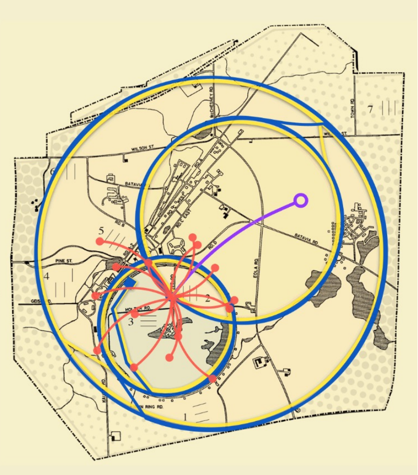


Inaugural US Muon Collider Meeting
FNAL – August 9, 2024

Overview of Detector R&D Needs

towards a multi-TeV Muon Collider experiment design

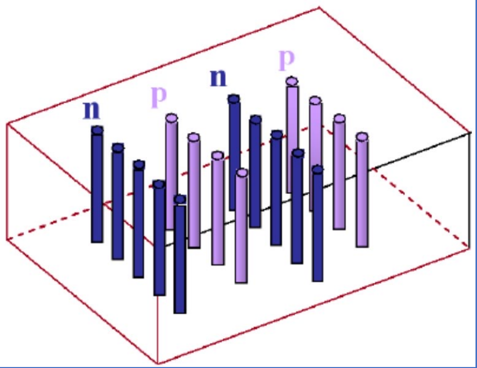
a collection of infos/hints from a lot of work, discussions, mistakes and great achievements of a community

Nadia Pastrone

From R&D to HEP: one example

Concept – Proof of principle

Late 90's



S. Parker et. Al. NIMA 395 (1997) 328, https://doi.org/10.1016/S0168-9002(97)00694-3

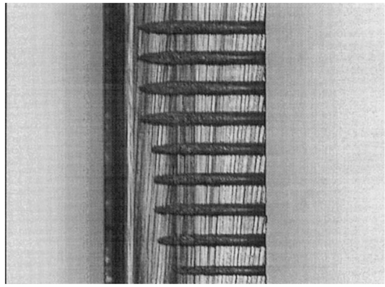
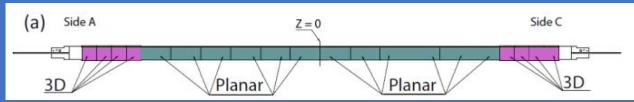


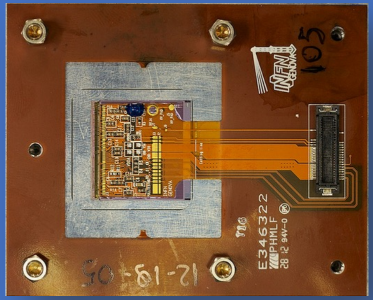
Fig. 4. A view of part of a set of etched holes, showing the increased depth reached by holes of larger diameters. The wafer was 540 μm thick and the etch time was 5 h. The photo-mask hole diameters from top to bottom are: four holes at 30 μm, four at 25 μm, and one at 20 μm.

C. Kenney, S. Parker, J. Segal and C. Storment,, IEEE Trans. Nucl. Sci. 46 (1999) 1224.

First applications in HEP

2014-18





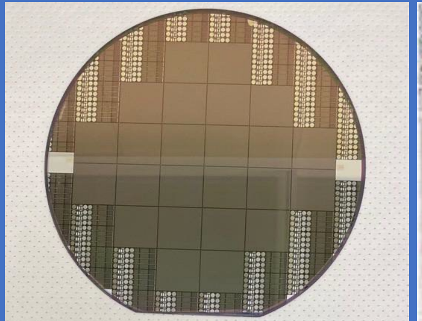
ATLAS Innermost layer, large eta, B. Abbot et al, *JINST 13 (2018) no.05, T05008*

Forward detectors in Phase–I

- ***AFP in ATLAS***
- ***PPS in CMS***

Key detector in HEP

2024-2028



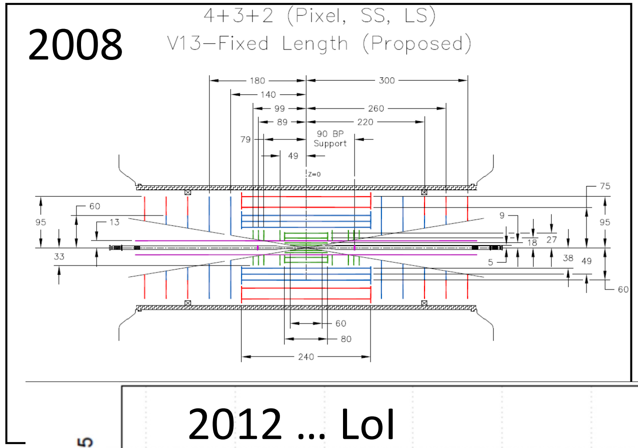
FBK 3D wafer

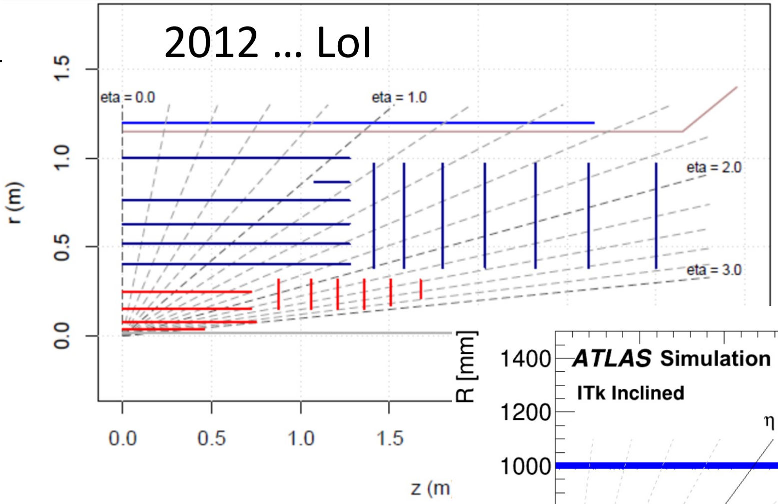
Modules for the innermost layer in ATLAS –CMS Phase2

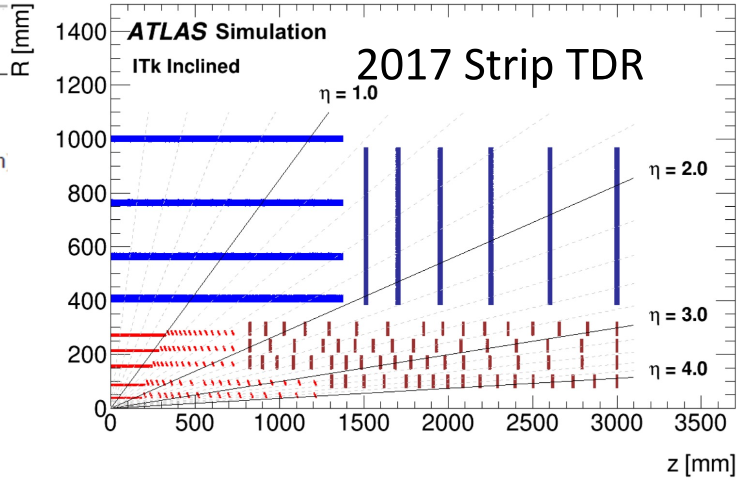
3D sensor technology:
A very long way between first ideas and key applications in an experiment!

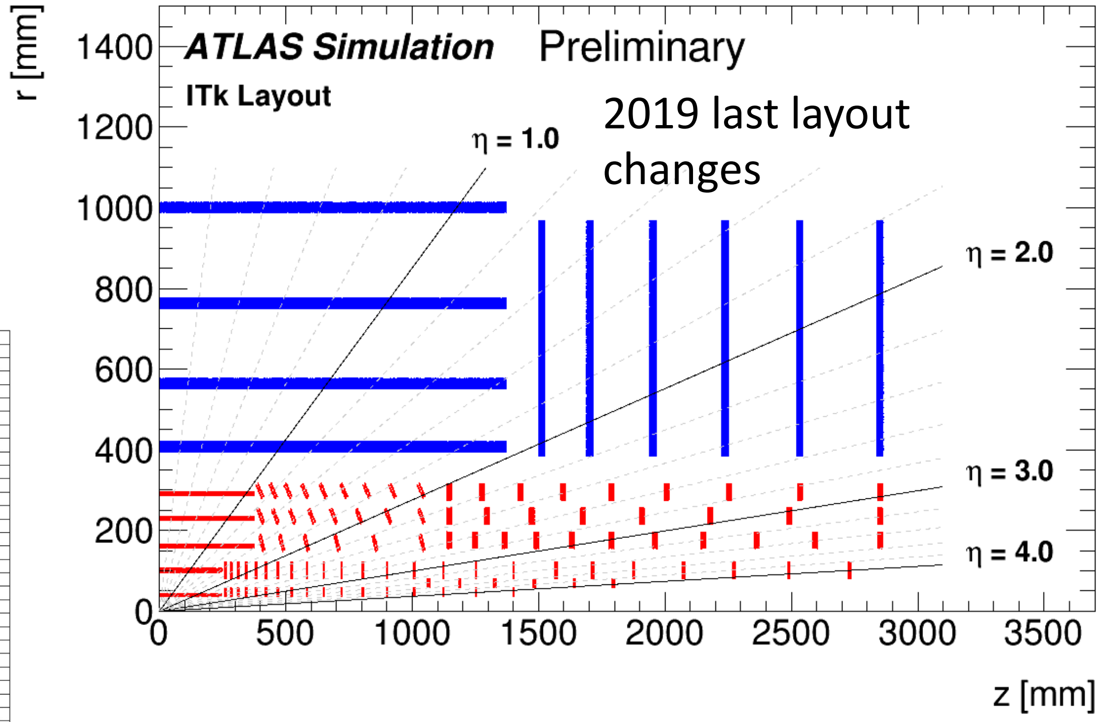
From ideas to HEP: one example

- ATLAS Inner tracker layout for Phase-2 had a very long story (intrinsically connected to technology, bkg…):
  - Discussion started in (at least) 2006 → Layout Advisory Committee → UTOPIA → Upgrade Layout TF, up to the ITk Layout Task force (2016) to finalize Layout for TDRs. Last minimal changes in 2019.









Towards a multi-TeV Muon Collider

***FINAL GOAL**: to exploit the physics potential of such a unique facility aiming at the highest energy and highest luminosity*

Advances in detector and accelerator pair with the opportunities of the physics case

- Muon Collider – a long story
- New Physics opportunities: Direct searches+Precision ➔ rich physics program

- New key technologies for both accelerator (not this talk - but strongly interlinked!) and experiments (detector sensors, electronics, data handling, AI…) are becoming available
  ➔ Time scale is becoming feasible for a multi-TeV collider facility to be ready by 2050

- **Synergies for enabling technologies opens new opportunities now and in the next 5-10 years**

- **The level of complexity requires to plan ahead evaluating the needs but with an open mind for ingenuity**

- **Detector field is a great playground to deeply understand Nature and benefit Society**

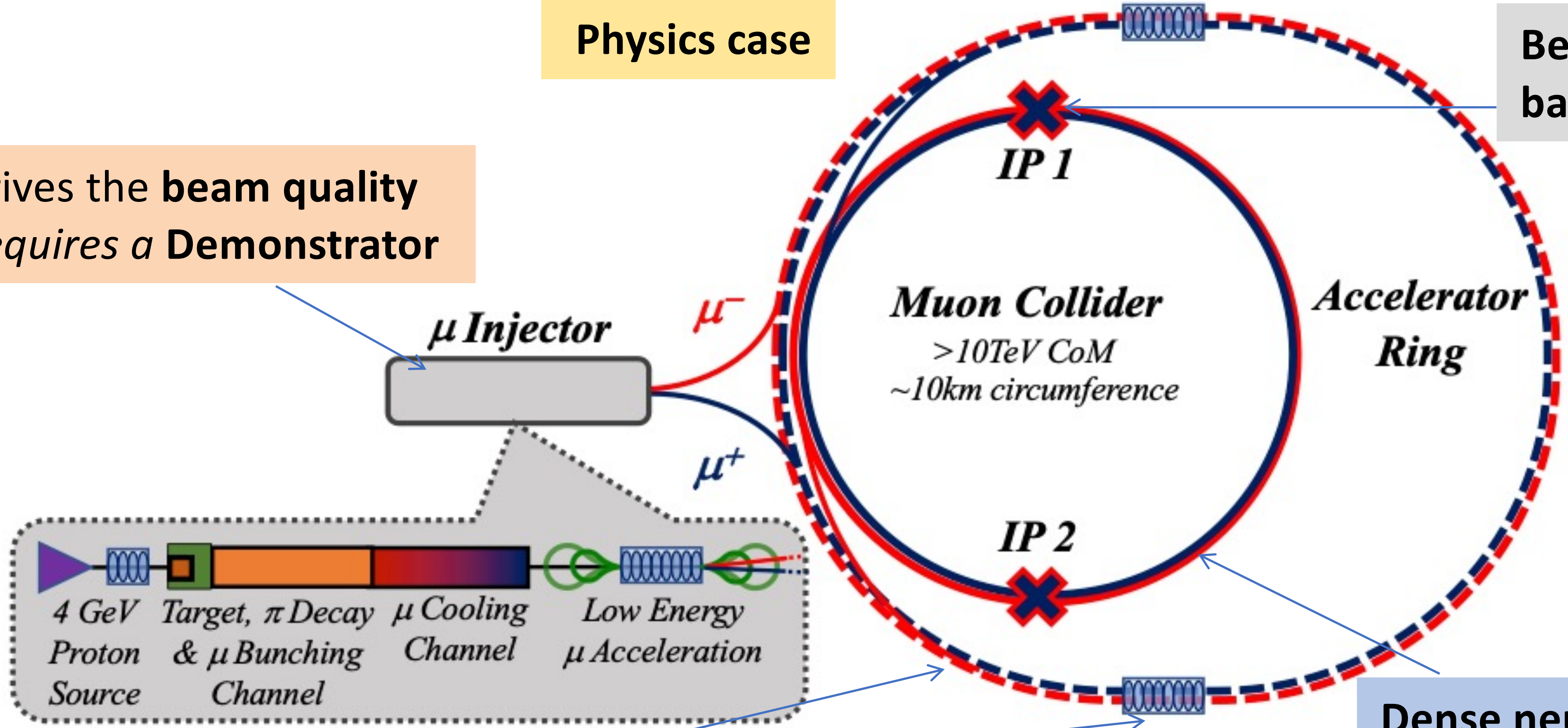
Key Challenges @ 10 TeV

Experiment design

Physics case

Beam-induced background

Drives the **beam quality**
Requires a **Demonstrator**



International MUON Collider Collaboration

Dense neutrino flux mitigated by mover system and **site selection**

Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

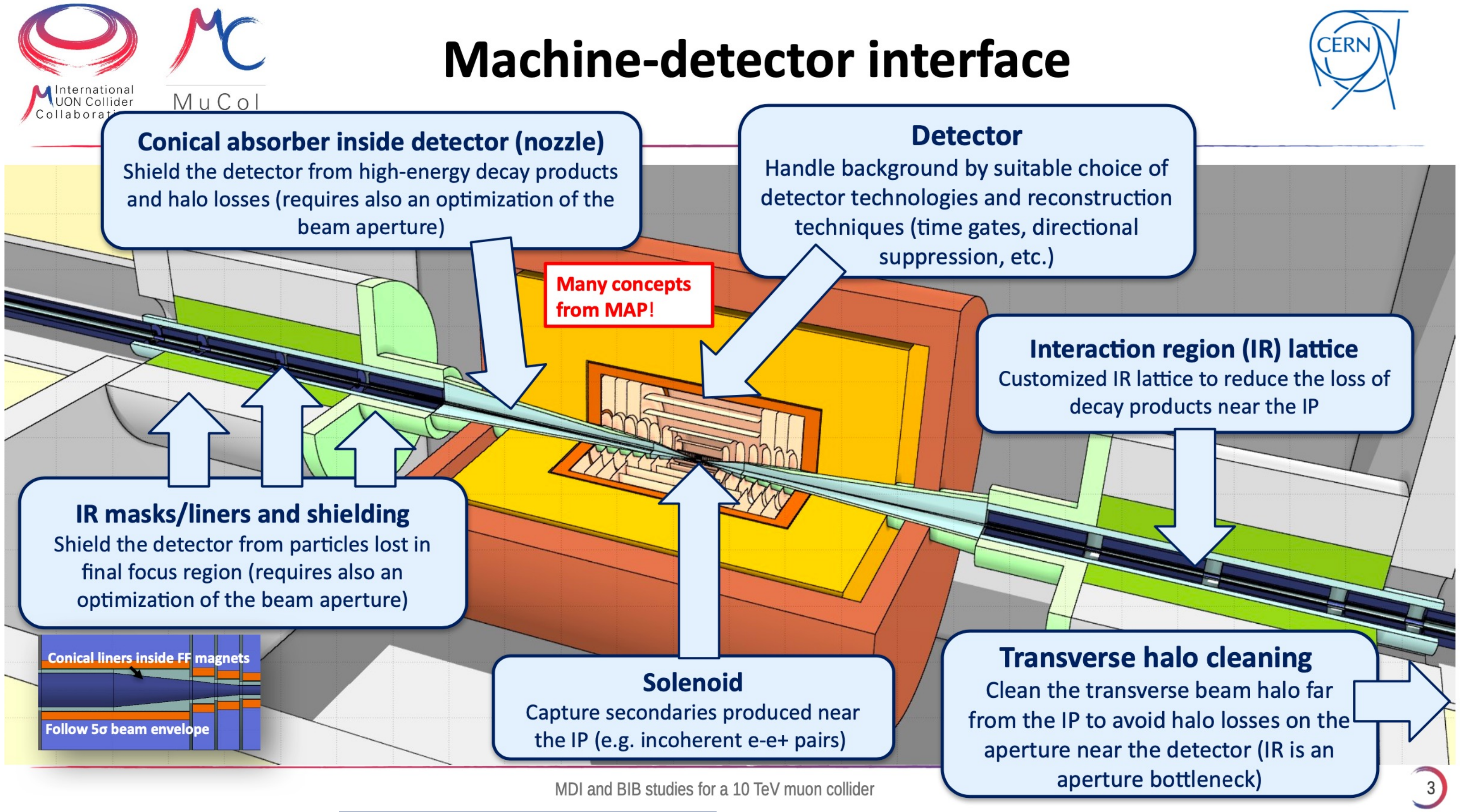
Mark Palmer et al.

The constraint & the challenge to design and operate an experiment

Machine Detector Interface - beam-induced background

Background is a significant driver for MDI design - background sources:

- **Muon decay**
- Beam halo losses and Beam-beam (mainly incoherent e-/e+ pair production)

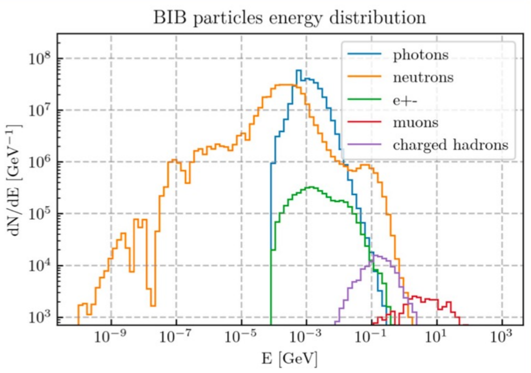


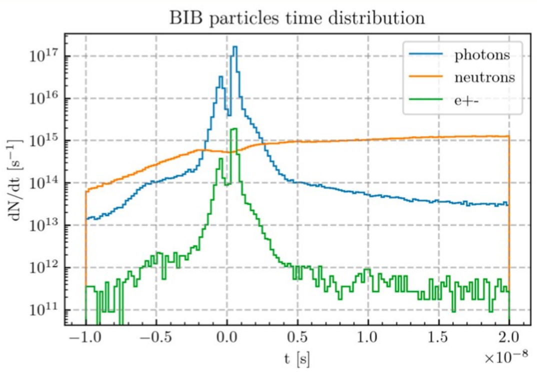
Workshop @ CERN 11 – 12 March 2024
Workshop @ CERN 25 – 26 June 2024

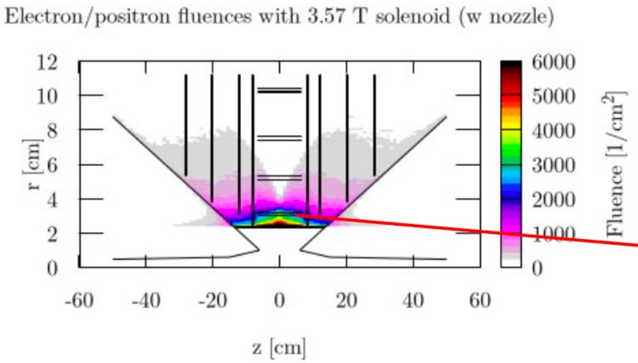
Daniele Calzolari – CERN

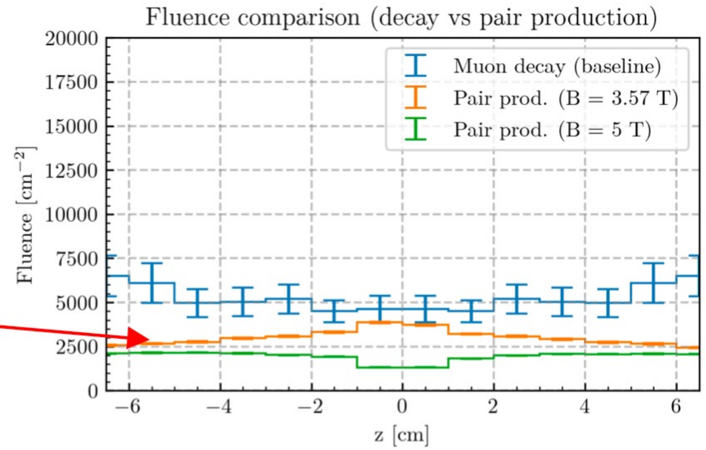
Experimental environment due to beam background

Time and energy spectra

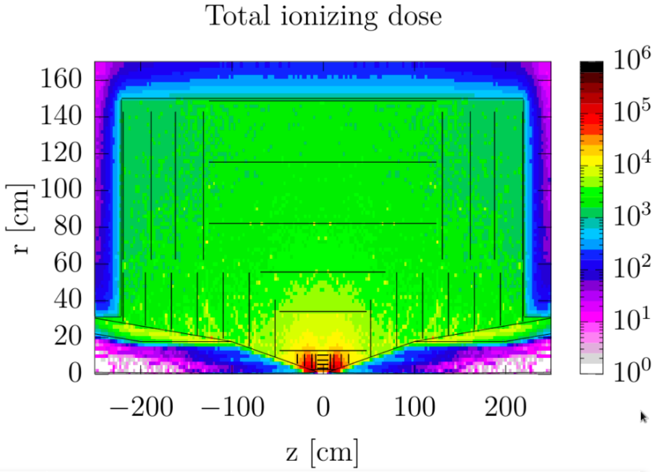


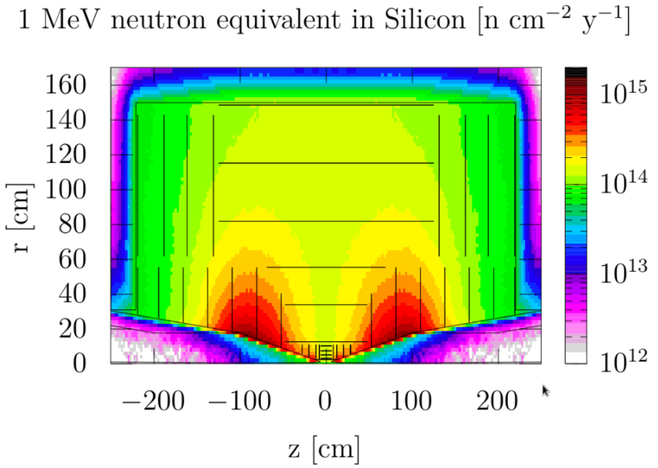






Radiation damage estimates for 10 TeV ***(MAP nozzle, CLIC-like detector)***
Includes only contribution of decay-induced background!



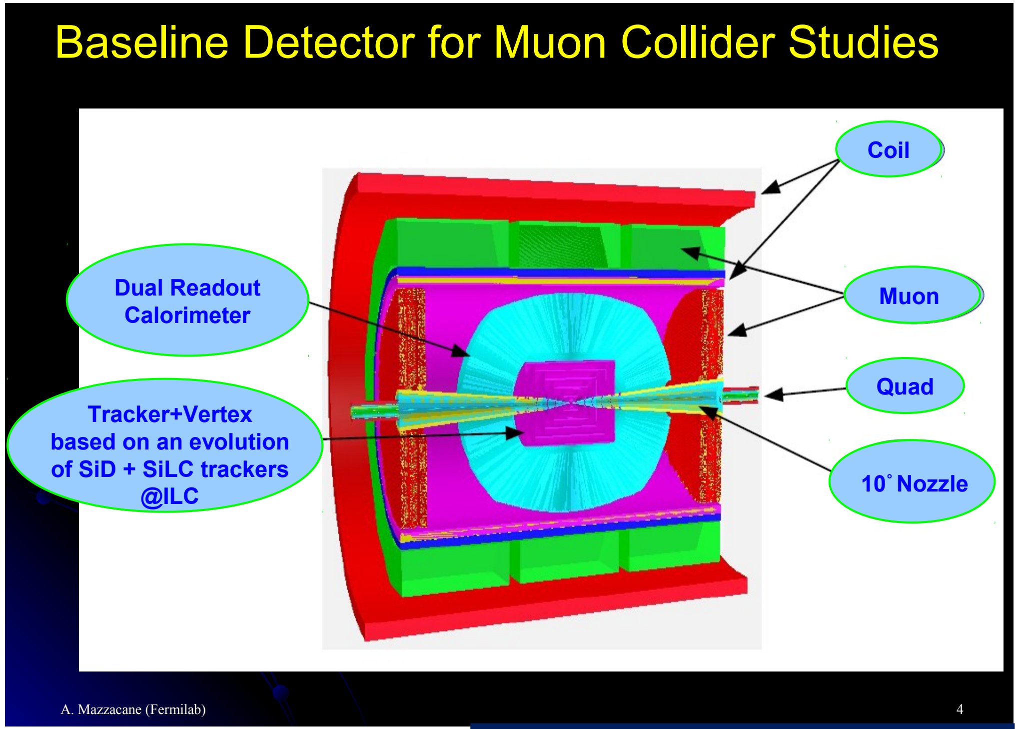


Donatella Lucchesi et al. – IMCC

Per year of operation (140d)	Ionizing dose	Si 1 MeV neutron-equiv. fluence
Vertex detector	200 kGy	3×10^{14} n/cm^2
Inner tracker	10 kGy	1×10^{15} n/cm^2
ECAL	2 kGy	1×10^{14} n/cm^2

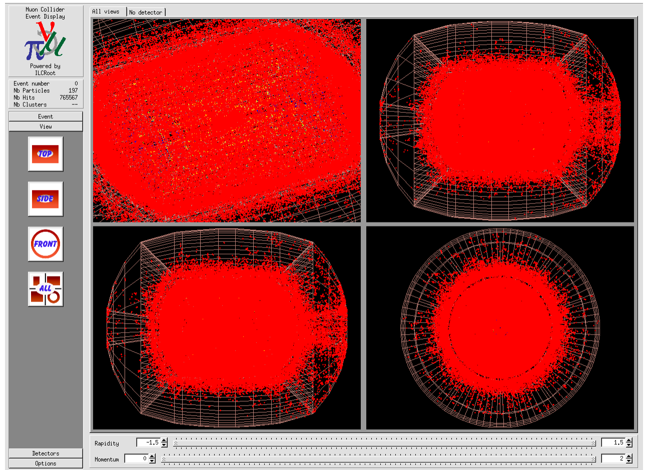
- **IMCC plans for final ESPPU report:**
  - Redo radiation damage calculations with optimized 10 TeV nozzle and lattice (and new detector design)
  - Calculate contribution of other source terms (e.g. incoherent pairs, halo losses)

Experiment design evolution



Anna Mazzacane – FNAL – MAP

No cuts: all hits

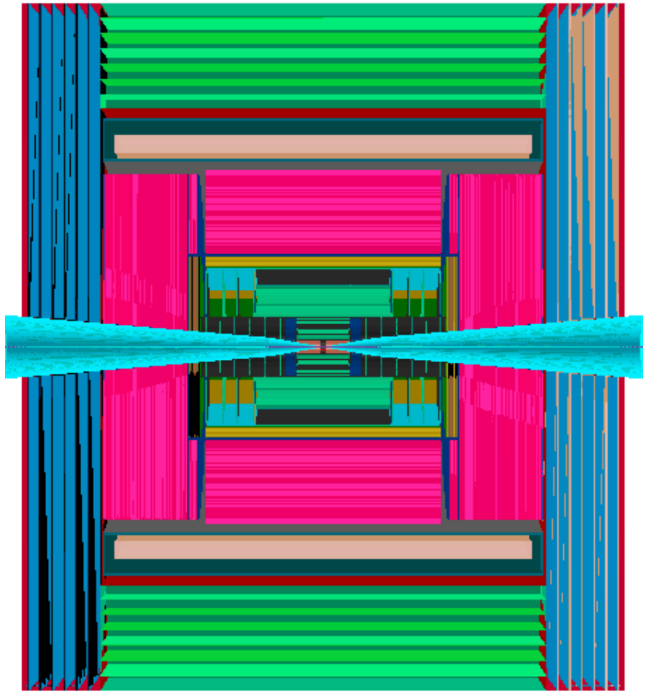


Muon Collider simulation:
MAP package
Background @ √s=125 GeV

Nikolai V. Mokhov – FNAL – MAP

Background (MARS simulation)
from muon decays and interaction with machine elements included

MuColl_v1 @ 3 TeV



Donatella Lucchesi et al. – IMCC

MUSIC design @ 10 TeV

New detector concepts:
MUSIC and **MAIA**
moving the solenoid inside the calorimeters

Crucial full simulation studies for
[Detector performance for low- and high-momentum ..]

Massimo Casarsa et al. – IMCC

Experiment design requirements @ 10 TeV

Aim at **10+ TeV** and potential initial stage at **3 TeV**
NEW OPTION: initial 10 TeV stage at reduced luminosity
Interim report **https://arxiv.org/abs/2407.12450**

Strong interest in developing:

- 4D vertex and tracker sensors
- new calorimeters 4D or 5D ideas
- sustainable muon detector
- front-end electronics with on-board intelligence
- powerful reconstruction algorithm
- AI simulation ans analysis tool

Detector technology R&D and design

- we can do the important physics with technology being implemented for HL-LHC upgrades or follow-ups
- available time will allow to improve further and exploit synergies and new emerging technologies

"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" ESPPU 2020

Detector R&D in US - CPAD

4a) Support vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build major test facilities and demonstrator facilities within the next 10 years [see sections 3.2, 5.1, 6.5, and also Recommendation 6]

RDC#	TOPIC
1	Noble Element Detectors
2	Photodetectors
3	Solid State Tracking
4	Readout and ASICs
5	Trigger and DAQ
6	Gaseous Detectors
7	Low-Background Detectors
8	Quantum and Superconducting Sensors
9	Calorimetry
10	Detector Mechanics
11	Fast Timing

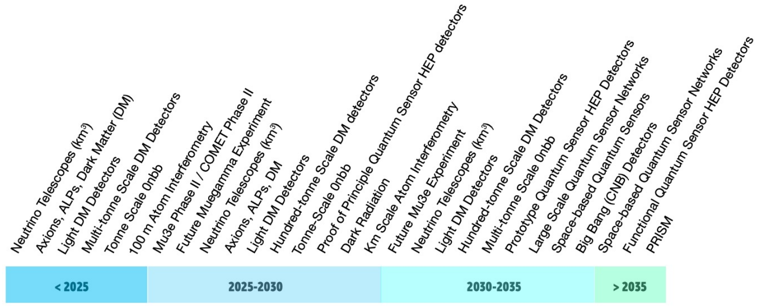
Jonathan Asaadi

After Snowmass recommendation to **create Detector R&D collaborations in the US**

- Organized by **CPAD** (Coordinating Panel for Advanced Detectors) of the APS/DPF (one chairperson from CPAD is in DRDC)
- They created **11 RDCs** (R&D Collaborations) and appointed coordinators (see CPAD website)
- Recently started to reach out to the community and work on detailed planning
- Overlap to DRDs through people/groups involved in both and liaisons

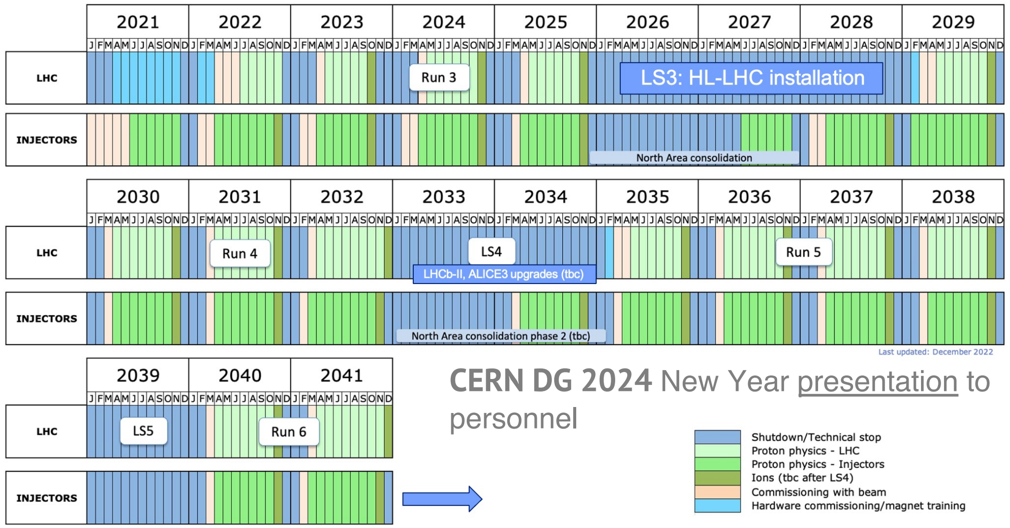
ECFA Detector Roadmap Timeline

- Five time periods defined, from now to 2045 and later.
  - the **Future Large Experiments**

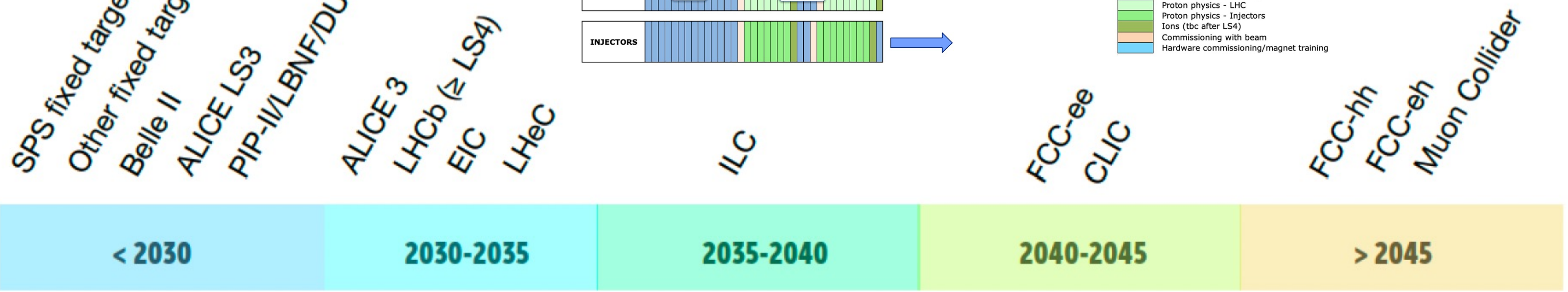


Future Smaller Experiments

Indicative timeline out to 2041 **for (HL)-LHC Schedule**



CERN DG 2024 New Year presentation to personnel

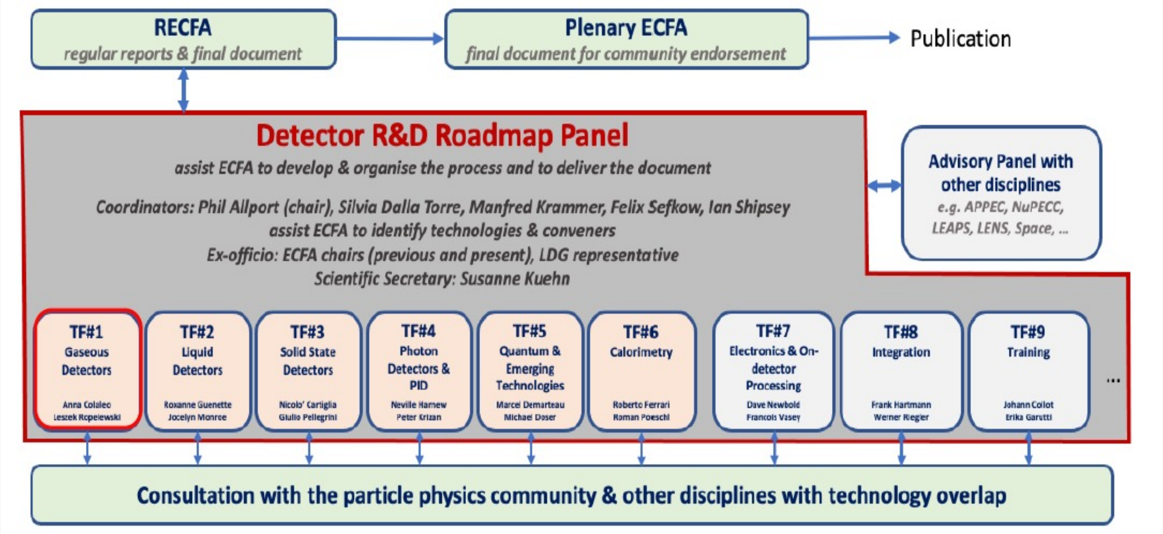


LHC LS3 **LHC LS4** *Large Accelerator Based Facility/Experiment Earliest Feasible Start Dates*

ECFA Detector R&D Roadmap

The 2021 ECFA detector research and development roadmap

- ESPP 2020 update: ECFA mandated to prepare a Detector R&D roadmap for future HEP projects
- Roadmap Panel: define Detector Research and Development areas & organise wide community consultation
  - establish strategic project performance requirements and their criticality to the physics program
  - assess potential of technology options and studies needed to fulfil the requirements in due time



Roadmap was approved by Plenary ECFA in Nov. 2021
10 General Strategic Recommendations
GSR4: international coordination & organization of R&D activities
GSR6: establish long term strategic funding program

↓

ECFA implementation proposal to form DRD collaborations hosted at CERN was endorsed by Council Sep. 2022

P. Allport chair - ex-officio ICFA-IIDP chair I. Shipsey

Didier Contardo @ ICFA Seminar 2023

Detector Research and Development – DRD
international collaborations anchored at CERN: implementation

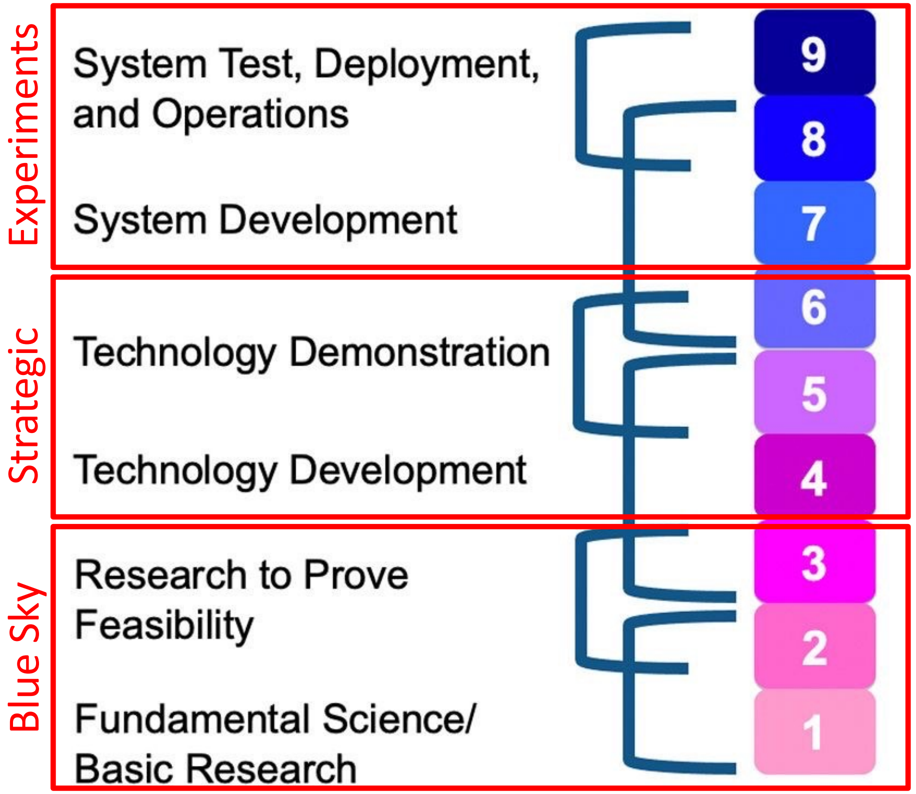
- The **General Strategic Recommendations** (GSR) topics are:
  - Supporting R&D facilities: **test beams, large scale generic prototyping and irradiation**
  - **Engineering support** for detector R&D
  - Specific **software** for instrumentation
  - **International coordination** and organisation of R&D activities
  - Distributed R&D activities with **centralised facilities**
  - Establish long-term **strategic funding programmes**
  - "**Blue-sky**" R&D
  - Attract, nurture, recognise and **sustain the careers of R&D experts**
  - **Industrial** partnerships
  - **Open Science**

- New **Detector R&D (DRD) collaborations** are now in place* to pave the way for the next decades.
  - Main goal: **instrumentation should not be limiting factor** to meet the needs of the long-term particle physics program
  - Collaborations will bring to **maturity a spectrum of techniques** where experiments will follow-up to their own needs

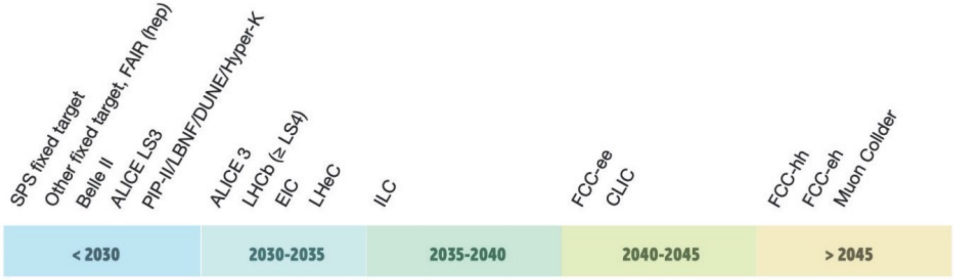
Roadmap implementation plan: Strategic vs Blue-Sky

- Strategic R&D bridges the gap between the **idea** (so-called **Blue Sky**, TRL 1-3) and the deployment and use in a HEP experiments (TRL 8-9)
  - **Detector R&D Collaboration should address Strategic R&D (TRL 3-6),** before experiment-specific engineering takes over.
  - Covers the development and maturing of technologies, e.g.
    - Improving radiation hardness
    - Speeding up readout
    - Simplification of designs
    - Iterating different options
  - Backed up by **strategic funding**, agreed with funding agencies (MoUs)
- DRD collaborations should also contain a small **Blue Sky** section
  - Allow new developments to emerge
  - Possibly financed by common fund + institute contributions (RD50/51 scheme)

Technology Readiness Levels (TRLs) *defined by NASA: Method for estimating the maturity of technologies*

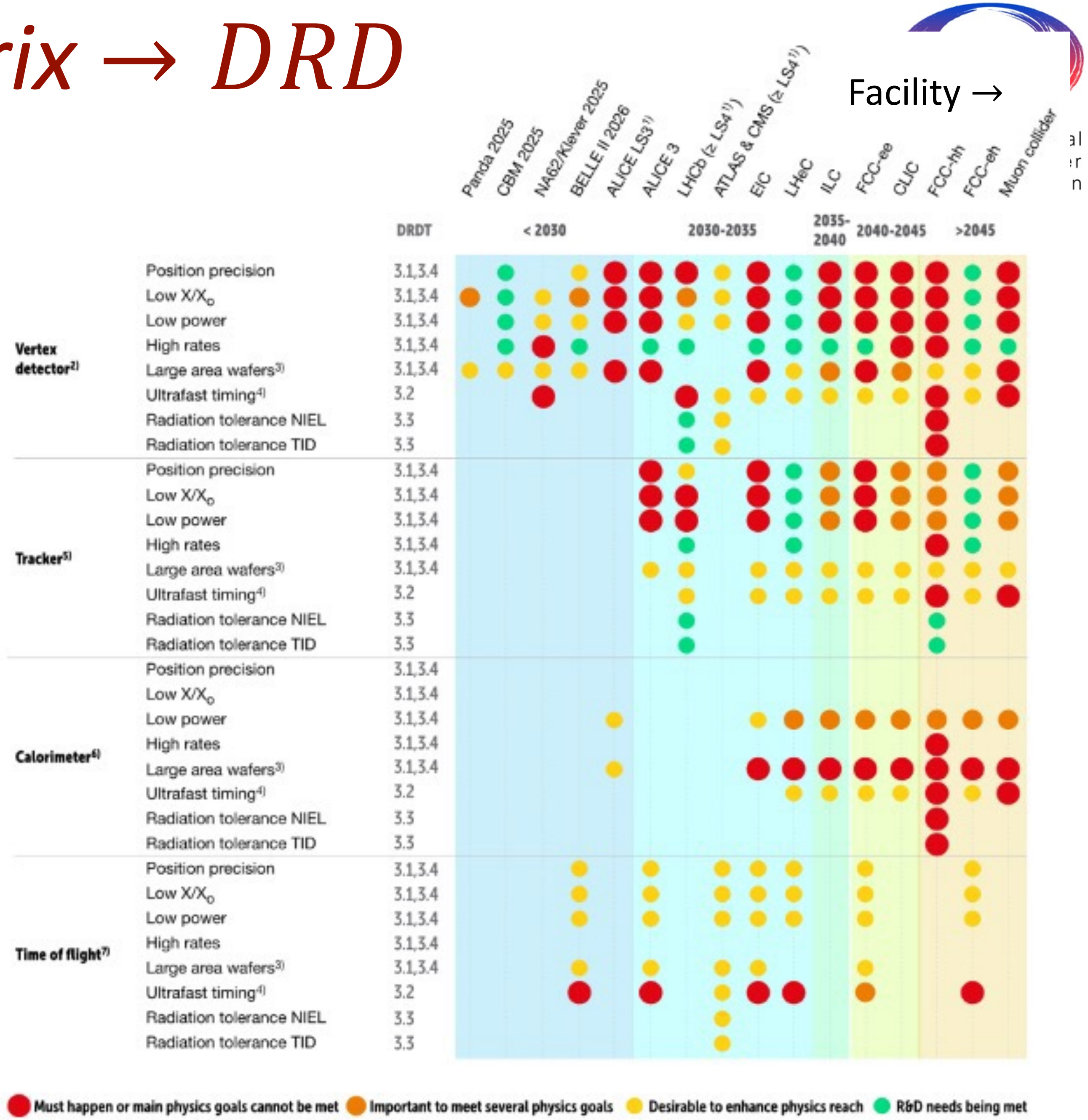


Detector Readiness matrix → DRD



Focus on the technical aspects of R&D requirements given the EPPSU list of "High-priority future initiatives" and "Other essential scientific activities for particle physics"

- Must happen or main physics goals cannot be met
- Important to meet physics goals
- Desirable to enhance physics reach
- R&D need being met

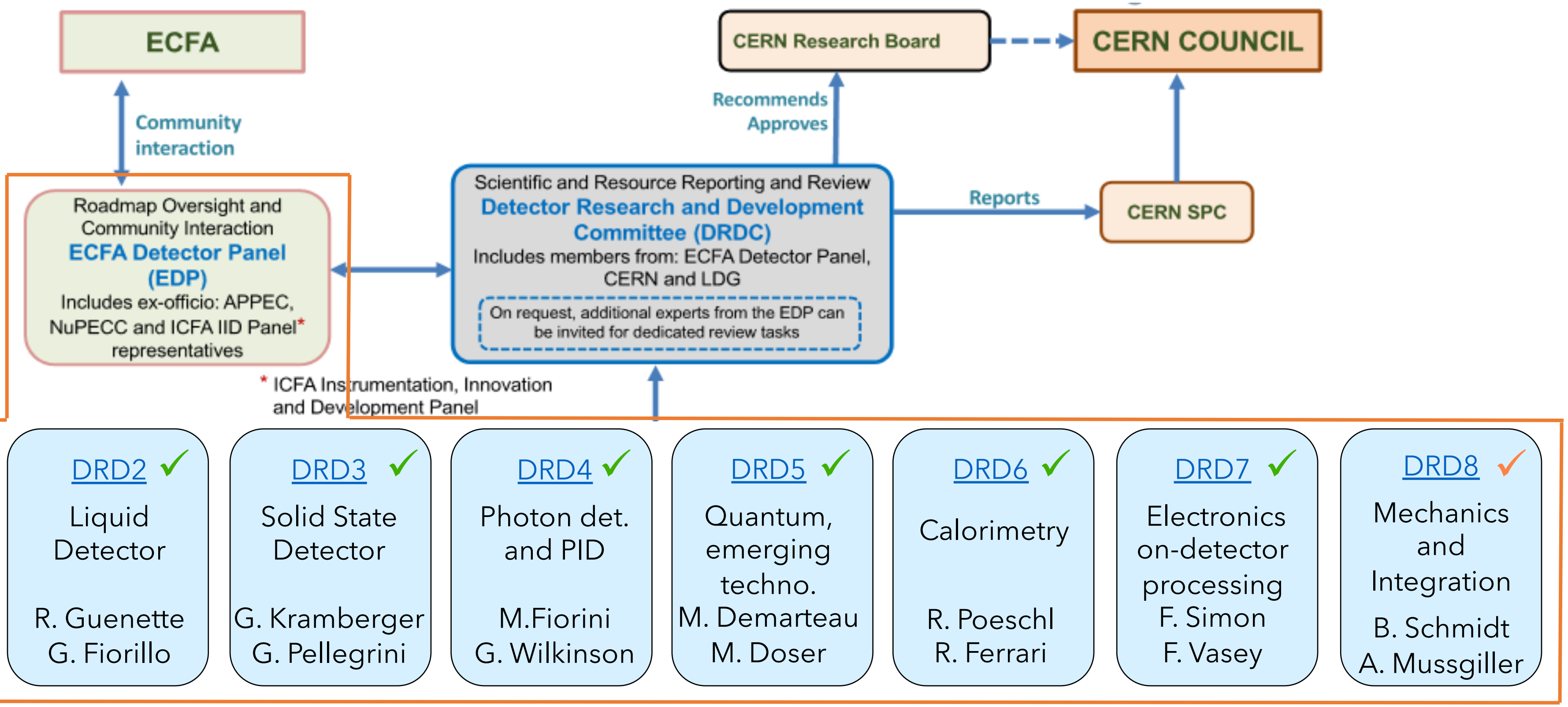


DRD collaborations hosted at CERN (framework)

follows general conditions for execution of experiments at CERN

EDP web page
- contact point for the community

EDP/DRD Managers Forum mandate
- common issues



✓ Approved by CERN RB*, ✓ DRD8 LoI submitted to DRDC, proposal aims end-2024

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DRDC wep page, presentations of DRDs at open sessions

* *approvals cover a period of three years – to be renewed*

DRD proposal content

- Scientific programme
  - breakdown in Work Packages with Deliverables due to achieve research goals Milestones
  - considering development of technologies for other DRDs and/or shared developments of similar components with different specifications or operating conditions
- Planning is focused on first R&D period of 3 - 4 years with prospect for longer term
  - stepping stone projects on the time scale of HL-LHC LS4
  - iterations toward new technologies - new materials - ultimate radiation tolerance for longer term
- Human resources and funding at the level of WPs to evaluate feasibility
  - in public document
    - list of institute wishes to contribute
    - estimate of human and funding resources required
    - sums of the available/additional expected resources
  - confidential to DRDC at the level of institutes
    - human and funding resources expected to be available/prolongated
    - new resources being requested to achieve the strategic scope

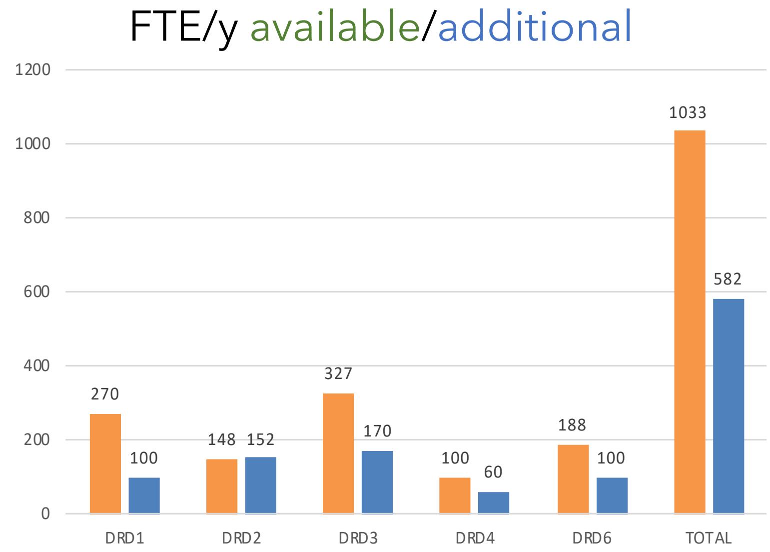
➢ Basis to establish Funding Agency commitments to WP deliverables in MoUs

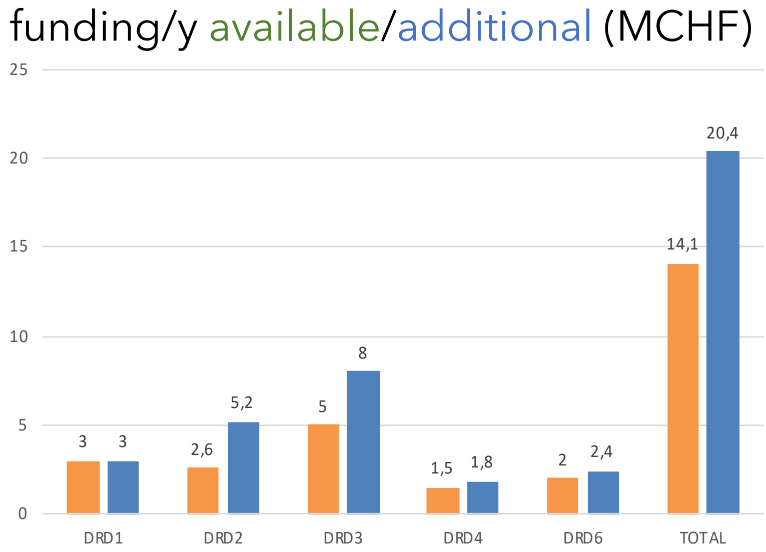
Didier Contardo @ ICFA Seminar 2023

DRD resources

- Initial estimates of resources in DRD proposals
  - based on a bottom-up approach (not commitments)
  - needs and pledges to be consolidated with MoU preparation
    - sufficient flexibility to accommodate progress & timeline evolutions & different sources and cycles of resources
- Resources appear to be on low side to fulfill entire program ≃ 2/3 & 1/2 for manpower & funding*
  - potential ramp-up, ex. expected with completion of on-going projects (HL-LHC upgrades…)
  - access to new technologies can be expensive, needing to widely gather contributions

expected FTE/y & funding/y
≃ average over 3 first years
available ≃ current situation
additional ≃ expected to fulfil progr.
break-down of FTE exists
Physicists/PhD/Technical Staff





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* *R&D programmes are running so far on presently available resources*

DRD1: Gaseous Detectors

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

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

Forum for discussion on common topics

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

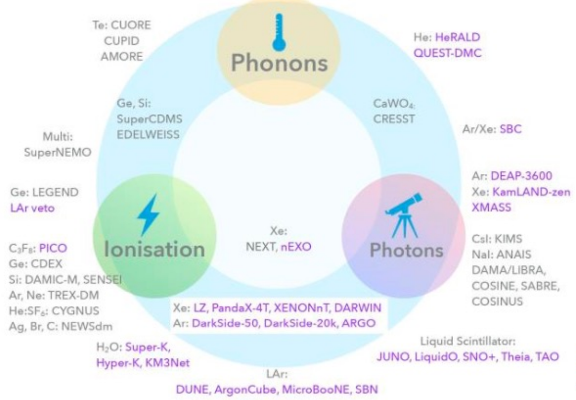
- Organized in
  - **Working Groups:** serving as the backbone of R&D
  - **Work Packages:** will reflect the DRDTs,
  - and **Common Projects** (blue sky) financed by fixed yearly fee (Common Fund)
- Large community of 170 institutes, 700 members, 33 countries
- Anticipated budget: 3 MCHF/y existing, additional 3 MCHF/y requested, 270/100 FTE
- Complete DRD1 management structure in place - CB board chair: Anna Colaleo, CB deputy: Leszek Ropelewski; Spokespersons: Eraldo Oliveri, Maxim Titov + MB + WG & WP leaders
- Collaboration website: https://drd1.web.cern.ch
- **DRD1 collaboration meetings**: Jan 29 –Feb 2, 2024 link, 2nd Collaboration Meeting June 17-21, 2024 link + regular WG meetings
- Started to work on MoU based on RD51 MoU, and started discussion with CERN
- Requested six weeks of beamtime at CERN SPS

Inés Gil Botella @ PECFA July 2024

DRD2: Liquid Detectors

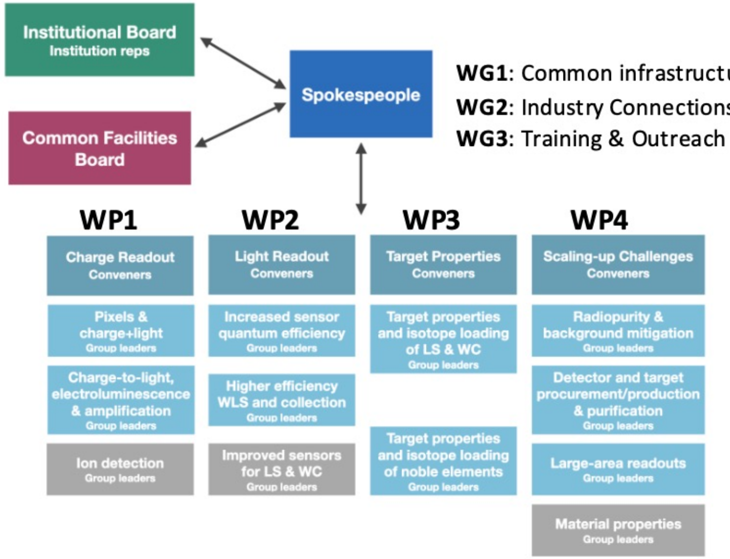
2
Liquid Detectors

- Covers **Dark Matter** and **Neutrino** experiments, accelerator and non-accelerator-based
- Several large-scale and many small-scale experiments running or foreseen with liquid detectors
- Technology: Noble Liquids (e.g. DUNE), Water Cherenkov (e.g. Super/Hyper-K) and Liquid Scintillator with light and ionization readout
- 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
- **Feb. 5-7, '24: inaugural DRD2 Collaboration Meeting at CERN** https://indico.cern.ch/event/1367848/
  - ✦ Exciting scientific programme! 156 participants, 91 contributed talks, from 71 institutes in 15 countries
  - ✦ Governance working group plan for definition of Collaboration Board (CB) and call for CB chair nominations
- CB Board chair election 1 March 2024: W. Bonivento; spokespersons election on June 2024: G. Fiorillo & R. Guenette. Election of WP/WG leaders in July.



[ECFA roadmap, Modified from L.Baudis]

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



WG1: Common infrastructures & facilities
WG2: Industry Connections & Tech Transfer
WG3: Training & Outreach

DRD3: Solid State Detectors

- DRD3 benefits from existing RD50 collaboration
  - ✦ Extended by diamonds (RD42) and 3D integration
  - ✦ Large interest in CMOS (DMAPS) sensors
- Large Collaboration: 143 institutes, 28 countries, ~900 interested people
  - ✦ ~ 70% are from Europe, 15% from North America,
  - ✦ Compare: RD50: 65 institutes and 434 members
- Budget:
  - ✦ ~5 MCHF/y (existing), ~8 MCHF/y (requested)
  - ✦ 327 FTE (existing), 170 FTE (requested)
- Collaboration website: https://drd3.web.cern.ch
- CB Board chair elected: Giulio Pellegrini (CNM Spain), deputy Roberta Arcidiacono (INFN Torino); Spokesperson elected: Gregor Kramberger (JSI Slovenia)
- Most of the WG conveners have been elected
- **1st Collaboration meeting**: 17-21 June 2024 at CERN https://indico.cern.ch/event/1402825/

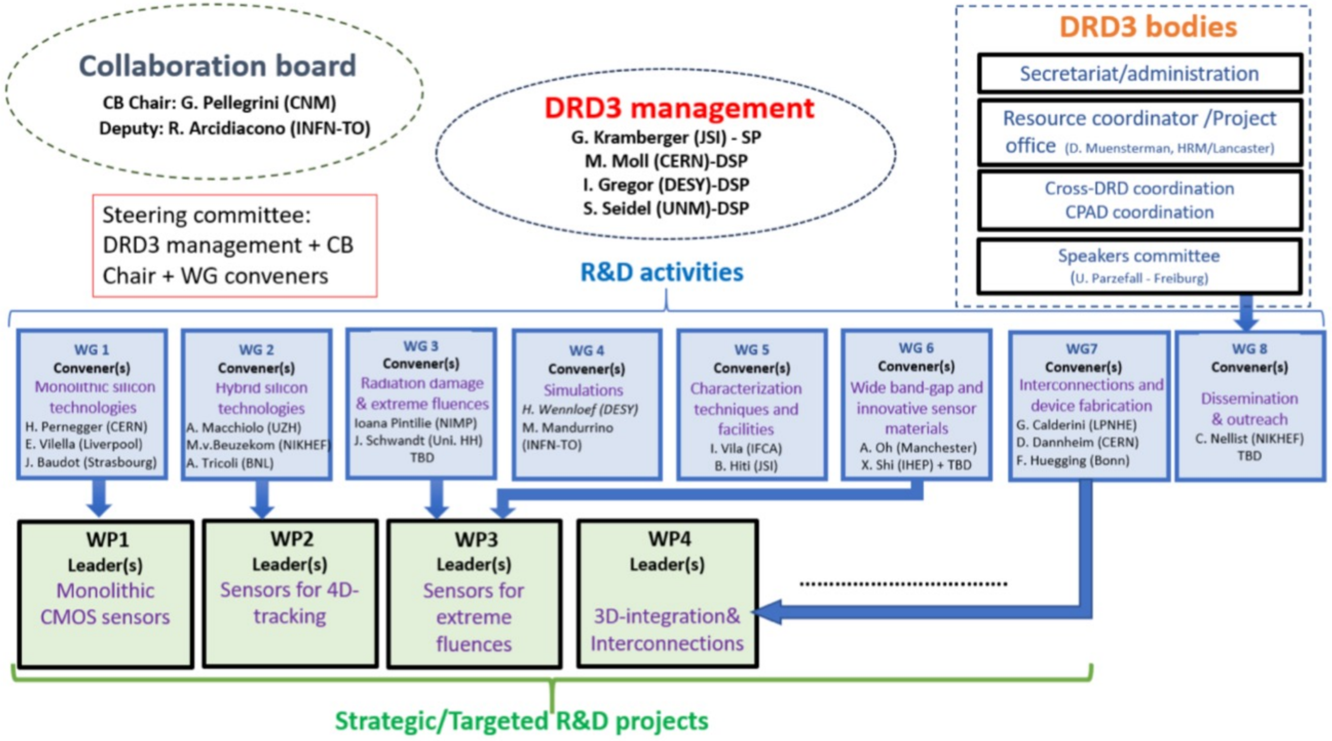
Solid state

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



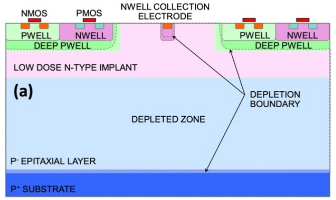
On-going R&D on tracking sensors – DRD3

International MUON Collider Collaboration

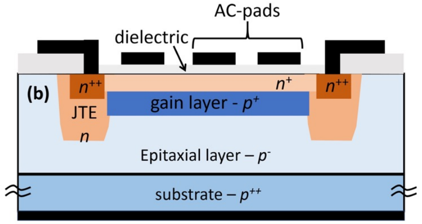
	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	$25\,\mu m \times 25\,\mu m$	$50\,\mu m \times 1\,mm$	$50\,\mu m \times 10\,mm$
Sensor Thickness	$50\,\mu m$	$100\,\mu m$	$100\,\mu m$
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	$5\,\mu m \times 5\,\mu m$	$7\,\mu m \times 90\,\mu m$	$7\,\mu m \times 90\,\mu m$

Sinergy with timing sensors development for HL-LHC

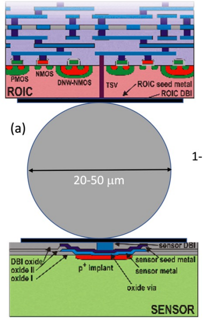
Promising technologies



Monolithic devices (CMOS):
Good timing and spacial resolution, but radiation hardness to be improved



Low Gain Avalanche Detectors (LGAD):
Large and fast signal (20-30 ps resolution), moderate radiation hardness



Hybrid small pixel devices:
No gain but fast timing (20-30 ps resolution) and good position resolution. Intrinsically radiation hard

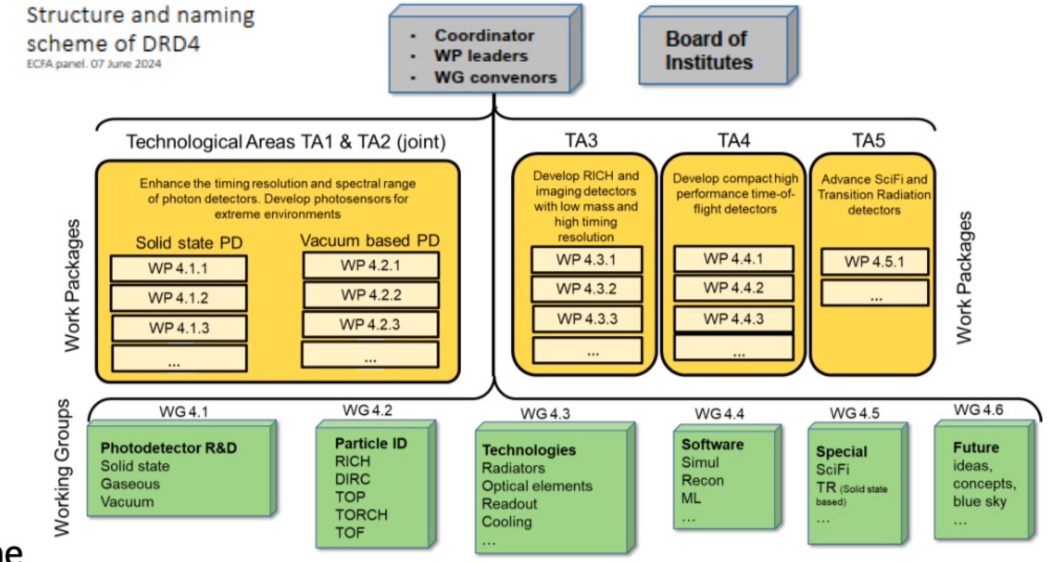
Silicon LGAD sensors for 4D tracking up to very high fluence:

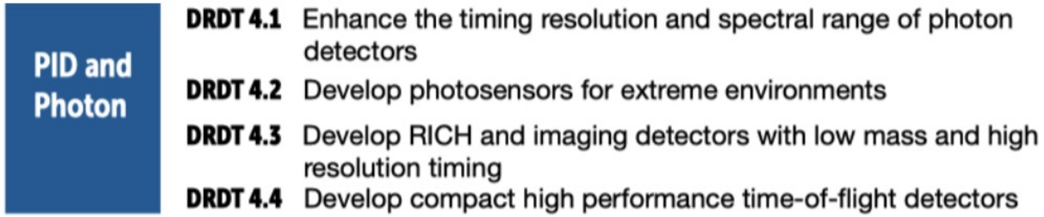
V. Sola et al., Nucl. Instrum. Meth. A 1040 (2022) 167232.

Project funded also by an EU ERC Consolidator Grant

DRD4: Photon Detectors & Particle ID

- Developments on PMTs, MCP-PMTs, SiPMs, APD, HPD, quantum devices, SciFi
  - ✦ Challenges for example for SiPMs: rad hard, dark rate, timing
- Applications in Ring Imaging Cherenkov Detectors (RICH), Time-of-Flight (ToF), TRD
- Connection to almost every other DRD collab. (gas, Silicon, Calo, electronics, SiPM at cryogenic temp.)
- Collaboration: 74 institutes from 19 countries, 7 (semi-) industrial partners
- Collaboration website: https://drd4.web.cern.ch
- **DRD4 constitutional meeting** happened at CERN (23-24 January 2024): https://indico.cern.ch/event/1349233/; 2nd collaboration meeting on 17-20 June 2024 at CERN: https://indico.cern.ch/event/1403486/
  - ✦ CB board chair: Guy Wilkinson
  - ✦ Spokesperson: Massimiliano Fiorini
  - ✦ WP/WG chairs elected





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

DRD5: Quantum Sensors

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

- Quantum Technologies are a rapidly emerging area of technology development to study fundamental physics
  - ✦ development of HEP detectors on the long term
- Full proposal developed in the last year
  - ✦ Effort driven by Michael Doser (CERN) and Marcel Demarteau (Oak Ridge)
  - ✦ Two community workshops [link]
- Re-structured the Roadmap topics into WPs
  - ✦ Many reports and documents as deliverables, but this is in the nature of this proposal (early TRL)
- Draft proposal was submitted to DRDC end of February 2024 and sent to interested institutions; 96 groups, 344 participants
  - ✦ **Approved in June 2024**

Roadmap topics

Proposal WP's

Sensor family → Work Package ↓	clocks & clock networks	superconducting & spin-based sensors	kinetic detectors	atoms / ions / molecules & atom interferometry	opto-mechanical sensors	nano-engineered / low-dimensional / materials
WP1 *Atomic, Nuclear and Molecular Systems in traps & beams*	X			X	(X)	
WP2 *Quantum Materials (0-, 1-, 2-D)*		(X)	(X)		X	X
WP3 *Quantum superconducting devices*		X				(X)
WP4 *Scaled-up massive ensembles* (spin-sensitive devices, hybrid devices, mechanical sensors)		X	(X)	X	(X)	X
WP5 *Quantum Techniques for Sensing*	X	X	X	X	X	
WP6 *Capacity expansion*	X	X	X	X	X	X

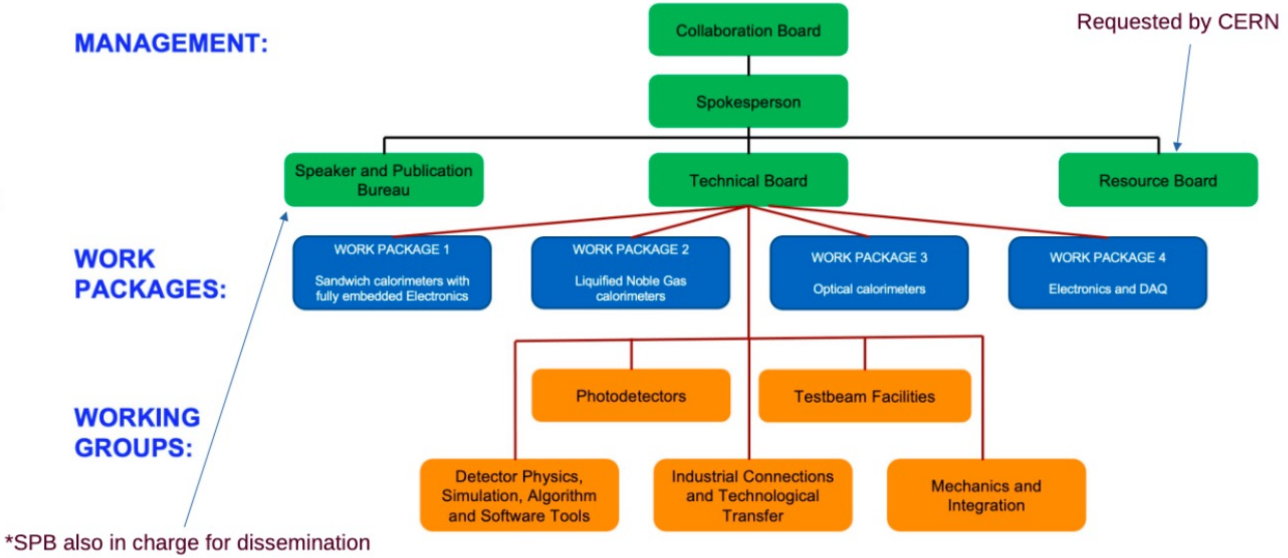
WP-2 (0-,1- and 2-D materials)

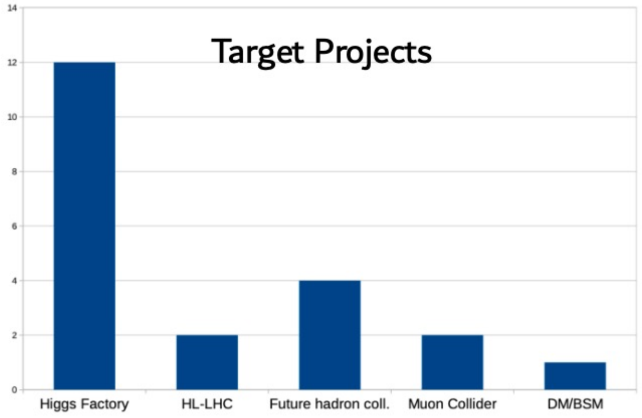
WP-2a → characterization protocol → database definition → populated db
(application-specific tailoring) *protocol* *Database prototype* *Functional database*
WP-2ab → workshop/conference → device designs → novel hybrid devices
(extended functionalities) *Device concepts* *Prototype devices* *Functional devices*
WP-2c → status & desiderata → prototype model → benchmarked simulations
(simulations) *Report* *Simulation SW designs* *Validation report*

DRD6: Calorimetry

- Collaboration emerged from several collaborations like CALICE and CrystalClear (RD18)
- 131 institutions; CB chair: Roberto Ferrari; Spokesperson: Roman Poeschl
- Targets: high granularity, timing resolution, hadronic energy resolution
- 1st Community Meeting 12/1/23 https://indico.cern.ch/event/1212696/
- Input proposals collected until 1st of April 2023
- 2nd Community Meeting 20th April 2023 https://indico.cern.ch/event/1246381/
- Input proposals have been condensed into a DRD final version proposal, submitted to DRDC on November 15th
- DRD-on-Calorimetry approved by CERN Research Board on December 6th to start on January 1st 2024
- **DRD6 Collaboration Meeting at CERN** (9-11 April 2024)
  - ✦ https://indico.cern.ch/event/1368231/

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





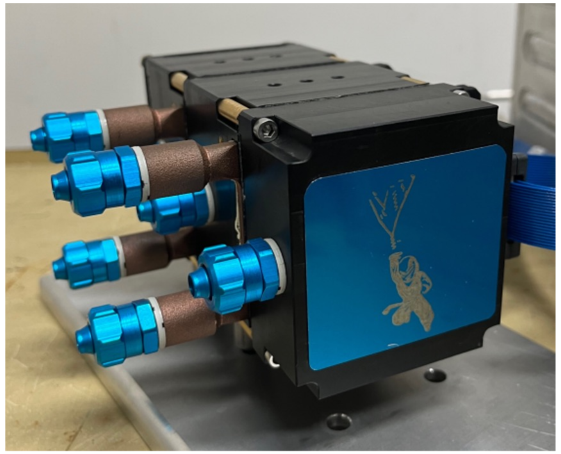
On-going R&D in e.m. calorimeters – DRD6

Crilin – CRystal calorImeter with Longitudinal InformatioN –

Crilin, *JINST* **17** P09033

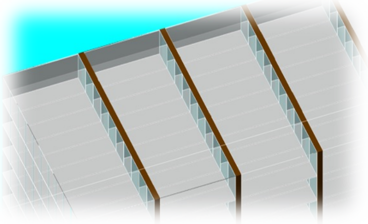
semi-homogeneous electromagnetic calorimeter based on **Lead Fluoride Crystals** (PbF_2) matrices where each crystal is readout by 2 series of 2 UV-extended surface mount **SiPMs**

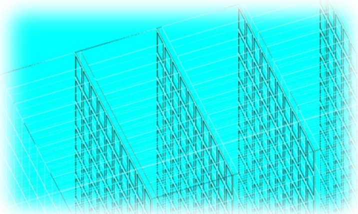
High-density crystal:
need for increased layer numbers with space constraints
Speed response:
Cherenkov crystals, ensuring accurate and timely particle detection
Semi-homogeneous:
strategically between homogeneous and sampling calorimeters
→ able to exploit the strengths of both kinds
Flexibility:
able to modulate energy deposition for each cell and adjust crystal size
Compactness:
Unlike segmented or high granularity calorimeters it can optimize energy detection while staying compact



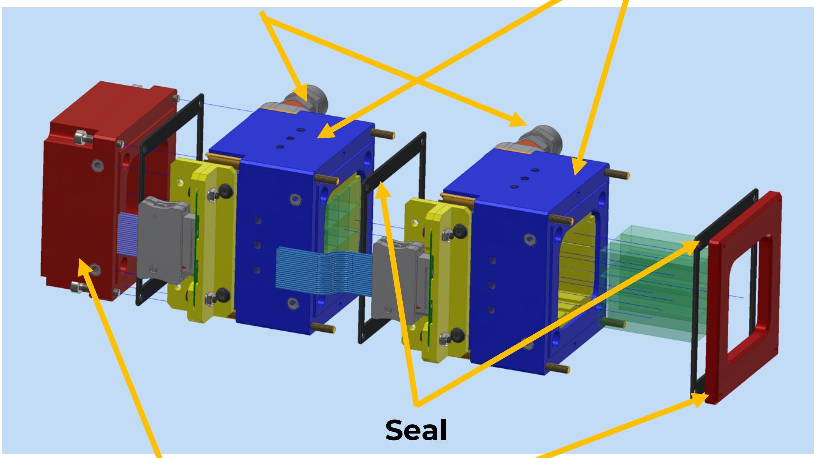
2-layer 3x3-crystal Crilin prototype

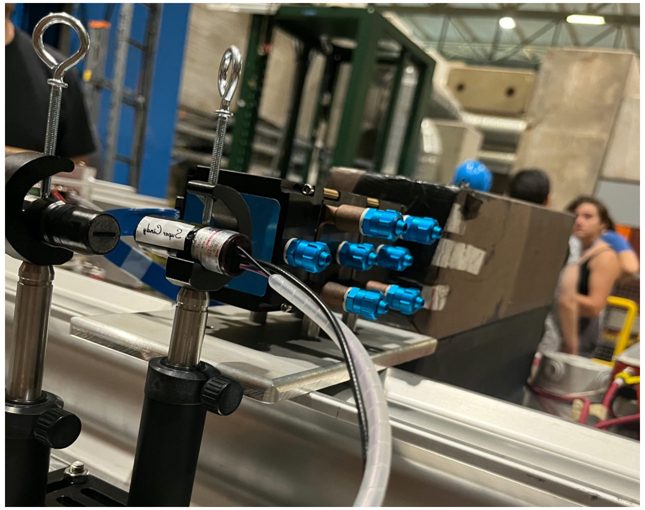
total ionising dose: ~1 kGy/year (100 krad)
total neutron fluence: $10^{14}\ n_{1MeVeq}/cm^2$ / year





Results from a 3 layers prototype of test beams





Crystal	PbF_2	PWO-UF
Density [g/cm^3]	7.77	8.27
Radiation length [cm]	0.93	0.89
Molière radius [cm]	2.2	2.0
Decay constant [ns]	-	0.64
Refractive index at 450 nm	1.8	2.2
Manufacturer	SICCAS	Crytur

For the expected radiation level **the choice for SiPMs was 10 µm Hamamatsu SMD** for minor dark current contribution

- **Time resolution**: < 40 ps for single crystals, for E_{dep} > 1 GeV
- **Radiation resistance:**
  PbF_2(PWO-UF) robust to > 35(200) Mrad
  SiPMs validated up to 10^{14} n_{1MeV}/cm^2 displacement-damage eq. fluence

IRRADIATION STUDIES

- **PbF_2:**
  - **after a TID > 350 kGy no significant decrease** in transmittance observed
  - Transmittance after neutron irradiation showed no deterioration
- **$PbWO_4$-UF:** for first layer
  - **after a TID > 2 MGy no significant decrease** in transmittance observed

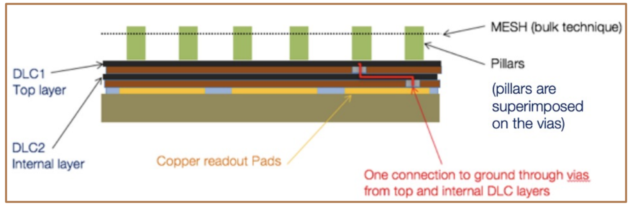
On-going R&D in hadronic calorimeters – DRD6

[MPGD-based hadronic calorimeter, Nucl. Instrum.Meth. A 1047 (2023) 167731](#)

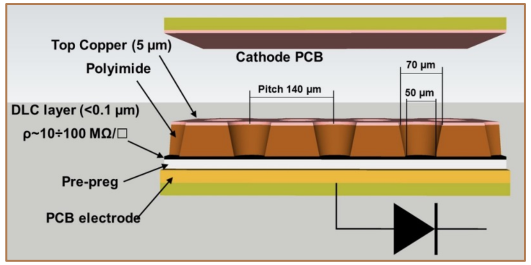
MPGD-HCAL

based on **resistive Micro-Pattern Gaseous Detectors**
as **readout layers for a sampling hadronic calorimeter**

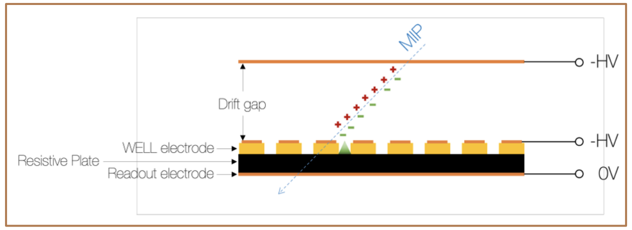
Micromegas (MM)



µRWELL



RPWELL



MPGD features:

- **cost-effectiveness** for large area instrumentation
- radiation hardness up to several **C/cm²**
- **discharge rate** not impeding operations
- rate capability O (**MHz/cm²**)
- high granularity
- time resolution of **few ns**

> one of the goals of such R&D is to choose the best technology for calorimetry @ Muon Collider

Past work:

- **CALICE collaboration**: a sampling calorimeter using **gaseous detectors** (RPC) but also tested MicroMegas
- **SCREAM collaboration**: a sampling calorimeter combining RPWELL and resistive MicroMegas

R&D plan → systematically **compare** three MPGD technologies for hadronic calorimetry: resistive MicroMegas, µRWELL and RPWELL, while also investigating **timing**

DRD7: Electronics

DRD7 workshop 9-10 September 2024 at CERN
https://indico.cern.ch/event/1436991/overview

- Full proposal received by 29 February 2024; **approved in June 2024**
- Objectives: Carry out strategic R&D in electronics, fulfilling DRDTs, Coordinate cross-European access to technologies, tools and knowledge, Interface with other DRDs (No orthogonal “Service-Provider” for other DRDs)
- Organization: 19 countries, 68 institutes
  - ✦ Somehow CERN-centric at present, e.g. 9/19 WG conveners
  - ✦ 1st workshop happened in March, 2nd workshop 25-27 Sept 2023, 1st collaboration meeting planned 9-10 Sept 2024

Electronics

DRDT 7.1 Advance technologies to deal with greatly increased data density

DRDT 7.2 Develop technologies for increased intelligence on the detector

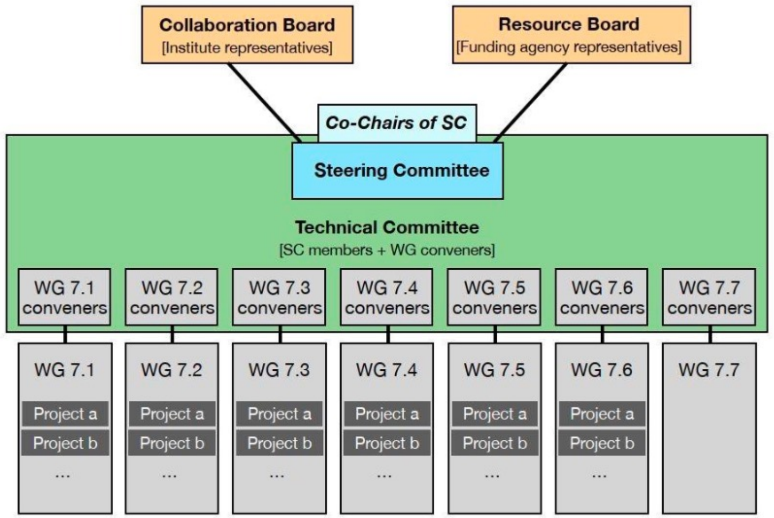
DRDT 7.3 Develop technologies in support of 4D- and 5D-techniques

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

WG 7.6 Complex imaging ASICs and technologies

WG 7.7. Transversal Tools and Technologies



Nomenclature to be adapted

DRD8: Integration

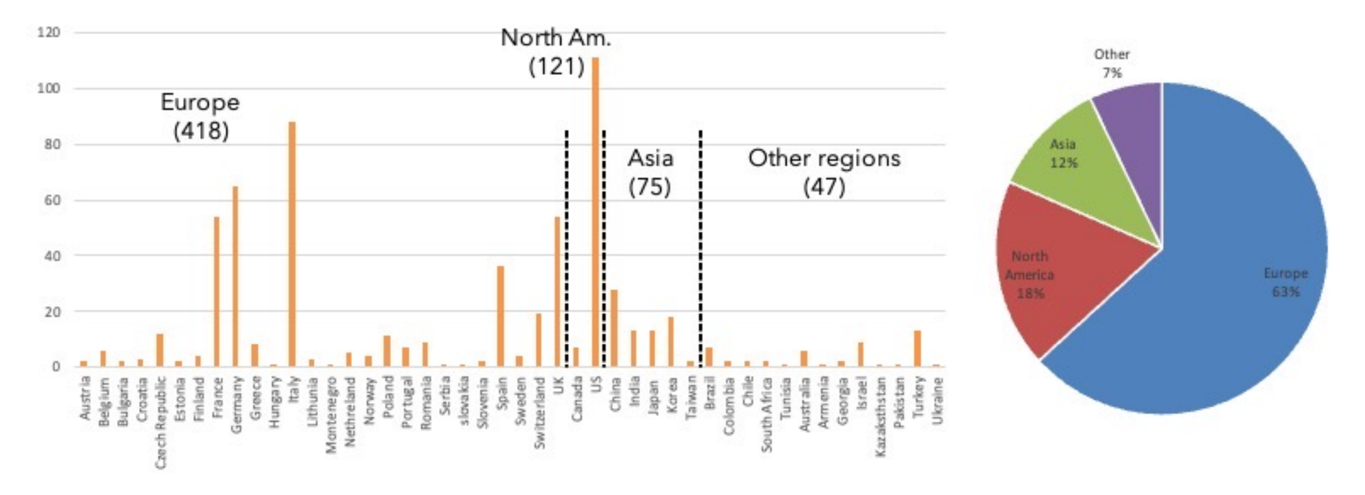
- Initial TF convenors did not continue as proposal preparation team
- New proponents had to be searched for, which were found by the group around the "Forum on Tracker Mechanics" workshop organizers
  - Burkhard Schmidt (CERN) and Andreas Mussgiller (DESY)
- Community survey replied that there is an interest in going forward
- Community Meeting on December 6, 2023
- LoI received by end of February 2024 with the aim to write a full proposal by the end of this year
  - LoI does not cover all DRDTs, as they are quite diverse
  - Focus on vertex detector mechanics and cooling
  - 22 institutes in 7 countries, 32 FTEs at the moment

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

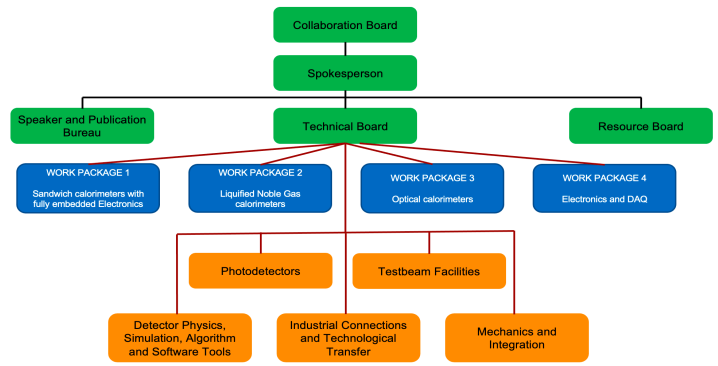
DRD collaboration facts

- Preamble referring to the ECFA Detector R&D Roadmap
- DRD collaboration implementation
  - referring to CERN hosting framework
  - work organisation to fulfil the ECFA detector roadmap DRDTs
  - community building
    - establishing areas of collaborative effort / common projects
  - balance achieved in community aspirations and R&D roadmap priorities
  - outreach, training and early career efforts

} still an ongoing process, also in preparation of MoUs



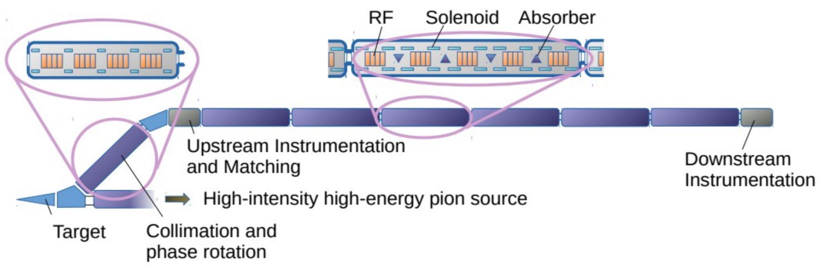
661 institute contributions in 46 countries
summed over DRD1, DRD2, DRD3, DRD4, DRD6 and DRD7



- management bodies
- Work Packages – contain "deliverables"
- Working Groups - transverse activity forums

typical organisation, ex. DRD6

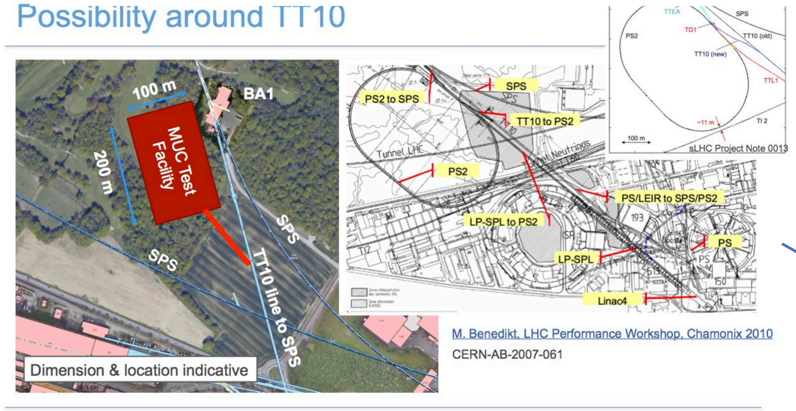
Demonstrator Facility: a crucial step forward!



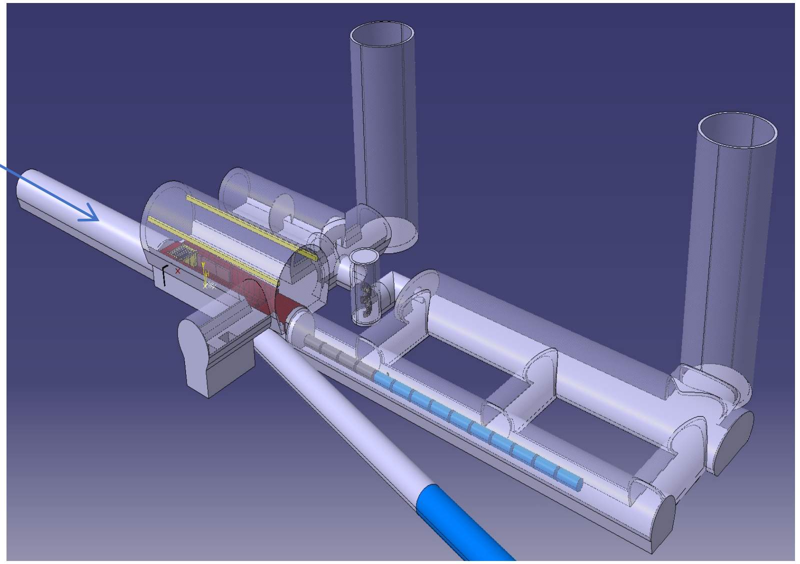
Planning **demonstrator** facility with muon production target and cooling stations

Suitable **site exists** on CERN land and can use **PS proton beam**

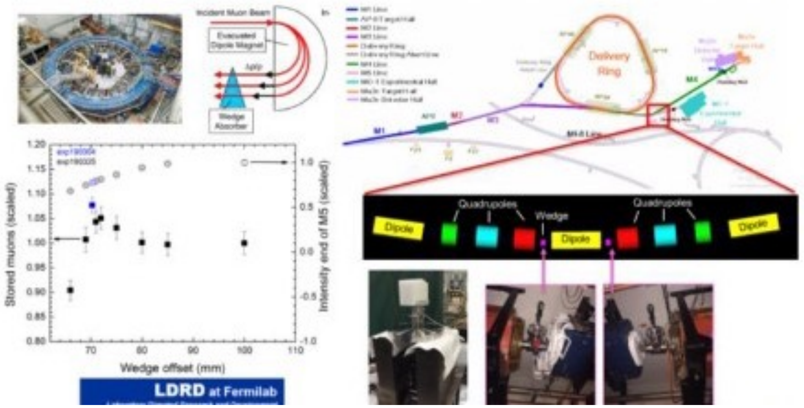
- could combine with **NuStorm** or other option



@ CERN



@ FNAL

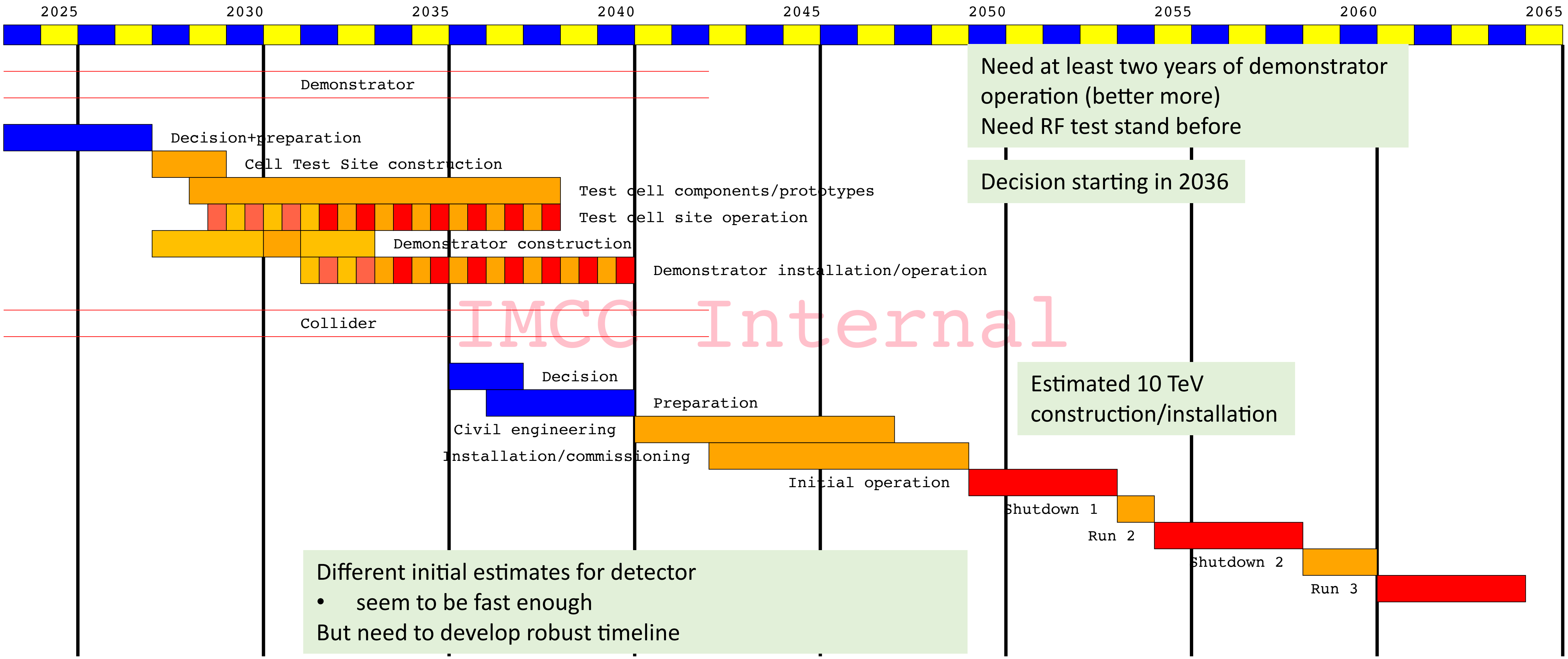


[International Muon Collider Collaboration: Demonstrator Workshop](#)

@ FNAL October 30 – November 1, 2024

Tentative Timeline (Fast-track 10 TeV)

Basis to start the discussion, will be reviewed this year



Need at least two years of demonstrator operation (better more)
Need RF test stand before

Decision starting in 2036

Estimated 10 TeV construction/installation

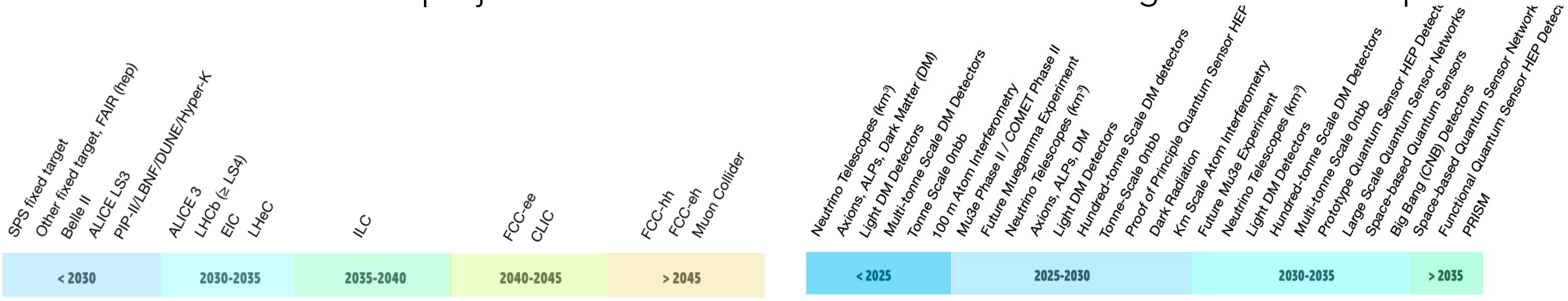
Different initial estimates for detector
- seem to be fast enough

But need to develop robust timeline

HEP projects for Detector Research & Development

upgrades and future large accelerators projects

small accelerators, nuclear reactors, cosmic rays second and third generation of experiments



DRD1 gaseous | DRD3 solid state | DRD4 photon & PID | DRD6 calorimeter | DRD2 liquid | DRD5 quantum & emerging techno.

DRD7 electronics and on-detector processing - DRD8 integration (?) - Training Panel

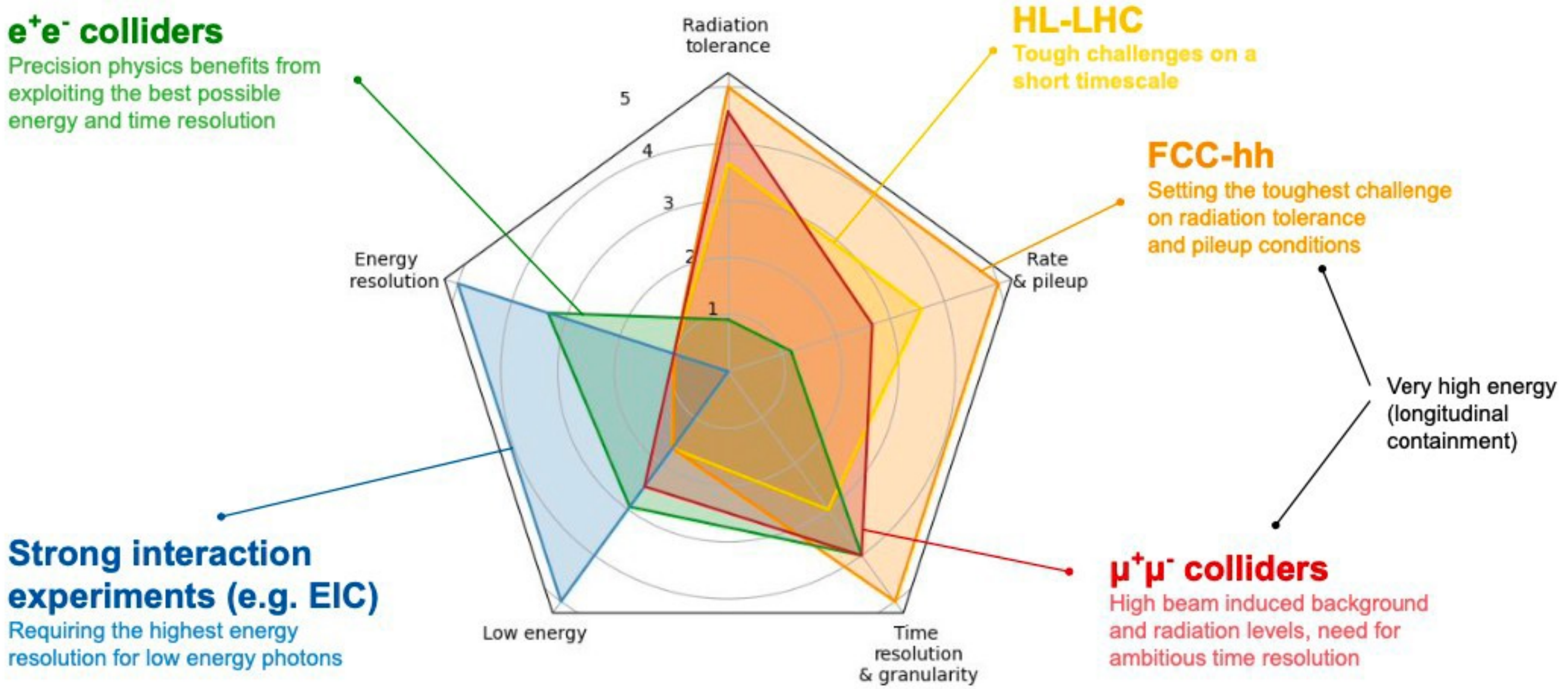
Strategic DRD programmes cover evolving TRLs* between 3 to 6

Didier Contardo @ ICFA Seminar 2023

* *Technology Readiness Level defined by NASA, low TRL < 3 also often referred as "blue sky" , TRL > 6 are experiment specific engineering*

*** Planning of projects is for physics start at the time of the roadmap, end of strategic R&D must consider project engin., constr. and instal. time*

Crucial synergies



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

Final remarks and next steps

- A key message ALWAYS is to **sustain the careers of R&D experts:**
  "Attract, nurture, recognise and sustain the careers of R&D experts"

No instrumentation → no "Physics" reach

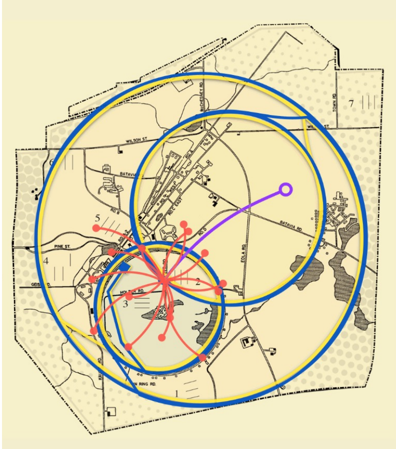
- To get people engaged, in particular the Early career scientists, it is important also to get **intermediate experimental setups/goals and synergies** where the new technologies in their infant status may be tested

➔ Muon Collider Demonstrator with physics cases

- **ECFA Detector Panel is planning to prepare an input document to be submitted end of March 2025**
  ➔ IMPORTANT to be on board as Muon Collider (material and draft input by end-2024)
  ➔ prepare incremental update of the ECFA Detector R&D Roadmap as needed (by ESPPU conclusion)

- The Update to the European Strategy for Particle Physics is the opportunity to revise previous work and launch collaborations on new studies

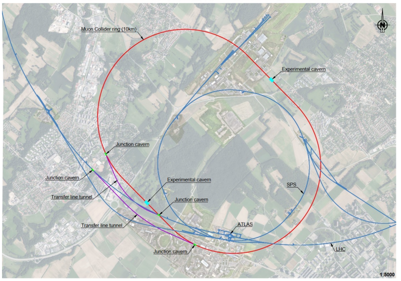
We have a great future ahead where we can exploit expertise from on-going project, new collaboration for near/mid-term R&Ds and ingenuity for future ideas!



Thanks to many teachers

detector & accelerator physicists, technicians and engineers, students

old and new friends

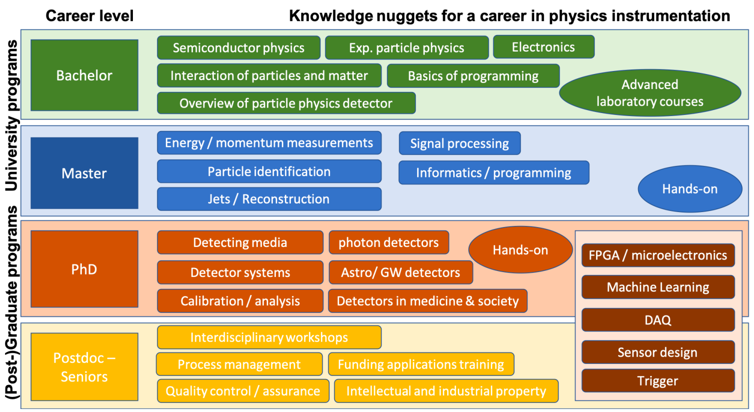


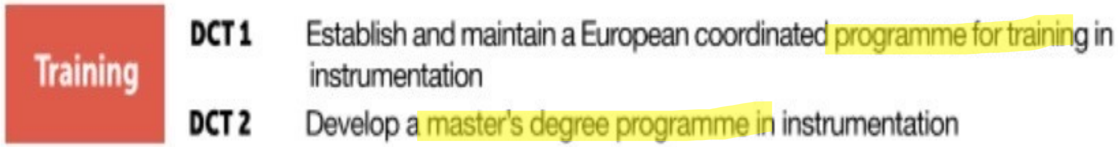
Thanks to you all for the attention

aiming for new collaboration ahead

and questions

Training





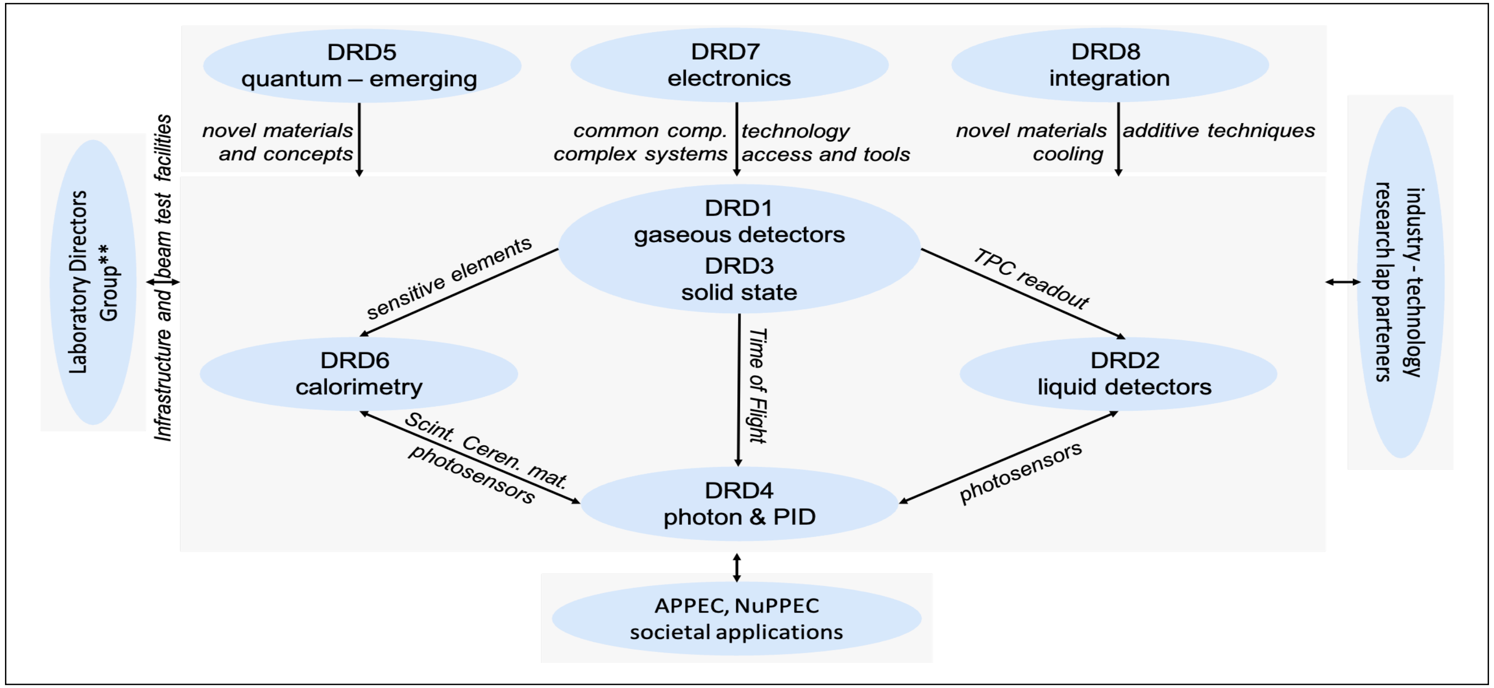
- One of the Recommendation of the detector R&D roadmap stresses the need to **train and maintain a work force** in instrumentation for Particle Physics, targeting primarily graduate students and Early Career Researchers (ECR).
  - Increase **participation of young scientists** in leading-edge instrumentation R&D
  - **foster growth of** future HEP instrumentation **experts** who can compete for permanent positions, **mandatory to the success** as well as the long-term health **of experimental particle physics as a whole**.

- **ECFA training panel** (link) has been setup (chairs: E. Garutti and J. Collot) with Goals:
  - Enhance the **synergies** between existing training programmes
  - creation of a **European master's degree program in HEP instrumentation**

From Didier Contardo @ PECFA July 2024

DRD interfacial areas

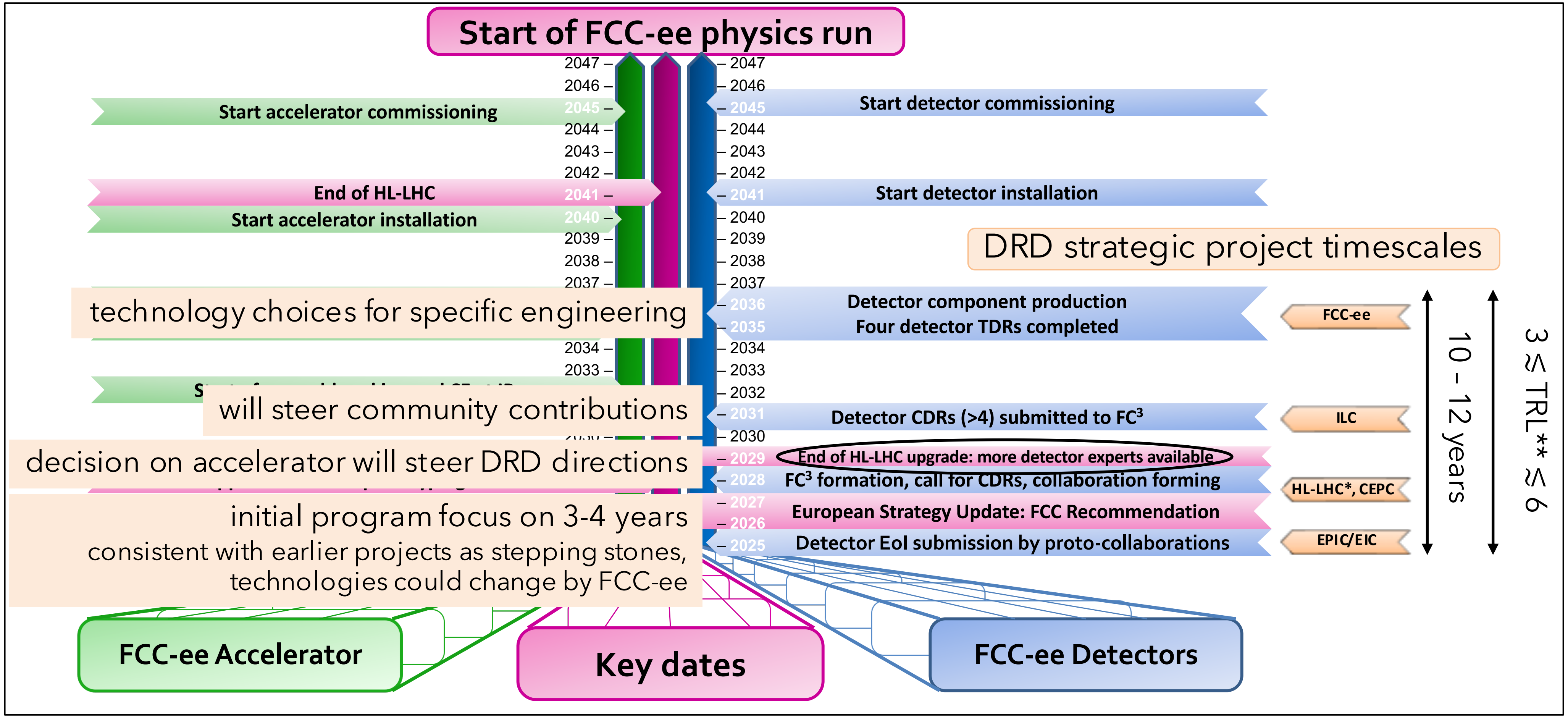
- Cross-DRD aeras (when DRDx can benefit from DRDy progress)
  - typical ex. 1 implementing new sensitive components provided by other DRDs in DRD6
  - typical ex. 2 implementing new electronics components provided DRD7 in any other DRDs
- Interface to other national or international programs (ex. US CPAD, AIDAInnova…)
- Relation and collaboration with industrial or academic partners & technology access
- Relation and collaboration with other scientific disciplines
- Availability of infrastructure for characterisation - in conjunction with LDG*
- ➢ Mechanisms to ensure coherence and synchronization of the above aspects



* CEA/IRFU-France, CERN-EU, CIEMAT-Spain, DESY-Germany, IJCLab-France, LNF-Italy, LNGS-Italy, Nikhef-Netherlands, PSI-Switzerland, STFC/Daresbury-UK, STFC/RAL-UK

Topics towards the EDP input content : DRD programme deployment

- Scientific outcome expected in the 1st phase of the R&D programs (3-4 years)
  - evaluation of technology areas performance potential
  - technical solution for medium term strategic projects; consider transitions to specific engineering (TRL ≳ 6)
- Preparation of 2nd R&D phase
  - ex. longer term collider term FCC-ee project; consider opportunities for new technology (TRL ≲ 3)

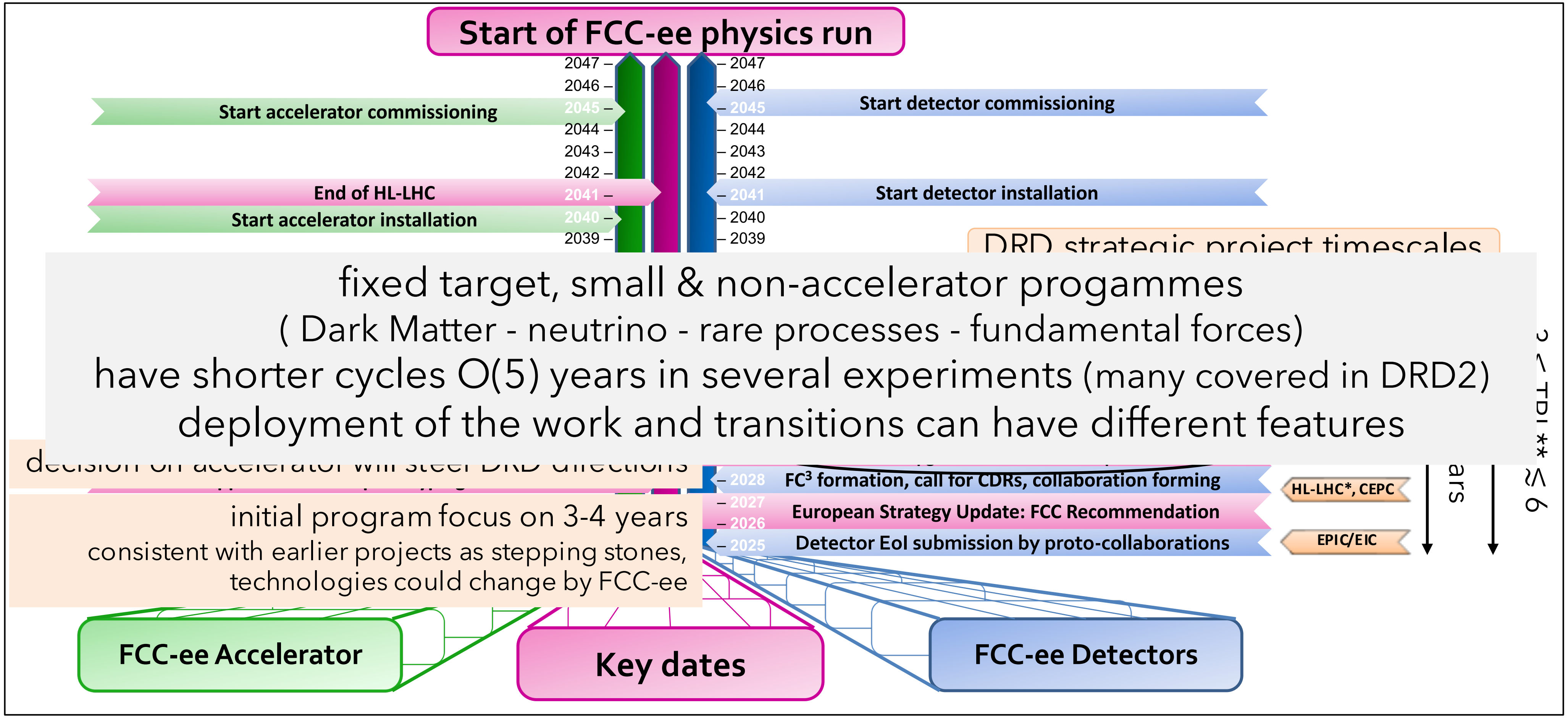


Transverse Areas DRD5, DRD7, (DRD8) also cover lower TRLs

** "blue sky" TRL ≲ 3 and speific experiment engineering TRL ≳ 6 at boundaries of DRD coverages

Topics towards the EDP input content : DRD programme deployment

- Scientific outcome expected in the 1st phase of the R&D programs (3-4 years)
  - evaluation of technology areas performance potential
  - technical solution for medium term strategic projects; consider transitions to specific engineering (TRL ≳ 6)
- Preparation of 2nd R&D phase
  - ex. longer term collider term FCC-ee project, consider opportunities for new technology (TRL ≲ 3)



fixed target, small & non-accelerator progammes
(Dark Matter - neutrino - rare processes - fundamental forces)
have shorter cycles O(5) years in several experiments (many covered in DRD2)
deployment of the work and transitions can have different features

Transverse Areas DRD5, DRD7, (DRD8) also cover lower TRLs

** "blue sky" TRL ≲ 3 and speific experiment engineering TRL ≳ 6 at boundaries of DRD coverages

ECFA Detector Panel

- represents the community in the CERN DRD collaboration framework
- help organise discussion of the common issues* through EDP - DRD Collaborations Managers Forum (mandate)
- advise DRDC on priorities wrt the Detector R&D roadmap
- helps plan future updates to the Detector R&D roadmap

New membership approved at this meeting
Felix Sefkow (DESY) replace Phil Allport as EDP co-chair
Jens Dopke (RAL) joining as mechanics & integration expert…
and as EDP secretary
Susanne Kuehn (CERN) replacing Doris Eckstein as SSD expert

Co-Chairs: Didier Contardo (IP2I Lyon) and Felix Sefkow (DESY) Scientific Secretary: Jens Dopke (RAL)

- Gaseous Detectors: Silvia Dalla Torre (Trieste)
- Liquid Detectors: Inés Gil Botella (CIEMAT, Madrid)
- Solid State Detectors: Susanne Kuehn (CERN)
- PID & Photon Detectors: Roger Forty (CERN)
- Quantum and em Tech: Steven Hoekstra (Groningen)
- Calorimetry: Laurent Serin (IJCLab)
- Electronics: Valerio Re (Bergamo)
- Mechanics & integration (DRD8) Jens Dopke (RAL)

Ex Officio:

- Thomas Bergauer (DRDC)
- Paris Sphicas (ECFA Chair)
- Ian Shipsey (ICFA Detector Panel)

Observer:

- Aldo Ianni (APPEC, LNGS),
- Eugenio Nappi (NuPECC, Bari)

also members of DRDC

web page

Didier Contardo @ PECFA July 2024

* *ex. cross-DRD areas, interfaces to: other R&D programs; ApPEC and NuPEC ; projects concept groups (of strategic physics programmes identified by ESPP)…*

European Strategy on Particle Physics

http://europeanstrategy.cern

International MUON Collider Collaboration

- Strategy first defined in 2006
- **Update in 2013** to launch the HL-LHC decision
- **Update in 2020** to envisage post-HL-LHC times:
  - *Europe, together with its international partners, should investigate the technical and financial feasibility of **a future hadron collider at CERN** with a centre-of-mass energy of at least **100 TeV** and with an **electron-positron Higgs** and electroweak **factory** as a possible **first stage**.*
  - *The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A **roadmap should prioritise the technology**, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. **Deliverables for this decade should be defined** in a timely fashion and coordinated among CERN and national laboratories and institutes.*
  - ***Successful completion of High-Luminosity LHC must remain key focus***

http://dx.doi.org/10.17181/CERN.JSC6.W89E