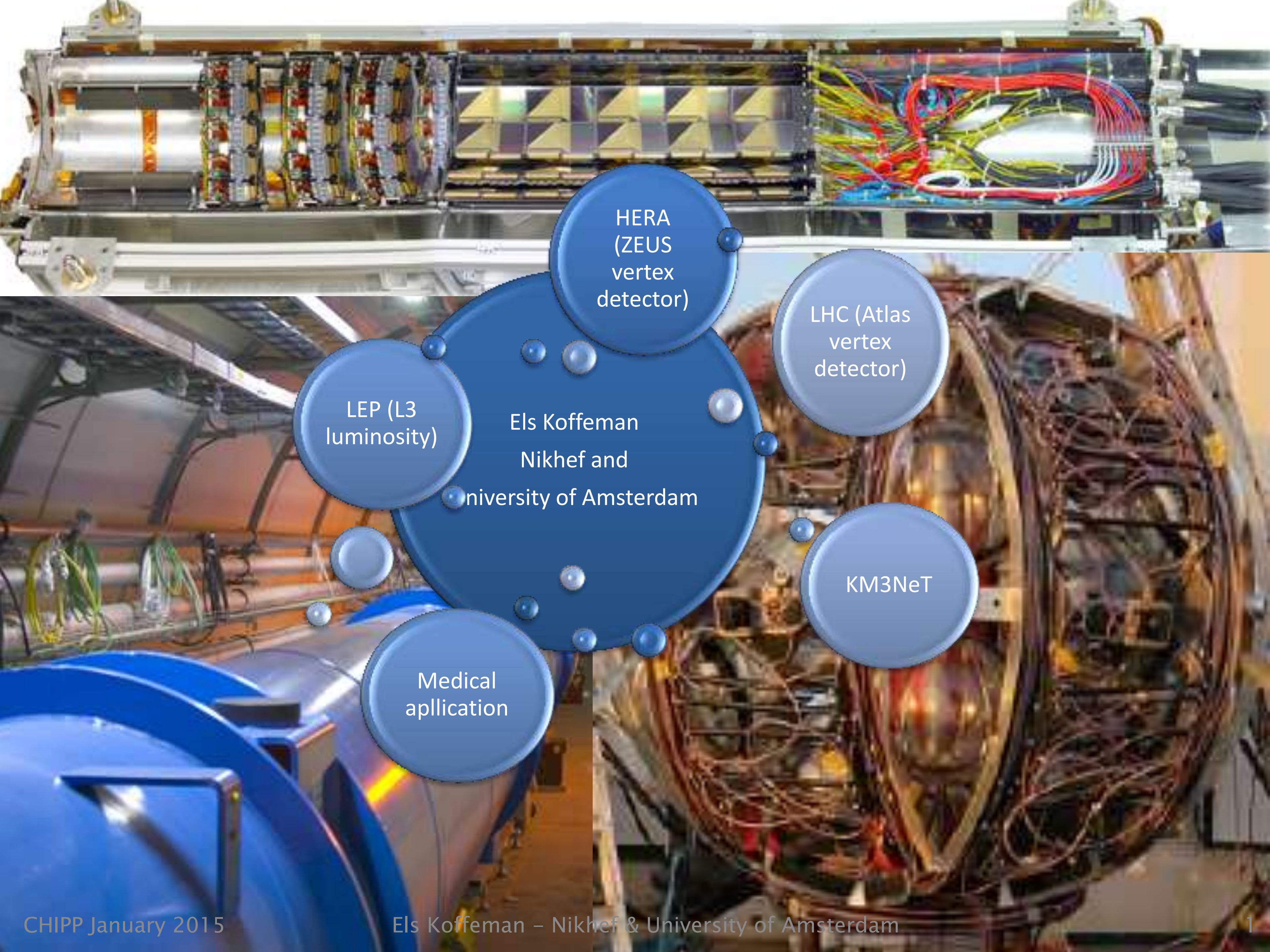


Els Koffeman

Nikhef and

niversity of Amsterdam

HERA (ZEUS vertex detector)

LHC (Atlas vertex detector)

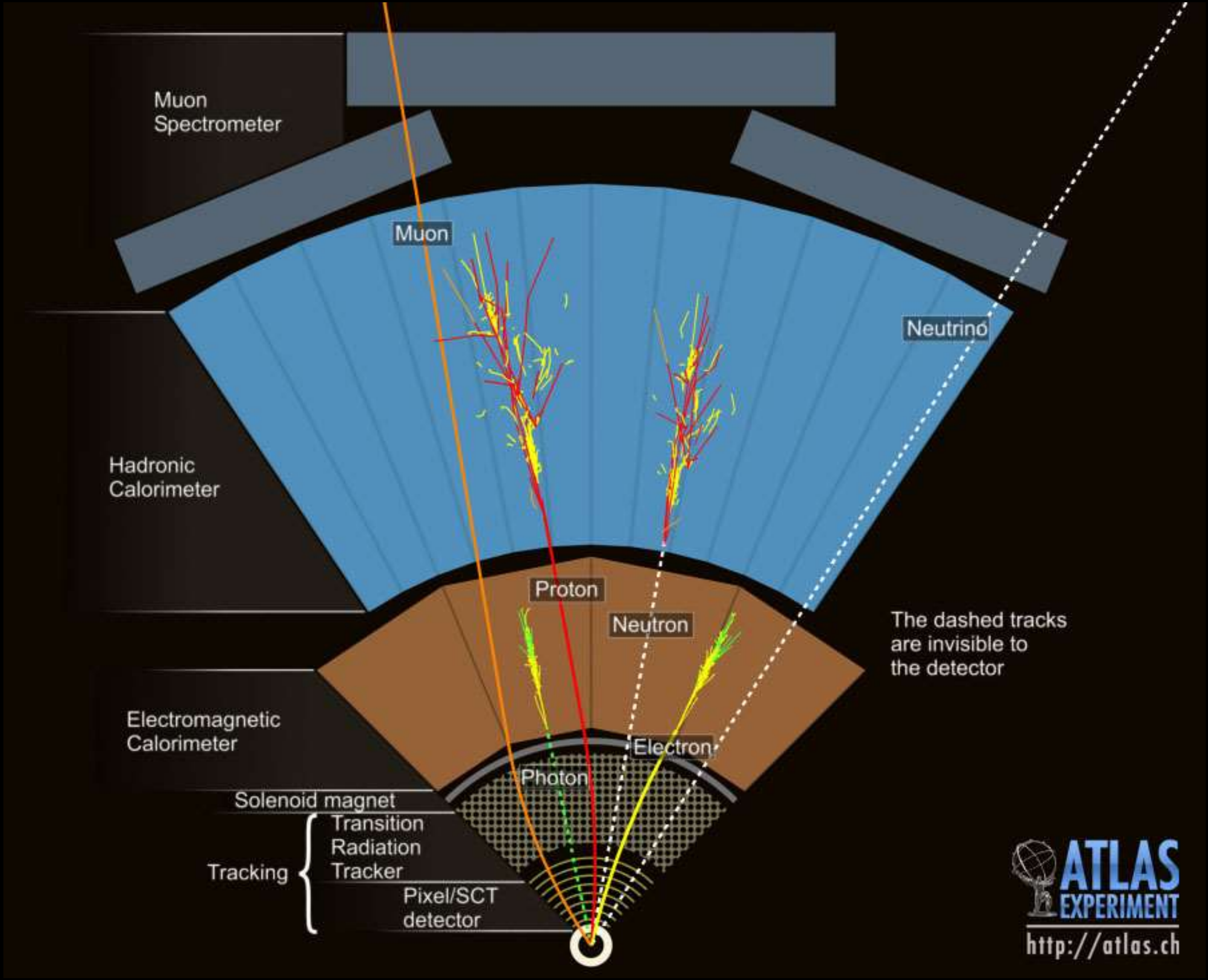
KM3NeT

Medical apllication

LEP (L3 luminosity)

I: Observables
II: Particle Interactions
III: Tracking
IV: Medical applications

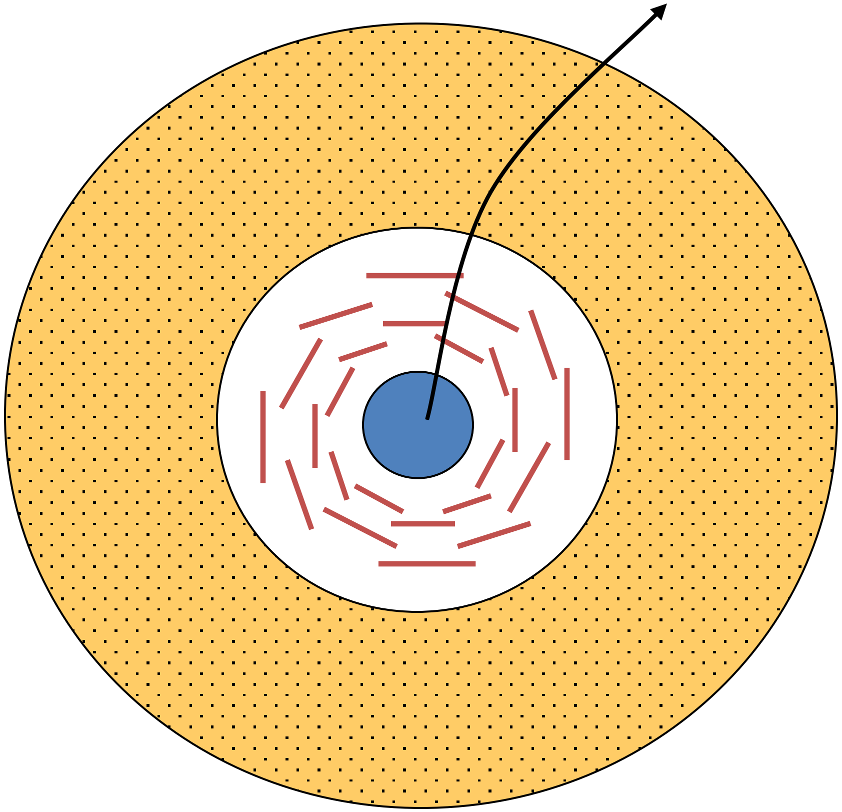
Els Koffeman
koffeman@nikhef.nl



The dashed tracks are invisible to the detector

Tracking and vertexing

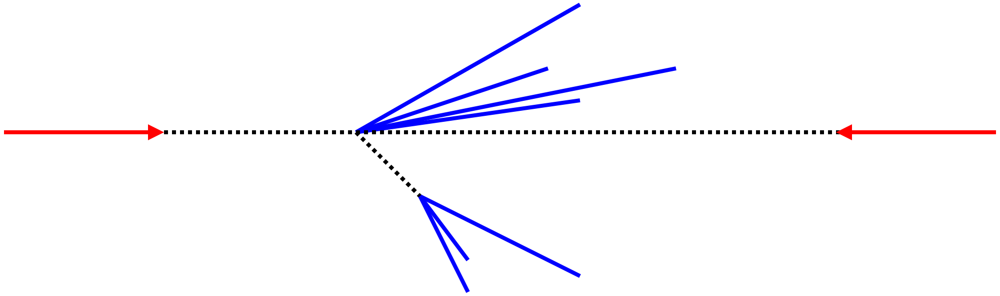
- Gas filled detector
  - Momentum measurement
  - Many points
  - accuracy O(0.1mm)
- Semiconductor detector
  - Vertex determination
  - Few points
  - accuracy O(0.001-0.01 mm)



Lifetime measurement

- Heavy quark mesons….
- Lifetime measured from secondary vertex
  - $c\tau \sim 100$ micron
- Take Lorentz boost into account

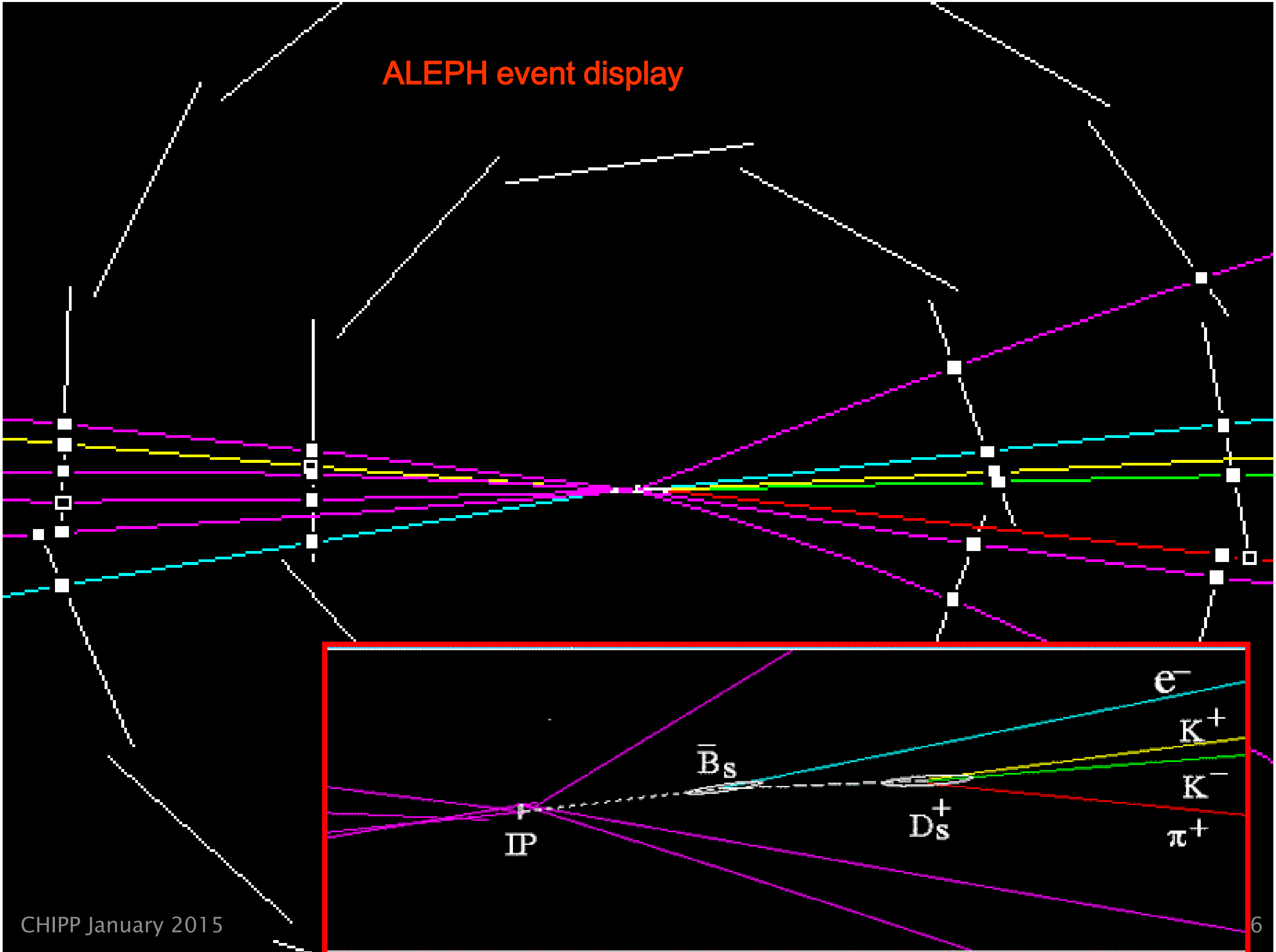
$$\gamma = \frac{E}{m}$$



$$D^{*} \rightarrow D^{\pm}\pi_{slow}$$

$$D^{\pm} \rightarrow K^{+}K^{-}\pi^{\pm}$$

ALEPH event display



Gaseous Detectors

- Introduction
  - Energy loss (reminder)
  - General principle
- Principle of operation
  - Drift Time
  - Lorentz Angle
  - Diffusion
  - Amplification
- Detector Types
  - MWPC
  - Single wire cells
  - Time projection Chamber

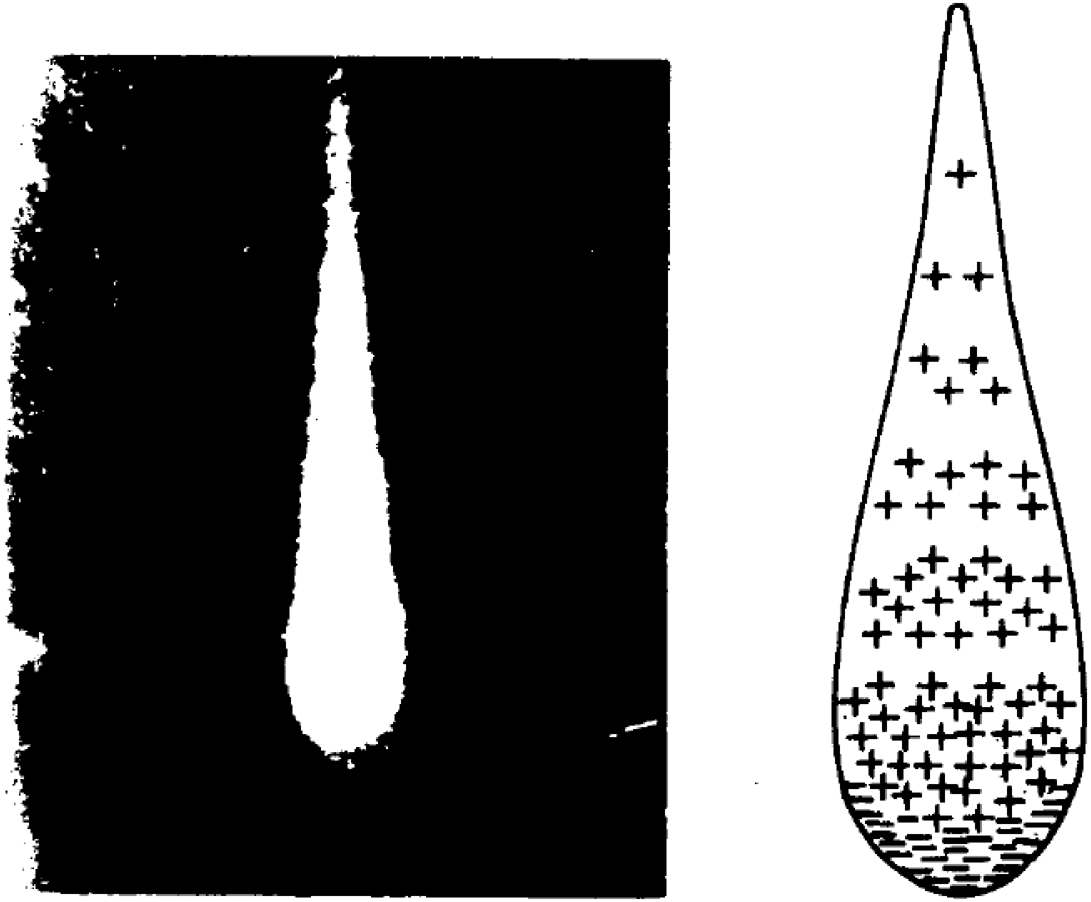
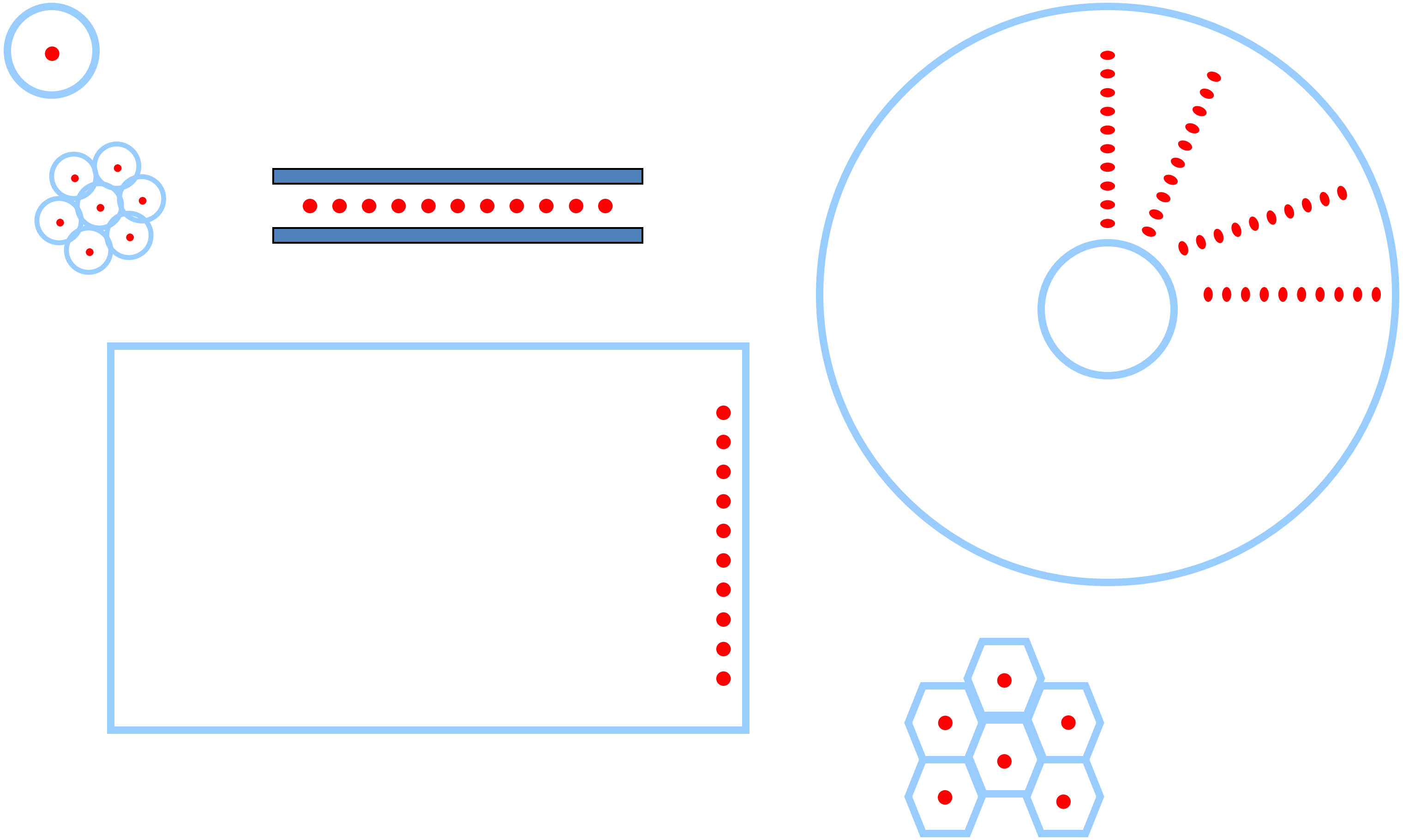


Fig. 46 Drop-like shape of an avalanche, showing the positive ions left behind the fast electron front. The photograph shows the actual avalanche shape, as made visible in a cloud chamber by droplets condensing around ions18).

Many configurations....

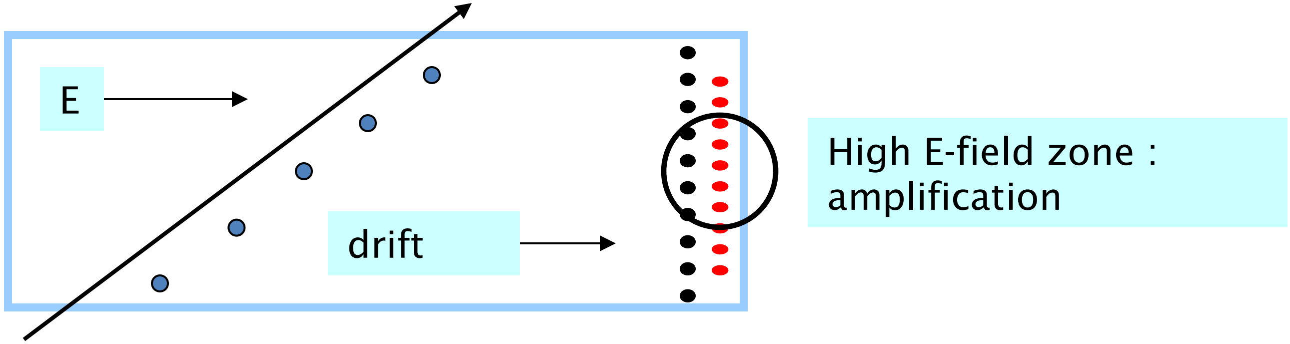


Gaseous Detectors

- Single Wire Chambers
  - Straw Tubes (Atlas TRT, LHCB)
  - Drift Tubes (Atlas Muon Chambers)
- Multiwire Proportional Chambers
- Drift Chambers
  - drift perpendicular to B-field (Drift or TEC)
  - drift along B-field (TPC) (Future Linear Collider)
- Micro Patterned Gas Detectors
  - GEM foil
  - Micromegas
  - INGRID (micromogas production integrated with the grid)

Time Projection Chamber

- Large drift volume
  - The track of the primary electrons is reconstructed from the arrival time of (single) electrons
- Amplification
  - The signal is generated by the avalanches close to the wire: The (positive) ion cloud drifts away from the (positive) wire.



Drift time

- General motion of charge in an EM–field

$$m\frac{d\vec{v}}{dt} = e\vec{E} + e\vec{v}\times\vec{B}$$

- But there is friction due to the gas

$$m\frac{d\vec{v}}{dt} = e\vec{E} + e\vec{v}\times\vec{B} + \vec{Q}(t)$$

- Solve for stationary operation or $\frac{d\vec{v}}{dt} = 0$

- Define $\mu = \frac{\vec{v}}{\vec{E}}$ $\vec{\omega} = \frac{eB}{m}$ and $Q(t) = mA(t)$

The average of mA(t) is obtained by considering that this force is equal to <dp/dt>, which can be written as: $\Sigma\, \mathbf{p}_i / t_N = N\, m\mathbf{v}_D / (N \langle\Delta t\rangle) = m\mathbf{v}_D / \tau$. The average force is balancing the force due to electric and magnetic fields, so mA(t) has to be replaced by $-mv_D / \tau$ in the time averaged equation:

$$e\mathbf{E} + e\mathbf{v_D} \times \mathbf{B} - m\mathbf{v_D} / \tau = 0$$

This can be written as:

$$\mathbf{v_D} = \frac{e\tau}{m}\left(\mathbf{E} + \mathbf{v_D} \times \mathbf{B}\right)$$

The quantity $e\tau/m$ is equal to the mobility for $P=P_0$ for the case that B = 0, as in that case: $\mu = v_D/E = eE\tau/(Em) = e\tau/m$, with τ the τ for the situation with drift field. From the equation it is seen that the definition of mobility can be generalized to make the mobility the proportionality constant between the drift velocity and the sizes of the electric and magnetic forces divided the electron charge. The equation is a vector equation in v_D with as solution

$$\mathbf{v_D} = \frac{\mu}{1+\mu^2 B^2}\left[\mathbf{E} + \mu\mathbf{E} \times \mathbf{B} + \mu^2\left(\mathbf{E} \bullet \mathbf{B}\right)\mathbf{B}\right]$$

For B perpendicular to E we have:

$$v_{D,//} = \frac{\mu E}{1+\mu^2 B^2} \qquad v_{D,\perp} = \frac{\mu^2 EB}{1+\mu^2 B^2}$$

Therefore: $v_{D,\perp} / v_{D,//} = \mu B$, i.e. drifting is still in a straight line, but under an angle of arctan (μB) with the electric field direction in the plane perpendicular to B. The angle is called the *Lorentz angle* and is independent of the electric field strength.

With ω = eB/m (cyclotron frequency) is μB equal to $\omega\tau$.
The expressions for B perpendicular to E then become:

$$v_{D,//} = \mu E \frac{1}{1+\omega^2\tau^2} = v_{D,//,\text{no B}} \frac{1}{1+\omega^2\tau^2}$$

-> the drift velocity in the field direction decreases for increasing B

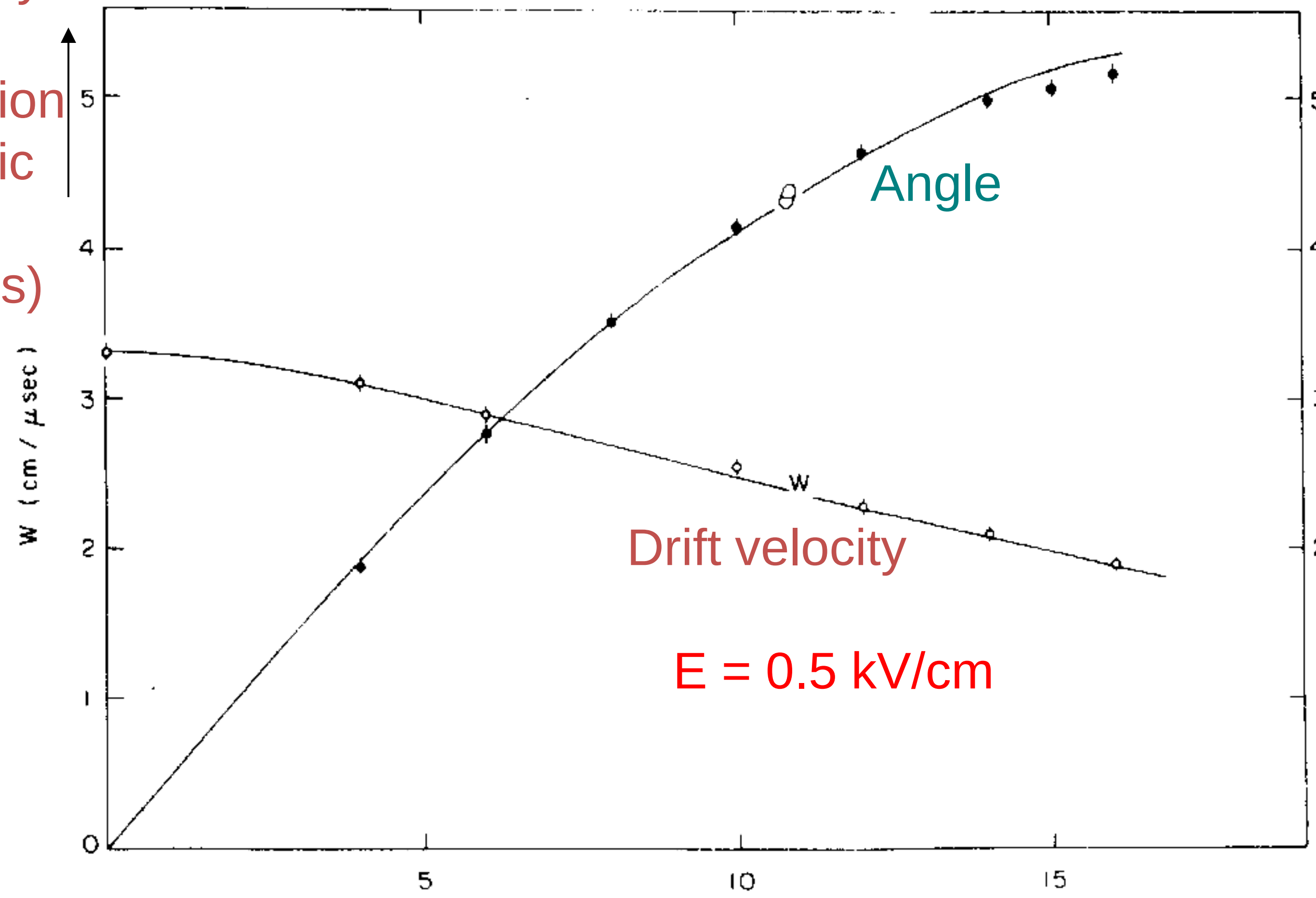
$$v_{D,\perp} = \mu E \frac{\omega\tau}{1+\omega^2\tau^2} = v_{D,//,\text{no B}} \frac{\omega\tau}{1+\omega^2\tau^2}$$

$$v_{D,\perp} / v_{D,//} = \omega\tau$$

$$v_D = \sqrt{v_{D,\perp}^2 + v_{D,//}^2} = \frac{\mu E}{\sqrt{1+\omega^2\tau^2}} = \frac{v_{D,//,\text{no B}}}{\sqrt{1+\omega^2\tau^2}}$$

-> the total drift velocity decreases for increasing B

Drift velocity in direction electric field (cm/μs)



Angle

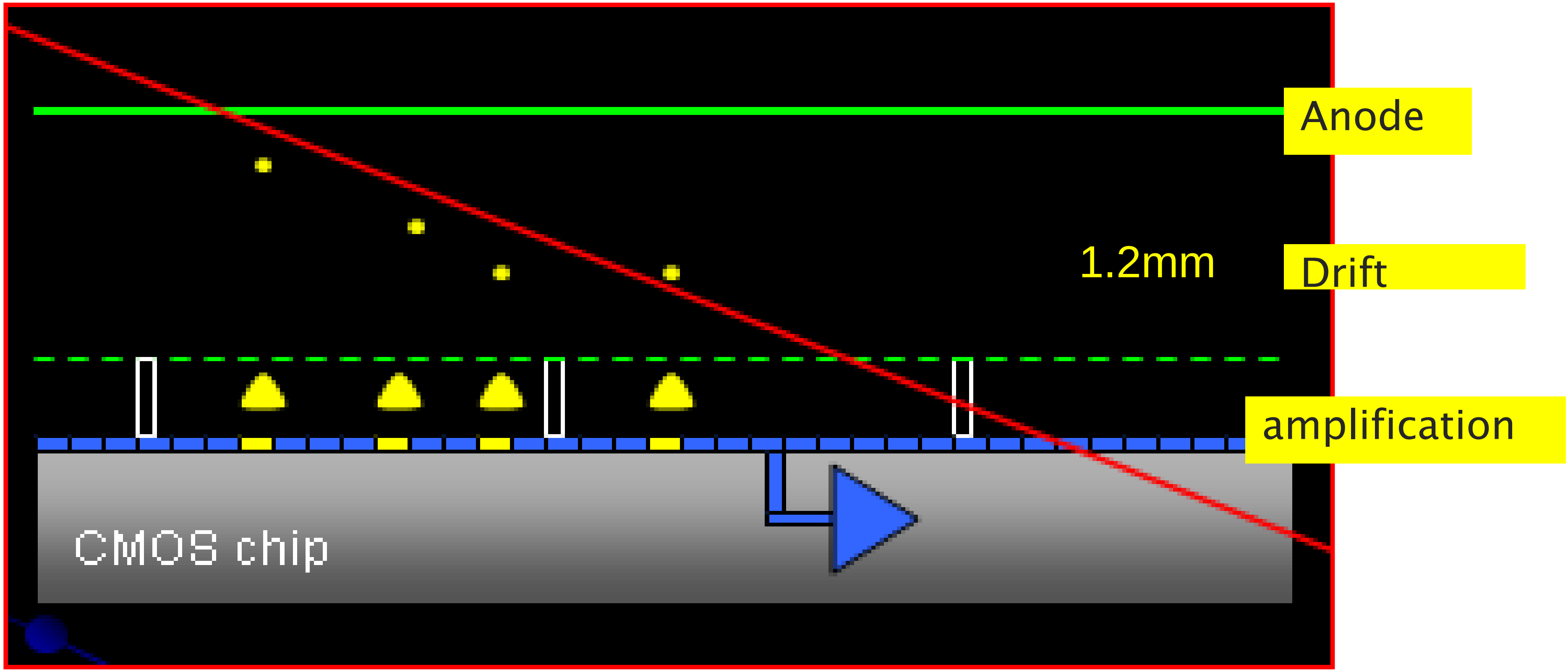
Lorentz angle

Drift velocity

E = 0.5 kV/cm

B (kG)

Gas detectors on Timepix

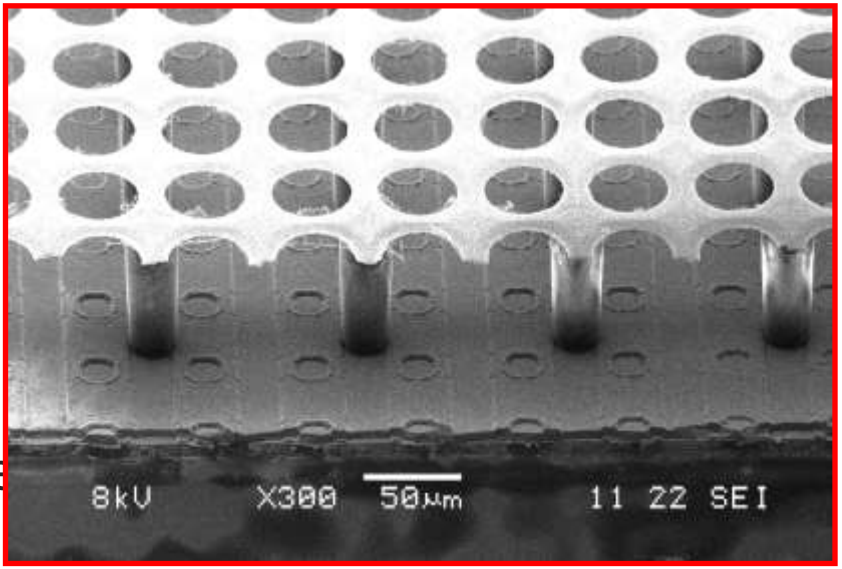


- ◆ Drift region: 300 – 3kV/cm
- ◆ Amplification: 400 – 600V/50μm (80 – 120kV/cm)

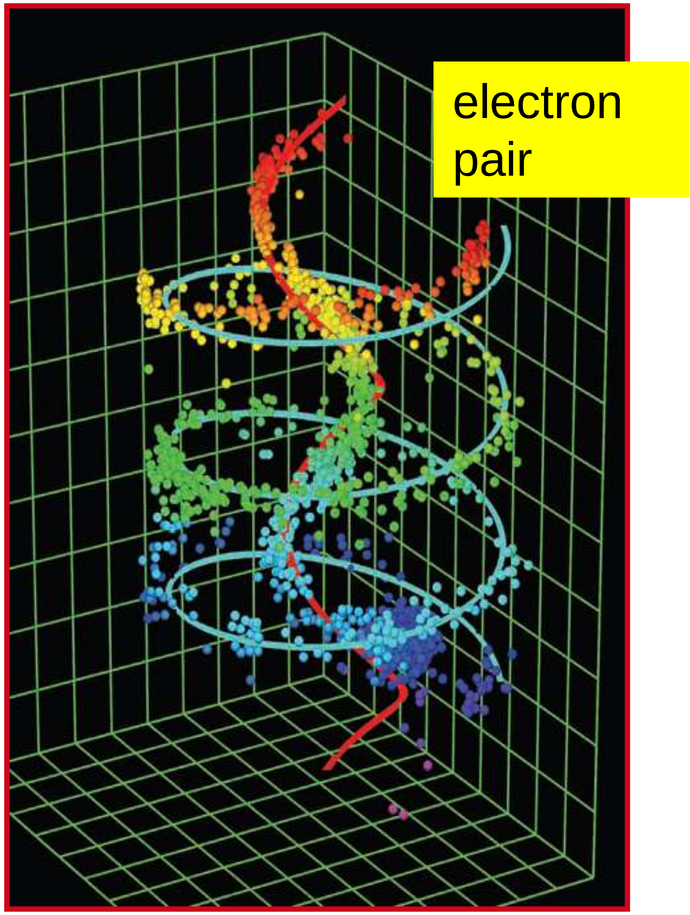
`

Gridpix

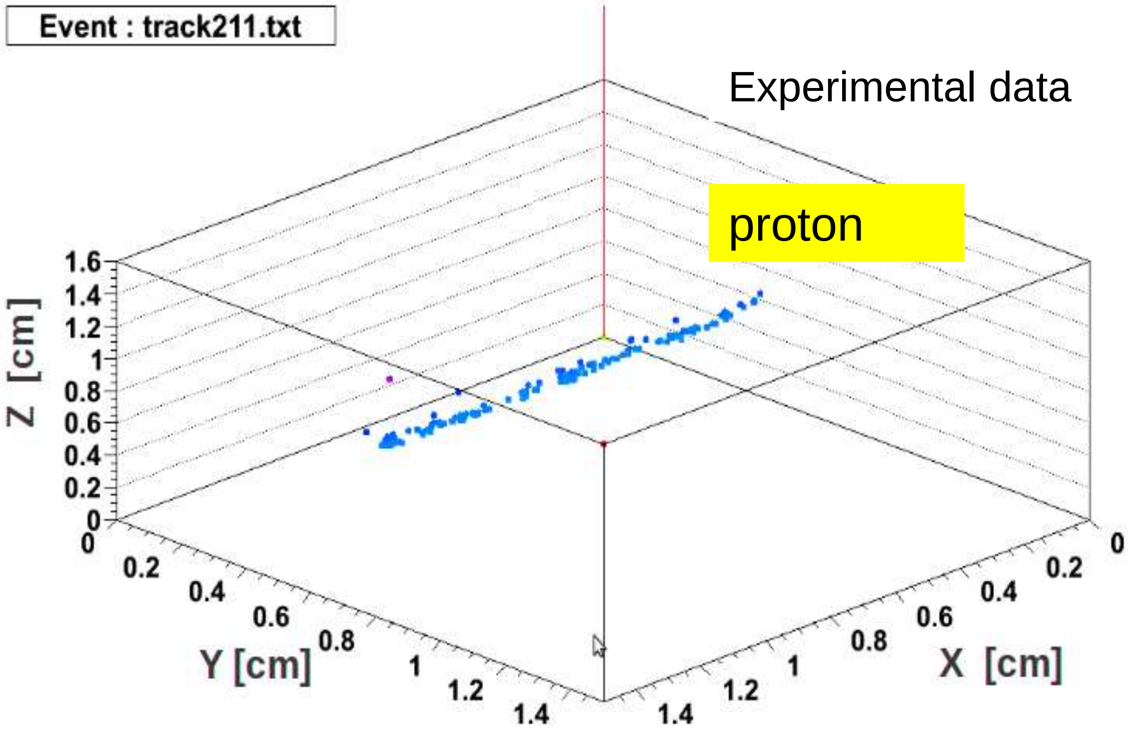
- Gaseous detector
  - Start with Timepix chip
  - Build pillars (SU8) to support grid
  - Place aluminium grid on top
  - Assemble onto PCB
  - Build into system providing anode



Track Reconstruction



electron pair

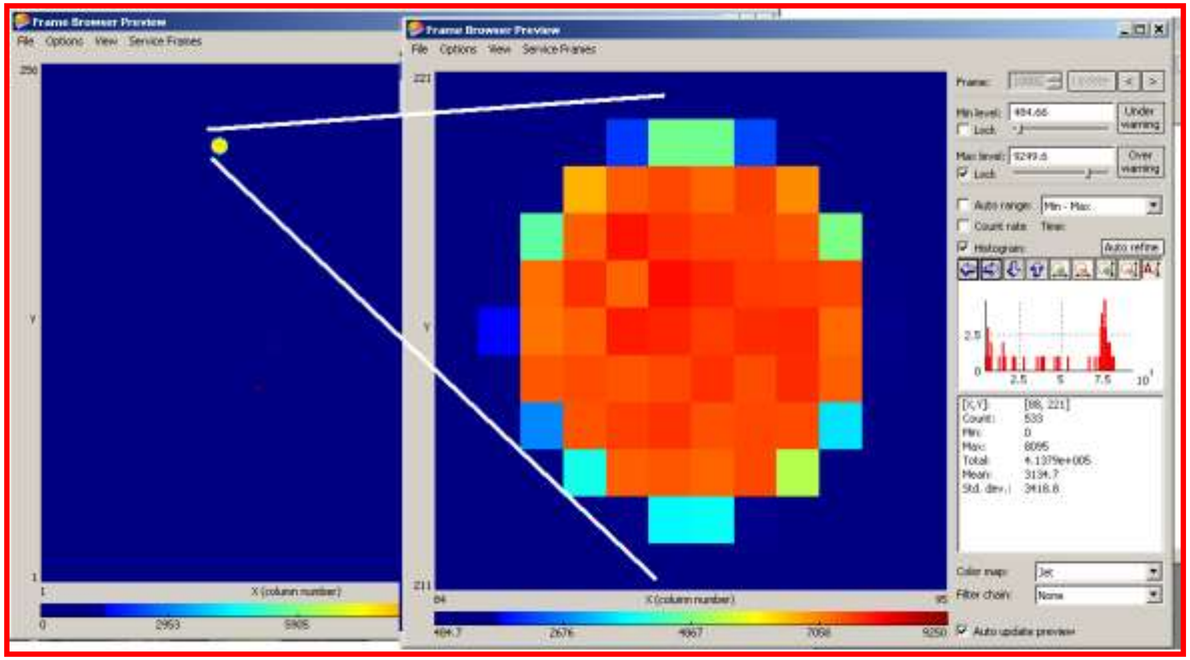


Experimental data

proton

Development

- Discharges
  - Will happen so need to survive them
- Scale
  - go from one chip to reliable production scheme



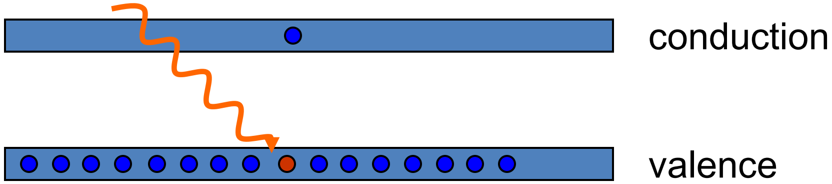
Min level: 484.66
☐ Lock
Max level: 9249.6
☑ Lock
☐ Auto range: Min - Max
☐ Count rate Time:
☑ Histogram

[X,Y]: [88, 221]
Count: 533
Min: 0
Max: 8095
Total: 4.1379e+005
Mean: 3134.7
Std. dev.: 3418.8

Color map: Jet
Filter chain: None
☑ Auto update preview

Semiconductor detectors

- Energy loss
  - – Ionisation (remember Bethe-Bloch equation)
  - – Photoelectric effect
- Deposited energy creates electron-hole pairs
    - Egap = Evalence – E conduction



- For a detector: apply electric field that induces current and signal

Semiconductors

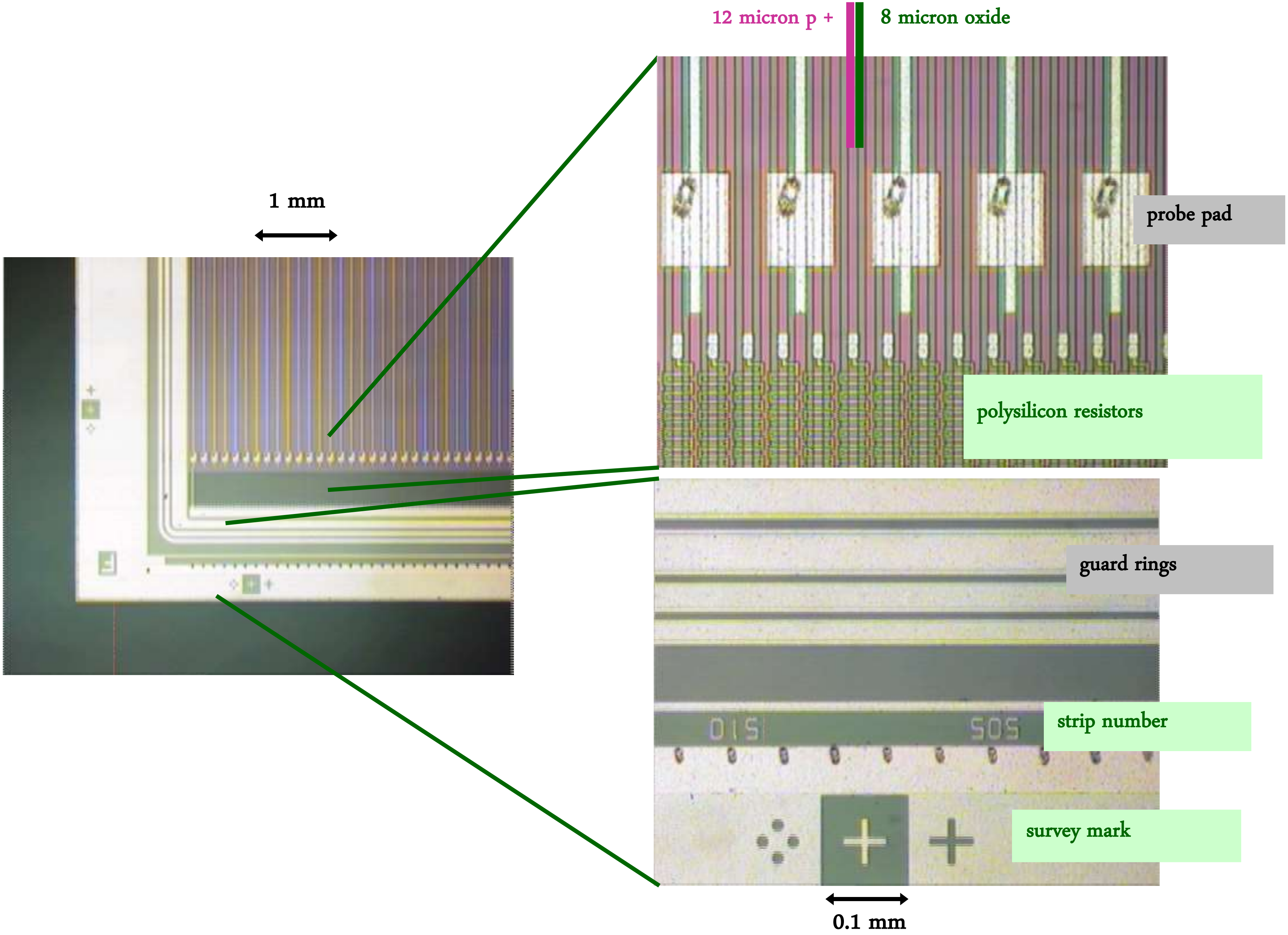
- Germanium, Silicon, GaAs, Diamond and many other exotics

	Germanium	**Silicon**	**GaAs**	**Diamond**
Egap (eV)	0,66	1,12	1,42	5,50
electron mobility (cm2V-1s-1)	3900	1500	8500	1800
hole mobility (cm2V-1s-1)	1900	450	400	1200
density (g/cm3)	5,33	2,33	5,32	5,40
intrinsic carrier density (cm-3)	2,4E+13	1,5E+10	1,8E+06	-
ε	16	12	13	6

Semiconductors

- Germanium
  - used in the past for spectroscopy
- Diamond
  - RADIATION hard but expensive and supply unreliable
- GaAs, CdTe,…
  - Quality too poor for tracking
  - needed to enhance Xrays attenuation in imaging

- Silicon is still the obvious choice
  - Band gap allows room temperature operation
  - Available with high purity and with large surface
  - Processing well known due to chip-industry



12 micron p +

8 micron oxide

1 mm

probe pad

polysilicon resistors

guard rings

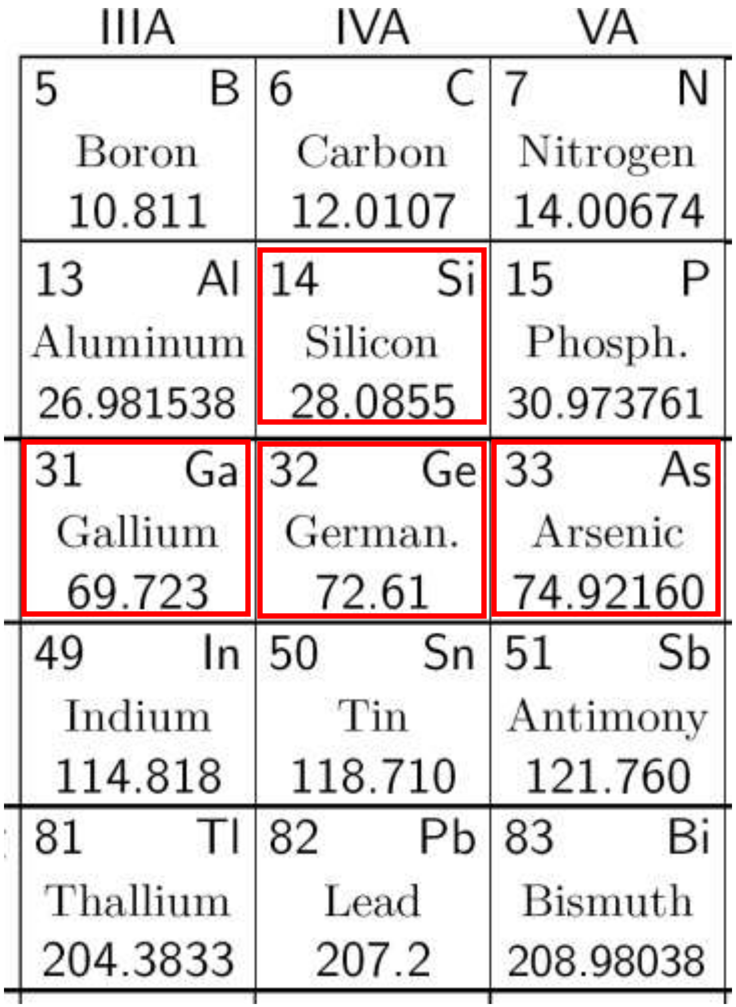
strip number

survey mark

0.1 mm

Semiconductors

- Various types…
- Germanium
- GaAs
- Silicon
- Diamond



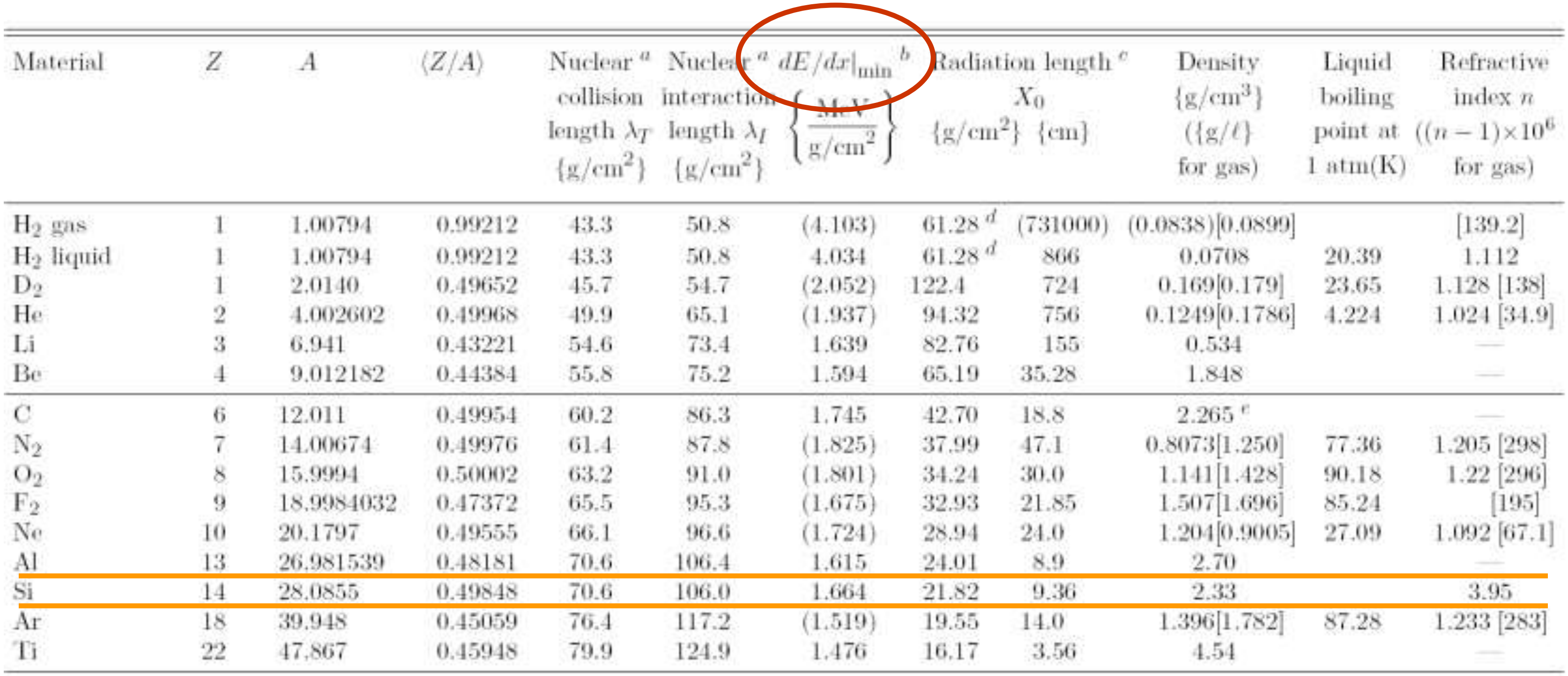
IIIA	IVA	VA
5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674
13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosph. 30.973761
31 Ga Gallium 69.723	32 Ge German. 72.61	33 As Arsenic 74.92160
49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760
81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038

K. Hagiwara *et al.*, Physical Review D**66**, 010001-1 (2002)

Available online Particle Data Group

Use the Particle Data Book !

- Material properties….

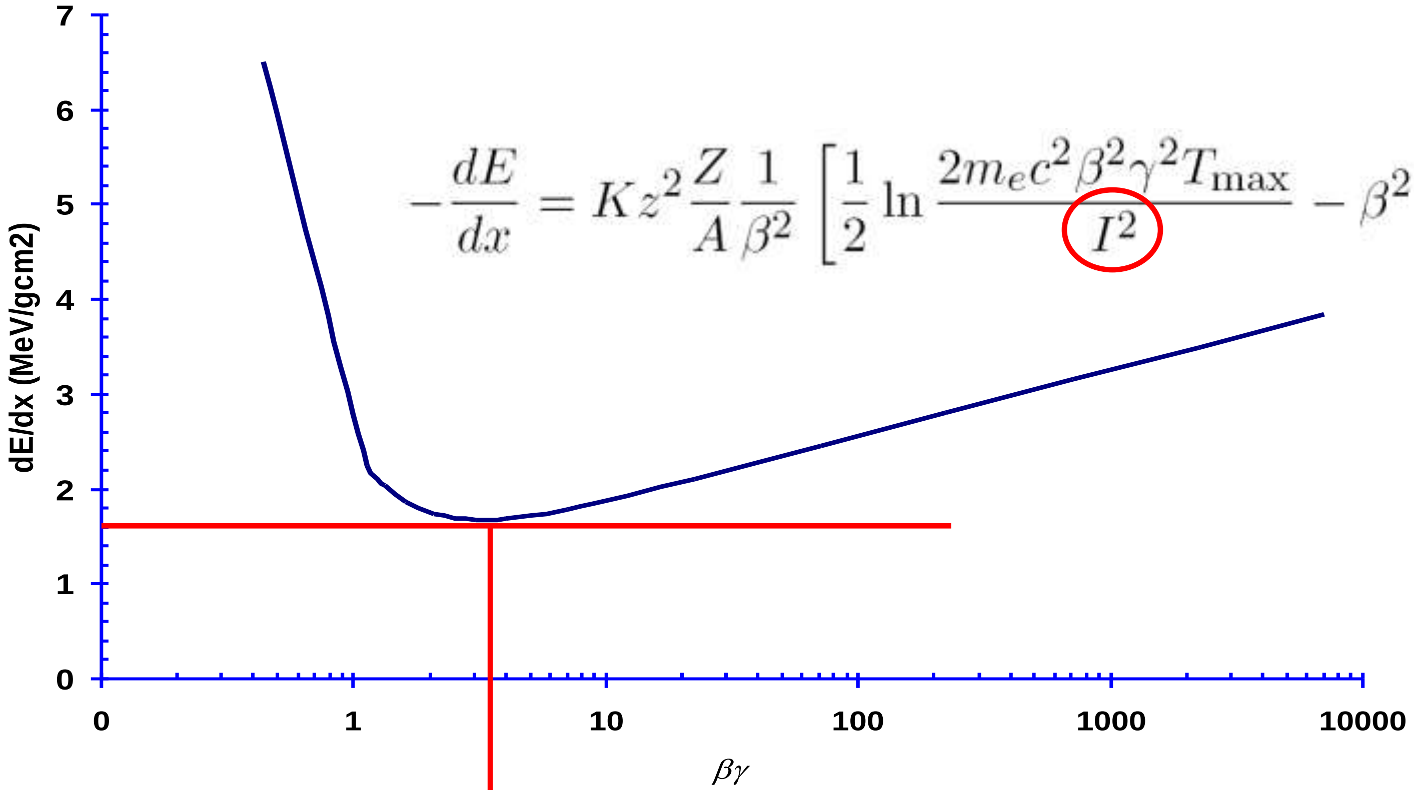


Energy loss of MIP

Material	Z	A	$\langle Z/A \rangle$	Nuclear [a] collision length λ_T {g/cm^2}	Nuclear [a] interaction length λ_I {g/cm^2}	$dE/dx\vert_{\min}$ [b] $\left\{\frac{\text{MeV}}{\text{g/cm}^2}\right\}$	Radiation length [c] X_0 {g/cm^2}	{cm}	Density {g/cm^3} ({g/ℓ} for gas)	Liquid boiling point at 1 atm(K)	Refractive index n (($n-1$)×10^6 for gas)
H_2 gas	1	1.00794	0.99212	43.3	50.8	(4.103)	61.28 [d]	(731000)	(0.0838)[0.0899]		[139.2]
H_2 liquid	1	1.00794	0.99212	43.3	50.8	4.034	61.28 [d]	866	0.0708	20.39	1.112
D_2	1	2.0140	0.49652	45.7	54.7	(2.052)	122.4	724	0.169[0.179]	23.65	1.128 [138]
He	2	4.002602	0.49968	49.9	65.1	(1.937)	94.32	756	0.1249[0.1786]	4.224	1.024 [34.9]
Li	3	6.941	0.43221	54.6	73.4	1.639	82.76	155	0.534		—
Be	4	9.012182	0.44384	55.8	75.2	1.594	65.19	35.28	1.848		—
C	6	12.011	0.49954	60.2	86.3	1.745	42.70	18.8	2.265 [e]		—
N_2	7	14.00674	0.49976	61.4	87.8	(1.825)	37.99	47.1	0.8073[1.250]	77.36	1.205 [298]
O_2	8	15.9994	0.50002	63.2	91.0	(1.801)	34.24	30.0	1.141[1.428]	90.18	1.22 [296]
F_2	9	18.9984032	0.47372	65.5	95.3	(1.675)	32.93	21.85	1.507[1.696]	85.24	[195]
Ne	10	20.1797	0.49555	66.1	96.6	(1.724)	28.94	24.0	1.204[0.9005]	27.09	1.092 [67.1]
Al	13	26.981539	0.48181	70.6	106.4	1.615	24.01	8.9	2.70		—
Si	14	28.0855	0.49848	70.6	106.0	1.664	21.82	9.36	2.33		3.95
Ar	18	39.948	0.45059	76.4	117.2	(1.519)	19.55	14.0	1.396[1.782]	87.28	1.233 [283]
Ti	22	47.867	0.45948	79.9	124.9	1.476	16.17	3.56	4.54		—

Energy loss

- MIP deposits 1.67 MeV/(g/cm2) in silicon
- Thus for typical layer of 300 micron thickness….
- Mark ionisation potential I=171 eV (silicon)



$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{\boxed{I^2}} - \beta^2 - \frac{\delta}{2}\right]$$

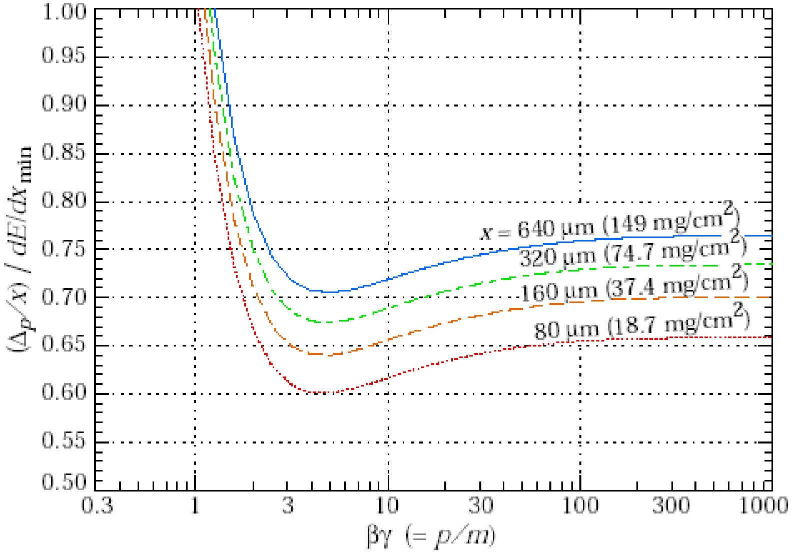
Energy loss

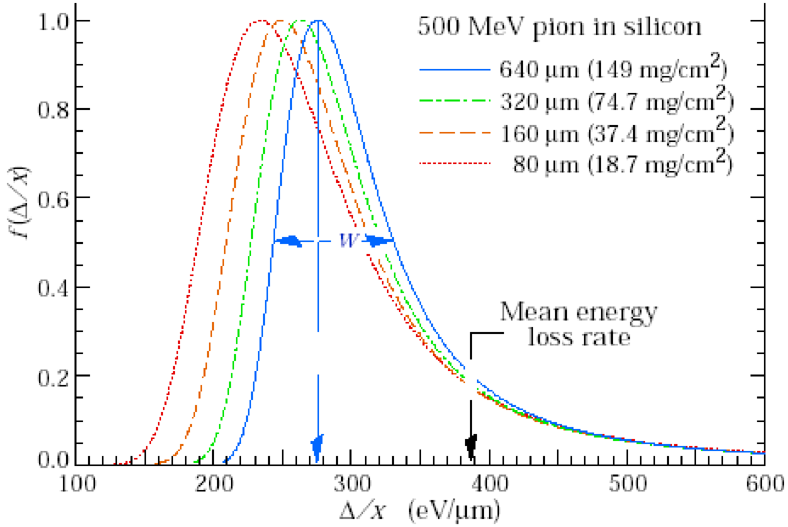
- High energy physics
  - MIP is the particle of interest in most particle detectors
  - 90 keV in 300 micron thick sensor
  - Energy needed for the creation of one electron–hole pair is 3.6 eV
  - Signal 25000 electrons in a 300 micron thick sensor

- Spectroscopy in Nuclear physics/ Medical aplication
  - For energy measurements of low energy x–rays (medical applications) total photon energy is converted
  - Example K–line of Aluminium is 1.4 keV
  - To improve quantum efficiency it can be interesting to take material with higher density

MIP in silicon

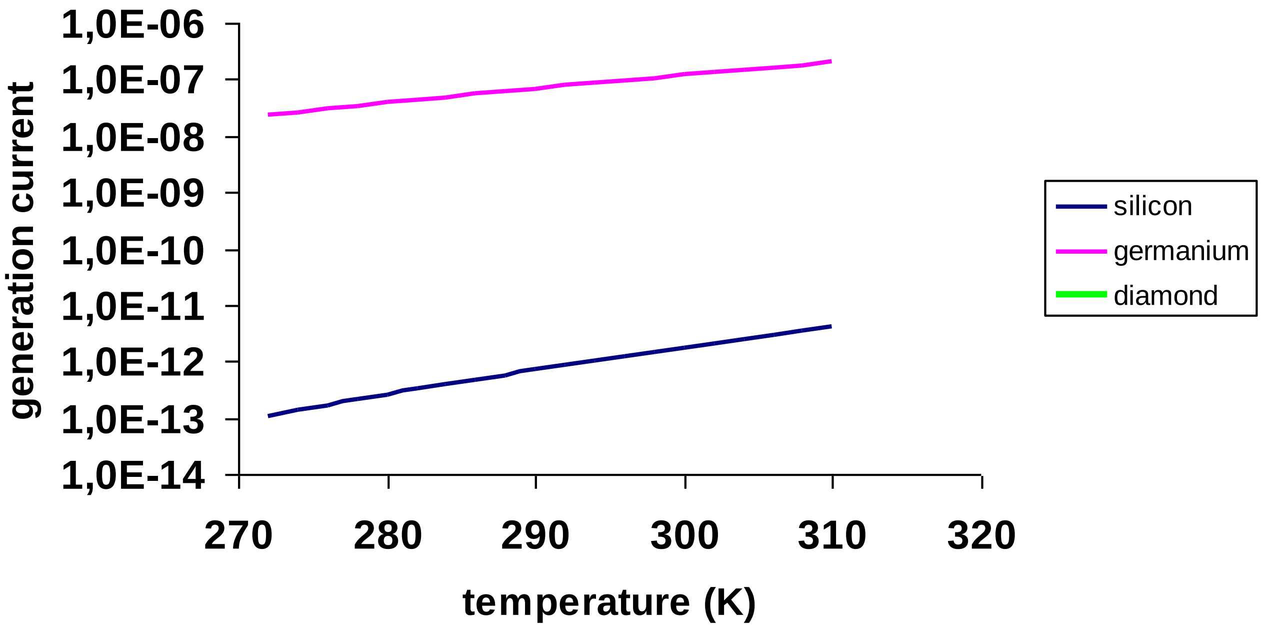
- Energy deposit follows statistical fluctuations: higher probability of larger energy deposits
- Mean not equal to most probable
- Mathematical description:
    - Landau distribution
    - This is thin layer approximatior
    - however the average ionisation potential used in Bethe Bloch (I=170 eV for silicon) is only valid above a certain thickness.





Leakage current

$$I \propto e^{-\frac{E_{gap}}{kT}}$$



- Compare signal with leakage current
- During charge collection the *fluctuation* causes noise

$$ENC = \sqrt{I_{leak} t_{collect}}$$

Noise

- Expressed in Equivalent Noise Charge
- Leakage current induced

$$= \sqrt{t_{\text{integration}} \cdot I_{\text{leak}}}$$

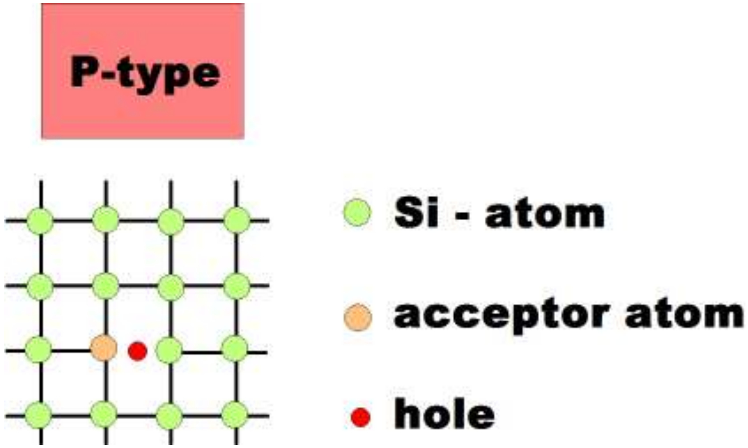
- Amplifier ~ Capacitance (ENC = a + bC)

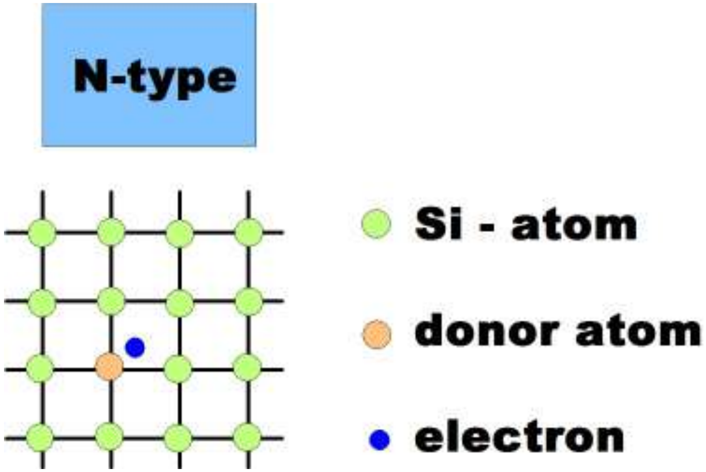
$$C_{\text{typical}} = \frac{\varepsilon A}{d} = \frac{12 \cdot 8.85 \cdot 10^{-14} \cdot A}{300 \cdot 10^{-4}} \left(\text{F}\,\text{cm}^{-1}\text{cm}^{2}\text{cm}^{-1}\right)$$

$$C_{\text{area}} = 0{,}35\ \text{pF/cm}^2$$

PN junction

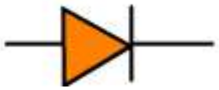
- Intrinsic silicon too much impurities
- Introduce doping
- P-type with type-III acceptors like Boron
- N-type with type-V donors like Phosphor
- Both types are electrically neutral !

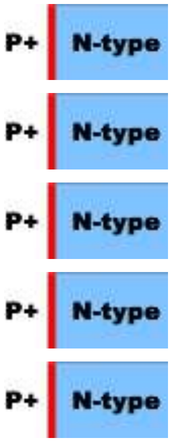


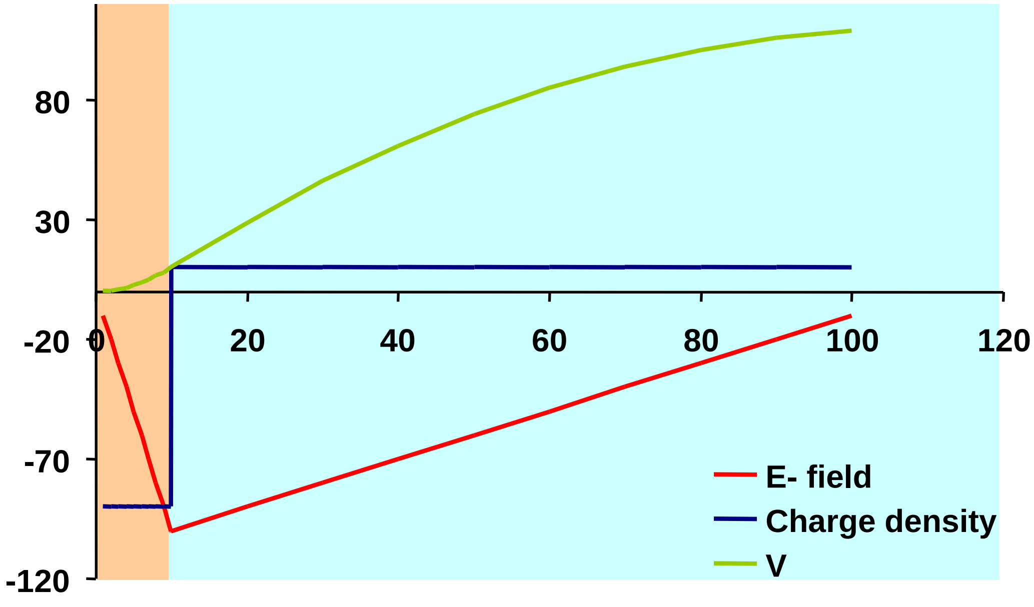


PN junction

- Sensors: small layer high concentration on thick bulk low concentration
- Diffusion leads to potential barrier







$$\frac{dV(x)}{dx^2} = \frac{\rho(x)}{\varepsilon_0 \varepsilon}$$

$$E(x) = \frac{-dV(x)}{dx}$$

$$\rho(x) = \begin{cases} -eN_D & \text{for} \quad x < 0 \\ eN_A & \text{for} \quad x > 0 \end{cases}$$

$$E(-a) = E(b) = 0$$

$$V(-a) = 0$$

$$V(b) = V_{bias}$$

$$\left(aN_A = bN_D\right)_{x=0}$$

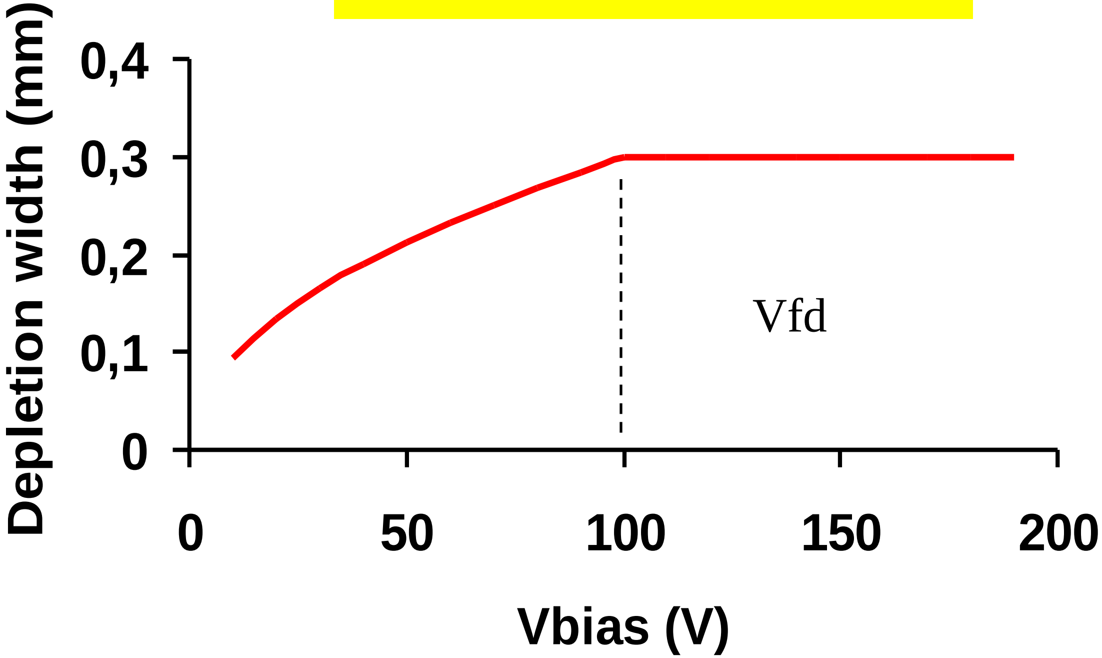
$$\frac{dV(x)}{dx} = \begin{cases} -eN_D(x+a) & \text{for} \quad x < 0 \\ eN_A(x-b) & \text{for} \quad x > 0 \end{cases}$$

$$V(x) = \begin{cases} -eN_D(x+a)^2 & \text{for} \quad x < 0 \\ eN_A(x-b)^2 & \text{for} \quad x > 0 \end{cases}$$

$$\text{depletion width} = a + b \approx b$$

Depletion region

$$\mathrm{width} \propto \sqrt{V_{\mathrm{bias}}}$$



Charge collection speed

$$v = \mu \cdot E$$

$$\tau = \frac{v}{d} = \frac{\mu \cdot E}{d}$$

$$\mu_{hole} = 450 \text{ cm/(Vs)}$$

$$\mu_{electron} = 1500 \text{ cm/(Vs)}$$

$$\mathrm{d}_{\mathrm{typical}} = 300\ \mu\mathrm{m}$$

$$\mathrm{V}_{\mathrm{depletion}} = 100 \text{ V}$$

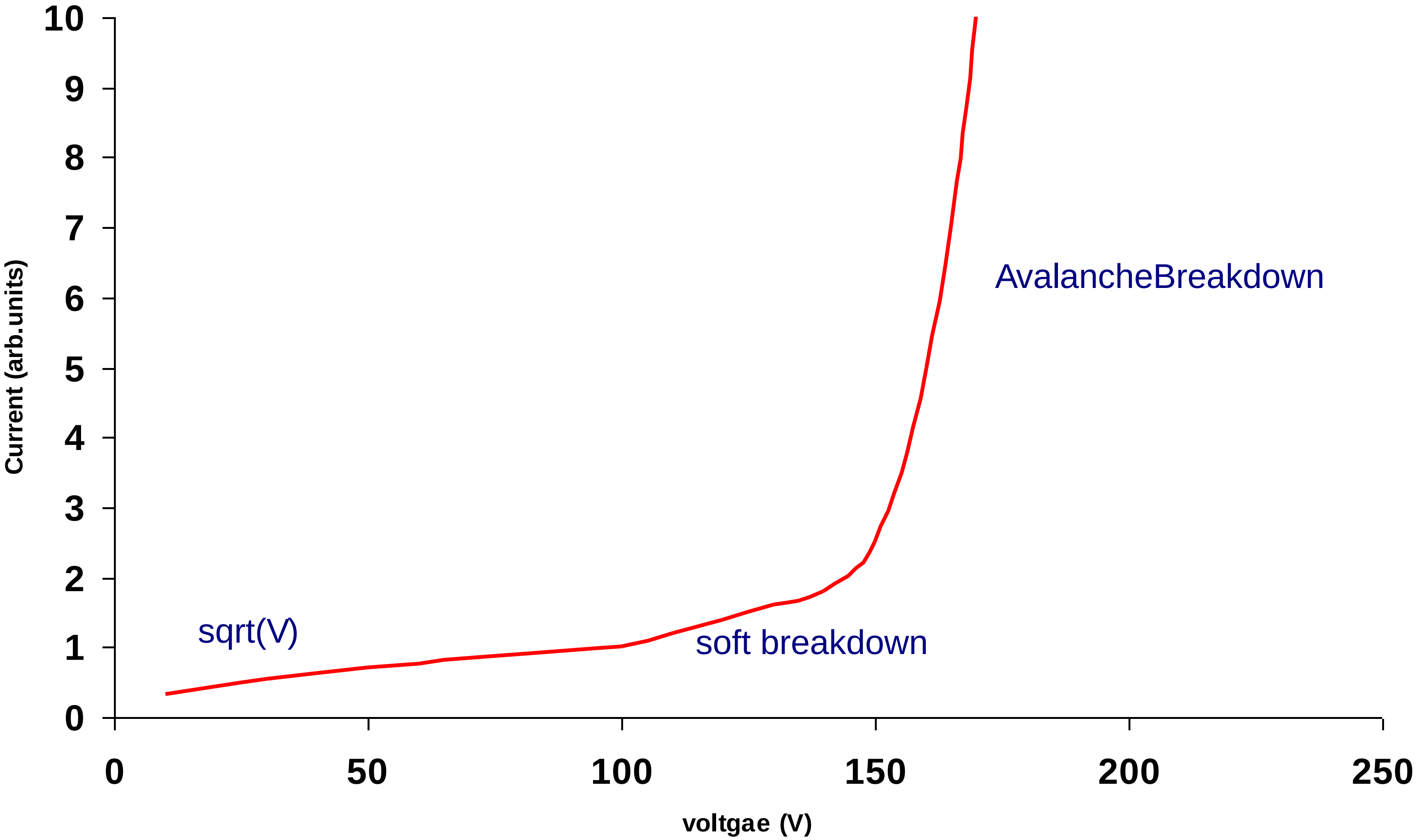
$$\mathrm{E}_{\mathrm{average}} = 3 \cdot 10^{3} \text{ V/cm}$$

$$\tau^{electron}_{collect} = 15 \text{ ns}$$

$$\tau^{hole}_{collect} = 50 \text{ ns}$$

Compare with time of particle passing detector !

Leakage current



Principle of production

- Make wafer from monocrystals
  - Low resistivity for micro electronics
  - High resistivity for sensor material
- lithography process
  - Make diodes, capacitances, resistors and transistors
- State of the art
  - PMOS, NMOS, CMOS
  - Size transistor 65 nm

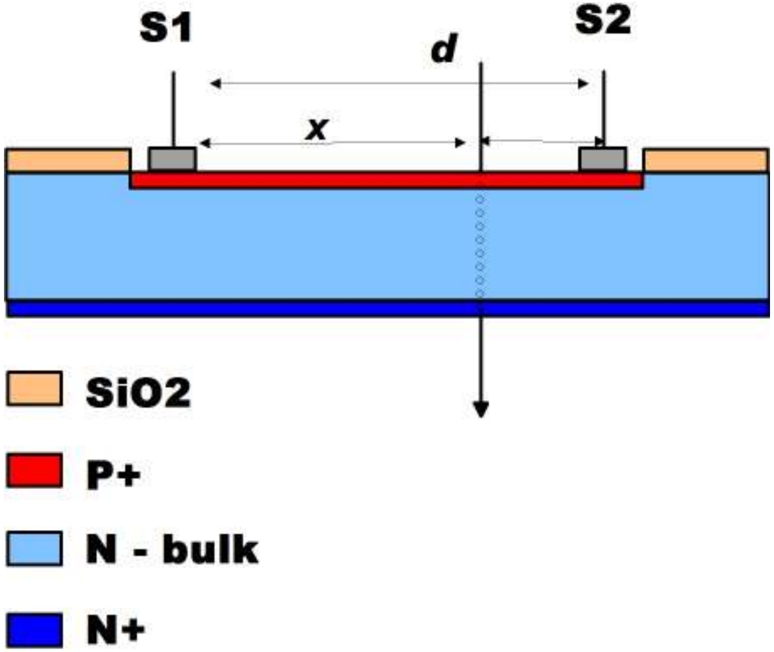
Silicon strip detector

- Array of P+ implants in N-type silicon
  - Large area sensors with diameter up to 20 cm
  - Strips several centimeters long,
  - Implants 10-20 micron wide
  - Pitch around 20-200 micron
- Strips connected to low noise amplifiers
- Double sided sensors give 2(3) coordinates
- Drift detector also 2(3) coordinates
- Charge collection -> see examples

Resistive Charge Division

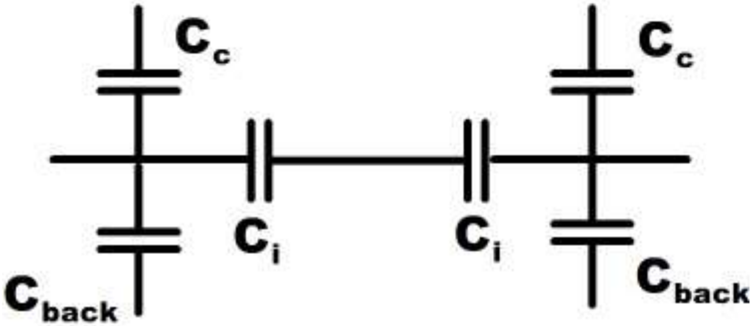
- Generated charge is divided over S1 and S2
- Reconstructed position:

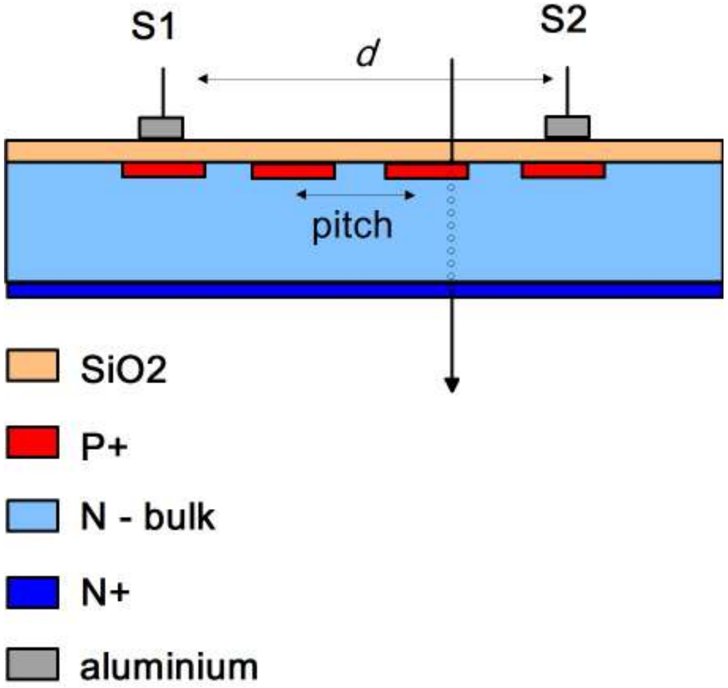
$$x_{impact} = \frac{Q1 \cdot x1 + Q2 \cdot x2}{Q1 + Q2}$$



Capacitive Charge Division

- Example: in a first order approximation the charge is distributed:
  - Charge on S1 =1/3
  - Charge on S2 =2/3
- Better prediction with equivalent scheme:



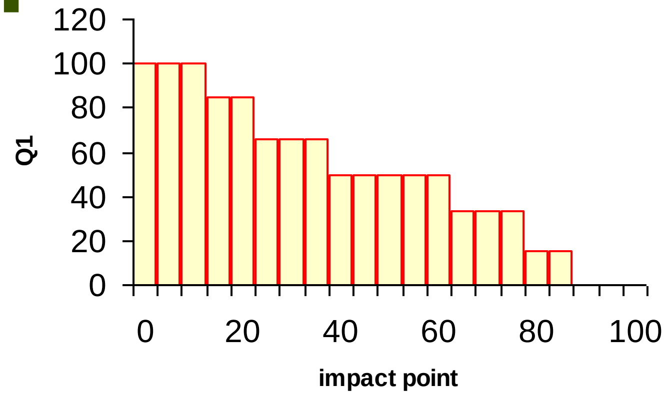


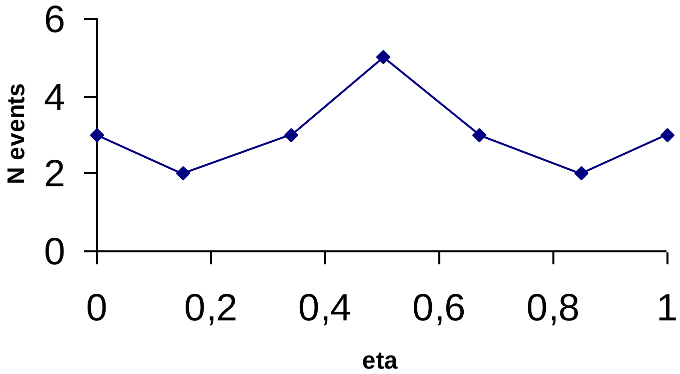
Charge distribution

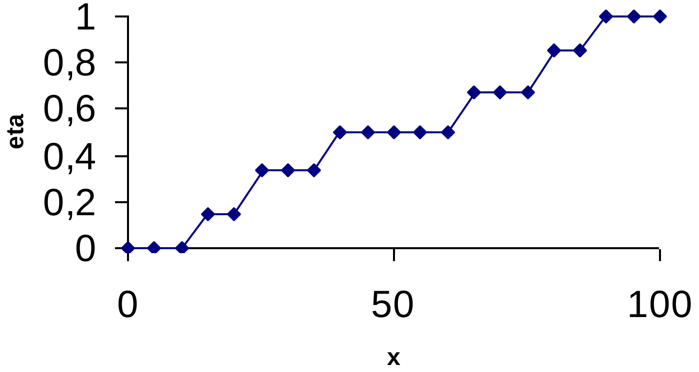
- Relate charge (Q) and impact point (x)

$$\eta = \frac{Q1}{(Q1+Q2)}$$

$$x(\eta_0) = \frac{1}{N}\int_0^{n0} \frac{dN}{d\eta}$$







Resolution

- Depends on signal to noise ratio
- With binary puls information:

$$\sigma = \text{pitch}/\sqrt{12}$$

- State of the art
  - Strip detectors: few micron
  - Pixel detectors: few tens of microns
  - CCD:micron

Radiation hardness

- Incoming particles are also destructive
- Non Ionising Energy Loss (NIEL) induced by all particles except photons and electrons (although not impossible)

  Referred to as bulk damage

- Ionisation in the oxide by all ionising particles

  Referred to as surface damage

Bulk Damage

- MECHANISM
  - Nuclear reactions
  - Knock silicon atom out -> vacancy
  - Intermediate levels in energy diagram
- EFFECT
  - Bulk leakage increases
  - Charge trapping
  - Effective donor removal leading to different depletion voltage
- Protection
  - Material Engineering, design

Surface Damage

- MECHANISM
    - Ionisation in the oxide
    - Charge build up in oxide due to low hole mobility
    - Electron accumulation in silicon underneath
- EFFECT
    - Leakage paths inside components (transistors)
    - Changing (interstrip) capacitance
- Protection
  - Design, technology

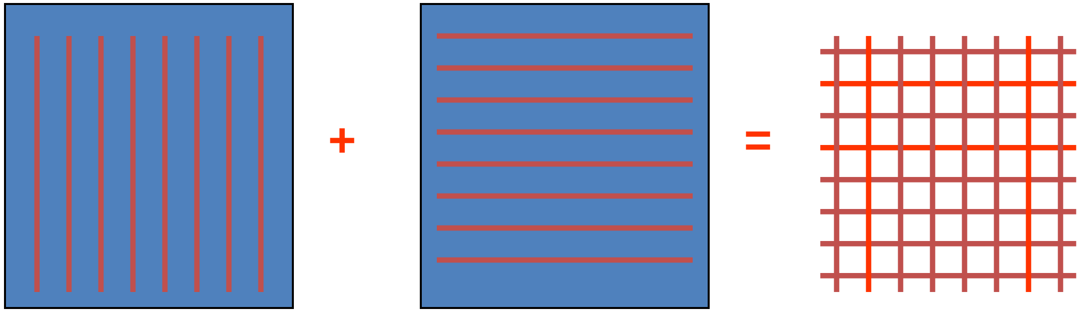
Resolution

- Momentum measurement improves as
  - Lever arm increases
  - Magnetic field increases
  - number of points increase/point resolution decreases
- Vertex measurement improves as
  - number of points increase/point resolution decreases
  - extrapolation length decreases
  - multiple scattering decreases

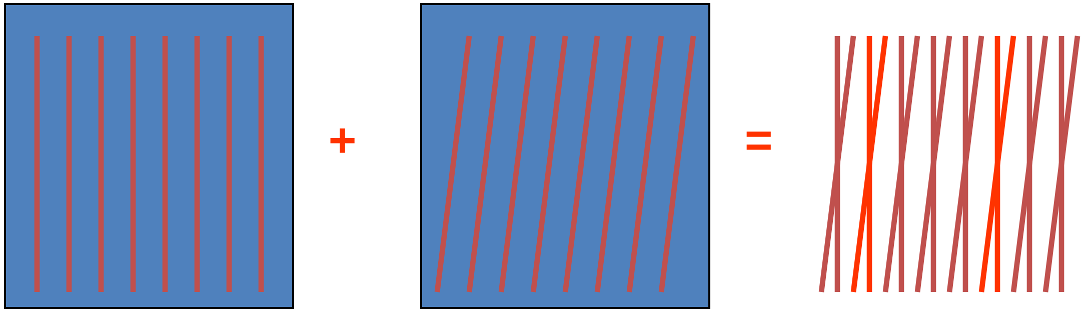
Some Examples

STRIP		
	past	Tevatron,HERA (Hamburg)
	existing	Atlas & CMS at LHC (Geneva)
PIXEL		
	Past	DELPHI at LEP (Geneva)
	existing	CMS & ATLAS at LHC (Geneva)
CCD		
	Past	SLD at SLAC (California)
	existing	Xray imagers
CMOS, DEPFET,…		
	Future	Xray imagers

Ghosthits or ambiguities



Two hits give 4
candidate crosses



Small stereo angle
Gives only two
combinations

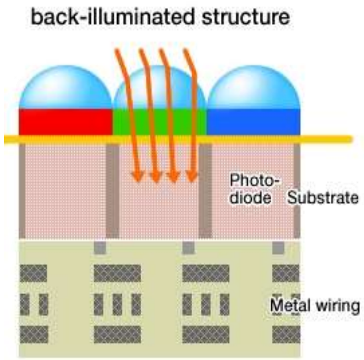
Pixel Detectors!

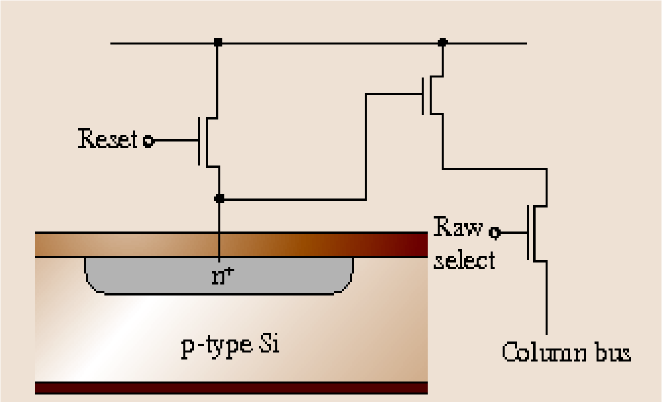
exp	num layers/ disks	num pixels	area	tech	timescale
atlas current	3 / 3	80M	50x400	hybrid, planar	operating 2009-
atlas IBL			50x250	hybrid, planar+3D	installing 2015
atlas upgrade			25x125?		design 2023
CMS					operating 2009-
CMS upgrade			25x125?		design 2023-
LHCb upgrade	0 / 26, 0.8% X0	41 M	55x55		design 2019
Belle II	2, 0.2% X0	7.6 M	50x55 – 50x85	depfet	installing
Alice current					
Alice upgrade					
ILC					design

Panda = hybrid planar 100x100 um
Star = MAPS (Mimosa)

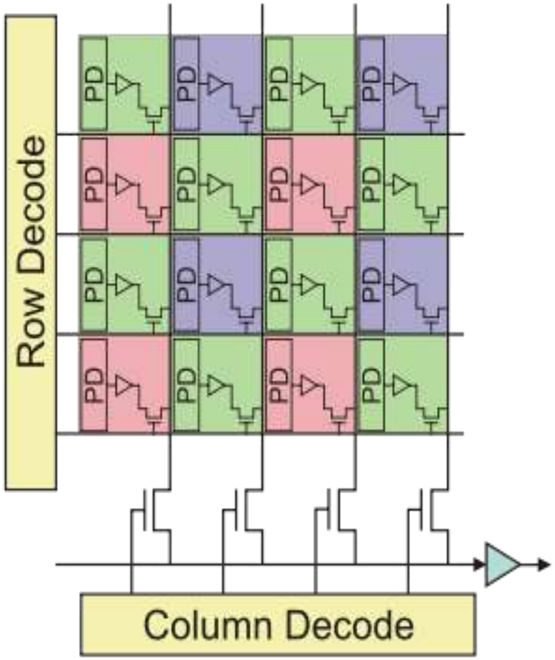
Use a camera for tracking?

- E.g. iphone5 camera has 8 Mpixels, ~ 1.5 μm pixel size
- It does detect charged particles
- inefficient
- slow (full frame readout)
- not radiation hard





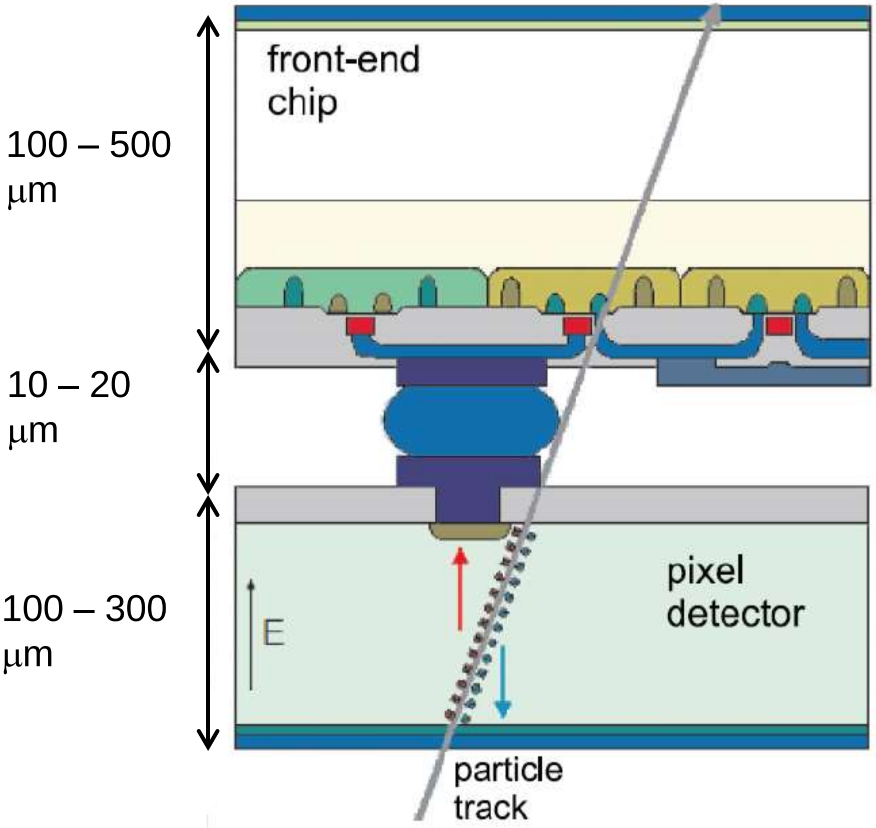
Courtesy of Springer

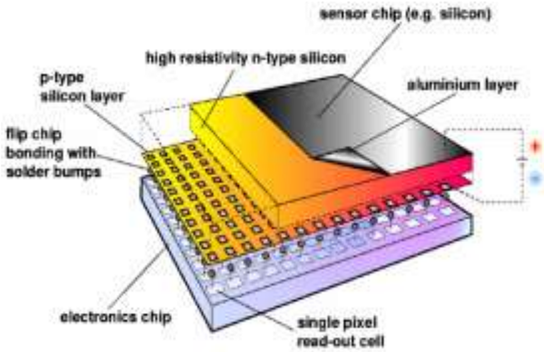


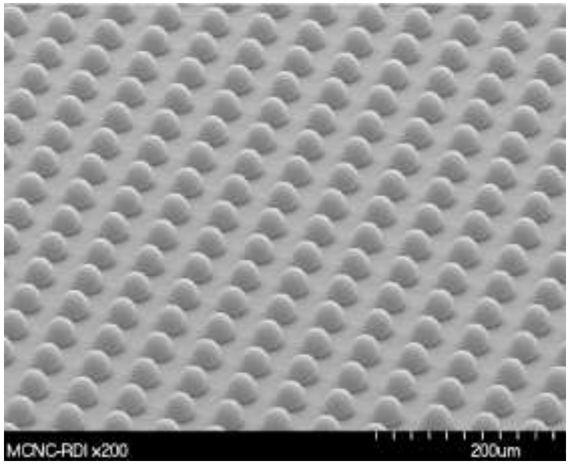
Detecting radiation with a 30 € webcam

Hybrid pixel detector

- High ohmic silicon sensors (few kΩ cm) bump-bonded to readout ASIC
- Typical electronics noise 100 e^- RMS







Courtesy of Michael Campbell (CERN)

ASIC technologies

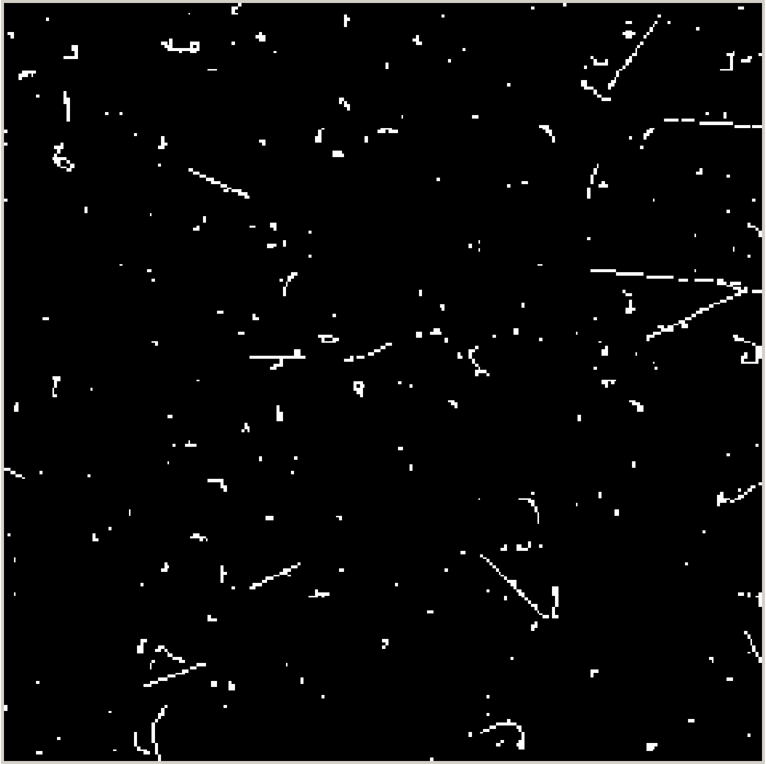
- We don’t use the latest technology
  - long time to develop complete pixel readout ASIC
  - but also availability of technology and $$$
- Current LHC experiments:
  - mostly 250 nm CMOS
  - Upgrades for 2018-2019: mostly 130 nm CMOS
  - Upgrades for 2023-2024: most likely 65 nm CMOS

Timepix3 with 256 x 256 pixels
- 1.6 ns time resolution
- 80 Mhits/s
- 130 nm CMOS, 170 M transistors
- Developed by CERN and Nikhef

Medipix chips

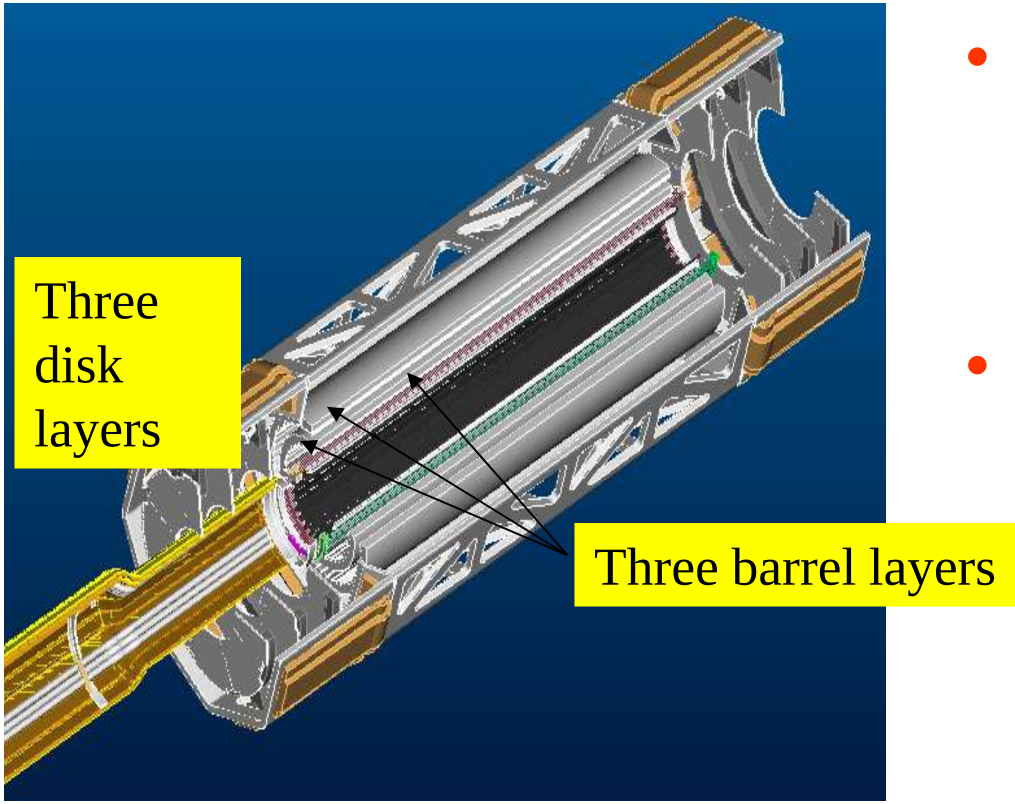
- Medipix1 (1 µm)
  - First attempt in late 1990s to take HEP results to other applications
- Medipix2 (0.25 µm)
  - Started in 1999 and still going strong!
  - First commercial application at PANalytical in x-ray diffraction field
- Timepix (0.25 µm)
  - Time of Arrival and Time over Threshold with a resolution of 10 ns (2006)
- Medipix3RX (0.13 µm)
  - New generation (2010), solving charge sharing issues
  - Multiple energy thresholds
- Timepix3 (0.13 µm)
  - Better time resolution of 1.6 ns and simultaneous ToA & ToT
- Medipix4 and Timepix4 (65 nm)
  - Specifications under discussion

Frames vs events



- Imaging
  - Medipix in principle reads all pixels in a frame (what you want in an image)
- Vertexing detectors
  - Few pixels every event

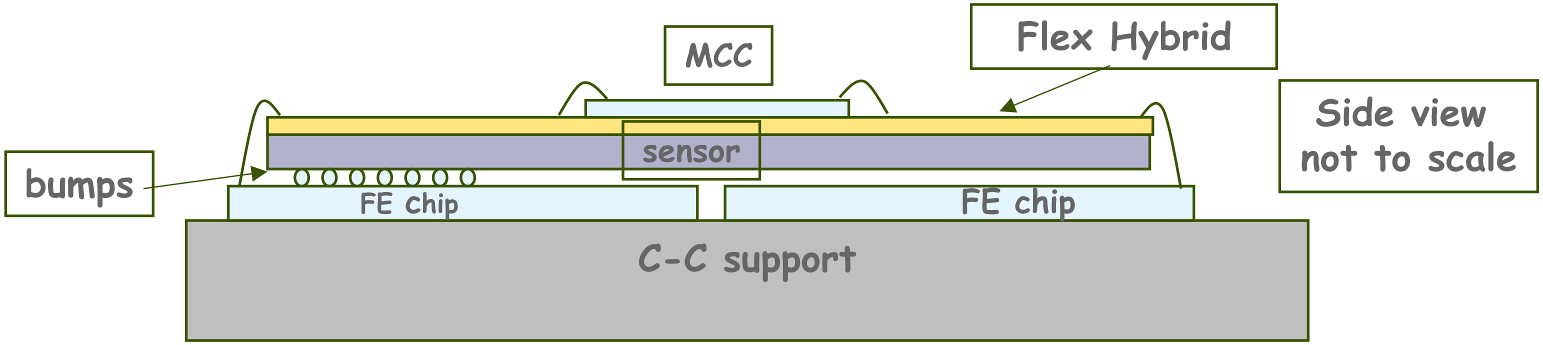
The ATLAS Pixel Detector

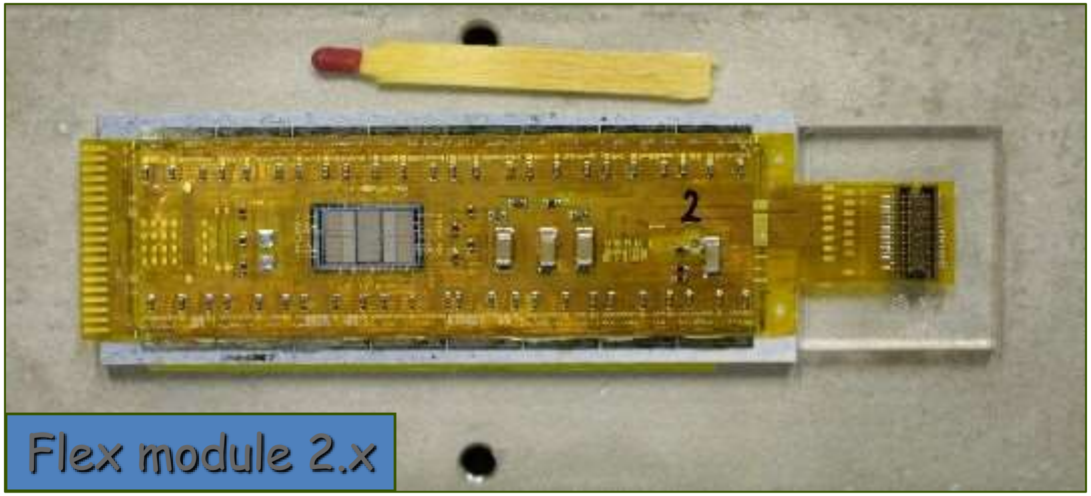

Three disk layers

Three barrel layers

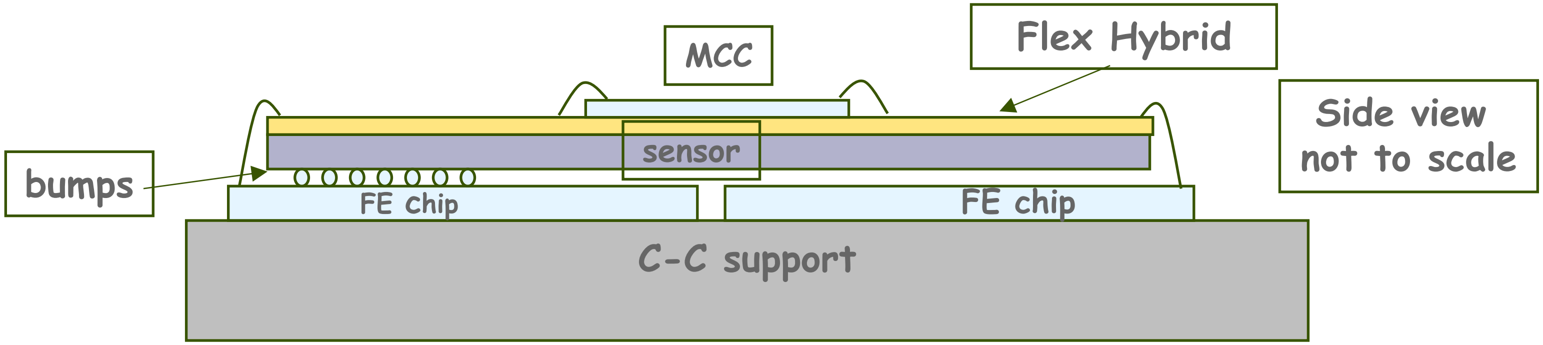
- ~2.0 m^2 of sensitive area with 0.8 × 10^8 channels
- 50 μm × 400 μm silicon pixels (50 μm × 300 μm in the B-layer)

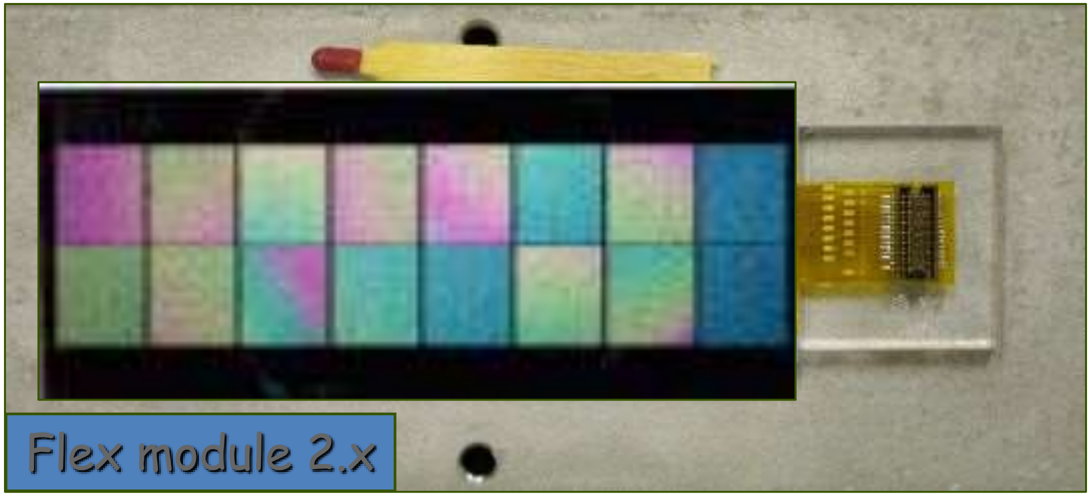
Atlas pixels



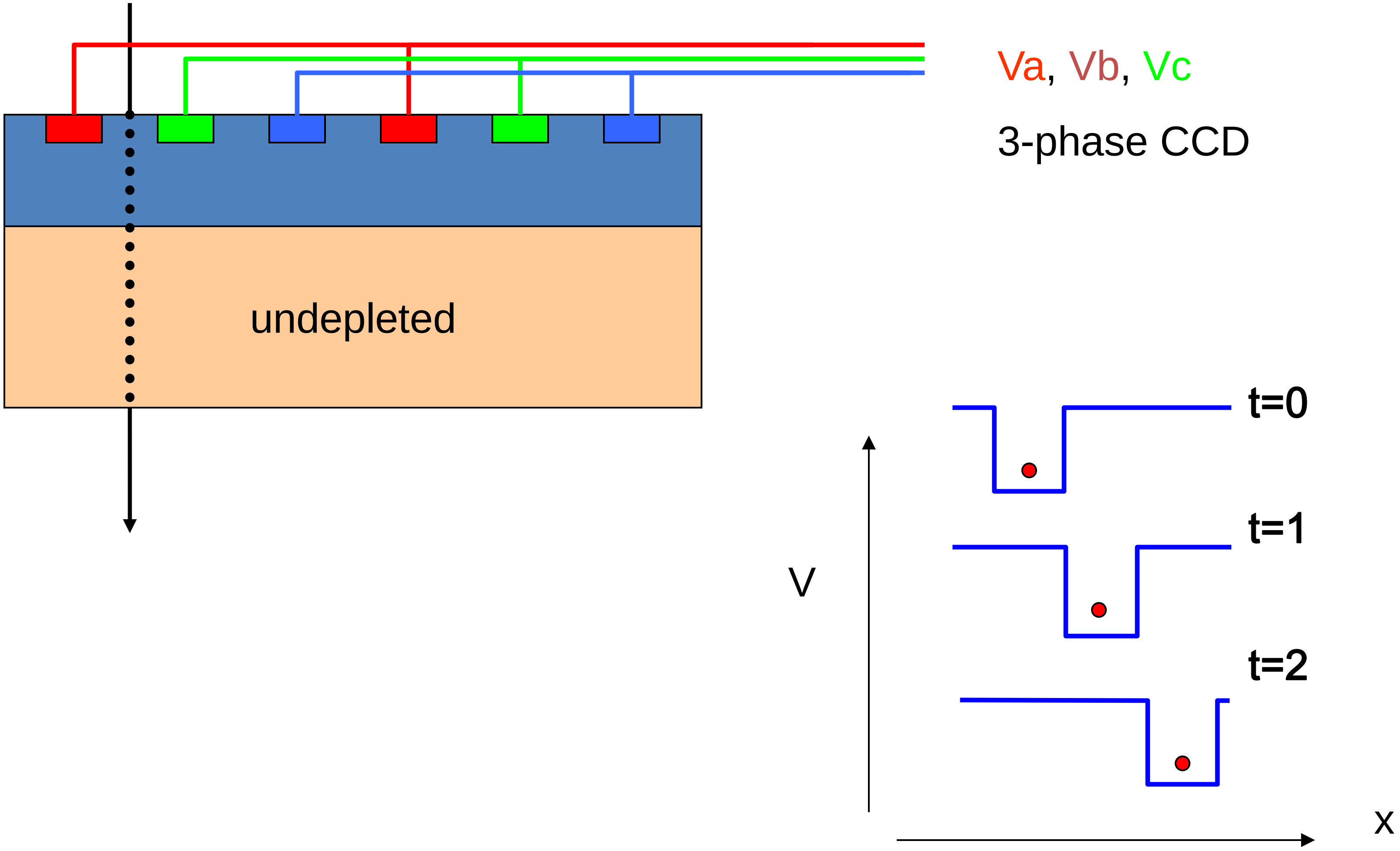


Atlas pixels





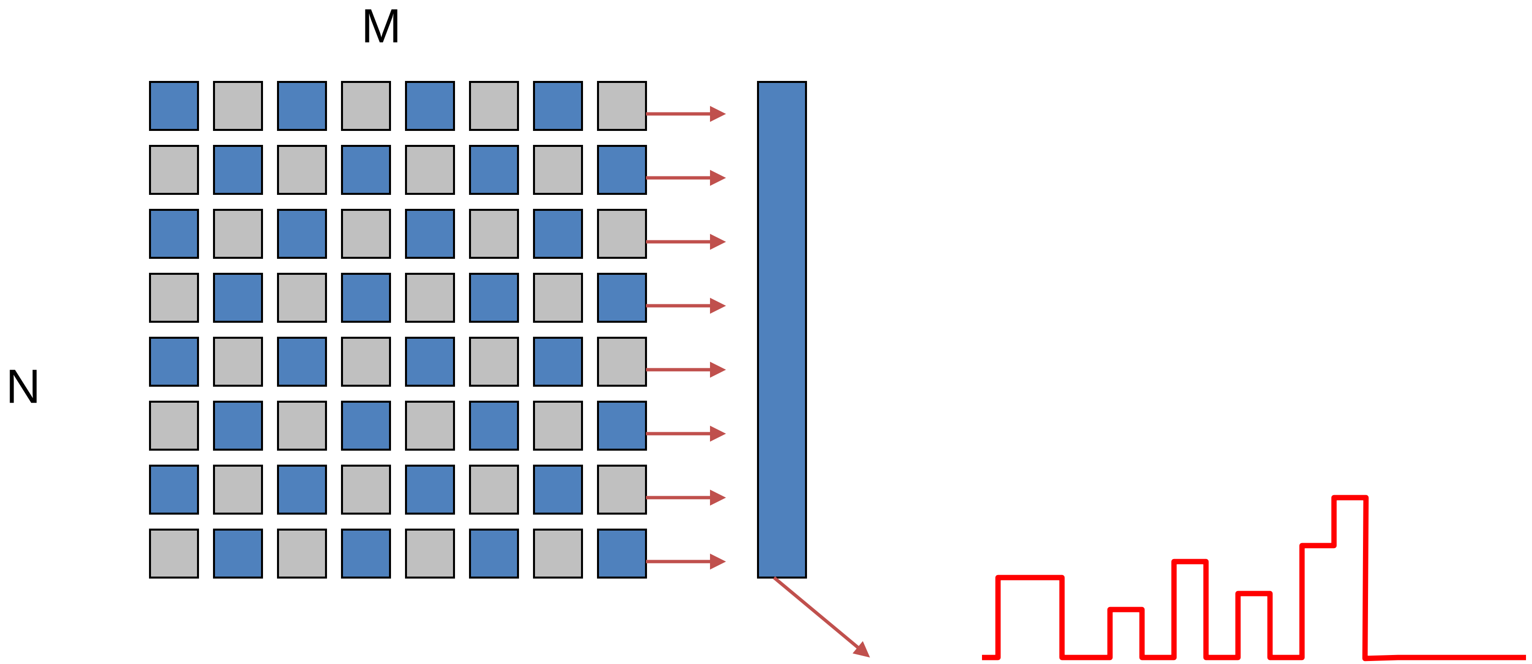
CCD detector



Va, Vb, Vc

3-phase CCD

CCD detector



Charge shifted out serially: total readout time is

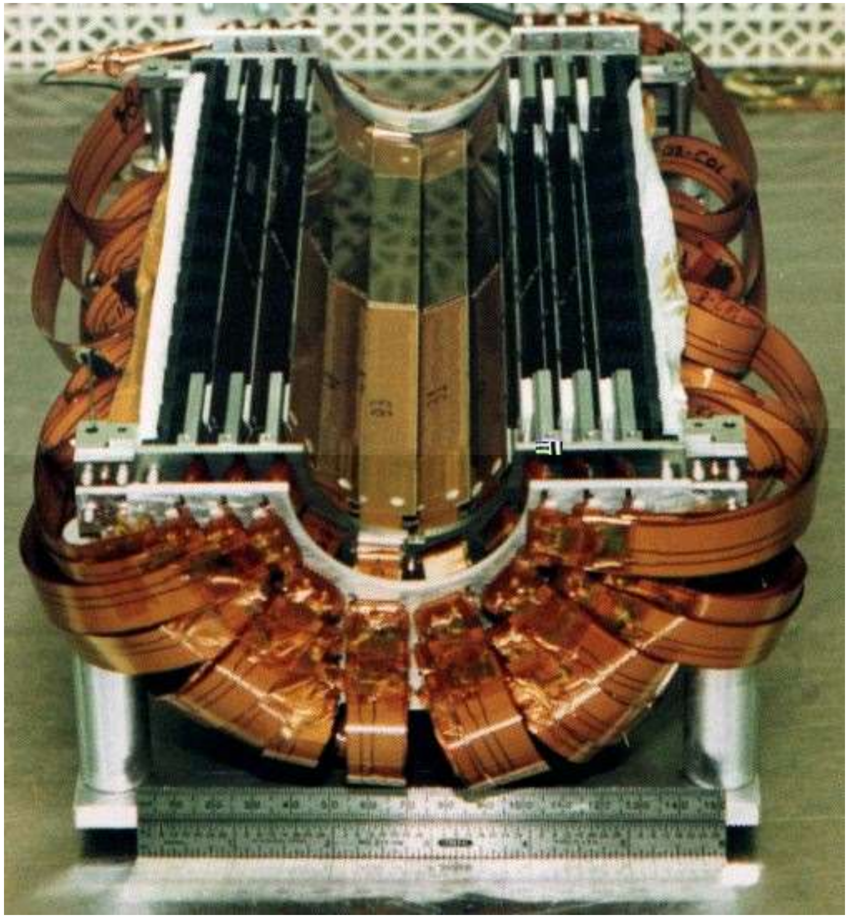
N x M x clock cycle….slow!

SLD at SLAC

- 3 concentric layers
- cells 20 x 20 μm^2
- 307 M pixels
- Point resolution 4 μm

$$\sigma(\mathrm{IP}) = 7.8\,\mu\mathrm{m} \oplus \frac{33}{p \sin^{\frac{2}{3}} \theta}$$

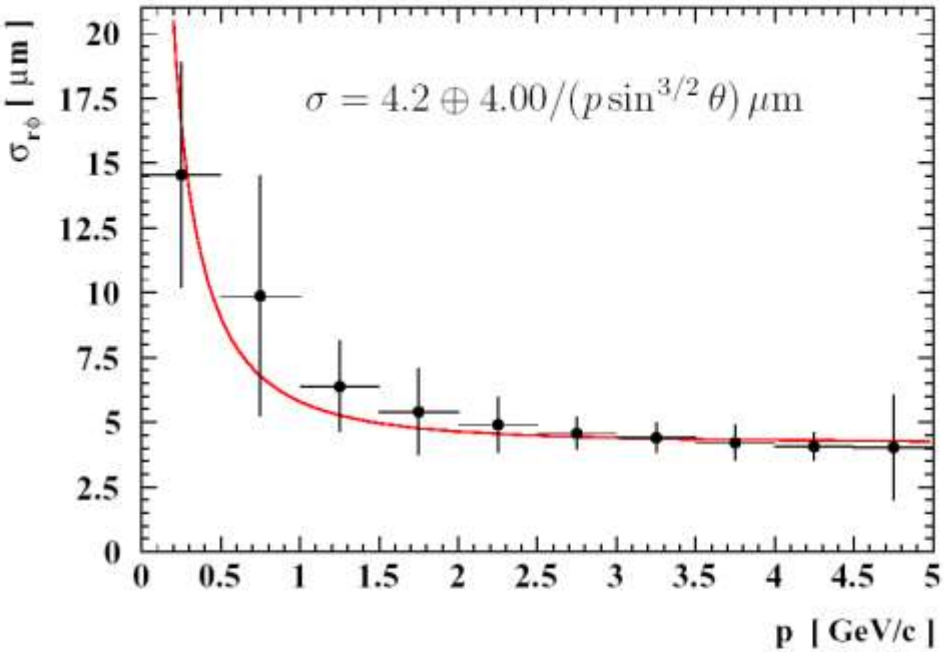
- “VXD3” operational from 1996
- Readout time 180 ms!



Future tracking : ILC

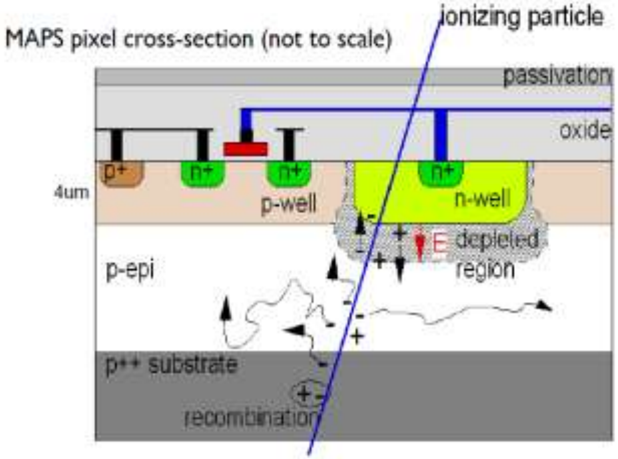
- Impact parameter resolution depends on point resolution and multiple scattering

$$\sigma = \sqrt{a^2 + \left(\frac{b}{p\sin^{\frac{3}{2}}\theta}\right)^2}$$



Monolithic active pixels

- Based on standard available CMOS processes
- Monolithic -> one foundry -> cheaper
- Lower power
- Lower mass
- But also less radiation hard
- Applied in many non-LHC particle physics experiments



Depfet (Belle)

Amplifying transistors in a **fully depleted** bulk

Internal gate forms **potential minimum for e^-**

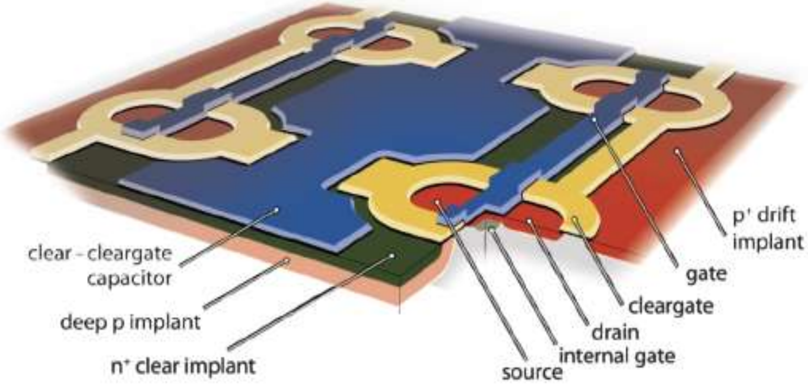
Stored charge **modulates the channel current**

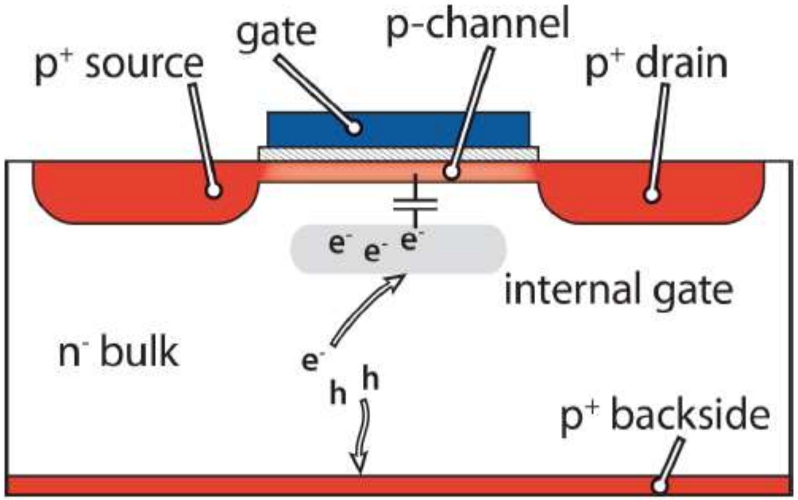
Small intrinsic noise: ~50 nA

Sensitive in the off-state: much reduced power consumption

Internal amplification: $g_q \approx 0.5$ nA/e^-

Charge has to be removed "properly and fast" from the internal gate





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