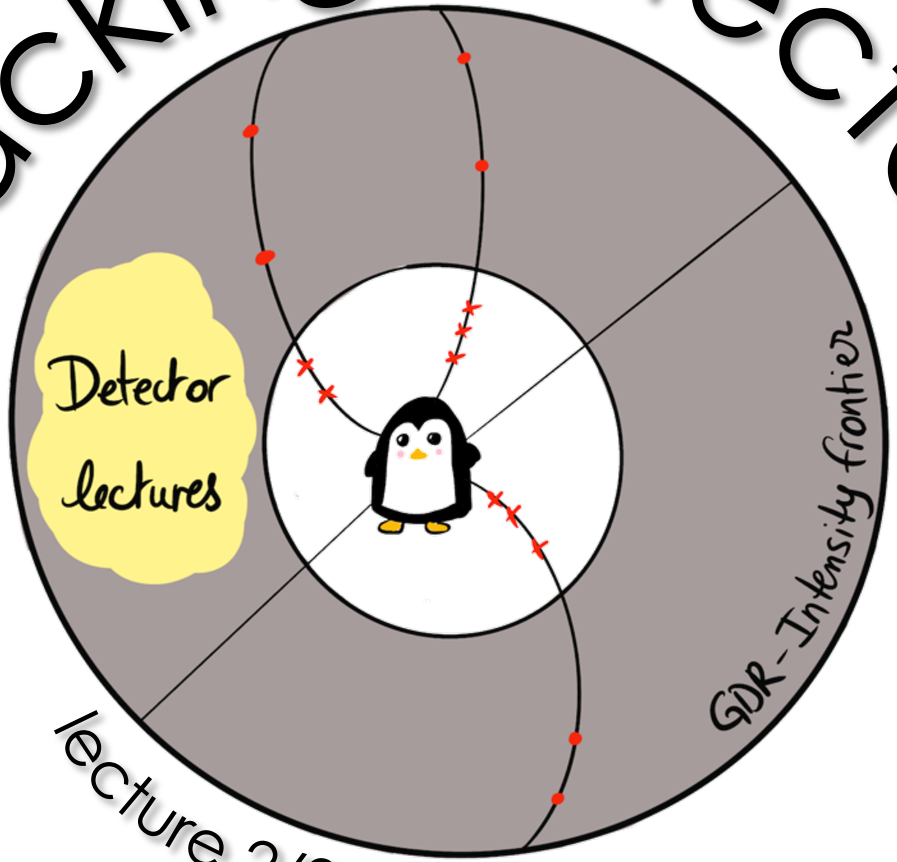
November 2021

https://indico.in2p3.fr/event/25006/

INTENSITY frontier

Tracking detectors



lecture 2/2

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Beyond detectors:
lecture on Tracking algorithms by P.Billoir

Reminders from lecture 1

Tracking involves:

FINDING & FITTING … and harsh environment

- Granular sensors in time
- Granular sensors in space
- Low material budget
- Layer close to each other
- Many measurement points
- Measurement over large lever arm
- Radiation tolerance

} Requirements

Various implementations

- Large gas volume embedding many measurement points
- Thin gas volumes over large area
- Scintillators strips, straw tubes to build large area and/or volume
- Semi-conductor based sensors for individual, thin & inner layers

} Technologies

Outline of lecture 2

- → Generalities about resolution
- → Large gas volume detectors
- → Micropattern gas chambers
- → Scintillators for tracking
- → Silicon detectors
- → Nuclear Emulsions

Resolutions

→ Signals & electrode segmentation

→ Segmentation & position resolution

→ Timing

Charged particles…why?

- **Tracking single particles required (at least) two points**
  - Prevents detection after which particle is gone

- **Neutrals?**
  - Neutral hadrons detected through strong interaction => vanish after first point
  - Photons disappear after photo-electric effect or pair-creation
    or trajectory severely impacted after Compton scattering

- **Ionization process ideal**
  - Low energy loss: for MIP (p ~1 GeV) in 300 µm Silicon: ΔE ~ 100 keV, much less in gas
  - Many points authorised
  - Quite democratic, ~independent of particle type
  - BUT electromagnetic process => only for charged particles

- **Scintillation works as well**
  - Detects also neutrals … but still on shot (stopped or transformed)

Segmentation and signal formation

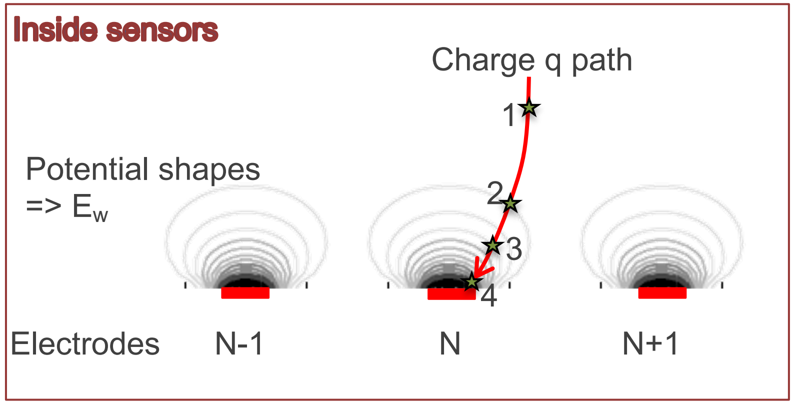
Basic signal formation with ionization:

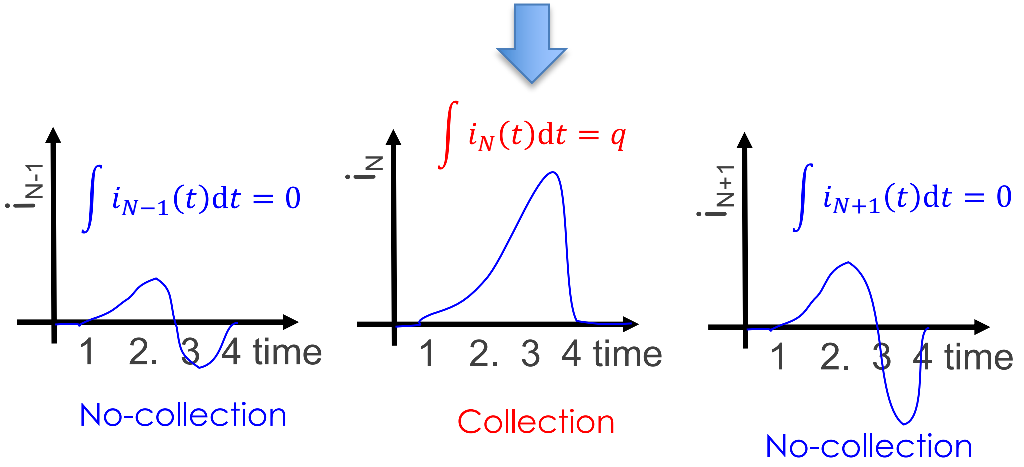
- key parameters for initial nb of primary charges {
  - Wi = average energy for charge pair generation
  - F = fano factor (<1) => variance$_{\#charges}$ = F <#charges>
- Schockley-Ramo theorem: current on electrode INDUCED by charge movement
  => electric field required

Collection and segmentation?

- $E_W(\vec{r})$ = field associated to ONE electrode at a position $\vec{r}$
- obtained with: THIS electrode has potential=1,
  all other electrodes have potential 0
- Current generated on THIS electrode
  for particle at $\vec{r}$ and with velocity $\overrightarrow{v(r)}$

$$i(\vec{r}) = q\, E_W(\vec{r})\ \mathrm{v}\,(\vec{r})$$





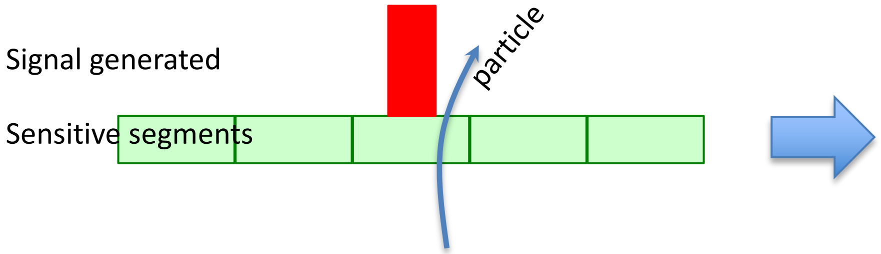
≠ Charge sharing:

- Many charges generated by one particle
- BUT their collection are shared among electrodes

=> each electrode collecting some charges
and has some signal!

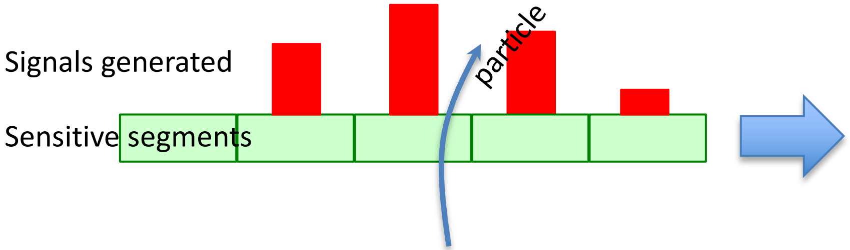
Spatial resolution

- Position measurement comes from segmentation
  - Pitch = segment size
- Digital resolution
  - Position = position of single fired segment



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

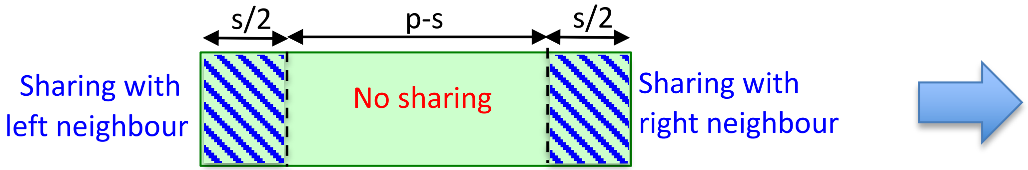
- Improvement from signal sharing
  - Position = weighting average of segment positions
  - Perfect algorithm if sharing linear with d(segment-hit)
    … however never true



$$\sigma \propto \frac{\text{pitch}}{\text{signal/noise}}$$

- For real sensor
  - Mixed of both cases

SIMPLE model: zoom over 1 sensitive segment



$\sigma_{sh} = \frac{s}{\sqrt{12}}$ $\sigma_{nosh} = \frac{p-s}{\sqrt{12}}$ $\sigma_{sh} = \frac{s}{\sqrt{12}}$

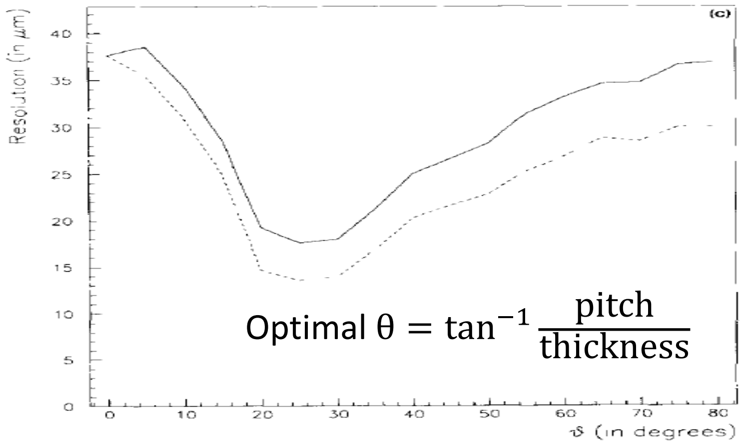
$$\sigma = \frac{s^2 + (p-s)^2}{p\sqrt{12}}$$

=> minimal for s = p/2

=> resolution always proportional to pitch
the proportionality factor depends on the details

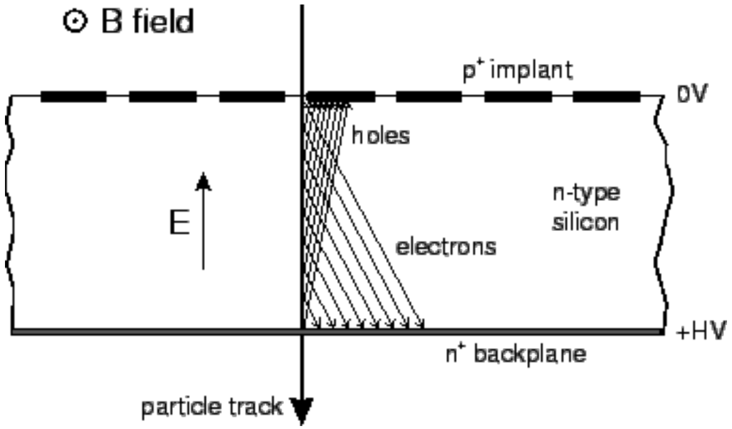
Spatial resolution – additional effects

- Incident angle
  - In real life, particles seldomly cross ⊥ sensor
    => charge sharing increases with angle
  - Beneficial for low angle
    - when sharing still depends on distance (segment-hit)
  - @ large angle, sharing is homogeneous over segments
    - change of algorithm compensates sligthly



$$\text{Optimal } \theta = \tan^{-1}\frac{\text{pitch}}{\text{thickness}}$$

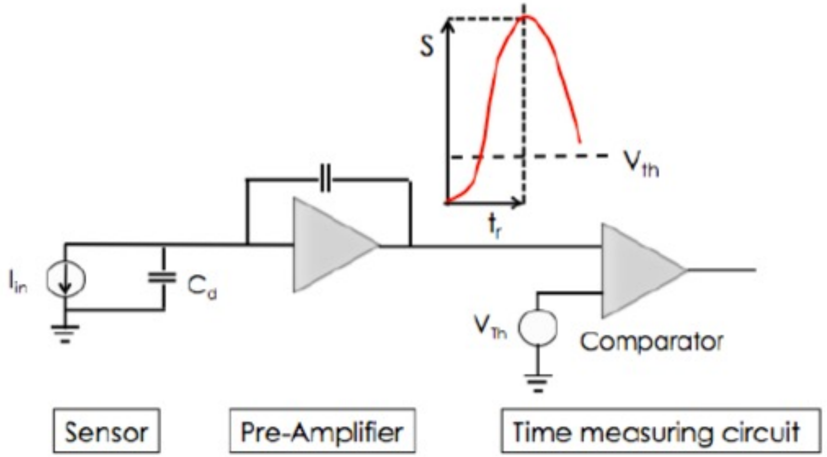
- A necessary trouble maker
  - Lorentz force from magnetic field B induces pseudo charge-sharing
  - Systematic effect => measurable and correctible



Timing

- **Various ways to qualify timing performance**
  - Integration time => Hit rate, potential bottleneck at data taking
  - Time resolution => Track finder step

- **Time resolution for single layer**
  - Here from the silicon point of view (but silimar for thin gas detectors)



Time is set when the signal crosses the comparator threshold

$$\sigma_t^2 = \left(\frac{Noise}{dV/dt}\right)^2 + (\Delta ionization)^2 + (\Delta shape)^2 + (TDC, Clock \ldots)^2$$

Usual "Jitter" term

Amplitude variation:

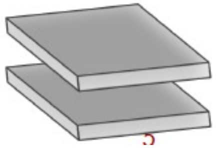
Sensor design: very uniform signals

Subleading, ignored here

From N.Cartiglia, INFN

Encouraging remark by the expert 😅

This is the ONLY good geometry



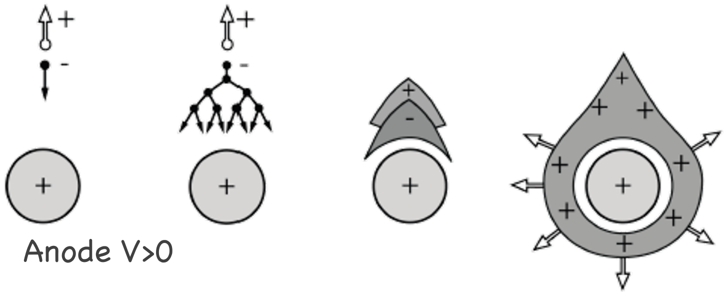
Large gas volume detectors

→ Drift chambers

→ Time projection chambers

Short reminder on gas-based detectors

- Ionization
  - Rather large W_i 20-40 eV combined with low density (gas). => primary nb of charges low
    => amplification is needed for good SNR!
  - Due to additional non-ionizing energy loss (e.g. light) => smart gas admixture
- Velocity-mobility $v_{\text{drift}} = \mu \frac{E}{P}$
  - μ is the mobility (P the pressure) => very different for e- and ions !
    - Typical v_{drift}(e-) > 10 cm/μs
  - Signal time characteristic quite different for e- and ions
- Amplification
  - With avalanche when large field (E>106 V/m)

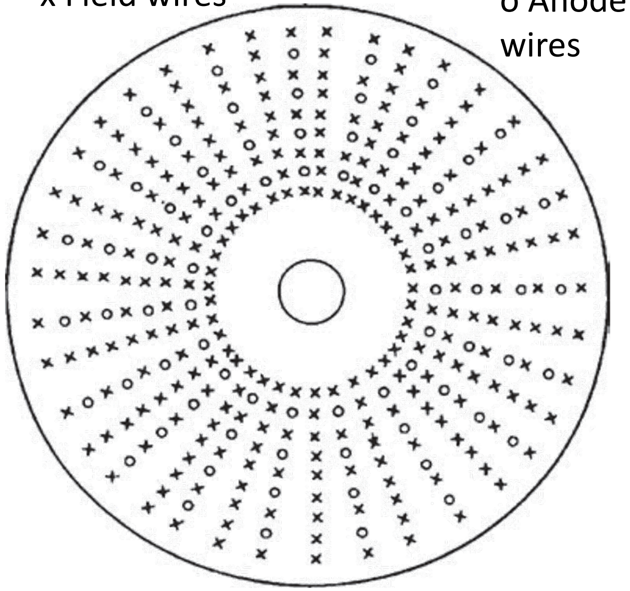


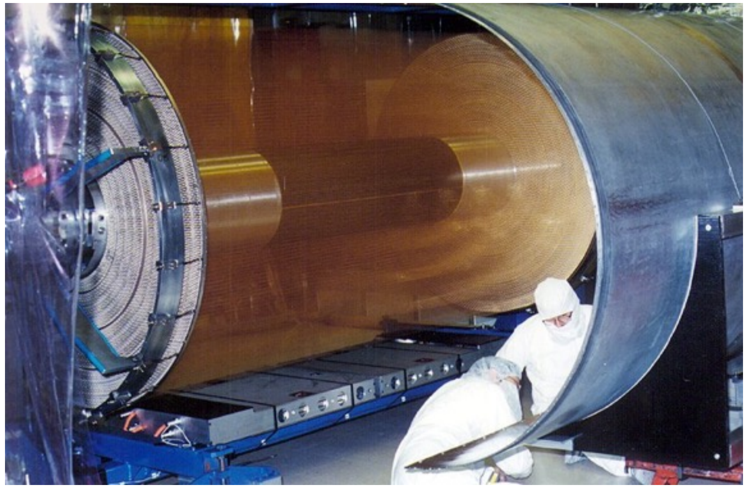
Observe +/- different behaviour

Drift chambers

Basic principle

- Alternate field and anode wires
  - Generate a drift
- Pressurize gas to increase charge velocity (few atm)
- 3D detector
  - 2D from wire position
  - 1D from charge sharing at both ends





Belle II drift Chamber

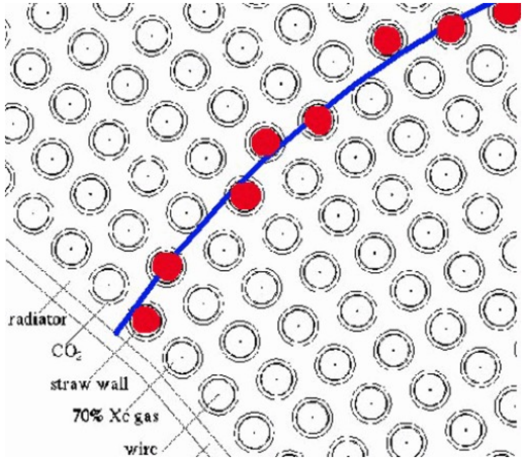
Spatial Resolution

- Related to drift path $\sigma \propto \sqrt{\text{drift length}}$
- Typically 100-200 µm

Remarks

- Could not go to very small radius
  - Mechanical precision for wires too difficult
  - Hit rate limitation due to charge density generated
- Aging process on wires (unwanted insulating layer)

Same principle with straw tubes



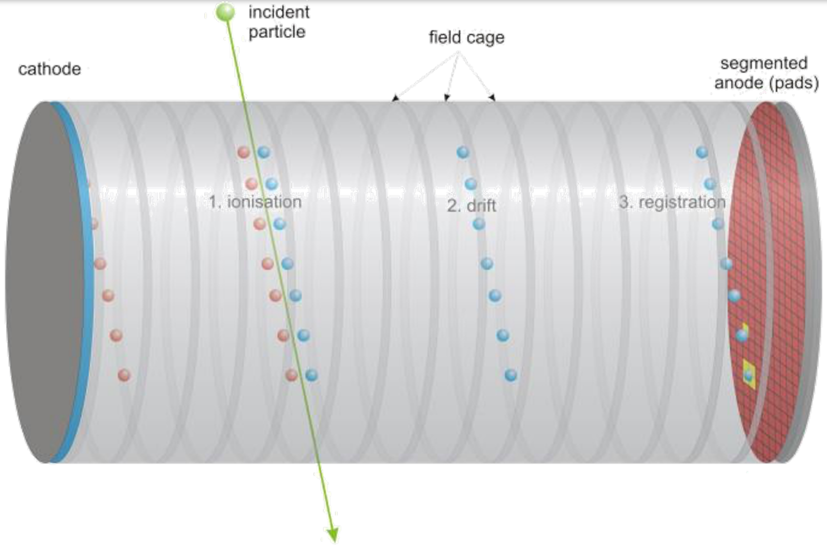
Time Projection Chambers - concept

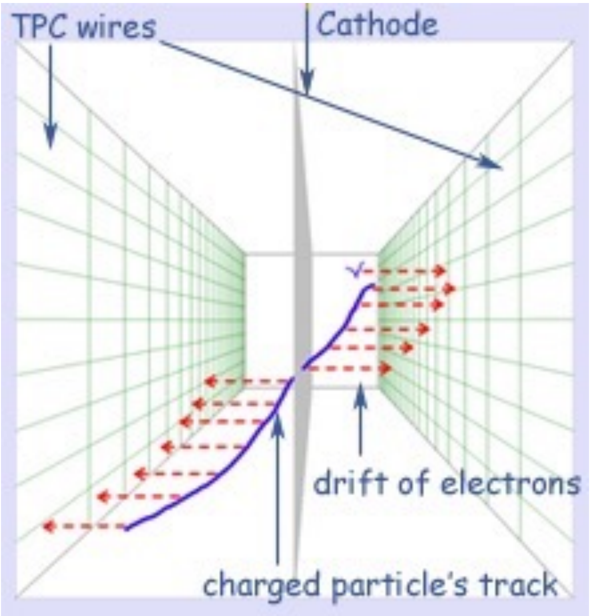
Benefits

- Large volume available
- Multi-task: tracking + Part. Identification

Basic operation principle

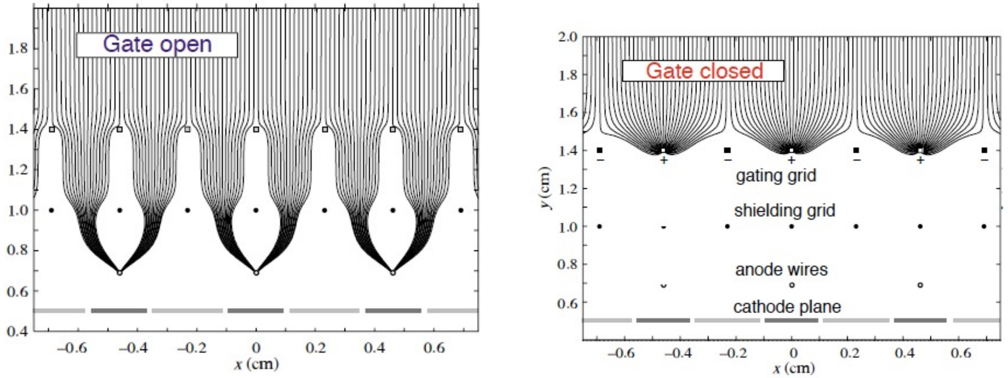
- Gas ionization → charges
- Electric field → charge drift along straight path
- Information collected
  - 2D position of charges at end-cap
  - 3rd dimension from drift time
  - Energy deposited from #charges
- Different shapes:
  - rectangles (ICARUS)
  - Cylinders (colliders)
  - Volumes can be small or very large





Time Projection Chambers 2/2

- End cap readout
  - Gas proportional counters
    - Wires+pads (old days)
    - GEM, Micromegas (see later): for



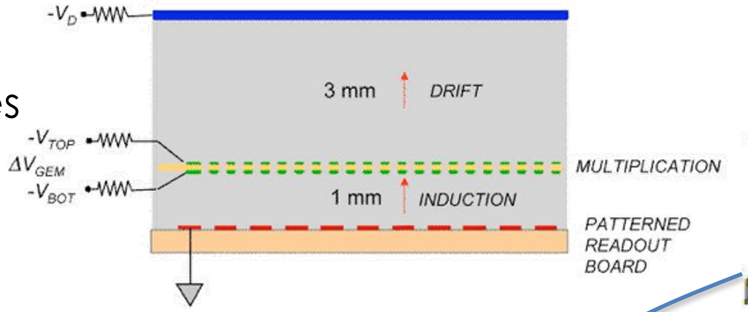
- Performances
  - Two-track resolution ~ 1cm
  - Transverse spatial resolution ~ 100 - 200 μm
  - Longitudinal spatial resolution ~0.2 - 1 mm
  - Longitudinal drift velocity: 5 to 7 cm/μs
    - ALICE TPC (5m long): 92 μs drift time
  - Pro
    - Nice continuously spaced points along trajectory
    - Minimal multiple scattering (inside the vessel)
  - Cons
    - Limiting usage with respect to collision rate
    - Could not go to very small radius

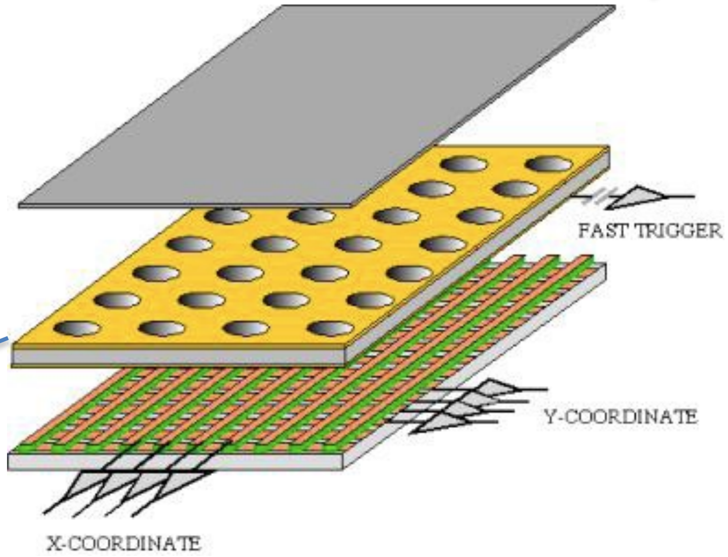
Micropattern gas chambers

- Gas electron multiplier
- Micromegas
- Resistive plate chamber

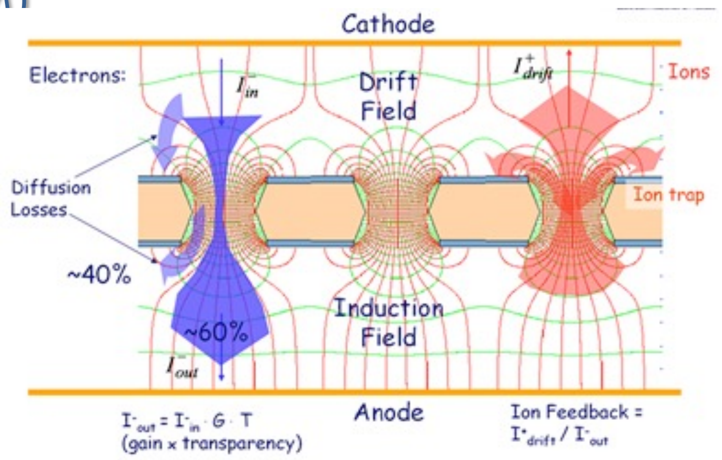
Wire chambers "advanced"

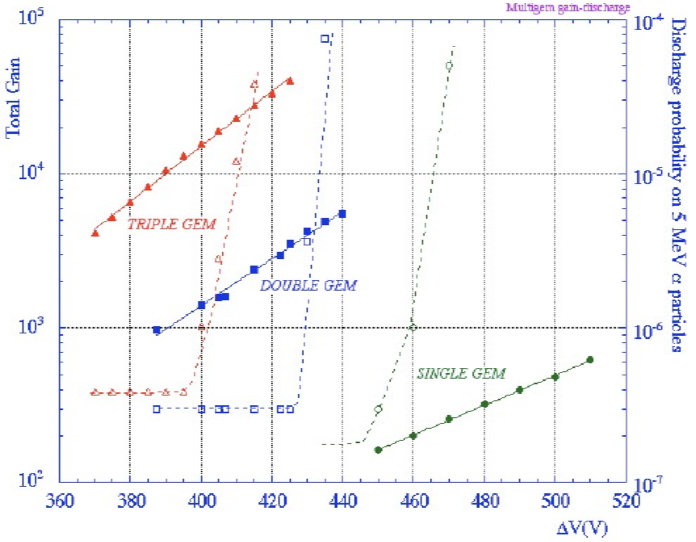
- Goal: reaching high hit-rate
  - Difficult with traditional gas chambers since drift volumes = amplification volumes =>





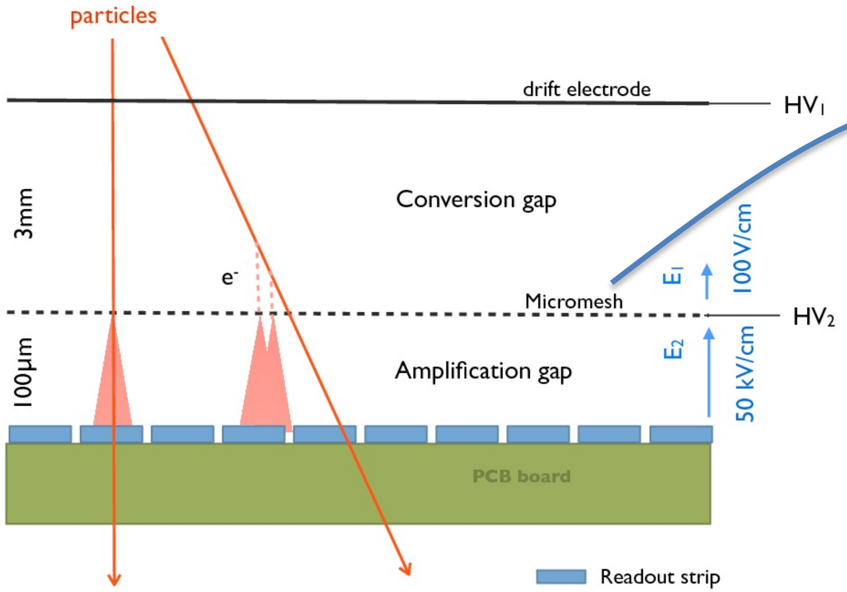
- Gas Electron Multiplier (GEM)
  - Gain 10^5
  - Hit rate 10^6 Hz/cm2

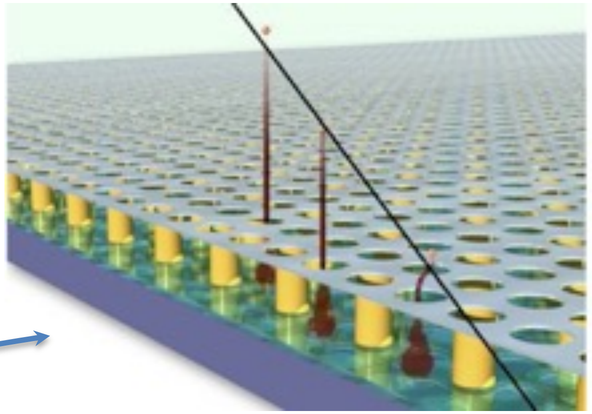


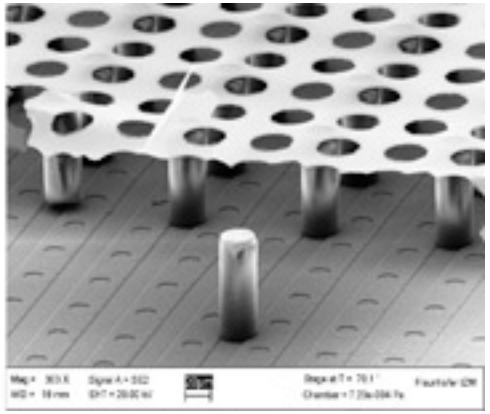


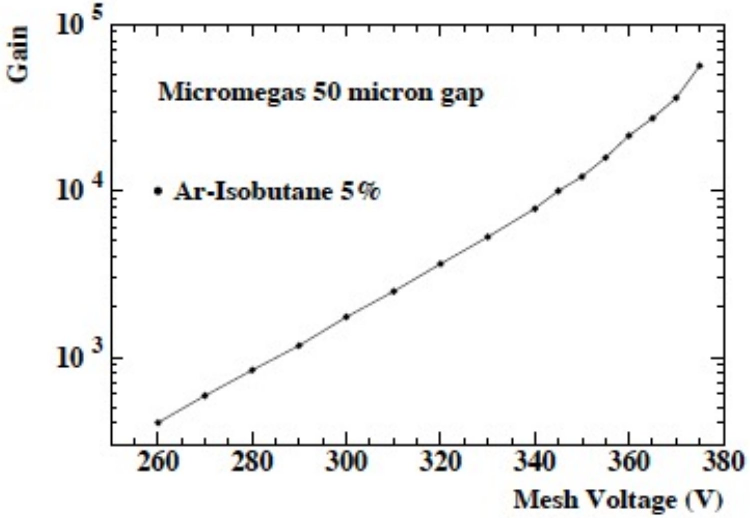
Wire chambers "advanced"

- MICROMEGAS
  - Even smaller distance anode-grid / GEM
  - Hit rate 10^9 Hz/cm2







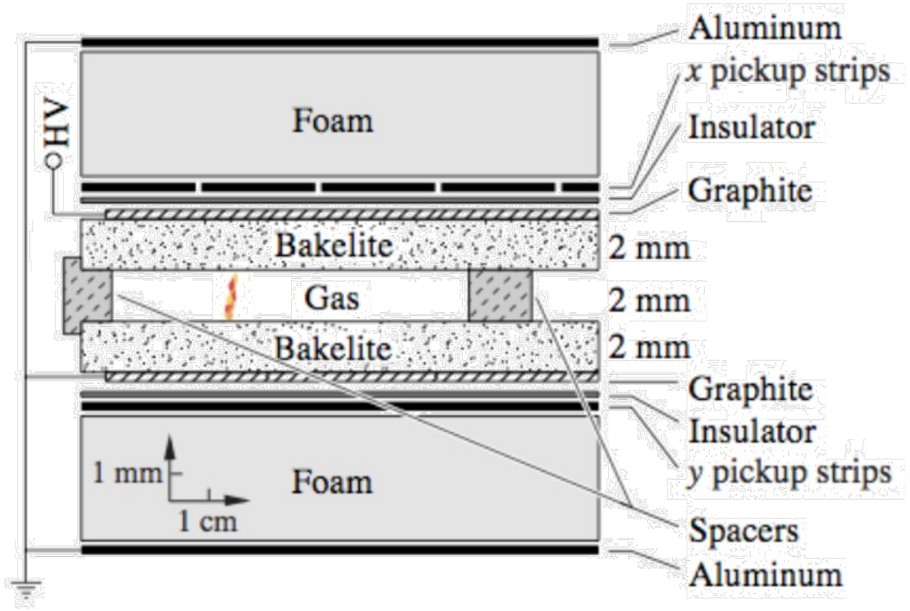


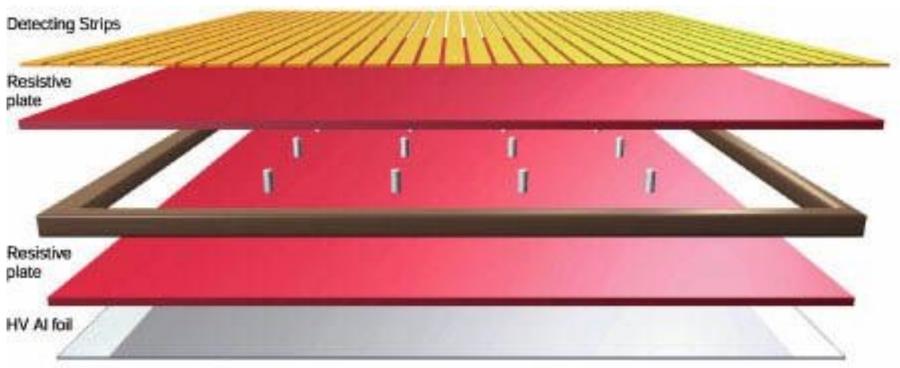
Resistive Plate Chamber

- **Getting to large planar area & being very fast**

Principle

- Electrodes = highly resistive material
  - Insulator => potential built up by static charge accumulation
  - Easy to built over many m²
- Small distance
  - large field => avalanche
  - fast collection => time resolution << ns





- Used in CMS, COMET, …

Silicon detectors

- → Detection in semiconductors
- → Strip detectors
- → (Hybrid) Pixel detectors
- → Monolithic pixels: DEPFET / CMOS / SOI
- →Low gain avalanche detectors

Detection in semiconductors

- Ionization is large
  - Small W_i range from 3 to 15 eV
  - Signal for MIP in 300 μm Silicon ~25000 e-
- 2 conditions to operate a solid as a ionization detector
  - Induced current (Shockley-Ramo) => cannot be insulator
  - Minimal noise => cannot be a conductor (huge I_{leak})

  } Solution = semiconductor with depleted P-N junction
- Depletion via junction reverse bias
  - charge mobility granted: v = μE > few cm/μs (μ=mobility)
    - Drift time over 300 μm Silicon ~ few 10 ns
  - Leakage current small enough: typically < μA
  - Reminder on depleted depth
    - Makes the sensitive volume (charge lifetime ~100 μs)
    - Driven by bias voltage (V) and resistivity (ρ)

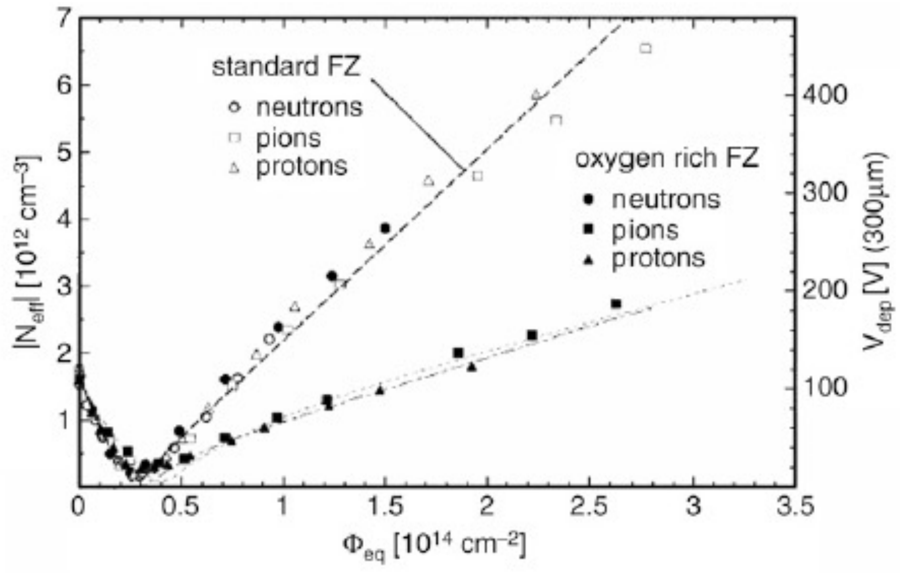
For planar P-N junction: $$d_{e/h} = \sqrt{2\mu\varepsilon V\rho} = \sqrt{\frac{2\varepsilon V}{e\ n_{e/h}}}$$

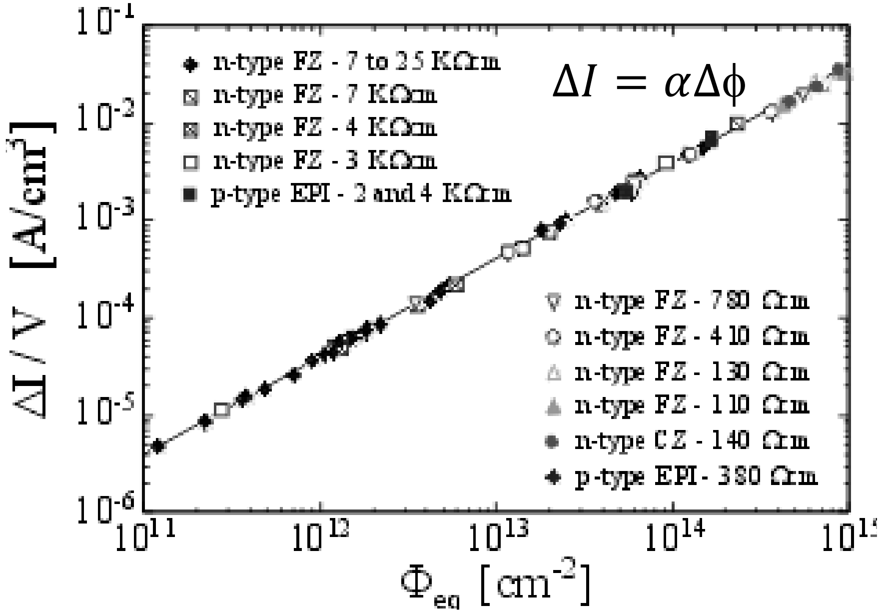
Benefits from semi-conductor industry:
- Small details can be etched
  => excellent spatial granularity
- Continuous R&D

Radiation effects in silicon sensors

- <u>Non-ionizing energy loss</u>
  - Damage crystal network
    - Generates higher leakage current (noise)
    - Generates charge traps (lower signal)
  - Modifies doping
    - Harder depletion (requires higher V_{bias})

- <u>Cumulated ionizing dose</u>
  - Parasitic charges trapped at interface with oxides
    - Released randomly ⇒ Noise !
  - Effect is temperature dependent
    - Mitigation by sub-0 cooling

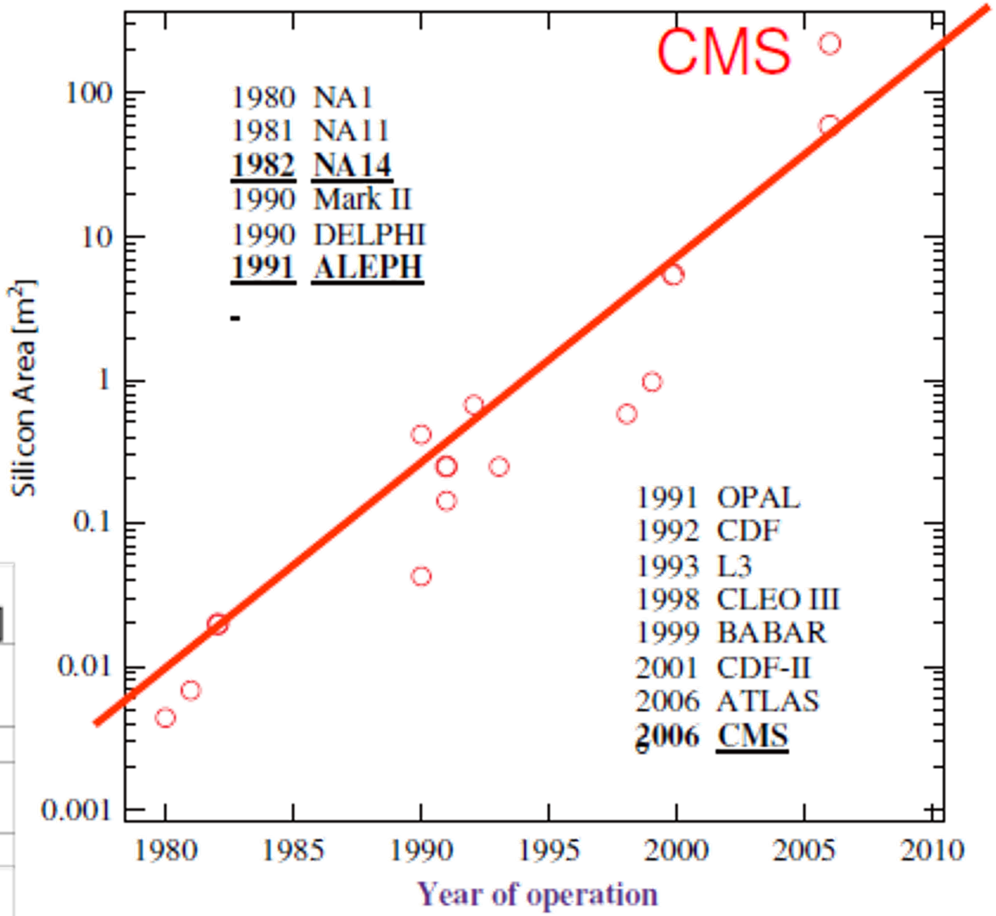




Silicon is spreading

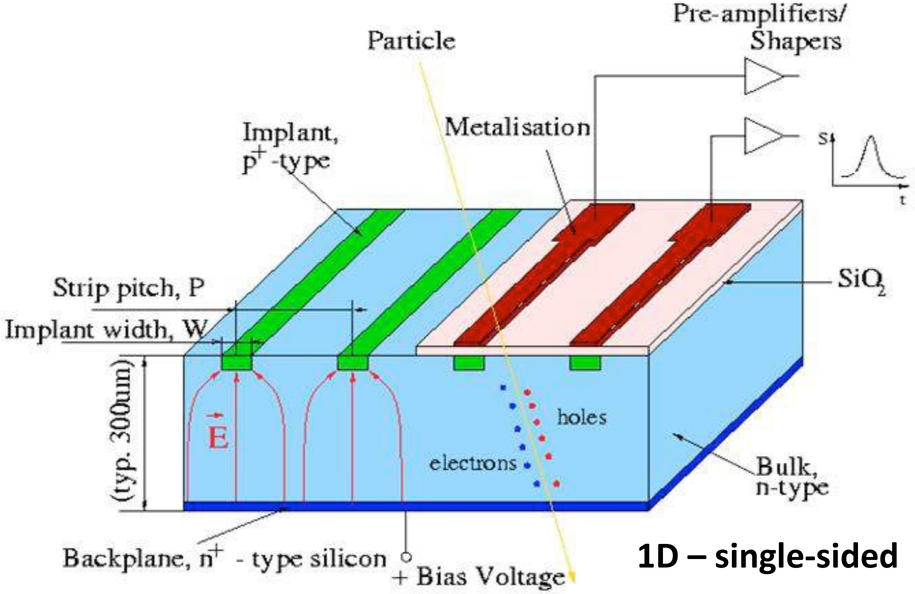
- Increasing popularity
  - Initially restricted to vertexing
    - LEP, B-factories
  - Gradually introduced for tracking
    - LHC
    - Possible due to dvpmt of integration techniques (bonding, …)

experiment	nb. of detectors	nb. of channels	silicon area [m²]
CMS	15.95 k	10×10^6	223
ATLAS	16.0/2 k	6.15×10^6	60
AMS 2	2.3 k	196 k	6.5
DO 2		793 k	4.7
CDF SVX II	720	405 k	1.9
Babar		140 k	0.95
Aleph	144	95 k	0.49
L3	96	86 k	0.23
ALICE-ITS2	24 k	12×10^9	10 (2021)

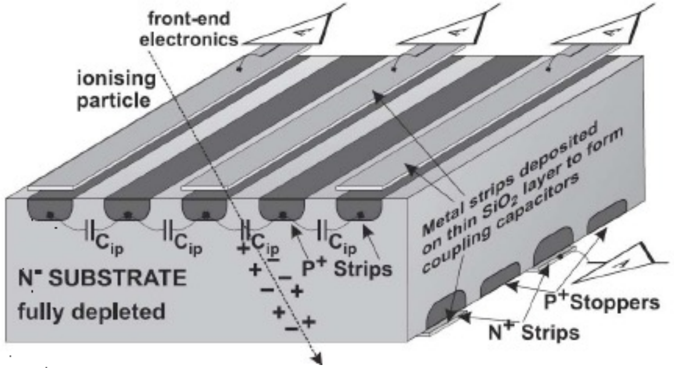


Silicon strip detectors

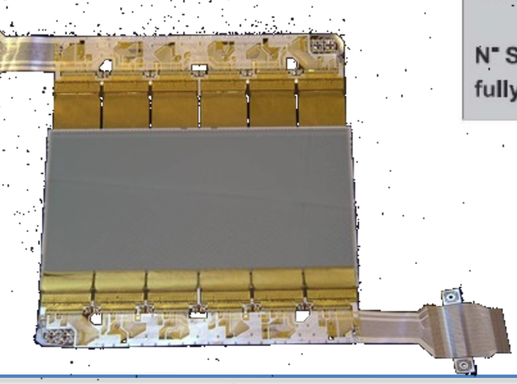
- Concept
  - Pattern P-N junction strips as collection electrodes
  - Connects each strip to a read-out channel (Integrated circuit)
    - Floating strip every 2 strips
  - Pitch from 25 μm to 100 μm
    - Spatial resolution down to ~3 μm possible
  - Full depletion (10 to 0.5 kV) over depth of few 100 μm
    - Usual depth 300-500 μm, 100 μm challenging / SNR
  - Single detector area up to ~10x20 cm^2
    - Rectangular or trapezoidal shapes
  - 1D if single sided
  - Pseudo-2D if double-sided
    - Stereo-angle useful against ambiguities



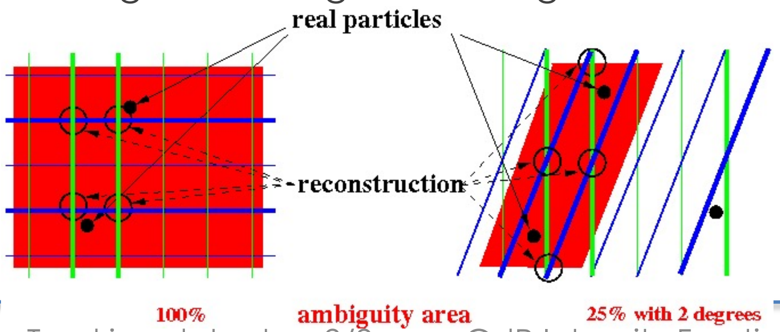
1D – single-sided



2D – double-sided

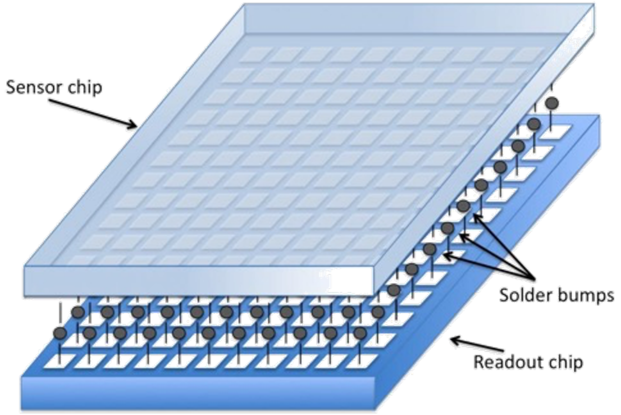


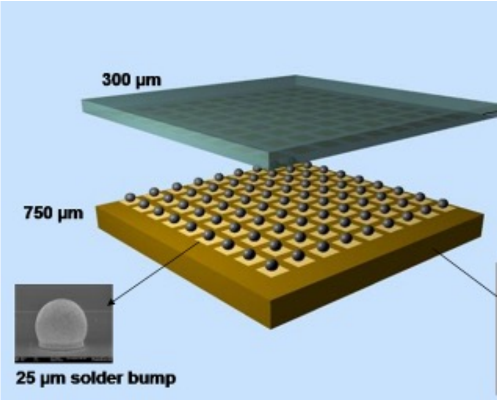
ALICE double-SSD



Silicon hybrid-pixel detectors

- Concept
  - Strips → pixels on sensor for real 2D
    - Large gain in hit-rate capability (>100 MHz/cm^2)
  - One to one connection from electronic channels to pixels => bump bonding
  - Pitch size limited by physical connection and transistor density in read-out pixels
    - minimal (today): 25x25 μm^2 / typical: 50x50 to 100x150/400 μm^2





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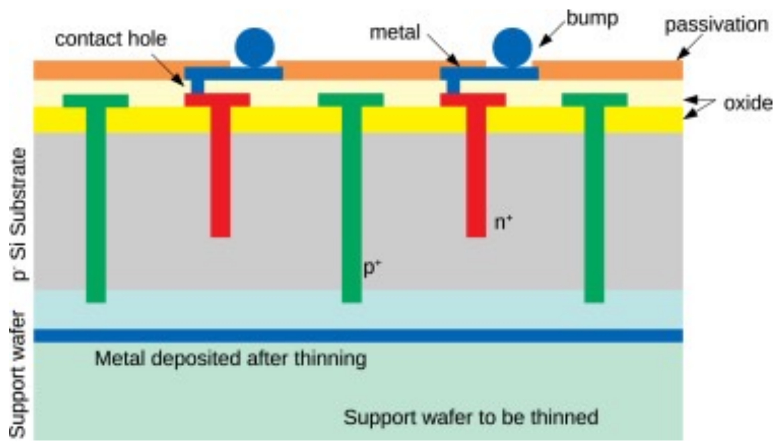
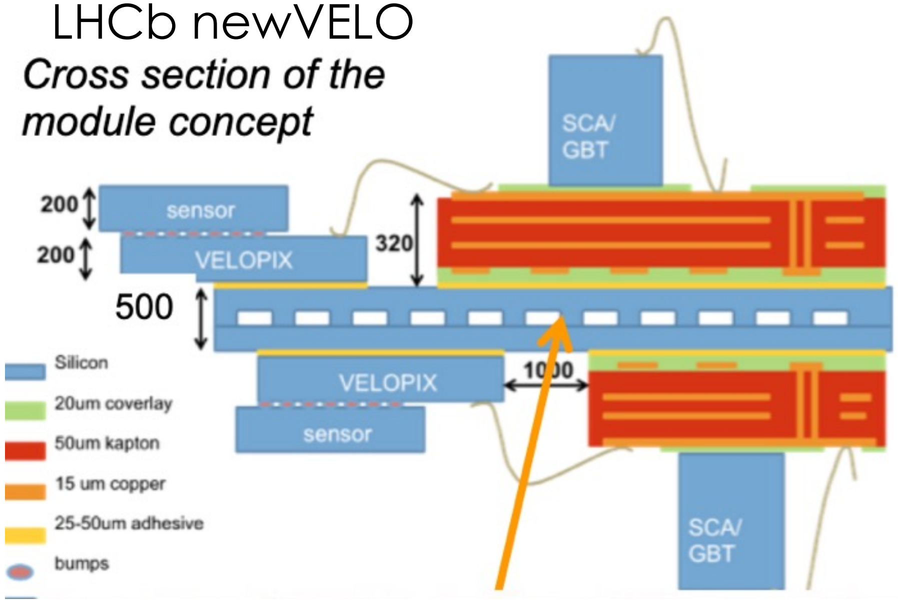


Performance highlight

- Excellent radiation tolerance >> 10^{15} $n_{eq(1\ MeV)}/cm^2$
  - Only technology surviving LHC innermost layers environment
  - Strong development in sensor techno, 3D-technology
- Timing resolution easily in the ns range
  - NA62 GigaTracker reached ~200 ps
- Material budget
  - Minimal(today): 100(sensor)+100(elec.) µm
- Power budget: ~10 µW/pixel
  - Require very active cooling strategy

LHCb newVELO

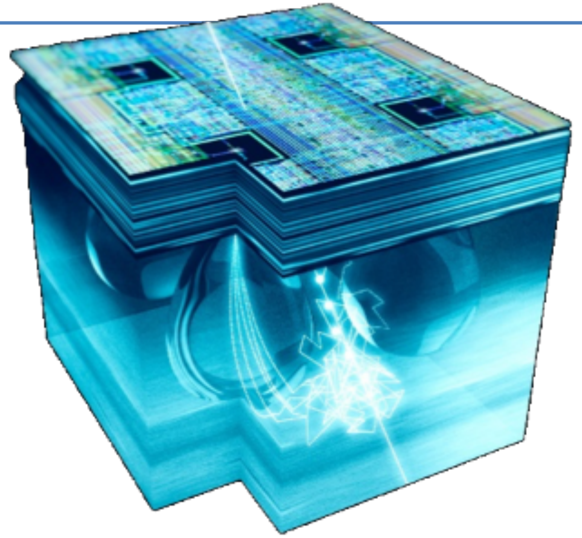
Cross section of the module concept



µChannel cooling # -20°C

Monolithic pixel sensors

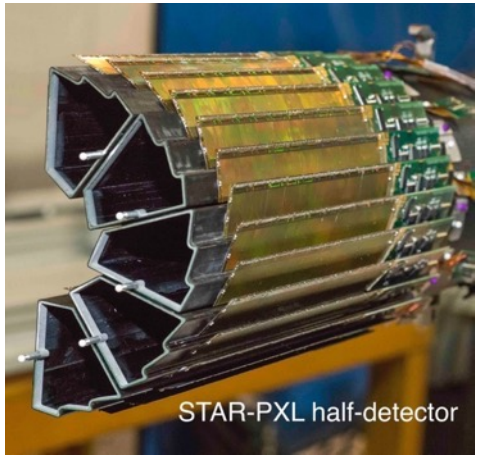
- Rationale
  - Limitations of hybrid-pixel sensors
    - material budget of sensor+read-out exceeds ~200 µm Si-equivalent
    - Very challenging to get pixels below 50 µm
  - Can we combine sensitive layer and read-out layer? => going monolithic



MPAS 2x2 submatrix view
thickness ~50 µm

- Various solutions
  - Historic CCD (applied in SLD/SLC)
  - CMOS (MAPS)
    - Developed since ~20 years
    - Applied since 2014 STAR, then ALICE, MU3e, …
  - SOI
    - Developed mainly in Japan for spectroscopic application
    - R&D toward ILC and Belle II vertex detector

Fully produced in industry

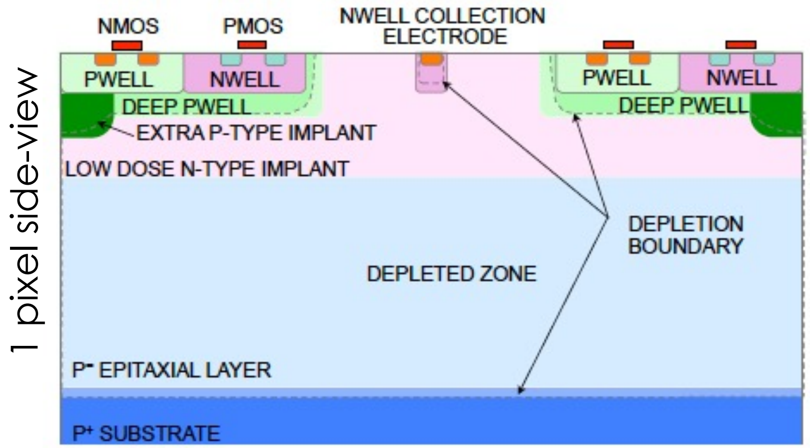


First MAPS detector (2014)

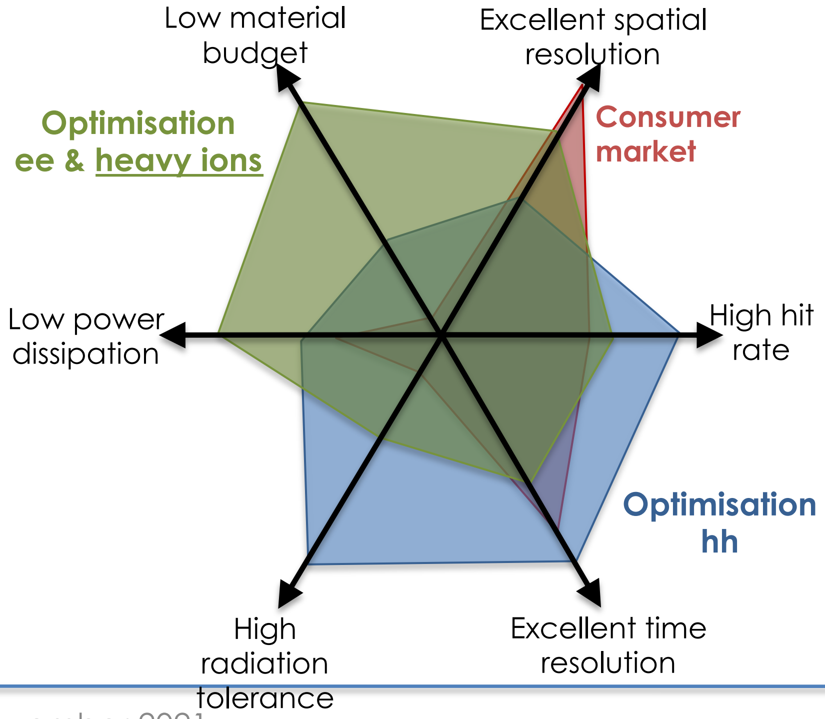
- DEPFET
  - R&D and sensor production in Münich
  - Not fully industrialized
  - Running in Belle II since 2019

CMOS pixel sensors

- **Concept**
  - Same technology as integrated circuit
    - with so-called low-doped epitaxial layer = sensitive volume
    - Read-out circuitry inside pixel (limitation / pixel size)
  - Benefit to
    - granularity: pixel pitch down to ~10 µm
    - Total thickness easily down to 50 µm

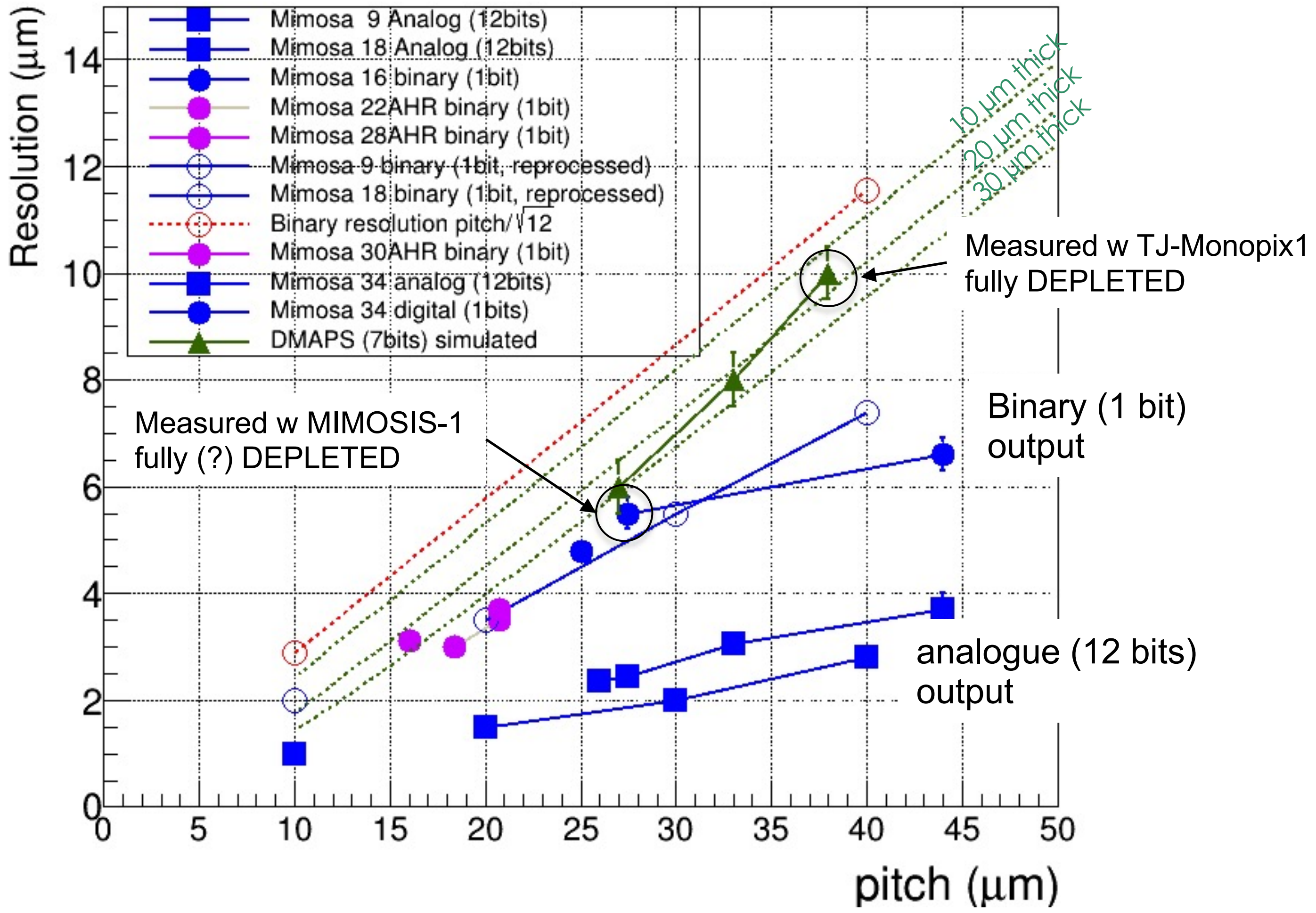


- **Performance highlight**
  - Pixel pitch in range 10-100 µm
  - Other performances correlated to pitch =>
  - Approach hybrid-pixel for pitch > 30 µm
  - Reach unique granularity-material budget
    3-4 µm resolution with budget ~0.1 % X0
  - R&D very active // industry push
    - Ex: ALICE-ITS2 ~2026
      30x10 cm^2 sensor thinned to ~30 µm
    - Ex: FASTpix R&D for ~100 ps time resolution



Position resolution from MAPS

MAINLY from the MIMOSA series designed in Strasbourg
with thin non-depleted sensitive layers



- Position derived from charge centroid
  - charge = 1 for binary output
- Resolution here = standard deviation of residuals = true – reconstructed pos.
  - For imaging ~ stdev of PSF

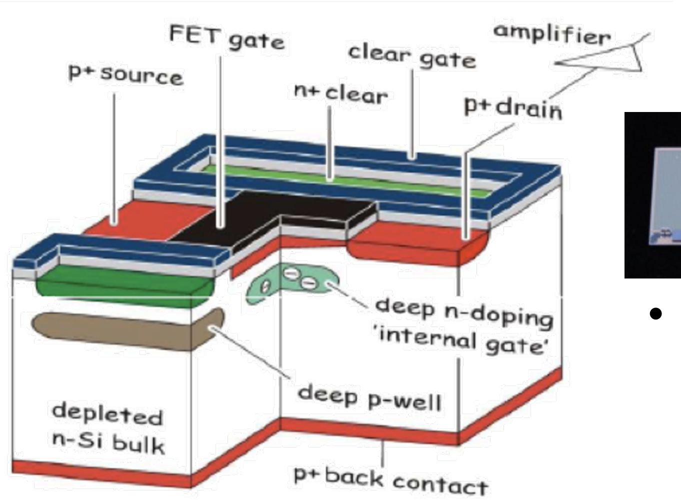
Key parameters

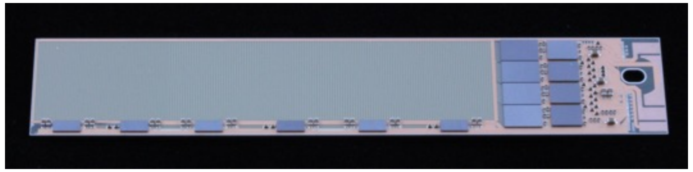
- Pixel pitch
- Charge digit precision
- Threshold for fired pixel detection
- Charge sharing, driven by $\sqrt{2D\frac{\text{distance}}{\text{velocity}}}$
  - Sensitive thickness (distance)
  - Level of depletion (velocity & distance)

Other active pixel sensors

■ DEPFET

- Depleted p-channel FET

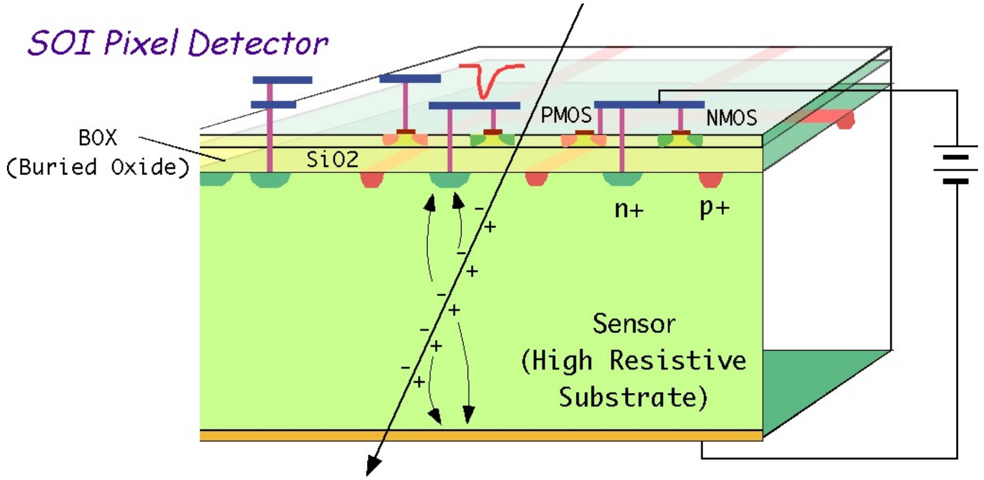




- Belle II DEPFET module
  - 50-70 µm pitch
  - 20 µs integration time
  - 0.2 % X0 material budget

- Fully depleted sensitive layer
- Large amplification
- Still require some read-out circuits
  - Not fully monolithic
  - Possibly limited in read-out speed

■ Silicon On Insulator (SOI)

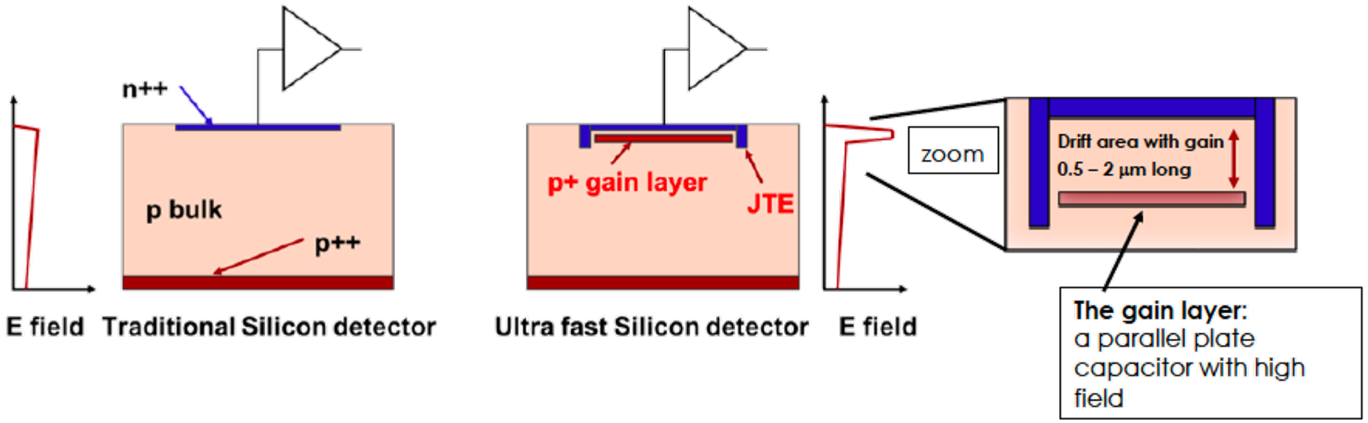


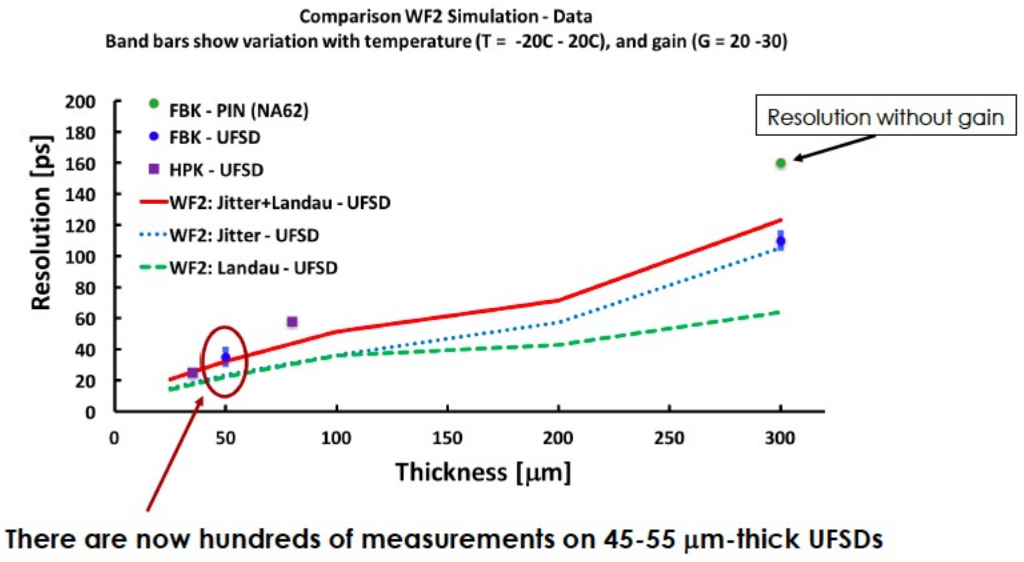
- Fully depleted sensitive layer
- Fully monolithic
- Electronics similar to MAPS
- DuTIP R&D for Belle II
  - 40 µm pitch for 60 ns time resolution
    low power expected
- SOIPix R&D for ILC
  - 20 µm pitch for ~1 µm resolution

Low Gain Avalanche Detector (LGAD)

- Goal
  - Reach time resolution ~10 ps range, still with some segmentation < 100 µm
    - Ultimately combine 1 µm with 1 ps !!

- Principle
  - Generate a controlled avalanche





From N.Cartiglia, INFN

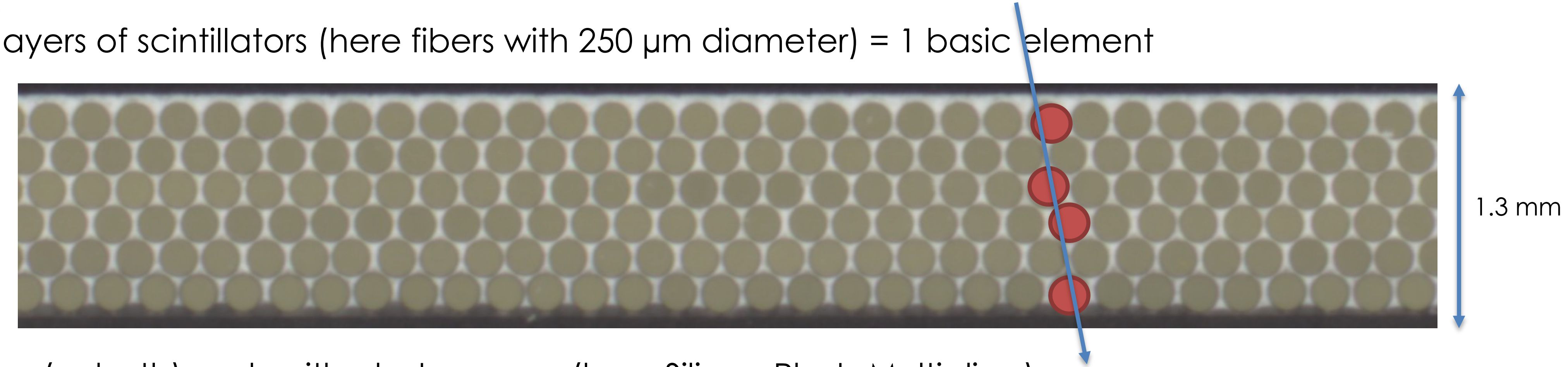
  - LGAD chosen by ATLAS & CMS for current upgrade

  - Connected technology: SPADS (basic elements of SiPM)
    - Still suffer large dark count (temperature)

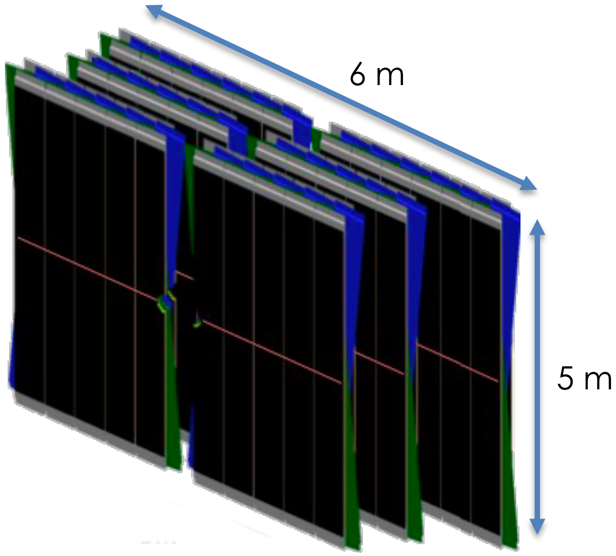
Scintillators for tracking

The example of the LHCb SciFi

- Concept
  - Stack thin layers of scintillators (here fibers with 250 µm diameter) = 1 basic element



  - Read at one (or both) ends with photosensors (here Silicon PhotoMultipliers)
  - Combine basic elements, possibly with different fiber orientation (2D sensitivity)
  - Spatial resolution < 100 µm for material budget <1 % X_0
  - Fast read-out @ 40 MHz



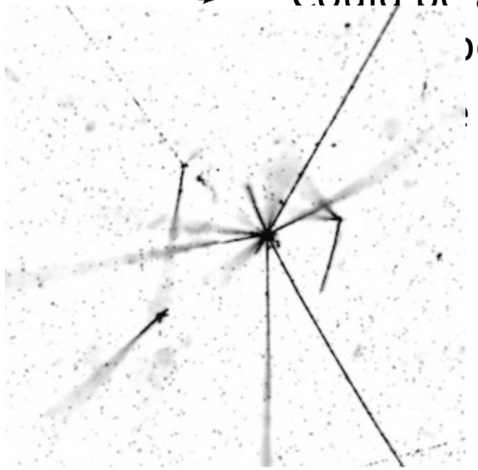
- Benefits
  - Cost effective technology (materials and nb of channels) for large area (340 m^2)
  - Similar (but less precise) concept employed in OPERA target tracker (and JUNO)

Missing & Wrap-up

Missing in this discussion

Some detector technologies

- Silicon drift detectors
  - Real 2D detectors made of strips
  - 1D is given by drift time
  - Rather complex to operate
- Diamond detectors
  - Very interesting for radiation tolerance
  - Comes in limited area
  - equip hybrid pixel detectors when suited
- Nuclear emulsion
  - Most precise ever < 1 μm
  - No timing information!
  - Requires long off-line image scan



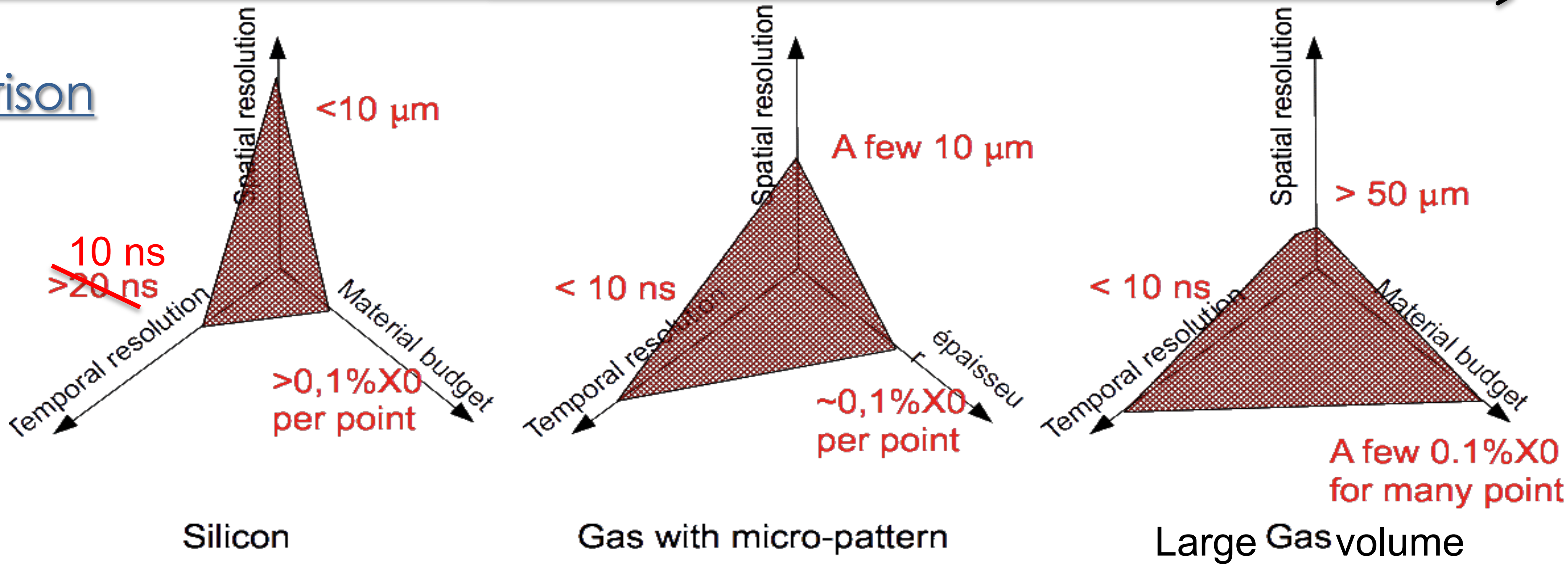
- **Scintillators**
  - Extremely fast (100 ps)
  - Could be arranged like
  - pes
  - thick (X_0 ~ 2

Sensors are not alone

- Read-out electronics
- Mechanical support
- Cooling
- Magnets!

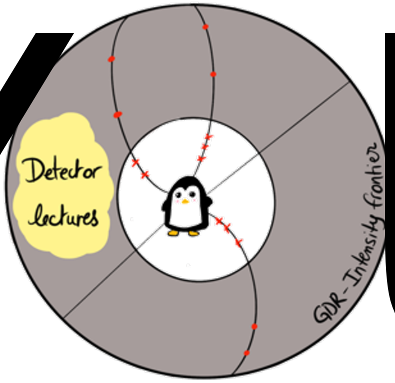
Conclusion on technologies

- Tentative Comparison



- Trend
  - Faster collision rates and higher particle multiplicities favour
    - Fast silicon sensors and micro-pattern gas chambers
    - Pixelization (and miniaturisation)
  - Still large gas volume suited for e+e- collider (BelleII, ILC, FCCee)
  - If affordable (complexity) combining various technologies is very beneficial

THANK Y



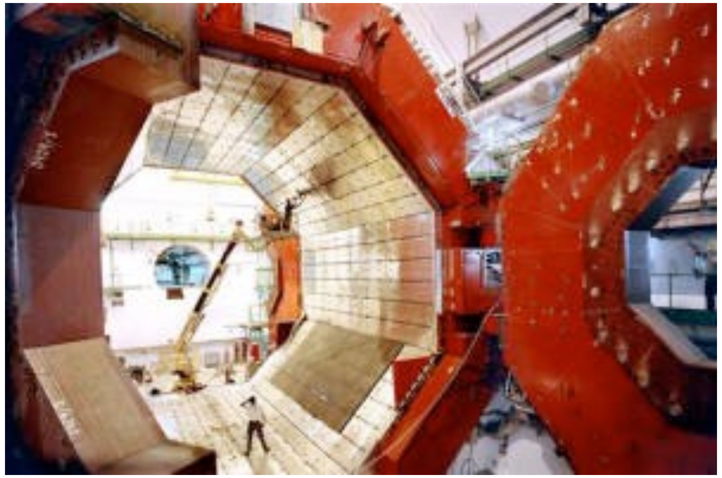
U!

Additional slides

Magnets

Solenoid

- Field depends on current I, length L, # turns N
  - on the axis $$B = \frac{\mu_0 N I}{\sqrt{L^2 + 4R^2}}$$
  - Typically: 1 T needs 4 to 8 kA
    ➛ superconducting metal to limit heat
- Field uniformity needs flux return (iron structure)
  - Mapping is required for fitting (remember B(**x**)?)
  - Usually performed with numerical integration
- Calorimetry outside ➛ limited material ➛ superconducting
- Fringe field calls for compensation



Superconduction

- cryo-operation ➛ quenching possible !
- Magnetic field induces energy:
  - Cold mass necessary to dissipate heat in case of quench

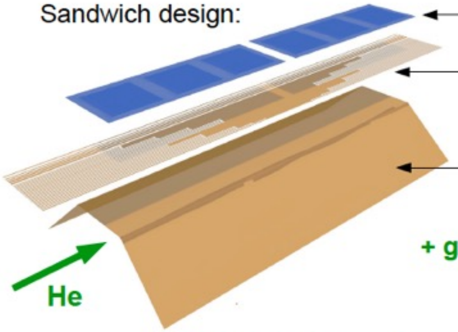
	Field (T)	Radius (m)	Length (m)	Energy (MJ)
ALICE	0.5	6		150
ATLAS	2	2.5	5.3	700
CMS	4	5.9	12.5	2700
ILC	4	3.5	7.5	2000

$$E \propto B^2 R^2 L$$

Mu3e – VTX concept

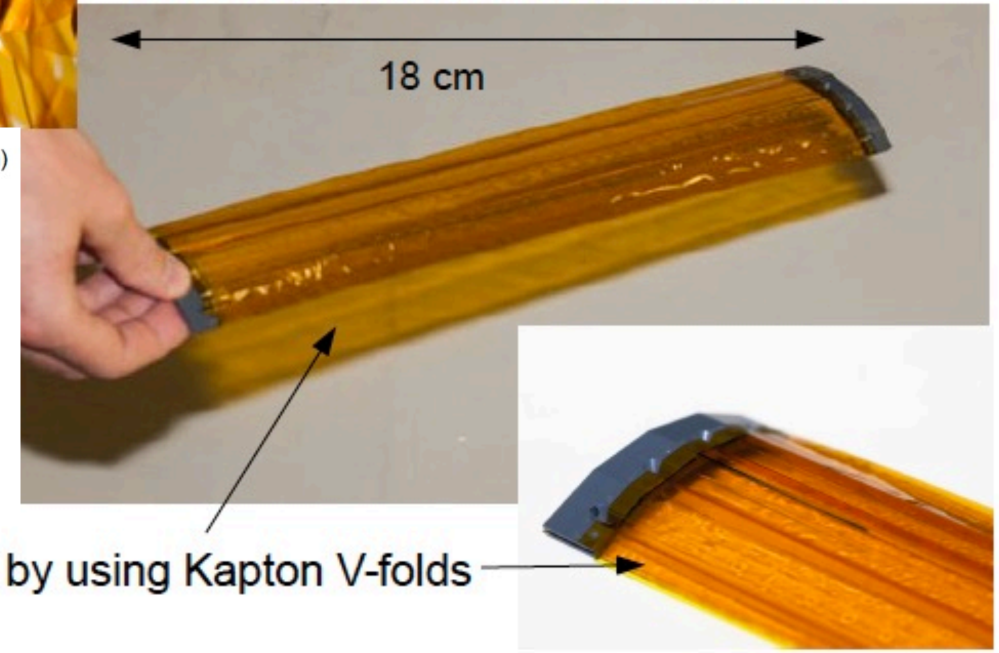
Ultra-thin mechanical mockup:

- sandwich of 25 µm Kapton®
- here 50 µm glass (instead of Si)



$X \leq 0.1\% \ X_0$ per layer possible

Even larger stable structures possible

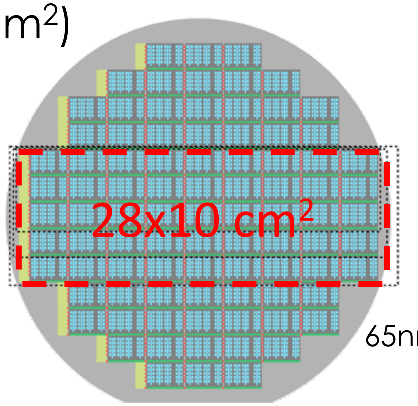


André Schöning, Heidelberg (PI) 25 Vertex2016, September 27, 2016

ALICE – ITS3 project

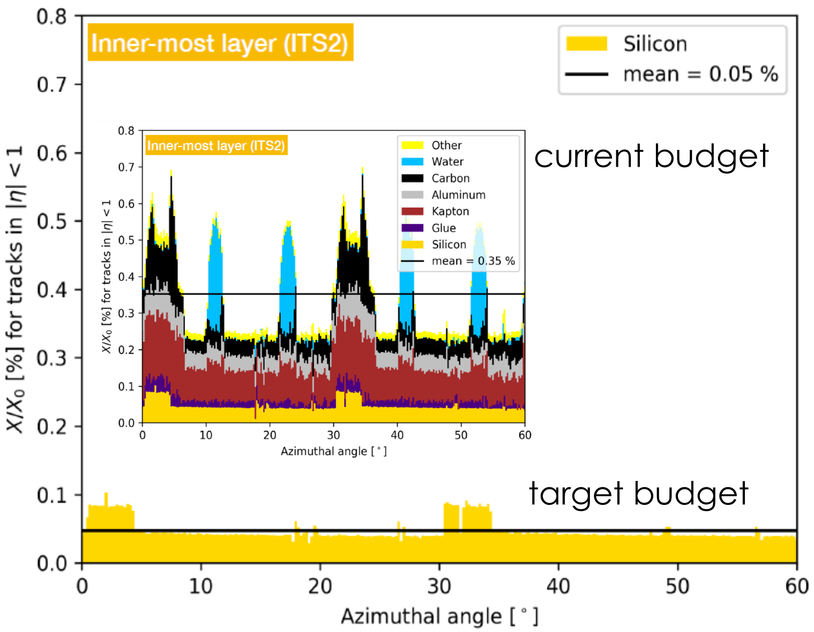
- [« Ultimate thinness » concept]
  - Get rid of cables, mechanical support, cooling
  - Requires: large ~300 cm^2, thinned (20-40 μm) & bended, low-power sensor (~20 mW/cm^2)

  => Stitching with Tower-65 nm process

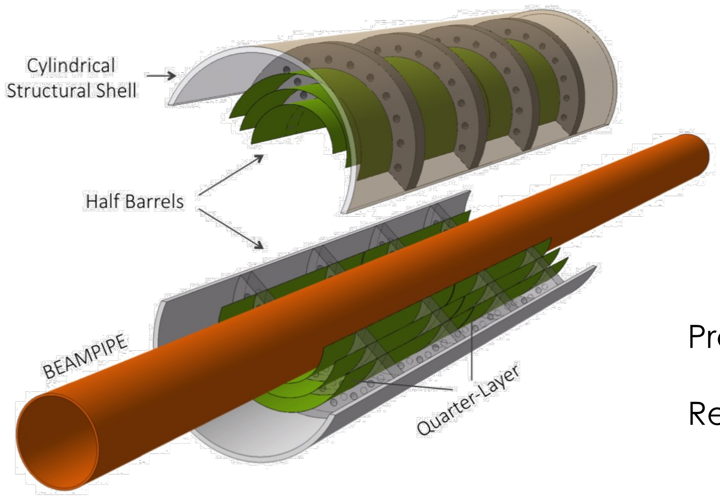


65nm ⟶ 12" wafers

  - Targets LHC long shutdown 3
    - 65 nm process exploration NOW
    - First stitched proto in 2022
    - Final sensor in 2024
    - Installation ~2026



Beam pipe Inner/Outer Radius (mm)	16.0/16.5		
IB Layer Parameters	Layer 0	Layer 1	Layer 2
Radial position (mm)	18.0	24.0	30.0
Length (sensitive area) (mm)	300		
Pseudo-rapidity coverage	±2.5	±2.3	±2.0
Active area (cm^2)	610	816	1016
Pixel sensor dimensions (mm^2)	280 x 56.5	280 x 75.5	280 x 94
Number of sensors per layer	2		
Pixel size (μm^2)	15x15 to 25x25 μm^2		

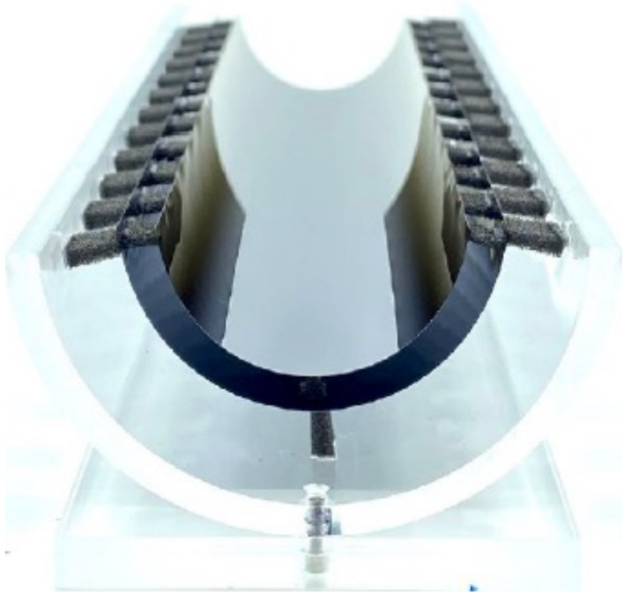


Proposal
[ALICE-PUBLIC-2018-013]
Recent news
[https://indico.cern.ch/event/1071914/]

Bending sensors

- [Preparatory work]

From https://indico.cern.ch/event/1071914/



2 layers assembled
with carbon foam