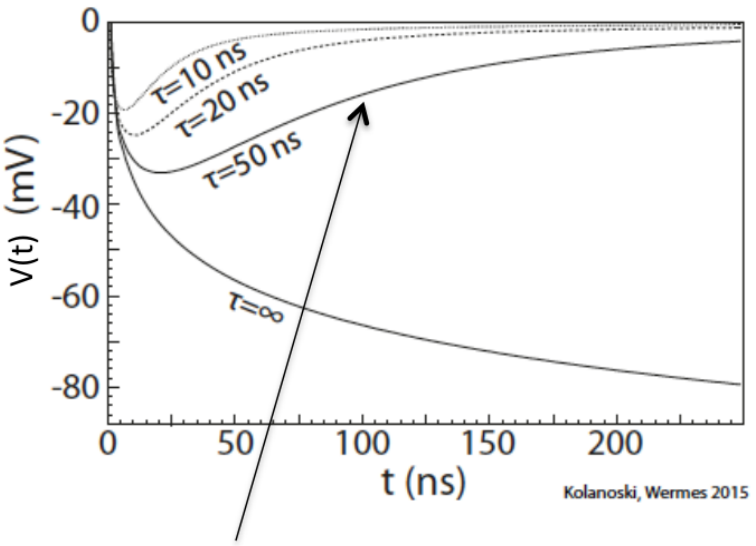


- For a=10 µm, b=1 cm
  - r_0= 13 µm : $Q_s^- / Q_s^+ = 0.01$ (near wire)
  - Away from wire, no multiplication, no signal..

Summary

- Signal induced by electrons is small
- Signal (on wire) governed by the ion cloud moving away from the wire to the cathode
- Signal only induced after avalanche close to the wire

Note that PC does not give position information!

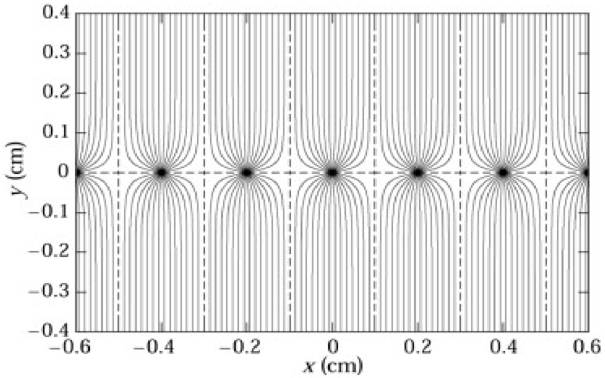


Kolanoski, Wermes 2015

with RC filter

Multi-Wire Proportional Chambers (MWPC)

► Back to “tracking”, reconstructing trajectory of particles...

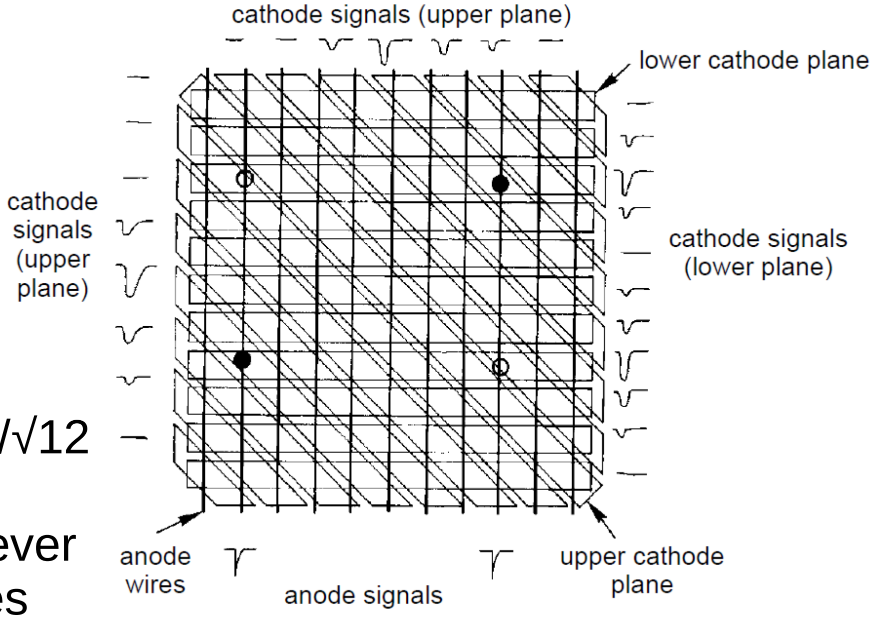


- Two cathodes planes with series of anode wires between the planes
- E field and gas properties chosen so that chamber operates in proportional mode (avalanche near wires, signal collected from wires and corresponding strips)
- The electric field geometry close to the anode wires is very similar to the field in a proportional counter → each individual anode wire behaves as a proportional counter
- Anode wires: 20 µm thick Au-plated W, Al; 2 mm spacing

  Counting gas: Ar, Kr, or Xe with admixture of CO_2 , CH_4 , isobutane, … (high electron mobility)

  Amplification: 10^5 ; efficiency: ~100%

Multi-Wire Proportional Chambers (MWPC)



Position resolution

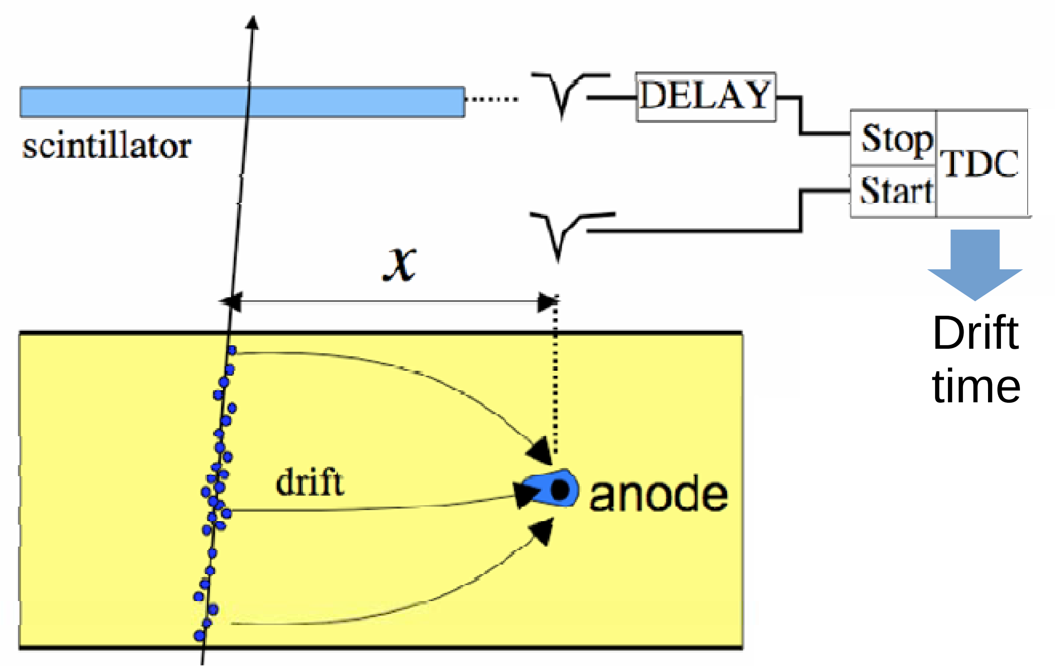
- Given by pitch, inter-wire distance, d: $\sigma(x) = d/\sqrt{12}$
  - $\sigma(x) = 577$ µm for $d = 2$ mm
- To improve resolution one can reduce d, however limited by electrostatic repulsion between wires
- Charge division to determine other coordinate (use wire resistivity, needs readout from both sides)

Further improve position resolution

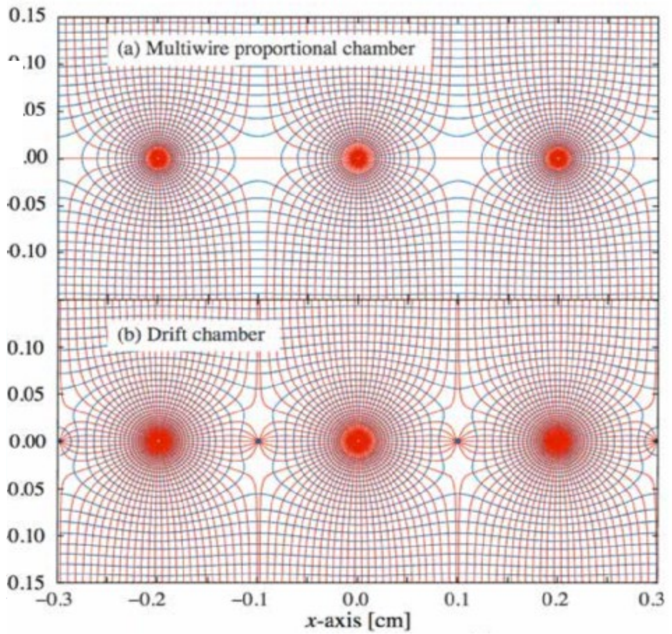
- Segment cathode planes into strips; strips run perpendicular (on one cathode) and at an angle or parallel (in the other) to the anode wires
  - Signal spread into several strips, use center of gravity to obtain position
  - Can achieve $\sigma(x) = 50\text{-}100$ µm (depending on chamber size)
  - Improve further…: 2D cathode segmentation!

Drift Chambers

- Another way to get position information: measure drift time of electrons to anode
  - Time measurement started by an external (fast) detector (scintillator counter)
- If constant drift velocity, then $x = v\,\Delta t$ (→ constant electric field is needed)
  - Introduce potential wires to produce suitable drift field



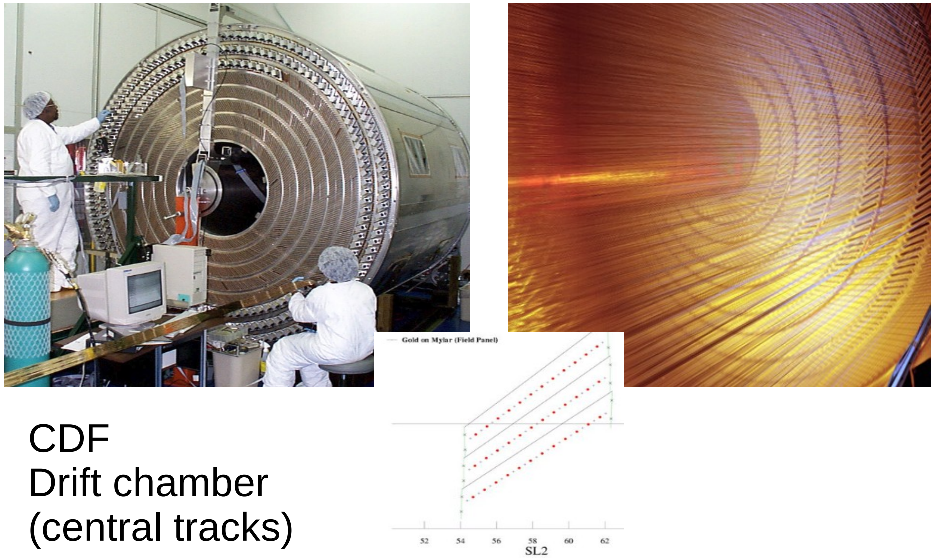
Drift time



- Typical of gas Ar-C_4H_{10}
- Use slower drift velocity to optimize spatial resolution
- Can achieve: for large DC: 50-200 μm, small DC: 30-70 μm

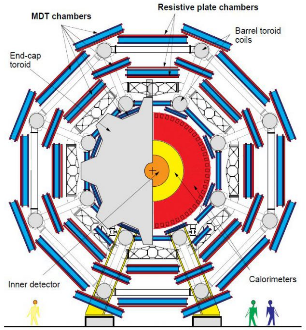
Drift Chambers

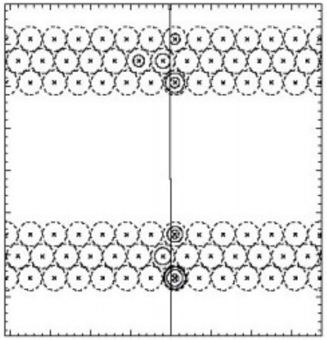
- Large drift chambers as central tracker in various collider experiments
    - Continuous segmentation allows powerful pattern recognition
    - Good solid angle coverage
    - Low material budget
    - Radiation hard (but not suitable for very high rates)
        - Gas flows through chamber, can react to chamber “aging” by tweaking gas
- Various geometries define cell sensing volumes

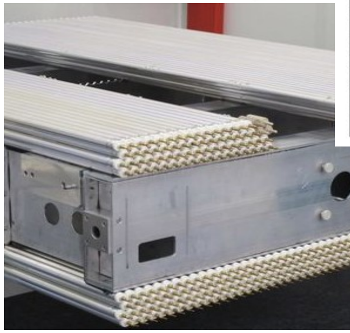


CDF
Drift chamber
(central tracks)

ATLAS
Proportional drift
tubes (μ tracks)

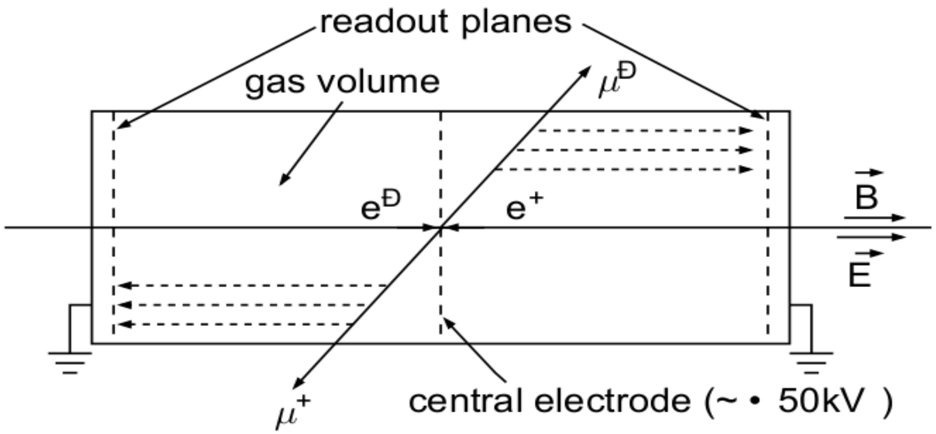


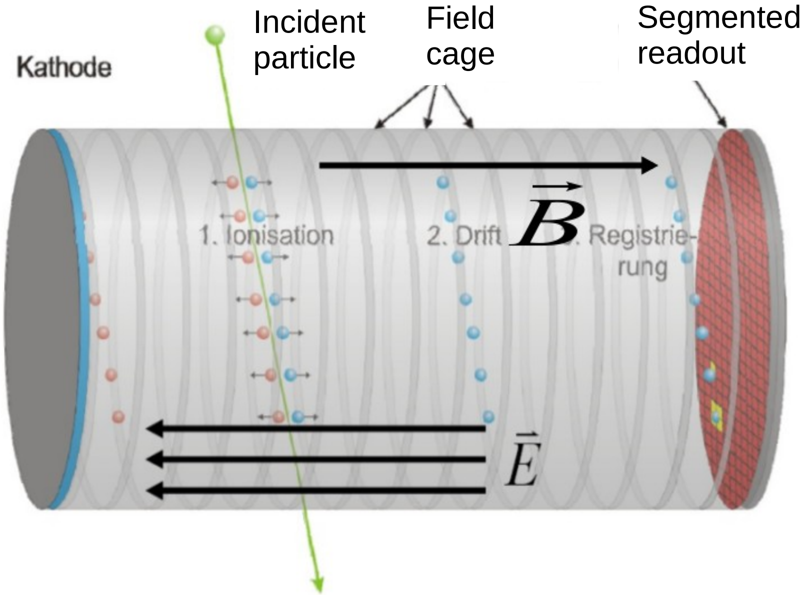




Time Projection Chamber (TPC)

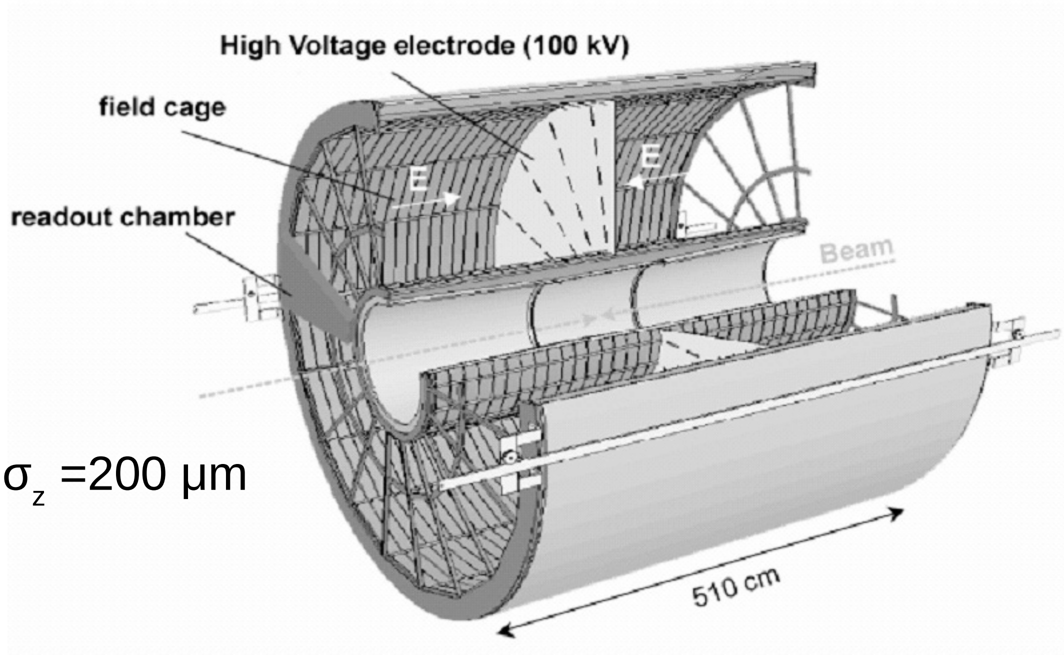
- The **Time Projection Chamber** combines principles of a **drift chamber** & **proportional chambers** to measure **3-dimensional space points**
- Get **X-Y** information from segmented readout in end-caps, **Z** information from drift time measurement (full 3D reconstruction)





- Central electrode separated chamber in two
- If B field (usually // to E field) → then momentum determination
  - Also reduces diffusion perpendicular to the field

Time Projection Chamber (TPC)

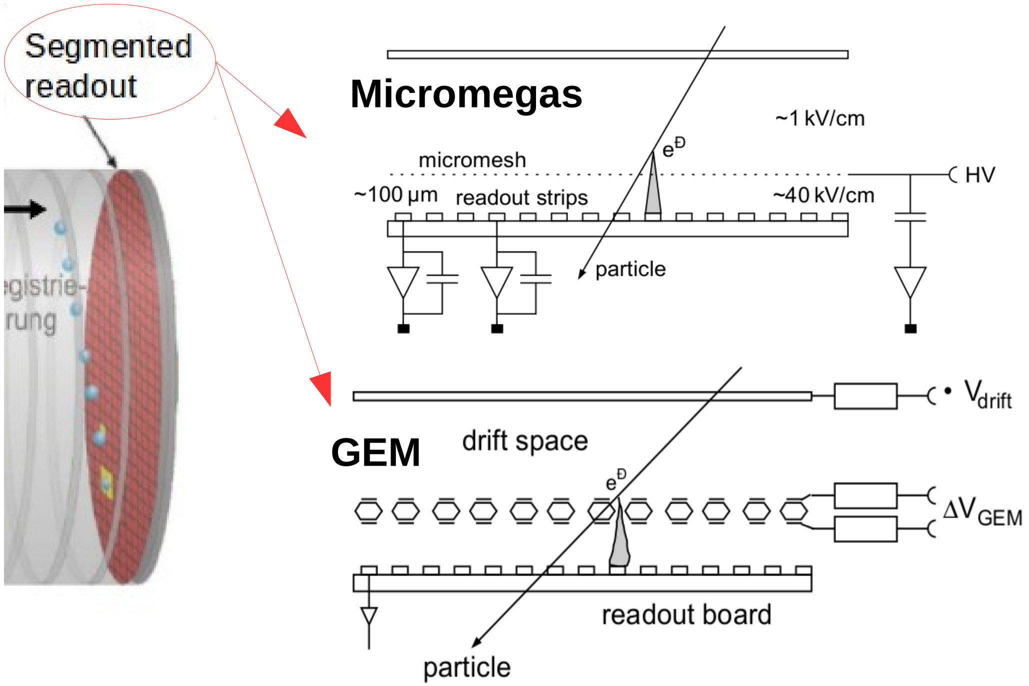


- **ALICE TPC:**
  - MWPC as segmented readout
  - Vol = 90 m^3, 845 < r < 2466 mm and 2 x 2.5m drift length
    - max drift time 95 µs
  - 550k readout channels
  - Spatial resolution: $\sigma_{r\Phi}$ =180 µm, σ_z =200 µm

- **Some limitation of wire-based readout**
  - Limited by diffusion and space charge effects to accuracies of 50-100 µm
  - Low rate capability

Micro Pattern Gas Detectors (MPGDs)

- Stability/flexibility of systems can be enhanced if anodes made in the form of strips or pads on insulating or semi-conducting surfaces instead of anode wires
- Two approaches in this direction
  - Foil with copper on both sides and large number of holes
    - **GEM**: Gas Electron Multiplier
  - Wire mesh just above the anode plane
    - **Micromegas:** micro mesh gaseous structure



MPGDs offer:

- excellent spatial resolution (smaller segmentation)
- low dead time: positive ions produced in avalanche drift a very short distance to cathode strips in vicinity of the anodes)
- improved the rate capability
- reduced radiation damage (smaller sensitive area per readout element)

Summary on Gas Detectors

Why gas-based tracking detectors?

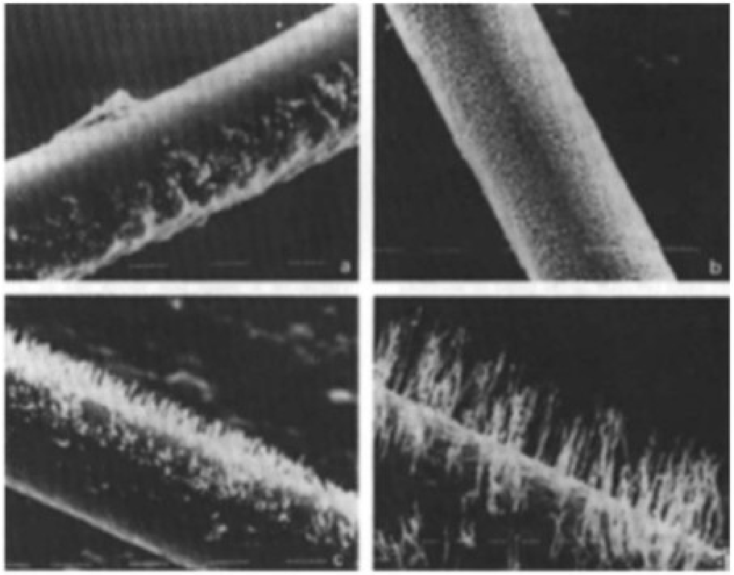
- Can be fully sensitive
- Offer good solid angle coverage
- Can achieve ~50 µm position resolution, but usually in the ~100 µm
- Cost effective technology to cover large area

However:

- Need tracking at high particle rates
- Usually better position resolution is required (e.g., for flavor tagging)

What technology can improve above?

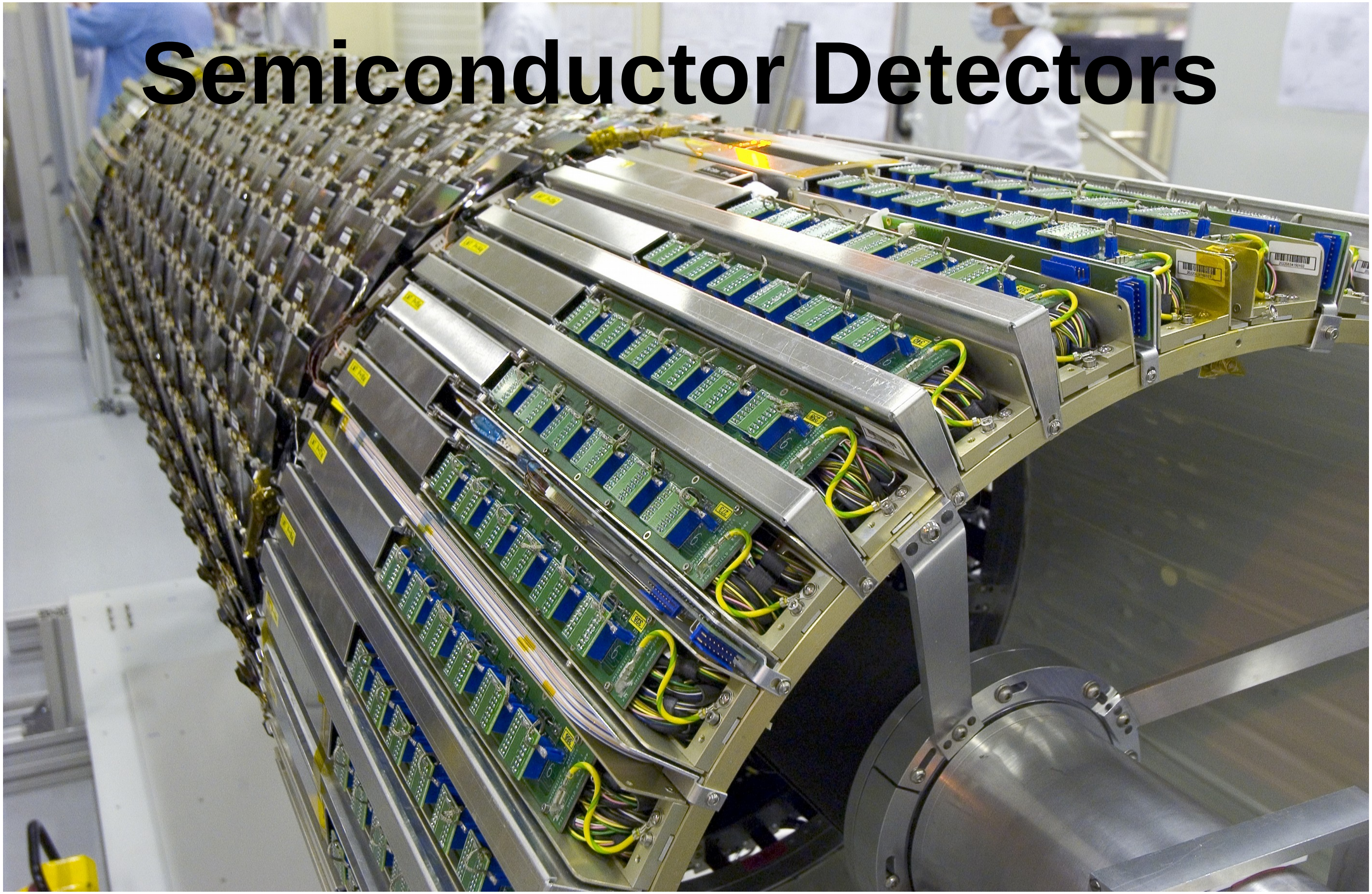
- Solid state detectors



***Aging**:*

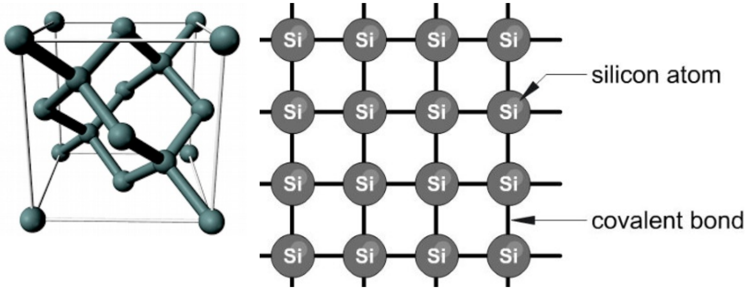
- *Caused by gas impurities (or from detector)*
- *avalanche formation → micro plasma discharge → create molecule fragments (polymers) → may attach to the electrodes → reduce gain*

Semiconductor Detectors



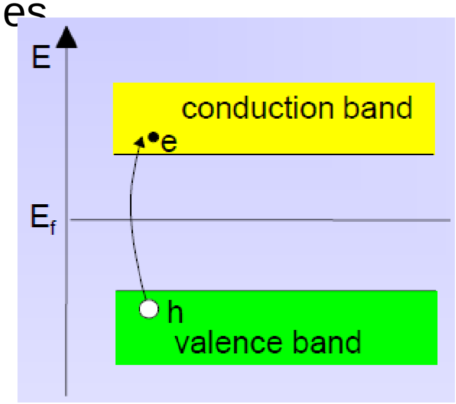
ATLAS Silicon Tracker – CERN

Solid State Detectors



What solid?

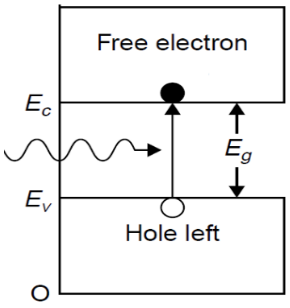
- Several materials used depending on specific needs...
- But silicon specially attractive for many HEP applications:
  - Silicon semiconductor that has 4 valence electrons
  - **Small band gap:** Eg = 1.12 eV; E(e-h pair) = 3.6 eV (≈ 30 eV for gas detectors)
  - **High specific density**: 2.33 g/cm^3 ; dE/dx (mip) = 3.8 MeV/cm → 100 e-h/µm (average)
  - **High carrier mobility**: μ_e=1450 cm^2/Vs, μ_h = 450 cm^2/Vs →fast charge collection (<10 ns)
  - **Very pure** < 1ppm impurities and < 0.1ppb electrical active impurities
  - **Rigidity** of silicon allows thin self supporting structures
  - Detector production by **microelectronic techniques**

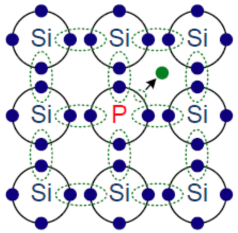


	Diamond	SiC (4H)	GaAs	Si	Ge
Atomic number Z	6	14/6	31/33	14	32
Bandgap E_g [eV]	5.5	3.3	1.42	1.12	0.66
E(e-h pair) [eV]	13	7.6-8.4	4.3	3.6	2.9
density [g/cm^3]	3.515	3.22	5.32	2.33	5.32
e-mobility μ_e [cm^2/Vs]	1800	800	8500	1450	3900
h-mobility μ_h [cm^2/Vs]	1200	115	400	450	1900

Well known industrial technology, relatively low price, small structures easily possible

Silicon Detectors





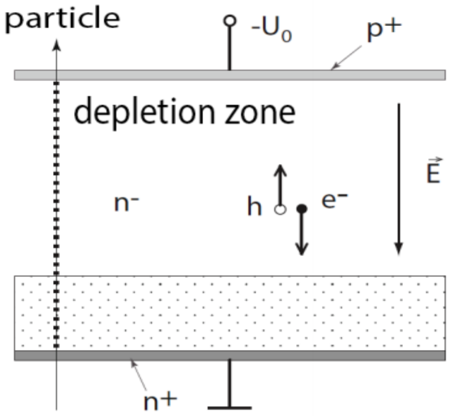
$$n = 2\left(\frac{2\pi m_n k_B T}{h^2}\right)^{3/2} e^{-(E_C - E_F)/(k_B T)}$$

Electron concentration in conduction band

- Incident radiation generates e-h pairs that are collected by electric field
- However, in pure intrinsic silicon electron (n) and hole (p) densities are equal and n = p = 1.45E10 /cm^3 (at room temp.)
  - But expected signal in typical (200 µm thick) sensor is much smaller, 20000 e-h pairs
  - Solution: dope Si to form a p–n junction → zone that is free of charge carriers (depleted), enlarged by applying a voltage
    - Elements with 3 valence e- (p-type, B)
    - Elements with 5 valence e- (n-type, P)

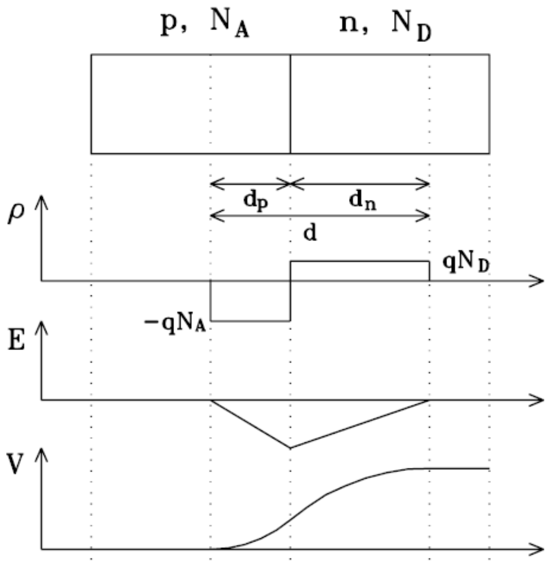
- Silicon detector is basically a reverse biased p-n junction
- Depleted region (ionization collection region) depends on external voltage

- *Key to sensor sensitivity is depletion depth, which can be adjusted with reverse bias and resistivity (both technology dependent)*



HASCO – July 2019

Silicon Detectors



$d = x_p + x_n$ (1) $N_A x_p = N_D x_n$ (2) charge neutrality

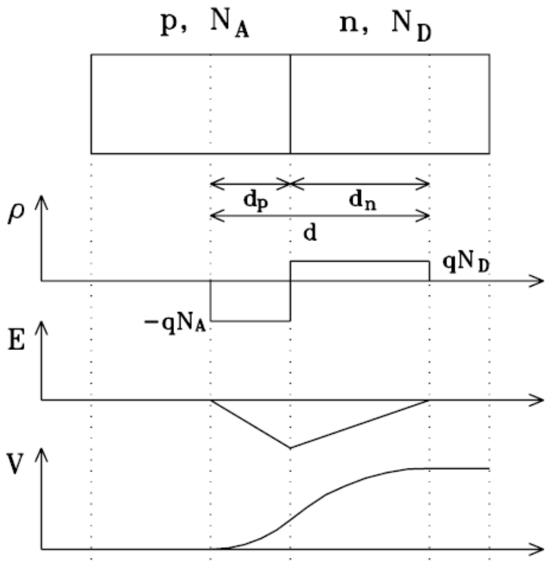
$$\rho(x) = \begin{cases} -eN_A, & -x_p < x < 0 \\ eN_D, & 0 < x < x_n, \\ 0 \end{cases} \qquad \frac{dE}{dx} = \frac{\rho(x)}{\varepsilon}$$

$$E(x) = \begin{cases} -eN_A(x + x_p)/\varepsilon, & -x_p < x < 0 \\ eN_D(x - x_n)/\varepsilon, & 0 < x < x_n, \\ 0 \end{cases}$$

$$V_{bi} = -\int_{-x_p}^{x_n} E(x)\, dx = \frac{e}{2\varepsilon}(N_A x_p^2 + N_D x_n^2) \quad (3)$$

→ using (1), (2) and (3): $d = \sqrt{\frac{N_A + N_D}{N_A N_D} \frac{2\varepsilon}{e} V_{bi}}$

Silicon Detectors



$$d = \sqrt{\frac{N_A + N_D}{N_A N_D} \frac{2\varepsilon}{e} V_{bi}}$$

Usually, Na >> Nd or Nd >> Na:

$$\boxed{d = \sqrt{2\epsilon V_{bi}/(eN_{eff})} \approx \sqrt{V\,\rho}}$$

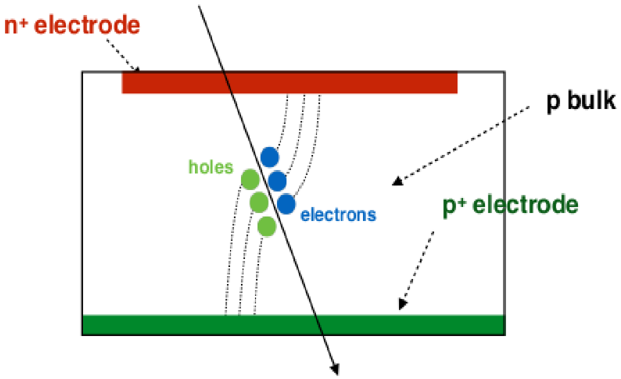
ρ is resistivity [Ω cm]

- For some typical values (Neff ~ 10^{12} cm^{-3}, Vbi~0.5V) → d ~ 20 μm
- Apply external voltage to increase depletion region into the low (high) doped (resistivity) substrate
- **Example**:
  - d = 300 μm
  - Neff = 1.5 10^{12} cm^{-3} *(ρ=1/(μeN)=3kΩcm)*
  - Vdep = 100V

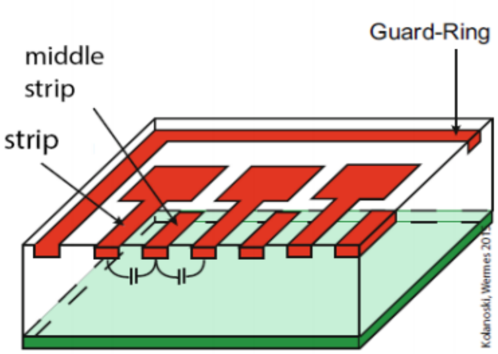
$$\boxed{V_{dep} = \frac{e}{2\,\epsilon} N_{eff}\, d^2}$$

Types of Silicon Detectors

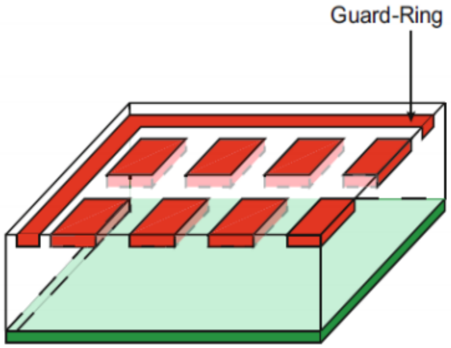
- Ideal silicon detector:
    - Provides excellent position resolution (~10µm)
    - Has ~100% efficiency
    - Sustain large radiation doses (both ionizing and non-ionizing radiation)
    - Maintain low fake trigger rate
    - Operate at 25ns clock (fast charge collection, fast electronics)



Pad detectors:
easiest to fabricate but poor position resolution

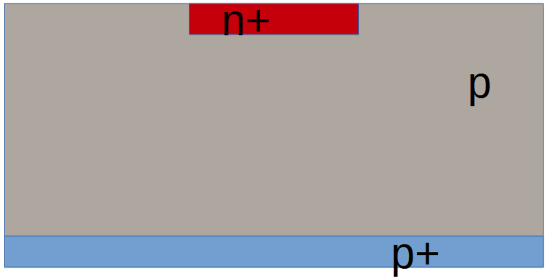


Strip detectors:
Pitch ~ 80 µm, but difficult to provide excellent 2D resolution

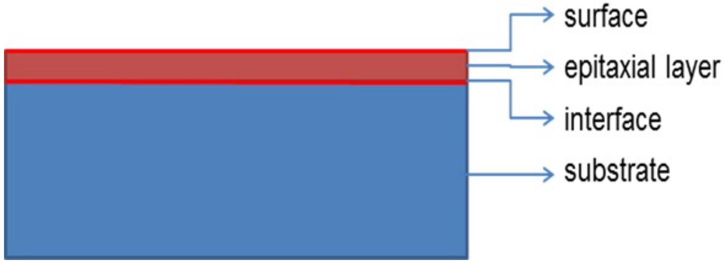


Pixel detectors:
Best position resolution, but: large power consumption & assembly cost

Types of Silicon Detectors: Substrates

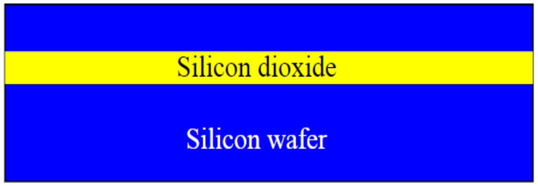


- Standard HEP detector on **high ρ silicon substrate**
- **n-on-p** for e collection (faster)



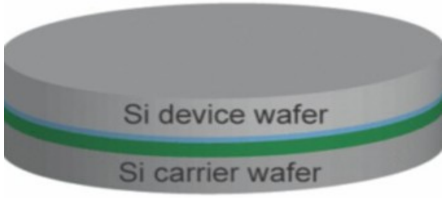
few µm

- **Epitaxial layer** on silicon bulk
- Usually deposited through CVD
- Used in CMOS processes



- **Silicon On Insulator** (SOI)
- SiO2 reduces parasitic capacitance
- Top layer varies with application
- Used in specialized processes

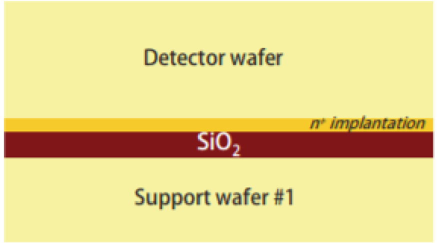
- Wafer to wafer bonding



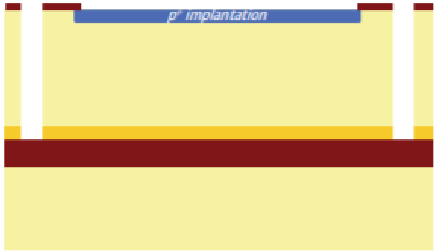
- **Technology selection** driven by experimental **conditions & requirements** and sensor fabrication strategies

Silicon Detectors: Fabrication

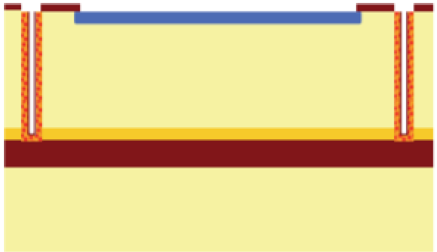
Silicon ingots → wafer starting point



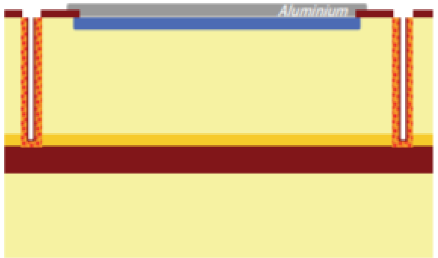
SOI wafer or fusioned wafers (detector + support) with buried n^+ implantation



Boron implantation
DRIE for trenches



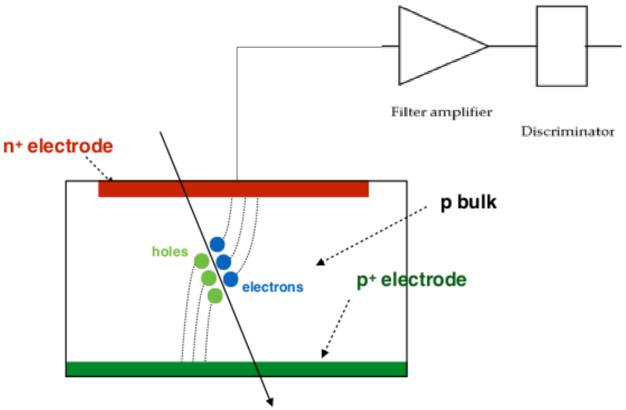
Polysilicon deposition + doping P
Sidewall doping diffusion



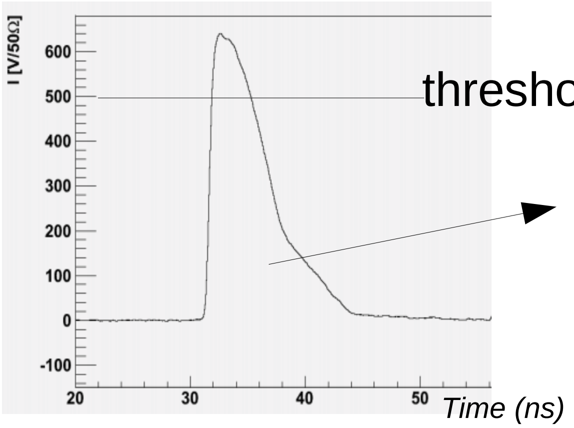
Metal deposition

Sensor fabrication takes about ~50-100 steps of processing (pattering, passivation, etching, etc) in dedicated facilities.

Signal Processing



DC (or AC) coupling



threshold

Charge is the integral, typical Q~2.5 fC (200µm thick)

$$I_i(t) = q\vec{v}_{dr}(\vec{E}(\vec{r}(t))) \cdot \vec{E}_{i,w}(\vec{r}(t))$$

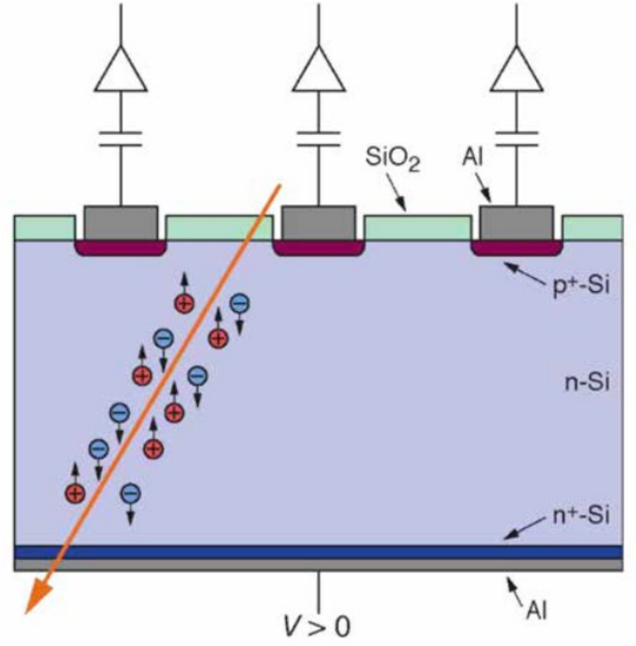
- Relatively small signals (20ke)
- Current induced in readout electrode as charge drift towards electrodes
- Need to amplify and discriminate signal

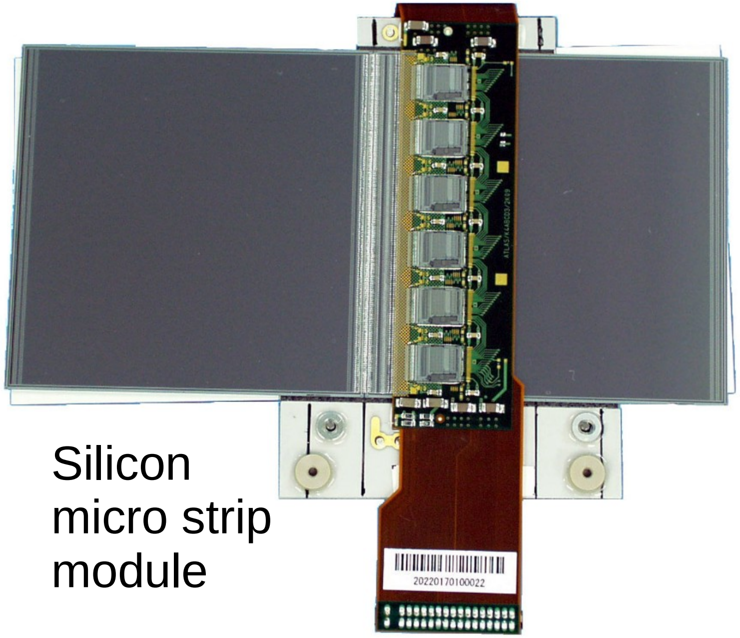
  - Signal processing done by electronics next to sensor (“front end”, Application-Specific IC: ASIC)
  - Noise is an important factor to determine detector performance
    - For silicon detectors most important contribution given by C_{det}: $\sigma \sim C_{det}/\tau$

      (τ is the peaking time of the shaped signal)
  - Signal-to-Noise: typical values >10-15, Radiation damage degrades the S/N

Silicon Micro-Strip Detectors

- Segmented electrode into strips on one side
- Using n type silicon with a resistivity of 2 kΩcm (N_D ~2.2 10^{12} cm^{-3}) results in a depletion voltage ~ 150 V
- Typical pitch about ~80 μm
  - For a position resolution σ ~ p/√12 ~ 20 μm
  - Better for cluster size > 1 with center of gravity method

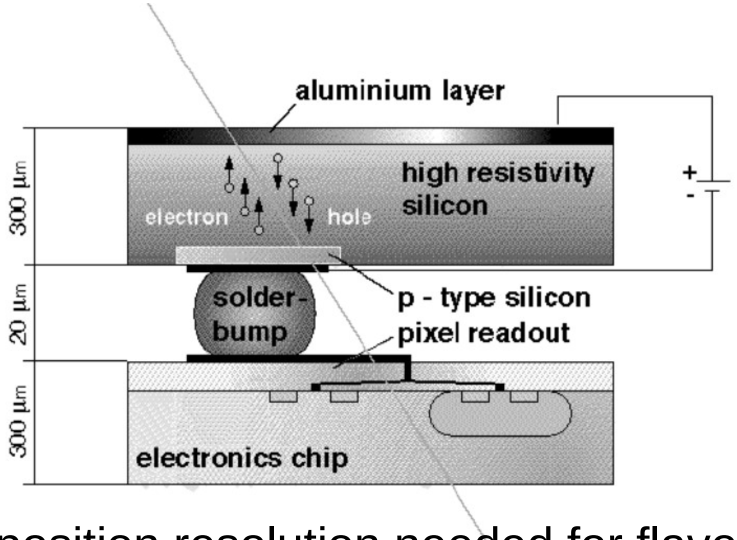


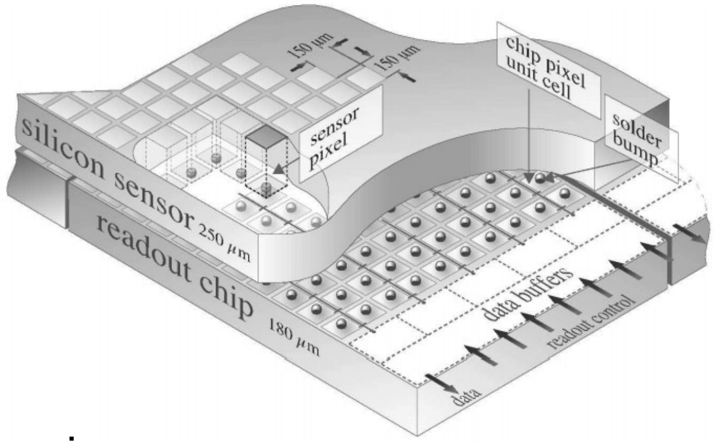


Silicon micro strip module

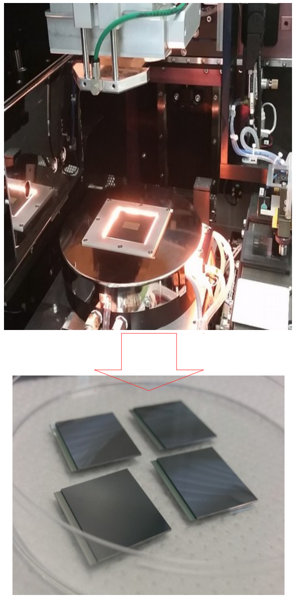
- Silicon strip detectors are frequently the core of the **tracking** detectors in hadron colliders

Pixel Detectors





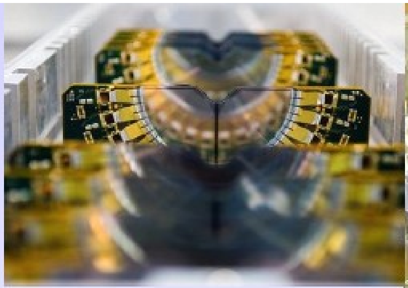
- Best position resolution needed for flavor tagging
  - Innermost layers critical for impact parameter resolution
- Typical (current) pixel size ~50x50 µm^2
- Need to connect each pixel to a readout channel
  - Hybrid pixel module
    - Allows optimization of design of ASIC and sensor (radiation hardness)
  - Usually done through a solder ball (~25 µm diameter)
  - Expensive process, ~same as (ASIC+sensor)/cm^2
    - *Can we avoid hybridization?*

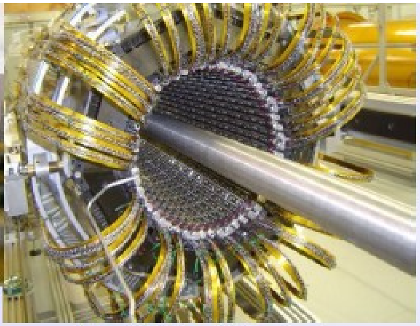


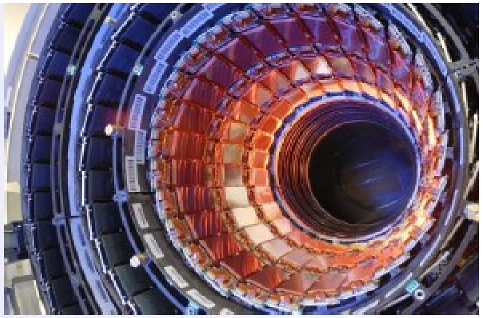
Flip-chip process

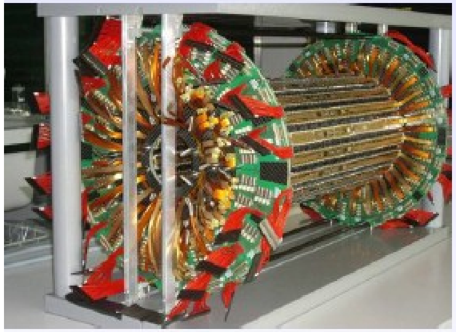
Silicon Detectors in Operation


ALICE Pixel Detector

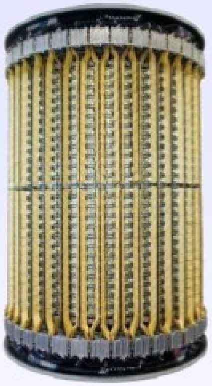

LHCb VELO

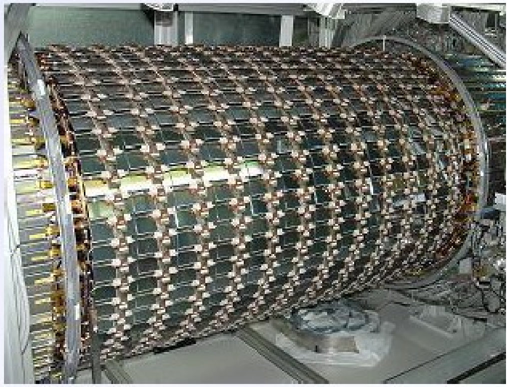

ATLAS Pixel Detector


CMS Strip Tracker IB


CMS Pixel Detector

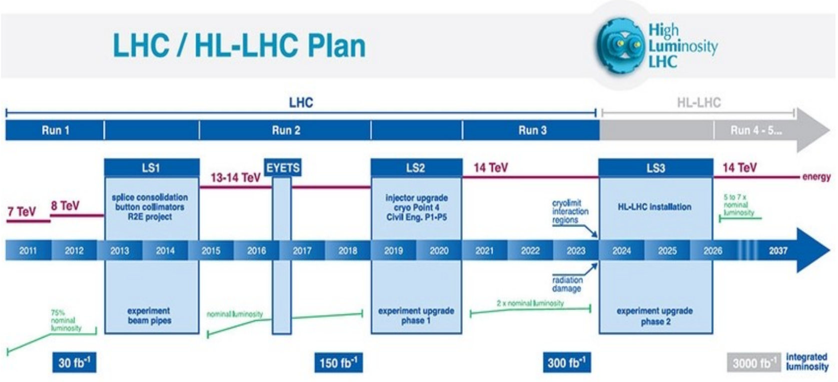

ALICE Drift Detector


ALICE Strip Detector


ATLAS SCT Barrel

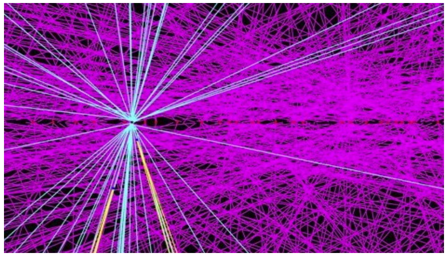
- Silicon tracking detectors are used in all LHC experiments:
- Different sensor technologies, designs, operating conditions,….

Radiation Damage



LHC accelerator upgraded periodically to keep exploring energy frontier

- Thus increase the amount of radiation experiments have to sustain



Two general types of radiation damage to the detector material:

- Bulk (crystal) damage due to Non Ionizing Energy Loss (NIEL)
  - Change of effective doping concentration & acceptor/donor removal (higher depletion voltage, under-depletion)
  - Increase of leakage current (increase of shot noise, thermal runaway)
  - Increase of charge carrier trapping (loss of charge)
- Surface damage due to Ionizing Energy Loss (IEL)
  - Accumulation of positive charge in the oxide (SiO2) and the Si/SiO2 interface
    - Affects: inter-strip/pixel capacitance (noise factor), breakdown behavior, ...

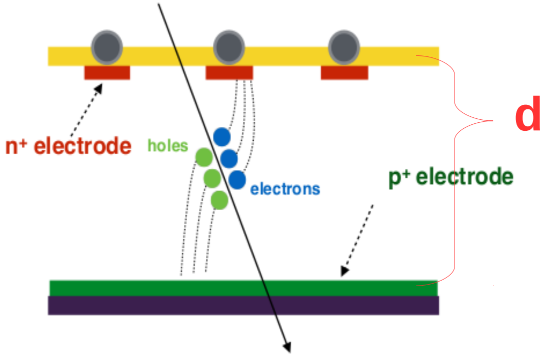
~1E15 1-MeV neutron (equivalent)/year

~100Mrad/year (1MGy)

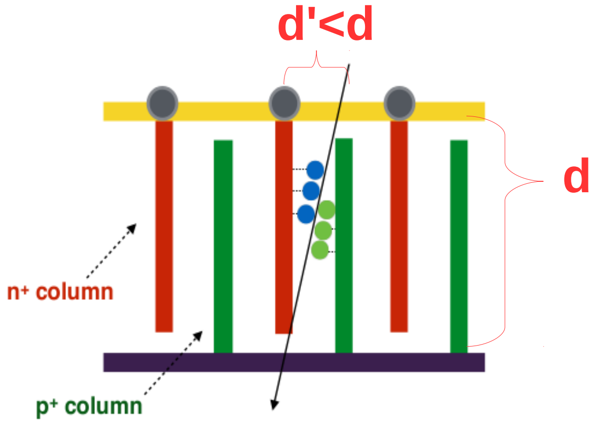
Impact on detector performance and charge collection efficiency (depending on detector type and geometry and readout electronics).
Radiation damage: usually **critical** factor in hadron colliders.

Other detector topologies: 3D sensors

- To reduce charge trapping, one should reduce the distance between electrodes
- But in standard planar sensors, this would reduce the amount of change collected



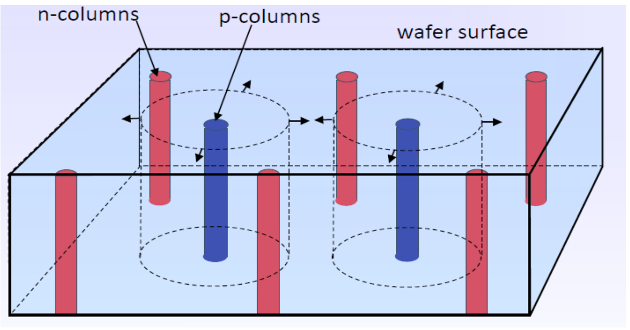
Planar detectors



3D detectors

- One could add a multiplication layer (à la APD), but:
  - Large multiplication is not desirable (no time for quenching, want to maintain E~Qcoll, increase of noise...)

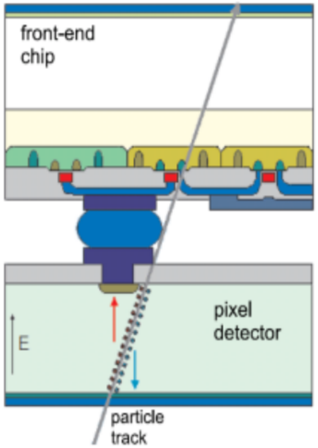
- 3D sensors improve radiation hardness through electrodes that penetrate the silicon bulk, thus decoupling the sensor thickness to the electrode distance
  - More radiation hard
  - But: more expensive (lower fabrication yield)



- Column diameter ~10 µm
- Inter column distance ~20 µm

Other detector technologies: monolithic devices

Hybrid detectors



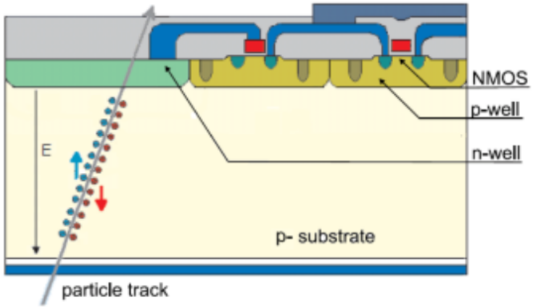
Electronics

Interconnect

Sensor

- Standard in current experiments
- Design allows for optimization of electronics and sensor
  - Radiation hardness, rate, power...

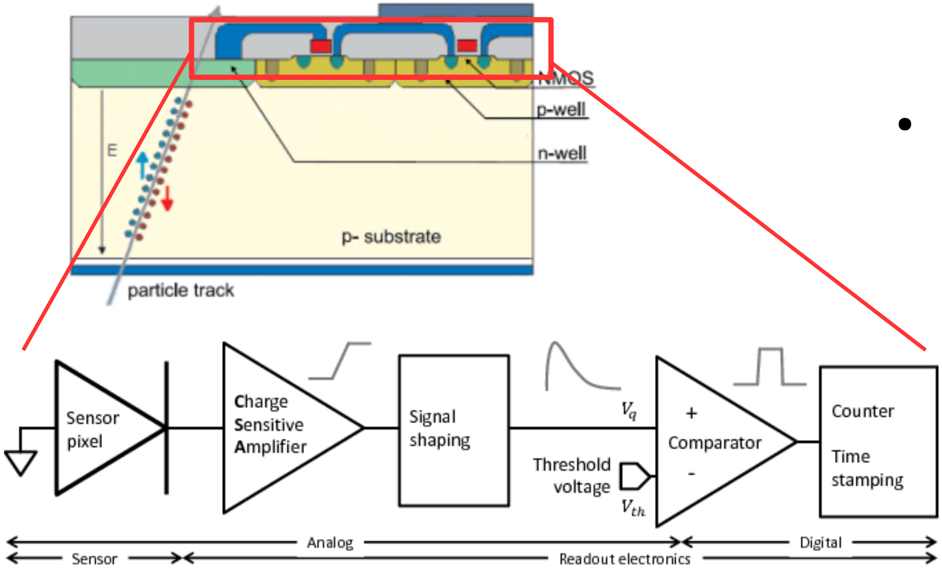
Monolithic detectors



Electronics + sensor in same substrate

- Less material, less complexity
  - And cost...
- Smaller pixel possible
  - No pixel size limitation due to interconnection

Other detector technologies: monolithic devices



Comparator and digital part can be in periphery of chip

- Why CMOS camera ≠ HEP-CMOS?
  - "CMOS camera" ~ little depletion/mostly diffusion of charge
  - Diffused charge slow and not collected after irradiation
  - Need to increase depletion region for HEP, two approaches
    - Increase V (HV-CMOS)
    - Increase resistivity (HR-CMOS)
    - Common name: Depleted Monolithic Active Pixels (DMAPS)

- Future of silicon detectors at low to intermediate fluences?

$$d \sim \sqrt{\rho \cdot V}$$

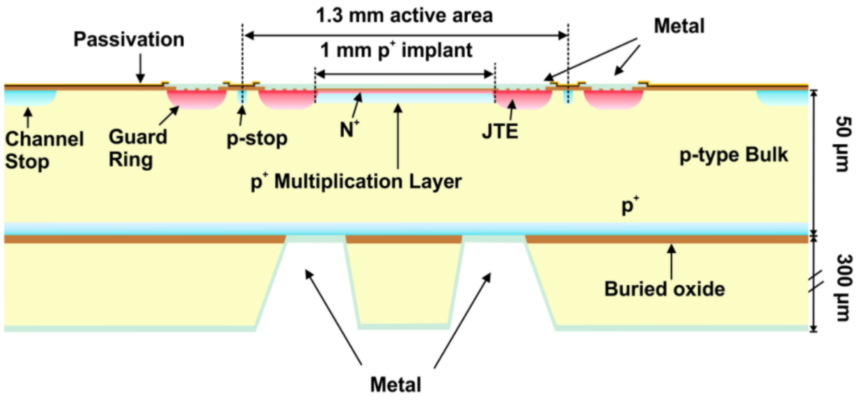
Timing with Silicon in HEP

- To reduce “pile-up” (effect of secondary interactions) LHC experiments plan to deliver silicon-based timing detectors
  - Timing+rad hardness+compactness
- The target is to achieve about ~60 ps/mip/layer resolution: **beyond standard silicon** devices

$$\sigma^2_{\rm det} = \sigma^2_{\rm Landau} + \sigma^2_{\rm elec}$$

$$\sigma^2_{elec} = \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2$$

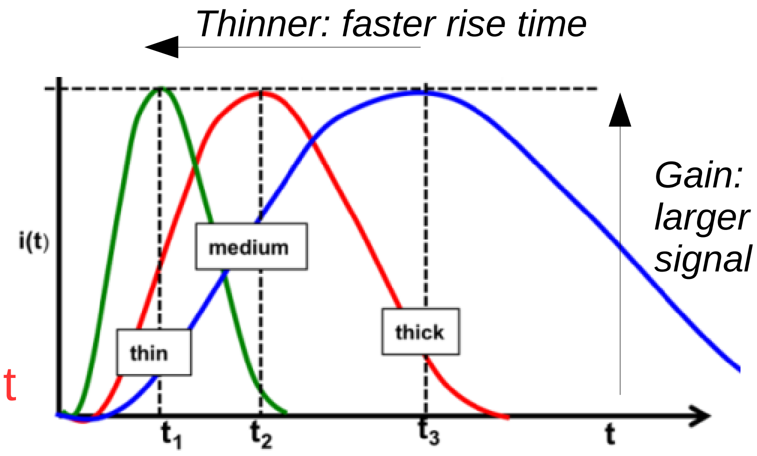
Jitter *Time-walk*



Low Gain Avalanche Detector (LGAD)

- Low gain (G=10-20): improve signal slope but control noise

- Need fast signal and excellent S/N
  - A multiplication layer increases signal slope
  - Time-walk contribution negligible with CFD
- Thin sensors (50 µm) to reduce intrinsic Landau contribution to resolution



LGAD achieve 30ps resolution before irradiation, but degrades after irradiation (on-going R&D).

Summary

- Instrumentation at LHC experiments critical to carry out physics program
- Tracking detectors fundamental for, well, track reconstruction and heavy flavor identification
- Both gaseous and semiconductor detectors undergoing heavy R&D to cope with LHC upgrades and future colliders
- In particular:
    - MPGD: fabrication, stability, long term operation...
    - Semiconductors: radiation hardness, further improve resolution...

HAVE FUN!

THE END