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European Strategy Update

INFN
Istituto Nazionale di Fisica Nucleare
Sezione di Pavia

Future of the Instrumentation and Detector Developments in Particle Physics

Roberto Ferrari
INFN Pavia

ASFAE 2024 Workshop
Alicante, March 5, 2024

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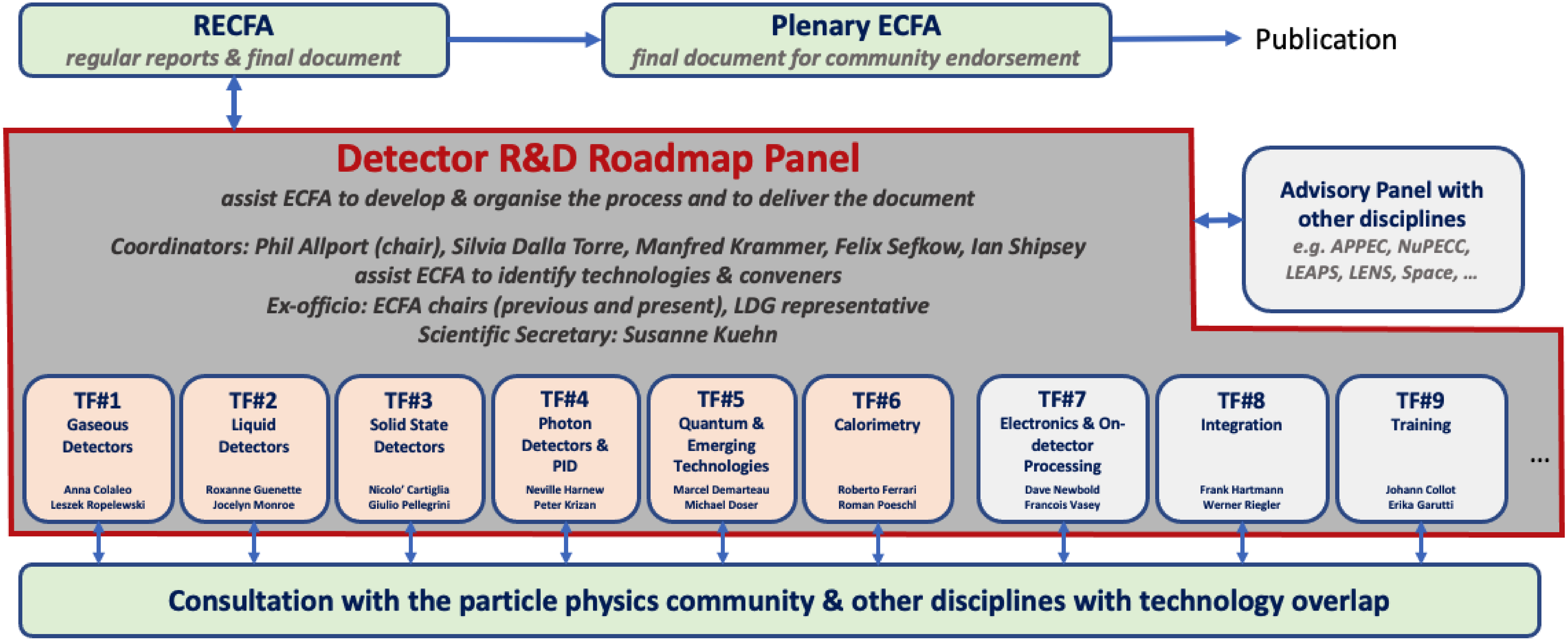
Detector R&D Roadmap Panel

European Strategy Update



Roadmap document(s)

- ECFA R&D Roadmap
  - CERN-ESU-017
  - 248 pages full text and 8 page synopsis
- Endorsed by ECFA and presented to CERN Council in December 2021

Roadmap identified:

  - General Strategic Recommendations (GSRs)
  - Detector R&D Themes (DRDTs) per task-force topic
  - Concrete R&D Tasks

Timescale of proposed future facilities

Timescale of projects as approved by European Lab Director Group (LDG)

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Timescale of proposed future facilities

European Strategy Update

Timescale of projects as approved by European Lab Director Group (LDG)

guiding principle: project realisation must NOT be delayed by detectors

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Detector R&D Themes

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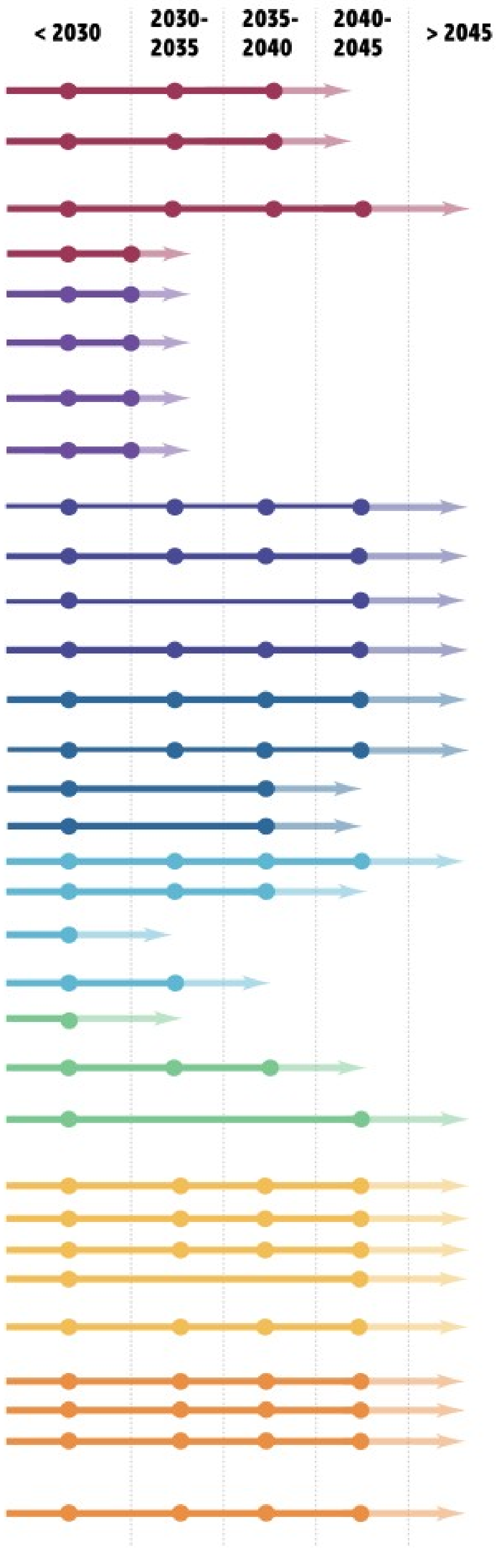
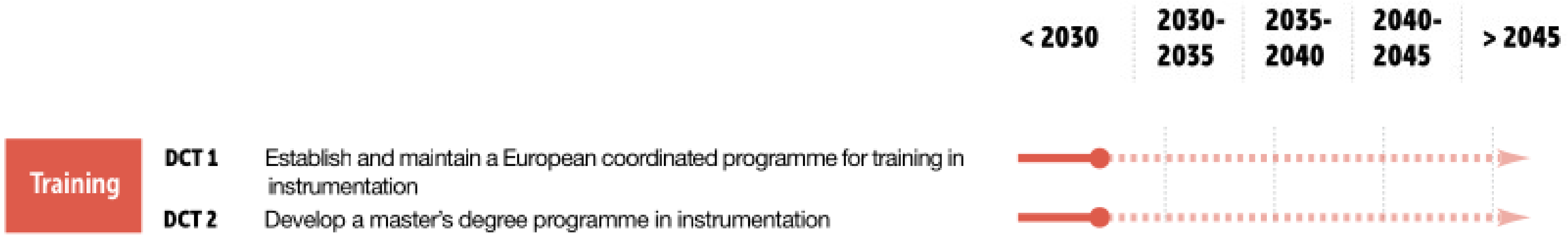
Gaseous	DRDT 1.1	Improve time and spatial resolution for gaseous detectors with long-term stability
	DRDT 1.2	Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes
	DRDT 1.3	Develop environmentally friendly gaseous detectors for very large areas with high-rate capability
	DRDT 1.4	Achieve high sensitivity in both low and high-pressure TPCs
Liquid	DRDT 2.1	Develop readout technology to increase spatial and energy resolution for liquid detectors
	DRDT 2.2	Advance noise reduction in liquid detectors to lower signal energy thresholds
	DRDT 2.3	Improve the material properties of target and detector components in liquid detectors
	DRDT 2.4	Realise liquid detector technologies scalable for integration in large systems
Solid state	DRDT 3.1	Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors
	DRDT 3.2	Develop solid state sensors with 4D-capabilities for tracking and calorimetry
	DRDT 3.3	Extend capabilities of solid state sensors to operate at extreme fluences
	DRDT 3.4	Develop full 3D-interconnection technologies for solid state devices in particle physics
PID and Photon	DRDT 4.1	Enhance the timing resolution and spectral range of photon detectors
	DRDT 4.2	Develop photosensors for extreme environments
	DRDT 4.3	Develop RICH and imaging detectors with low mass and high resolution timing
	DRDT 4.4	Develop compact high performance time-of-flight detectors
Quantum	DRDT 5.1	Promote the development of advanced quantum sensing technologies
	DRDT 5.2	Investigate and adapt state-of-the-art developments in quantum technologies to particle physics
	DRDT 5.3	Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies
	DRDT 5.4	Develop and provide advanced enabling capabilities and infrastructure
Calorimetry	DRDT 6.1	Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution
	DRDT 6.2	Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods
	DRDT 6.3	Develop calorimeters for extreme radiation, rate and pile-up environments
Electronics	DRDT 7.1	Advance technologies to deal with greatly increased data density
	DRDT 7.2	Develop technologies for increased intelligence on the detector
	DRDT 7.3	Develop technologies in support of 4D- and 5D-techniques
	DRDT 7.4	Develop novel technologies to cope with extreme environments and required longevity
	DRDT 7.5	Evaluate and adapt to emerging electronics and data processing technologies
Integration	DRDT 8.1	Develop novel magnet systems
	DRDT 8.2	Develop improved technologies and systems for cooling
	DRDT 8.3	Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces.
	DRDT 8.4	Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects



Detector Community Themes



w/ key focus on inclusivity and diversity

Generic Strategic Recommendations

GSR1- Supporting R&D facilities

GSR2- Engineering support for detector R&D

GSR3- Specific software for instrumentation

GSR4- International coordination and organisation of R&D activities

GSR5- Distributed R&D activities with centralised facilities

GSR6- Establish long-term strategic funding programmes

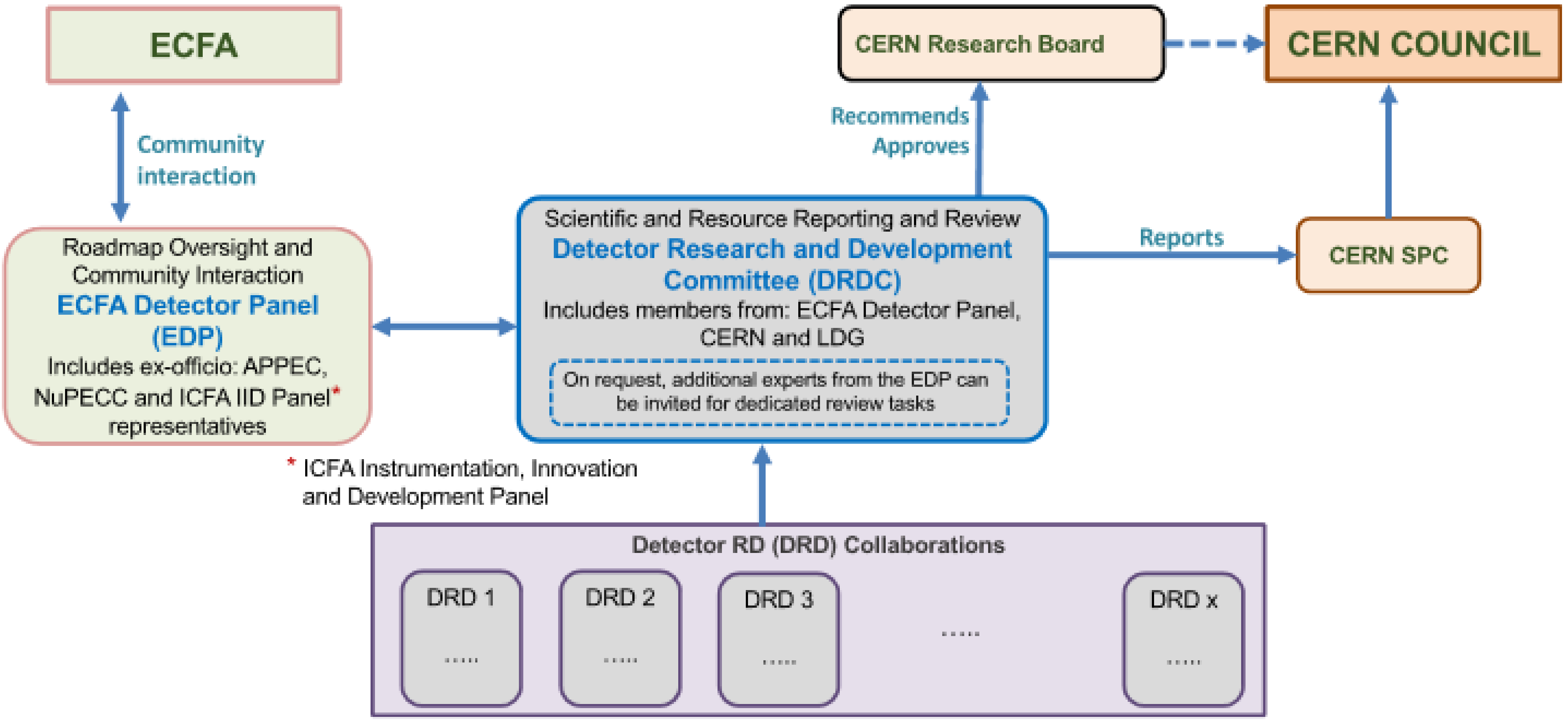
GSR7- Blue-sky R&D

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

GSR 9 - Industrial partnerships

GSR 10 - Open Science

Implementation



Detector R&D Collaborations

Fully Approved
- Gaseous Detectors (DRD1) [ex RD51]
- Liquid Detectors (DRD2)
- Photodetectors & Particle ID (DRD4)
- Calorimetry (DRD6)

Conditionally approved
- Semiconductor Detectors (DRD3) [ex RD50, RD42,..]

Full proposals submitted last week for review
- Quantum Sensors (DRD5)
- Electronics (DRD7)

Letter of Intent submitted
- Integration (DRD8)

DRD Collaborations

- World-wide collaborations
- Built upon established detector R&D communities (RD50, RD51, Calice, Crystal Clear, ...) as well as (proto-)colloaborations for present or proposed facilities
- As inclusive as possible
- Identify and/or develop synergies → minimise duplications / optimise resource utilisation
- Try to assure that nothing was left or fell out ...
- Huge programme with short-term, middle-term, long-term targets

DRD Collaborations (2)

- Community-driven “resource-loaded” Work Packages (WPs) w/ dedicated (independent) funding lines
- Scientific organisation in Working Groups (Wgs): forum for sharing expertise and identifying joint projects
- Common projects (in case): short-term blue-sky R&D or common tool development

Each DRD independently formed & organised
→ community-driven process

Breakdown

Technology driven → gaseous detectors, liquid detectors, ... but calorimetry

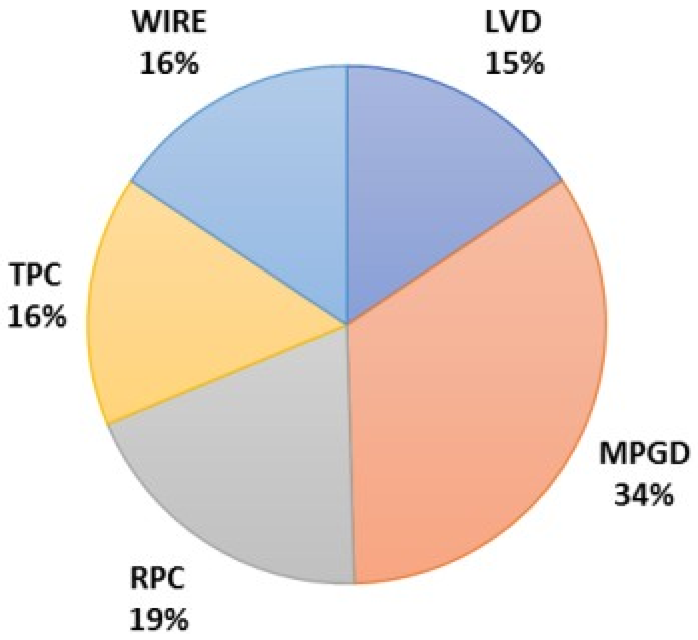
→ calorimeters: big, complex systems with system issues

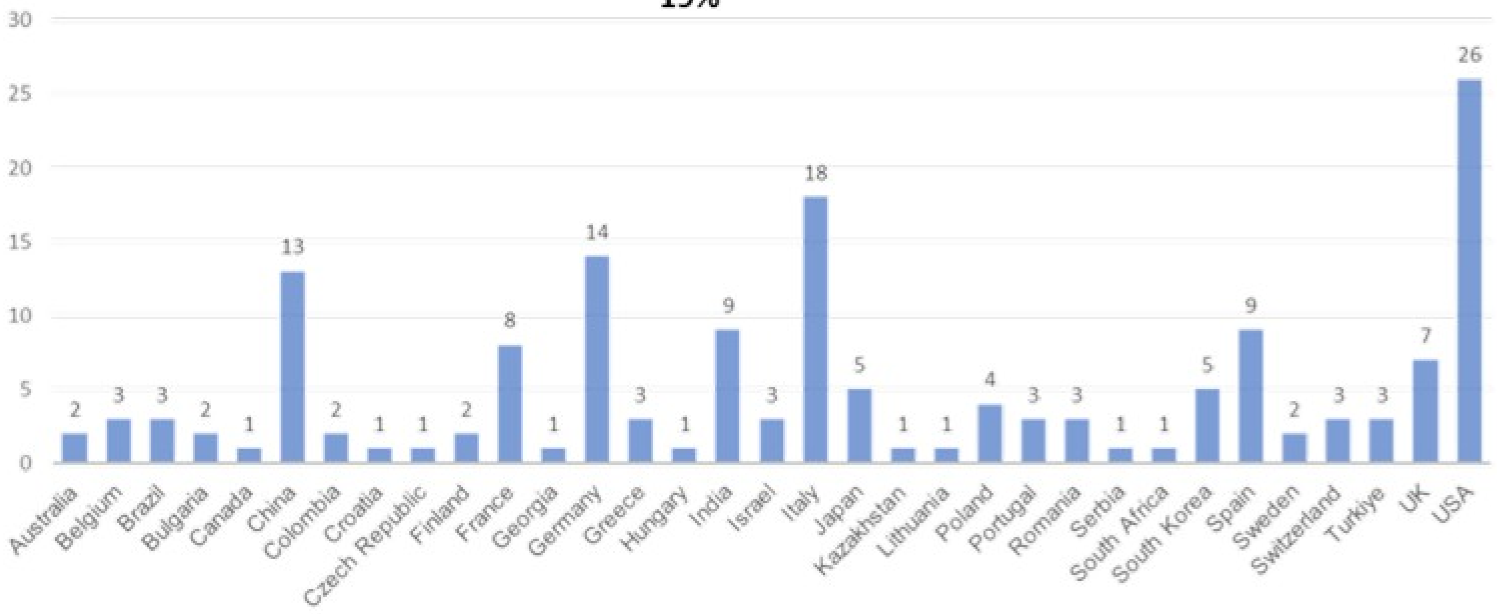
→ strong bidirectional relations with other DRDs

DRD1 – Gaseous Detectors

ECFA Gaseous Detectors (DRD1) – Large and diversified community

- **161 Institutes**
- **5 Industrial, Semi-Industrial and Research Foundations**
- **33 Countries**
- **More than 700 members**





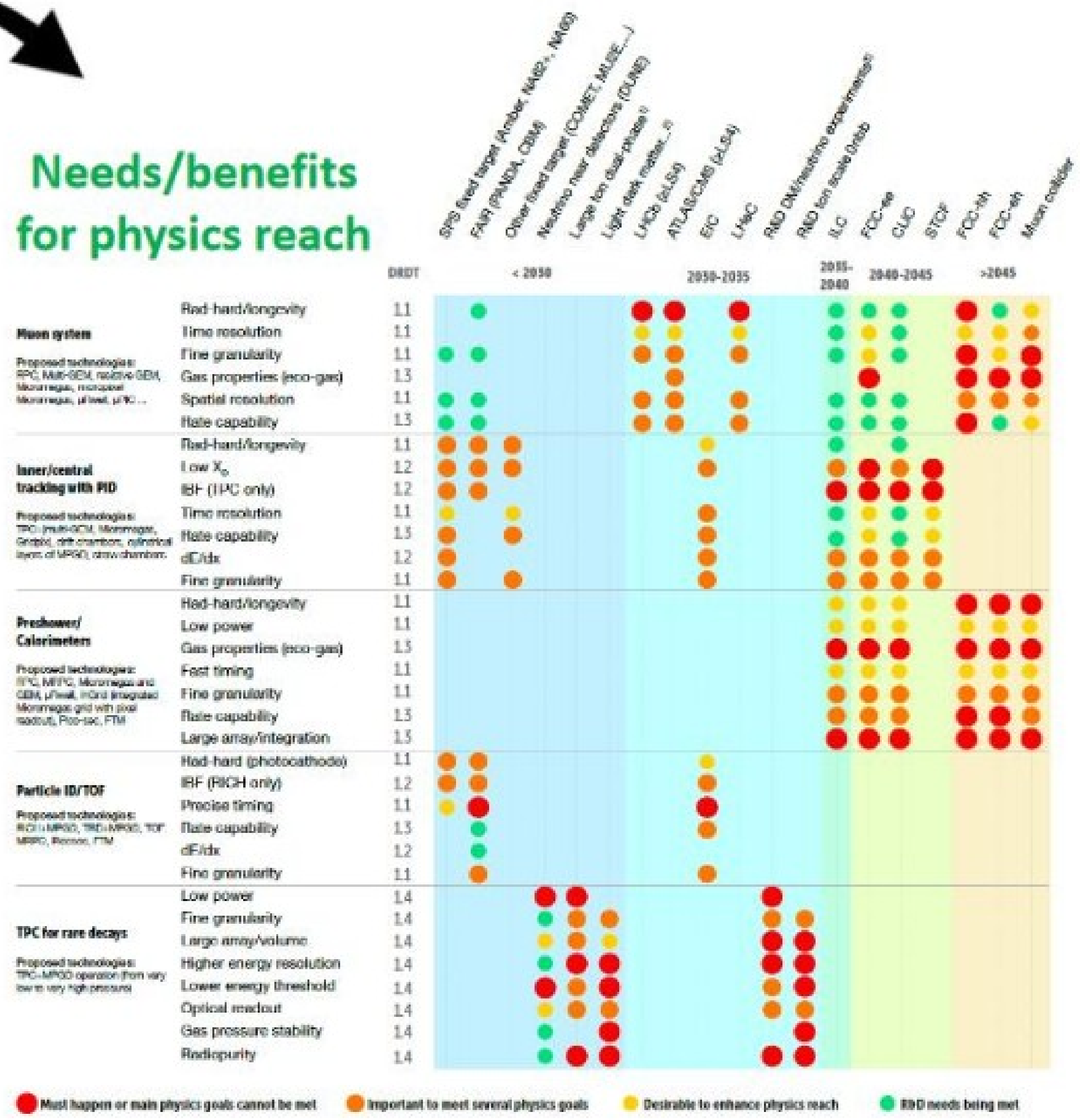
Countries of DRD1 Institutes (today)

ECFA Detector R&D Roadmap (TF1)

Performance targets and main drivers from facilities

Facility	Technologies	Challenges	Most challenging requirements at the experiment
HL-LHC	RPC, Multi-GEM, resistive-GEM, Micromegas, micro-pixel Micromegas, μ-RWELL, μ-PIC	Ageing and radiation hard, large area, rate capability, space and time resolution, miniaturisation of readout, eco-gases, spark-free, low cost	**(LHCb)**: Max. rate: 900 kHz/cm^2 Spatial resolution: ~ cm Time resolution: O(ns) Radiation hardness: ~ 2 C/cm^2 (10 years)
Higgs-EW-Top Factories (ee) (ILC/FCC-ee/CepC/SCTF)	GEM, μ-RWELL, Micromegas, RPC	Stability, low cost, space resolution, large area, eco-gases	**(IDEA)**: Max. rate: 10 kHz/cm^2 Spatial resolution: ~60-80 μm Time resolution: O(ns) Radiation hardness: <100 mC/cm^2
Muon collider	Triple-GEM, μ-RWELL, Micromegas, RPC, MRPC	High spatial resolution, fast/precise timing, large area, eco-gases, spark-free	Fluxes: > 2 MHz/cm^2 ($\theta<8^0$) < 2 kHz/cm^2 (for $\theta>12^0$) Spatial resolution: ~100μm Time resolution: sub-ns Radiation hardness: < C/cm^2
Hadron physics (EIC, AMBER, PANDA/CMB@FAIR, NA60+)	Micromegas, GEM, RPC	High rate capability, good spatial resolution, radiation hard, eco-gases, self-triggered front-end electronics	**(CBM@FAIR)**: Max rate: <500 kHz/cm^2 Spatial resolution: < 1 mm Time resolution: ~ 15 ns Radiation hardness: 10[illegible] neq/cm^2/year
FCC-hh (100 TeV hadron collider)	GEM, THGEM, μ-RWELL, Micromegas, RPC, FTM	Stability, ageing, large area, low cost, space resolution, eco-gases, spark-free, fast/precise timing	Max. rate 500 Hz/cm^2 Spatial resolution ~ 50 μm Angular resolution ~ 70 μrad (η~0) to get $\Delta p/p \leq 10\%$ up to 20 TeV/c

Example: Muon systems



Detector R&D themes

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

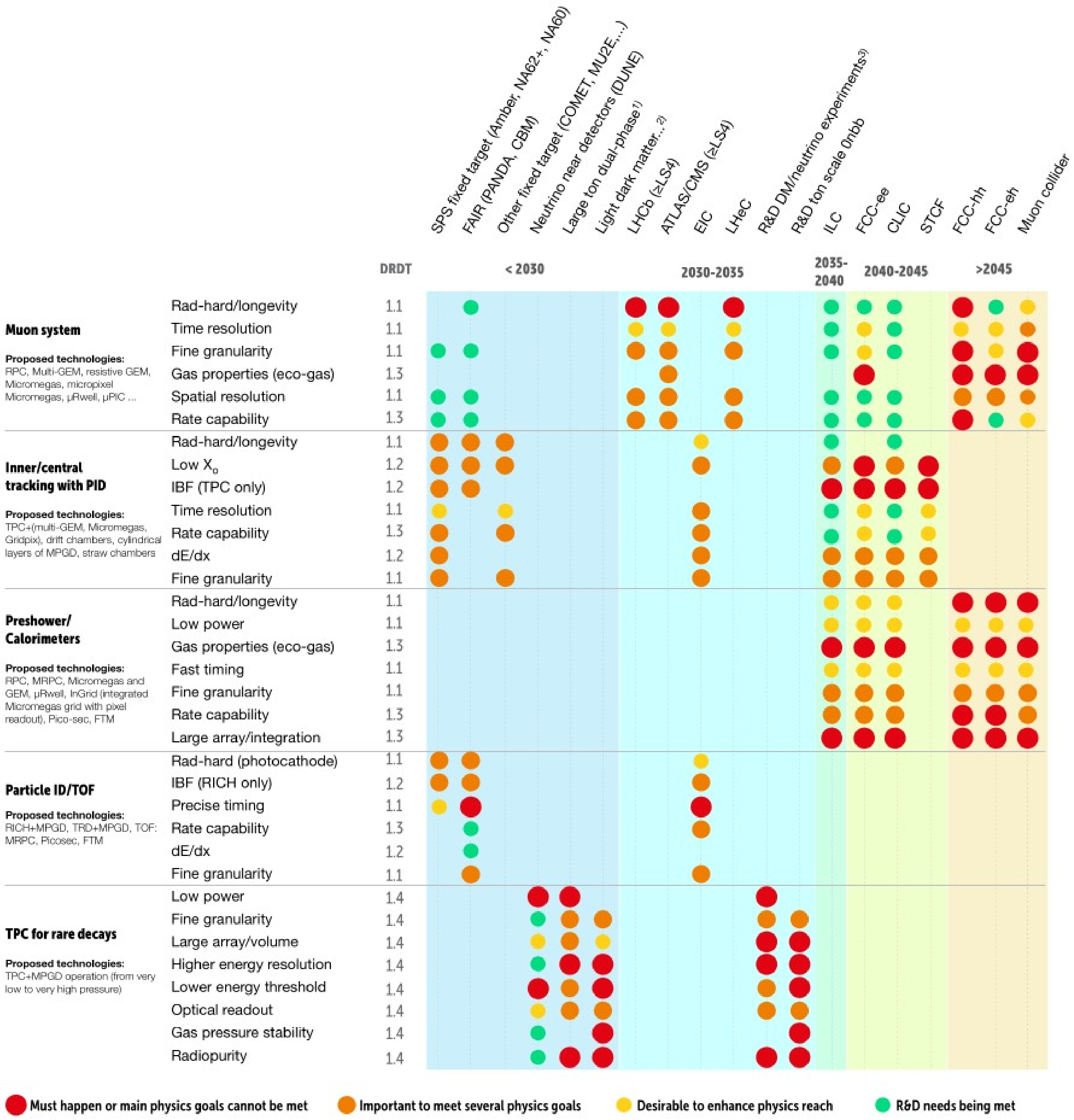
< 2030 | 2030-2035 | 2035-2040 | 2040-2045 | > 2045

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

P. Gasik, DRD1 Proposal: Development of Gaseous Detectors Technologies, **1st meeting of the DRDC** 4 Dec 2023, CERN

R&D needs



- Most severe needs for hadr. coll.s (radiation hardness, rate, granularity, ...)
- e+e-: IBF (TPC), PID (dE/dx, dN/dx), low X_0
- Search rare decays → high sensitivity TPCs
- Precise timing for TOF detectors
- General requirement: ecocompatible gases
- Exploit more and more MPGDs

DRD1 organisation

Strategic R&D and long-term funding based on Work Packages

DRDTs

1.1	1.2	1.3	1.4	Work Packages
●		●		Trackers/hodoscopes
●	●	●		Drift chambers
●	●	●		Straw chambers
●	●	●	●	Tracking TPCs
●		●		Calorimetry
●	●	●		Photon detection (PID)
●		●		Timing detectors
●	●	●	●	Reaction/decay TPCs
●		●		Beyond HEP

- WG1: Technologies
- WG2: Applications
- WG3: Gas and material studies
- WG4: Detector physics, simulations and software tools
- WG5: Electronics for gaseous detectors
- WG6: Detector production
- WG7: Common test facilities
- WG8: Training and dissemination

R&D framework based on Working Groups (scientific organisation)

RD51 (2008-2023) – DRD1 forerunner

Seven working groups (WG) defined through set of tasks. Working-group convenors coordinate R&D tasks of respective working groups

Early list of RD51 Working Group convenors

RD51 – Micropattern Gas Detectors

	WG1 New Structures and Technologies	WG2 Detector Physics and Performance	WG3 Training and Dissemination	WG4 Modelling of Physics Processes & Software Tools	WG5 Electronics for MPGDs	WG6 Production and Industrialisation	WG7 Common Test Facilities
Objectives	Design optimization Development of new geometries and techniques	Common test standards Characterization and understanding of physical phenomena in MPGD	Organisation of dissemination and training events for the MPGD community	Development of common software and documentation for MPGD simulations	Readout electronics optimization and integration with MPGD detectors	Development of cost-effective technologies and industrialization	Sharing of common infrastructure for detector characterization
Tasks	Large Area MPGDs Design Optimization New Geometries Fabrication Development of Rad-Hard Detectors Development of Portable Detectors	Common Test Standards Discharge Protection Ageing & Radiation Hardness Charging up and Rate Capability Study of Avalanche Statistics	Topical Workshops Schools (Eletronics, Simulation, ...) Academy-Industry Matching Events Dissimination of MPGD applications	Algorithms Simulation Improvements Common Platform (Root, Geant4) Electronics Modeling	FE electronics requirements definition General Purpose Pixel Chip Large Area Systems with Pixel Readout Portable Multi-Channel System Discharge Protection Strategies	Common Production Facility Industrialization Collaboration with Industrial Partners	Testbeam Facility Irradiation Facility

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DRD1 Working Group tasks

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The collaborative structure of DRD1 keeps RD51 structure in Working Groups

Working-group conveners coordinate R&D tasks of the respective working groups. Two coordinators elected through a nomination process, approved by MB and CB

WG 1	WG 2	WG 3	WG 4	WG 5	WG 6	WG 7	WG 8
Technologies	Applications	Gas and material studies	Detector physics, simulations, and software tools	Electronics	Detector production	Common test facilities	Training and dissemination
Large Volume Detectors (Drift chambers, TPCs)	Trackers/Hodoscope	Measurement of Gas Properties	Garfield++	Front-End Electronics for Gaseous Detectors	Common Production Facilities and Equipments	Detector Laboratories Network	Knowledge Exchange and Facilitating Scientific Collaborations
MPGDs	Inner and Cenral Tracking with PID Capabilities: - Drift Chambers - Straw tubes - TPC	Studies on Eco-friendly Mixtures	Simulation of Large Charges and Space Charge	Modernised Readout Systems (DAQ): high performances	QA/QC	Test Beam Common Facilities	Training and Dissemination Initiatives
RPCs, MRPCs	Calorimetry	Ageing and Outgassing studies	Simulation of Detectors with Resistive Elements	Modernised Readout Systems (DAQ): FE Integration	Collaboration with Industrial Partner	Irradiation Common Facilities	Career Promotion
TPC	Photon Detector (PID)	Gas sytems	Modelling and Simualtion of Eco-friendly Mixtures	Modernised Readout Systems (DAQ): portability	Gaseous Detector FORUM (know-how)	Specialized laboratories (outgassing/ageing, gas analysers, photocathodes)	Outreach and Education
Straw tubes, TGC, CSC, drift chambers, and other wire detectors	Timing Detectors (PID & Trigger)	Materials studies: - novel material (nanomaterial) - new material for wire - new converter	Optimization of Simulations (time, hw/sw resources)	Instrumentation (e.g. HV,LV, monitoring)		Common instrumentation and sofware	
New amplifying structures	TPC as reaction and decay chambers	Photocathodes	Specific Proceses (e.g. Electroluminescence)				
	Beyond HEP - Medical Application - Neutron Science - Muography - Space Applicatios - Oher (Dosimetry, Beam Monitoring, Cultural Heritage, Homeland Security,..)	Precision Mechanics					

| Piotr Gasik | 1st meeting of the DRDC | DRD1 Proposal | CERN | 04.12.2023

P. Gasik, DRD1 Proposal: Development of Gaseous Detectors Technologies, **1st meeting of the DRDC** 4 Dec 2023, CERN

DRD-1 Working Groups

WG1: Technologies

WG2: Applications

WG3: Gas and material studies

WG4: Detector physics, simulations and sw tools

WG5: Electronics for gaseous detectors

WG6: Detector production

WG7: Common test facilities

WG8: Training and dissemination

Examples of Working Group activities

(contributions at 1st DRD1 Collaboration Meeting)

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WG1 - Technologies

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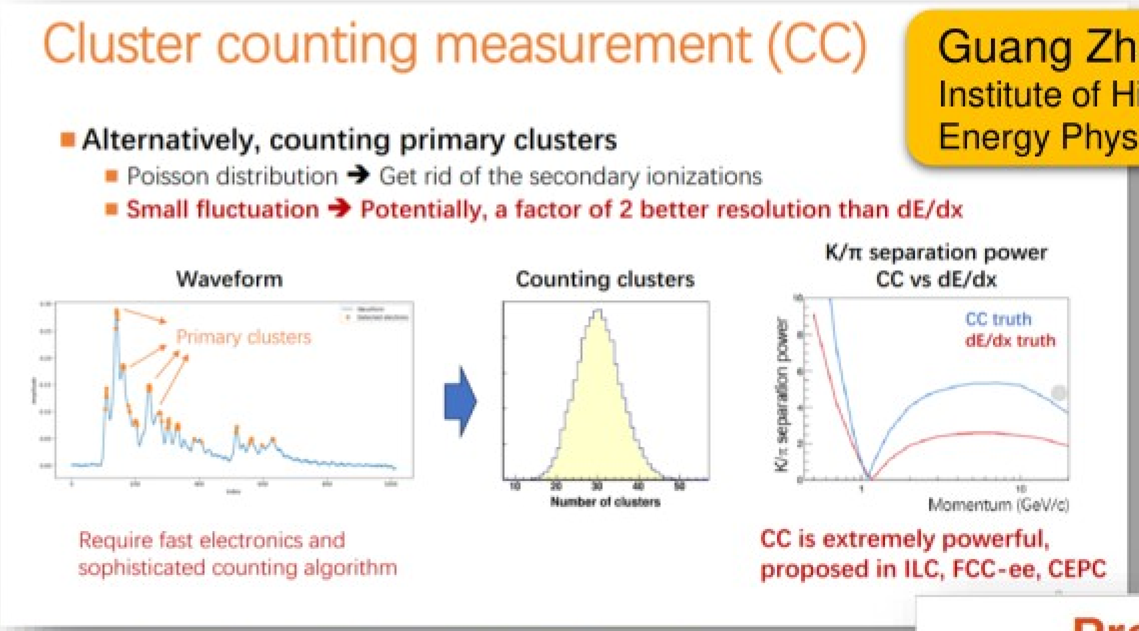
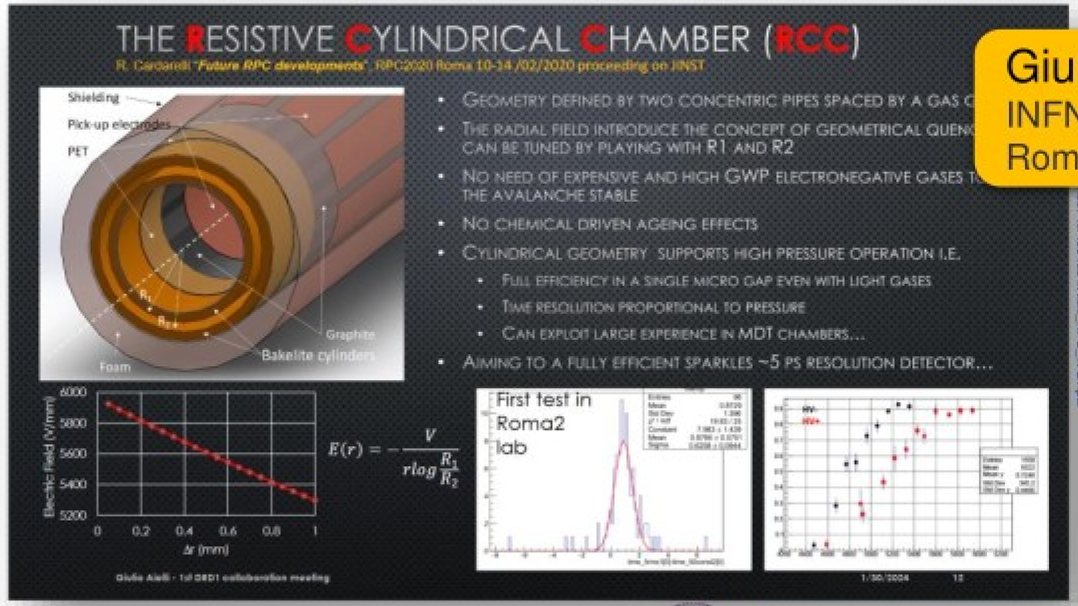
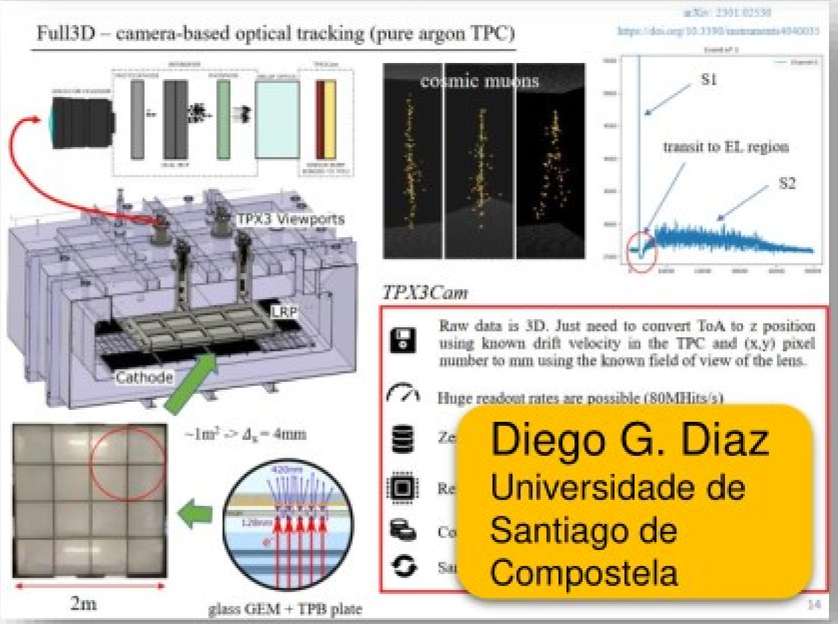


Guang Zhao
Institute of High Energy Physics

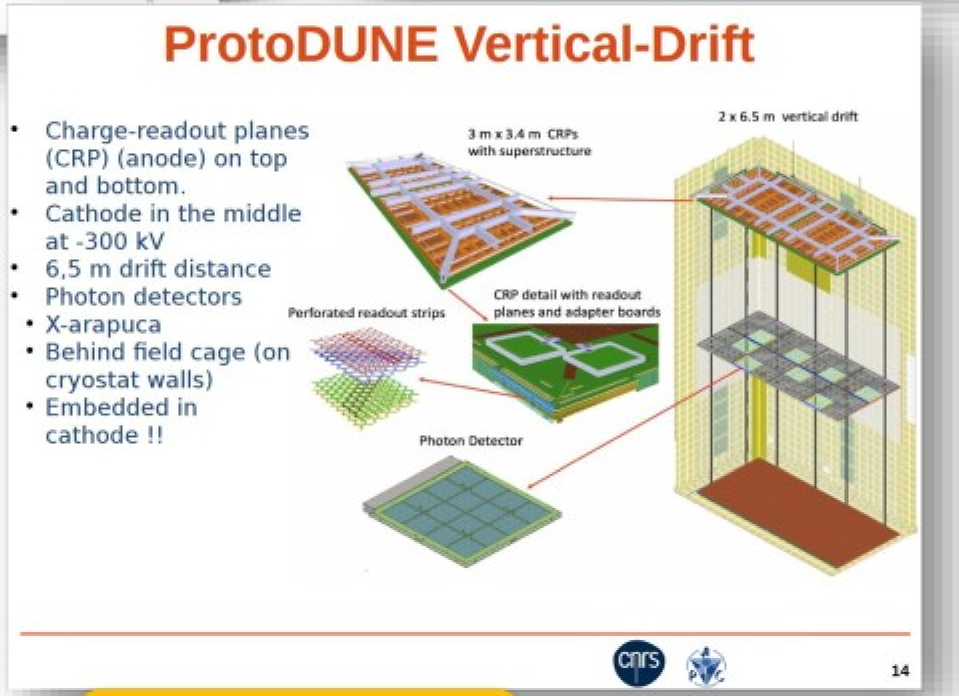


Giulio Aielli
INFN e Universita Roma Tor Vergata

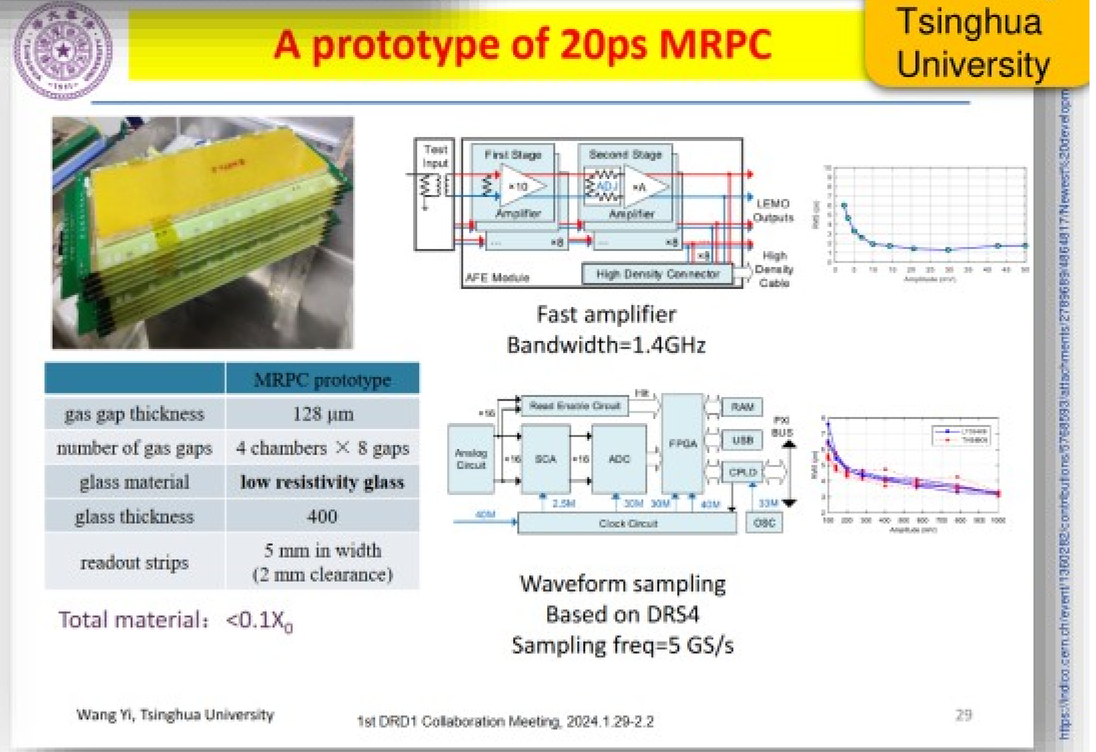
Conveners:
P. Colas,
F. Resnati,
P. Wintz,
I. Deppner,
M. Tytgat,
L. Moleri



Diego G. Diaz
Universidade de Santiago de Compostela



Jaime V. Dawson
Centre National de la Recherche Scientifique



Yi Wang
Tsinghua University

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WG5 - Electronics

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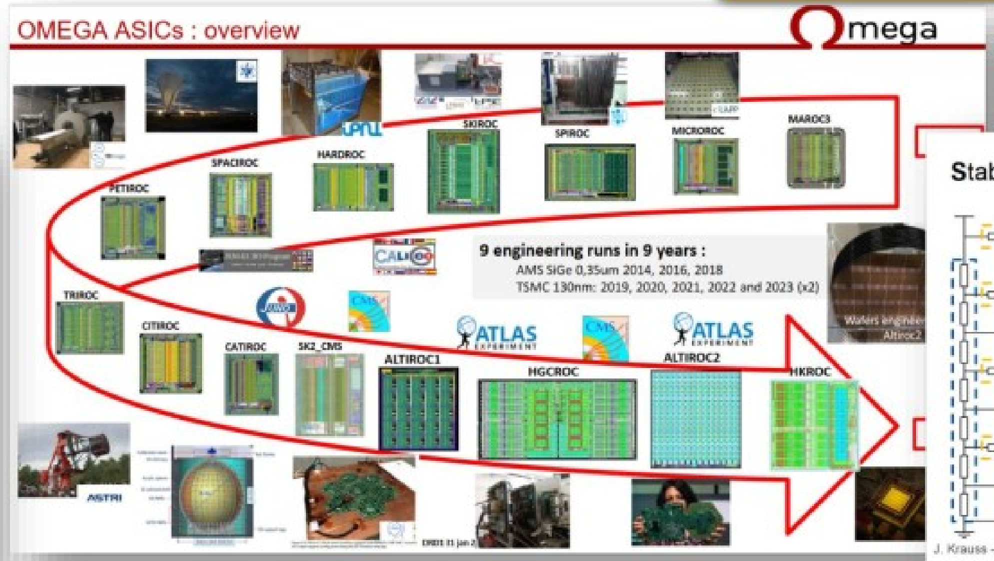
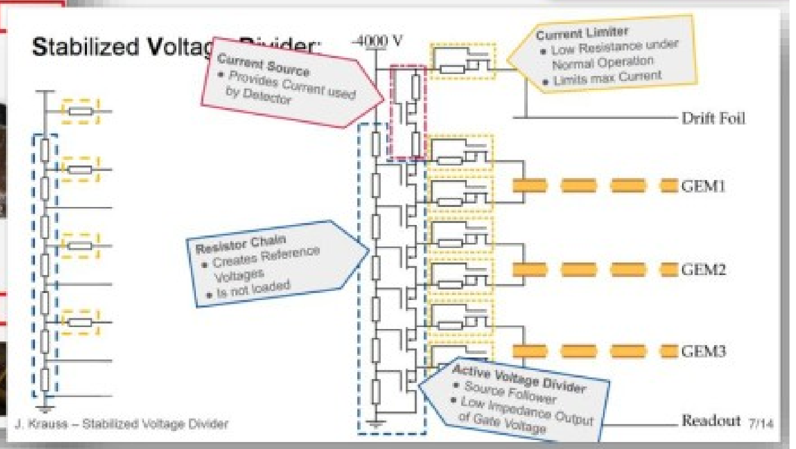
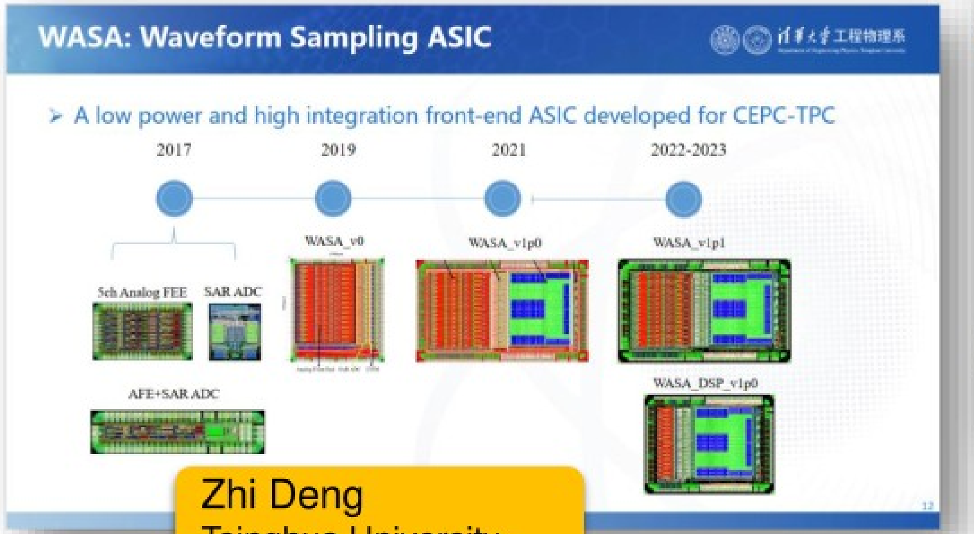
Christophe De La Taille
OMEGA

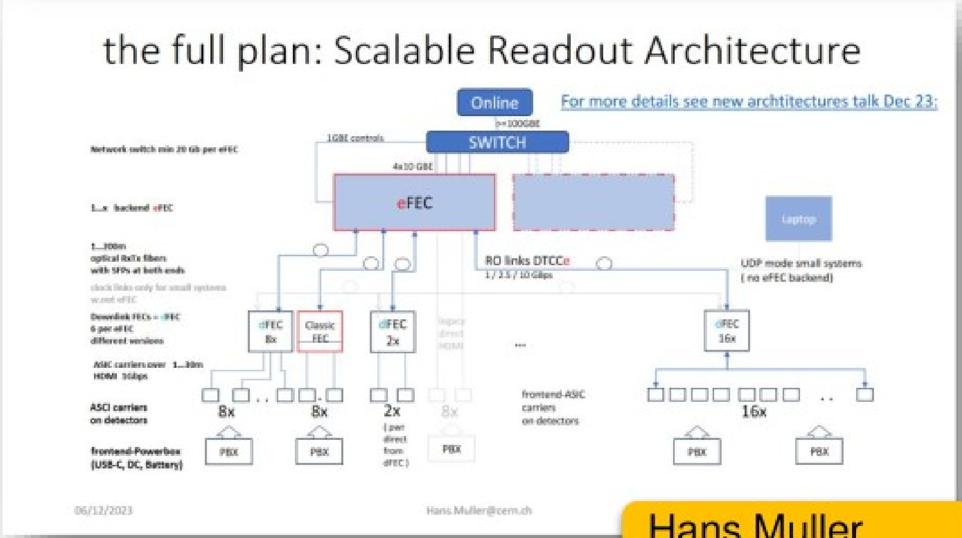


Jakob Kraus
UBONN

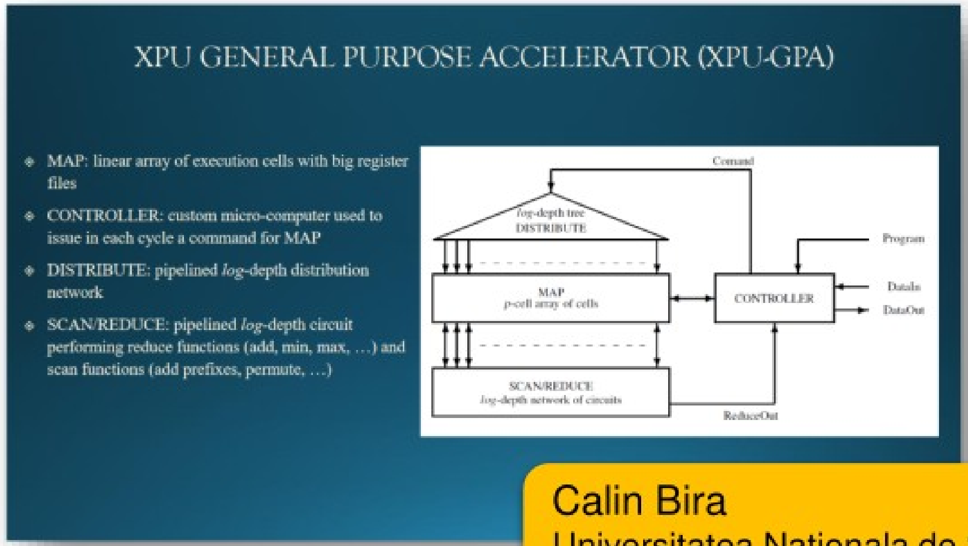




Zhi Deng
Tsinghua University



Hans Muller
CERN and UBONN



Calin Bira
Universitatea Nationala de Stiinta si Tehnologie Politehnica Bucuresti

Conveners:
M. Gouzevitch,
J. Kaminski,
M. Lupberger ,
H. Muller

DRD1, E. Oliveri, M. Titov - 2nd DRDC meeting 4 March 2024 21

WG8 – Knowledge Transfer, Training, Career Promotion

Conveners: F. Brunbauer, M. Iodice, E. Baracchini, B. Liberti, A Paoloni

Topical Workshops

Format

- 1-2 day events in combination with other meetings (e.g. in same week as DRD1 collaboration meetings)
- Stand-alone workshops of several days / week-long
- (Very) specific topics of current community interest

PROPOSAL: Organize 1 day topical workshop coupled to DRD1 meeting in Summer 2024

Possible topics for topical workshops:

- Negative-ion drift (O)TPCs
- Hybrid detectors (gaseous detectors + pixel readout ASICs)
- Alternative gases (green gases, new methods, ...)?
- Advanced materials and manufacturing methods
- Resistive materials and detector geometries
- High-performance simulations (GPU, parallel computing, AI, ...)
- Signal formation and processing (experimental & simulation)
- ... your ideas?

Mauro Iodice
INFN Roma Tre

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Education

Laboratory activities are crucial part of physics education for young students.
They help in learning experimental techniques and builds teamwork and collaboration skills.
These skills are essential for success in physics and other scientific fields.

- Ensuring high quality educational Lab activities focusing on Gas Detectors should be among the scopes of DRD1 WG8
  - Share experience (e.g. lab descriptions) , distribute knowledge
  - Schools for students and for teachers
  - Seminars and Tutorials
  - Construction of simple setups /demos – development of portable or closed gas systems

Exploiting the experience gained from the successful RD51 MPGD School, we can explore the option of assembling several dedicated setups for distribution as pilot tests to (interested) university laboratories within the DRD1 Collaboration.

Florian Brunbauer
CERN

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https://drd1.web.cern.ch/other

- Resources
- Mailing lists / e-groups
- Forum
- Job Opportunities
- Training Opportunities
- Conferences
- DRD1 Notes
- Detector Laboratories Network
- Software resources

Alessandro Paoloni
INFN- LNF

DRD1 Young Researchers Awards - a concrete proposal

Establish awards to recognise outstanding work of students or young researches in the DRD1 collaboration.

- 2x Awards for presentations given at DRD1 Collaboration Meetings
- 1x Award for exceptional contributions and developments

Starting now, considering contributions in 2024
Nominations & input from WG convenors, selection by small selection committee
Eligibility: students (BSc, MSc, Phd, early-career postdocs up to 3 years after completion of PhD)

A preparatory work is needed starting in the coming weeks, defining:
- the prizes
- the Selection Committee and selection criteria
- advertisements, ...

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Outreach

Outreach is a crucial tool for attracting students to physics research and ensuring that the field remains diverse and inclusive.

- It must help dispel misconceptions about physics being too difficult or abstract and should demonstrate the practical applications of physics research.
- By providing opportunities for students to learn about and engage with physics research, outreach programs can inspire the next generation of physicists.
- Outreach can also provide opportunities for students to engage with researchers, ask questions, and get hands-on experience with physics concepts and tools

→ Could the CERN Science Gateway serve as an opportunity to initiate outreach activities and share our experience with gaseous detectors? (Establishing a connection with CERN outreach.)

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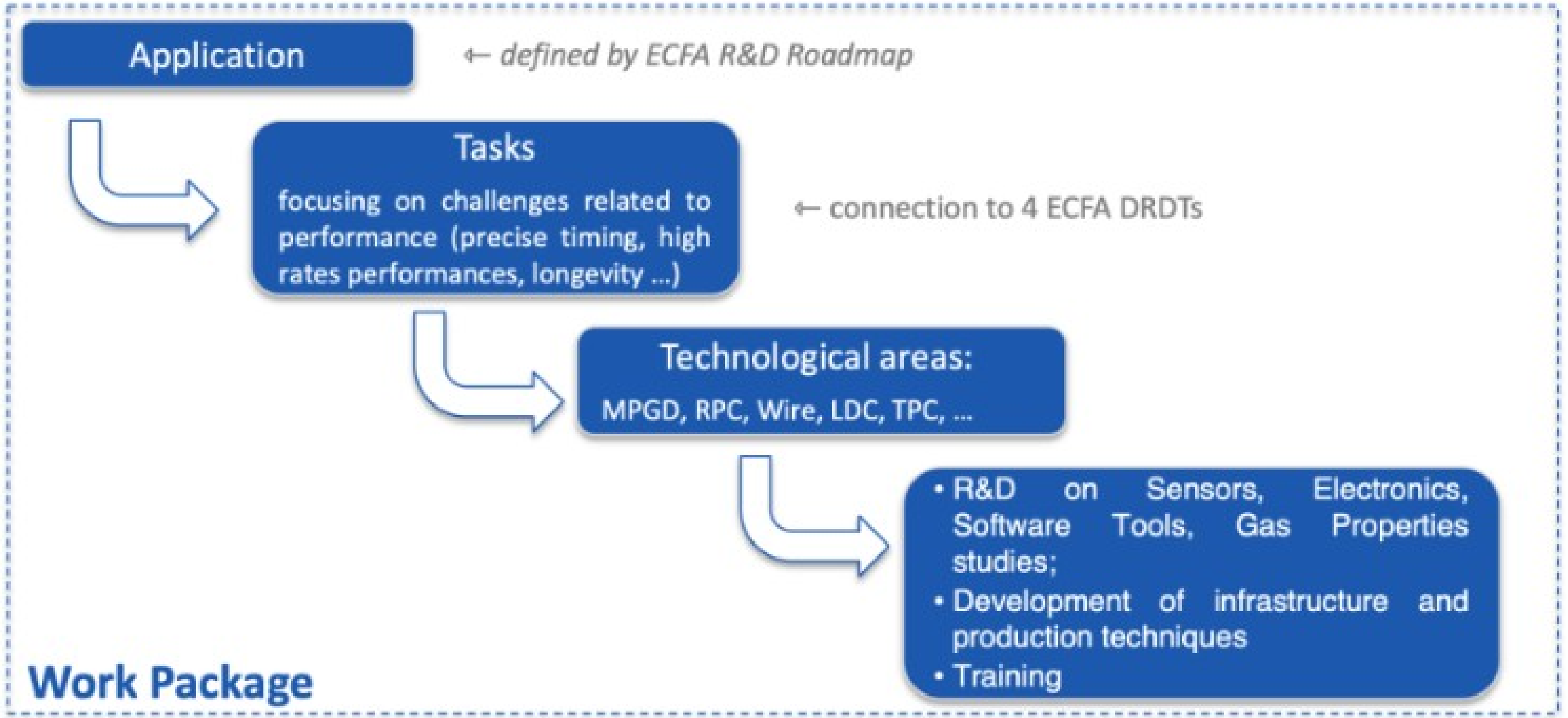
https://indico.cern.ch/event/1360282/sessions/525034/attachments/2791402/4868283/DRD1%20WG8%20-%20Collaboration%20Jan%202024.pdf

Work Packages

Strategic R&D (according to the ECFA Detector R&D Roadmap) **is organized in Work Packages**

- group activities of the Institutes with **shared research interests** around **Applications** with a focus on a **specific task(s)** devoted to a specific DRDT challenge, typically related to specific **Detector Technologies and** to the development of **specific tools or infrastructure**



Currently envisaged WPs:

- **WP1: Trackers/hodoscopes**
- **WP2: Drift chambers**
- **WP3: Straw chambers**
- **WP4: Tracking TPCs**
- **WP5: Calorimetry**
- **WP6: Photo-detectors**
- **WP7: Timing**
- **WP8: Reaction/Decay TPCs**
- **WP9: Beyond HEP**

- **There is no obligation to participate in a WP to be a member of DRD1.**

P. Gasik, DRD1 Proposal: Development of Gaseous Detectors Technologies, **1st meeting of the DRDC** 4 Dec 2023, CERN

Examples of Work Packages and interplay/synergies with Working Group activities

WP1: Genuine trackers/hodoscopes (large area muon systems, inner tracking/vertexing)

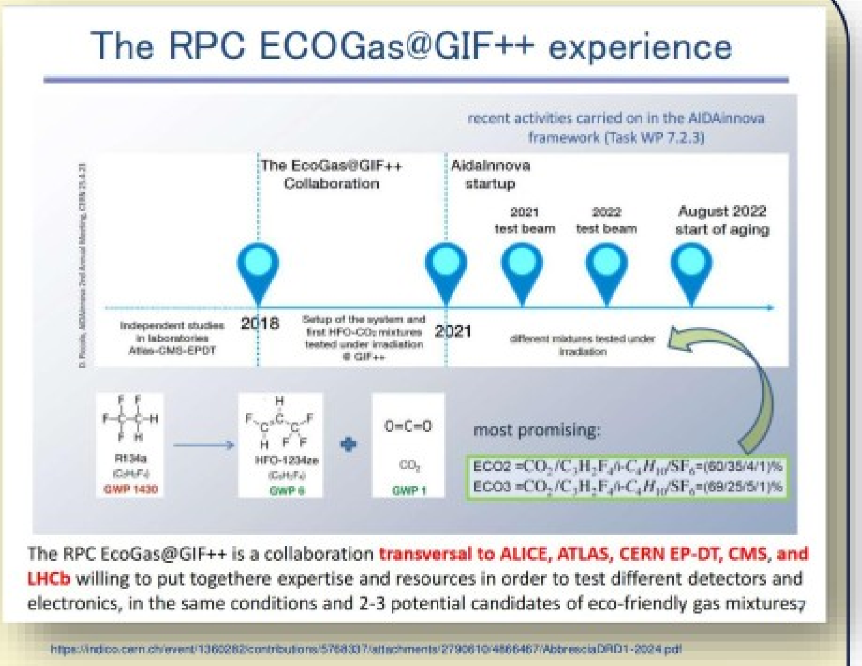
https://drd1.web.cern.ch/wp/wp1

StatusUpdate:[*https://indico.cern.ch/event/1360282/contributions/5761367/attachments/2789107/4863480/DRD1_WP1_29Jan2024_v1.pdf*](https://indico.cern.ch/event/1360282/contributions/5761367/attachments/2789107/4863480/DRD1_WP1_29Jan2024_v1.pdf)

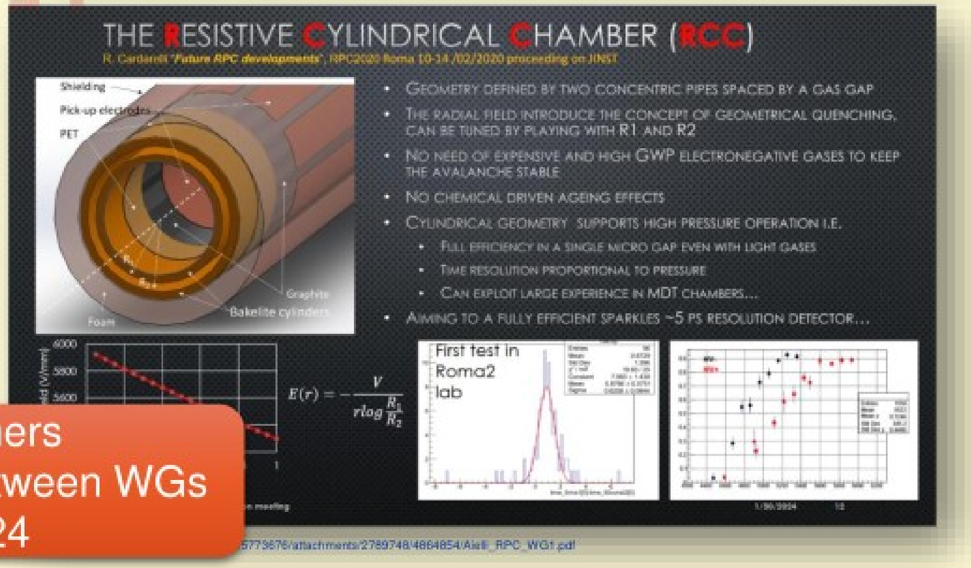
The primary objective of the project is to strategically advance R&D in the domain of **resistive gaseous detectors for applications as trackers, hodoscopes, and large-area muon systems** for new challenges at future facilities. The goal is to strengthen their stability, robustness, and long-term performance, as well as to optimize a cost-effective manufacturing together with industrial partners.

T1: New RPC Structures
T2: New Resistive MPGD Structures
T3: New Front-end electronics
T4: Optimization of scalable multichannel readout systems
T5: Eco-friendly gases
T6: Manufacturing
T7: Longevity on large detector areas
T8: New detector structures

WG3



WG1



Extracting 2 examples (several others existing) of interplay/Synergies between WGs & WP taken from 1st DRD1 CM 2024

WP4: Inner and central tracking with PID (Tracking TPCs)

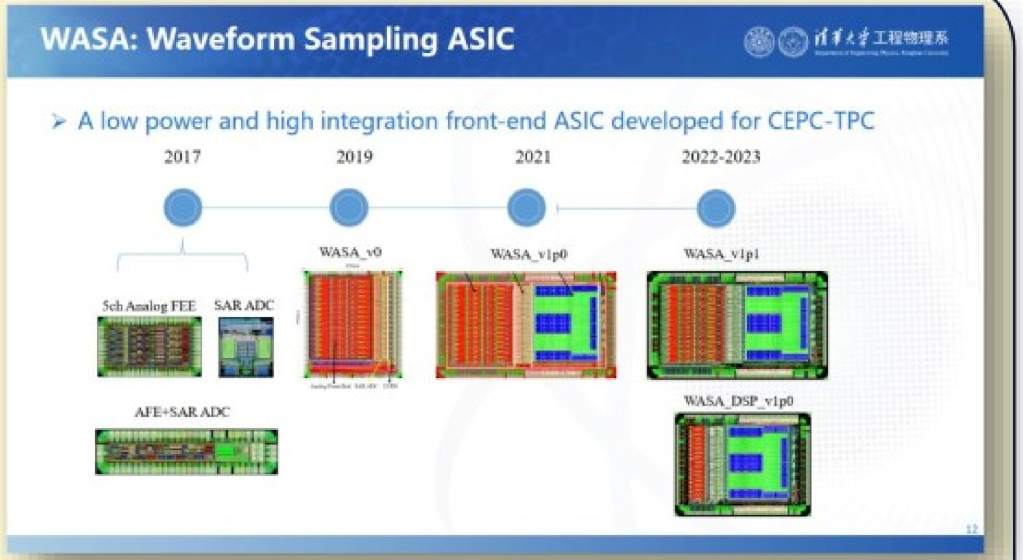
https://drd1.web.cern.ch/wp/wp4

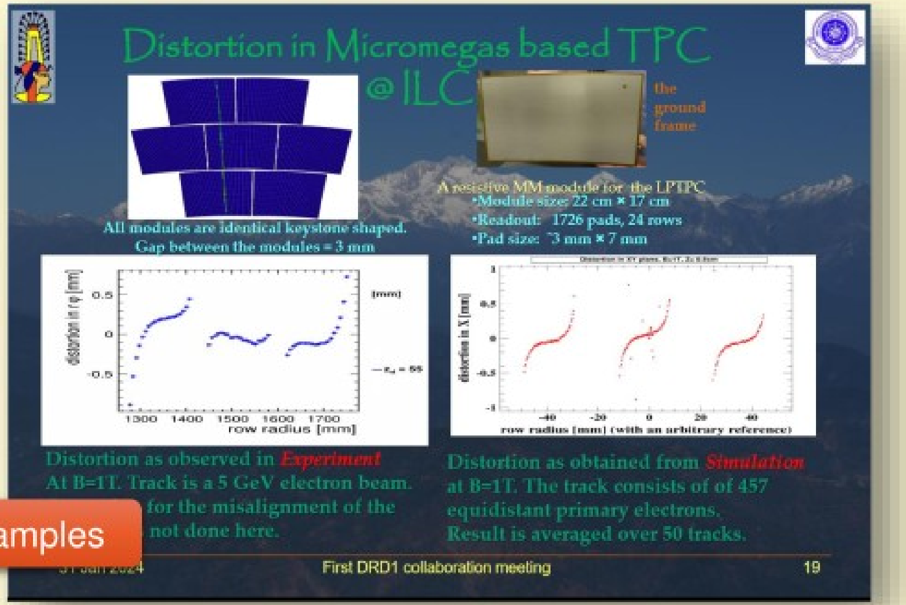
StatusUpdate:*https://indico.cern.ch/event/1360282/contributions/5761372/attachments/2789303/4863818/WP4_presentation.pdf*

Time Projection Chambers (TPCs) have been extensively studied and used in many fields especially in particle, nuclear and neutrino physics experiments. Also smaller size TPCs are a good choice for beam diagnostics operating in high particle rate environments.

T1: IBF reduction
T2: pixel TPC development
T3: Optimization of the amplification stage and its mechanical structure, and development of low X/X0 field cages
T4: FEE for TPCs
T5: Gas mixture

WG5





WG4

Extracting 2 examples

WP5: Calorimetry

https://drd1.web.cern.ch/wp/wp5

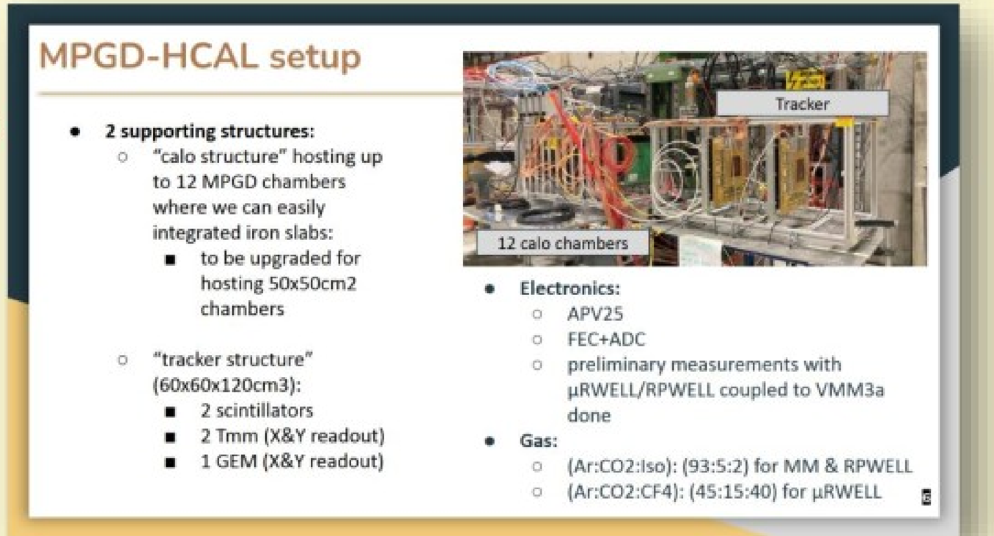
StatusUpdate:https://indico.cern.ch/event/1360282/contributions/5761374/attachments/2789352/4864124/WP5_kick-off.pdf

Gaseous detectors have been playing an important role in sampling calorimeters since the birth of this kind of instruments. The possibility to produce large area detectors at affordable cost but still with excellent efficiency and high spatial precision make of them a choice of reference. Although many sampling calorimeters of the LHC experiments have opted for scintillators-based active media, **gaseous detectors are being proposed again to equip future sampling calorimeters that use the Particle Flow Algorithm (PFA) concept**.

WG5

https://indico.cern.ch/event/1360282/contributions/5786550/attachments/2790728/4866705/CdLT_DRD1_31jan24.pdf

WG7



https://indico.cern.ch/event/1360282/contributions/5768394/attachments/2791972/4869090/DRD1_HCal_testbeam.pdf

T1 : Construction of large gaseous detectors for granular calorimeters
T2 : Timing performance of gaseous detectors for calorimeters
T3 : Readout electronics for calorimeter gaseous detectors
T4 : High-rate capability gaseous detectors for circular collider calorimeters

Extracting 2 examples

Some challenges for tracking ...

Drift chambers:

- high rate, unique volume, high granularity, low mass
- hydrocarbon-free gas mixture for long-term and high-rate operation
- prove cluster-counting principle
- wiring procedure, wire materials
- integration: accessibility for repairing

TPCs:

- R&D on detector sensor to suppress IBF ratio
- optimise IBF & energy resolution
- gain optimisation
- response uniformity
- gas mixture: stability, drift velocity, ion mobility, ageing
- influence of magnetic field on IBF
- high spatial resolution
- very low material budget (few %) but robust and stable mechanics
- integration: cooling

Main drivers for muon systems

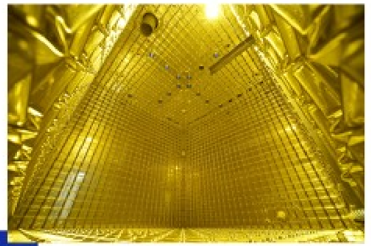
Facility	Technologies	Challenges	Most challenging requirements at the experiment
HL-LHC	RPC, Multi-GEM, resistive-GEM, Micromegas, micro-pixel Micromegas, μ-RWELL, μ-PIC	Ageing and radiation hard, large area, rate capability, space and time resolution, miniaturisation of readout, eco-gases, spark-free, low cost	**(LHCb)**: Max. rate: 900 kHz/cm² Spatial resolution: ~ cm Time resolution: O(ns) Radiation hardness: ~ 2 C/cm² (10 years)
Higgs-EW-Top Factories (ee) (ILC/FCC-ee/CepC/SCTF)	GEM, μ-RWELL, Micromegas, RPC	Stability, low cost, space resolution, large area, eco-gases	**(IDEA):** Max. rate: 10 kHz/cm² Spatial resolution: ~60-80 μm Time resolution: O(ns) Radiation hardness: <100 mC/cm²
Muon collider	Triple-GEM, μ-RWELL, Micromegas, RPC, MRPC	High spatial resolution, fast/precise timing, large area, eco-gases, spark-free	Fluxes: > 2 MHz/cm² ($\theta<8^0$) < 2 kHz/cm² (for $\theta>12^0$) Spatial resolution: ~100μm Time resolution: sub-ns Radiation hardness: < C/cm²
Hadron physics (EIC, AMBER, PANDA/CMB@FAIR, NA60+)	Micromegas, GEM, RPC	High rate capability, good spatial resolution, radiation hard, eco-gases, self-triggered front-end electronics	**(CBM@FAIR):** Max rate: <500 kHz/cm² Spatial resolution: < 1 mm Time resolution: ~ 15 ns Radiation hardness: 10^{13} neq/cm²/year
FCC-hh (100 TeV hadron collider)	GEM, THGEM, μ-RWELL, Micromegas, RPC, FTM	Stability, ageing, large area, low cost, space resolution, eco-gases, spark-free, fast/precise timing	Max. rate 500 Hz/cm² Spatial resolution = 50 μm Angular resolution = 70 μrad (η=0) to get $\Delta p/p \leq 10\%$ up to 20 TeV/c

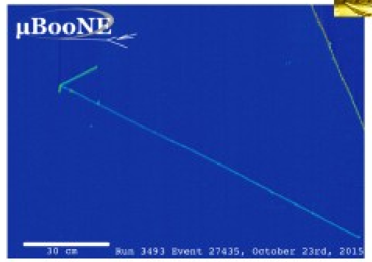
DRD2 – Liquid Detectors

Liquid Detectors – scientific landscape

Neutrinos

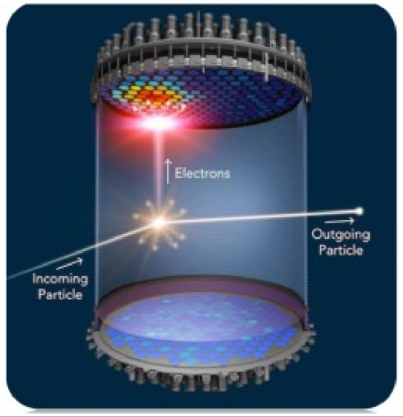
- Oscillation precision measurements (δ_{CP}, mass ordering, θ_{23} octant, sterile νs)
- Neutrino interactions (from CEvNS to DIS)
- Astro neutrinos





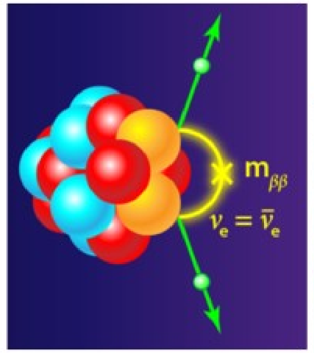
Dark Matter

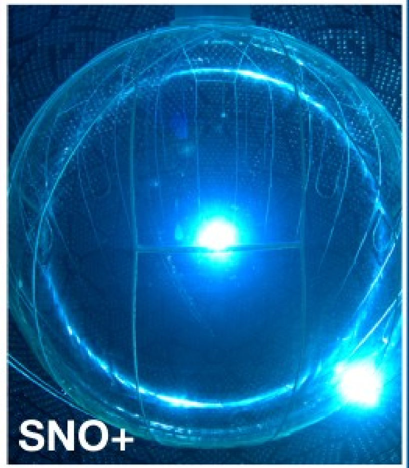
- Direct detection (WIMPs, …)

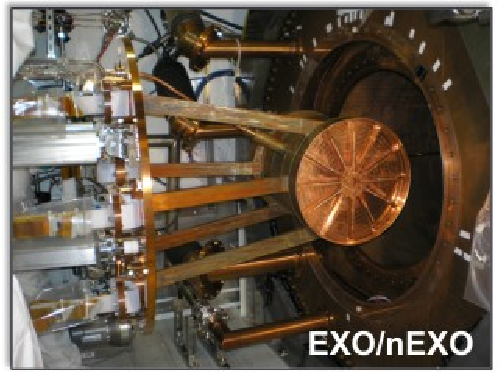


0νββ

- Search for Majorana neutrinos







2

Liquid Detectors – scientific requirements

Neutrinos

- **Push Energy thresholds down** to ~1MeV to enhance oscillation physics, supernovae νs study, to enable solar νs …
- **Unambiguous readout**
- **Scalability**

Dark Matter

- **Push Energy thresholds down** to 1 meV/10 eV/1 keV to enable low mass DM/1 GeV DM/ WIMPs.
- **Reduce background rates**
- **Scalability**

0νββ

- **Improve Energy Resolution** to sub-% FWHM
- **Reduce background rates**
- **Scalability**

3

Liquid Detectors – current ecosystem

Neutrinos

- Current generation:
  - ✓ MicroBooNE & SBN
  - ✓ LArIAT
  - ✓ protoDUNEs
  - ✓ CAPTAIN
  - ✓ COHERENT
  - ✓ Borexino
  - ✓ SK
  - ✓ Antares
  - ✓ KM3Net
- Future generation:
  - ✓ DUNE modules 1 & 2
  - ✓ DUNE near detectors
  - ✓ DUNE modules 3 & 4
  - ✓ HK
  - ✓ Future neutrino telescopes

Dark Matter

- Current generation:
  - ✓ LUX / LZ
  - ✓ XENON 10/100/1T/nT
  - ✓ Dark Side 50/20k
  - ✓ DEAP-3600
  - ✓ Panda-X
- Future generation:
  - ✓ XLZD
  - ✓ GADMC/Argo
  - ✓ HeRALD
  - ✓ SBC

0νββ

- Current generation:
  - ✓ EXO-200
  - ✓ KamLand-Zen
  - ✓ SNO+
- Future generation:
  - ✓ nEXO
  - ✓ KL-Z+
  - ✓ Upgrades to SNO+

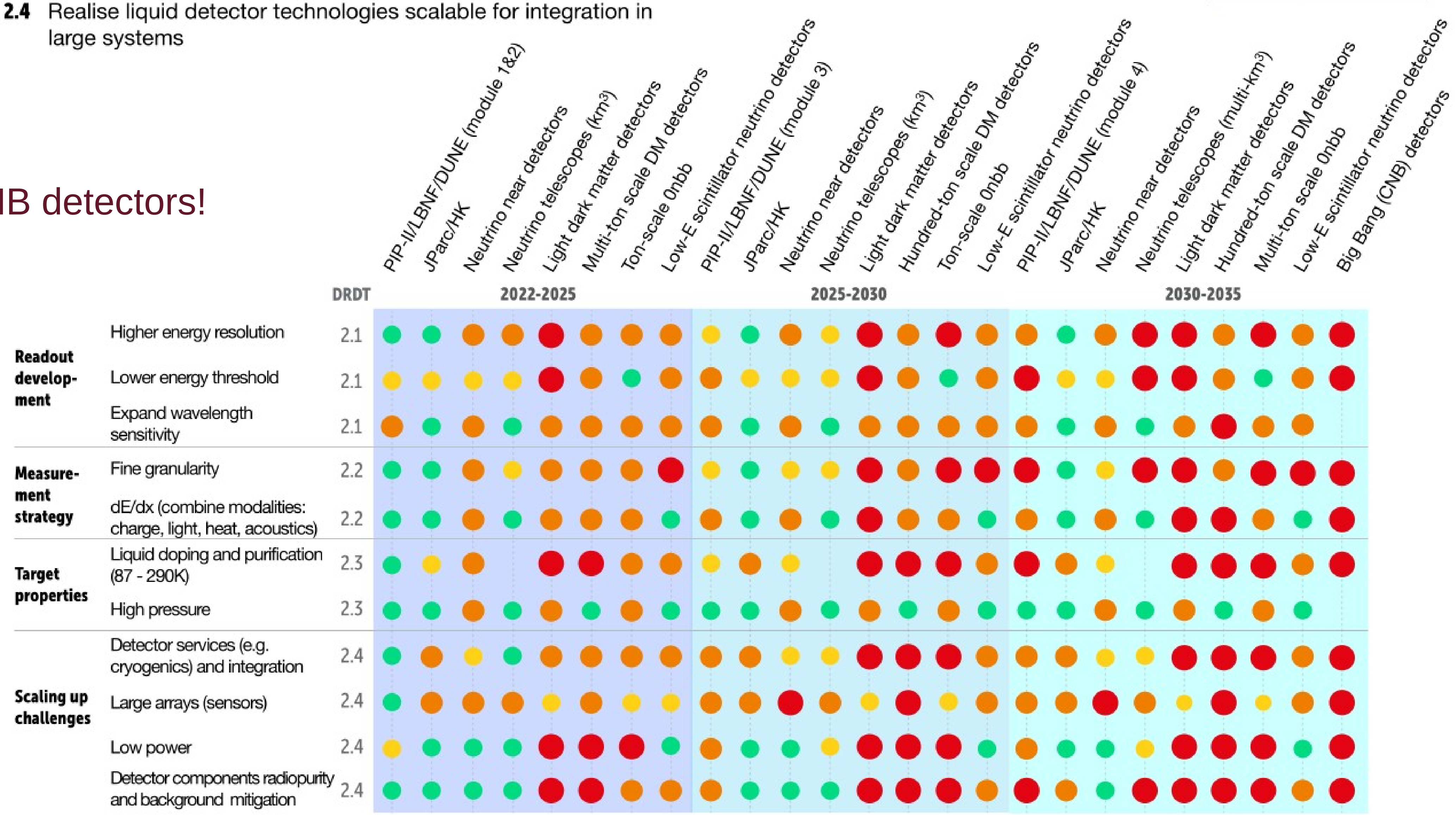
4

R&D Roadmap for Liquid Detectors (DRD2)

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

Many very hard channels:
light dark matter & CNB detectors!



Liquid Detectors – proposed structure

Work Packages, Tasks & Drafting Team Leaders

- Coordinators: Roxanne Guenette & Jocelyn Monroe
- Proposal Work Package Writing leads:

Charge Readout Conveners

- **Pixels & charge+light** Group leaders: J. Asaadi (US) & E.Gramellini(UK)
- **Charge-to-light, electroluminescence & amplification** Group leaders: A. Deisting (DE) & K. Mavrokoridis (UK)
- **Ion detection** Group leaders — No current representation, but topic to consider for future

Light Readout Conveners

- **Increased sensor quantum efficiency** Group leaders: J. Monroe(UK), F. Retiere (CA) & P. Agnes(IT)
- **Higher efficiency WLS and collection** Group leaders: C. Cuesta (ES), M. Kuzniak (PO) & J. Martin-Albo (ES)
- **Improved sensors for LS & WC** Group leaders: M. Bongrand (FR) & T. Lachenmaier (DE) — Entirely covered by DRD4, serves as liaison

Target Properties Conveners

- **Target properties and isotope loading of LS & WC** Group leaders: S. Schopmann (DE), H.Steiger (DE) & M. Wurm(DE)
- **Target properties and isotope loading of noble elements** Group leaders: C. Franco (FR), M.C. Piro (CA), A. Szelc(UK) & A. Zani (IT)

Scaling-up Challenges Conveners

- **Radiopurity & background mitigation** Group leaders: J. Dobson (UK) & R. Santorelli (ES)
- **Detector and target procurement/production & purification** Group leaders: W. Bonivento (IT) & Y. Meh (US)
- **Large-area readouts** Group leaders: J. Crespo (ES) & G. Fiorillo (IT)
- **Material properties** Group leaders — No current representation, but topic to consider for future

Proposal Task Leaders, now Interim Conveners

Liquid Detectors WP2 - Light Readout

Light Readout Conveners

Increased sensor quantum efficiency Group leaders

Higher efficiency WLS and collection Group leaders

Improved sensors for LS & WC Group leaders

DRD4

O(0.1-10) kT experiments are, and are planned, to use liquid noble targets which scintillate in the VUV wavelength range (Ar, He, Xe)

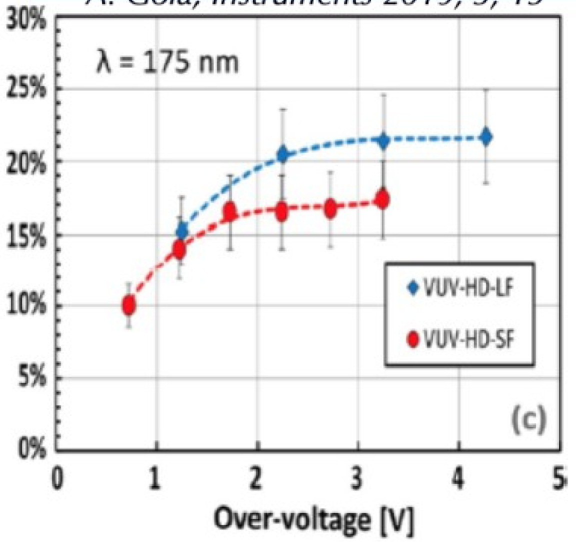
- Aim: photon readouts reaching O(100 m^2), *cryogenic temperature*

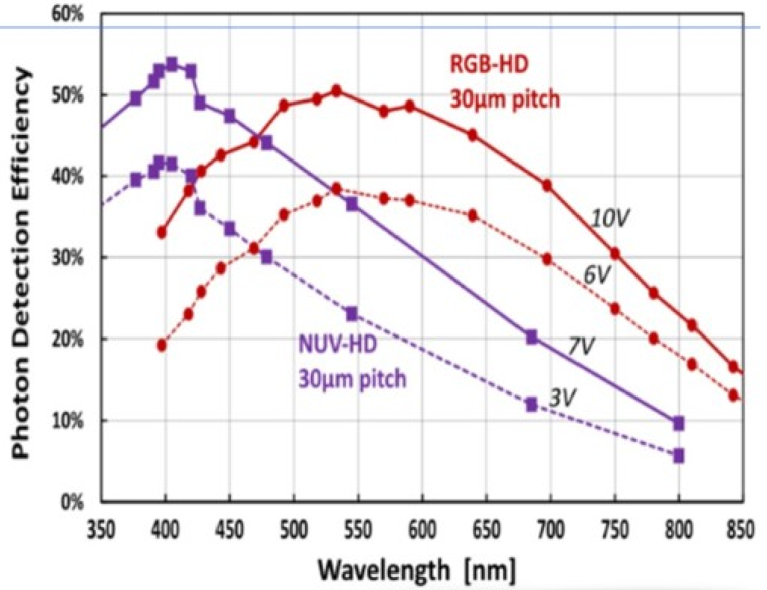
Conventional strategy: either accept photon detection efficiency << in visible range, or, wavelength shift using thin films with ~isotropic emission

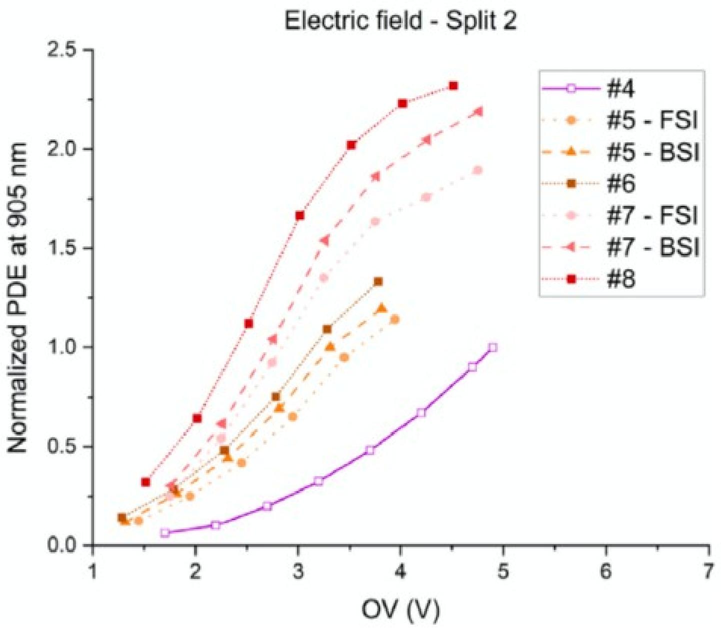
- Key challenges: decrease reflectivity, increase collection efficiency, increase quantum efficiency

Exploration of new materials, i.e. better wavelength shifters, light traps with dichroic filters, coatings optimised for range of angles of incidence, metalenses, and new processes (i.e. BSI-SPAD + passivation)

A. Gola, Instruments 2019, 3, 15



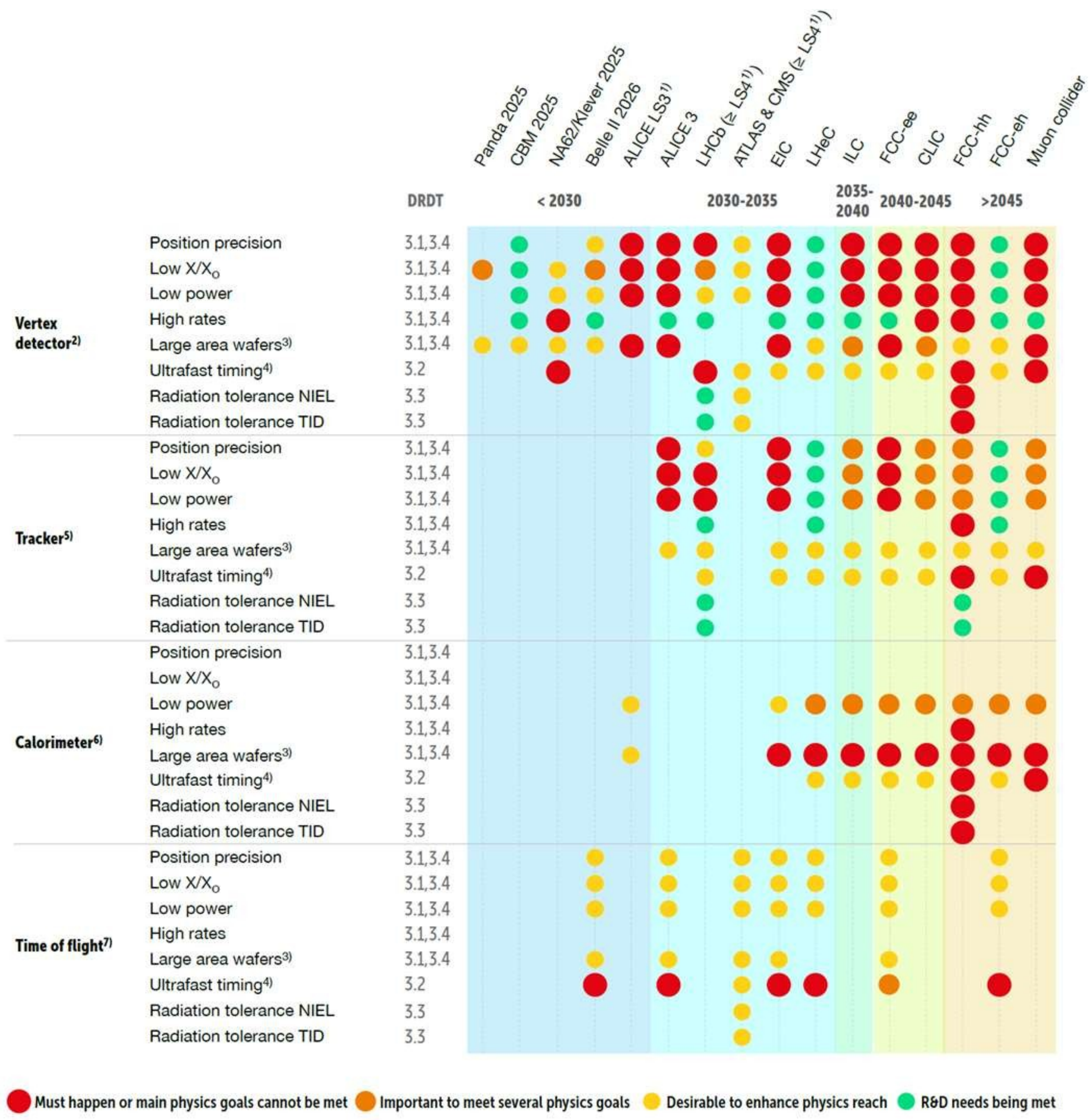


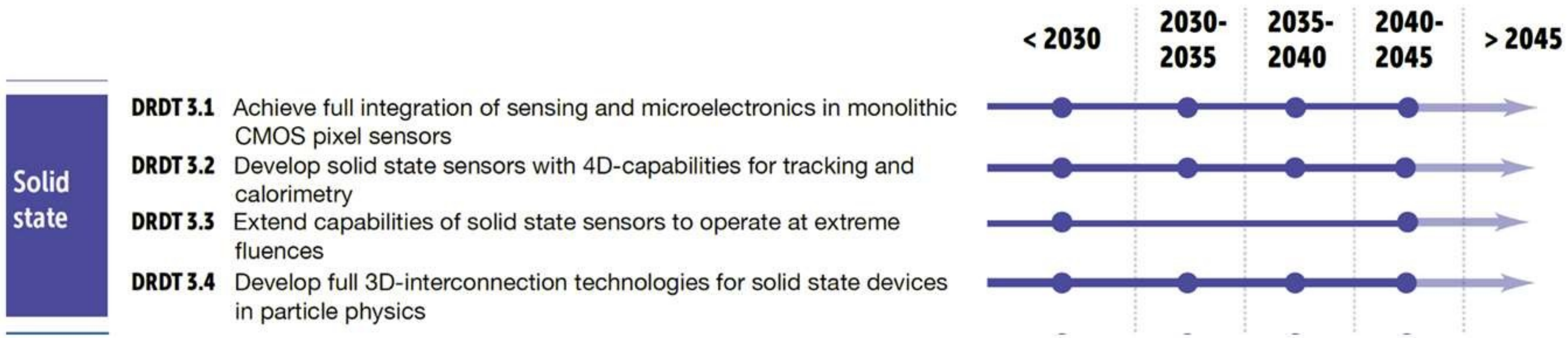


Ilada-Monreal et al., NIM A 1049(2023) 168042

DRD3 – Semiconductor Detectors

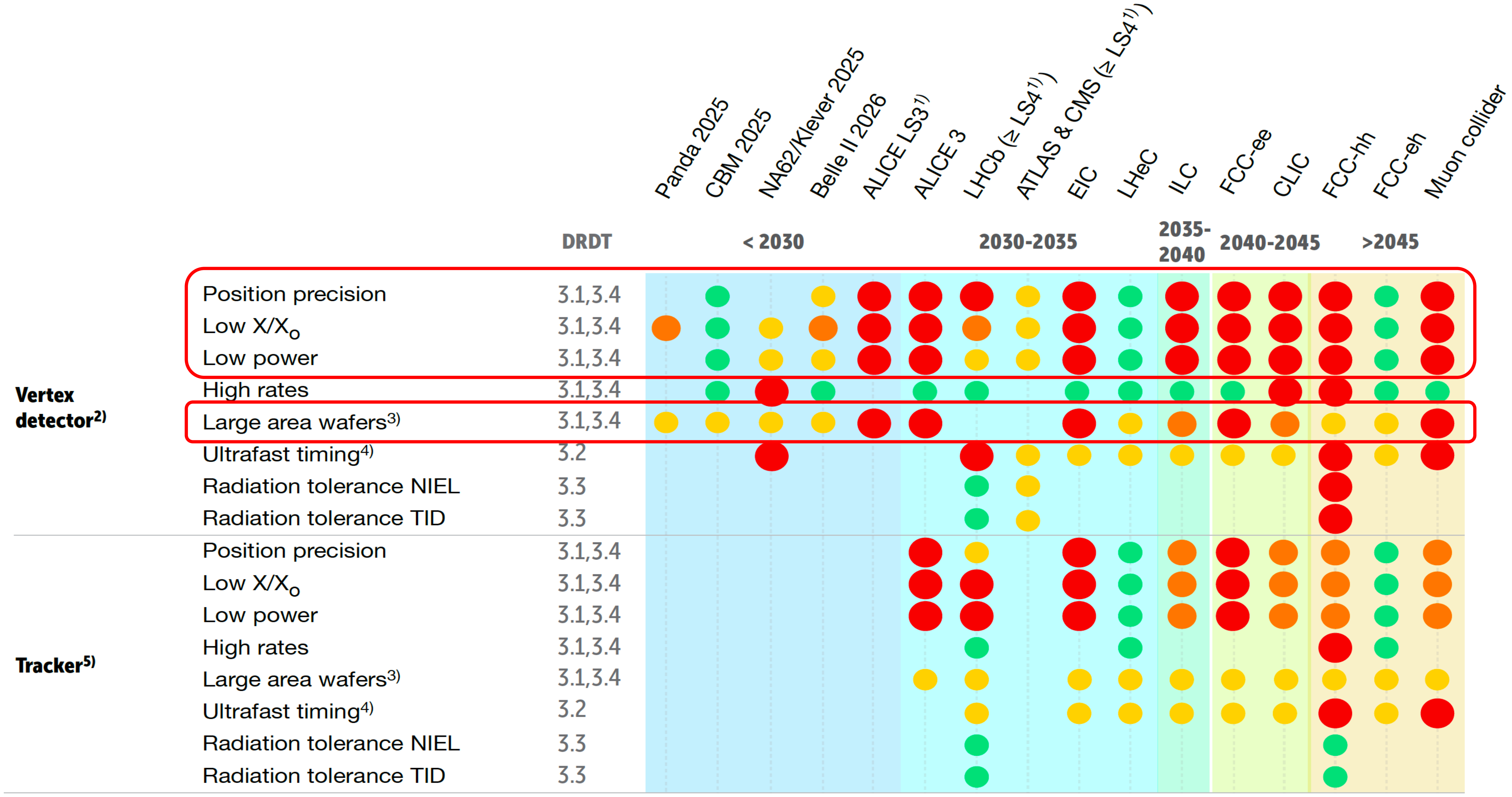
Semiconductor Detectors (DRD3) – R&D needs





- Some common requirements for tracking/vertexing:
  - Precision
  - Low material budget
  - Low power consumption
  - Large-area wafers
- Large-area wafers critical for calorimetry
- Ultra-fast timing critical for ToF measurement

Semiconductor Detectors (DRD3) – R&D needs



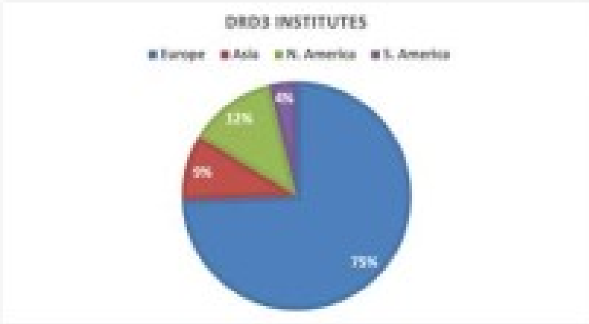
Vertex Detector and Tracker – Requirements

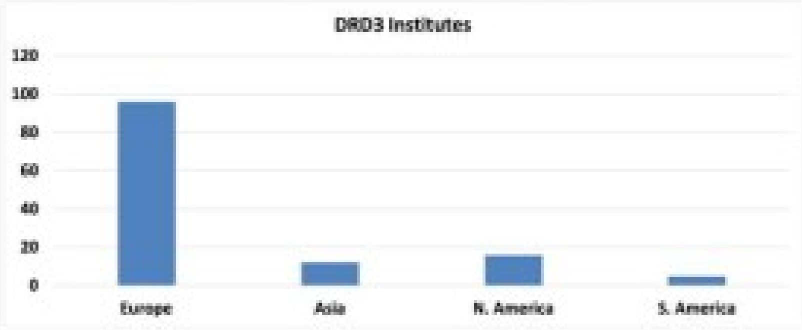
"Technical" Start Date of Facility (This means, where the dates are not known, the earliest technically feasible start date is indicated - such that detector R&D readiness is not the delaying factor)				< 2030					2030-2035					2035 - 2040	2040-2045			> 2045	
				Panda 2025	CBM 2025	NA62/Klever 2025	Belle II 2026	ALICE LS3 [1]	ALICE 3	LHCb (≥LS4) [1]	ATLAS/CMS (≥ LS4) [1]	EIC	LHeC	ILC [2]	FCC-ee	CLIC [2]	FCC-hh	FCC-eh	Muon Collider
Vertex Detector [3]	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.1 DRDT 3.4	Position precision σ_{hit} (μm)		$\simeq 5$		$\lesssim 5$	$\simeq 3$	$\lesssim 3$	$\lesssim 10$	$\lesssim 15$	$\lesssim 3$	$\simeq 5$	$\lesssim 3$	$\lesssim 3$	$\lesssim 3$	$\simeq 7$	$\simeq 5$	$\lesssim 5$
			X/X_0 (%/layer)	$\lesssim 0.1$	$\simeq 0.5$	$\simeq 0.5$	$\lesssim 0.1$	$\simeq 0.05$	$\simeq 0.05$	$\simeq 1$		$\simeq 0.05$	$\lesssim 0.1$	$\simeq 0.05$	$\simeq 0.05$	$\lesssim 0.2$	$\simeq 1$	$\lesssim 0.1$	$\lesssim 0.2$
			Power (mW/cm^2)		$\simeq 60$			$\simeq 20$	$\simeq 20$			$\simeq 20$		$\simeq 20$	$\simeq 20$	$\simeq 50$			
			Rates (GHz/cm^2)		$\simeq 0.1$	$\simeq 1$	$\lesssim 0.1$		$\lesssim 0.1$	$\simeq 6$		$\lesssim 0.1$	$\simeq 0.1$	$\simeq 0.05$	$\simeq 0.05$	$\simeq 5$	$\simeq 30$	$\simeq 0.1$	
			Wafers area (") [4]					12	12			12			12		12		12
		DRDT 3.2	Timing precision σ_t (ns) [5]	10		$\lesssim 0.05$	100		25	$\lesssim 0.05$	$\lesssim 0.05$	25	25	500	25	$\simeq 5$	$\lesssim 0.02$	25	$\lesssim 0.02$
		DRDT3.3	Radiation tolerance NIEL ($\times 10^{16}$ neq/cm^2)							$\simeq 6$	$\simeq 2$						$\simeq 10^2$		
			Radiation tolerance TID (Grad)							$\simeq 1$	$\simeq 0.5$						$\simeq 30$		
Tracker [6]	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.1 DRDT 3.4	Position precision σ_{hit} (μm)						$\simeq 6$	$\simeq 5$		$\simeq 6$	$\simeq 6$	$\simeq 6$	$\simeq 6$	$\simeq 7$	$\simeq 10$	$\simeq 6$	
			X/X_0 (%/layer)						$\simeq 1$	$\simeq 1$		$\simeq 1$	$\simeq 1$	$\simeq 1$	$\simeq 1$	$\simeq 1$	$\lesssim 2$	$\simeq 1$	
			Power (mW/cm^2)						$\lesssim 100$	$\simeq 100$		$\lesssim 100$		$\lesssim 100$	$\lesssim 100$	$\lesssim 150$			
			Rates (GHz/cm^2)							$\simeq 0.16$									
			Wafers area (") [4]						12			12		12	12	12	12		12
		DRDT 3.2	Timing precision σ_t (ns) [5]						25	$\lesssim 25$		25	25	$\lesssim 0.1$	$\lesssim 0.1$	$\lesssim 0.1$	$\lesssim 0.02$	25	$\lesssim 0.02$
		DRDT3.3	Radiation tolerance NIEL ($\times 10^{16}$ neq/cm^2)							$\simeq 0.3$							$\lesssim 1$		
			Radiation tolerance TID (Grad)							$\simeq 0.25$							$\lesssim 1$		

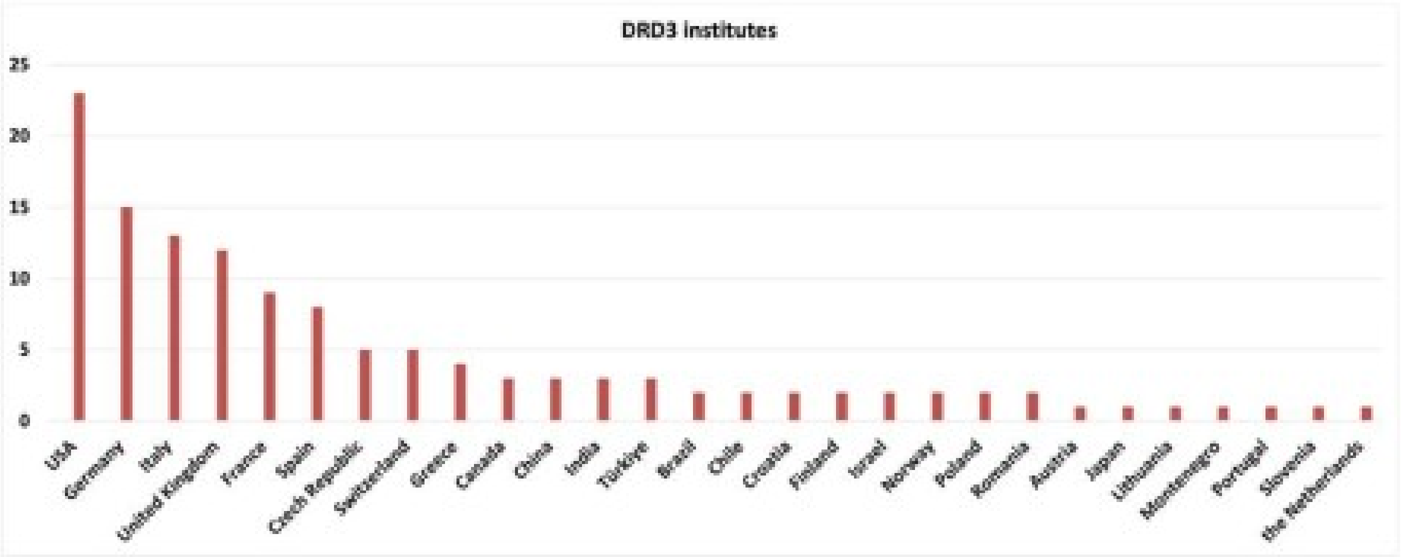
The size of the collaboration

As of yesterday:

- **537 people** have subscribed to the CERN drd3-community-subscribers mailing list
- **132 Institutes** have subscribed to the CERN DRD3 institute egroup.







DRD3 Structure

DRD3 management

- **G. Kramberger (JSI)** (res.: WG2, WG4)
- x (res.: WG1, WG7)
- y (res.: WG3, WG8)
- z (res.: WG5, WG6)

Institute board

Chair - G. Pellegrini (CNM-CSIC)
Deputy - R. Arcidiacono(INFN-TO)

R&D activities

WG 1 convener	WG 2 convener	WG 3 convener	WG 4 convener	WG 5 convener	WG 6 convener	WG7 convener	WG 8 convener
Monolithic silicon technologies	Hybrid silicon technologies	Radiation damage characterization	Simulation	Characterization techniques, facilities	Non-silicon-based detectors	Interconnect technologies	Dissemination & outreach

- Secretariat/administration
- Speakers committee
- Resource coordinator /Project office
- Cross-DRD coordination

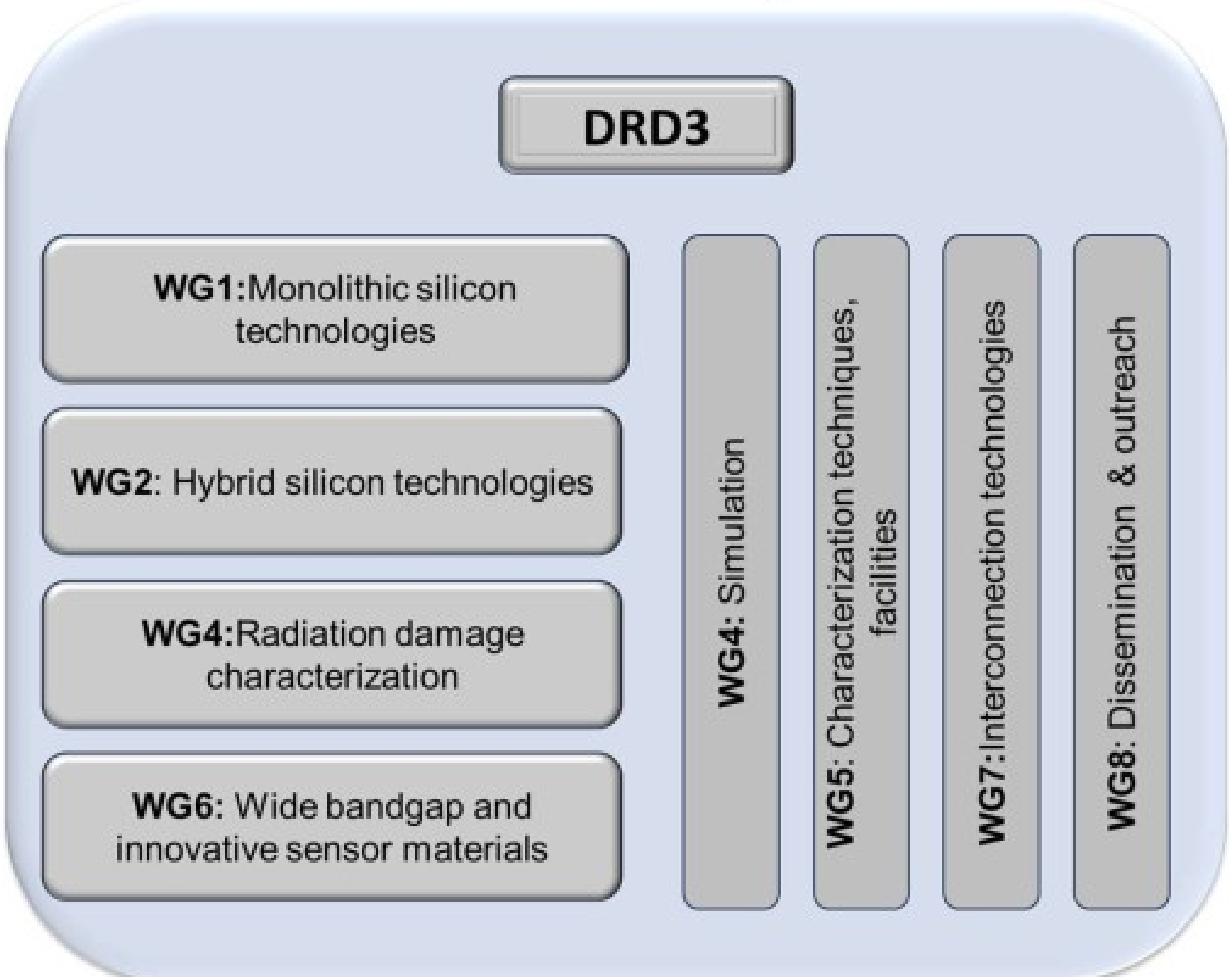
Strategic/Targeted R&D projects

WP1	WP2	WP3	WP4	
Monolithic CMOS sensors	Sensors for 4D-tracking	Sensors for extreme fluences	3D-integration& Interconnection	…….

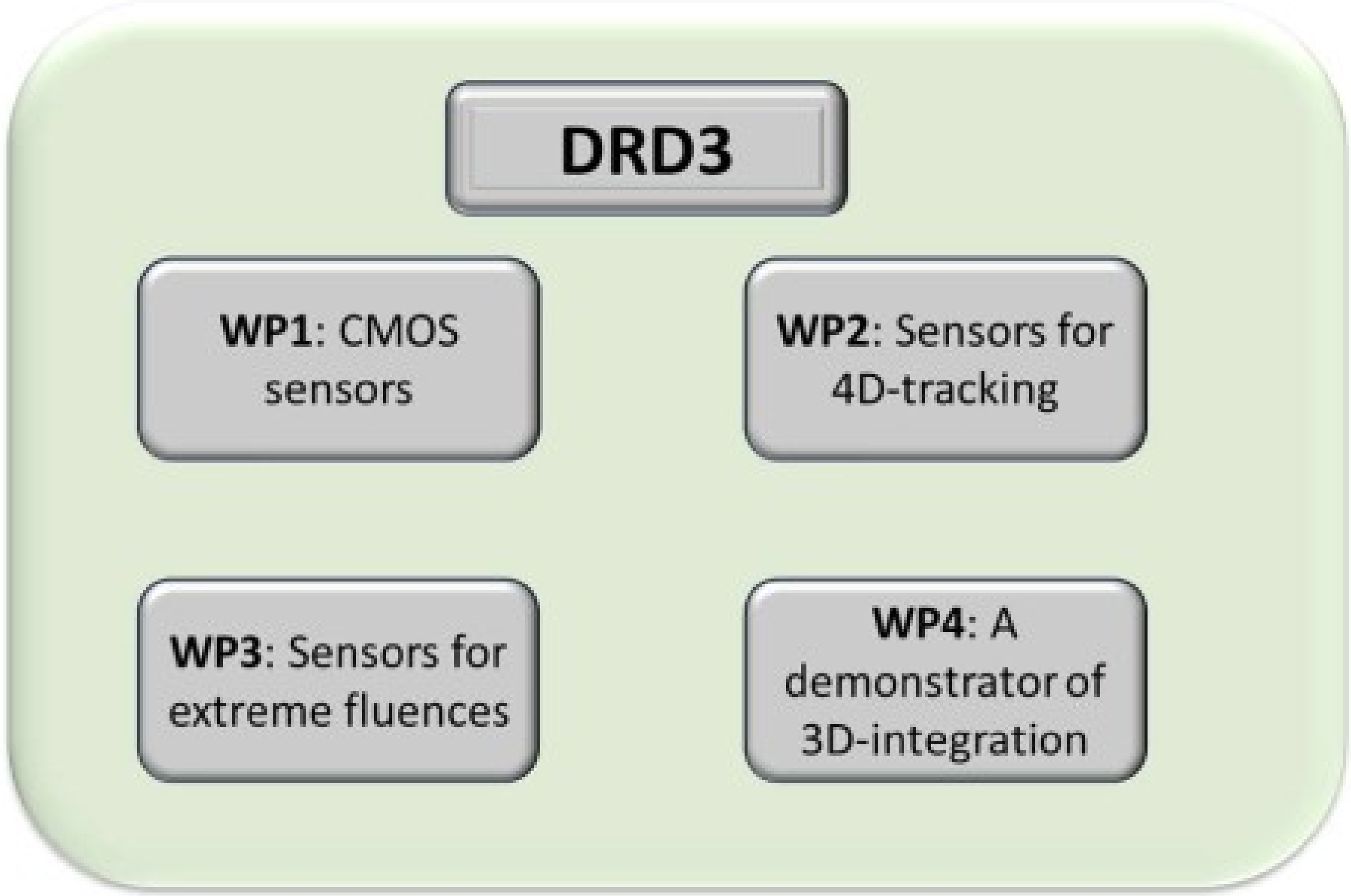
Steering committee:
DRD3 management + CB Chair + WG conveners

DRD3 WGs and WPs

Working group (WG) long term R&D activity linked to certain technology/purpose/application/method aiming to fulfil the research goals



Work Packages (WP)
Strategic/Targeted R&D activities linked to DRDT (4).



The number of WP projects is not limited

DRD3 Research projects

Working Packages		Work Package Projects	WG1- Monolithic silicon technologies	WG2- Hybrid silicon technologies	WG3- Radiation hardening	WG4- Simulation	WG5- Characterization techniques, facilities	WG6- Wide bandgap and innovative sensor materials	WG7- Interconnection technologies	WG8-Outreach and dissemination
	WP1 - CMOS sensors	1.1 Spatial resolution	■			■	■			■
		1.2 Timing resolution	■			■	■			■
		1.3 Read-out architectures	■							■
		1.4 Radiation tolerance	■		■	■	■			■
		1.5 Low-cost large-area CMOS sensors	■	■	■	■	■		■	■
	WP2- Sensors for 4D-tracking	2.1 3D sensors		■	■	■	■	■	■	■
		2.2 LGAD		■	■	■	■	■	■	■
	WP3- Sensors for extreme fluences	3.1 wide band-gap materials (SiC, GaN)		■	■	■	■	■	■	■
		3.2 diamond-based detectors		■	■	■	■	■		■
		3.3 Extreme fluence: silicon detectors		■	■	■	■			■
	WP4- 3D-integration and Interconnection	4.1 Integration: fast and maskless interconnect	■	■					■	■
		4.2 3D In house post-processing for hybridization	■	■					■	■
		4.3 Advanced interconnection techniques for detectors	■	■				■	■	■
		4.4 Mechanics and cooling	■	■					■	■

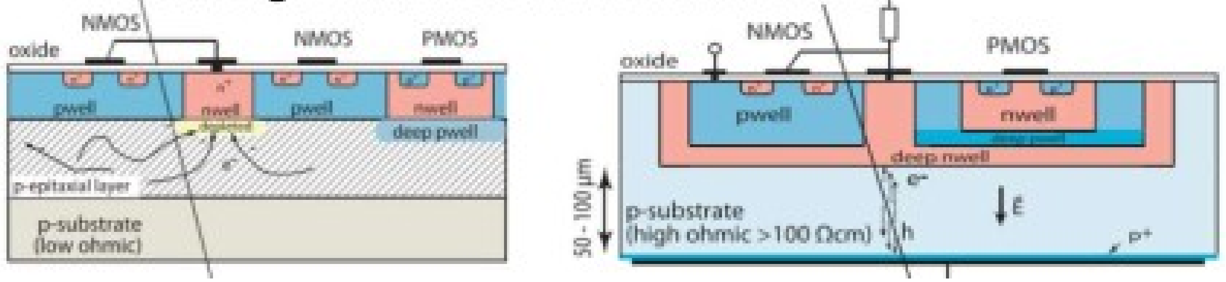
WG1 – Monolithic silicon sensors

Aim is to advance the performance of monolithic CMOS, combining sensing and readout elements, for future tracking applications, tackling the challenges of:

- very high spatial resolution;
- Good timing performances;
- high data rate;
- high radiation tolerance;
- keeping an affordable cost;
- low mass;
- covering large areas;
- reducing power;
- **and ultimately combining these requirements in one single sensor device.**

WG1 research goals <2027	
	Description
RG 1.1	Spatial resolution: ≤3 μm position resolution
RG 2.2	Timing resolution: towards 20 ps timing precision
RG 1.3	Readout architectures: towards 100 MHz/cm^2, 1 GHz/cm^2 with 3D stacked monolithic sensors, and on-chip reconfigurability
RG 1.4	Radiation tolerance: towards 10^{16} n_{eq}/cm^2 NIEL and 500 MRad
RG 1.5	Low-cost large-area CMOS sensors

Putting a drift field in Monolithic Pixels



Maurice Garcia-Sciveres and Norbert Wermes 2018 Rep. Prog. Phys. 81 066101
Peric I 2007 , Nucl. Instrum. Methods A 582 876–85

WG6 – Wide bandgap and innovative sensor materials

WG6 is well aligned with the DRDT3.2 and DRDT3.3 since WBG semiconductors can be used for **timing applications** due to the high carrier saturation velocity, and their **radiation hardness** make them suitable materials to be used at extreme fluences with the added advantage that they can be operated without cooling.

WG6 research goals <2027	
	Description
RG 6.1	3D diamond detectors, cages / interconnects, base length 25 µm , impact ionization
RG 6.2	Fabrication of large area SiC and GaN detectors, improve material quality and reduce defect levels.
RG 6.3	Improve tracking capabilities of WBG materials
RG 6.4	Apply graphene and/or other 2D materials in radiation detectors, understand signal formation.

ECFA

DRD3 – Synergies with other DRDs

European Strategy Update

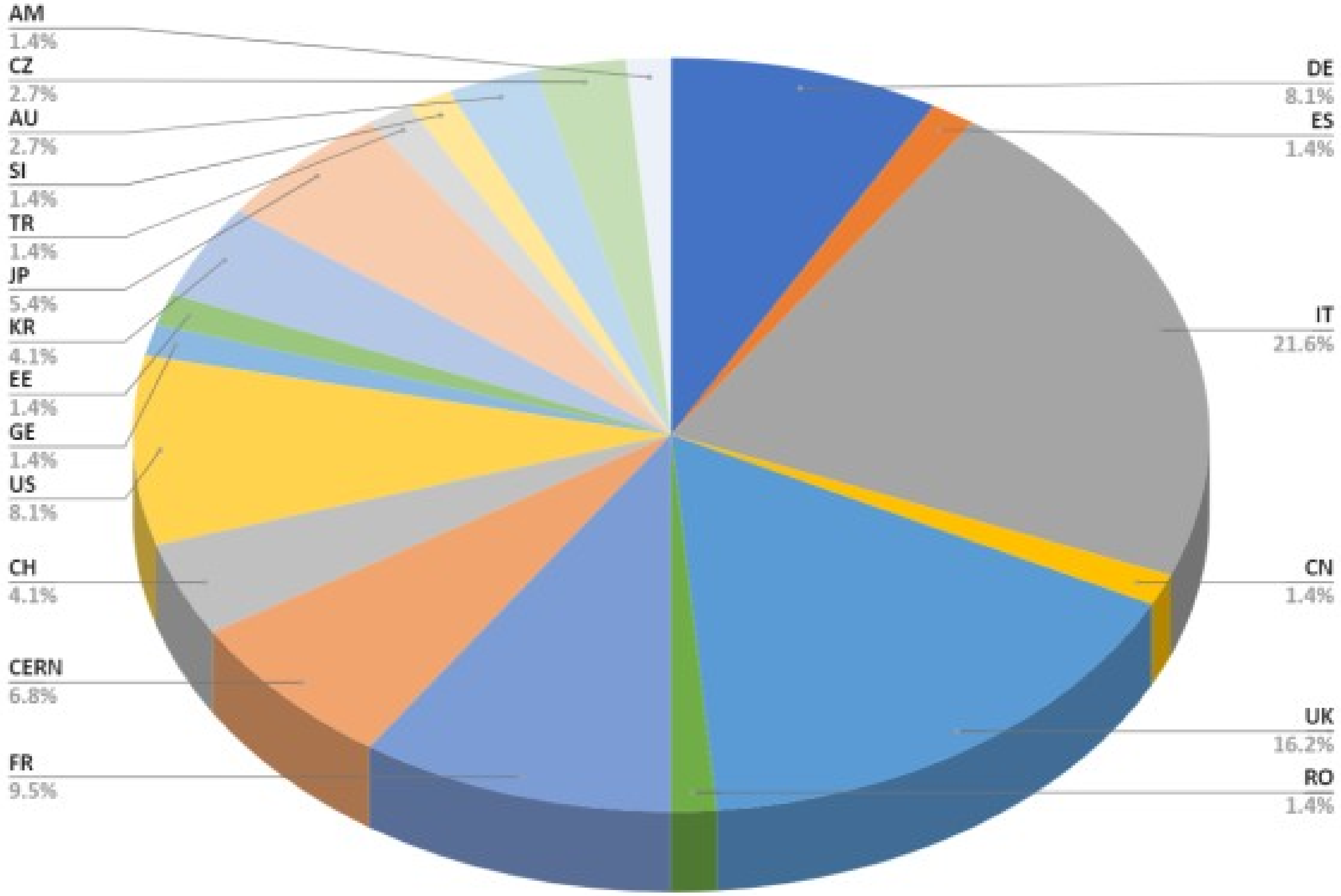
Cross-DRD coordination

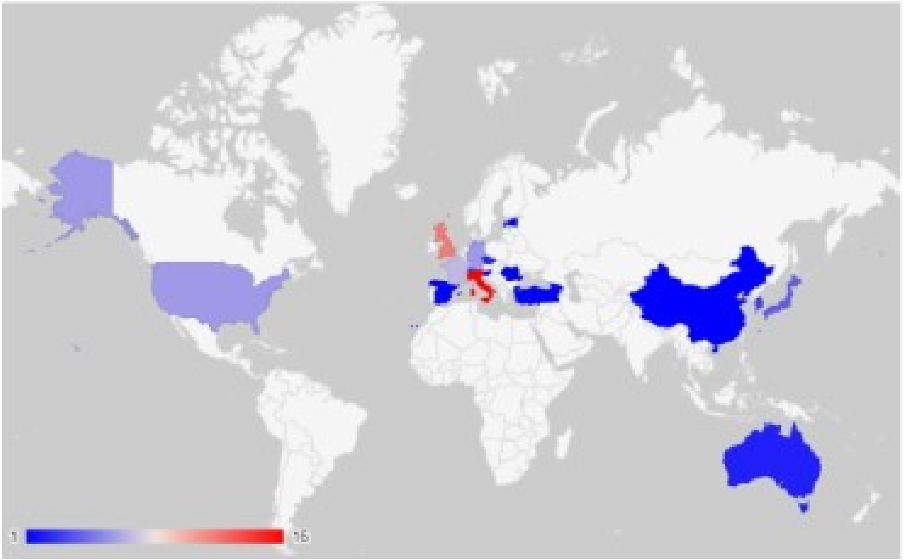
- **Strong synergies** between DRD3 and DRD7
  - Development of readout ASICs/architectures;
  - Evaluation (e.g. evaluate the readout ASIC with the sensor connected).
- **Possible joint developments**
  - Designs and joint submissions in TPSCo 65 nm, and perhaps in other technologies too;
  - Development of complex readout architectures that eventually could be ported to other technologies (e.g. digital blocks in 65 nm TPSCo ported to another technology process);
  - An independent digital chip for 3D integration with a sensitive CMOS chip;
  - Stitching;

DRD4 – Photodetectors and Particle ID

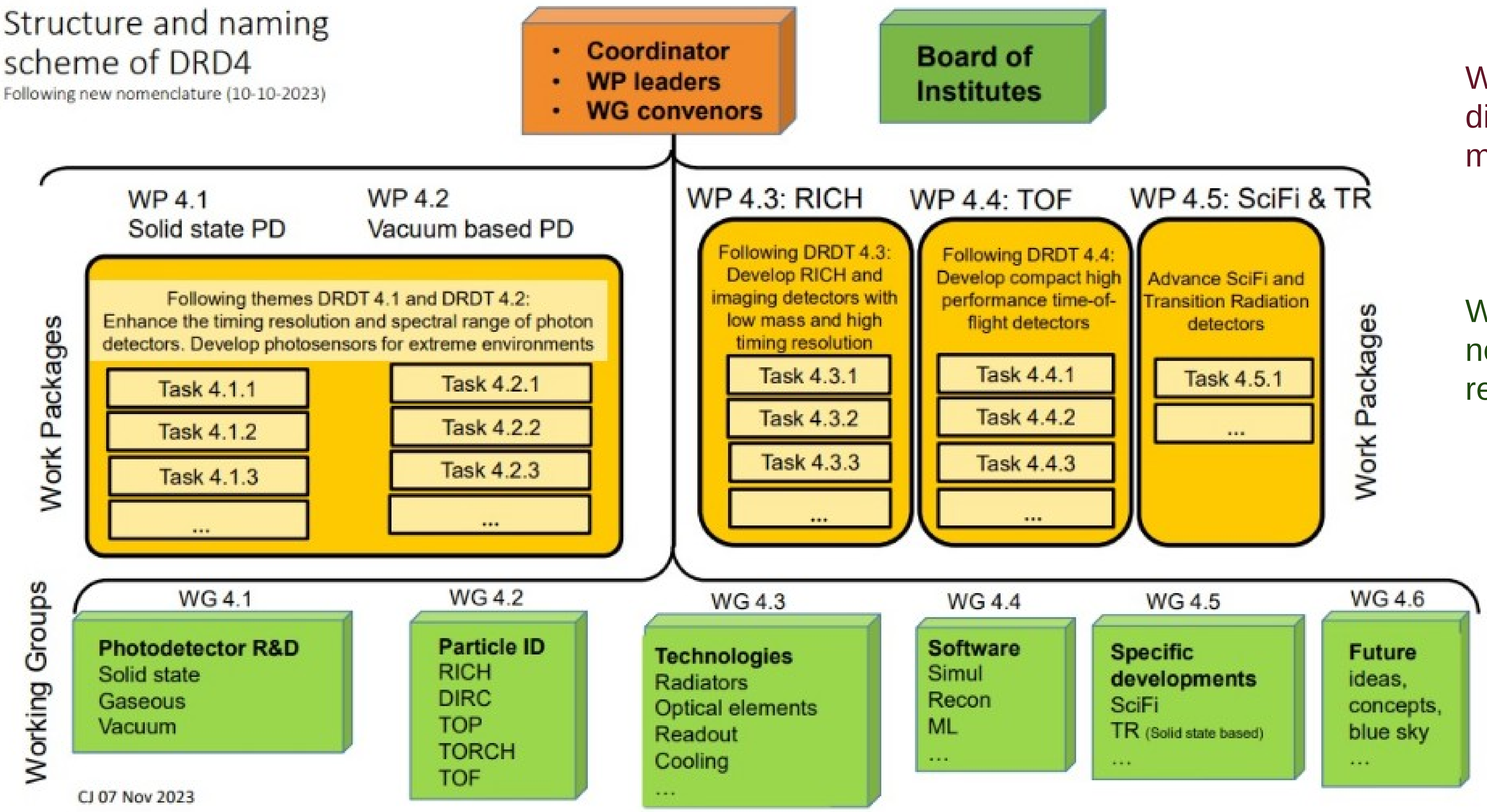
DRD4 – Collaboration

- 74 institutes wanted to join the DRD4 collaboration at the time of the Proposal (more in the pipeline)
  - 19 nationalities
  - Many small groups, many with no prior experience in large R&D collaborations
  - Includes 7 industrial and semi-industrial partners (very important asset)





DRD4 – Structure



WPs are run like projects: divided in tasks, have goals, milestones, deliverables, funding

WGs serve as scientific forums: no agreed tasks, no committed resources

ECFA

DRD4 WG1 – Photodetectors

European Strategy Update

- Scientific forum for studies and development of novel photodetectors with focus on PID for future experiments (59 groups)
- Topics (selection):
  - Radiation hardness; timing resolution; high-rate capabilities; longevity
  - Extreme conditions: e.g., cryogenic and high magnetic field
  - Large-area (e.g. SiPMs arrays, LAPPDs, etc.)
  - Fine granularity detectors for future high-rate experiments
  - New technologies: CMOS-SPADs, new SiPM structures, BSI SiPMs
  - New photocathode structures and materials
  - Novel materials for photon detection: e.g., Ge-on-Si APDs;
  - Hybrid photon detectors
  - Read-out electronics for extreme environments, fast timing and high channel density; optimal sensors and R/O electronics integration
  - Simulations of photo-detector response
- Standardization of procedures for photodetectors characterization
- Regular knowledge exchange with other DRDs

DRD4 WG5 – SciFi and TR Detectors

- R&D of segmented detectors based either on scintillating fibers or on pixelated semiconductor detectors for high precision tracking, eventually exploiting the transition radiation for PID (17 groups)
- WG5.A - Scintillating Fibers
  - Novel fast & radiation-hard scintillating fibers
  - Tracking with photon timing information in high occupancy environments
  - Micro-lenses on SiPMs
  - Fiber ribbon and detector plane production techniques (flexible ribbons)
  - Cryogenic cooling of SiPMs
- WG5.B - Transition Radiation Detectors
  - Development of a novel TRD based on highly segmented pixel semiconductor detectors (Si, GaAs, CdTe) for measuring both the energies and the emission angles of TR X-rays, for hadron ID in the TeV range

DRD4 WP1 – Solid-State Photodetectors

- Task 1 - SSPD with new configurations and modes (16 groups)
  - Development of back-side illuminated SiPM (potential for better PDE and radiation tolerance); development of ultra-granular SiPM that integrates with the electronics by using 2.5D or 3D interconnection techniques; development of CMOS-SPAD light monolithic sensors for HEP; study of new materials for light detection
- Task 2 - Fast radiation hard SiPMs (17 groups)
  - Standardize procedures for quantification of radiation effects; irradiated SiPMs characterization in wide temperatures range (down to -200 °C); study of annealing; study and quantify other measures enabling the use of SiPM in highly irradiated areas (e.g. smaller SiPMs, macro- and micro-light collectors)
- Task 3 - Timing of SSPD, including readout electronics (16 groups)
  - Study and improve the timing of SiPMs; co-design of a multi-ch. readout ASIC exploiting the timing potential; integration and packaging with integrated cooling; vertical integration of SiPM arrays to FEE (better timing via reduction of interconnections' parasitic inductances and capacitances)

WP1 Leader: Rok Pestotnik (Ljubljana)

ECFA

DRD4 WP3 – RICH and Other Imaging Detectors

European Strategy Update

- Task 1 - New Materials Radiators and Components (11 groups)
  - Gas alternatives; optimized aerogel modules; precise interferometric measurement of refractive index
- Task 2 - Development of new RICH detector concepts for improved performance (6 groups)
  - High-pressure gas radiator; fast timing, combined RICH/TOF; cryo-RICH; modular RICH; technological demonstrators & proof of concepts
- Task 3 - Prototype Single-Photon Sensitive Module for Imaging Arrays from sensor to DAQ and self-calibration systems (12 groups)
  - Fully functional autonomous modules (SiPM, LAPPD); scalable R/O electronics; integration to arrays with cooling; on-detector calibration/alignment/monitoring
- Task 4 - Study of RICH detectors for future e^+e^- colliders (3 groups)
  - Prototype a cell for the ARC concept
- Task 5 - Software and Performance (11 groups)
  - Fast simulation; reconstruction for high occupancy, high background

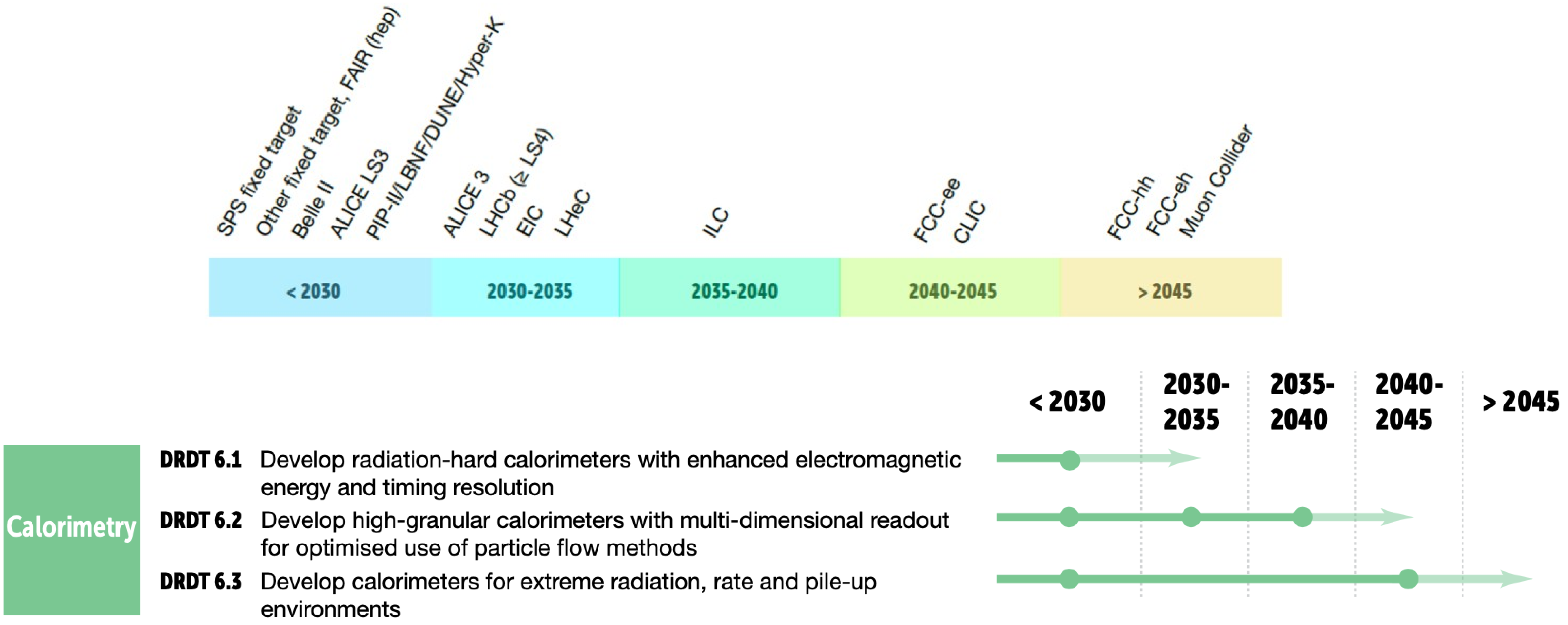
WP3 Leader: Roberta Cardinale (Genova)

DRD4 WG and WP activities

- Scientific activity is starting even without signature of the MoU (which might still need several weeks)
  - First WP/WG meetings organized
- These meetings allow building our community, enabling discussion of planned activities and the spread of information
  - Scientific and technological interests; expertise in the specific topics; expected contributions
  - For WP only: discussion on available and needed resources (persons, materials, equipment, funds); milestones and deliverables; sharing of responsibilities and synergies among the various groups
  - Availability (and/or need) of equipment and infrastructures for specific activities (and possibility of sharing or use by other DRD4 members)
- Monitor progress and proper inclusion of new teams and members

DRD6 – Calorimetry

DRD6 – Future facilities and DRDTs for calorimetry



- DRDTs and (provisional) time scale of facilities set high-level boundary conditions
- Both as well as GSRs should be taken into account when formulating R&D proposals

few details in next slides

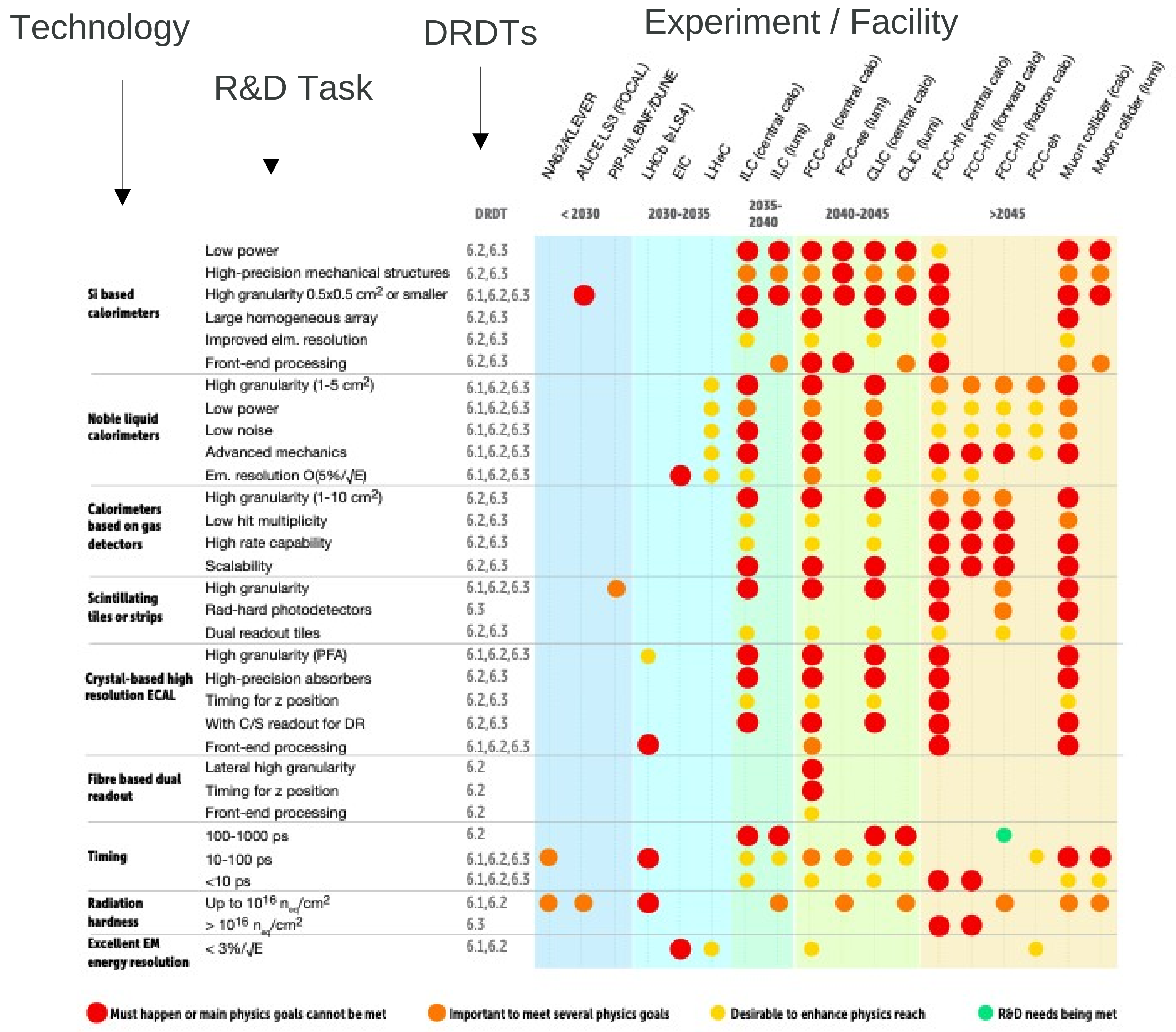
DRD6 – Calorimetry overview table

Project	~Earliest Start of data taking	Current Calorimeter options					
		Solid state	Scintilling tiles/strips	Crystals	Fibre based r/o (including DR)	Gaseous	Liquid Noble Gas
HL-LHC (>LS4)	2030			✔	✔		
SuperKEKb (>2030)	2030			✔			
ILC	2035	✔	✔			✔	
CLIC	2045	✔	✔				
CEPC	2035	✔	✔	✔	✔	✔	✔
FCC-ee	2045	✔	✔	✔	✔	✔	✔
EiC	2030		✔	✔	✔		
FCC-hh (eh)	>2050	✔	✔				✔
Muon Collider	> 2050	✔	✔	✔	✔	✔	
Fixed target	"continous"		✔	✔	✔		✔
Neutrino Exp.	2030		✔				(✔)

in most cases, final choices still to be made

DRD6 – Identified key technologies and R&D tasks

- Key technologies and requirements identified in roadmap
  - Si based calorimeters
  - Liquid Noble Gas calorimeters
  - Calorimeters based on gas detectors
  - Scintillating tiles and strips
  - Crystal based high-resolution ECal.s
  - Fibre-based dual readout
- R&D should in particular enable
  - Precision timing
  - Radiation hardness
  - High granularity
- R&D Tasks grouped into
  - Must happen
  - Important
  - Desirable
  - Already met



ECFA

DRD6 – Reminder on today's “ecosystem” for calorimetry

European Strategy Update

AIDA innova

EURO-LABS EUROPEAN LABORATORIES FOR ACCELERATOR BASED SCIENCES

- European projects such as AIDAinnova and EURO-Labs
- CERN EP-Programme
- Existing collaborations (LHC Experiments, Belle II, DUNE, NA62, KLEVER, ...)
- R&D Collaborations and communities (CALICE, FCAL, Crystal Clear, GranuLAr, CalVision, ...)
- Proto collaborations (ILD, SiD, CLICdp, FCC Detector with LAr, IDEA, EpIC, ...)

→ongoing DRD process must successfully integrate existing R&D activities

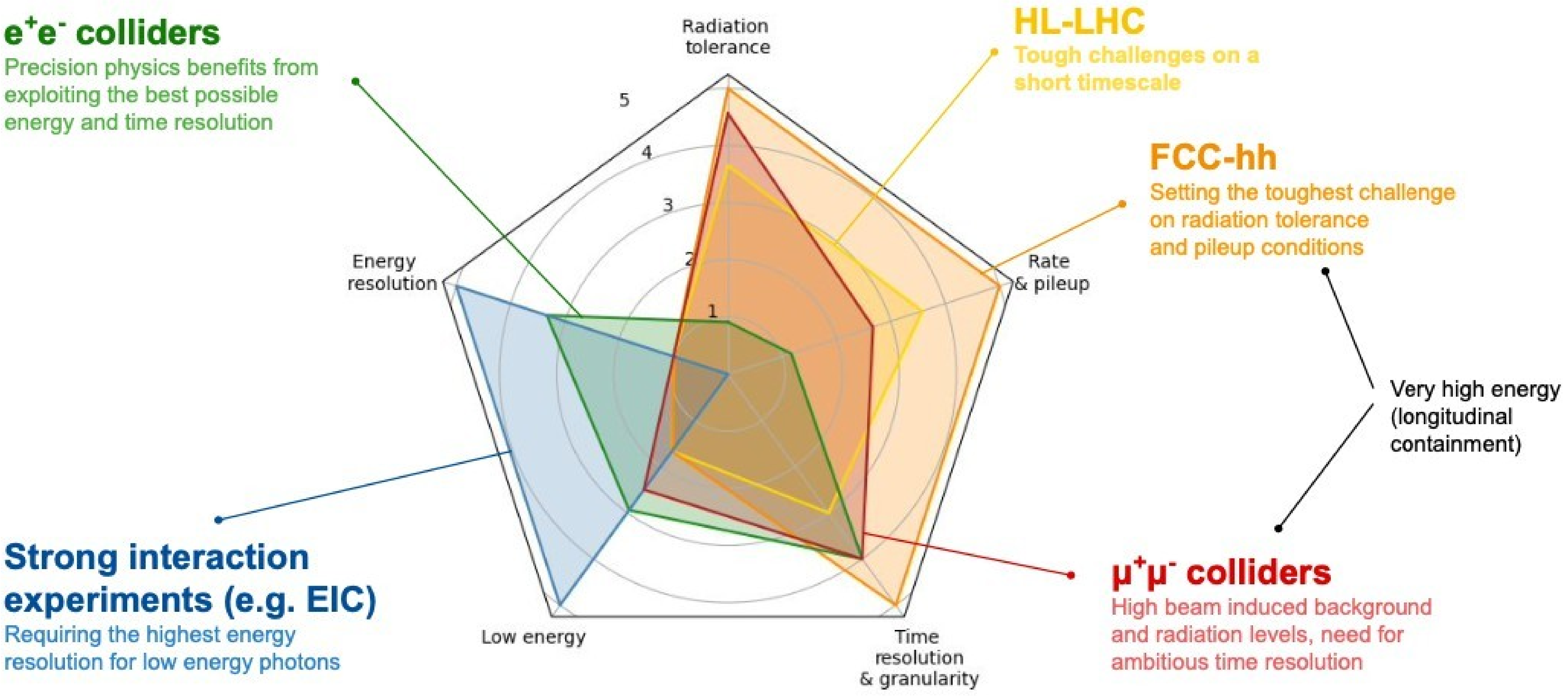
DRD6 – Few common keywords from input proposals

High granularity → critical for PFA (but not only)

Timing resolution → critical for hadron colliders (but not only)

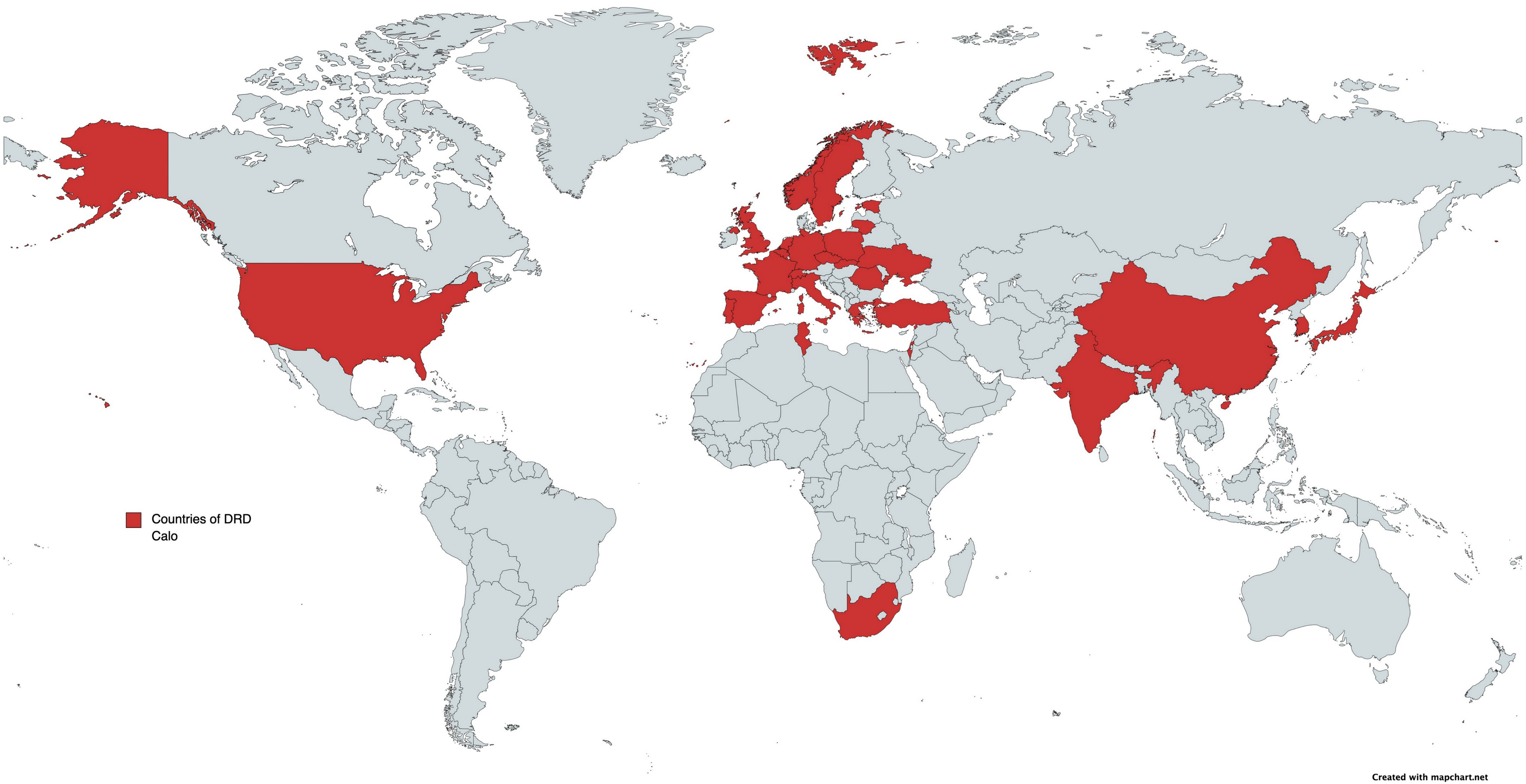
Hadronic energy resolution → critical for lepton colliders

DRD6 – Requirements for calorimetry at future colliders

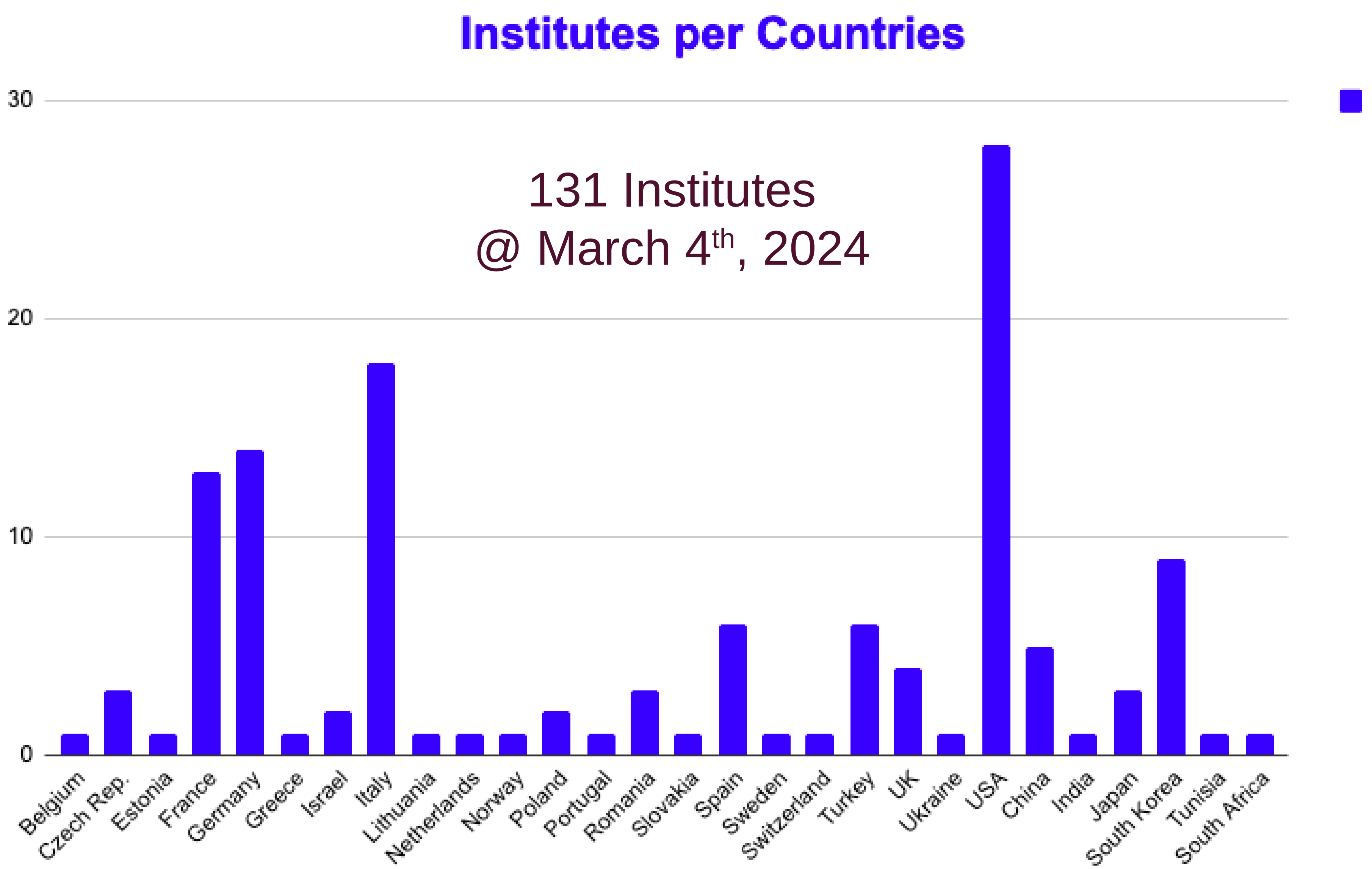


Inspired from https://indico.cern.ch/event/994685/

DRD6 Collaboration

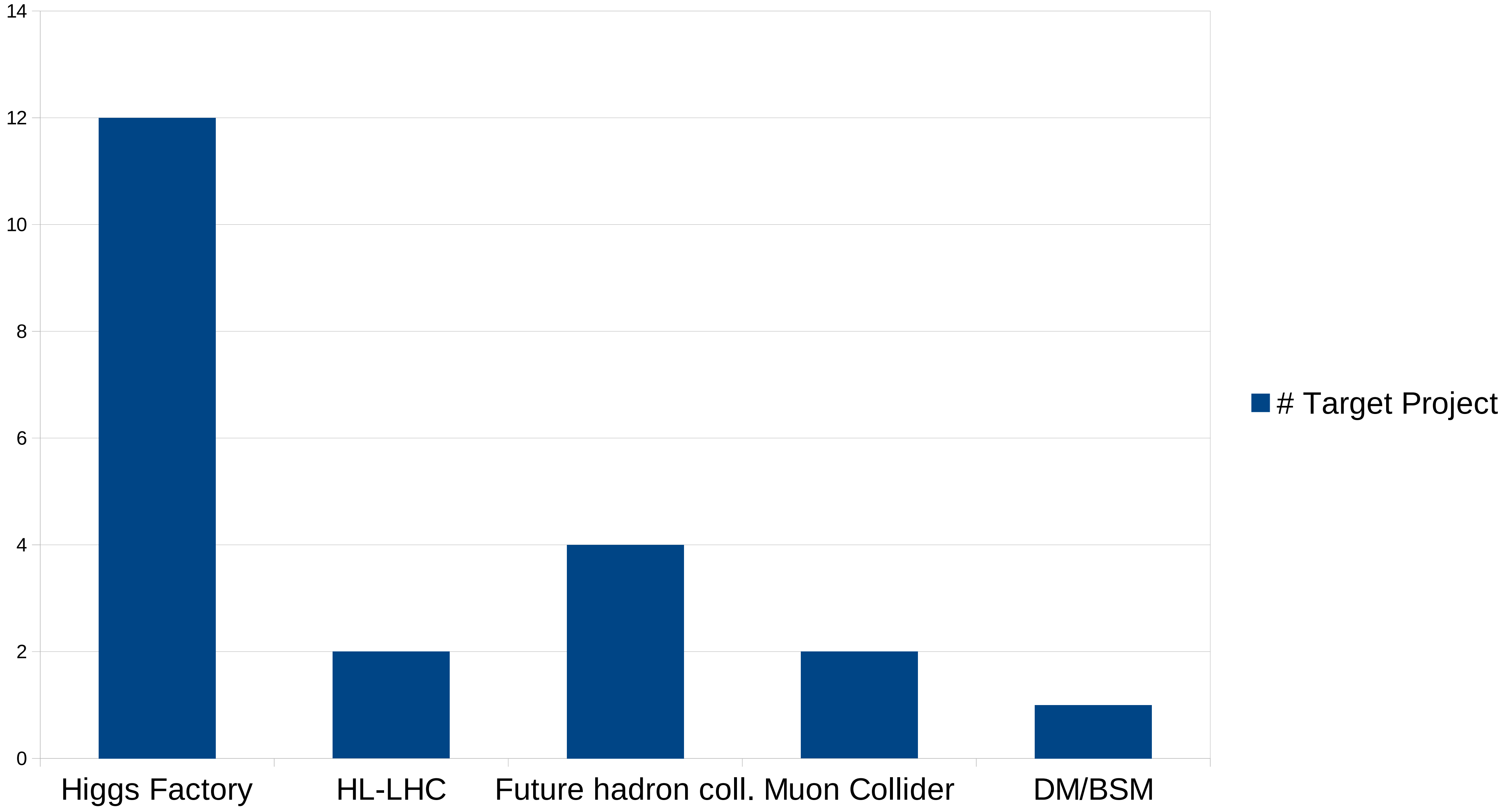


DRD6 Collaboration



- Mainly European Groups but interest from all over world (37%)
  - US biggest single participation → close contact to emerging effort in US
  - Very visible Asian participation

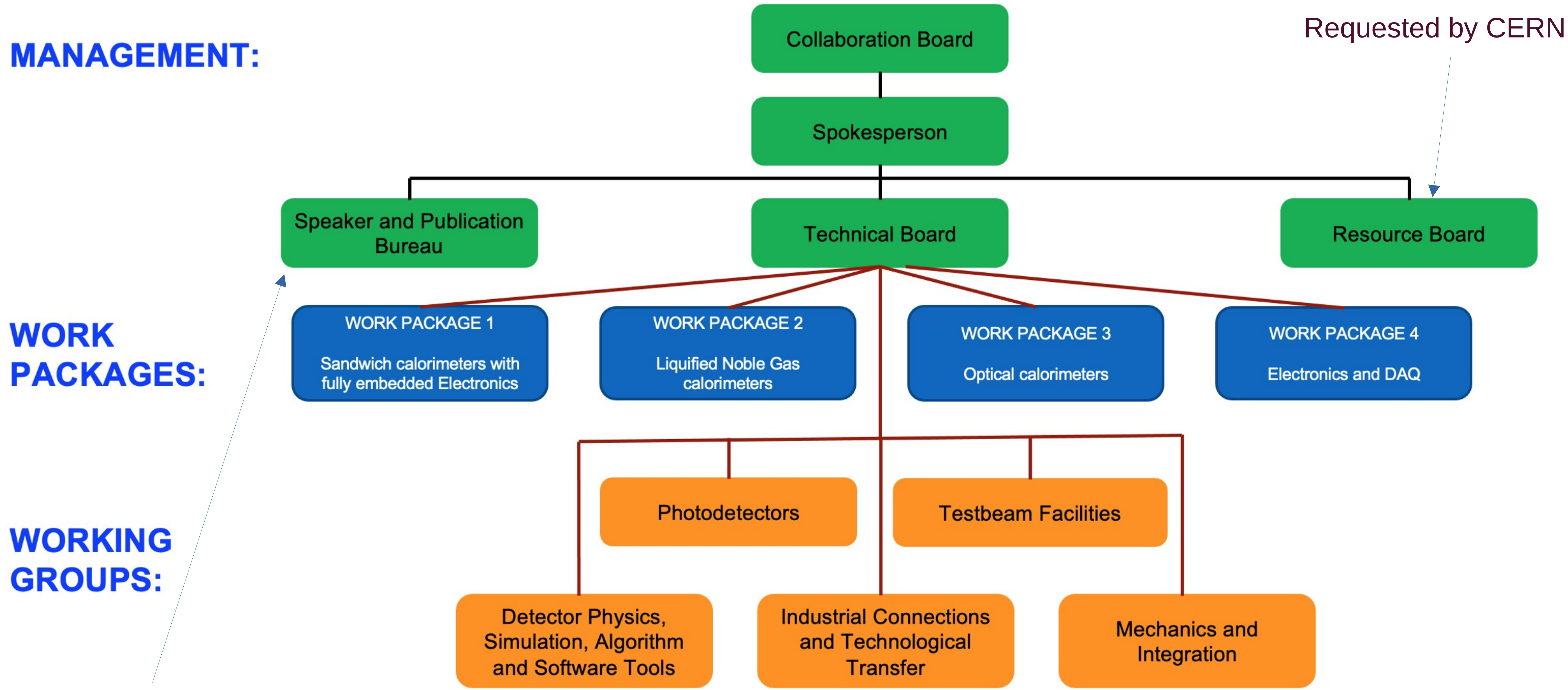
DRD6 – Target projects



- Higgs factories dominate → heavy-flavour physics programme often requires superb em energy resolutions
- Already now, orientation towards future hadron collider and muon collider

DRD6 – Proposed structure

After input-proposal collection and feedback from CERN and DRDC:



*SPB also in charge for dissemination

DRD6 – Work Packages and Tasks

WP 1: Sandwich calorimeters with fully embedded electronics

- » Task 1.1: Highly pixelised electromagnetic section (4 sub-tasks)
- » Task 1.2: Hadronic section with optical tiles (2 sub-tasks)
- » Task 1.3: Hadronic section with gaseous readout (3 sub-tasks)

WP 2: Liquefied-noble-gas calorimeters

WP 3: Optical calorimeters: scintillating-based sampling and homogeneous calorimeters

- » Task 3.1: Homogeneous and quasi-homogeneous EM calorimeters (3 sub-tasks)
- » Task 3.2: Innovative sampling EM calorimeters (3 sub-tasks)
- » Task 3.3: Hadronic sampling calorimeters (2 sub-tasks)
- » Task 3.4: Materials (2 sub-tasks)

WP 4: Electronics and DAQ

DRD6 – WP1 Tasks and Subtasks (→ Projects)

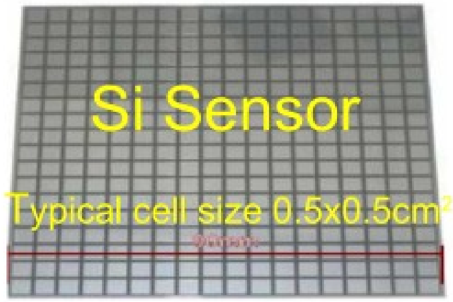
Elm. sections

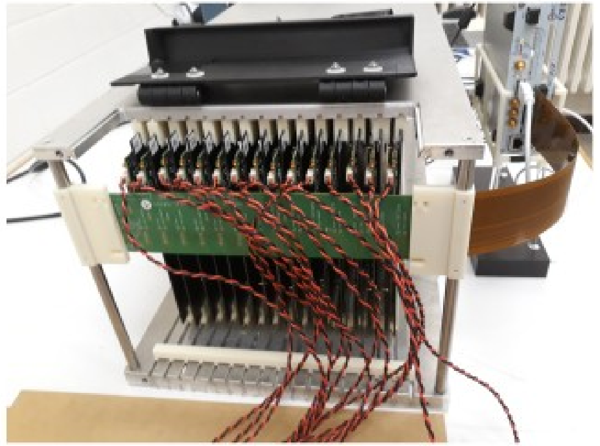
Hadronic sections

Task/Subtask	Sensitive Material/ Absorber	DRDT
Task 1.1: Highly pixelised electromagnetic section		
Subtask 1.1.1: SiW-ECAL	Silicon/ Tungsten	6.2
Subtask 1.1.2: Highly compact calo	Solid state (Si or GaAs)/Tungsten	6.2
Subtask 1.1.3: DECAL	CMOS MAPS/Tungsten	6.2, 6.3
Subtask 1.1.4: Sc-Ecal	Scintillating plastic strips/Tungsten	6.2
Task 1.2: Hadronic section with optical tiles		
Subtask 1.2.1: AHCAL	Scintillating plastic tiles/Steel	6.2
Subtask 1.2.2: ScintGlassHCAL	Heavy glass tiles/Steel	6.2
Task 1.3: Hadronic section with gaseous readout		
Subtask 1.3.1: T-SDHCAL	Resistive Plate Chambers/Steel	6.2
Subtask 1.3.2: MPGD-HCAL	Multipattern Gas Detectors/Steel	6.2, 6.3
Subtask 1.3.3: ADRIANO3	Resistive Plate Chambers+Scintillating plastic tiles/ Heavy Glass	6.1, 6.2, 6.3

DRD6 Task 1.1 - Highly pixelised e.m. section

Silicon W(olfram) ECAL

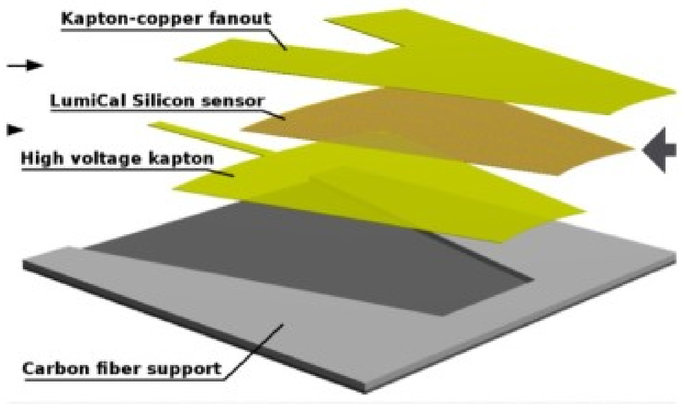




Main R&D Topics

- High level integration
- Power pulsing <-> continuous operation
- Reduction of power consumption;
- Cooling?
- Timing, if and how
- Real-size layers

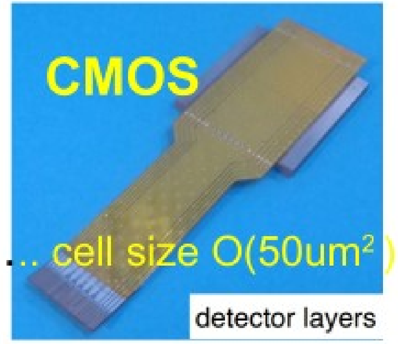
Compact Calo

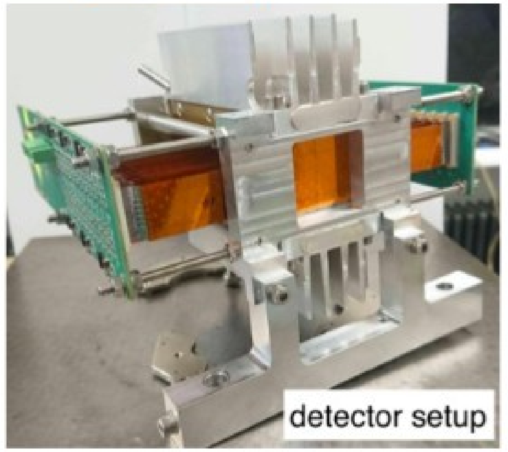


Main R&D Topics

- Testing of sensors with readout strips
- High level integration
- Study of conductive glue
- Wireless data transfer

Digital ECAL

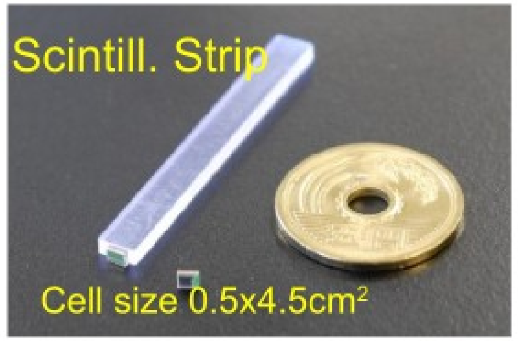




Main R&D Topics

- CMOS MAPS-based optimised for calorimetry
- Reduction of the power consumption to 1mW/cm²
- Stitching technologies for large surfaces

Scintillator ECAL



Main R&D Topics

- Power pulsing <-> continuous operations
- Reduction of power consumption
- Cooling?
- Timing, if and how
- Real-size layers

DRD6 – WP3 Tasks and Subtasks (→ Projects)

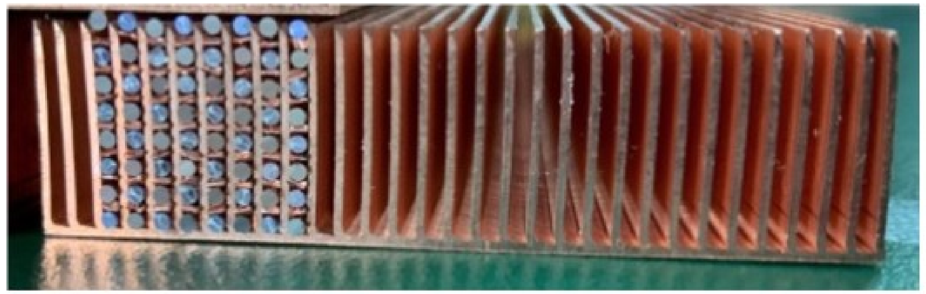
Project	Scintillator/WLS	Photodetector	DRDTs	Target
Task 3.1: Homogeneous and quasi-homogeneous EM calorimeters				
HGCCAL	BGO, LYSO	SiPMs	6.1, 6.2	e^+e^-
MAXICC	PWO, BGO, BSO	SiPMs	6.1, 6.2	e^+e^-
Crilin	PbF_2, PWO-UF	SiPMs	6.2, 6.3	$\mu^+\mu^-$
Task 3.2: Innovative Sampling EM calorimeters				
GRAiNITA	$ZnWO_4$, BGO	SiPMs	6.1, 6.2	e^+e^-
SpaCal	GAGG, organic	MCP-PMTs,SiPMs	6.1, 6.3	e^+e^-/hh
RADiCAL	LYSO, LuAG	SiPMs	6.1, 6.2, 6.3	e^+e^-/hh
Task 3.3: (EM+)Hadronic sampling calorimeters				
DRCal	PMMA, plastic	SiPMs, MCP	6.2	e^+e^-
TileCal	PEN, PET	SiPMs	6.2, 6.3	e^+e^-/hh
Task 3.4: Materials				
ScintCal	-	-	6.1, 6.2, 6.3	$e^+e^-/\mu^+\mu^-$/hh
CryoDBD Cal	TeO, ZnSe, LiMoO NaMoO, ZnMoO	n.a.	-	DBD experiments

DRD6 Task 3.3 – (EM+) Hadronic Sampling Calorimeters

Task 3.3: (EM+)Hadronic sampling calorimeters				
DRCal	PMMA, plastic	SiPMs, MCP	6.2	e^+e^-
TileCal	PEN, PET	SiPMs	6.2, 6.3	e^+e^-/hh

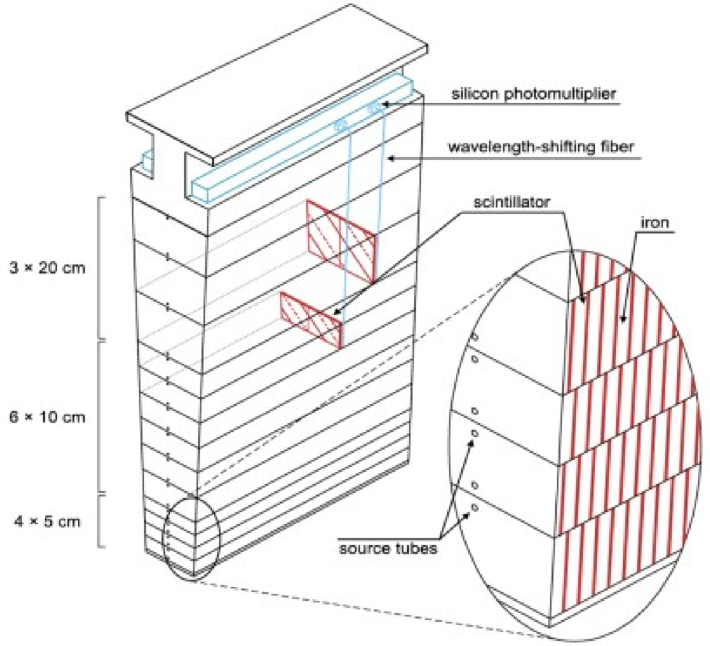
DRCal

- High resolution Electromagnetic and hadronic calorimeter based on Dual-Readout Technique
- Organic scintillating fibres in brass or steel absorber (different solutions under development).
- SiPM or MCP-PMT photon detectors integration of a large number of SiPMs



TileCal

- Hadron calorimeter with scintillating tiles and WLS fibre readout and SiPMs
- Cost-effective production of tiles, radiation hardness for FCC-hh
- Organic scintillating tiles, Steel (+Pb for FCC-hh) absorber



DRD6 WP3 – Milestones and deliverables

	Milestone	Deliverable	Description	Due date
HGCCAL	M3.1		Specifications of crystal, SiPM and electronics for highly granular EM crystal calorimeter prototype	2024
		D3.1	Development of 1-2 crystal EM modules to be exposed to beam tests	2024
	M3.2		Beam tests characterisation of a full containment highly granular EM crystal calorimeter prototype	2025
	M3.3		A first mechanical design for a final detector with crystal modules	2025
	M3.4		New reconstruction software for the long-bar design and updated PFA	2026
		D3.2	Large crystal module for hadronic performance, system integration studies and combined testbeam with HCAL	>2026
MAXICC	M3.5		Completion of qualification tests on components and selection of crystal, filter and SiPM candidates for prototype	2025
	M3.6		Report on the characterisation of crystal, SiPM and optical filter candidates and their combined performance for Cherenkov readout	2025
		D3.3	Full containment dual-readout crystal EM calorimeter prototype and testbeam characterisation	2026
	M3.7		Joint testbeam of EM module prototype with dual-readout fibre calorimeter prototype (DRCAL)	>2026
Crilin		D3.4	Acquisition and tests of crystals and SiPMs; design and production of electronics boards; design and production of the mechanical components	2024
		D3.5	Calorimeter fully assembled	2025
	M3.8		Beam test characterisation of a full containment EM calorimeter prototype	2025
	M3.9		Report on testbeam results	2026
GRAiNITA	M3.10		Characterisation of materials, wavelength shifters and SiPMs and identification of best technological choices	2024
		D3.6	Development of a GRAiNITA demonstrator as EM calorimeter prototype for e+e- collider (full shower containment)	2026
SpaCal		D3.7	Tungsten and lead absorbers for module-size prototypes	2024
	M3.11		Design of optimised light guides	2025
		D3.8	Set of crystal samples, SPIDER ASIC prototype	2026
	M3.12		Specification of photon detector and improved simulation framework available	2026
		D3.9	Module-size prototypes (significantly larger than EM showers) built and validated in beam tests	>2026
RADiCAL		D3.10	Single module with prototype scintillating crystals, SiPMs and front-end electronics cards built and tested.	2024
		D3.11	3x3 array of RADiCAL modules built and tested	2026
	M3.13		Paper on beam-test results for EM shower position, timing and energy	2026
	M3.14		Continue beam testing with alternative scintillation and wavelength shifting materials - for improved cost/performance.	>2026
DRCal		D3.12	Construction of full-scale dual readout module with hadronic shower containment	2025
	M3.15		Testbeam campaign to assess module performance: result paper	2026
	M3.16		Continue beam testing with alternative readout elx	>2026
TileCal	M3.17		Characterisation of PEN- and PET-based scintillating tiles including optimisation of readout with WLS fibres and SiPMs	2025
		D3.13	Construction of up to 3 prototypes of a sampling tile calorimeter module with WLS fibres and SiPM readout (for beam tests after 2026)	2026
	M3.18		Paper on beam test results	>2026
		D3.14	Full hadron-shower containment prototype built and tested	>2026
ScintCal	M3.19		Dataset of scintillation and radiation hardness properties of various scintillation materials studied	2026
		D3.15	Samples of a set of scintillators produced and characterised	2026
		D3.16	Samples of most promising glasses produced and characterised	>2026
	M3.20		Material selected for future detectors	>2029
CryoDBDCal	M3.21		Report crystals in terms of optimisation of growing/doping procedures	2024
		D3.17	Scintillating polymer for 3D-printing, with optimal mechanical and light-production properties, produced and tested	2025

3 Milestones and 4 deliverable in 2024

- **Milestones**
  - Task 3.1
    - HGCCAL: Specifications of crystal, SiPM and electronics for highly granular EM crystal calorimeter prototype
  - Task 3.2
    - GRAiNITA: Characterisation of materials, wavelength shifters and SiPMs and identification of best technological choices
  - Task 3.4
    - CryoDBDCal: Report crystals in terms of optimisation of growing/doping procedures
- **Deliverables**
  - Task 3.1
    - HCCCAL: Development of 1-2 crystal EM modules to be exposed to beam tests
    - Crilin: Acquisition and tests of crystals and SiPMs; design and production of electronics boards; design and production of the mechanical components
  - Task 3.2
    - SpaCal: Tungsten and lead absorbers for module-size prototypes
    - Radical: Single module with prototype scintillating crystals, SiPMs and front-end electronics cards built and tested

DRD6 WP4 – Electronics and DAQ

Name	Track	Active media	readout
LAr	2	LAr	cold/warm elx"HGCROC/CALICElike ASICs"
ScintCal	3	several	SiPM
Cryogenic DBD	3	several	TES/KID/NTL
HGCC	3	Crystal	SiPM
MaxInfo	3	Crystals	SIPM
Crilin	3	PbF2	UV-SiPM
DSC	3	PBbGlass+PbW04	SiPM
ADRIANO3	3	Heavy Glass, Plastic Scint, RPC	SIPM
FiberDR	3	Scint+Cher Fibres	PMT/SiPM,timing via CAENFERS, AARDVARC-v3,DRS
SpaCal	3	scint fibres	PMT/SiPMSPIDER ASIC for timing
Radical	3	Lyso:CE, WLS	SiPM
Grainita	3	BGO, ZnWO4	SiPM
TileHCal	3	organic scnt. tiles	SiPM
GlassScintTile	1	SciGlass	SiPM
Scint-Strip	1	Scint.Strips	SiPM
T-SDHCAL	1	GRPC	pad boards
MPGD-Calo	1	muRWELL,MMegas	pad boards(FATIC ASIC/MOSAIC)
Si-W ECAL	1	Silicon sensors	direct withdedicated ASICS (SKIROCN)
Si/GaAS-W ECAL	1	Silicon/GaAS	direct withdedicated ASICS (FLAME, FLAXE)
DECAL	1	CMOS/MAPS	Sensor=ASIC
AHCAL	1	Scint. Tiles	SiPM
MODE	4	-	-
Common RO ASIC	4	-	common R/O ASIC Si/SiPM/Lar

Diffferent calorimeter technology but similar challenges:

- # channels,
- Power budget (cooling?)
- Noise
- Data reduction

DRD6 WP4 – Electronics and DAQ

- Avoid parallel developments
  - Take CALICE as example
- ASICs needed for prototypes >2025/26 possibly produced in common MPW run serving more projects
  - ASICs should be available ~ one year before data taking at latest

→ common ASIC production: overarching goal of DRD Calo

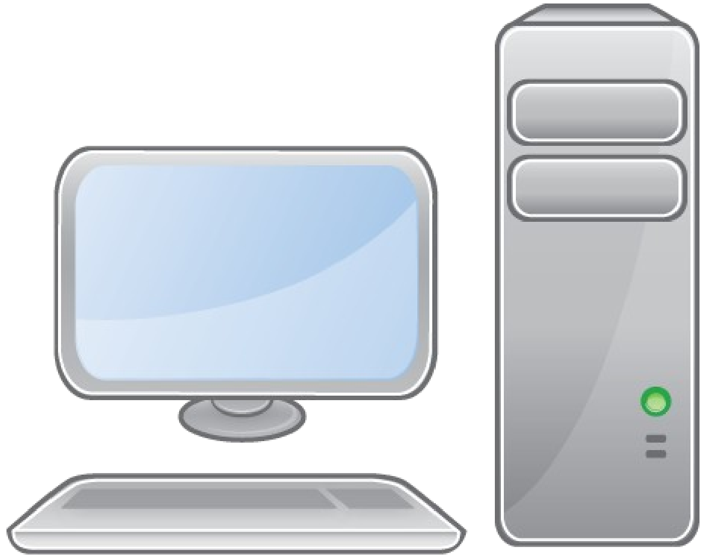
- Evoke possibility to hook onto production for other large projects (EiC?)
  - Agree on sharing among DRD Calo institutes and maybe with MPW runs in other DRDs
- Requires close communication with DRD3 and DRD7 (and maybe also DRD4)

DRD6 Working Groups – general scope

- Working Groups will address work that is common to all work packages in the DRD
- They thus ensure coherence and synergy of the scientific program of the DRD itself
- In general Working Groups ensure that scientific goals can be reached
  - Funds and personpower need to be included in the budget of the corresponding Work Packages
- Some Working Groups cover service tasks
  - Organisation and conduction of beam tests, if possible in a dedicated beam line for calorimetry
  - Software tools
  - The funding of these service tasks should be the subject of dedicated discussions in the course or shortly after the formation of the DRD
- The detailed organisation of the work within each working group is under the responsibility of dedicated coordinator(s) or directly under the responsibility of Technical Coordination

DRD6 Working Groups – Testbeams

Generic equipment and tools

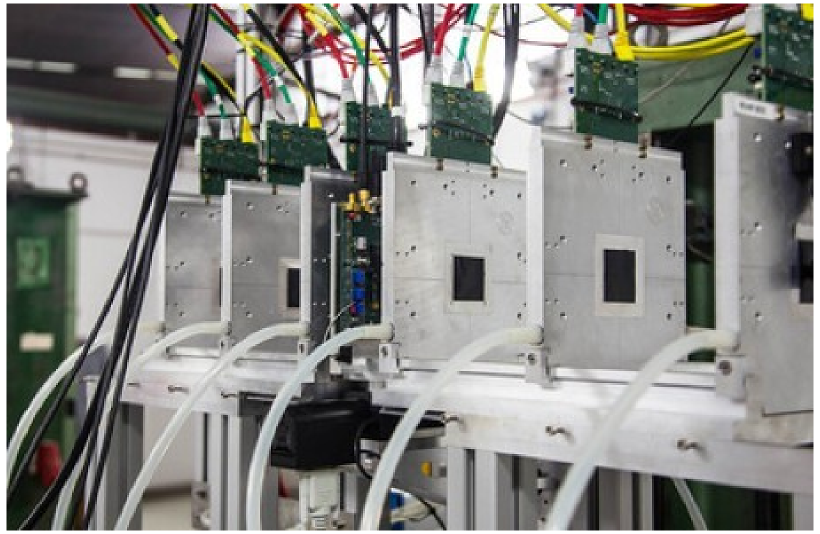


Overall planning

Your favorite
Calo Prototype(s)

Communication with operators

Beam line infrastructure



- Many items are common to all projects
- Common coordination will streamline beam test programme

DRD6 Working Groups – Testbeams

Calorimetric beam tests → small experiment, quite common requirements:

wide energy range
several kinds of beam particles
beam purity and energy
beam instrumentation for time, position and PID
big moving tables for big detectors
magnetic field

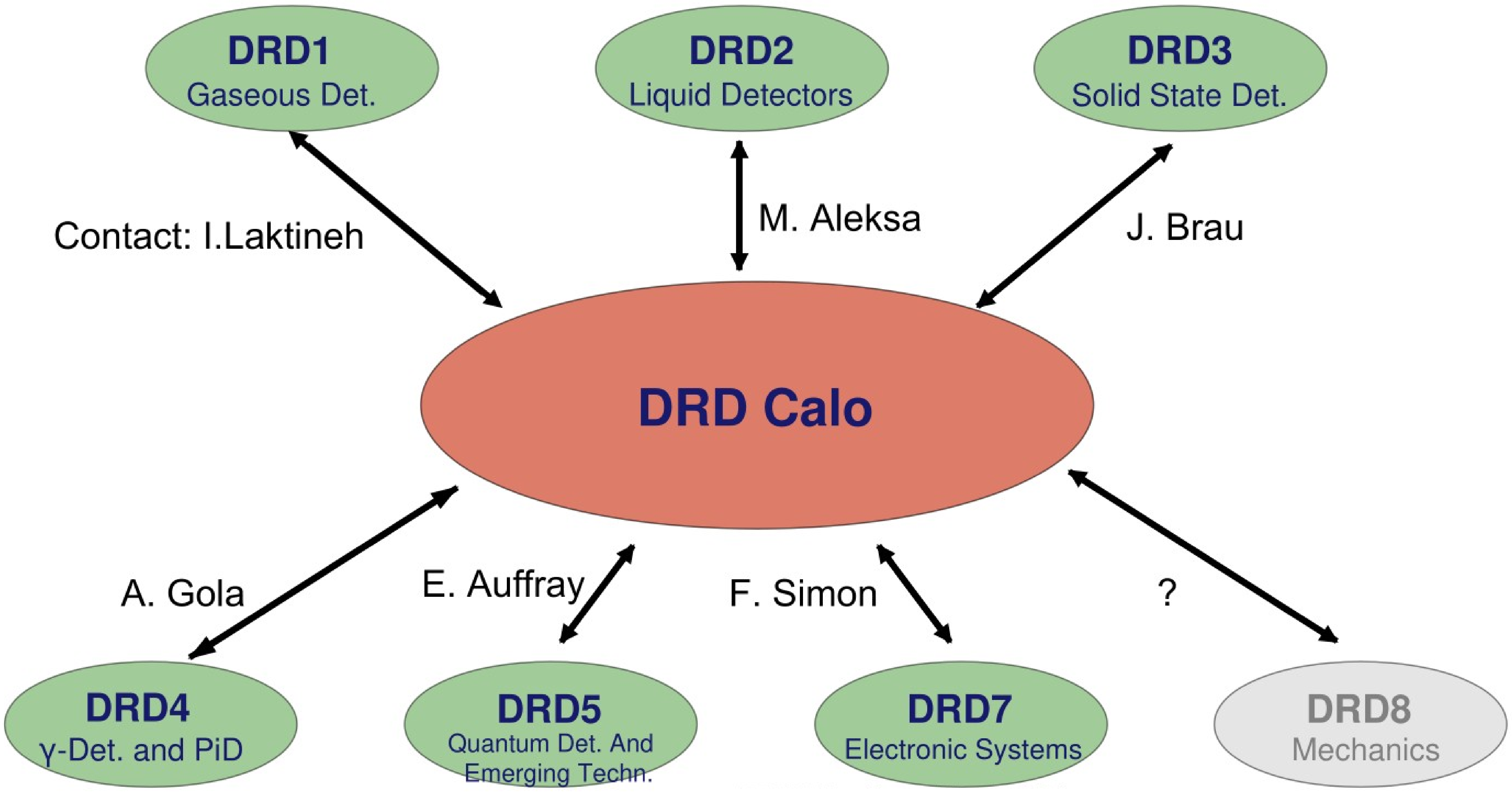
coordination of beam requests
coordination of and support for data taking

→ dedicated calorimetry beamline (in dedicated time slots) ?

→ default facility: SPS

DRD6 – Interplay with other DRDs

No R&D on primary elements (apart from scint. materials) but adaptation, tuning and integration



Conclusions

Following the EU particle physics strategy update and the ECFA detector R&D roadmap, 8 new collaborations have been formed:

- Bottom-up process with a worldwide participation
- Common basis
- Custom implementation (depending on community experience and story)
- Structure based on Work Packages (resource loaded) and Working Groups (NO resource load)
- All future facilities in the focus
- Setting up the collaboration NOW

Whoever would like to join, is welcome

Backup

Detector R&D Roadmap: 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.

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.

Detector R&D Roadmap: 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.

DRD6 – Common issues – lot of room for collaboration

New active materials:

- Fast, high-density, low-cost, scintillating materials
- Fast and rad-hard WLS fibres

Sensors + FE elx:

- Low x-talk, low-noise, low-power budget
- High granularity → high integration → embedded FE elx
- High-precision timing → from O(100) ps down to O(10) ps
- Radiation hardness
- Si/GaAs sensors: high integration, very-front-end integration, sensor bonding
- CMOS sensors: MAPS, digital SiPMs
- Photosensor architecture: MCP-PMTs, SiPMs, LGADs, ...,
- Photosensor performance: dynamic range, light yield, timing, UV sensitivity, ...
- ASICs: architecture, timing performance
- Components / connectors reliability
- High data rate → on-chip processing (DNN) for data selection and compression

DRD6 – Common issues – lot of room for collaboration (2)

Mechanics / production issues:

- Low-material budget
- High mechanical precision
- Industrialisation, engineering, scalability → relation w/ industry
- High-density absorber (e.g. W) production → (e.g.) 3D-printing

Services:

- Cooling
- Powering and control
- Clock distribution for O(10) ps timing

Others:

- Beam test infrastructure, setup & DAQ software (EUDAQ)
- Beam line features + common beam requests
- MC samples → common benchmarks
- Software tools (DD4hep, EDM4hep, Key4hep, ...), event-data format (?)
- Test benches, but also ... PFA and dual readout

add transversal package to cover overarching topics?

DRD6 – External synergies

With respect to other DRDs:

- Gaseous Detectors (TF1) for hadron calorimetry
- Solid State Detectors (TF3) for CMOS sensors
- PID and Photon Detectors (TF4) for all optical readout calorimetry
- Electronics and On-detector Processing (TF7)
- Integration (TF8) for cooling

Other fields: above all, medical imaging

DRD6 – Short-term applications

Several Phase-II and Phase-III HL-LHC upgrades:

CMS ECAL, LHCb ECal, ALICE FoCal

and also:

LUXE (XFEL), BELLE II ECal, EIC EEMCal

but ... all, except FoCal, EM calorimeters

DRD6 – Short-term applications (2)

High-performance hadron calorimetry only relevant for future Higgs/EWK factories?

Only rate capability and radiation hardness look to matter for hadron colliders (not surprising)