Tracking/Vertex Detector (I)

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Outline

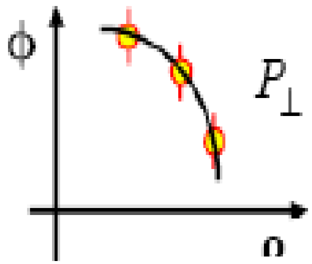
- Introduction
- Silicon Detectors
  - Working Principle
  - Characteristics
  - Radiation Damages
- Design Consideration of Silicon Tracker
- Reconstruction in Tracking Detector

Tracking of Charged Particle

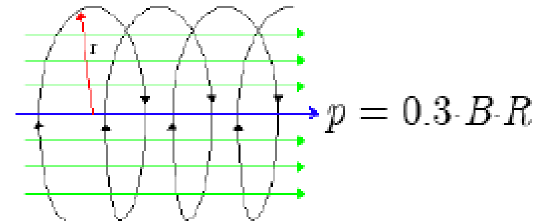
- Tracking : measurement of the charged particle trajectory (track) i.e the direction and magnitude of it's momentum
- How Tracking is done?
  - Charged particles leave trails in detector active layers due to its interaction with matter
  - Such trails are “reconstructed” as “Hits”
  - “Hits” are connected together (pattern recognition) to find the trajectory of charged particle (track)
  - Point from where tracks are originated, reconstructed as vertex
- Momentum of track is measured from its curvature in the magnetic field

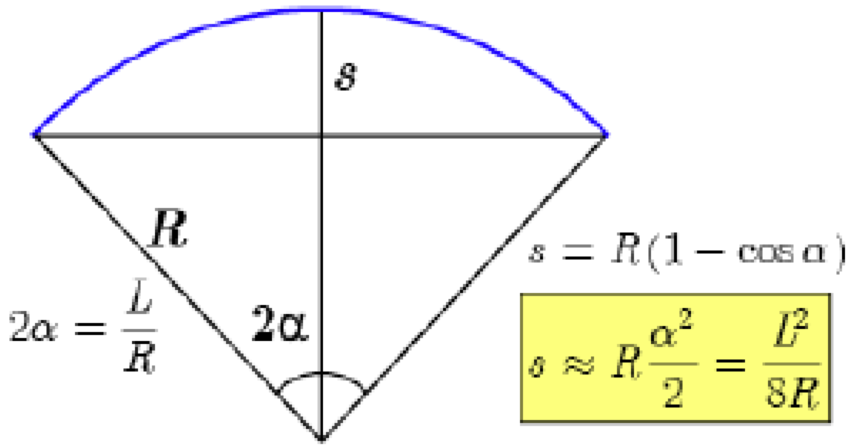
What do we measure

- Momentum in magnetic field



$$P_\perp = P\cos\lambda = 0.3BR$$





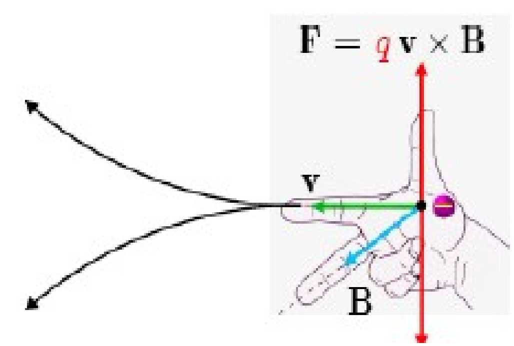
At 2T magnetic field

- $P_\perp$ = 1GeV R = 1.67m
- $P_\perp$ = 10 GeV R = 16.7cm

Assuming a track of length 1 m

- $P_\perp$ = 1GeV s = 7.4 cm
- $P_\perp$ = 10 GeV s = 0.74 cm

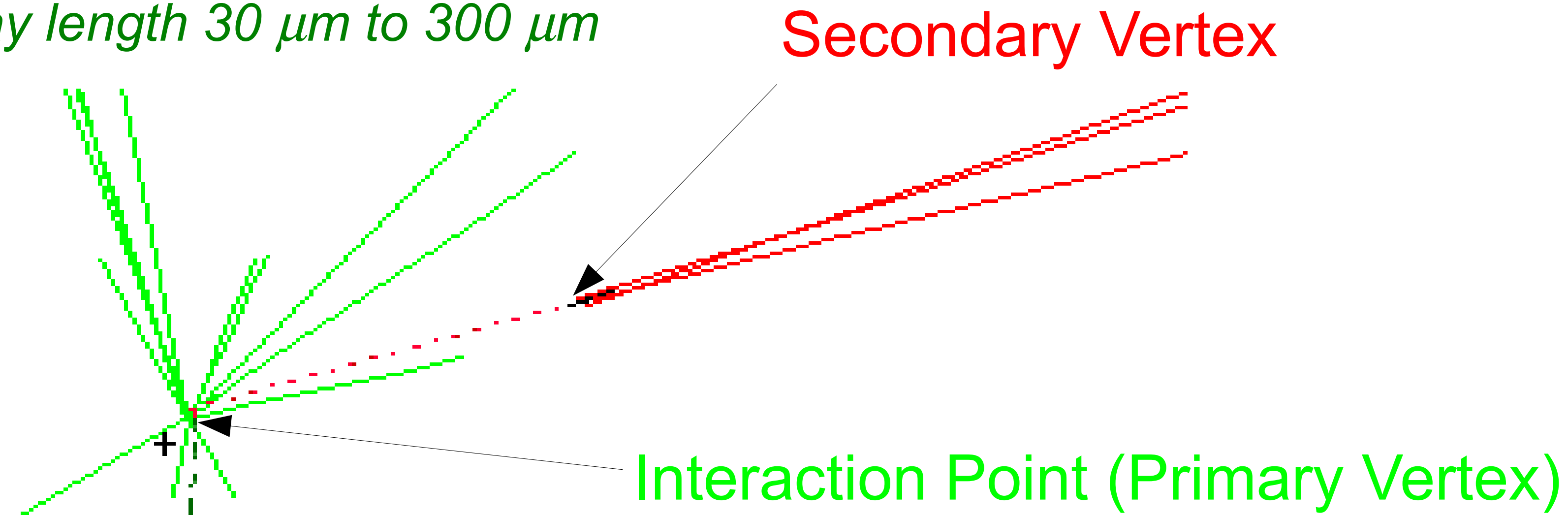
- The sign of the charge from the bending in the magnetic field



Why Silicon in Tracking System (I)

High Energy Physics in mid 70's

- *New quarks (c, b) and leptons (τ)*
- *Life time 10^{-13} s <= $c\tau$ <= 10^{-12} s*
- *Decay length 30 μm to 300 μm*

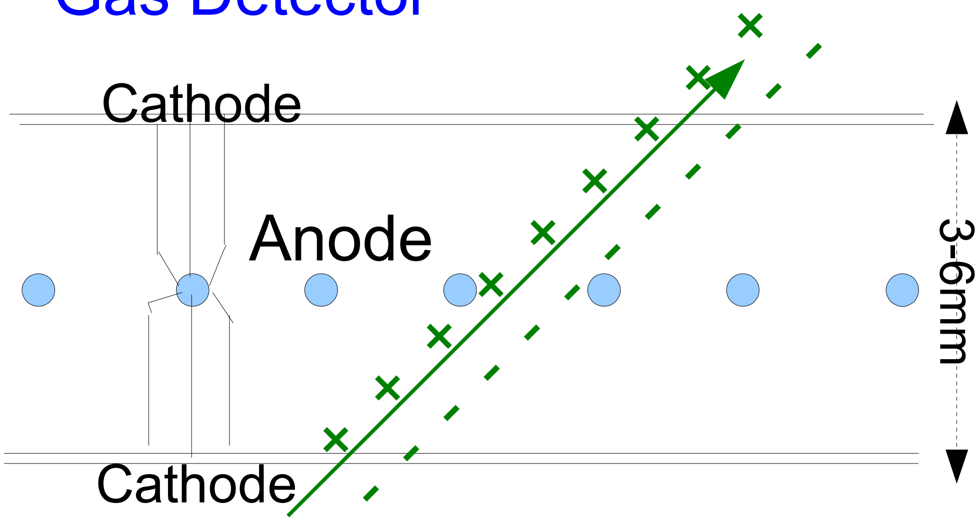


- Standard Tracking Detectors (wire chambers) resolution of 100-200 μm became less sensitive to measure such distances
- A new tracking device with of spatial resolution of 10-20μm became very important

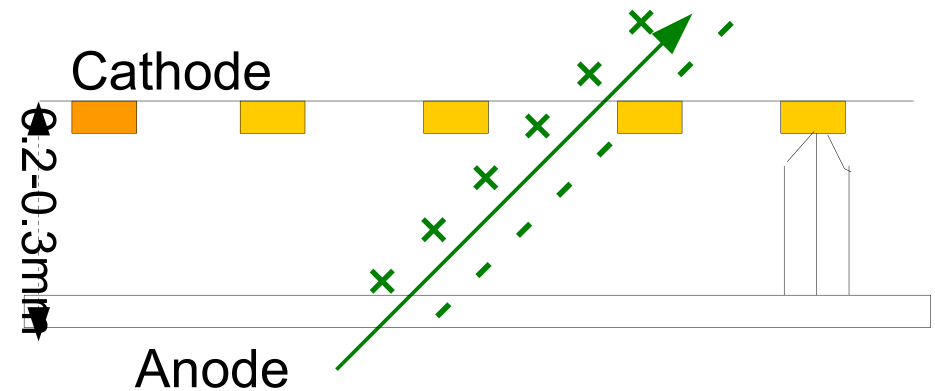
Why Silicon Detector (II)

- *The Idea : the array of silicon diodes can be used as tracking detector (1978-1980)*

Gas Detector



Silicon Microstrip Detector

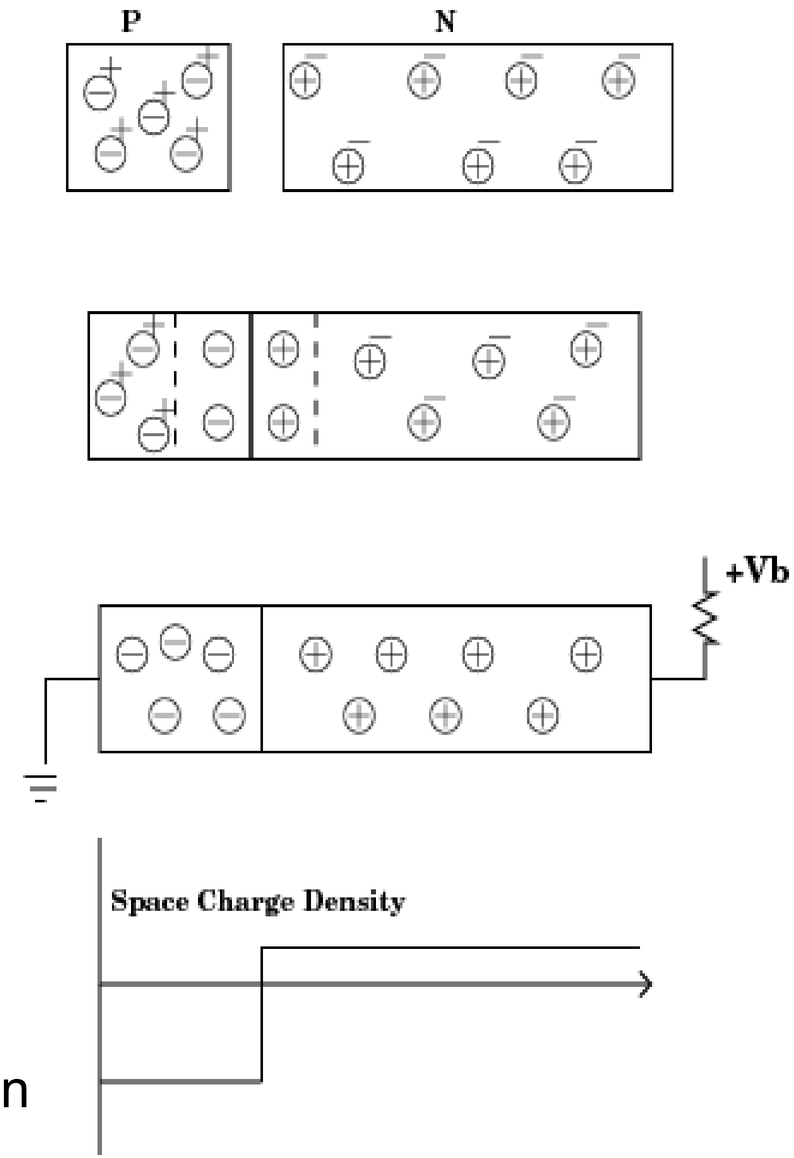


- Gain : 10^4 None (ionisation μ thickness)
- Ionisation Energy : 30 eV 3.6 eV
- Spatial Resolution : 100-200 μm 10-50 μm (density)
- Response Time : 100 ns 10-50 ns
- Size : Not compact Compact

Working Principle

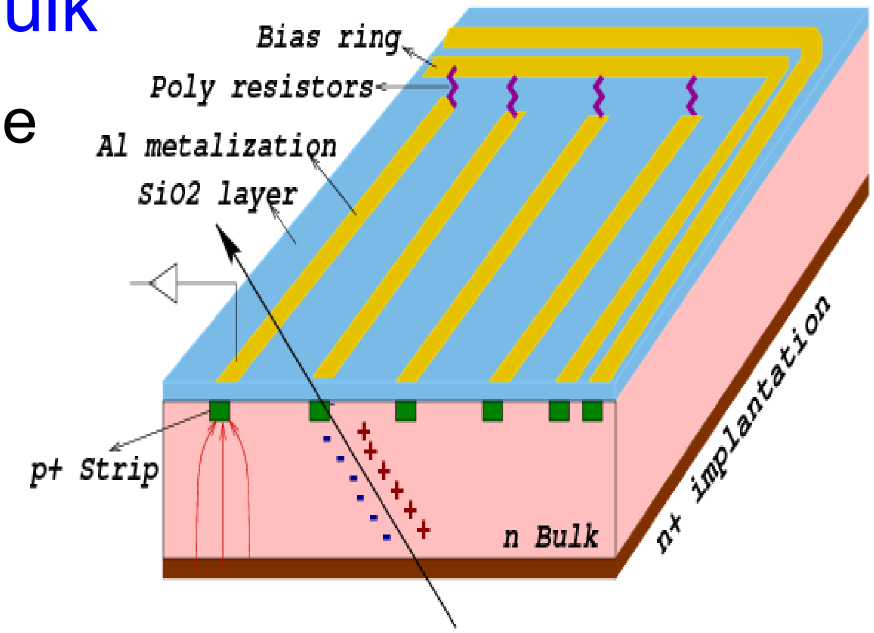
- The device should be free of charge carriers for efficient signal collection
- Reversed bias p-n junction
  - Depletion at the junction extends in the bulk
  - Behaves like a resistor drawing no currents under applied voltage
- Depleted junction acts as detector for particle trajectory
  - Charge (e-h pair) created due to passage of charged particle and collected at the junction
- Very low ionisation energy (3.6eV) and large energy loss by minimum ionizing particles...
  - large (~24k) e-h pairs created in a 300µm silicon

Reversed Bias p-n junction



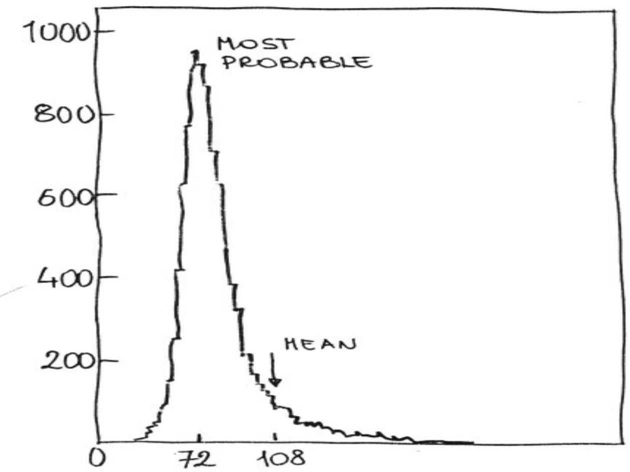
The Layout

- p^+ micro-strips on n-type silicon bulk
  - Bias voltage applied at the back side
  - Charge collected from p+ strips, electronics AC coupled
  - n+ implant at the back and at the cutting edge
- The pitch of the strips defines spatial resolution in ideal case



The Signal

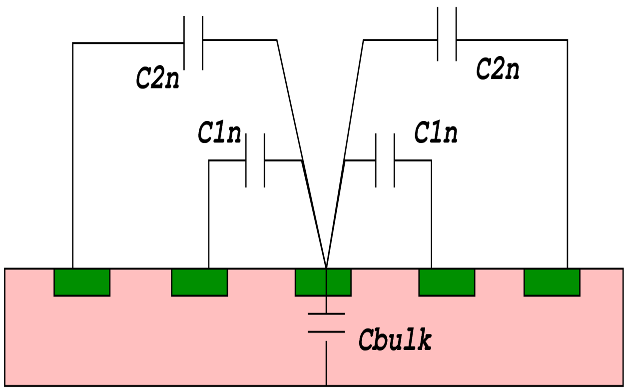
- Ionization produced in the depleted region by minimum ionizing particles
- Large energy loss due to low ionization energy
  - Landau distribution
- Fluctuations due to knock on electr
  - $(dE/dx)_{\text{most prob}} = 0.26$ KeV/μm
  - $(E_{\text{Loss}})_{\text{most-prob}} \sim 72$ e-h pairs
  - $\langle E_{\text{loss}} \rangle_{\text{mean}} \sim 108$ e-h pairs
  - 300μm thickness => 24K electrons
- Full depletion needed to collect the created charge efficiently



The Noise

Possible sources

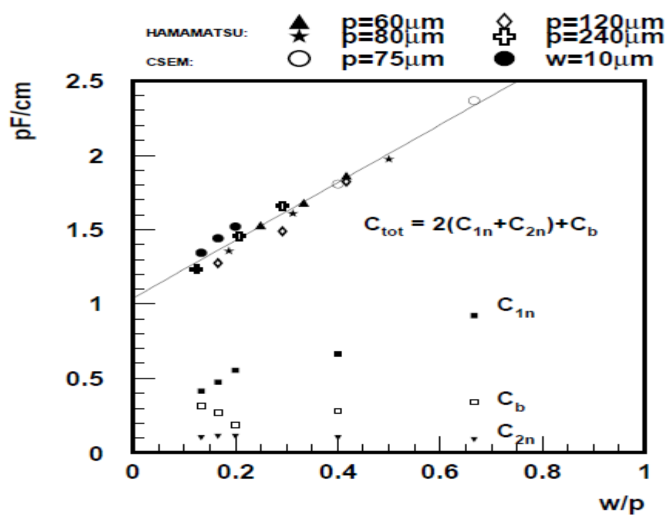
- Leakage current : drift of thermally generated minority carriers
  - $I_{leak} = 0.5\, q\, W\, (n/\tau_0)$ [W depletion depth, τ_0 life time of charges]
  - No direct temperature term but enters through charge density n
- Capacitive coupling to the electronics



$$ENC = A + B\, C_{tot}$$

$$C_{tot} = C_{bulk} + 2\,(C_{1n} + C_{2n} + ...)$$

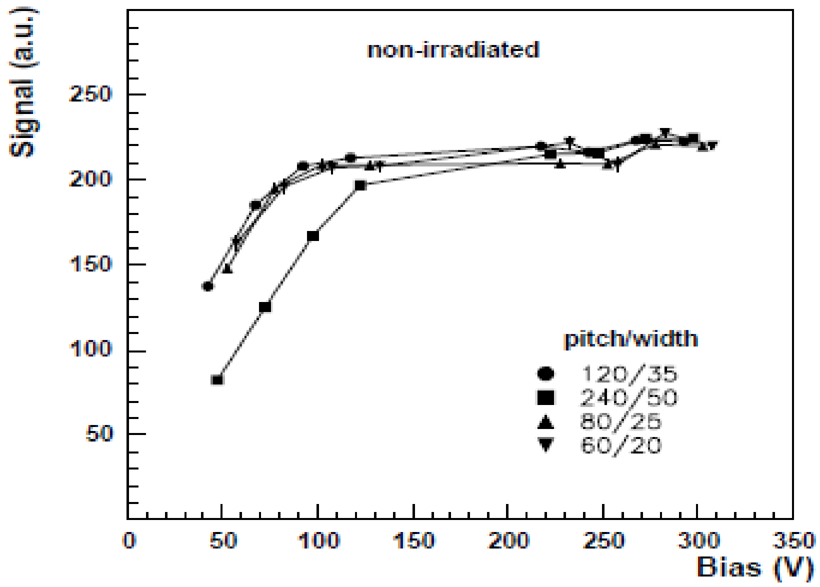
  - Ctot µ strip width/strip pitch



- Bias resistors

Characteristics

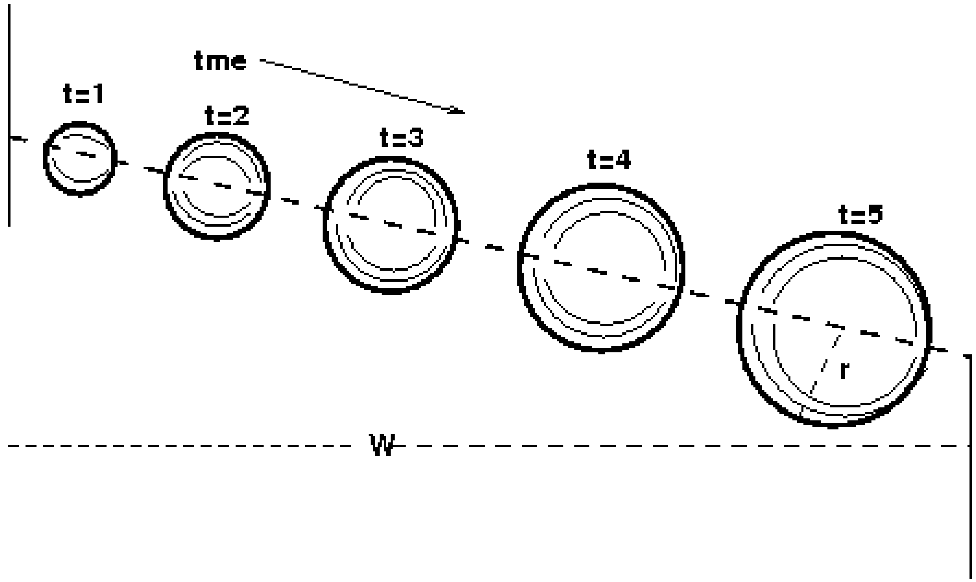
- Working point of a detector is define by the Signal to Noise (S/N) ratio of a detector
  - The most probable value of the landau fit to the distribution is defined as the Signal (S)
  - Noise is the fluctuation of charge in absence of signal
    - Mean of the Gaussian distribution



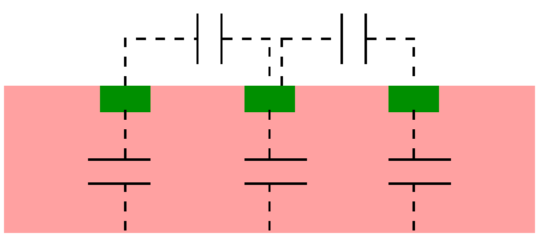
➥ Signal/Noise (S/N) defines working point of the detector

Spatial Resolution

- Physical process:
  - Fluctuation in energy loss
  - Diffusion of charge ($r \propto \sqrt{Dt}$)[*]



- External parameters
  - Strip pitch
  - Electronic noise
  - Charge sharing with neighbouring strips
    - 100-200μn pitch : σ = 10-20 μm
    - 25μm pitch : σ = 2-3 μm



(*) r = radius of charge cloud

D = diffusion constant

t = elapsed time

Effect of Harsh Radiation Environment

- Secondaries from p-p interaction and their products
- Back scattered neutrons from calorimeter produce
  - Irreversible damage in silicon
    - Increase in leakage current
    - Increase in depletion voltage
    - Deterioration of spatial resolution
- Recovery through annealing not enough
  - Short term beneficial annealing
  - Long term reverse annealing (changes Depletion Voltage)

Substantially degrades performance affecting both aspects : charge collection and spatial resolution

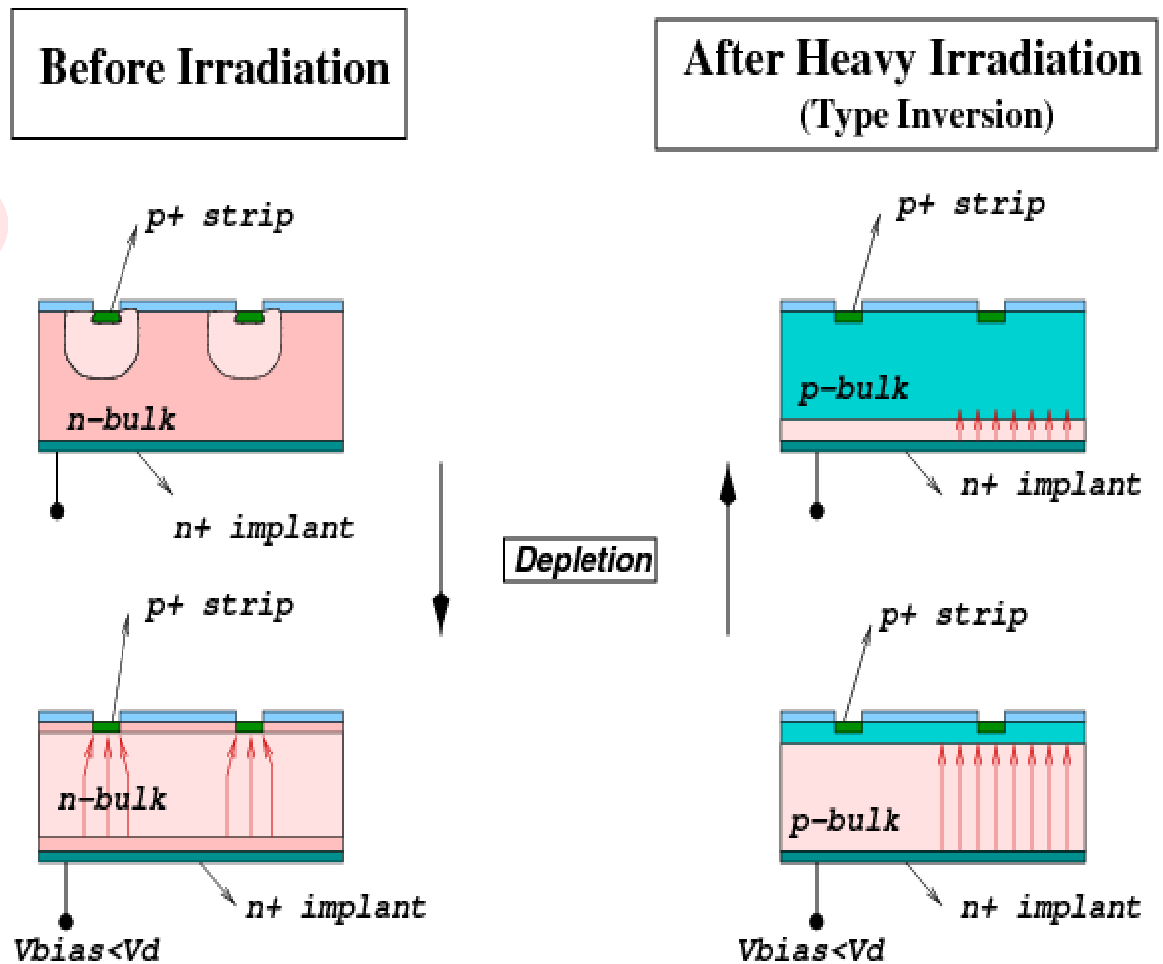
Radiation Damage in Silicon

- Surface damage
  - Decrease in interstrip isolation
  - Possible increase in interstrip capacitance

Signal Spread and Higher Noise

- Bulk damage
  - Increase in leakage current
    - $\Delta J_v = \alpha \varphi$
  - Decrease in charge collection
    - Ballistic deficit
  - Change in doping concentration
    - Type inversion

Lower S/N and Higher V_{depl}



Radiation Resistant Silicon

- Radiation hardness of silicon sensor depends on
  - Initial dopant concentration, resistivity
  - Crystal orientation
  - Processing purity/quality

It required years of R&D in collaboration with silicon industry

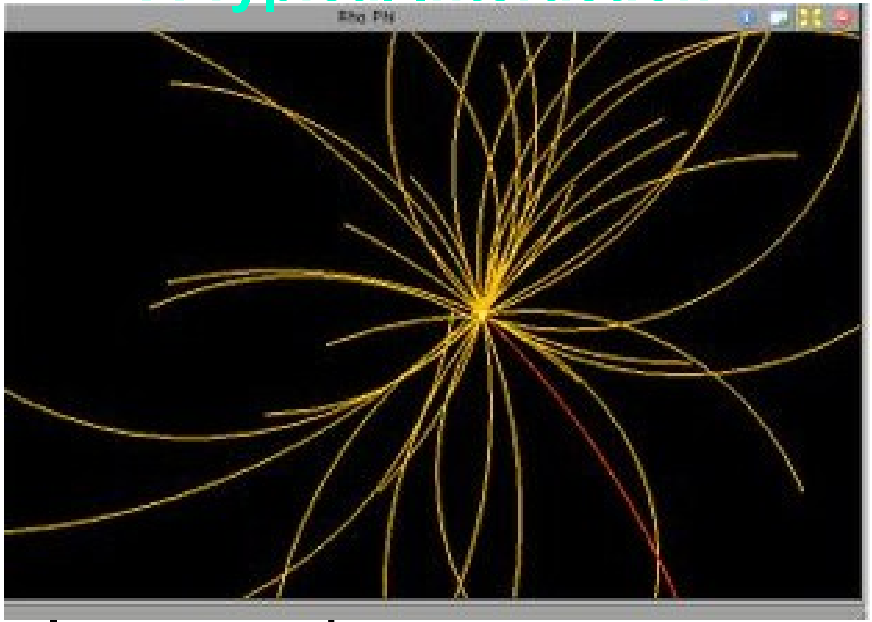
- Low temperature operation (-10^{0}C) to
  - reduce leakage current
  - control reverse annealing
  - improve charge collection
- High Voltage Operation for
  - effective charge collection

to finally develop radiation hard silicon sensors that can work efficiently for ~ 10 years in extreme LHC conditions

Detector Design Optimization

- Physics performance
- Experiment specific condition
  - Track density, affecting occupancy
  - Occupancy (# of fired strips)
    - Number of strips
    - Pitch (separation)
    - Number of readout channel
  - Trigger rate, available time for signal processing
  - Data size
- Best available industrial facilities
- Mechanical constraint considering overall detector design
- Efficient cooling
- As light as possible for efficient tracking
- Finally, the cost !!

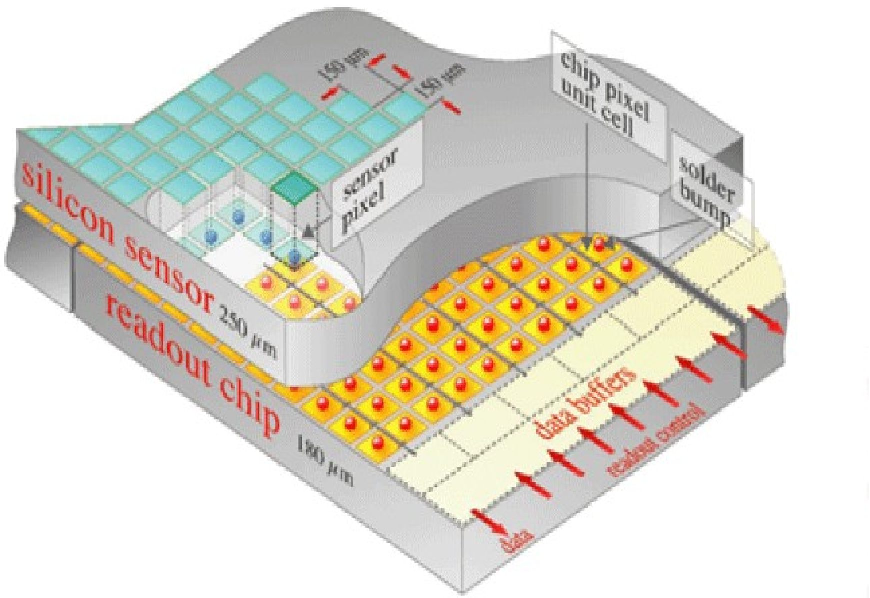
A Typical Interaction

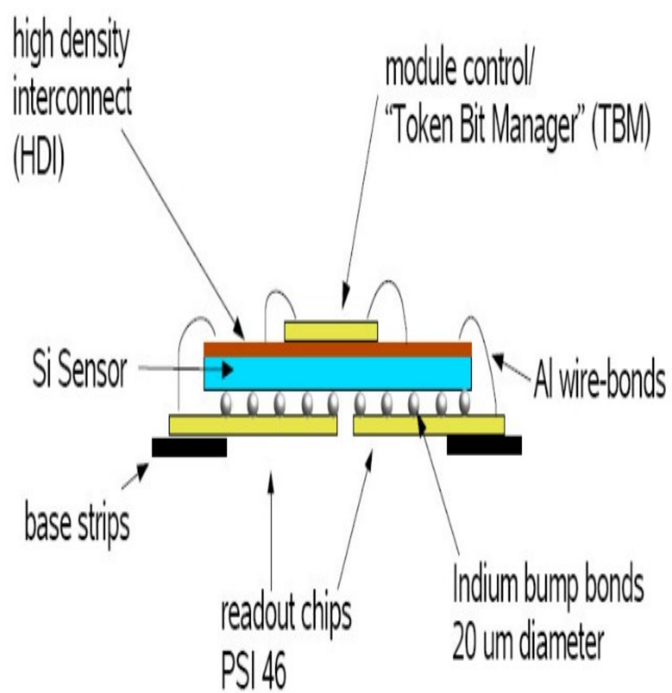


Pixel Detectors (I)

Trcking/vertexing is needed to extend a
close as possible to the interaction point

- In very dense environment like LHC, strip detectors are not suitable for this purpose
    - Instead of strips, rectangular pixels used
- Highly segmented detectors
    - Greatly helps in pattern recognition
    - Provides true (3D) high resolution space points
- Readout chips integrated directly on the sensor by bump bonding
    - The pixel size is influenced by the area needed by frond-end chip





Pixel Detector(II)

- Design consideration
  - Distance of the layers from the interaction region
  - Hit Resolution
  - Material budget
  - Extremely high power density requires efficient cooling
  - Radiation environment
  - Size of the signal charge
  - Incident angle of tracks

The Generic Tracking Detector

- Overall detector geometry very much experiment specific
  - But almost in all cases :
    - a few layers of pixel detectors used close to the interaction point
    - Followed by layers of Strip detectors

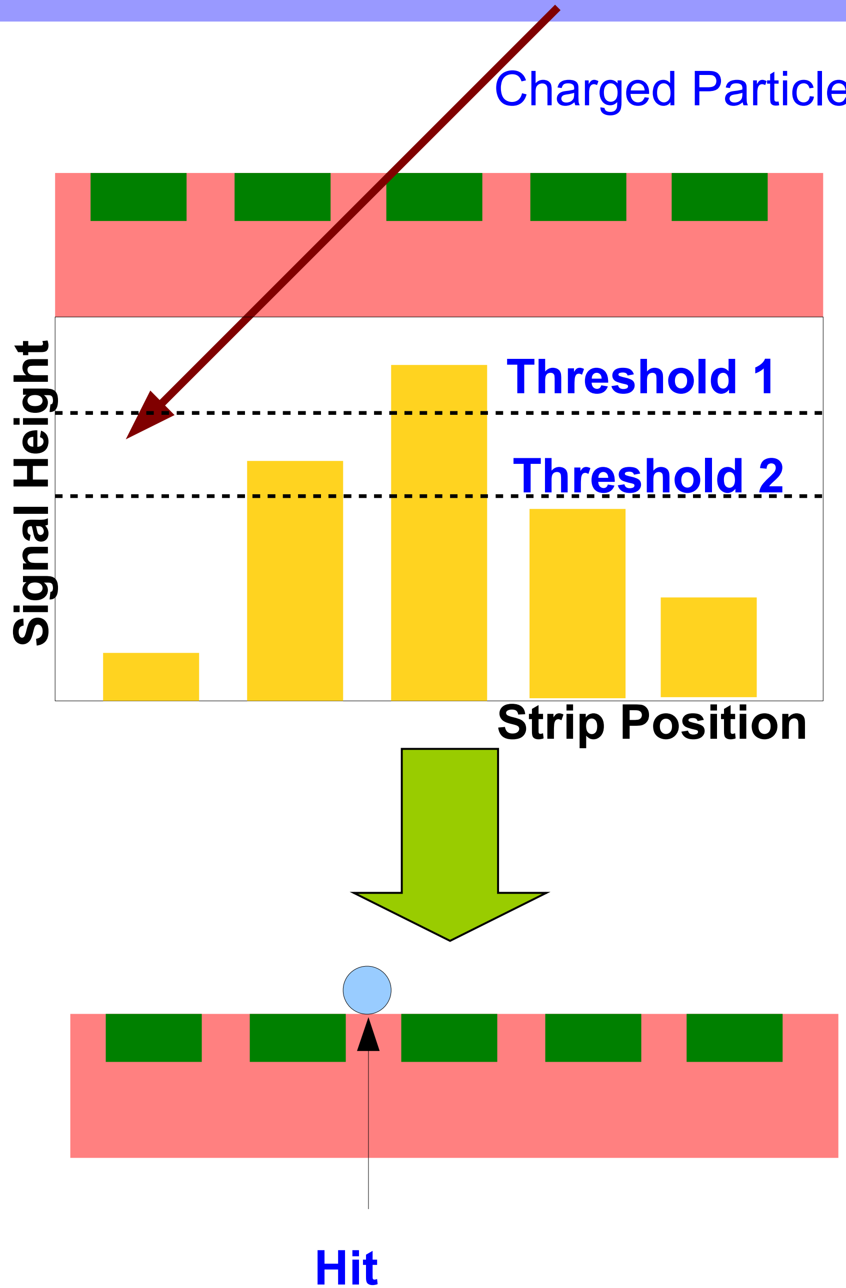
Pixel : Vertex, IP, angle

Strip : Momentum (range depends on the length of the tracker)

Hit Reconstruction

Charged Particle traversal through silicon sensor

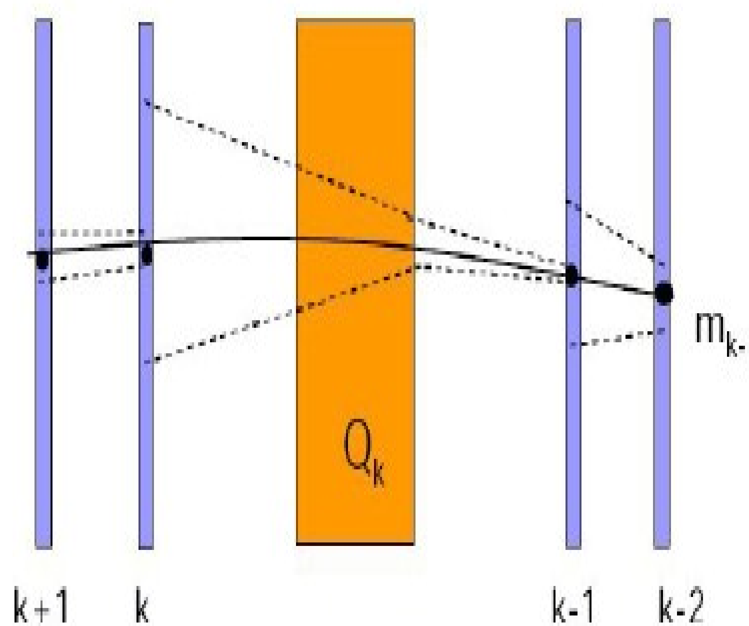
- Charge Collection
  - measure S/N
  - particle identification (dE/dx)
- Hit position
  - 3-threshold Clustering algorithm
  - weighted average of strip position and corresponding charges

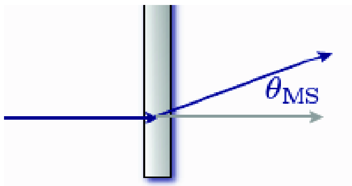


Once hits are found in different layers of the tracker we can proceed with the track reconstruction

Track Reconstruction

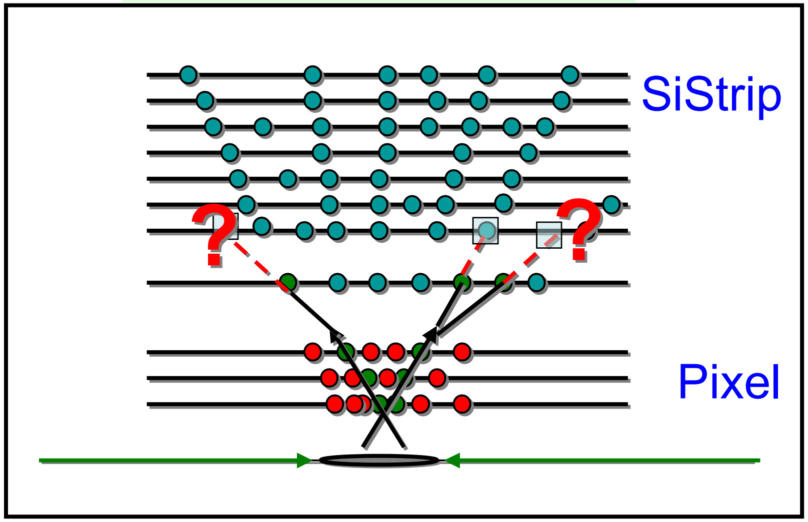
- Define an initial track segment using a few hits (seed)
- Follow a track candidate picking up hits iterativelv
- Use track model to extrapolated to the next layer
- Consider material to be traversed to define search and measurement error
  - Multiple scattering
    - Θ_{MS} = 0.9 mrad in 300 μm silicon
- Include hits inside the search window
  - If more hits, create separate branches
- Consider detector inefficiencies
  - If no hits found, in a layer, move to at least next layer
  - All known efficiencies should be considered
  - Track candidate missing hits in several layers do not consider the





Track Reconstruction

Step 1 : finding Seed

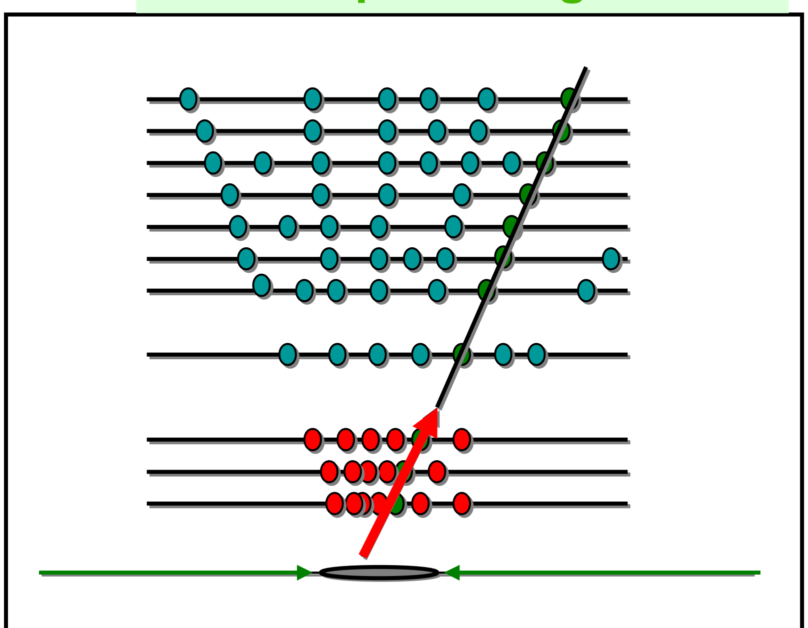


Pattern recognition :

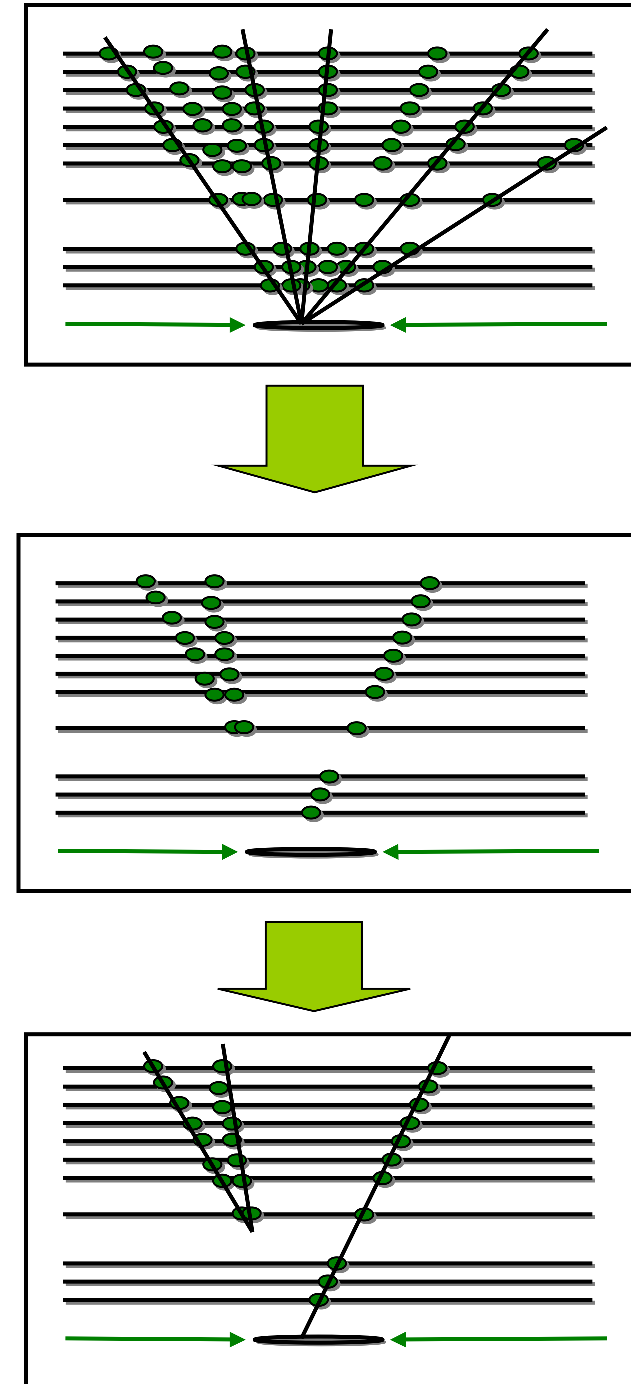
- difficult with higher occupancy

- easier with better position resolution

Final Step : Fit to get Track



Step 2 : a few iteration to find candidates



Measured Parameters

- Momentum (p)
- Charge (q)
- Pseudo rapidity (η)
- Azimuthal angle (ϕ)
- Distance (dxy, dz)

Vertex Reconstruction (I)

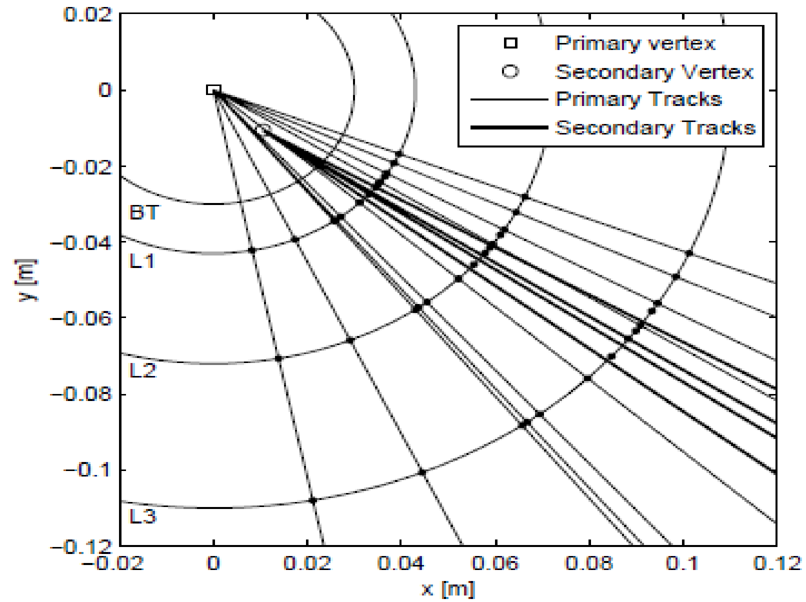
Classification of reconstructed tracks in an event such that all tracks associated with a candidate originate at the vertex

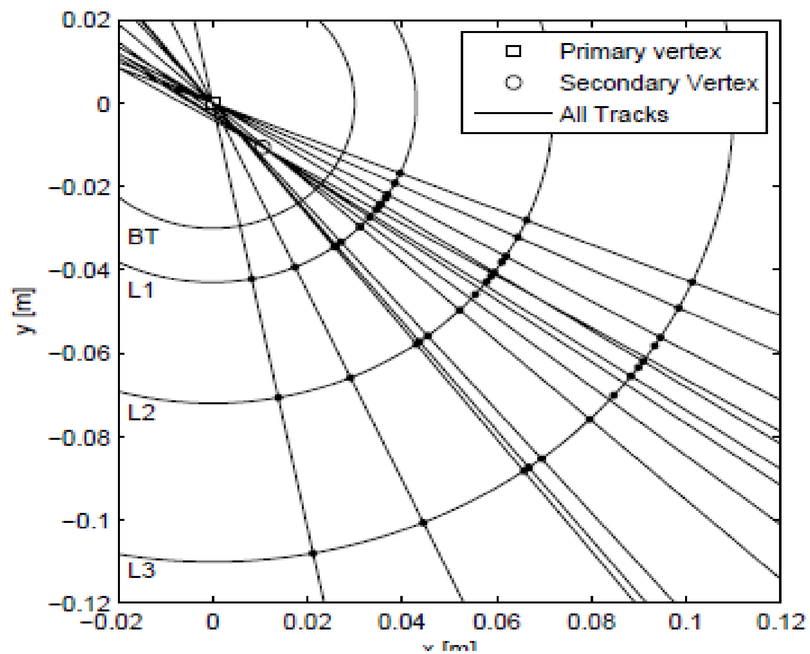
- In collider and fixed target experiments interaction vertex is called "primary vertex"
- If particles are created due to decay of unstable particles, the decay vertex is called "secondary vertex"
- If the particles are produced due to interaction with detector material, it is "secondary interaction vertex"

- Different techniques and algorithms used to reconstruct vertices
  - Primary vertex finding relatively easier than secondary vertex finding

Vertex Reconstruction (II)

- Primary vertex
  - Very high multiplicity
  - Needed as reference many other reconstruction steps apriori
- Secondary vertex
  - Needed for reconstruction of long lived particle
  - Low multiplicity
  - Track association and vertex separation is a challenging





Steps in Primary Vertex finding (III)

- Find approximate vertex position first
  - Crossing point for each track pair
  - Define weight of each track proportoinal to the distance of the tracks
  - Mode of crossing points
- Weight tracks according to their standardized distance wrt vertex
- Apply specified algorithms to clean the vertex removing non compatible tracks
- Discarded tracks re-clustered to find new vertex
- Iterate over last three steps
- Stop the procedure when distance between different vertexes are smaller than a predefined value after N iterations