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Progress on silicon detectors from high-energy physics for small and large-scale systems

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PHYSICS WITH INTEGRATED CMOS SENSORS AND ELECTRON MACHINES

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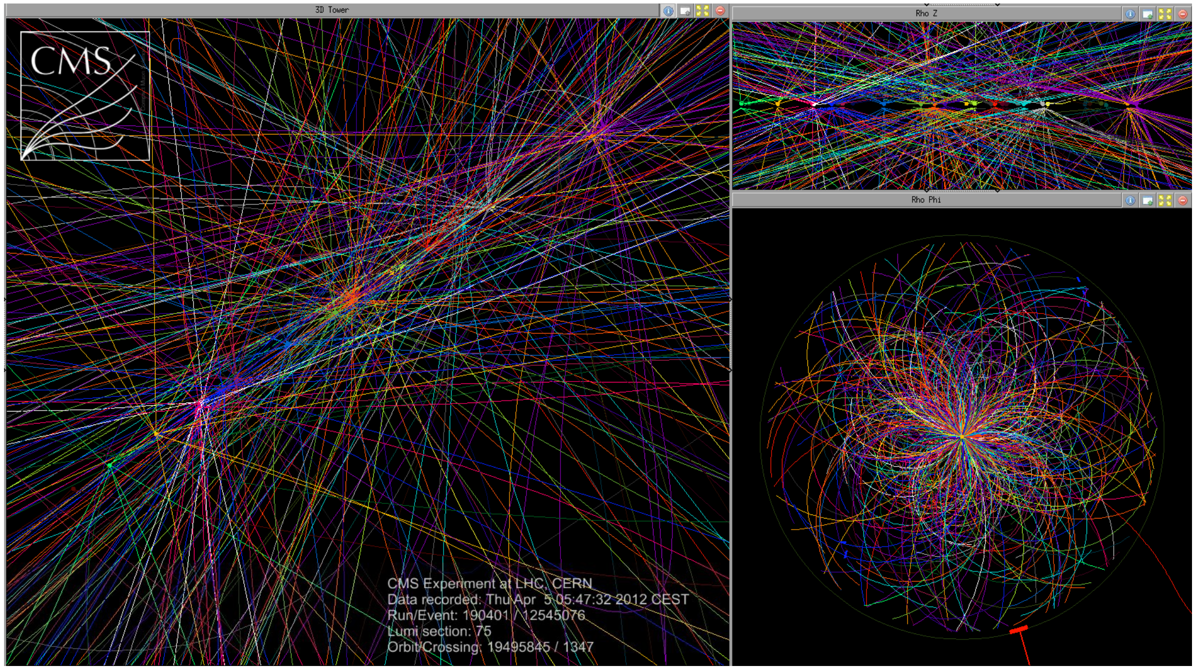
- → Trend in HEP tracking
- → Silicon technologies
- → Applications in dosimetry and life science

Trend in HEP tracking

- Goals
- Constraints on sensors
- Various optimisation:
  - e+e- colliders
  - p+p colliders

Tracking & vertexing goals in HEP

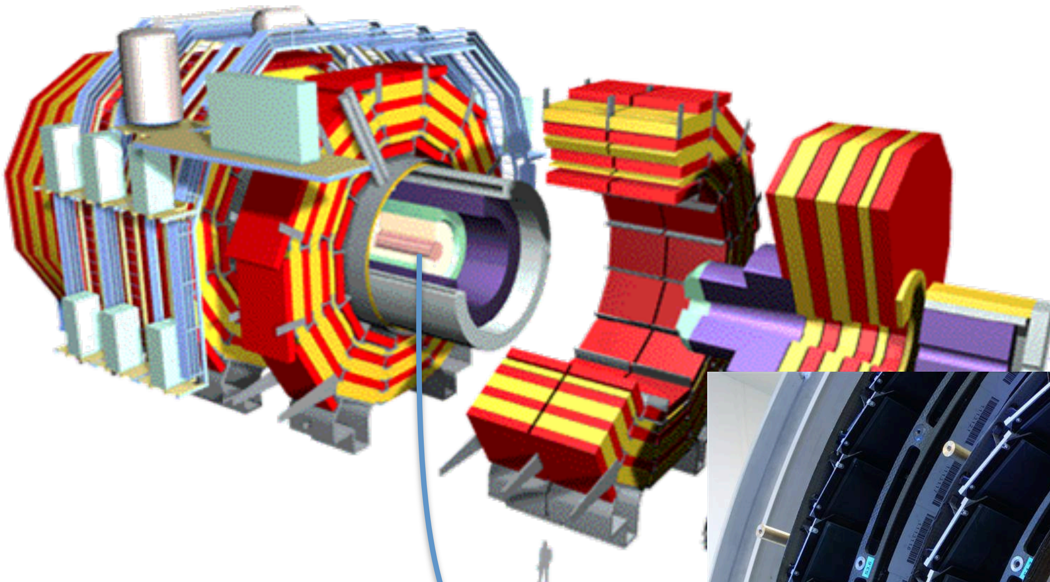
- Measuring
  - Particle trajectories
  - Particle origins (vertex)

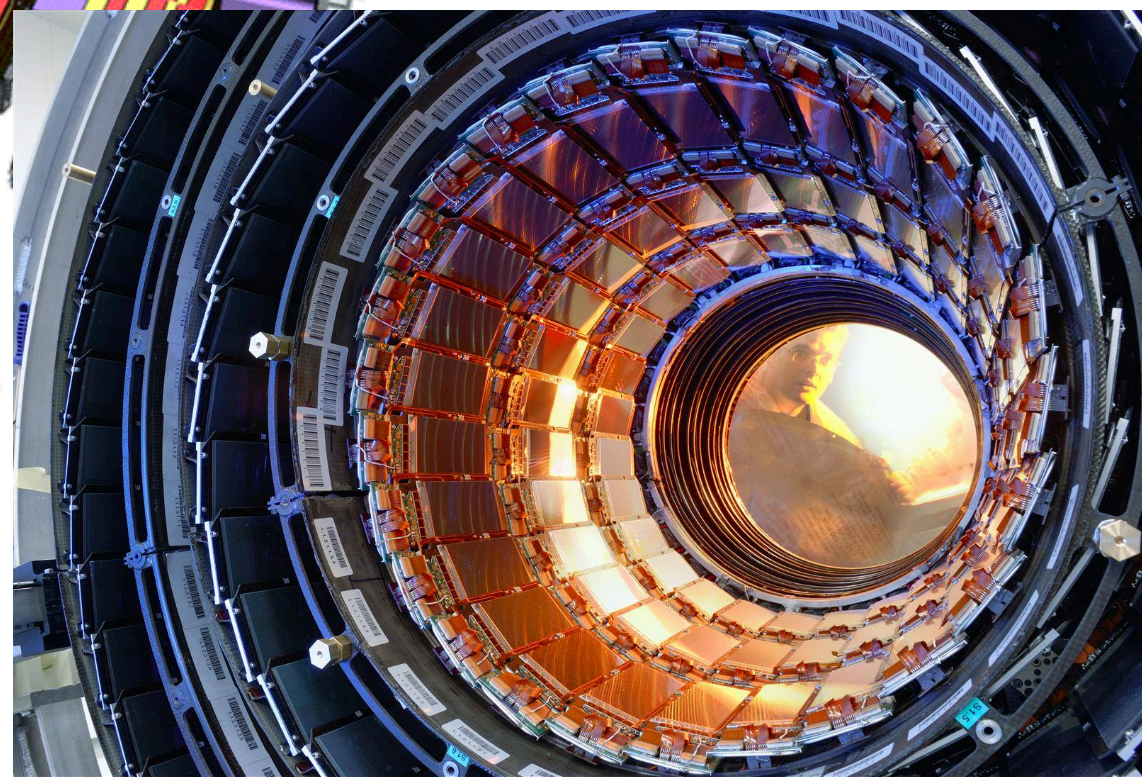


- Main assets / pure tracking performances
  - Best resolution on particle crossing point
  - Many measured points (K)
  - Lowest material budget

$$\frac{\sigma_{p_T}}{p_T} = \frac{\sqrt{720}}{0.3q}\frac{1}{BL^2}\frac{\boxed{\sigma}}{\sqrt{\boxed{K}+6}}p_T \oplus f(\underline{\text{mult.scattering}})$$

Example: the CMS tracker (LHC)

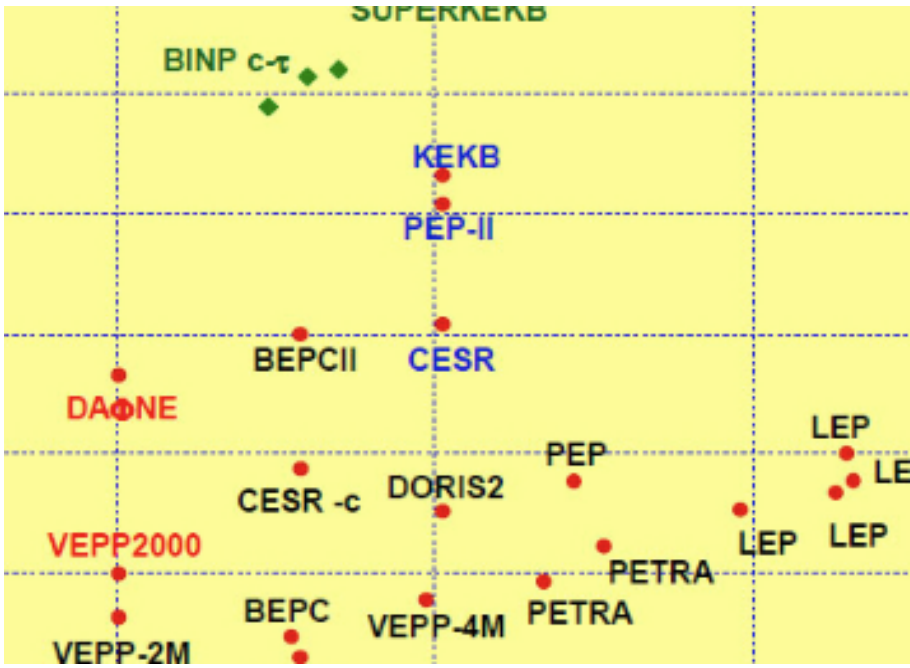




- Full silicon technology
  - 210 m^2
  - 9.6 x 10^6 channels
  - few 10 Tbits/s

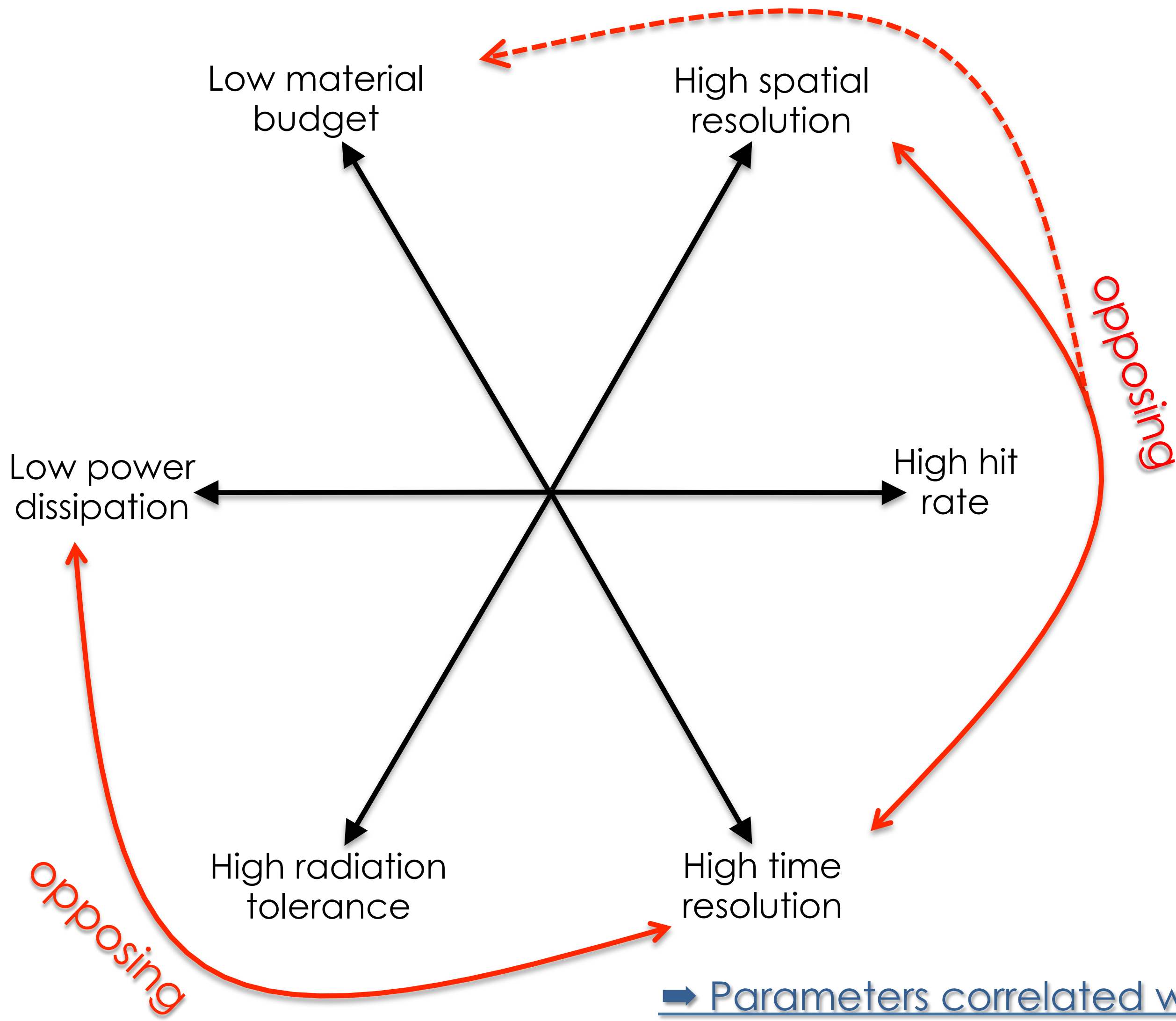
Constraints from HEPhysics goals

- New processes ⇒ 2 main frontiers
  - Heavy new particles ➙ high energy
    - $m_{Higgs\ boson}$~125 GeV/c^2, $m_{top\ quark}$~170 GeV/c^2
  - Rare processes ➙ high luminosity
    - cross sections of interest ~ fractions of picoBarns



- Consequences on detectors
  - Hit rate could reach 10^7 particles/cm^2/s
  - BUT tracking algo max occupancy < few %
    ➙ time resolution
  - Radiation environment
    Ionizing (MGy) & non-ionizing (10^{16} n_{eq}/cm^2)
    ➙ tolerance through high SNR
  - many points + speed + low mass
    ➙ minimal power dissipation

Requirements on sensing layers



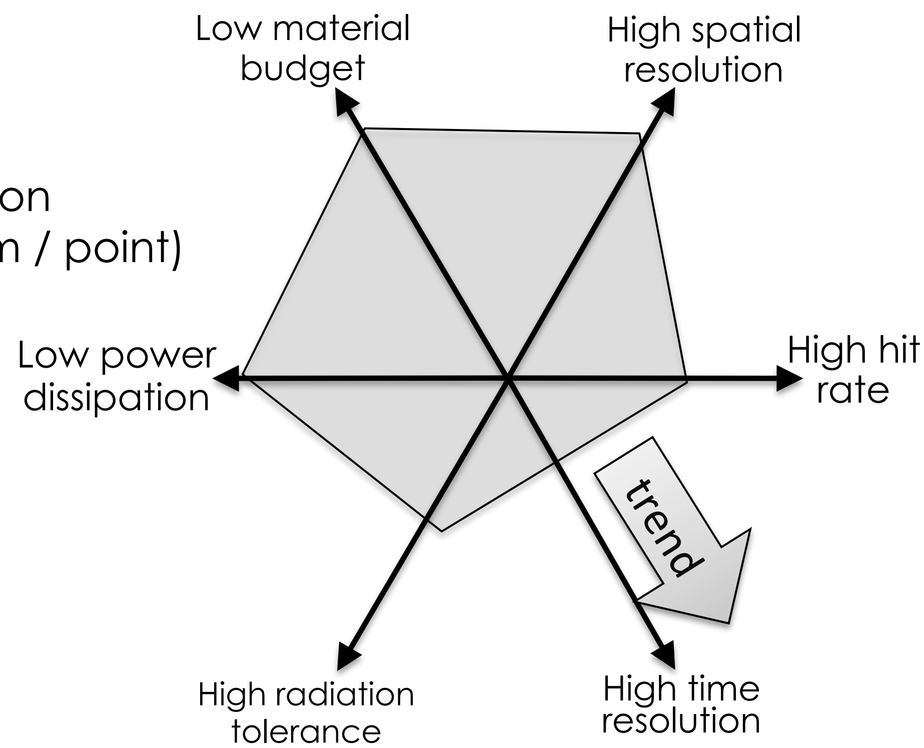
➡ Parameters correlated within one technology

…more or less trivially

Leptonic e+e- collisions

History (20th century <2010)

- **SLD** had the first and only CCD-based vertex detector
- **LEP** introduced strips and pixel hybrid
- **B-factories** most precise vtx det. so far
- ~10-20 tracks /event, almost no radiation
  BUT need for tracking precision (~10 µm / point)



SuperKEKB / Belle II (2018)

- x100 luminosity ⇒ σ_{time}~10 ns

Next linear colliders (~2030)

- > 100 tracks / event
- Single point resolution $\sigma_{point} \lesssim 3$ µm
- Material budget 0.1 - 0.2 % X_0
- Separating primary collision
  - ILC needs σ_{time}~100 ns
  - CLIC needs σ_{time}~10 ns

Technical choice ⇒ monolithic & hybrid

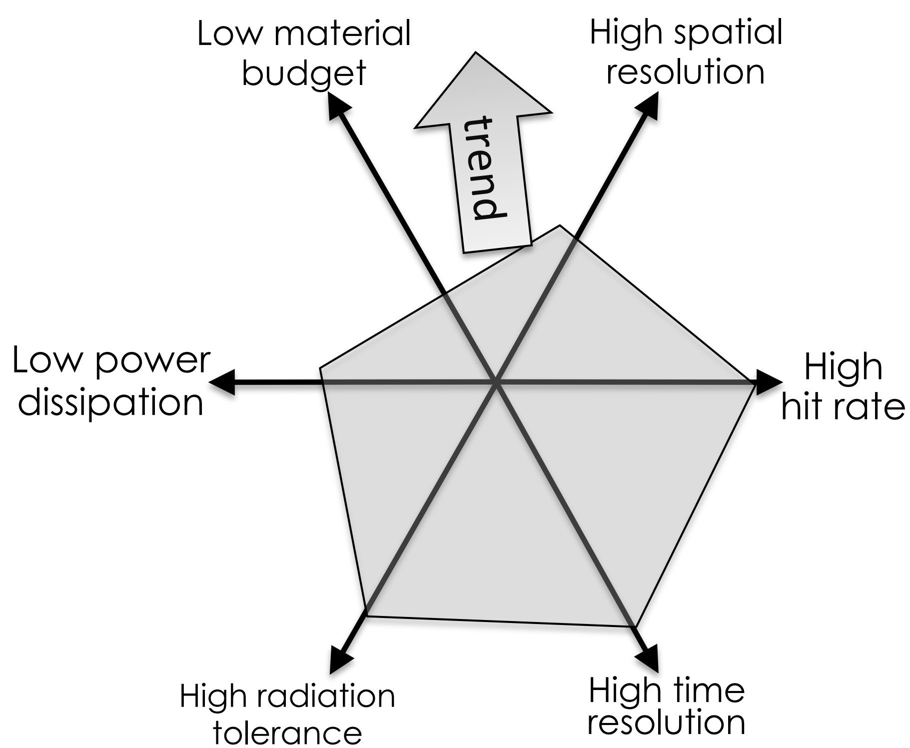
Hadron colliders (ATLAS, CMS, LHCb)

Current LHC (2008-21)

- Beam-crossing every 25 ns
  - 40 collisions / beam crossing
  - Few 1000 tracks / event
- Radiation at 4-5 cm
  - 500 kGy / year
  - few 10^{14} n_{eq}(1 MeV)/cm^2

High-luminosity LHC (>2024)

- Instantaneous lumi x10
  - Pile-up of 200-400 p+p collisions
- Radiation
  - 15 MGy / year
  - few 10^{16} n_{eq}(1 MeV)/cm^2
- Improved track param. resolution
  - material budget ~ % X_0
  - Single point resolution σ_{point} ~ 10 µm



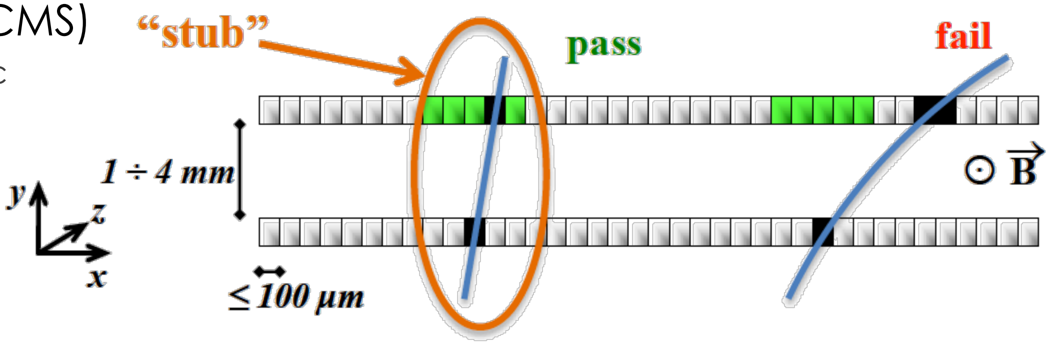
Technical choice ⇒ hybrid

Still on High Lumi. - LHC

- Key aspect on hadron machine = triggering

  ← Huge gap in cross-sections (from milli to pico barns)

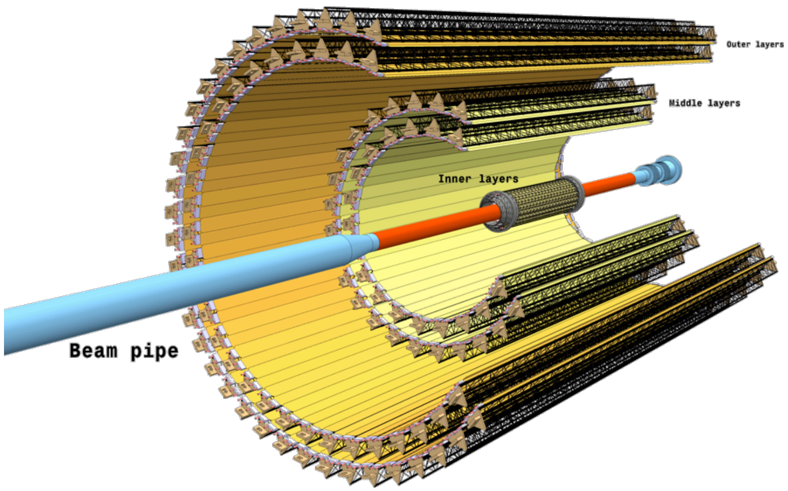
  - Online momentum measurement through tracking
  - Double-sided measurement (CMS)
    - for tracks with $p_T > 2\text{-}3$ GeV/c



  - Smart & fast algorithm in FPGA (ATLAS, CMS)
    - Typically < 2 μs to take decisions
  - LHCb has given up "hardware" trigger

Additional systems

- Heavy ion collisions
  - STAR @ RHIC, ALICE @ LHC
  - Rather similar to e+e- requirements
    - Low momentum
    - Lower luminosity (large cross-sections)
  - But some radiation hardness required



ALICE new-ITS, 10 m^2, 12.5 Gpixels
technology ⇒ monolithic

- Fixed target experiments
  - Usually high luminosity
    - Radiation tolerance important
    - Time resolution
  - Spatial resolution & material budget depends on momentum produced

Silicon technologies

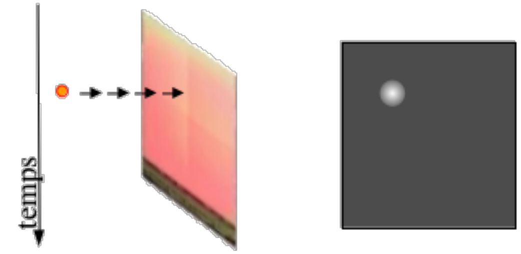
- CCD
- Hybrids

- DEPFET
- CMOS sensors
- Silicon On Insulator

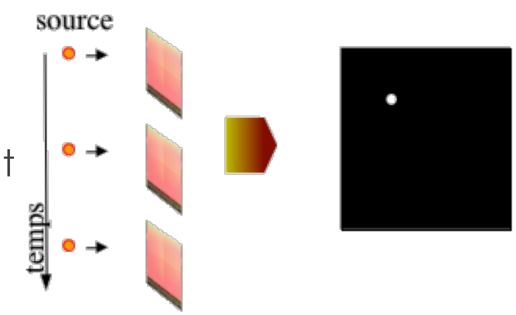
\+

Preliminary remark: read-out

- Read-out : “Imaging” vs HEP
  - Std imaging sensors ⇔ usually INTEGRATION
    - One channel signal = several
    - Key parameters: dynamic, point spread function, noise
    - Single frame 100% occupied



  - Tracking sensors ⇔ COUNTING single particles
    - Key parameters: resolution (E, t, position), SNR, dark count
    - Single frame ≲1% occupied



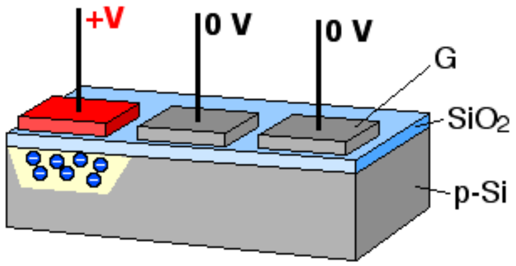
  - Both can build image…with various qualities
    - Strong impact on read-out electronic design

Preliminary remark: exhaustiveness

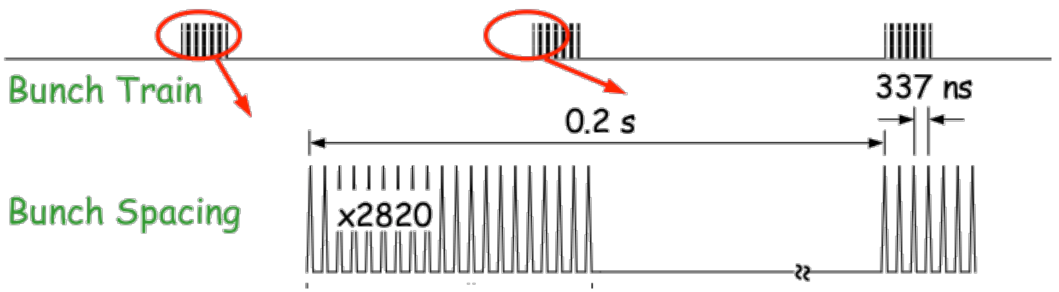
- Non-exhaustive talk
  - Silicon pads (large diode array)
    - Large pixel = mm range
  - Silicon drift detector (SDD)
    - Marginal in HEP (STAR, ALICE)
    - X-ray detection
  - CMOS avalanche detector
    - Including SPADs in CMOS
    - Combine 100 ps & few μm resolution
    - Still in development
  - … (← this is for what I've forgotten)

CCD

- **THE standard imaging sensors**
  - Already challenged by sCMOS on scientific market
  - Integrating sensor, by structure
  - Full depletion possible

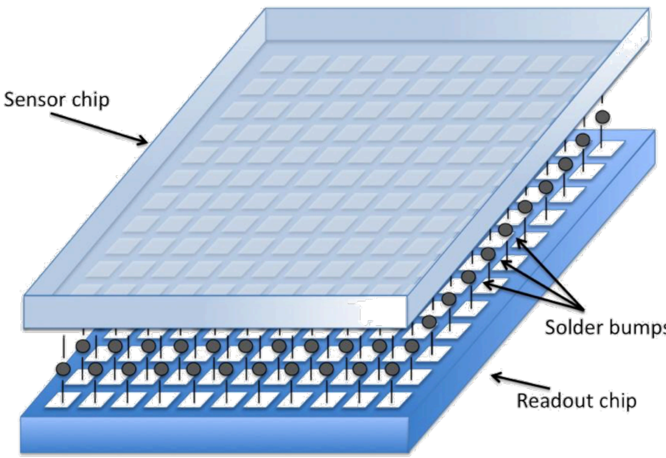


- **In HEP**
  - First application at SLC e+e-(<2000)
    - Super precise, Low mass, super-slow read-out
  - Proposed for ILC
    - Fine-pixel CCD
    - 5-6 μm pixel size
    - Delayed readout / specific ILC time-structure



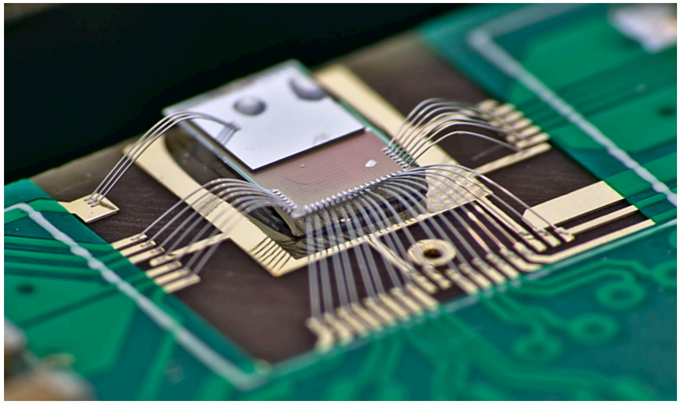
Hybrids (strips & pixels)

- THE standard approach in HEP
  - Implement powerful processing
    - Pre-ampli + shaper ⇒ time & energy resol.
  - Radiation hardness
    - Si type adapted
    - 3D sensors
  - Recently edgeless sensors



- "limitations" / pixels
  - Relatively large pixel size
    - Limited by bump-bonding & processing
    - Current ATLAS 50x250 μm^2, CMS 100x150 μm^2
  - Relatively thick ⇐ 2 thickness of silicon
  - Sensitivity to low ionizing particles
    - Typical minimal threshold ~1000 e-

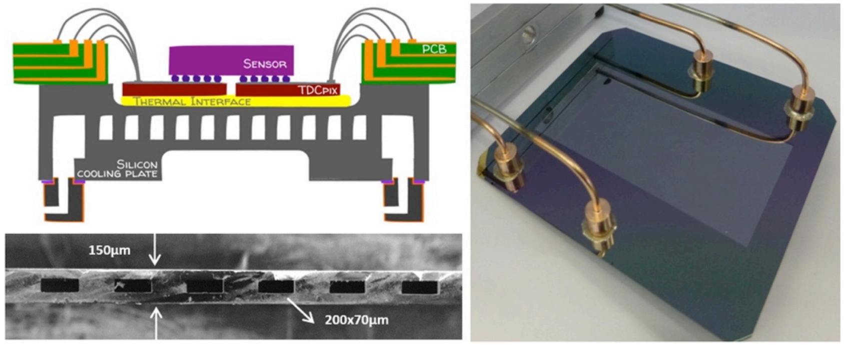
- Developments / CLIC
  - targets pitch 25x25 μm^2
  - with thickness 50 µm (ASIC) + 50 µm (Sensor)
  - Some functional prototypes



Hybrids (strips & pixels)

- Developments / LHC

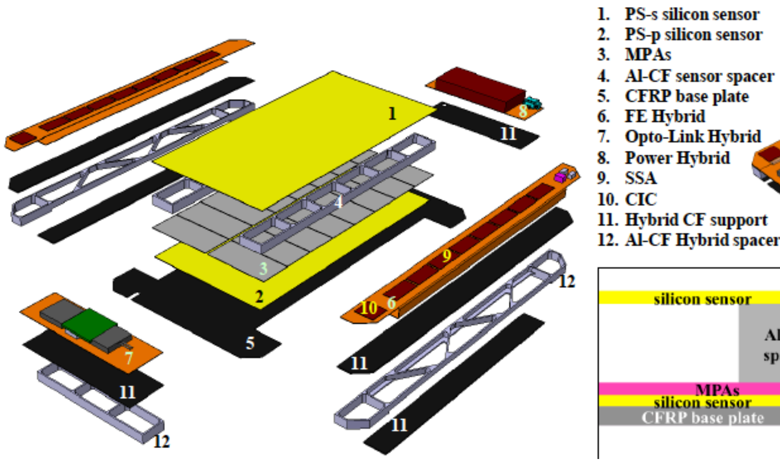
  - New cooling techniques
    (power hungry >100 µW / pixel)
    - Micro-channel in Si (⍉~100 µm) for few W/cm^2

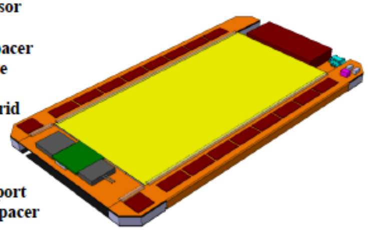


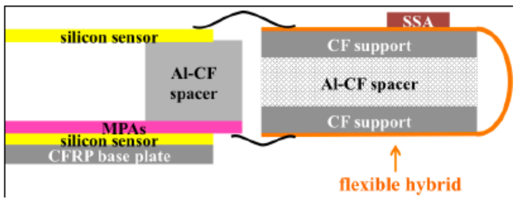
NA62 GigaTracker

  - New ASIC process 65 nm (CERN-RD53 dvpmt)
    - Tolerance to 5-10 Mgy
    - Allows for few 100 px time resolution

  - CMS Track-trigger with double-sided modules separated by few mm

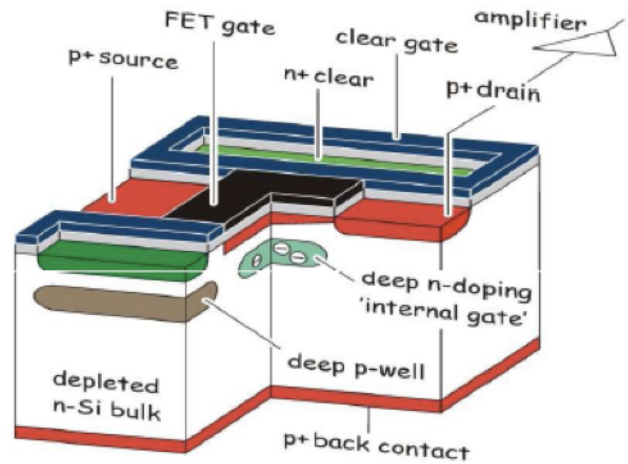


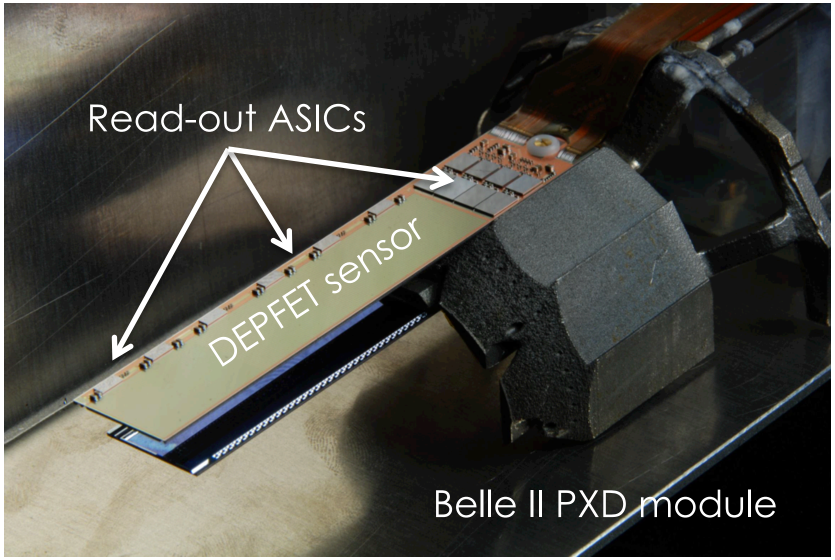




DEPFET

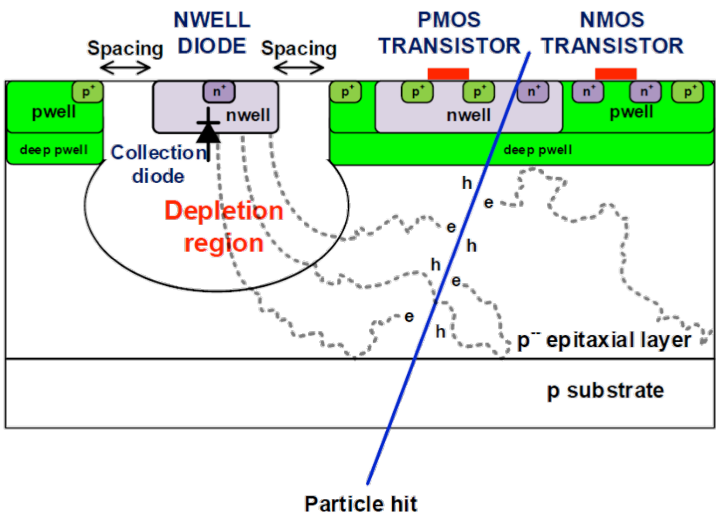
- A "monolithic" approach
  - Driven by imaging (X-rays, electrons)
  - Amplification in-pixel but no processing
  - Fully depleted volume
    300 to 50 µm (thinned)
- First detector for HEP in 2018
  - Belle II vertex detector (PXD)
  - The thinnest detector 0.18 % X_0 / layer
  - Pitch not crucial: 70 µm
  - 20 µs integration/read-out time
- Toward ILC
  - Smaller pixel 20 µm



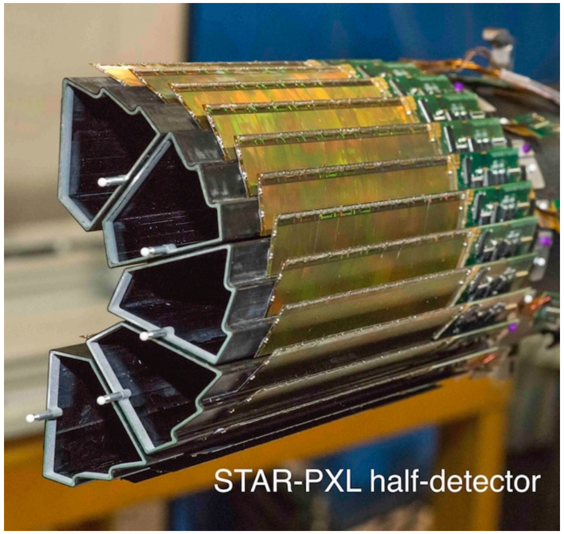


CMOS Pixel Sensor

- Monolithic Active Pixel Sensors
  - Inherited from commercial camera
    - First proposed in 1998 @ Strasbourg for HEP
  - Assets
    - Small pixels
    - Sensitivity to low signals
    - Low material budget
    - Embedded processing -> easy integration



- First detector in HEP: 2013
  - STAR vertex detector (PXL)
  - Small pitch 20 µm
  - Small material budget 0.37 % X_0 / layer
  - "Slow" read-out 180 µs

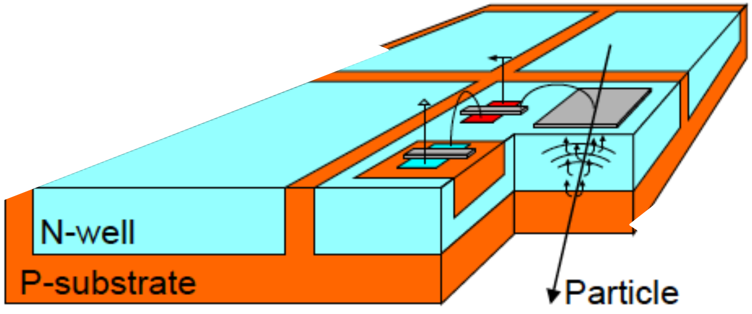


- First tracker in HEP: 2019
  - ALICE Inner Tracking System 10 m^2
  - Small pitch 25 µm & material budget ~0.4 % X_0 /layer
  - Very low power dissipation ~70 mW/cm^2
  - Fast read-out with short integration time <10 µs

CMOS pixel sensors: on-going

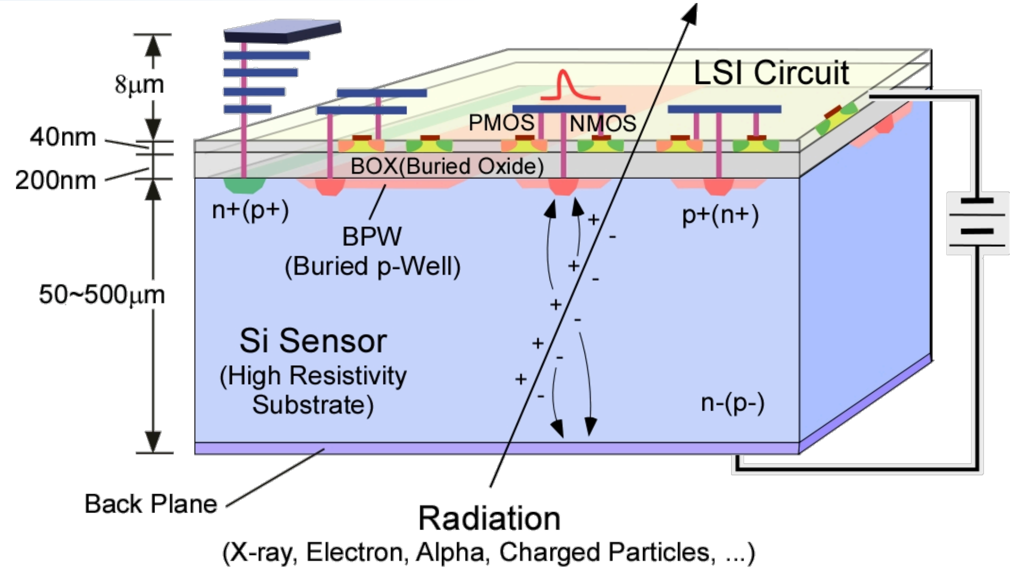
- Limitations
  - Processing power / pixel size
    - Impact time resolution
  - Radiation hardness
    - Std techno not fully-depleted

- Developments
  - Full depletion (achieved)
    - High voltage (>10 V) and/or high resistivity (kΩ.cm)
  - Faster
    - Few 100 ps for Mu3e (HV-CMOS)
    - 7 ns for CLIC (HR-CMOS)
    - Few 100 ns timestamp at ILC
  - More tolerant / radiation
    - ATLAS tracker (HR-CMOS)
    - CBM vertex @ FAIR-GSI (HR-CMOS)
  - 3D-like bonding for CLIC pixel 25 vm
    - Capacitive coupling HV-CMOS+ASIC
  - Super low-power -> ATLAS tracker



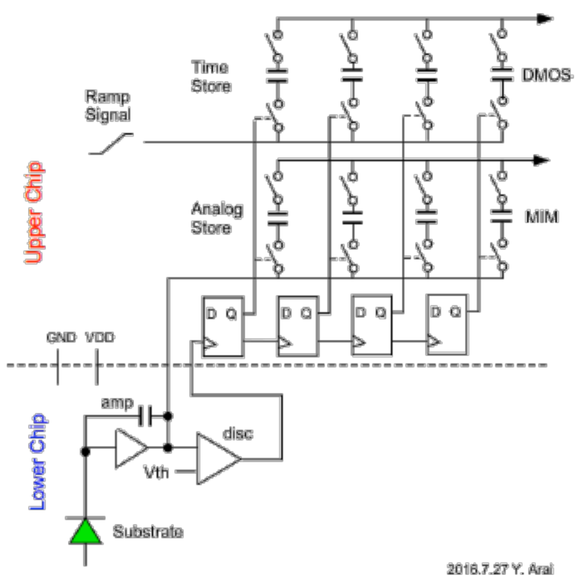
SOI

- **A monolithic-hybrid ?**
  - Includes fully depleted sensitive layer 50-700 µm
  - Includes processing power
    - less constraint / CMOS sensors
  - Large SNR
  - Relatively weak to radiation
    - thick oxyde



- **Current usage**
  - Mostly for imaging (X-rays)
    - Synchrotron, medical, astronomy, …

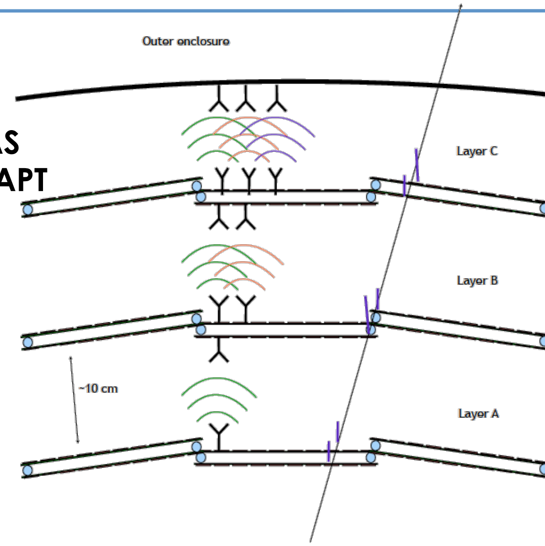
- **Project in HEP: ILC**
  - Enhanced signal treatment within 20 µm pixel
    - Spatial & time resolution
  - Still prototyping



"Miniaturisation"

- Wireless
  - Alleviate the cable conundrum
  - ATLAS project for Si-strip tracker
    - Goal is 100 Tbps with multi Gbps repeaters
    - 60 GHz band @ small-distance
    - Power ? ~150 mW/cm^2

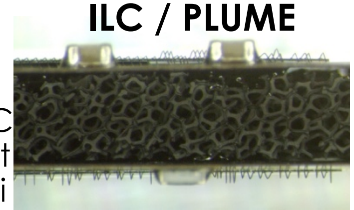
ATLAS / WADAPT

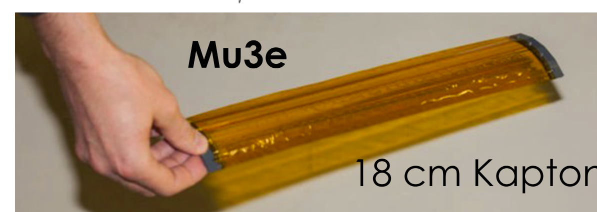


- Mechanical support
  - 50 µm Si + ? = 0.1-0.2 % X_0
  - ILC, CLIC, MU3e

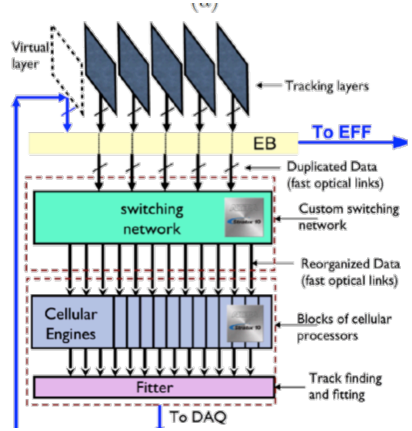
ILC / PLUME

2 mm SiC
100 µm Kapt
50 µm Si





- Online tracking (LHC)
  - FPGA-farms
  - highly parallelized structures



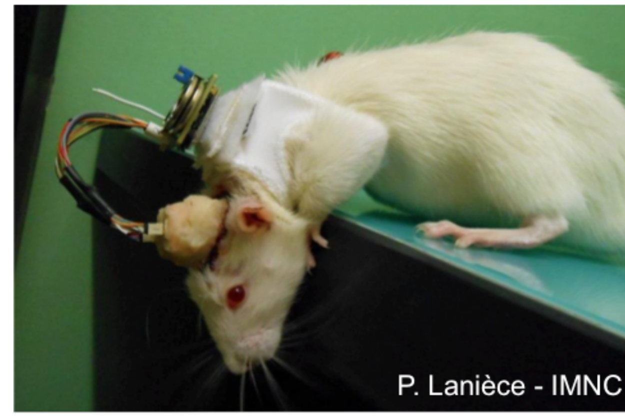
Devmpt / LHCb

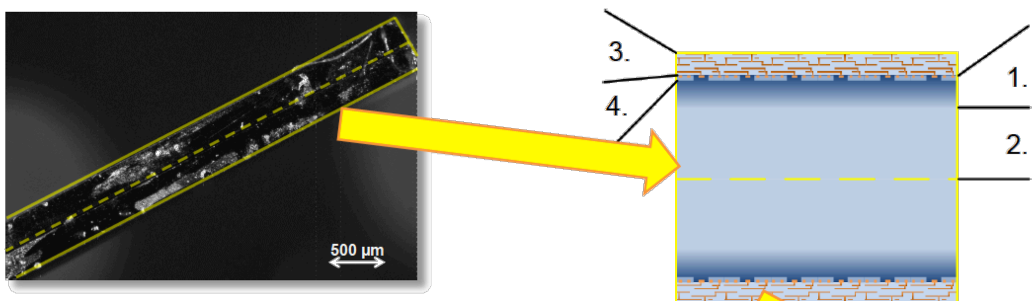
Applications in dosimetry and life science

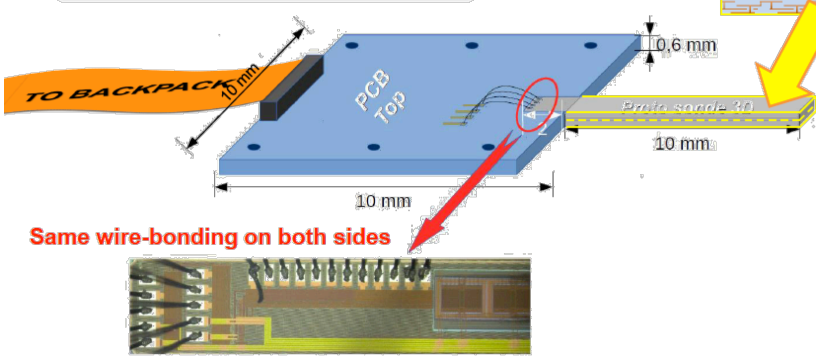
- Skipping all imaging X-rays, electrons, neutrons
- Highlights with CMOS pixel sensors
  - Still tracking
  - "extreme" integration
- 1 dream

Charged particles dosimetry

- <u>Molecular imaging with β+ emitters in moving rodent</u>
  - MAPSSIC: extreme integration in specific environment
    - Constraint on size and power dissipation
    - IMNC, IPHC, CPPM, CERMEP, NeuroPSi
  - Exploit CMOS sensors derived from ALICE
    - One active probe = 160 µW
    - For few counts / s
    - Wireless connection







1. Epi-layer (18 µm)
2. P-type Substrate
3. Metallization (~ 10 µm)
4. Process

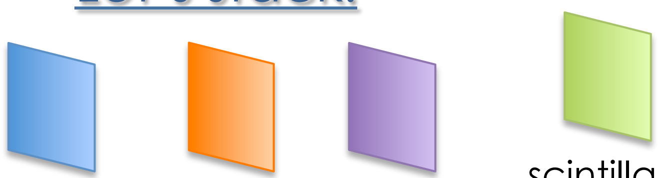
1.+2.+3. ~ 250 µm

probe in the brain :
- section ~500x500 µm²
- senstive volume (18 um) immune to γ

Currently integrating prototype sensor …

DREAM of electronic emulsion

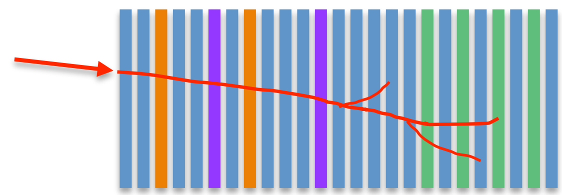
- Let's stack!

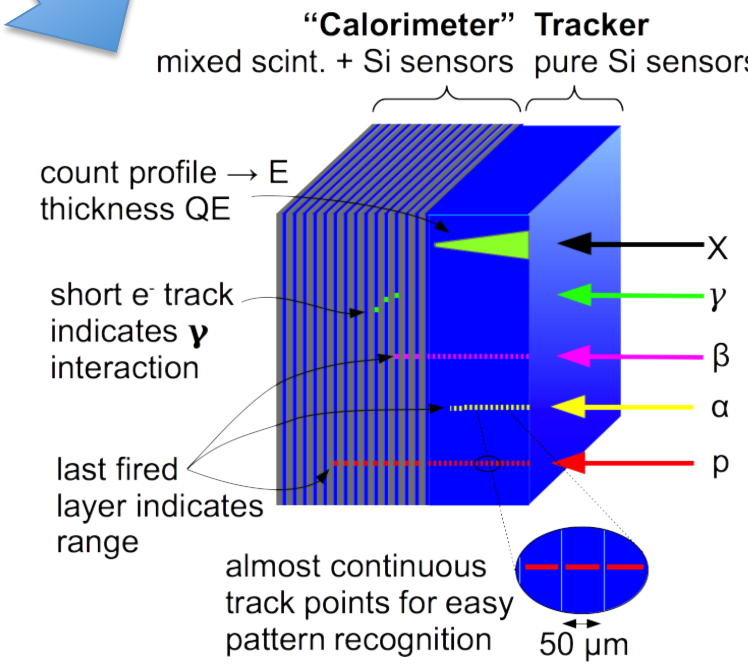


σ_{space} σ_{energy} σ_{time}

scintillator /converter

CMOS pixel flavours with sense layer ~ 100 % thickness





➡ **Fast electronic equivalent of a nuclear emulsion**

- **8D measurements**
  - 3D position + 3D direction
  - 1D time
  - 1D energy (range / sampling)
- **Adjustable performances**
  - Stack re-shaping (~~sensor redesign~~)

Conclusion

- Miniaturisation is helpful
  - Easier to integrate sensors
  - Smarter sensors ➝ helps getting exactly what you need (limit bandwidth)
  - But could be costly
- Who are the technology drivers
  - HEP community very active … tends to :
    - But optimisation always needed
  - Wrt miniaturisation,
    main player = micro-electronic industry !
    - High development costs
    - Moderate production costs