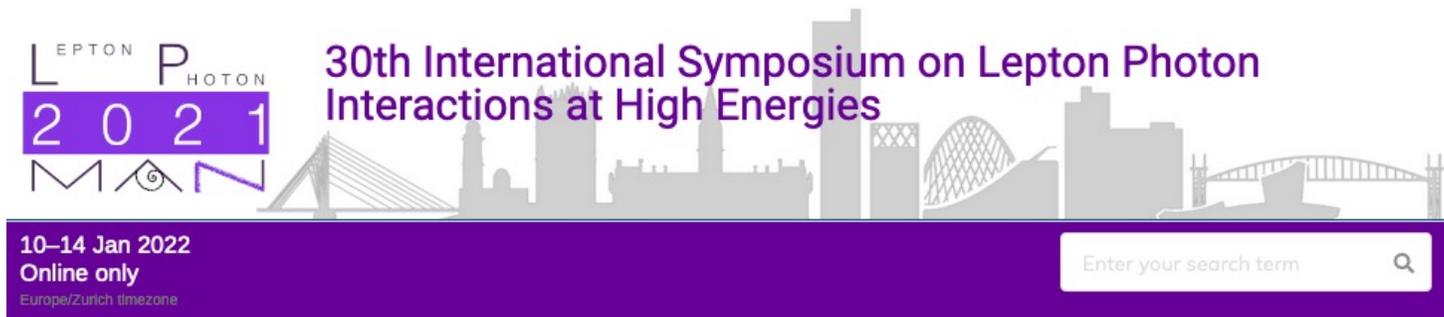


Overview of Detector R&D

14.1.2022

Susanne Kuehn, CERN



The banner features a purple background with a white silhouette of a city skyline. On the left, the text 'LEPTON PHOTON' is written in a stylized font, with '2021' in a purple box below it. To the right, the title '30th International Symposium on Lepton Photon Interactions at High Energies' is written in purple. Below the title, the dates '10-14 Jan 2022' and 'Online only' are listed, along with 'Europe/Zurich timezone'. A search bar with the placeholder text 'Enter your search term' and a magnifying glass icon is located on the right side.

LEPTON PHOTON
2021
MAGN

30th International Symposium on Lepton Photon
Interactions at High Energies

10-14 Jan 2022
Online only
Europe/Zurich timezone

Enter your search term



Overview

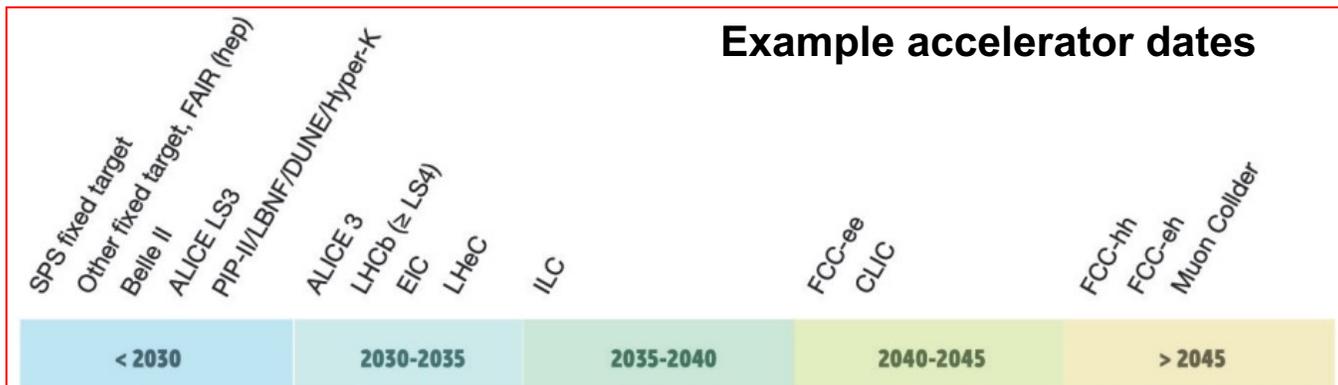


- Overview of future facilities
- R&D organisation
- Details on R&D of several detector technologies
 - Gaseous, Liquid and Solid State Detectors
 - Calorimetry, Particle identification and photon detectors, Quantum and emerging technologies
 - Microelectronics, Integration
- Observations and Conclusions

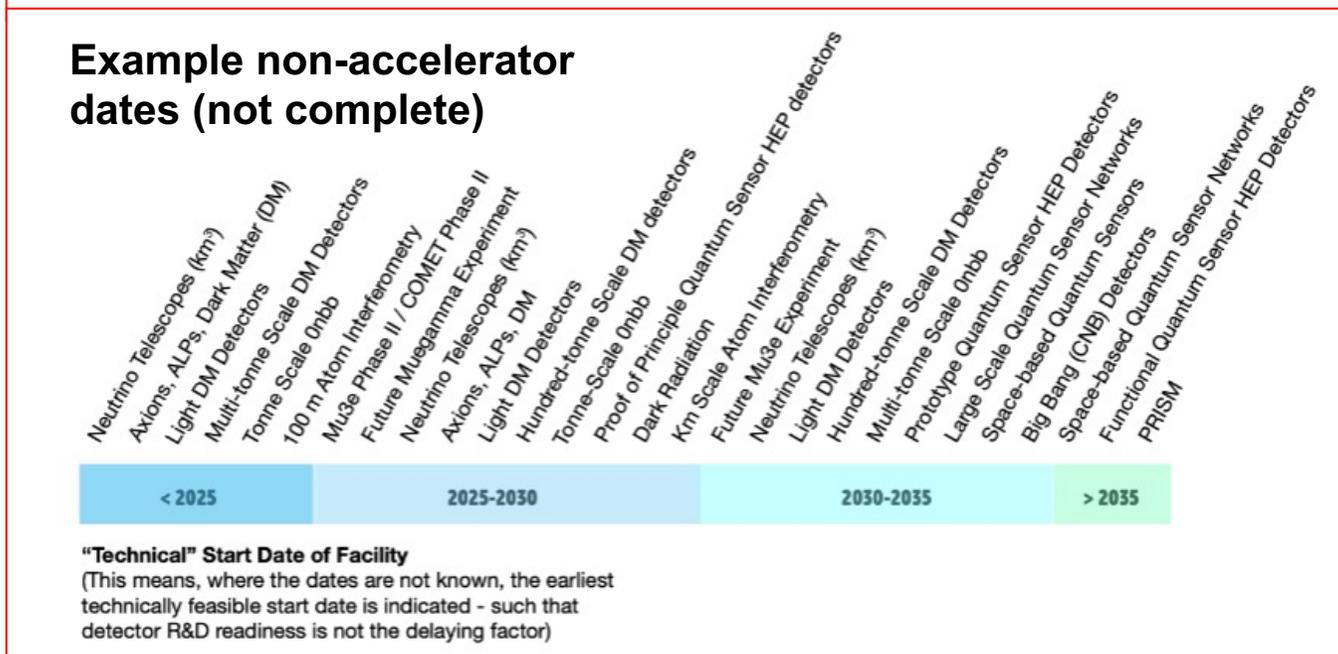
Disclaimer: by far not complete list and coverage of all experiments. Many specific talks during other sessions of this conference.

Overview of future facilities

- Many different future facilities proposed/foreseen based on accelerators and non-accelerators
- Overview from ECFA Detector R&D Roadmap Document (CERN-ESU-017, [10.17181/CERN.XDPL.W2EX](https://cds.cern.ch/record/10.17181/CERN.XDPL.W2EX))



The dates used in these diagrams have a deliberately low precision, and are intended to represent the earliest ‘feasible start date’ (where a schedule is not already defined), taking into account the necessary steps of approval, development and construction for machine and civil engineering. They do not constitute any form of plan or recommendation, and indeed several options presented are mutually exclusive.



Furthermore, the projects mentioned here are usually limited to those mentioned in the 2020 EPPSU*, although it should be noted that detector R&D for other possible future facilities is usually aligned with that for programmes already listed.

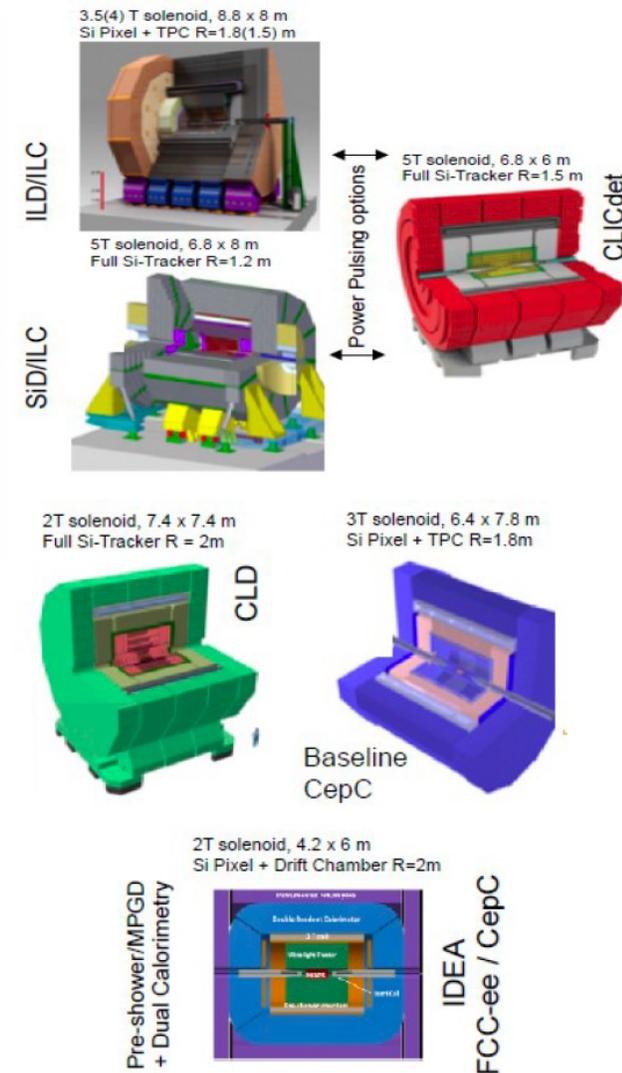
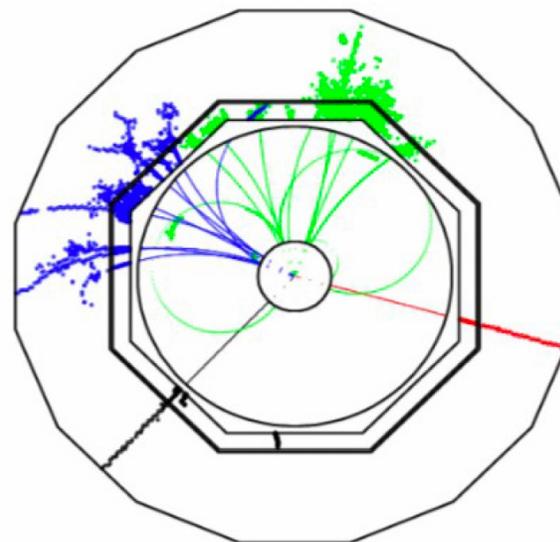
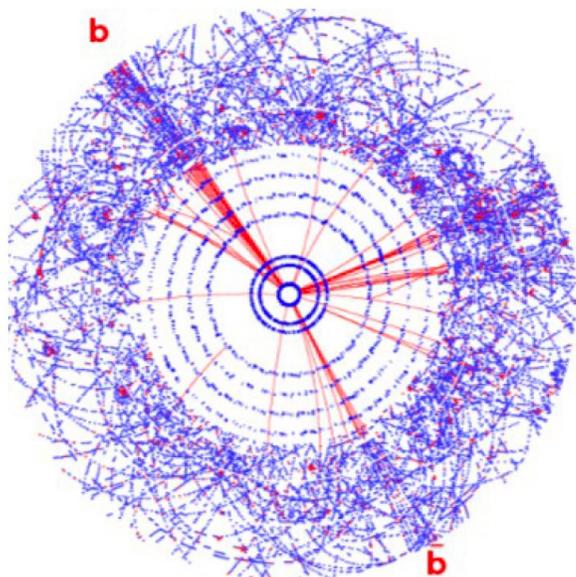
→ Many detector concepts at different future facilities

* 2020 European Particle Physics Strategy Update
<https://europeanstrategyupdate.web.cern.ch/>

Example of future detectors at accelerators

Hadron-hadron collisions e.g. LHC

e^+e^- -collisions



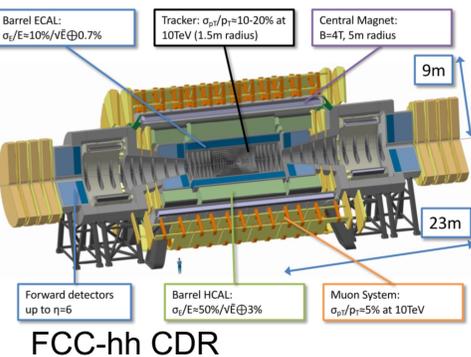
- Busy events
- Require hardware and software triggers
- High radiation levels

- Clean events
- No trigger
- Full event reconstruction

- One of the many challenges: radiation hardness. Radiation levels of e.g. $300 \text{ MGy}/5\text{-}6 \cdot 10^{17} n_{\text{eq}}/\text{cm}^2$ in first tracker layers go well beyond what any currently available microelectronics can survive ($\lesssim \text{MGy}$) and few sensor technologies can cope beyond $\sim 10^{16} n_{\text{eq}}/\text{cm}^2$

→ Many details in the session afterwards

→ Detector R&D essential



FCC-hh CDR

Detector R&D organisation

- Looking in the past:

Detector R&D

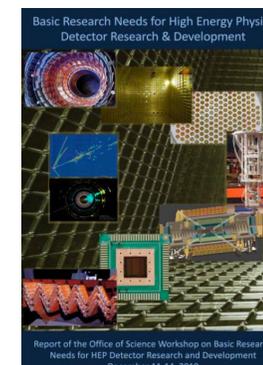
- From 1986, vigorous CERN programme with 40 MCHF funding from Italian government (Zichichi's LAA Project)
- CERN Detector R&D Committee set up mid 1990. By March 1992: 35 proposals, 24 approved – involving 800 people in 170 institutes

Detector Research and Development Committee (DRDC), 1990 - 1995

The Detector Research and Development Committee (DRDC) was set up in July 1990. It received proposals for detector R&D involving people from Member States, other countries, and CERN itself. The committee operated in the same way as the other experimental committees of CERN, and forwarded its recommendations to the Research Board for final decision. It held its last meeting in January 1995. Its role was taken over by the [LHC Committee \(LHCC\)](#).

- Several processes conducted/ongoing to organise the Detector R&D (more details in spare slides)

- Technology oriented RD Collaborations: [RD42](#), [RD50](#), [RD51](#), [RD53](#), ...
- US [Basic Research Needs](#) and [Snowmass](#)
- [CERN EP R&D](#)
- [AIDAInnova](#)
- [ECFA Detector R&D Roadmap](#) ([Slides](#), [Webpage](#))
-

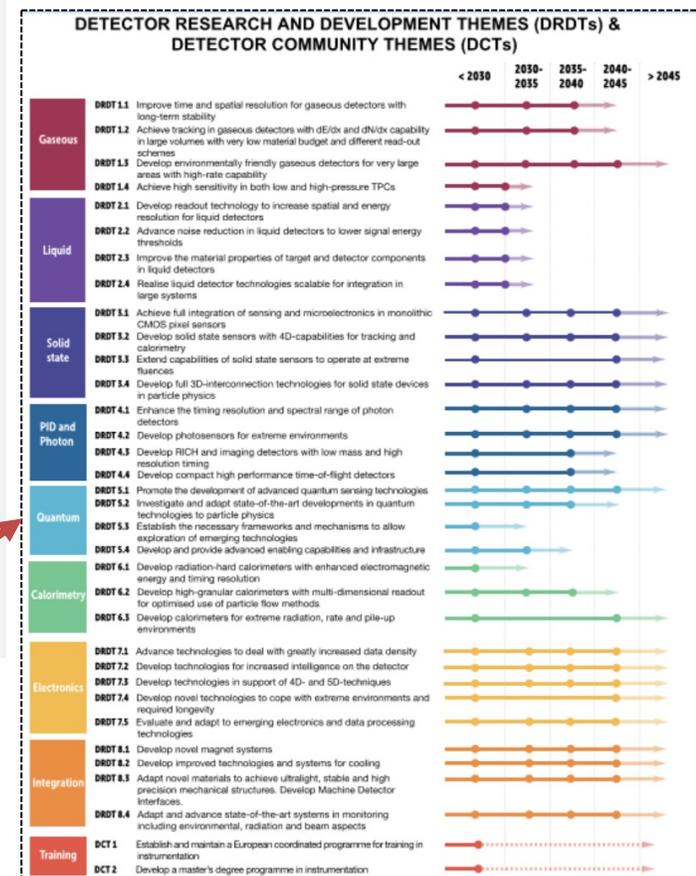


Detector R&D readiness should not be the determining factor in the future of particle physics

ECFA Detector R&D Roadmap

- “Organised by ECFA, a roadmap should be developed by the community to balance the detector R&D efforts in Europe, taking into account progress with emerging technologies in adjacent fields”
- Focus on the technical aspects of detector R&D requirements given the [2020 EPPSU deliberation document](#) listed “High-priority future initiatives” and “Other essential scientific activities for particle physics” as input and organise material by Technology/Task Force.
- Task Forces start from **the future science programme** to identify main detector technology challenges to be met (both mandatory and highly desirable to optimise physics returns) and estimate the period over which the required detector R&D programmes may be expected to extend.
- Within each Task Force the aim is to propose a time ordered detector R&D programme in terms of **capabilities not currently achievable**.

Process organised by Panel and nine Task Forces with input sessions and open symposia with wide community consultation (1359 registrants)
Thank you for all input, contributions and comments!



Main Document published (approval by RECFA at [19/11/21](#)) and 8 page synopsis brochure prepared for less specialists audience

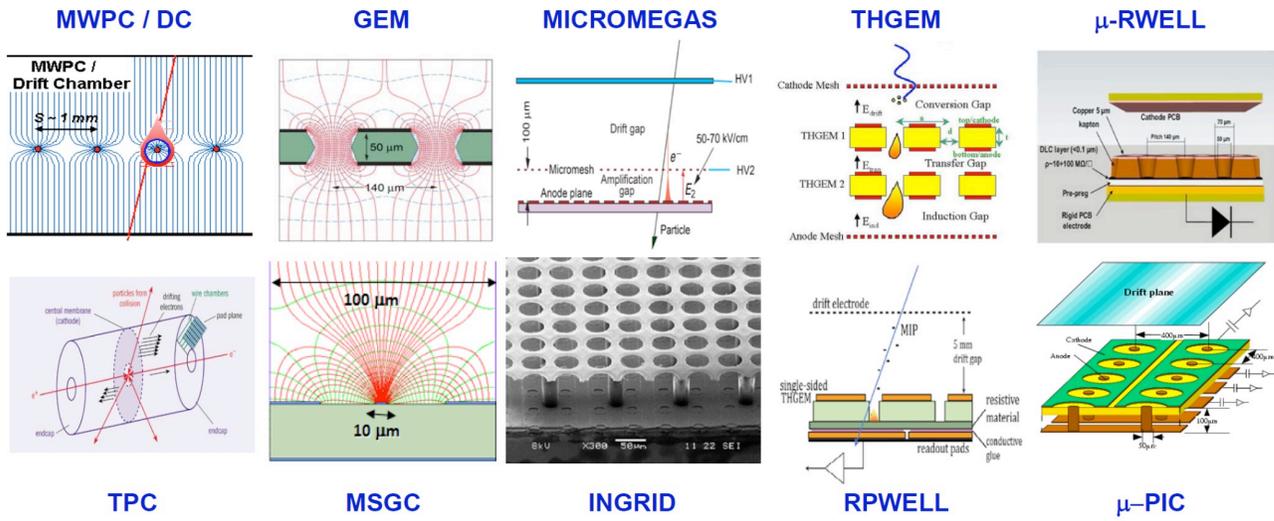


ECFA Detector R&D Roadmap Panel web pages at:
<https://indico.cern.ch/e/ECFADetectorRDRoadmap>
Documents CERN-ESU-017:
[10.17181/CERN.XDPL.W2EX](https://cds.cern.ch/record/2811111/files/10.17181/CERN.XDPL.W2EX)

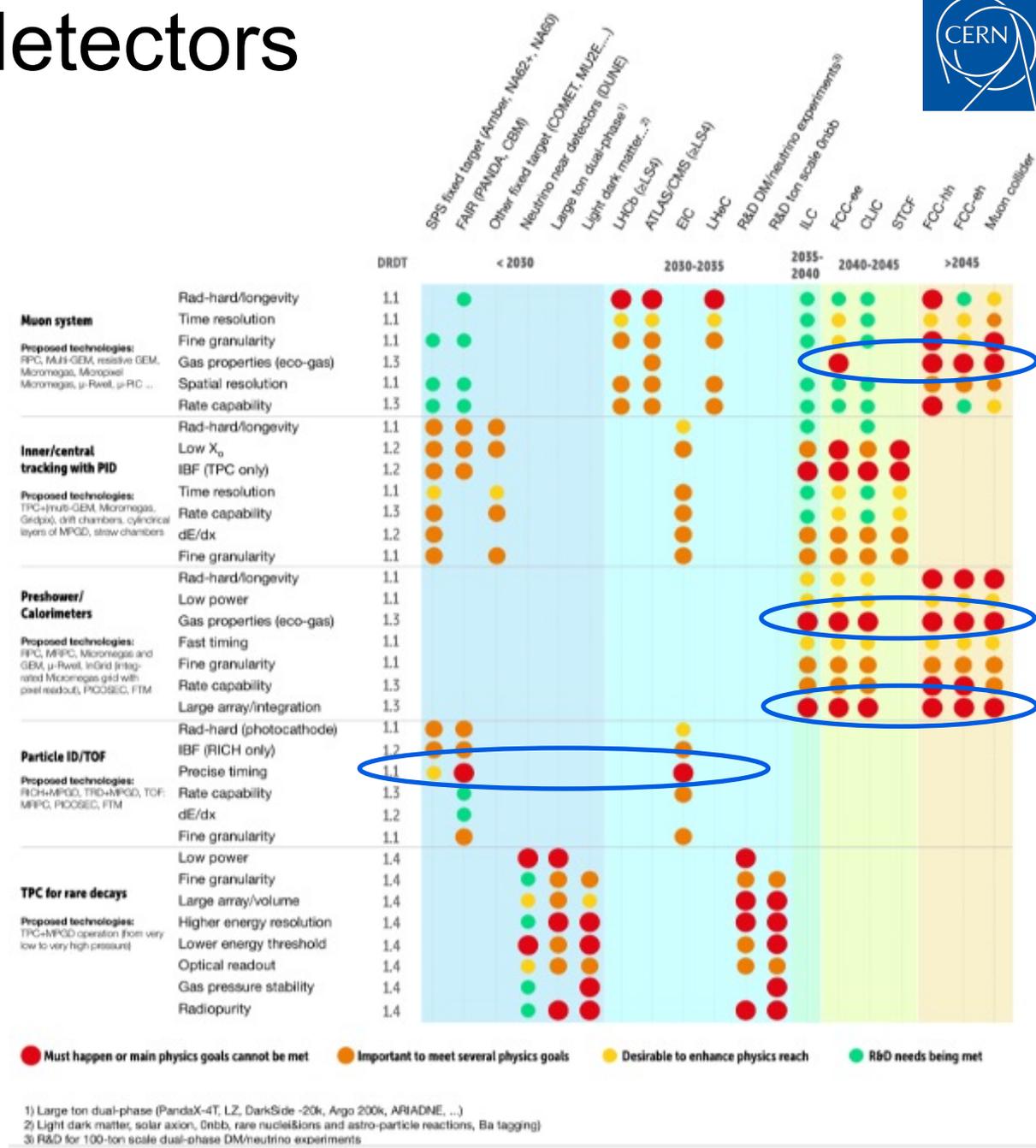
Gaseous detectors



- Gaseous detectors: from Wire/Drift Chamber → Time Projection Chamber (TPC) → Micro-Pattern Gas Detectors
- Primary choice for large-area coverage with low material budget & dE/dx measurement (TPC, Drift chamber) & TOF functionality (MRPC, PICOSEC)



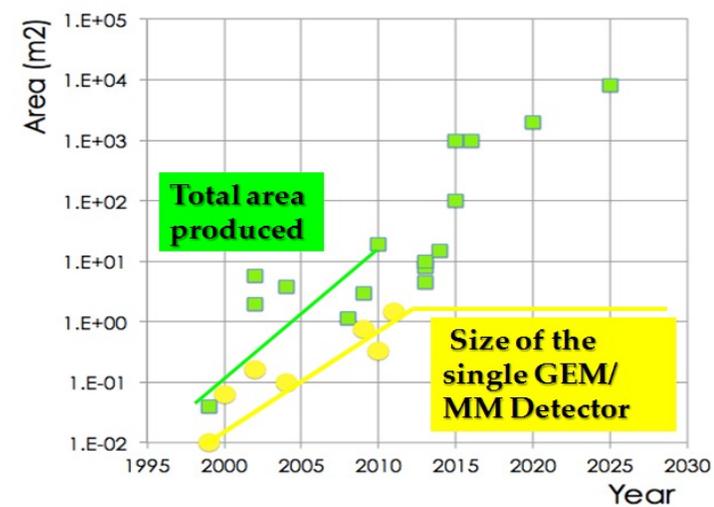
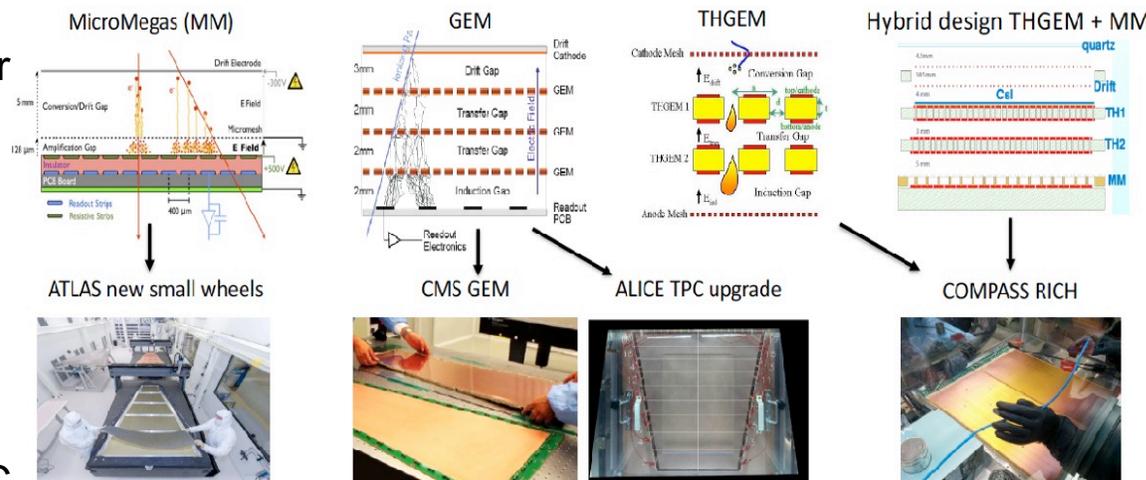
- Detector Readiness Matrices of each Task Force chapter** focus on the extent to which the R&D topic is *mission critical* to the programme than the intensity of R&D required
 - Must happen or main physics goals cannot be met
 - Important to meet physics goals
 - Desirable to enhance physics reach
 - R&D need being met



1) Large ton dual-phase (PandaX-4T, LZ, DarkSide-20k, Argo 200k, ARIADNE, ...)
 2) Light dark matter, solar axion, Dnbb, rare nuclei/ions and astro-particle reactions, Ba tagging)
 3) R&D for 100-ton scale dual-phase DM/neutralino experiments

Gaseous detectors: area and timing

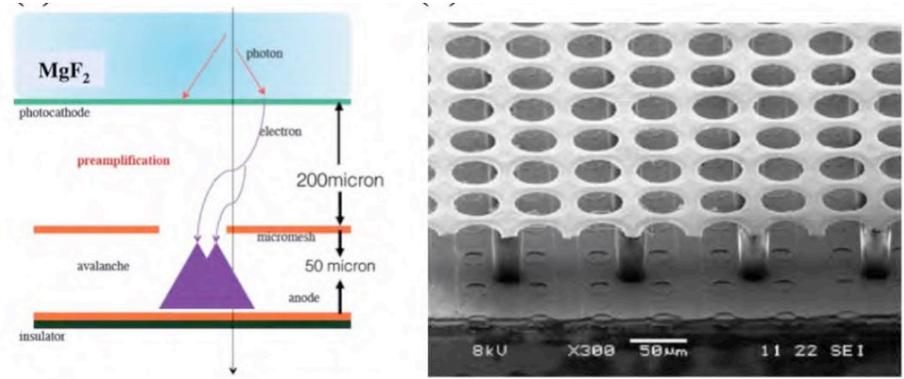
- **Upgrades to a number of systems used at the LHC for tracking, muon spectroscopy and triggering have taken advantage of the renaissance in gaseous detectors (esp MPGDs)**
- **New generation of TPCs use MPGD-based readout:** e.g. ALICE Upgrade, T2K, ILC, CepC



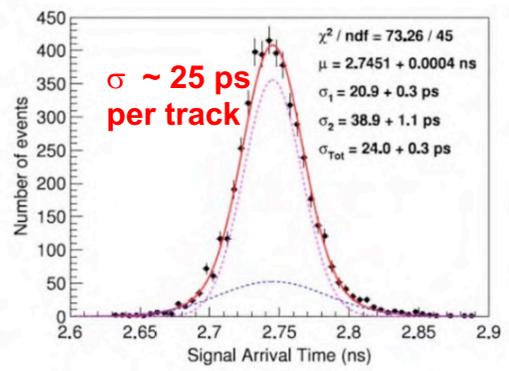
- **Gaseous detectors offer very competitive timing through e.g.**
 - **Multi-gap Resistive Plate Chambers** (down to 60 ps time resolution) (ALICE TOF Detector, Z.Liu, NIM A927 (2019) 396)
 - An enabling emerging R&D: **Micromegas with timing** (PICOSEC concept)

J. Bortfeldt, NIM A903 (2018) 317

Cherenkov radiator + Photocathode + MM



Timing (MIP test-beam):



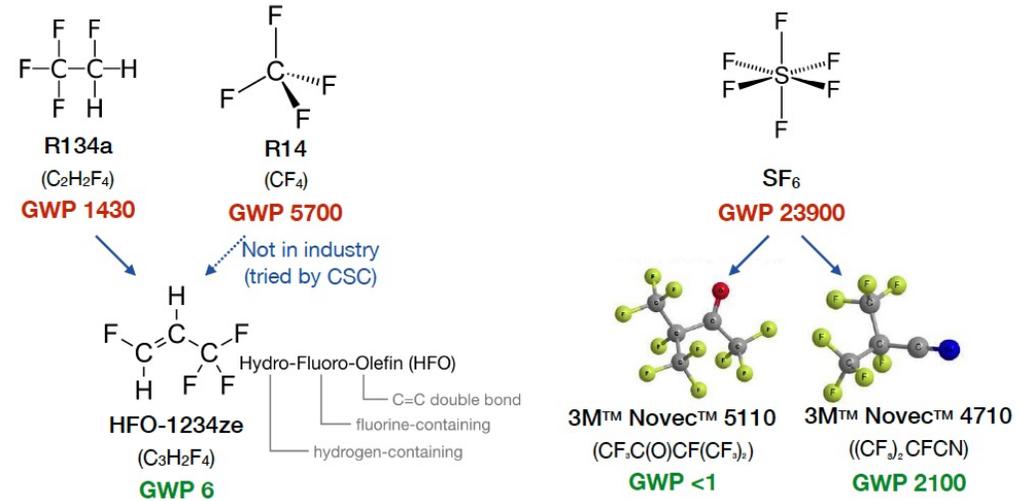
→ Many developments emerged from the R&D studies within the RD51 Collaboration

Gaseous Detectors: eco-friendly gases

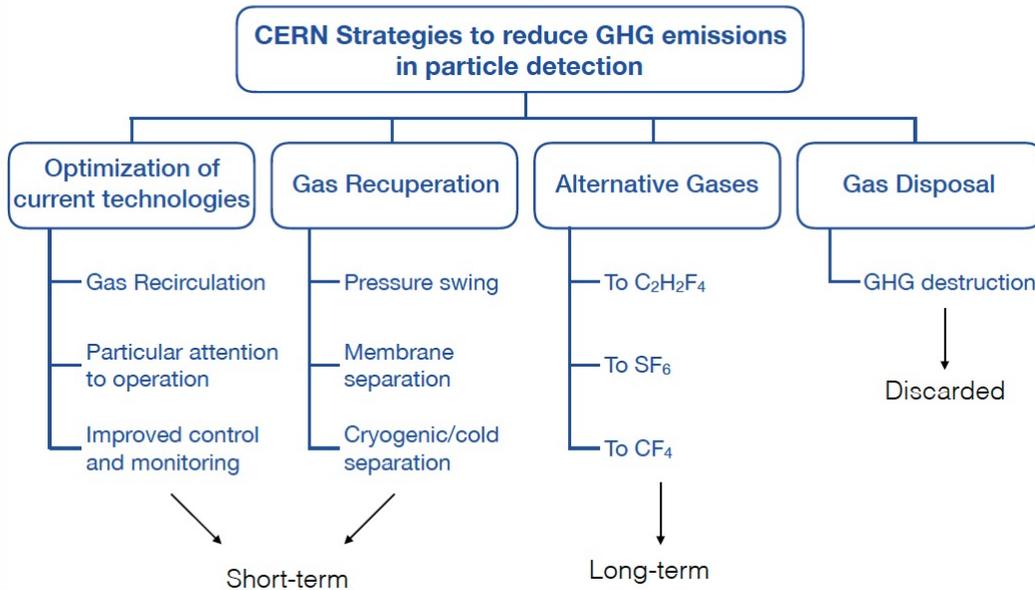
- 92% of emission at CERN related to large LHC experiments
- Thanks to gas recirculation GHG emission already reduced by > 90% wrt. to open mode systems!
- Many LHC gas systems with gas recuperation

Possible alternatives to GHG gases

New eco-friendly liquids/gases have been developed for industry as refrigerants and HV insulating medium... ionisation properties in particle detection not well known



CERN strategies for GHG reduction



- Alternative gases:
 - A lot of work especially in RPC community to search for alternative to C₂H₂F₄
 - Not an easy task to find new eco-friendly gas mixture for current detectors

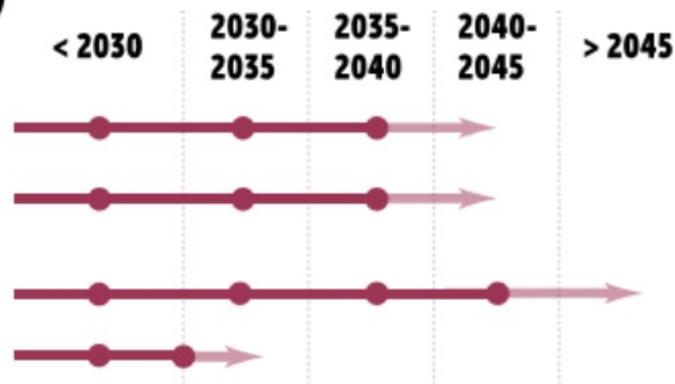
Gaseous detectors

→ Within each Task Force chapter of the Roadmap document created a time-ordered technology requirements driven R&D roadmap in terms of capabilities not currently achievable

DETECTOR RESEARCH AND DEVELOPMENT THEMES (DRDTs) & DETECTOR COMMUNITY THEMES (DCTs)

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



To highlight the most important drivers for research in each technology area

To not limit a feasible start date of a future facility

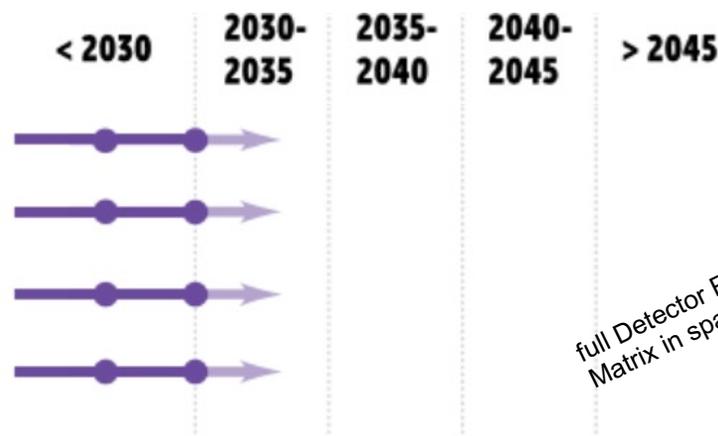
- The faded region acknowledges the typical time needed between the completion of the R&D phase and the readiness of an experiment at a given facility.
- Stepping stones are shown to represent the R&D needs of facilities intermediate in time.
- It should be emphasised that the future beyond the end of the arrows is simply not yet defined, not that there is an expectation that R&D for the further future beyond that point will not be needed.

Liquid detectors

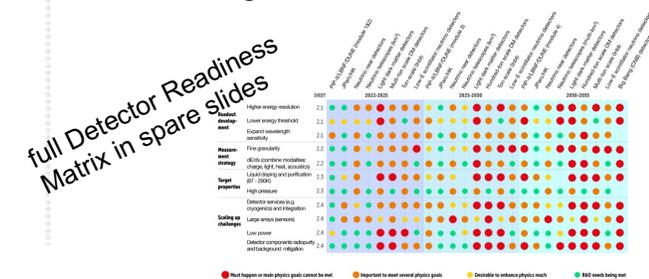
- The DRDTs are

Liquid

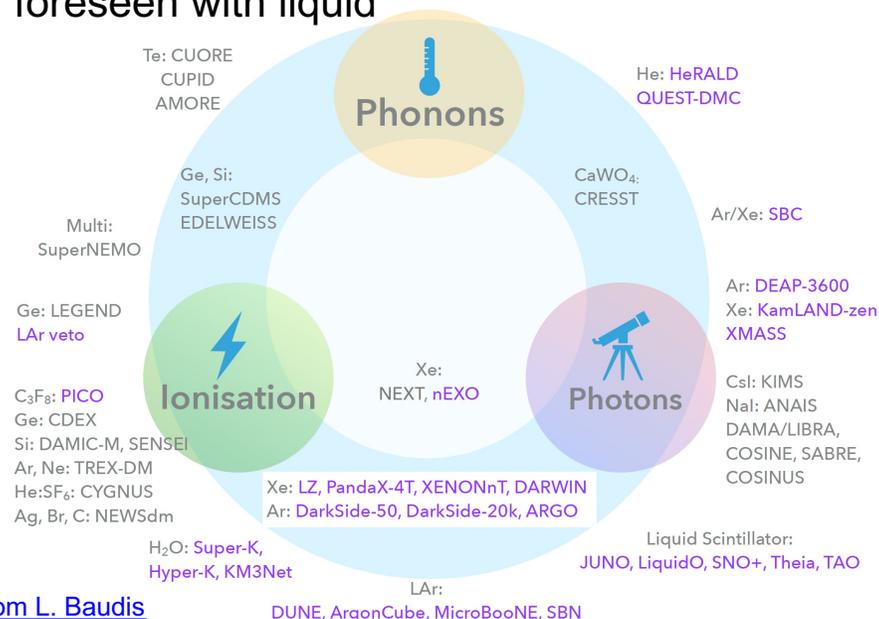
- DRDT 2.1** Develop readout technology to increase spatial and energy resolution for liquid detectors
- DRDT 2.2** Advance noise reduction in liquid detectors to lower signal energy thresholds
- DRDT 2.3** Improve the material properties of target and detector components in liquid detectors
- DRDT 2.4**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



Note: Developments in this field are rapid and it is not possible today to reasonably estimate the dates for projects requiring longer-term R&D



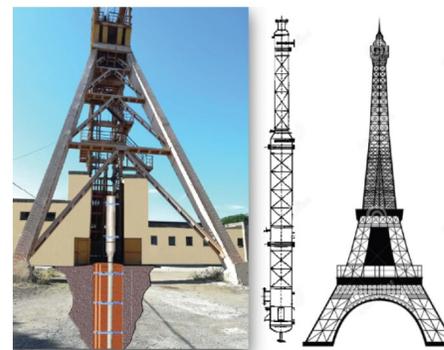
- Several large-scale and many small-scale experiments running or foreseen with liquid detectors



Modified from L. Baudis

Underground Dark Matter Experiments – small and rare signals R&D for multi-ton scale noble liquids:

- Target doping and purification
- Detector components radiopurity and background mitigation



ARIA underground purification system for argon (DarkSide-20k)

Low-radioactivity argon: extraction (Urania plant, 330 kg/d), purification (ARIA facility, 10 kg/d)

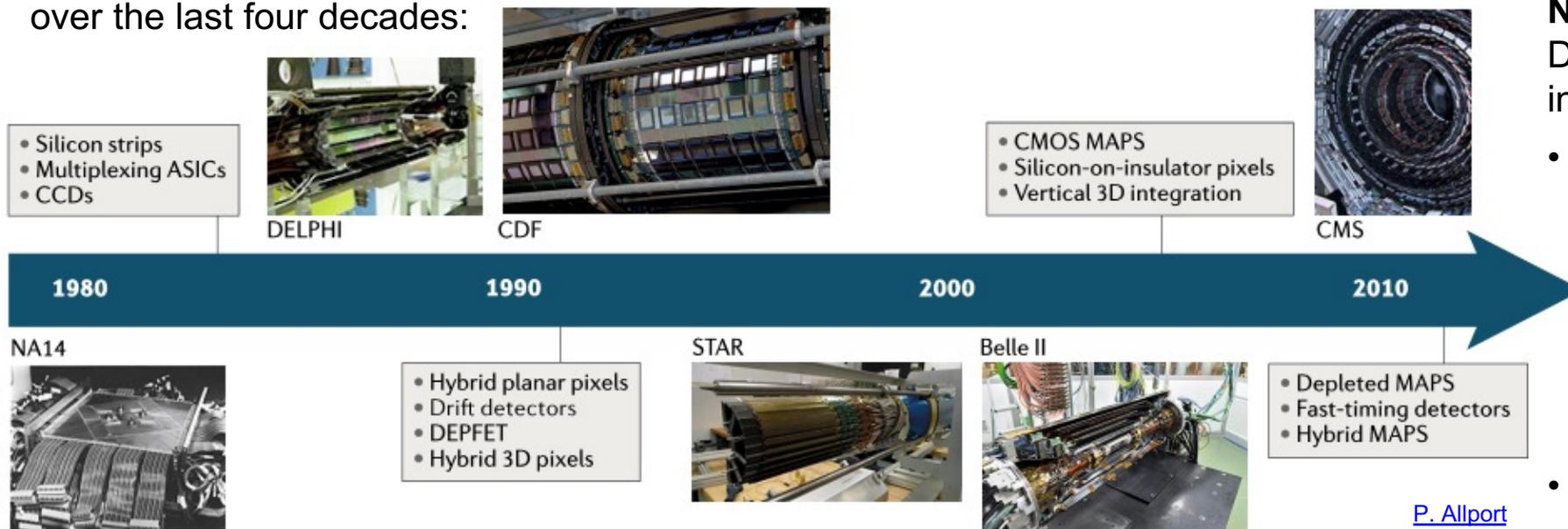


Distillation columns for krypton and radon, material screening and selection, radon emanation

Rn distillation column for XENONnT (reduce ²²²Rn - hence also ²¹⁴Bi - from pipes, cables, cryogenic system)

Solid State Detectors

- Many different silicon detector technologies for **particle tracking** have been developed over the last four decades:



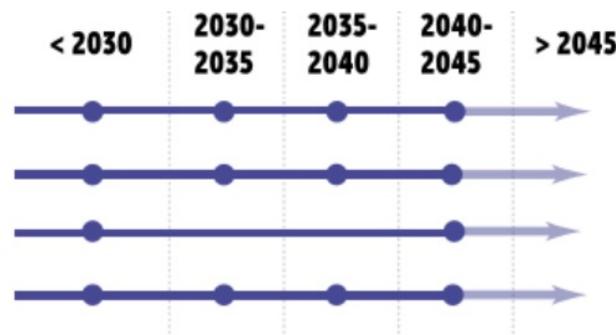
Remarkable: **every decade** the instrumented areas have increased by **a factor of 10** while the numbers of channels in the largest arrays have increased by **a factor of 100**

- Solid state detectors more and more used for **calorimetry and time-of-flight**

They lead to these DRDTs:

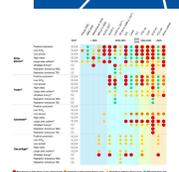
Solid state

- 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



New Challenges (see Detector Readiness Matrix in spare slides):

- Vertex detectors with low mass, high resolution** (Target per layer spatial resolution of $\leq 3\mu\text{m}$ and $X/X_0 \leq 0.05\%$ for FCC-ee), **low power and high radiation hardness** (up to $8 \times 10^{17} n_{\text{eq}}/\text{cm}^2$ for pp-colliders)
- Trackers: **affordable sensors** with low mass, high resolution, **low power**
- Large area and granular** devices for calorimeters
- Detectors with **ultra-fast timing** ($O(10-100 \text{ ps})$) for PID, TOF
- Fully integrated with electronics, mechanics, services, ...



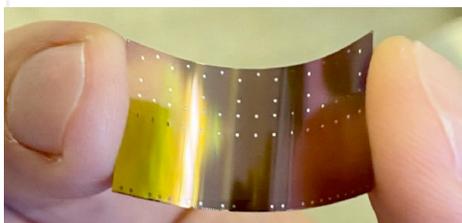
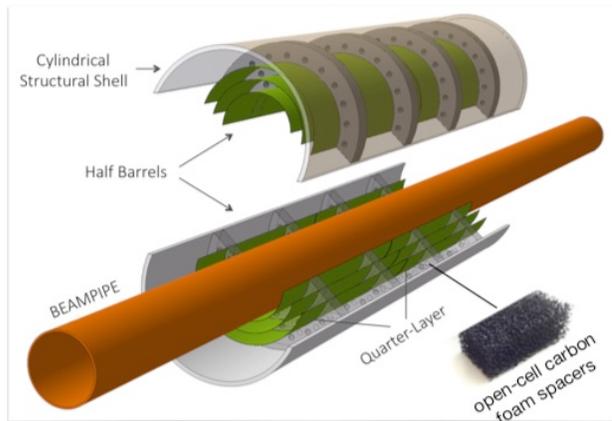
CMOS MAPS

- Monolithic sensors combining sensing and readout elements
- Example: For FCC-ee vertex detector targeting spatial resolution per layer of $\leq 3\mu\text{m}$ and $x/x_0 \leq 0.05\%$, essential to have low power. Plus radiation-hardness up to $8 \times 10^{17} \text{ n}_{\text{eq}}/\text{cm}^2$ for pp-collider.

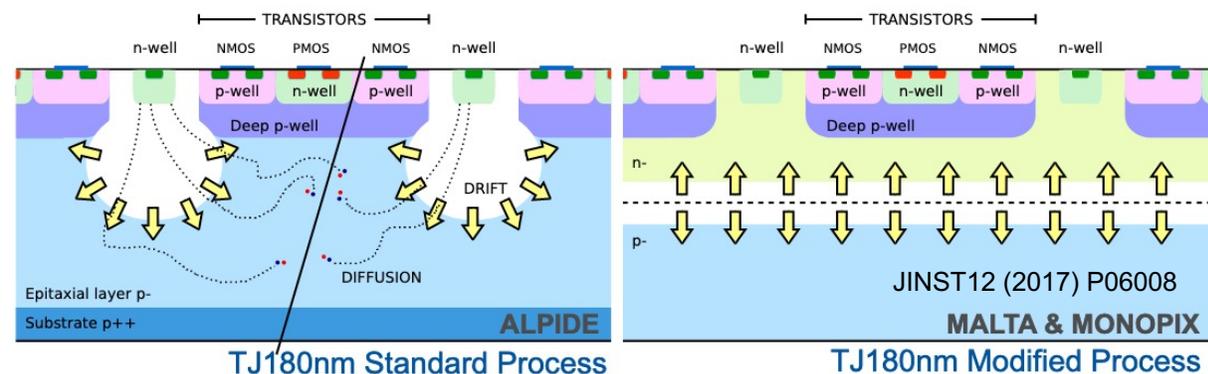
CMOS MAPS for ALICE ITS3 (Run 4):

(LOI: CERN-LHCC-2019-018, [M. Mager](#))

- Three fully cylindrical, wafer-sized layers based on curved ultra-thin sensors (20-40 μm), air flow cooling
- Very low mass (IB), $< 0.02\text{-}0.04\%$ per layer



Radiation hardness of MAPS: From ALPIDE to MALTA/Monopix with modified Tower Jazz 180 nm process



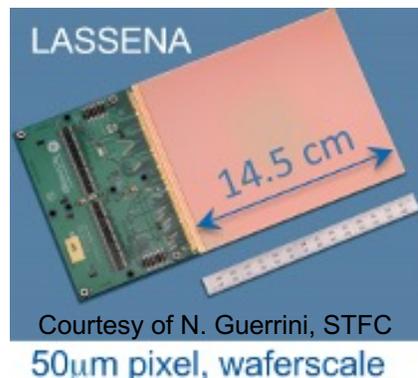
→ Up to 97% efficiency after fluence of $1 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ [H. Pernegger](#)

MIMOSA @ EUDET BeamTest

Telescope → 3 μm track resolution achieved



Large area:
stitching
INMAPS process



Courtesy of N. Guerrini, STFC
50 μm pixel, waferscale

To achieve higher radiation hardness: Hybrid technologies with thin, 3D-structures (columns/trenches) silicon and/or high bandgap materials (e.g. diamond) are mostly considered for really high radiation environments.

Silicon timing detectors

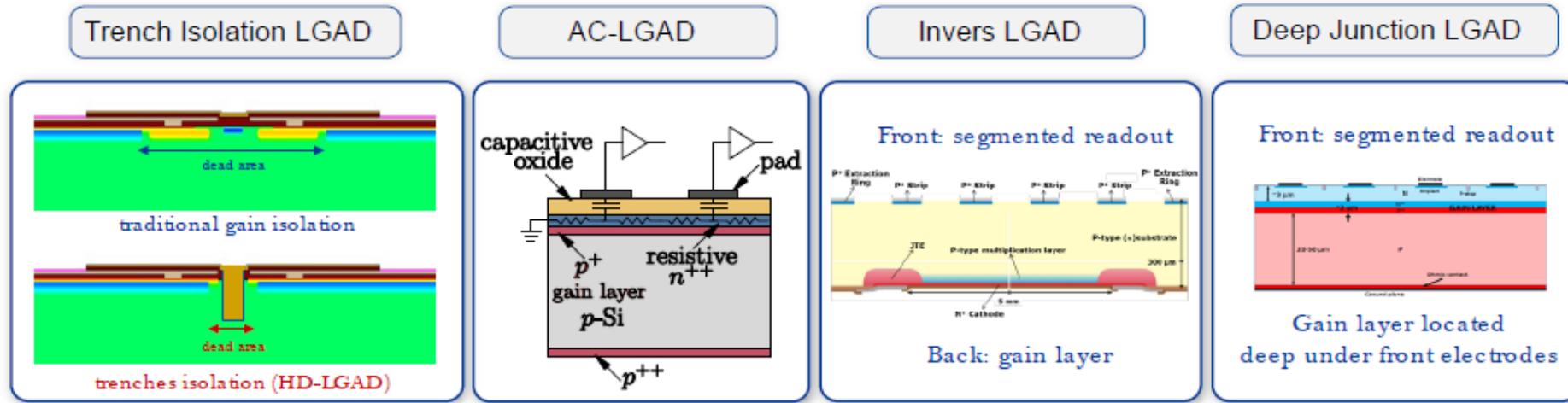
Sensors for 4D-Tracking: position and time resolution → Development of Radiation Hard Timing Detectors (Low Gain Avalanche Detectors)

- For LGADs, three main foundries (CNM, FBK, HPK), more producers interested
- Time information hugely beneficial to suppress pile-up in pp-collisions

LGAD: Fill factor & performance improvements



- Two opposing requirements:
 - Good timing reconstruction needs homogeneous signal (i.e. no dead areas and homogeneous weighting field)
 - A pixel-border termination is necessary to host all structures controlling the electric field
- Several new approaches to optimize/mitigate followed:

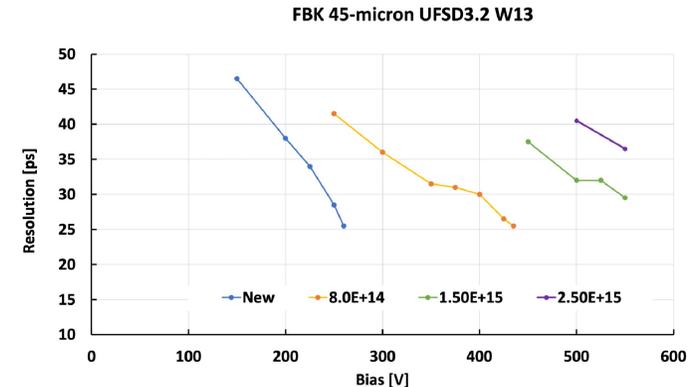


Concepts simulated, designed, produced and tested in 2018/19

...new concept 2020

Areas of LGAD developments within RD50 Collaboration:

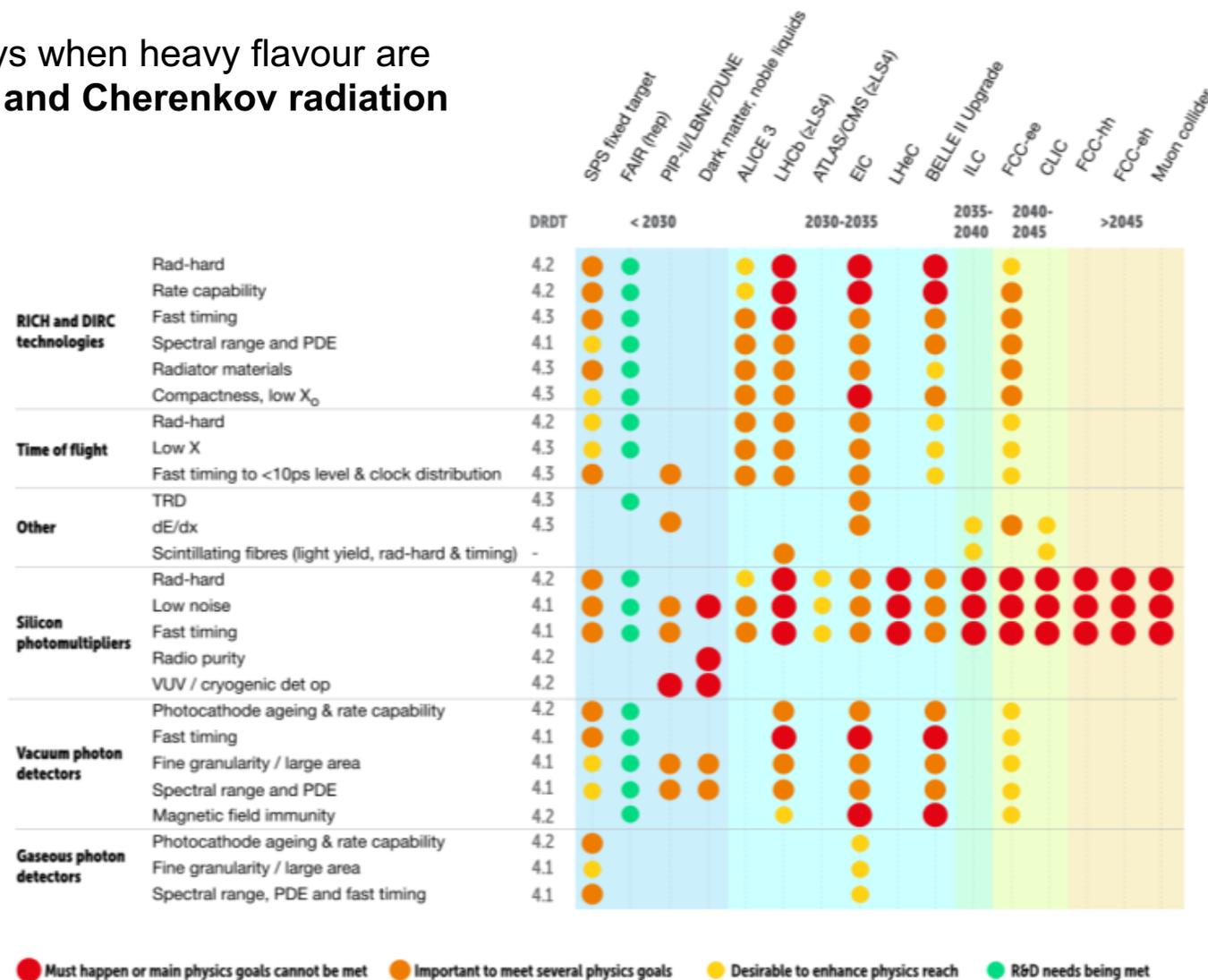
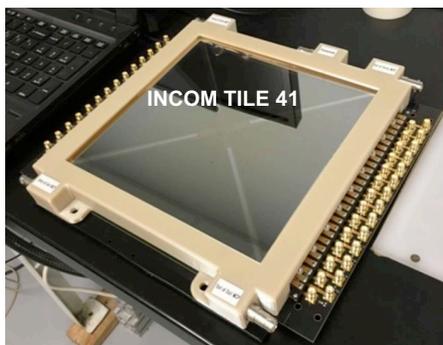
- Timing performance (~ 25 ps for 50 μm sensors)
- Fill factor and signal homogeneity
- Position resolution is about 5% of the distance between electrodes O(5-15 μm) (AC-LGAD)
- Radiation Hardness (~2x10¹⁵ n_{eq}/cm²)
- Performance Parameterisation Model



N. Cartiglia

PID and Photon Detectors

- **Particle Identification (PID)** essential to identify decays when heavy flavour are present: everywhere. **Used are dE/dx, Time-of-Flight and Cherenkov radiation**
- **Many developments on vacuum photon detectors, solid state, gas-based and superconducting photon detectors**
- Challenges for example for **SiPMs**: the high dark count rate and moderate radiation hardness prevented their use in RICH detectors where single photon detector required at low noise
- Challenges for **MCP-PMTs** is their price and they are not tolerant to magnetic fields, similarly **Large-Area Picosecond Timing Detectors (LAPPD)** which are promising but need in addition pixellation

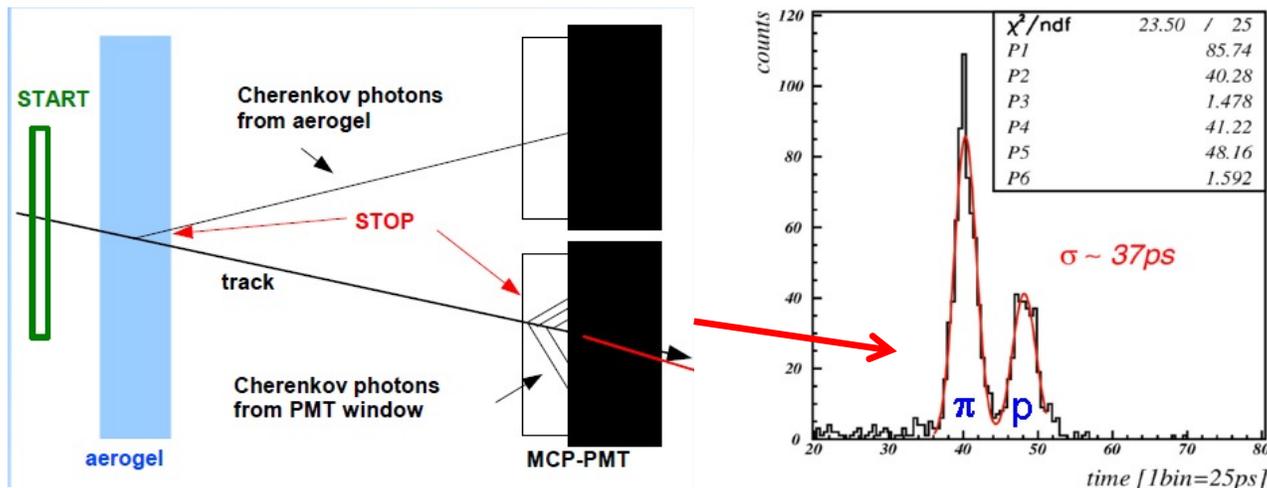


● Must happen or main physics goals cannot be met ● Important to meet several physics goals ● Desirable to enhance physics reach ● R&D needs being met

PID and Photon Detectors: RICHes

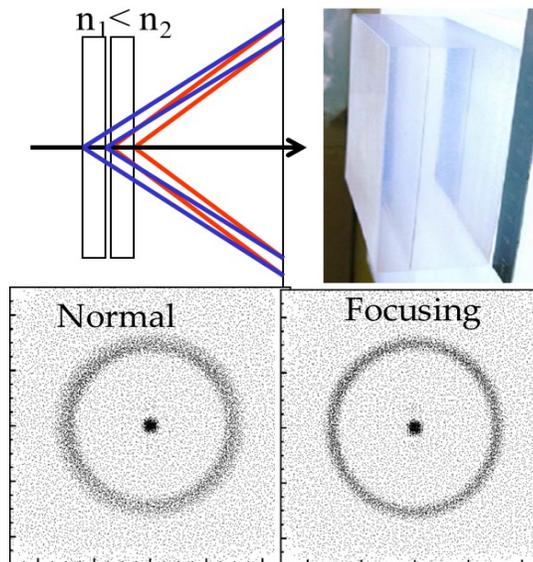
Examples of trends in proximity focusing aerogel radiator RICHes:

- **Combination of proximity focusing RICH + TOF with fast new photon-sensors** → MCP-PMT or SiPM using Cherenkov photons from PMT window
- Use of focusing configuration, e.g. ARICH (Belle), Forward RICH (Panda)



Cherenkov photons from PMT window can be used to positively identify particles below threshold in aerogel

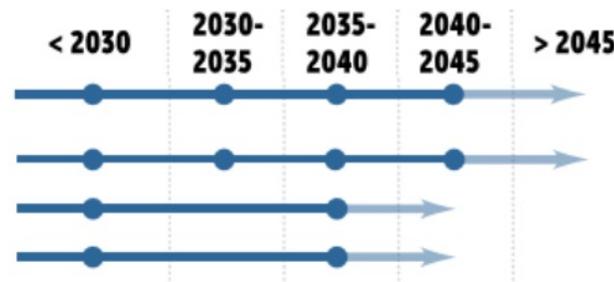
P. Krizan @INSTR2020
T. Credo, 2004 IEEE NSS/MIC Conference Record



- RICHes with proximity focusing: thin radiator (liquid, solid, aerogel) and low momenta
- Time-Of-Flight (TOF) detectors: use prompt Cherenkov light, fast gas detector
- RICHes with focalisation: extended radiator (gas), mandatory for high momenta

DRDTs:

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

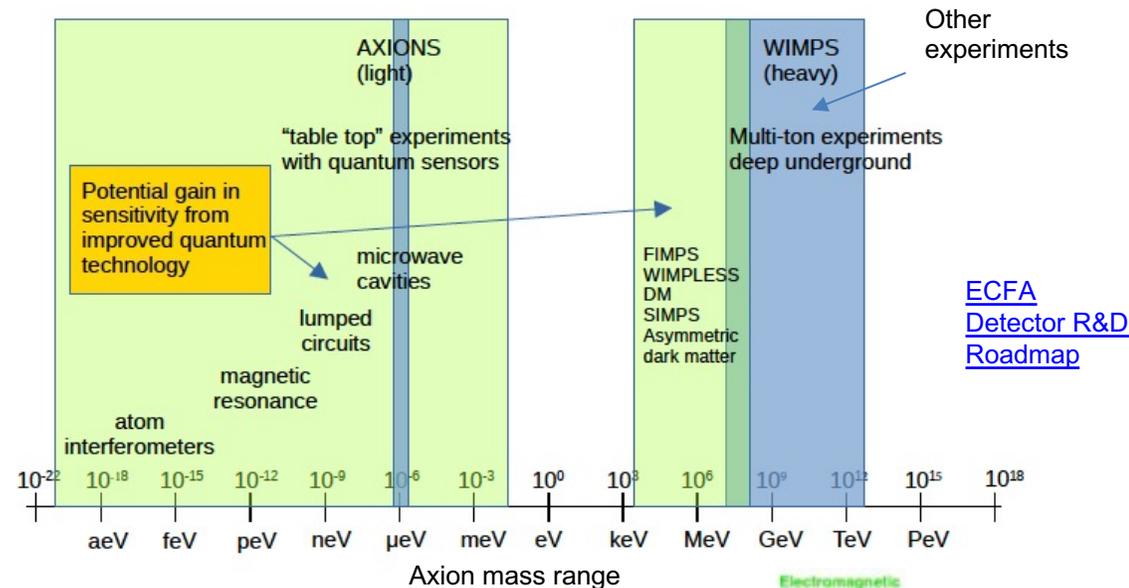


Quantum and emerging technologies

- **Quantum Technologies** are a rapidly emerging area of technology development to study fundamental physics
- The ability to engineer quantum systems to improve on the measurement sensitivity holds great promise
- **Many different sensor and technologies being investigated:** clocks and clock networks, kinetic detectors, spin-based, superconducting, optomechanical sensors, atoms/molecules/ions, interferometry, ...
- Several initiatives started at CERN, DESY, UK, ...



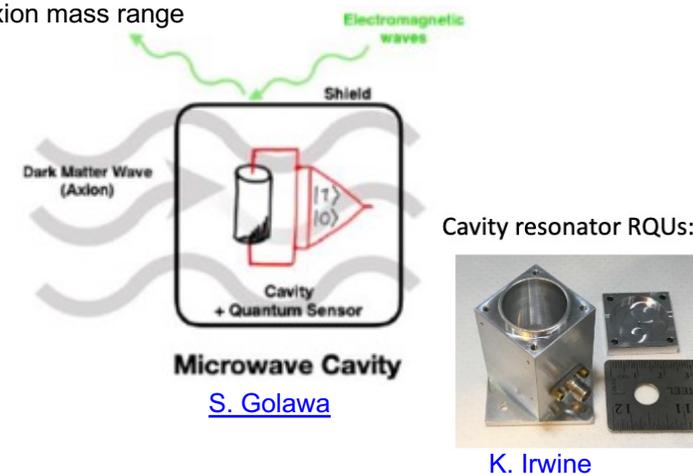
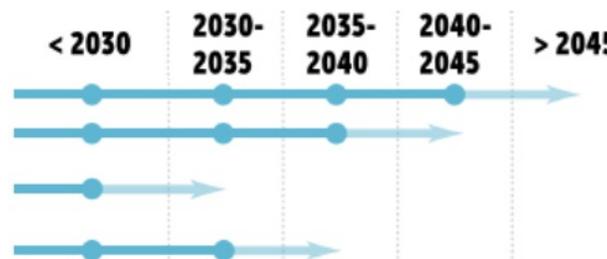
Example: potential mass ranges that quantum sensing approaches open up for Axion searches



DRDTs



- 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



Microwave Cavity

[S. Golawa](#)

Cavity resonator RQUs:



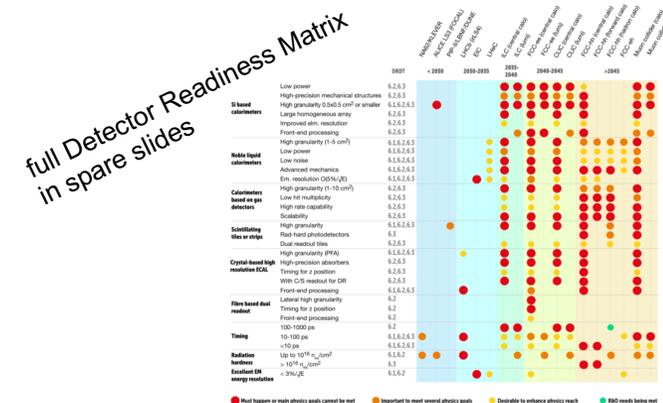
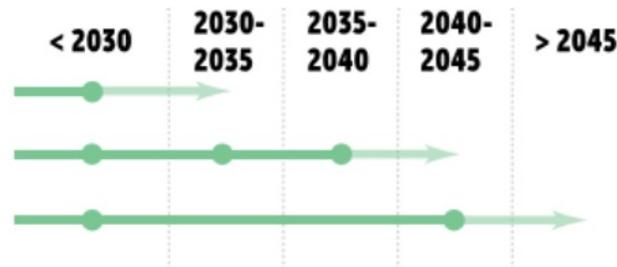
[K. Irwine](#)

Calorimetry

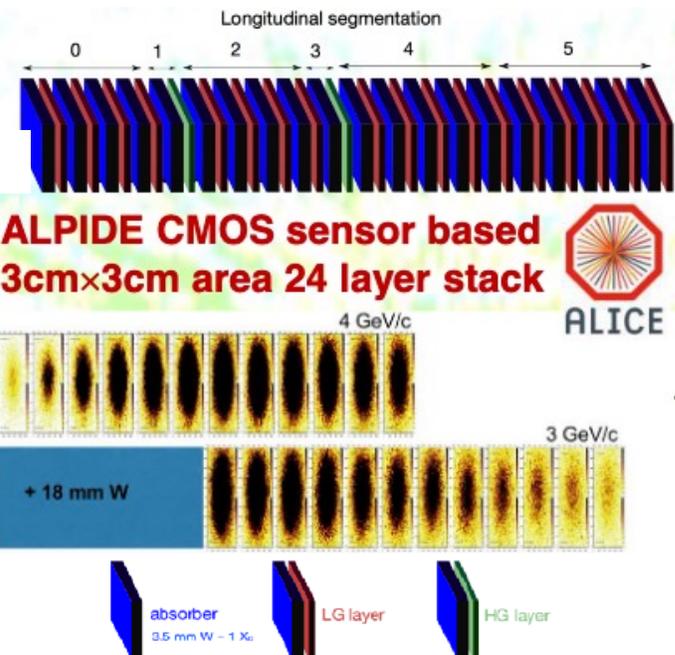
- **R&D in calorimetry has a particularly long lead-time** due to the duration of the stage for experiment specific final prototyping, procurement, production, assembly, commissioning and installation
- DRDTs:

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



ALICE FoCAL



DRDT 6.1: The enhanced electromagnetic energy and timing resolution most relevant in next decade for upgrades of ALICE and LHCb.

Example: MAPS based SiW ECALs

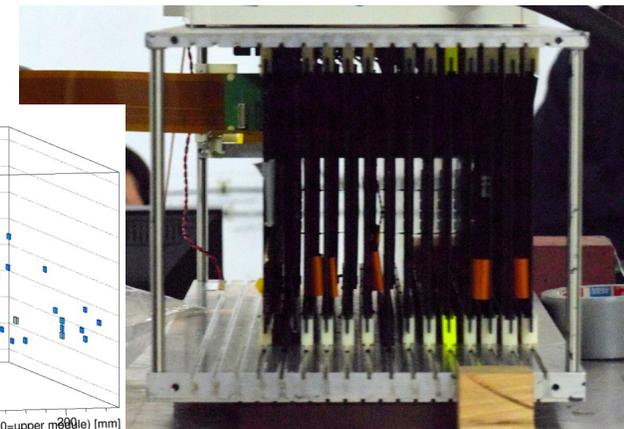
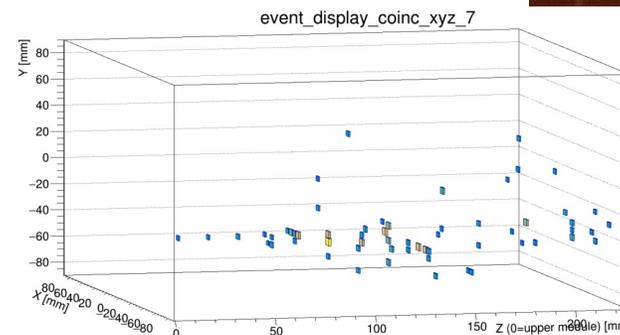
Good energy resolution

[T. Peitzmann](#), H. Yokoyama: "Test beam performance of a digital pixel calorimeter",
T. Rogoschinski: "Simulation of a SiW pixel calorimeter": TIPP 26/5/21

CALICE

Integrated front-end and digital electronics
15 layers with 15360 channels
2.1 mm (x11) and 4.2 mm (x3) tungsten
Culmination of 10 years of prototyping

<https://aitanatop.ific.uv.es/aitanatop/siwecal-tb2021/>

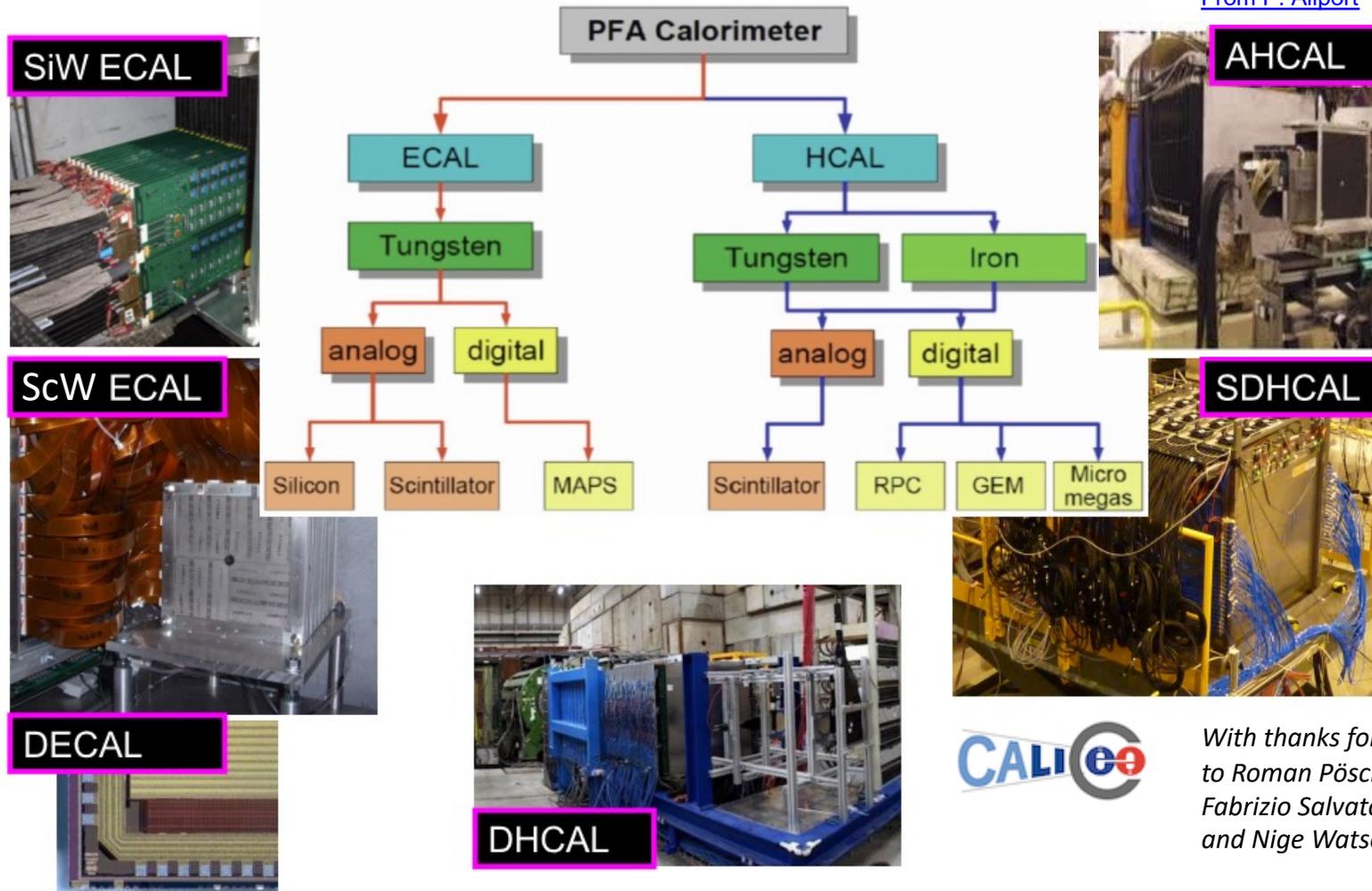


Calorimetry

DRDT 6.2: Particle Flow based on high granularity calorimeters particularly important for e^+e^- Higgs-EW-top factories and to be considered for EIC. Separation of signals by charged and neutral particles in **highly granular calorimeters**.

Options are:

- **Dual-readout** (e.g. DREAM/RD52 Collaboration) f_{EM} from absorber with combined scintillator parallel plates for non-relativistic (hadronic) component and Cherenkov for relativistic (EM) component (PMMA fibres);
- High granularity **LAr/LKr**: LAr proven technique but high granularity challenging;
- Finely segmented **crystals**;
- **Particle Flow based “tracking calorimeter”** concept with very fine sense element segmentation for precise reconstruction of each particle within the jet. Up to $\sim 100M$ channels and 10000 m^2 active elements



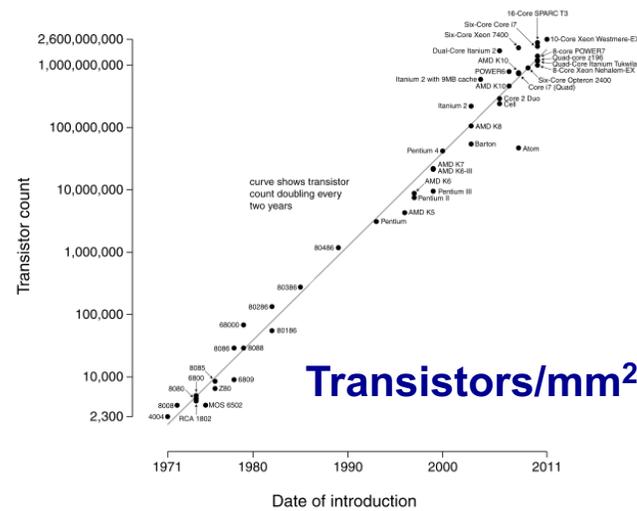
With thanks for help to Roman Pöschl, Fabrizio Salvatore and Nige Watson

DRDT 6.3: Extreme radiation hardness and pile-up rejection critical for FCC-hh in particular

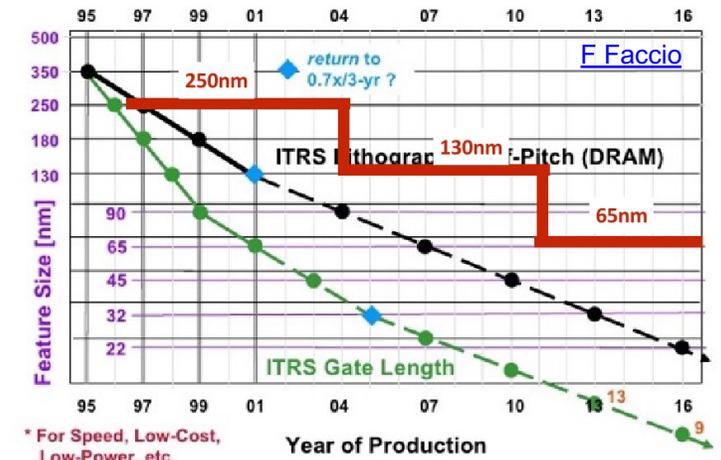
Electronics

- **Precision timing (ToF; 4D tracking), ultra-high granularity** and improved signal resolution all come at a cost in terms of data handling, processing, complexity and power.
- These inevitably require exploiting the latest advances in commercial microelectronics and high-speed links.
- The need for bespoke solutions for even modest radiation or magnetic fields is a further problem as these are not commercial drivers, with HEP at best a niche low volume market.
- For example: Long time to develop radiation tolerance in 65 nm O(GRad) and large cost → technology is not straightforward;

Microprocessor Transistor Counts 1971-2011 & Moore's Law

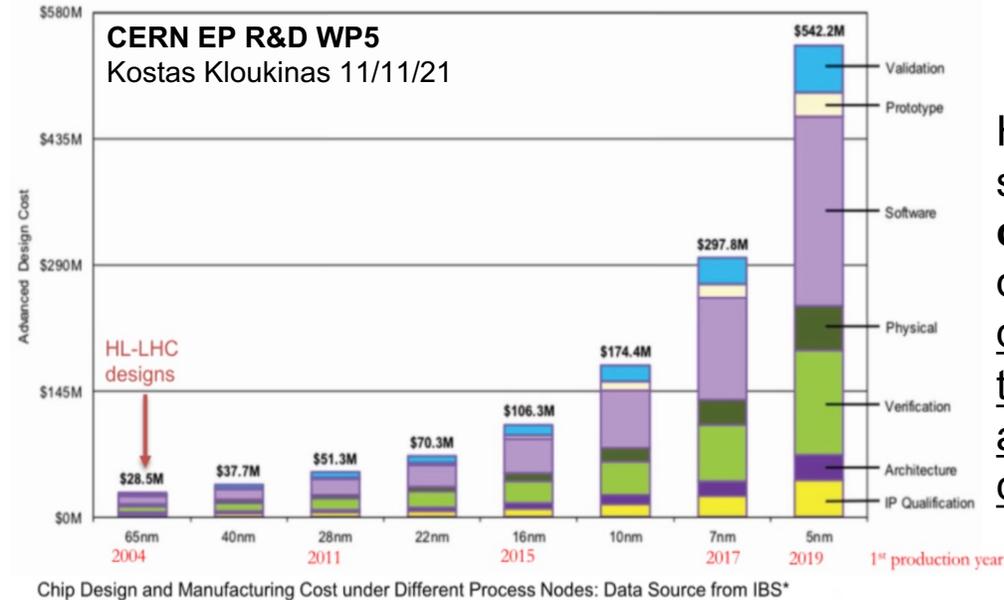


Scaling -- Traditional Enabler of Moore's Law*



RD53 Collaboration
(65 nm ASIC for HL-LHC)

- HEP Community now looks into 28 nm for the future and dedicated 130/65 nm technologies for monolithic pixels

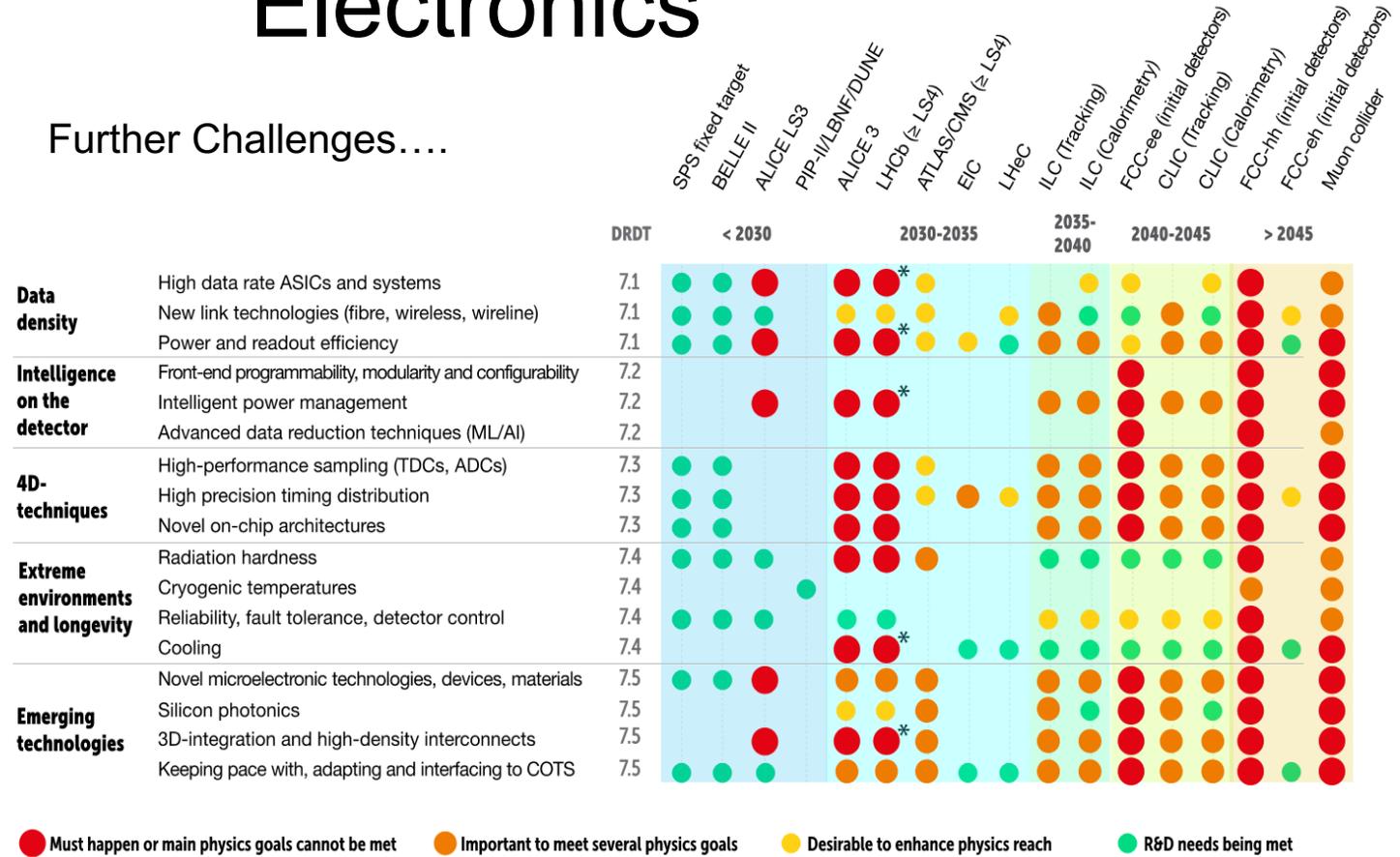


However, increasing sophistication, entry cost and complexity demand radically different approaches to those historically adopted by the HEP community

Electronics

→ Much of the ECFA Detector R&D Roadmap is dedicated to discussion of the need for better organisation and coordination across Europe to cope with these considerable challenges

Further Challenges....



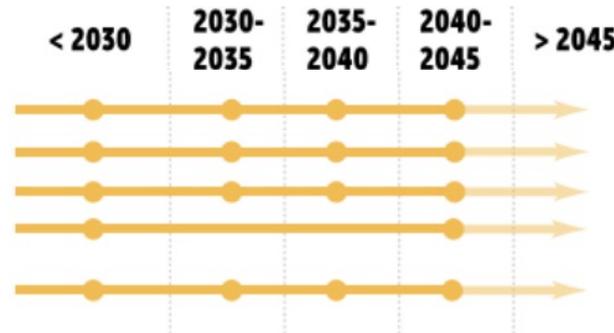
● Must happen or main physics goals cannot be met
 ● Important to meet several physics goals
 ● Desirable to enhance physics reach
 ● R&D needs being met

* LHCb Velo

The DRDTs are

Electronics

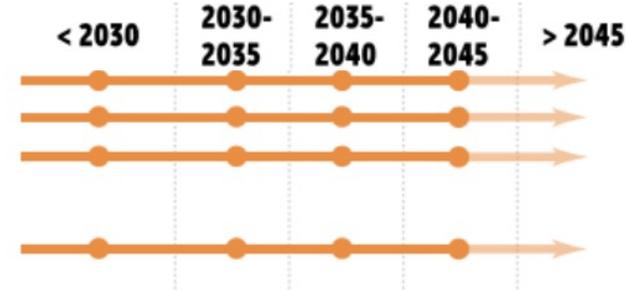
- DRDT 7.1** Advance technologies to deal with greatly increased data density
- DRDT 7.2** Develop technologies for increased intelligence on the detector
- DRDT 7.3** Develop technologies in support of 4D- and 5D-techniques
- DRDT 7.4** Develop novel technologies to cope with extreme environments and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



Integration

- DRDTs:

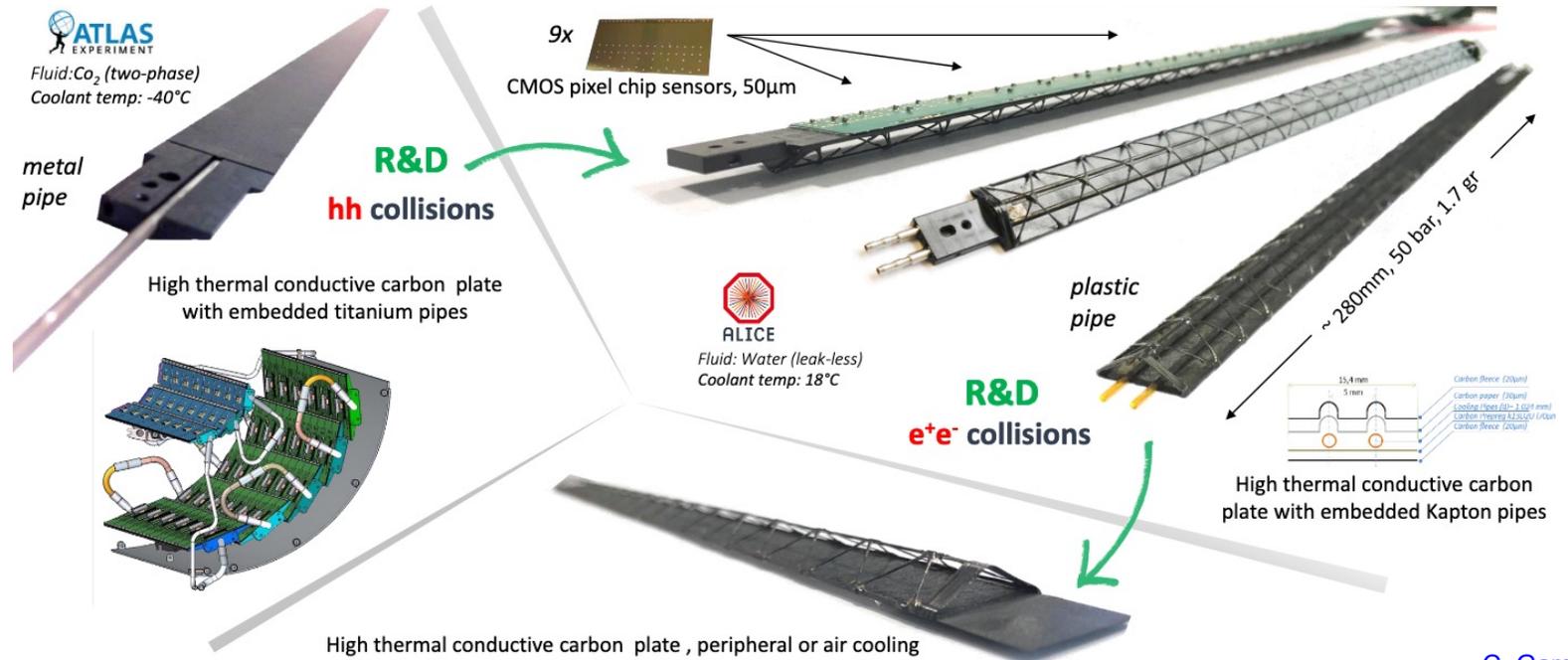
Integration	DRDT 8.1 Develop novel magnet systems
	DRDT 8.2 Develop improved technologies and systems for cooling
	DRDT 8.3 Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces.
	DRDT 8.4 Adapt and advance state-of-the-art systems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



- Investigation of **novel superconductors for magnet systems** as well as support of expert design capabilities and modelling software for future experiments is vital.
- Cooling technologies** for cryogenics and low-mass heat removal from on-detector electronics and semiconductor sensors require dedicated generic R&D activities.

- Ultra low mass, stable, precision mechanics and machine detector interface design** are major topics

- Example: Pipe design



General Strategic Recommendations



- **GSR 1 - Supporting R&D facilities**

It is recommended that the structures to provide Europe-wide coordinated infrastructure in the areas of: **test beams, large scale generic prototyping and irradiation** be consolidated and enhanced to meet the needs of next generation experiments with adequate centralised investment to avoid less cost-effective, more widely distributed, solutions, and to maintain a network structure for existing distributed facilities, e.g. for irradiation

- **GSR 2 - Engineering support for detector R&D**

In response to **ever more integrated detector concepts**, requiring holistic design approaches and large component counts, the R&D should **be supported with adequate mechanical and electronics engineering resources**, to bring in expertise in state-of-the-art microelectronics as well as advanced materials and manufacturing techniques, to tackle generic integration challenges, and to maintain scalability of production and quality control from the earliest stages.

- **GSR 3 - Specific software for instrumentation**

Across DRDTs and through adequate capital investments, the availability to the community of **state-of-the-art R&D-specific software packages must be maintained and continuously updated**. The expert development of these packages - for core software frameworks, but also for commonly used simulation and reconstruction tools - should continue to be highly recognised and valued and the community effort to support these needs to be organised at a European level.

- **GSR 4 - International coordination and organisation of R&D activities**

With a view to creating a vibrant ecosystem for R&D, connecting and involving all partners, there is a need to refresh the CERN RD programme structure and encourage new programmes for next generation detectors, where CERN and the other national laboratories can assist as major catalysers for these. It is also recommended to revisit and streamline the process of creating and reviewing these programmes, with an extended framework to help share the associated load and increase involvement, while enhancing the visibility of the detector R&D community and easing communication with neighbouring disciplines, for example in cooperation with the ICFA Instrumentation Panel.

General Strategic Recommendations



- **GSR 5 - Distributed R&D activities with centralised facilities**

Establish in the relevant R&D areas a distributed yet connected and supportive tier-ed system for R&D efforts across Europe. Keeping in mind the growing complexity, the specialisation required, the learning curve and the increased cost, consider more focused investment for those themes where leverage can be reached through centralisation at large institutions, while addressing the challenge that distributed resources remain accessible to researchers across Europe and through them also be available to help provide enhanced training opportunities.

- **GSR 6 - Establish long-term strategic funding programmes**

Establish, additional to short-term funding programmes for the early proof of principle phase of R&D, also **long-term strategic funding programmes to sustain both research and development of the multi-decade DRDTs** in order for the technology to mature and to be able to deliver the experimental requirements. Beyond capital investments of single funding agencies, international collaboration and support at the EU level should be established. In general, the cost for R&D has increased, which further strengthens the vital need to **make concerted investments**.

- **GSR 7 – “Blue-sky” R&D**

It is essential that adequate resources be provided to support more speculative R&D which can be riskier in terms of immediate benefits but can bring significant and potentially transformational returns if successful both to particle physics: unlocking new physics may only be possible by unlocking novel technologies in instrumentation, and to society. Innovative instrumentation research is one of the defining characteristics of the field of particle physics. **“Blue-sky” developments in particle physics have often been of broader application and had immense societal benefit.** Examples include: the development of the World Wide Web, Magnetic Resonance Imaging, Positron Emission Tomography and X-ray imaging for photon science.

Conclusions

- The progress in experimental particle physics was driven by the advances and breakthrough in instrumentation, leading to the development of new, cutting-edge technologies.
- Many technological challenges and several examples were presented, mainly based on the [ECFA Detector R&D Roadmap](#)
- It starts from the principle of needing to identify the mission critical detector R&D for all the future programmes considered as viable options in the 2020 Update to the European Strategy for Particle Physics. The next step will be for mechanisms to be proposed for implementing the final recommendations.
- Mission critical for different facilities means different things.
- Major R&D funding for the LHC detector R&D programme was in place from 1986. Without the required investment in detector R&D the opportunities the future facility offer will be squandered.
- Personnel, retention and training of detector experts are detailed in the ECFA Detector R&D Roadmap as mandatory to the success as well as the long-term health of experimental particle physics as a whole.

Thank you!

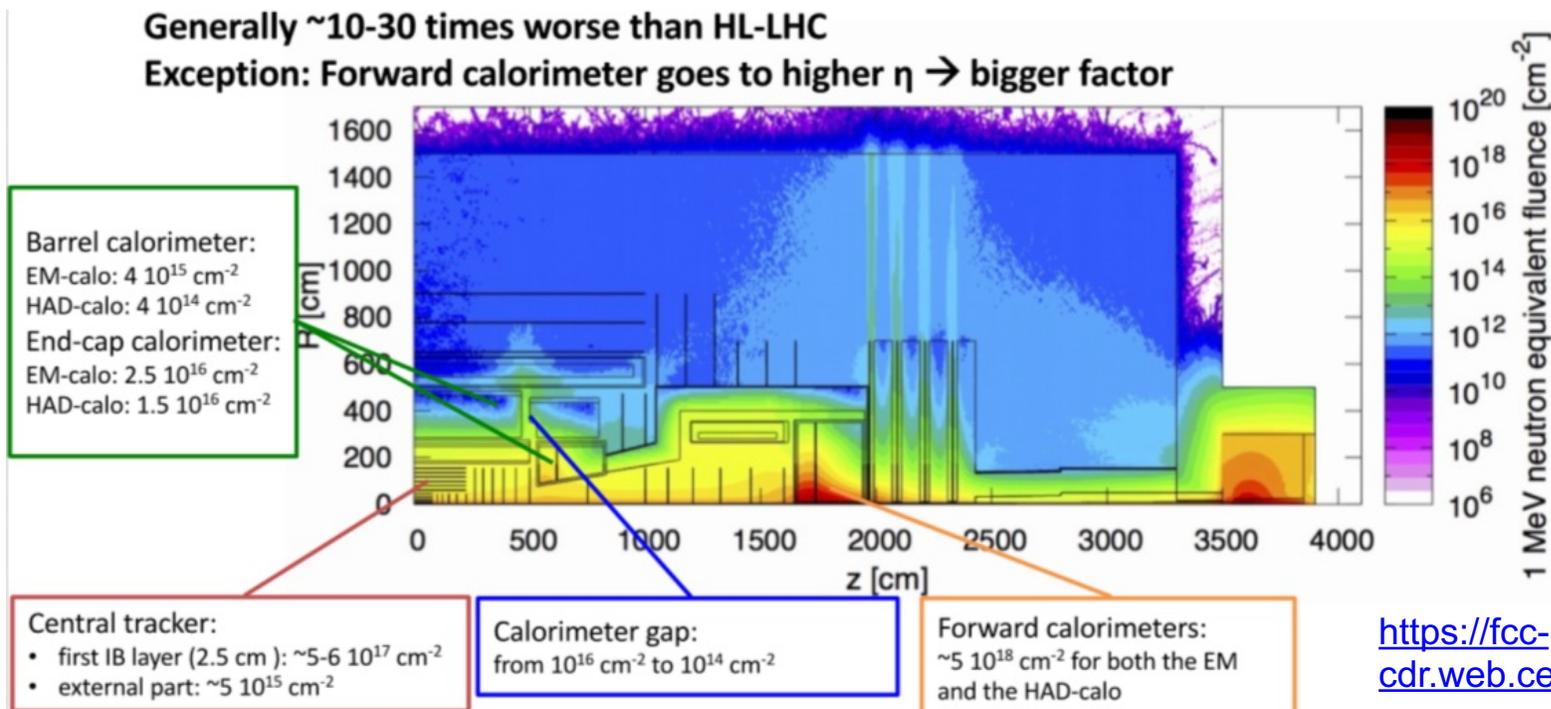
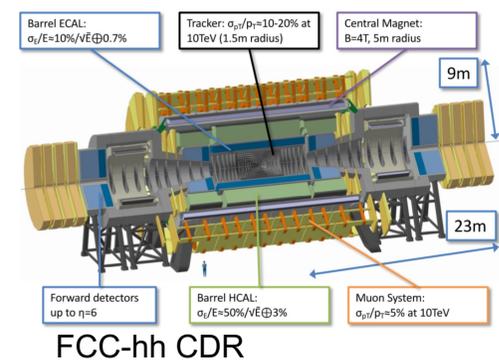
Acknowledgment

Phil Allport, Kerstin Borrás, Maxim Titov, Roman Pöschl,
Christian Joram, Laura Baudis, Corrado Gargiulo, Thomas
Peitzmann, Frank Simon, Sunil Gowala
the ECFA Roadmap Panel

SPARE



Example of future detectors at accelerators

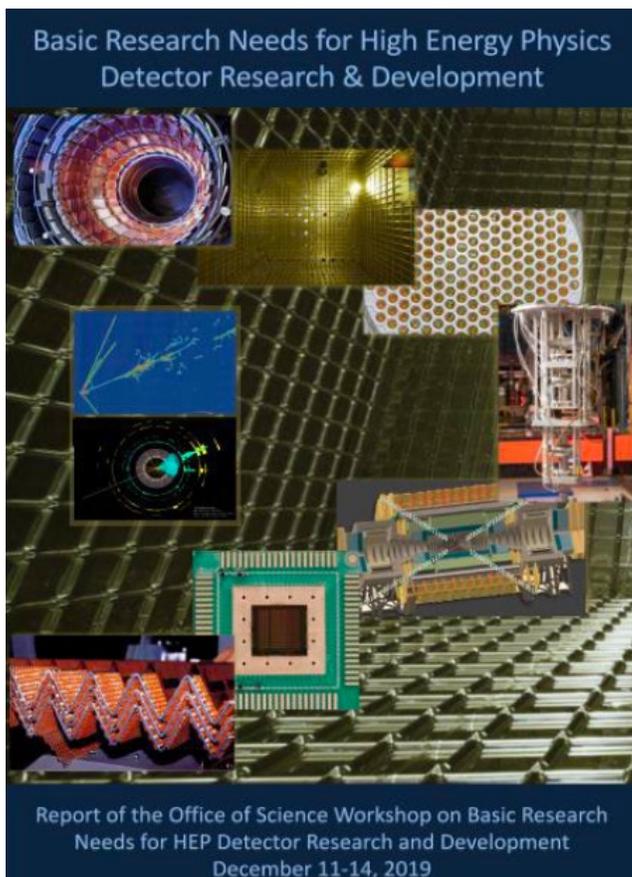


Largest challenge is that radiation levels go well beyond what any currently available microelectronics can survive (\lesssim MGy) and few sensor technologies can cope beyond $\sim 10^{16} n_{\text{eq}}/\text{cm}^2$ (HL-LHC vertex layers)

US: Basic Research Needs Report, Snowmass Process

DOE-BRN Report published (Sep. 2020)

<https://science.osti.gov/hep/Community-Resources/Reports>



Snowmass Instrumentation Frontier: The Snowmass Process is organized by the DPF of the American Physical Society: <https://snowmass21.org>

- Identify and document a vision for the future of particle physics (PP) in the US in a global context
- Communicate opportunities for discovery in PP to broader community and to the (US) government.
- Aim for Snowmass Book and online archive by end of 2022
- <https://snowmass21.org/instrumentation/start> Conveners: P. Barbeau, P. Merkel, J. Zhang

- Snowmass Summary for Public
 - 2 pages

- Snowmass Summary Report
 - ~50 pages

- Snowmass Book
 - ~500 pages

- Topical Group Reports

- Reports of Multi-Frontier Topics

- Contributed Papers
 - = White Papers

Snowmass Report « Community-Driven »:

- Executive Summary: ~10 pages
- Introduction
- 10 Frontier Executive Summaries
- Executive Summaries of Multi-Frontier Topics
- Conclusion

- Snowmass Summary Report (~50 pages)
- Frontier Summaries (~400 pages with 10 Frontiers)
- Multi-Frontier Topic Summaries (~50 pages)

IF Frontier Summary: 40 pages

(Written by TG members including early careers)

- Topical Group Reports: short reports

- Multi-Frontier Topics spanning multiple Frontiers.
- Each Multi-Frontier Topic Summary: ~10 page

(Written by the community including early careers)

- References

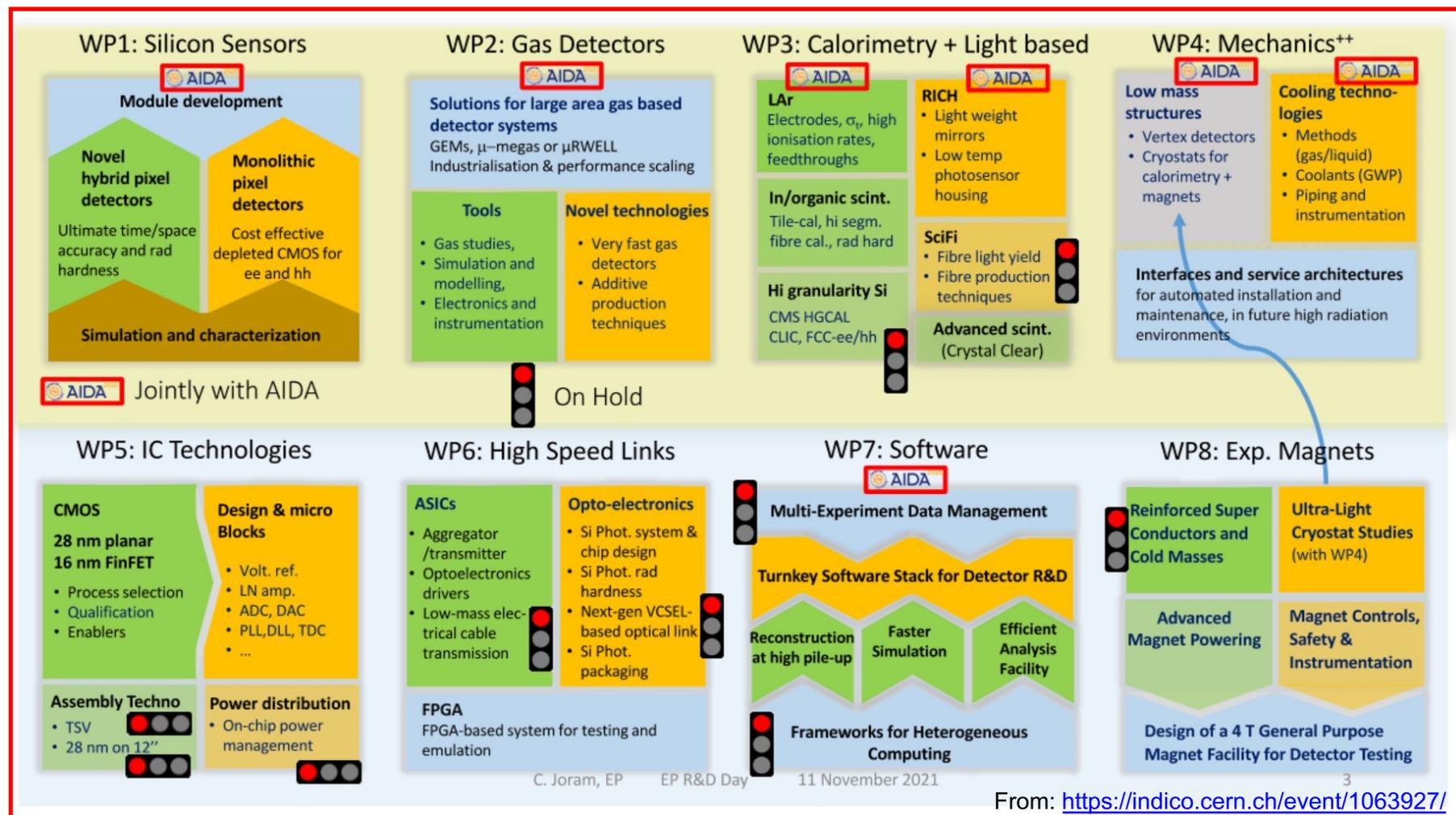
CERN EP R&D



- Following tradition of **DRDC** (LHC Phase-0), White Paper R&D (LHC Phase-I)
- Target **beyond approved LHC upgrades**: e.g. FCC-ee/eh/hh
- Strong links/overlap with RD50, RD51, RD18 and AIDAInnova



- See materials at <https://ep-rnd.web.cern.ch>



From: <https://indico.cern.ch/event/1063927/>

EU: AIDAInnova Project and Detector R&D for Higgs Factories



New AIDAInnovaCall / Objectives:

- Support research **infrastructure** networks developing and implementing a **common strategy/ roadmap** including technological development required for improving their services through **partnership with industry**
- Support **incremental innovation** and cooperation with industry
- Complementarity to ATTRACT
- Increased focus on industrial partners
- No Transnational Access Proposed
- Funding 10 M€ for 4 years

Some targeted applications:

- Higgs Factories
- ATLAS, CMS LS4, ALICE, LHCb LS3 pre-TDR
- Accelerator-based neutrino experiments

Higgs Factory Detector R&D



Detector Technology	Linear & Circular Colliders common R&D	Differences
All	test infrastructure prototype electronics software for reconstruction and optimisation	readout rates power and cooling requirements
Silicon Vertex and Track Detectors	highest granularity and resolution, timing ultra-thin sensors and interconnects simulation and design tools low-mass support structures cooling micro-structures	emphasis on timing (background) and position resolution
Gaseous Trackers and Muon Chambers	ultra-light structures for large volumes industrialisation for large area instrumentation eco-friendly gases	DC and TPC presently considered only at some colliders
Calorimeters and Particle ID	highly compact structures and interfaces advanced photo-sensors and optical materials ps timing sensors and electronics	emphasis on granularity and stability DR and LAr presently only considered for circular

F. Sefkow: <https://indico.cern.ch/event/932973/contributions/4066737/attachments/2140131/3606033/Ainnova-HiggsF-FSefkow20201110.pdf>

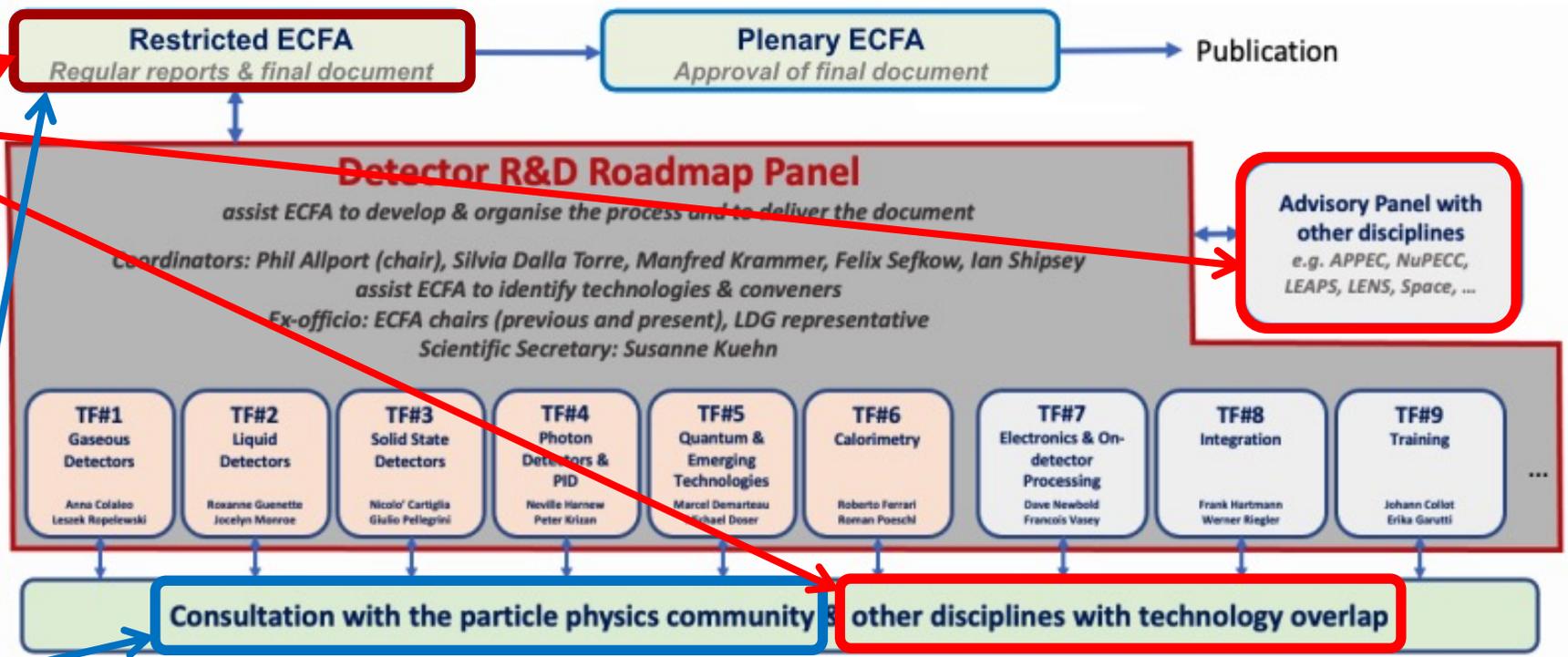
Technology oriented R&D Collaborations

- Originally: "Cell" approach, oriented to select the different LHC experiment detector technologies within CERN DRDC program (90's): <http://committees.web.cern.ch/Committees/obsolete/DRDC/Projects.html>
- **Today: Successful approach to streamline efforts/resources, handle new techniques and common components to on-going detector engineering challenges/production:**
 - RD42 Diamond detectors
 - RD50 Silicon radiation hard devices
 - RD51 Micropattern gas detectors
 - RD53 Pixel readout chip for ATLAS and CMS (65 nm)
- In general, large collaborations of interacting institutes, mostly EU-based with world-wide participation
- Good model, allows to consolidate resources, especially people
- CERN is central, but support needed from other labs and agencies
- **Detector R&D Programs –originally focused on ILC and CLIC Linear Colliders** to exploit complementary/ commonalities of technological developments for different facilities
- **CALICE high granularity electromagnetic and hadronic calorimeters (since 2001 for ILC)**
 - CALICE enabled high granularity calorimetry for CMS HL-LHC upgrade

ECFA Detector R&D Roadmap: Organisation

“Organised by ECFA, a roadmap should be developed by the community to balance the detector R&D efforts in Europe, taking into account progress with emerging technologies in adjacent fields” *

“The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels” *



ECFA Detector R&D Roadmap Panel web pages at:
<https://indico.cern.ch/e/ECFADetectorRDRoadmap>

- Nine Task Forces for six detector technologies and three transversal topics
- Process with input sessions and open symposia (1359 registrants)

* 2020 European Particle Physics Strategy Update
<https://europeanstrategyupdate.web.cern.ch/>

ECFA Detector R&D Roadmap

Main Document published (approval by RECFA at 19/11/21 <https://indico.cern.ch/event/1085137/>) and 8 page synopsis brochure prepared for less specialists audience



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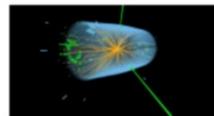


8 page synopsis brochure also prepared for less specialist audience

Building the Foundations

"Strong planning and appropriate investments in Research and Development (R&D) in relevant technologies are essential for the full potential, in terms of novel capabilities and discoveries, to be realised."

The field of particle physics builds on the major scientific revolutions of the 20th century, particularly on the experimental discoveries and theoretical developments which culminated in the Nobel Prize-winning discovery of the Higgs boson at CERN in 2012. The ambitions for the field going forward are set out from a European perspective in a global context in the European Strategy for Particle Physics (ESPP) which was updated in 2020. This strategy lays down a vision for the coming half-century, with a science programme which, in exploring matter and forces at the smallest scales and the Universe at earliest times, will continue to provide answers to questions once thought only to be amenable to philosophical speculation, and has the potential to reveal fundamentally new phenomena or forms of matter never observed before.



3D visualization of a simulated Higgs boson decaying into two photons as observed by the CMS experiment. (© CERN)

The ESPP recognises the huge advances in accelerator and detector technologies since the world's first hadron collider, the Intersecting Storage Rings, started operation at CERN 50 years ago. These advances have not only supported, and in turn benefited from, numerous other scientific disciplines but have spawned huge societal progress through developments such as the World Wide Web, Magnetic Resonance Imaging, Positron Emission Tomography and 3D X-ray



Installation of the CMS Central Tracking Detector with 10 million read-out channels using silicon detectors covering an area of over 200 m². (© CERN)

The far-reaching plans of the ESPP require similar progress over the coming decades in accelerator and detector capabilities to deliver its rich science programme. Strong planning and appropriate investments in Research and Development (R&D) in relevant technologies are essential for the full potential, in terms of novel capabilities and discoveries, to be realised.

The 2020 update of the ESPP called on the European Committee for Future Accelerators (ECFA) to develop a global Detector R&D Roadmap defining the backbone of detector R&D required to deploy the community's vision. This Roadmap aims to cover the needs of both the near-term and longer-term programme, working in synergy with neighbouring fields and with a view to potential industrial applications.



Particle spectrometer, which covers and measures the paths of particles produced by the Large Hadron Collider. (© CERN)

Identifying the Tools

"It is vital to build on Europe's world-leading capabilities in sensor technologies for particle detection."

The figure opposite illustrates the "Detector R&D Themes" (DRDTs) and "Detector Community Themes" (DCTs) identified in the roadmap process, grouped according to the areas addressed by the new task forces set up by ECFA to develop a strategy for future detector R&D priorities. All the themes are critical to achieving the science programme outlined in the ESPP and are derived from the technological challenges that need to be overcome for the scientific potential of the future facilities and projects listed in the ESPP to be realised. It is important to ensure that, for each of the future facilities mentioned in the ESPP, detector readiness should not be the limiting factor in terms of when the facility in question can be realised. In many cases, less demanding developments are required for experiments scheduled in the medium term, which can then act as "stepping stones" (illustrated by the in-between dots) towards achieving the final specifications.



Illustration of microelectronics circuitry integrated with a detecting medium as a single monolithic active-state detector. (© ALICE collaboration)

The R&D priorities are outlined for the key detector types: those based on gaseous, liquid or solid sensing materials; along with those required for sensing aspects specific to photon detection, particle identification (PID) or energy measurement (calorimetry). In addition, quantum sensors are already offering radically new opportunities in particle physics, and their further development will widen their applicability to the field. Sophisticated read-out technologies are essential to all detector types and are often the limiting factor when very large numbers of channels are to be instrumented, especially given the ever more demanding sensitivity and robustness required for operation in the extreme conditions of many particle physics experiments. Unique advanced engineering solutions are needed to complement all these detector developments and, as with accelerators, the field drives many aspects of progress in magnet technology. Last but not least, environmental sustainability is a central requirement for all future research and innovation activities.



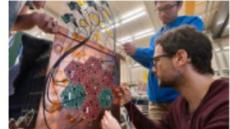
Paul Scherrer Institute (Switzerland) facility for delivering high-targeted radiotherapy with beams of accelerated protons (proton therapy). (© Scandinavian Super Proton Therapy)

Given the vital importance of expertise in a wide range of cutting-edge technologies, the Detector R&D Roadmap also contains specific recommendations in terms of training. Detector Community Themes with emphasis on providing better coordination between the many different training schemes available across Europe, and exploring mechanisms to establish a core syllabus for a Masters qualification in particle physics instrumentation that brings together the crucial elements from the large number of diverse existing courses. Given the uneven access to training in the area of instrumentation in all regions of the world, a key focus is to greatly improve the inclusivity of future programmes, workshops and schools, encouraging the widest possible diversity of participants.



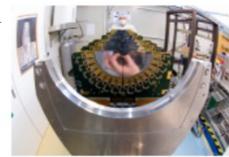
Detector R&D testing and assembly laboratory (LHC upgrades, future collider facilities and medical applications). (© BFLPA, University of Birmingham)

While defining the priorities within particle physics, as outlined above, the ECFA Detector R&D Roadmap also emphasises the vital importance of benefiting from synergies with adjacent research fields, knowledge institutions and high-technology industries.



Students and young scientists working on the construction of prototype detector modules. (© CERN)

Person and study necessities



Linear Collider (ILD) of the LHC experiment allowing after-hadron particle physics to be measured with precision at a tenth of a picosecond. (© CERN)

The Higgs boson and study other deepest questions in physics necessitates a roadmap for the required detector technologies (in much the same way as the LHC and its upgrades significantly guided R&D planning for previous decades). The ECFA Detector R&D Roadmap addresses this need whilst highlighting synergies with other projects on nearer timescales and showing how they are also embedded in the longer-term context.



Insertion of lead tungstate crystals (over three times the density of conventional glass) into the high-granularity electromagnetic calorimeter of the ALICE detector giving percent scale energy measurements. (© CERN)

In the area of detector development, it is vital to build on Europe's world-leading capabilities in sensor technologies for particle detection, using gas and liquid-based or solid-state detectors, as well as energy measurement and particle identification. Also required are cutting-edge developments in bespoke microelectronics solutions, real-time data processing and advanced engineering. Adequate resourcing for such technology developments represents a vital component for future progress in experimental particle physics. Talented and committed people are another absolutely core requirement. They need to be enthused, engaged, educated, empowered and employed. The ECFA Detector R&D Roadmap brings forward concrete proposals for nurturing the scientists, engineers and technicians who will build the future facilities and for incentivising them by offering appropriate and rewarding career opportunities.



ProtonDRAC: three hundred cubic metre volume proton detector. (© CERN)

SYNOPSIS OF THE 2021 ECFA DETECTOR RESEARCH AND DEVELOPMENT ROADMAP
by the European Committee for Future Accelerators Detector R&D Roadmap Process Group

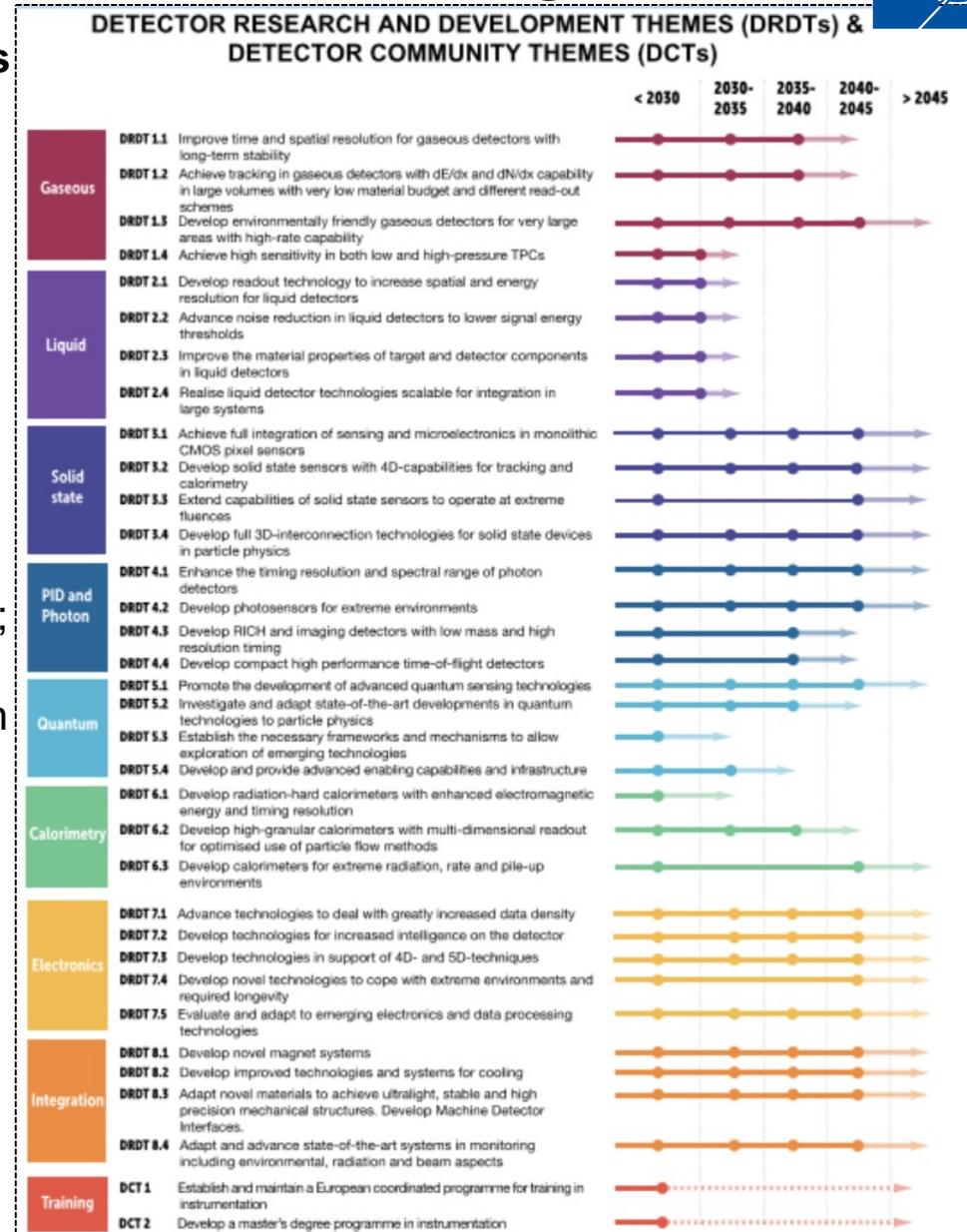


ECFA
European Committee for Future Accelerators

ECFA Detector R&D Roadmap: Technologies



- Within each Task Force created a time-ordered technology requirements driven R&D roadmap in terms of capabilities not currently achievable. It is also noted that in many cases, the programme for a nearer-term facility helps enable the technologies needed for more demanding specifications later, providing stepping stones towards these.
- The principle is that for the earliest feasible start dates of a proposed facility (including those which are still considered in the EPPSU, but would be mutually exclusive):
 - the basic detector R&D phase is not the time limiting step, i.e. that R&D is started sufficiently early and prioritised correctly to meet the needs of the long-term European particle physics programme in its global context;
 - the outcomes of the R&D programme are able to provide the necessary information on the feasibility and cost of future deliverables to allow such decisions to be made.
- Developed and defined “**Detector R&D Themes**” (DRDTs) to highlight the most important drivers for research in each technology area and **Detector Community Themes** in the context of the training area (TF9).
- The relevant Task Forces have then **identified a set of detector R&D areas** which are required if the physics programmes of experiments at these facilities are not to be compromised → **Examples in following slides for few technologies and concepts**



European Particle Physics Strategy Update



“Main report: *“Recent initiatives with a view towards strategic R&D on detectors are being taken by CERN’s EP department and by the ECFA detector R&D panel, supported by EU-funded programmes such as AIDA and ATTRACT. Coordination of R&D activities is critical to maximise the scientific outcomes of these activities and to make the most efficient use of resources; as such, there is a clear need to strengthen existing R&D collaborative structures, and to create new ones, to address future experimental challenges of the field beyond the HL-LHC. Organised by ECFA, a roadmap should be developed by the community to balance the detector R&D efforts in Europe, taking into account progress with emerging technologies in adjacent fields.”*

Deliberation document: *“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. Collaborative platforms and consortia must be adequately supported to provide coherence in these R&D activities. The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels.”*

Extracted from the documents of 2020 EPPSU, <https://europeanstrategyupdate.web.cern.ch/>

More roadmap process details at: <https://indico.cern.ch/e/ECFADetectorRDRoadmap>

ECFA Detector R&D Roadmap: All involved



Task Force convenors, Task Force expert members and Panel members of the ECFA Detector R&D Roadmap Process

Task Force 1 Gaseous Detectors: Anna Colaleo¹, Leszek Ropelewski² (Convenors)
Klaus Dehmelt³, Barbara Liberti⁴, Maxim Titov⁵, Joao Veloso⁶ (Expert Members)

Task Force 2 Liquid Detectors: Roxanne Guenette⁷, Jocelyn Monroe⁸ (Convenors)
Auke-Pieter Colijn⁹, Antonio Ereditato^{10,11}, Ines Gil Botella¹²,
Manfred Lindner¹³ (Expert Members)

Task Force 3 Solid State Detectors: Nicolo Cartiglia¹⁴, Giulio Pellegrini¹⁵ (Convenors)
Daniela Bortoletto¹⁶, Didier Contardo¹⁷, Ingrid Gregor^{18,19}, Gregor Kramberger²⁰,
Heinz Pernegger² (Expert Members)

Task Force 4 Particle Identification and Photon Detectors: Neville Harnew¹⁶,
Peter Krizan²⁰ (Convenors)
Ichiro Adachi²¹, Eugenio Nappi¹, Christian Joram²,
Christian Schultz-Coulon²² (Expert Members)

Task Force 5 Quantum and Emerging Technologies: Marcel Demarteau²³,
Michael Doser² (Convenors)
Caterina Braggio²⁴, Andy Geraci²⁵, Peter Graham²⁶, Anna Grasselino²⁷,
John March Russell¹⁶, Stafford Withington²⁸ (Expert Members)

Task Force 6 Calorimetry: Roberto Ferrari²⁹, Roman Poeschl³⁰ (Convenors)
Martin Aleksa², Dave Barney², Frank Simon³¹,
Tommaso Tabarelli de Fatis³² (Expert Members)

Task Force 7 Electronics: Dave Newbold³³, Francois Vasey² (Convenors)
Niko Neufeld², Valerio Re²⁹, Christophe de la Taille³⁴, Marc Weber³⁵ (Expert Members)

Task Force 8 Integration: Frank Hartmann³⁵, Werner Riegler² (Convenors)
Corrado Gargiulo², Filippo Resnati², Herman Ten Kate³⁶, Bart Verlaet²,
Marcel Vos³⁷ (Expert Members)

Task Force 9 Training: Johann Collot³⁸, Erika Garutti^{18,39} (Convenors)
Richard Brenner⁴⁰, Niels van Bakel⁹, Claire Gwenlan¹⁶, Jeff Wiener²,
ex-officio Robert Appleby⁴¹ (Expert Members)

The Task Force Convenors just listed below to compose the Detector R&D Roadmap Panel.

Panel coordinators: Phil Allport⁴² (Chair), Silvia Dalla Torre⁴³, Manfred Krammer²,
Felix Sefkow¹⁸, Ian Shipsey¹⁶

Ex-officio Panel members: Karl Jakobs⁴⁴ (Current ECFA Chair),
Jorgen D'Hondt⁴⁵ (Previous ECFA Chair), Lenny Rivkin⁴⁶ (LDG Representative)

Scientific Secretary: Susanne Kuehn²

ECFA Two Days of Input Sessions

Input session speakers provided detailed specifications and continued giving support for the process ... particularly for checking if there were any unmet detector R&D needs for the ESPP identified programme which may have been overlooked in the symposia programmes.

Speaker	Presentation Topic
1 Chris Parkes	Detector R&D requirements for HL-LHC
2 Luciano Musa	Detector R&D requirements for strong interaction experiments at future colliders
3 Johannes Bernhard	Detector R&D requirements for strong interaction experiments at future colliders
4 Frank Simon	Detector R&D requirements for future linear high energy e+e- machines
5 Mogens Dam	Detector R&D requirements for future circular high energy e+e- machines
6 Martin Aleksa	Detector R&D requirements for future high-energy hadron colliders
Nadia Pastrone	Detector R&D requirements for muon colliders
Diego Nesi	Detector R&D requirements for future short and long baseline neutrino experiments
De Jong	Detector R&D requirements for future astro-particle neutrino experiments
	Detector R&D requirements for future dark matter experiments
	Detector R&D requirements for future rare decay processes experiments
	Detector R&D requirements for future low energy experiments

19th November 2021

covered all the future facilities and (see back-up).
focused full-day public community input.

Date	Topic
30 Apr	ECFA Detector R&D Roadmap Symposium of Task Force 9 Training
29 Apr	ECFA Detector R&D Roadmap Symposium of Task Force 1 Gaseous Detectors
23 Apr	ECFA Detector R&D Roadmap Symposium of Task Force 3 Solid State Detectors
12 Apr	ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies
	ECFA Detector R&D Roadmap Symposium of Task Force 2 Liquid Detectors
	ECFA Detector R&D Roadmap Symposium of Task Force 8 Integration
	ECFA Detector R&D Roadmap Symposium of Task Force 7 Electronics and On-detector

Common registration for the participants by the end of the last session.
Received extensive feedback during symposia.

Surveys were also employed to receive direct feedback from individuals and via RECA delegates or their National Committees.

APOD appointed experts consulted where needed by Task Force convenors for advice on developments in their disciplines.

19th November 2021

Full-day Public Symposia

Date	Topic
07 May	ECFA Detector R&D Roadmap Symposium of Task Force 6 Calorimetry
06 May	ECFA Detector R&D Roadmap Symposium of Task Force 4 Photon Detectors and Particle Identification Detectors
30 Apr	ECFA Detector R&D Roadmap Symposium of Task Force 9 Training
29 Apr	ECFA Detector R&D Roadmap Symposium of Task Force 1 Gaseous Detectors
23 Apr	ECFA Detector R&D Roadmap Symposium of Task Force 3 Solid State Detectors
12 Apr	ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies
	ECFA Detector R&D Roadmap Symposium of Task Force 2 Liquid Detectors
	ECFA Detector R&D Roadmap Symposium of Task Force 8 Integration
	ECFA Detector R&D Roadmap Symposium of Task Force 7 Electronics and On-detector

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ECFA Detector R&D Roadmap

19th November 2021

ECFA National Contacts

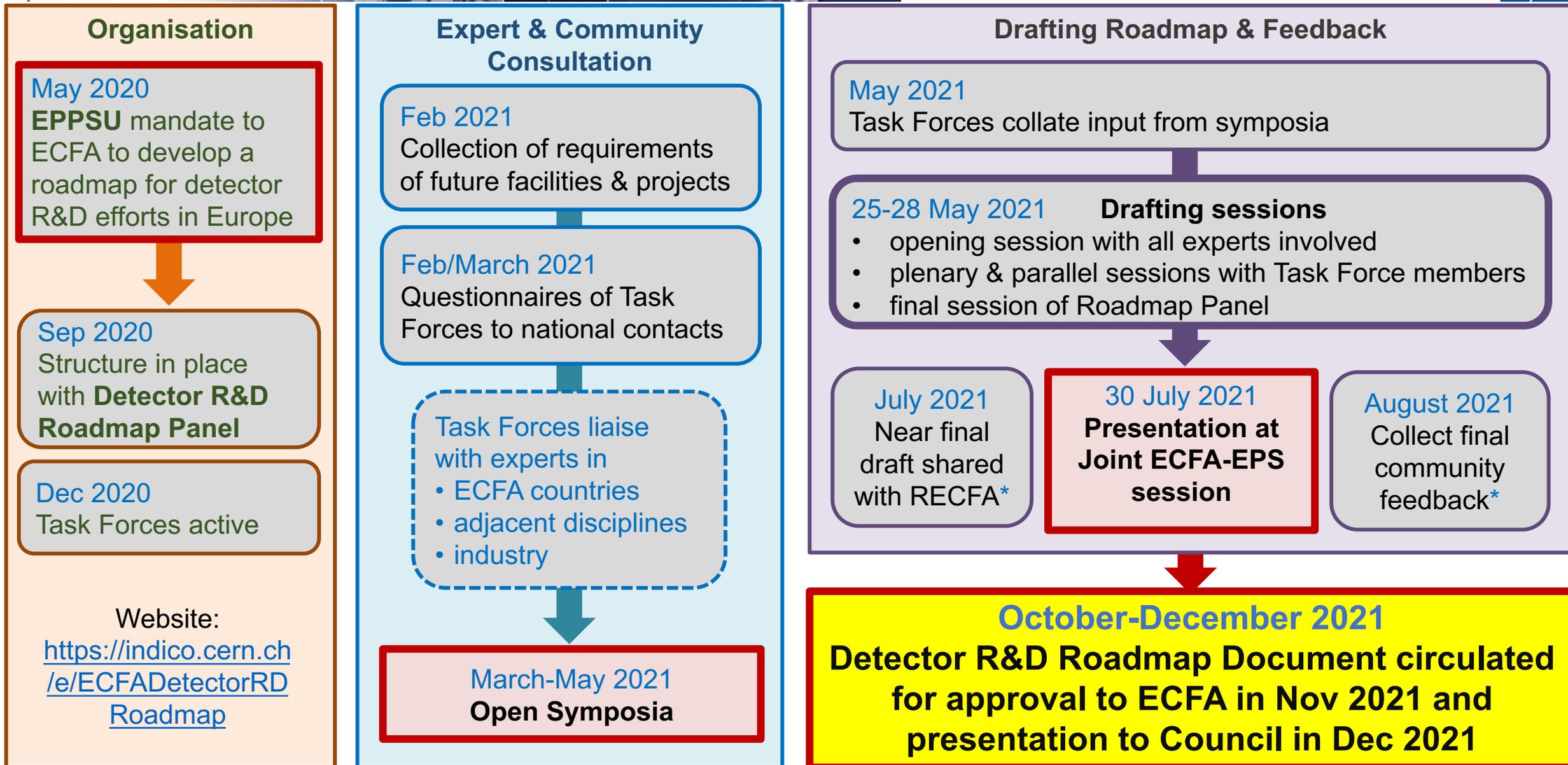
Country	Name	Country	Name
Austria	Manfred Jeitler	Finland	Panja Lukka
	Gilles De	France	Didier Contardo
Belgium	Lentdecker	Germany	Lutz Feld
	Venelin	Greece	Dimitris Loukas
Bulgaria	Koshuharov	Hungary	Dezso Varga
Croatia	Tome Anticic	Italy	Nadia Pastrone
Cyprus	Panos Razis	Israel	Erez Etzion
Czech Republic	Tomáš Davidek	Netherlands	Niels van Bakel
Denmark	Mogens Dam	Norway	Gerald Eigen
		Poland	Marek Idzik
		Portugal	Paulo Fonte
		Romania	Mihai Petrovici
		Serbia	Lidija Zivkovic
		Slovakia	Pavol Strizenc
			Gregor
		Slovenia	Kramberger
		Spain	Mary-Cruz Fouz
		Sweden	Christian Ohm
		Switzerland	Ben Kilminster
		Turkey	Kerem Cankocak
United-Kingdom			Iacopo Vivarelli
Ukraine			Nikolai Shulga
CERN			Christian Joram

Advisory Panel with Other Disciplines

APPEC: Astro-Particle Physics European Consortium
ESA: European Space Agency
LEAPS: League of European Accelerator-based Photon Sources
LENS: League of advanced European Neutron Sources
NuPECC: Nuclear Physics European Collaboration Committee

Country	Name
LENS	171 Bruno Guenard (ILL)
	172 Manfred Lindner (MPI Heidelberg)
	173
	174
	175 Helmut Schuber (ILL)
	176
	177 Bruno Guenard (ILL)
	178
	179 Nick Helms
	181 Nick Helms
	182 Brian Shortt
	183 Nick Helms
	184 Alessandra Santoni
	185 Alessandra Constantino Mucio
	186 Brian Shortt
	187 Peter Verhoeven
	188 Sarah Wittig
	189 Nick Helms
	190 Christian Joram
	191 David Blazevic Joram
	192 Christian Joram
	193 Werner Riegler (CERN)
	194 Lars Schmitt
	195 Michael Devezoux
	196
	197 Jorg Tor Haar
	198 Christiane Hornwald
	199 Nick Helms
	200 Alessandra Constantino Mucio
	201 Massimo Ingrosso
	202 Christophe Hornwald

Thanks also due to the expert Input Session speakers, the 121 Symposia attendees and the 44 APD TF topic specific contacts.



Links for Roadmap Process

<https://indico.cern.ch/event/957057/page/21633-mandate> (Panel Mandate document)

<https://indico.cern.ch/event/957057/page/21653-relevant-documents>

<https://home.cern/resources/brochure/cern/european-strategy-particle-physics>

<https://arxiv.org/abs/1910.11775> (Briefing Book)

https://science.osti.gov/-/media/hep/pdf/Reports/2020/DOE_Basic_Research_Needs_Study_on_High_Energy_Physics.pdf

<https://ep-dep.web.cern.ch/rd-experimental-technologies> (CERN EP R&D)

<https://aidainnova.web.cern.ch> (linking research infrastructures in detector development and testing)

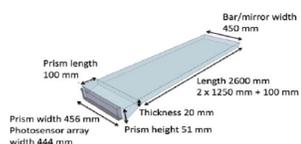
<https://attract-eu.com/> (ATTRACT: linking to industry on detection and imaging technologies)

https://ecfa-dp.desy.de/public_documents/ (Some useful documents from the ECFA Detector Panel)

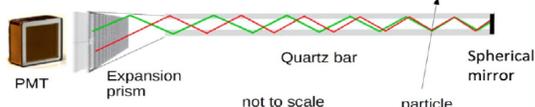
Concepts of Picosecond (a few 10's) Timing Detectors

- Several types of technologies are considered for “Picosecond-Timing Frontier”:
 - Ionization detectors (silicon detectors or gas-based devices)
 - Light-based devices (scintillating crystals coupled to SiPMs, Cherenkov absorbers coupled to photodetectors with amplification, or vacuum devices)

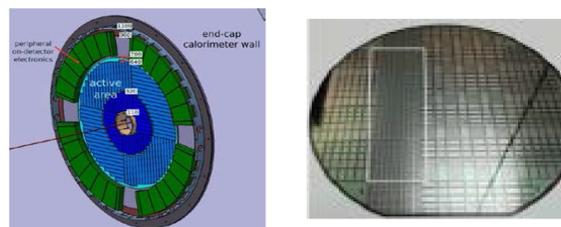
CONVENTIONAL MCP – PMT APPLICATIONS:



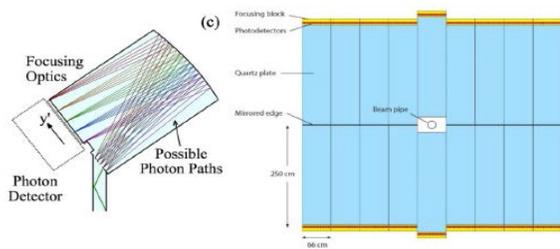
BELLE II TOP:



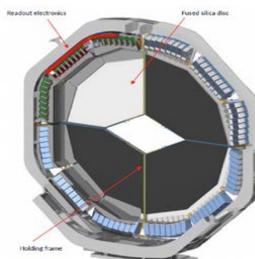
ATLAS HGTD (CMS ETL) TIMING WITH LGAD:



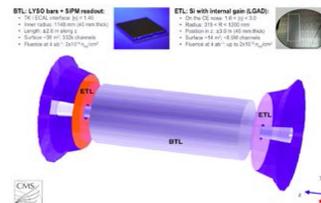
LHCb TORCH DIRC:



PANDA ENDCAP

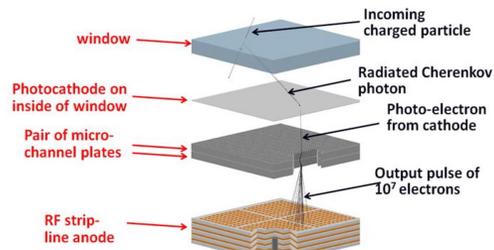


CMS BTL TIMING WITH LYSO:Ce / SiPMs



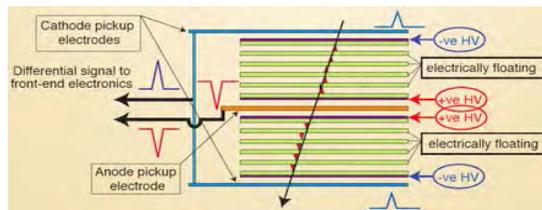
Examples of timing detectors at a level of ~ 30 ps for MIPs and ~ 100 ps for single photons

LAPPD TIMING PROJECT:

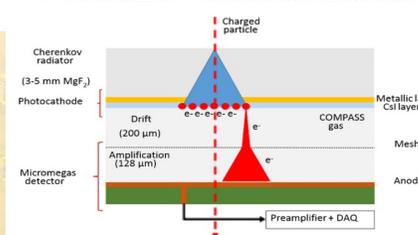


GASEOUS DETECTORS APPLICATIONS:

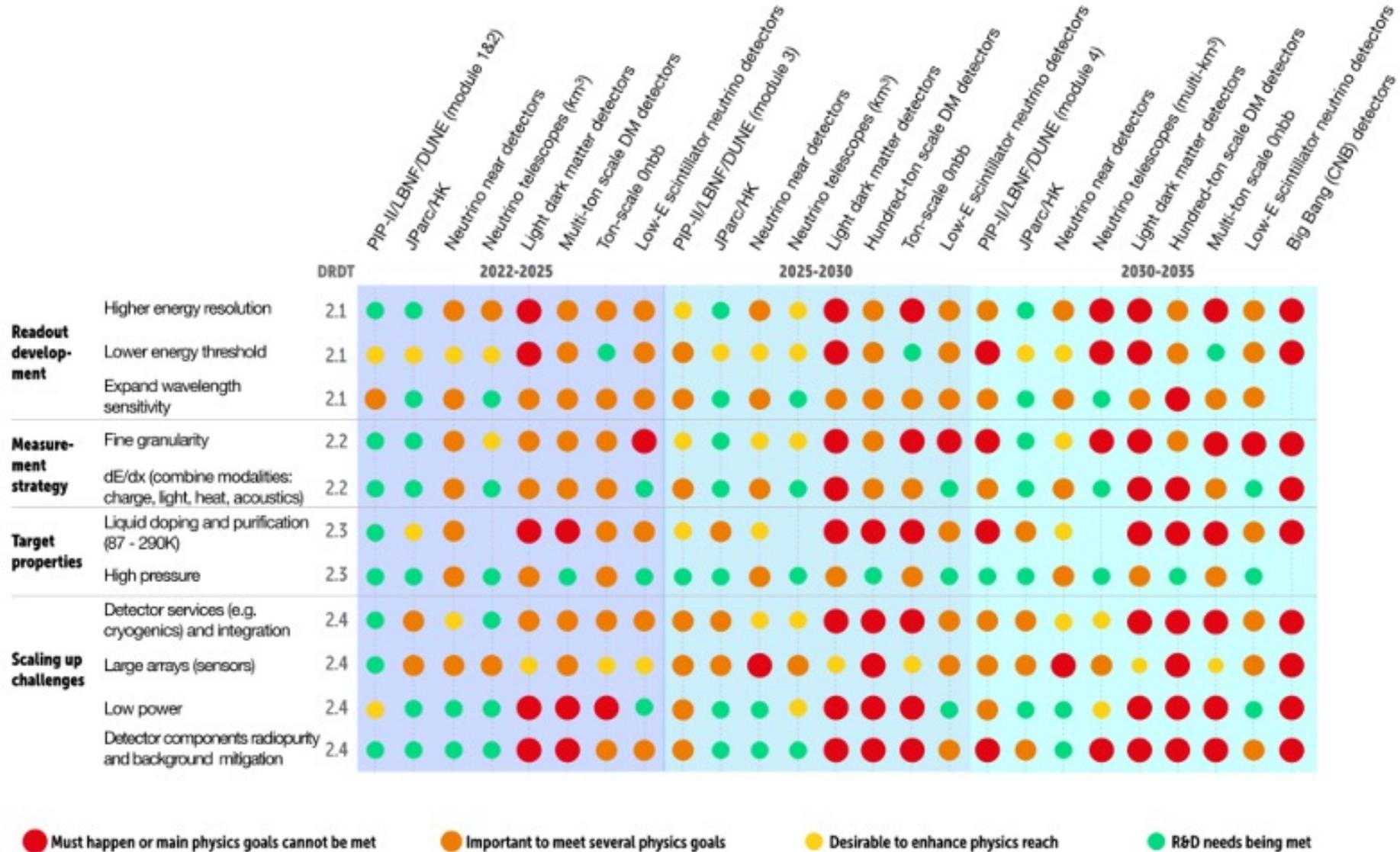
ALICE MPRC TOF:



PICOSEC - MICROMEGAS:



Liquid detectors

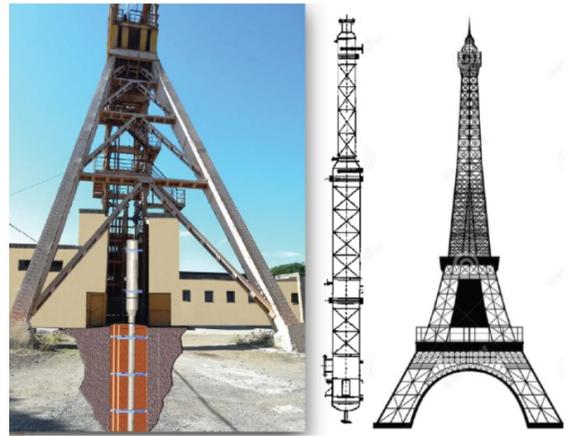


Liquid detectors: Underground Dark Matter experiments

- Variety of DM experiments with small and rare signals need extreme control of background sources (radiopurity) coupled with high sensitivity and discrimination of signal from residual backgrounds
- R&D for multi-ton scale noble liquids: **Target properties**
 - Low-radioactivity argon: extraction (Urania plant, 330 kg/d), purification (ARIA facility, 10 kg/d)
 - Fast purification in liquid phase for large e-lifetime (removal of O₂ and H₂O impurities) → high light and charge yield; radon-free filters
- R&D for multi-ton scale noble liquids: **Detector performance and background control**
 - Single phase versus two-phase TPCs
 - Distillation columns for krypton and radon, material screening and selection, radon emanation

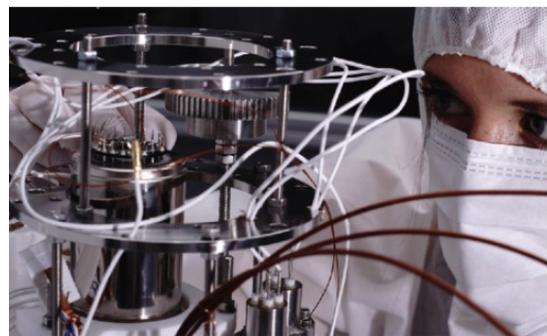
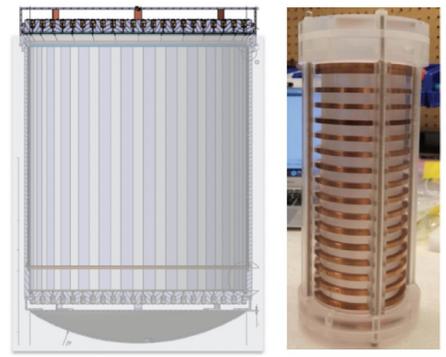


LXe purification system (5 L/min LXe, faster cleaning; 2500 slpm) for XENONnT

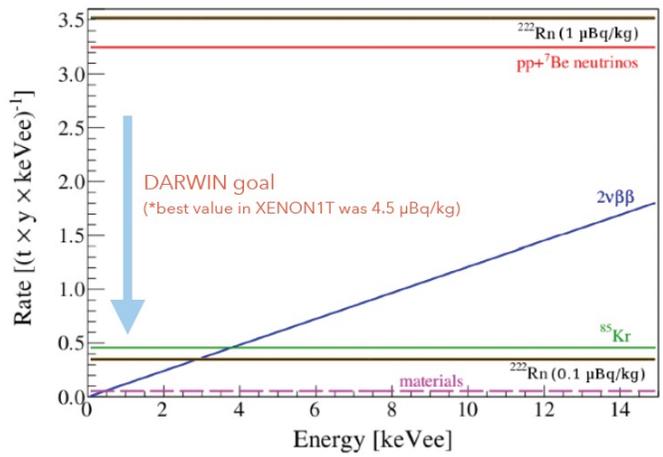


ARIA underground purification system for argon (DarkSide-20k)

R&D on sealed TPC for DARWIN; JINST 16 P01018 (2021)

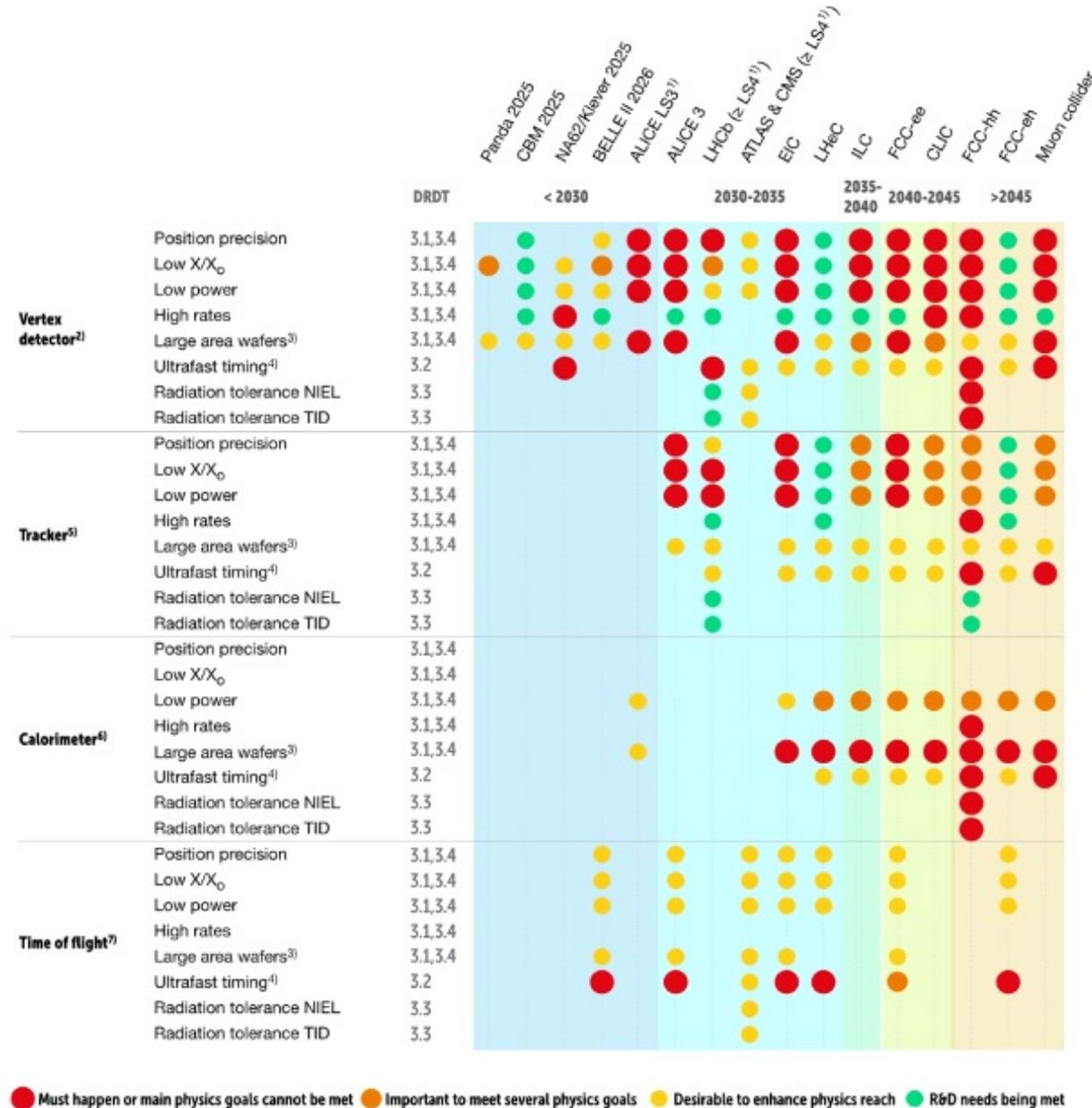


Hermetic TPC R&D for DARWIN

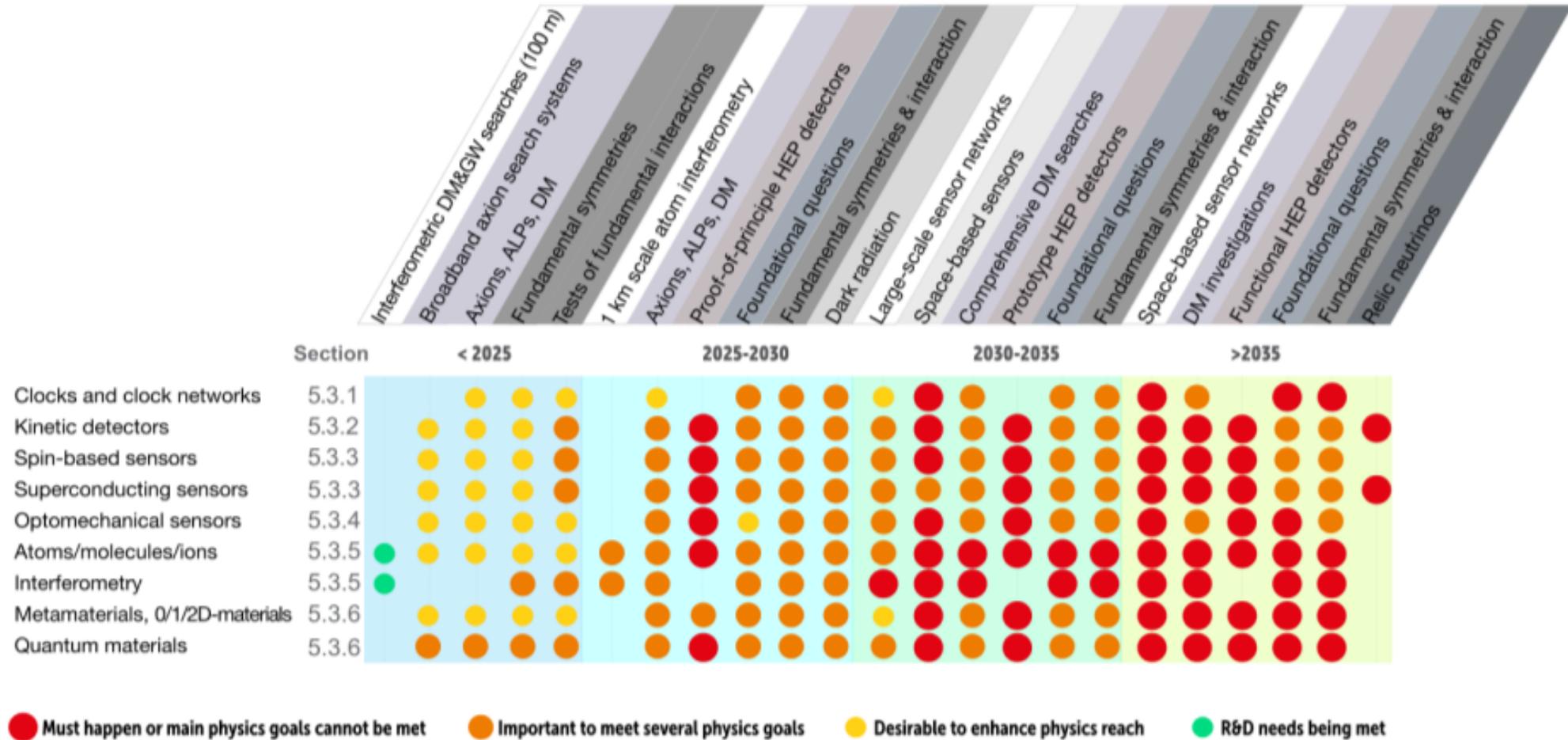


Rn distillation column for XENONnT (reduce ²²²Rn - hence also ²¹⁴Bi - from pipes, cables, cryogenic system)

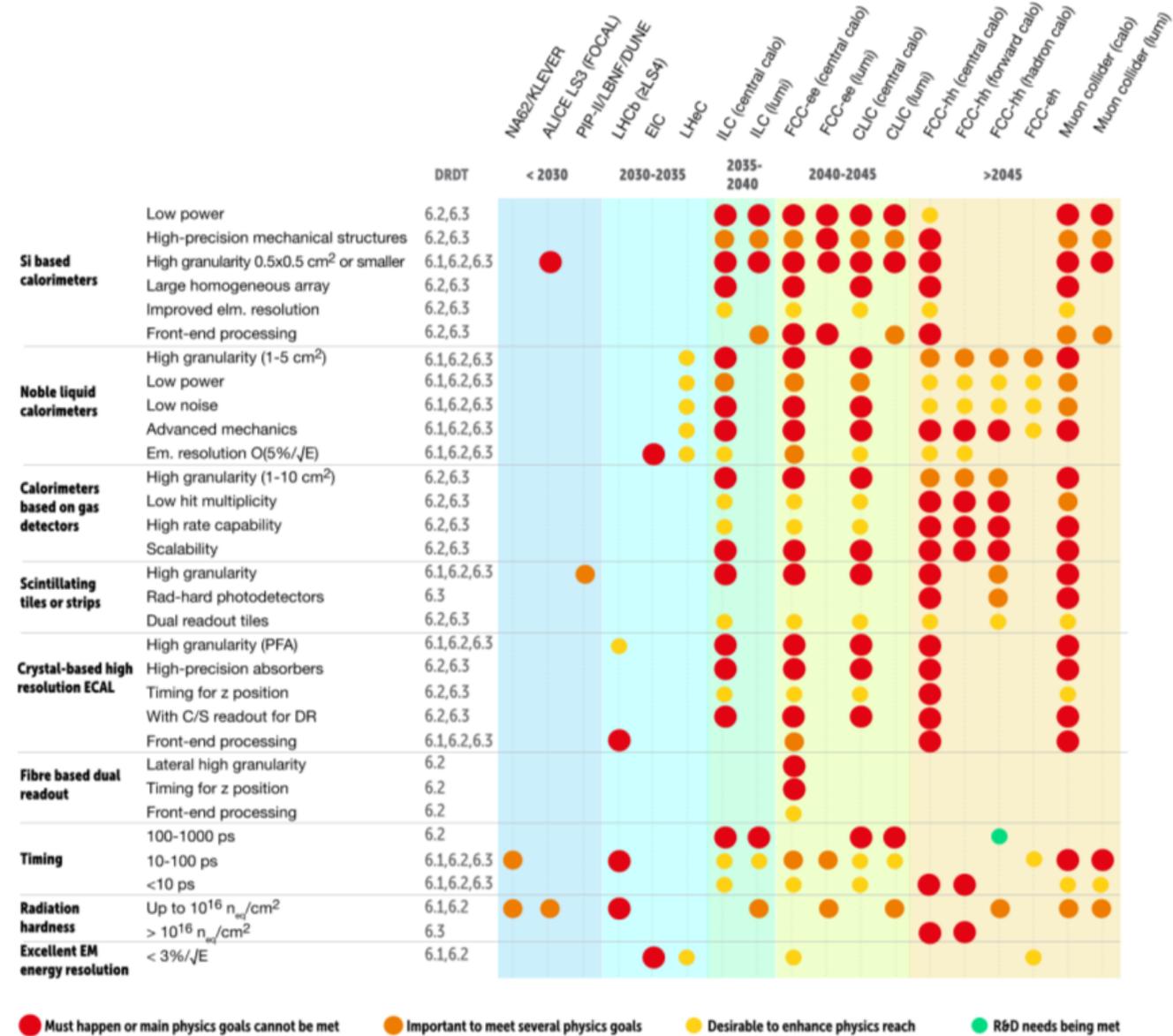
Solid State Detectors



Quantum and emerging technologies



Calorimetry



Training for instrumentation

Personnel, retention and training of detector experts are detailed in the [ECFA Detector R&D Roadmap](#) as mandatory to the success as well as the long-term health of experimental particle physics as a whole.



* See “Results of the 2021 ECFA Early-Career Researcher Survey on Training in Instrumentation”
[ECFA ECR Panel](#) [arXiv:2107.05739](#)

Summary on ECFA Detector R&D Roadmap



- The ECFA Detector R&D Roadmap has been prepared by a large team of internationally recognised leaders in this area with access to a much wider pool of other instrumentation experts.
- It has been the product of wide community consultation with very broad participation.
- The draft document was iterated with the RECFA delegates and National Contacts with numerous helpful comments received from committees looking at this in a number of countries.
- We also have benefited from very valuable feedback from neighbouring disciplines where there are strong synergies between instrumentation needs.
- The main messages were presented to the particle physics community at the ECFA Plenary Session of the EPS-HEP2021 Conference and remain unchanged in those shown on 19th November 2021.
- The results of all the feedback have been implemented in the final 248 page version and additional non-expert 8 page synopsis which was formally approved by Plenary ECFA on 18th November 2021.
- These were then presented to the CERN Scientific Policy Committee and Council last week by the Chair of ECFA and we understand they have been very well received, with the SPC congratulating the Roadmap Panel and endorsing the recommendations.
- The next step will be for mechanisms to be proposed for implementing the final recommendations.