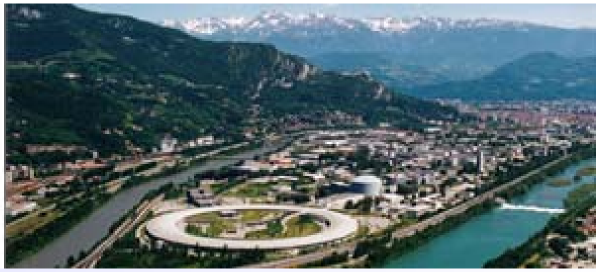
EIROforum School on Instrumentation (ESI 2011)
European Photon & Neutron Science Campus - **Grenoble** / France
15-22 May 2011



Charged Particle Tracking in High Energy Physics

Michael Moll, CERN PH-DT

High Energy Collider Detectors

this lecture

- **Tracking Detectors (or Trackers)** = *momentum measurement*
  - **closest to interaction point: vertex detectors** (mainly silicon pixel detectors)
    - measure the **primary interaction vertex** and **secondary vertices** from decay particles
  - **main or central tracking detectors**
    - measure the **momentum** by curvature in magnetic field
    - two main technologies: silicon detectors (e.g. strip sensors) and gaseous detectors (e.g. TPC, TRT)
- **Calorimeters** = *energy measurement*
  - **electro-magnetic calorimeters**
    - measure **energy of light EM particles** (electrons, positrons, photons) based on electro-magnetic showers by bremsstrahlung and pair production
    - two concepts: homogeneous (e.g. CMS) and sampling (e.g. ATLAS) calorimeters
  - **hadron calorimeters**
    - **measure energy of heavy (hadronic) particles** (pions, kaons, protons, neutrons) based on nuclear showers created by nuclear interactions
- **Muon Detectors** = *momentum measurement for muons*
  - *outermost detector layer, basically a tracking detector*

Tracker Technologies

3 major technologies are used for tracking detectors:

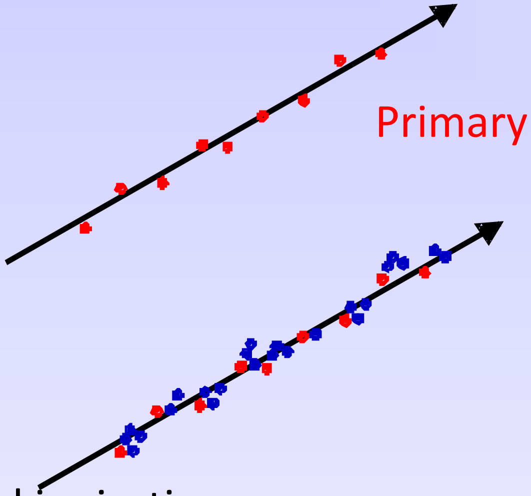
- **Gaseous detectors**
  - **Ionization in gas (creation of electron – ion pairs)**
    - typically ~100 electrons/cm
    - not sufficient to create significant signal height above noise for standard amplifiers
  - **Gas amplification needed**
    - gas amplification ~10^4 to reach sufficient signal height over noise
- **Silicon detectors**
  - **Ionization (creation of electron – hole pairs) in solid state material**
    - typically ~100 electron- hole pairs/µm
  - **No amplification needed**
    - signal height in a ~300 µm thick detector high enough
    - no impact ionization (like used e.g. in avalanche photodetectors) needed

this lecture

- **Fiber trackers**
  - **Scintillating fibers**
    - scintillating light detected with photon detectors (sensitive to single electrons)

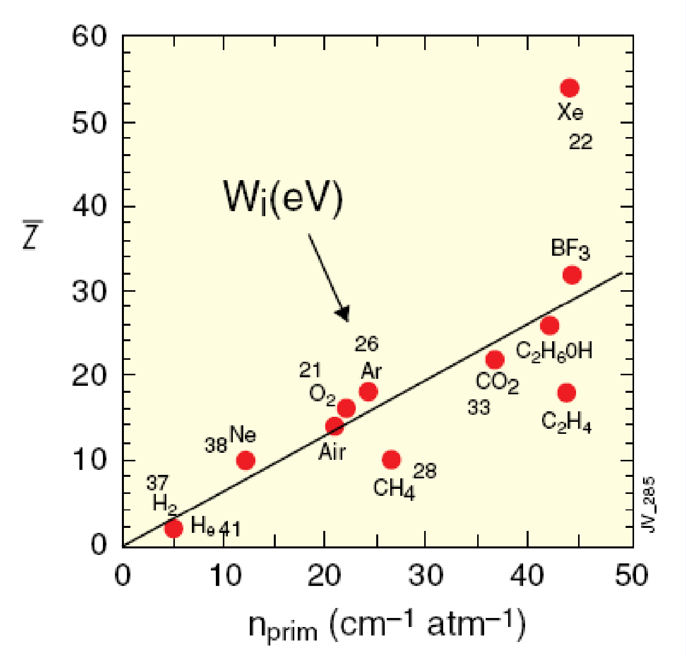
Gaseous Detectors – Ionization of Gases

- **Primary number of ionizations per unit length is Poisson-distributed**
  - **typically ~30 primary electrons/cm in gas at 1 atm**



Primary ionization

Total ionization
= primary + secondary ionization



Lohse and Witzeling, Instrumentation In High Energy Physics, World Scientific, 1992

n_{total} - number of created electron-ion pairs

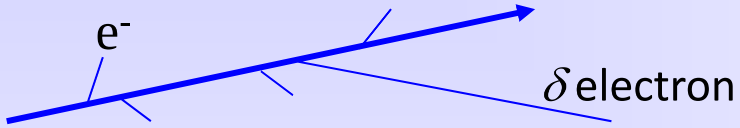
W_i = effective <energy loss>/pair

- **However, primary electrons sometimes receive large energies**
  - **can ionize other atoms (secondary ionization, production of ionization clusters)**
  - **can even create secondary visible track ("delta electrons")**
  - **<u>large fluctuations</u> of energy loss by ionization**
  - **typically: total ionization = 3 x primary ionization**
    - **on average ~ 90 electrons/cm in gas**

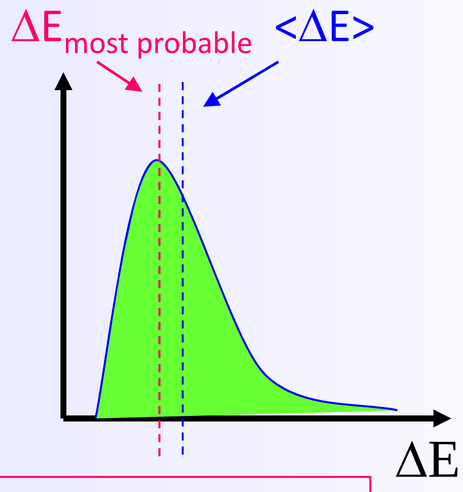
Energy Loss Distribution in detectors

- Real detectors can not measure <dE/dx>
  - The energy ΔE deposited in a layer of finite thickness δx *is measured*.

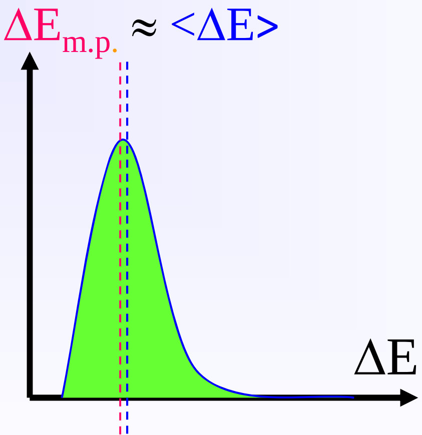
- For thin layers of solids or low density materials:
  - Few collisions, some with high energy transfer.



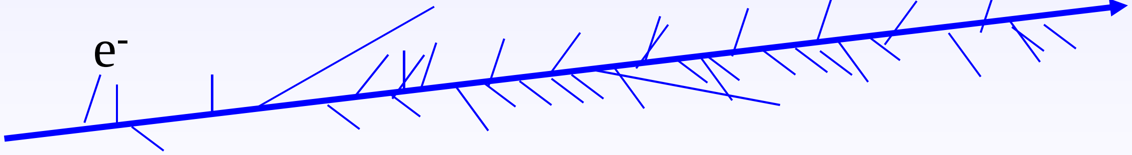
  - Energy loss distributions show large fluctuations towards high losses; Landau distribution with tails



Example: Si sensor: 300 μm thick. $\Delta E_{\text{most probable}}$ ~ 82 keV $<\Delta E>$ ~ 115 keV

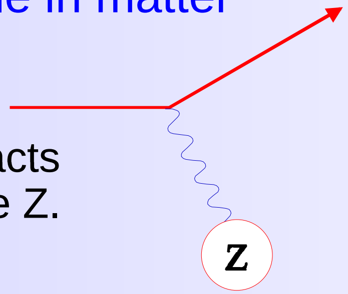


- For thick layers and high density materials:
  - Many collisions
  - Central Limit Theorem ➔ Gaussian shaped distributions



Elastic Scattering

- Most basic interaction of a charged particle in matter
  - elastic scattering with a nucleus
    = Rutherford (Coulomb) scattering
  - An incoming particle with charge z interacts elastically with a target of nuclear charge Z.

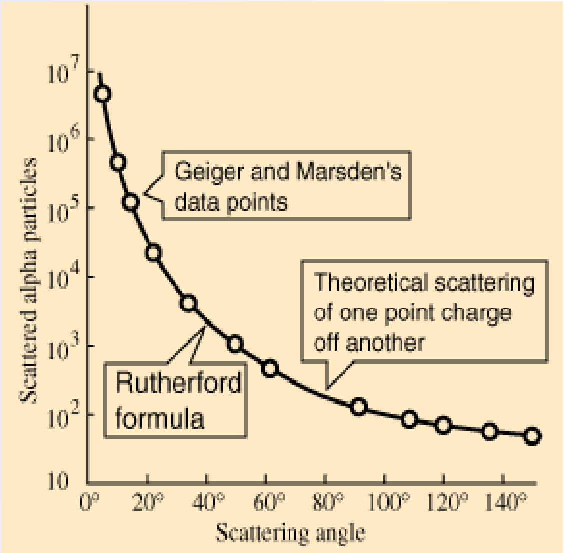


'The scattering of alpha and beta particles by matter and the structure of the atom', Philosophical Magazine, vol. 21 (1911), 669-688.

Ernest Rutherford
May 1911

Cross section for this e.m. process is given by the Rutherford formula:

$$\frac{d\sigma}{d\Omega} = 4zZr_e^2\left(\frac{m_e c}{\beta p}\right)^2 \boxed{\frac{1}{\sin^4\theta/2}}$$



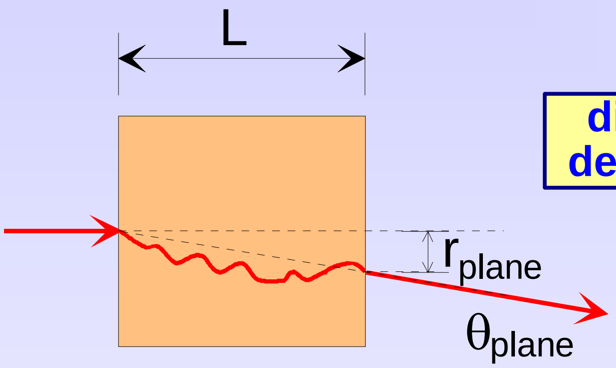
UK Science Museum

- Approximations
  - non-relativistic
  - no spins

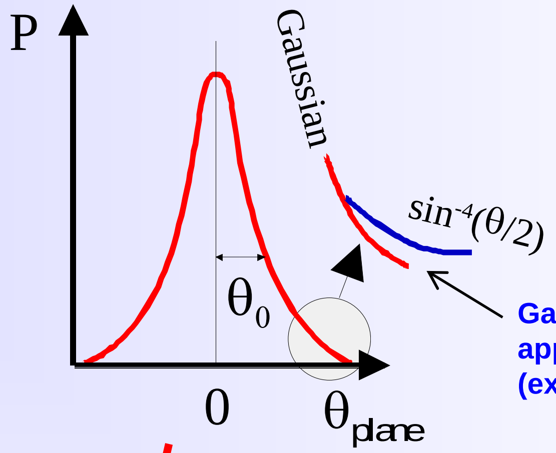
- Scattering angle and energy transfer to nucleus usually small
  - No (significant) energy loss of the incoming particle
  - Just change of particle direction

Multiple Scattering

- In a sufficiently thick material layer a particle will undergo **multiple scattering**
  - **after passing material layer of thickness L particle leaves with some displacement r_{plane} and some deflection angle Θ_{plane}**



distribution of deflection angle

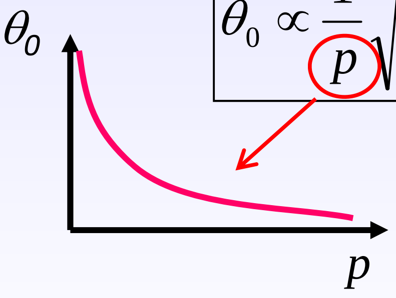


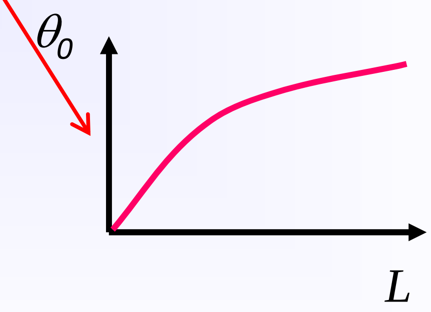
Gaussian is good approximation (except for tails)

Θ_0 = width of distribution

$$\theta_0 \propto \frac{1}{p}\sqrt{\frac{L}{X_0}}$$

- Multiple scattering dominates the momentum measurement resolution for low momenta (see later)
  - X_0 = radiation length (see later)





Momentum Measurement

- Moving charged particles are deflected by magnetic fields
  - In a homogeneous ***B*** field particle follows circle with radius ***r***

$$\boxed{p_t[GeV/c] = 0.3 \cdot B[T] \cdot r[m]}$$

Lorentz Force

$$\vec{F}_L = q \cdot \vec{v} \times \vec{B}$$

Centripetal Force

$$F_c = {m \cdot v^2}/{r}$$

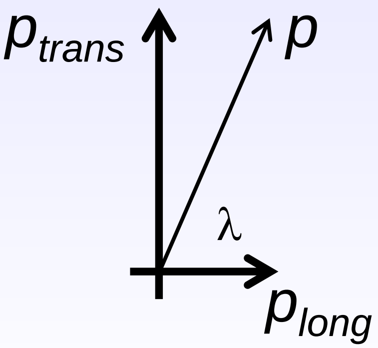
$$p = q \cdot B \cdot r$$

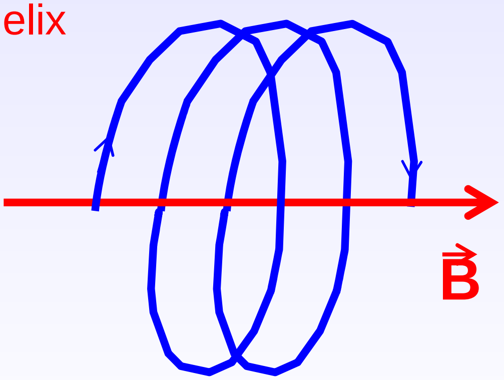
  - p_t is the component of the momentum orthogonal to ***B*** field

measurement of p_t via measuring the radius

p_t : transverse momentum

  - no particle deflection parallel to magnetic field
  - if particle has longitudinal momentum component, the particle will follow a helix



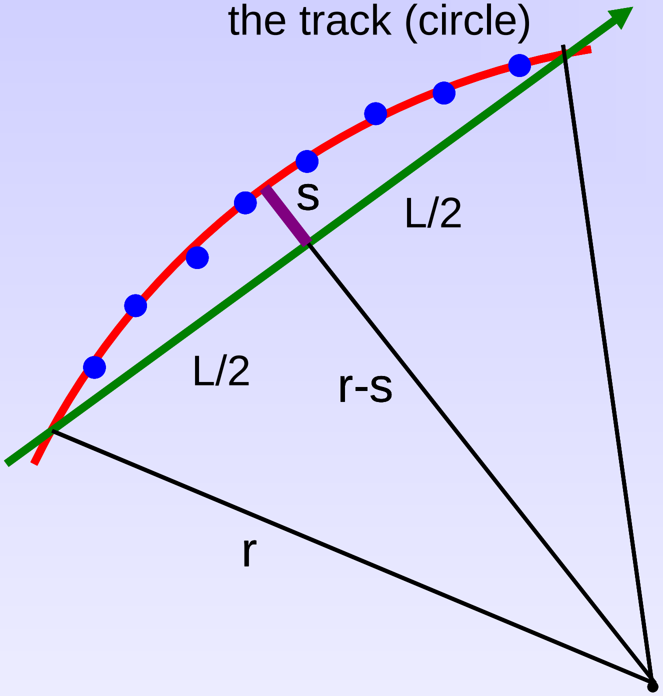


total momentum p to be measured via dip angle λ

$$p = \frac{p_t}{\sin \lambda}$$

Momentum measurement – Relative Error

- How to measure the radius r (curvature) ?
  - Tracking Detectors measure the positions of the track along various points along the track (circle)



measure the sagitta s of the track

$$r = \frac{L^2}{8s} + \frac{s}{2}$$ if s << L $$r \approx \frac{L^2}{8s}$$

sagitta s / radius r is obtained by a circle fit through measurement points along the track with point resolution $\sigma_{r\phi}$ for each point

sagitta error $$\sigma_S = \sqrt{\frac{A_N}{N+4}} \cdot \frac{\sigma_{r\phi}}{8}$$

with statistical factor $A_N = 720$

R.L. Gluckstern, NIM 24 (1963), 381

relative transverse momentum resolution σ_{pt}/p_t

- degrades linearly with momentum
- improves linearly with B field
- improves quadratically with radial extension of detector

$$\frac{\sigma_{p_T}}{p_T} = \frac{8 p_T}{0.3 B L^2} \cdot \sigma_S \rightarrow \boxed{\frac{\sigma_{p_T}}{p_T} \propto p_T}$$

Momentum resolution

- The (transverse) momentum resolution is dominated by two contributions
  - **contribution from measurement error**

$$\frac{\sigma_{p_T}}{p_T} \propto p_T$$

  - **contribution form multiple scattering** (remember)

$$\theta_0 \propto \frac{1}{p_T}\sqrt{\frac{L}{X_0}} \qquad \left.\sigma_{r\varphi}\right|^{MS} \propto \theta_0 \qquad \frac{\sigma_{p_T}}{p_T} \propto p_T \cdot \sigma_{r\varphi}$$

$$\boxed{\left.\frac{\sigma_{p_T}}{p_T}\right|^{MS} = \text{constant}}$$

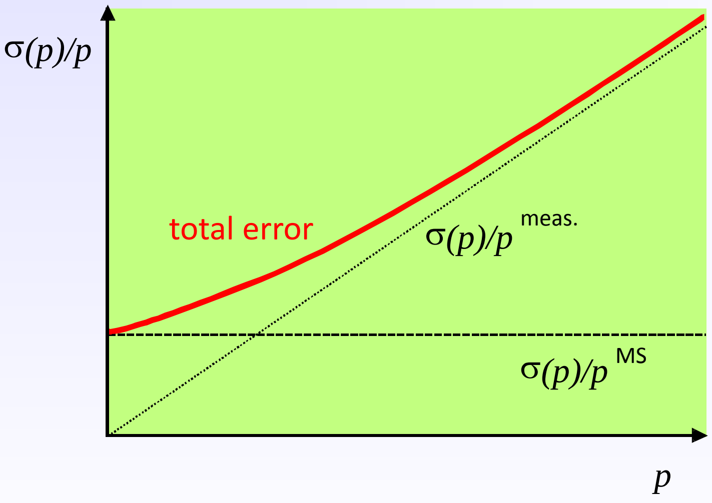
multiple scattering contribution to the transverse momentum error is constant (i.e. independent of the momentum)

More precise:

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{MS} = 0.045\frac{1}{B\sqrt{LX_0}}$$

Example: Detector (L=1m) filled with 1atm Argon gas (X_0=110m); B=1T

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{MS} = 0.5\%$$

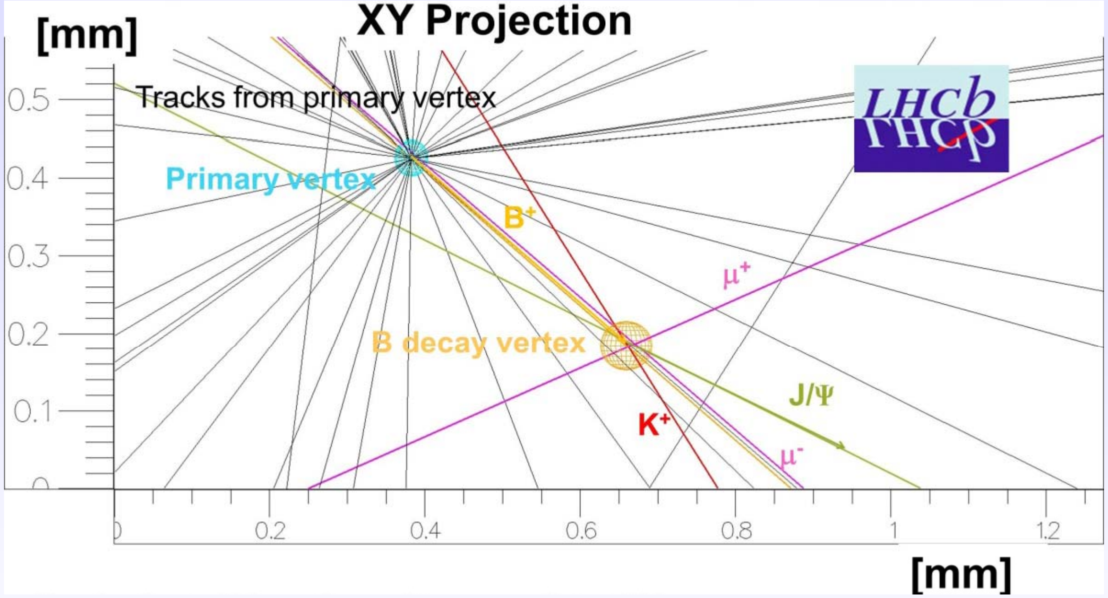


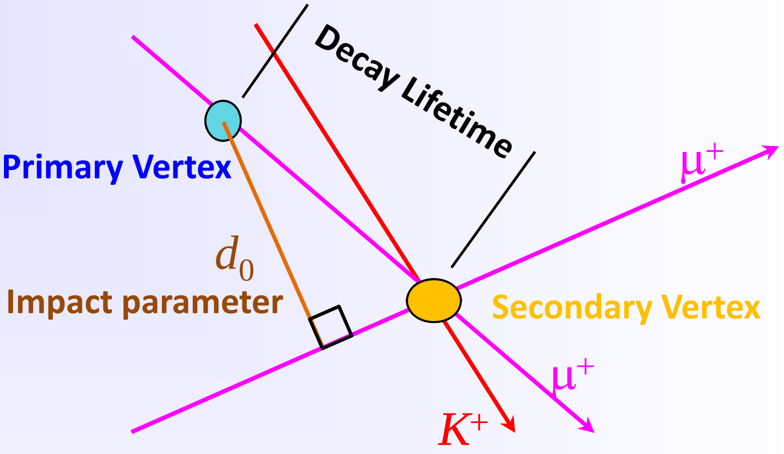
Vertex Detectors

Besides momentum measurement tracking detectors have to measure:

- Primary and Secondary Decay Vertices
  - *Example*: B lifetime $\tau_B \sim 1.6$ ps $\Rightarrow \gamma c\, \tau_B = \gamma \cdot 500\ \mu\text{m}$ with $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$
  - Figure of merit: **Impact parameter resolution**

  - Physics example from LHCb (2010) : $\boldsymbol{B^+ \to J/\Psi\ \ K^+}$

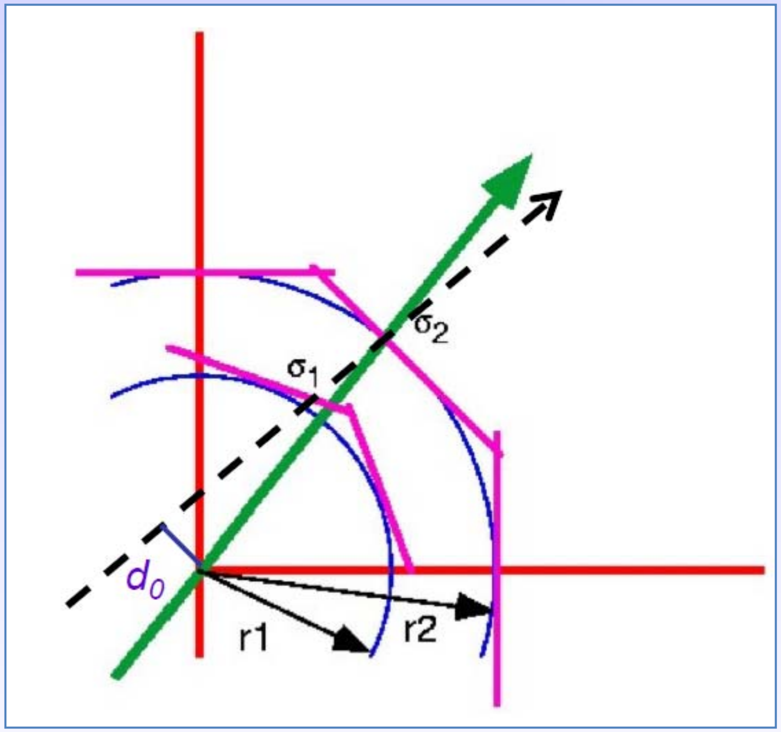




Impact parameter resolution

- Uncertainty on the transverse impact parameter, d0, depends on the detector radii and space point precisions.

- Simplified formula for just two layers:



$$\sigma_{d_0}^2 = \frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{\left(r^2 - r^1\right)^2} + \sigma_{MS}^2$$

  - Suggests small r_1, large r_2, small σ_1, σ_2

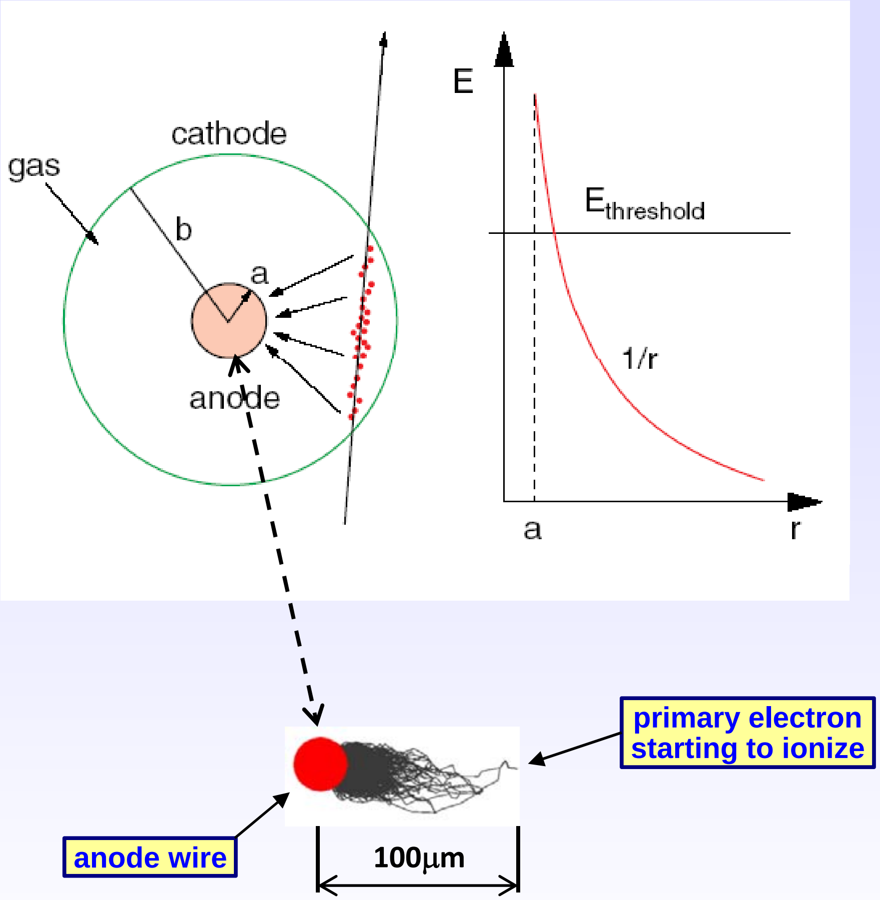
  - But precision is degraded by multiple scattering….

Example: **LHCb (VELO)**

σ(IP)= (10 + 29/p_T[GeV/c]) μm [PoS VERTEX2010:014,2010.]

Gaseous Detectors – Geiger-Müller Tube

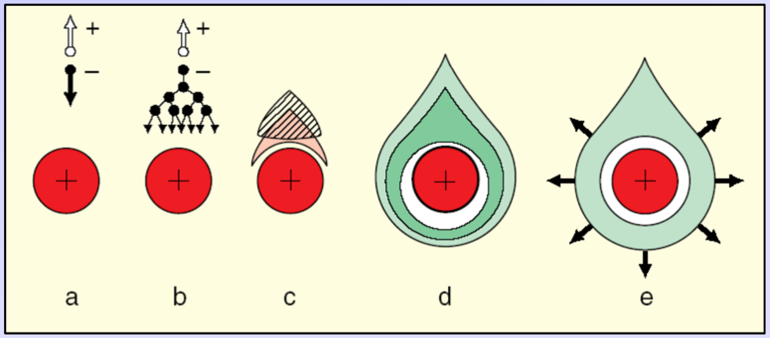
- The Geiger-Müller tube (1928 by Hans Geiger and Walther Müller)
  - Tube filled with inert gas (He, Ne, Ar) + organic vapour
  - Central thin wire (20 – 50 µm ∅) , high voltage (several 100V) between wire and tube



- Strong increase of E-field close to the wire
  - Electrons gain more and more energy
- above some threshold (>10 kV/cm)
  - electron energy high enough to ionize other gas molecules
  - newly created electrons also start ionizing
- **avalanche effect:** exponential increase of electrons (and ions)
- **measurable signal** on wire
  - organic substances responsible for "quenching" (stopping) the discharge

Wire Chamber – Signal Formation

- Signal formation depending on electron and ion drift



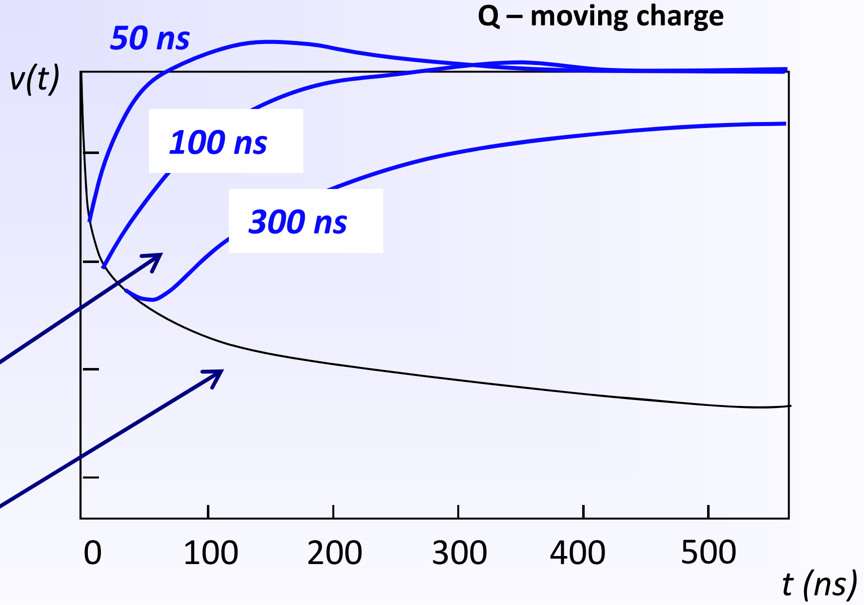
  – signal on cathode and anode is induced by the moving electrons and ions
  – electrons from the avalanche are produced very close to the wire and collected in a very short time (t < ns)

  ⇒ small contribution of electrons to signal

$$dv = \frac{Q}{lCV_0}\cdot\frac{d\varphi(r)}{dr}\cdot dr$$

l - length of cylinder
C – capacitance
V_0 – voltage applied
Q – moving charge

- Main part of signal produced by ions
  – Ions drift back to cathode over long distance (several mm or cm) and time (many µs or even ms)



signal after electronics shaping (RC high-pass filter with different time constants)

pure signal (no electronics shaping) from ions drifting away from anode wire

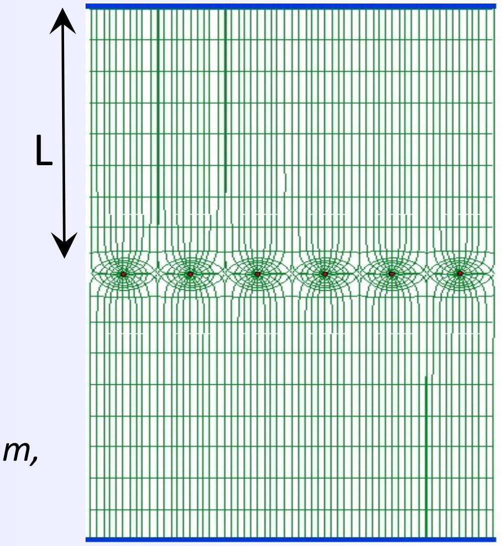
MWPC and Drift Chambers

- **MWPC – Multi Wire Proportional Chamber**
  - Simple idea: Multiply the SWPC *(Nobel Price by Charpak in 1992)*
  - Usually binary read out
  - ⇒ Resolution limited to (*d* = distance between wires):

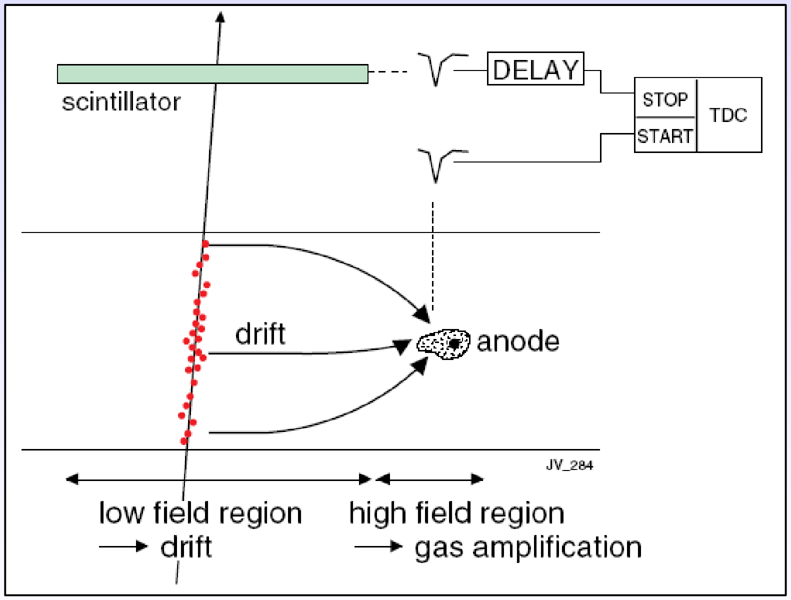
$$\sigma_x \approx \frac{d}{\sqrt{12}}$$

for d = 1 mm σ_x = 300 μm

Typical geometry
L ~ 5mm, d ~ 1mm,
$\varnothing_{\text{wire}}$ ~ 20 μm



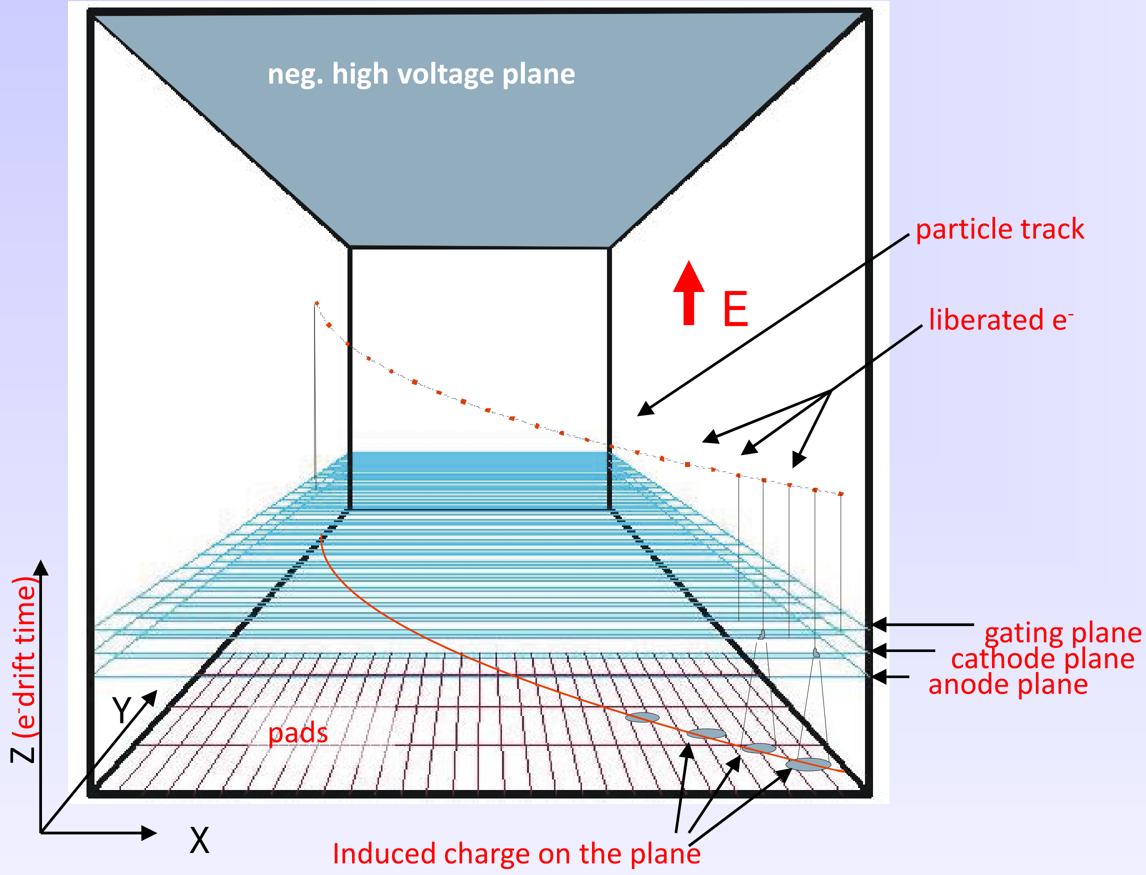
- **Drift Chamber**



- Obtain position from drift time of electrons
- ⇒ Advantage: requires less wires, less channels
- ⇒ needs external source for start signal (scintillator or beam crossing signal)
- ⇒ need to know drift velocity v_D to calculate distance s to wire

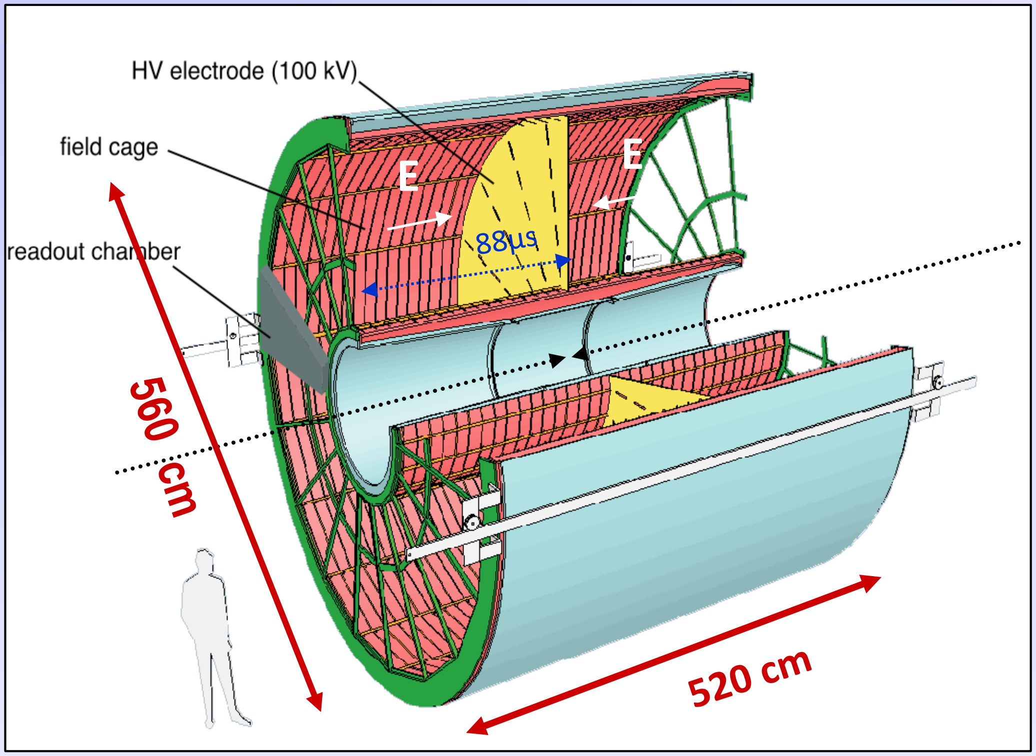
$$s = \int_{t_{start}}^{t_{stop}} v_D \, dt$$

TPC – Time Projection Chamber



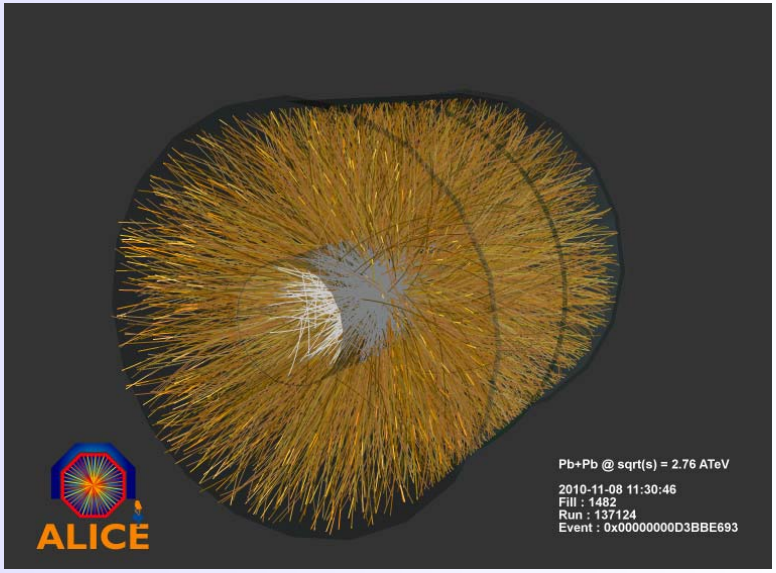
- Full 3D track reconstruction
  - x-y from wires and segmented cathode of MWPC (or GEM)
  - z from drift time
- Momentum resolution
  - Space resolution + B-Field
- Energy resolution
  - Measure of primary ionization
- Positive Ion backflow
  - Needs a gating plane to stop ions from backdrift into chamber

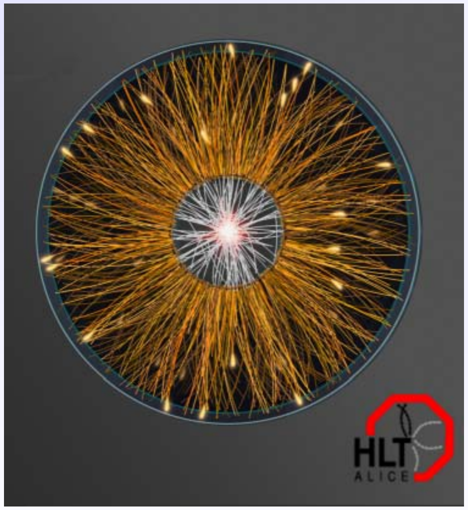
ALICE – TPC – Taking Data



- Alice TPC
  - HV central electrode at –100 kV
  - Drift length: 250 cm at E=400 V/cm
  - Gas: Ne-CO_2 90-10
  - Space point resolution ~500 μm
  - dp/p = 2%@1GeV; dp/p = 10%@10GeV

- Alice: Heavy Ion Event Display

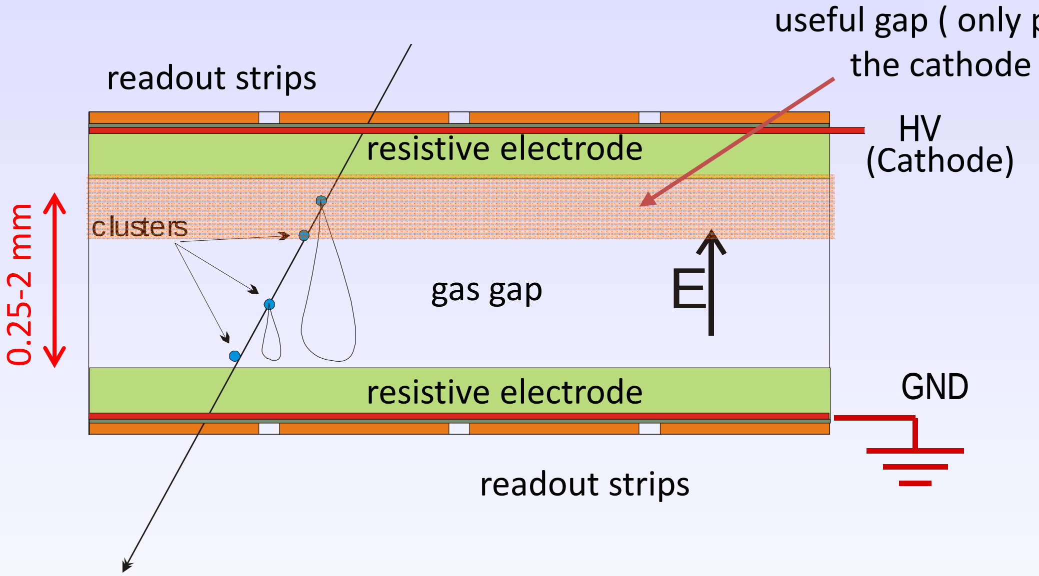




- *08.Nov.2010*
- *Pb+Pb*
- *sqrt(s)*
  = 2.76 ATeV
  = 575 TeV/ion

RPC - Resistive Plate Chambers

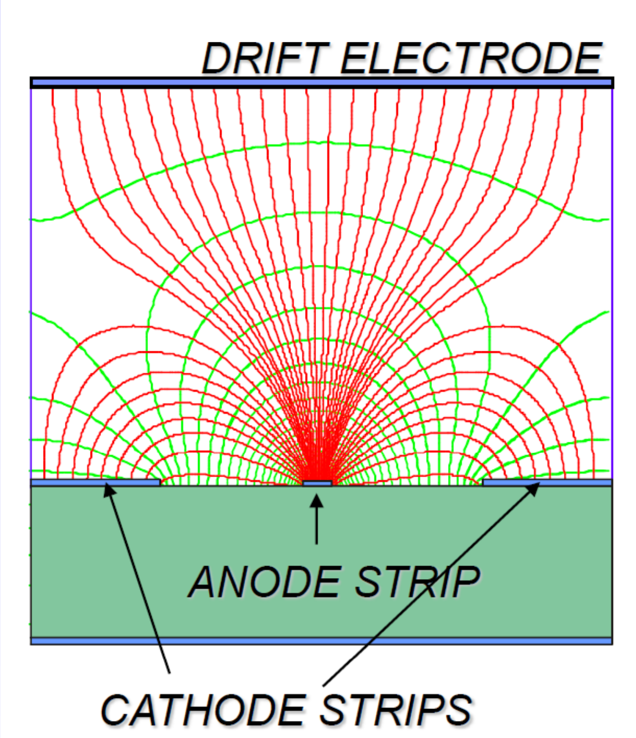
- RPC - No wires! - Resistive plates from Bakelite ($\rho=10^{10}$-$10^{12}\Omega$cm) or window glass ($\rho=10^{12}$-$10^{13}\Omega$cm) in front of metal electrodes
  - gas gap: 0.25 – 2 mm; electric fields: 50-100 KV/cm
  - time resolution: 50ps (100 KV/cm), 1ns (50KV/cm)
  - **Application:** Trigger Detectors, Time of Flight (TOF)
  - Resistivity limits rate capability (kHz/cm^2 for $10^{10}\Omega$cm)
    - Time to remove avalanche charge from the surface of the resistive plate is in ms to s range.

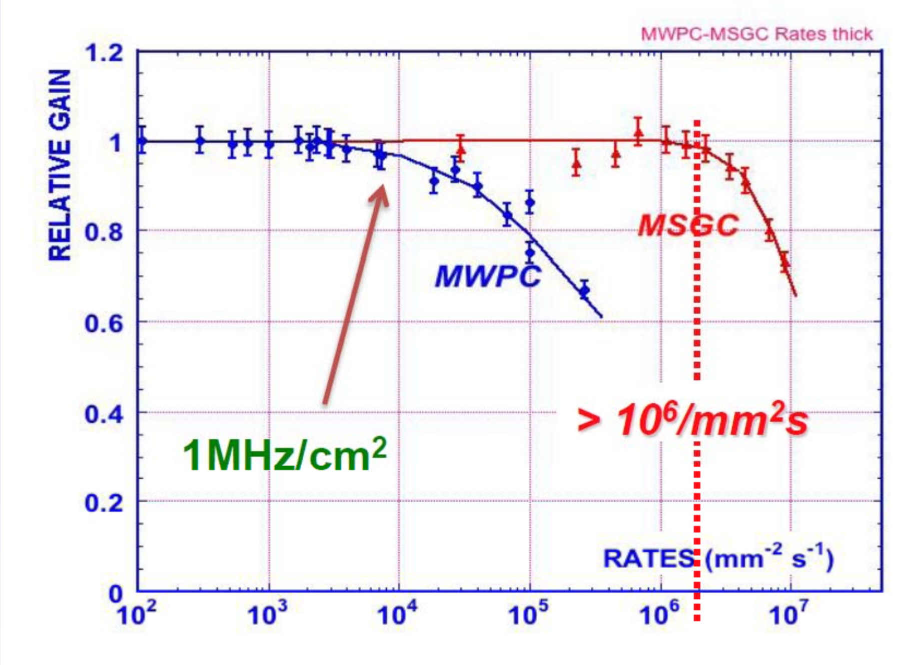


- MRPC – Multi gap RPC
  - higher efficiency
  - exceptional time resolution

Micro Strip Gas Chambers - MSGCs

- Gain is not provided by wires but by metal strips on resistive electrodes.
- Due to small pitch and fast ion collection MSGCs have very high rate capability.

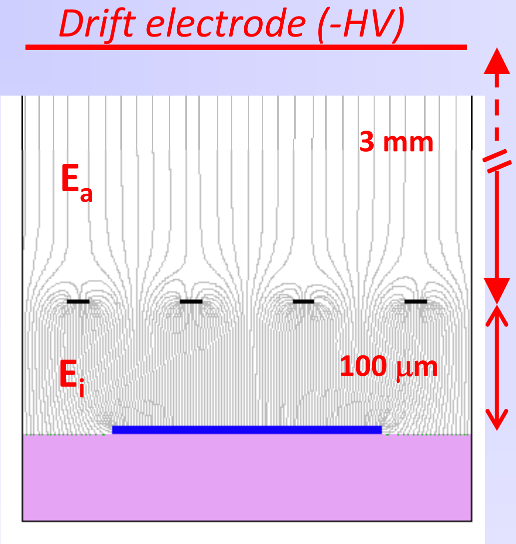




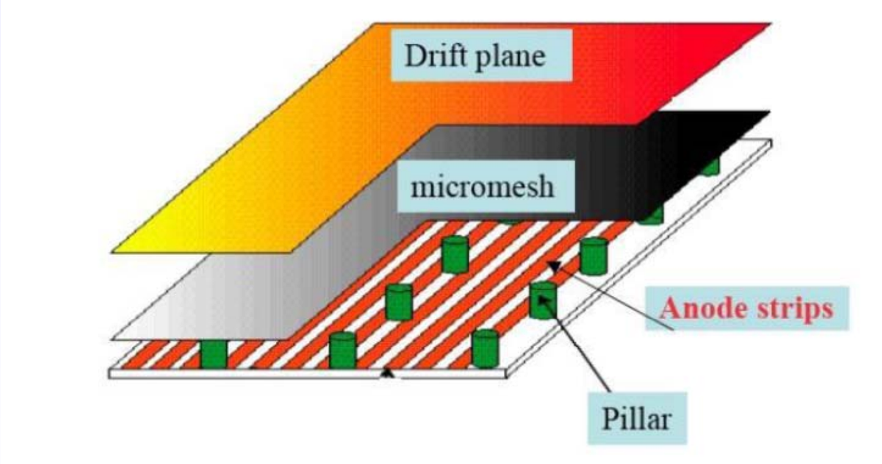
- 1990s: Candidates for inner tracking system of ATLAS and CMS
- Unfortunately MSGCs are rather prone to discharge, particularly in hostile environments.

MPGDs - Micro Pattern Gas Detectors

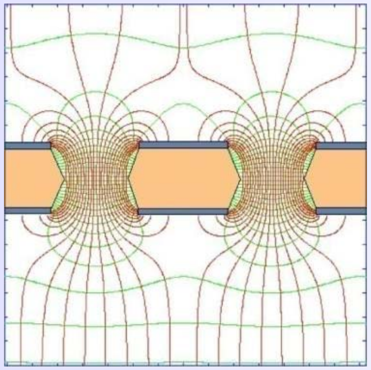
- **MICROMEGA** Micro Mesh Gas detector



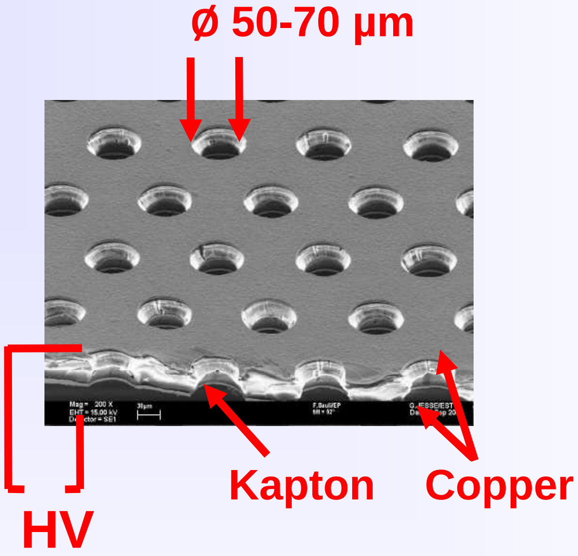
  - E_a/E_i ~ 50: - secure electron transparency
    - positive ion flowback supression.



- **GEM** Gas Electron Multiplier



thin metal-coated polmer foils with holes



… being implemented now in HEP experiments
… many ongoing developments (see CERN RD51)

Solid State Detectors – Why Silicon?

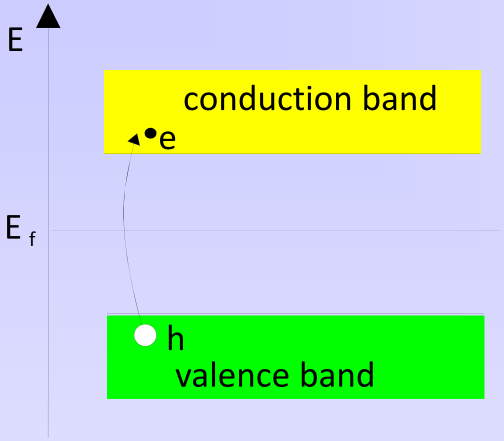
- **Some characteristics of Silicon crystals**
  - Small band gap E_g = 1.12 eV ⇒ E(e-h pair) = 3.6 eV (≈ 30 eV for gas detectors)
  - High specific density 2.33 g/cm^3 ; dE/dx (M.I.P.) ≈ 3.8 MeV/cm ≈ 106 e-h/μm (average)
  - High carrier mobility μ_e =1450 cm^2/Vs, μ_h = 450 cm^2/Vs ⇒ fast charge collection (<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

    ⇒ well known industrial technology, relatively low price, small structures easily possible

- **Alternative semiconductors**
  - Diamond
  - Gallium arsenide (GaAs)
  - Silicon Carbide (SiC)
  - Germanium (Ge)

	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

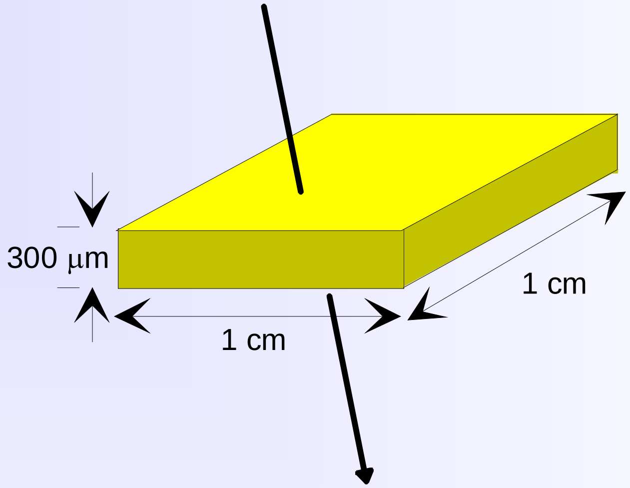
How to obtain the signal?



In a pure intrinsic (undoped) semiconductor the electron density *n* and hole density *p* are equal.

$n = p = n_i$ For Silicon: $n_i \approx 1.45 \cdot 10^{10}\ \mathrm{cm}^{-3}$

$4.5 \cdot 10^{8}$ free charge carriers in this volume, but only $3.2 \cdot 10^{4}$ e-h pairs produced by a M.I.P.

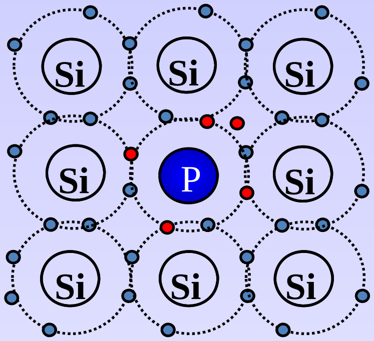


⇒ Reduce number of free charge carriers, i.e. deplete the detector

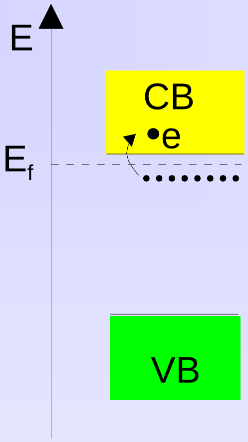
⇒ **Most detectors make use of reverse biased p-n junctions**

Doping, resistivity and p-n junction

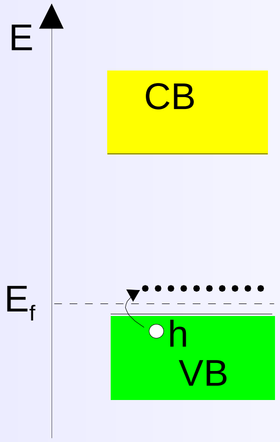
e.g. Phosphorus



- Doping: n-type silicon
  - – add elements from V^{th} group
    ⇒ **donors** (P, As,..)
  - – electrons are majority carriers



- Doping: p-type silicon
  - – add elements from III^{rd} group
    ⇒ **acceptors** (B,..)
  - – holes are majority carriers



- resistivity ρ
  - – carrier concentration n, p
  - – carrier mobility μ_n, μ_p

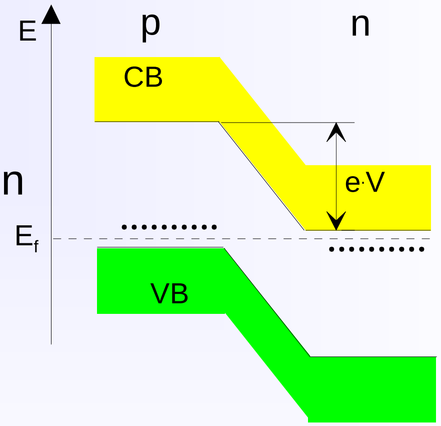
$$\rho = \frac{1}{q_0(\mu_n n + \mu_p p)}$$

	detector grade	**electronics grade**
doping	**≈ 10^{12} cm^{-3}**	**≈ 10^{17} cm^{-3}**
resistivity ρ	**≈ 5 kΩ·cm**	**≈1 Ω·cm**

- p-n junction

  There must be a single
  Fermi level!

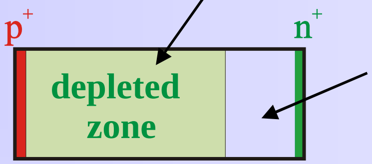
  ⇒ band structure deformation
  ⇒ potential difference
  ⇒ depleted zone



Reverse biased p-n junction

Poisson's equation

$$-\frac{d^2}{dx^2}\phi(x) = \frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}$$



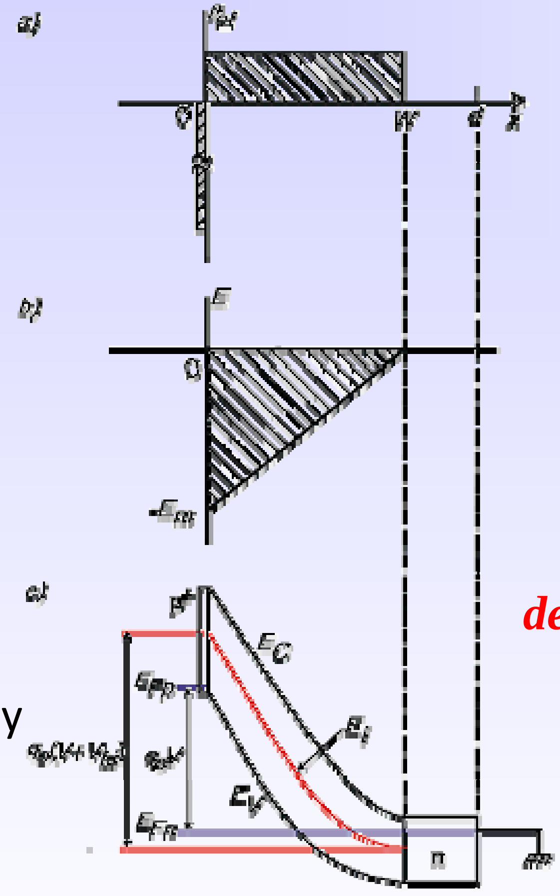
Positive space charge, N_{eff} =[P]
(ionized Phosphorus atoms)

neutral bulk
(no electric field)

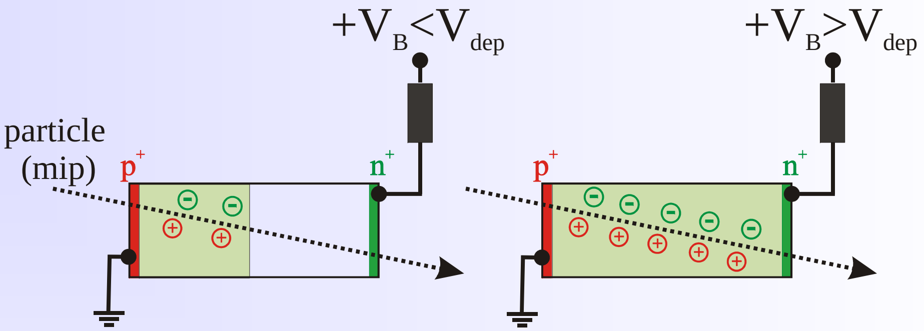
Electrical charge density

Electrical field strength

Electron potential energy



- Depleted zone growth with increasing voltage ($w \propto \sqrt{V_B}$)



- Full charge collection only for *fully depleted detector* ($V_B>V_{dep}$)

depletion voltage V_{dep}

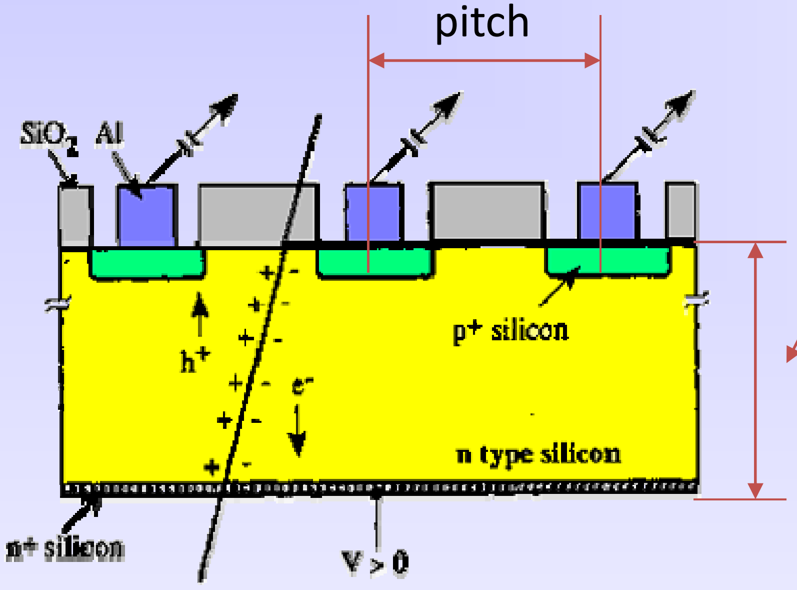
detector thickness d

$$\boxed{V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0}\cdot\left|N_{eff}\right|\cdot d^2}$$

effective space charge density N_{eff}

Single Sided Strip Detector

- Segmentation of the p^+ layer into strips (Diode Strip Detector) and connection of strips to individual read-out channels gives spatial information



typical thickness: 300µm (150µm - 500µm used)

- using n-type silicon with a resistivity of

  ρ = 2 KΩcm (N_D ~$2.2 \cdot 10^{12}$cm^{-3})

  results in a depletion voltage ~ 150 V

- Resolution σ depends on the pitch p (distance from strip to strip)

  - e.g. detection of charge in binary way (threshold discrimination) and using center of strip as measured coordinate results in $\sigma = \frac{p}{\sqrt{12}}$

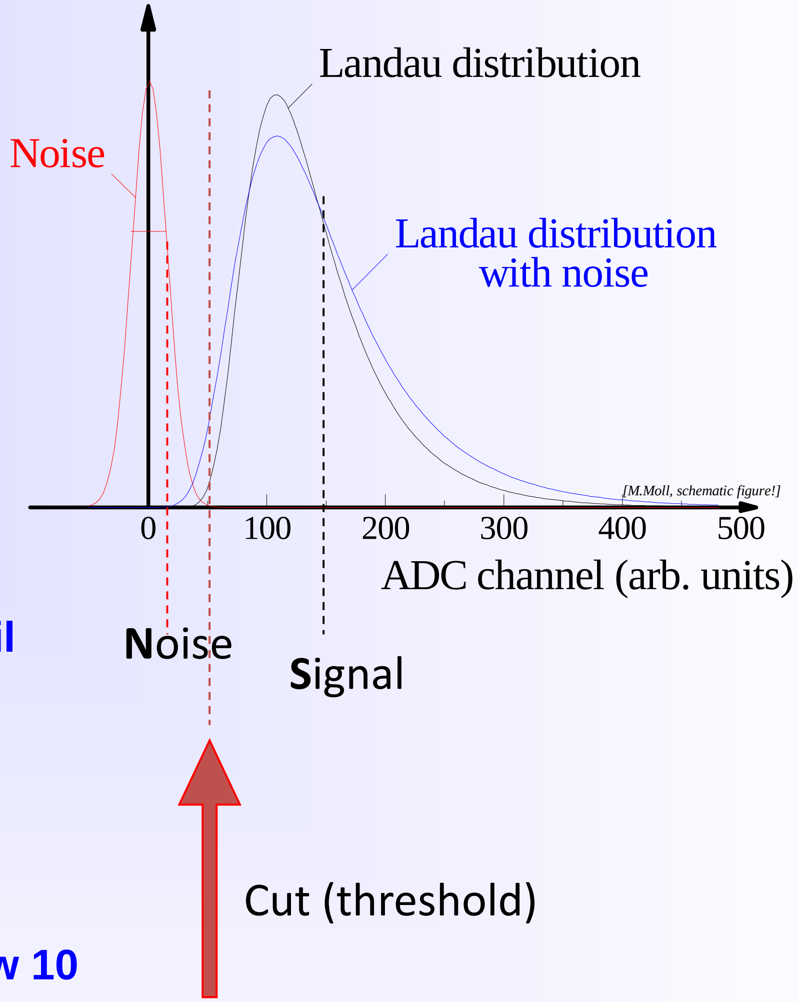
typical pitch values are 20 µm– 150 µm ⇒ 50 µm pitch results in 14.4 µm resolution

Signal to noise ratio

- **Landau distribution has a low energy tail**
  - becomes even lower by noise broadening

Noise sources: (ENC = Equivalent Noise Charge)

- **Capacitance** $ENC \propto C_d$
- **Leakage Current** $ENC \propto \sqrt{I}$
- **Thermal Noise** (bias resistor) $ENC \propto \sqrt{k_B T / R}$



- **Good hits selected by requiring N_{ADC} > noise tail**

  If cut too high ⇒ efficiency loss

  If cut too low ⇒ noise occupancy

- **Figure of Merit: Signal-to-Noise Ratio S/N**
- **Typical values >10-15, people get nervous below 10**

Radiation damage severely degrades the S/N !

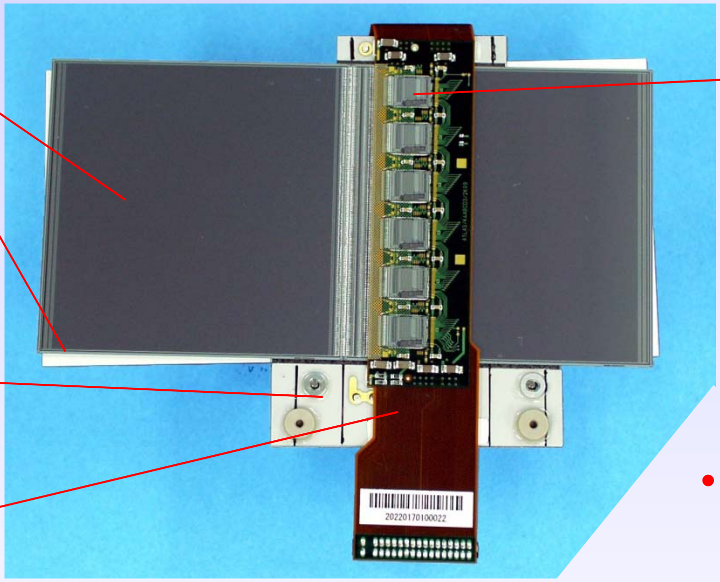
Detector Module

- **Detector Modules** “Basic building block of silicon based tracking detectors”
  - Silicon Sensors
  - Mechanical support (cooling)
  - Front end electronics and signal routing (connectivity)

- **Example: ATLAS SCT Barrel Module**

SCT = SemiConductor Tracker
ASICS = Application Specific Integrated CircuitS
TPG = Thermal Pyrolytic Graphite

128 mm



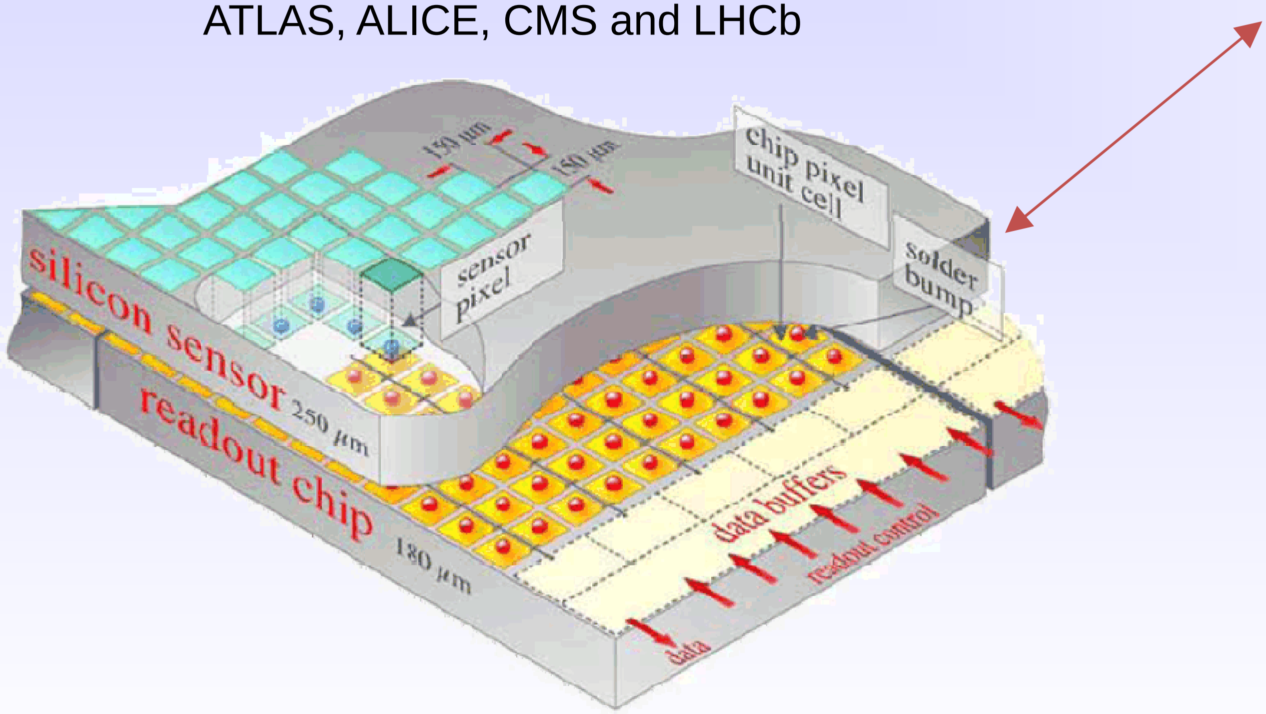
- **Silicon sensors (x4)**
  - 64 x 64 mm^2
  - p-in-n, single sided
  - AC-coupled
  - 768 strips
  - 80μm pitch/12μm width
- **Mechanical support**
  - TPG baseboard
  - BeO facings
- **Hybrid (x1)**
  - flexible 4 layer copper/kapton hybrid
  - mounted directly over two of the four silicon sensors
  - carrying front end electronics, pitch adapter, signal routing, connector
- **ASICS (x12)**
  - ABCD chip (binary readout)
  - DMILL technology
  - 128 channels
- **Wire bonds** (~3500)
  - 25 μm Al wires

$\sigma(r\phi) \sim 16\ \mu m$, $\sigma(z) \sim 850\mu m$ [NIMA538 (2005) 384]

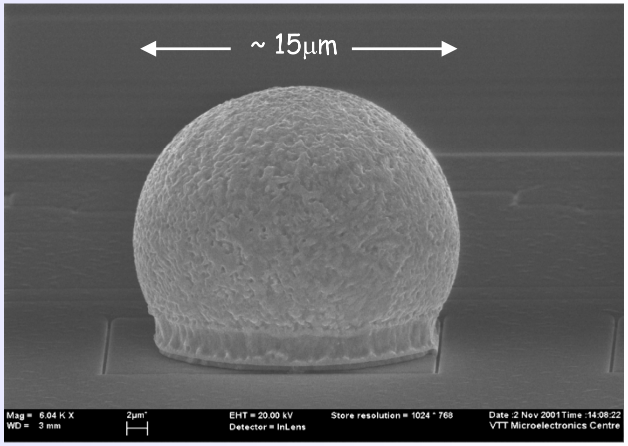
- **ATLAS – SCT**
  - 15.552 microstrip sensors
  - 2.112 barrel modules
  - 1.976 forward modules
  - 61 m^2 silicon, $6.3 \cdot 10^6$strips

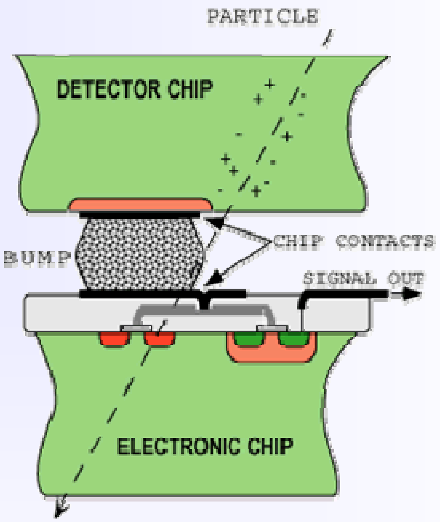
Pixel Detectors

- **HAPS – Hybrid Active Pixel Sensors**
  - segment silicon to diode matrix with high granularity (⇒ true 2D, no reconstruction ambiguity)
  - readout electronic with same geometry (every cell connected to its own processing electronics)
  - connection by “bump bonding”
  - requires sophisticated readout architecture
  - Hybrid pixel detectors are used in all LHC experiments: ATLAS, ALICE, CMS and LHCb



Solder Bump: Pb-Sn

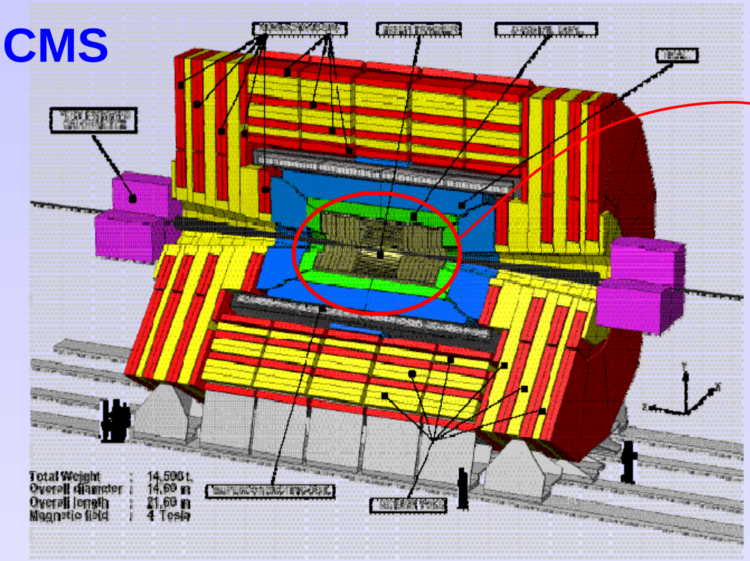




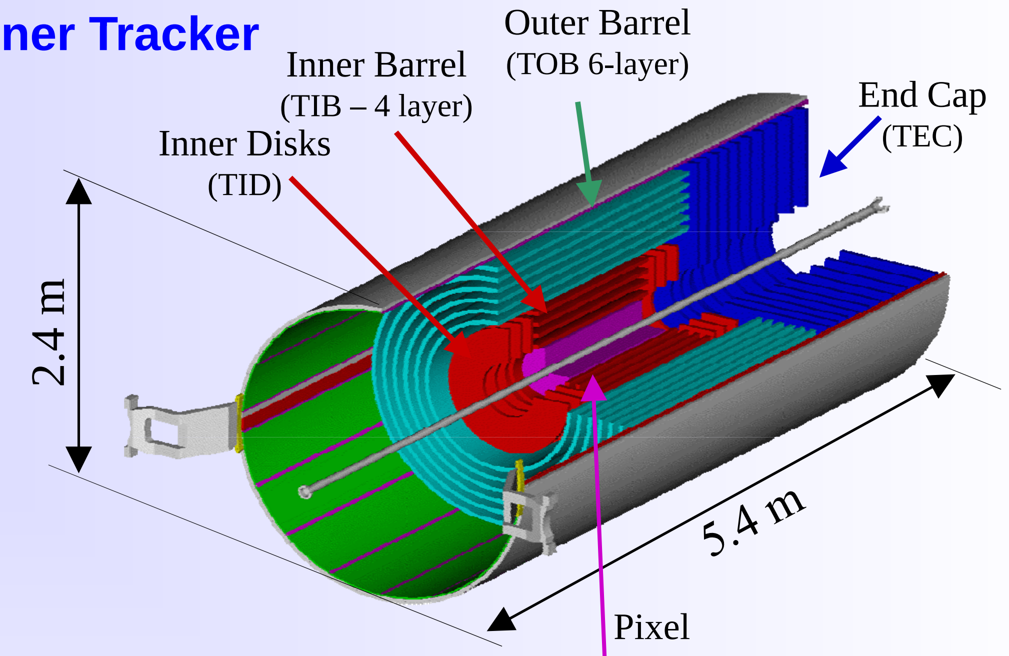
Flip-chip technique

Example: The CMS Silicon Tracker

- **CMS**



- **Inner Tracker**



- **CMS – Compact Muon Solenoid**

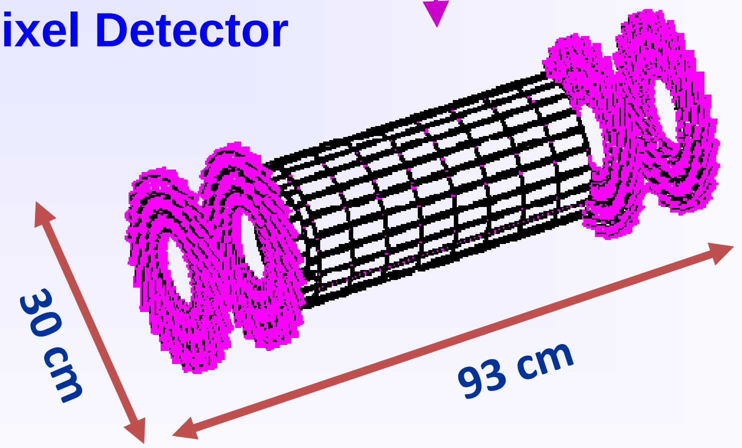
Micro Strip:

- ~ 214 m^2 of silicon strip sensors
- 11.4 million strips

Pixel:

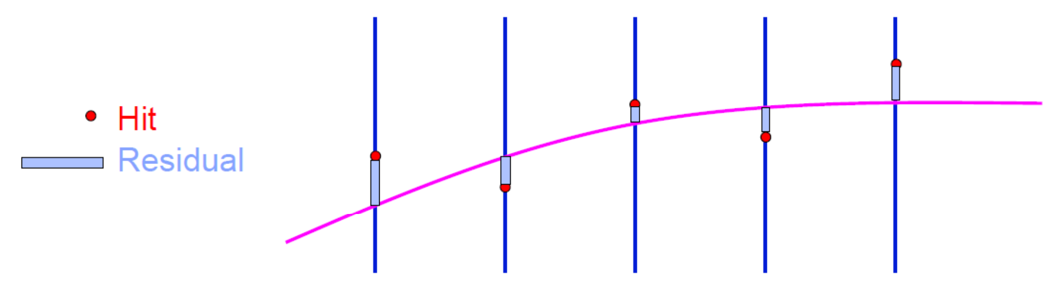
- Inner 3 layers: silicon pixels (~ 1m^2)
- 66 million pixels (100x150μm)
- Precision: $\sigma(r\phi) \sim \sigma(z) \sim 15\mu$m
- Most challenging operating environments (LHC)

- **Pixel Detector**



Alignment

- Silicon Detectors have a very good point resolution ~10 µm
  - but where is the point exactly in space w.r.t. the global detector coordinate system?
  - resolution is not absolute accuracy



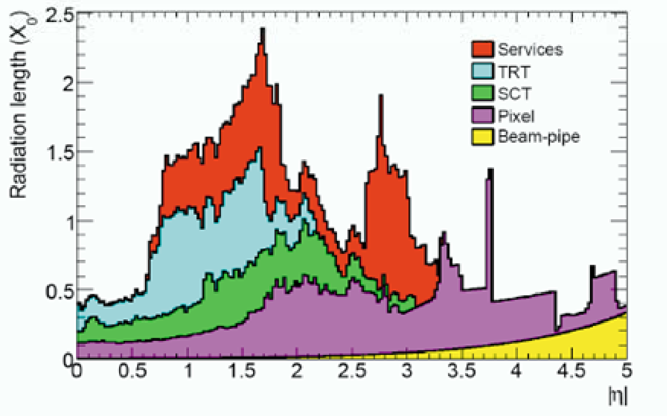
- Point is usually defined by strip number or pixel number
  - i.e. within the local Si detector frame (10 x 10 cm^2 scale)
  - Limited mechanical positioning of one Si detector element to each other
    - Shift and rotation of the elements, bowing (non flatness) etc.
    - Need to know all positions of the detector elements

- Possible alignment strategies
  - Can measure positions in the lab before installation (survey)
    - Stability after installation?
    - Use alignment system (e.g. laser tracks, piezo) to measure positions
    - Align with LHC tracks, e.g. minimize deviations from track in χ2 fit

Material Budget

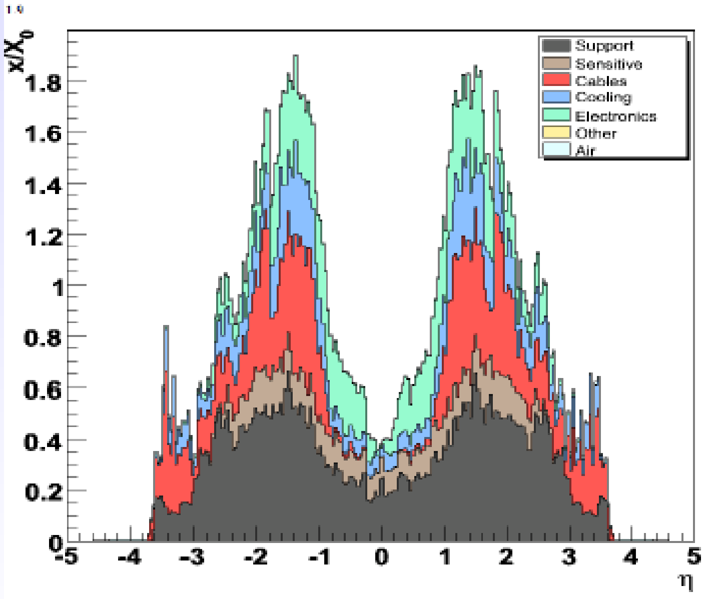
- Tracking Detectors should be light-weighted and thin
  - multiple scattering by material degrades resolution at low momenta
  - unwanted photon conversions in front of calorimeters
  - material often very inhomogeneous (in particular Si detectors)
- Power & cooling adds most of the material
  - not the Si sensor material

ATLAS



$\lvert\eta\rvert$	radiation length	interaction length
< 1	$\sim 0.2\,X_0$	$\sim 0.05\,\lambda$
< 3.3	$\lesssim 0.5\,X_0$	$\lesssim 0.2\,\lambda$

CMS

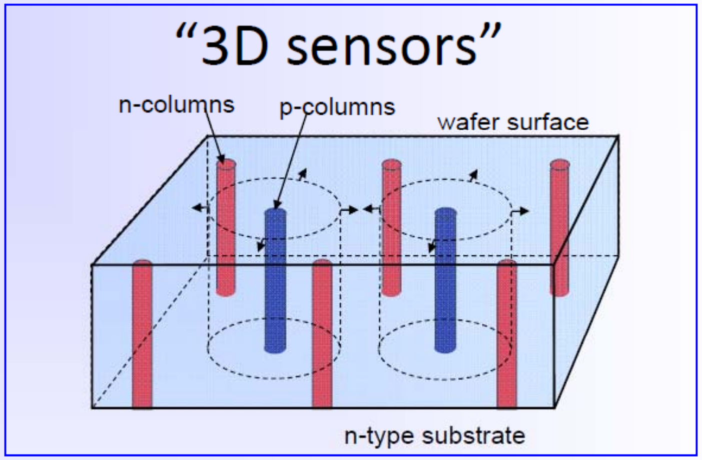


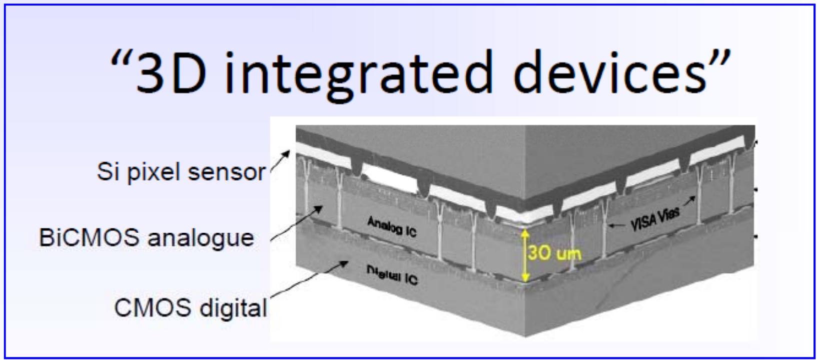
Ongoing R&D activities *(LHC upgrade)*

Tracking Detector Developments ongoing for several projects

Example: LHC upgrade (High Luminosity LHC):
Larger Occupancy and Higher Radiation levels

- **Need higher granularities at larger radius**
  - Pixel detectors reaching out further in radius and coming closer to beam
  - Silicon Strip Sensors with shorter strips
  - New trigger concepts using silicon detectors
- **Need radiation tolerant detectors**
  - **R&D on sensor materials** (Defect Engineered Silicon, Diamond, ..)
  - **R&D on sensor concepts** (n-in-p sensors, 3D sensors, …)
- **Exploit industrial developments**
  - *'3D integration'* (Combine sensor and electronics)
- **Many other issues**
  - Powering, cooling, reduction of power consumption, cost, mass reduction, …


"3D sensors"


"3D integrated devices"

Summary

***Tracking*: Particle Track Reconstruction**

- **Vertexing**
  - **distinguish primary vertices**
  - **measure impact parameter and secondary vertices, lifetime tagging**

- **Momentum Measurement** (from curvature of track in magnetic field)
  - **Momentum resolution** has two main contributions
    - **Error from multiple scattering**, independent of momentum, dominates at low momentum, requires thin/light detectors
    - **Error from point measurements**, dominates at high momenta, large track length and strong B-Field helps: $\propto 1/(BL^2)$, need big detectors and strong B-Field to measure high momenta

- **Tracking Performance**
  - Material budget (Trade off between precision and material!)
  - Alignment (Improve quality of tracks)

- **Tracking Detectors (Choice of Technology)**

  Mainly two (three) types of track detectors
  - **Silicon detectors** since early 1990s, very good point resolution, many electronics channels, “thick” compared to wire chambers
  - **Gaseous detectors** (with wires) since 1960s, point resolution limited to ~50-150 µm
  - Fiber trackers with scintillating fibers + photon detectors

- **Intensive tracking detector R&D ongoing for LHC upgrade, LC, CLIC, ….**

Acknowledgements and Literature

- Some material taken from the following presentations
  - Michael Hauschild, CERN, *Tracking* Detectors (ESI 2009)
  - Leszek Ropelewski, CERN, *Gas Detectors (CERN Academic Training 2005)*
  - Christian Joram, CERN, *Particle Interactions with Matter (ICFA School 2010)*
    Particle Detectors (CERN Summer Student Lectures 2003)
  - *Werner Riegler, CERN, Fundamentals of Particle Detectors (CERN Academic Training 2008)*
  - *Gregor Herten, Uni Freiburg, Particle Detection:Trackers (HCP School 2009)*
  - Pippa Wells, CERN, *Tracking at the LHC* (EDIT 2011 School)

- Literature – Further Reading
  - C.Grupen and B.Shwartz, *Particle Detectors*, Cambridge University Press
  - G.Lutz, *Semiconductor Radiation Detectors*, Springer
  - H.Spieler, *Semiconductor Detector Systems*, Oxford University Press
  - G.Knoll, *Radiation Detection and Measurement*, John Wiley and Sons
  - M.Sze, *Physics of Semiconductor Devices*, Wiley-Interscience
  - L.Rossi, *Pixel Detectors*, Springer
  - F.Hartmann*, Evolution of Silicon Sensor Technology in Particle Physics, Springer*