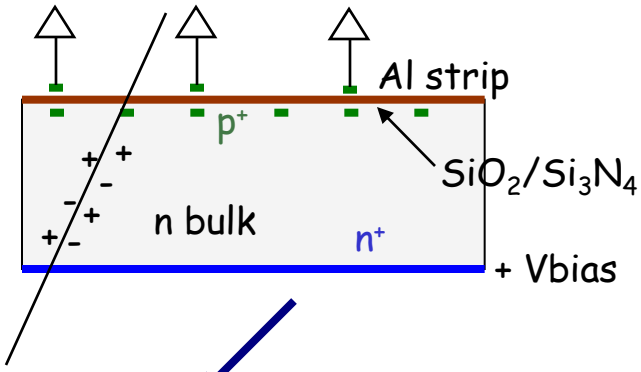
Silicon Detector "Basics"

- The Rise and Rise of silicon in HEP
- Why silicon?
  - Basic principles & performance
  - More exotic structures; double sided, double metal, pixels…
  - Radiation Damage
- Real Life
  - Quality Control & Large Systems
  - Testbeams: what can you expect?
  - Operational experience

Silicon Trends

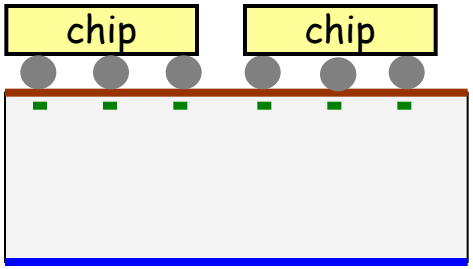
Basic idea



Start with high resistivity silicon

More elaborate ideas:

- n+ side strips – 2d readout
- Integrate routing lines on detector
- Floating strips for precision
- make radiation hard

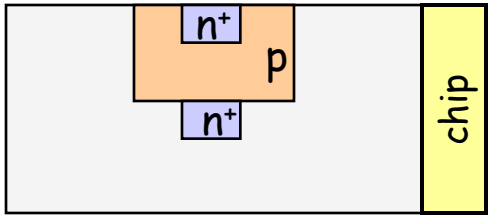


Hybrid Pixel sensors

Chip (low resistivity silicon)

bump bonded to sensor

Floating pixels for precision



DEPFET:

Fully depleted sensor

with integrated preamp

CCD: charge collected in thin layer

and transferred through silicon

MAPS: standard CMOS wafer

Integrates all functions

3d

integration

techniques

Historical Interlude

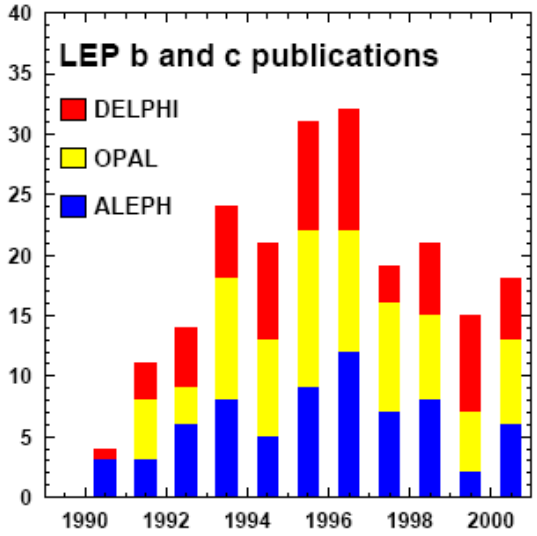
The LEP era

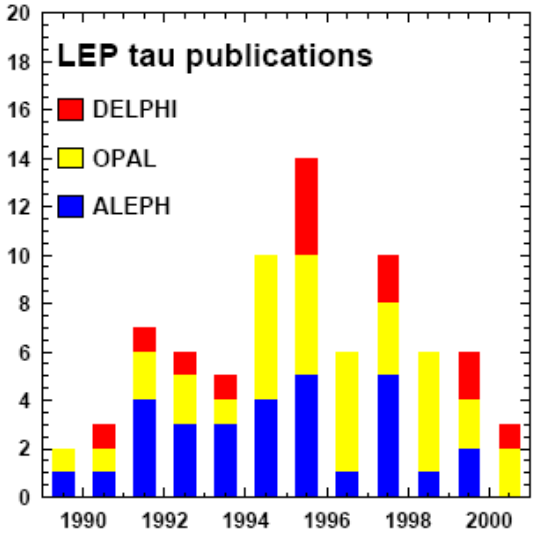
Singapore Conference, 1990

'The LEP experiments are beginning to reconstruct B mesons… It will be interesting to see whether they will be able to use these events'

Gittleman, Heavy Flavour Review

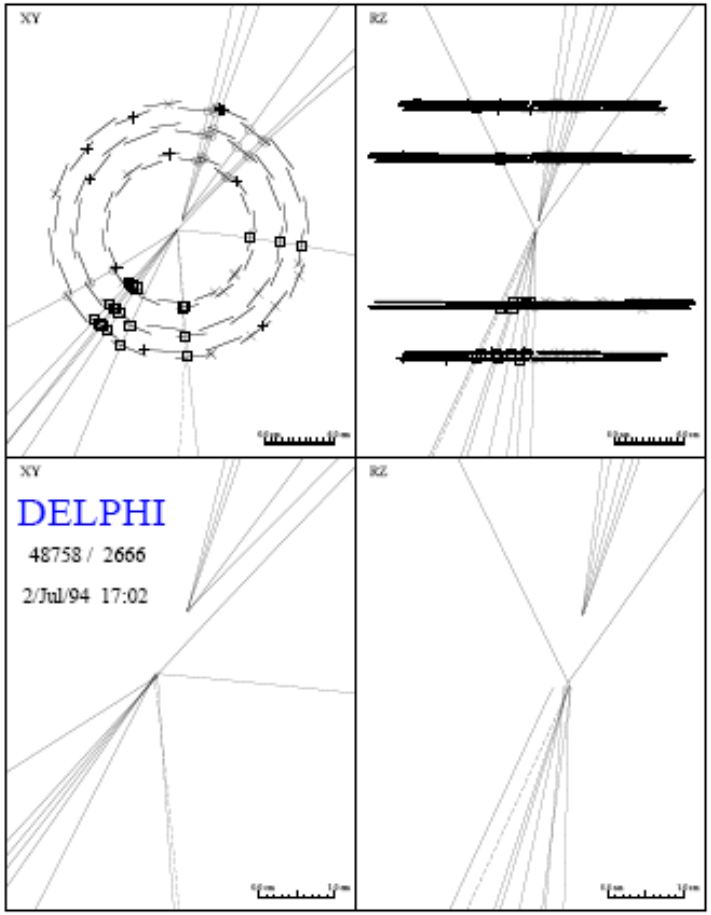
10 fun packed years later, heavy flavour physics represented 40% of LEP publications



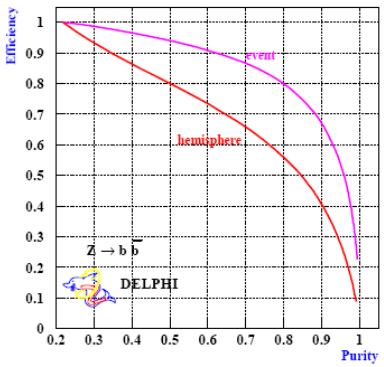


What did Vertex Detectors do?

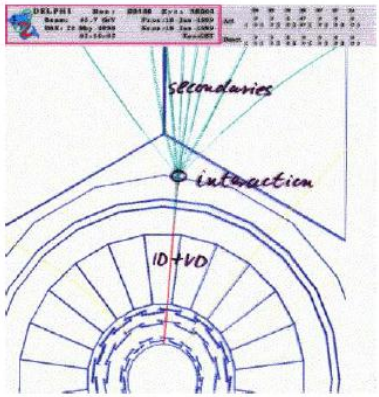
Reconstruct Vertices



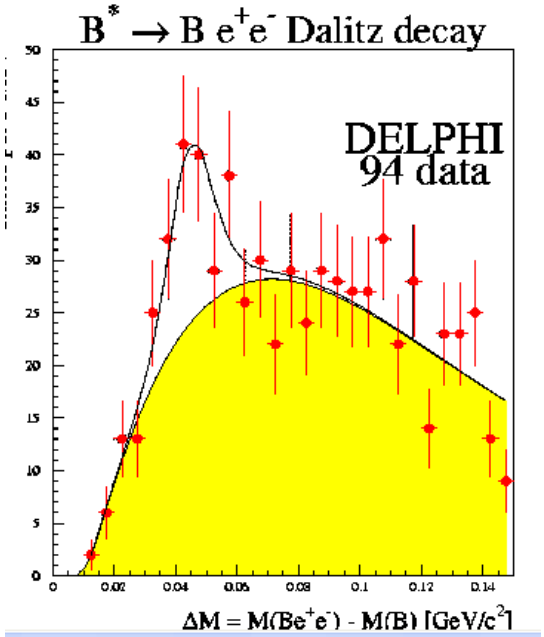
Flavour tagging



Some help in tracking

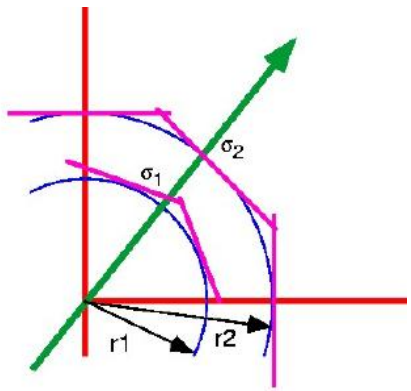


Even some dE/dx!



Vertex Detector Performance

Dependent on geometry

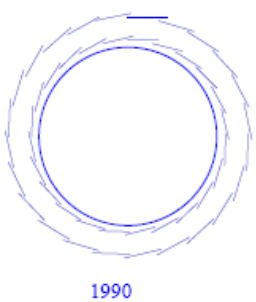


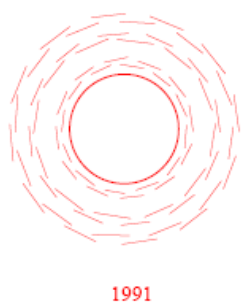
$$\sigma = \frac{r_2\sigma_1 + r_1\sigma_2}{(r_2 - r_1)^2}$$

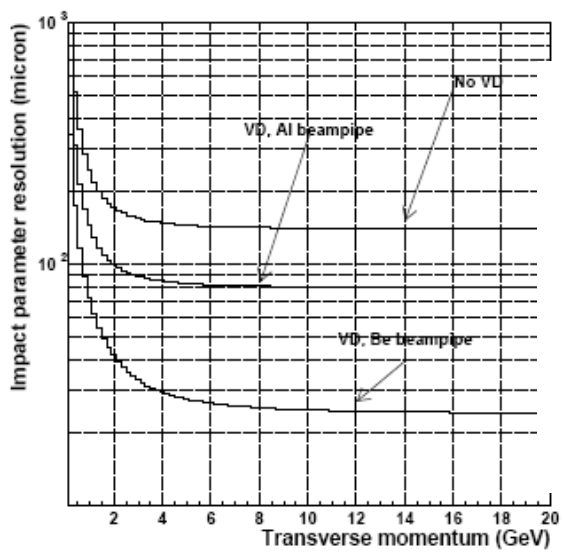
We want:

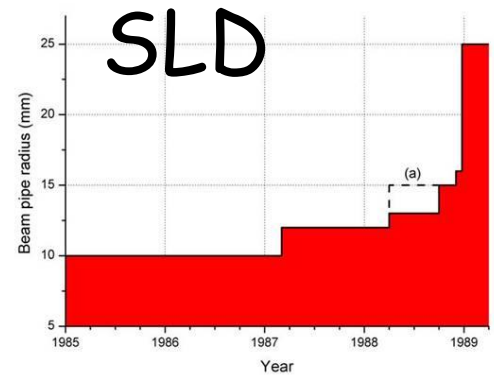
r_1 small, r_2 large, σ_1,σ_2 small

Hence the drive at LEP and SLD to decrease the radius of the beampipe and add more layers









Vertex Detector performance

And on multiple scattering

$$\sigma^2 = A^2 + \left(\frac{B}{p \sin^{3/2}\theta} \right)^2$$

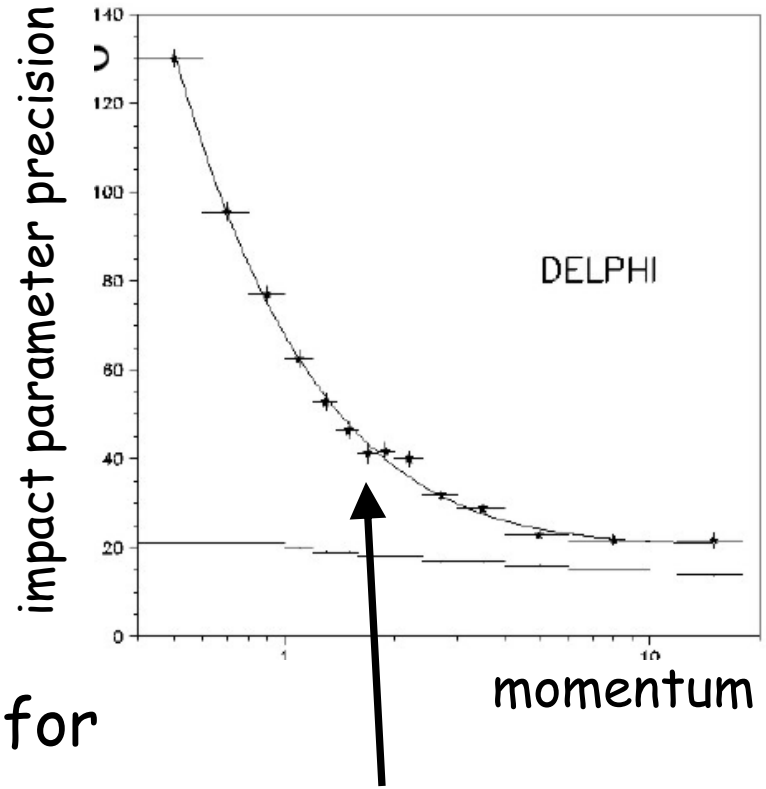
where

A comes from geometry and resolution

and

B from geometry and MS

On DELPHI, A=20 and B=65 μm



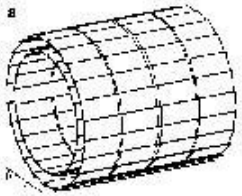
Hence the drive at LEP/SLD for

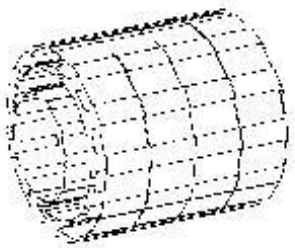
- Beryllium beampipe
- Double sided detectors
- super slim CCD's
- etc.

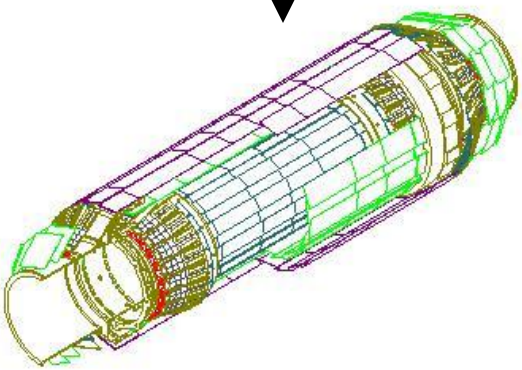
b physics is here!

LEP vertex detector timeline

1989, ALEPH & DELPHI
install prototype modules
1990, ALEPH & DELPHI
install first complete barrels
ALEPH read rz coordinate with "double sided" detectors
1991, all
Beampipes go from Al with r=8 cm to r=5.3 cm Be
DELPHI installs three layer vertex detector
OPAL construct and install detector in record speed
1992, L3
2 layer double sided vertex detector
1993, OPAL
install rz readout with back to back detectors
1994, DELPHI
double sided detectors and "double metal" readout
1996, DELPHI
install "LEP II Si Tracker" with μstrips, ministrips & pix

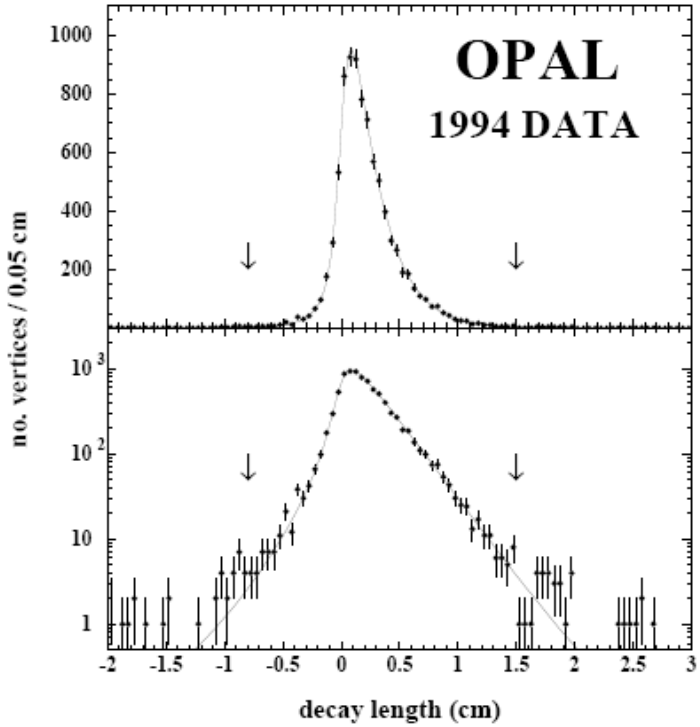


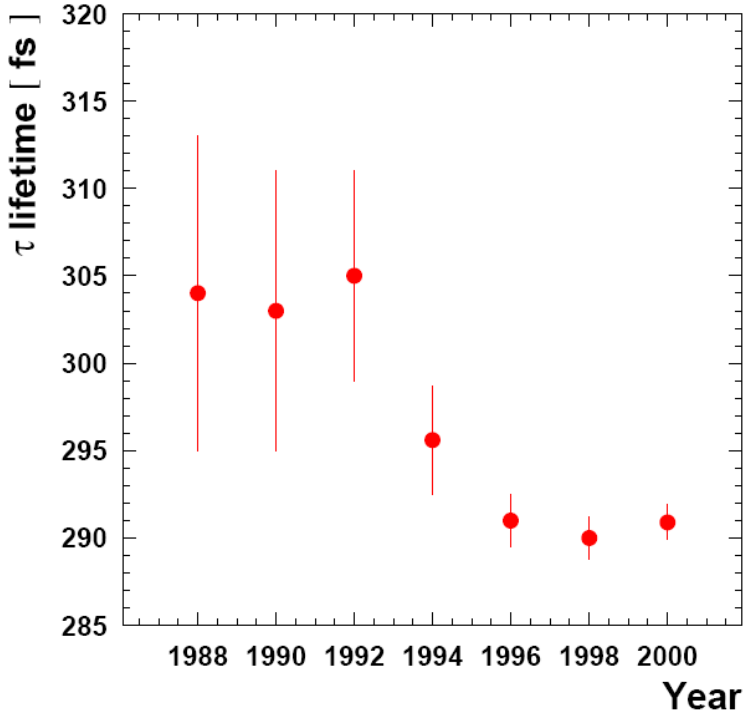




Impact on τ physics

A delicate measurement!

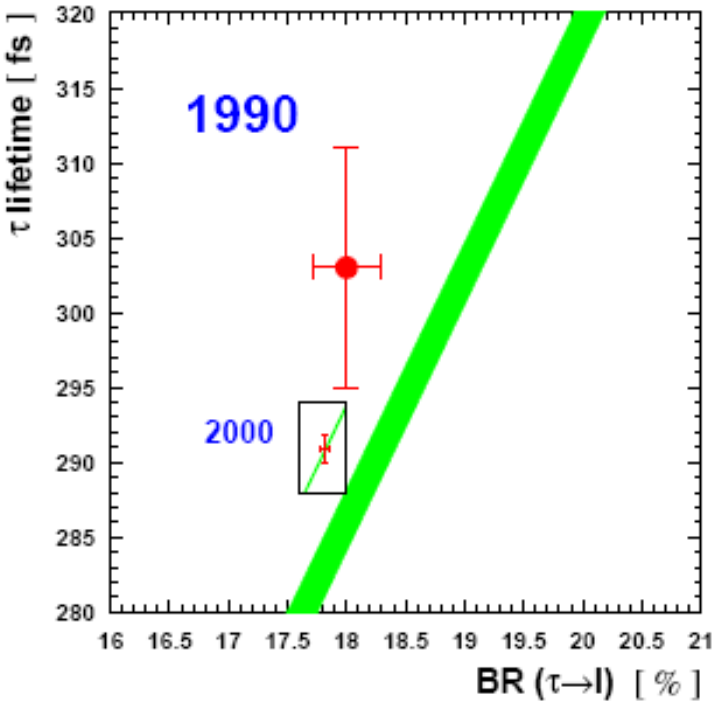


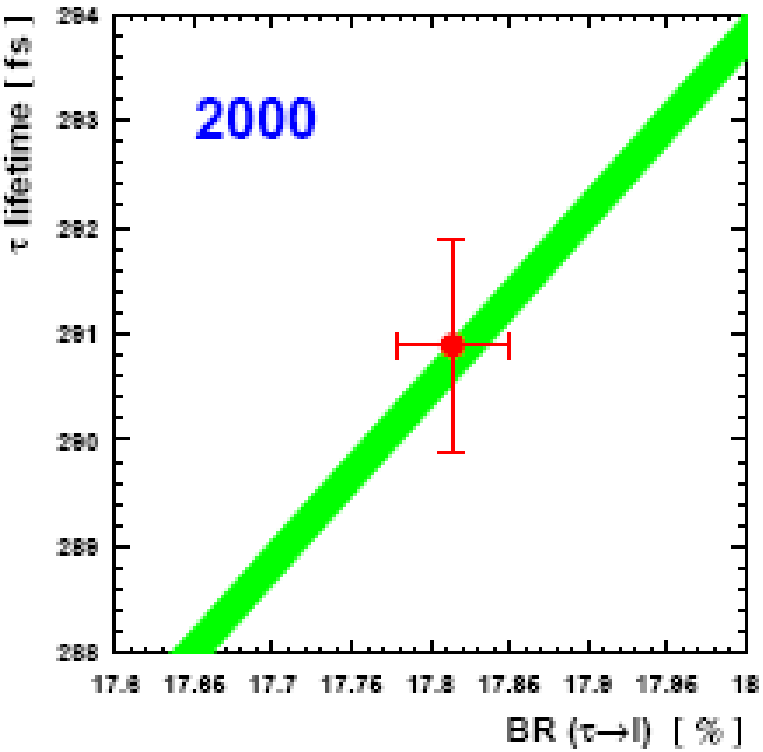


3 prong vertices

Impact on τ physics

Dawn of LEP…





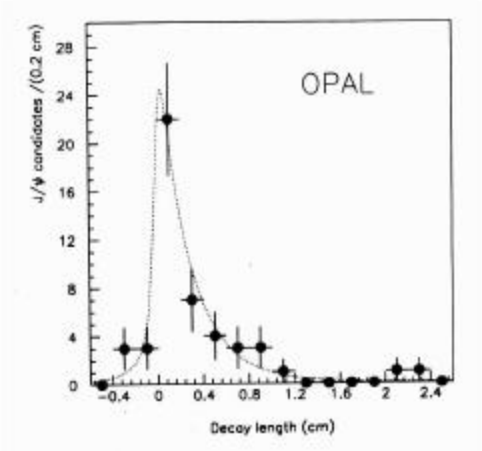
NB prediction also moved due to mτ – non LEP

Impact on b physics

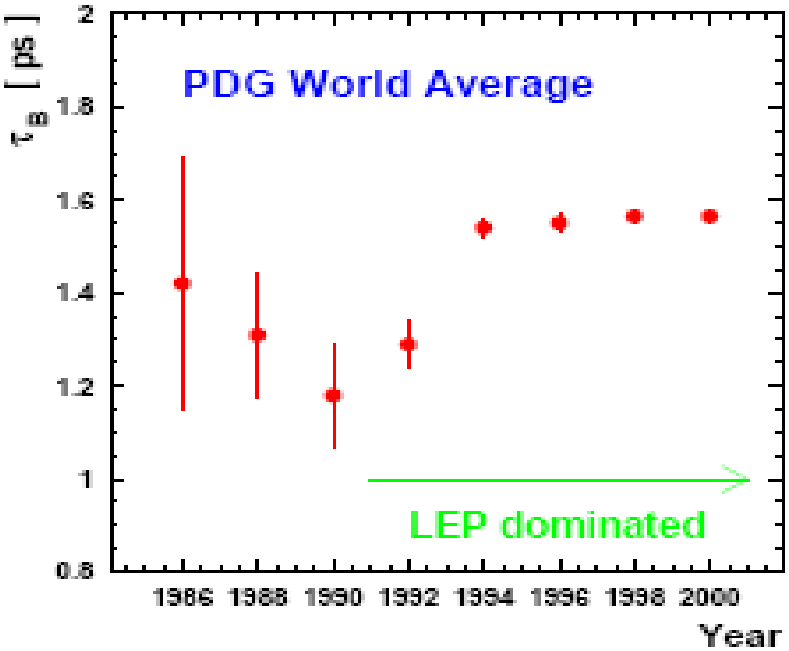
e.g. lifetimes:

Early measurements relied on

- o inclusive impact parameter methods
- o $B \longrightarrow J\psi X$



with, at first, some odd results



Also, a rich programme

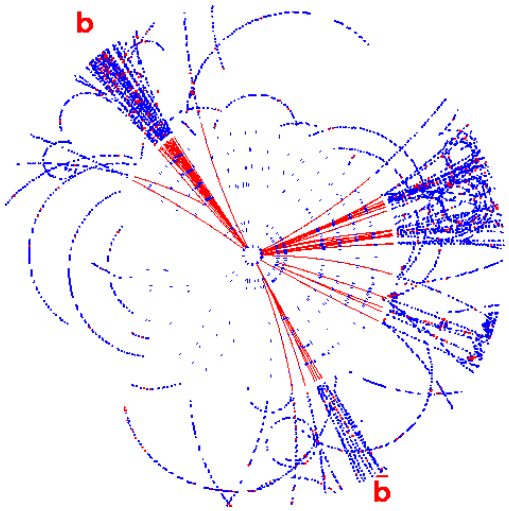
- lifetime heirarchy
- Bs observation
- spectroscopy
- baryons
- Z0 couplings
- mixing
- QCD
- CKM
- etc. etc.

The LHC Era: High Rates, High Multiplicity

at full luminosity $L=10^{34}$ cm^{-2} s^{-1}:

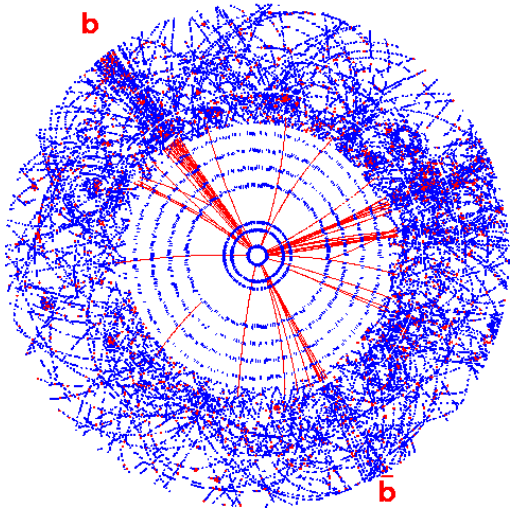
- ~23 overlapping interactions in each bunch crossing every 25 ns (= 40 MHz)
- inside tracker acceptance ($|\eta|<2.5$) 750 charged tracks per bunch crossing
- per year: ~5×10^{14} bb; ~10^{14} tt; ~20,000 higgs; but also ~10^{16} inelastic collisions
- severe radiation damage to detectors
- detector requirements: speed, granularity, radiation hardness

a H->bb event

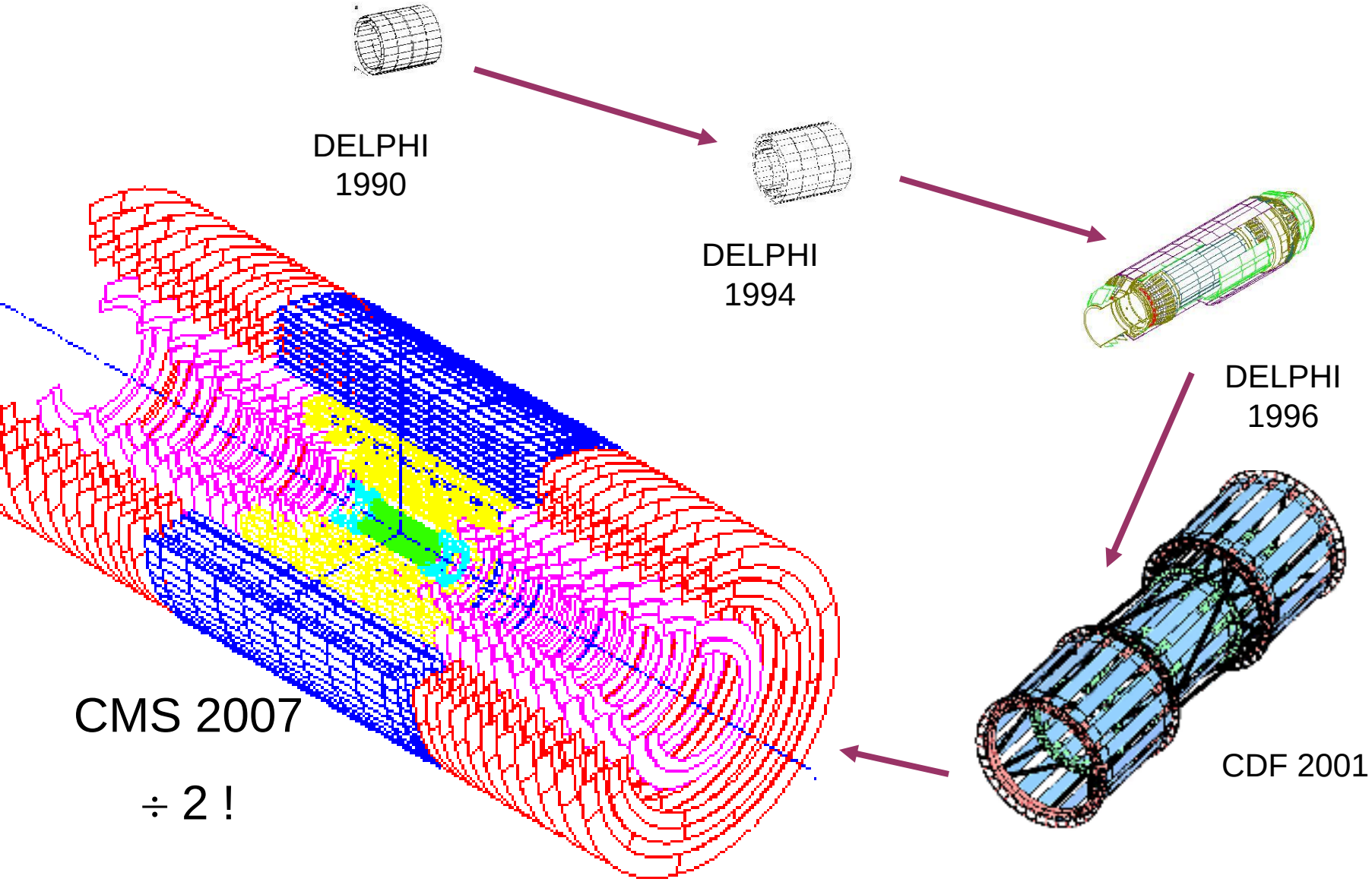


plus 22 minimum bias interactions

a H->bb event as observed at high luminosity



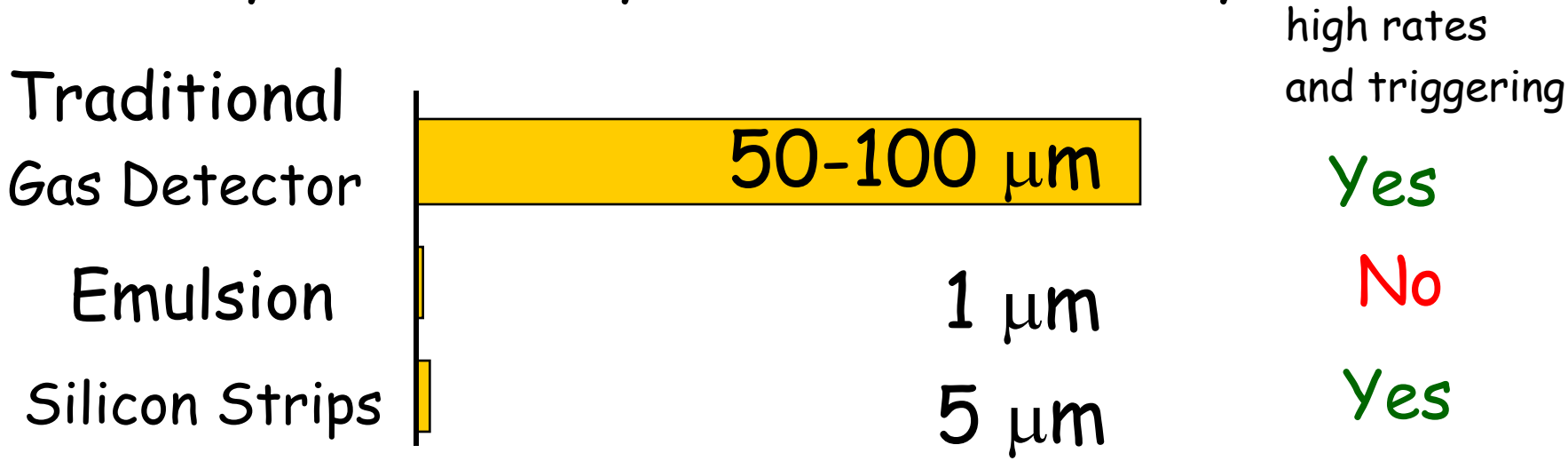
Large Systems



Sensor Basics

Why Use Silicon?

- First and foremost: Spatial resolution
- Closely followed by cost and reliability



★ This gives vertexing, which gives

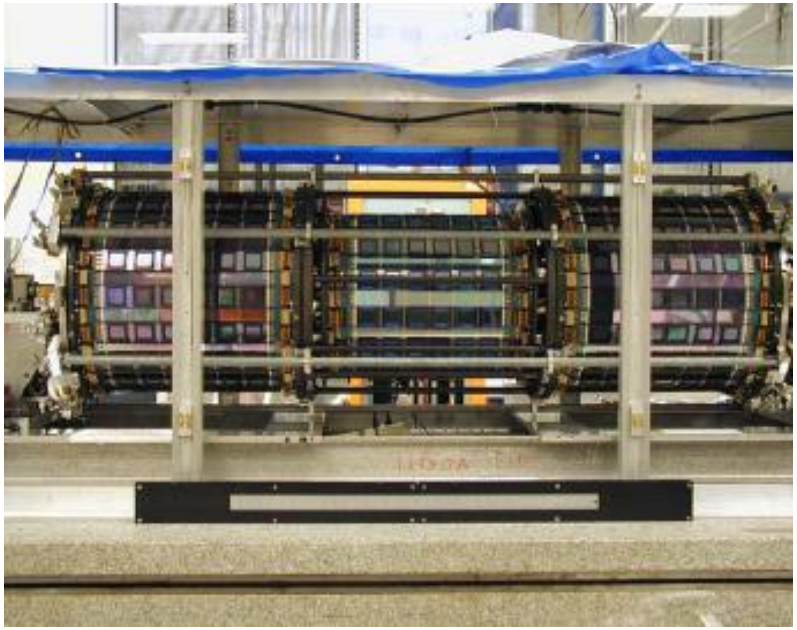
lifetimes, quark identification

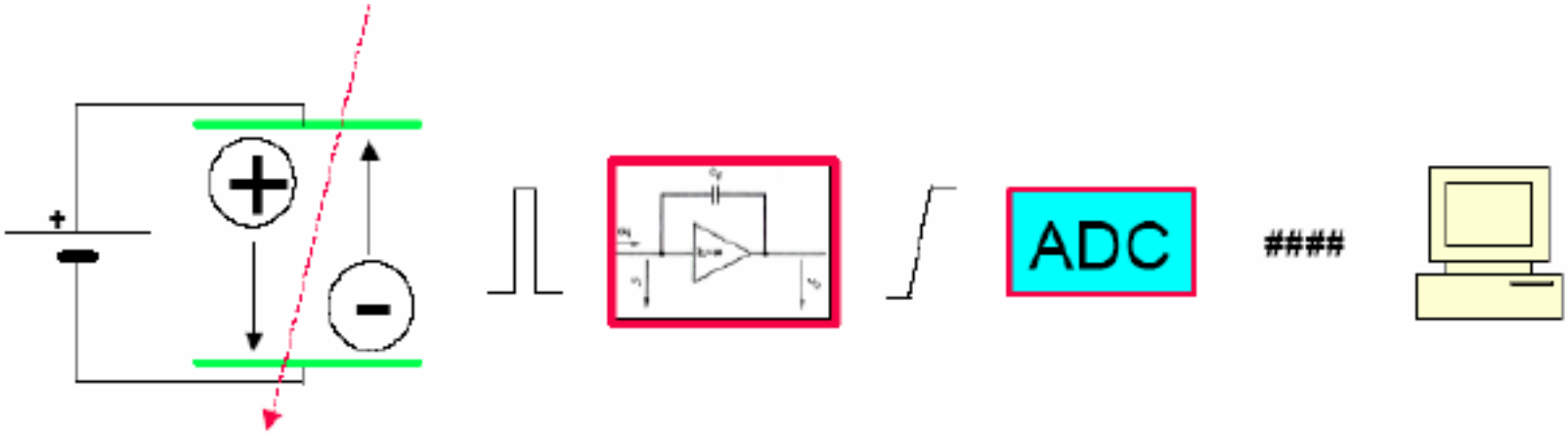
mixing background suppression

B tagging …… and a lot of great physics!

Basic Principles

- A solid state detector is an ionisation chamber
  - Sensitive volume with electric field
    - Energy deposited creates e-h pairs
    - Charge drifts under E field
    - Get integrated by ROC
    - Then digitized
    - And finally is read out and stored



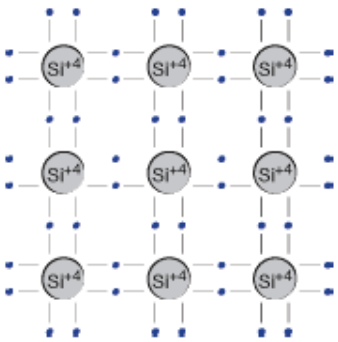


Material Properties
Semiconductors and Energy bands

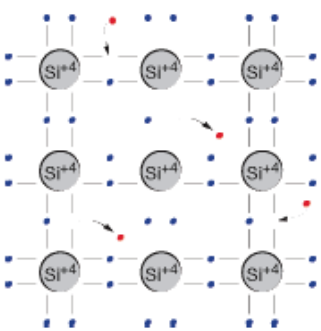
- Silicon is a group IV semiconductor. Each atom shares 4 valence electrons with its four closest neighbours through covalent bonds
- The intrinsic carrier concentration n_i is proportional to

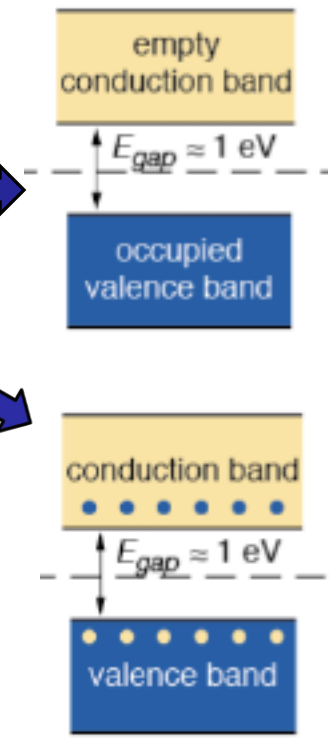
$$T^{\frac{3}{2}} \cdot \exp\left(-\frac{E_g}{2kT}\right)$$

where E_g, the band gap energy is about 1.1 eV and kT=1/40 eV at room temperature



- At low temperature all electrons are bound and the conduction band is empty
- At higher temperature thermal vibrations break some of the bonds, causing some electrons to jump the gap to the conduction band
- The remaining open bonds attract other e- and the holes change position (hole conduction)





Valence electron

Conduction electron

In pure silicon the intrinsic carrier concentration is 1.45×10^{10} cm^{-3} and about 1 in 10^{12} silicon atoms are ionised

... occupied levels .. empty levels

..... single empty levels (electron)

..... single occupied levels (holes)

Material Properties
Mobility, Resistivity, and ionisation energy

Drift Velocity of charge carriers:

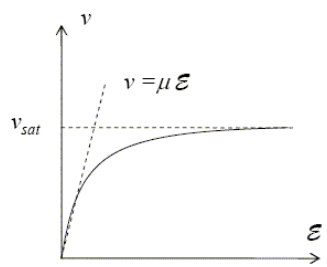
$$v = -\mu \times E$$

Mobility of the charge carriers depends on the mean free time between collisions

$$\mu = \frac{e\tau}{m}$$

electron mobility > hole mobility

μ_n(Si, 300 K) ≈ 1450 cm²/Vs
μ_p(Si, 300 K) ≈ 450 cm²/Vs



Eventually, the drift velocity saturates. Values of up to 10^7 cm/s for Si at room temperature are reasonable

Resistivity of the silicon depends on
The electron and hole mobility
The densities of electrons (n) and holes (p) (for doped material one type will dominate)

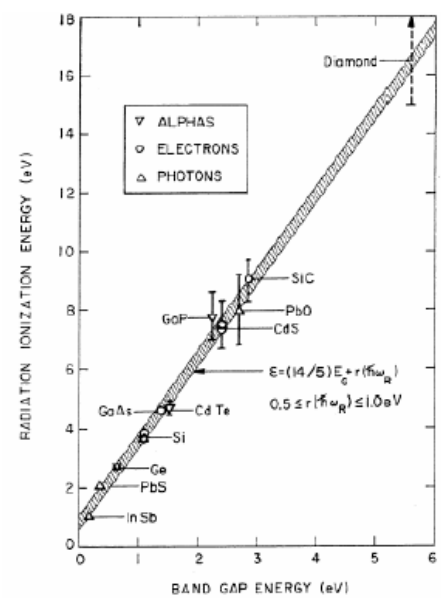
$$\rho = \frac{1}{q(\mu_e n + \mu_h p)}$$

Typical values are 300 kΩcm for pure silicon and 5-30 kΩcm for doped samples, depending on requirement

Ionization energy is the energy loss required to ionise an atom.

For silicon this is 3.6 eV, with the rest of the energy going to phonon excitations.

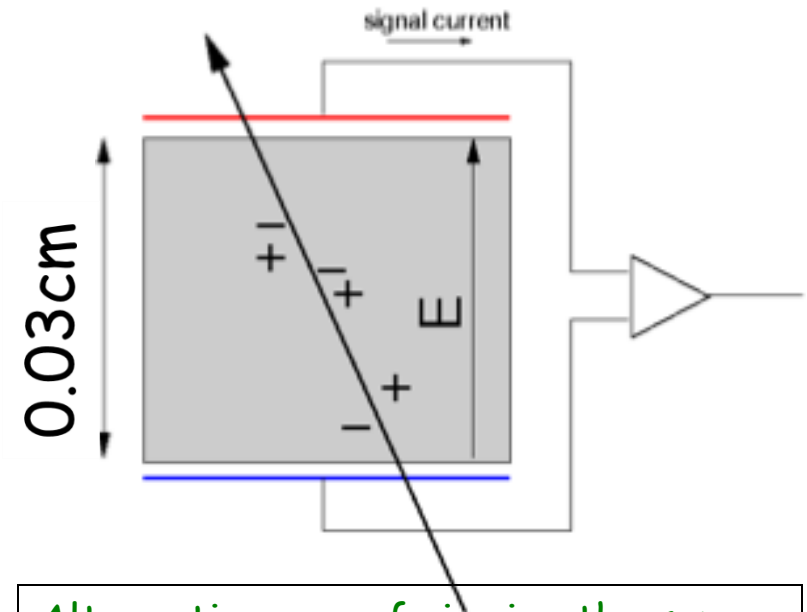
For a charged particle, typical energy loss is 3.9 MeV/cm



C.A. Klein, J. Applied Physics 39 (1968) 2029

Constructing a detector
Simple calculation of currents in silicon detector

- Thickness : 0.03 cm
- Area: 1 cm^2
- Resistivity: 300 kΩcm
- Resistance (ρd/A) : 9 kΩ
- Mobility (electrons) : 1400 cm^2/Vs
- Collection time: ~ 10 ns
  - This needs a field of E=v/μ = 0.03 cm/10ns/1400cm^2/Vs ~ 2100 V/cm or V=60V
- Charge released : ~ 25000 e^- ~ 4 fC



What currents can we expect?

Signal current: I_s = 4 fC/10 ns = 400 nA

Background current: I_R = V/R ~ 60V/9000Ω ~ 7 mA

Alternative way of viewing the same problem:

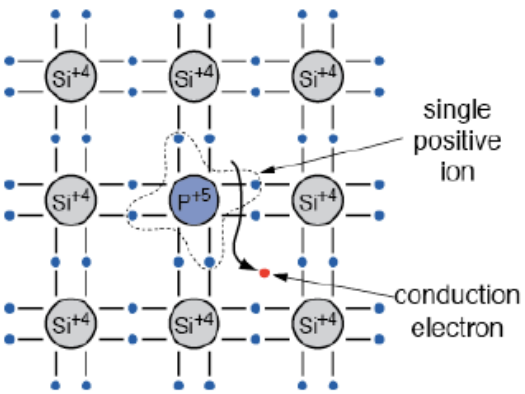
Number of signal e-h+ pairs: 25000

Number of background e-h+ pairs: 1.4 x 10^{10} x 0.03cm x 1 cm^2 = 4 x 10^8

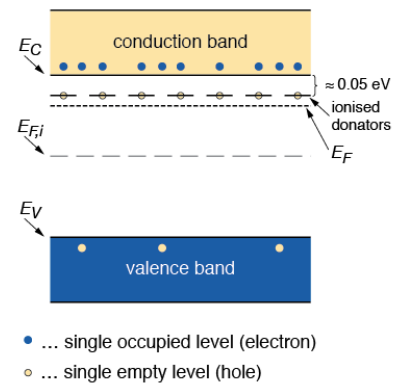
Background is four orders of magnitude higher than signal!!

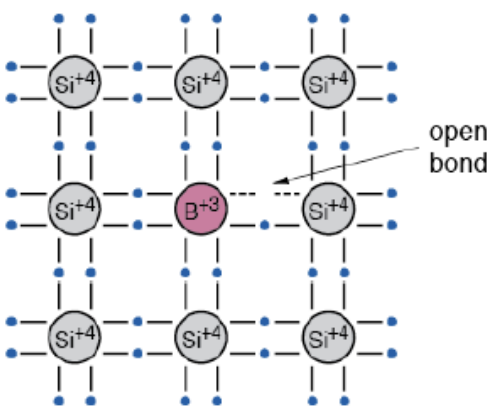
Creating a pn junction
Doped materials

Doping is the replacement of a small number of atoms in the lattice by atoms of neighboring columns from the atomic table (with one valence electron more or less compared to the basic material). The extra electron or hole is loosely bound. Typical doping concentrations for "high resistivity" Si detectors are 10^{12} atoms/cm^3 for the bulk material

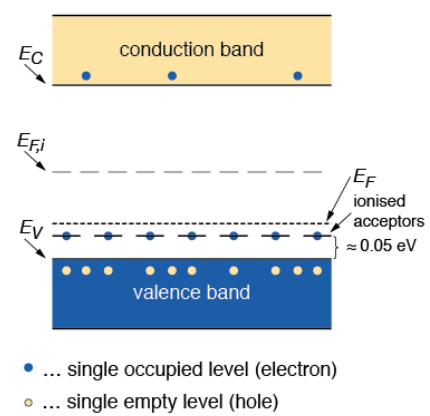


In an "n" type semiconductor, electron carriers are obtained by adding atoms with 5 valence electrons: arsenic, antimony, phosphorus. Negatively charged electrons are the majority carriers and the space charge is positive. The fermi level moves up.



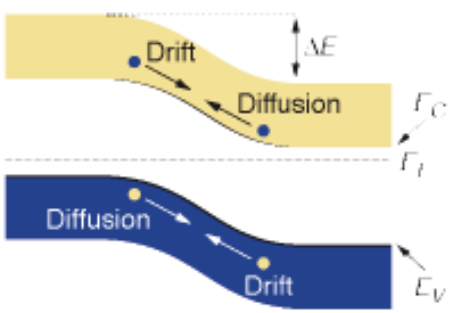


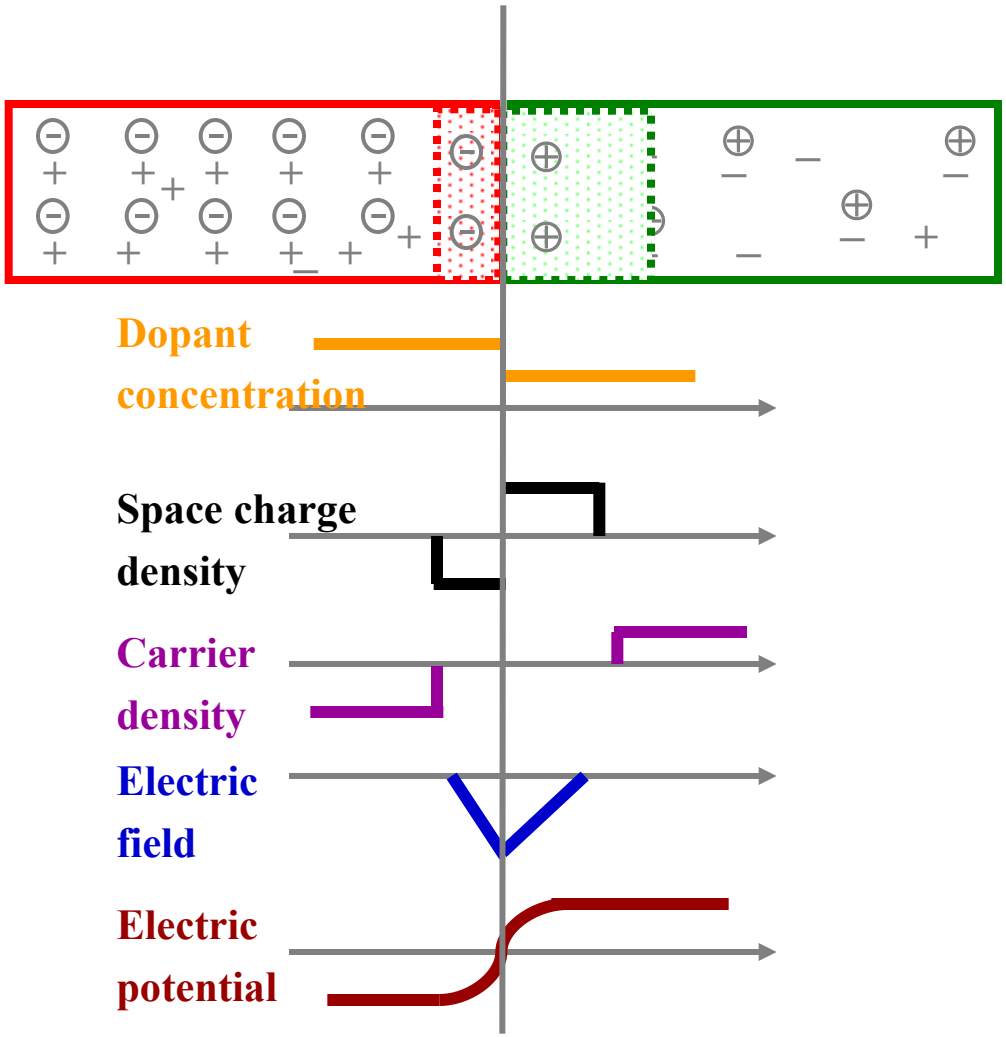
In a "p" type semiconductor, hole carriers are obtained by adding atoms with 3 valence electrons: Boron, Aluminimum, Gallium. Positively charged "holes" are the majority carriers and the space charge is negative. The fermi level moves down.



Creating a pn junction
Doped materials

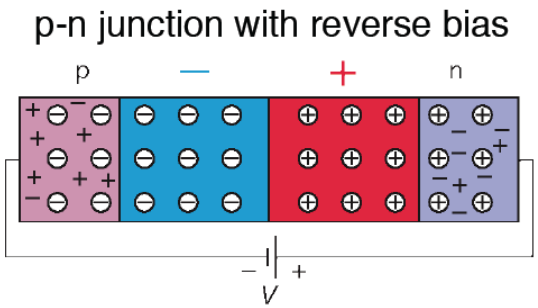
When brought together to form a junction, the majority diffuse carriers across the junction. The migration leaves a region of net charge of opposite sign on each side, called the space-charge region or depletion region. The electric field set up in the region prevents further migration of carriers.

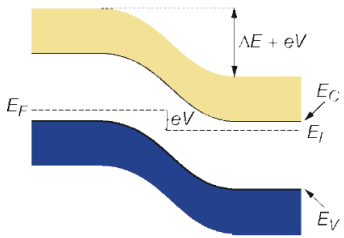


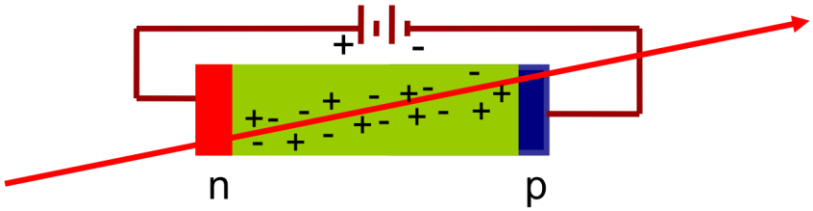


Creating a pn junction
Reverse Bias Operation

The depleted part is very nice, but very small. Apply a reverse bias to extend it, putting the cathode to p and the anode to n. This pulls electrons and holes out of the depletion zone, enlarges it, and increases the potential barrier across the junction. The current across the junction is very small "leakage current"







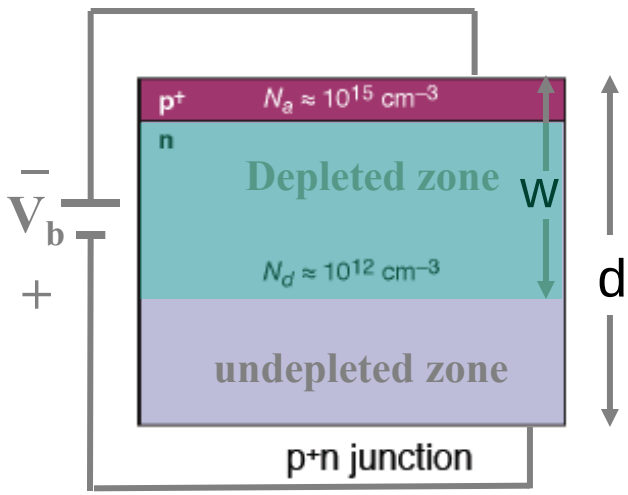
Now, electron-hole pairs created by the traversing particles dominate., and can drift in the electric field

That's how we operate the silicon detector!

Properties of the depletion zone (1)

Depletion width is a function of the bulk resistivity, charge carrier mobility m and the magnitude of the reverse bias voltage V_b. If $N_d >> N_A$ then

$$w \sim \sqrt{2\epsilon_0 \epsilon_r \mu \rho |V|}$$



The voltage needed to completely deplete a device of thickness d is called the depletion voltage, Vd.

$$V_d = \frac{d^2}{2\epsilon\rho\mu}$$

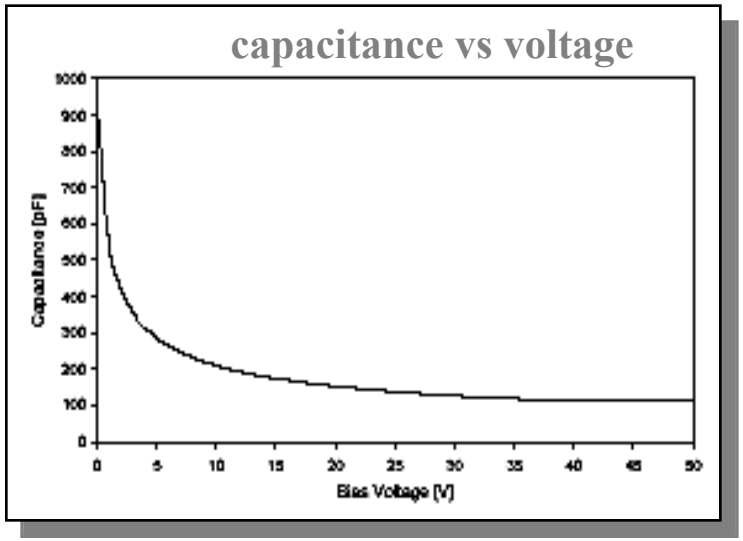
- Need a higher voltage to fully deplete a low resistivity material.
- The carrier mobility of holes is lower than for electrons

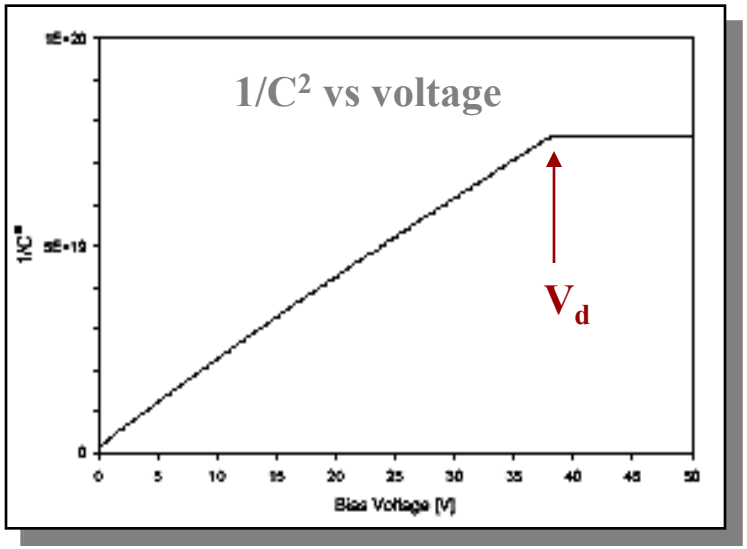
- Thickness : 0.03 cm
- $N_d = 10^{12}$ cm^{-3}
- Silicon permitivity: $11.7 \times 8.8 \times 10^{-14} = 1 \times 10^{-12}$ cm^{-1}
- $q = 1.6\ e^{-19}$
- Mobility (electrons) : 1400 cm^2/Vs
- Resistivity: $1./(q \times \mu \times N_d) = 4.5$ kΩcm
- $V_d = 50$V

Properties of the depletion zone (2)

- The capacitance is simply the parallel plate capacity of the depletion zone. One normally measures the depletion behaviour (finds the depletion voltage) by measuring the capacitance versus reverse bias voltage.

$$C = A \ \mathrm{sqrt}\left(\varepsilon / 2\rho\mu V_b \right)$$





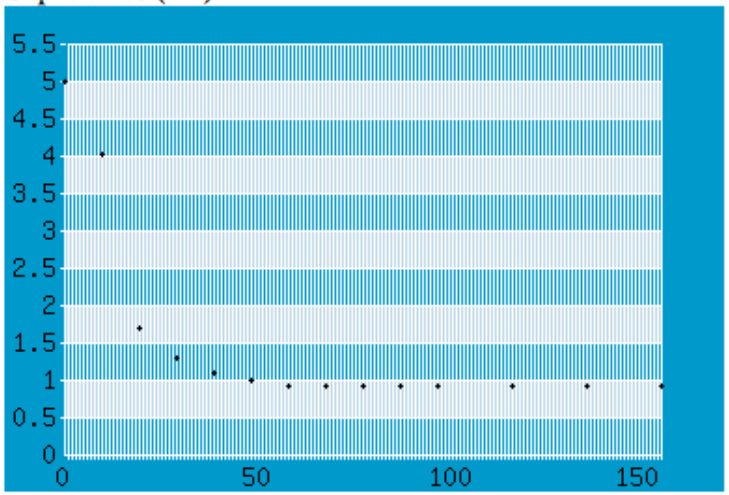
Routinely used

LHCb Velo - CV data for 2391-02C

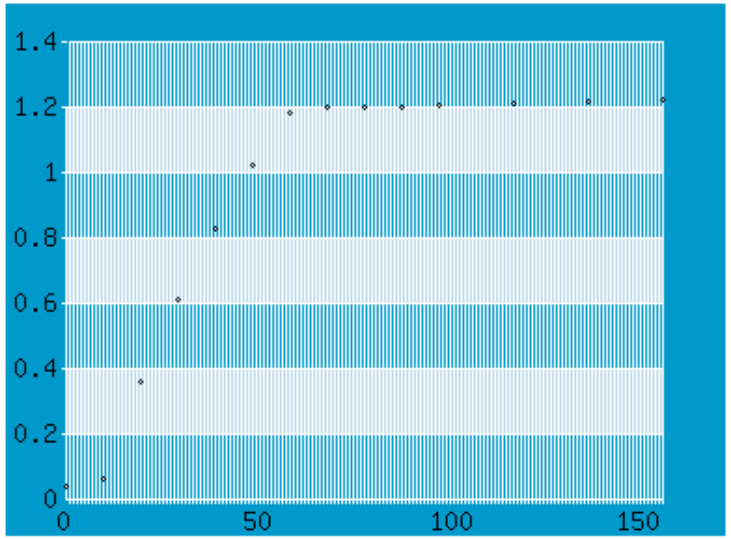
Data from file 2391-02C.Lvpool.CV.473.txt

2391-02C Sensor CV Measurements. 20.2C 46.1%

Capacitance (nF)



1/nF **2

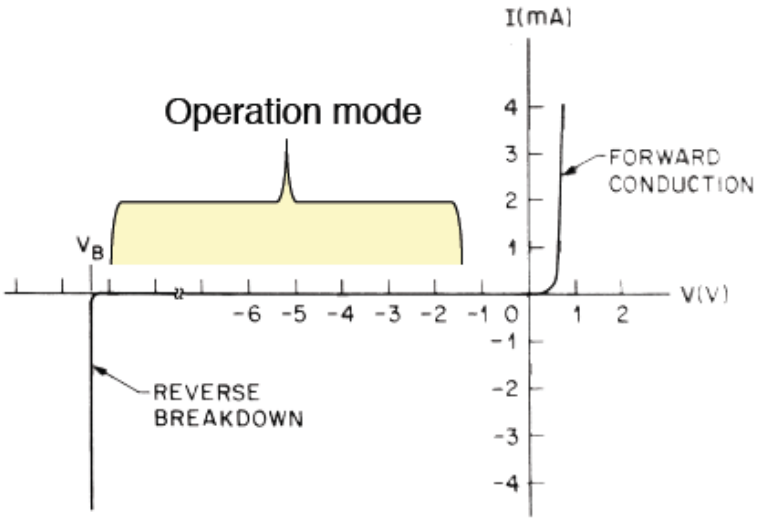


Turn over at 60 Volts.
Plateau 0.91 nF

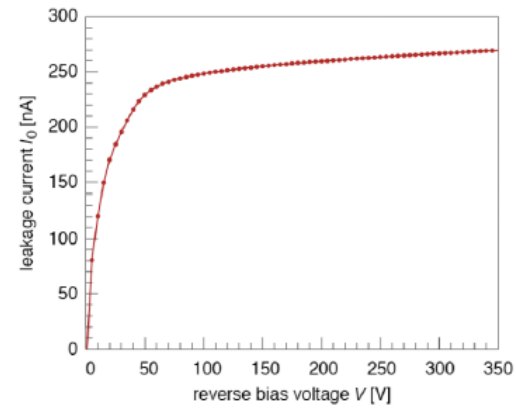
LHCb VELO Production Database

The p-n junction
Current-Voltage Characteristics

Typical current-voltage of a p-n junction (diode): exponential current increase in forward bias, small saturation in reverse bias



The actual current drawn under reverse bias is very important for routine operation. It is dominated by thermally generated e-h+ pairs and has a exponential temperature dependence

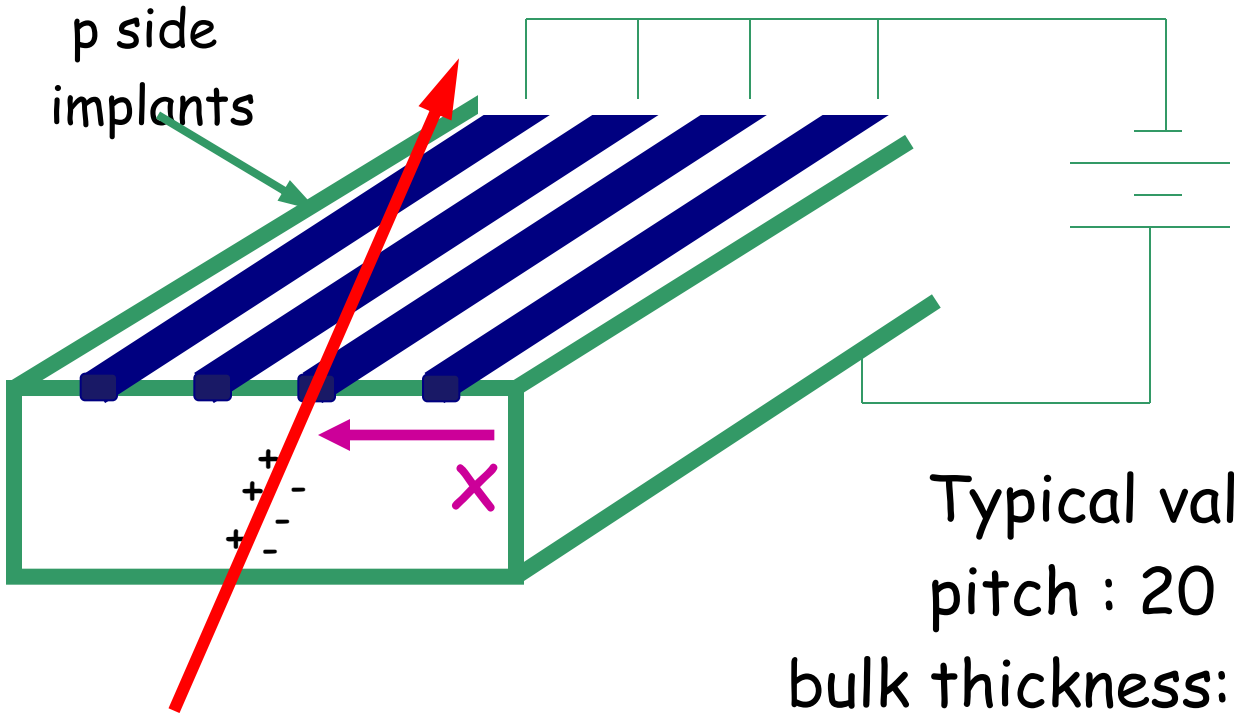


Room temperature leakage current measurement from CMS strip detector

The Silicon Sensor

Position Reconstruction

So far we described pad diodes. By segmenting the implant we can reconstruct the position of the traversing particle in one dimension



Typical values used are

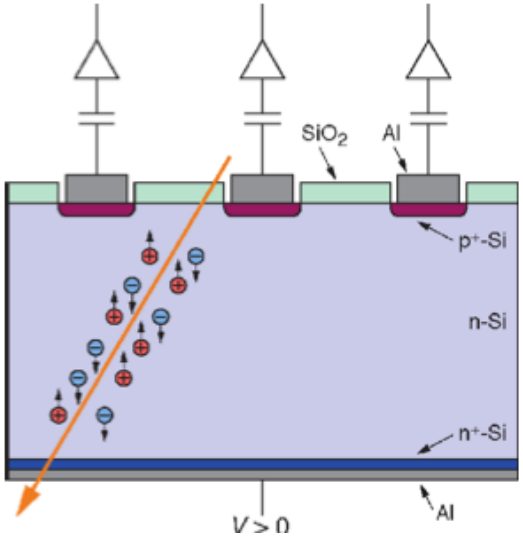
pitch : 20 μm – 200 μm

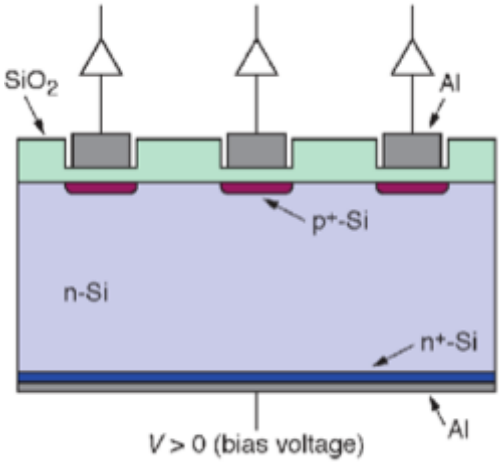
bulk thickness: 150 μm – 500 μm

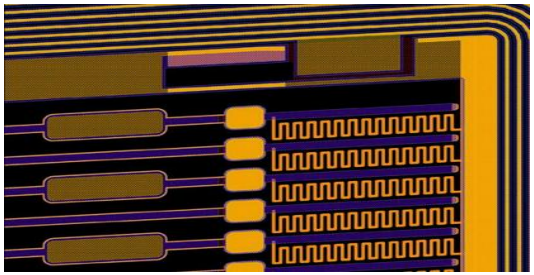
Position Reconstruction
DC and AC coupled strips

- Strips: heavily implanted boron
- Substrate: Phosphorus doped (~2-10 kΩcm and ~ 300 μm thick; V_{fd} < 200V)
- Backside Phosphorus implanct to establish ohmic contact
- High field region close to electrodes

- Bias resistor and coupling capacitance integrated directly on sensor
- Capacitor as single or double SiO_2/Si_3N_4 layer ~ 100 nm thick
- Long snakes of poly resistors with R>1MΩ

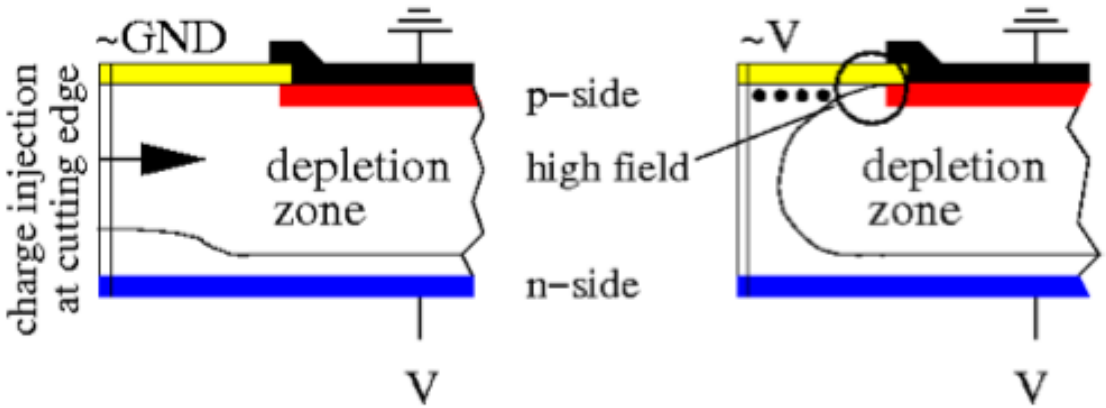


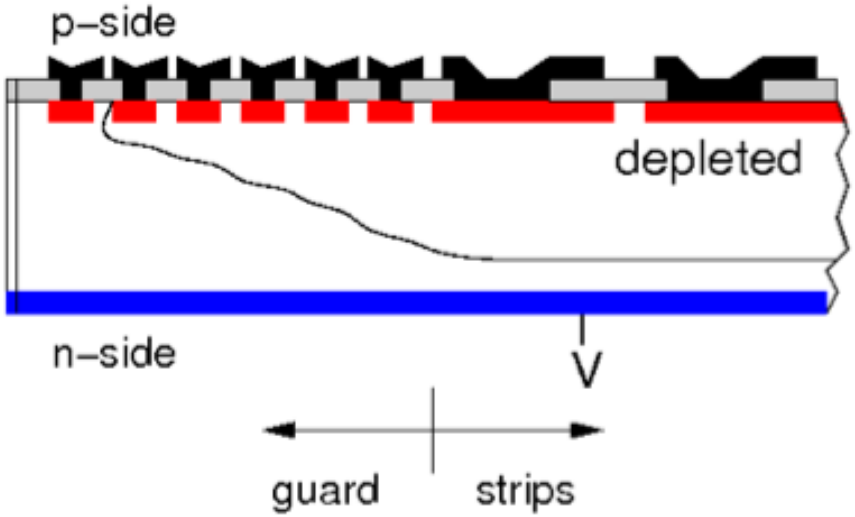




Protecting the edges

- Needed to prevent
  - Edge break down by reducing gently the potential between strips and edge
  - Injection by preventing the space charge region from reaching the scribe line





Slide taken from T. Rohe

Signal size I

Ionising energy loss is governed by the Bethe-Bloch equation

$$\frac{dE}{dx} = 4\pi N r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} [ln \frac{2m_e c^2 \gamma^2 \beta^2}{I(Z)} - \beta^2 - \frac{\delta}{2}]$$

We care about high energy, minimum ionising particles, where

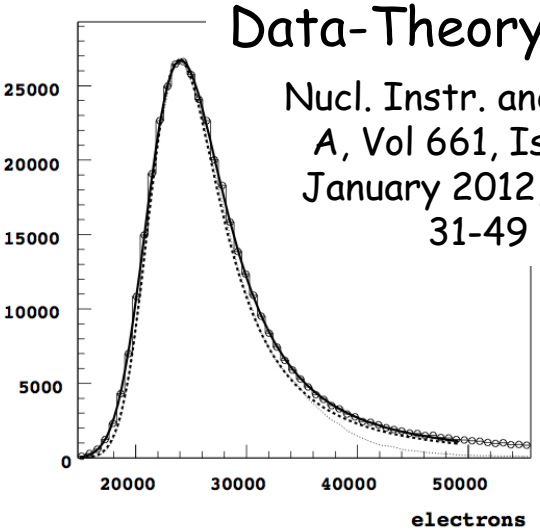
dE/dx ~ 39 KeV/100 μm

An energy deposition of 3.6 eV will produce one e-h pair

So in 300 μm we should get a mean of 32k e-h pairs

Data-Theory comparison

Nucl. Instr. and Meth. A, Vol 661, Issue 1, January 2012, Pages 31-49



Fluctuations give the famous "Landau distribution"

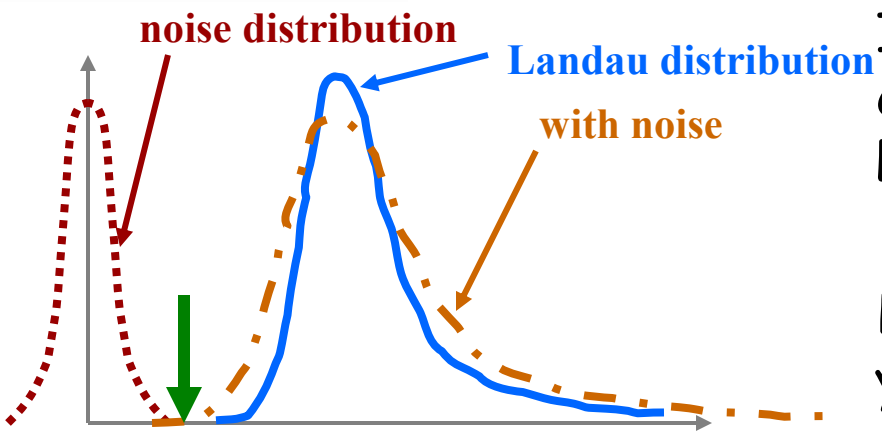
The "most probable value" is 0.7 of the peak

For 300 μm of silicon, most probable value is

~23400 electron-hole pairs

Noise I

Noise is a big issue for silicon detectors. At 22000e^- for a 300 μm thick sensor the signal is relatively small. Signal losses can easily occur depending on electronics, stray capacitances, coupling capacitor, frequency etc.



If you place your cut too high you cut into the low energy tail of the Landau and you lose efficiency.

But if you place your cut too low you pick up fake noise hits

Performance of detector often characterised as its S/N ratio

Noise II

Usually expressed as equivalent noise charge (ENC) in units of electron charge e. (Here we assume the use of most commonly used CR-RC amplifier shaper circuit)

- Main sources:
  - Capacitive load (C_d). Often the major source, the dependence is a function of amplifier design. Feedback mechanism of most amplifiers makes the amplifier internal noise dependent on input capacitive load. $ENC \propto C_d$
  - Sensor leakage current (shot noise). $ENC \propto \sqrt{I}$
  - Parallel resistance of bias resistor (thermal noise). $ENC \propto \sqrt{(kT/R)}$
  - Total noise generally expressed in the form (absorbing the last two sources into the constant term a): $ENC = a + b \cdot C_d$
  - Noise is also very frequency dependent, thus dependent on read-out method
- Implications for detector design:
  - Strip length, device quality, choice of bias method will affect noise.
  - Temperature is important for both leakage current noise (current doubles for $\Delta T \approx 7^\circ C$) and for bias resistor component

Noise IV

- Some typical values for LEP silicon strip modules (OPAL):
  - ENC = 500 + 15 $\cdot C_d$
  - Typical strip capacitance is about 1.5 pF/cm, strip length of 18cm so C_d=27pF

so ENC = 900e. $\Rightarrow$ S/N $\approx$ 25/1

- Some typical values for LHC silicon strip modules
  - ENC = 425 + 64 $\cdot C_d$
  - Typical strip capacitance is about 1.2pF/cm, strip length of 12cm so C_d=14pF

so ENC = 1300e $\Rightarrow$ S/N $\approx$ 17/1

Capacitive term is much worse for LHC in large part due to very fast shaping time needed (bunch crossing of 25ns vs 22μs for LEP)

Signal Diffusion

- Diffusion is caused by random thermal motion
- Size of charge cloud after a time t_d given by

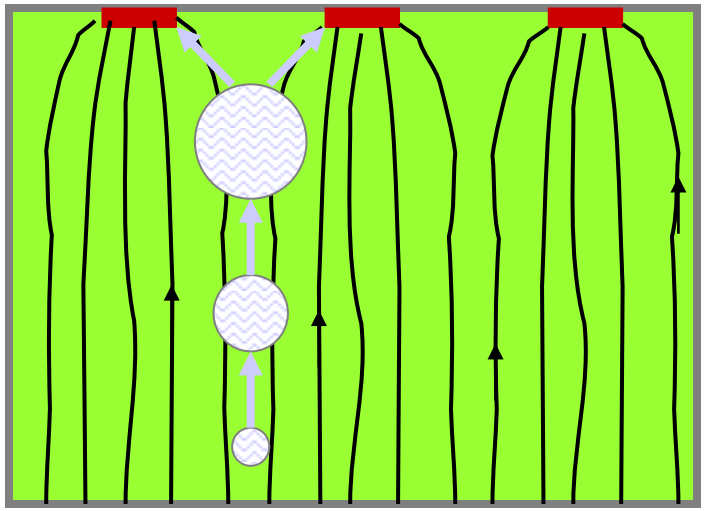
  $\sigma = \sqrt{2Dt_d}$, where D is the diffusion constant, $D=\mu kT/q$
- Charges drift in electric field E with velocity $v = E\mu$

  μ = mobility cm^2/volt sec, depends on temp + impurities + E: typically 1350 for electrons, 450 for holes
- So drift times for: d=300 mm, E=2.5Kv/cm:

  $t_d(e) = 9$ ns, $t_d(h)=27$ ns
- For electrons and holes

diffusion is roughly the same!

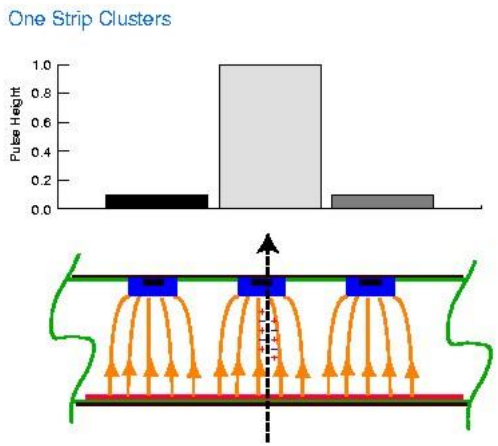
Typical value: 8 μm for 300 μm drift. Can be exploited to improve position resolution



Position Resolution I

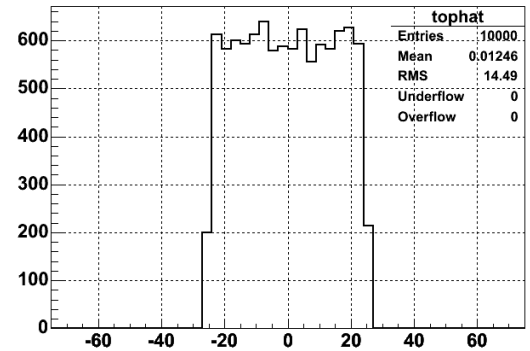
Resolution is the spread of the reconstructed position minus the true position

For one strip clusters

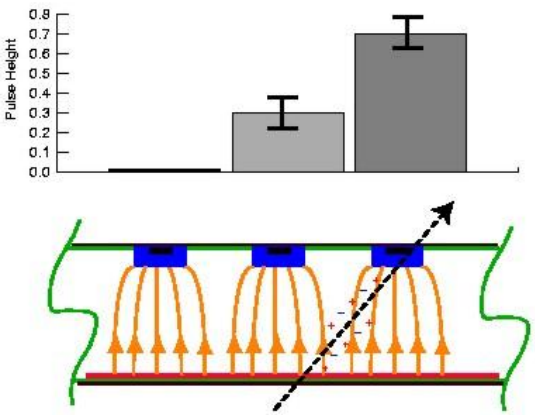


$$\sigma = \frac{\text{pitch}}{\sqrt{12}}$$

"top hat" residuals

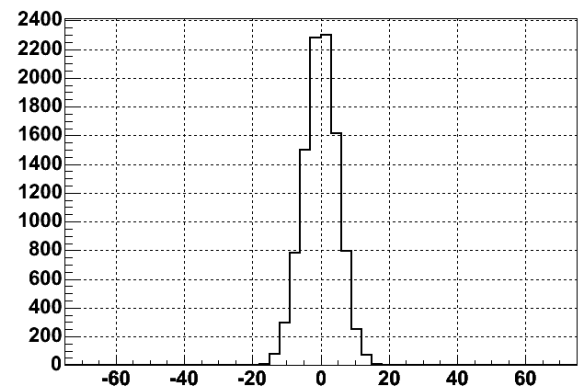


For two strip clusters



$$\sigma \approx \frac{\text{pitch}}{1.5 * (S/N)}$$

"gaussian" residuals



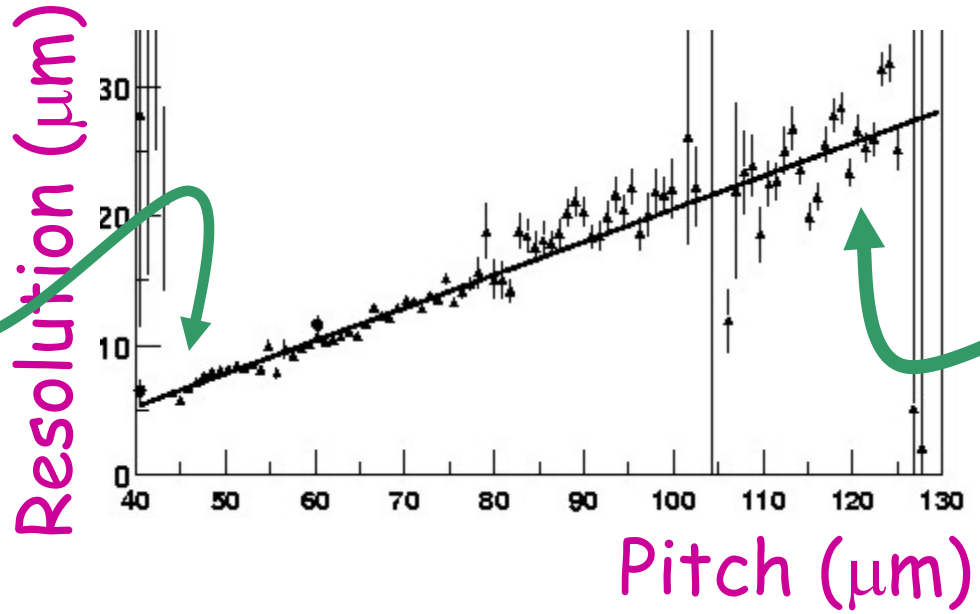
Position Resolution II

In real life, position resolution is degraded by many factors

- relationship of strip pitch and diffusion width (typically 25-150 μm and 5-10 μm)
- Statistical fluctuations on the energy deposition

Typical real life values for a 300μm thick sensor with S/N=20

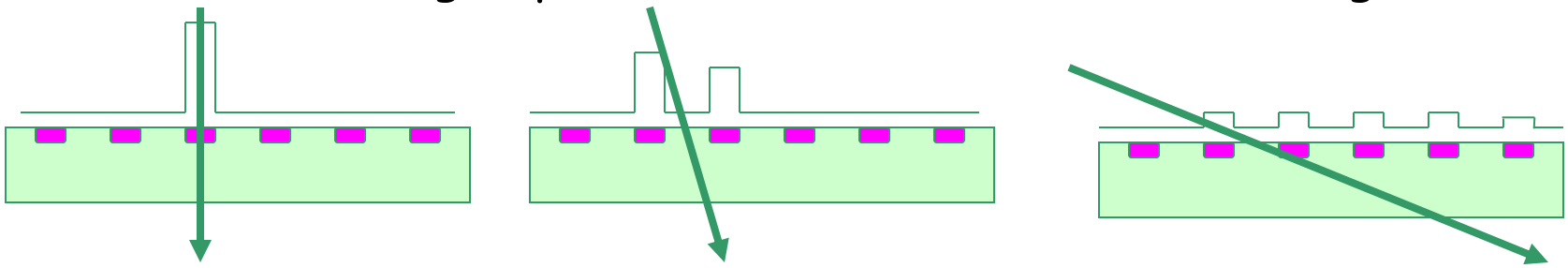
Here charge sharing dominates

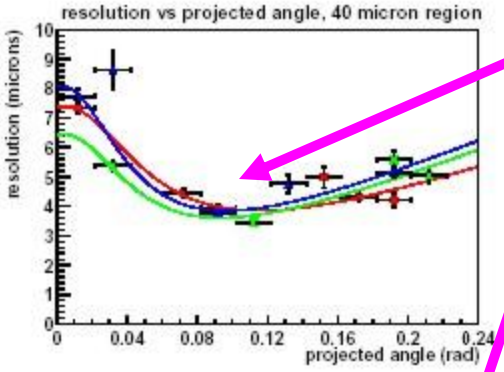


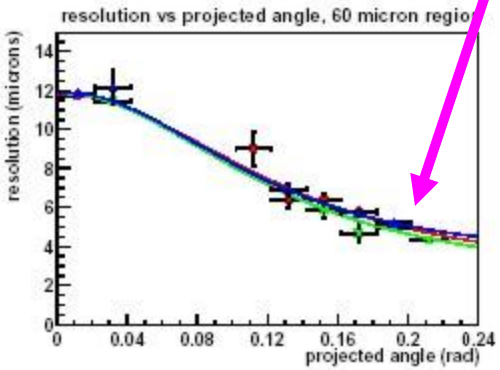
Here single strips dominate

Position Resolution III

There is also a strong dependence on the track incidence angle

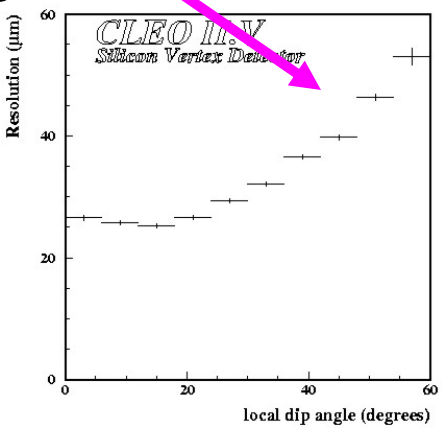






At small angles you win

At large angles you lose
(but a good clustering algorithm can help)



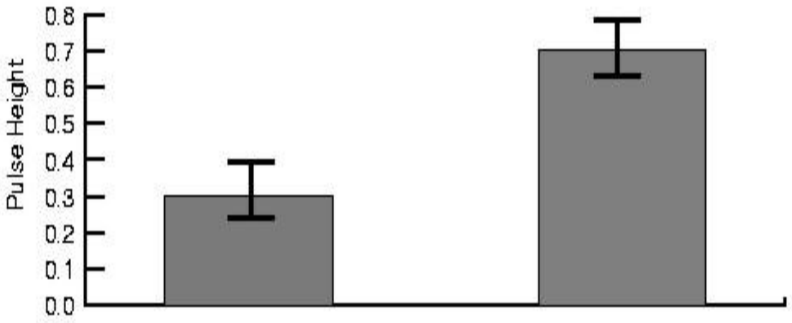
Optimum is at

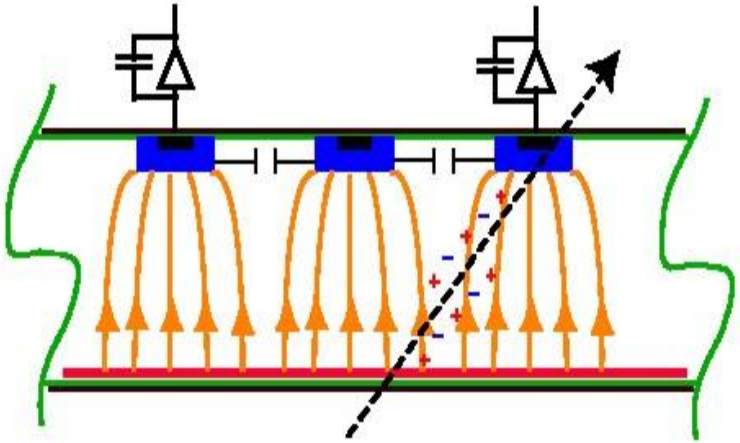
$$\tan^{-1}\frac{\text{pitch}}{\text{width}}$$

Position Resolution IV

Fine pitch is good… but there is a price to pay! $$$$$

The floating strip solution can help



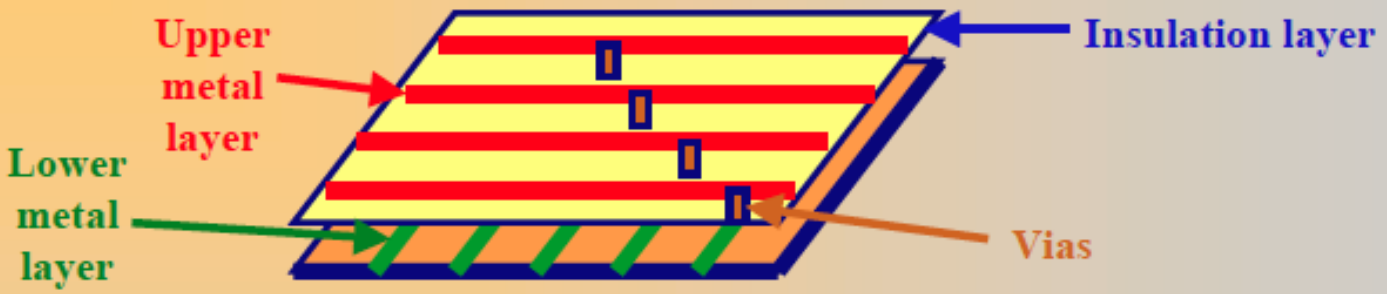


- The charge is shared to the neighboring strips via capacitative coupling. We don't have to read out every strip but we still get great resolution

- This was a very popular solution. ALEPH for instance obtained $\sigma \approx 12\ \mu m$ using a readout pitch of 100 μm and an implant pitch of 25 μm

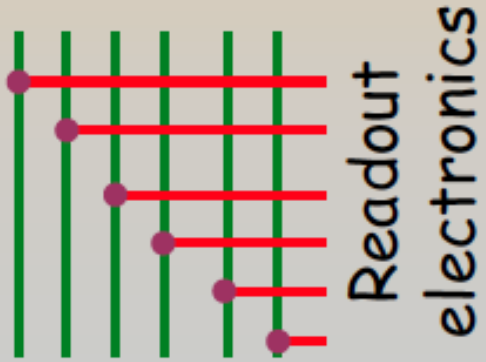
- But you can't have everything for nothing! You can lose charge from the floating strips to the backplane, so you must start with a good signal to noise

Double Metal Technology

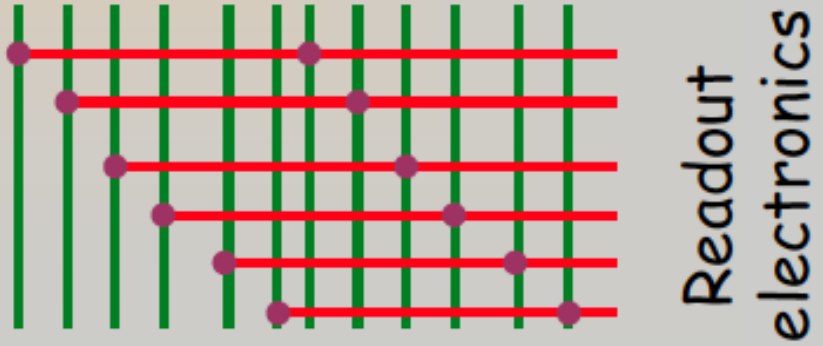


Add an insulation layer, and above that add another layer of strips which are going in the right direction – the direction of the readout electronics. This might be orthogonal to the strips and might not – many weird and wonderful patterns are possible

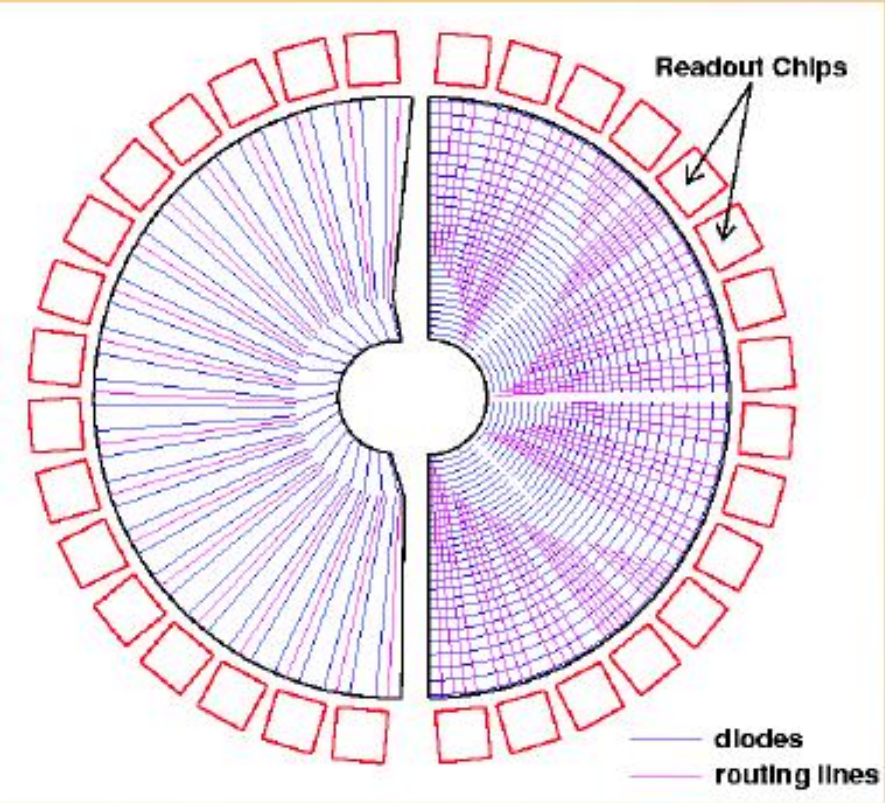
a simple solution..



.... a solution with multiplexing



Challenging, but elegant



The LHCb sensors must measure R and Phi and must keep the electronics on the outside – an obvious application for double metal technology!

These detectors are single sided and n-on-n

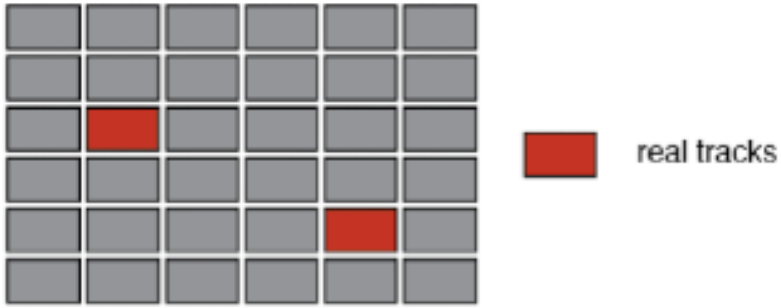
Hybrid Pixels

★ A strip detector measures 1 coordinate only. Two orthogonal arranged strip detectors could give a 2 dimensional position of a particle track. However, if more than one particle hits the strip detector the measured position is no longer unambiguous. “Ghost”-hits appear!

True hits and ghost hits in two crossed strip detectors in case of two particles traversing the detector:

★ Pixel detectors produce unambiguous hits!

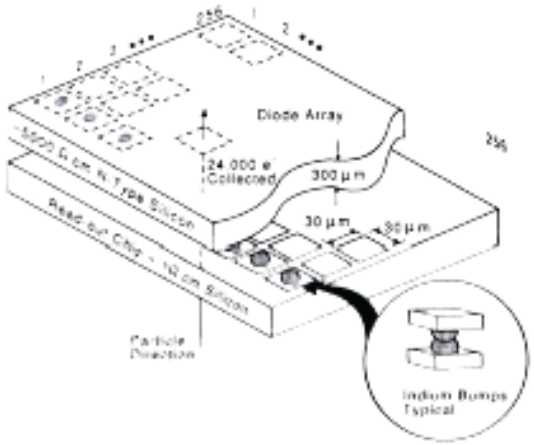
Measured hits in a pixel detector in case of two particles traversing the detector:



(stolen from Hartmann/Krammer/Trischuk..)

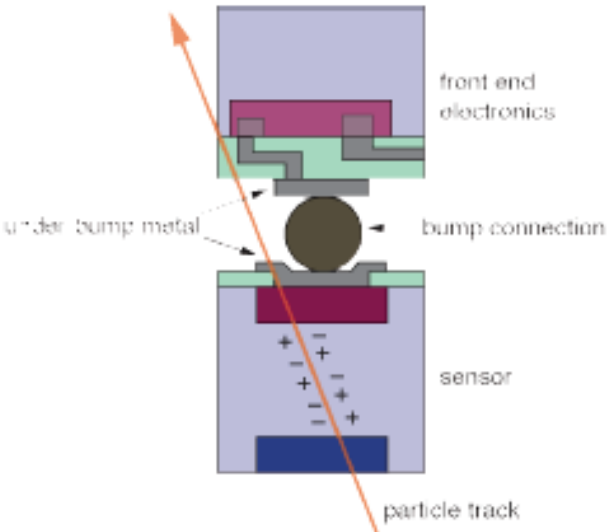
Hybrid Pixels

"Flip-Chip" pixel detector:
On top the Si detector, below the readout chip, bump bonds make the electrical connection for each pixel.



S.L. Shapiro et al., *Si PIN Diode Array Hybrids for Charged Particle Detection*, Nucl. Instr. Meth. A **275**, 580 (1989)

Detail of bump bond connection. Bottom is the detector, on top the readout chip:

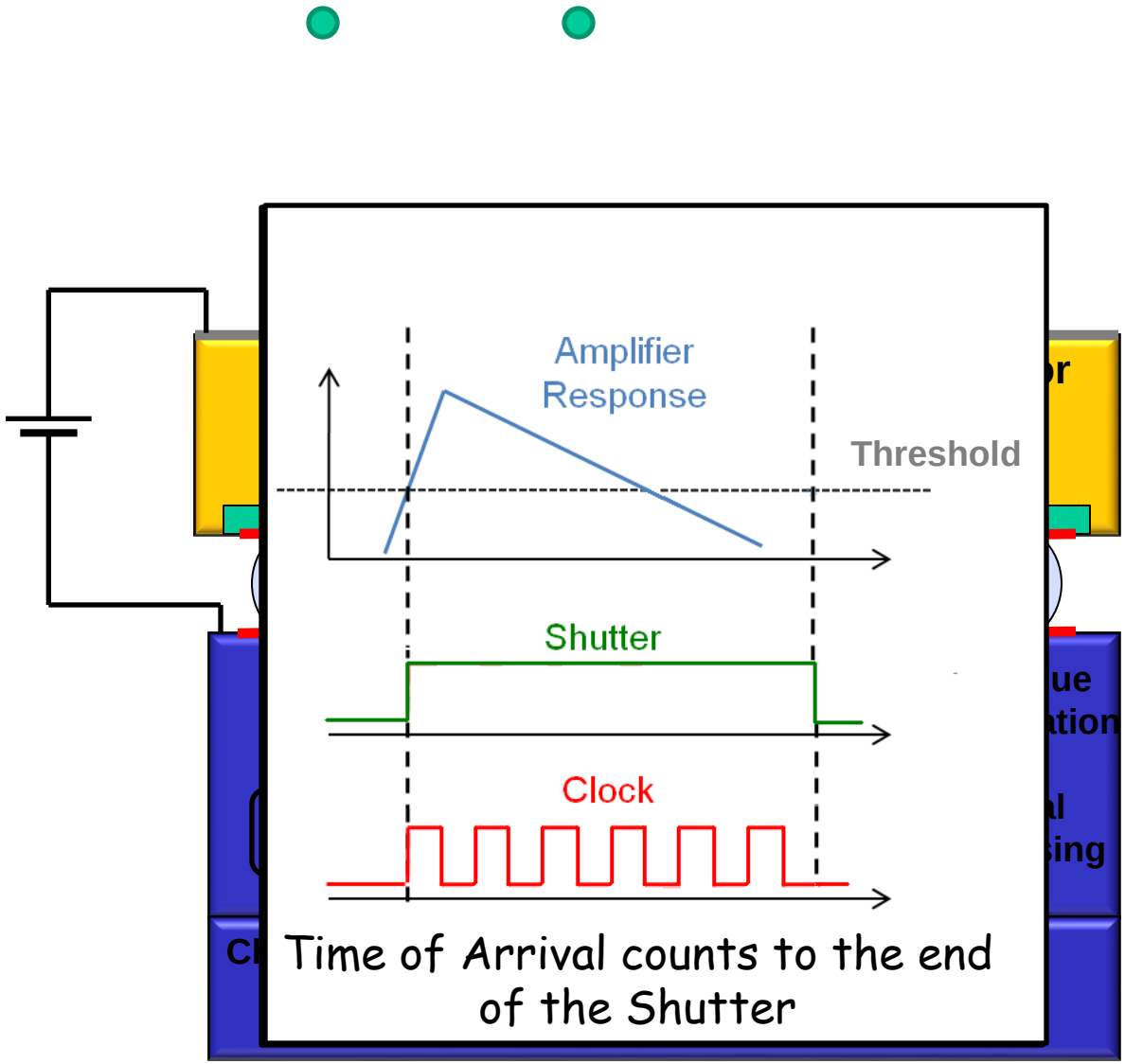


L. Rossi, *Pixel Detectors Hybridisation*, Nucl. Instr. Meth. A **501**, 239 (2003)

Drawback of hybrid pixel detectors: Large number of readout channels

→ Large number of electrical connections and large power consumption.

Intelligent Pixels



Timepix design requestedand funded by EUDET collaboration

Conventional Medipix2 counting mode remains.

Addition of a clock up to 100MHz allows two new modes.

Time over Threshold

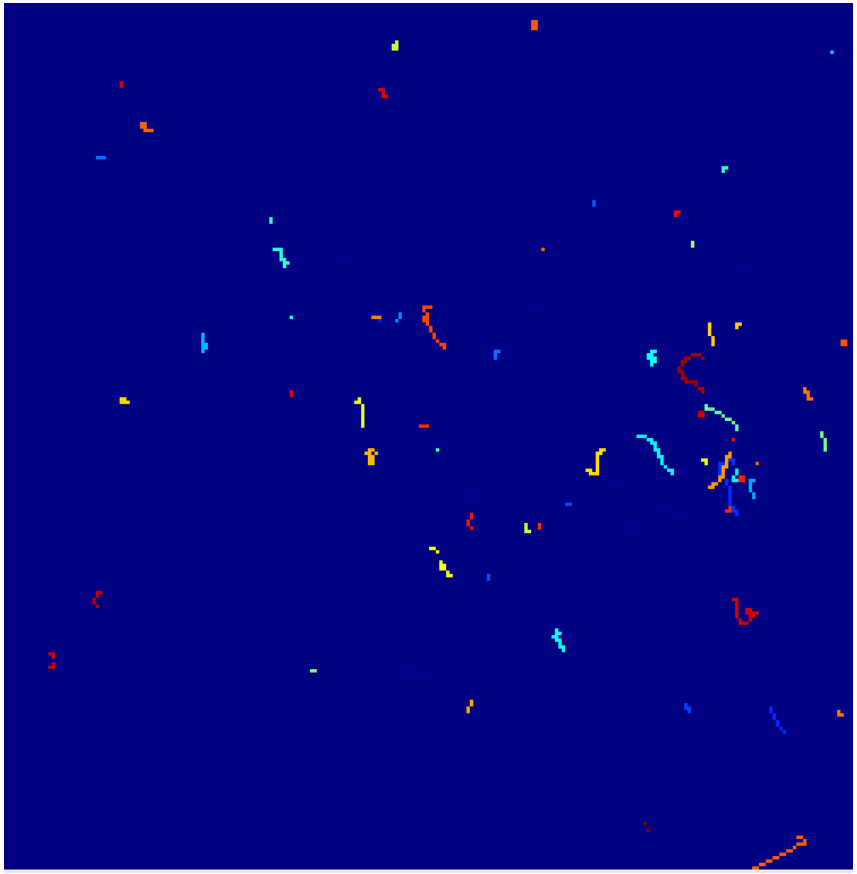
Time of Arrival

Pixels can be individually programmed into one of these three modes

Or As Results…

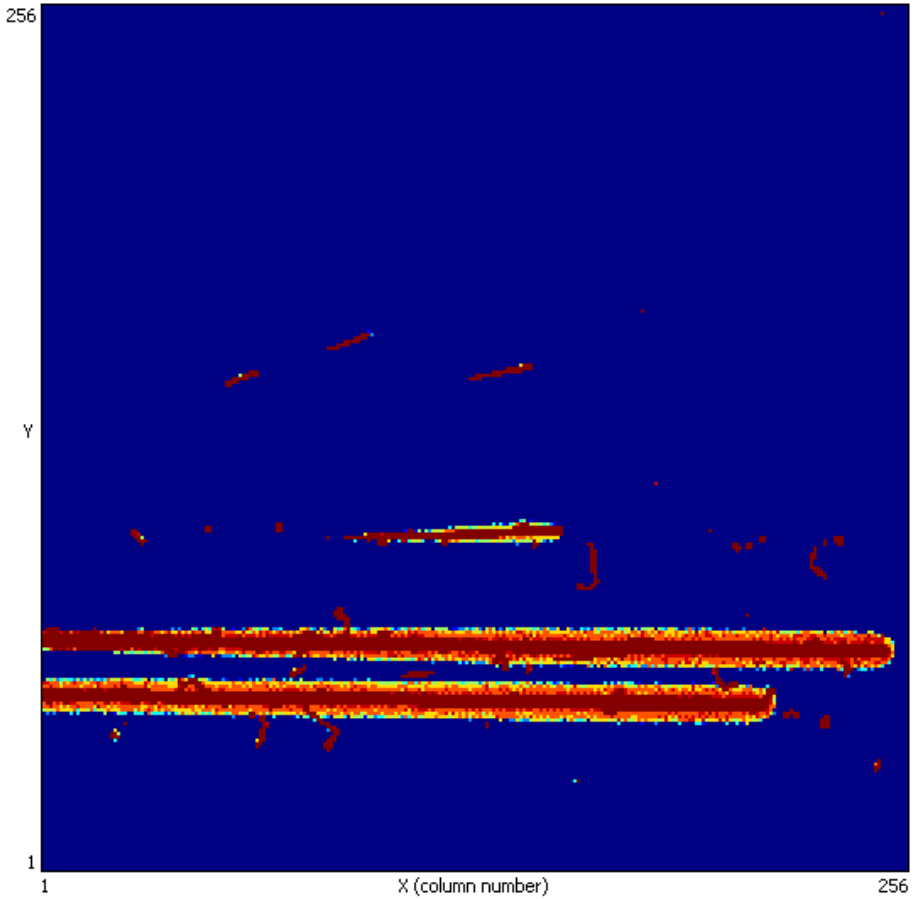
Time of Arrival

Strontium Source



Time over Threshold

Ion Beams at HIMAC



Charge deposition studies with various Isotopes
Space Dosimetry

Courtesy L. Pinsky, Univ. Houston

Irradiation

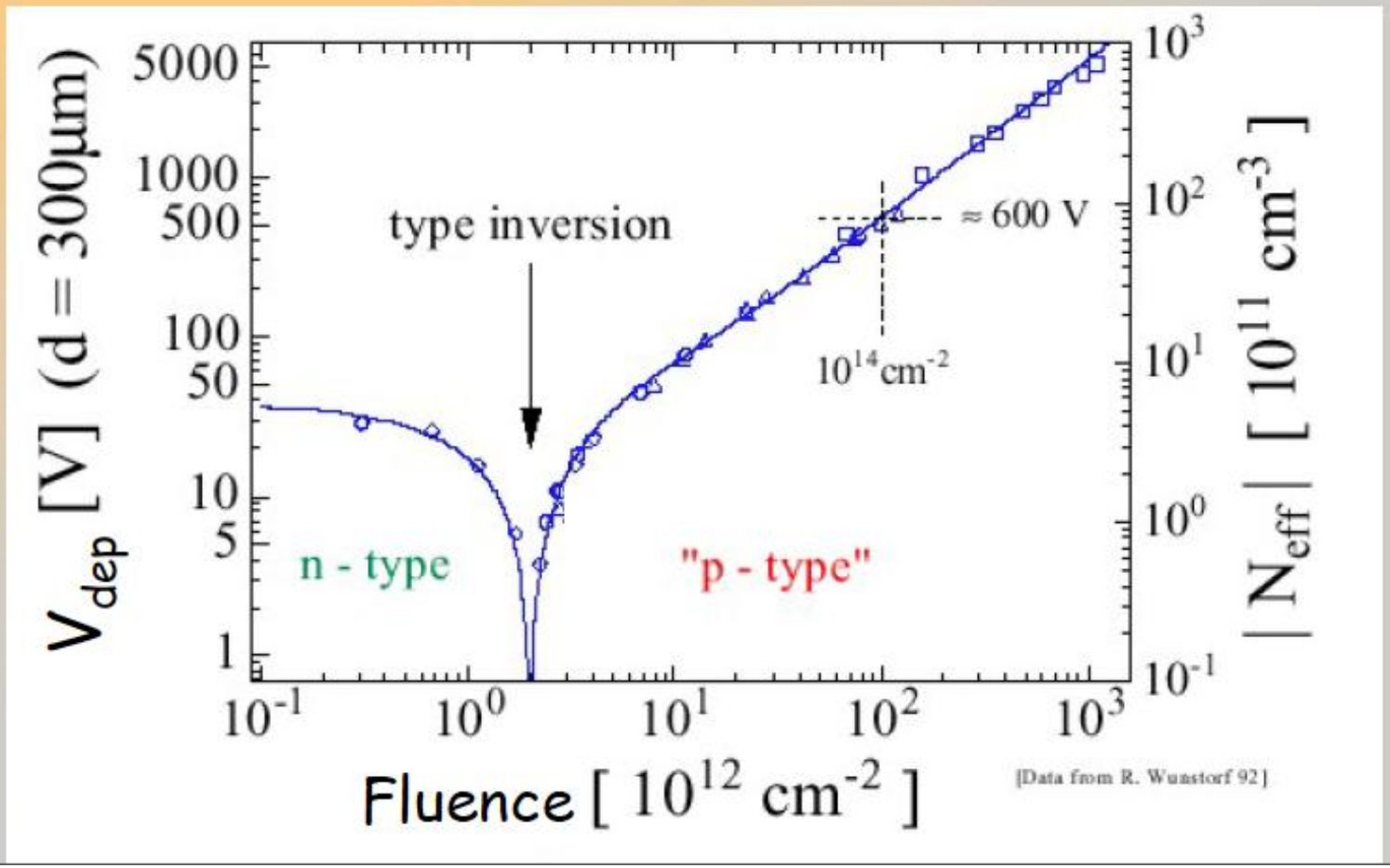
Irradiation

- Change of depletion voltage
  - Due to defect levels that are charged in the depleted region -> time and temperature dependent, and very problematic!
- Increase of leakage current
  - Bulk current due to generation/recombination levels
- Damage induced trapping centers
  - Decrease in collected signal charge

Changes in depletion voltage

$V_{dep} \propto |N_{eff}|\, d^2$

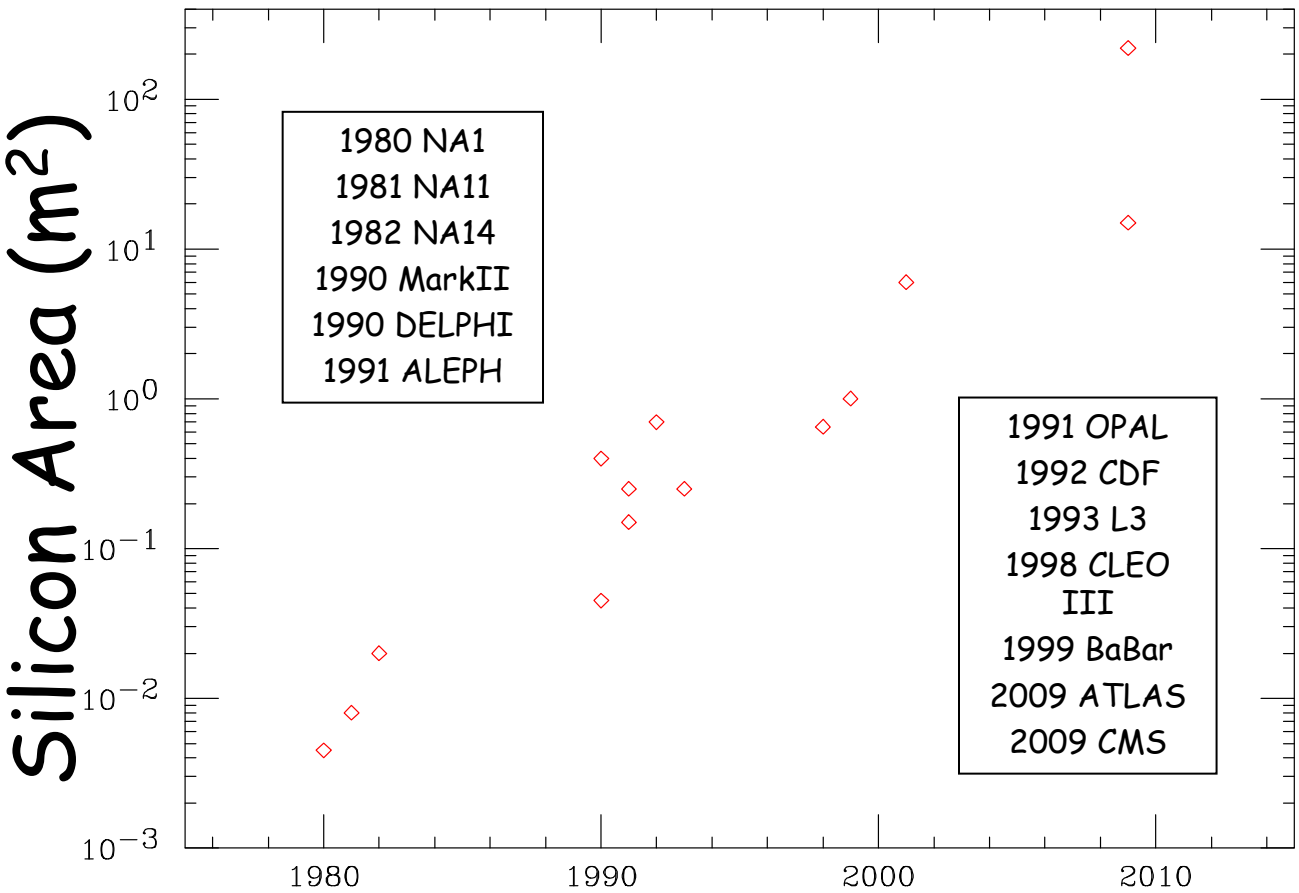
N_{eff} +ve -> n type silicon (e.g. Phosphorus doped - Donor)
N_{eff} -ve -> p type silicon (e.g. Boron doped - Acceptor)



Real Life

1. Large Systems and Quality Control

Plot from D. Christian



Year of initial operation

what can go wrong, will go wrong

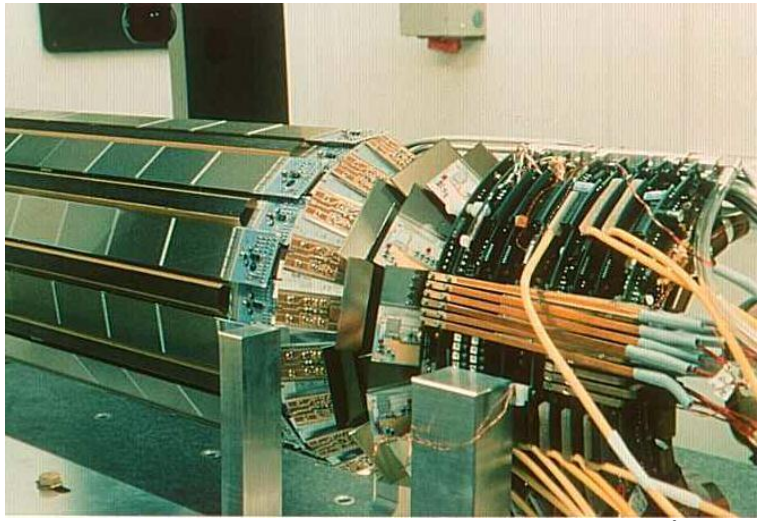
DELPHI "sticky plastic saga"

Received sensors from vendor, tested and distributed to assembly labs. All = OK

Assembly labs got worse results – confirmed at CERN

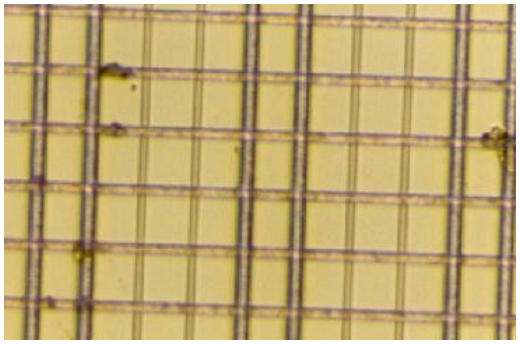
US TO VENDOR: YOUR SENSORS AGE!

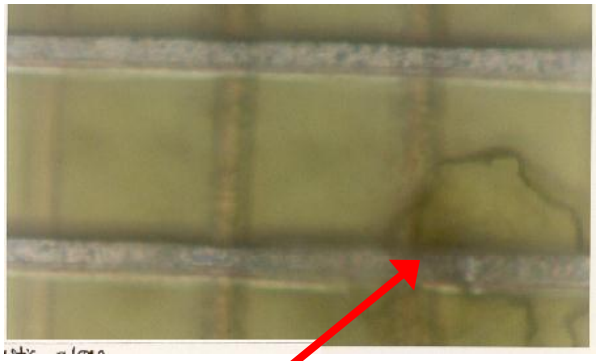
VENDOR: YOU ARE RUINING THEM!

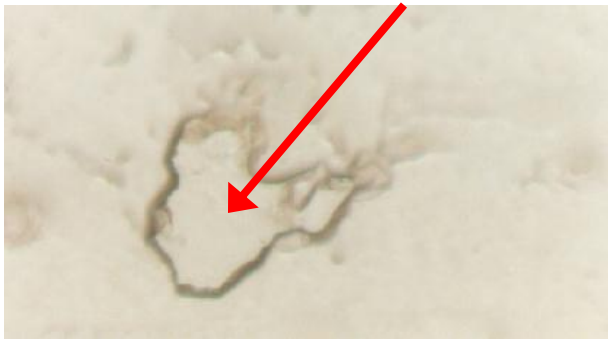


Zoom on packing

Finally found "flakes"







Zoom on flake thru packing

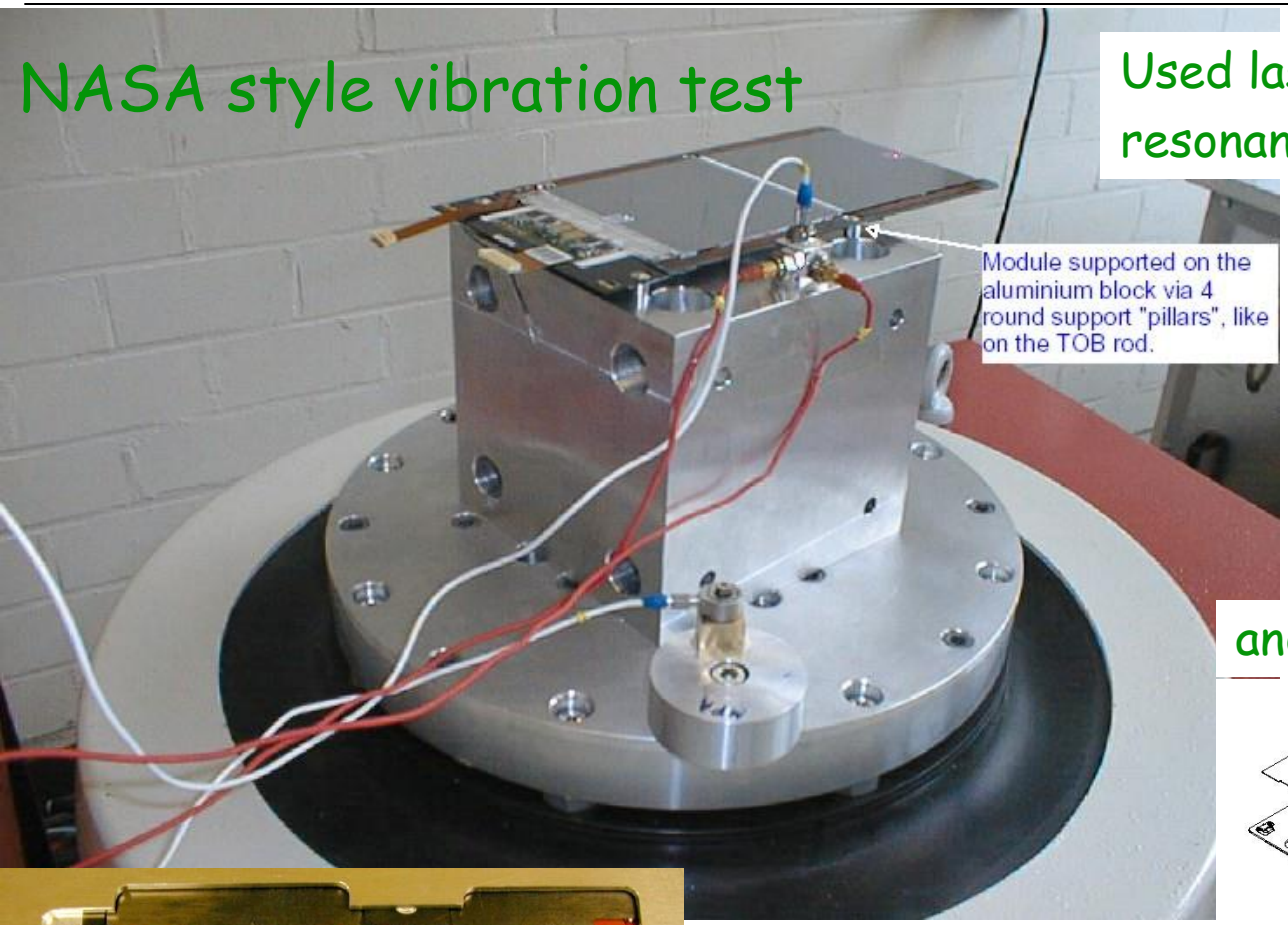
A story repeated with variations elsewhere

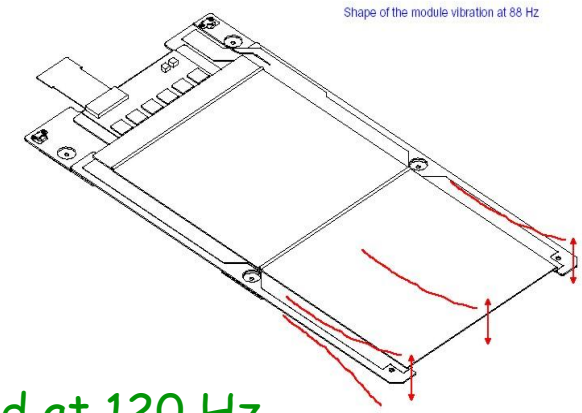
Vendor had changed anti static packing plastic
– 60 sensors affected, big delay

what can go wrong, will go wrong

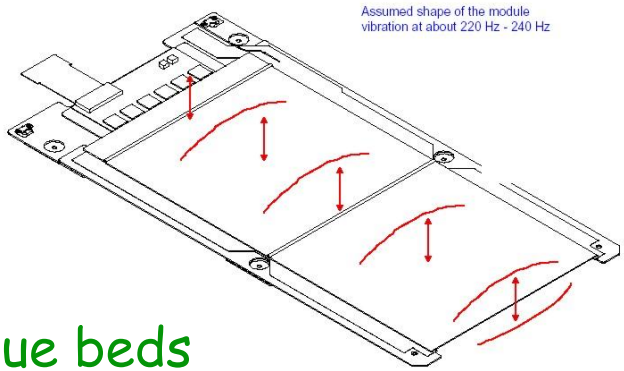
NASA style vibration test

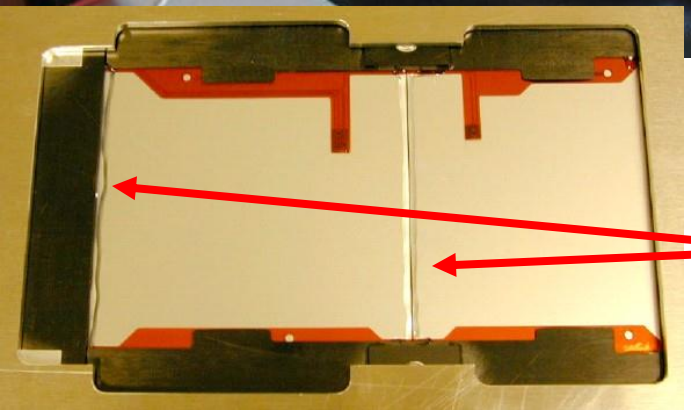
Used laser to identify cantilever resonances at 88 Hz





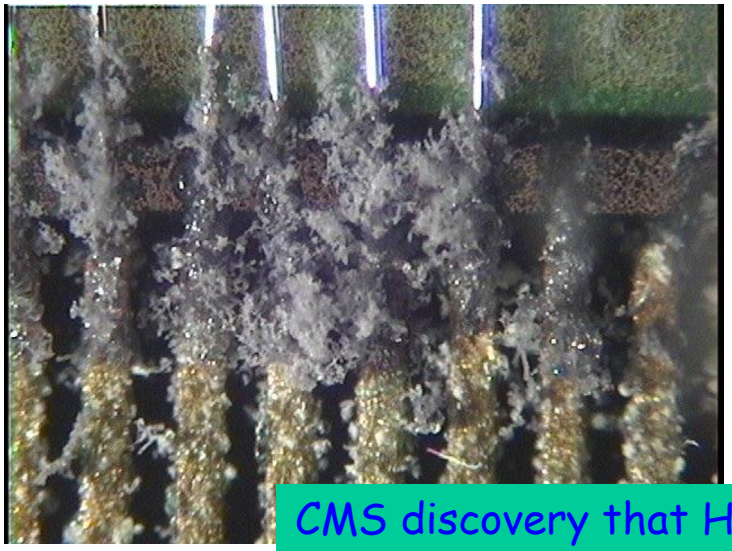
and at 120 Hz

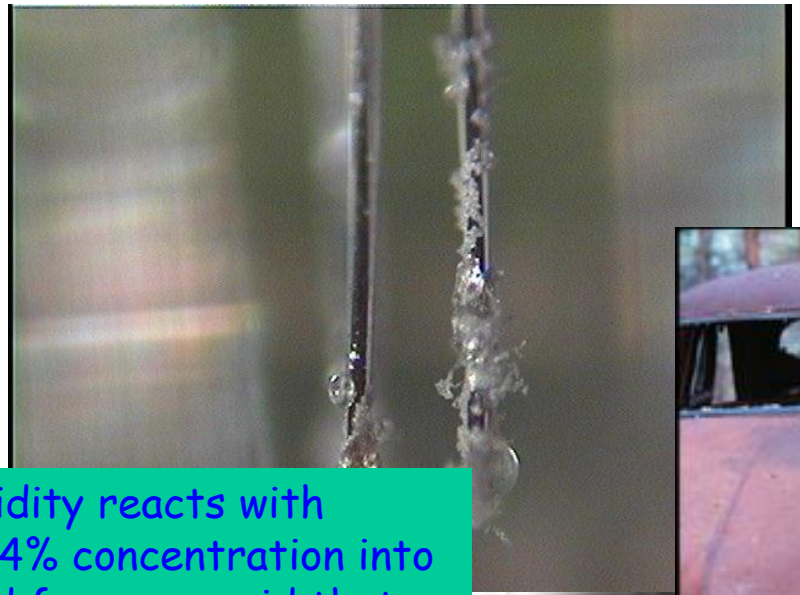




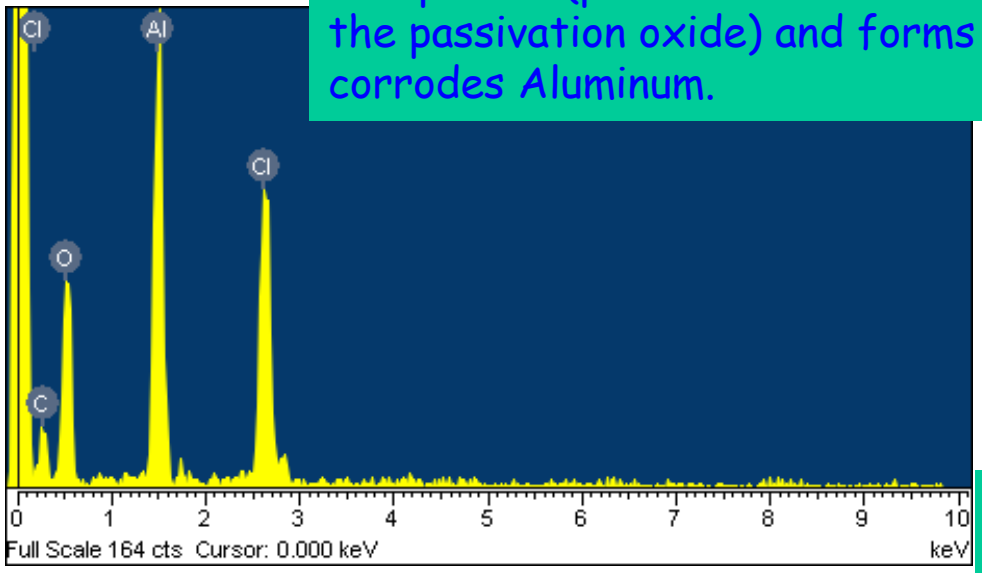
Reinforcement glue beds totally solved the problem

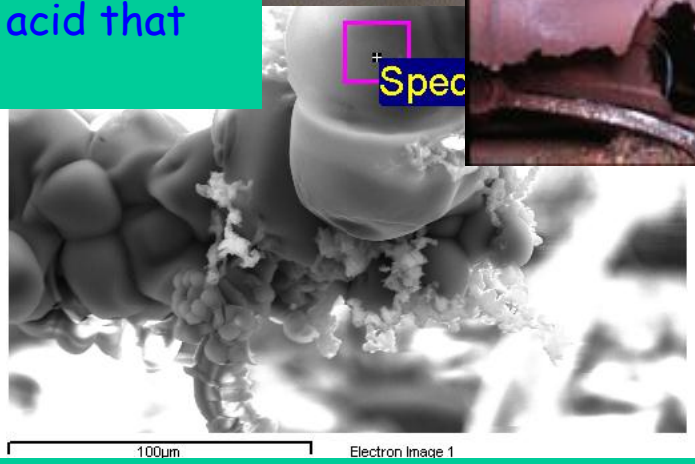
and other things can go wrong too!





CMS discovery that Humidity reacts with Phosphorus (present in a 4% concentration into the passivation oxide) and forms an acid that corrodes Aluminum.

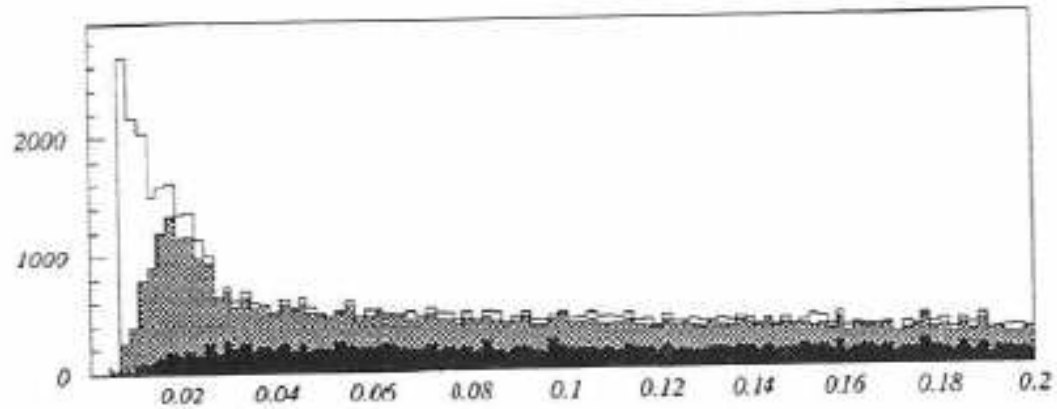




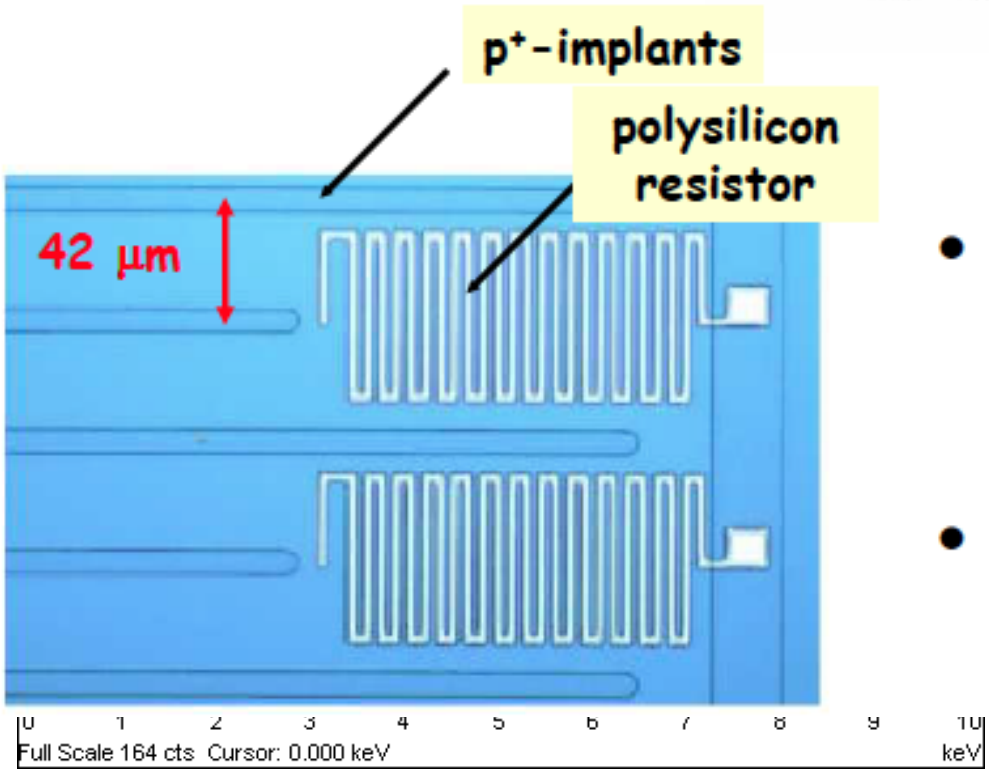
For a nice up to date summary of QA issues see https://indico.cern.ch/conferenceDisplay.py?confId=148944

Data Driven Analyses

- Clusters can be split by dead strips
- Also by design features:



Distance to the closest cluster before/after cluster repair

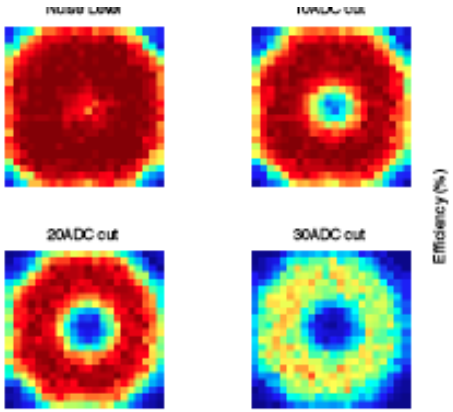


- Double strip pitch to accommodate polySi resistors caused split clusters (DELPHI VD)
- Fixed by a software algorithm

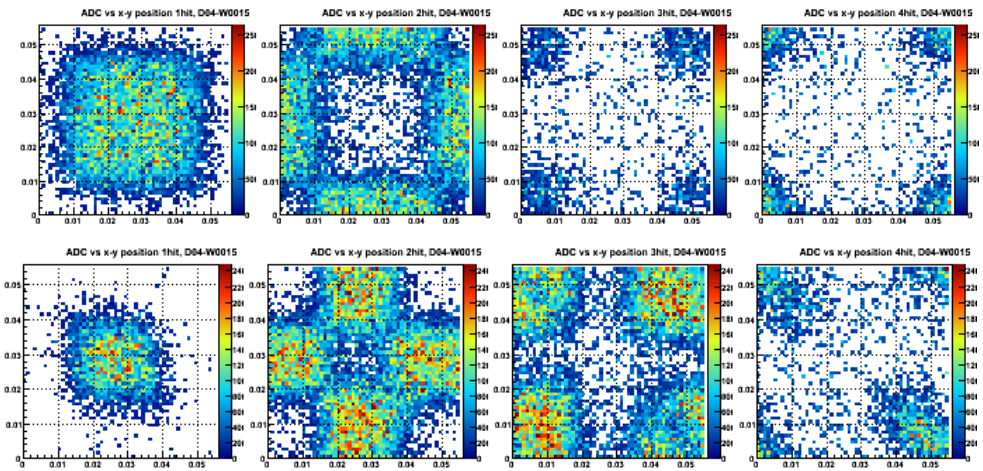
2. Tracking & resolutions

Testbeam Telescopes

- In a telescope we are interested primarily in the "track pointing resolution" which tells us how precisely we can probe the device under test.



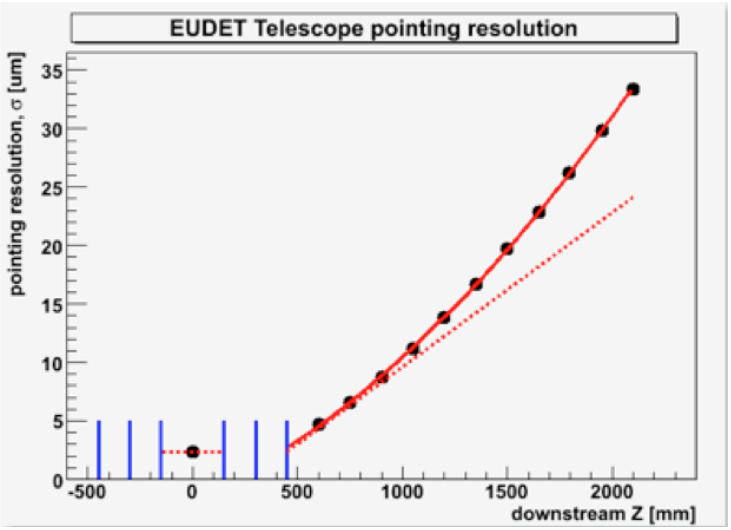
Timepix telescope images (pointing resolution of 1.8 μm) of 55 mm pixels



Eudet telescope:

<2 μm at telescope centre

Possibility to mount detectors outside telescope for more coarse resolution studies

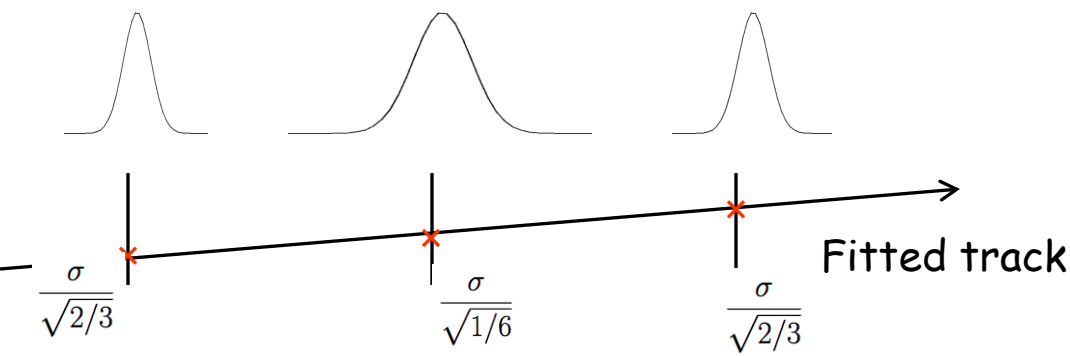


Resolution depends on

- Track energy and multiple scattering
- Intrinsic plane resolution
- Telescope geometry (number and position of planes)

Testbeam Telescopes

- Data driven concepts (again)
- Resolution of planes can be inferred from (biased) residuals per plane – distance between fitted tracks and hits in each plane



- Simplest possible case: 3 equally spaced planes
- Resolution of each plane = σ
- Biased residuals are
  - Outer planes $\frac{\sigma}{\sqrt{2/3}}$
  - Inner planes $\frac{\sigma}{\sqrt{1/6}}$
- Infinite number of planes: biased residuals of σ in all planes

Useful reference, if you don't have a Geant simulation handy and you are not MS limited

$$\sigma_{\mathrm{pred}(z_n)} = \sqrt{\sum_i (\sigma_i \cdot A(z_{n,i}))^2}.$$

$$A(z_{n,i}) = \frac{\sum_j \frac{(z_j)^2 + z_n \cdot z_i}{(\sigma_j)^2 \cdot (\sigma_i)^2}}{\sum_j \frac{1}{\sigma_j^2} \sum_j \frac{z_j^2}{\sigma_j^2}},$$

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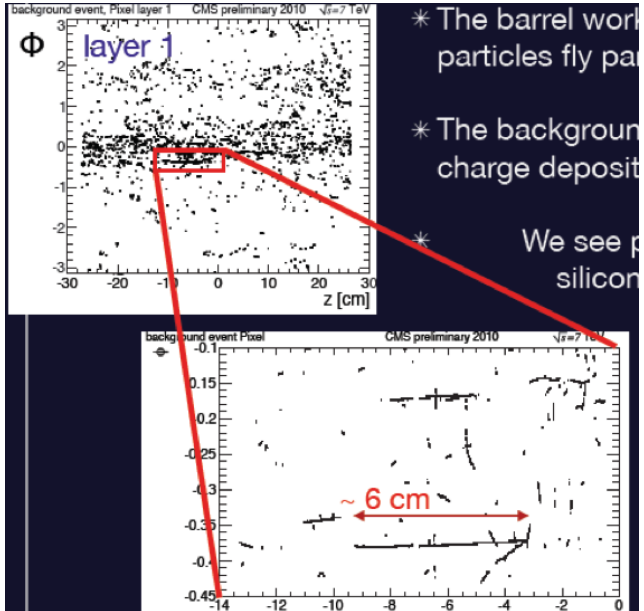
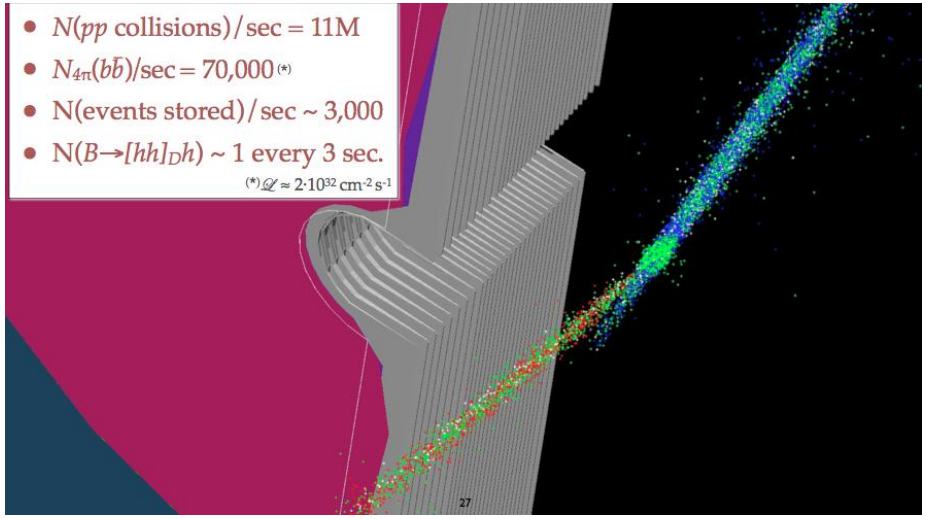
Operational Experience

- In real life you have to be prepared to monitor
  - Some of the things you thought about
  - Plus all of the things you didn't
- Get creative with the data!





Conclusions

- Silicon strip detectors are going (very) strong and the 30 year bubble shows no sign of bursting
- Silicon detectors are precise, efficient, reliable, cost effective and versatile
- Pixel detectors of the future bring a host of applications in HEP, Photon science and medical imaging
- Have fun!

This talk was based on…

- T. Rohe, MC Pad Training event
- https://indico.cern.ch/getFile.py/access?contribId=4&resId=0&materialId=slides&confId=75452
- P.Collins, Itacuruca X ICFA school, http://lhcb-doc.web.cern.ch/lhcb-doc/presentations/lectures/CollinsItacuruca03-2nd.pdf
- P.Collins, ICHEP 2002 Detector R&D, http://lhcb-doc.web.cern.ch/lhcb-doc/presentations/conferencetalks/2002.htm
- P.Collins, Vertex detector techniques for heavy flavour physics, Sheldon-fest http://www.physics.syr.edu/~lhcb/sheldon_fest/
- P.Collins, DESY Instrumentation seminar (VELOPix) http://instrumentationseminar.desy.de/e70397/
- Manfred Krammer, Frank Hartmann, Andrei Nomorotski, EDIT 2011 Silicon sensor lectures, http://edit2011.web.cern.ch/edit2011/
- Richard Plackett, The LHCb Upgrade, https://indico.cern.ch/contributionDisplay.py?contribId=0&confId=127444
- P.Collins, M. Reid, A. Webber, J. Harrison, M. Alexander, G. Casse, Contributions to HSTD-8, http://www-hep.phys.sinica.edu.tw/~hstd8/
- P.Collins, J. Buytaert, Contributions to CERN QA workshop, http://indico.cern.ch/internalPage.py?pageId=2&confId=148944

Suggestions for further reading

- H. Spieler, Semiconductor Detector Systems, Oxford Science Publications, 2005
See also: http://www-physics.lbl.gov/~spieler/
- G. Lutz, Semiconductor Radiation Detectors: Device Physics , Springer (July 11, 2007)
- G. Knoll, Radiation Detection and Measurement Wiley; 4 edition (August 16, 2010)
- A.S. Grove, Physics and Technology of Semiconductor Devices, (1967) John Wiley & Sons; ISBN: 0471329983
- S.Sze, Physics of Semiconductor Devices, J.Wiley, 1981
- T. Ferbel, Experimental Techniques in High Energy Nuclear and Particle Physics, World Scientific, 1992
- K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37**, 075021 (2010)
http://pdg.lbl.gov/2009/reviews/rpp2009-rev-particle-detectors-accel.pdf

...and references therein