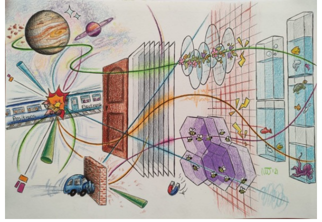


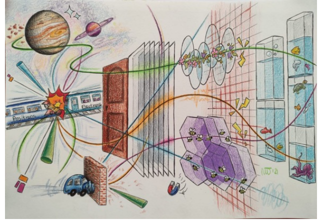
DRD3

ECFA detector roadmap on Solid-State detectors and Implementation

DRD3 Status and plans

G. Calderini

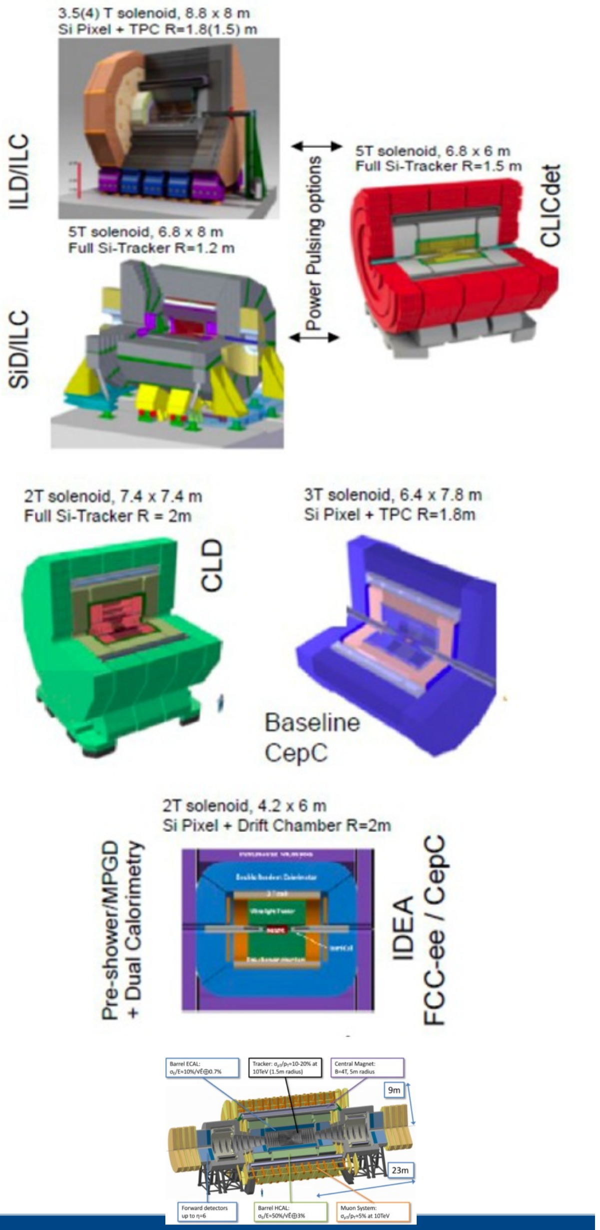
LPNHE/IN2P3



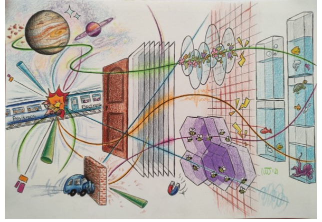
Physics and Detectors

DRD3

- **The success of particle physics experiments relies on innovative instrumentation and state-of-the-art infrastructures.**
- To prepare and realise future experimental research programmes, the community must maintain a **strong focus on instrumentation**.
- Detector R&D programmes and associated infrastructures should be **supported** at CERN, national institutes, laboratories and universities.
- **Synergies** between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development process and increase opportunities for more technology transfer **benefiting society** at large.



FCC-hh CDR

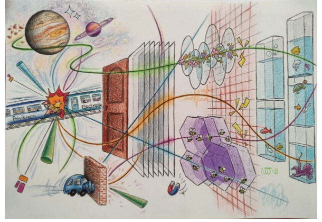


The 2021 ECFA Detector R&D Roadmap (How?) DRD3

Organized by **ECFA** (The European Committee for Future Accelerators), the **roadmap** is developed by the community to balance the **detector R&D effort in Europe**, taking into account progress with **emerging technologies** in adjacent field.
The roadmap should **identify and describe a diversified detector R&D portfolio** that has the largest potential to **enhance** the performance of the particle physics programme in the near and long term.

- Roadmap developed in 2021, approved by Plenary ECFA on 18 Nov 2021
- Released in December 2021, after presentation to CERN Council
- Documents available: https://indico.cern.ch/event/957057/

The European Strategy of Particle Physics is reviewed and updated every five to ten years.



Detector R&D Themes

DRD3

These themes, identified in the Roadmap, are **critical** to achieve the science programme outlined in the ESPP (The European Strategy for Particle Physics) and are **derived from the technological challenges** that need to be overcome for the scientific potential of the future facilities.

Gaseous
- **DRDT 1.1** Improve time and spatial resolution for gaseous detectors with long-term stability
- **DRDT 1.2** Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes
- **DRDT 1.3** Develop environmentally friendly gaseous detectors for very large areas with high-rate capability
- **DRDT 1.4** Achieve high sensitivity in both low and high-pressure TPCs

Liquid
- **DRDT 2.1** Develop readout technology to increase spatial and energy resolution for liquid detectors
- **DRDT 2.2** Advance noise reduction in liquid detectors to lower signal energy thresholds
- **DRDT 2.3** Improve the material properties of target and detector components in liquid detectors
- **DRDT 2.4** Realise liquid detector technologies scalable for integration in large systems

Solid state
- **DRDT 3.1** Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors
- **DRDT 3.2** Develop solid state sensors with 4D-capabilities for tracking and calorimetry
- **DRDT 3.3** Extend capabilities of solid state sensors to operate at extreme fluences
- **DRDT 3.4** Develop full 3D-interconnection technologies for solid state devices in particle physics

PID and Photon
- **DRDT 4.1** Enhance the timing resolution and spectral range of photon detectors
- **DRDT 4.2** Develop photosensors for extreme environments
- **DRDT 4.3** Develop RICH and imaging detectors with low mass and high resolution timing
- **DRDT 4.4** Develop compact high performance time-of-flight detectors

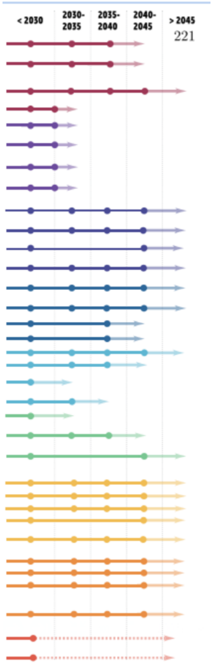
Quantum
- **DRDT 5.1** Promote the development of advanced quantum sensing technologies
- **DRDT 5.2** Investigate and adapt state-of-the-art developments in quantum technologies to particle physics
- **DRDT 5.3** Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies
- **DRDT 5.4** Develop and provide advanced enabling capabilities and infrastructure

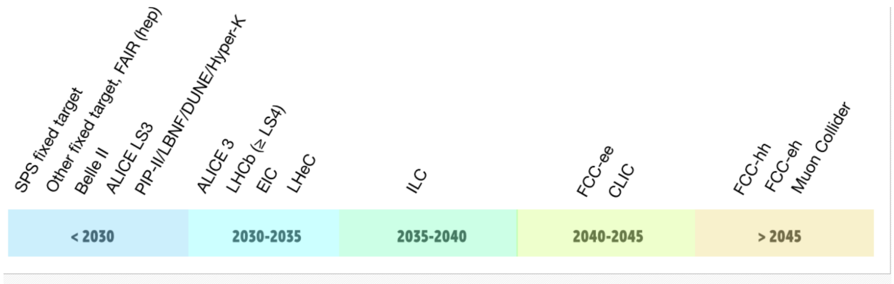
Calorimetry
- **DRDT 6.1** Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution
- **DRDT 6.2** Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods
- **DRDT 6.3** Develop calorimeters for extreme radiation, rate and pile-up environments

Electronics
- **DRDT 7.1** Advance technologies to deal with greatly increased data density
- **DRDT 7.2** Develop technologies for increased intelligence on the detector
- **DRDT 7.3** Develop technologies in support of 4D- and 5D-techniques
- **DRDT 7.4** Develop novel technologies to cope with extreme environments and required longevity
- **DRDT 7.5** Evaluate and adapt to emerging electronics and data processing technologies

Integration
- **DRDT 8.1** Develop novel magnet systems
- **DRDT 8.2** Develop improved technologies and systems for cooling
- **DRDT 8.3** Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces.
- **DRDT 8.4** Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects

Training
- **DCT 1** Establish and maintain a European coordinated programme for training in instrumentation
- **DCT 2** Develop a master's degree programme in instrumentation





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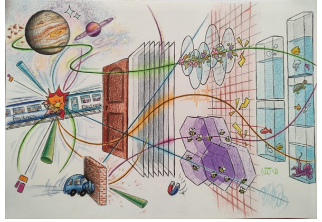

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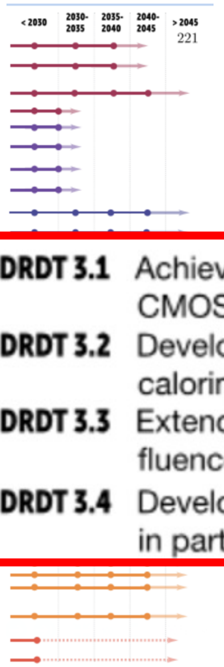

Solid state

- **DRDT 3.1** Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors
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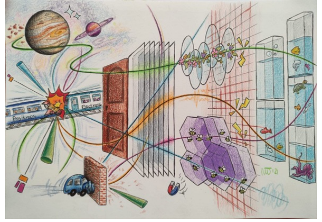


Implementation of DRDT into WGs

DRD3

Within the ECFA roadmap
4 Detector R&D Themes (DRDTs)
have been identified for the
Solid State Detectors in particle physics.

- We are covering all ECFA DRDTs
- Additional WGs were added to cover simulations, facilities and dissemination corresponding to **General Strategic Recommendations (GSRs)** in the ECFA roadmap

DRDT3.1. Achieve full integration of sensing and microelectronics in **monolithic CMOS** pixel sensors → **WG1:** Monolithic CMOS Sensors

DRDT3.2. Develop solid state sensors with **4D-capabilities for tracking and calorimetry** → **WG2: Sensors for Tracking & Calorimetry**

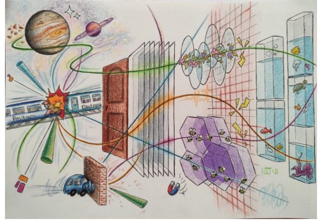
DRDT3.3. Extend capabilities of solid state sensors to operate at **extreme fluences** → **WG3: Radiation damage & extreme fluences**

WG6: Non-silicon based detectors

DRDT3.4. Develop full **3D-interconnection technologies** for solid state devices in particle physics. → **WG7: Interconnect and device fabrication**

DRD3

- **WG4:** Simulation
- **WG5:** Characterization techniques, facilities
- **WG8:** Dissemination and outreach



DRD3 proposal

DRD3

WG animation

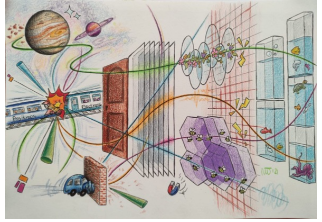
- WG1: Monolithic CMOS Sensors
  D. Bortoletto, D. Contardo, E. Vilella, H. Pernegger
- WG2: Sensors for Tracking & Calorimetry
  N. Cartiglia, C. Gemme, A. Macchiolo
- WG3: Radiation damage & ultrahigh fluences
  - M. Mikuz, M. Moll, I. Pintilie, S. Seidel
- WG4: Simulation
  - M. Bomben, G. Kramberger, A. Morozzi, F. Moscatelli, J. Schwandt, S. Spannagel
- WG5: Characterization techniques, facilities
  - D. Dannheim, M. Fernandez Garcia, M. Jakšić, I. Vila
- WG6 Non-silicon based detectors
  - T. Bergauer, T. Koffas, A. Oh, G. Pelligrini, X. Shi
- WG7: Interconnect and device fabrication
  - G. Calderini, D. Dannheim, T. Fritzsch, F. Hügging
- WG8: Dissemination and outreach
  - N. Cartiglia et al.

DRD3 proposal core team

- To coordinate a community-driven effort to produce a DRD3 proposal and the formation of a DRD3 Collaboration.
- Surveys
- Community-wide workshop
  https://indico.cern.ch/event/1214410/
- Proposal document
- Constitutional workshop

Regular meetings since October 2022

Giovanni Calderini, Nicolo Cartiglia, Gianluigi Casse, Gregor Kramberger, Michael Moll, Giulio Pellegrini, Ioana Pintilie, Ivan Vila Alvarez, Eva Vilella



Timeline

DRD3

22-23 March 2023
DRD3 community meeting: To gather inputs from the community + to propose a way forward (milestones & deliverables)

June 2023
Circulate DRD3 for feedback from the community

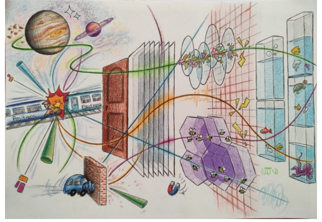
July 2023
Submit DRD3 proposal document to DRDC

We are here

December 2022
DRD3 proposal team formed to lead the preparation of the DRD3 proposal + questionnaires sent out to the community

16 March 2023
Latest day to be included in the first questionnaires evaluation (as presented in the DRD3 community workshop)
88 replies by then, **~100 replies as of today**

April-May 2023
DRD3 proposal developed based on the detector roadmap and community interest:
Final questionnaires evaluation + further meetings and discussions with experts (~20 pages)



WG1: monolithic CMOS sensors

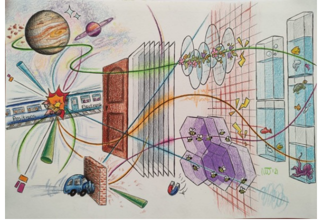
DRD3

Four Research axes (Milestones): 2028-2029 and 2030-2035

- Highest position precision at lowest power dissipation up to large wafer size
  (ALICE-3, LHCb-2, Belle-3, EIC: VertexDet/CentralTrack)
  -> pitch 10 - 30 µm @ O(100) MHz/cm2, O(1) ns
  then extended to <10um in large wafersize on horizon 2035
- Enhanced timing
  (ALICE-3, LHCb-2, Belle-3, EIC, ATLAS/CMS Timing Layers, Calorimeters)
  -> 20-50 ps timing performance
  then extended to < 20 ps @ low power dissipation
- High density and rate readout architecture
  (LHCb-2 CentralTracker, ATLAS/CMS Timing Layers)
  -> 25-50 µm @ O(5) GHz/cm2, 50 ps timing
  then increase channel density
- High radiation tolerance
  (LHCb-2 CT, ATLAS/CMS Timing Layers)
  -> beyond 1015 neq/cm2 and 300 Mrad
  then extend toward O(10^{18}) neq/cm2 TID O(>30) GRad

Present technologies under study

Technology
TPSCo 65 nm
TowerJazz 180 nm
LFoundry 150 nm
TSI 180 nm
LFoundry 110 nm
IHP 130 nm



WG2: sensors for tracking and calo

LGADs: timing for tracking and calorimetry

Demonstration of the feasibility of producing pixelated LGAD sensors to achieve a position resolution better than 10 µm, with a timing resolution of the order of 30 ps before irradiation.
A possible application is the replacement of outer pixel layers or disks in the CMS/ATLAS pixel systems in Phase-3. The requested radiation tolerance is in the order of at least 3-5x10^{15} n_{eq}/cm^2.

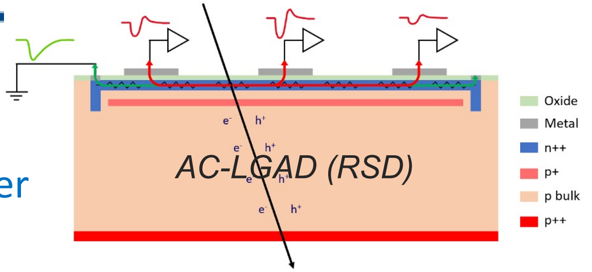
Can also be a cheap solution for large areas in future experiments (tracking and calorimetry)

Short-term deliverables are the characterization of the different technological solutions through small matrices connected with timing-performant matching chips (28nm)

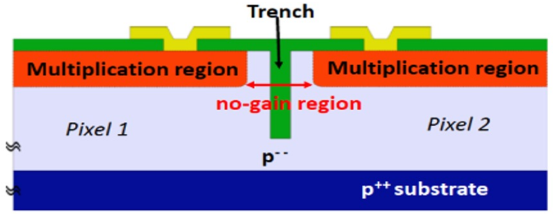
- Improvement of fill-factor
- Optimization of spatial and time resolution
- Development of radiation-hardening technologies (implantations and design)

In the longer-term, development of full-scale sensors and connection to matching electronics

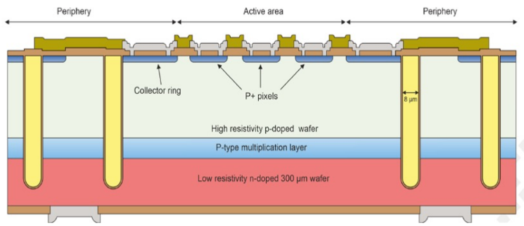
- Optimization of system parameters
  Total power dissipation (RSD for larger pixels?)



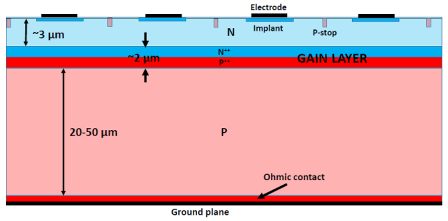
Trench Isolated LGAD



Inverse-LGAD (I-LGAD)



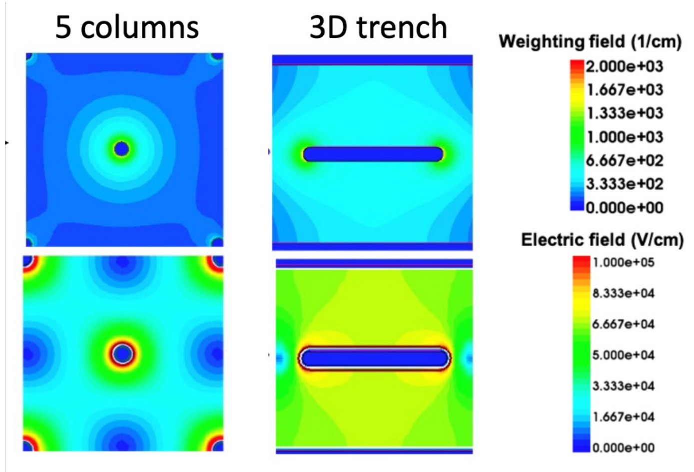
Deep junction LGAD



3D sensors for 4D tracking applications at extreme fluence

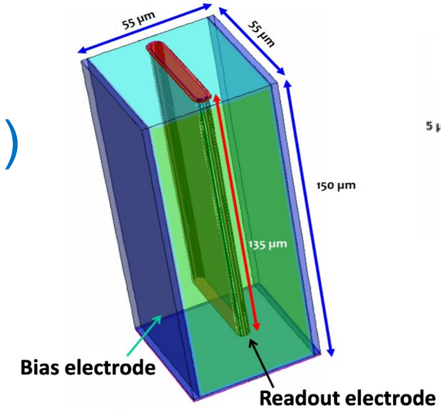
Demonstration of fine pitch cell size

Demonstration of innovative more performant processes (flat trenches)



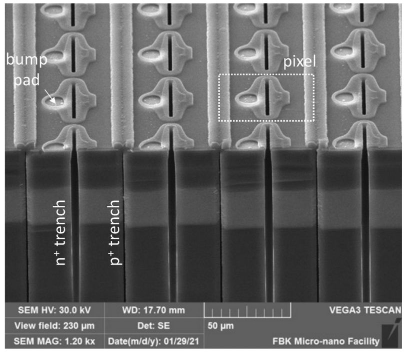
Applications in:

- ATLAS/CMS Phase-3 (Run5 ~2035) where the use of 28 nm CMOS technology for the ASICs could allow for finer pixel sizes to improve hard scattering track reconstruction and pile-up rejection
- Possible application for replacing the present VELO vertex detector at LHCb (Upgrade-II).
- All future experiment with timing capability required in extreme fluence



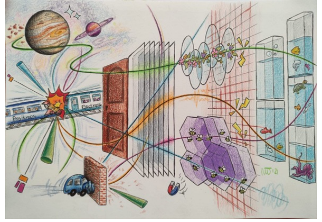
Short-term deliverables are the development of small matrices optimized for timing properties and reduced pixel size at high and extreme fluences (10^{17} n_{eq}/cm^2)

In the longer-term, development of full-scale larger sensors matched to future timing performant front-end chips (28nm)



Validation of the production yield and cost reduction

Validation of interconnection technologies



WP3: Radiation damage at ultra high fluences

DRD3

Silicon sensors - Characterization and modelling of radiation damage effects. Enhance the radiation tolerance and understand limits of operation

- Develop and characterize Si devices for enhanced radiation tolerance after extreme fluences - $1E^{16} – 10^{18}$ n/cm^2
- Development of radiation damage models for Silicon at extreme fluences, including NIEL scaling

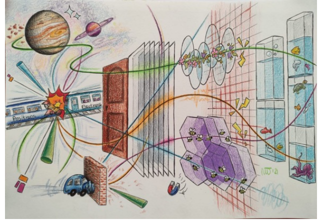
Non-Silicon sensors (SiC, diamond, Gallium composite**) -** Characterization and modelling of radiation damage effects. Understand the limit of operation

Research axes

Develop radiation damage models based on microscopically measured point and cluster defects for irradiation fluences up to 10^{16} n_{eq}/cm^2

Characterize the defects induced by irradiation with fluences 10^{16}-10^{18} n_{eq}/cm^2

Defect engineered optimized devices with increased radiation tolerance



WP4: Simulations

- Development & extension of common Monte Carlo tools
  - Continue development of flexible, universal framework for semiconductor MC simulations
  - Validation of algorithms / models

- Model building for adaptive electric fields
  - LGADs - gain screening
  - Plasma effects - high local charge densities, heavy ions, high gamma fluxes
  - Dynamic trapping/de-trapping models

- Time-weighted simulation approach - dynamic weighting field

- Development of commonly-used front-end circuit models
  - Hit digitization modeling, possibility of tuning towards specific applications
  - Interface to SPICE simulators

- Continue documentation & training effort
  - User workshops & tutorials / trainings
  - Providing reference manual with models, simulation flow description, …

WP7: Interconnection and device fabrication

DRD3

Solid state	DRDT 3.1	Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors
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Different technological levels for different scopes

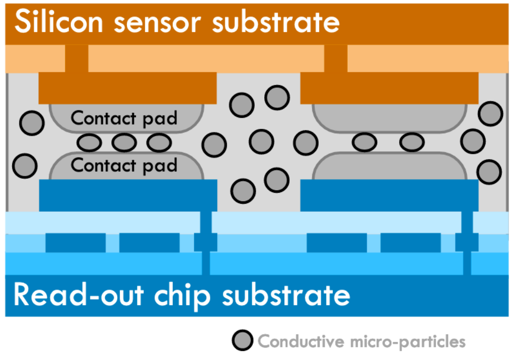
- Cheap and fast interconnection for prototyping applications
- Improvements of “standard” interconnection technologies
- Development of “advanced” technologies in collaboration with industrial vendors

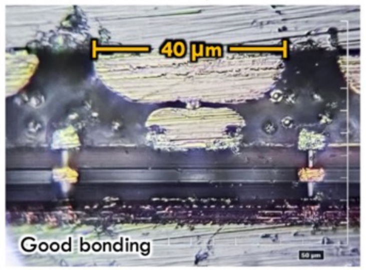
In-house fast connections (ACF/ACP)

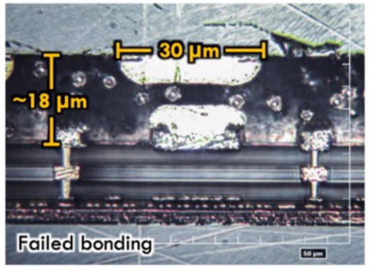
Ideal for testing and fast prototyping

Also useful for permanent interconnections

- in-house techniques, maskless, cheap
- avoid turnaround time with interconnection vendors

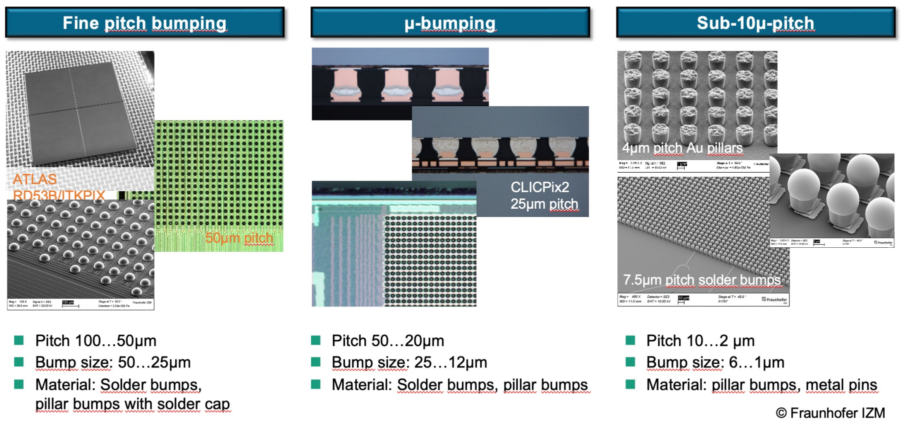






Short-term deliverables are the consolidation of connection yield and small pitch
Mid-term deliverable is the demonstration of radiation hardness

Bringing “standard” technologies to lab capability



Industrial and RTO Vendors busy and expensive

- Move part of process to laboratories (example: stud ball bumping)

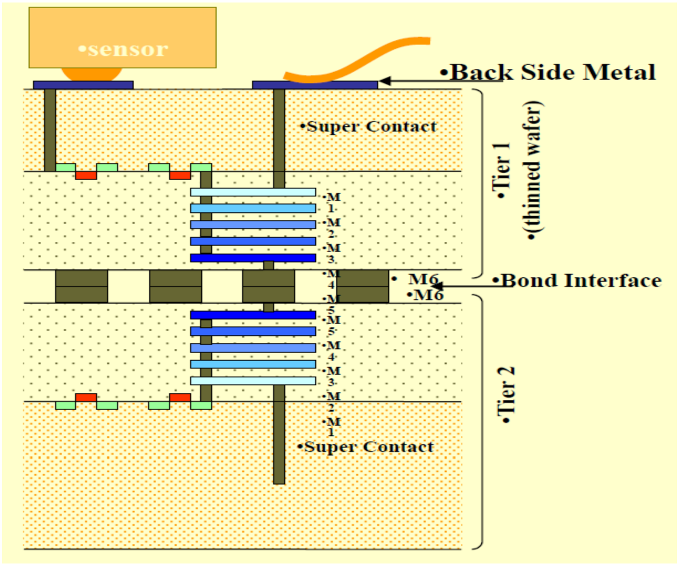
Different features from different technologies can address specific complex issues

- small pitch
- process-temperature constraint
- electrical properties (current, C)
- connection flow (wafer-wafer, device-wafer)

Short-term deliverables: develop maskless post-processing

Mid-term deliverables: - process possible in selected labs
- device-to-wafer

Introduction of advanced 3D and vertical integration in our detectors



Via industry, it will profit of commercial drive

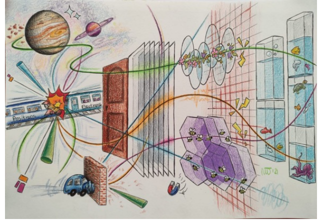
Stack to match digital/analog many reasons to do so

Could allow complex communication between different connected devices

Allow to contact/power/read a lower layer through an upper one

Short term: demonstrate the w2w process for FE-sensor connection
use TSV to access lower tiers through sensors

Mid-long term: connection made possible for post-processed devices

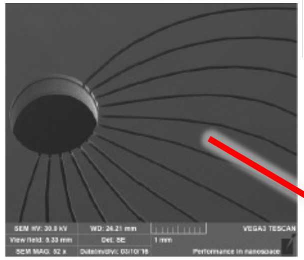


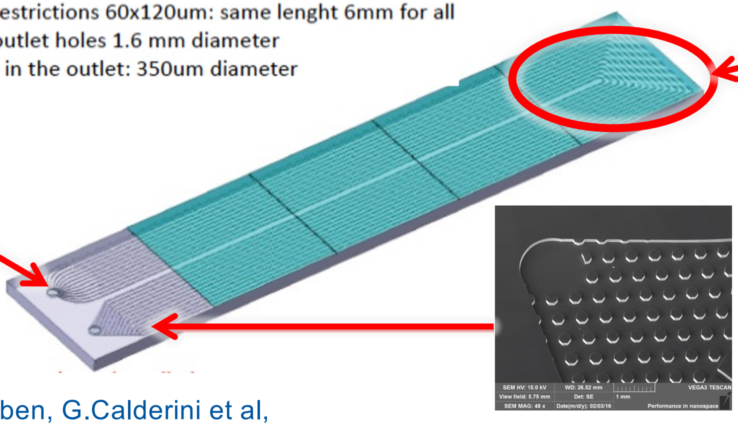
Bonus WP: Advanced Mechanics

This is a WP which is most likely going to be added to DRD3 due to scarce interest of DRD8
Some topics might enter. Interests of LPNHE: u-channels, fabrication additive etc

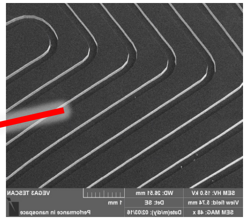
Prototypes produced by LPNHE with FBK and IEF Orsay

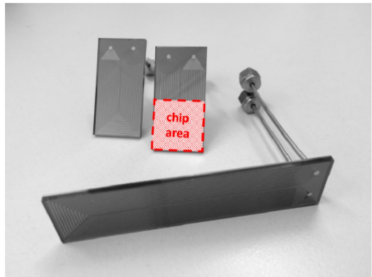
13 channels 200x120 um
Silicon walls 500um
Inlet restrictions 60x120um: same lenght 6mm for all
Inlet outlet holes 1.6 mm diameter
Pillars in the outlet: 350um diameter



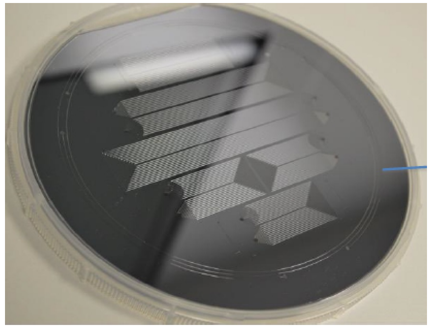


Details of the channel design

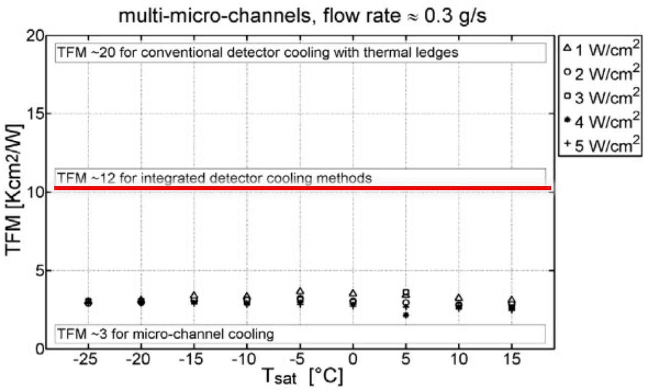




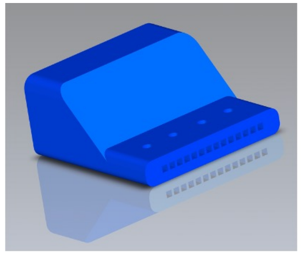
D.Hellenschmidt, M.Bomben, G.Calderini et al,
Nucl. Instrum. Meth. A 958 (2020) 162535

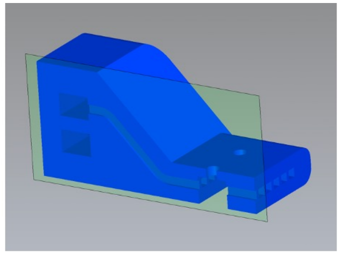


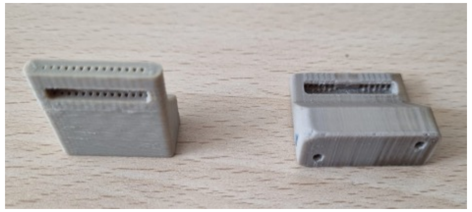
FONDAZIONE BRUNO KESSLER



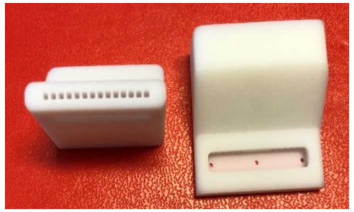
Interconnectivity for micro-tubes



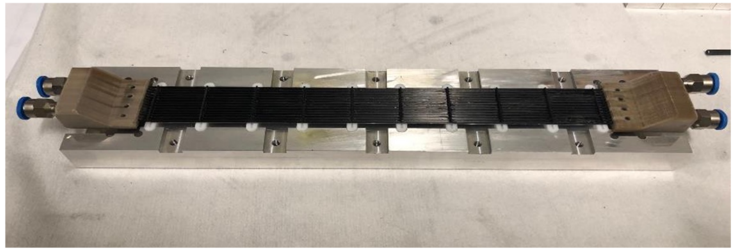




Y. Orain - LPNHE
(peek)



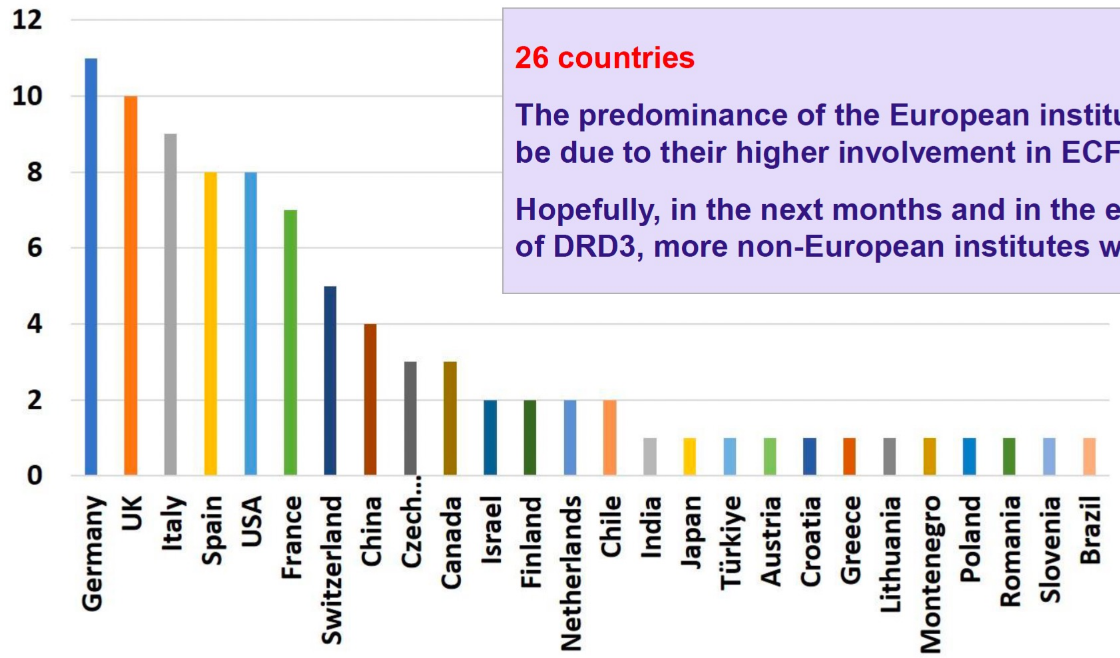
INFN Pisa
(ceramic)



Short stave demonstrator

Interests of groups/laboratories

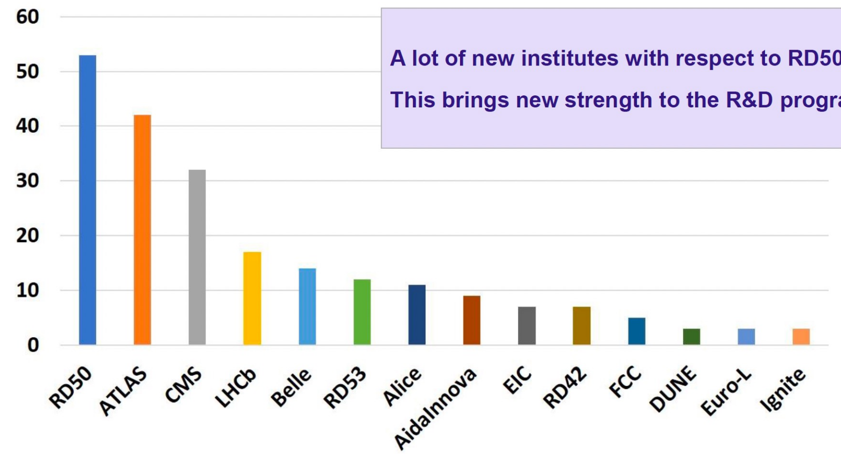
Questionnaire circulated to the community early in the year to understand interest of groups/labs



26 countries

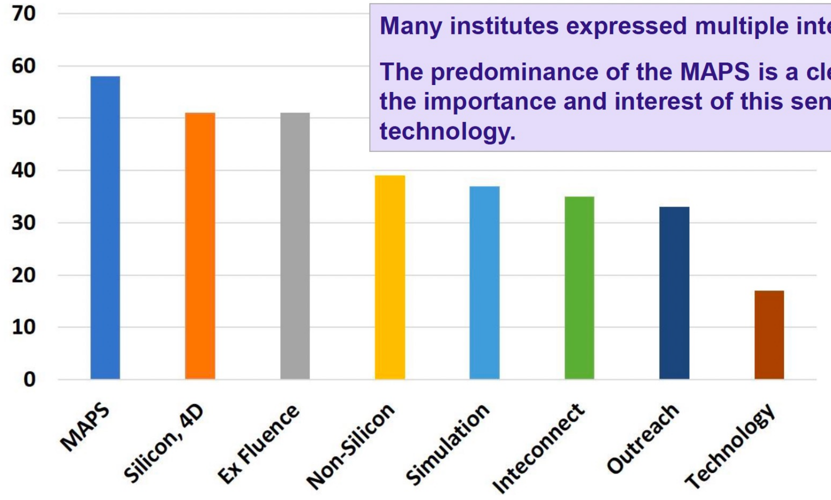
The predominance of the European institutes might be due to their higher involvement in ECFA.

Hopefully, in the next months and in the early stage of DRD3, more non-European institutes will join.



A lot of new institutes with respect to RD50.

This brings new strength to the R&D program.

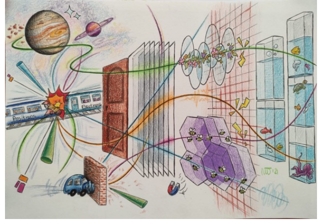


Many institutes expressed multiple interests.

The predominance of the MAPS is a clear sign of the importance and interest of this sensor technology.

New questionnaire is going to be circulated in the next few weeks with more detail and options

I think LPNHE should position on a number of subjects!



Interests of groups/laboratories

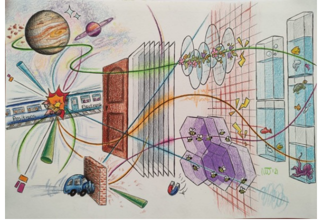
Previous survey: analysis of France

In my answer for pixels I had taken the freedom to add additional tentative and generic interest of LPNHE for a number of subjects

I think in the next questionnaire we should refine this with interested persons

Lab	Involved experiments related to DRD3/DRD7	WG 3.1 (CMOS)	WG 3.2 (4D tracking & Calorimetry)	WG 3.3 (Radiation damage & high fluences)	WG 3.6 (Non silicon - Diamond)	WG 3.4 (simulations)	WG 3.7 (interconnect & fabrication)	WG 3.5 (Characteri-zation technics)	WG 3.8 (outreach)
APC	ATLAS, FCC	TPSCo 65nm							
CPPM	RD50, RD53, AIDAInnova, ATLAS, Belle 2	TPSCo 65nm, TJ180nm							
IJCLab	ATLAS, EIC		AC-LGADs, planar				TSV		
IP2I	CMS	TPSCo 65nm							
IPHC	ALICE, CMS, Belle II, CBM-MVD, e+e- colliders (FCC, ILC, etc.)	TPSCo 65nm, TJ180nm							
LPNHE	ATLAS, RD50, RD53, AidaInnova		3D, LGADS, planar				ACF, 3D		
LPSC	RD42				Diamonds				
IRFU	RD51, ATLAS, CMS, ALICE, LHCb, T2k, Dune, CUPID, BINGO, NUCLEUS, GBAR, DESI, HESS,	LF150							

Strong interest | Expressed interest | No expressed interest



DRD3

Backup slides

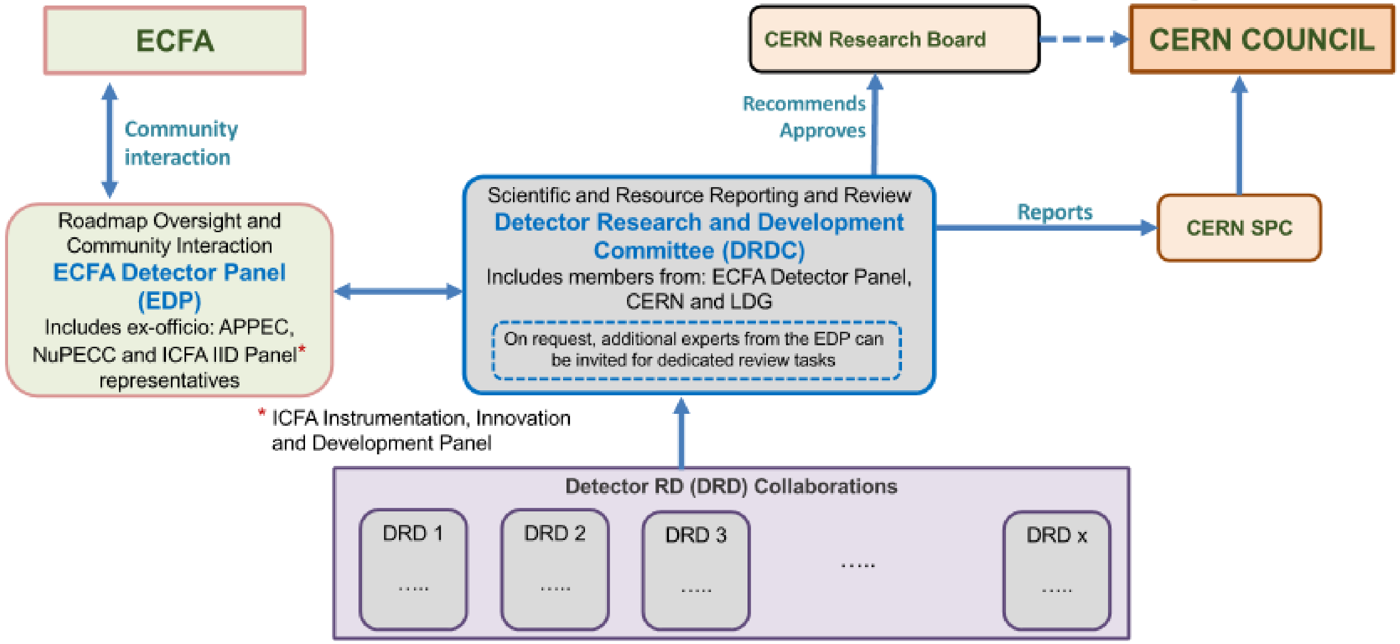
Proposed Implementation plan

DRD3

ECFA **Roadmap Coordination Group** worked out a proposal to organise long-term R&D efforts into: **newly established Detector R&D (DRD) Collaborations anchored at CERN.**

Three areas of Detector R&D:

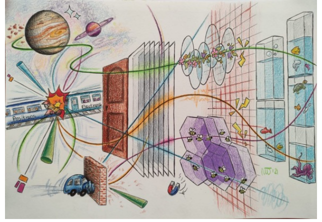
1. **Strategic R&D via DRD Collaborations** (long-term strategic R&D lines) (address the high-priority items defined in the Roadmap via the DRDTs)
2. **"Blue-sky" R&D** (competitive, short-term responsive grants, nationally organised).
3. **Experiment-specific R&D** (with very well defined detector specifications) (funded outside of DRD programme, via experiments).



7 DRDs

DRD9 is taken care of by a new ECFA Training Panel while **DRD8** felt their area is too experiment specific to be the topic of a "Strategic R&D" bid.

https://cds.cern.ch/record/2838406?ln=en

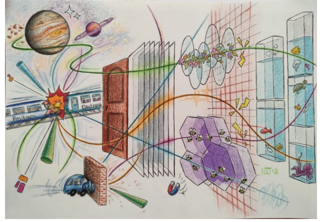


Funding

DRD3

Given the diverse funding and costing models for different Funding Agencies it was decided to utilise the existing understood framework for funding long-term investments in particle physics experiments at CERN as the basis for supporting **Detector R&D (DRD) Collaborations** to deliver the multi-decadal Strategic R&D programmes to meet requirements identified by the DRDTs in the Roadmap documents.

- The clear need for “strategic” R&D was emphasised as separate from, but additional to, that for “blue-sky” and “experiment-specific” activities.
- Such funding should be expected to continue being sought by participating researchers where it is more appropriate (**=National funding!**).



Timeline for Establishing DRD Collaborations

DRD3

Q4 2022

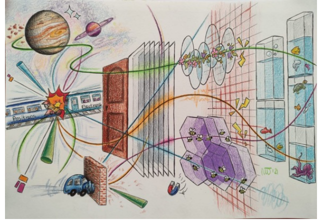
- Identify **key players and stakeholders** from the wider international community.
- Where current relevant detector R&D collaborations exist, their **managements** need to be fully involved from the beginning of this process.
- **DRD proposal teams**, to lead the preparation of the more detailed DRD proposals in each area, should be identified as a result of this process.

Q1 2023:

- Outcomes of **community workshops** are collated and each DRD proposal team calls for expressions of interest from institutes.
- DRDC **mandate formally defined and agreed with the CERN Management**; DRDC membership appointments begin; EDP mandate plus membership updated to reflect additional roles .

Q2 2023:

- **Develop the new DRD proposals** based of the detector roadmap and community interest in participation, and ramp up to a steady state in 2026.
- "Strategic R&D" proposals (**materials and total FTE**). The primary aim is to create a dedicated funding line for *Strategic R&D*.
- Mechanisms **agreed with funding agencies** for structuring country-specific DRD collaboration funding requests.



Timeline for Establishing DRD Collaborations

DRD3

Q3 2023

- **The DRD proposal teams submit full DRD proposals** , indicating estimates of the resources needed (including both those requested and those that are already available, as well as details of who covers what, i.e. pledges by institutes/ funding agencies).

Q4 2023:

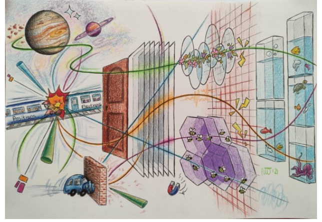
- Following the review and revision (if required) of proposals, the DRDC recommends the formal establishment of the DRD collaborations.
- Formal **approval** is given by the CERN Research Board

2024

Collection of MoU signatures. The areas of interest per institute and the expected support for the long-term commitments involved should be specified in the MoUs.

Formal start of the DRD collaborations (01/01/2024).

(-> End of actual RD´s)



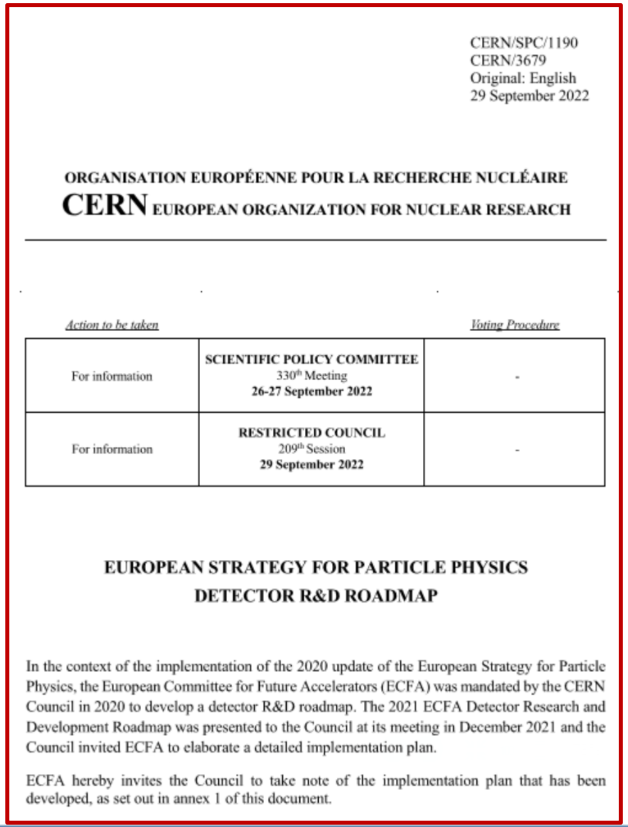
Work to do! -> proposal document

DRD3

- For each DRDT, we should highlight the following:
- Technologies to be studied and performances to be expected with respect of the set goals
- Key R&D deliverables in the coming three years
- Estimated costing
- List of institutes
- Resources available:
  - Manpower (FTE)
  - Estimated available budget
  - Additional budget

Suggested proposal lengths are ~20 pages (case for R&D provided by the Roadmap itself) and the request is for *reasonable estimates informed by discussions with the Funding Agencies*.

More details in next talks.



CERN/SPC/1190
CERN/3679
Original: English
29 September 2022

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Action to be taken		Voting Procedure
For information	SCIENTIFIC POLICY COMMITTEE 330th Meeting 26-27 September 2022	-
For information	RESTRICTED COUNCIL 209th Session 29 September 2022	-

EUROPEAN STRATEGY FOR PARTICLE PHYSICS
DETECTOR R&D ROADMAP

In the context of the implementation of the 2020 update of the European Strategy for Particle Physics, the European Committee for Future Accelerators (ECFA) was mandated by the CERN Council in 2020 to develop a detector R&D roadmap. The 2021 ECFA Detector Research and Development Roadmap was presented to the Council at its meeting in December 2021 and the Council invited ECFA to elaborate a detailed implementation plan.

ECFA hereby invites the Council to take note of the implementation plan that has been developed, as set out in annex 1 of this document.