European Strategy for Particle Physics: le prospettive per i rivelatori

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INFN - Trieste

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Challenges in future accelerator experiments

	RHIC STAR	LHC - ALICE ITS	CLIC	HL-LHC Outer Pixel	HL-LHC Inner Pixel	FCC pp
NIEL [n_{eq}/cm^2]	10^{12}	10^{13}	$<10^{12}$	10^{15}	10^{16}	10^{15}-10^{17}
TID	0.2Mrad	<3Mrad	<1Mrad	80 Mrad	1 Grad	40 Grad
Hit rate [MHz/cm^2]	0.4	10	<0.3	100-200	2000	200-20000

Pixel size (granularity) & Radiation hardness ⇒ HL-LHC, FCC-hh and other high-rate experiments
Pixel-size (resolution) ⇒ Future e+ e- and other precision experiments
Timing resolution ⇒ Tracking and Calorimetry in high-density environments
Collection thickness ⇒ HG Calorimetry (MIP counting)
Large area (cost) ⇒ Tracking and HG Calorimetry at collider experiments
Low power and material budget ⇒ All

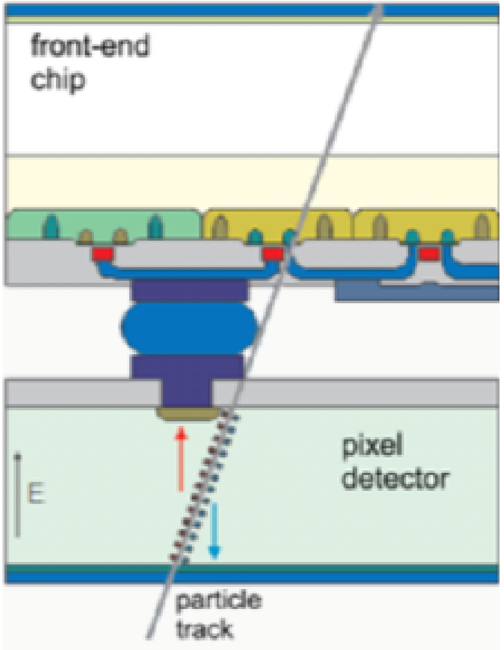
Silicon sensors

Monolithic Active Pixel Sensors (MAPS)

- Advances in commercial CMOS technologies combined with dedicated designs allowed significant progress (e.g. from STAR to ALICE to ATLAS) in areas like radiation hardness, response time, hit rates
- **Strong interest for R&D to fully exploit the potential of MAPS in future Trackers and Calorimeters:**
  - **High granularity, low material budget and power, large area at reduced cost (wrt hybrid)**
  - **CMOS foundries offer substantial processing power to enable significant performance gain**

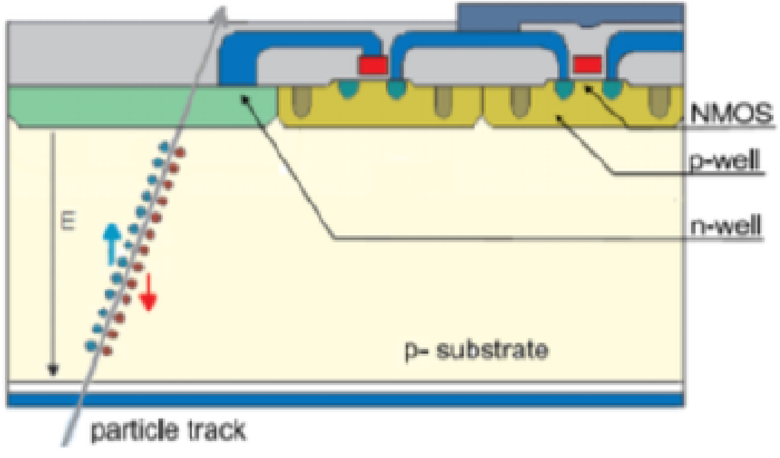
Silicon pixel detectors: Hybrid vs. CMOS MAPS

Hybrid Pixel Sensor



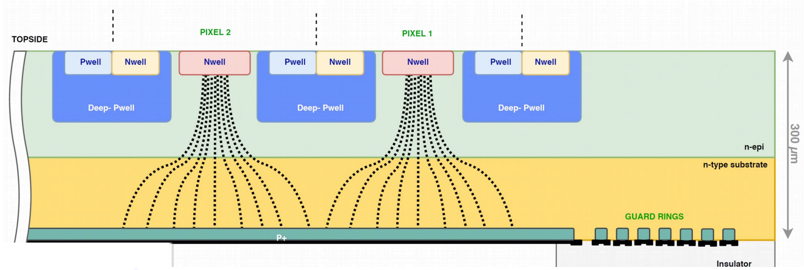
- Today's standard, also for HL-LHC
- Sensor and FE can be optimized separately

Depleted Monolithic Active Pixel Sensor

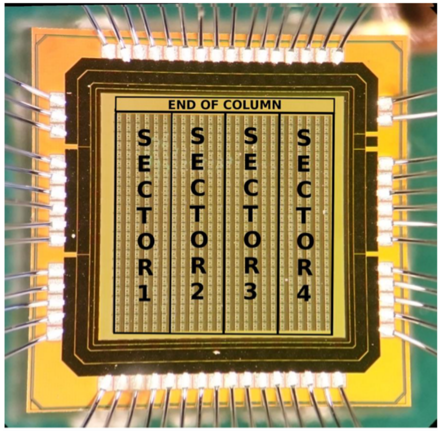


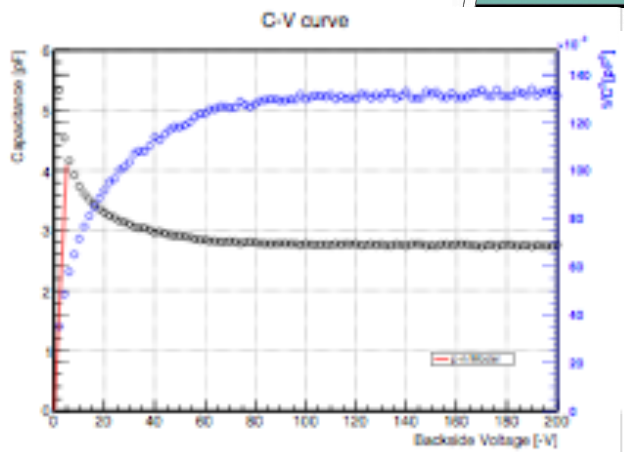
- Full depletion is key for fast response and radiation hardness
- Thin detector with high granularity

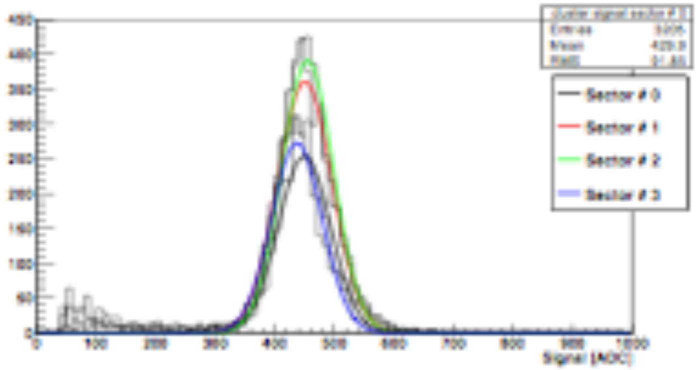
Depleted MAPS: R&D in INFN



Development of fully depleted monolithic CMOS sensors in 110 nm with LFoundry process (SEED)







Combines for the first time in a single device:

- Fully depleted substrate with full wafer depletion of 300 um, small collection capacitance (< 40fF)
- Full CMOS electronics in the pixel

- Obtained through:

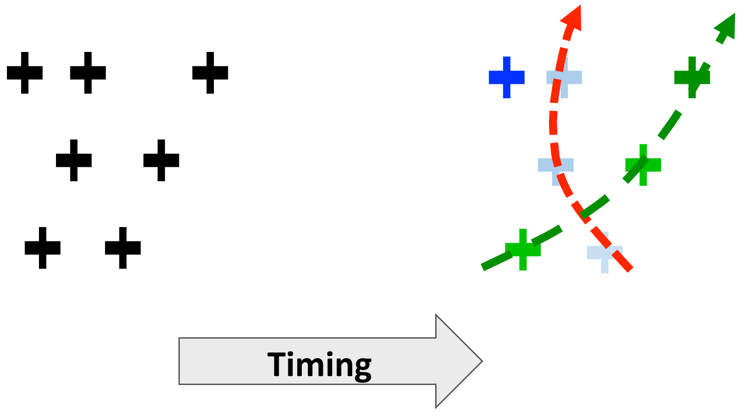
- Double-sided processing with simple and cheap back-side patterning
- Close and very positive collaboration with the foundry

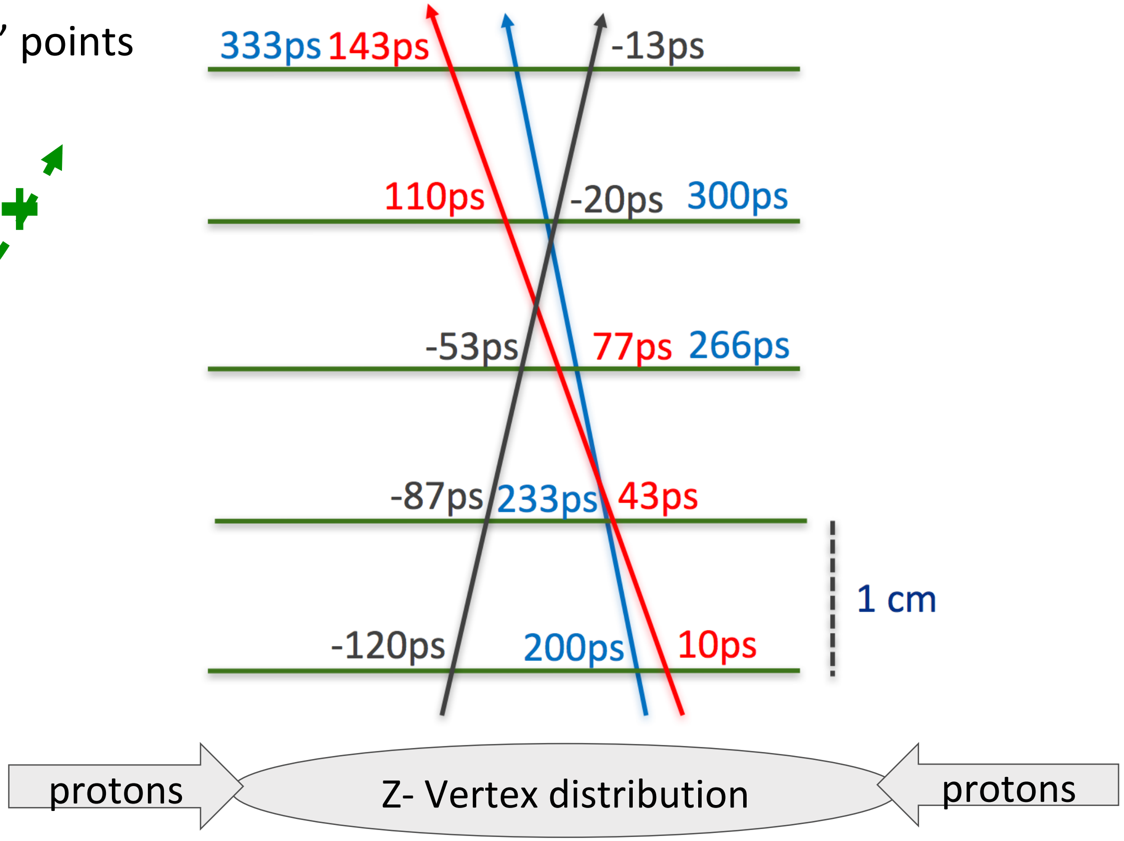
- Technology patent pending

Next step: large sensors with high-speed readout

4D Tracking

- Timing at each point along the track:
  - Massive simplification of pattern recognition, new tracking algorithms will be faster even in very dense environments
    - ⇒ e.g. the RETINA project: implementing a fast, "neural-like" tracking algorithm in fast digital electronics
  - Use only "time-compatible" points

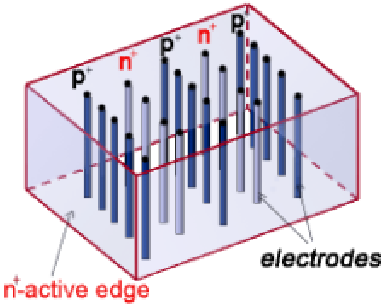




3D sensors with timing (call TIMESPOT)

Sensors: 3D silicon (WP1)

Highly rad-hard, possible excellent timing performance (electrode proximity)



S. Parker et. al. NIMA 395 (1997) 328

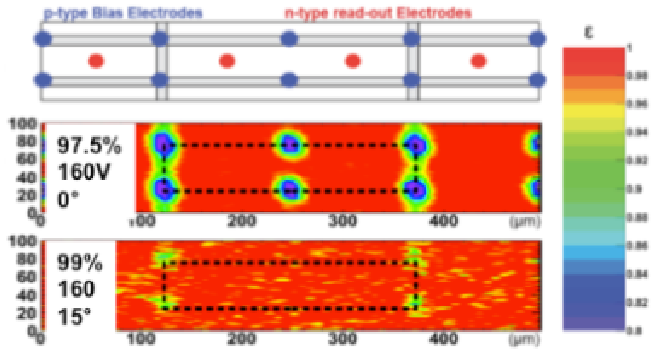
Electrode distance (l) and active substrate thickness (d) are decoupled

→ $l << d$ by layout

High radiation hardness at relatively low voltage (low power dissipation)

State of the art: ATLAS IBL 3D pixels

- **Double-sided 3D, produced by CNM and FBK**
- Excellent performance up to 5×10^{15} n_{eq} cm^{-2}: **99% hit reconstruction efficiency at 15° tilt and -15°C temp.** (~10 mW/cm² power dissipation)
- **Also pushed to ~1×10^{16} n_{eq} cm^{-2} in AFP tests and being further increased for HL-LHC (Phase2): reduced pitch and thickness**



ATLAS IBL, JINST 7 (2012) P11010

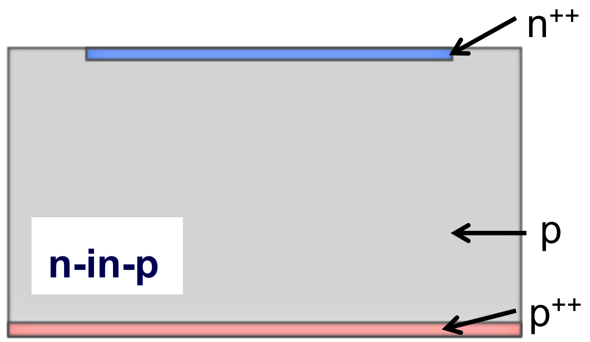
... But NEVER duly optimized for timing !!

28 nm CMOS technology for the read-out!

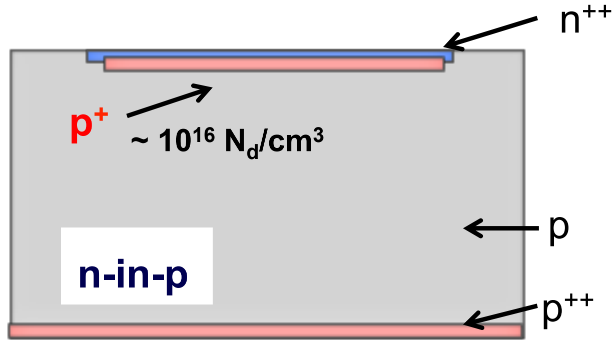
LGAD (UFSD)

Must have:

- Large dV/dt to minimize jitter
- Segmentation
- Radiation hard



Traditional silicon detector



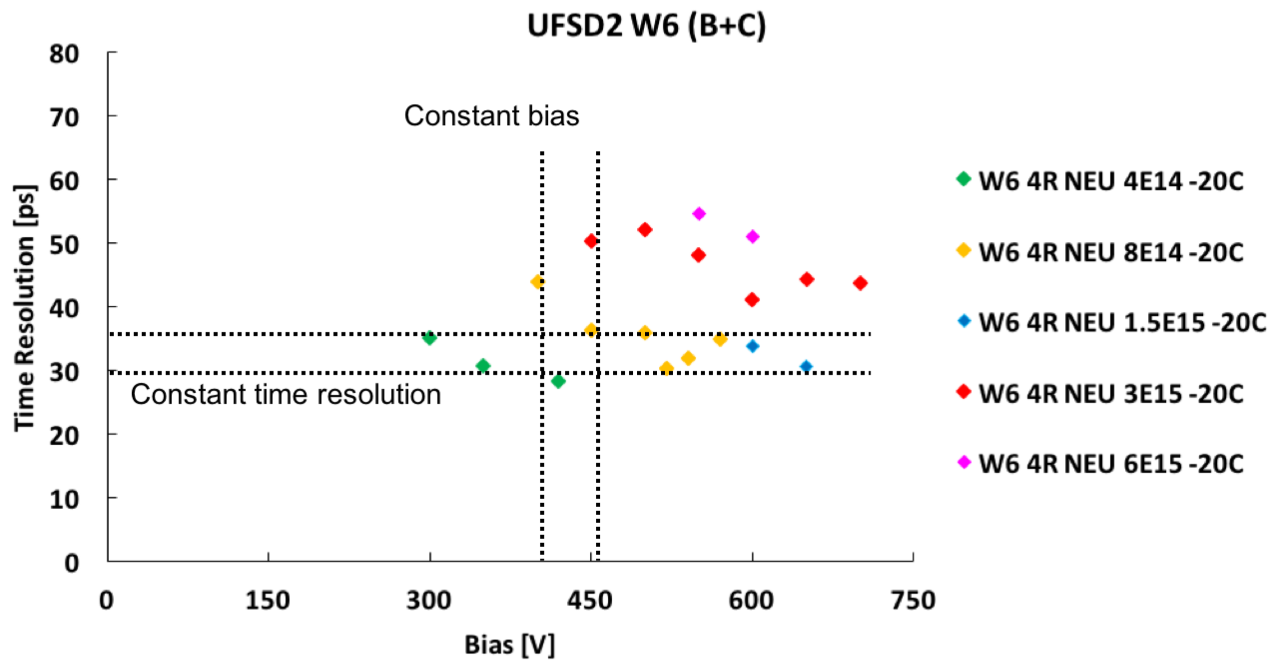
Low gain avalanche detectors

The **LGAD** idea:

- Add a thin layer of doping to produce low controlled multiplication.
- This idea retains almost all the benefit of standard silicon sensors: segmentation, low noise, rad-hard up to a few 10^{15} n/cm^2
- **UFSD:** LGAD sensors, optimized for timing.
- LGADs already foreseen for Hi-LUMI (CMS and ATLAS forward timing layers)

Radiation hardness

FBK production of UFSD sensors: time resolution for different fluence



Achieved:

- Unchanged time resolution of ~ 35 ps, up to ~ $2{\cdot}10^{15}$ n/cm^2
- time resolution of 60 ps up to $6{\cdot}10^{15}$ n/cm^2

R&D in the next 5 years:

- Unchanged time resolution of ~ 35 ps, up to ~ $5{\cdot}10^{15}$ n/cm^2

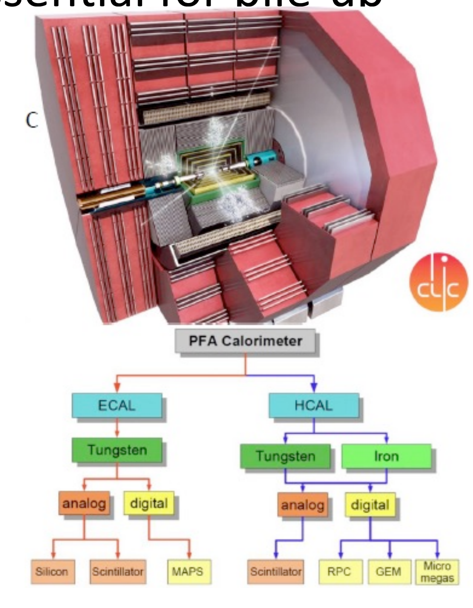
Calorimetry

Calorimetry

- What are the challenges required for future accelerator experiments (LHC beyond HL-LHC, FCC-ee, FCC-hh, CLIC, ILC, CepC,…)?
  - Pile-up, radiation hardness, high resolution, PID, boosted objects, particle flow, timing
  - Active materials: Scintillator/crystals, Si, noble liquids, gas, … $\Rightarrow$ Radiation hardness, low-temperature operation, …
  - Photosensors
- Which R&D to ensure that future accelerator experiments could/will be built in O(20) years?
  - R&D on promising technologies
  - Including special focus on timing capabilities

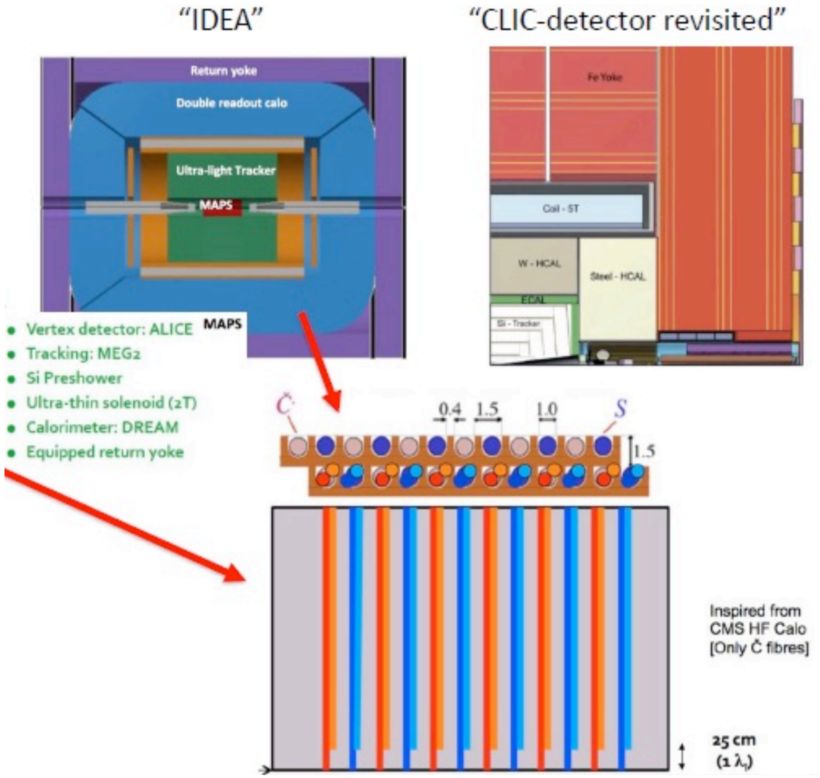
CLIC/ILC

- CLIC/ILC calorimeters optimized for particle flow
  - Radiation tolerance and bandwidth requirements benign wrt to LHC, but:
  - Higher precision requirements (2x for jet energies, 10x for track momenta)
  - Requires fine 3D segmentation (and sophisticated reconstruction software)
  - Granularity and timing (sub-ns resolution) essential for pile-up rejection
- Technologies considered:
  - Large area silicon arrays (DMAPS)
  - New segmented gas amplification structures (RPC, GEM, MicroMegas)
  - SiPM on scintillator tiles or strips



FCC-ee (CepC)

- Calorimetry requirements:
  - Excellent jet energy resolution (~ 30%/√E)
  - PID
  - Radiation tolerance and bandwidth requirements benign wrt to LHC
- Calorimetry also based on particle flow
  - Same technologies as for ILC/CLIC under study
  - On top of that, fiber-sampling dual-readout calorimetry can be a very interesting option for future lepton colliders
    - Fine transverse granularity
    - Excellent hadronic resolution



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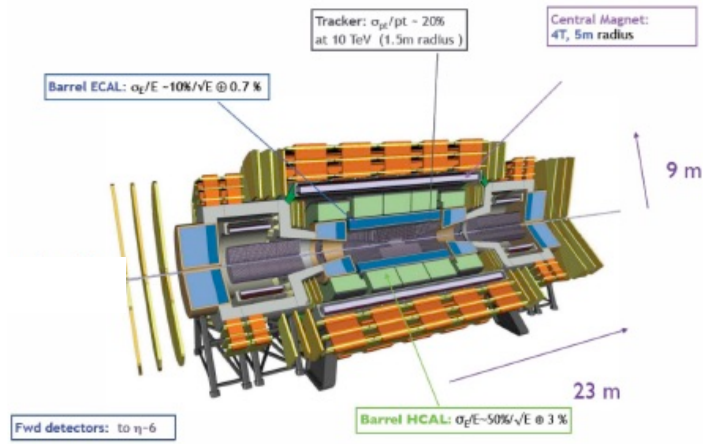
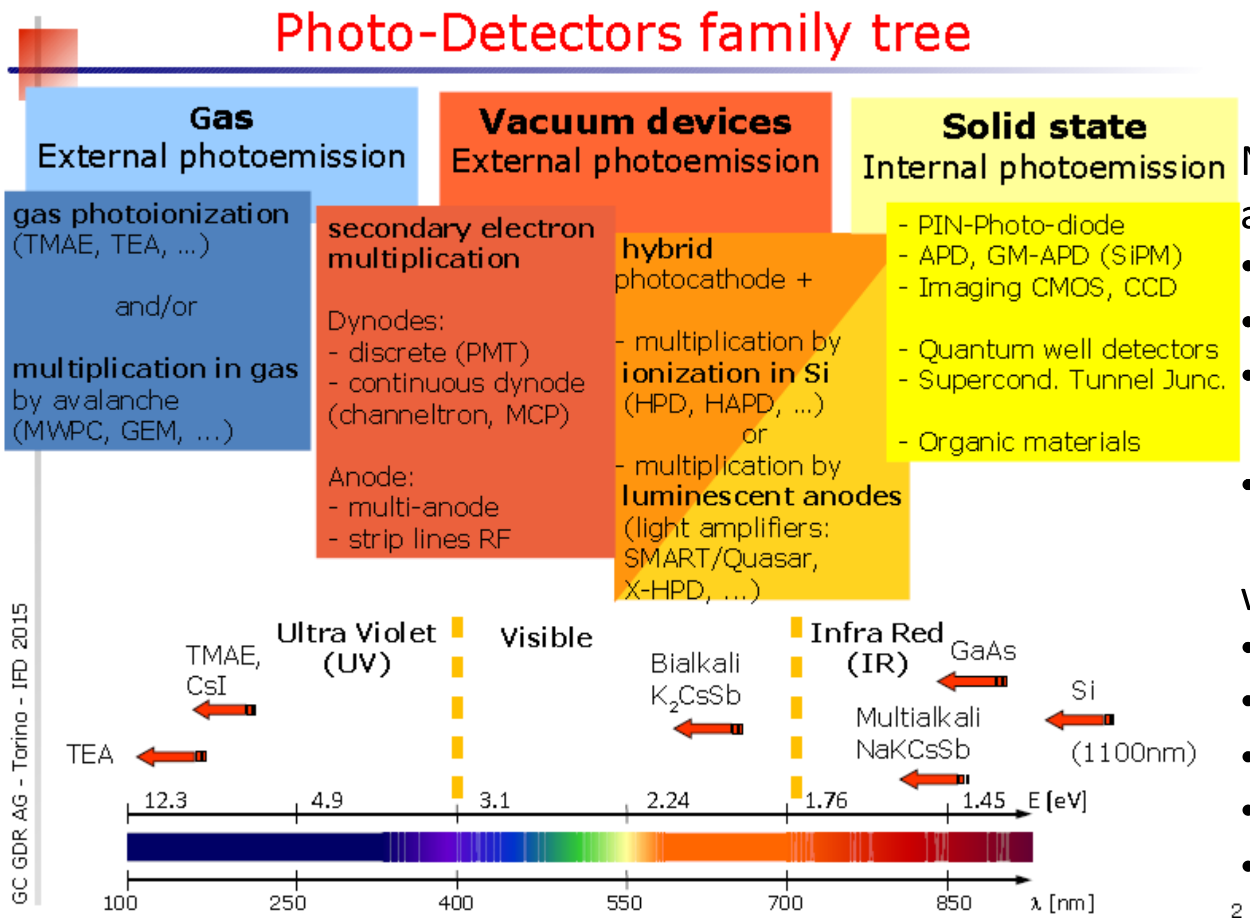
FCC-hh



- Calorimetry requirements:
  - High luminosity ⇒ high pile-up (up to 10^3 per BC)
  - High radiation ⇒ 10-30 times more than HL-LHC (!)
  - High granularity
  - High resolution
    - EM constant term < 1% e.g. for Higgs self-couplings ($H \rightarrow bb\gamma\gamma$)
    - Hadronic constant term < 2-3%
  - Timing resolution
  - Combined measurements with Tracker
- Possible technologies:
  - HG ECAL based on noble liquids (e.g. LAr/Pb) or Si/W in barrel region (radiation probably too high in endcaps)
  - HCAL: Scintillator/steel in the barrel, noble liquid based (e.g. LAr/Cu) in the endcaps and forward calorimeter

Photosensors

Photosensors



New developments in photosensors are essential everywhere:

- HEP experiments
- Large Neutrino Detectors
- Large Telescope Arrays (Gamma telescopes/Cosmic rays)
- DM experiments

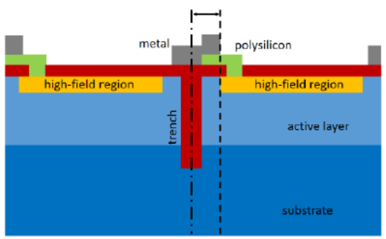
with a number of specific issues:

- High pressure environments
- Operation in magnetic fields
- Low temperature
- Radio purity
- …

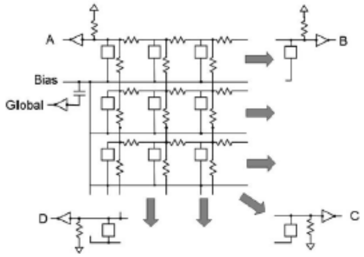
SiPM present

- Outstanding progress in the last years in many key aspects:
  - Increase Fill Factor (also for small area cells) $\Rightarrow$ PDE
  - Primary dark noise reduction
  - Optical X-talk (primary and delayed) reduction
  - Linearity and dynamic range
  - Radiation hardness verified up to $\sim 2 \cdot 10^{14}$ n_{eq} cm^{-2}
- SiPM used and/or to be used in a number of PP experiments. Some examples
  - T2K, first large scale application ($\sim 6 \cdot 10^4$ devices)
  - CMS HCAL upgrade ($\sim 2 \cdot 10^4$ large area SiPM)
  - CMS barrel timing layer (LYSO:Ce crystals + SiPM)
  - LHCb SciFi Tracker
  - DARKSIDE-20k @ LNGS (15 m^2 of optimized SiPM)

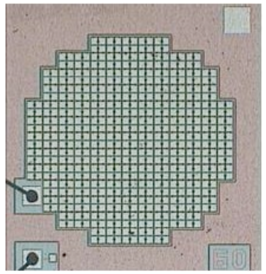
SiPM future



- UHD SiPM: FBK cell size ~ 10 µm with ~ 60-70% FF

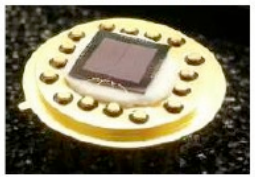


- Position-sensitive SiPM

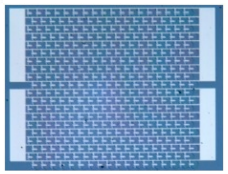


- SiPM with Bandpass Dichroic Filters

Packaged SiC SSPM



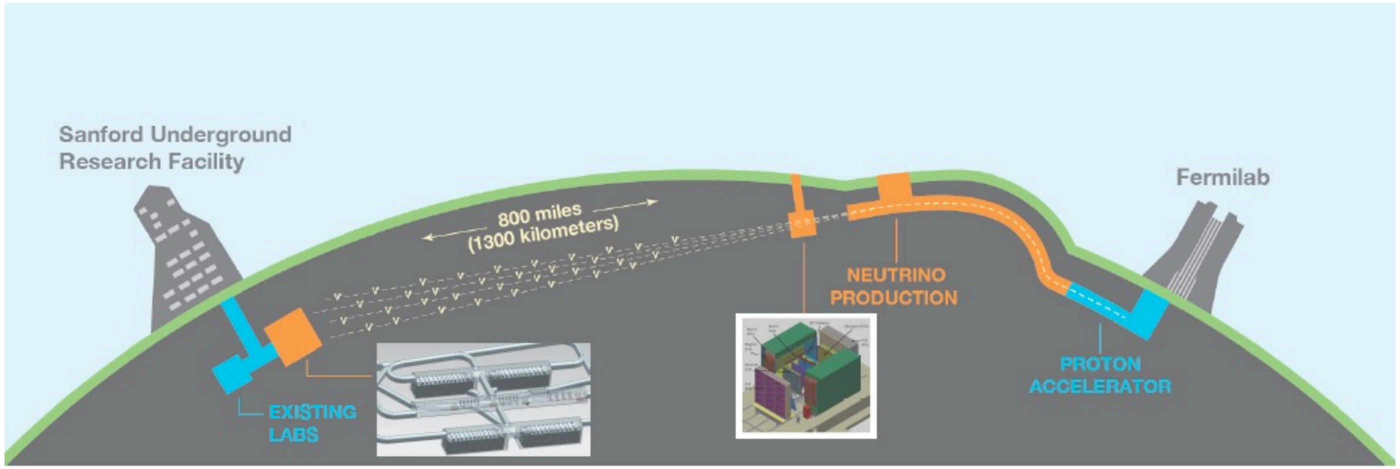
- New materials: SiC SiPM



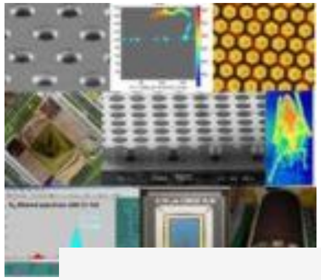
- New materials: GaAS SiPM
- TSV technology (no bonding wire)

SiPM future: affordable costs

- Let us consider as an example DUNE
  - $\geq$ 100 m^2 of SiPM (considering LArTPC and ECAL read-out)
  - $\Rightarrow$ Mandatory to ensure mass production capability at affordable costs!



Gas detectors

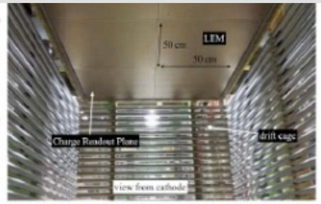


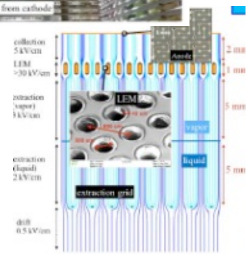
MPGD

MicroPattern Gaseous Detectors:

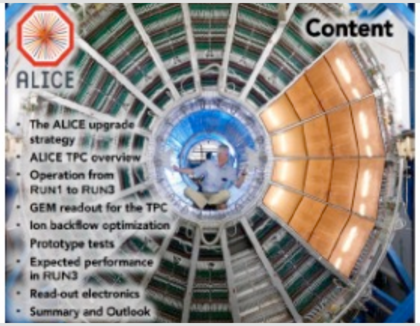
- Introduced at the end of the 20th century
  (MSGC: 1988, MICROMEGAS: 1996, GEM: 1997)
- Pioneered at COMPASS (~2000)
- 2018: **at the base of major upgrades and projects in fundamental research**

LBNO-DEMO at CERN: LAr TPC sensors (ThickGEMs)

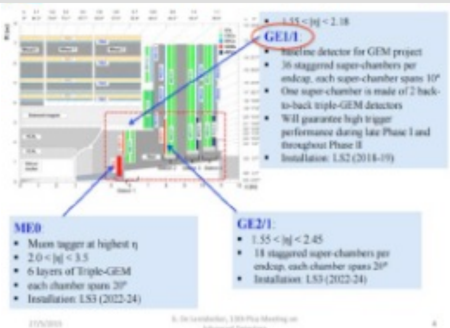




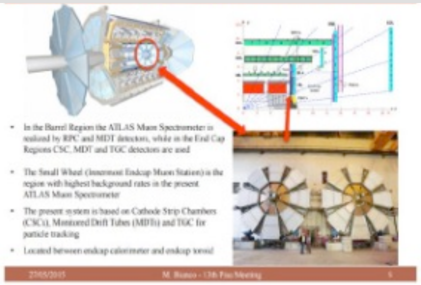
ALICE: TPC sensor upgrade (GEMs)

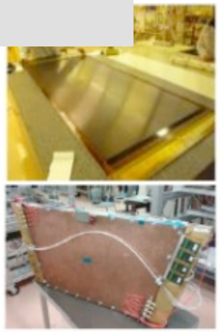


CMS: upgrade muon detectors(GEMs)

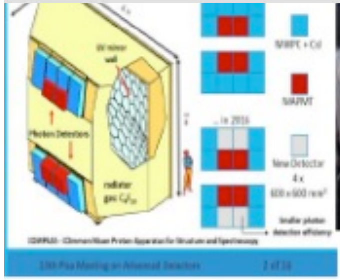


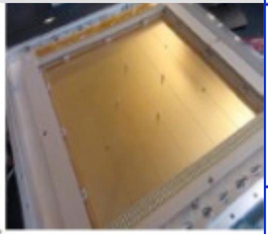
ATLAS: NEW SMALL WHEELS (MICROMEGAS)

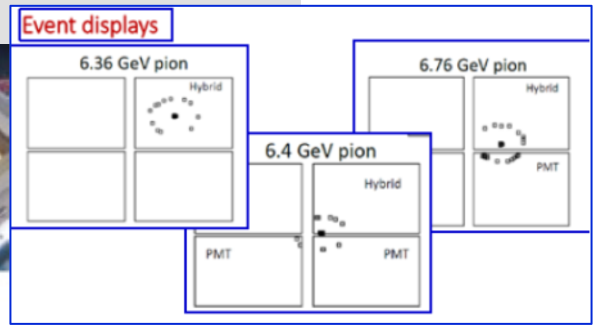




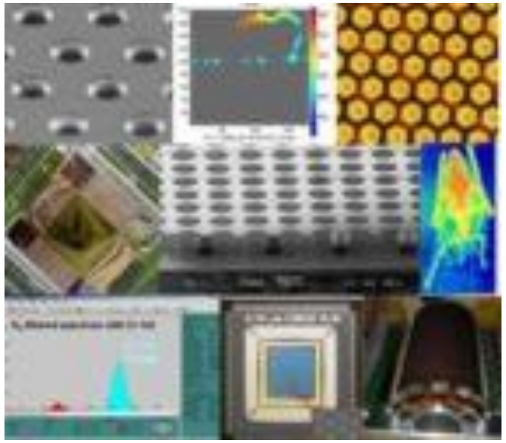
COMPASS RICH: NEW PHOTON DETECTORS (ThickGEMS, MICROMEGAS)







MPGD: new technologies and developments



- MicroMegas:
  - Resistive MicroMegas for sampling calorimeters
  - Fast timing
- GEM:
  - New materials (Glass GEM)
- μ-RWELL:
  - New large-area, thin detectors, candidates for the Muon Chambers of LHCb Upgrade II

MPGD activity (present and future)

- At national level:
  - CSN5: MPGD_NEXT and MPGD_FATIMA (grant giovani)
  - CSN1: RD_FA
- At international level:
  - RD51 collaboration
    - Large international collaboration (90 Institutions from 25 countries, ~ 500 collaborators)
    - Important role of the Italian community (S. Dalla Torre co-spokeperson)
    - RD51 extension until 2023 recently approved
    - General comment: CERN RD50, RD51, RD53,... collaborations provide a long term platform (beyond the lifetime of single detector projects) and have been important drivers of progress in their respective fields. These should continue to be supported.

Electronics: a “transversal” R&D

ASIC technologies

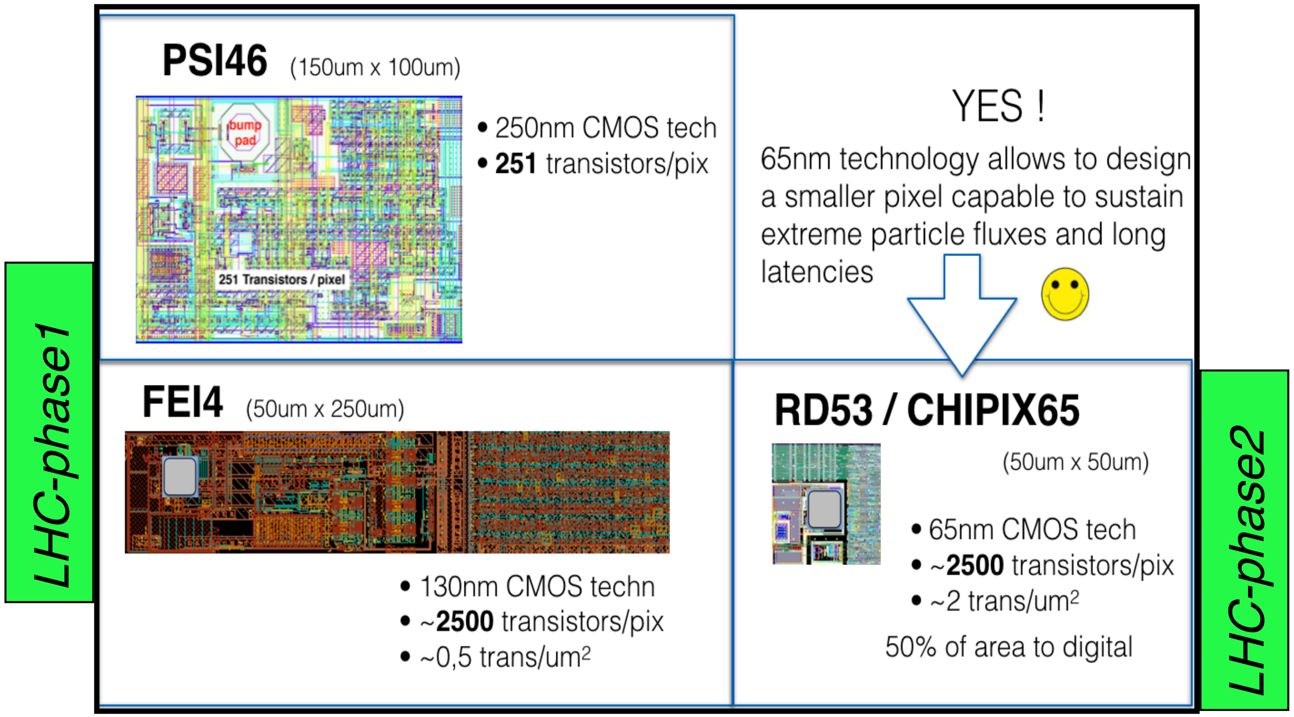
- Examples: ATLAS $8 \cdot 10^5$ chips (majority ASICs), CMS 1 M chips ($7 \cdot 10^5$ ASICs)

The key is the reduction of transistors size, therefore capacitance.

A factor 2 towards a smaller technology determines almost a 4 times smaller (and faster) circuits with ~ same power consumption/ unit area. (NB: radiation hardness complicates this simple rule!)

Benefits are visible : CMOS 0,25um technology allowed LHC detectors to be made; lot of upgrades for Phase-1 are based on 130nm; CMOS 65nm allows us to bridge the frontier of HL-LHC.

Pixel Cell Unit@LHC



ASIC technologies

- Industry development is extremely fast and complexity associated to the introduction of a new technology grows exponentially at each change of technology node.
  - ⇒ Fundamental to have a well coordinate effort and growing collaborations among experts/research institutes/laboratories.
- At national level CHIPIX65 managed to achieve a massive synergy within INFN;
  - ⇒INFN has reached a VERY relevant position within the RD53 community (ex.: almost all circuit blocks of the RD53A chip are IP, INFN holds ~ 50% of them!!!)
- At international level, a large collaborative effort such as RD53 and the involvement of CERN/EP-ESE were the right approach.

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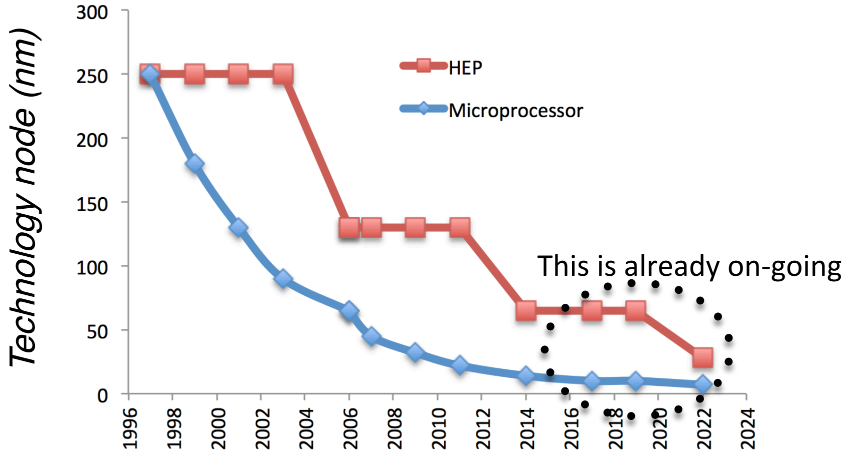
Key functions in on-going (and future) upgrades

- Enhanced radiation hardness
- New architectures – with highly complex digital functions – to deal with higher pile-up
- Fast timing layers/4D tracking also for pile-up mitigation
- Serial powering or DC/DC converters

Looking ahead – scaling!

- With the 65 nm process we cannot increase I/O speed beyond 10 Gbps
  - 65 nm ok for HL-LHC, might be ok for HE-LHC, definitely not ok for FCC-hh (if any…)
  - Industry has scaled down 6 times more…
- We cannot stand still, but going forward requires significant resources.



- Next promising technology is 28 nm. CMOS 28 nm is already being explored in back-end electronics (like FTK-Atlas-Phase2 project). INFN started since few years R&D projects exploring the 28nm node for front-end electronics (Scaltech28, then the Call TimeSpot) and CERN interest is growing. Preliminary results show that radiation hardness of 28 nm seems even higher than for 65nm. Also cost and access to the technology is improving.
- Below 28 nm, FINFET becomes the workhorse ⇒ FINFET16-V2.

Superconductors & Quantum Sensors

New technologies for single-photon detection

- Low-mass frontier of Dark Matter, measurement of the neutrino mass, CEνNS, search for new light bosons in laboratory experiments $\Rightarrow$ detectors sensitive to excitations of meV or smaller.
- Primordial B-mode polarization anisotropies.
- Superconducting devices:
  - TES (Transition Edge Sensors)
  - Josephson Junctions
  - KIDs (Kinetic Inductance Detectors)
    - Significant INFN expertise in these areas

QT sensors for Particle Physics

- December 2017 $\Rightarrow$ 1st Workshop on “Quantum Sensing for HEP” at Argonne National Lab, organized by the Coordinating Panel for Advanced Detectors (CPAD) of the APS Division of Particles and Fields
- Q: “What areas of PP will be the early adopters and beneficiaries of the quantum paradigm”?
- A: “experiments in the light dark matter world (e.g. axions, hidden photons) where the signal would result from the coupling of two harmonic oscillators, i.e. the dark matter field and the electromagnetic field through the medium of a microwave resonator and/or a magnetic field”.

For discussion - I

- Areas of European collaboration: access to industry
  - Detector development requires access to a range of commercial/industrial technologies:
    - Software for design and simulations, and associated training
    - Access to foundries
    - Custom wafer processing: implantation, metallisation, dicing and thinning
    - Uniform photolithographic process for large area MPGD
    - O(μm) planarity for the read-out PCBs in MicroMegas
    - Interconnection techniques

For discussion - II

- Areas of European collaboration in which INFN can play a significant role:
  - <u>Assembly and lab testing</u>: Wire bonding, Wafer probing, lab facilities, readout electronics and firmware. Although not every institute can provide all, these can usually be accessed by inter-institute collaborations.
  - <u>Irradiation facilities</u>. In general we benefit from existing facilities. Access often through associated PP groups that are themselves active in detector R&D.
  - <u>Beam test campaigns</u>. Access to beam –typically at the major labs; Access to beam telescopes -typically available for test beam campaigns.

For discussion - III

- Possible further recommendations for the Strategy Update:
  - A strong message that the physics reach of PP experiments is and remain closely linked with progress in detector R&D.
  - Affordable access to design software, provided by EuroPractice, is critical and should be maintained.
  - Detector R&D is expensive. The provision of common infrastructure and tools could enhance lower the threshold for and speed up R&D.
  - Similarly, the development of common libraries (similar to open source software) for design blocks in different technologies could provide a substantial boost to development work.
  - Access to beam test facilities as well as irradiation facilities is critical to detector developments and should be maintained.
  - Keep open mind on scope for more RDXX collaborations in R&D areas that require particularly high resource (e.g. CMOS sensors, TSV, wafer-to-wafer bonding,...).
  - Looking VERY ahead: can we exploit (for what is possible) the QT Flagship for R&D in quantum sensors?

Final remarks

- The INFN detector community is at the forefront of many (~all!) of the developments discussed.
- This ensures high-quality standards for the INFN participation in future enterprises.
- The constant commitment in cutting-edge technology for particle detectors has been so far one of the key ingredients which made INFN a driving force in the high-energy physics community, and this will be even more relevant in the future, also due to the increasing importance of technology-transfer processes from research to society.

Grazie per l’attenzione!