JOURNÉES DE PROSPECTIVE IN2P3-IRFU
Presqu'île de GIENS
du 2 au 5 Avril 2012

GT14: Instrumentation et detection
Tracking detectors

perspectives in France

Huge subject in terms of detection principles / experimental applications. Impossible to give an exhaustive review here, more material in the report

I'll try to focus on technologies more than experiments

- Main technologies which are undergoing important R&D with implications in France
  - Tracking applications in different sectors
    - Different materials
    - Different configurations
    - Many detection mechanisms
  - State-of-the-art and future requirements
    - Present and future development
  - Common problems
- Perspectives

General overview

- Solid state / Semiconductor detectors

  Materials: Si, diamond (+ Ge, CdTe, CdZnTe)

  Configuration (Pixels, columns, pads, strips)

- Gaseous detectors

  Drift and Micro Pattern Gaseous detectors

  State of the art (bulk/resistive)

Applications

- High-Energy physics, Nuclear Science, Astro, Space applications

Semiconductor detectors

- e-holes production in the medium,
- charge collection inside the depletion region

Signal (typical: Si):	80e- /um of depleted region
Space resolution	a few um to tens of um
Energy resolution	(not relevant for this talk)
O(10 eV) @ KeV up to	O(50KeV) @ high energy
Sensor material budget	0.1% X0 / 100um

but then services and in some cases electronics inside the tracking region

Radiation hardness	depends…
Price	depends…

1) High resistivity (KΩ cm) Silicon sensors

- Traditional solution: factorizes sensors and electronics

  Polarized - Extended depletion region

  Can work at rather elevated voltages

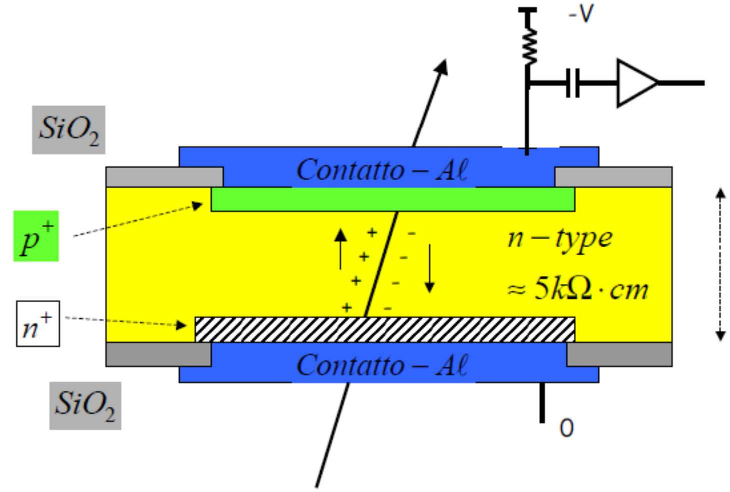
  Good radiation hardness (especially for certain geometries)

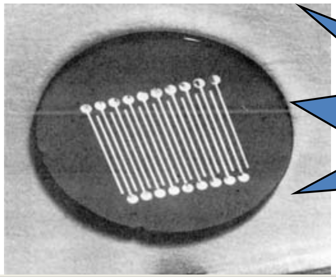
- Sensor physically separated from electronics

  -> may result in increased material budget
  -> bonding/bumping costs

High-resistivity: strips

Strips (SSSD or DSSD)

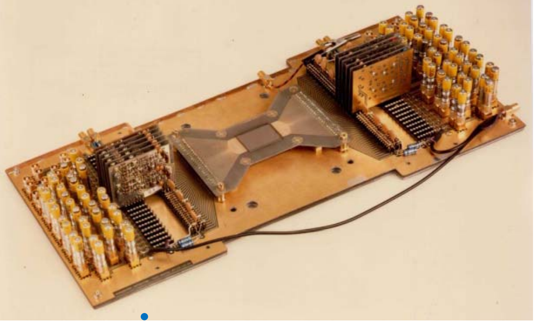




1980-81

S. R. Amendolia et al., A Multi-Electrode Silicon Detector for High Energy Experiments, Nucl. Instr. Meth. 176 (1980)

E.H.M. Heijne et al., A Silicon Surface Barrier Microstrip Detector Designed for High Energy Physics, Nucl. Instr. Meth, 178 (1980)



Rather simple to produce, even DSSD

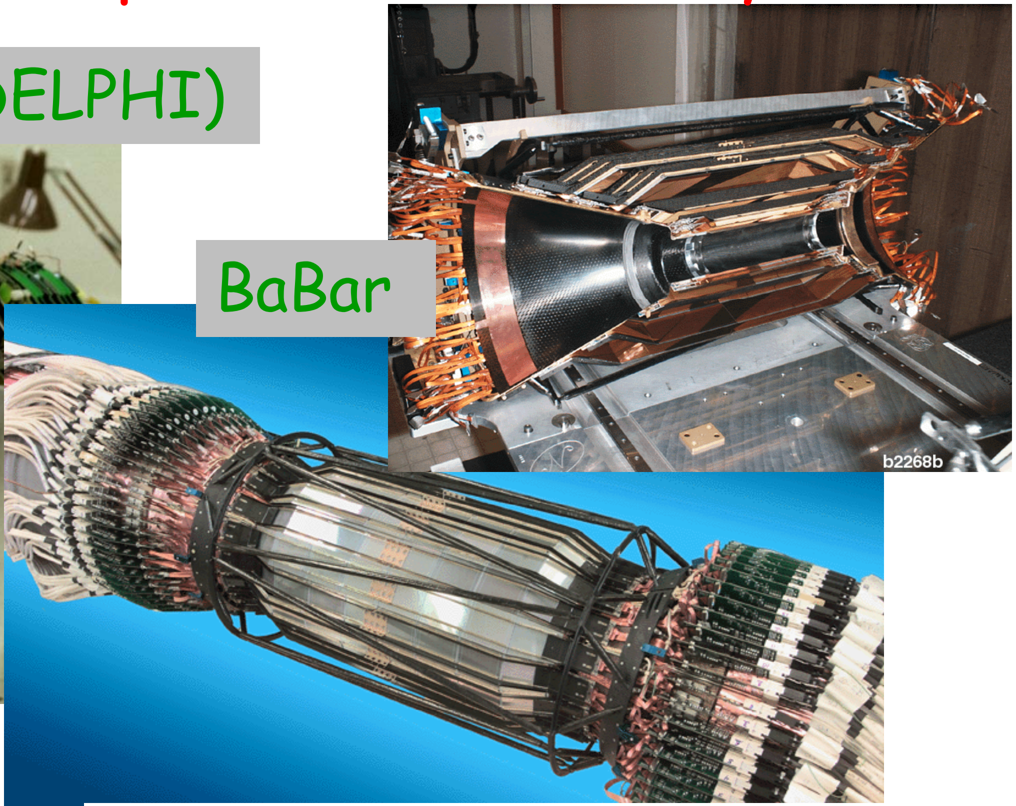
FE electronics can be kept our of tracking region

Good space-resolution O(10um) but not too good in high-occupancy environments

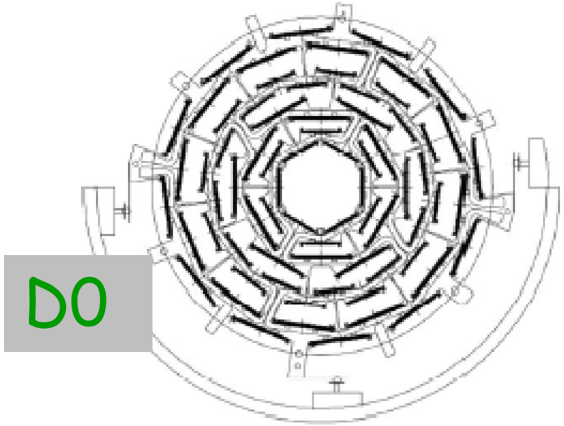
Fast detector, even if the readout depends on applications (short shaping-> time, long shaping ->charge)

Good experience of strips trackers since years

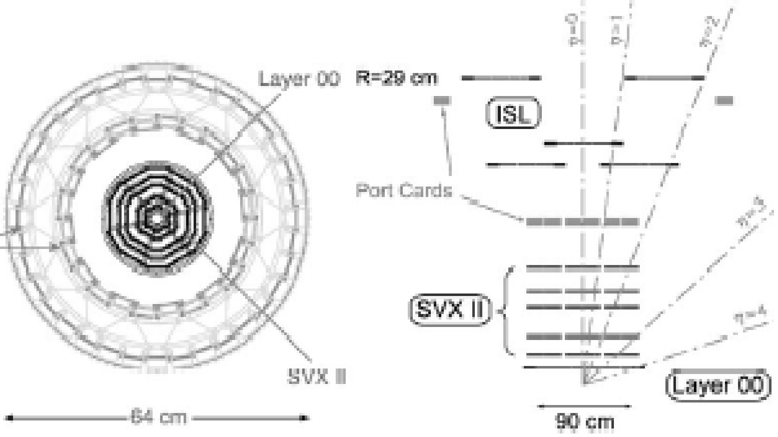
LEP (here DELPHI)



BaBar



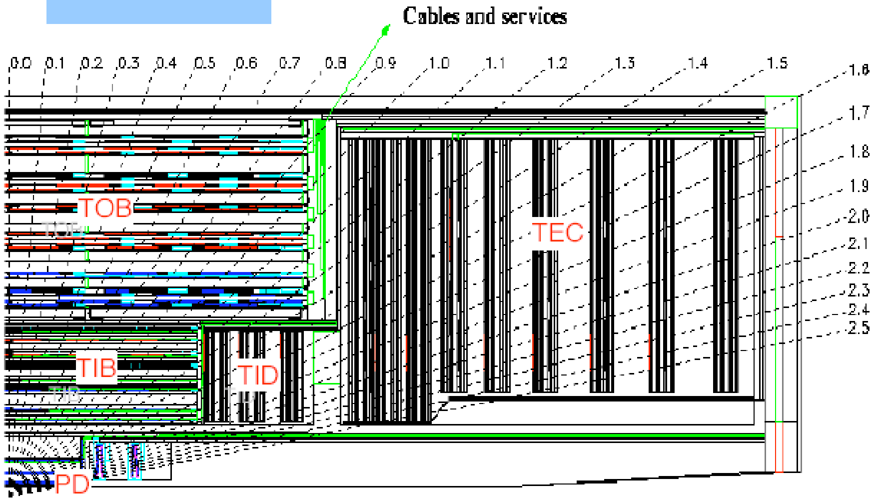
D0



CDF

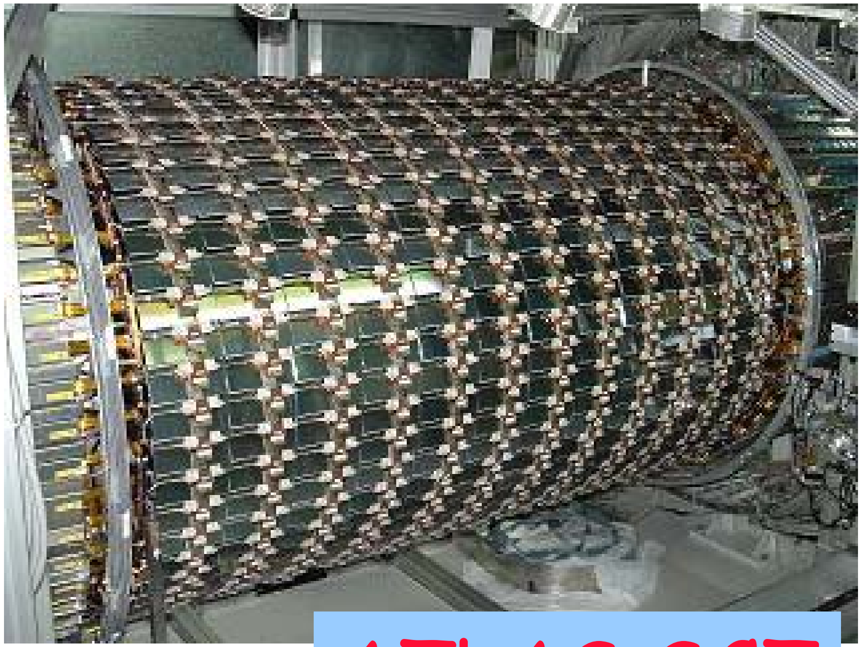
More recently, strips used in outer layer of LHC experiments

CMS



Full Silicon Tracker

210 m^2 of silicon sensors, 10^7 strips, 6.7 10^7 pixels



ATLAS SCT

But also in present and future astro-particle projects with strong France implication:

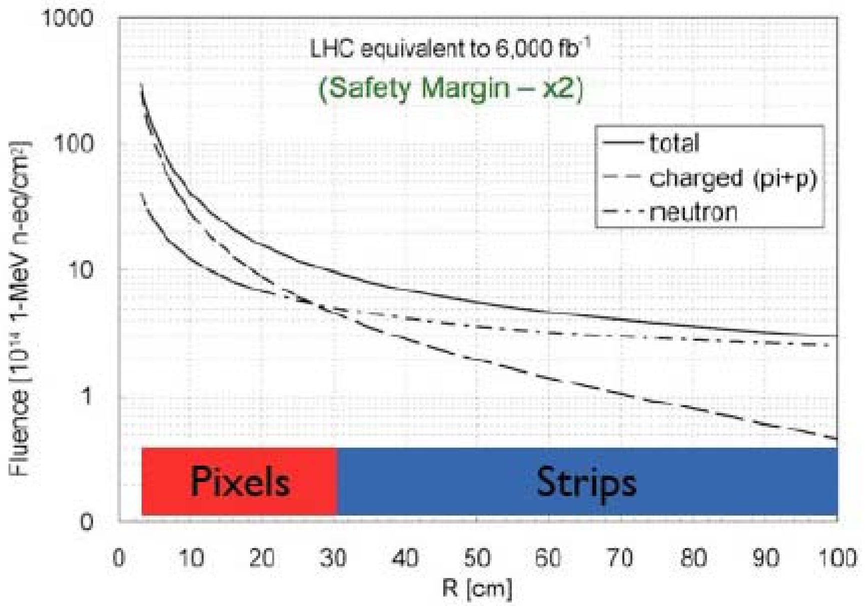
LOFT, Compton Telescope, etc

Perspective / future

- Improve the radiation hardness (10^{15} neq/cm^2)

  p-type bulk to avoid type inversion

Dose requirements at LHC, 6000fb-1



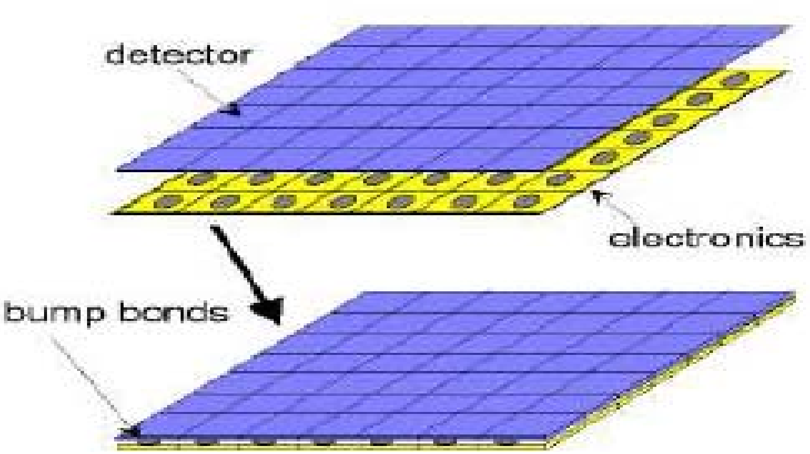
- Reduce the thickness

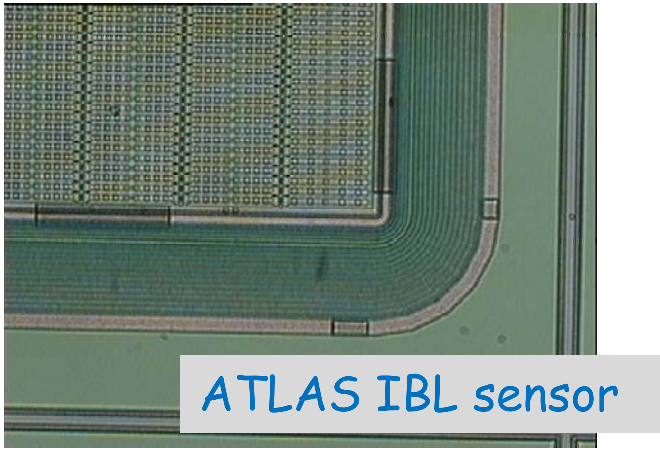
  Down to less than 50um to improve material budget

- Improve the cost

  Production on 8" and 12" wafers

High-resistivity: pixels (and pads)





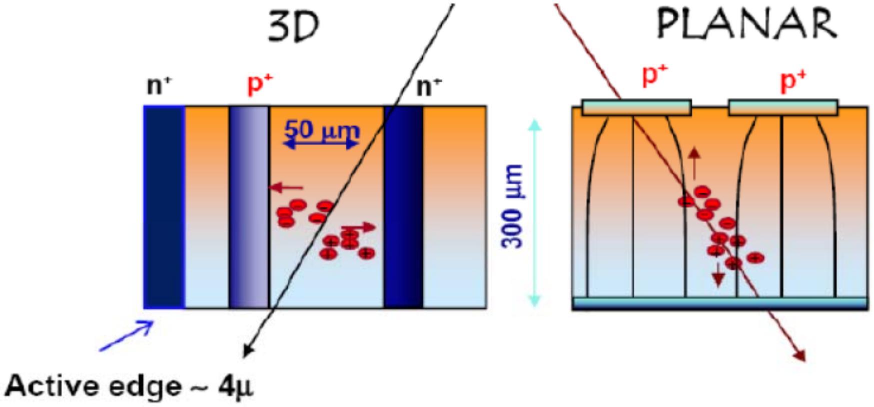
- Useful to replace strips in high-occupancy conditions

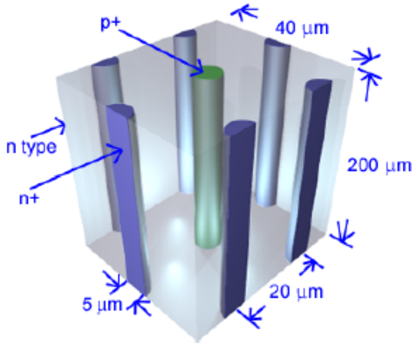
  Good segmentation, no track ambiguities
  Good space-resolution O(10-50um)

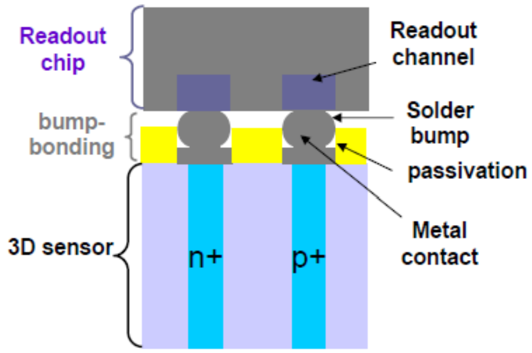
- FE electronics bump-bonded to the sensor
  - material budget
  - cost

Given the high segmentation they can be placed closed to the interaction point: good radiation hardness is necessary

To improve radiation hardness: 3D vs planar







Electrodes are not pads on the surfaces but columns passing from one side to the other

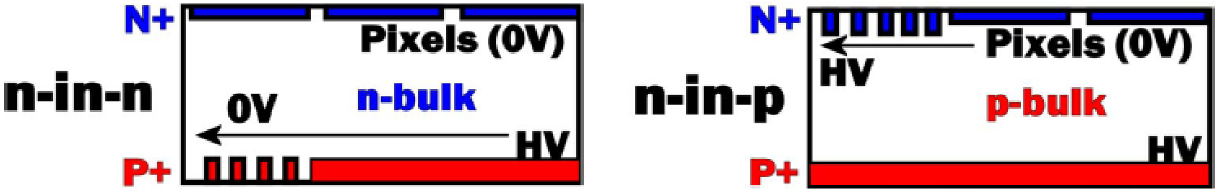
Collection distance is not related to the detector thickness but to the inter-pixel distance O(50um)
-> less sensitive to radiation damage
-> lower operating voltage

Draw-back: more complex process, much more expensive

Perspective I

- New technologies for radiation hardness (goal 2×10^{16} neq/cm^2)

  p-type bulk to avoid type inversion and reduce the costs (single-side process)



- Reduced thickness

  Due to the relevant material budget of hybrid-systems it is critical to reduce the sensor thickness. Going to < 100um would be advisable

  Consider also that at high fluence (2-3×10^{15} neq/cm^2) the sensor would start to be not full-depleted in any case, so a thickness larger than the depleted region would just sink charge, without producing it

Perspective II

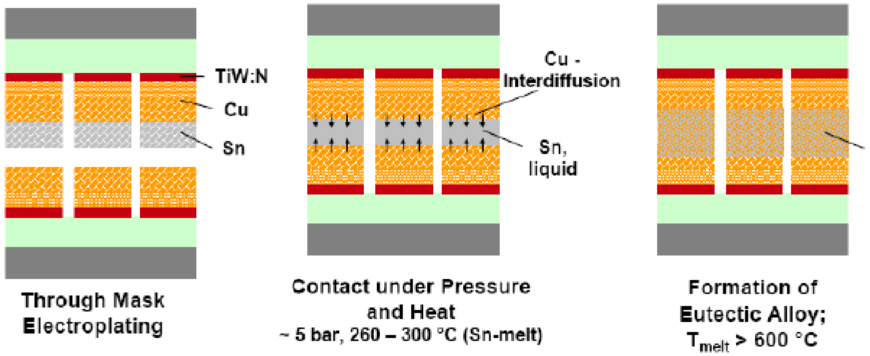
- Reduction of cost of sensor production

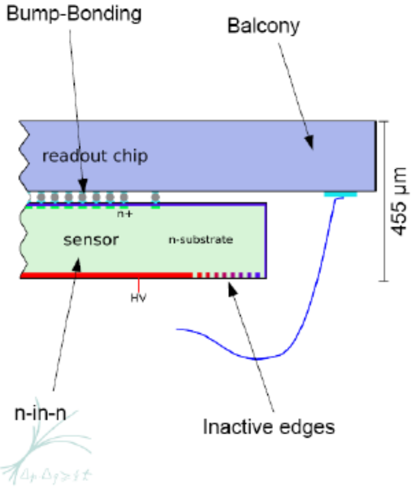
  From 6" to 8" and 12" wafers

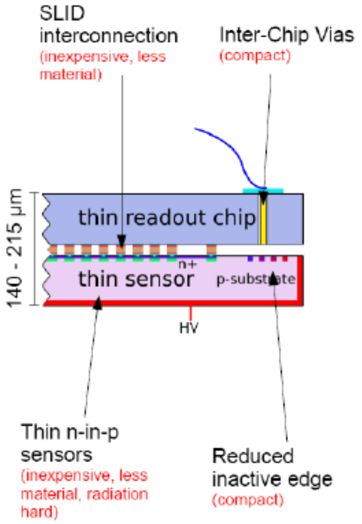
- Reduction of cost of bonding (significant fraction of the total)

  R&D on SLID/TSV interconnections

Metallization SLID (Solid Liquid Interdiffusion)

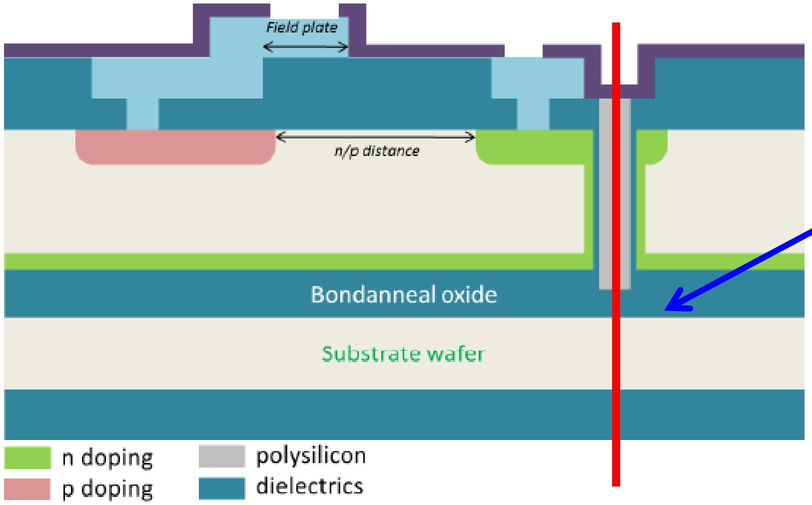






Perspective III

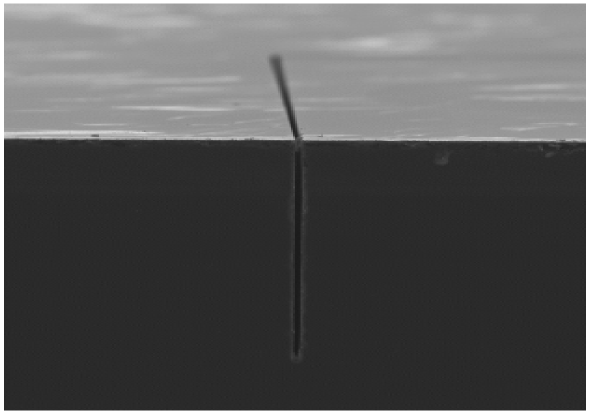
- Improve fill-factor (active edge)

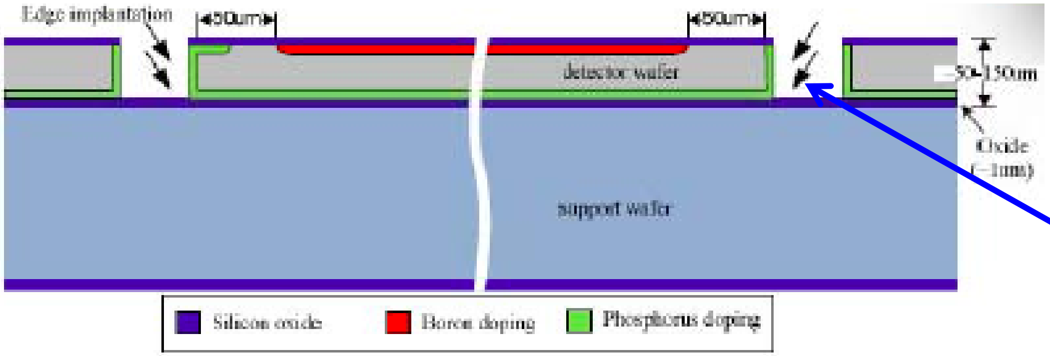


Cut line

Deep trench diffusion (to prevent electrical field on the damaged cut)

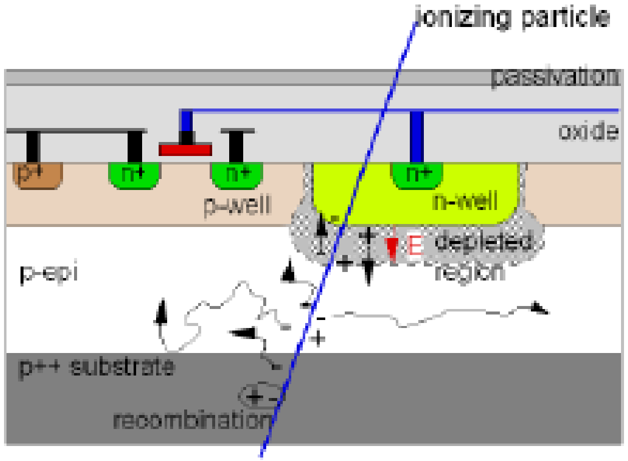
4,5μm wide
220μm deep





Similar result can be obtained with border implantation

2) “Low” resistivity - CMOS



- Integrates sensor and electronics

  Single monolithic block saves the cost of bonding

  Intrinsically thinner than hybrid detector

  Option: double-correlated readout -> low noise !

  Take the advantage of the features of a commercial process (large wafers, big margin of cost reduction)

- Reduced depletion region (at least in the standard technologies – see next slides)

  Charge collected by diffusion

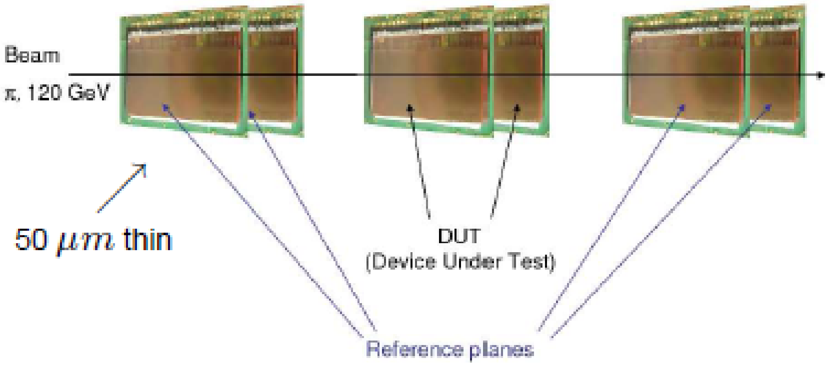
  Medium radiation hardness

Since some time, CMOS processes available with higher resistivity epitaxial layer (400 Ω cm)

This improves the charge collection and detection performance

- **M.i.p. detection with LOW & HIGH resistivity CMOS sensors combined in a Beam Telescope (BT)**
  - 4 EUDET ref. sensors & 2 sensors under test
  - June 2010 at CERN-SPS (∼ 120 GeV pions)
  - sensor variants : standard epitaxy (14 μm thick)

    & high-resistivity epitaxy (10 & 15 μm thick)

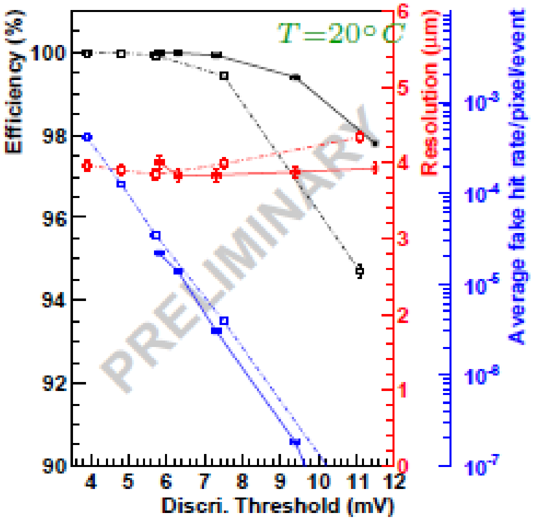


Eff. ~100%   (SNR~40)
for very low fake rate

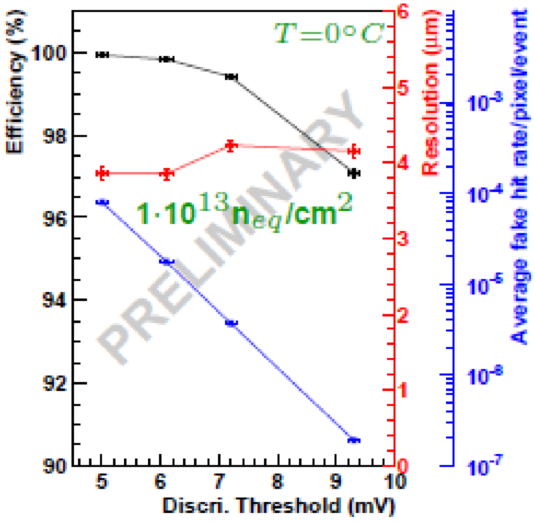
Resolution ~4um

Eff. ~100% even after irradiation at 1x10^{13} n$_{eq}$/cm^{2} (right plot)

MI26 HR-15 and HR-10 Efficiency, Fake rate and Resolution

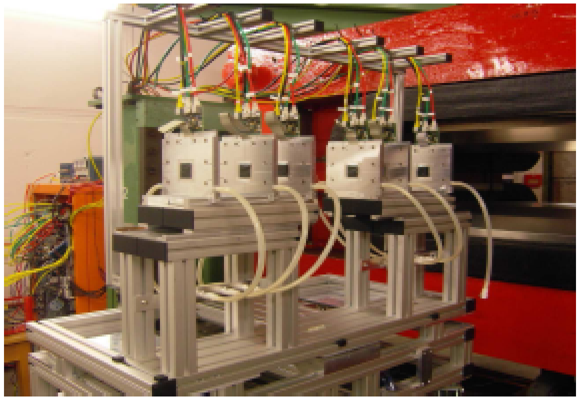


MI26 HR-15 Efficiency, Fake rate and Resolution
for a chip irradiated with a 1.10^{13}N$_{eq}$ dose at T$_{op}$ ~ 0° C

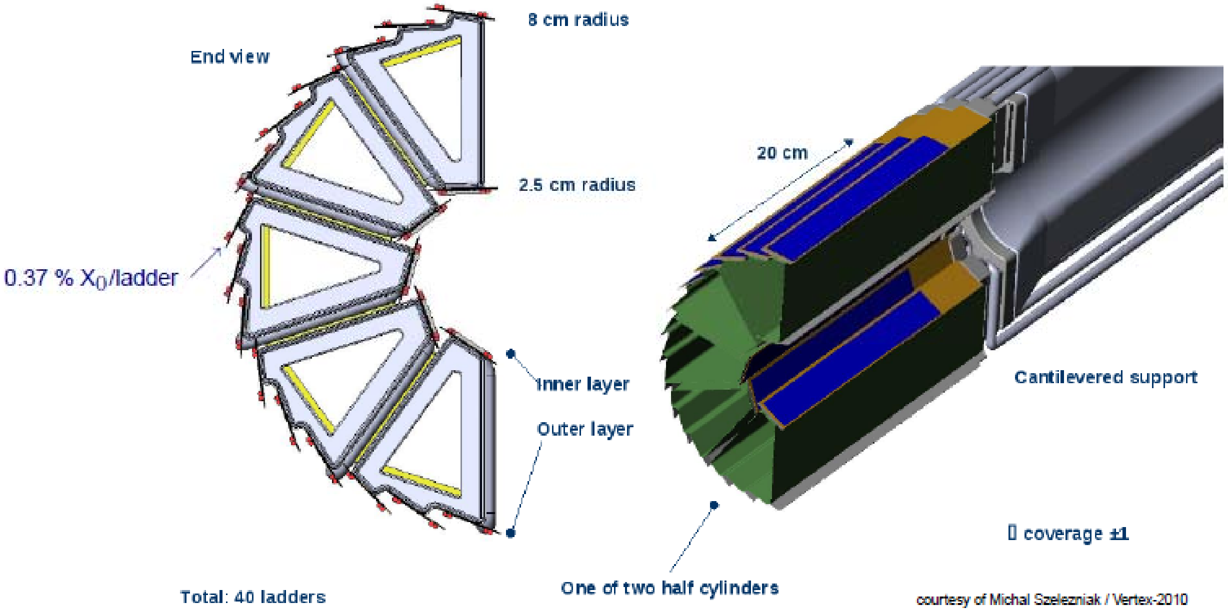


Direct Applications of MIMOSA-26

- Beam telescope of the FP6 project EUDET
  - ⁜ 2 arms of 3 planes (plus 1-2 high resolution planes)
  - ⁜ MIMOSA-26 thinned to 50 μm
  - ⁜ $\sigma_{extrapol.} \sim$ 1-2 μm EVEN with e^- (3 GeV, DESY)
  - ⁜ frame read-out frequency $O(10^4)$ Hz
  - ⁜ running since ’07 (demonstrator: analog outputs)
    at CERN-SPS & DESY (numerous users)



Vertex detector of STAR-PXL



courtesy of Michal Szelezniak / Vertex-2010

▷▷▷ **1st vertex detector equipped with CMOS pixel sensors** ⟼ **1st data taking in 2013**

Application of CMOS sensors to the CBM Experiment

Compressed Baryonic Matter (CBM) experiment at FAIR (GSI):

Micro-Vertex detector made of 2 of 3 stations located behind fixed target
Double-sided stations equipped with CMOS pixel sensors

Negative temperature in vacuum operation

Each station < 0.5% X_0

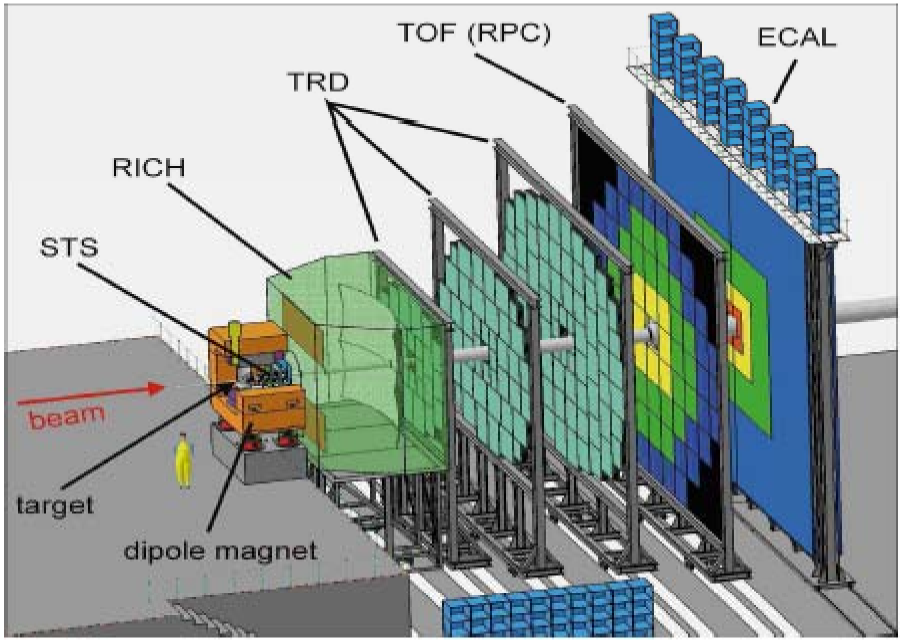
Sensor architecture close to ILC version

Most demanding requirements:

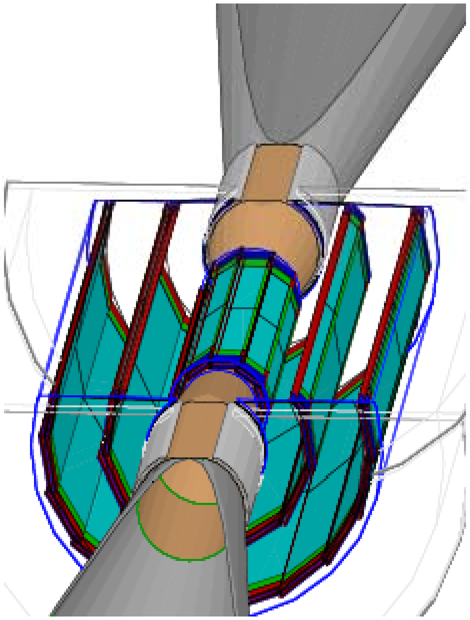
Ultimately (~2020): 3D sensors
<10us, $>10^{14}$neq/cm^2, >30 MRad

Intermediate steps : 2D sensors
<30-40us, $>10^{13}$neq/cm^2, >3 MRad

First sensors for SIS-100
(data taking > 2016)



CMOS sensors for the ILD-VTX



Inner layers (<~ 300 cm2)

Priority to readout speed and spatial resolution

Small pixels (16x16/80 um2)
Readout time ~50/10us
Space resolution ~3/5um

Outer layers (<~ 3000 cm2)

Priority to power consumption and good resolution

Large pixels (35x35 um2)

Readout time ~100us
Space resolution ~4um

Perspectives

3D Integration technologies to integrate high-density signal processing inside small pixels by stacking (~10um) thin tiers interconnected at pixel level

3DIT expected to be very beneficial for CMOS sensors:
Combine different fab. processes -> chose the best ones for each tier/application

Split signal collection and processing on different tiers

The path to the nominal exploitation of CMOS pixel potential:

Full depleted 10-20um thick epitaxy -> < 5ns collection time

FEE with <10ns time resolution -> solution for fast applications

CVD Diamonds

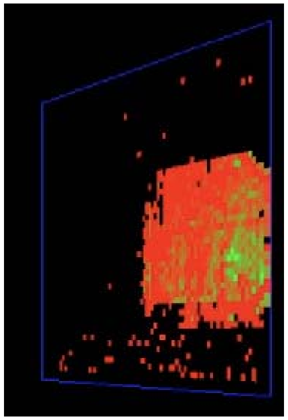
Already used for monitoring (BaBar – CDF- ATLAS - CMS)

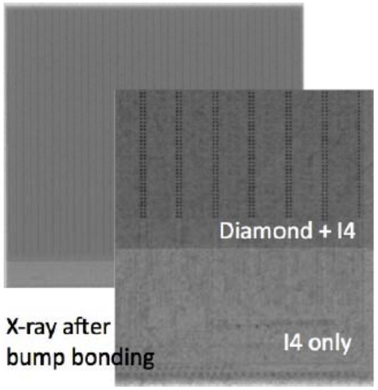
Potentially very interesting as position sensors

Excellent radiation hardness

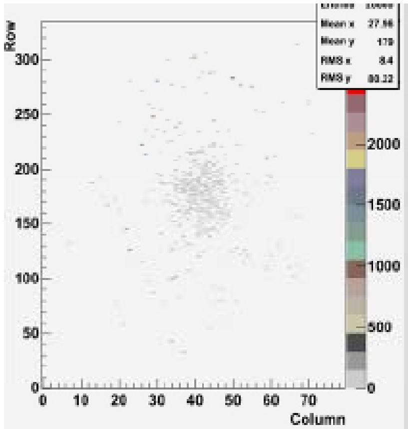
Negligible leakage current (and not T-dependent)

Now available as good-quality pCVD on 12" wafers and high quality sCVD on 4 x4 mm^2





Bump-bonded to an ATLAS FE-I4

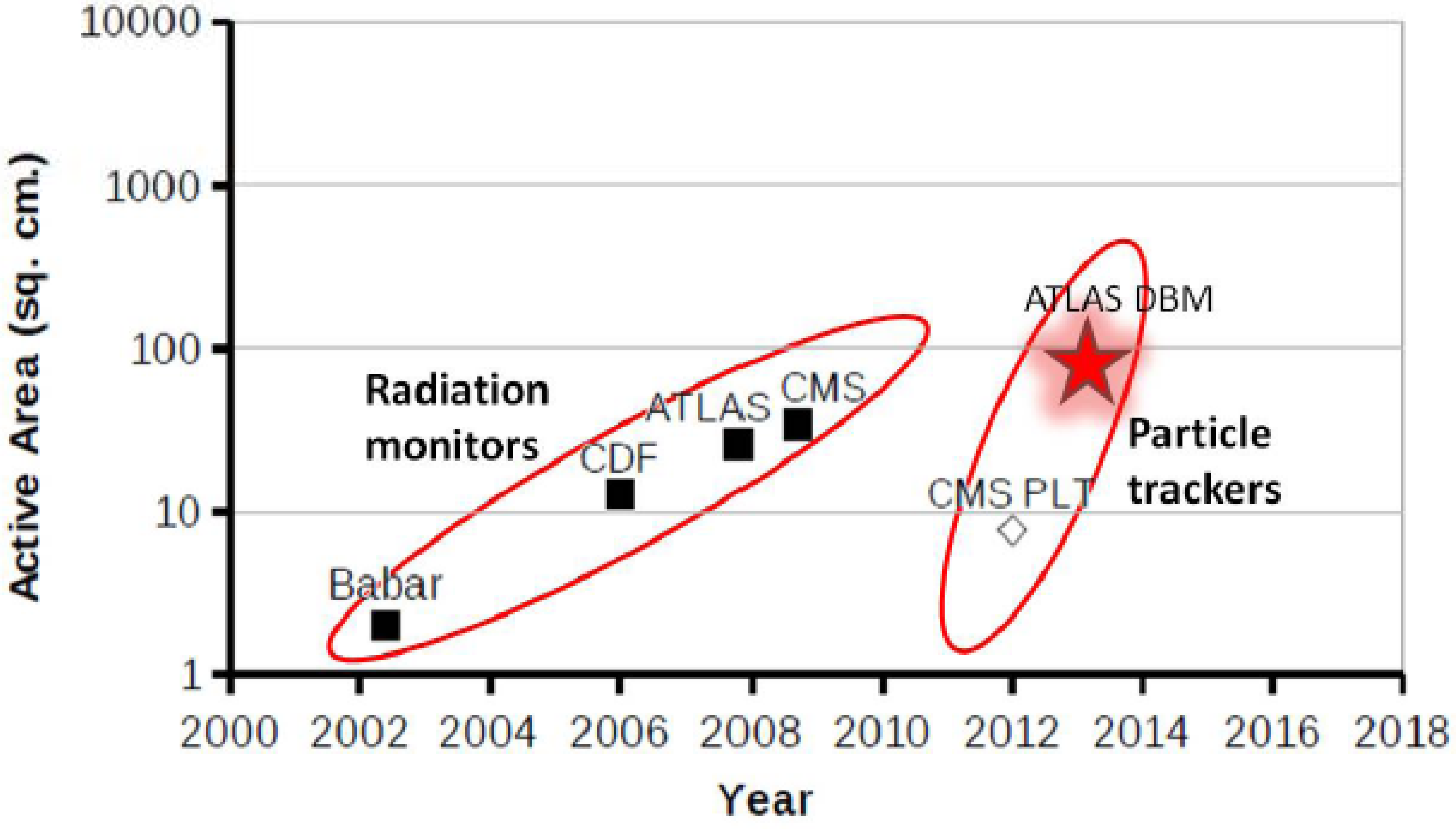


ATLAS testbeam 2011

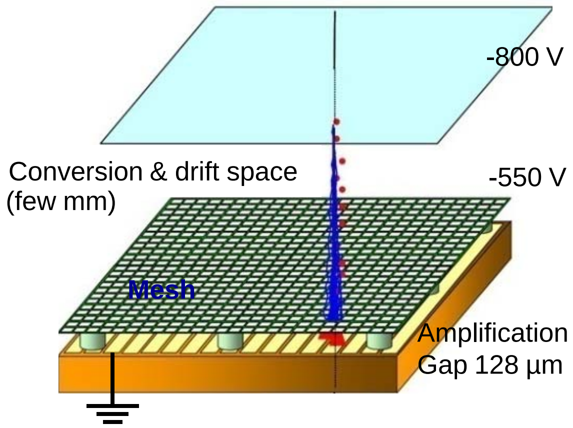
In France implication of
IPHC / LPSC Grenoble
INeSS Strasbourg
LSPM Paris XIII

Diamond Detector Systems in HEP

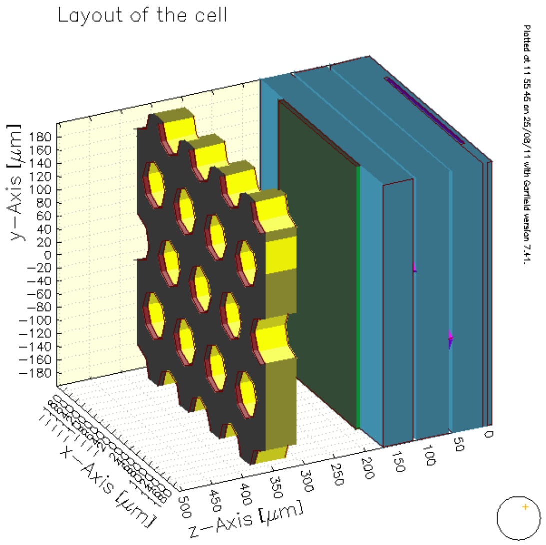
CMS Pixel Luminosity Telescope already in commissioning phase
ATLAS Diamond Beam Monitor already approved and in construction



Micro-pattern gaseous detectors (MPGD)



Micromegas (Micro-Mesh Gaseous Structure)



GEM (Gas Electron Multiplier)

Assets

Large range of applications
PCB technology
Cost and robustness
Large area achievable
Versatile geometry

Very large area (>1m^2) and high rate environment (sparks)

µM: bulk for large area and resistive for spark

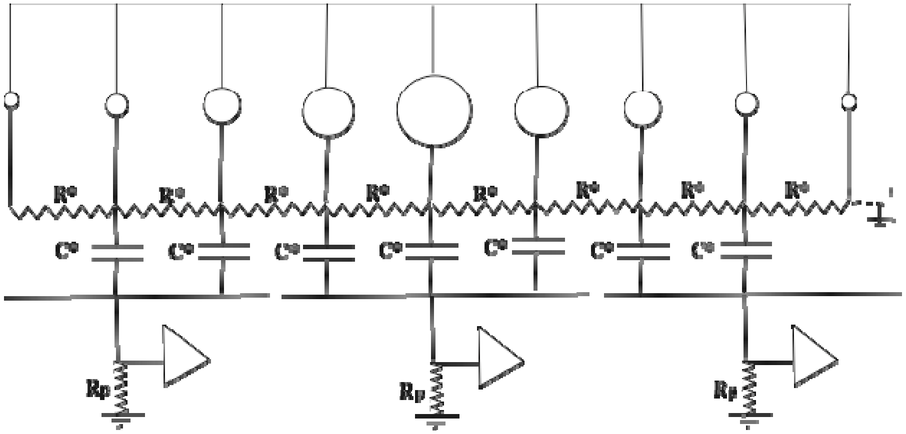
GEM: foil segmentation and 3-GEM amplification to reduce spark probability

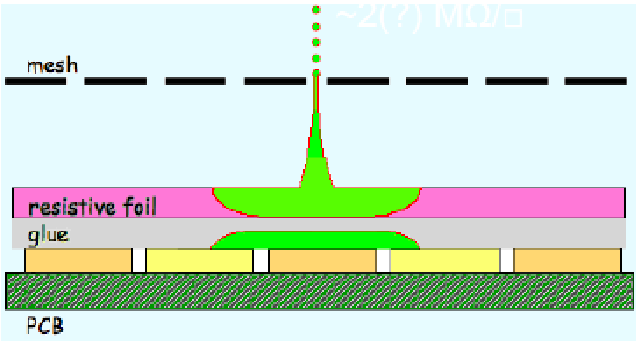
Worldwide active collaboration for development of MPGD → RD51

Resistive-anode μM

Resistive layers technology developed initially to improve position resolution vs granularity (charge spreading).

Resistive coating on top of an insulator: Continuous RC network which spreads the charge: improves position sensitivity



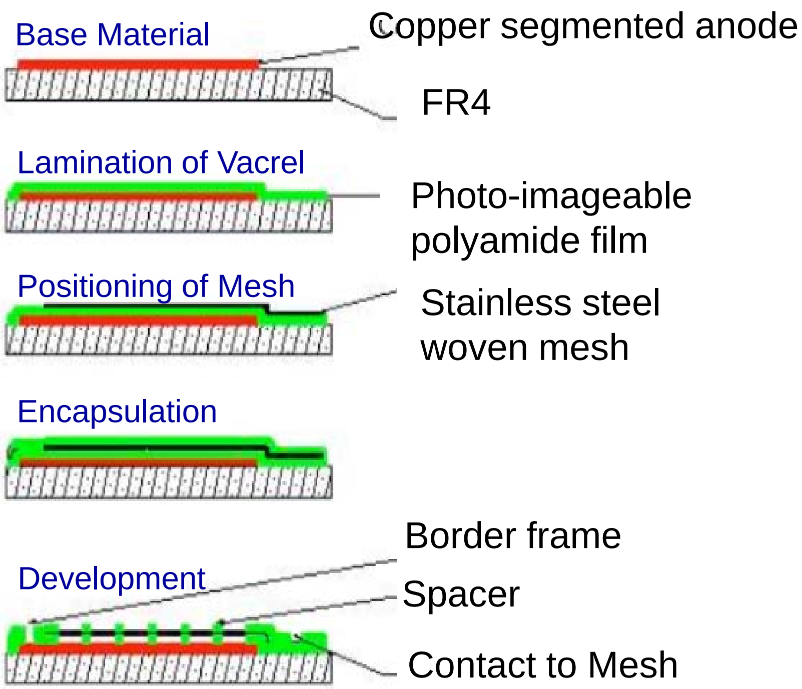


M. Dixit, A. Rankin, NIM A 566 (2006) 28

Various resistive coatings have been tried: Carbon-loaded Kapton (CLK), 3 and 5 Mohm/square, resistive ink.

Bulk technology

- Result of a CERN-Saclay collaboration (since 2004)
- Workshops @ CERN and Saclay
- Motivations for using bulk Micromegas
  - the mesh is held everywhere: no dead space, no frame
  - robustness (closed to dust)
  - can be segmented
  - Gain uniformity
  - Low cost
  - Industrial process
  - Large area detectors



Base Material

Copper segmented anode

FR4

Lamination of Vacrel

Photo-imageable polyamide film

Positioning of Mesh

Stainless steel woven mesh

Encapsulation

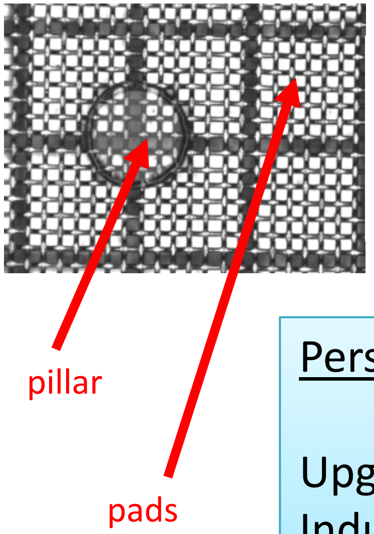
Development

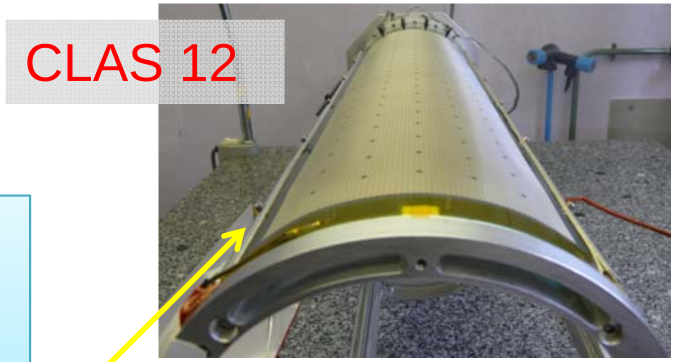
Border frame

Spacer

Contact to Mesh

I. Giomataris *et.al.*, NIM A560 (2006) 405





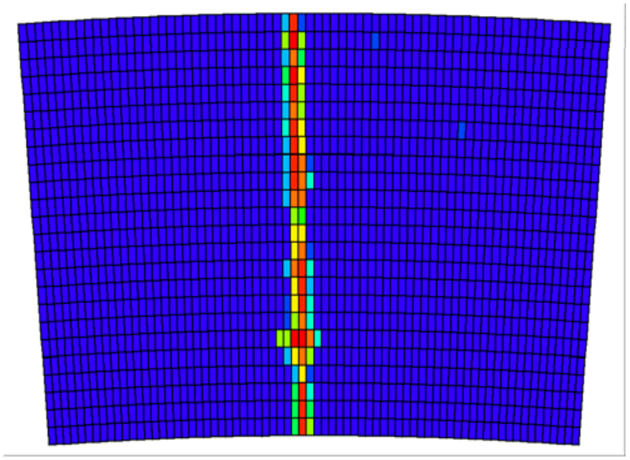
CLAS12 (Jefferson Lab)
Micromegas central and forward tracker

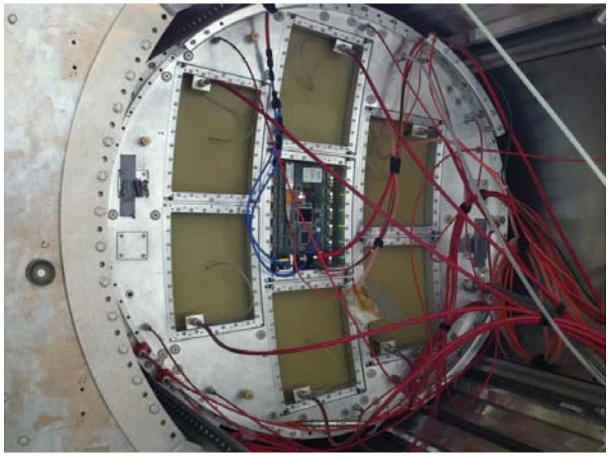
P. Konczykowski et al. NIM A612:274-277,2009

Perspectives

Upgrade workshop CERN → area up to 2 m^2
Industrial transfert (ANR SPLAM)
Various geometries → cylindrical detectors

Micromega-based TPC for the Linear Collider

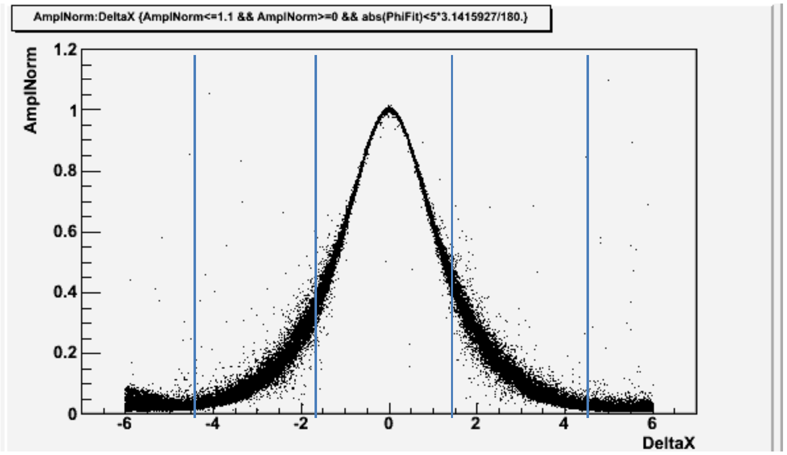




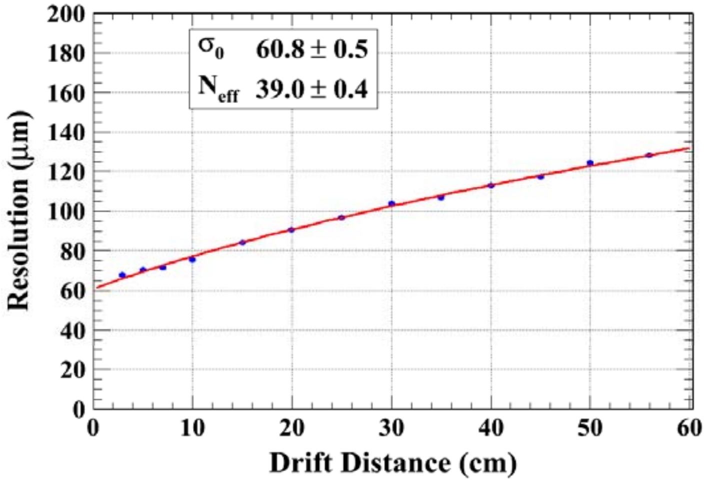
24 rows x 72 columns of 3 x 6.8 mm^2 pads

Relative fraction of 'charge' seen by the pad, vs x(pad)-x(track)

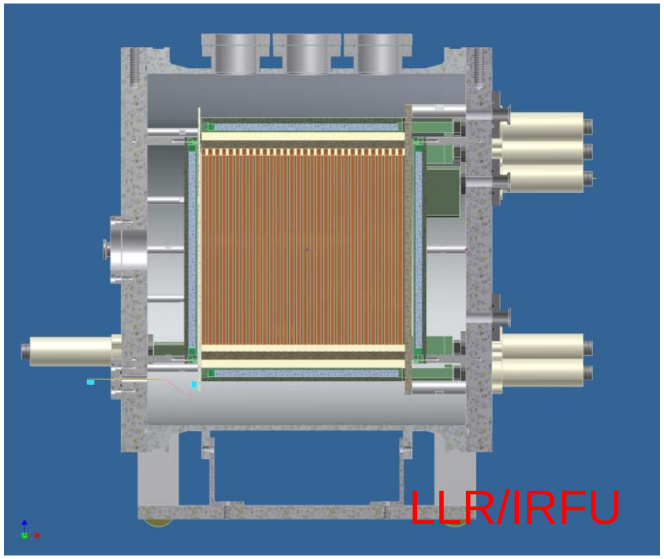
Z=20cm, 200 ns shaping



x(pad) – x(track) (mm)



TPC for gamma astronomy and polarimetry: HARPO



Gamma telescope for a future post-Fermi mission (HARPO)

Goal: angular resolution 10x better than Fermi/EGRET

Polarization measurement capability on the energy range

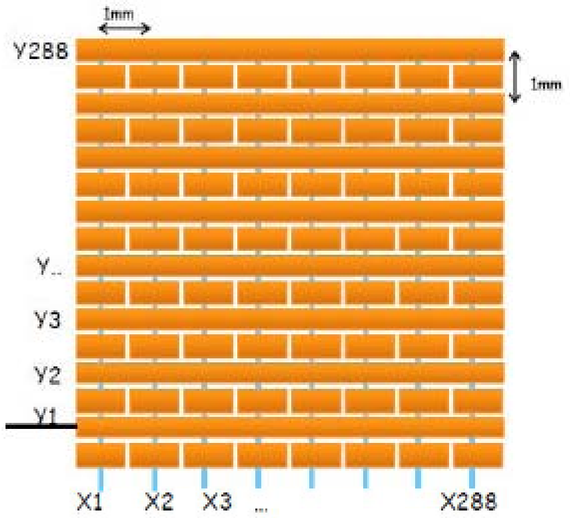
Demonstrator:
30cm cubic TPC, 5 bar, Argon based mixture
pitch 1mm, spatial resolution 1mm

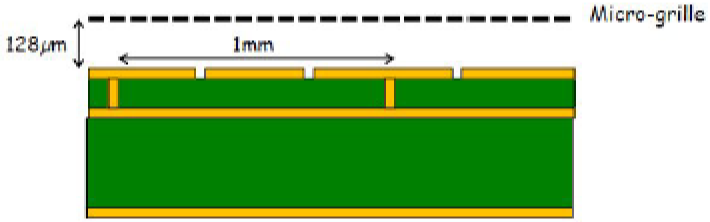
This could give the first TPC working in space !

Amplification/collection

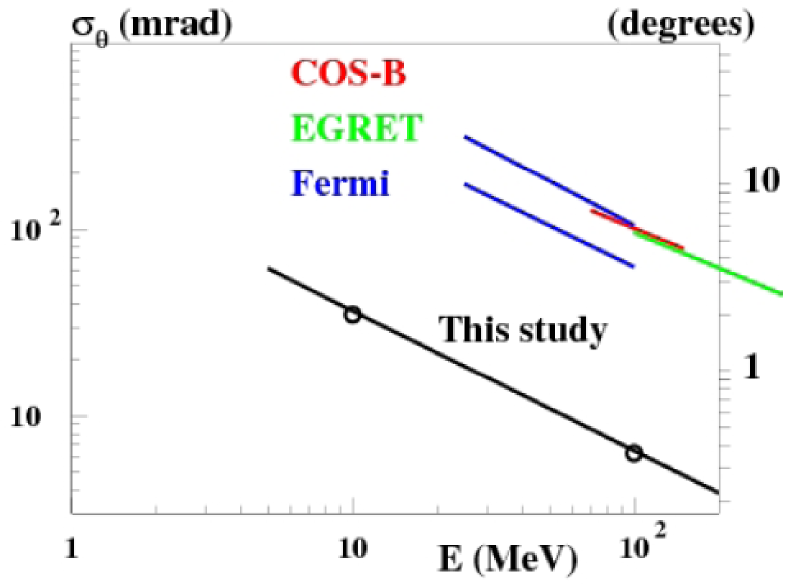
Micro-mesh micromegas
Strips on PCB, pitch 1mm
2D readout using two planes
Readout by AFTER chip

P. Baron *et al.*, IEEE Trans. Nucl. Sci. 55 (2008) 1744.



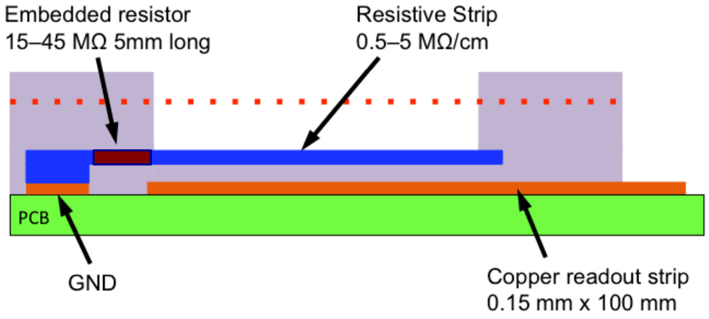


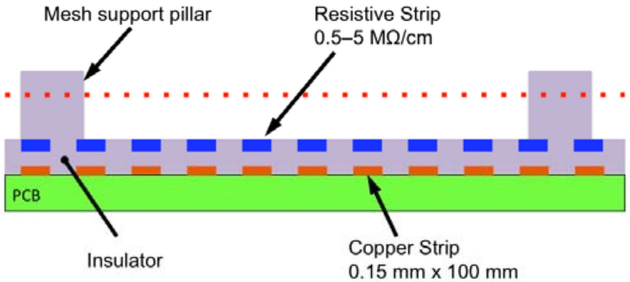
NIM A 608 (2009) 259

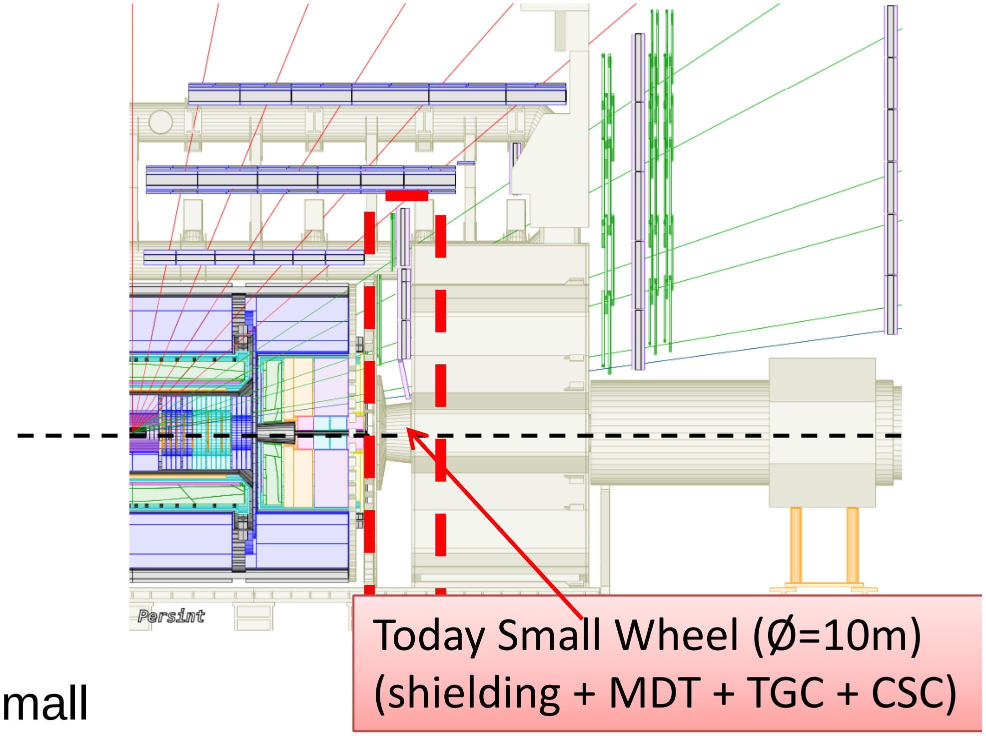


See Isabelle Grenier talk

ATLAS muon chambers upgrade







Today Small Wheel (Ø=10m)
(shielding + MDT + TGC + CSC)

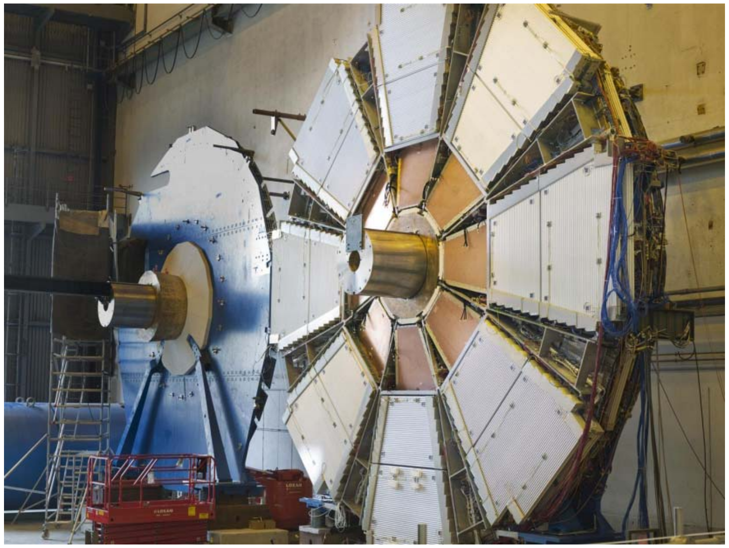
<u>Proposal:</u>

Replace muon chambers of the ATLAS Small Wheels with µM chambers (trigger and tracking)

Rates in the hottest regions: 10-15 kHz/cm^2
Timescale: 2017/2018

2 options:TGC+µM or TGC+µM+sMDT

→ 64 / 128 µM chambers (0.5 to 2.5 m^2)
→ 200 / 1000 m^2
→ 400k / 2M readout channels



Low pressure gaseous detectors for beam tracking

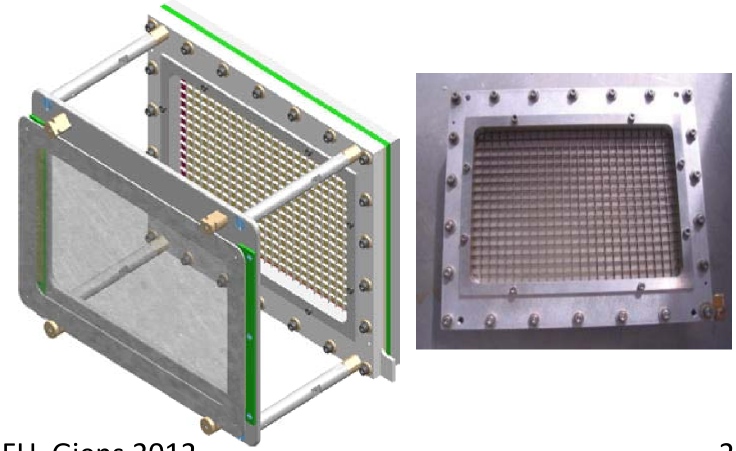
- Beam tracking mandatory to reconstruct reaction kinematics (resolution of 1.5 mm and 250 ps, high counting rates 10^5 pps/cm2) either for beams of large emittance or at the focal plane of spectrometers
    - Low energy and angular straggling ⇒ thin window detectors at very low pressure (10 mbar of pure isobutane), generally wire chambers
    - Detectors in the beam at higher energy (> 10 MeV/n, 500 µg/cm2) or outside the beam for low energy with Secondary Electrons Detectors (2 to 10 MeV/n, emissive foil thickness<150 µg/cm2)

- In the forthcoming years SPIRAL2 (S3 or NFS) will need detectors for heavy nuclei or fission fragments at low energy (< 6-7 MeV/n)
    - An R&D program has been initiated 4 years ago (collaboration between IRFU and in2p3) to cover the needs in this type of detection for the next 10 years
    - Different topics of work: detectors at low pressure with wire chambers or MPGD (micromegas), secondary electron detection, use of new electronics like GET

Some of the recent developments:

VAMOS (GANIL) focal plane
1 m large detection set-up with
1 MWPPAC, 2 DC, 3 CHIO, 40 Si

S3 focal plane and FALSTAFF(NFS)
2 SED prototypes: wire chambers and micromegas



Conclusions

Tracking detectors will face demanding applications in the next few years

LHC high luminosity upgrade will require large area, radiation hard Silicon detectors.

ILC will require high segmentation, thin sensors

Need to develop thin radiation-hard cheap sensors and new interconnections techniques. In addition, cheap large-area technologies will also play a major role, and gas tracking detectors remain and will be an important component

High energy / nuclear physics experiments are not the only actors in the game. Astro-particle applications, beam monitoring, spectroscopy, imaging play an important role.

Critical interconnection with electronics R&D