ECFA Detector R&D Roadmap

23.2.2022

Susanne Kuehn, CERN

Helmholtz Alliance

PHYSICS AT THE TERASCALE

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14th Workshop on Detector Development

Overview

- The ECFA Detector R&D Roadmap process
- Overview of future facilities considered in the Roadmap
- Examples on R&D of few detector technologies
  - Gaseous, Solid State Detectors, Calorimetry
  - Training
- Observations – General Strategic Recommendations
- Summary

Disclaimer: In the slides by far not complete list and coverage of all Detector R&D areas.

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."*

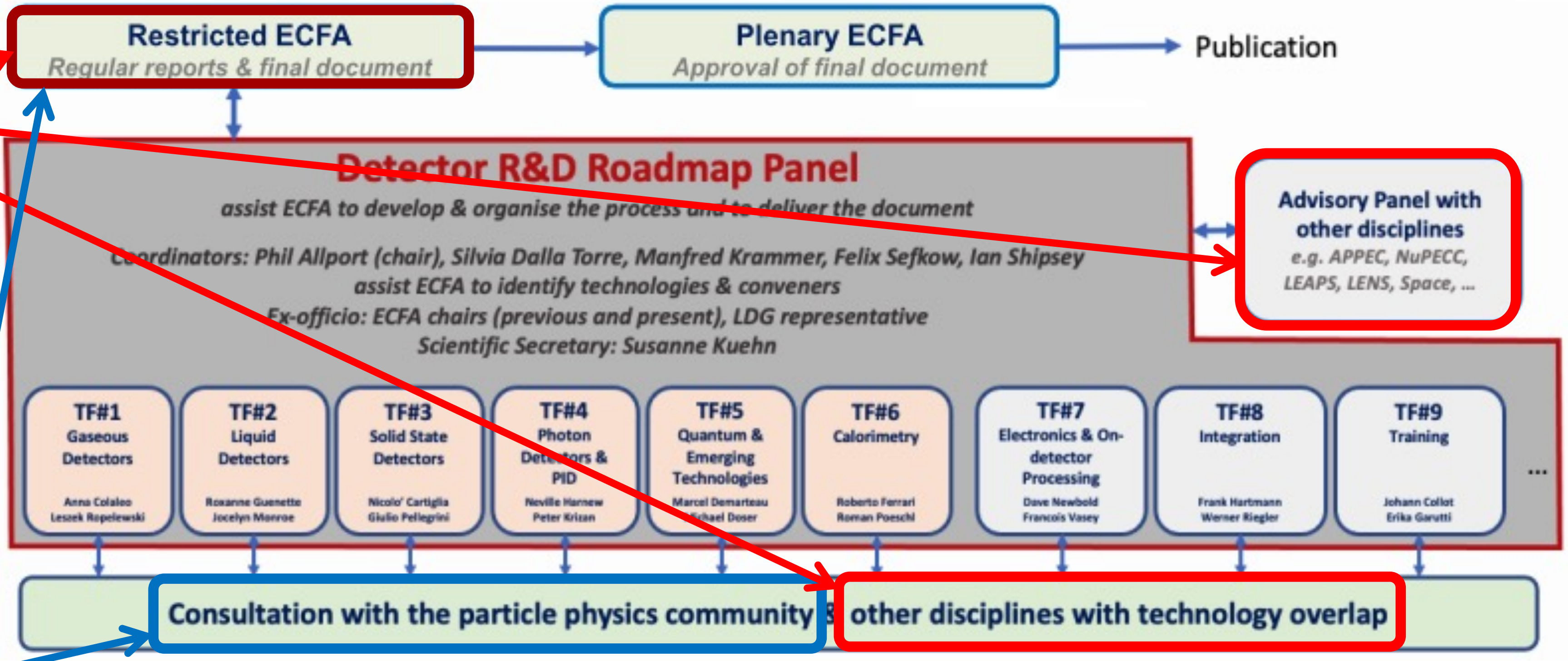
Deliberation document: *"Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities. Synergies between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development 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 process

“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

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

→Nine Task Forces for six detector technologies and three transversal topics

→Process with input sessions and open symposia (1359 registrants)

Process and Timeline

Organisation

May 2020
EPPSU mandate to ECFA to develop a roadmap for detector R&D efforts in Europe

Sep 2020
Structure in place with **Detector R&D Roadmap Panel**

Dec 2020
Task Forces active

Website:
https://indico.cern.ch/e/ECFADetectorRDRoadmap

Expert & Community Consultation

Feb 2021
Collection of requirements of future facilities & projects

Feb/March 2021
Questionnaires of Task Forces to national contacts

Task Forces liaise with experts in
- ECFA countries
- adjacent disciplines
- industry

March-May 2021
Open Symposia

Drafting Roadmap & Feedback

May 2021
Task Forces collate input from symposia

25-28 May 2021 **Drafting sessions**
- opening session with all experts involved
- plenary & parallel sessions with Task Force members
- final session of Roadmap Panel

July 2021
Near final draft shared with RECFA*

30 July 2021
Presentation at Joint ECFA-EPS session

August 2021
Collect final community feedback*

October-December 2021
Detector R&D Roadmap Document circulated for approval to ECFA in Nov 2021 and presentation to Council in Dec 2021

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 Colaleo[1], Leszek Ropelewski[2] *(Conveners)* Klaus Dehmelt[3], Barbara Liberti[4], Maxim Titov[5], Joao Veloso[6] *(Expert Members)*

Task Force 2 Liquid Detectors: Roxanne Guenette[7], Jocelyn Monroe[8] *(Conveners)* Auke-Pieter Colijn[9], Antonio Ereditato[10,11], Ines Gil Botella[12], Manfred Lindner[13] *(Expert Members)*

Task Force 3 Solid State Detectors: Nicolo Cartiglia[14], Giulio Pellegrini[15] *(Conveners)* Daniela Bortoletto[16], Didi… …ntardo[17], Ingrid Gregor[18,19] Gregor Kramberger[20], He… …[2] *(Expert Members)*

Task Force 4 Particle I… …etectors: Neville Harnew[16], … Ichiro A… Chr…

Task Force 5 Quantum and E… Michael Doser[2] … Caterina Braggio[24], Andy Geraci[25], Peter Graham… John March Russell[16], Stafford Withington[28] *(Expert Me…)*

Task Force 6 Calorimetry: Roberto Ferrari[29], Roman Poeschl[30] *(Conveners)* Martin Aleksa[2], Dave Barney[2], Frank Simon[31], Tommaso Tabarelli de Fatis[32] *(Expert Members)*

Task Force 7 Electronics: Dave Newbold[33], Francois Vasey[2] *(Conveners)* Niko Neufeld[2], Valerio Re[29] Christophe de la Taille[34], Marc Weber[35] *(Expert Members)*

Task Force 8 Integration: Frank Hartmann[35], Werner Riegler[2] *(Conveners)* Corrado Gargiulo[2], Filippo Resnati[2], Herman Ten Kate[36], Bart Verlaat[2], Marcel Vos[37] *(Expert Members)*

Task Force 9 Training: Johann Collot[38], Erika Garutti[18,39] *(Conveners)* Richard Brenner[40], Niels van Bakel[9] Claire Gwenlan[16], Jeff Wiener[2], ex-officio Robert Appleby[41] *(Expert Members)*

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

Panel coordinators: Phil Allport[42] *(Chair)*, Silvia Dalla Torre[43], Manfred Krammer[2], Felix Sefkow[18], Ian Shipsey[16]

Ex-officio Panel members: Karl Jakobs[44] *(Current ECFA Chair)*, Jorgen D'Hondt[45] *(Previous ECFA Chair)*, Lenny Rivkin[46] *(LDG Representative)*

Scientific Secretary: Susanne Kuehn[2]

Thanks to the expert Input Session speakers, ECFA National Contacts, respondents to the Task Force surveys, the 121 Symposia presenters, the 1359 Symposia attendees and the 44 APOD TF topic specific contacts.

ECFA
European Committee for Future Accelerators

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
7	Nadia Pastrone	Detector R&D requirements for muon colliders
8	Marzio Nessi	Detector R&D requirements for future short and long baseline neutrino experiments
9	Maarten De Jong	Detector R&D requirements for future astro-particle neutrino experiments
10	Laura Baudis	Detector R&D requirements for future dark matter experiments
11	Cristina Lazzeroni	Detector R&D requirements for future rare decay processes experiments
12	Alexandre Obertelli	Detector R&D requirements for future low energy experiments

ECFA National Contacts

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

ECFA
European Committee for Future Accelerators

Full-day Public Symposia

Two days of Input Sessions covered all the future facilities and …eas identified in the EPPSU (see back-up).
…ere nine technology focussed full-day public … collect community input.

TF4 TF6

May 2021
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

April 2021
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
…CFA Detector R&D Roadmap Symposium of Task Force 3 Solid State Detectors
…oadmap Symposium of Task Force 5 Quantum and Emerging
… Force 2 Liquid Detectors
…etector

Common regi… participants by the end o…

Received extensive feedback during symp…

Surveys were also employed to receive direct inputs from individuals and via RECFA delegates or their National Contacts.

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

19th November 2021 ECFA Detector R&…

Advisory Panel with Other Disciplines

Organisation name	Co…
APPEC	Andreas Haungs (…
NuPECC	Marek Lewitowicz (Chair)
LEAPS	Caterina Biscari (Chair)
LENS	Helmut Schober (Chair)
ESA	Guenther Hasinger (Director of Science) Franco Ongaro (Director of Technology, Engineering and Quality)

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

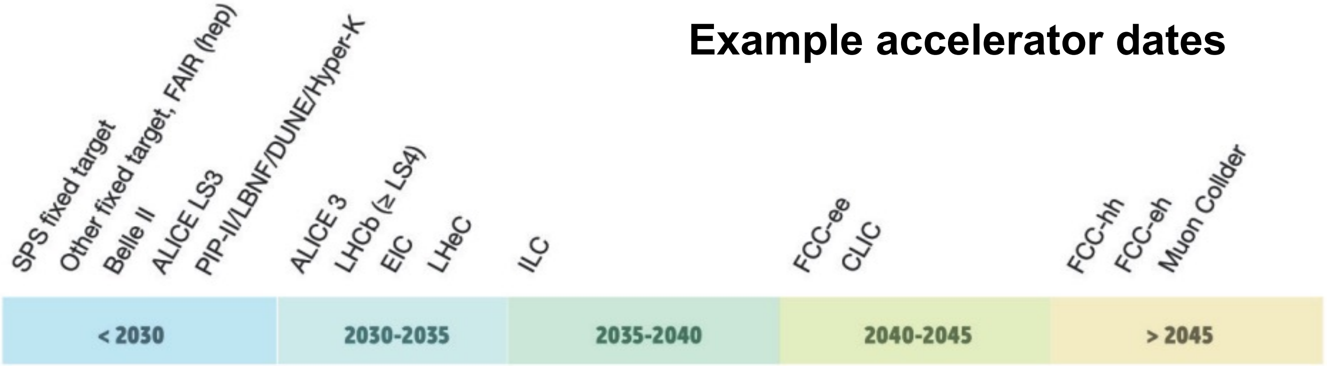
Named expert contacts

Named contacts for each TF where appropriate

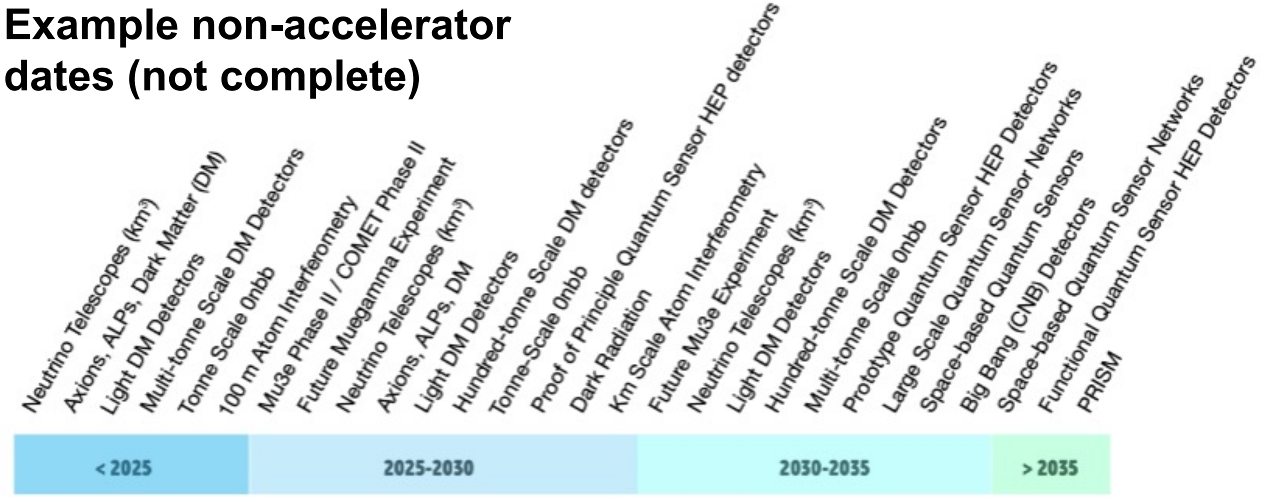
Overview of future facilities

- Many different future facilities proposed/foreseen based on accelerators and non-accelerators
- 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

Example accelerator dates



Example non-accelerator dates (not complete)



"Technical" Start Date of Facility
(This means, where the dates are not known, the earliest technically feasible start date is indicated - such that detector R&D readiness is not the delaying factor)

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.

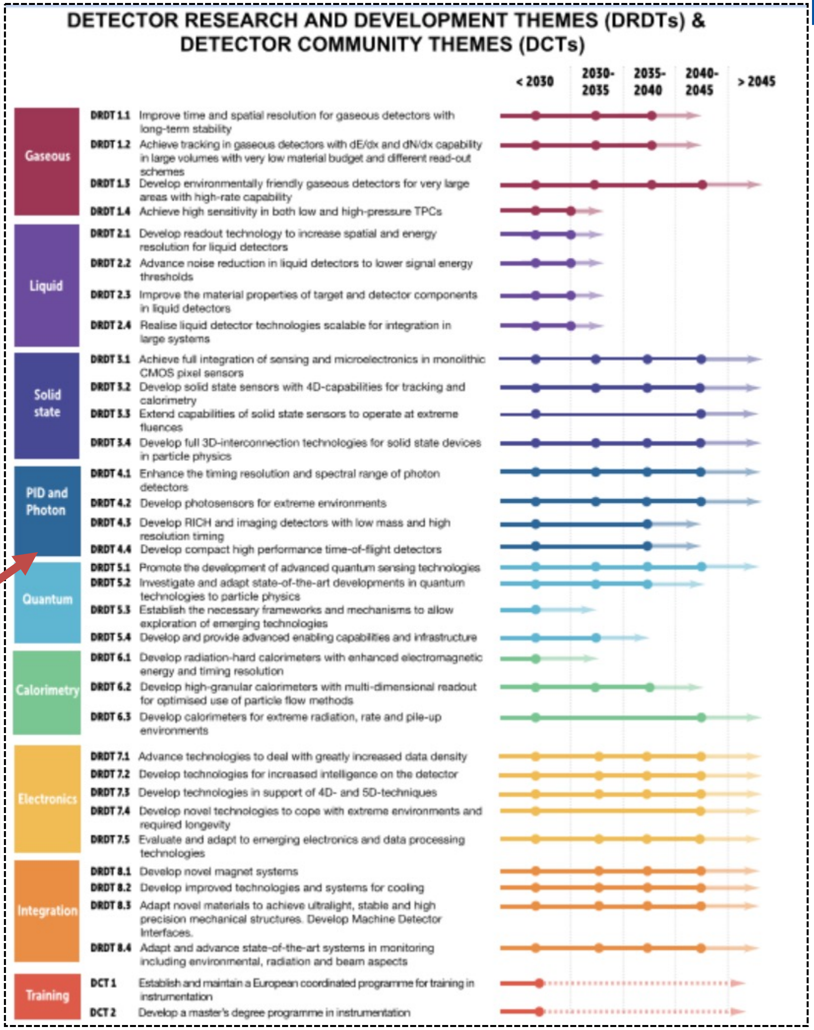
Furthermore, the projects mentioned here are usually limited to those mentioned in the 2020 EPPSU, although it should be noted that detector R&D for other possible future facilities is usually aligned with that for programmes already listed.

The facilities are aligned with recently published Accelerator R&D Roadmap http://arxiv.org/abs/2201.07895

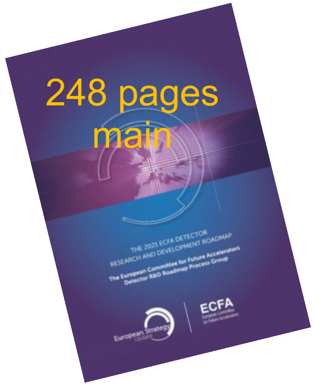
→ Many detector concepts at different future facilities

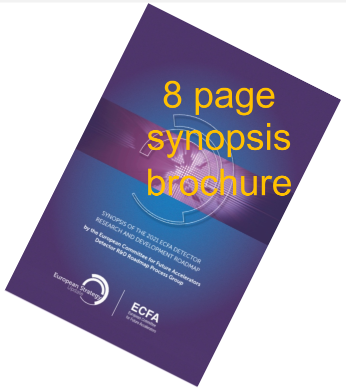
ECFA Detector R&D Roadmap

- Task Forces **started from the future science programme to identify main detector technology challenges** to be met (both mandatory and highly desirable to optimise physics returns) and estimated the period over which the required detector R&D programmes may be expected to extend.
- 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, <u>the programme for a nearer-term facility helps enable the technologies needed for more demanding specifications later</u>, providing stepping stones towards these.
- **Developed and defined "Detector R&D Themes" (DRDTs) to highlight the most important drivers for research in each technology area and Detector Community Themes (DCTs)** in the context of the training area (TF9).
- **General strategic recommendations for our field** are collected in the chapter of general observations and considerations.



Main Document published (approval by RECFA at [19/11/21](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

Detector R&D organisation

- **Looking in the past:**

Detector R&D

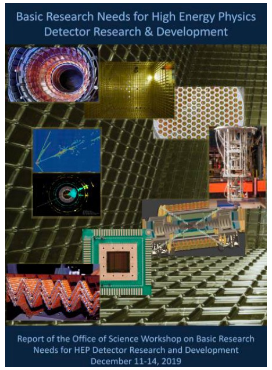
- From 1986, vigorous CERN programme with 40 MCHF funding from Italian government (Zichichi's LAA Project)
- CERN Detector R&D Committee set up mid 1990. By March 1992: 35 proposals, 24 approved – involving 800 people in 170 institutes

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: RD18, RD42, RD50, RD51, RD53, …
  - US Basic Research Needs report and Snowmass Instrumentation Frontier process
  - CERN EP R&D
  - AIDAInnova
  - ECFA Detector R&D Roadmap (Slides, Webpage)
  - ….

Snowmass 2021

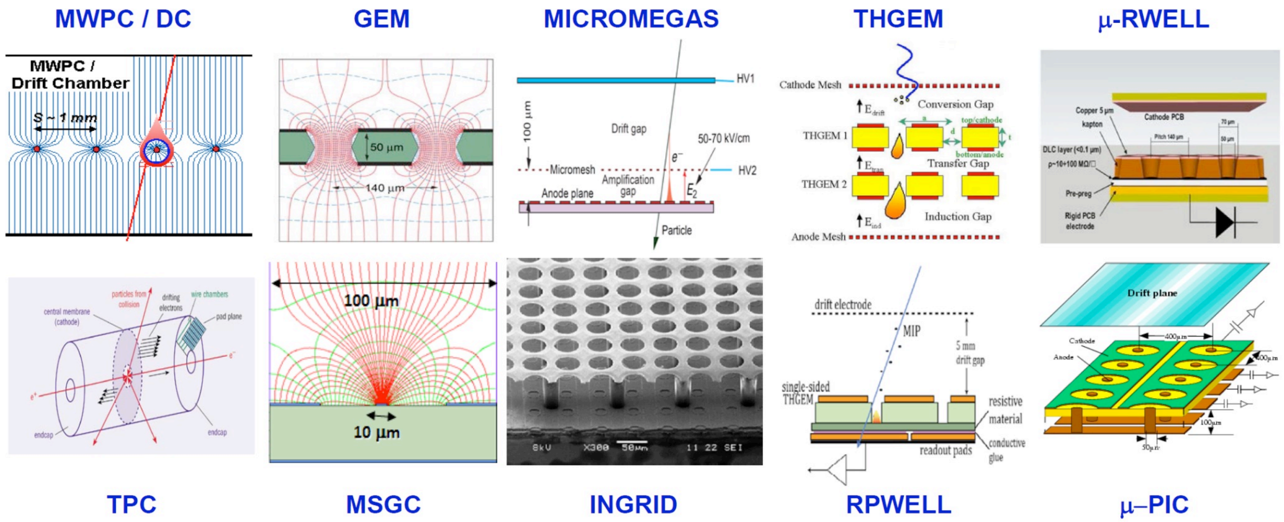


AIDA innova

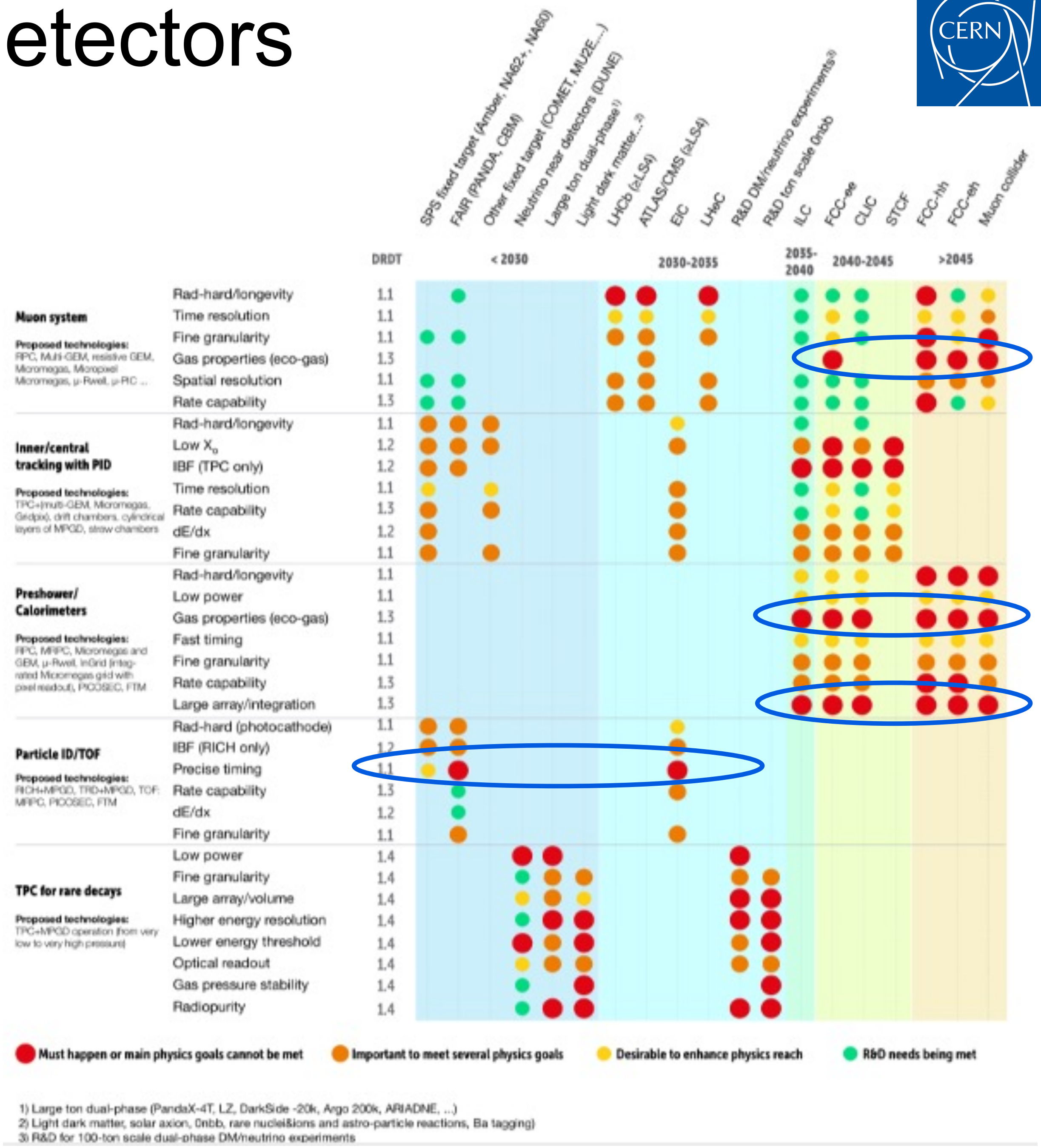
Detector R&D readiness should not be the determining factor in the future of particle physics

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)

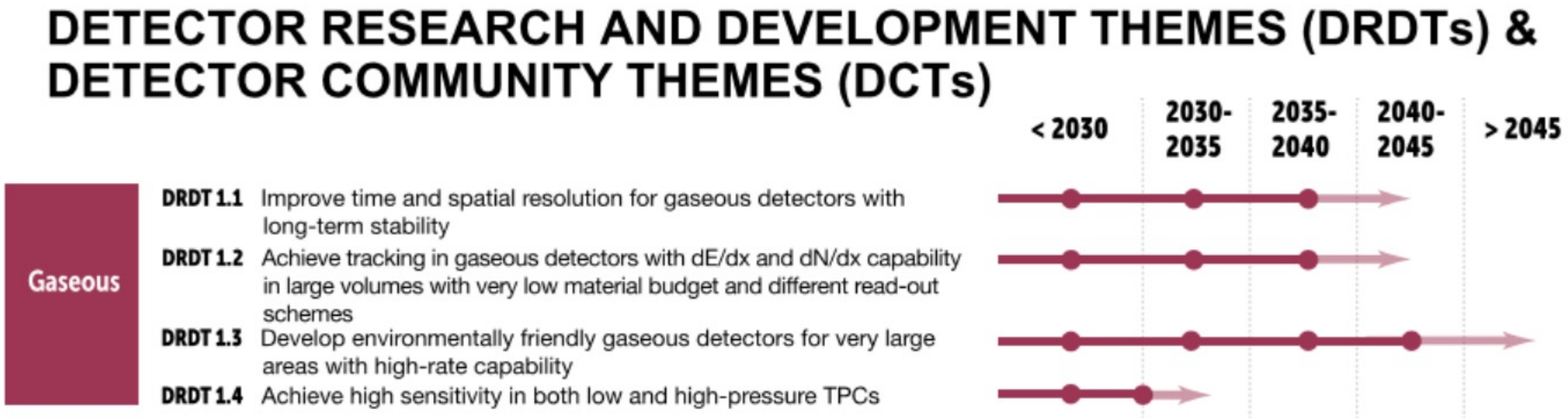


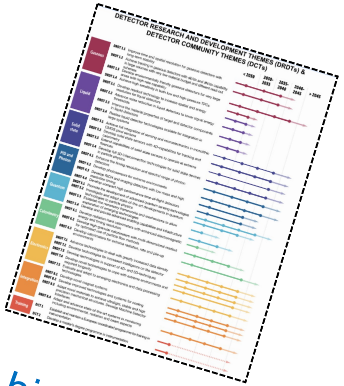
- **Detector Readiness Matrices of each Task Force chapter** focus on the extent to which the R&D topic is *mission critical* to the programme than the intensity of R&D required
  - Must happen or main physics goals cannot be met
  - Important to meet physics goals
  - Desirable to enhance physics reach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



Gaseous detectors

→ **The DRDTs of Task Force 1 Gaseous detectors**





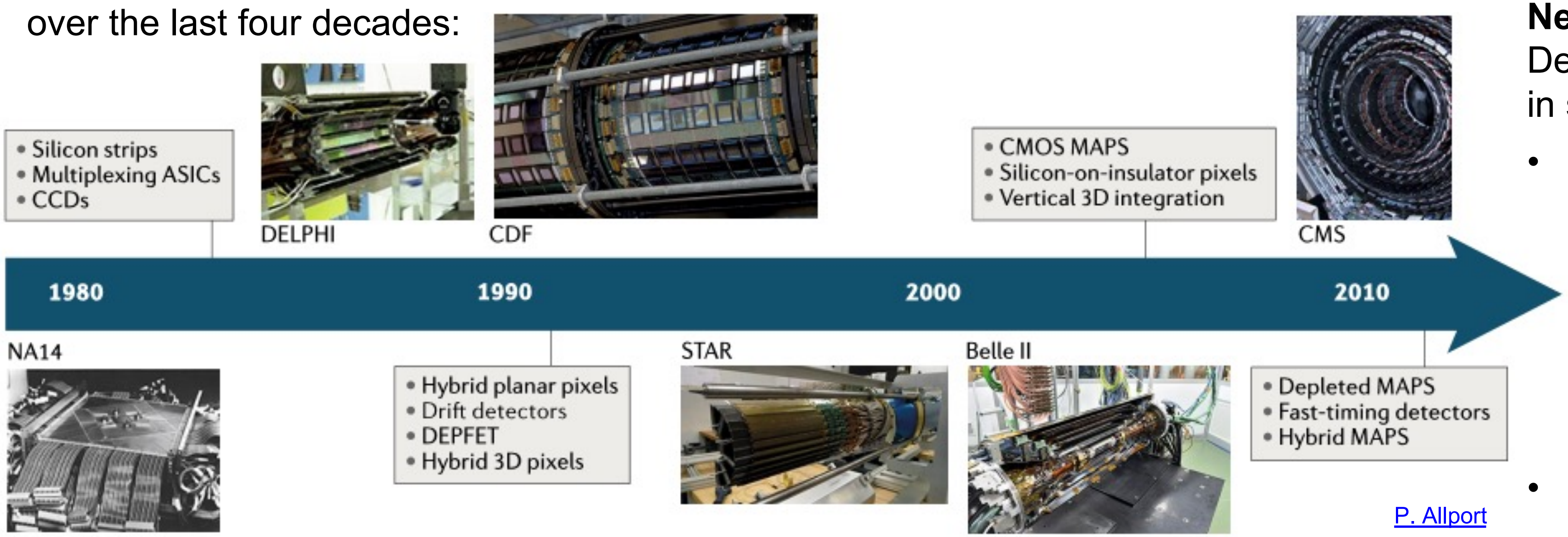
To highlight the most important drivers for research in each technology area

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, <u>not that there is an expectation that R&D for the further future beyond that point will not be needed</u>.

Solid State Detectors

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

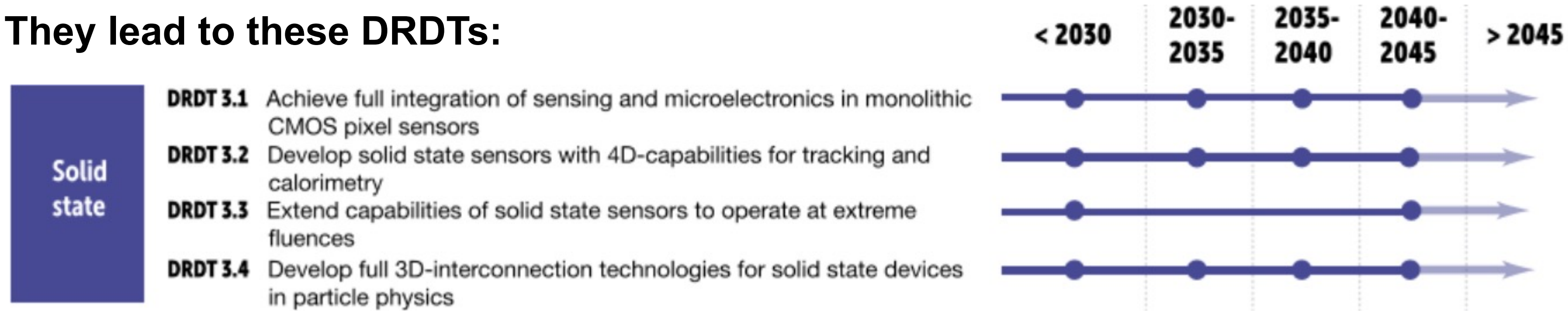


P. Allport

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:

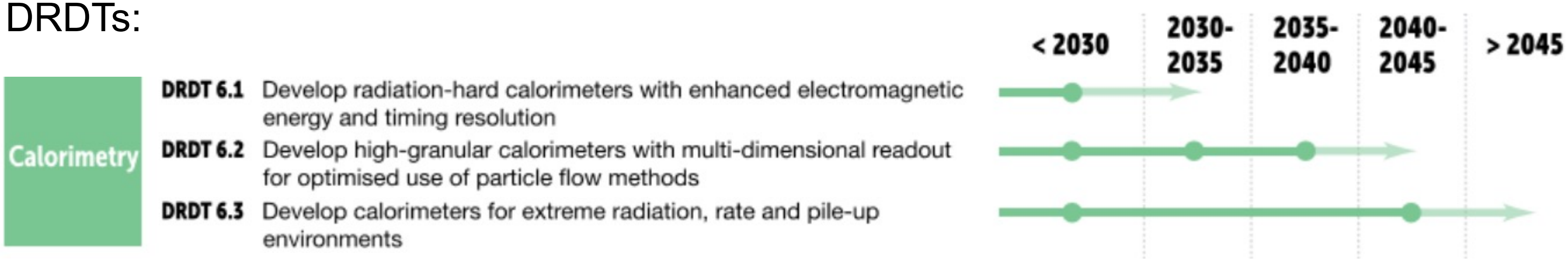


New Challenges (see Detector Readiness Matrix in spare slides):

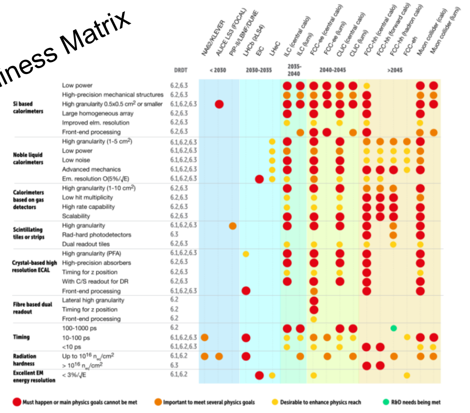
- **Vertex detectors with low mass, high resolution** (Target per layer spatial resolution of ≤ 3µm and X/X_0 ≤ 0.05% for FCC-ee), **low power and high radiation hardness** (up to $8\times10^{17} n_{eq}/cm^2$ for pp-colliders)
- Trackers: **affordable sensors** with low mass, high resolution, **low power**
- **Large area and granular** devices for calorimeters
- Detectors with **ultra-fast timing** (O(10-100 ps)) for PID, TOF
- Fully integrated with electronics, mechanics, services, …

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:



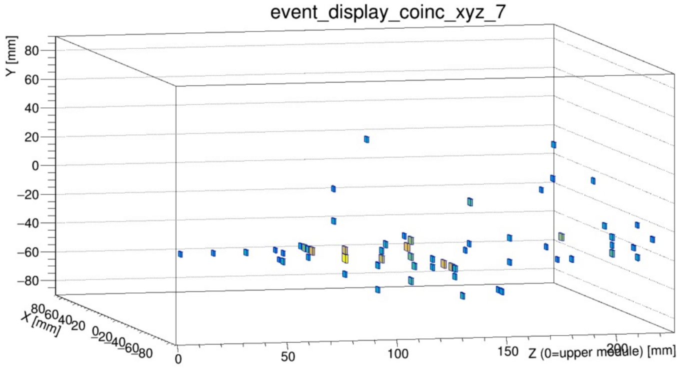
full Detector Readiness Matrix in spare slides

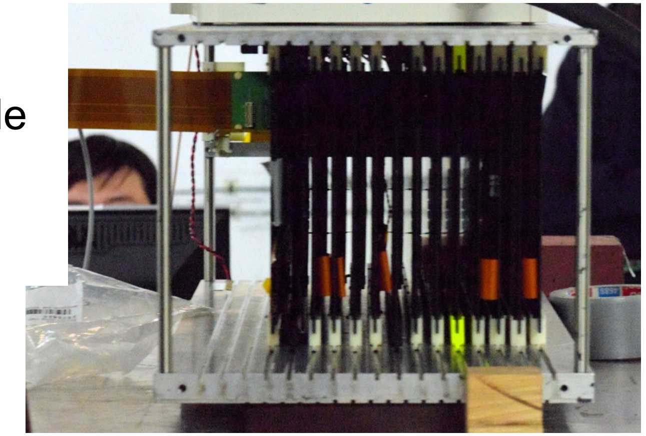


DRDT 6.1: The enhanced electromagnetic energy and timing resolution most relevant in next decade for upgrades of ALICE and LHCb.

Example: MAPS based SiW ECALs

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





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

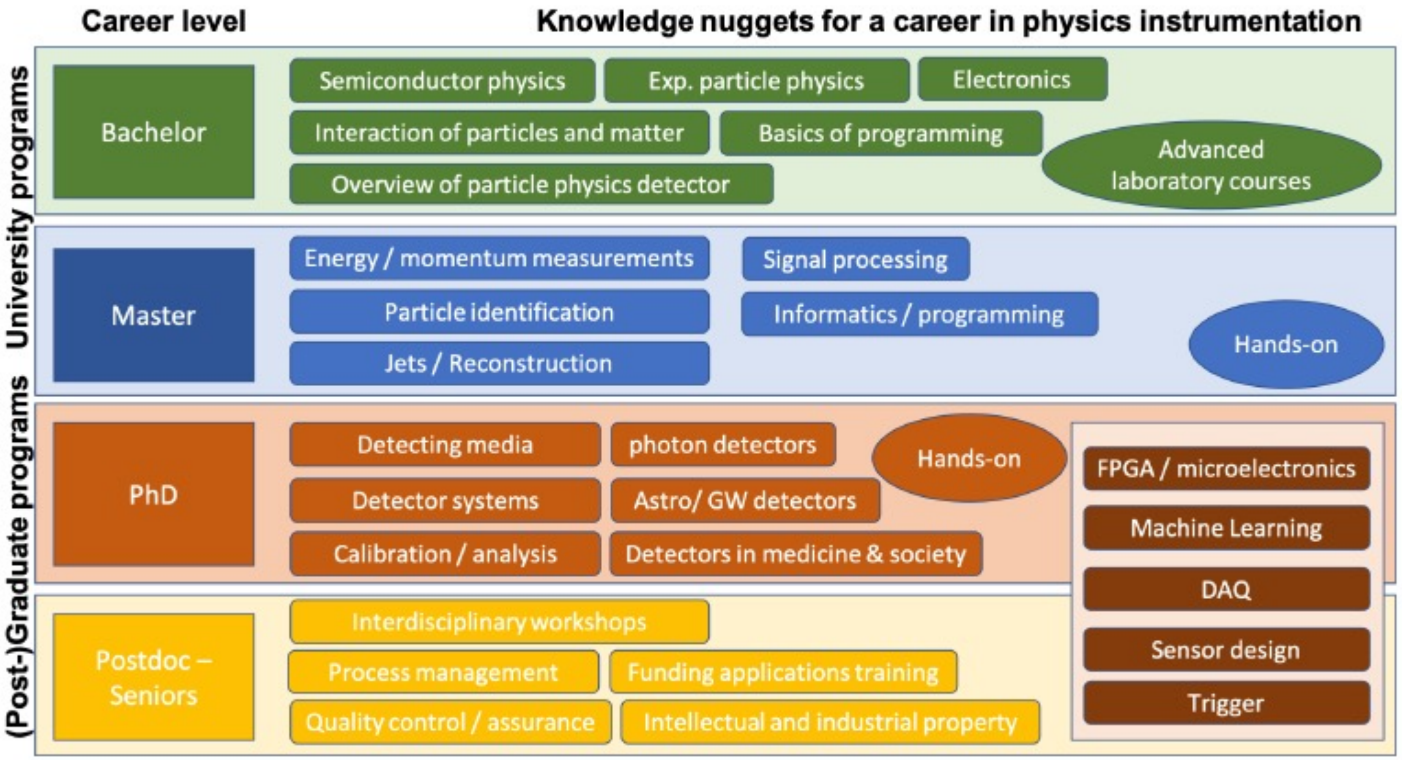
DRDT 6.2: Particle Flow based on high granularity calorimeters particularly important for e^+e^- Higgs-EW-top factories and to be considered for EIC. Separation of signals by charged and neutral particles in highly granular calorimeters.

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

Training for instrumentation

* See "Results of the 2021 ECFA Early-Career Researcher Survey on Training in Instrumentation" ECFA ECR Panel *arXiv:2107.05739*

- **A structured training programme shall support the scientists in their career**
- **Increase participation of young scientists**, in particular graduate students**, in leading-edge instrumentation R&D**, and to foster growth of future HEP instrumentation experts who can compete for permanent positions



Possible structure of a training plan recommendation

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.

General Strategic Recommendations

In addition to the Detector R&D Themes described above and discussed in each chapter the following General Strategic Recommendations are made under the following headings.

GSR 1 - Supporting R&D facilities

GSR 2 - Engineering support for detector R&D

GSR 3 - Specific software for instrumentation

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

GSR 5 - Distributed R&D activities with centralised facilities

GSR 6 - Establish long-term strategic funding programmes

GSR 7 - Blue-sky R&D

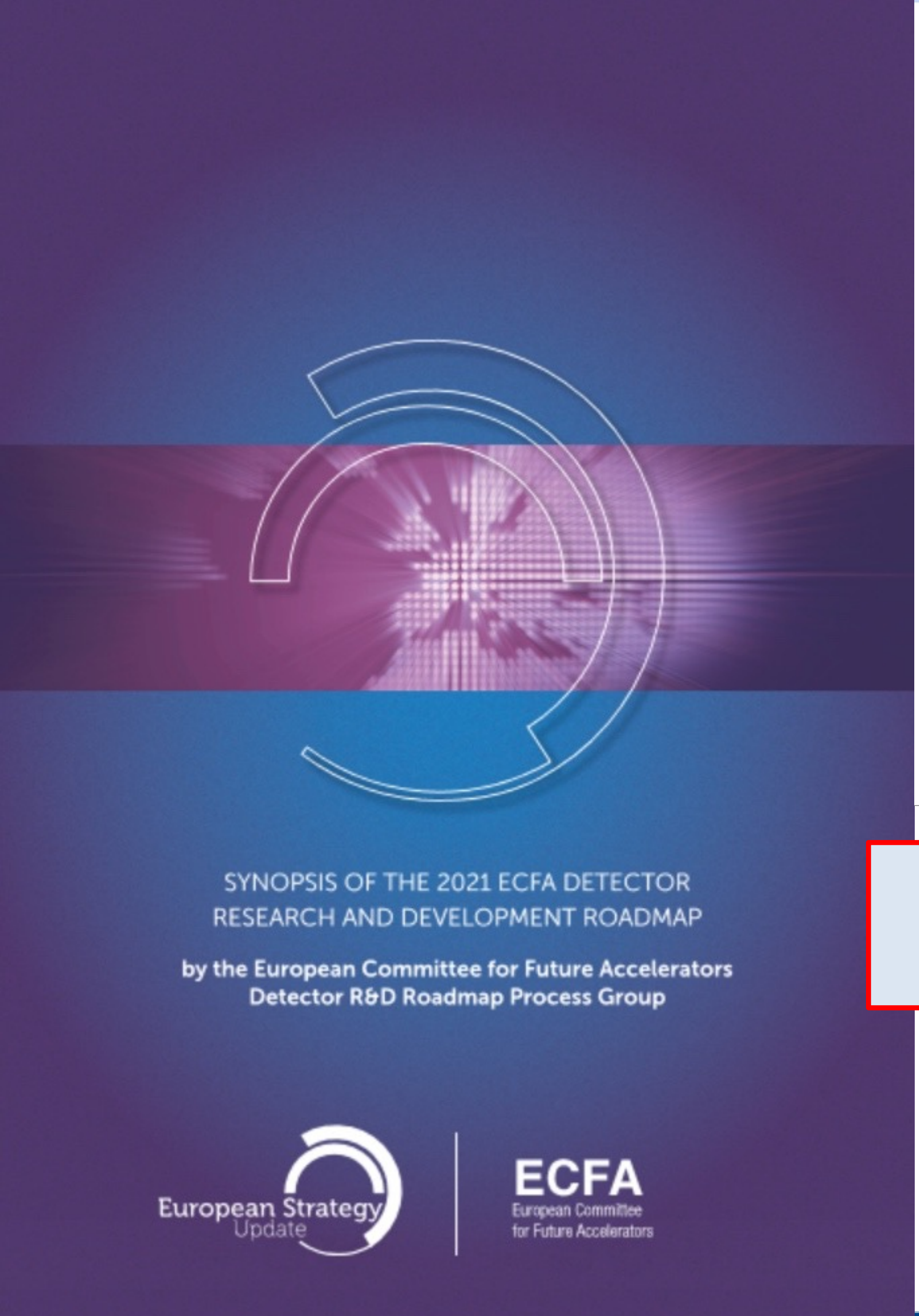
GSR 8 - Attract, nurture, recognise and sustain the careers of R&D experts

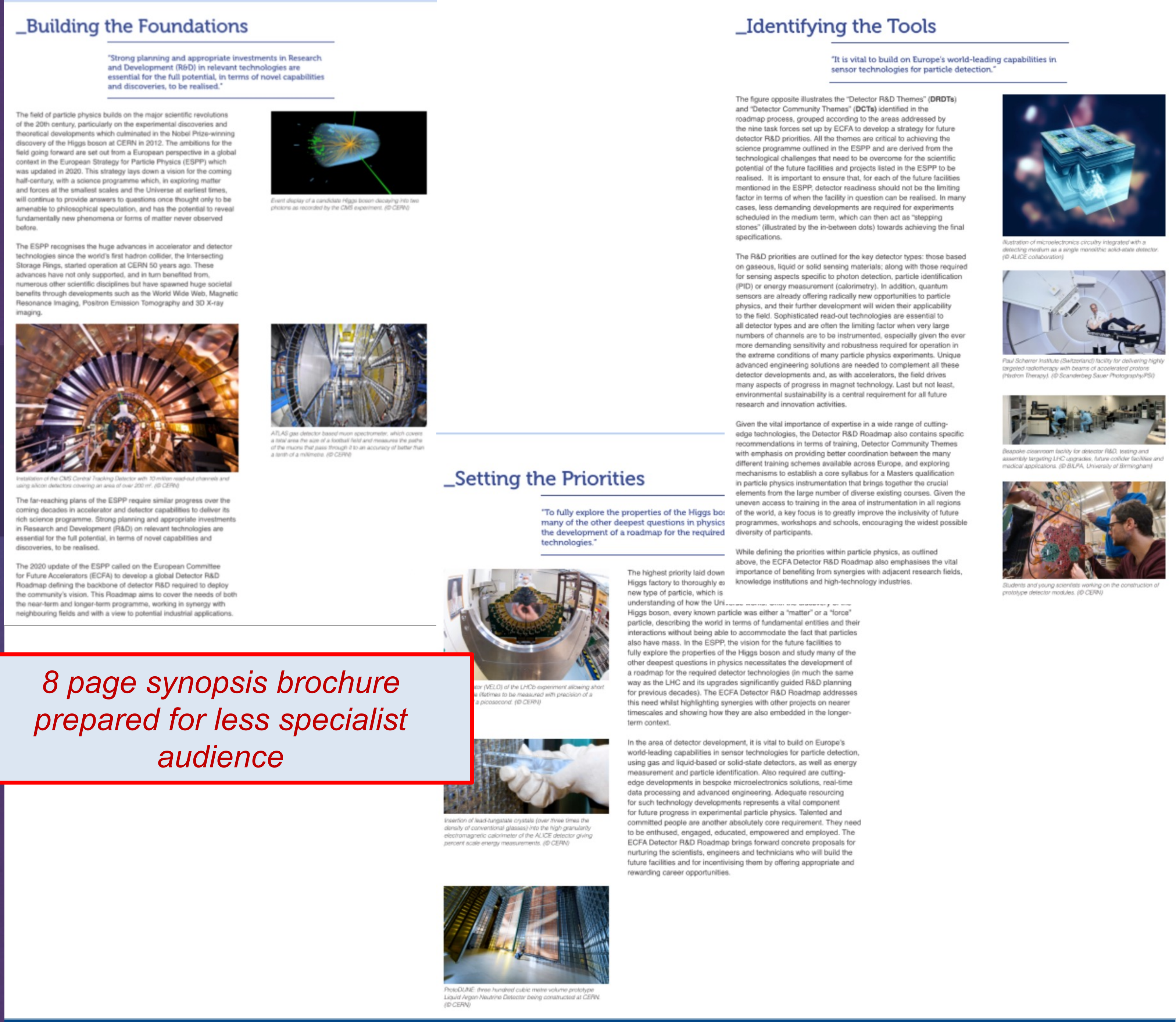
GSR 9 - Industrial partnerships

GSR 10 - Open Science

Contents

248 pages document





_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.

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 benefits through developments such as the World Wide Web, Magnetic Resonance Imaging, Positron Emission Tomography and 3D X-ray imaging.

Installation of the CMS Central Tracking Detector with 10 million read-out channels and 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) on 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.

_Setting the Priorities

The highest priority laid down … Higgs factory to thoroughly e… new type of particle, which is … understanding of how the Uni… Higgs boson, every known particle was either a "matter" or a "force" particle, describing the world in terms of fundamental entities and their interactions without being able to accommodate the fact that particles also have mass. In the ESPP, the vision for the future facilities to fully explore the properties of the Higgs boson and study many of the other deepest questions in physics necessitates the development of 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.

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.

_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 nine 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.

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 to 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.

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.

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.

8 page synopsis brochure prepared for less specialist audience

Summary

- 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 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.**

- A few technological challenges and examples were presented in this talk → **There is the need for a lot of further Detector R&D in different areas. Experts in various fields required.**

- 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 facilities offer will be squandered.

- The next step will be for **mechanisms to be proposed for implementing the final recommendations**.

Thank you!

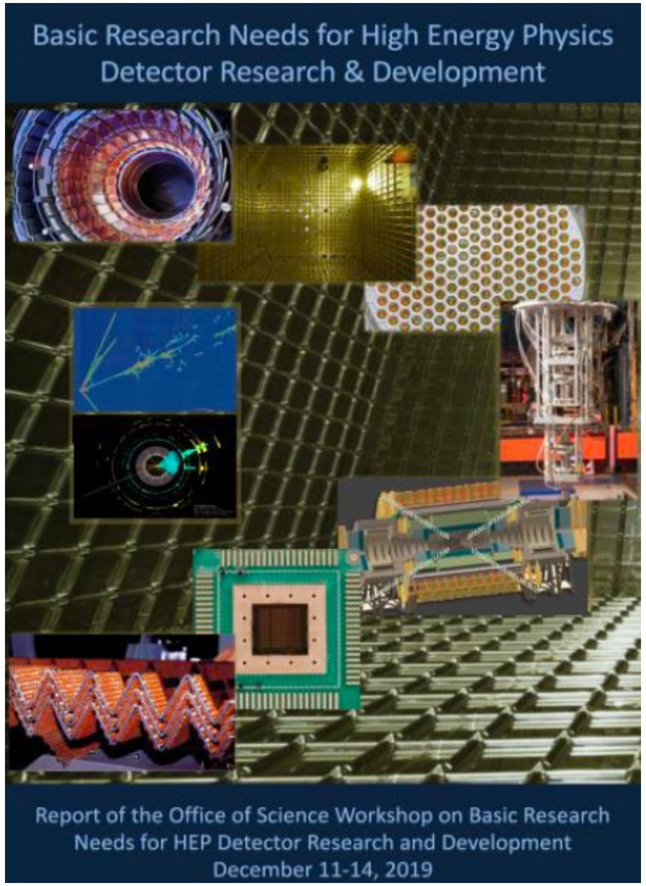
Acknowledgment

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

SPARE

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 Report « Community-Driven »:

- **Snowmass Summary for Public**
  - 2 pages
- **Snowmass Summary Report**
  - ~50 pages
    - Executive Summary: ~10 pages
    - Introduction
    - 10 Frontier Executive Summaries
    - Executive Summaries of Multi-Frontier Topics
    - Conclusion
- **Snowmass Book**
  - ~500 pages
    - Snowmass Summary Report (~50 pages)
    - Frontier Summaries (~400 pages with 10 Frontiers)
    - Multi-Frontier Topic Summaries (~50 pages)
- **Topical Group Reports**
  - Topical Group Reports: short reports
- **Reports of Multi-Frontier Topics**
  - Multi-Frontier Topics spanning multiple Frontiers.
  - Each Multi-Frontier Topic Summary: ~10 page
- **Contributed Papers** **= White Papers**
  - References

IF Frontier Summary: 40 pages

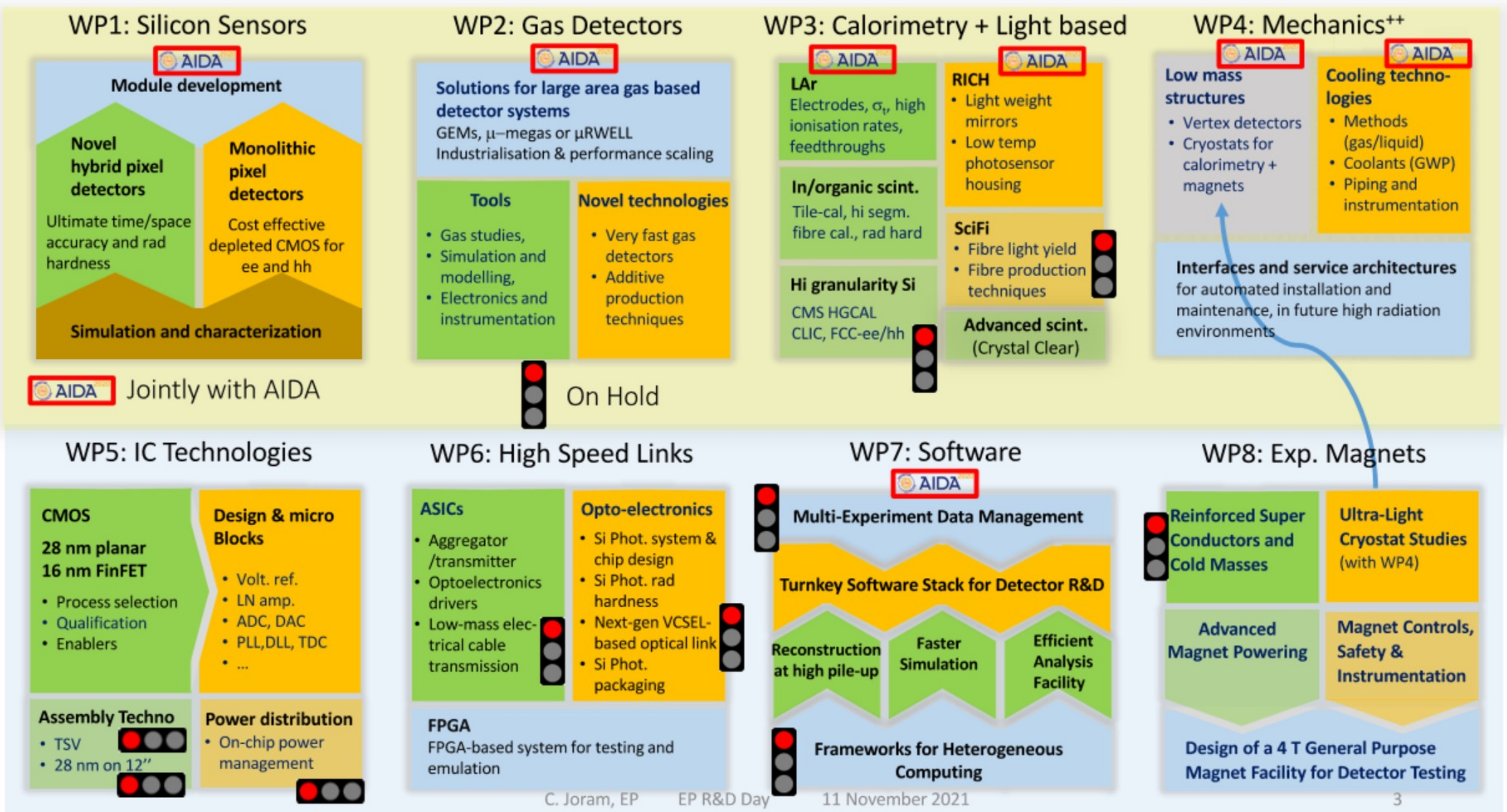
(Written by TG members including early careers)

(Written by the community including early careers)

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

AIDA innova

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 pesresently 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:**
  - RD18 Crystal Clear, inorganic scintillators for crystal electromagnetic calorimeters at LHC
  - RD42 CVD Diamond radiation detector development
  - RD50 Radiation hard semiconductor devices for very high luminosity colliders
  - RD51 Development of Micro-Pattern gas detectors technologies
  - RD53 Pixel readout chip for ATLAS and CMS (65 nm) at HL-LHC
- 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

Full-day Public Symposia

Two days of Input Sessions covered all the future facilities and topic areas identified in the EPPSU (see back-up).

Following these were nine technology focussed full-day public symposia as the main fora to collect community input.

Task Force	TF7	TF8	TF2	TF5	TF3	TF1	TF9	TF4	TF6
Dates	25/3/21	31/3/21	9/4/21	12/4/21	23/4/21	29/4/21	30/4/21	6/5/21	7/5/21
Unique users	369 + 123 (webcast)	154 + 17 (webcast)	197 + 5 (webcast)	220	504	339	105	207	201
Max. number of concurrent viewers	230 + 123 (webcast)	76 + 17 (webcast)	130 + 5 (webcast)	100	275	191	59	110	115

Common registration for the symposia had logged 1359 participants by the end of the last one.

Received extensive feedback during symposia and after by email.

Surveys were also employed to receive direct inputs from individuals and via RECFA delegates or their National Contacts.

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

May 2021

- 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

April 2021

- 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
- 09 Apr ECFA Detector R&D Roadmap Symposium of Task Force 2 Liquid Detectors

March 2021

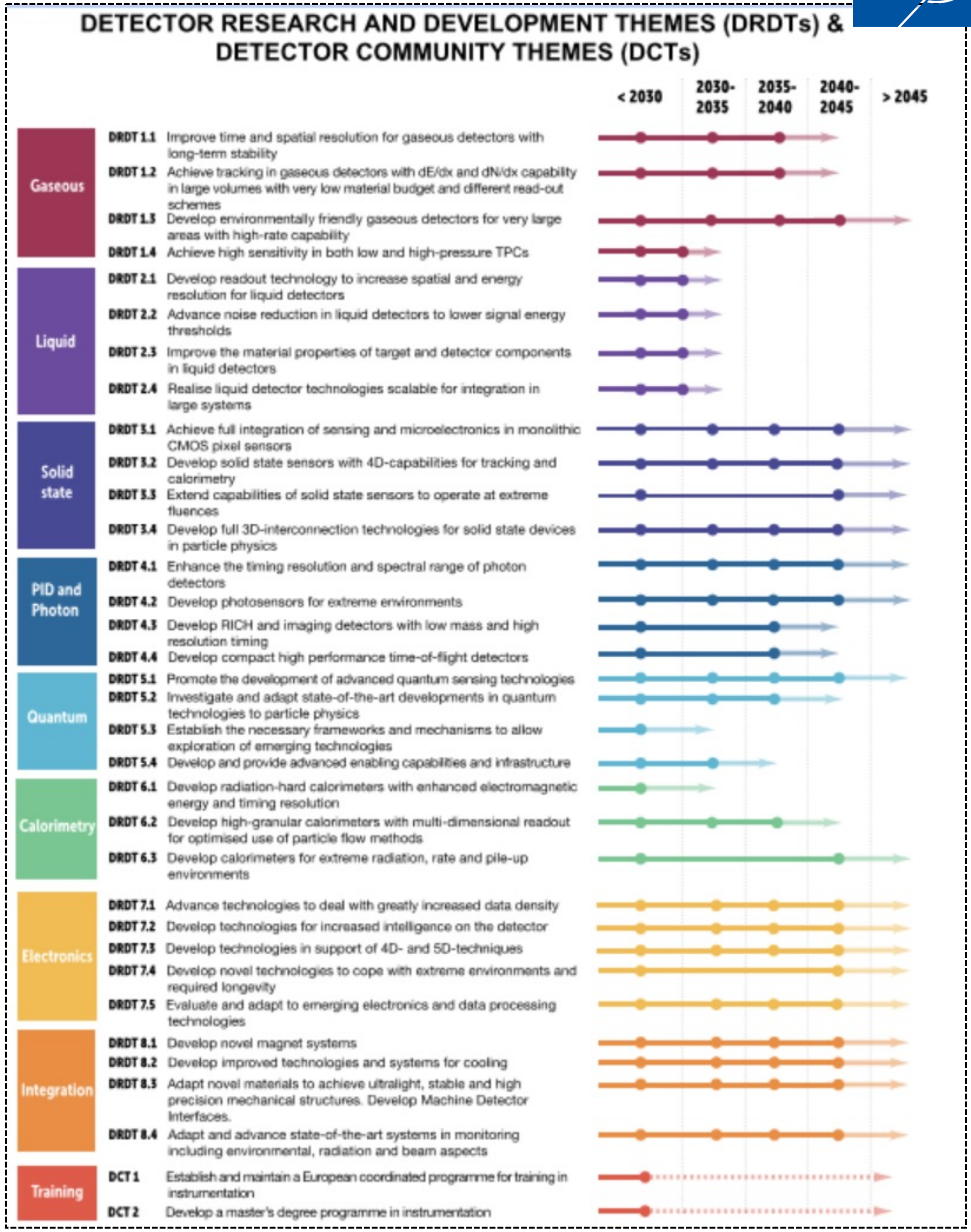
- 31 Mar ECFA Detector R&D Roadmap Symposium of Task Force 8 Integration
- 25 Mar ECFA Detector R&D Roadmap Symposium of Task Force 7 Electronics and On-detector Processing

Materials from past Symposia, Input Sessions and other components of the ECFA Detector R&D Roadmap Process can be found at https://indico.cern.ch/e/ECFADetectorRDRoadmap

Many thanks to the 121 presenters, the 1359 attendees and all who provided feedback

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**



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)

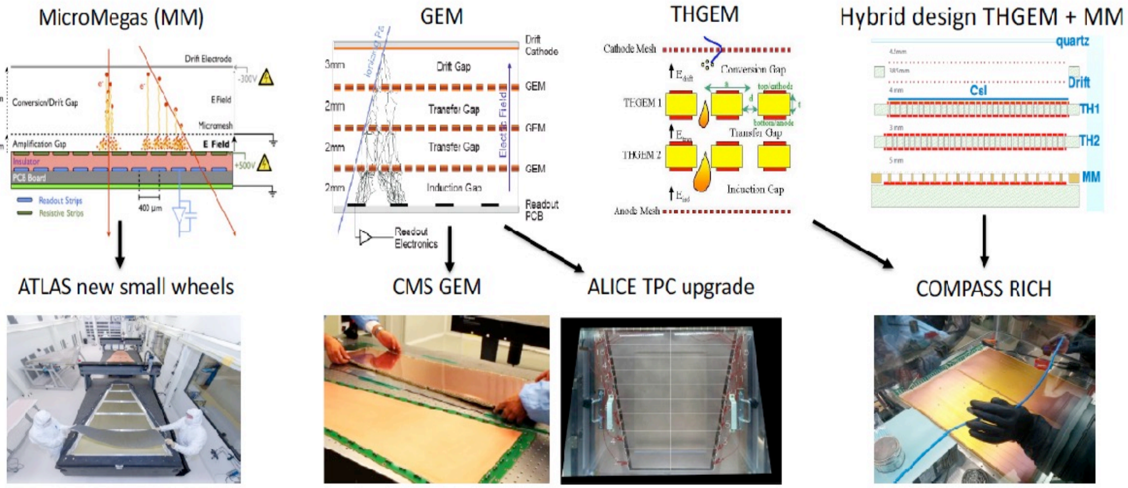
https://attract-eu.com/ (ATTRACT: linking to industry on detection and imaging technologies)

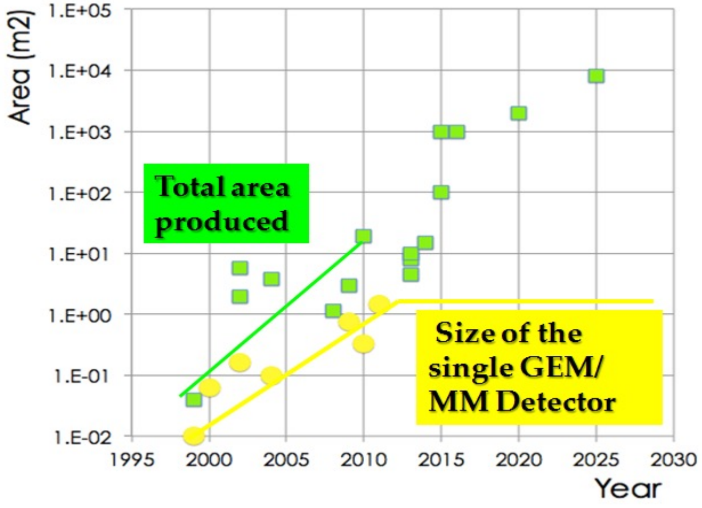
https://ecfa-dp.desy.de/public_documents/ (Some useful documents from the ECFA Detector Panel)

Gaseous detectors: area and timing

M. Titov

- **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

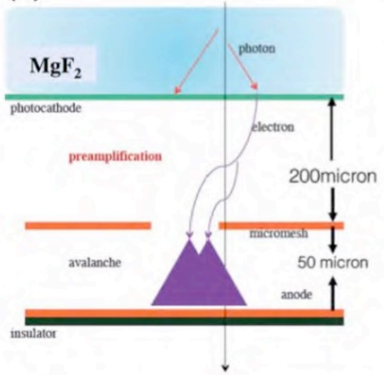


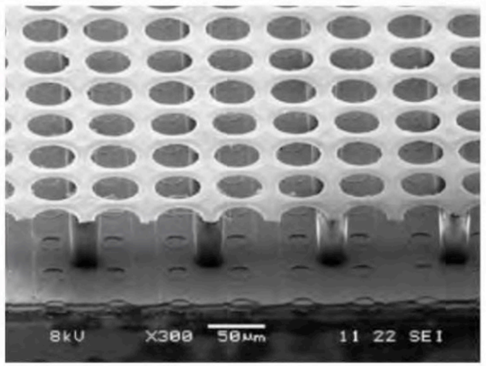


- **Gaseous detectors offer very competitive timing** through e.g.
  - **Multi-gap Resistive Plate Chambers** (down to 60 ps time resolution) (ALICE TOF Detector, Z.Liu, NIM A927 (2019) 396)
  - An enabling emerging R&D: **Micromegas with timing** (PICOSEC concept)

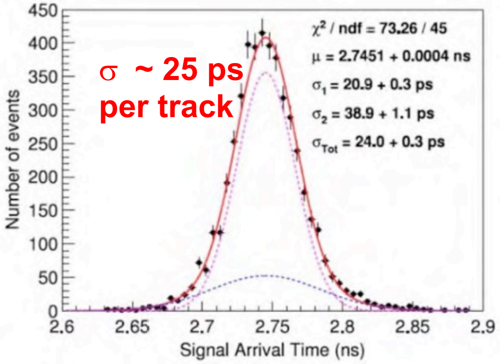
Cherenkov radiator + Photocathode + MM

J. Bortfeldt, NIM A903 (2018) 317





Timing (MIP test-beam):

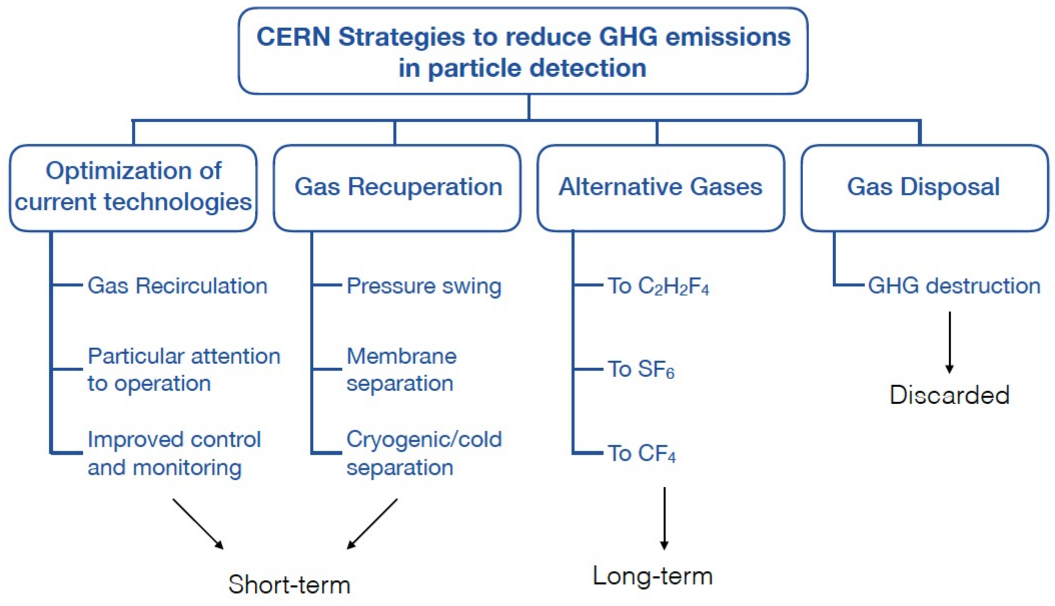


→ Many developments emerged from the R&D studies within the RD51 Collaboration

Gaseous Detectors: eco-friendly gases

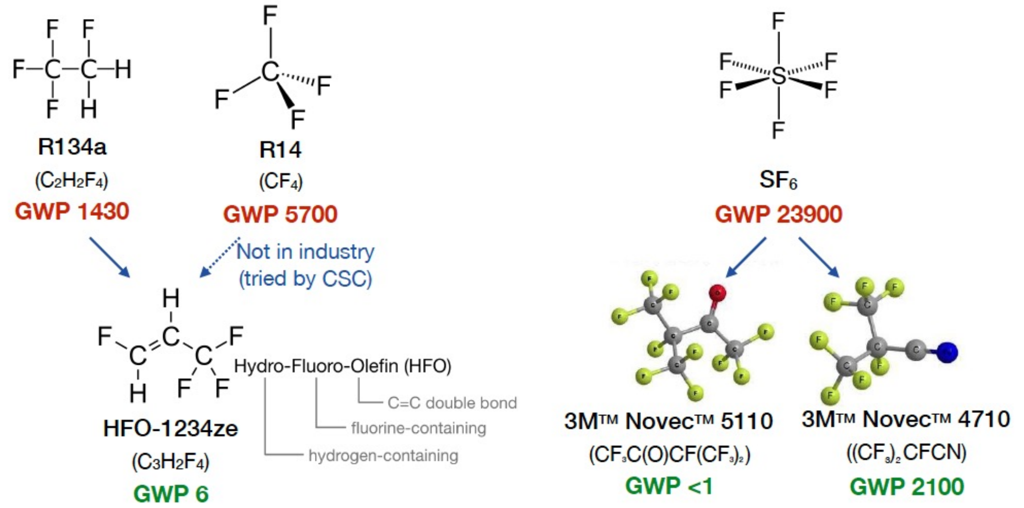
- 92% of emission at CERN related to large LHC experiments
- Thanks to gas recirculation GHG emission already reduced by > 90% wrt. to open mode systems!
- Many LHC gas systems with gas recuperation

CERN strategies for GHG reduction



Possible alternatives to GHG gases

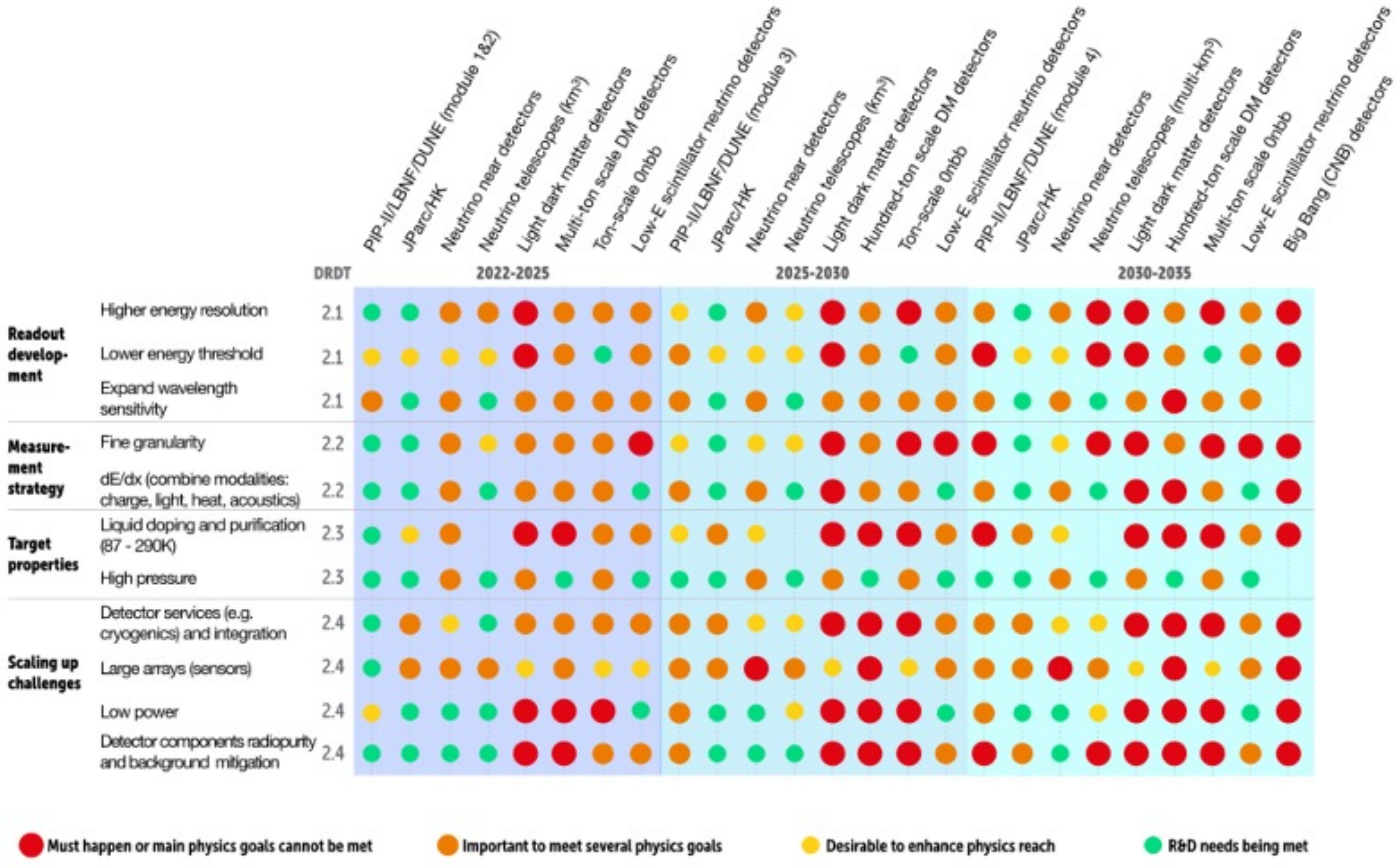
New eco-friendly liquids/gases have been developed for industry as refrigerants and HV insulating medium... ionisation properties in particle detection not well known



- Alternative gases:
  - A lot of work especially in RPC community to search for alternative to $C_2H_2F_4$
  - Not an easy task to find new eco-friendly gas mixture for current detectors

B. Mandelli

Liquid detectors



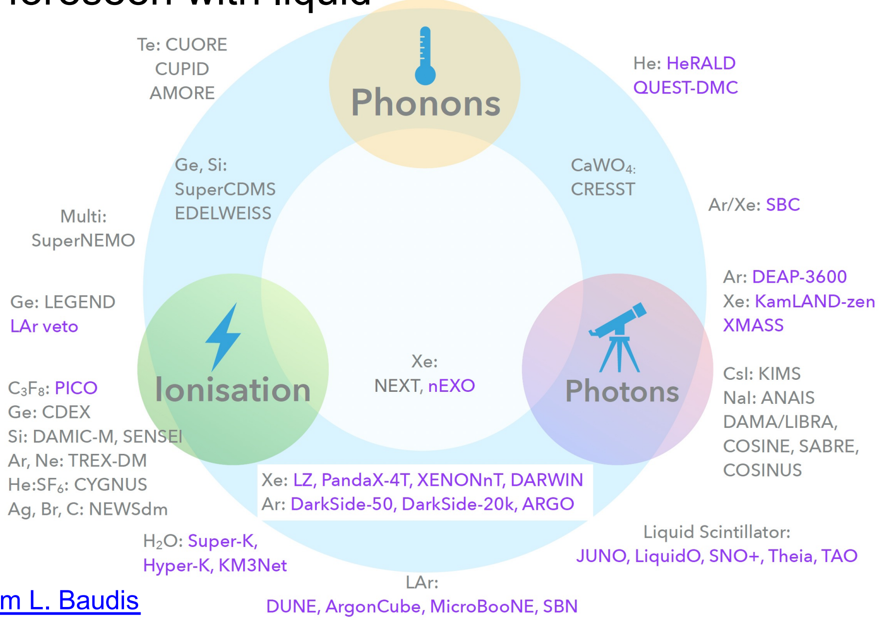
Liquid detectors

- The DRDTs are

Liquid		< 2030	2030-2035	2035-2040	2040-2045	> 2045
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 reason-ably estimate the dates for projects requiring longer-term R&D

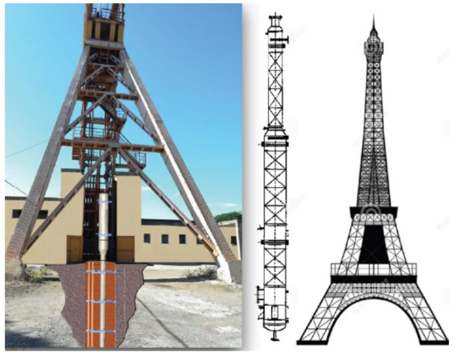
- Several large-scale and many small-scale experiments running or foreseen with liquid detectors



[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



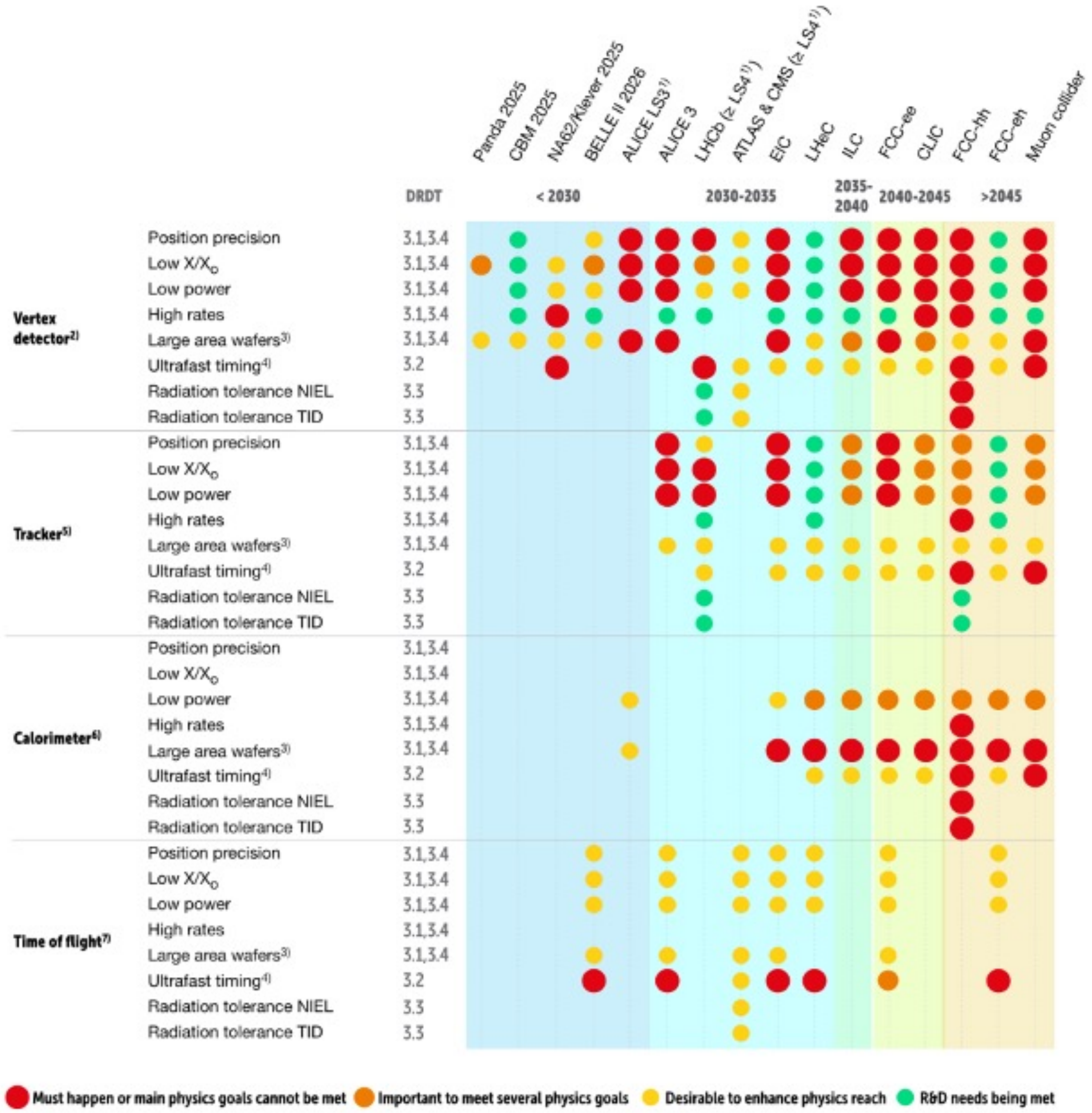
ARIA underground purification system for argon (DarkSide-20k)

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

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

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

Solid State Detectors

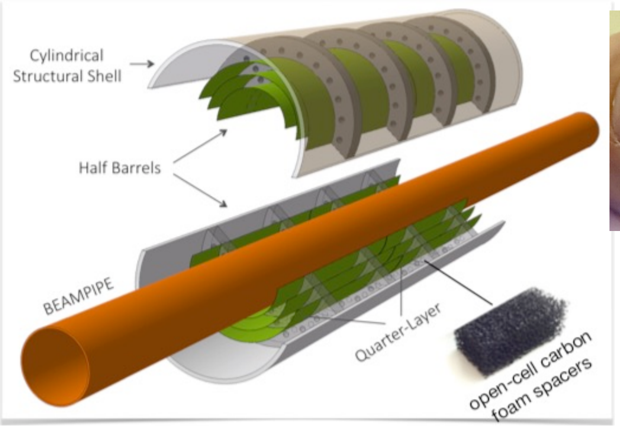


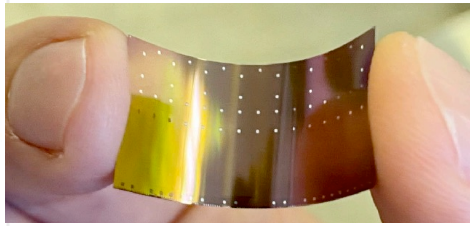
CMOS MAPS

- **Monolithic sensors combining sensing and readout elements**
- Example: For FCC-ee vertex detector targeting spatial resolution per layer of ≤ 3μm and X/X_0 ≤ 0.05%, essential to have low power. Plus radiation-hardness up to $8\times10^{17} n_{eq}/cm^2$ for pp-collider.

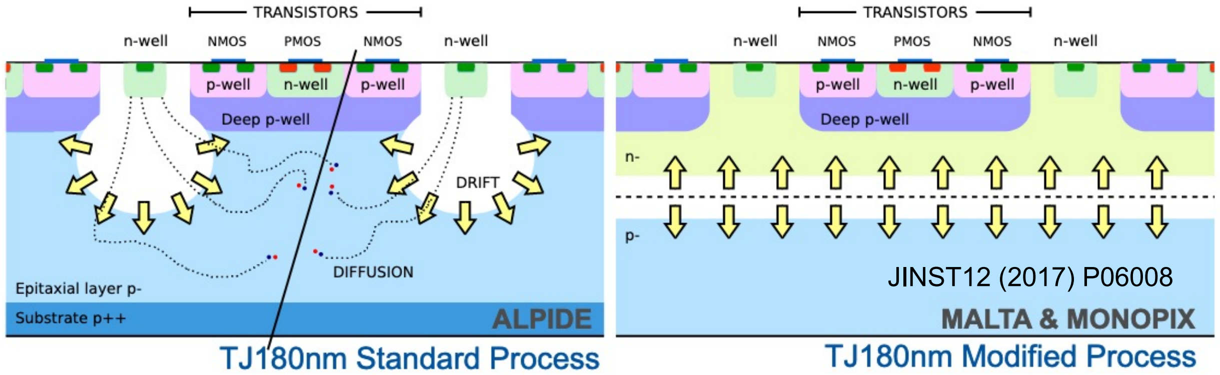
CMOS MAPS for ALICE ITS3 (Run 4):
(LOI: CERN-LHCC-2019-018, M. Mager)

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





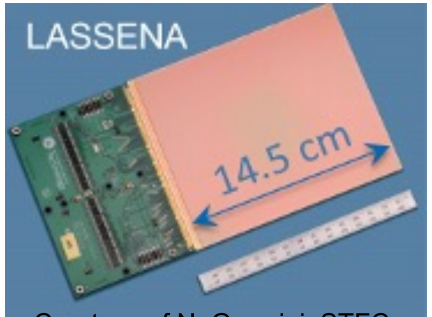
Radiation hardness of MAPS: From ALPIDE to MALTA/Monopix with modified Tower Jazz 180 nm process



→ Up to 97% efficiency after fluence of $1\times10^{15} n_{eq}/cm^2$ H. Pernegger

MIMOSA @ EUDET BeamTest
Telescope → 3 μm track resolution achieved

Large area: stitching
INMAPS process



Courtesy of N. Guerrini, STFC

50μm 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

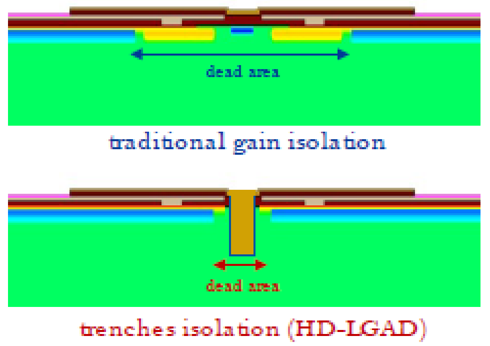
Sensors for 4D-Tracking: position and time resolution → Development of Radiation Hard Timing Detectors (Low Gain Avalanche Detectors)

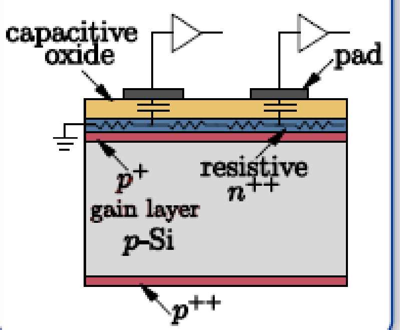
- For LGADs, three main foundries (CNM, FBK, HPK), more producers interested
- Time information hugely beneficial to supress pile-up in pp-collisions

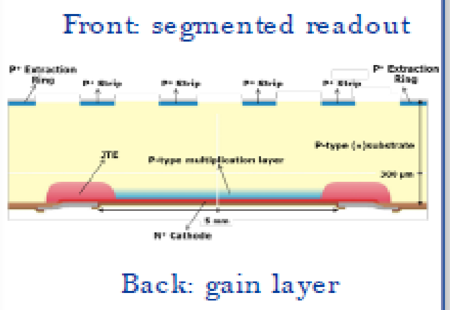
LGAD: Fill factor & performance improvements

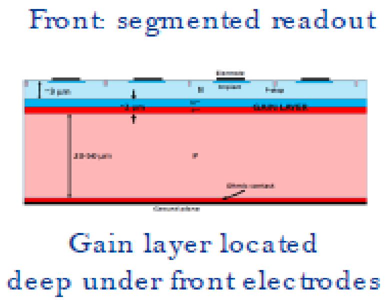
- Two opposing requirements:
  - Good timing reconstruction needs homogeneous signal (i.e. no dead areas and homogeneous weighting field)
  - A pixel-border termination is necessary to host all structures controlling the electric field
- Several new approaches to optimize/mitigate followed:

Trench Isolation LGAD | AC-LGAD | Invers LGAD | Deep Junction LGAD





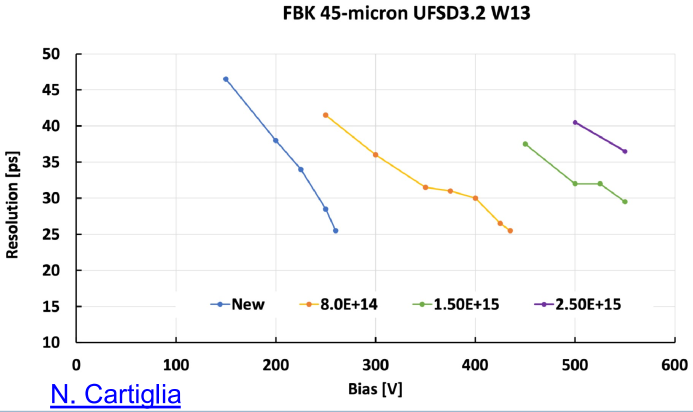




Concepts simulated, designed, produced and tested in 2018/19 ..new concept 2020

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 (~2×10^{15} n_{eq}/cm^2)
- Performance Parameterisation Model

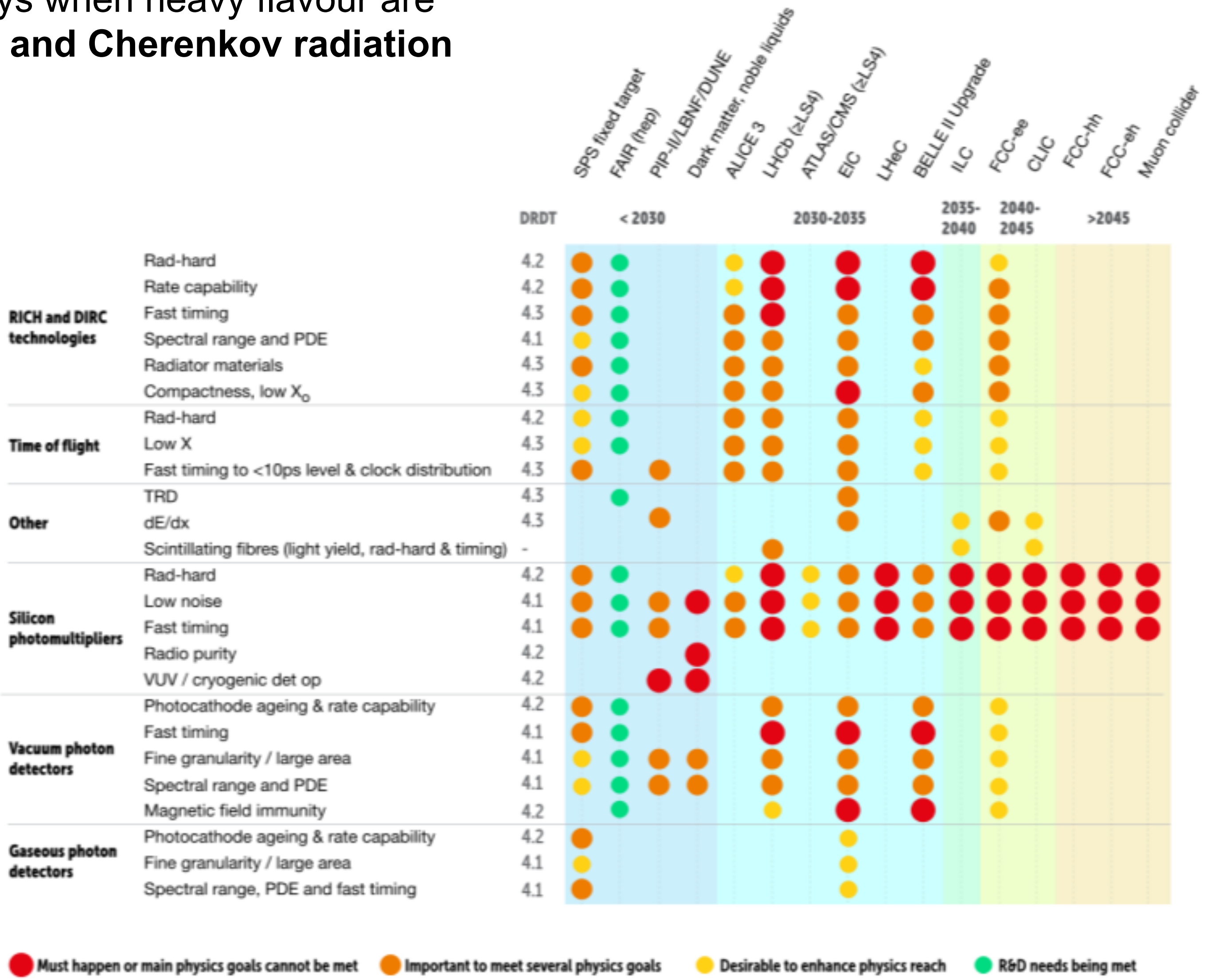


N. Cartiglia

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**

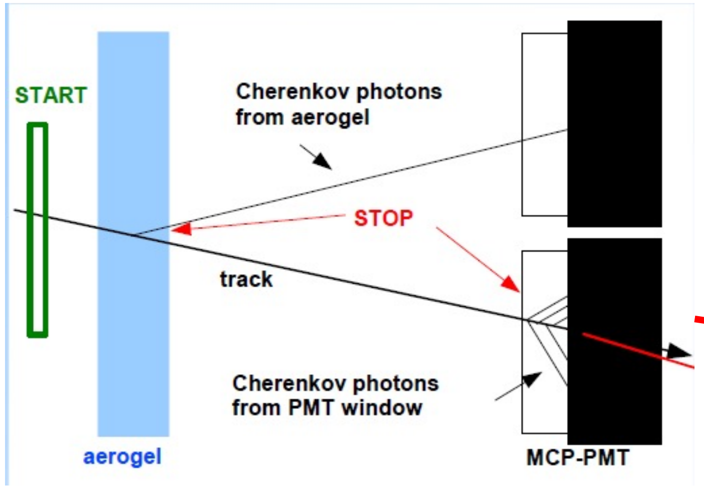
- Challenges for example for **SiPMs**: the high dark count rate and moderate radiation hardness prevented their use in RICH detectors where single photon detector required at low noise
- Challenges for **MCP-PMTs** is their price and they are not tolerant to magnetic fields, similarly **Large-Area Picosecond Timing Detectors** (LAPPD) which are promising but need in addition pixellation

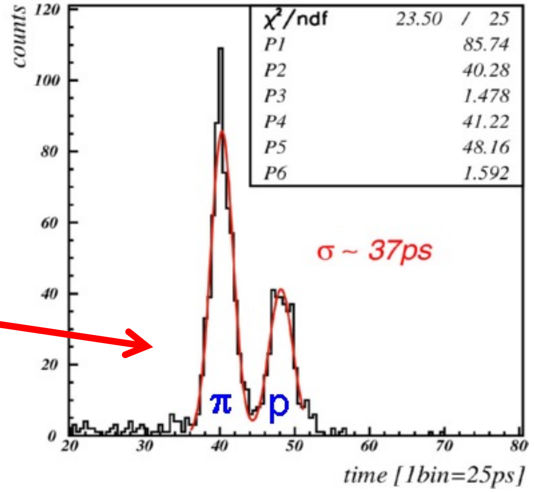


PID and Photon Detectors: RICHes

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

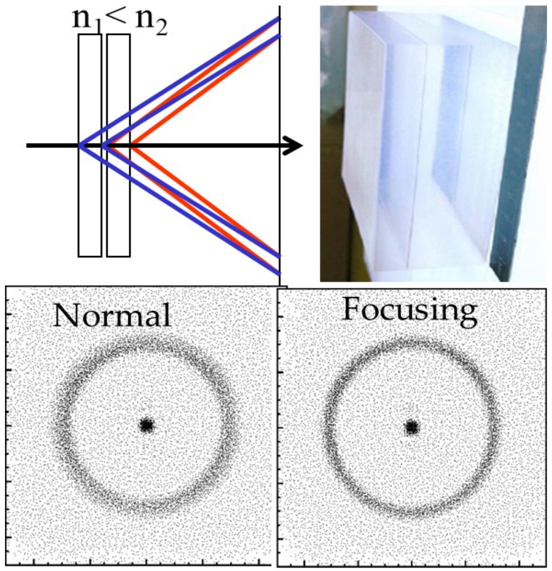




Cherenkov photons from PMT window can be used to positively identify particles below threshold in aerogel

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

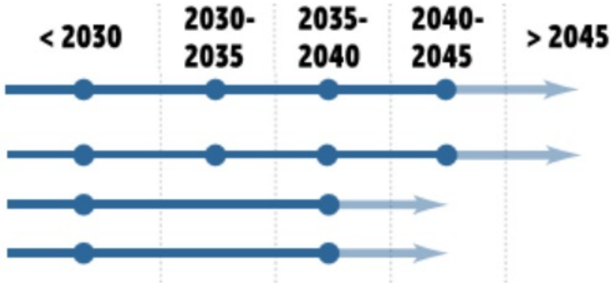
- Use of focusing configuration, e.g. ARICH (Belle), Forward RICH (Panda)



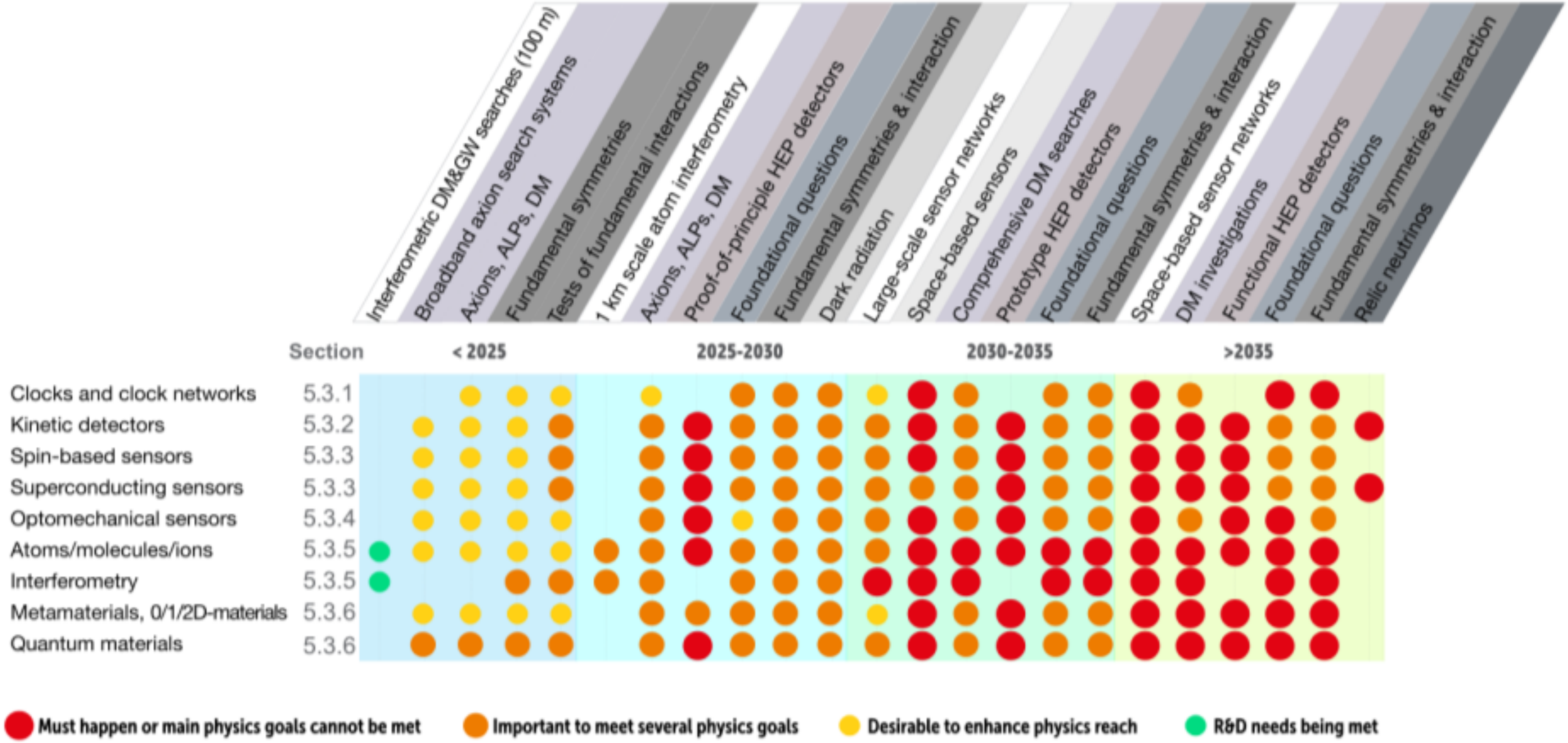
- RICHes with proximity focusing: thin radiator (liquid, solid, aerogel) and low momenta
- Time-Of-Flight (TOF) detectors: use prompt Cherenkov light, fast gas detector
- RICHes with focalisation: extended radiator (gas), mandatory for high momenta

DRDTs:

PID and Photon		
	DRDT 4.1	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 and emerging technologies

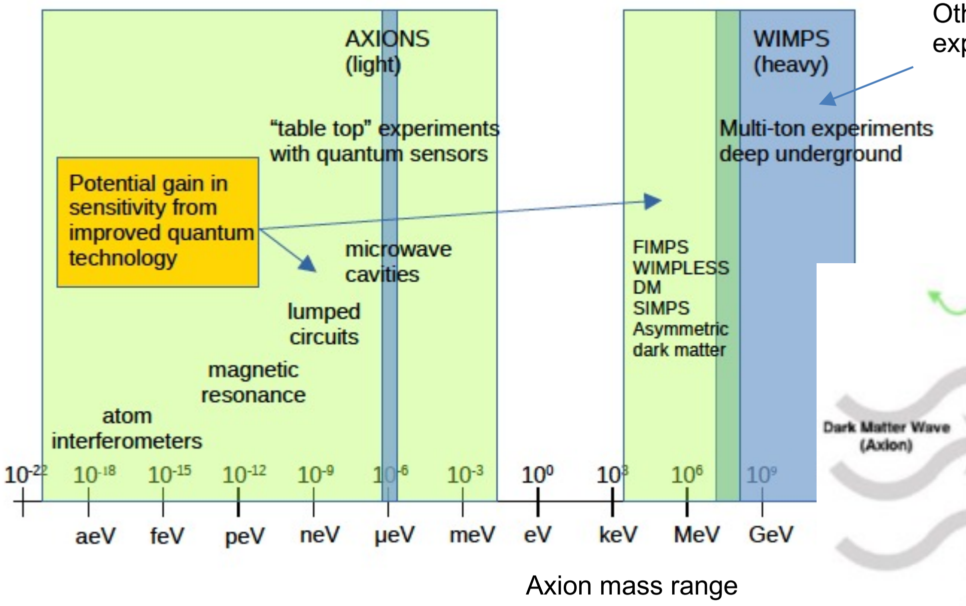


Quantum and emerging technologies

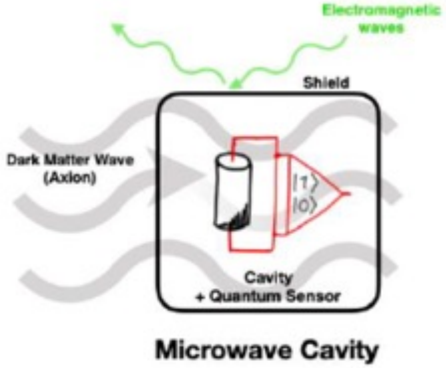
- **Quantum Technologies are a rapidly emerging area** of technology development to study fundamental physics
- The ability to engineer quantum systems to improve on the measurement sensitivity holds great promise
- **Many different sensor and technologies being investigated**: clocks and clock networks,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

CERN QUANTUM TECHNOLOGY INITIATIVE

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



ECFA Detector R&D Roadmap



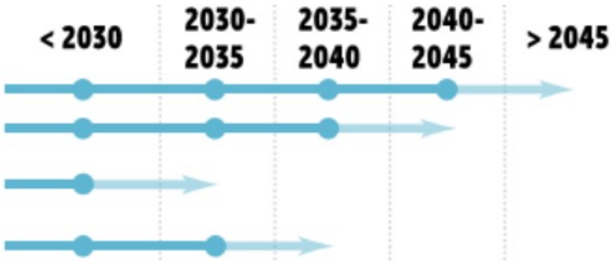
Microwave Cavity

S. Golawa

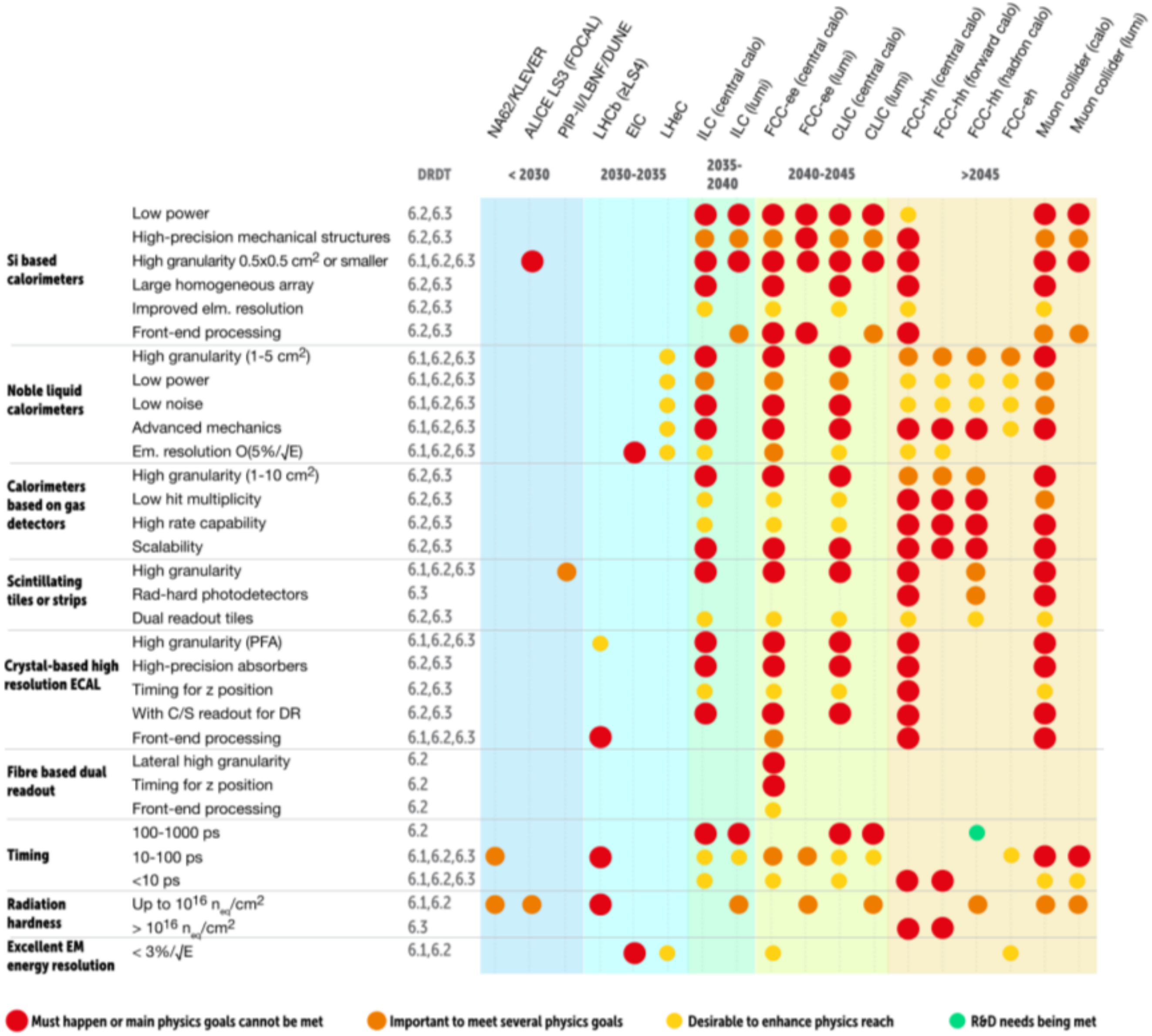
DRDTs

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



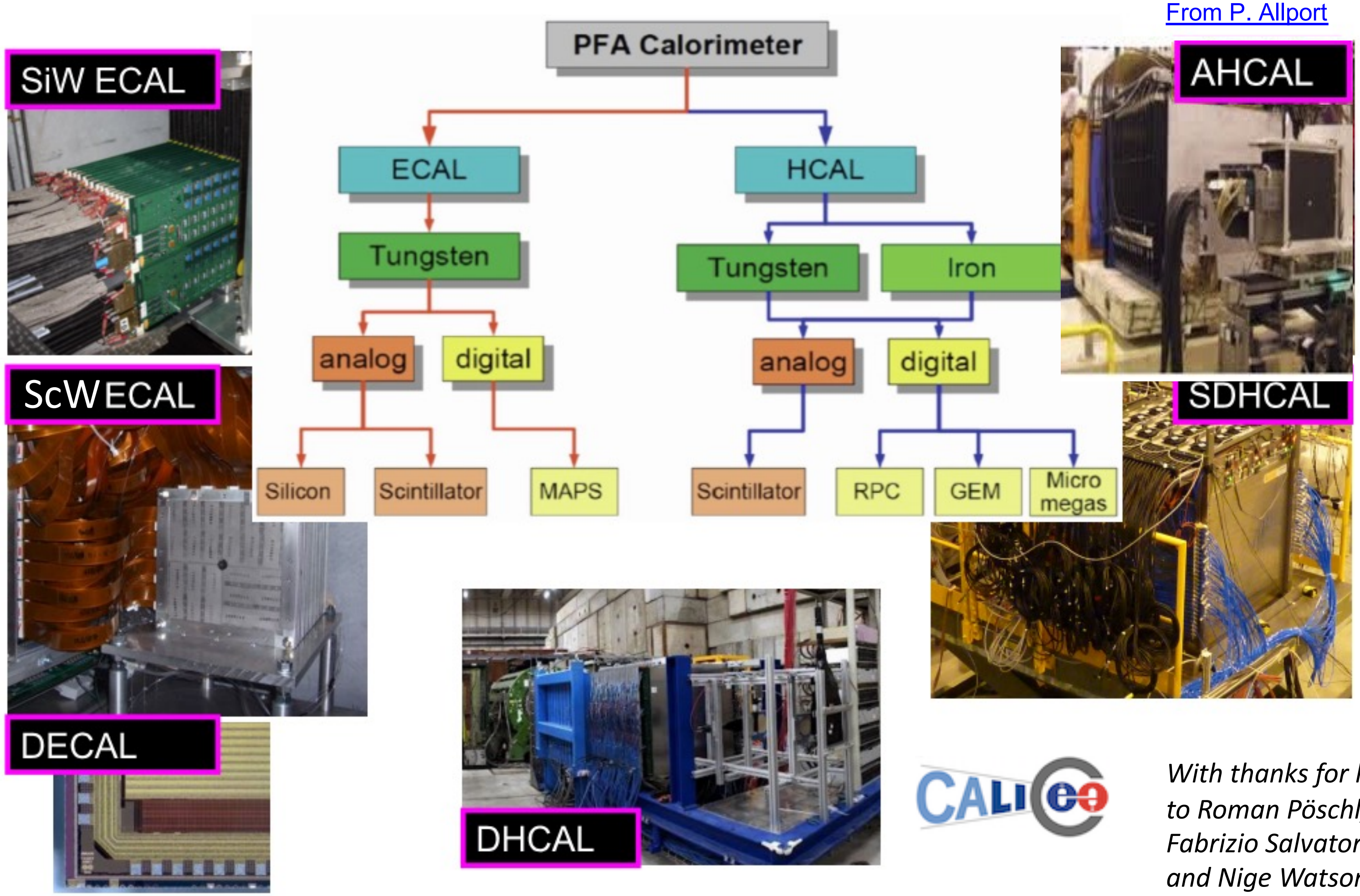
Calorimetry

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, FCC-ee IDEA): 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** (RD18 Collaboration);
- **Particle Flow based "tracking calorimeter"** concept with very fine sense element segmentation for precise reconstruction of each particle within the jet. Up to ~100M channels and 10000 m^2 active elements

From P. Allport

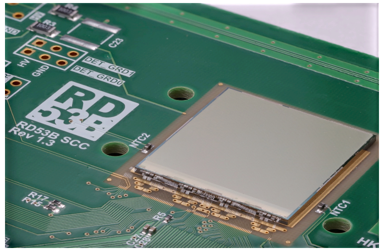


With thanks for help to Roman Pöschl, Fabrizio Salvatore and Nige Watson

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

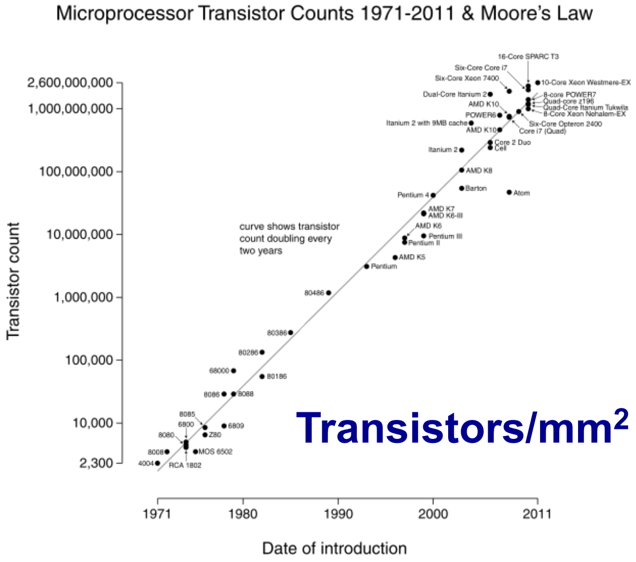
Electronics

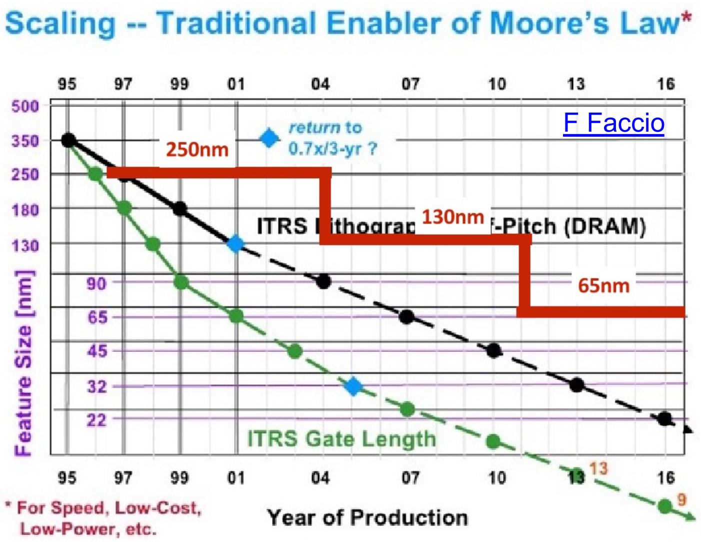
- **Precision timing** (ToF; 4D tracking), **ultra-high granularity** and improved signal **resolution** all **come at a cost in terms of data handling, processing, complexity and power.**
- These inevitably **require exploiting the latest advances in commercial <u>microelectronics</u> and <u>high-speed links</u>**.
- 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;

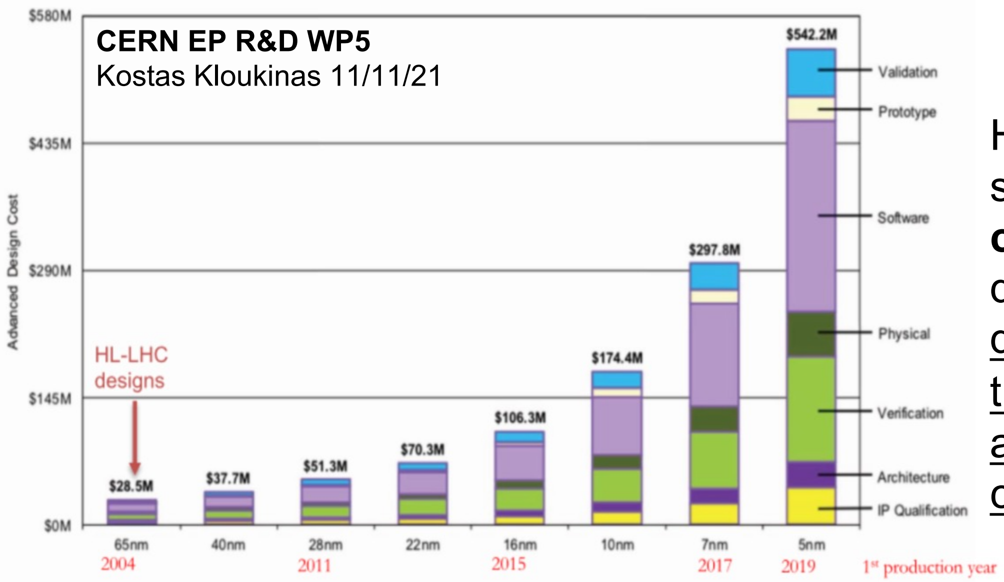


RD53 Collaboration (65 nm ASIC for HL-LHC)

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







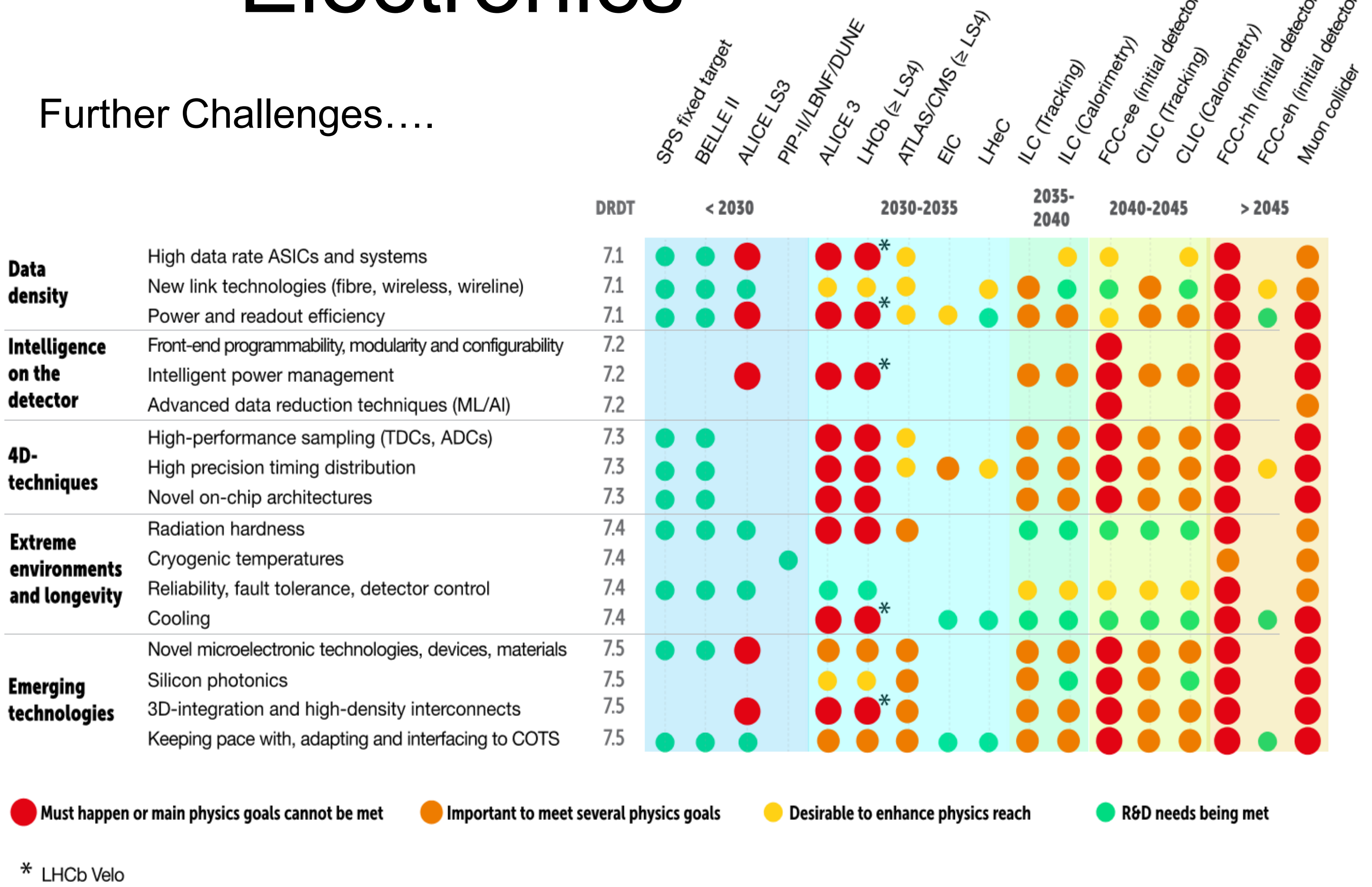
Chip Design and Manufacturing Cost under Different Process Nodes: Data Source from IBS*

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

Electronics

Further Challenges….

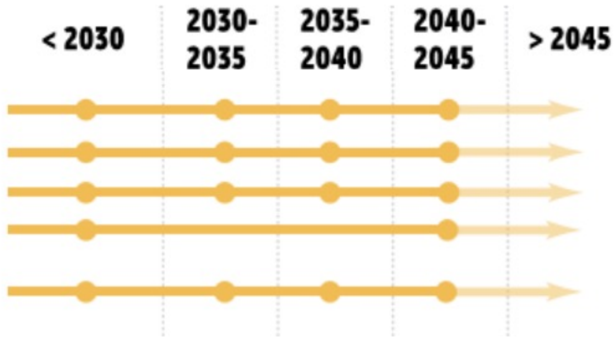
→ Much of the ECFA Detector R&D Roadmap is dedicated to discussion of the need for better organisation and coordination across Europe to cope with these considerable challenges



The DRDTs are

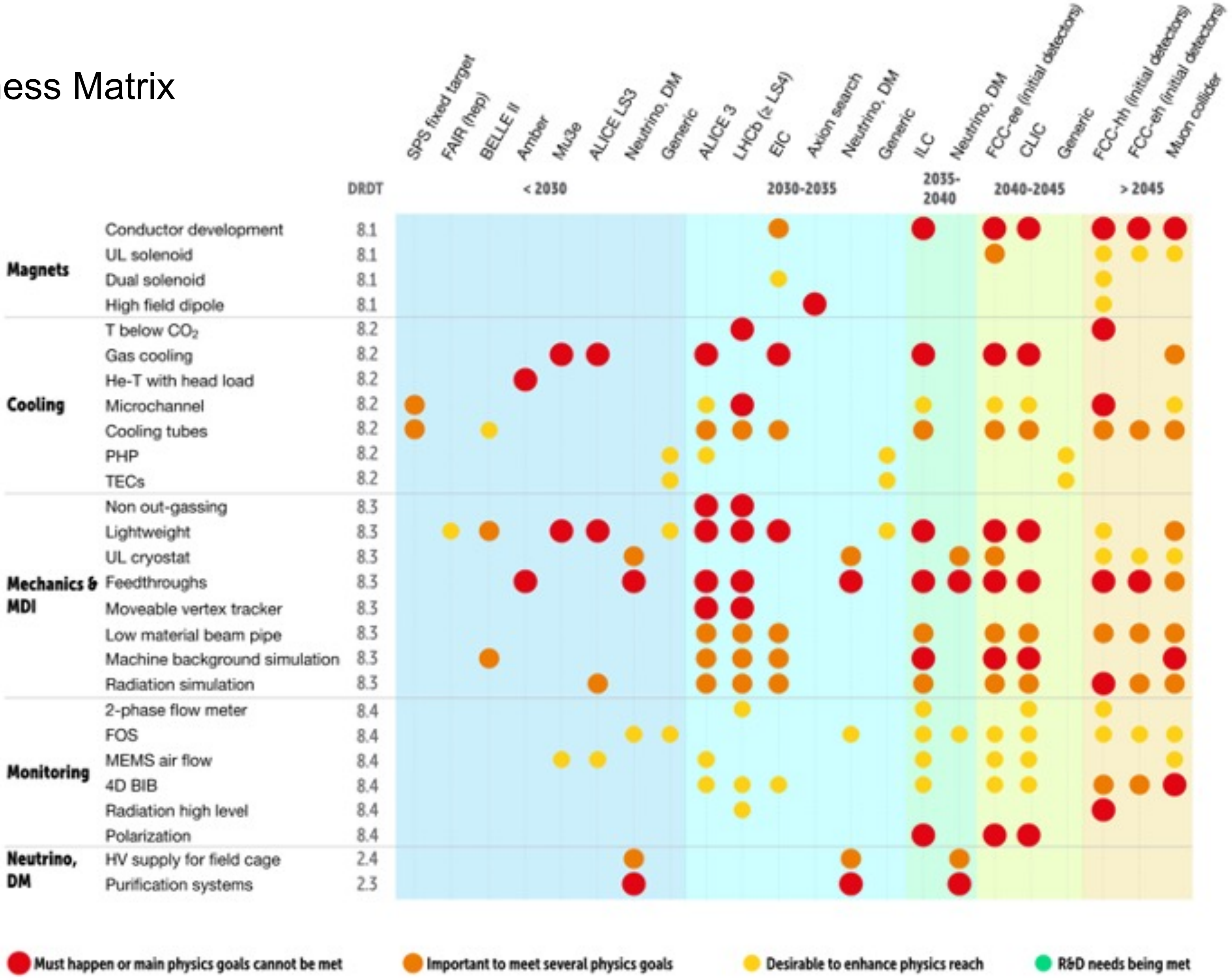
Electronics

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

- Detector Readiness Matrix

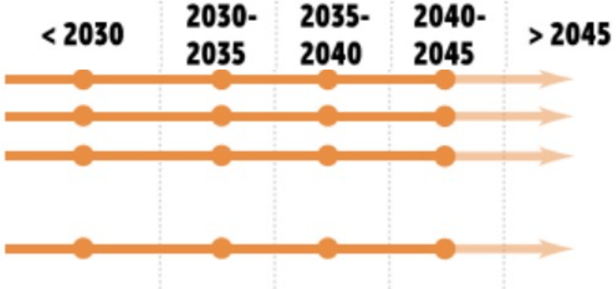


Integration

- DRDTs:

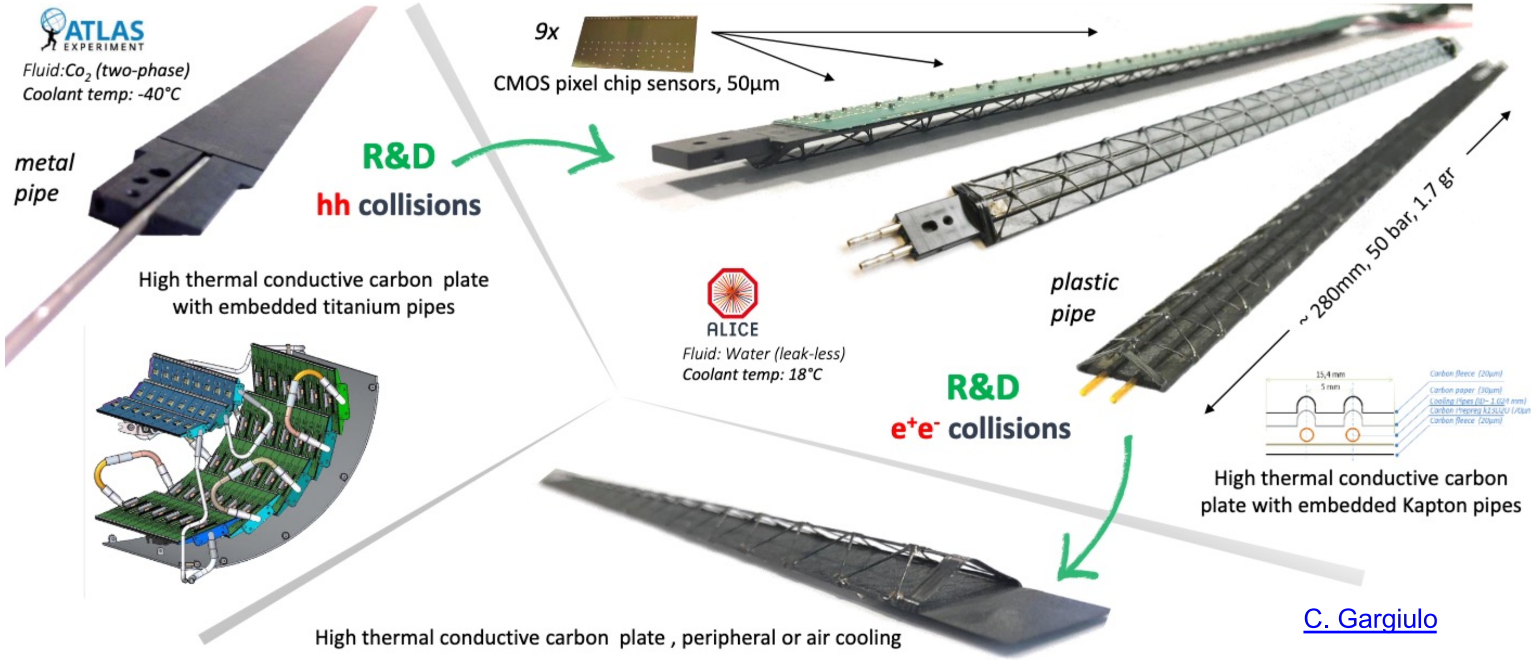
Integration

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/cooling design



C. Gargiulo

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.

General Strategic Recommendations

- **GSR 8 - Attract, nurture, recognise and sustain the careers of R&D experts**

Innovation in instrumentation is essential to make progress in particle physics, and **R&D experts are essential for innovation**. It is recommended that ECFA, with the involvement and support of its Detector R&D Panel, continues the **study of recognition with a view to consolidate the route to an adequate number of positions with a sustained career in instrumentation R&D** to realise the strategic aspirations expressed in the EPPSU. It is suggested that **ECFA should explore mechanisms to develop concrete proposals in this area and to find mechanisms to follow up on these in terms of their implementation**. Consideration needs to be given to creating sufficiently attractive remuneration packages to retain those with key skills which typically command much higher salaries outside academic research. It should be emphasised that, in parallel, society benefits from the training particle physics provides because the knowledge and skills acquired are in high demand by industries in high-technology economies.

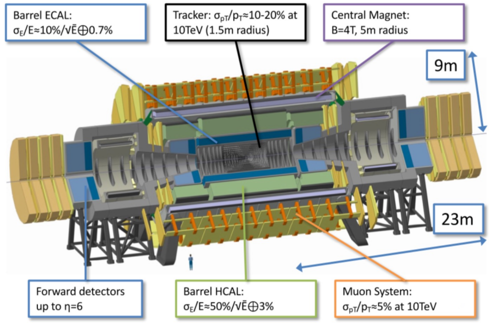
- **GSR 9 - Industrial partnerships**

It is recommended to **identify promising areas for close collaboration between academic and industrial partners**, to create international frameworks for exchange on academic and industrial trends, drivers and needs, and to **establish strategic and resources-loaded cooperation schemes on a European scale to intensify the collaboration with industry**, in particular for developments in solid state sensors and micro-electronics.

- **GSR 10 – Open Science**

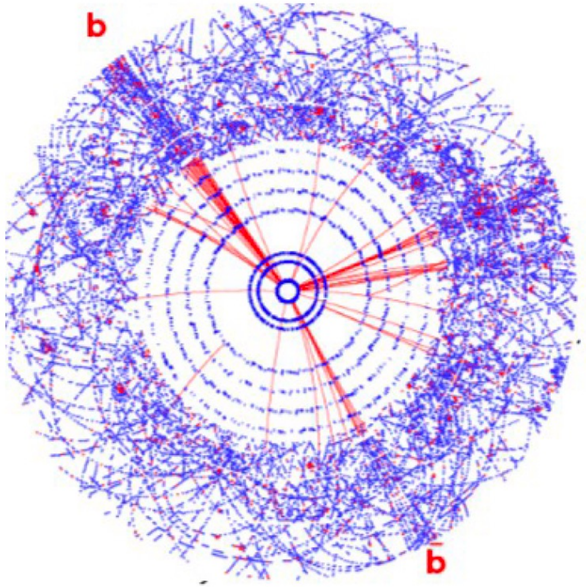
It is recommended that **the concept of Open Science be explicitly supported in the context of instrumentation**, taking account of the constraints of commercial confidentiality where these apply due to partnerships with industry. Specifically, for publicly-funded research the default, wherever possible, should be open access publication of results and it is proposed that the Sponsoring Consortium for Open Access Publishing in Particle Physics (SCOAP^3) should explore ensuring similar access is available to instrumentation journals (including for conference proceedings) as to other particle physics publications.

Example of future detectors at accelerators



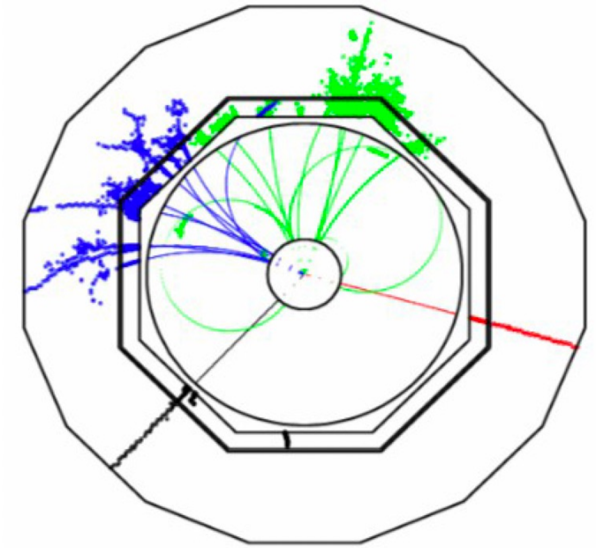
FCC-hh CDR

Hadron-hadron collisions e.g. LHC

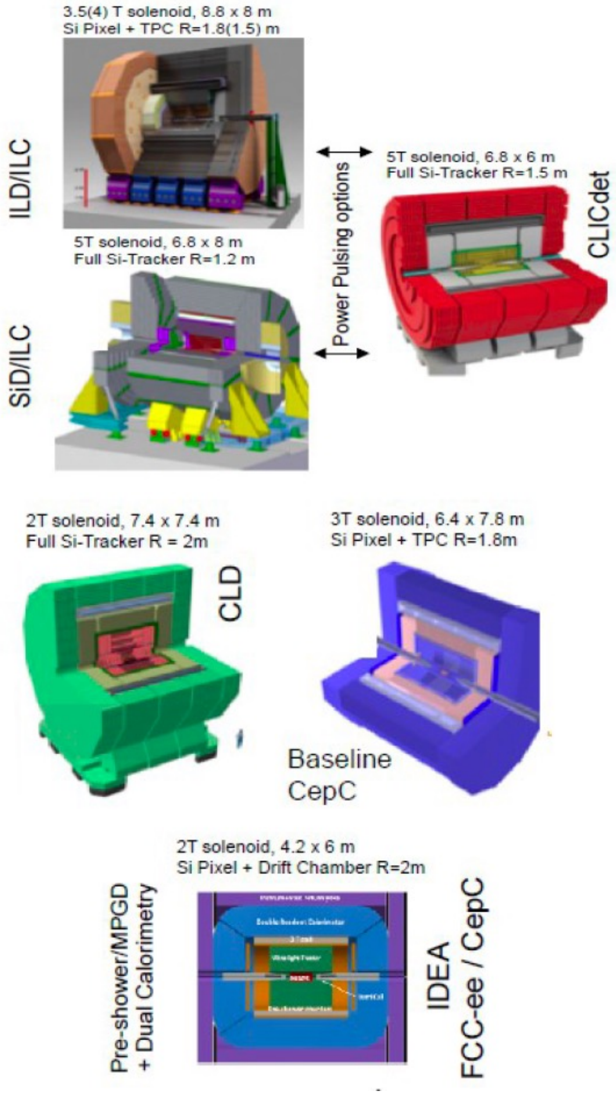


- Busy events
- Require hardware and software triggers
- High radiation levels

e^+e^--collisions



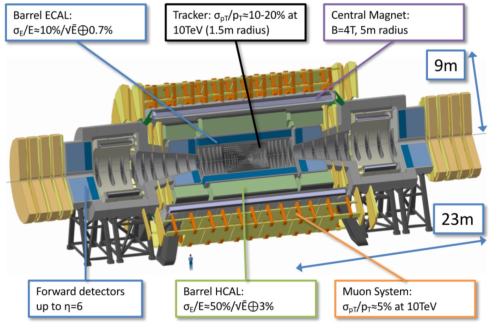
- Clean events
- No trigger
- Full event reconstruction



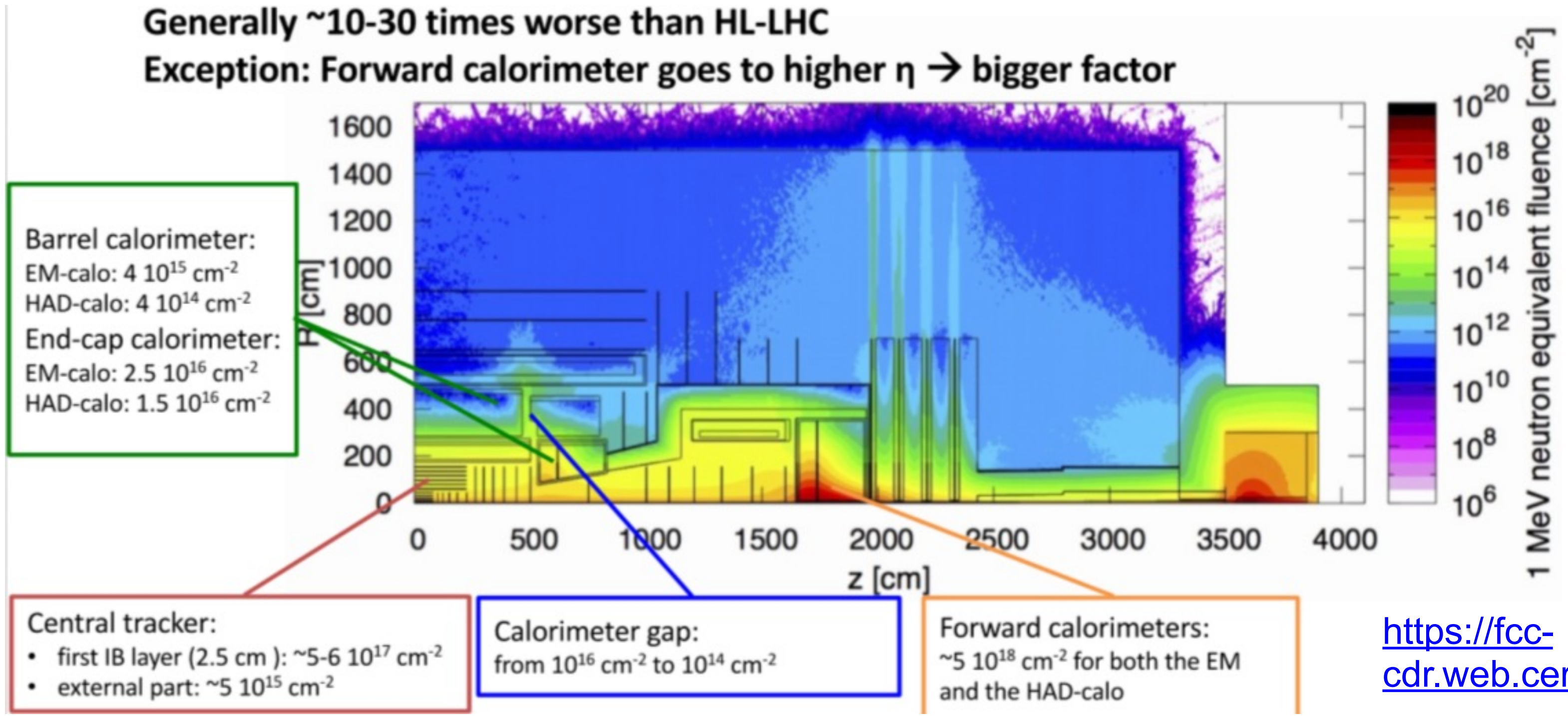
- One of the many challenges: radiation hardness. Radiation levels of e.g. 300 MGy/5-6 10^{17} n_{eq}/cm^2 in first tracker layers go well beyond what any currently available microelectronics can survive ($\lesssim$ MGy) and few sensor technologies can cope beyond ~10^{16} n_{eq}/cm^2

→ Detector R&D essential

Example of future detectors at accelerators



FCC-hh CDR



https://fcc-cdr.web.cern.ch/#FCCHH

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