Roger Rusack   The University of Minnesota

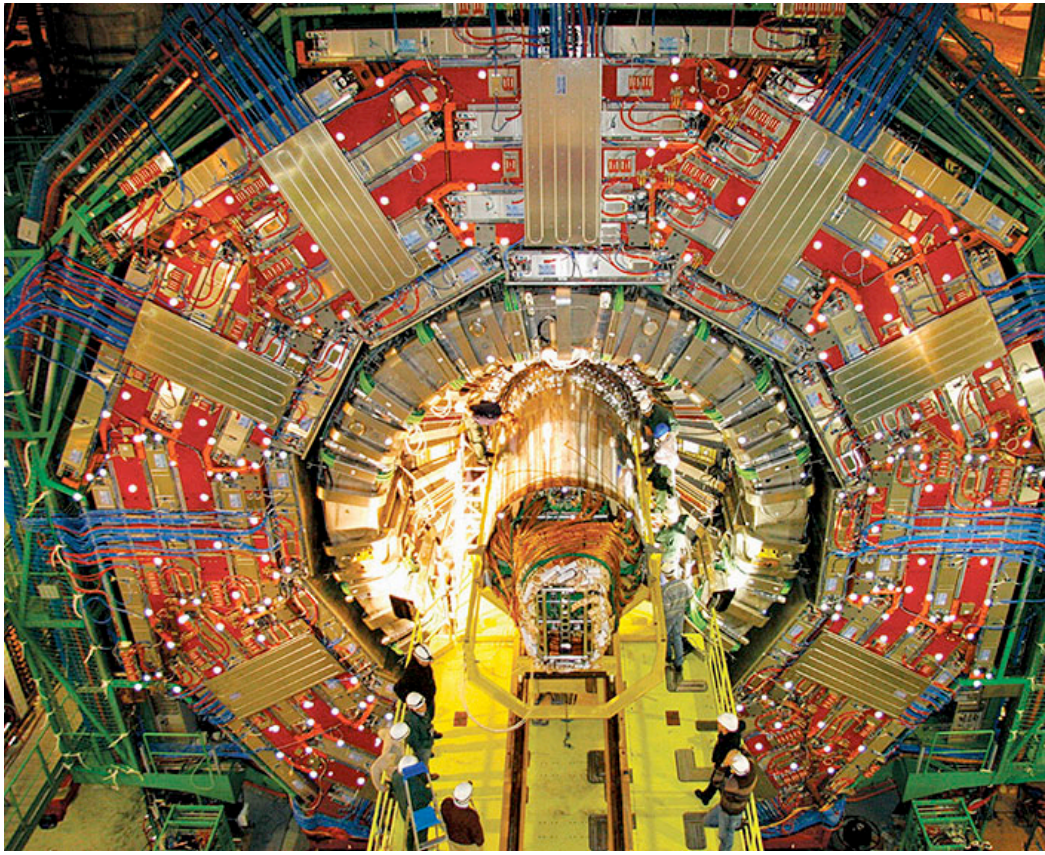
DETECTORS WITH SILICON

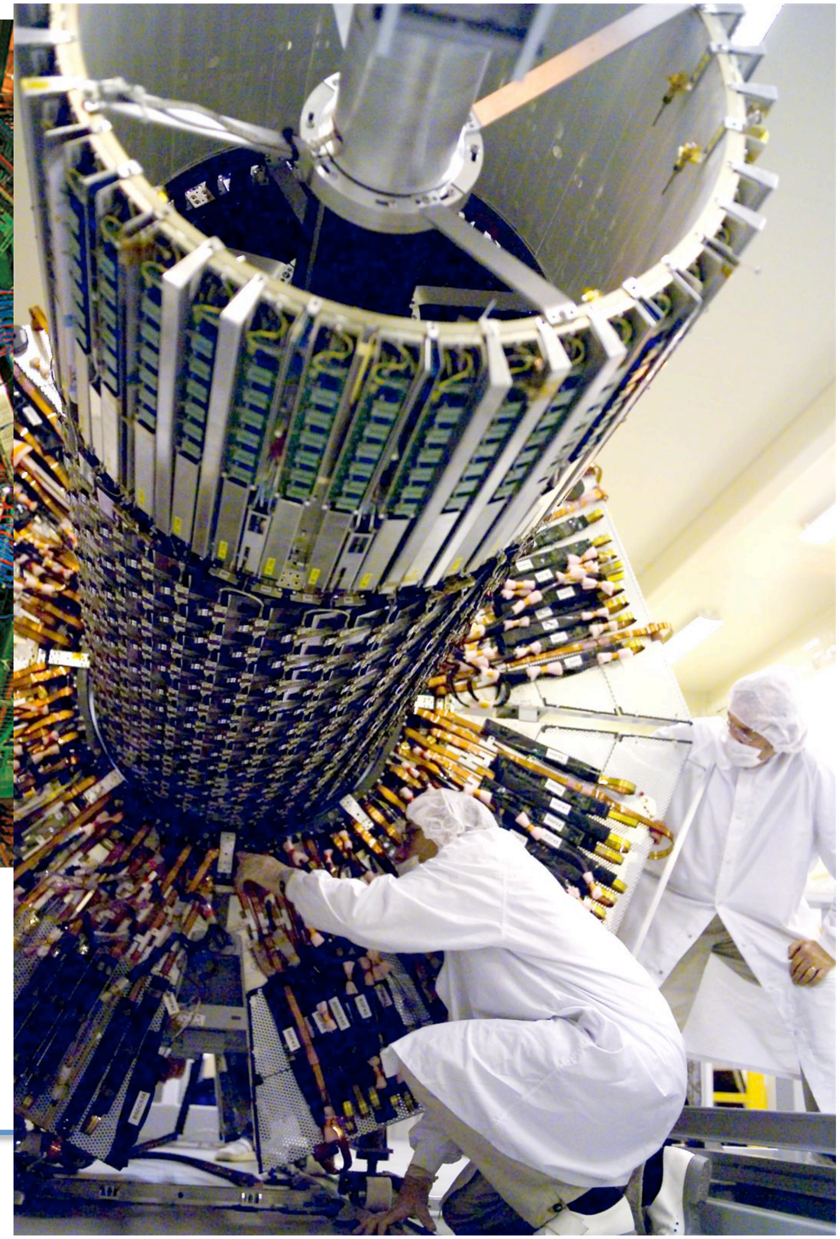
Outline

Explanation of the basics of principles of silicon detectors used for particle detection in our field.

Again I emphasize this is not an exhaustive discussion – more of an introduction to the main components we use in our detectors.

ATLAS and CMS trackers





All four of the LHC detector shave silicon trackers.

Basics

Silicon is the second most abundant element on the earth and the best understood material.

Production of silicon crystals and wafers is an extremely well defined process. In Taiwan TSMC processes 80 million wafers a year.

Semiconductors are ‘doped’ tri-valent and penta-valent elements to make *p*-type and *n*-type semiconductors.

In *n*-type silicon electrons are loosely bound and are ‘majority’ carriers.
In *p*-type silicon the holes are the majority carriers.

The central element of a silicon detector is p-n junction where two types of material meet.

In practice the surface of p-type silicon is implanted with As, P or Sb to make an n-p junction, or n-type has B, Ga or In.

Semiconductor Basics

In a high purity 'intrinsic' semiconductor there is a continuous thermal generation of electron hole pairs. The Fermi level is in the bandgap and the carrier concentrations (n and *p)* are:

$$n = N_C \exp\left(\frac{E_F - E_C}{kT}\right) \text{ and } p = N_V \exp\left(\frac{E_V - E_F}{kT}\right)$$

assuming exponential behavior of the unoccupied states and N_c and N_V are the 'effective' number of states in the conduction and valence bands and E_g is the bandgap.

$$np = n_i^2 = N_c N_v \exp\left(\frac{(E_V - E_c)}{kT}\right) = N_c N_v \exp\left(\frac{-E_g}{kT}\right)$$

The concentration of electrons in the material is then

$$n_i = \sqrt{N_c N_v} \exp\left(\frac{-E_g}{2kT}\right) = AT^{3/2} \exp\left(\frac{-E_g}{2kT}\right)$$

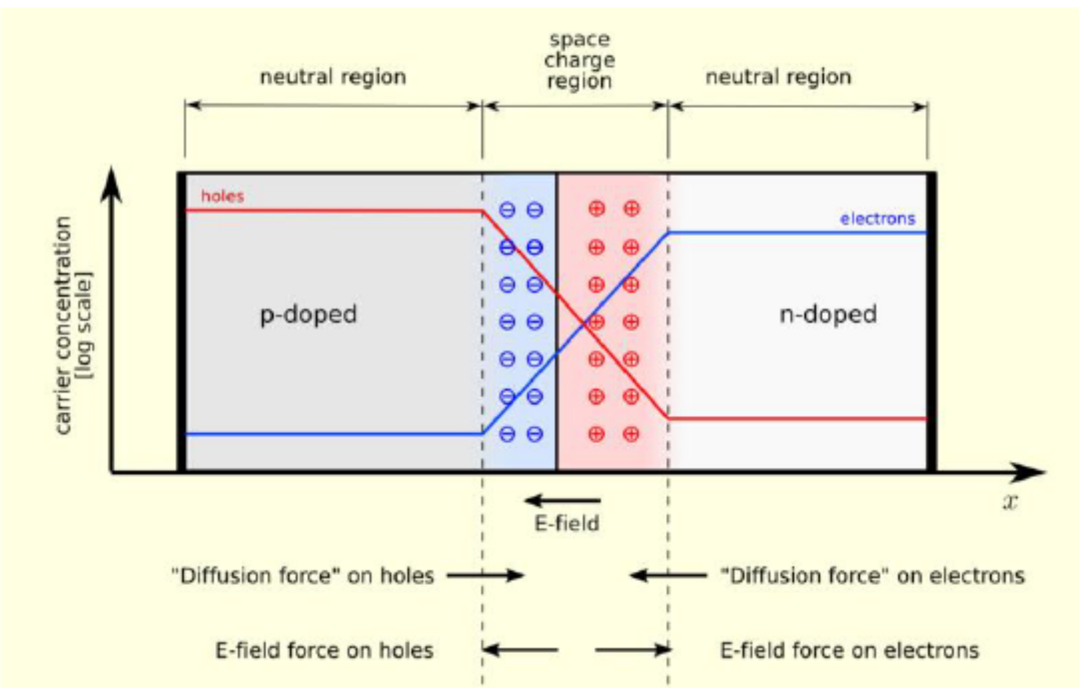
and the product concentrations $np = n_i^2$ independent of the doping.

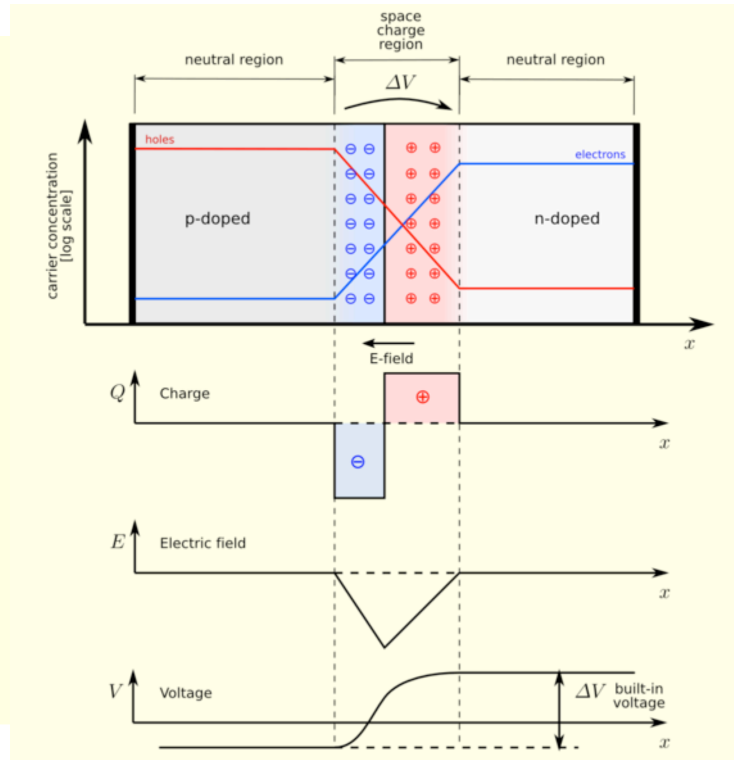
Properties of silicon

Density	2.33 $g.cm^3$
Dielectric Constant	12
Energy Gap at 300K	1.12 eV
Charge Carrier density	1.5×10^{10}
Electron mobility @ 300K	1350 $cm^2/V.s$
Hole mobility @ 300K	480 $cm^2/V.s$
Energy per electron hole pair	3.62 eV

The *p-n* junction diode

In an unbiased *p-n* junction diode majority carriers migrate from one side to the opposite side, until the potential difference - ΔV – due to the charge distribution halts the process.





The at the junction there is on either side a depletion region where the number of free carriers is at the intrinsic level. This the ‘depletion region’.

The *p-n* diode

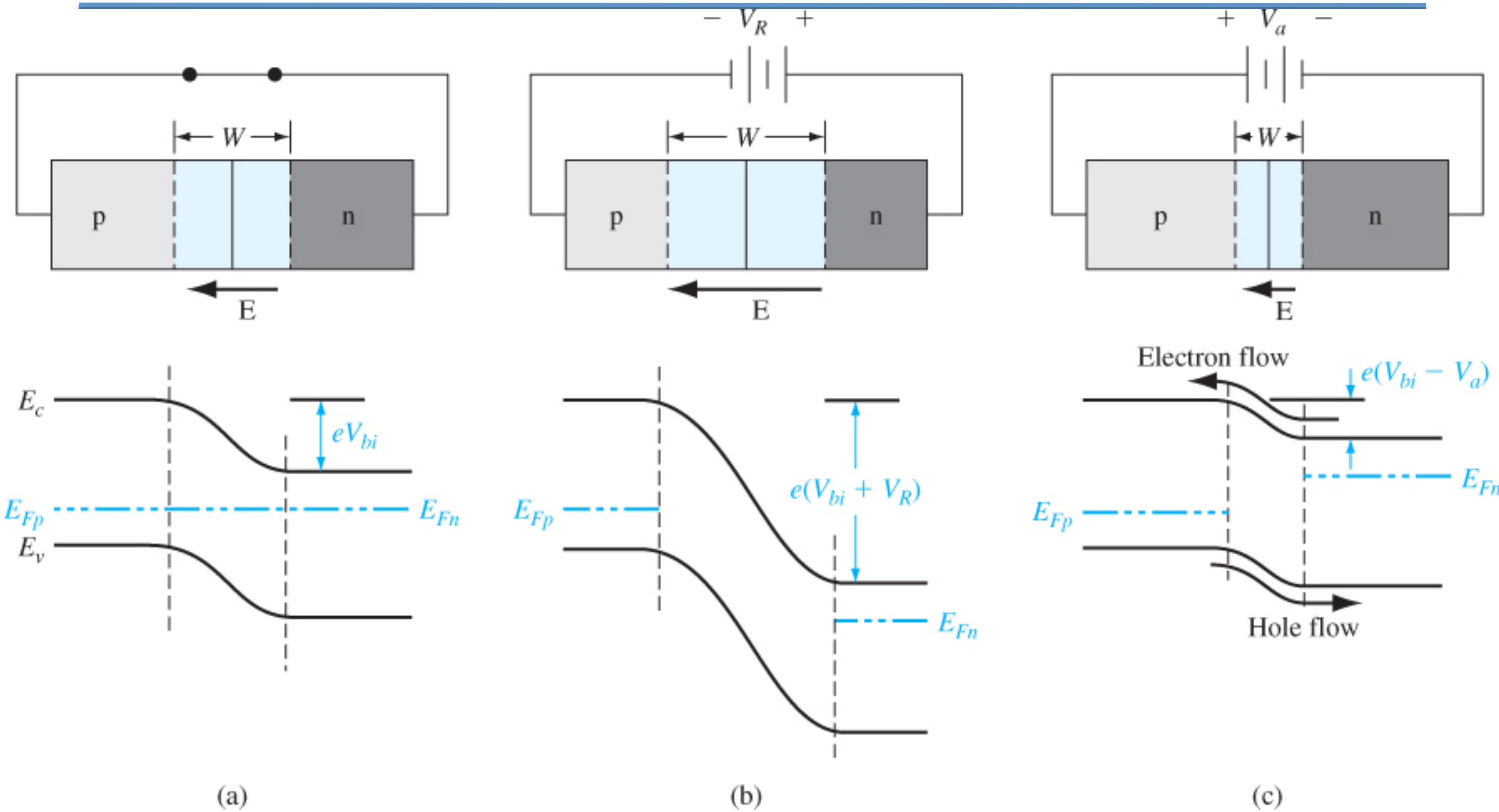


Figure 8.1 | A pn junction and its associated energy-band diagram for (a) zero bias, (b) reverse bias, and (c) forward bias.

Semiconductor Basics

- Specific resistivity ρ

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

- In an n-type semiconductor n ≫ p ⇒ $\rho_n \approx \frac{1}{en\mu_e}$
- The depletion thickness *d* is:

$$d = \sqrt{2\varepsilon(U + U_c)\mu\rho_n} \quad \text{or} \quad d \approx 0.3\sqrt{U.\rho_n}\ \mu\text{m}$$

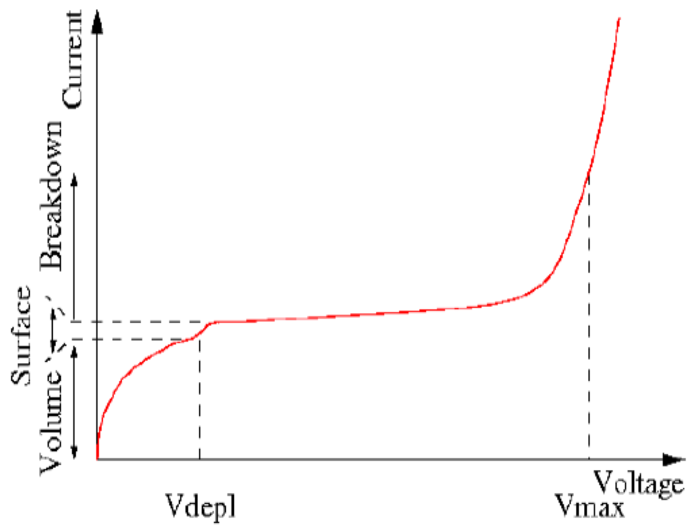
- For an p-type sensor

$$d \approx 0.5\sqrt{U.\rho_p}\ \mu\text{m}$$

For a typical sensor with ρ = 5×10^3 Ω.cm and U = 100 V, *d* is ~350μ

The *p-n* diode – Dark Current

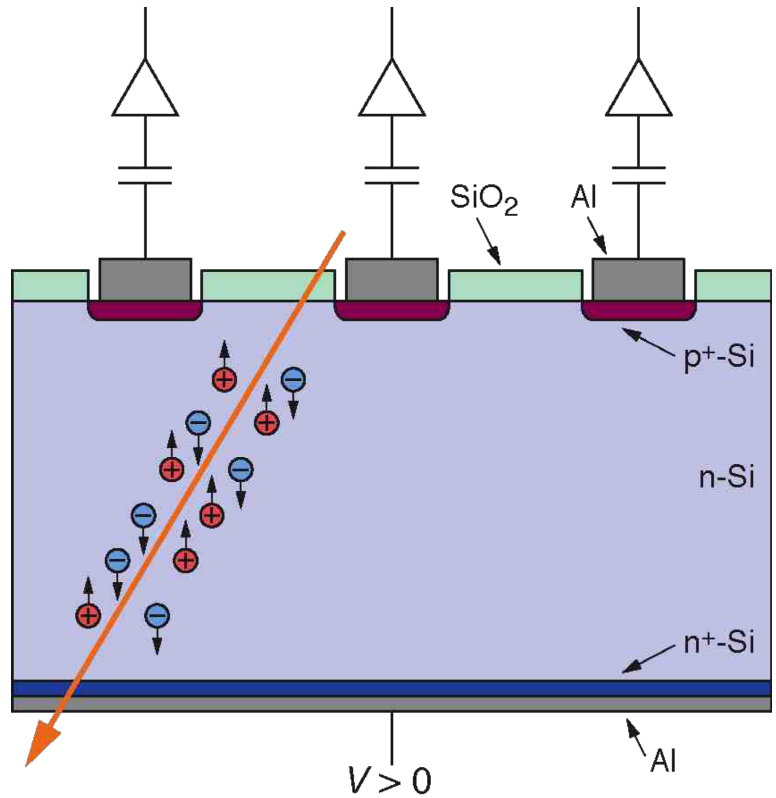
There is a continuous thermal generation of electron-hole pairs in the depletion region. This is the dark current seen. As the bias increases the depletion region grows and the dark current also grows. Once the whole wafer is depleted the dark current will be remain constant



The dark current reduces with temperature as $$I_{dark} \propto T^{\frac{3}{2}} \exp\left(\frac{-E_g}{kT}\right)$$

Decreasing about a factor of 2 for every 7 °C.

Silicon trackers:



In a silicon sensor the wafer is a fully depleted pn-junction

The diode acts like a ionization chamber. All charge travels to the anode and cathodes.

As the mobilities of holes are similar the charge is collected simultaneously.

Charge collection time is $T = \frac{d}{\mu E} = \frac{d^2}{\mu U}$

$$T = \frac{d}{6}$$

With μ = 1350 cm^2/V.s and d = 350 μ and U = 100 V, T ≈ 10 ns.

Silicon Trackers

This has become the "baseline" technology for the energy frontier. It is:

- Precise ~ micron-level resolution
- Moderate to low mass (depends on density, cooling, electronics)
- Fast ~ can achieve sub-nanosecond resolution
- Radiation hard – can be designed to operate to $10^{16}/cm^2$ fluence
- Costly? < $\$10/cm^2$ for CMS sensors $\$3/cm^2$ for CMOS electronics,=.

We profit from the huge technical advances and infrastructure in the semiconductor industry

Signal and Noise

- Signal
  - With 3.62 eV for energy loss per e-h pair a minimum ionizing particle will generate ~ 80 e-h pairs per micron.
  - Bandgap of 300 µ ⇒ signal is 24,000 e-h pairs.
  - ~ 4 fC /mip
- Noise:
  - Noise is determined by several parameters
    - detector geometry
    - Readout electronics.
    - Dark current
    - Etc.
  - Noise is usually defined in terms of the *Equivalent Noise Charge* (ENC).

$$ENC = \sqrt{ENC_C^{\,2} + ENC_I^{\,2} + ENC_S^{\,2} + ENC_R^{\,2} + \ldots}$$

Signal to Noise

- ENC in a strip detector is usually dominated by the detector capacitance with:

$$ENC^2 = (C_{\det} + C_{gate})^2 \frac{a_1 \gamma 2kT}{g_m t_s}$$

g_m = amplifer gain and t_s is the shaping time.

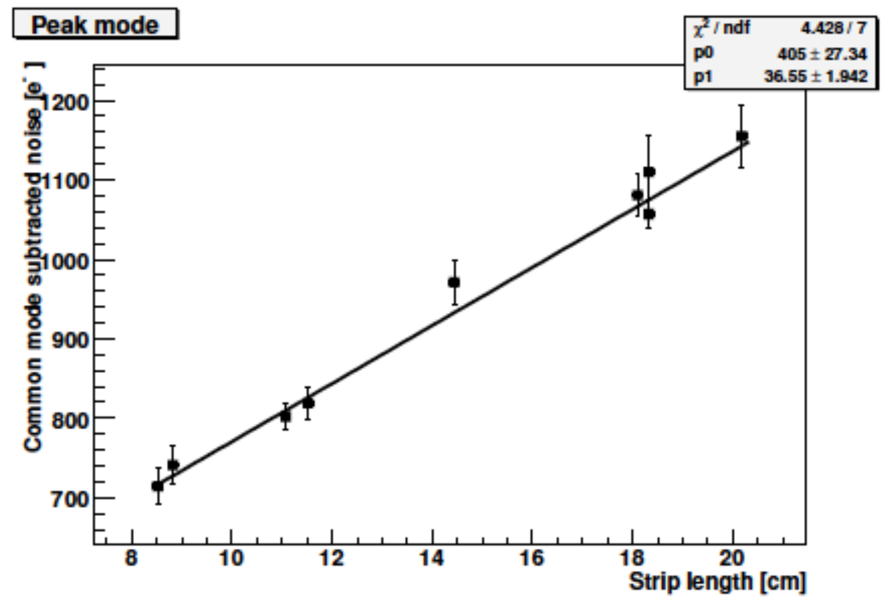
- ENC increases as the detector capacitance.
- ENC decreases with $\sqrt{t_s}$ and $\sqrt{g_m}$.
- Detector capacitance determined by
  - Strip area and the depletion depth and
  - the inter-cell capacitance.
- Shaping time is determined by the beam conditions.
- Amplifier gain is determined by the power ($g_m \propto I$).

Signal to Noise

- Noise can usually be parameterized as:

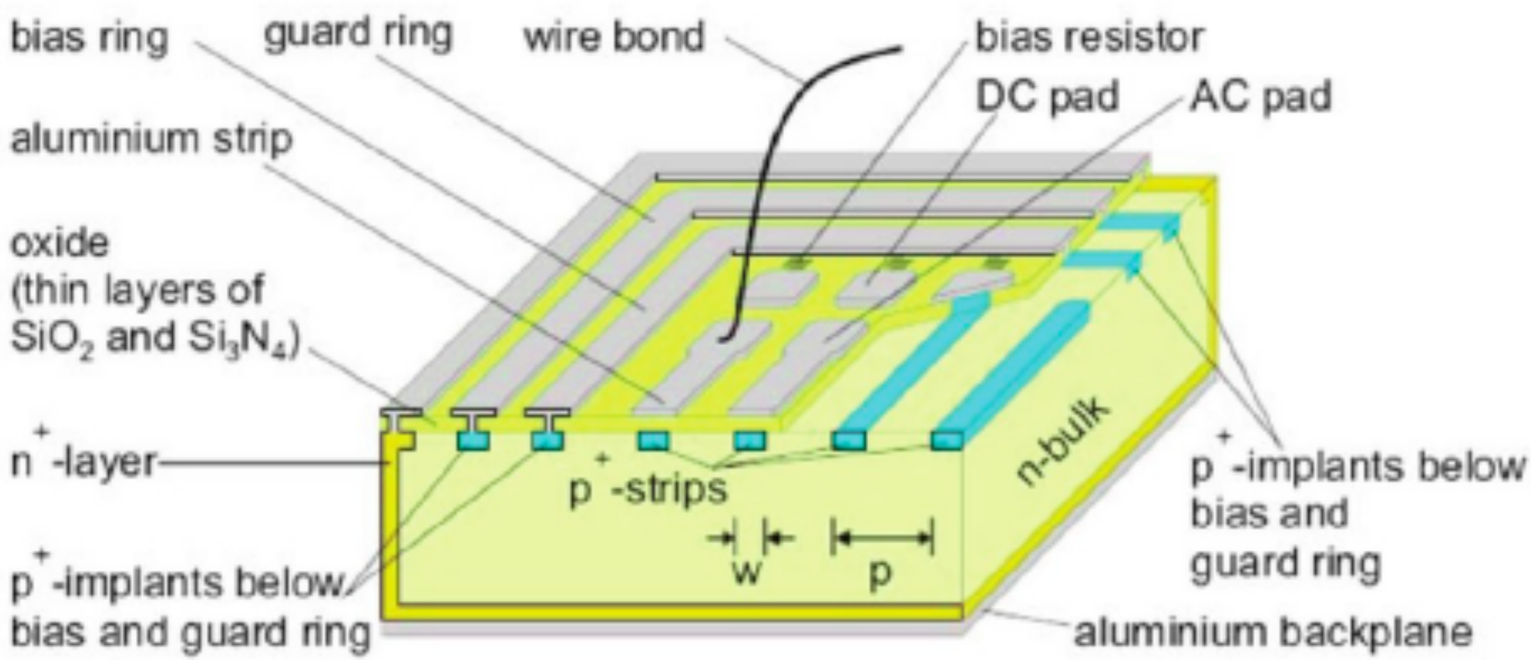
$$ENC = a + bC_{\text{det}}$$

- CMS parameters:
  - Shaping time 50 ns.
  - Amplifier 2.3 mW/channel.
  - Strip capacitance is ~ 1.6 pF/mı
  - Strip length ~ 10 - 20 cm.
  - ENC = 270e + 38 e/pF*C_{det}
  - ENC ~ 1000
- Signal-to-Noise ratio ~ 25:1



CMS - Silicon tracker

The CMS tracker structure:

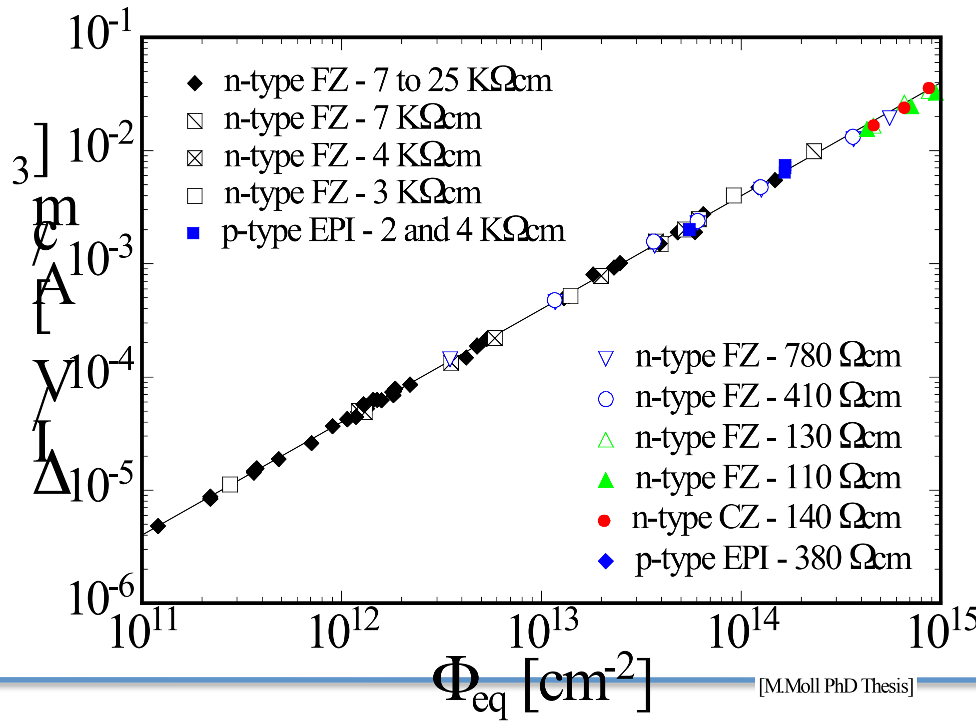


Radiation Damage

The principle source of radiation damage in silicon sensors is from non-ionizing-energy-loss (NIEL). It is normally expressed in terms of 1 MeV neutron equivalent for silicon.

Effects are the conversion of material from *n*- to *p*-type ⇒ increased bias.

Increase in the number of traps in the forbidden zone ⇒ Increase in dark current..



[M.Moll PhD Thesis]

$$I_{det} = I_0 + \alpha \Phi \times Volume$$

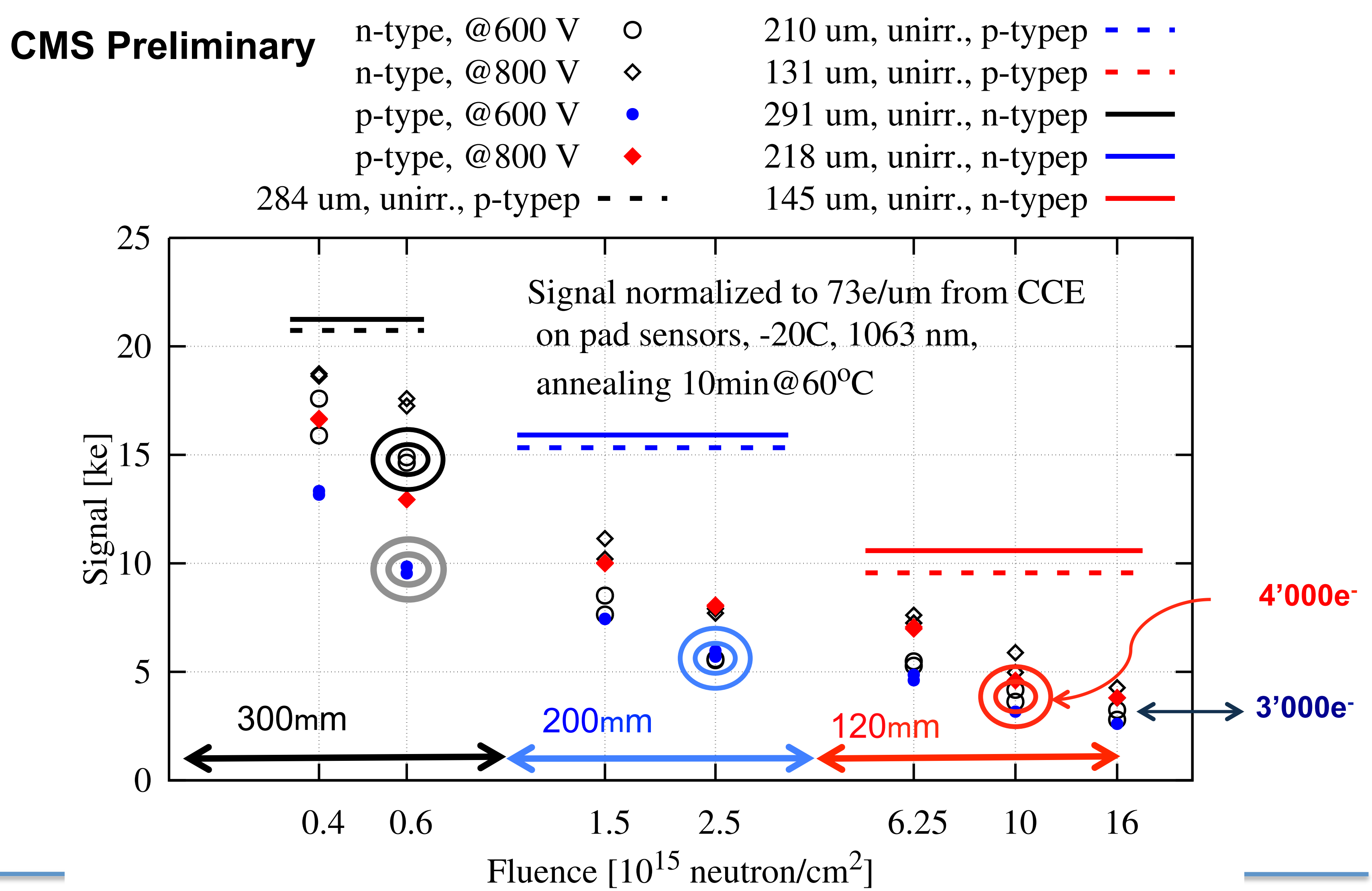
$$\alpha = 2 - 3 \times 10^{-17} A / cm$$

Radiation Damage

- Other effects:
  - Increase in traps reduces carrier lifetime. At some point the charge collection efficiency (CCE) is reduced as the carriers do not cross the depletion zone.
  - Increase in the dark current can lead to local heating – as dark current increases with temperature this could lead to thermal run away.
  - Increasing the dark current $\Rightarrow$ increase in ENC.

In high radiation environments the detectors are run cold (-20^{o} C) to reduce the dark current and to minimize the risk of thermal runaway.

Highly Irradiated Silicon

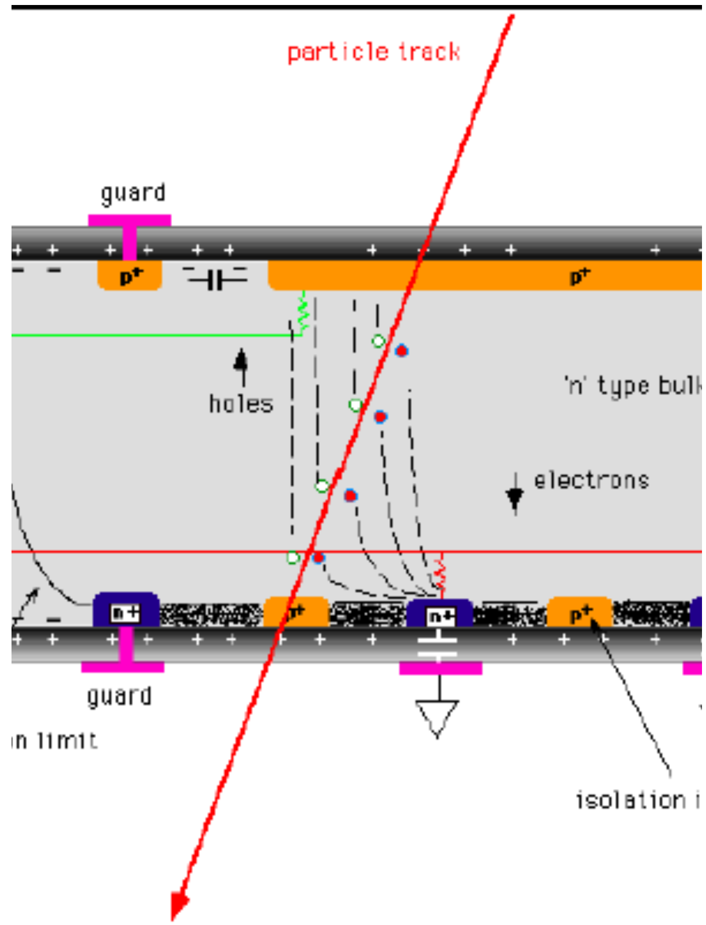


Pixel detectors

Pixel detectors were first discussed in the mid-1980's and are now a major tool in colliding experiments.

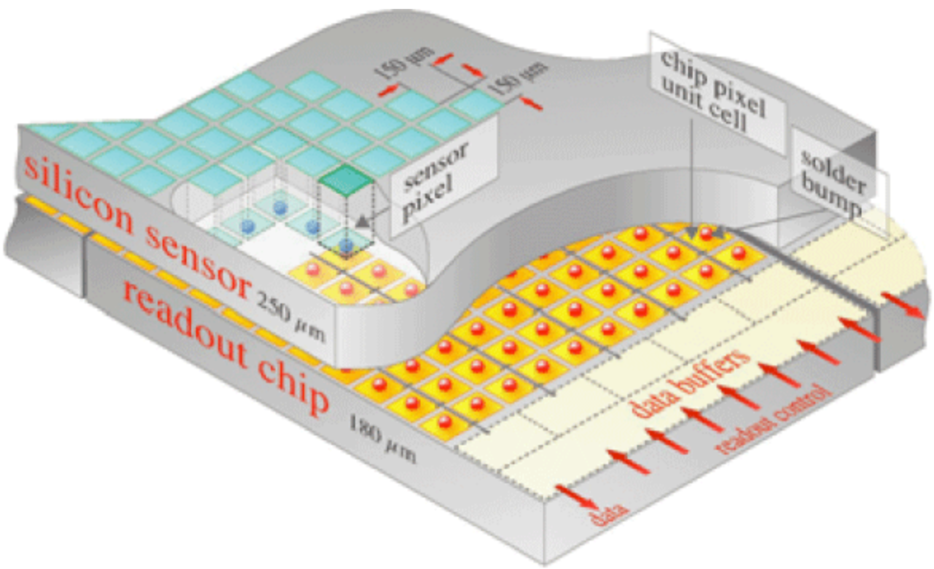
Basic idea is to divide the silicon sensor into small cells and readout each cell individually.

The major component is the readout ASIC which is bump bonded to the pixel sensor.

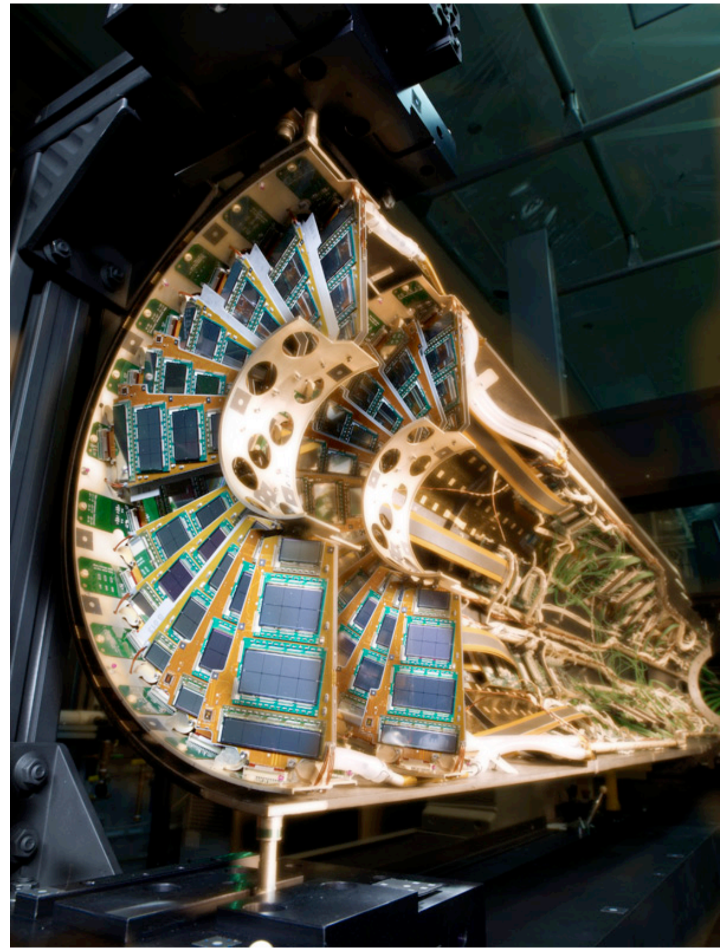


Pixel Detector

The CMS pixel detector has pixels that are 100 × 150 μm^2



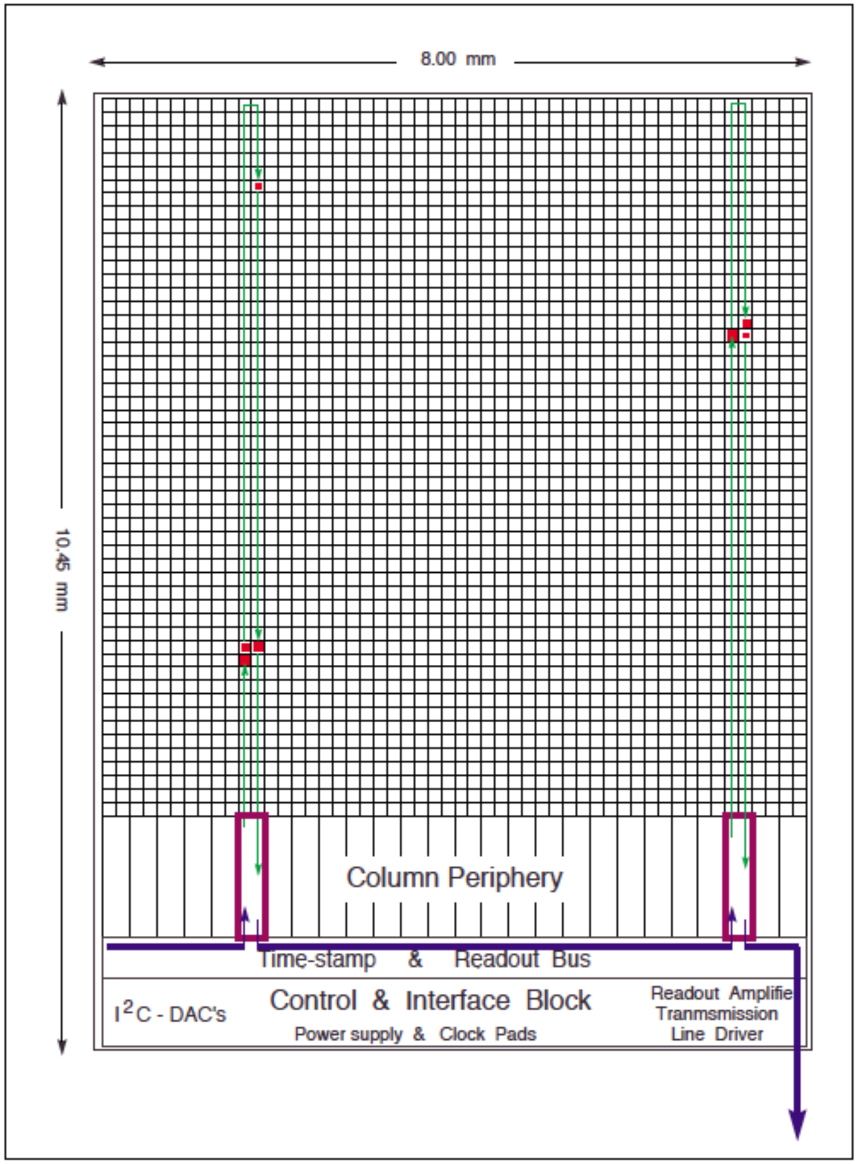
The interconnect is made with PbS bump bonds with a pitch of 50μm.



Readout of a Pixel Detector

In CMS there are 60 million pixels ⇒ extracting all the signal information off detector at the bunch crossing rate is impossible.

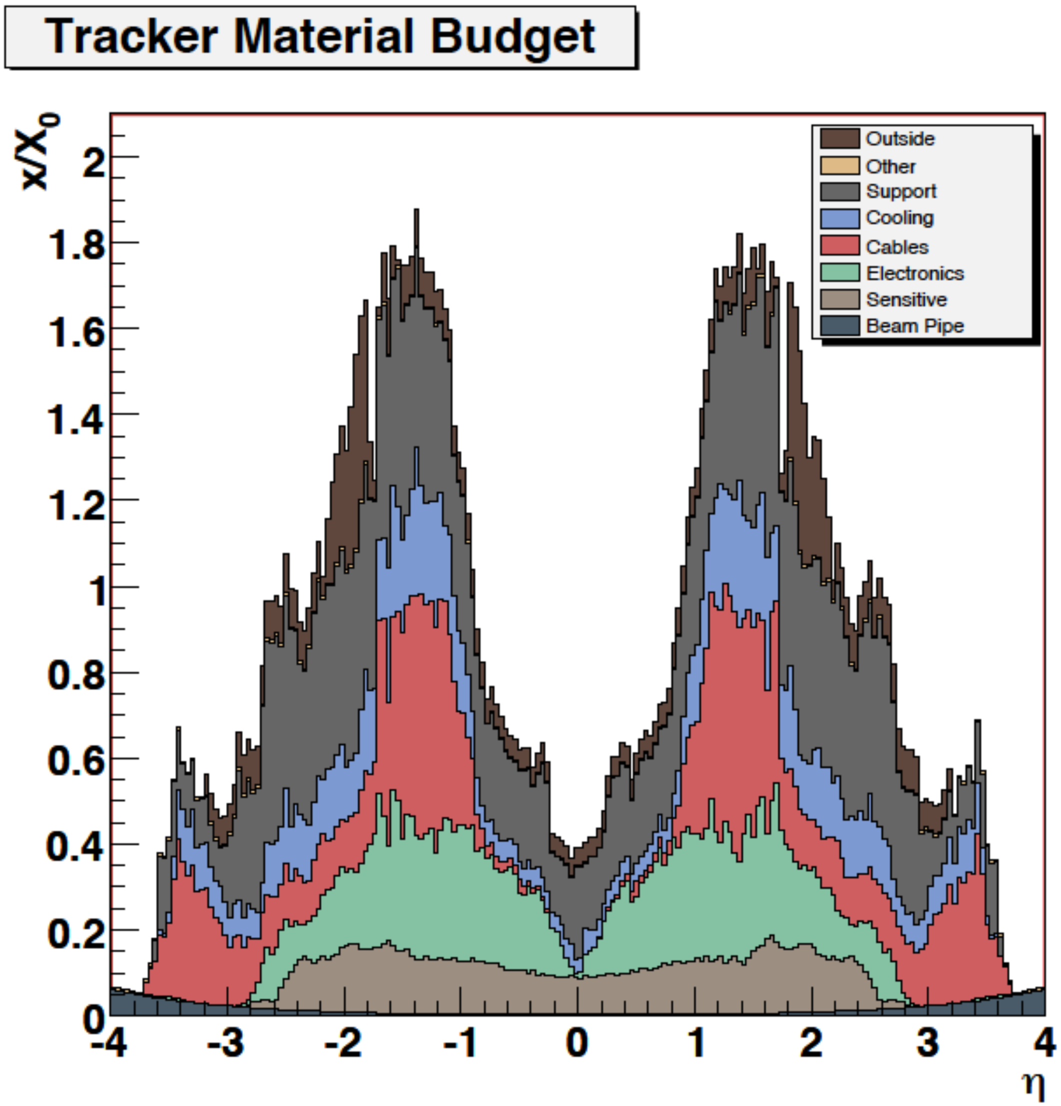
After a collision the analog information stored until a level 1 accept is received, zero-suppressed analog signal is transmitted off the detector to the off-detector readout.



Practical matters

- Designing a detector requires services:
  - Power in:
    - The silicon tracker consumes ~2.3 mW/channel. There are 9 million channels ⇒ total power consumption is ~ 20 kW.
  - Heat out
    - Need to remove the power in as heat.
    - Design uses C_6F_{14} as the coolant for operation at -20^o C.
  - Signals out.
    - CMS uses an analog optical fiber clocked at 40 MHz for the tracker.
    - Other (sub-)detectors use digital optical readout.
  - Mechanics
    - To support the detector you need a mechanical support that is rigid and thin. Essential to achieve the position resolution of the ~10 μm.

Tracker material budget

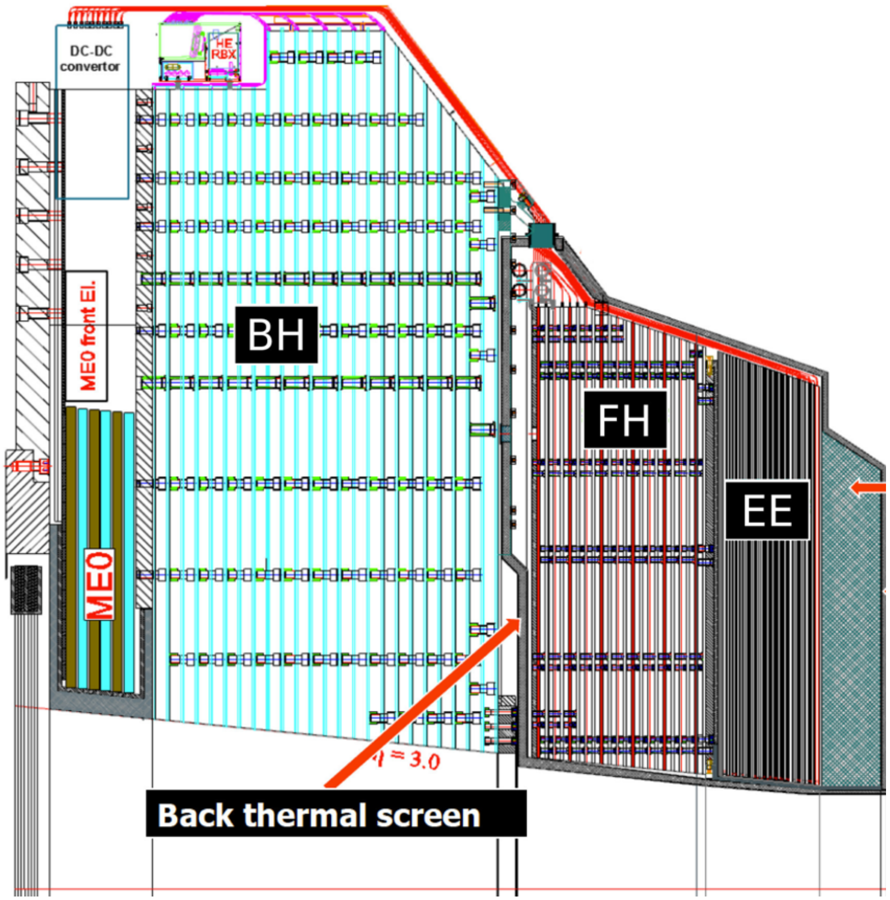


Design a new Calorimeter

Inspired by the progress in calorimetry in the context of the ILC with colleagues we have proposed for the forward region of CMS an imaging calorimeter.

Extending the tracker into the calorimeter to have multiple layers of sampling.

The CMS HGC Design



Construction:

- *Hexagonal Si-sensors built into modules.*
- *Modules with a W/Cu backing plate and PCB readout board.*
- *Modules mounted on copper cooling plates to make wedge-shaped cassettes.*
- *Cassettes inserted into absorber structures at integration site (CERN)*

Key parameters:

- *593 m^2 of silicon*
- *6M ch, 0.5 or 1 cm^2 cell-size*
- *21,660 modules (8" or 2x6" sensors)*
- *92,000 front-end ASICS.*
- *Power at end of life 115 kW.*

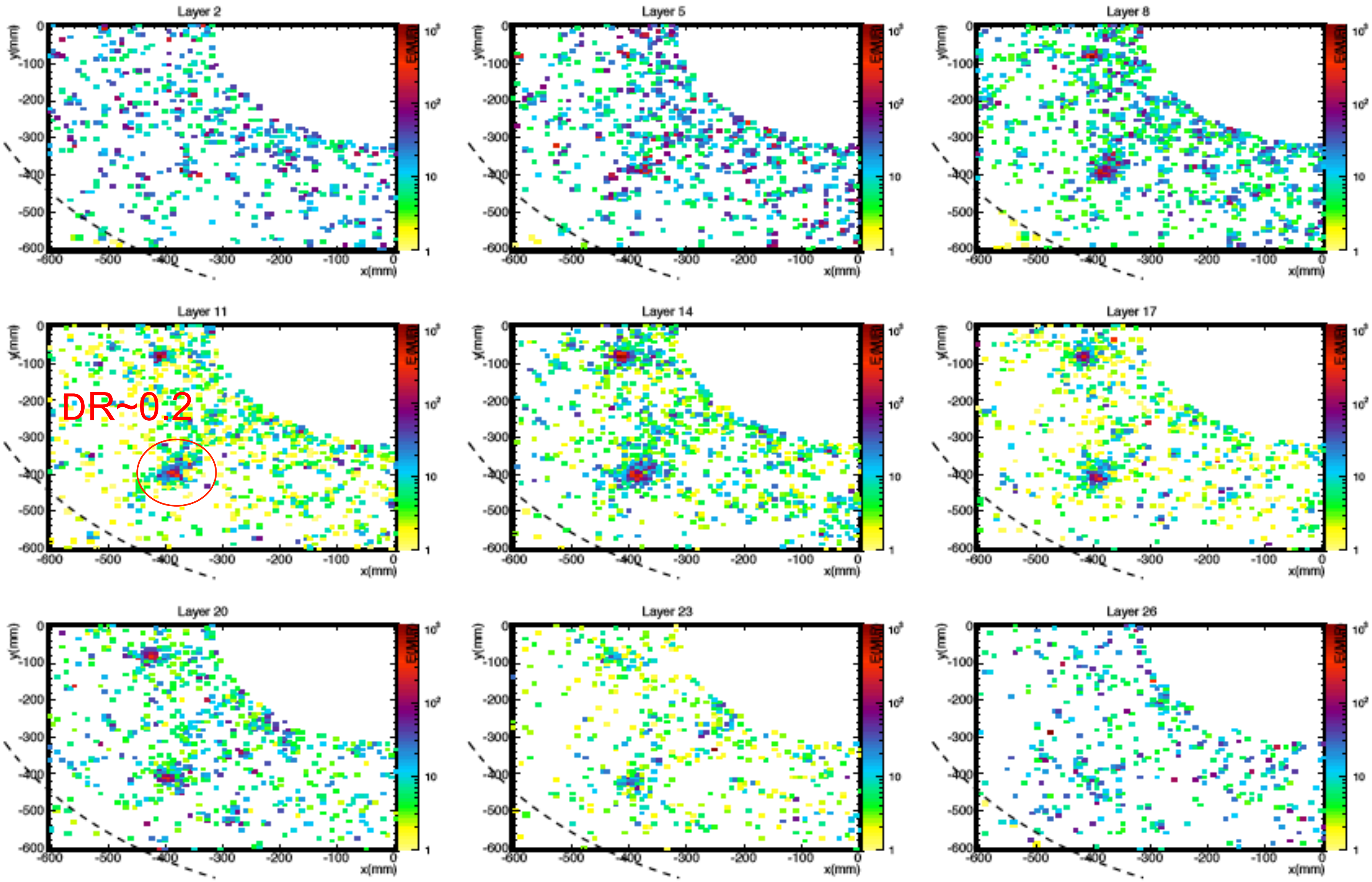
System Divided into three separate parts:

EE – Silicon with tungsten absorber – 28 sampling layers – 25 X_o + ~1.3 λ
FH – Silicon with brass absorber – 12 sampling layers – 3.5 λ
BH – Scintillator with brass absorber – 11 layers – 5.5 λ

EE and FH are maintained at – 30°C. BH is at room temperature.

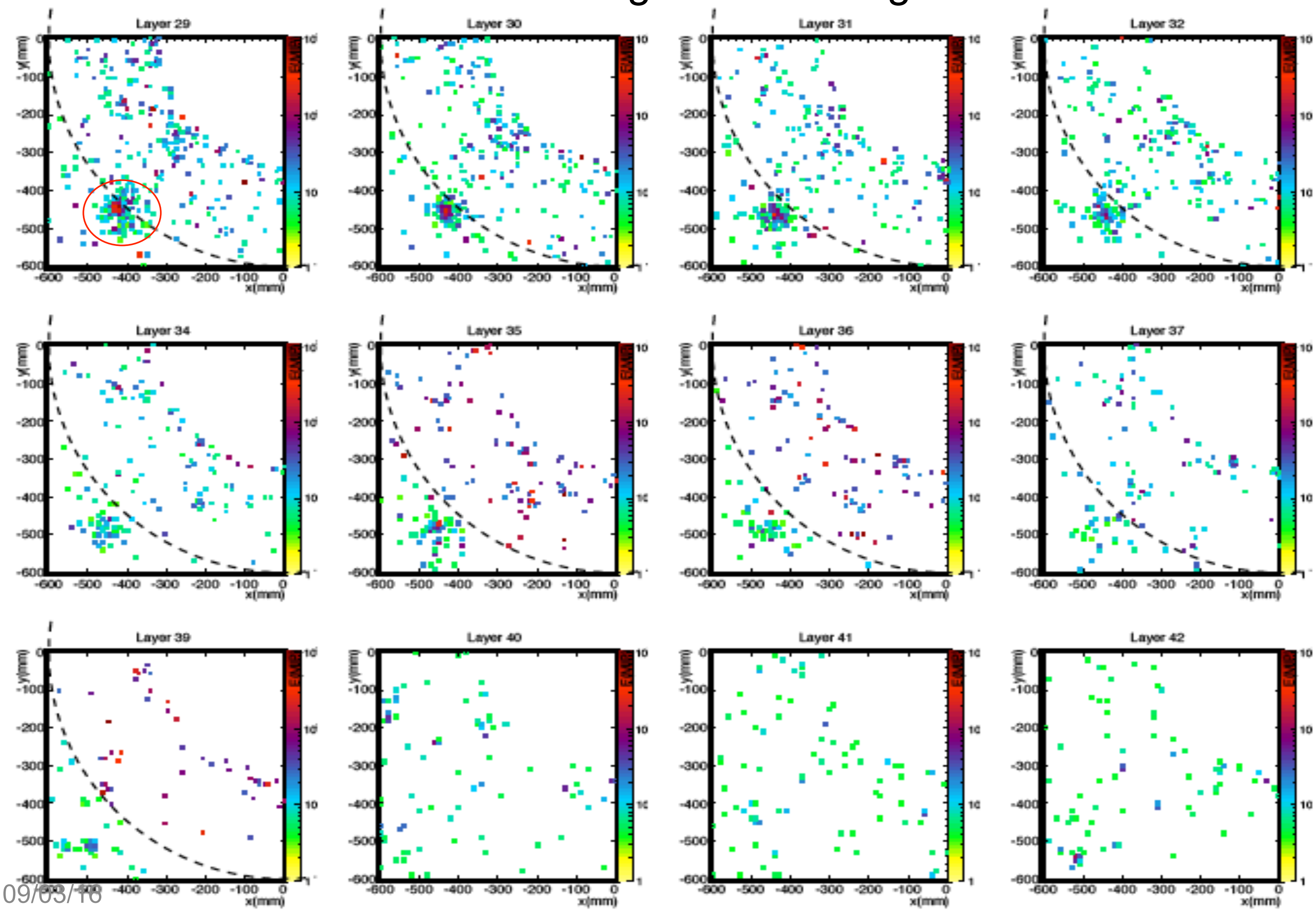
Event Display of VBF Jets (VBF H→γγ)

Standalone simulation: Taking Slices through ECAL section



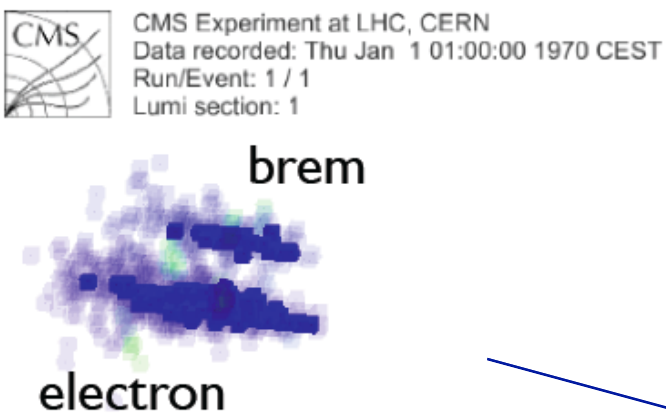
Event Display of VBF Jets (VBF H→γγ)

Standalone simulation: Taking Slices through Si- HCAL section

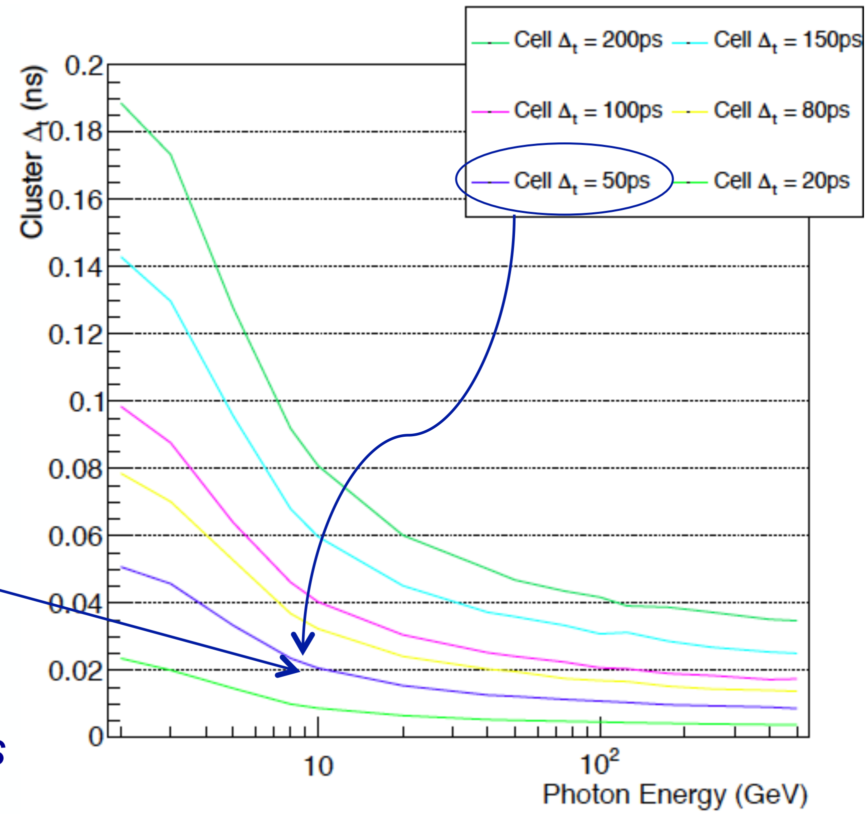


HGC Cluster Timing

Transparent cells => no timing
Solid cells = > timing information < 50ps
Nb 25MIP threshold was assumed



~35GeV p_T e^-

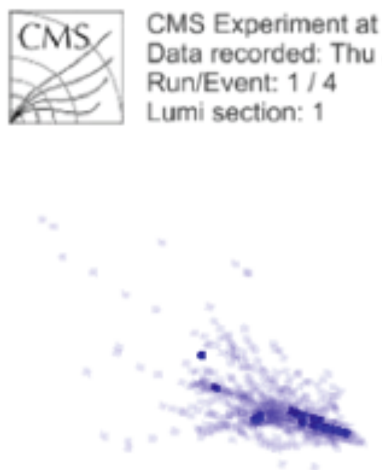


Δ_t is 68% effective RMS
20ps * c = 6mm

50ps cell timing provides better than 20ps timing for 10GeV EM clusters

HGC Cluster Timing

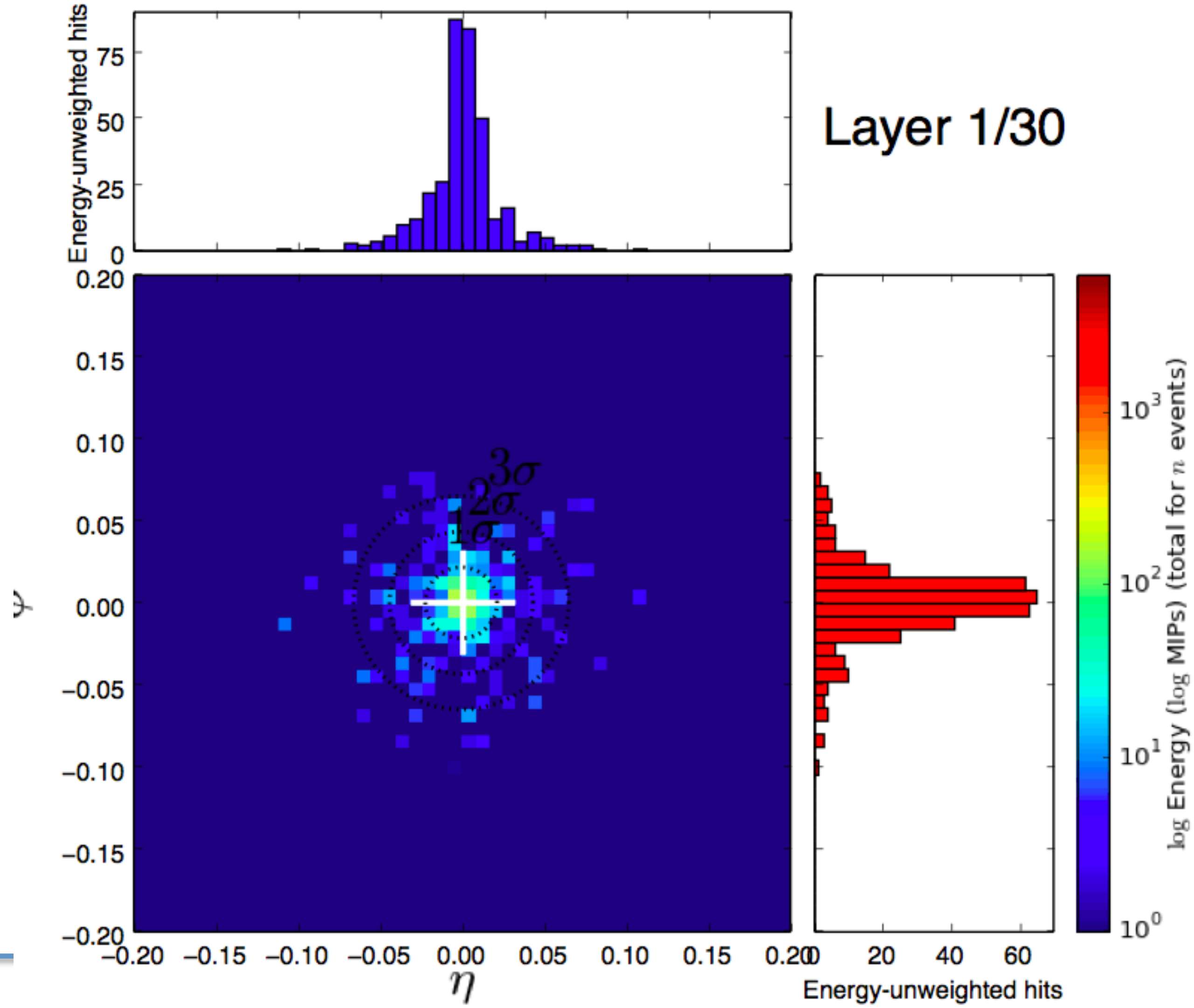
Transparent cells => no timing
Solid cells = > timing information < 50ps
Nb 25MIP threshold was assumed



10GeV p_T p^+

Charged hadrons more challenging:
rely on EM component of hadronic shower
⇒lower cell thresholds
⇒ optimize response for precision timing

Dedicated discriminator/TDC channel under study
To fully benefit from intrinsic timing resolution



Layer 1/30
Energy-unweighted hits
0
25
50
75
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
−0.20 −0.15 −0.10 −0.05 0.00 0.05 0.10 0.15 0.20
η
φ
1σ
2σ
3σ
0 20 40 60
Energy-unweighted hits
10^0
10^1
10^2
10^3
log Energy (log MIPs) (total for n events)

Summary

Detector design and developments based on progress in technology is one of the major drivers in our field.

It is both challenging a interesting, calling on expertise from many fields of engineering and basic science.