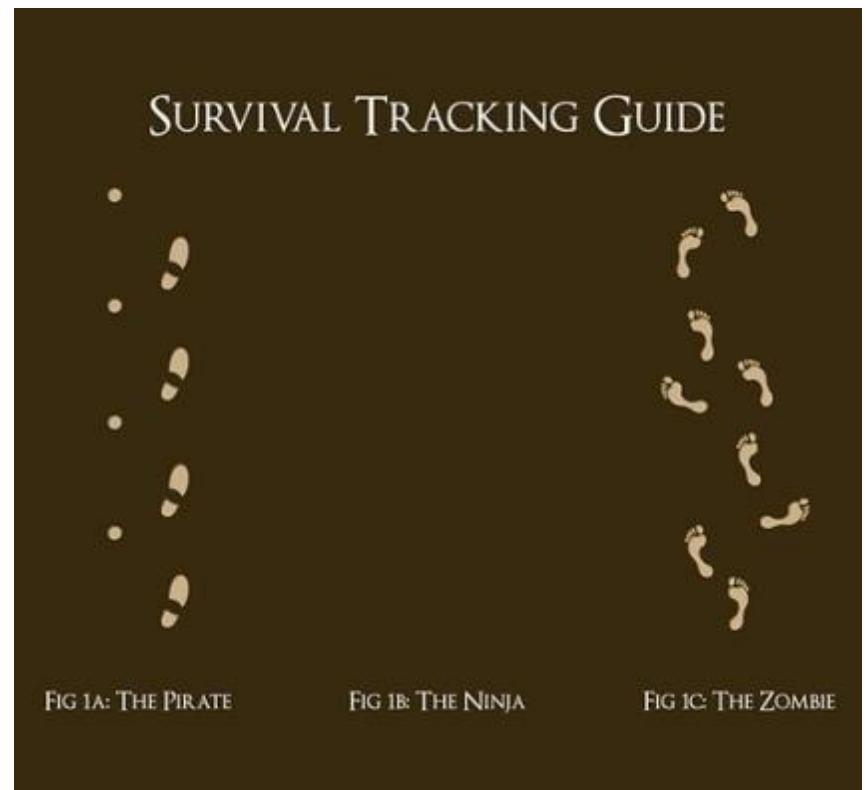


Silicon Tracking

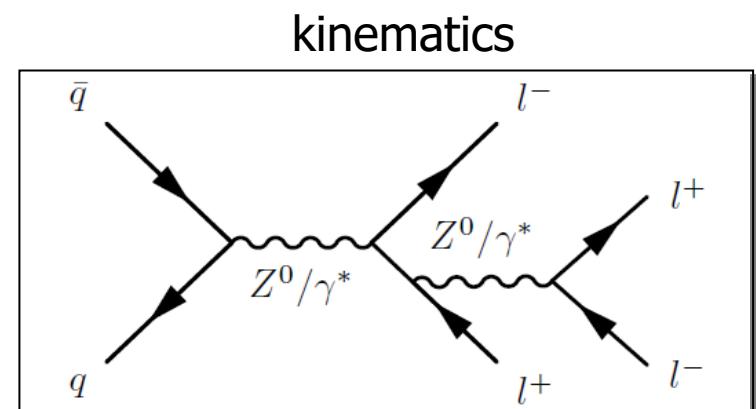
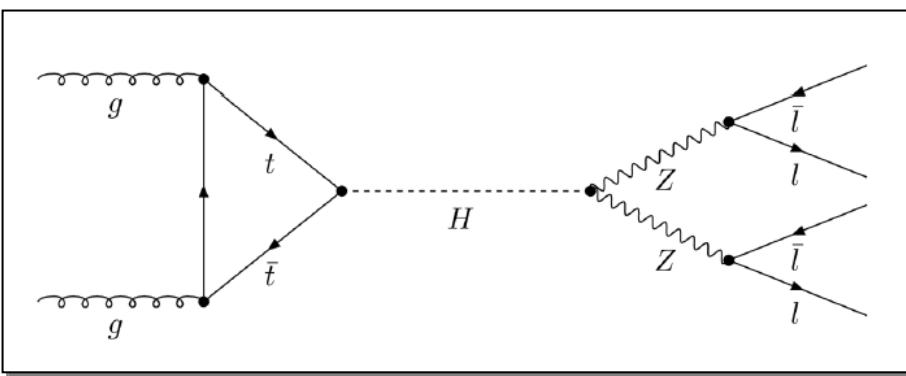
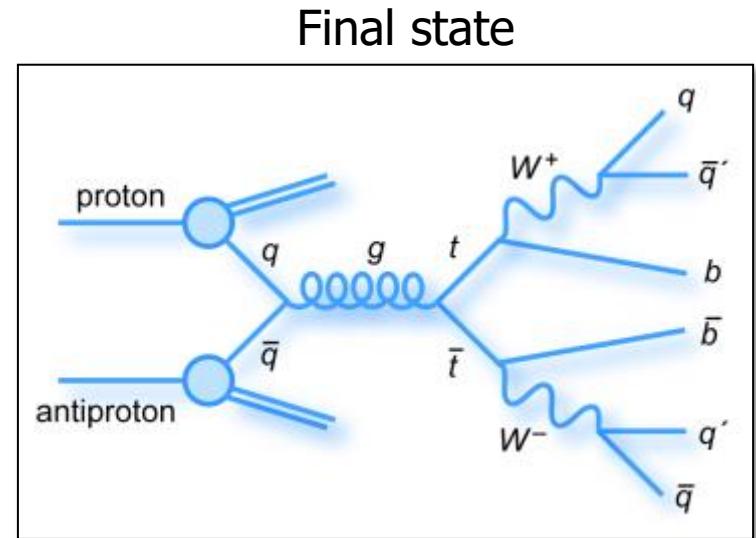
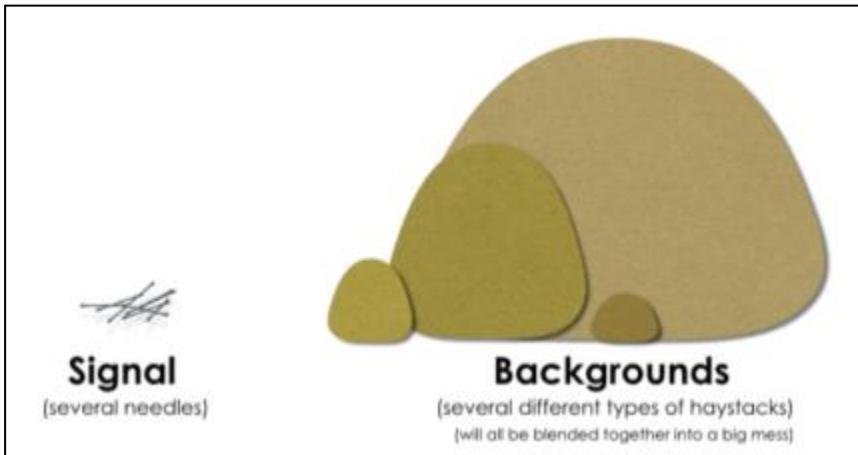
(Not a semiconductor lecture)

1. What is tracking for ?
2. Silicon detectors
3. Technologies

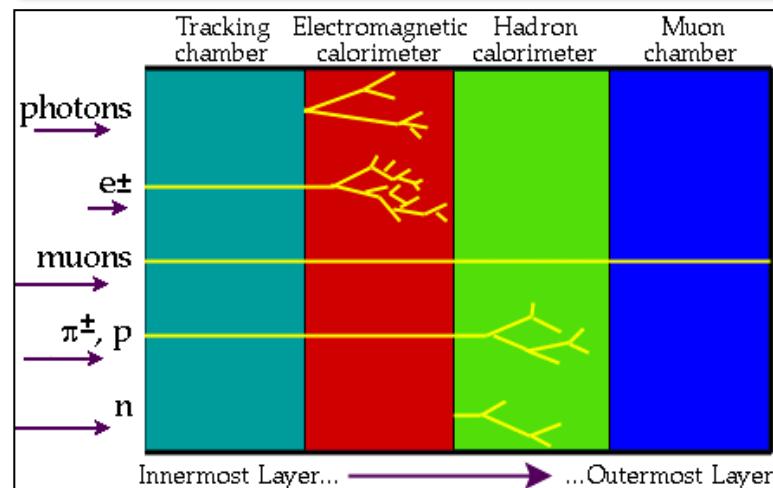
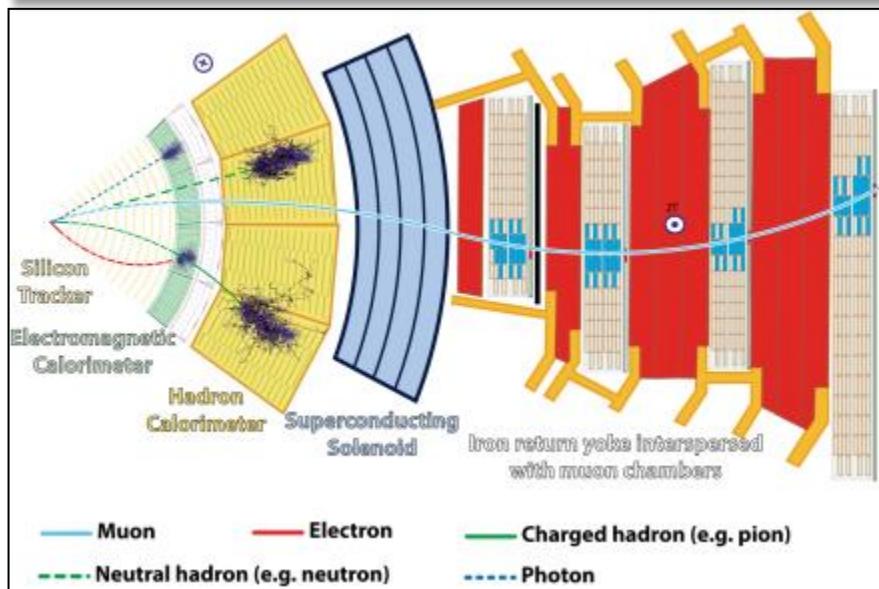
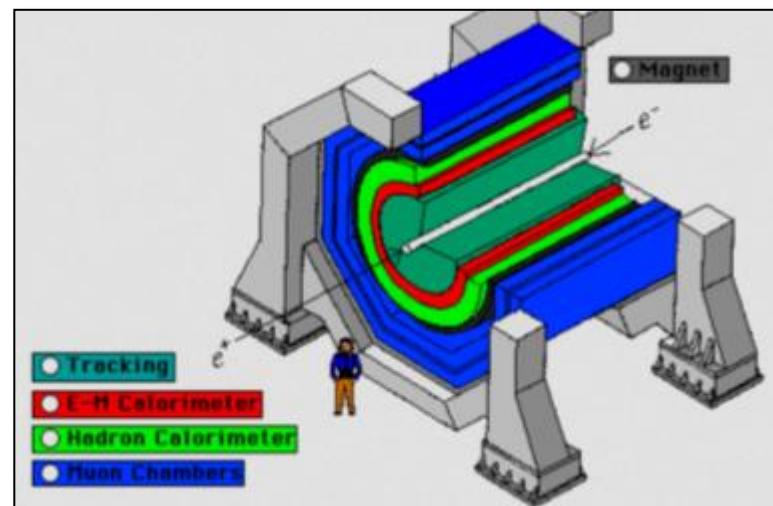
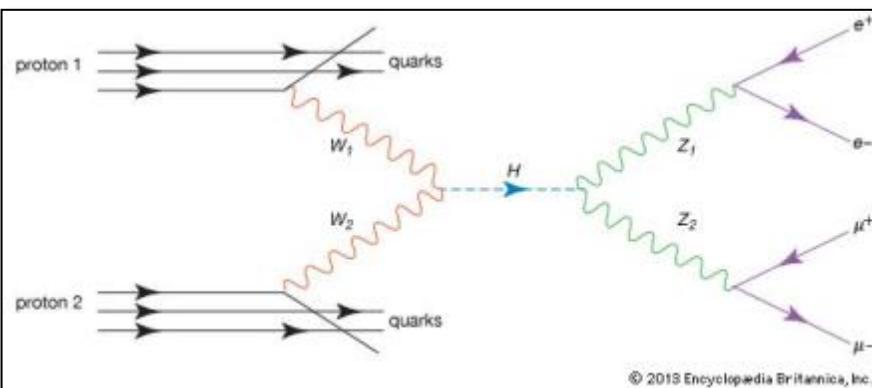


Particle physics

- It's all about Signal and background



Detectors in particle physics



Ideally, we would like to know :

- Identify all particles
- Vertex and decay chain
- 4-vectors (E, p_x, p_y, p_z) of all particles

Detection chain

What you want to detect



What You measure



interaction

- ✓ electrons
- ✓ photons (X, visible, γ , etc.)
- ✓ neutrons
- ✓ protons, hadrons (π^\pm , K, etc.)
- ✓ ν

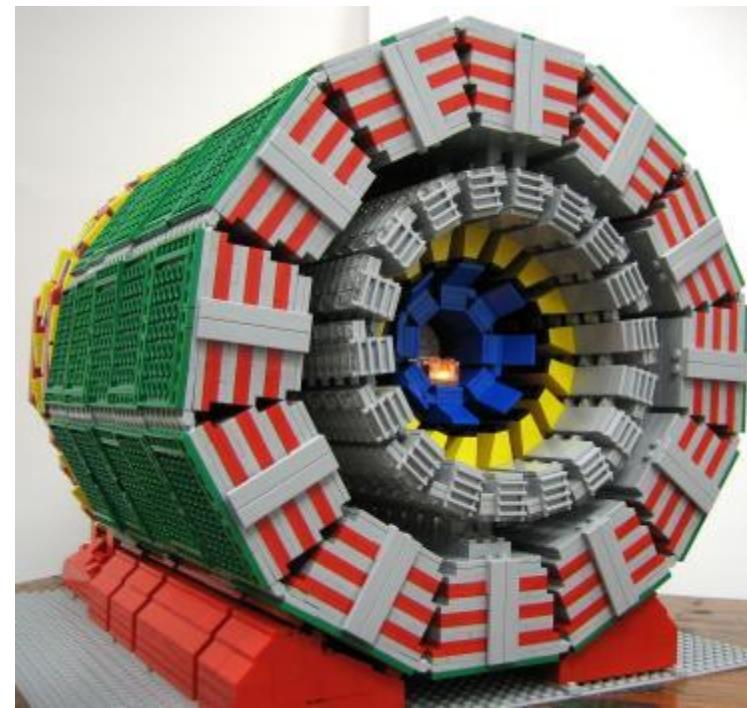
- ✓ position
- ✓ energy
- ✓ time
- ✓ flux (counting)

- ✓ scintillation
- ✓ ionization
- ✓ temperature
- ✓ Cerenkov
- ✓ etc.

experimental constraints

- ✓ Detection efficiency
- ✓ Spatial resolution
- ✓ Cost
- ✓ read-out speed
- ✓ Radiation tolerance
- ✓ Material budget

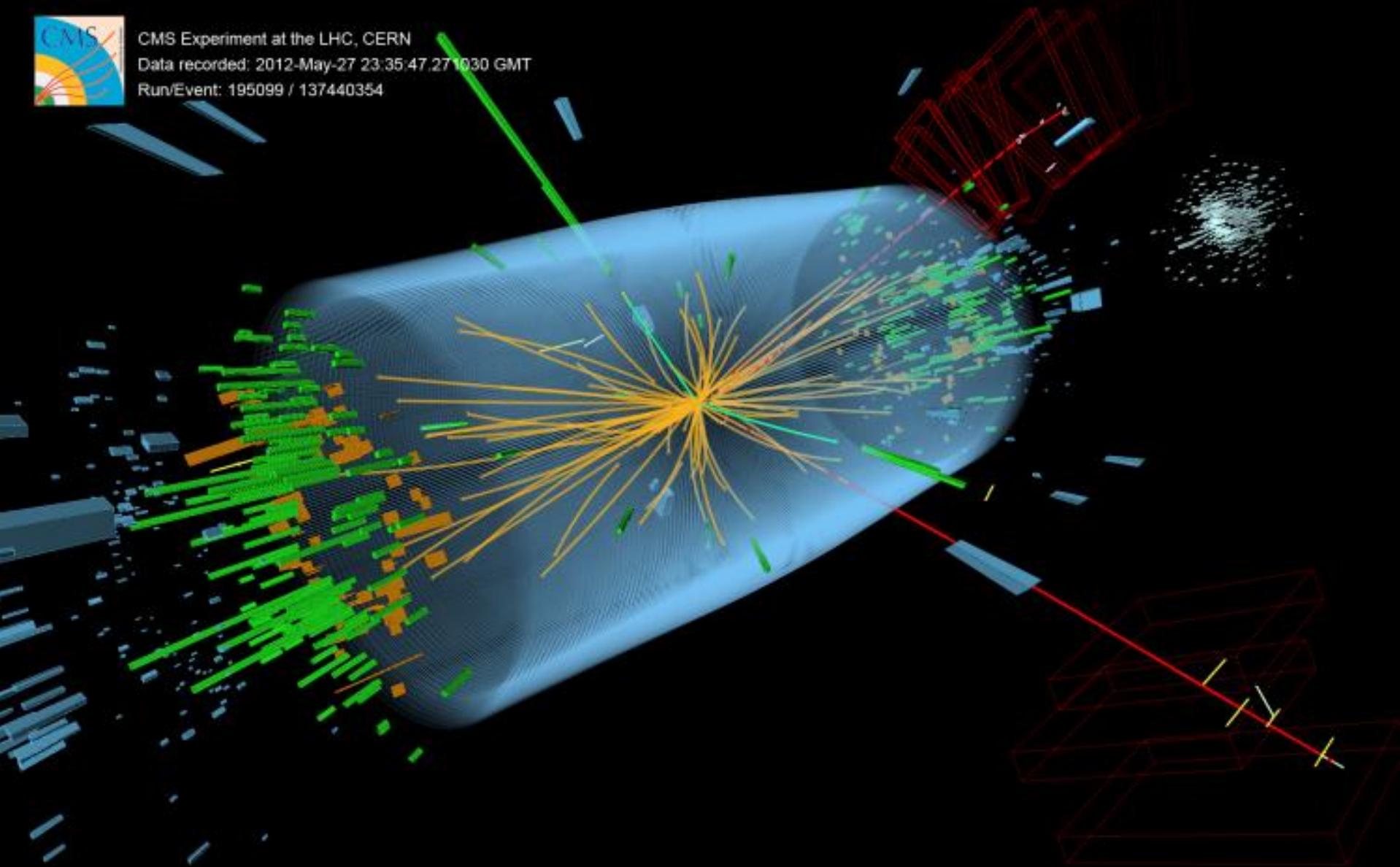
- ✓ Timing resolution
- ✓ Power consumption
- ✓ Mechanical integration
- ✓ Data flux
- ✓ Geometry and acceptance
- ✓ Cooling
- ✓ etc.



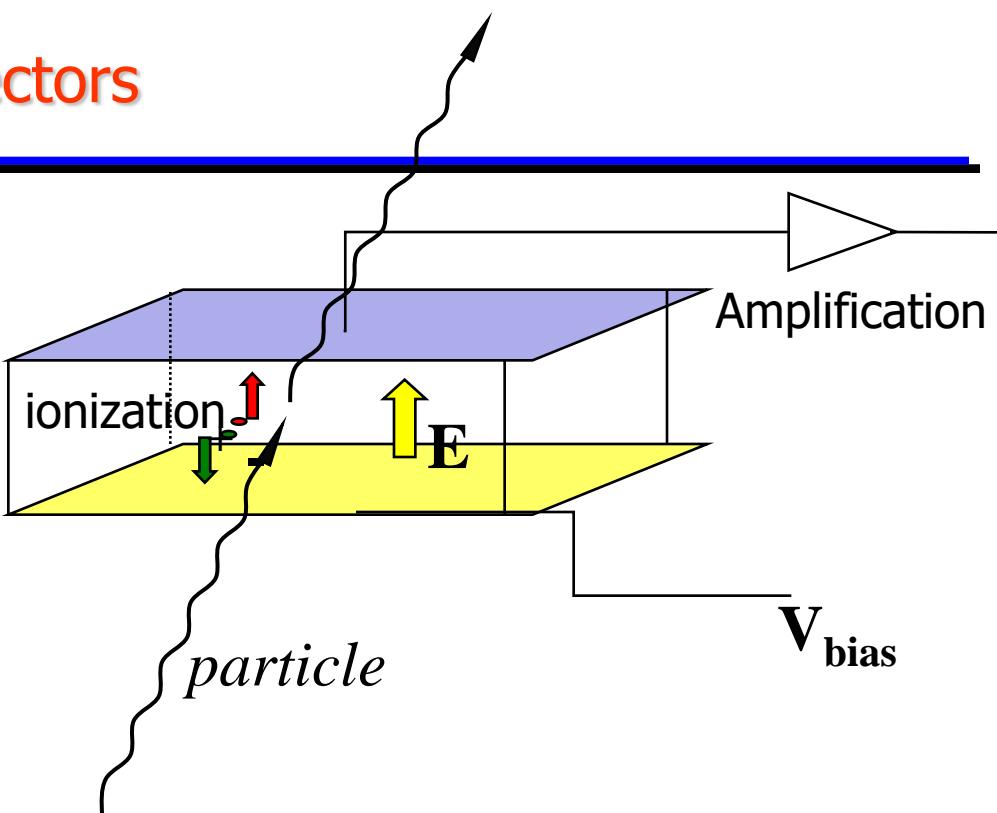
$pp \rightarrow h \rightarrow ZZ \rightarrow e^+e^- \mu^-\mu^+$



CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354



Semiconductor detectors



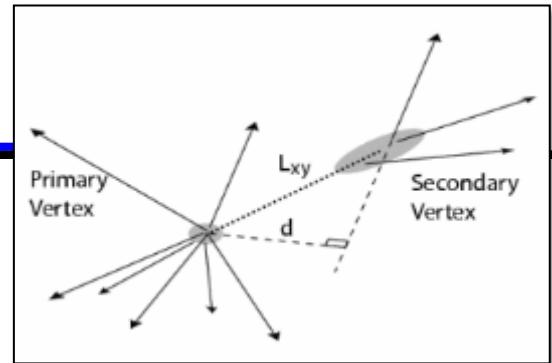
- Detection principles
 - Incident charged particle
 - Ionization of sensitive volume
 - e^- / ions (holes) pairs creations
 - Charge transport through an electric field
 - Induced current
 - Electrodes collects this signal
- Signal amplification and treatment inside a (micro)-electronic circuitry
- Signal transmitt up to the acquisition system and data storage
- A good detector = optimization of all these steps depending on the requirements

Why do we need tracking ?

- Measure:

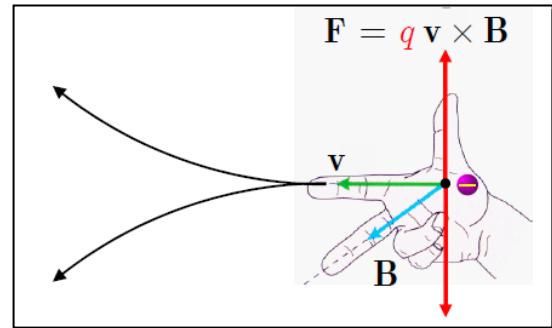
- Origin of the particles = Vertexing

- Identify decays: primary and secondary vertex
 - Measure flight distance
 - Flavor tagging (distinguish light quarks from b/c quarks)



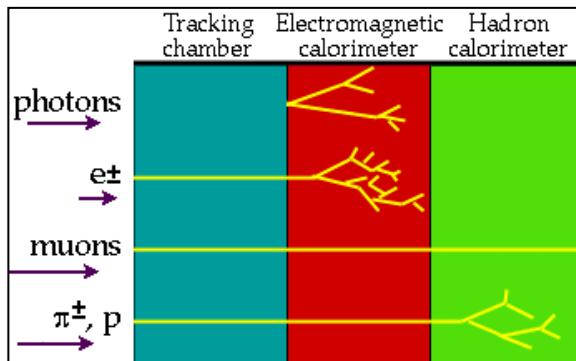
- Momentum and electric charge sign

- Curvature in a B magnetic field (see next slides)



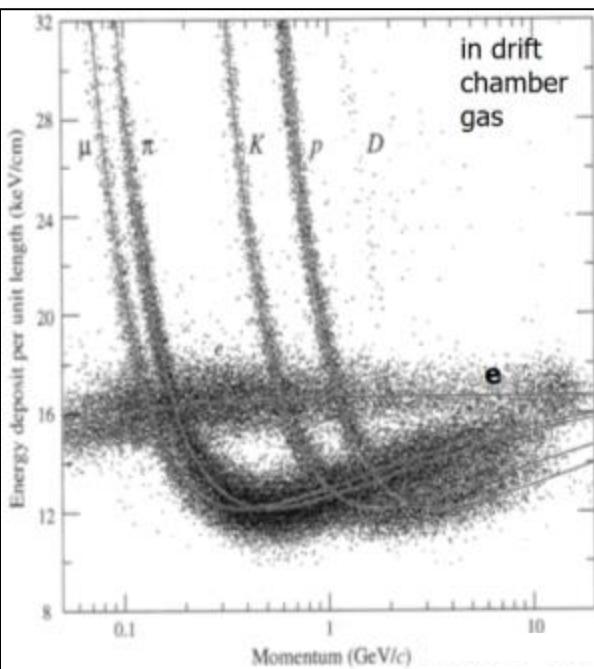
- Reconstruction:

- Association of tracks (momentum) with calorimetric information (Energy)
 - Jet energy
 - Invariant mass



- Mass: momentum + dE/dx measurement

- mass \Rightarrow particle identification



Particle motion in a magnetic field (solenoid)

Lorentz Force: $\vec{F} = q\vec{v} \times \vec{B}$

Centripetal force: $F = \frac{m \cdot v^2}{R}$

$$p_t = qBR = 0.3 B R = \sqrt{p_x^2 + p_y^2}$$

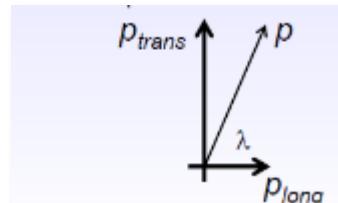
(B in Tesla; Radius in m)

- p_t = transverse momentum
 - p component \perp to B field (\perp to beam axis)

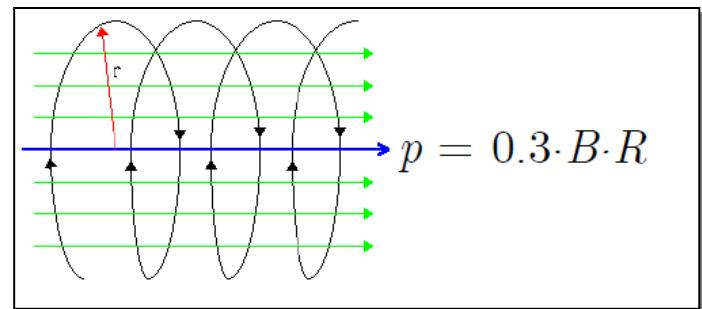
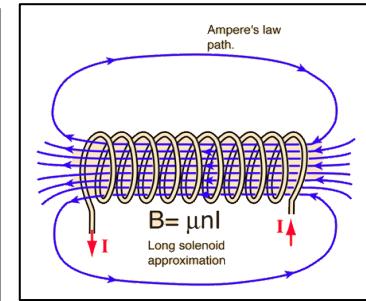
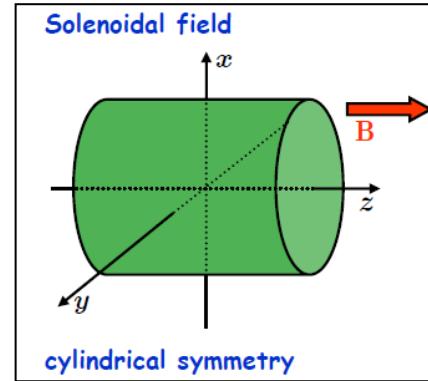
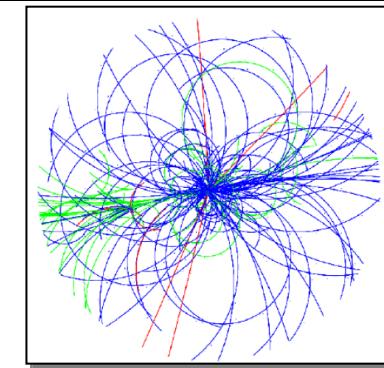
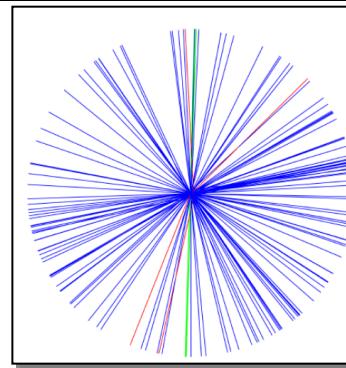
$$p = \frac{p_t}{\sin \lambda}$$

- p_l = longitudinal momentum
 - p component // to B field (// to beam)

$$p_z = p_l$$



- λ = dip angle

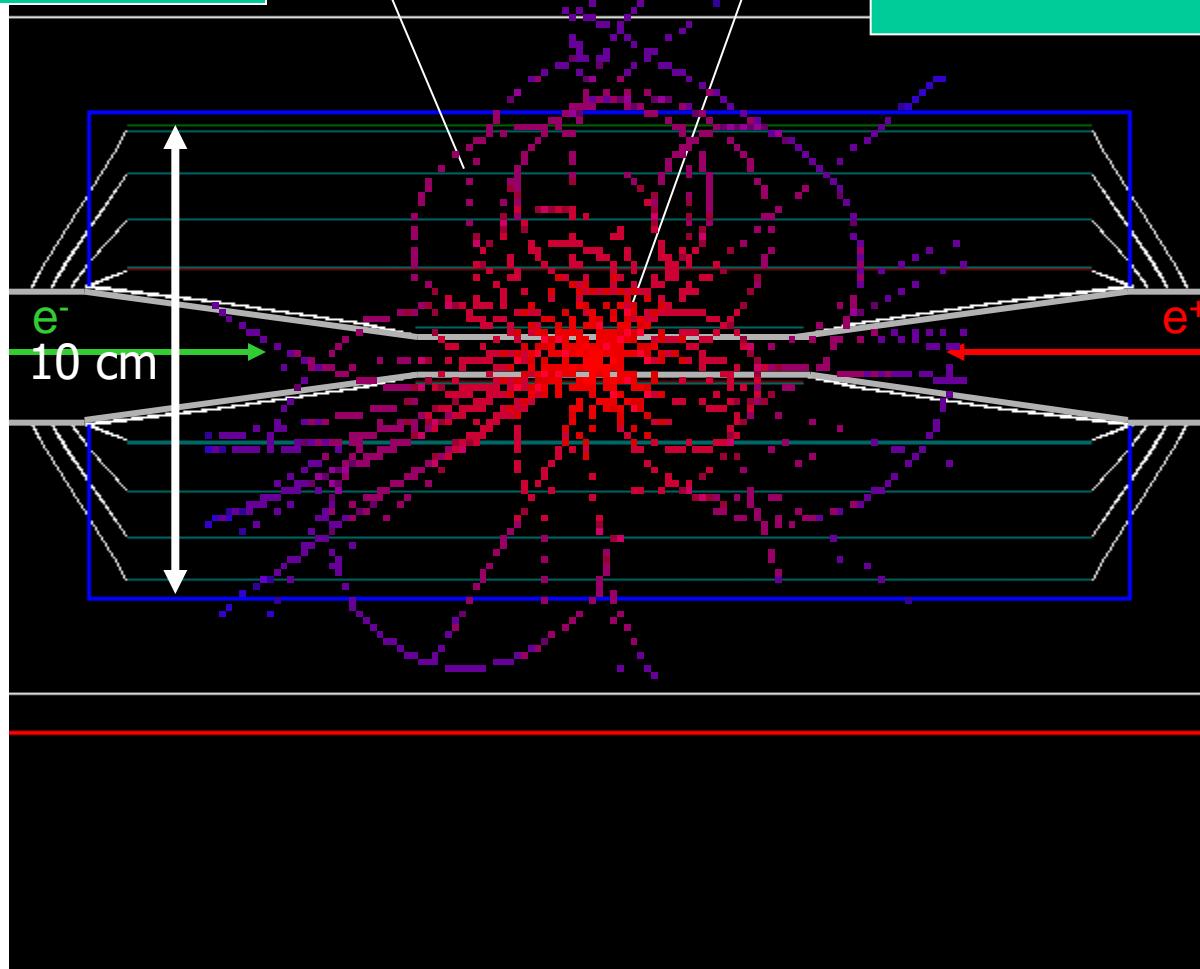


⇒ The charged particle follows an helix
 ⇒ The radius allows to measure the momentum

A tracking device

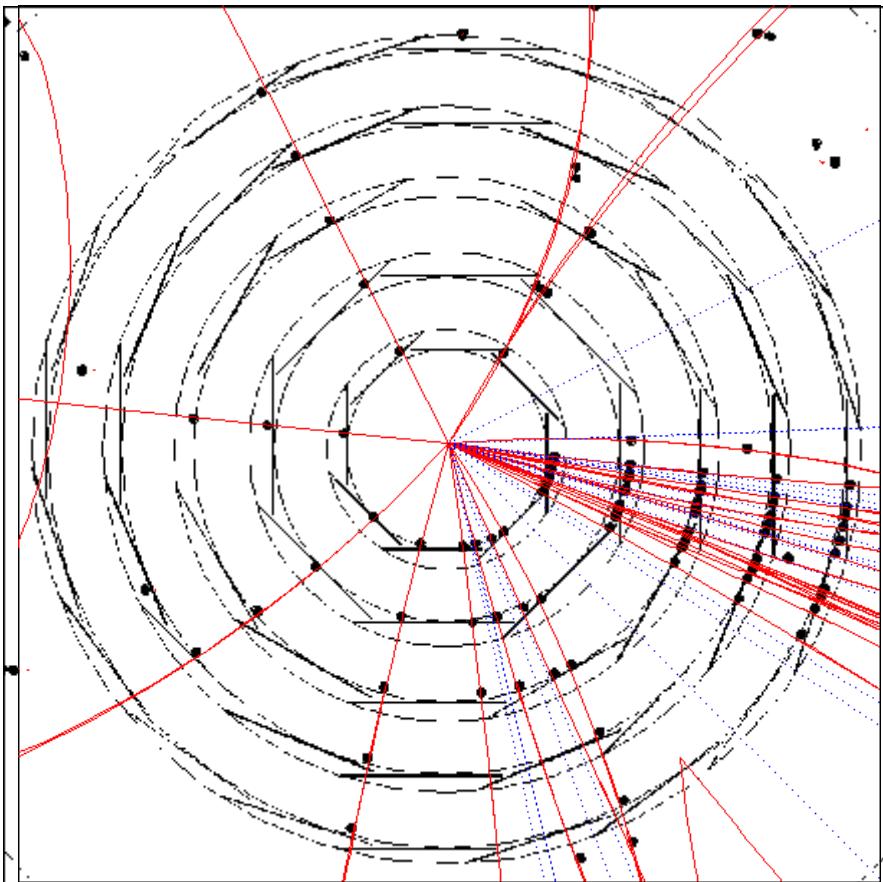
Barrel of ladders with sensors

Initial particle collision point.
Newly created particles are emitted in all directions



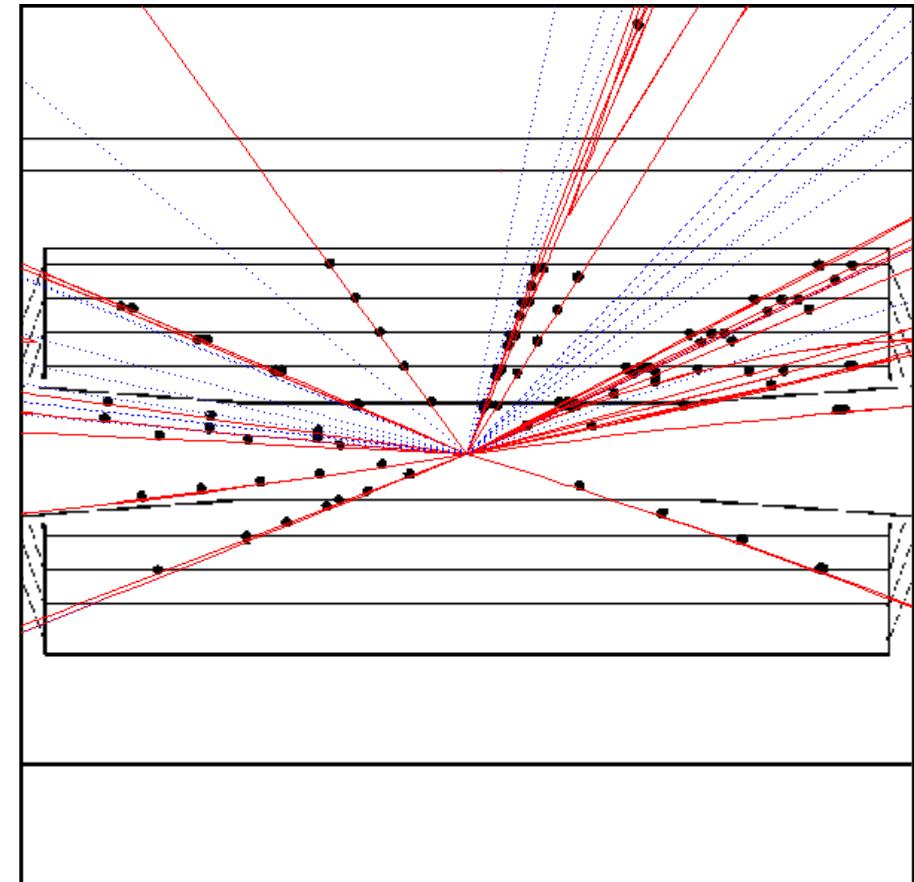
Knowing the particle crossing point with a high accuracy,

allows algorithms to reconstruct the full trajectory of each particle.

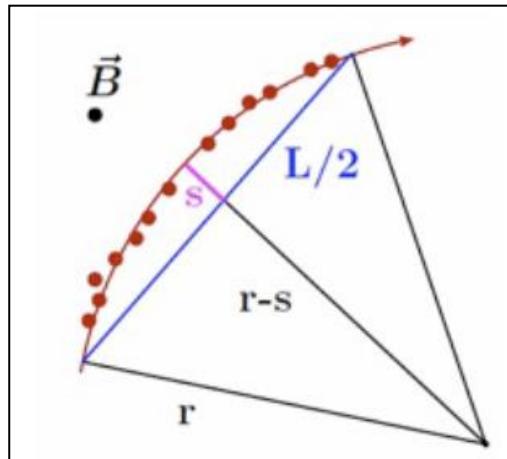
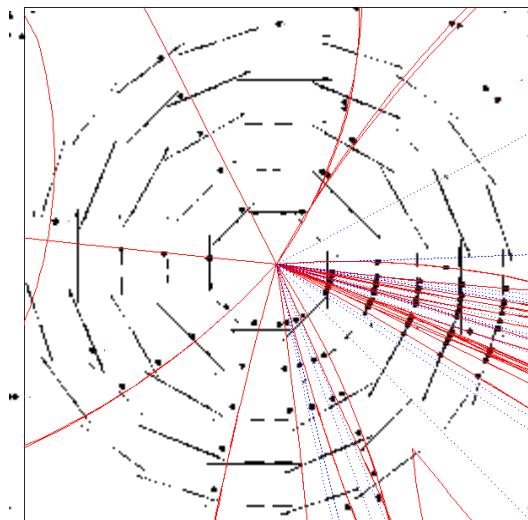


France-China School,
July 2018

Auguste Besson



Momentum measurement



$$\left| \frac{\sigma(p_T)}{p_T} \right|^{meas.} = \frac{\sigma(x) \times p_T}{0.3 \times B L^2} \sqrt{720/(N+4)} \quad (\text{for } N \geq \approx 10)$$

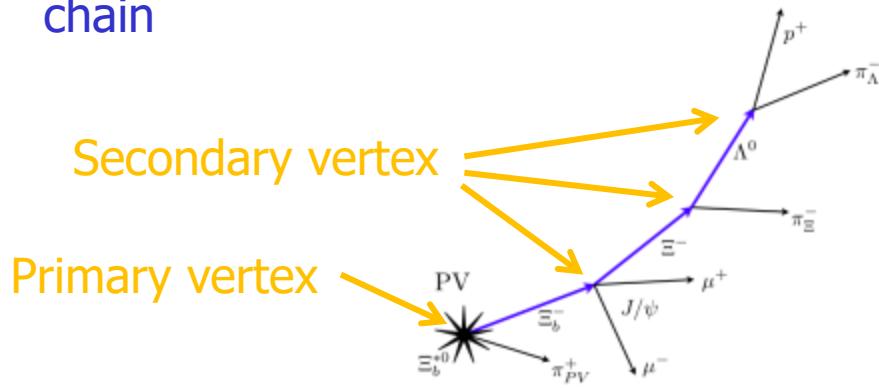
for N equidistant measurements,
(R.L. Gluckstern, NIM 24 (1963) 381)

⇒ Maximum precision with:
good spatial resolution
low momentum
High level arm
High B field
High number of layers (N)

⇒ Caveat:
The trajectory should not be disturbed
by the measurements
⇒ Minimize material budget

Why do we need vertexing ?

- Reconstruct vertex to reconstruct the decay chain

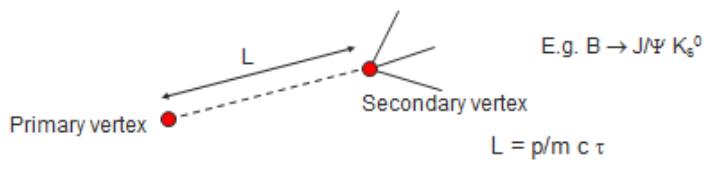


- Heavy flavour particles (b/c/τ)
 - Need to tag them in many physics analysis
 - Unstable but flying particles

$$\langle d \rangle = \beta \cdot \gamma \cdot c \cdot \tau$$

$$\beta = v/c$$

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}}$$



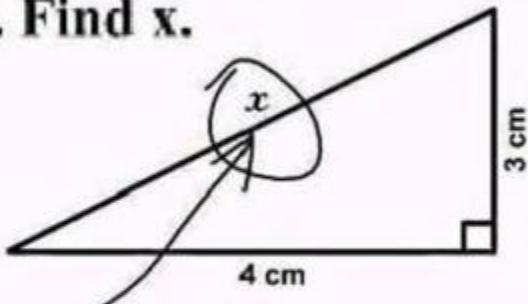
Stable particles	$\tau > 10^{-6}$ s	$c\tau$
n		2.66km
μ		658m
Very long lived particles $\tau > 10^{-10}$ s		
π, K^\pm, K_L^0	2.6×10^{-8}	7.8m
K_S^0, E^\pm, Δ^0	2.6×10^{-10}	7.9cm
Long lived particles $\tau > 10^{-13}$ s		
τ^\pm	0.3×10^{-12}	$91\mu\text{m}$
B_d^0, B_s^0, Δ_b	1.2×10^{-12}	$350\mu\text{m}$
Short lived particles		
π^0, η^0	8.4×10^{-17}	$0.025\mu\text{m}$
ρ, ω	4×10^{-23}	$10^{-9}\mu\text{m}!!$

Jets containing b and c quarks
 Tau leptons :
 \Rightarrow Typical $\langle d \rangle \sim O(10-100s \mu\text{m})$

⇒ Necessary resolution on these vertex position (impact parameter): $\sim O(10 \mu\text{m})$

2.Silicon detectors

3. Find x.



Here it is

Why semiconductor detectors ?

- Advantages
- Lot of various technologies
 - Can be adapted to a lot of applications
- Silicon is massively used in industry
 - Micro-electronics is everywhere
 - Use industry investment to take advantage on costs, performances, smaller sizes
- Generated signal
 - ~10x compared to gas detector for a given amount of deposited energy
 - Very good Signal to Noise ratio
- Spatial resolution (granularity)
 - O(1-100 μm)
- Fast signal generation
 - O(1-10 ns)
- Charge collection
 - Electric field
 - Fast and efficient signal collection
- Fdata flux
 - High read-out speed = low occupancy
 - Data flux is a key factor in high energy physics (HEP).
- Signal treatment
 - Silicon = detector + support for micro-electronics
- Mechanical constraints
 - rigidity: alignment, integration
 - Compacity: fenêtre d'entrée, budget de matière
- weaknesses
 - Costs (high variations)
 - Relatively fragile
 - Long R & D needed
 - Strong expertise needed
 - Cooling
 -)
 - Maximum surface
 - Radiation hardness
 - (in some cases)
 - Material budget
 - (in some cases)

Charged particles through matter

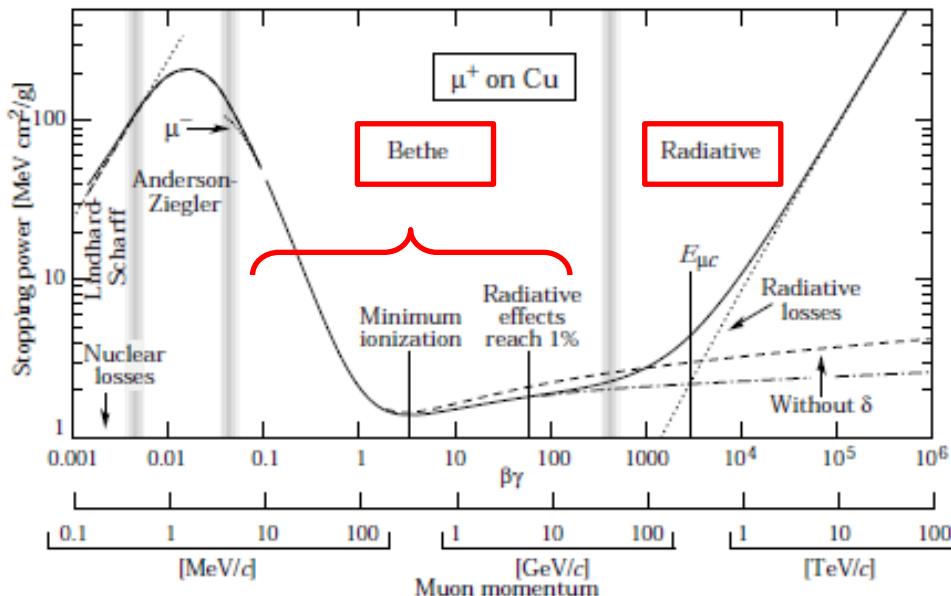
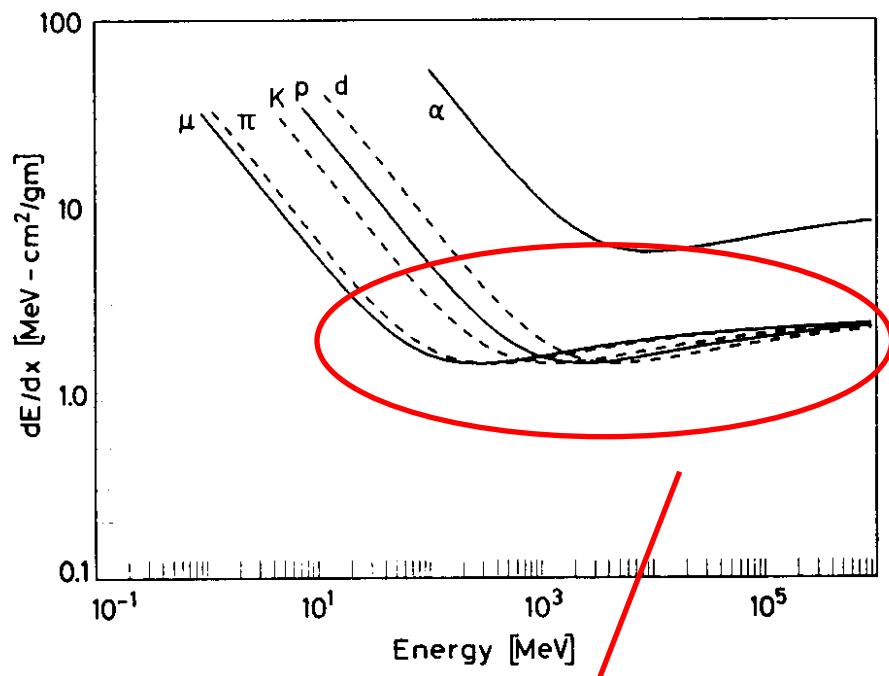


Fig. 27.1: Stopping power ($= \langle -dE/dx \rangle$) for positive muons in copper as a



- Bethe Bloch formula:
- $\propto Z$ absorber
- $\propto z^2$ incident particle
- $E_{\text{loss}} \sim dE/dx \times \text{thickness} \times \text{density}$

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln \left(\frac{2m_e c^2 \beta^2}{I \cdot (1 - \beta^2)} \right) - \beta^2 \right]$$

ε_0 vacuum permittivity

Here, the electron density of the material can be calculated by $n = \frac{N_A \cdot Z \cdot \rho}{A \cdot M_u}$, where ρ is the density of the material, Z its atomic number and mass number, respectively, N_A the Avogadro number and M_u the Molar mass constant.

Best

dE/dx
 ~ almost constant
 ~ equivalent for all charged particles in
 this range : (~0.1 GeV – 1000 GeV)
 ⇒ (M.I.P. = Minimum Ionizing Particle)

$\beta = v/c$
 v vitesse de la particule
 E énergie de la particule
 x longueur du chemin
 c vitesse de la lumière
 z charge de la particule
 e charge élémentaire
 m_e masse au repos de l'électron
 n densité numérique des électrons du matériau
 I potentiel d'excitation moyen du matériau

Multiple Coulomb Scattering

Low momentum charged particles can have their direction modified by interaction through matter

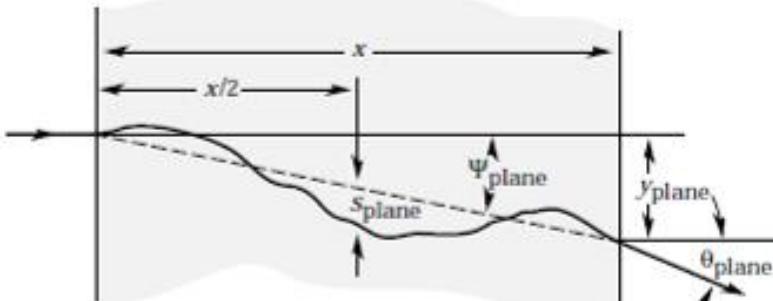


Figure 27.9: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

Thickness of
the material

$$\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right) \right]$$

X_0 = radiation length

momentum

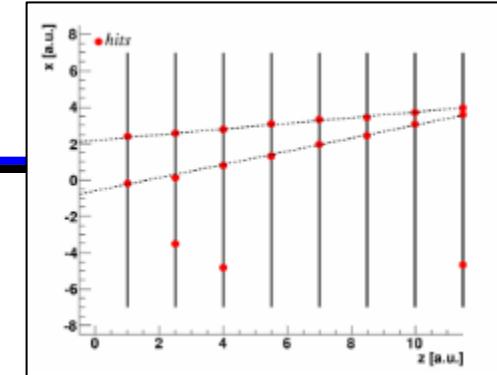
Radiation length
of the material
(9.4 cm for Si)

Here p , βc , and z are the momentum, velocity, and charge number of the incident particle, and x/X_0 is the thickness of the scattering medium in radiation lengths

$$10^{-3} < x/X_0 < 100.$$

Tracking procedure (very simplified !)

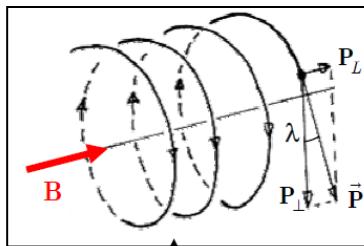
- Pattern recognition:
 - Find all the hits belonging to a track
- Track fitting
 - Find the parameters of the helix equation with a minimization method



$$x(s) = x_o + R \left[\cos\left(\Phi_o + \frac{hs \cos \lambda}{R}\right) - \cos \Phi_o \right]$$

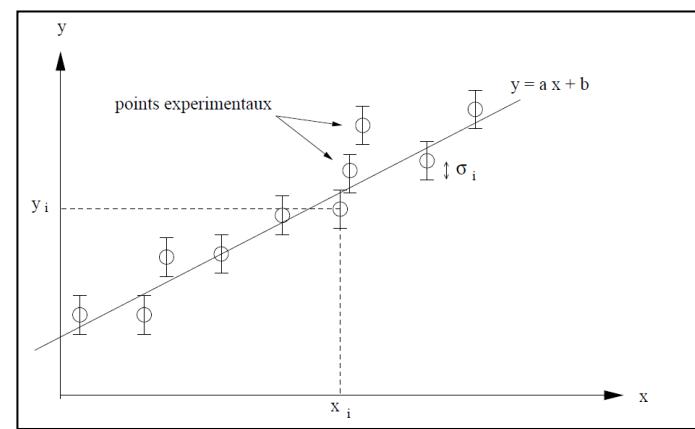
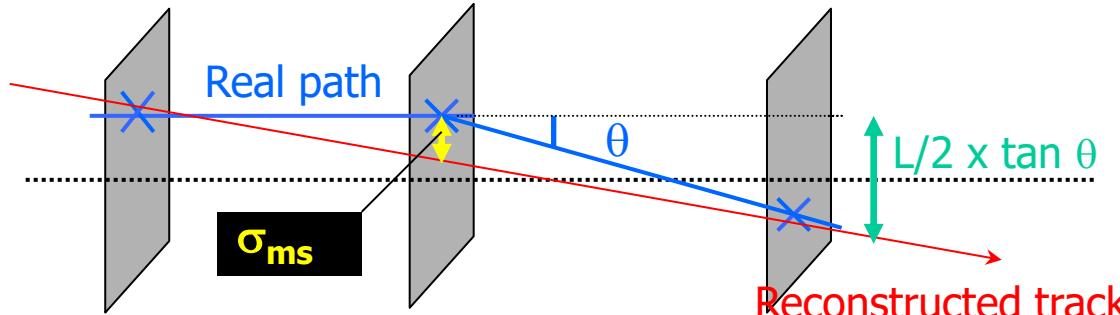
$$y(s) = y_o + R \left[\sin\left(\Phi_o + \frac{hs \cos \lambda}{R}\right) - \sin \Phi_o \right]$$

$$z(s) = z_o + s \sin \lambda$$



$$\chi^2 = \sum_{i=1}^n \left(\frac{y(x_i) - y_i}{\sigma_i} \right)^2$$

– Take into account multiple scattering !



y_i = measured points
 σ_i = errors
 $y(x_i)$ = fitted function

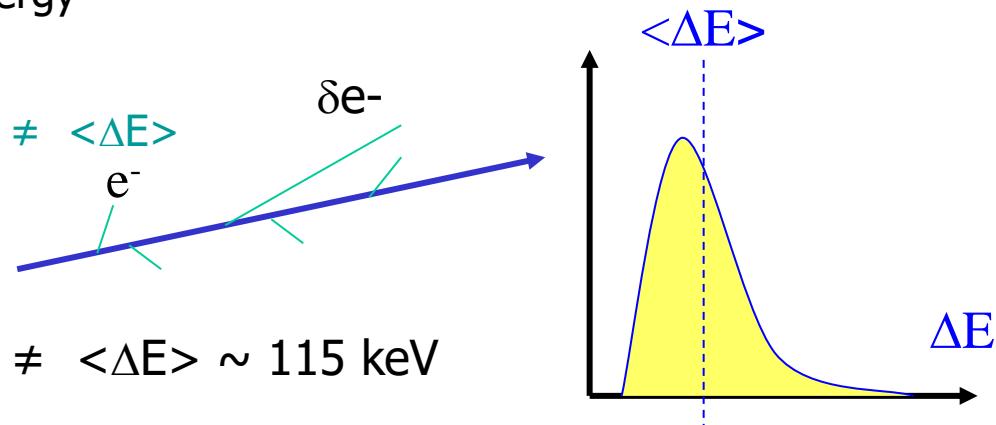
- The whole procedure can be repeated several times
 - Maximise tracking efficiency
 - Minimise « fake tracks »

M.I.P. in a silicon detector

- Ionising energy:
 - 3.6 eV to create a e⁻-hole pair
 - Number of pair per μm $\sim 80 \text{ pairs}/\mu\text{m}$ (most probable value)
 - Example 1: strip detector or hybrid pixel:
 - $\sim 300 \mu\text{m}$ thickness for the sensitive volume
 - Created pairs: $300 \mu\text{m} \times 80 \sim 24\,000 \text{ e/h}$.
 - Equivalent charge ($\times 1.6 \times 10^{-19}$) $\sim 4 \times 10^{-15} \text{ C} \sim 4 \text{ fC}$!
 - Deposited energy (in the sensitive volume): $3.6 \times 80 \times 300 \sim 85 \text{ keV}$
 - Example 2: CMOS pixel sensor:
 - $\sim 10 \mu\text{m}$ thickness for the sensitive volume
 - Created pairs: $10 \mu\text{m} \times 80 \sim 800 \text{ e/h}$. ($\sim 0.1 \text{ fC}$!)
 - Deposited energy: $3.6 \times 80 \times 10 \sim 2.9 \text{ keV}$
- Very low Signal \Rightarrow needs to control Noise

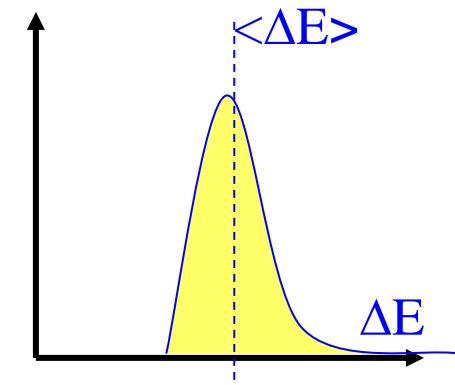
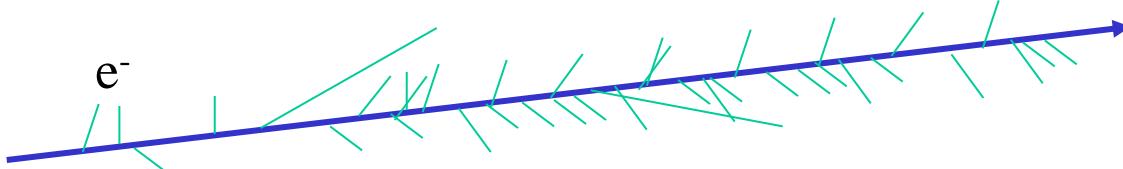
Thin detectors: Landau distribution

- Real detector:
 - Deposited energy ΔE in a finite thickness δx
 - $\neq \langle dE/dx \rangle$
 - Thin layers : some collisions may have a large energy transfer
 - Large fluctuations of deposited energy
- Thin layers
 - Most probable value (MPV): $\Delta E(\text{MPV}) \neq \langle \Delta E \rangle$
 - Landau distribution (right tail)



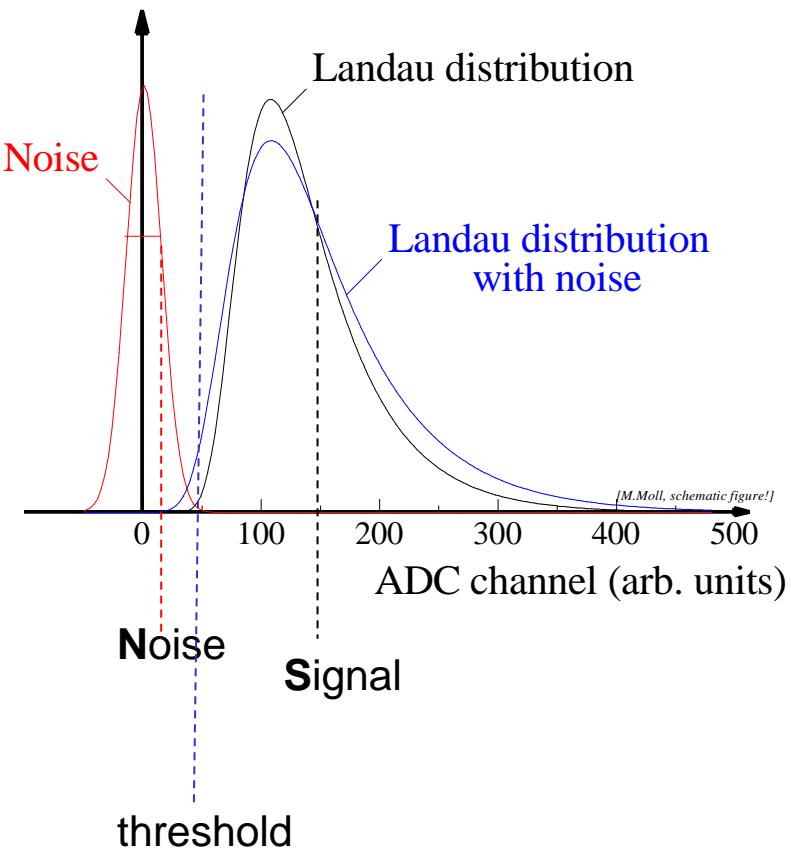
Example: 300 μm : $\Delta E(\text{MPV}) \sim 82 \text{ keV} \neq \langle \Delta E \rangle \sim 115 \text{ keV}$

- Thick layers:
 - Higher number of collisions
 - Central limit theorem \Rightarrow gaussian distribution



Signal to Noise ratio (S/N)

- Hit selection
 - S/N:
 - Figure of merit of the detector
 - S/N threshold:
 - Too low \Rightarrow Fake hits
 - Too high \Rightarrow efficiency loss
 - Typical thresholds: 5-15
 - Non gaussian part of the noise
 - Increases fakes
- One wants the highest S/N
 - Fake vs efficiency
 - Radiation hardness
 - Spatial resolution

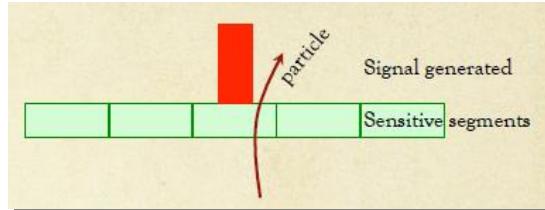


Spatial resolution of a detector

- Output can be digital (0-1) / N bits ADC / Analog

Digital:

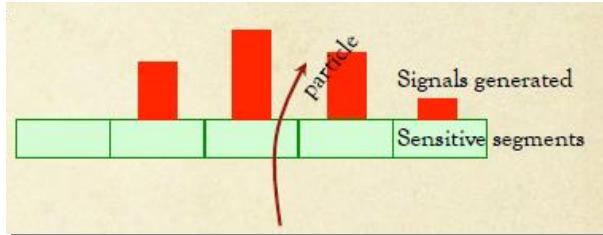
$$\sigma_{sp} \sim \frac{p}{\sqrt{12}}$$



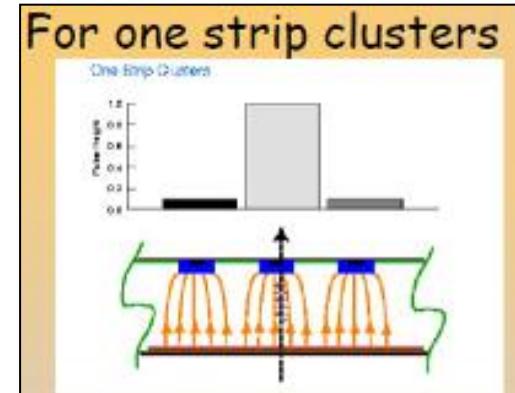
$$\sigma_x^2 = \langle (x - \langle x \rangle)^2 \rangle = \int_{-d/2}^{d/2} x^2 P(x) dx = \frac{d^2}{12}$$

Analog:

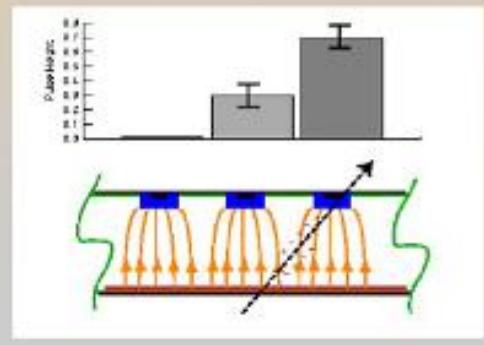
$$\sigma_{sp} \sim \frac{p}{2 \cdot (S/N)}$$



⇒ Center of gravity or more complex methods (η functions)



For two strip clusters

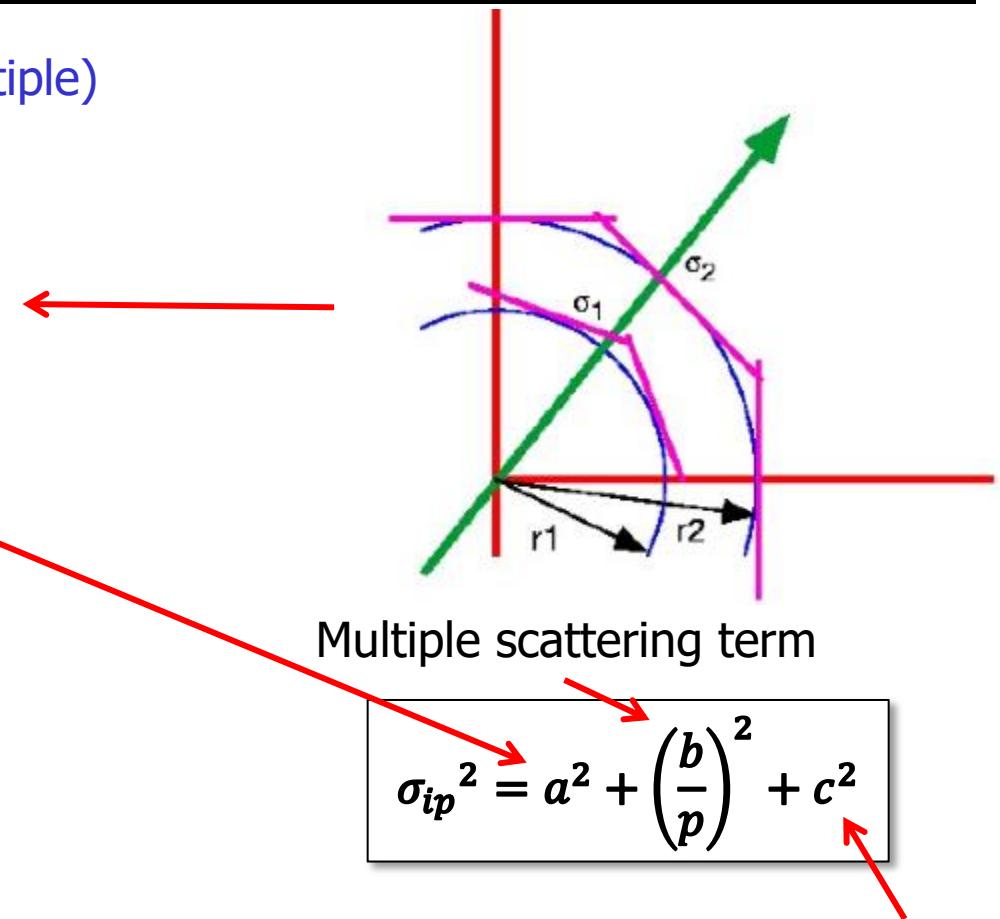


Impact parameter resolution (vertex detector)

- Simple model (sans diffusion multiple)
 - Impact parameter resolution

$$\sigma_{d_0}^2 = \frac{r_2^2 \sigma_1^2 + r_1^2 \sigma_2^2}{(r_2 - r_1)^2}$$

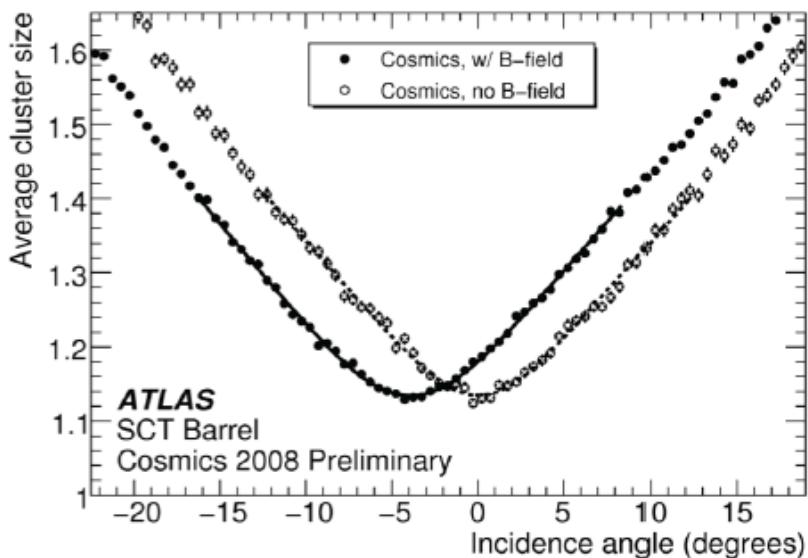
- One needs to
 - Minimize r_1
 - Maximize r_2
 - Minimize $\sigma_1 \sigma_2$
- But also:
 - Number of layers
 - Material budget
 - Alignment



Lorentz Force and collected signal (Hall Effect)

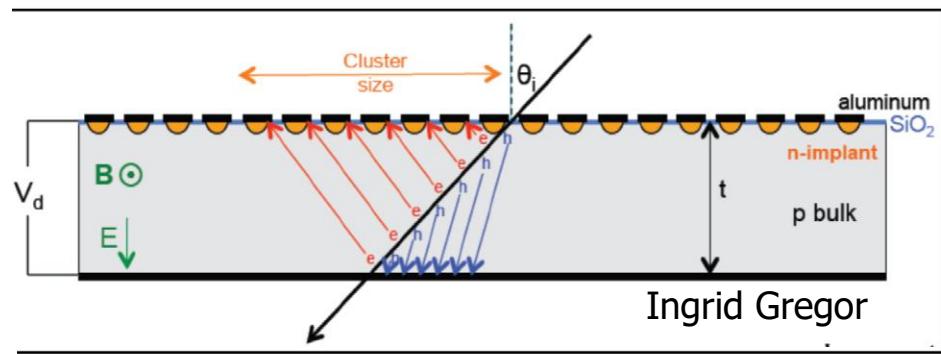
- Charge carriers path modified by B field
 - e.g. Inside a solenoid
 - Most common case in particle physics detectors
 - Drift of charge carriers (h & e^-) is modified by an angle θ_L
 - Depends on mobility ($\mu_{e^-} \neq \mu_h$)
 - Can be computed and corrected in simulation
 - Depends on B and thickness

$$F = q \left(E + \frac{v}{c} \times B \right)$$



Measurement in ATLAS after full installation

Modified cluster size



$$\tan \theta_L = \mu^H \cdot B_\perp \approx \mu \cdot B_\perp$$

B_\perp = B component \perp to E

e.g. Silicium (@ room T), $B = 1\text{T}$

$$\mu_{e^-}^H = 1670 \text{ cm}^2/\text{Vs}$$

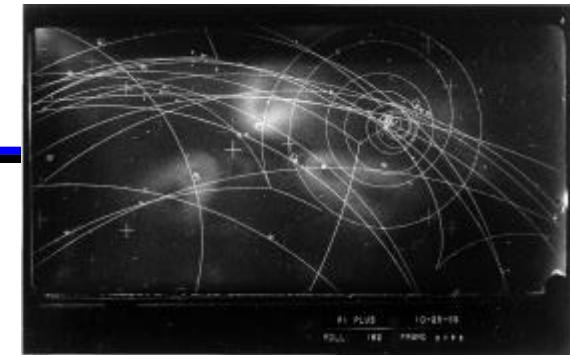
$$\mu_h^H = 370 \text{ cm}^2/\text{Vs}$$

$\theta_{e^-} \sim 10^\circ$
 $\theta_h \sim 2^\circ$

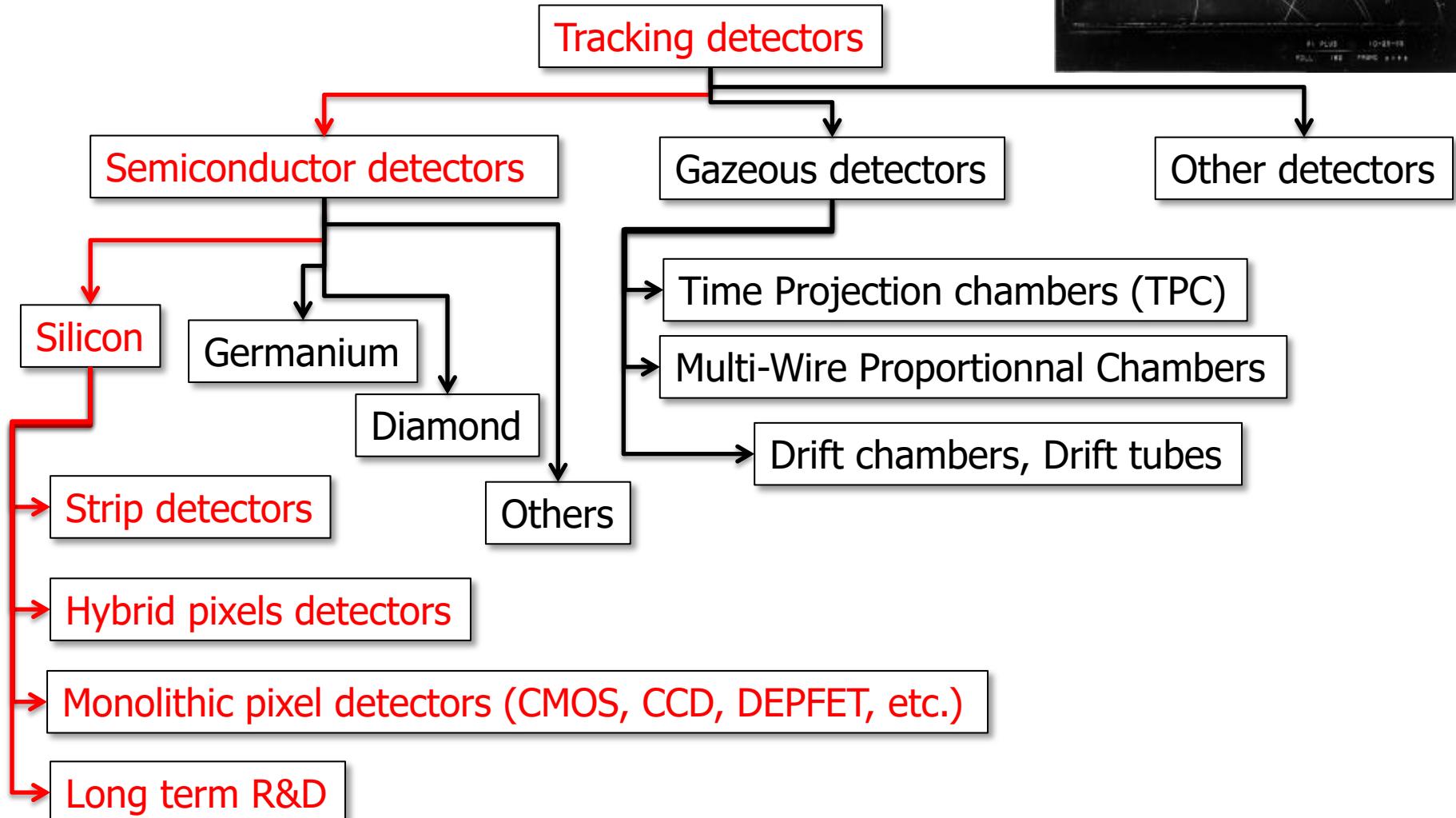
3. Technologies



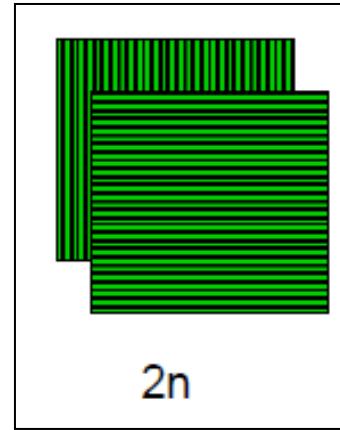
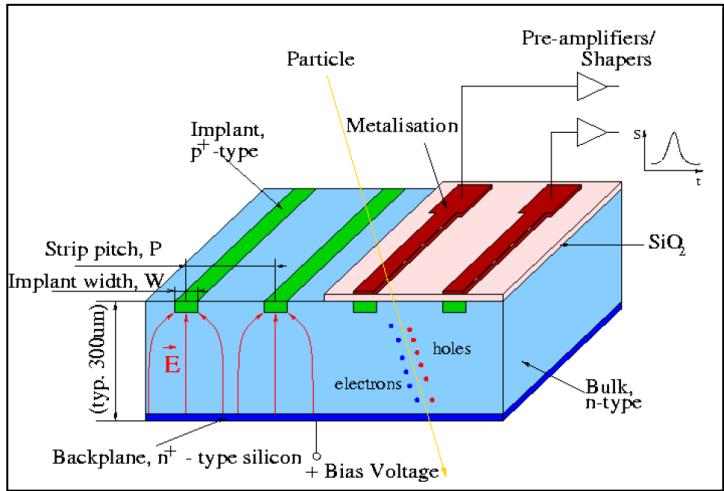
Tracking and semiconductors



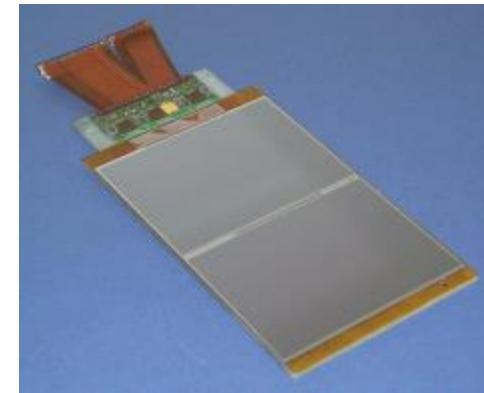
- Tracking detectors are a large family...



Single sided microstrip detectors



CMS tracker module



- Principle and features

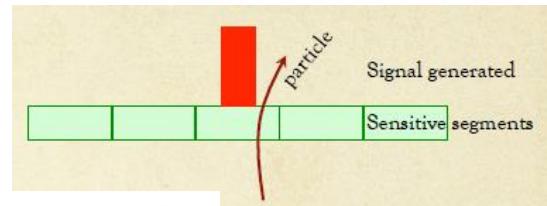
- Holes and e⁻ moving to the electrodes \Rightarrow induced current (Ramo theorem)
- Only one dimension measurement
- Fast and moderate data flow
- Large surfaces

- Typical values

- Voltage ~ 100 V, thickness $\sim 300\mu\text{m}$, pitch $\sim 50\ \mu\text{m}$, resolution $\sim 1.5\ \mu\text{m}$; surface $\sim 10 \times 10\ \text{cm}^2$, time resolution $\sim \mathcal{O}(10\text{-}100\ \text{ns})$
- Resolution :

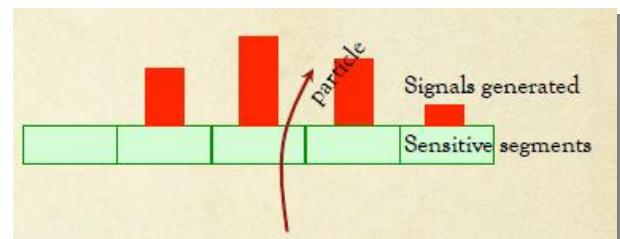
Digital:

$$\sigma_{sp} \sim \frac{p}{\sqrt{12}}$$



Analog:

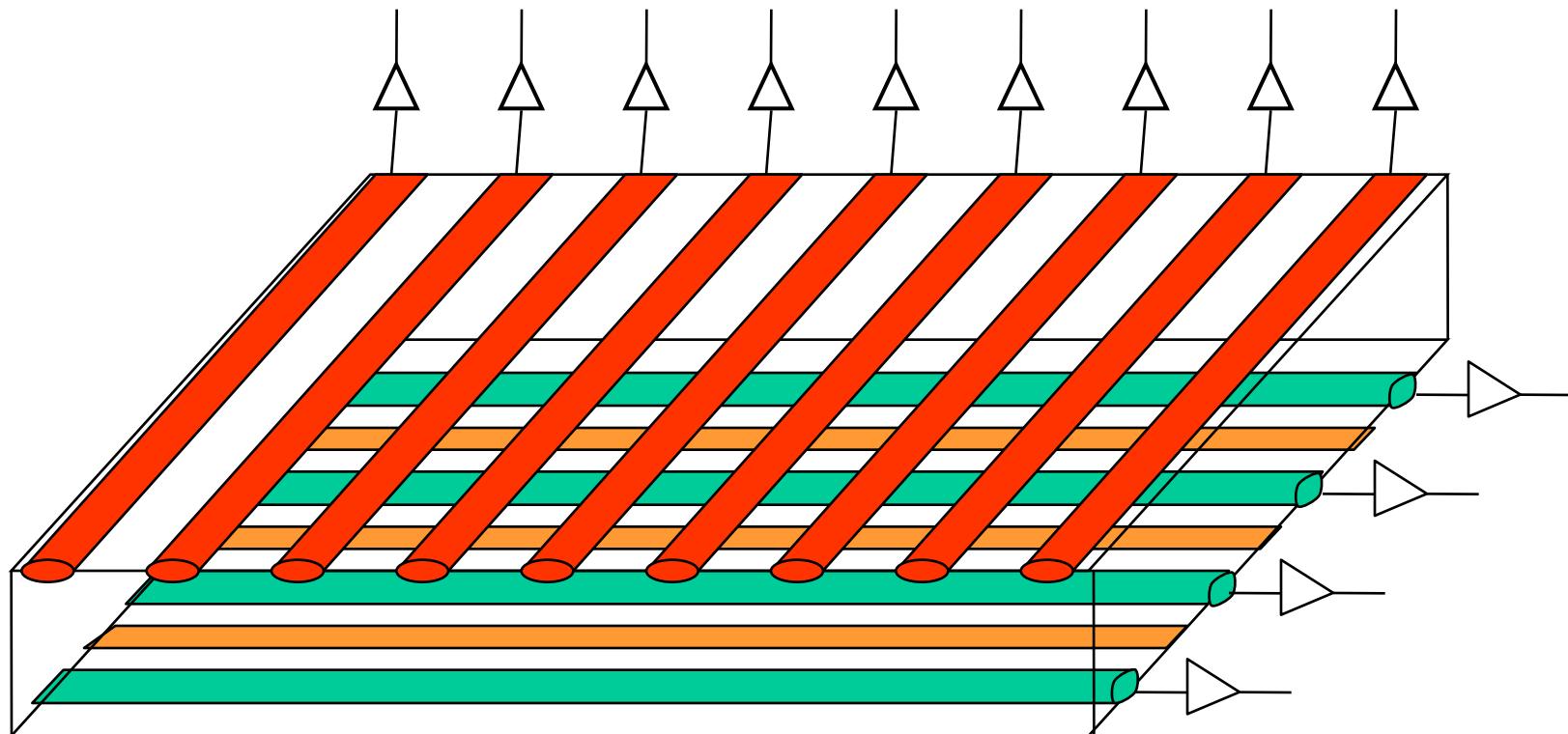
$$\sigma_{sp} \sim \frac{p}{2 \cdot (S/N)}$$



$$\sigma_x^2 = \langle (x - \langle x \rangle)^2 \rangle = \int_{-d/2}^{d/2} x^2 P(x) dx = \frac{d^2}{12}$$

J. Besson

Double Sided Microstrip Detector

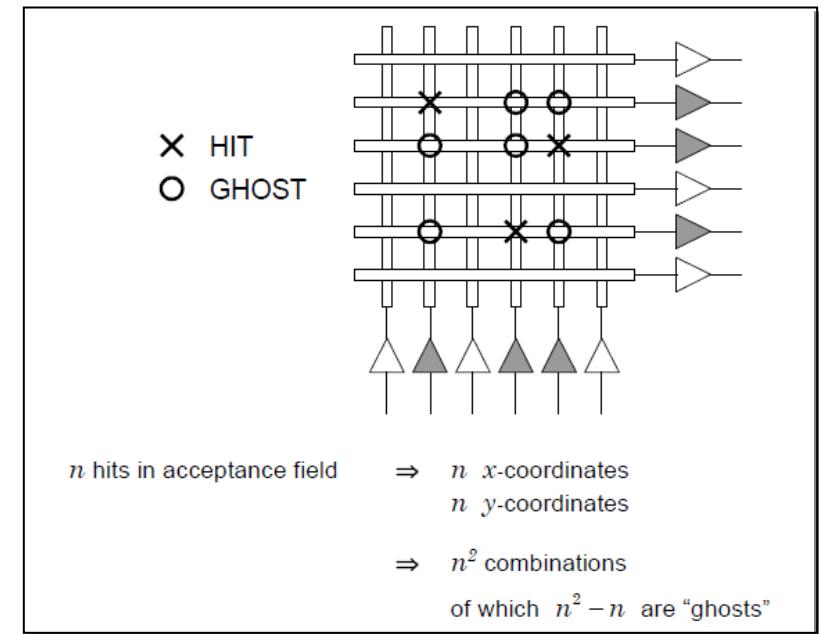
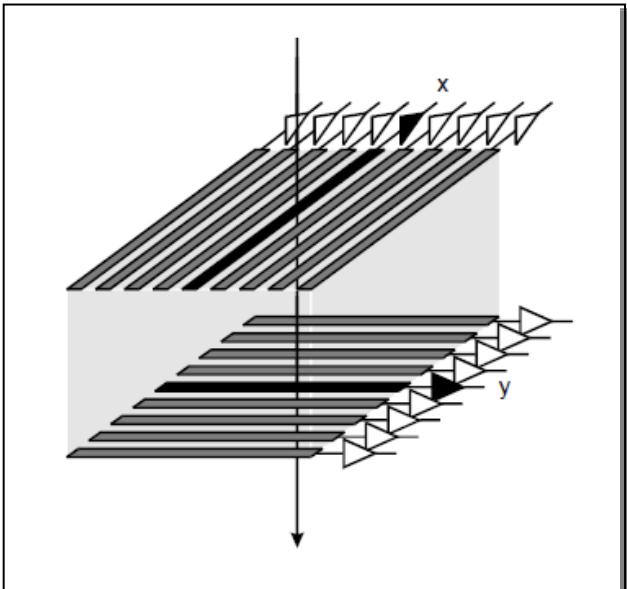


- Principle and features

- 2D information with less material than $2 \times$ single sided detectors
- More complex to build (Potential V on one side) and more expensive
- Multi-hits ambiguities
- Both faces must be processed and read-out

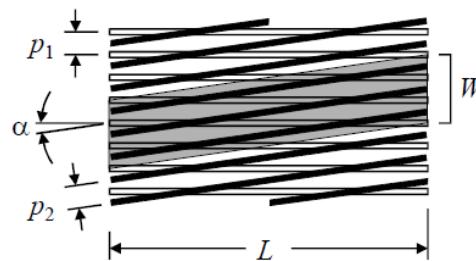
Strip detectors: Ambiguities problem

- One hit is ok...
- Multi-hits...



In collider geometries often advantageous, as z resolution less important than $r\phi$

Low stereo angle



Reduces ambiguities surface to the price of a degraded resolution in one dimension

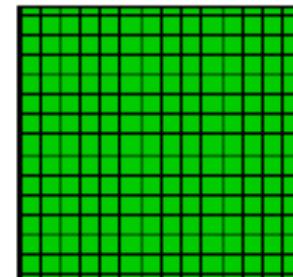
The width of the shaded area subject to confusion is $L \frac{p_2}{p_1} \tan \alpha + p_2$

Example: ATLAS SCT uses 40 mrad small-angle stereo

Two single-sided strip detectors glued back-to-back

Pixel detectors (hybrids, CCDs, CMOS, etc.)

- Features
 - N^2 channels
 - No ambiguities
 - Data flux / occupancy
 - Inner layers (Vertex detectors)
- Many different technologies
 - Hybrid pixels
 - CCD
 - CMOS
 - DEPFET
 - SOI
 - Etc.

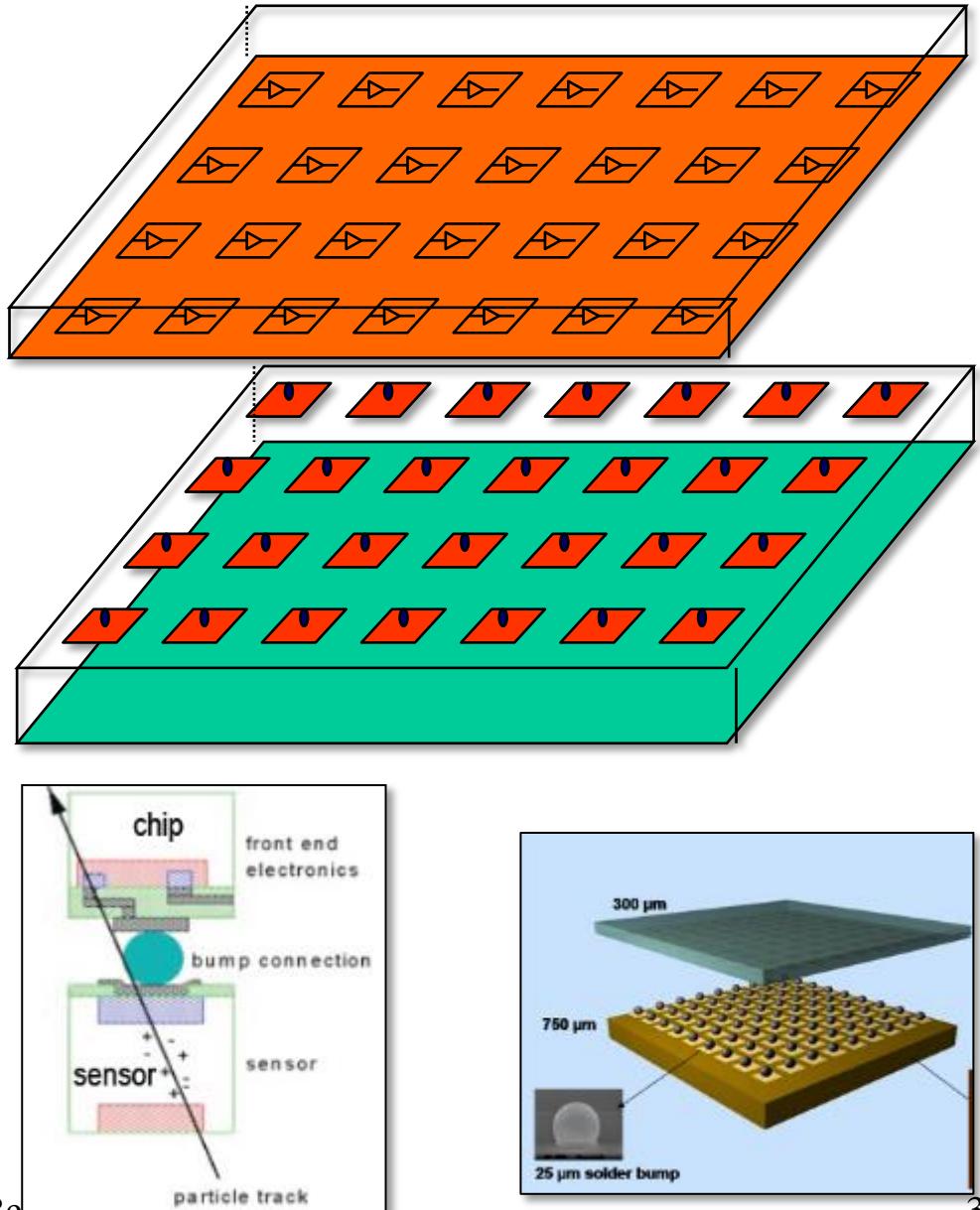


n^2



Hybrid pixel detectors

- Features
 - 2D detectors
 - Read-out chip mounted on the detector
 - Connexion between 2 wafers
 - bump bonding
 - Complex and expansive
- Standard pixel detector @ LHC
- Advantages:
 - Read-out speed (key factor for LHC)
 - Mature technology
 - Very radiation hard (key factor for LHC)
- weaknesses
 - Large pitch
 - Read-out and bonding limits
 - e.g. $50 \times 400 \mu\text{m}^2$, $150 \times 150 \mu\text{m}^2$
 - Material budget
 - Power consumption



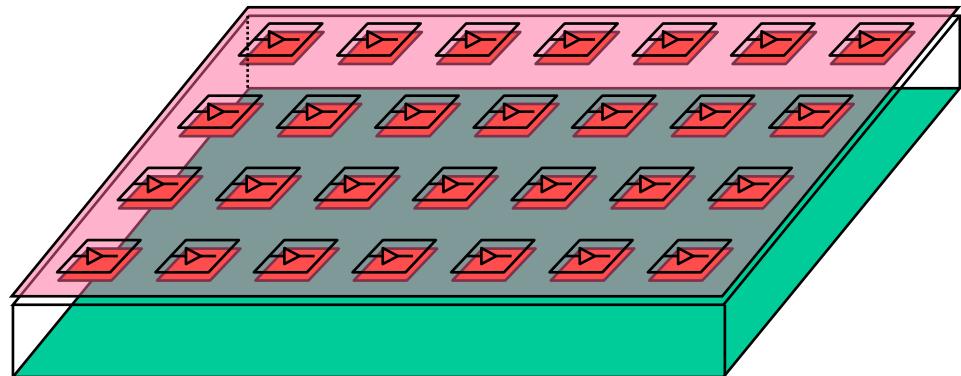
Monolithic pixel detectors

- Idea:

- Sensitive volume and read-out electronic in the same wafer

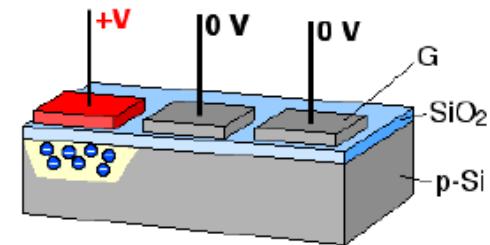
- Advantages

- Material budget
 - Granularity (pitch down to $\sim < 10 \mu\text{m}$ if necessary)
 - Low noise (the closer the electronic to the signal the better)

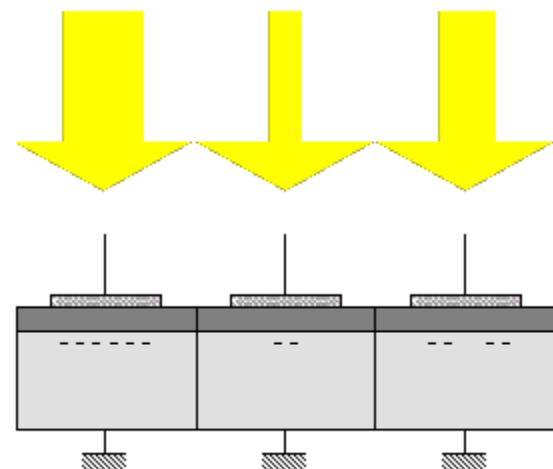


CCD (Charged Coupled Devices)

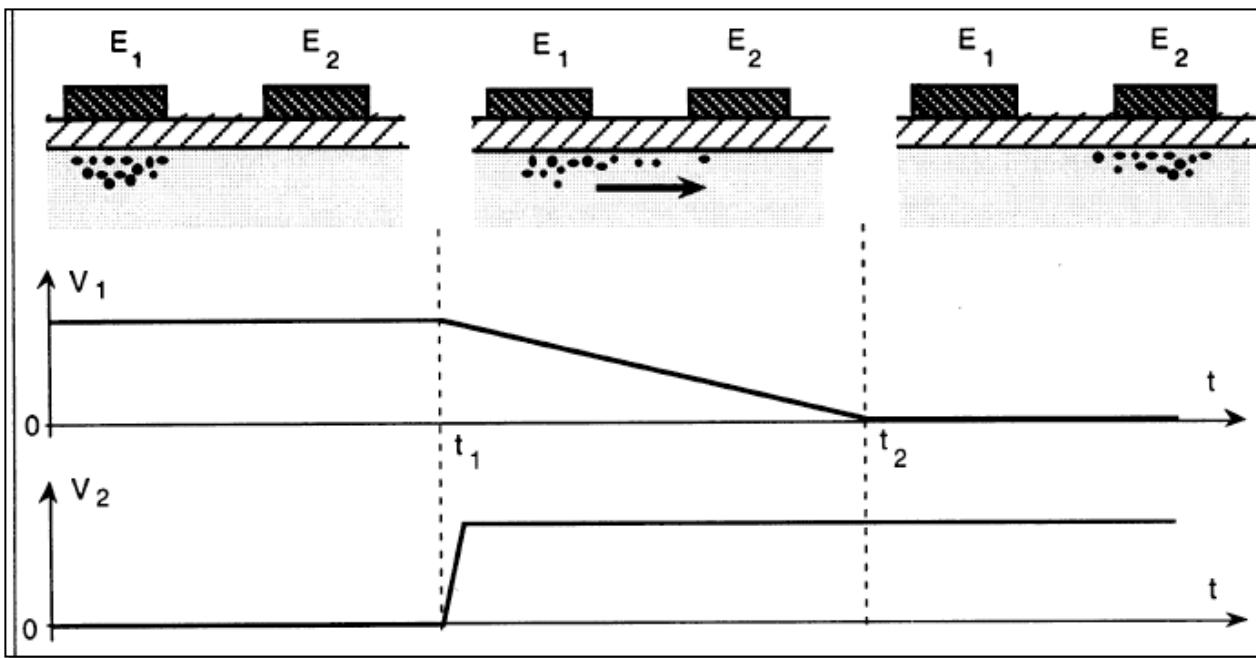
- History
 - Old idea (1960s)
 - Used in digital cameras (light)
 - Nobel prize in 2009
 - Applications: visible, en astrophysique, imagerie médicale, etc.
- Principle
 - In each pixel = electrode separated by an insulator
 - ~ charge carriers stored as in a capacitance
 - Read-out by charge transfer from a pixel to another up to the end of each row.
 - High quantum efficiency($>\sim 70\%$)
- weaknesses
 - Slow read-out speed
 - Not radiation hard
 - Charge transfer losses
 - Needs cooling ($\sim <-10\text{--}20^\circ\text{C}$)



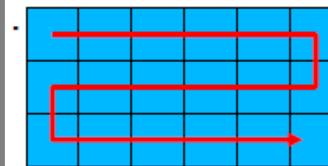
la cellule de base du capteur CCD



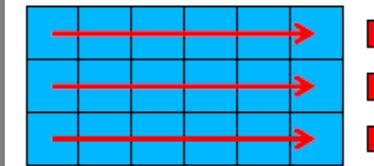
CCD: charge transfer



Sequential read-out



Signal treatment

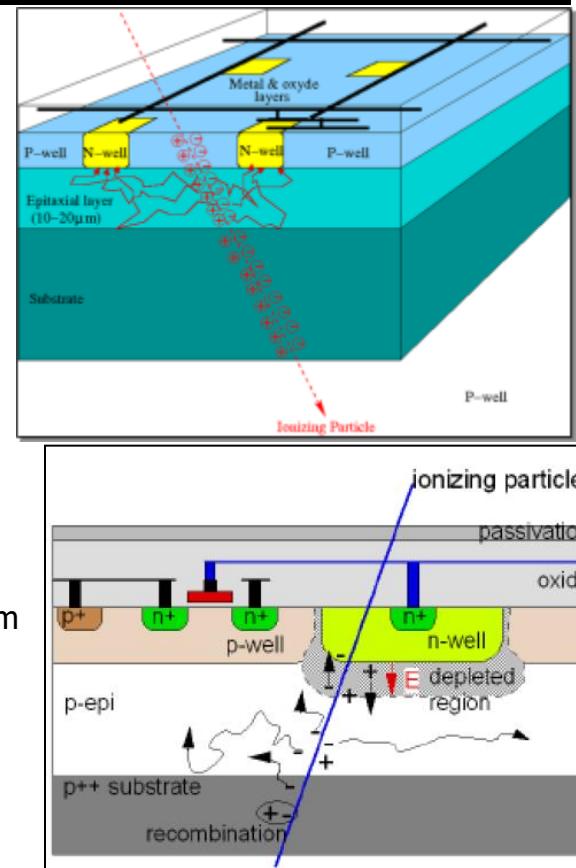


Parallel read-out

Playing with voltage
on each electrodes
allows charge
transfer

CMOS pixel sensor (CPS) for charged particle detection

- Main features
 - Monolithic, p-type Si
 - Signal created in low doped thin epitaxial layer $\sim 10\text{-}20 \mu\text{m}$
 - $\sim 80 \text{ e-}/\mu\text{m} \Rightarrow$ total signal $\sim \mathcal{O}(1000 \text{ e-})$
 - Thermal diffusion of e-
 - Limited depleted region
 - Interface highly P-doped region: reflection on boundaries
 - Charge collection: N-Well diodes
 - Charge sharing \Rightarrow resolution
 - Continuous charge collection
 - No dead time
- Main Avantages
 - Granularity
 - Pixel pitch down to $10 \times 10 \mu\text{m}^2 \Rightarrow$ spatial resolution down to $\sim 1 \mu\text{m}$)
 - Material budget
 - Sensing part $\sim 10\text{-}20 \mu\text{m}$ \Rightarrow whole sensor routinely thinned down to $50 \mu\text{m}$
 - Signal processing integrated in the sensor
 - Compacity, flexibility, data flux
 - Flexible running conditions
 - From $\leq 0^\circ\text{C}$ up to $30\text{-}40^\circ\text{C}$ if necessary
 - Low power dissipation ($\sim 150\text{-}250 \text{ mW/cm}^2$) \Rightarrow material budget
 - Radiation tolerance: $>\sim 100\text{s kRad}$ and $\mathcal{O}(10^{12} \text{ n}_\text{eq}) \Rightarrow f(T, \text{pitch})$
 - Industrial mass production
 - Advantages on costs, yields, fast evolution of the technology, Possible frequent submissions
- Main limitation
 - Industry addresses applications far from HEP experiments concerns
 - Different optimisations on the parameters on the technologies
 - Recently: new accessible processes:
 - Smaller feature size, adapted epitaxial layer
 - Open the door for new applications



Let's cut a pixel.

We see its composition and what happens when a particle goes through

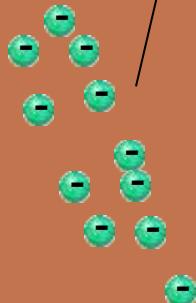
Free charges are

collected
brought to
amplified
signal

Micro-circuits for signal treatment

Collector

Layer sensitive to particles



Supporting bulk (insensitive)

Road map in the lab

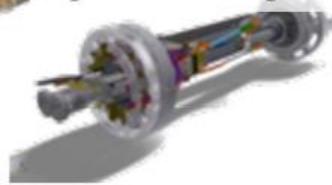
ALICE 2020

LHC/CERN



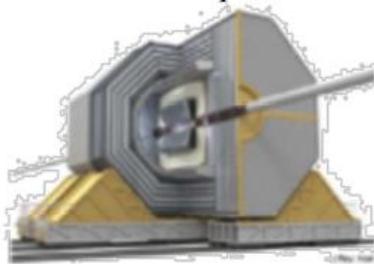
BEAST 2018

SuperKEKB-Japon



ILD ~2030

ILC-Japon



CEPC

Tracking of charged particles

Subatomic Physics

Beam instrumentation

Hadrontherapy

Imaging

β -rays, low energy e^-

X-rays

Dosimetry

Hybrid photo-detector

bio-inspired vision

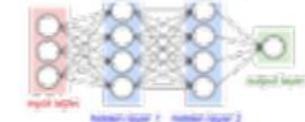
SOLEIL 2018



Sonde β



CIRENE



en discussion

BELLE-II

Tests industrie
non-destructifs

TRACKCAL

FOOT

Channeling

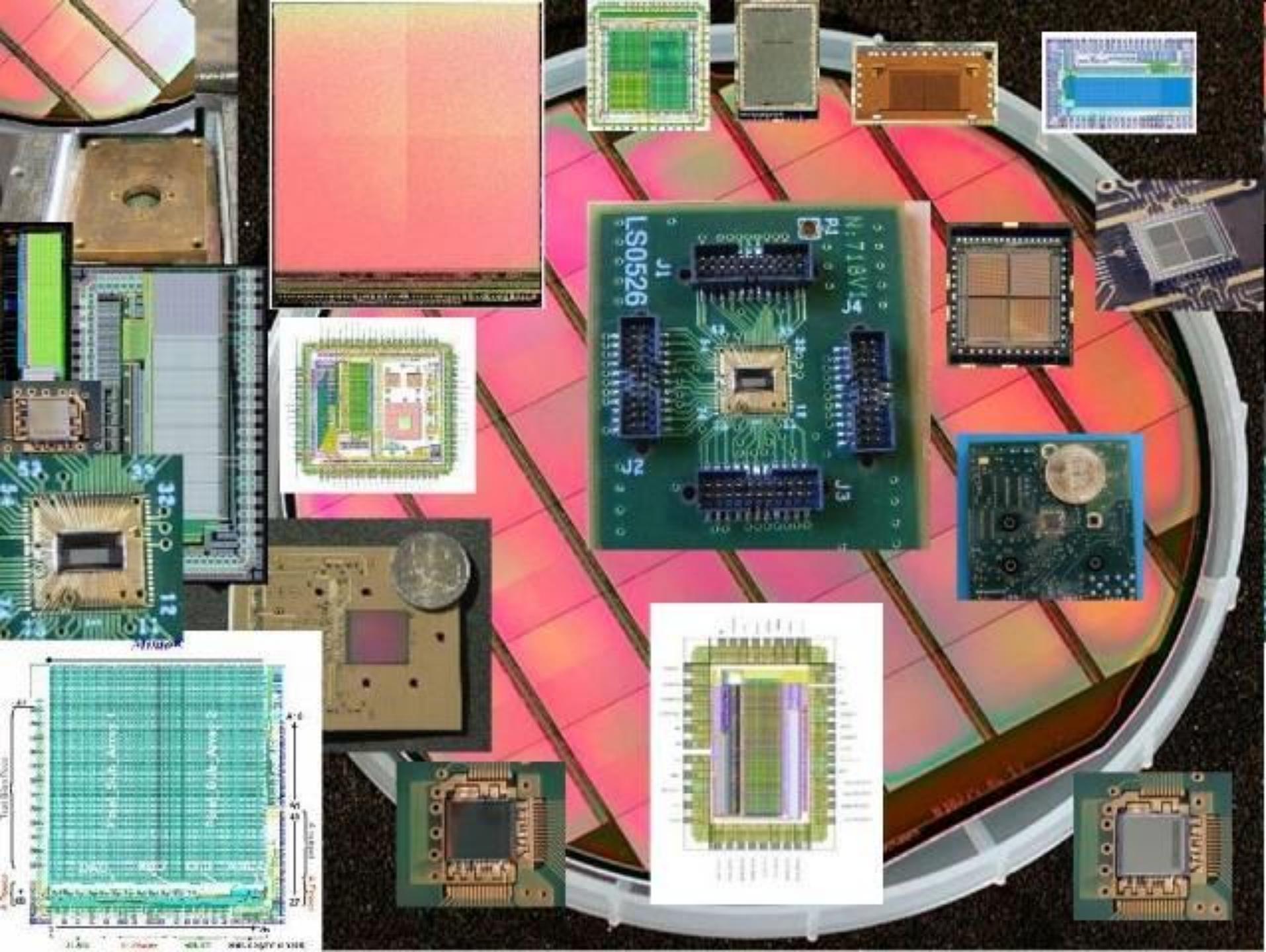
$\beta\beta-0\nu$

CBM upgrade



CBM >2020

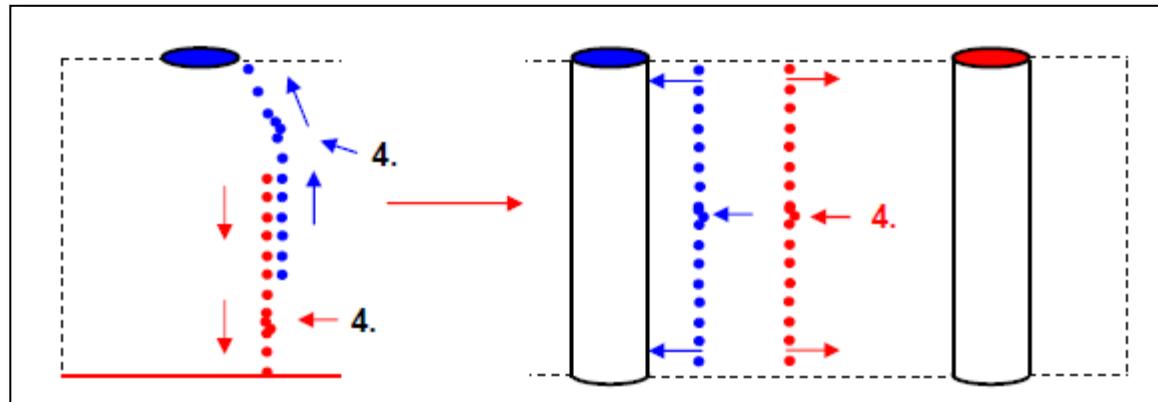
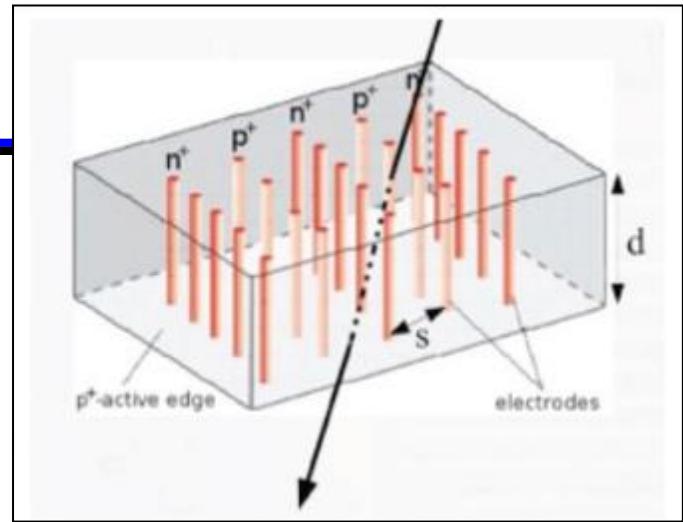
FAIR/GSI-Germany



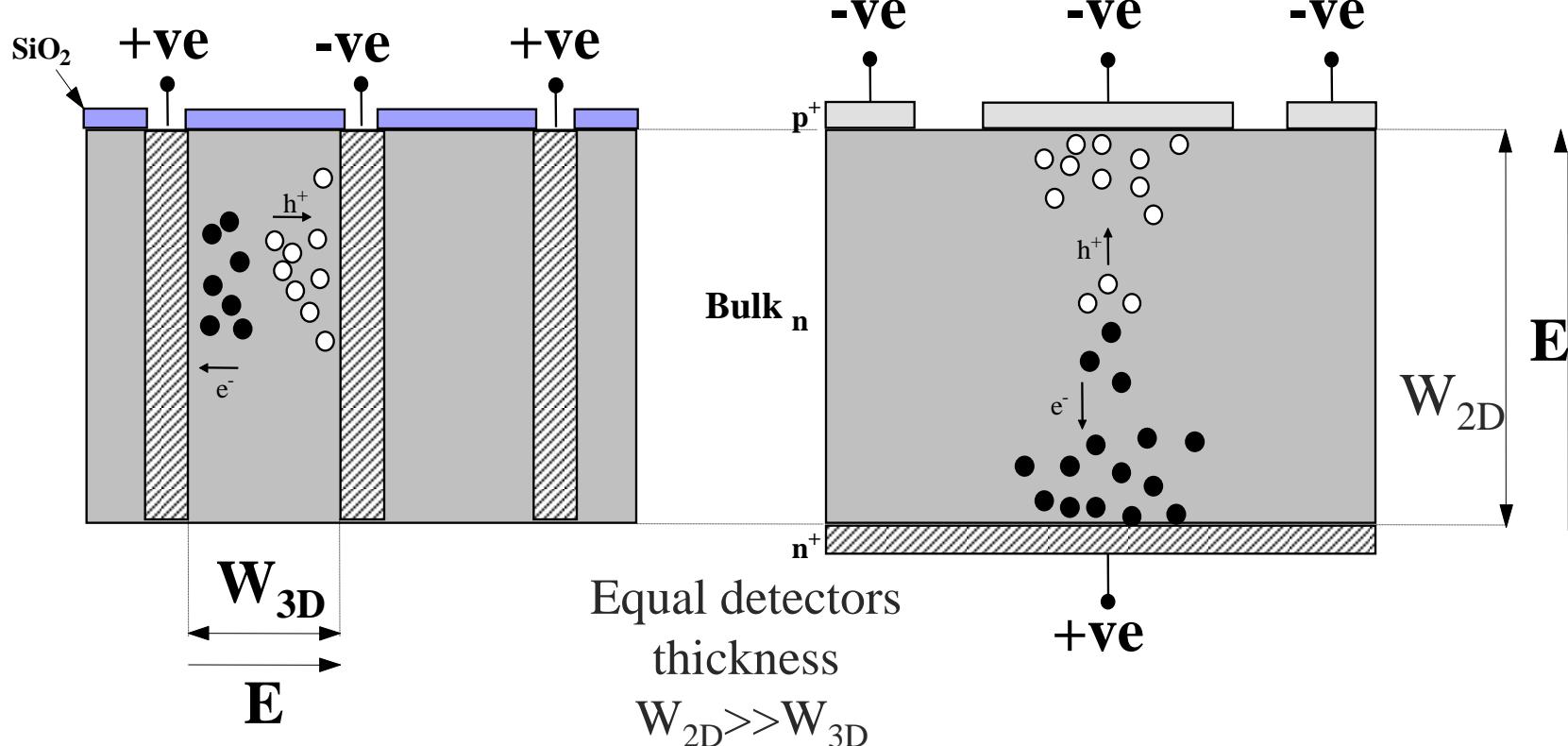
Some challenging technologies

3D sensors

- Motivations: LHC upgrades (idea \sim 1985)
- Principle
 - vertical electrodes (p^+ / n^+)
 - In the sensitive volume
 - Transverse charge drift
 - Thickness of active layer = determines signal
 - Collecting distance (recombination due to radiation damages) = distance between electrodes
 - Faster collecting time (few ns)
 - Reduced depletion voltage
 - Can enhance thickness: \uparrow signal (other applications: X-rays)
 - Reduced charge sharing
 - Potentially very rad hard.
- Limitations
 - non standard technology
- In a R & D phase



3D sensors

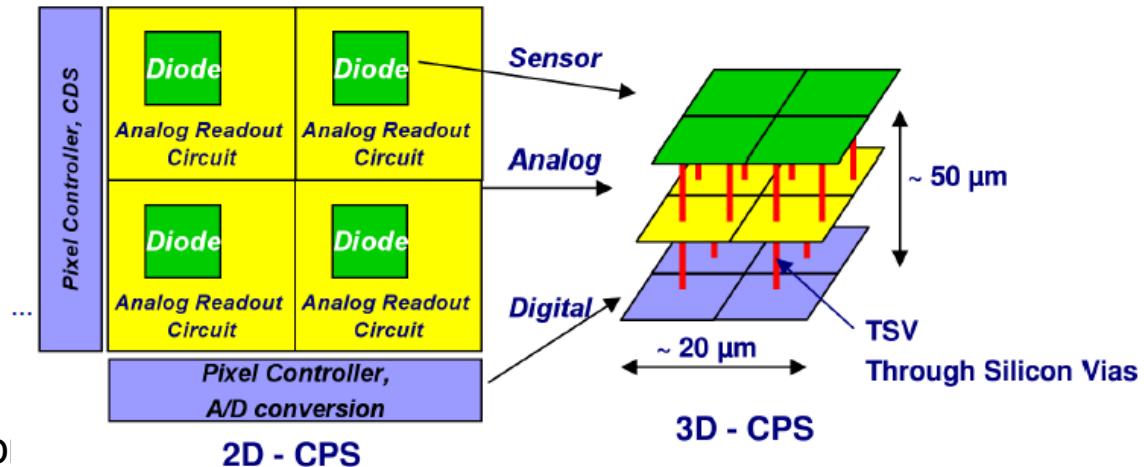


3D technologies

- Idea:

- Detector
- Analog treatment
- Digital treatment
- Data transfer

➤ Chose the best process for

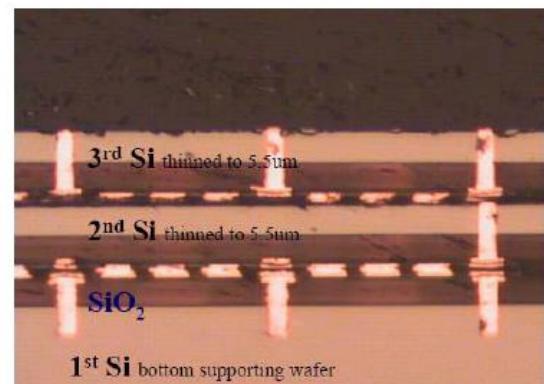


- Advantage

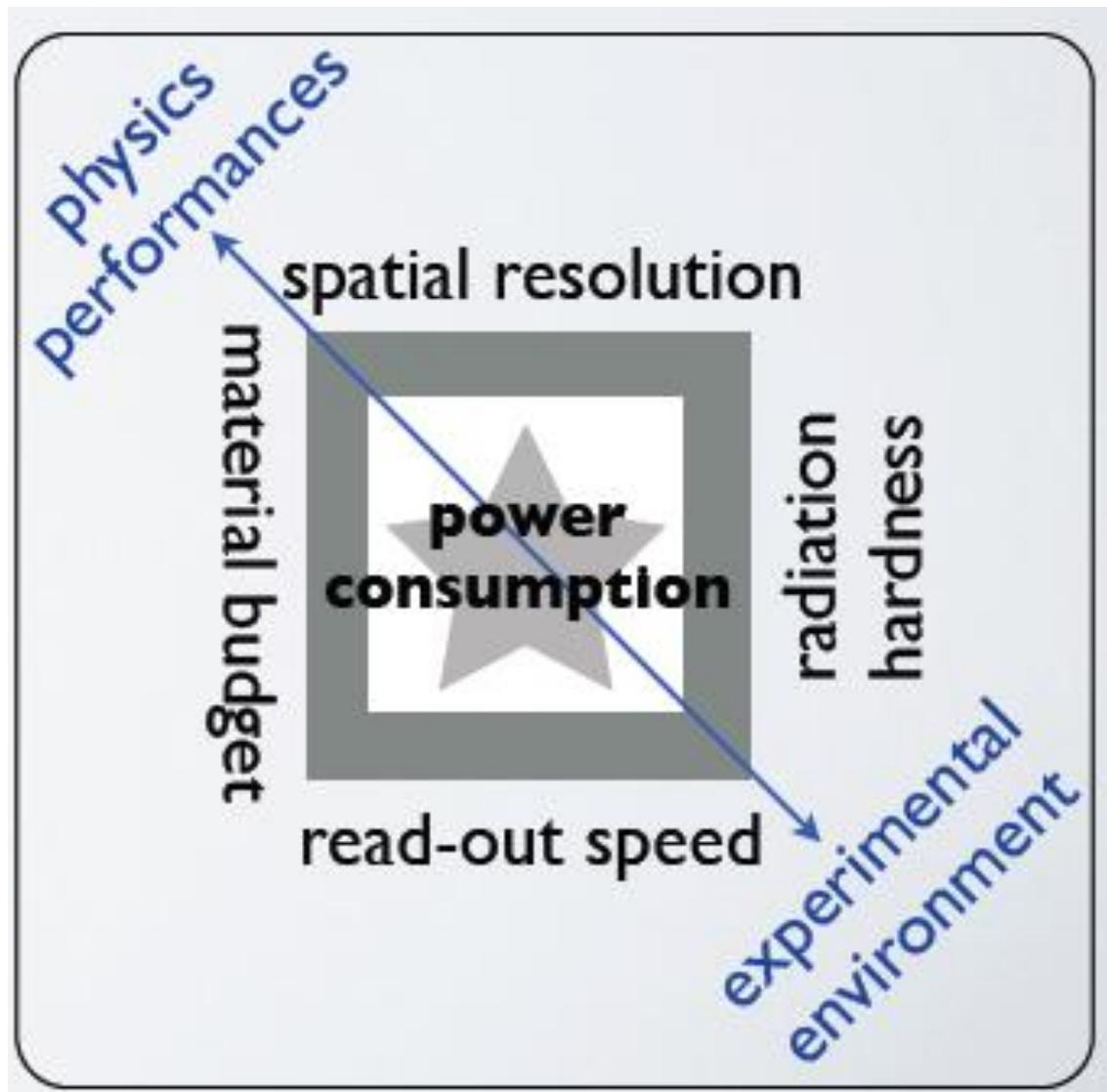
- 100 % acceptance (no chips in the periphery)
- Better integration (read-out speed, data treatment, sparsification, etc.)

- R & D (very long term)

- connectors
- Material budget (vias, etc.)
- Power consumption



Squaring the circle



Summary

- Tracking
 - Essential part of reconstruction process in particle physics
 - Pattern recognition + track fitting is a complex process
- Silicon detectors
 - Very active R & D
 - Industrial process for some of them (e.g. CMOS)
 - Strong expertise needed (integration, data acquisition, design, etc.)
 - A lot of applications
 - Tracking, vertexing
 - Calorimetry, spectroscopy, identification
 - Imaging
- PICSEL & microelectronic group @ IPHC
 - World leader in CMOS pixel sensor technology for subatomic physics.
 - Opportunities for internship and PhD.
 - Hardware AND physics analysis

END



Additionnal material

Bibliography

- G. Lutz, *Semiconductor radiation detector*, Springer (1999)
- H.G. Moser, *Silicon detector systems in high energy physics*, Progress in Particle and Nuclear Physics 63 (2009) 186-237
- Helmuth Spieler, *Semiconductor Detector Systems*, Oxford University Press (2005)
- L.Rossi, P.Fischer, T.Rohe, N.Wermes, *Pixel Detectors From fundamental to Applications*, Springer (2006)
- G.F. Knoll, *Radiation detection and measurement*, New York, Wiley (2000)

Bibliography (Moll)

- Some material taken from the following presentations
 - Michael Hauschild, CERN, *Tracking Detectors* (ESI 2009)
 - Leszek Ropelewski, CERN, *Gas Detectors* (*CERN Academic Training 2005*)
 - Christian Joram, CERN, *Particle Interactions with Matter* (*ICFA School 2010*)
Particle Detectors (*CERN Summer Student Lectures 2003*)
 - Werner Riegler, CERN, *Fundamentals of Particle Detectors* (*CERN Academic Training 2008*)
 - Gregor Herten, Uni Freiburg, *Particle Detection: Trackers* (*HCP School 2009*)
 - Pippa Wells, CERN, *Tracking at the LHC* (*EDIT 2011 School*)
- Literature – Further Reading
 - C.Grupen and B.Shwartz, *Particle Detectors*, Cambridge University Press
 - G.Lutz, *Semiconductor Radiation Detectors*, Springer
 - H.Spieler, *Semiconductor Detector Systems*, Oxford University Press
 - G.Knoll, *Radiation Detection and Measurement*, John Wiley and Sons
 - M.Sze, *Physics of Semiconductor Devices*, Wiley-Interscience
 - L.Rossi, *Pixel Detectors*, Springer
 - F.Hartmann, *Evolution of Silicon Sensor Technology in Particle Physics*, Springer

Back up

Radiation length X_0

- Length for which electrons loses 1/e of its initial energy (7/9 for photons)

$$X_0 = \frac{716.4 \text{ g cm}^{-2} A}{Z(Z+1) \ln(287/\sqrt{Z})} \quad (\text{g/cm}^2) \quad Z = \text{atomic number}$$

A = atomic mass

Depends also on volumic mass

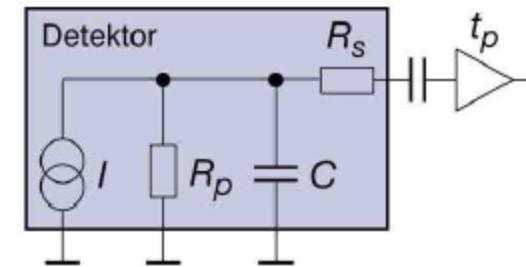
Exp: Silicon. Z = 14, A = 28

$X_0 = 22.01 \text{ g/cm}^2 \Rightarrow$ divided by $\rho(\text{solide}) = 2.3 \text{ g/cm}^3$

$X_0 = 9.55 \text{ cm}$ (real value = 9.4)

Noises sources

- En l'absence de signal, il existe toujours un bruit résiduel
 - Le bruit = fluctuation de la « charge » collectée en l'absence de signal
 - Exprimée en ENC (Equivalent Noise Charge $\Rightarrow e^-$)
 - Typiquement de qqs e^- à qqs 1000s e^-
 - Généralement gaussien ?
 - Pas toujours...
- Le Bruit peut dépendre de nombreux paramètres:
 - Irradiation
 - Vitesse de lecture
 - noise contribution from reverse current less significant
 - Courant de fuite $ENC_I \propto \sqrt{I}$
 - Bruit thermique $ENC_R \propto \sqrt{k_B T / R}$
 - Bruit capacitif
 - capacitance plus faible \Rightarrow bruit plus faible $ENC_c \propto C_d$



Alternate circuit diagram of a silicon detector.

- Le bruit s'ajoute en quadrature

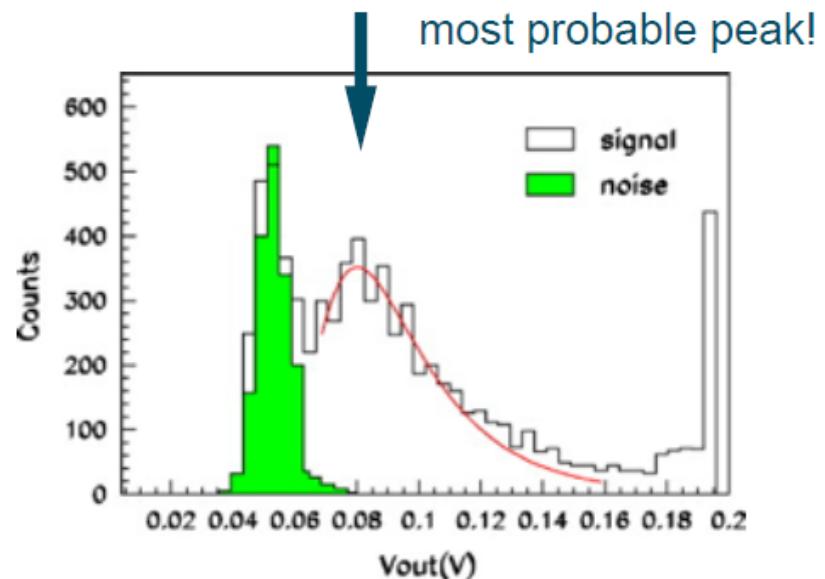
$$ENC = \sqrt{ENC_C^2 + ENC_I^2 + ENC_{Rp}^2 + ENC_{Rs}^2}$$

- Préamplifier le signal le plus tôt possible dans la chaîne de lecture

- **Signal/noise ratio:** signal size for a certain input signal over the intrinsic noise of the detector
 - parameter for analog signals
 - good understanding of **electrical noise**
 - charge needed
 - leakage current (ENC_I)
 - detector capacity (ENC_C)
 - det. parallel resistor (ENC_{Rp})
 - det. series resistor (ENC_{Rs})
 - signal induced by source or laser (or test beam particles)
 - optimal S/N for a MiP is larger than 20

$$ENC = \sqrt{ENC_C^2 + ENC_I^2 + ENC_{Rp}^2 + ENC_{Rs}^2}$$

example for silicon detector



Les S.C. dans la table périodique

IA																	0	
1	H																2 He	
2	Li	Be																
3	Na	Mg	IIIB	IVB	VB	VIIB	VIIIB	— VII —	IB	IB								
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	31	32	33	34	35	
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	49	In	Sn	Sb	Te	
6	Cs	Ba	*La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	81	Tl	Pb	Bi	Po	
7	Fr	Ra	+Ac	Rf	105	Ha	106	107	108	109	110						At	Rn

*Lanthanide
Series

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

+ Actinide
Series

90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr
-------	-------	------	-------	-------	-------	-------	-------	-------	-------	--------	--------	--------	--------

Legend - click to find out more...

H - gas



Non-Metals

Li - solid



Transition Metals

Br - liquid



Rare Earth Metals

Tc - synthetic

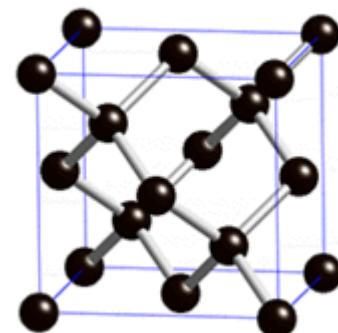


Halogens

En pratique
(dans nos disciplines)



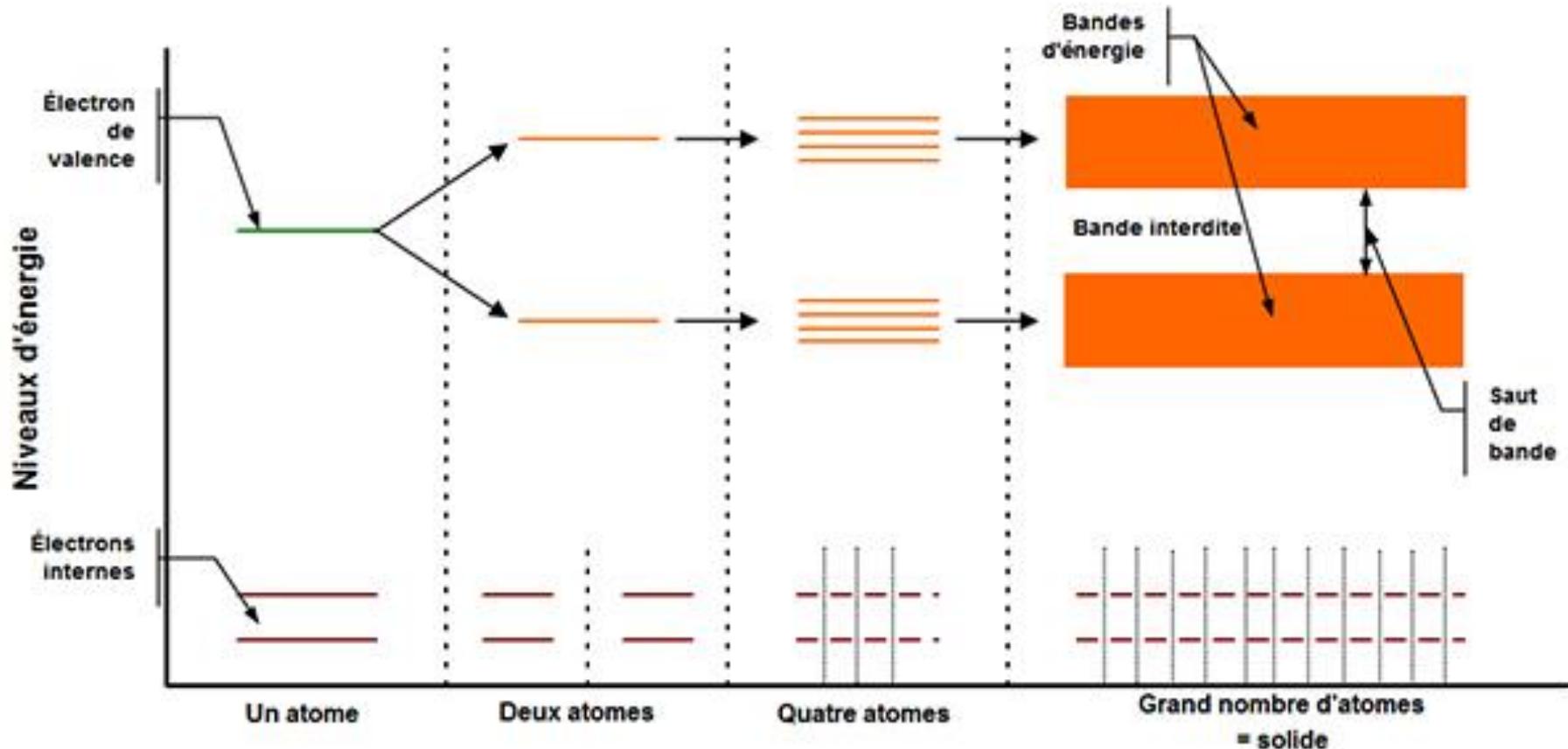
Silicium
Germanium
Diamant (C)
+quelques autres



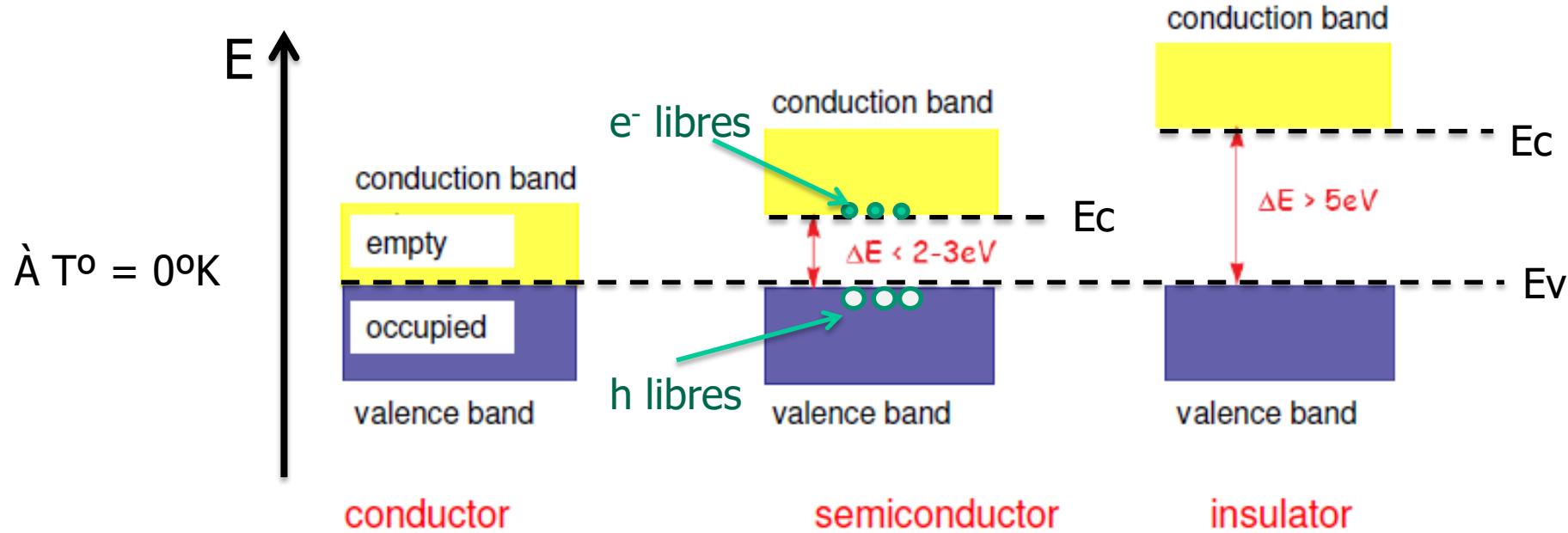
Niveaux d'énergie: de l'atome au solide

1 Atome: Niveaux d'énergie discrets

Grand nombre d'atomes = Solide: niveaux d'énergie « continus »



Le semi-conducteur



Distribution de Fermi-Dirac
pour les e^- :

$$f_e(E) = \frac{1}{e^{(E-E_F)/kT} + 1}$$

Pour les trous
(h=holes):

$$f_h(E) = 1 - f_e(E) = \frac{1}{e^{(E_F-E)/kT} + 1}$$

probabilité
d'occupation
d'un niveau
d'énergie E

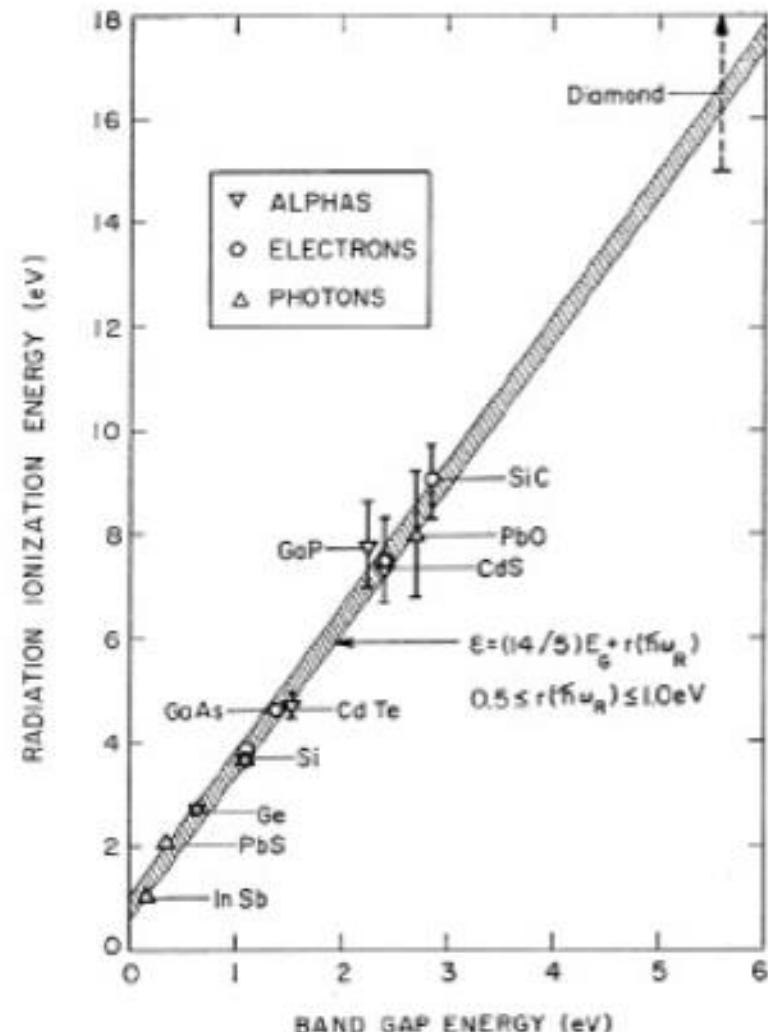
Pour les semiconducteurs intrinsèques (mêmes concentrations d' e^-/h):

$$\text{Énergie de Fermi} = E_F = E_{\text{gap}}/2$$

- **Band de valence (BV)** : dernière bande permise «pleine», d'énergie E_v
- **Band de conduction (BC)** : première bande permise «vide», d'énergie E_c
- **Gap** : bande interdite, d'énergie $\Delta E = E_g = E_c - E_v$

Energie gap \neq Energie d'ionisation

- A priori
 - pour arracher un électron de valence, il faut apporter E_{gap}
- Observation
 - ce n'est pas ce que l'on constate
 - $E_{\text{ionisation}} \sim 3 \times E_{\text{gap}}$ (indépendant du S.C et de la particule incidente)
- Contrainte
 - conservation de l'impulsion et de l'énergie
 - transfert de quantité de mouvement au cristal sous forme de phonons
 - cette quantité de mouvement se traduit par un transfert d'énergie au cristal qui n'est pas utilisé pour la ionisation



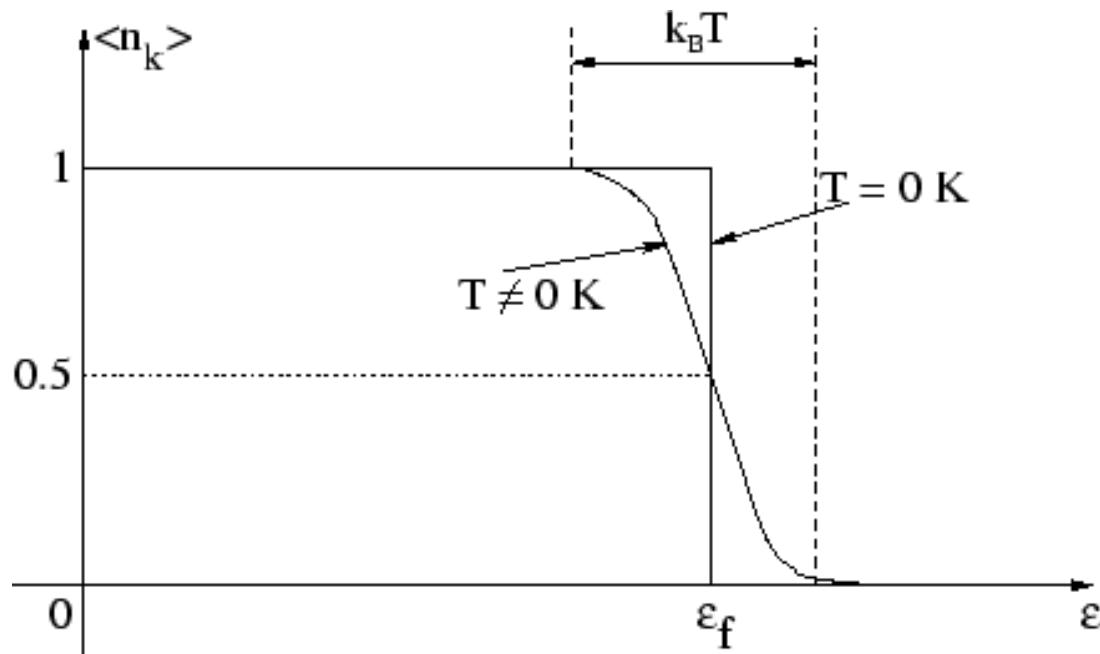
Quelques propriétés de S.C. courants

Material	Z	Bandgap [eV]	Mobility [cm ² /Vs]		Density g/cm ³
			electrons	holes	
Si	14	1.1	1350	480	2.3
Ge	32	0.7	3800	1800	5.3
Diamond	6	5.5	1800	1200	3.5
GaAs	31-33	1.5	8600	400	5.4
AlSb	13-51	1.6	200	700	4.3
GaSe	31-34	2.0	60	250	4.6
CdSe	48-34	1.7	50	50	
CdS	48-16	2.4	300	15	4.8
InP	49-15	1.4	4800	150	
ZnTe	30-52	2.3	350	110	
WSe ₂	74-34	1.4	100	80	
Bil ₃	83-53	1.7	680	20	
Bi ₂ S ₃	83-16	1.3	1100	200	6.7
Cs ₃ Sb	55-51	1.6	500	10	
Pbl ₂	82-53	2.6	8	2	6.2
Hgl ₂	89-53	2.1	100	4	6.3
CdTe	48-52	1.5	1100	100	6.1
CdZnTe	48-30-52	1.5-2.4			

Distribution de Fermi-Dirac

Fermi-Dirac-Distribution:

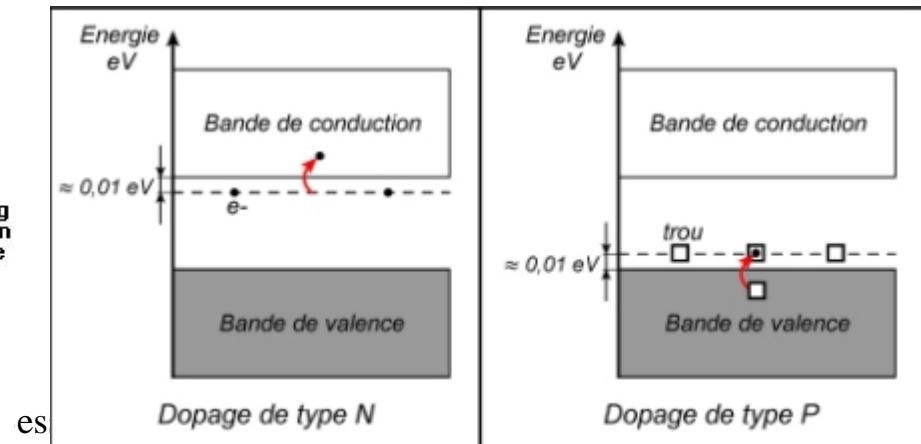
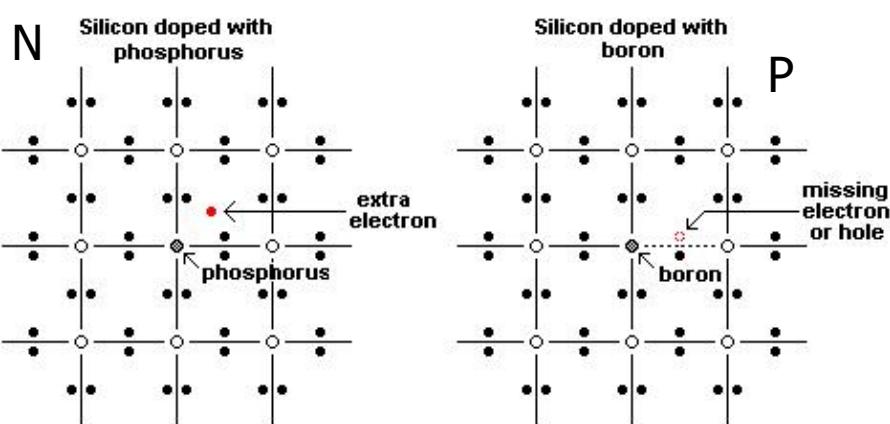
$$f_e(E) = \frac{1}{e^{(E-E_F)/kT} + 1}$$



- $f(E_F) = 1/2$
- Quand $T \rightarrow 0$
 - Tous les niveaux les plus bas sont occupés
 - isolant
- Quand T augmente
 - La probabilité que des niveaux d'énergie supérieurs à E_F soit occupés augmente
- La conductivité dépend de la température
 - Solution: le dopage.

Dopage

- Principe:
 - Remplacement d'une petite fraction des atomes par d'autres atomes ayant un e- de plus (N) ou de moins (P) sur leur couche de valence
 - Dopage P: Bore, N: Phosphore, Arsenic, etc.
 - Intrinsèque = non dopé ; extrinsèque = dopé
 - Ces atomes prennent la place du matériau de départ (Si, Ge, etc.)
 - Concentrations typiques: $10^{12} - 10^{18} / \text{cm}^3 >> n_i$
 - Ces dopants « ajoutent » des niveau d'Energie supplémentaires
 - e- supp. \Rightarrow niveau supp. N près de la bande de conduction
 - A T ambiante \Rightarrow e- libre sur la bande de conduction
 - h supp. \Rightarrow niveau supp. P près de la bande de valence
 - e- manquant sur la bande de valence
 - Trou libre supplémentaire
- \Rightarrow Dopage = porteurs de charge libres supplémentaires
Modification de la conductivité du matériau

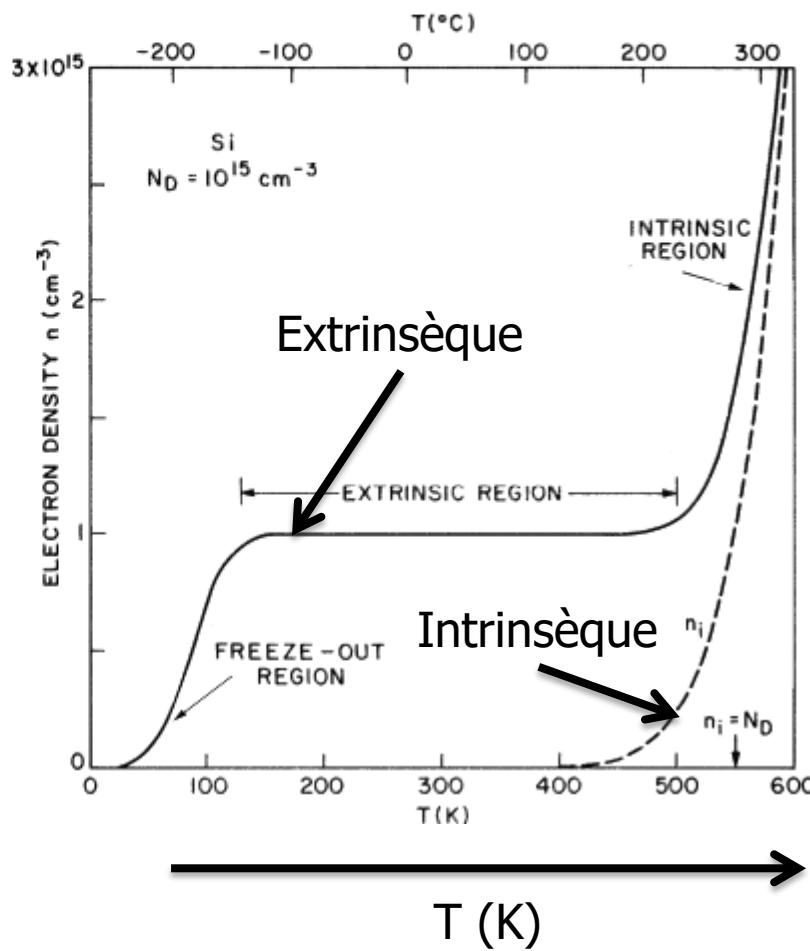


Dopage et conductivité

- Intrinsèque :
 - La Température gouverne la densité de porteurs libres
- Extrinsèque
 - Le dopage gouverne la densité de porteurs libres
 - (jusqu'à une certaine T)
 - On impose la conductivité

- ★ At low temperatures the thermal energy is not sufficient to ionize all donors. Some e- are frozen at the donor level.
- ★ As the temperature increases all donors become ionized ("extrinsic region").
- ★ At even higher temperature ($kT \approx E_g$) the intrinsic carrier concentration becomes comparable to the donor concentration. Beyond this point the semiconductor becomes intrinsic.

Electron density as a function of temperature for a Si sample with a donor concentration of 10^{15} cm^{-3} :



Source: S.M. Sze, *Semiconductor Devices*, J. Wiley & Sons, 1985

Signal et concentration des porteurs de charge

- Nombre d'atomes

➤ $\sim 10^{22}$ atomes/cm³

Nc et Nv = densités d'états effectives respective des électrons dans la bande de conduction et des trous dans la bande de valence.

- Silicium pur (intrinsèque) à T ambiante

- Electrons sur la bande de conduction et trous sur la bande de valence
- Equilibre \Rightarrow excitation = recombinaison
- Concentration intrinsèque des porteurs de charge

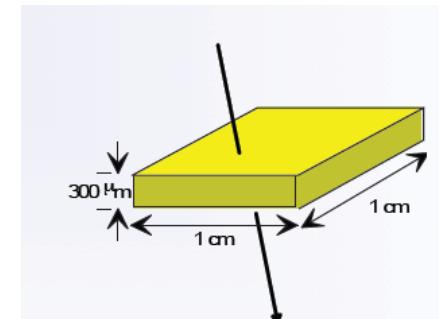
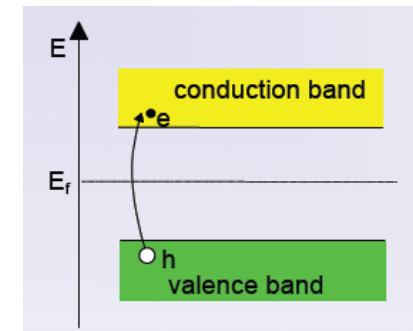
➤ $n_i = n_{e^-} = n_h =$

$$n_i = \sqrt{N_C N_V} \cdot \exp\left(-\frac{E_g}{2kT}\right) \propto T^{\frac{3}{2}} \cdot \exp\left(-\frac{E_g}{2kT}\right)$$

➤ Silicium à 300K: $n_i \sim 1.45 \times 10^{10} / \text{cm}^3 \Rightarrow 1/10^{12}$ atomes ionisés

- Exemple: signal créé par le passage d'une particule au minimum d'ionisation (MIP)

- Détecteur d'épaisseur 300µm, surface 1cm², énergie d'ionisation=3.6 eV,
- Nombre d'ionisations ~ 100 e-h / µm
- Signal ~ 3000 e⁻ ; porteurs libres $\sim 4.5 \times 10^8$
- \Rightarrow Comment changer ce rapport ? (déplétion, dopage)



The Helix Equation

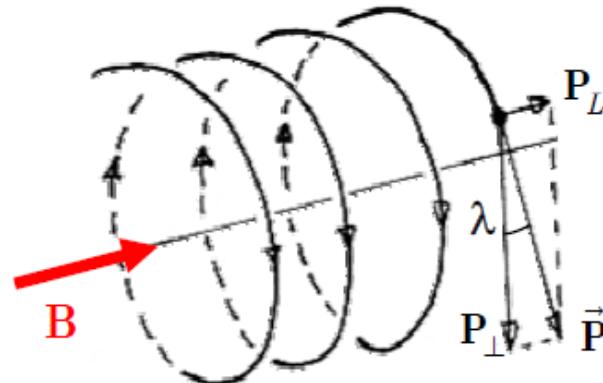
The helix is described in parametric form

$$x(s) = x_o + R \left[\cos\left(\Phi_o + \frac{hs \cos \lambda}{R}\right) - \cos \Phi_o \right]$$

$$y(s) = y_o + R \left[\sin\left(\Phi_o + \frac{hs \cos \lambda}{R}\right) - \sin \Phi_o \right]$$

$$z(s) = z_o + s \sin \lambda$$

$$R(m) = \frac{p_{\perp}(\text{GeV})}{0.3B(T)}$$



λ is the dip angle

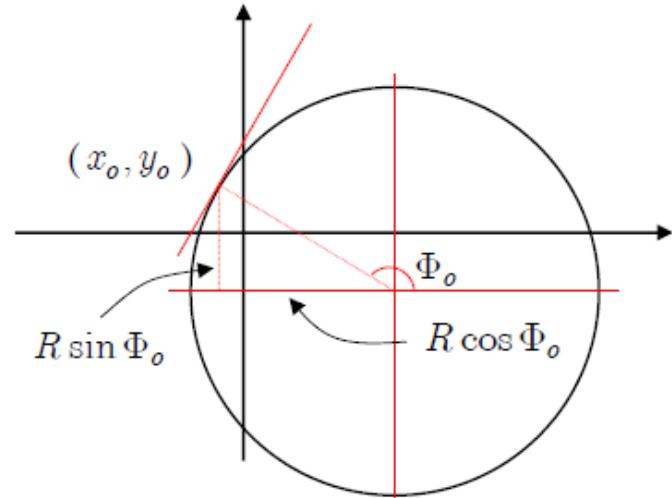
$h = \pm 1$ is the sense of rotation on the helix

The projection on the $x-y$ plane is a circle

$$(x - x_o + R \cos \Phi_o)^2 + (y - y_o + R \sin \Phi_o)^2 = R^2$$

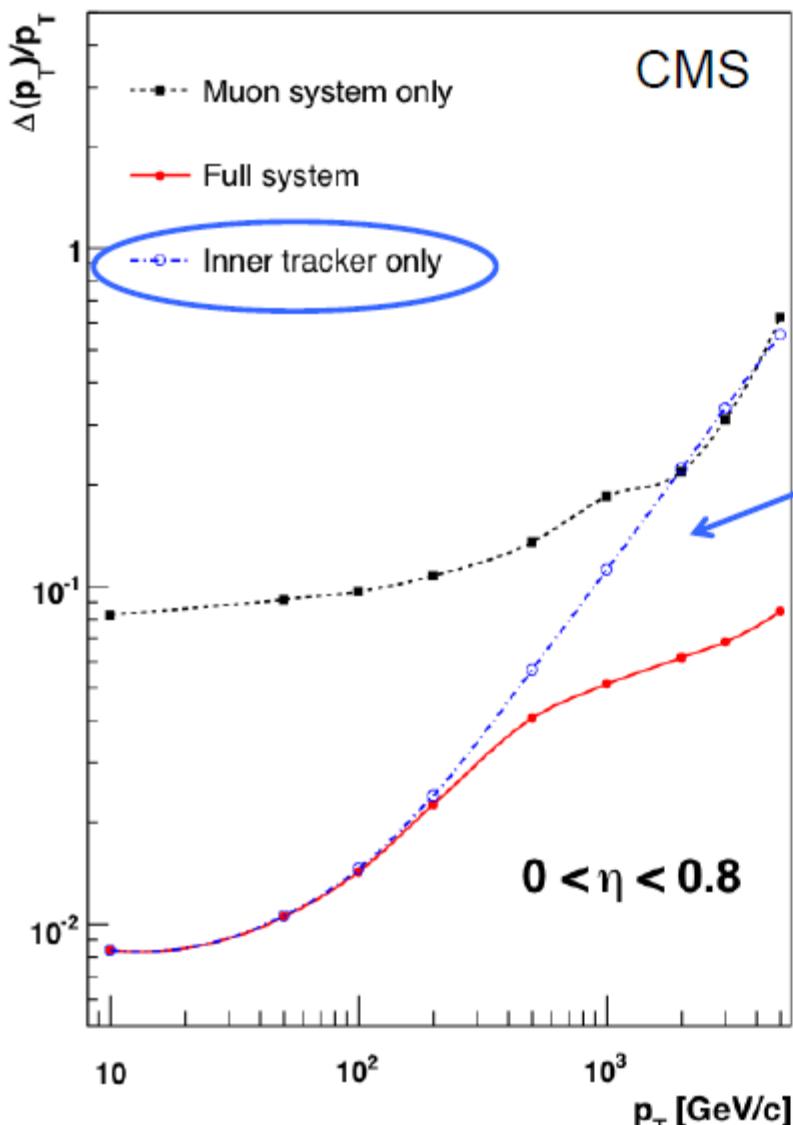
x_o and y_o the coordinates at $s = 0$

Φ_o is also related to the slope of the tangent to the circle at $s = 0$



Momentum resolution

2008 JINST 3 S08004 CMS Experiment
2008 JINST 3 S08003 ATLAS Experiment



Expected relative p_T resolution
for muons vs $|\eta|$ and p_T .

$$\frac{\sigma_{p_T}}{p_T} \approx a \cdot p_T \oplus \frac{b}{\sin^{1/2} \theta}$$

