


ÖAW


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The European Strategy Update and the DRD Collaborations

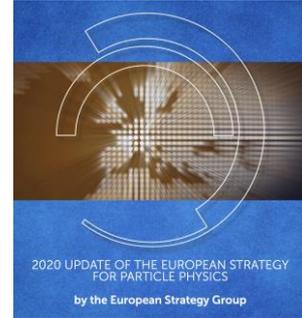
CPAD 2025 Workshop (Oct 7, 2025)

Thomas Bergauer

DRDC chair, PPG member of European Strategy

European Strategy on Particle Physics

<http://europeanstrategy.cern> and <https://europeanstrategyupdate.web.cern.ch>



Continuous process driven by the community:

- First defined **2006**
- **Update 2013** brought us HL-LHC decision
- **Update 2020** brought us decisions for post-HL-LHC times (future Higgs factory, followed by 100TeV hadron machine) and *ECFA Detector Roadmap*
- **Update 2026** on the horizon with process currently ongoing, approval by CERN Council in spring 2026

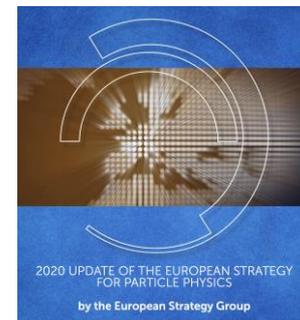
Strategy Update 2020

- *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**.*
- ***Detector R&D programmes** and associated infrastructures should be supported at CERN, national institutes, laboratories and universities. **Synergies** between the needs of different scientific fields and **industry should be identified** and exploited to boost efficiency in the development process and increase opportunities for more **technology transfer benefiting society** at large. [... **The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels.***
→ Brought us the ECFA Detector Roadmap (see later)
- Successful completion of High-Luminosity LHC must remain key focus

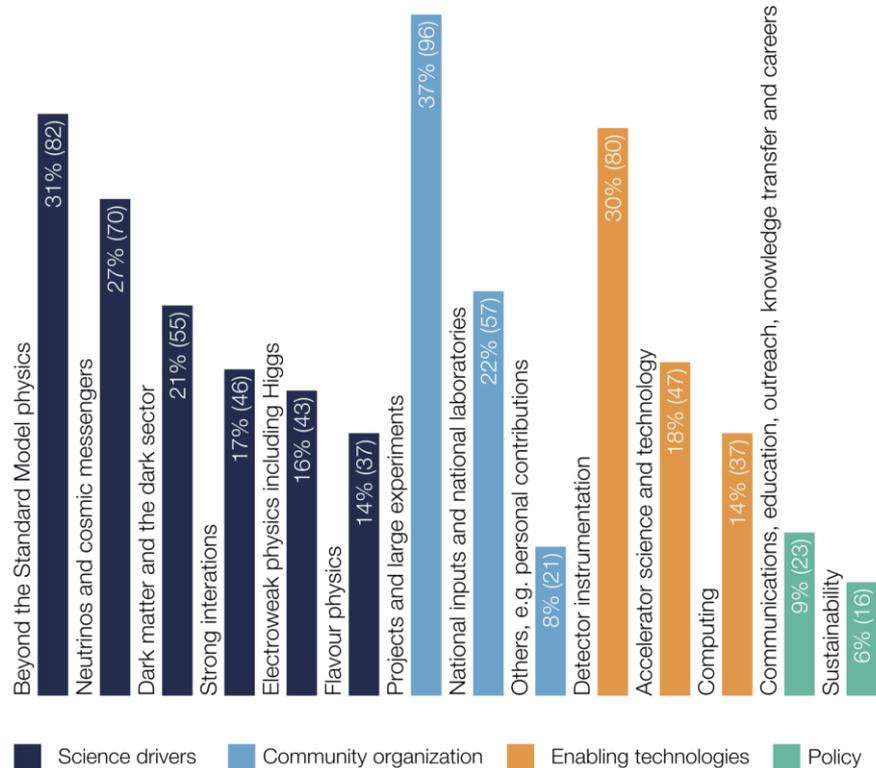
Strategy Update 2026

<http://europeanstrategy.cern> and <https://europeanstrategyupdate.web.cern.ch>

263 input proposals



Input Proposals submitted by spring



Full text of all input proposals at [this link](#) or use [Input Explorer](#), an AI-enhanced search tool

- **National inputs:** official statements of CERN member states about their preference for the next collider
- **Topical inputs on:**
 - **Accelerator projects:** Linear Collider (#140), CLIC (#78), LEP3 (#188), LHeC (#174, #214), CLIC (#78), Muon Collider (#152, #207), FCC integrated program (#241)
 - **Full detector concepts and study reports:** ePIC (#17), ATLAS Upgrade (#189), ALICE3 (#70), LHCb Upgrade II (#148), Belle II (#205), [MUSIC Muon Collider Detector (#32)], SHiP (#145)
 - **FCC/Higgs Factory projects:** Physics Experiments and Detector (PED) of FCC feasibility study (#95), ECFA HET Study (#141), SiD (#94), ILD (#102), ALLEGRO (#211)
 - **Subdetectors:** Si-W ECAL (#77), Muon Detectors for ALLEGRO (#133), Straw tracker (#142), beamstrahlung-monitoring (#160), MAPS-ToF (#262), 3D-pixel-Calo (#266)
 - **DRD Collaborations:** ECFA Detector Panel (#157), DRD1-gas (#229), DRD6-calo (#108), DRD5-quantum (#204)

Open Symposium and Briefing Book

Open Symposium Venice



CERN-ESU-2025-001

30 September 2025

Physics Briefing Book

Input for the 2026 update of the European Strategy for Particle Physics

<https://cds.cern.ch/record/2944678>

250-page summary of input proposals, discussion topics and community view, compiled by [Physics Preparatory Group](#) and contains chapters on

- Intro and Theory
- Six Physics PPG groups: Electroweak, QCD, flavor, neutrino, cosmic messenger, BSM, dark sector
- Technology PPGs: accelerators, computing, detector instrumentation
- Projects comparison (based on [ID281](#))



Proposed projects

FCC-ee

FCC-ee (e⁺e⁻, circular, 91 – 365 GeV)

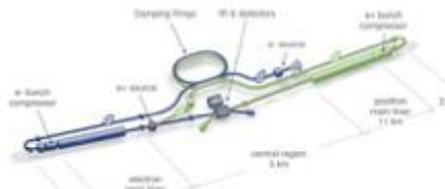


e⁺e⁻ colliders ("Higgs factories")

Up to 365GeV

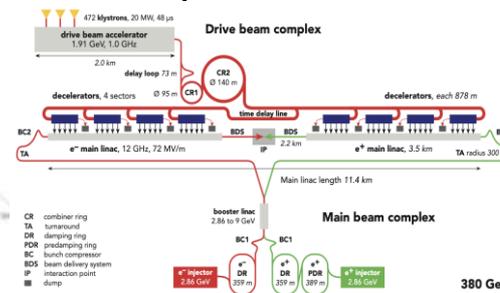
Cost: 15.3 billion CHF (incl. 4 experiments)

Linear Collider Facility (based in ILC technology)



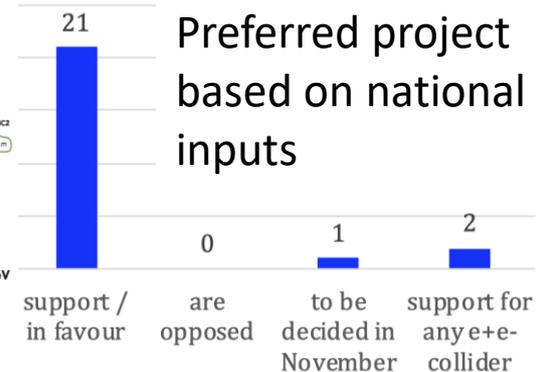
Cost: ~9.3BCHF (250GeV) +5.4 BCHF (550 MeV upgrade)

CLIC w/wakefield acc.



Cost: ~8.2 BCHF (380GeV) +7.1 BCHF (1,5TeV upgrade)

CERN Member States (MS)



Preferred project based on national inputs

Intermediate projects

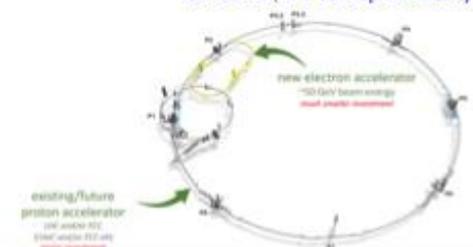
(Leave room (time, budget, resources) for further development of THE machine that can probe directly the energy frontier at the 10 TeV parton scale)

Cost: 4 billion CHF (with upgrades of two existing Xpts)

LEP3 (e⁺e⁻, circular, 91 – 230 GeV)

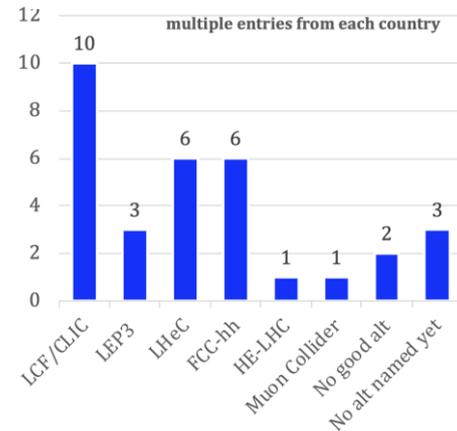


LHeC (ep, circular, electron ERL, 50 GeV e⁻, > 1 TeV ep collisions)



Cost: ~2.4 billion CHF (including 1 exp)

Alternative project:



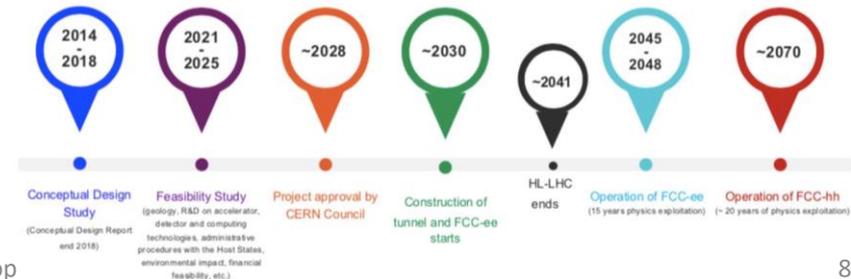
Cost numbers from Future Colliders Comparative Evaluation - Working Group Report [ID281](#)

(Possible) Next Big Collider



FCC Integrated Program:

- Stage 1, Precision Frontier: **FCC-ee** electron-positron collisions at 88-365 GeV
 - Construction: 2030-2045
 - Physics operation: 2045-2060
- Stage 2, Energy Frontier: **FCC-hh** proton -proton collisions at ≥ 100 TeV
 - Physics operation: ~ 2070



FCC Feasibility Study (2020-2025)

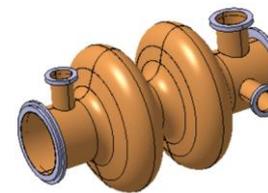
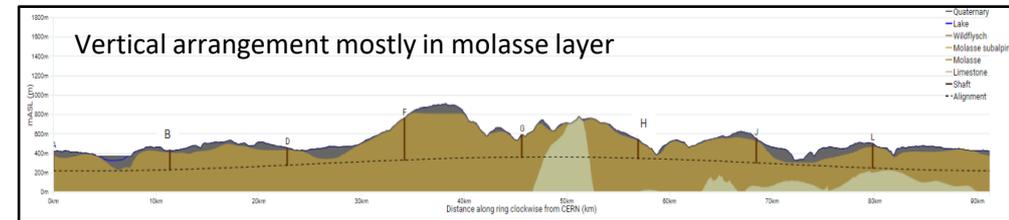
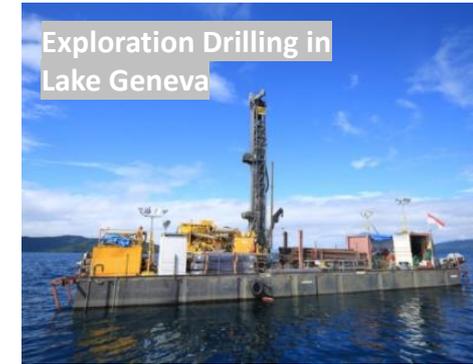
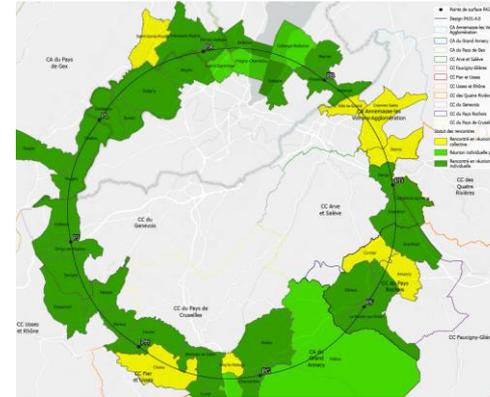
Feasibility Study Reports [released 31 March as input to ESPP](#):

- [Vol. 1](#): Physics, Experiments and Detectors (~200 pages)
- [Vol. 2](#): Accelerators, Technical Infrastructures, Safety Concepts (~400 pages)
- [Vol. 3](#): Civil Engineering, Implementation & Sustainability (~200 pages)

Reference layout and implementation: PA31 - 90.7 km

- Layout chosen out of ~ 100 initial variants, based on geology and surface constraints (land availability, access to roads, etc.), environment, (protected zones), infrastructure (water, electricity, transport), machine performance etc.
- Meetings with municipalities
- Site investigations to identify the exact location of geological interfaces with >30 drillings
- Excavation material: transformation from waste to resource
- Machine optimization: RF cavities, optics, Machine-Detector-Interface (MDI) with final focussing magnets far into experiments

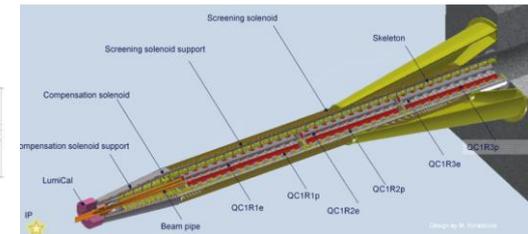
[Futher info in talk by M.Benedikt](#)



400MHz cavity for Z, W, ZH

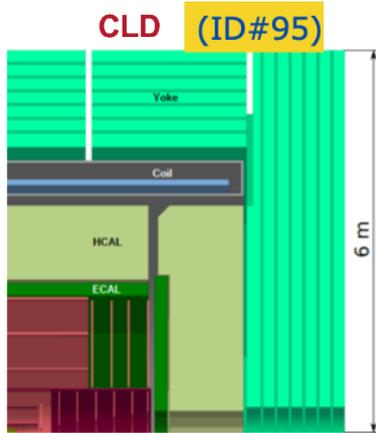


Tunnel cross section



MDI with final focus

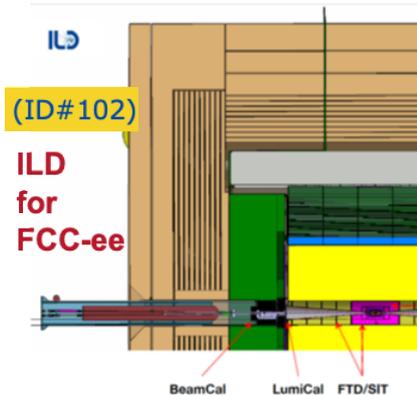
Detectors for FCC-ee



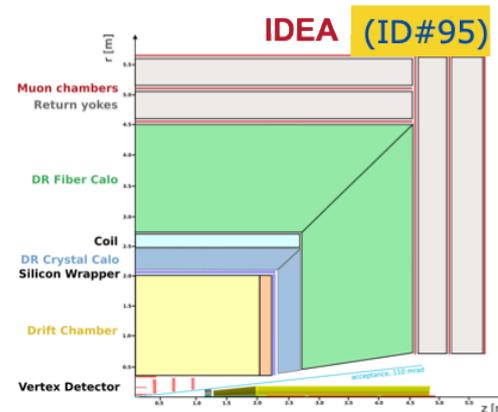
- VTX MAPS
- Main Tracker: Silicon
- Very high granularity (CALICE) inside the Solenoid
 - ECAL Si+W
 - HCAL Fe+scintillator
- PID: RICH and TOF
- Muons ID with RPC



- VTX MAPS
- Main Tracker:
 - Drift Chamber/Straw/Si
- Si/LGAD wrapper (TOF)
- ECAL: Pb+L-Ar/W-L-Kr
- HCAL: Fe+scintillator outside the Solenoid
- PID: RICH (in case of Silicon main tracker)
- Muons with RPC



- VTX MAPS
- Main Tracker: TPC
- Very high granularity (CALICE) inside the Solenoid
 - HCAL Fe+scintillator
 - ECAL Si-W
- Muons with scintillator



- VTX MAPS
- Main Tracker:
 - He+Isob drift chamber
- Si/LGAD wrapper (TOF)
- DR calorimetry (fibres):
 - ECAL: Crystals
- HCAL: Iron **outside** the Solenoid
- HTS Solenoid (up to 3T)
- Muon ID: μ -RWELL

FCC-ee Detector Requirements

• Vertex Detectors

- Resolution (single point: 3 μm , time: 5 ns)
- Hit rate/density (up to 200 MHz/cm²)
- Power consumption (50 mW/cm²)
- Radiation hardness (TID: 100 kGy, NIEL: $\sim 10^{13}/\text{cm}^2$)
- Material budget (0.3% of a radiation length per layer)

• Trackers

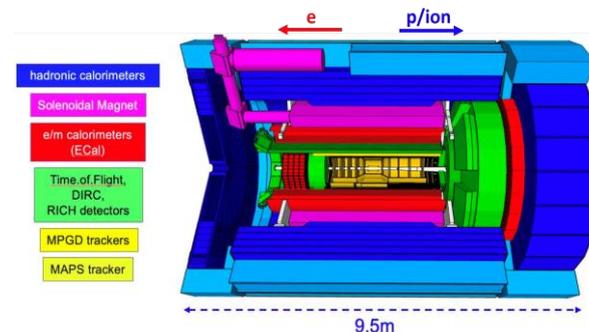
- Small number silicon detector layers
- gaseous detectors

• TOF wrappers to provide PID

• High granularity calorimeters

Experiments/upgrades starting in the 2030s with similar concepts to FCC-ee:

ALICE3, LHCb Upgrade 2, ePIC@EIC, Belle II Upgrade



	ITS3	ALICE 3 VTX	ALICE 3 TRK	ePIC	FCC-ee
Single-point res. (μm)	5	2.5	10	5	3
Time res. (ns RMS)	2000	100	100	2000	20
In-pixel hit rate (Hz)	54	96	42		few 100
Fake-hit rate (/pixel/event)	10^{-7}	10^{-7}	10^{-7}		
Power cons. (mW/cm ²)	35	70	20	<40	50
Hit density (MHz/cm ²)	8.5	96	0.6		200
NIEL (1 MeV $n_{\text{eq}}/\text{cm}^2$)	$4 \cdot 10^{12}$	$1 \cdot 10^{16}$	$2 \cdot 10^{14}$	few 10^{12}	10^{14} (/year)
TID (Mrad)	0.3	300	5	few 0.1	10 (/year)
Material budget (X_0/layer)	0.09%	0.1%	1%	0.05%	$\sim 0.3\%$
Pixel size (μm)	20	10	50	20	15-20

DRDs in Strategy Update

European Strategy
for Particle Physics
Update 2026

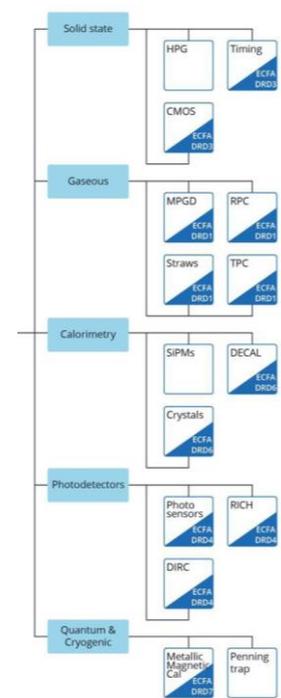
European Strategy
for Particle Physics

DRD collaborations are often referenced and seen as an already **established concept** in many input proposals (e.g. in many national submissions)

Neighboring fields:

- **Nuclear Physics:** large overlap with all DRD collaborations for high-energy NP, referenced in NuPPEC [long-range plan 2024](#) in detail; Also e.g. 40% groups in DRD1
- **Astroparticle physics:** connection with DRD2 and DRD4, Intensifying cooperation suggested (e.g. German astroparticle submission #126,..)

APPEC welcomes the 2021 ECFA detector R&D roadmap for particle physics and acknowledges the synergy with particle physics detector R&D (APPEC Roadmap Update 2023)



The DRD Collaborations

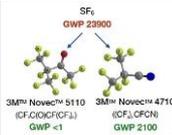
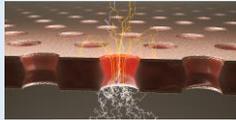
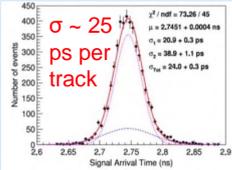
Eight DRD collaborations have been approved for an initial period of 3 years (extendable) with different histories and “maturity”:

- Based on previous R&D collaborations:
 - **DRD1: Gaseous detectors** (based on RD51): *161 institutes, 700++ people*
 - **DRD3: Semiconductor Detectors** (previously RD42, RD50): *145 institutions / 700++ people*
 - **DRD6: Calorimetry** (CALICE, other proto-experiment collabs.): *135 institutes*
- Completely new: (community building, building trust, and finding benefit of being “CERN hosted”)
 - **DRD2: Liquid Detectors:** *86 institutes, 205 members*
 - **DRD4: Photodetectors & PID:** *74 institutes*
 - **DRD5: Quantum Sensors and emerging technologies:** *112 involved groups*
- Transversal activities: no service provider, but with genuine R&D interest (TF9 → ECFA Training Panel)
 - **DRD7: Electronics:** *67 Institutes*
 - **DRD8: Mechanics & Integration:** *38 institutes*

DRD Collaborations

DRD1: Gaseous Detectors

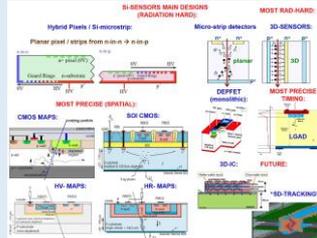
Large · Fast · eco-friendly
gases · MPGD, e.g. GEMs



PICOSEC: NIMA903
(2018) 317

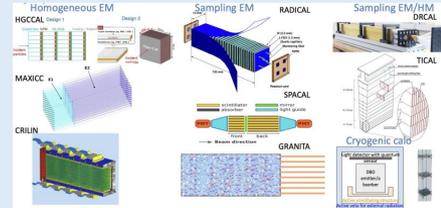
DRD3: Semiconductor Det.

Monolithic CMOS · LGADs ·
radiation hardness · interconn.



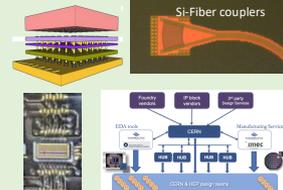
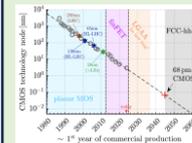
DRD6: Calorimetry

Energy resolution · High
granularity · dual readout ·
particle flow · sandwich · optical



DRD7: Electronics

ADC/TDC IP Blocks · Opto-
electronics · packaging · power ·
extreme environments · COTS ·
intelligence on detector · foundry
access



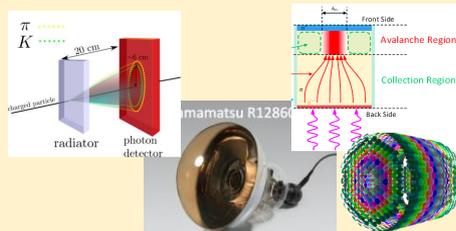
DRD2: Liquid Detectors

for Neutrinos · Dark Matter
· Ovbb

Noble Elements	Liquid Scintillators	Water Cherenkov
<ul style="list-style-type: none"> Argon & Xenon Ionisation charge & transport VUV Scintillation, light propagation & detection 	<ul style="list-style-type: none"> Visible Scintillation, light propagation Scintillator properties Isotope loading 	<ul style="list-style-type: none"> Cherenkov light, light propagation Doping for n-capture

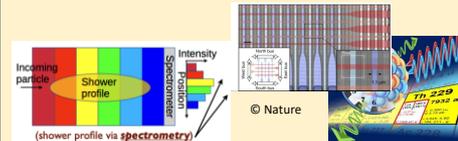
DRD4: Photon detectors

vacuum, solid-state (SiPM), hybrid
single-photon and SciFi detectors ·
applications in PID, RICH, tracking



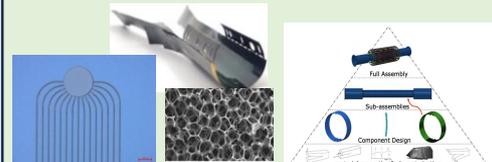
DRD5: Quantum Sensors

Quantum dots · superconduct.
nanowires · bolometers · TES ·
MMC · nuclear clocks
Applications in LEPP, first
projects in HEPP happening



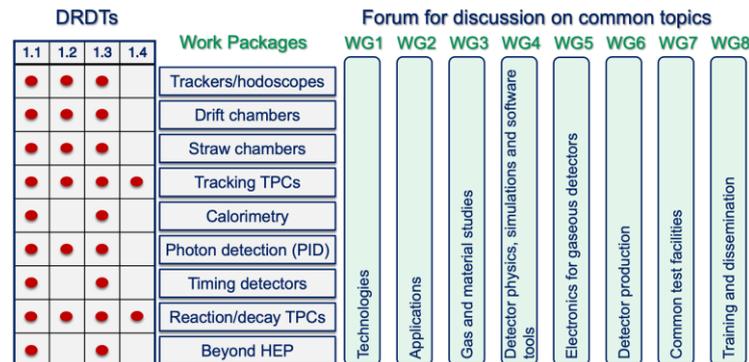
DRD8: Mechanics

Ultra-thin beam pipes · CF foam and
new materials · curved, retractable
sensors · air & micro-channel cooling
· eco-friendly cooling fluids · robots ·
augmented reality



All DRDs in similar shape

- Approved for an **initial period of three years** based on work programs in the proposals
 - Annual review by the DRDC committee
- Collaborations are organized in
 - **Working Groups:** (WG) serving as the backbone of R&D
 - **Work Packages:** resource-loaded; will reflect the DRDTs
- All administrative positions (WP/WG convenors) filled, but most work started in working groups so far
- CERN Greybook entries exist; Users can be registered to DRD collaborations
- Websites for all DRDs exist following the schema <https://drd3.web.cern.ch/>
- Certain DRD collaborations ask for a fixed **yearly membership fee** (Common Fund), targeting common projects, but also blue-sky R&D projects
 - However, DRD collaborations are not funding proposals!
 - MoU's (with resource requests) to be signed by funding agencies → ongoing



DRD1 input proposal #229

MoU for DRD Collaborations

DRD Collaborations are basically open to any group

- “Membership” is defined by signing a Memorandum of Understanding with the respective DRD Collaboration, following a CERN template for “small experiments”
- MoU process got stuck by “chicken-and-egg” discussion about commitments to resources; Two approaches for mitigation:
 - DRD1 went forward with signing MoU without resource requests and commitments, just listing planned activities per institution
 - *DRD Jamboree*: Meeting on 28 Oct to present DRD program to funding agencies ([Indico](#))
- CERN discussed U.S. participation in DRD collaborations with DoE and NSF
 - DoE cannot sign the standard MoUs
 - DoE questioned Common Fund payments, fearing limited funds left for active work, though some universities might pay small amounts independently.
 - A letter exchange between DoE and CERN confirming participation was considered but never realized.
 - Hence, e.g. DRD1 MoU lists U.S. groups but no funding agencies.

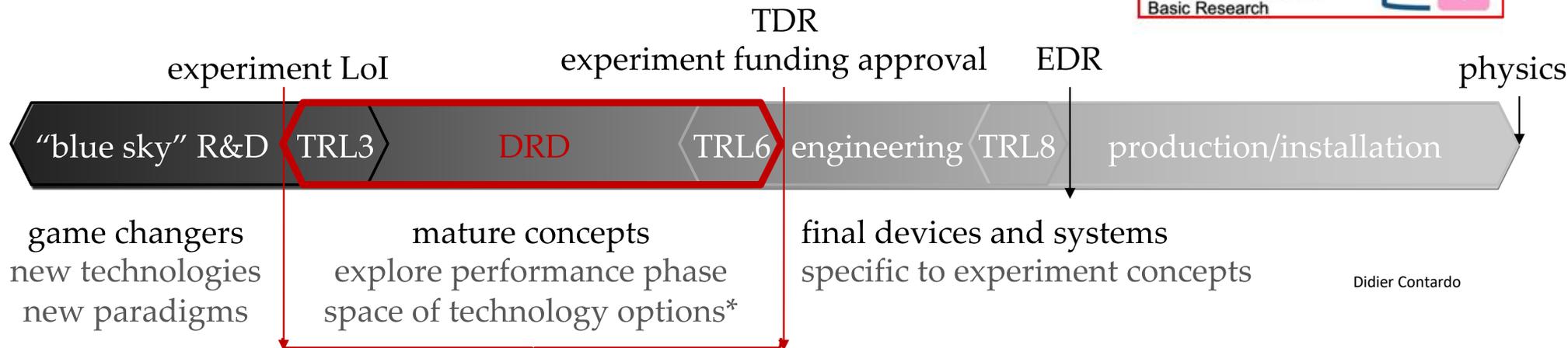
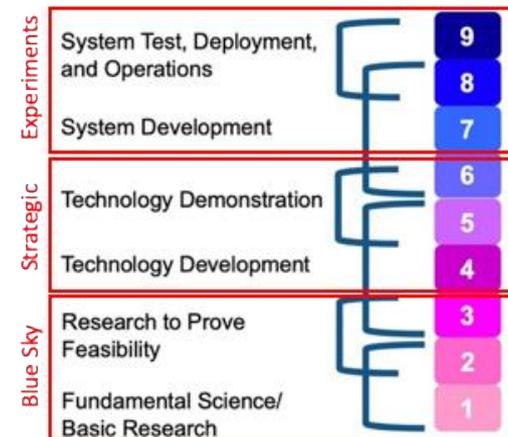
DRDs should cover Strategic R&D

Strategic R&D bridges the gap between the idea (“blue sky research”, low TRLs) and the **deployment and use in a HEP experiment** (TRL 8-9)

Covers the **development and maturing of technologies**, e.g.

- Iterating through different options
- Improving radiation hardness
- Scaling up challenges: detector area, number of channels, layers,..
- ...

Technology Readiness Levels (TRL):



Didier Contardo

Example of the need for strategic R&D

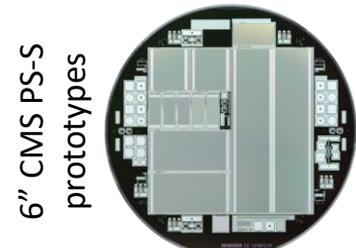
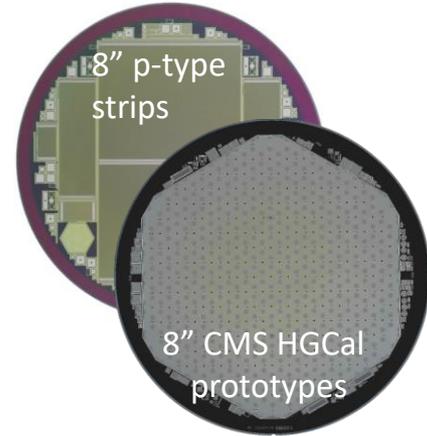
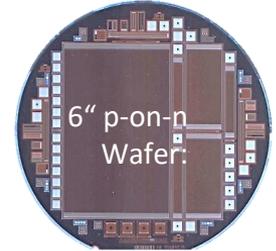
Large-area position-sensitive silicon sensors are the main technology for vertex and tracking detectors

Several efforts initiated in the past to establish second source for large-area planar silicon sensors, e.g.

- For “Phase-0” : INFN institutes with **STMicroelectronics**
→ Influenced the decision for “full silicon tracker” in CMS
- For “Phase-II” Upgrades: **Infineon (Europe), Nhandced/Novati (US)**
→ Pushed hexagonal sensors on 8” wafers, now used for CMS HGCal

Both projects stopped due to a lack of funds

Several more R&D wafer submissions would have been necessary to mature the technology and to transfer it to series production

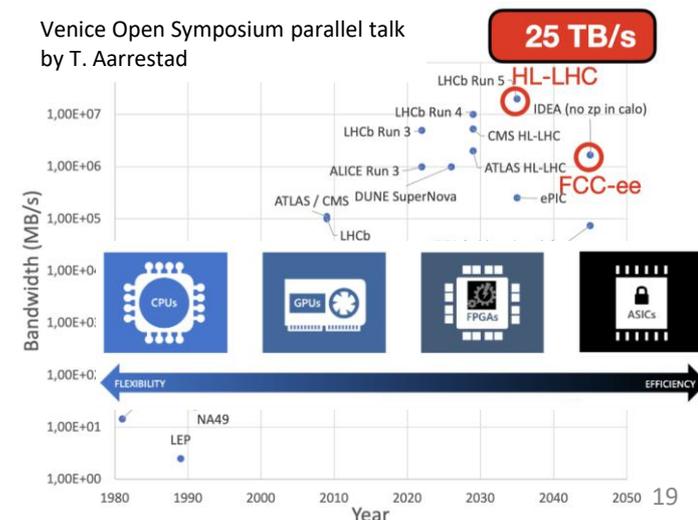


What is beyond the current DRDs?

- **Superconducting Experimental Magnets** (initial in TF8)
 - Al-stabilized Nb-Ti conductor technology used >20 years ago for LHC experiments,
 - No qualified vendor now, but needs by ALICE3 (Al) and ePIC (Cu-stabilized)
 - Research aligned with CERN activities, see 2022 [workshop](#) and arXiv:2203.07799
 - HTS as an alternative with possible synergy to accelerator magnet R&D
- **Rare event detectors**
 - Many submissions (e.g. #112), but DRD5 would also provide a suitable host for e.g. bolometers, TES, MMC,..
- **New TDAQ methods** with AI and intelligence on the detector
 - “triggerless” DAQ creates high data rate, throughput challenge (e.g. #127)
 - AI-RDs collaborations proposed as a parallel structure to DRDs (#167)
 - Boundary between electronics (partly covered by DRD7) and computing
- New approach in **microelectronics** (#161)
- **Attracting more person power, funding,** and engaging new communities (#30, #95, #157,..) → establish partnerships



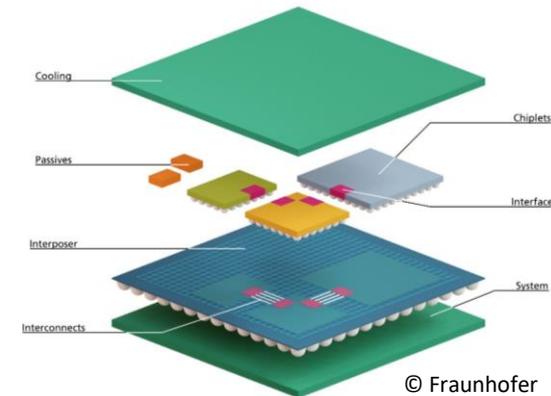
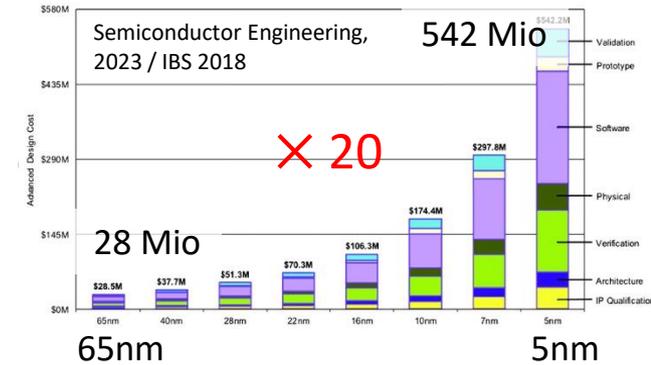
CMS Solenoid 2005



Microelectronics Challenge

#161, GSR 2, GSR 5, GSR 9

- The **cost and complexity** of developing advanced CMOS technologies have risen dramatically. **HEP is now lagging behind commercial technology**
 - In 1999: APV25 (CMS Tracker ASIC) and Pentium-III shared the same technology (250 nm)
 - Now: 3 nm at TSMC (e.g. Apple M4) vs. 28 nm in FE-ASIC and 65 nm in MAPS
- Mitigation by **seeking resources beyond HEP** and forming **broader collaborations**, actively encourages cross-disciplinary developments
 - **Fewer, common developments with higher volumes**
 - Use modern technologies with standardized, common **chiplets** combined to chips tailored to different needs
 - DRD collaborations can be instrumental by e.g. closer collaboration and developing common chiplet blocks (inter-DRD workshop on electronics needed?)
- Advances in Electronics are also connected to lower power consumption
 - Sustainability topic, less material budget for MAPS vertex detectors



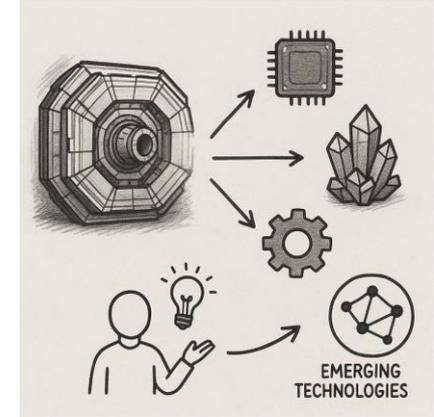
© Fraunhofer

Partnerships in Engineering

Input proposals #95, #161

HEP detectors are electronic detectors with highly specific, “niche” requirements

- Many technologies critical for HEP do not have a lucrative commercialization path, i.e. radiation hardness, but need high level of “cutting edge” technologies
- Each experiment is a prototype. Many different sub-systems with (too many) different technologies
- **Welcoming expertise from outside the traditional HEP** becomes necessary due to increasing complexity, size and large material count of HEP detectors, e.g. in
 - Chip design, Material science, Advanced manufacturing, Mechanics, QA experts
 - **Bring in disruptive ideas and technologies**, e.g. in quantum sensing
- **Involve the industry early** in R&D processes and co-develop
 - Connecting with the right company is a challenge, so networking efforts can help, e.g. by exploiting Alumni networks
- Sustainable **Career Models** necessary to ensure a stable talent pipeline
 - Enabling long-term career paths, competitive salaries, mobility between academia and industry.
- **General Public:** Showcase the benefits to society, e.g. medical imaging, cancer therapy, environmental and geo science, space, safety, materials research, information technologies



General Strategic Recommendations

Formulated in the ECFA Detector Roadmap as ten "action items"

- **International coordination** and organization of R&D activities (GSR 4)
- Establish long-term strategic **funding programs** (GSR 6) → MoU's
- Support "**Blue-sky**" R&D (GSR 7) → MoU's *DRD Collaborations*
- Supporting **R&D facilities**: test beams, large-scale prototyping, irradiation (GSR 1)
- **Engineering support** for detector R&D (GSR 2)
- Specific **software** for instrumentation (GSR 3)
- Distributed R&D activities with **centralized facilities** (GSR 5)
- Attract, nurture, recognize, and sustain the **careers of R&D experts** (GSR 8)
- Establish and maintain **Industrial partnerships** (GSR 9)
- Support **Open Science** (GSR 10)

All topics still valid
and highly relevant

Outlook

A healthy environment in detector instrumentation is more than DRD Collaborations:

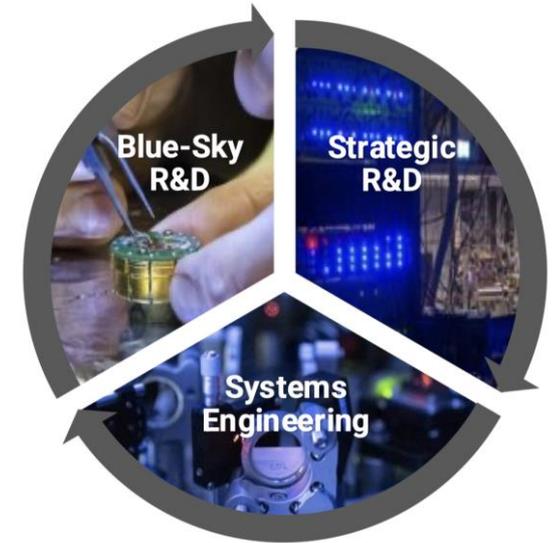
- **Blue-sky R&D** as an integral part of the R&D portfolio
- **Systems engineering** to be integrated in R&D efforts

DRD collaborations are still in their infancy

- Evolve on a coherent work program over the next years
- Expected to grow once the LHC Phase-II Upgrades are finished
- Engage with funding agencies to **secure funding** via MoU's

Need to be supported by:

- Excellent lab and test facilities, good career opportunities with training programs, openness for disruptive ideas, strong partnerships and collaborations beyond HEP
 - Many of these statements have been made already, being more important than ever

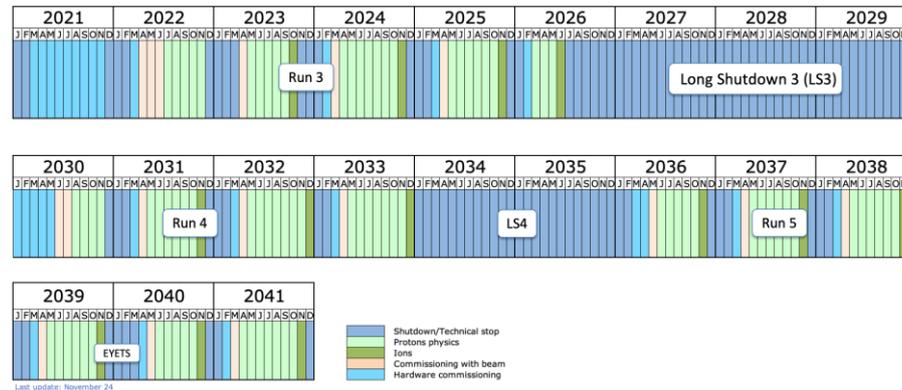
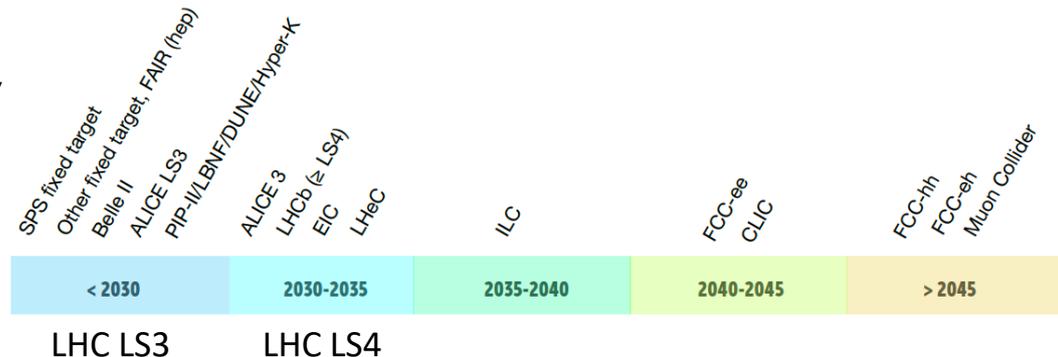


Thank you very much for your attention

Backup slides follow

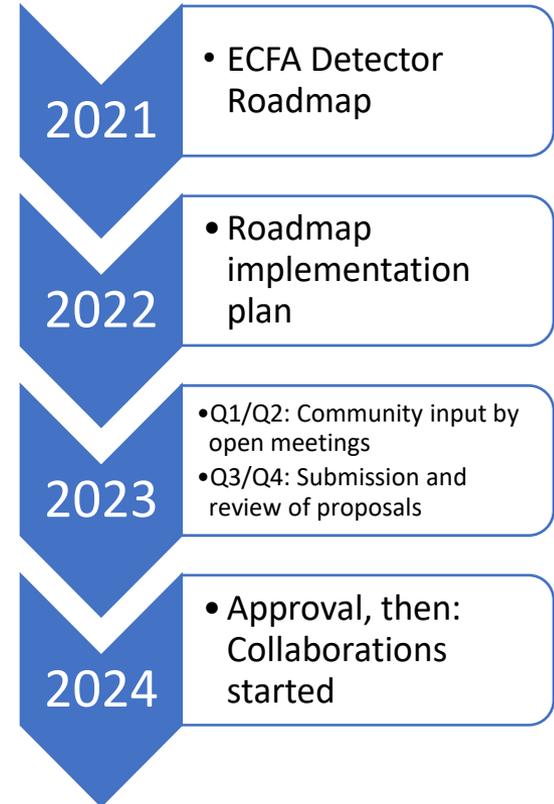
Time Periods and Experiments

- Time periods for “Large experiments”
 - synchronized with LHC schedule
- Time periods for “Smaller Experiments”
 - DM and Neutrino



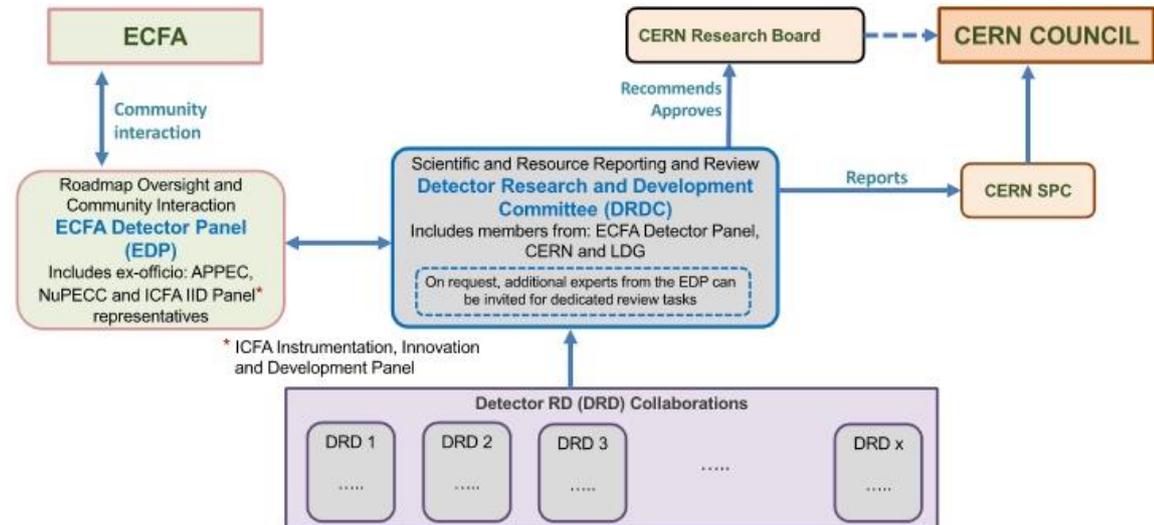
From Roadmap to DRD collaborations

- **Roadmap implementation plan** defined that CERN will host the DRD collaborations
 - Approved by CERN SPC and Council in fall 2022 ([CERN/SPC/1190](#) ; [CERN/3679](#))
 - New committee created as reviewing body, the DRDC at the same level as LHCC, SPSC and others
- Most of the chapter's convenors (“Task Forces”) from ECFA Roadmap process became part of *Proposal Writing Teams* for new DRD collaborations
 - Collected input from the communities in open meetings happening in the first half of 2023
- **Approval of DRD collaborations** by CERN Research Board:
 - DRD1,2 4 & 6 in December 2023, DRD3, 5 and 7 in June 2024, DRD 8 in December 2024
 - Initial period of three years (renewable by prolongation request)



Roadmap implementation plan

- Approved by CERN SPC and Council in fall 2022 ([CERN/SPC/1190](https://cern.ch/spc/1190); [CERN/3679](https://cern.ch/council/3679))
- **CERN will host DRD collaborations**
 - Interaction between DRD collaborations and committees through DRDC
 - Interface to ECFA via ECFA Detector panel: <https://ecfa-dp.desy.de>
- Distinction between reviewing body (DRDC) and advising body (EDP)
- EDP also provides input to the next Strategy update

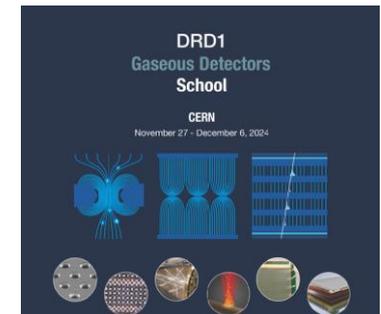


Training, Education and Careers

- Sustainable **Career Models**: Addressing long-term career paths
 - **Competitive salaries** enable mobility between academia and industry to ensure a stable talent pipeline → Academia cannot compete with industry, thus alternatives necessary
 - **Find partnerships and open career paths** from closely connected technological domains **within academia**, i.e. undergraduates electrical/electronics engineering faculties
 - Start with engagement even earlier: Outreach in high schools
- Establishing a **European Curriculum in Instrumentation**
 - **Beginner level**: through university master's and graduate programs, supported by material compiled by HEP
 - **Intermediate level**: Erasmus Mundus Master in Instrumentation
 - **Advanced level**: (PhD and postdoc level): dedicated schools in instrumentation (e.g. EDIT) or DRD-specific schools
 - Establish a CERN-hosted instrumentation school similar to *CERN Accelerator School* and the *CERN School of Computing*



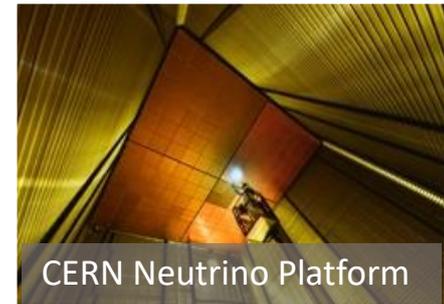
#30, GSR8



Infrastructures

FNAL #11, DESY #72, #244, GSR1

- Crucial for further advances in detector instrumentation
 - Most common include **test-beam** and **irradiation facilities**
 - But also CERN **neutrino platform**, facilities for **quantum sensor tests**, **magnet tests**, specialized **characterization** setups, **laser facilities**,...
- **European projects** were instrumental to access irradiation and testbeam facilities and develop them further, e.g. beam telescopes
 - AIDA(-2020)/AIDAinnova, Euro-LABS for TNA
- Accelerator upgrades also affect the interruption of testbeam facilities
 - No testbeam activity during CERN LS3



<https://cern.ch/international-facilities>

Last Update 23/04/2025	
Running	1
Winter/Summer Shutdown	2
Longer Shutdown	3
Unclear	4
Likely	5
Pending Approval	6
Equipment failure	7

ESPP Input Submissions

- Classified by submitters in instrumentation track: 80 submissions
- Classified in Excel Table by Strategy Secretariat:
 - “Instrumentation” as secondary track (yellow): 55 submissions
 - “Instrumentation” as primary track (green field): 19 submissions

B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
Title	Submitter															Comment	B	missid	Authors	
17	Enabling future detector technology within ePIC at the EIC	Silvia Dalla Torre														ePIC at EIC detector technologies		#####	Silvia Dalla Torre	
46	Search for feebly interacting particles with the Lohengrin experiment at the ELSA accelerator	Matthias Hamer														FIP experiment at ELSA		#####	Philip Bechtle; K	
70	Frontier sensor R&D for the ALICE 3 apparatus	Marco Van Leeuwen														ALICE3 technology		#####	Marco Van Leeu	
77	A Silicon-Tungsten ECAL for Higgs Factory Detectors	Vincent Boudry														Si-W ECAL for HF		#####	Vincent Boudry	
93	Strengthening the Instrumentation Programme	Jinlong Zhang														US CPAD instrumentation		#####	Jonathan Asaad	
102	The ILD Detector: A Versatile Detector for an Electron-Positron Collider at Energies up to 500 GeV	Ties Behnke														ILD detector concept		#####	Ties Behnke <tie	
108	DRD 6 Calorimetry - Input to European Strategy of Particle Physics Update (ESPPU)	Roman Poeschl														DRD6 (calorimetry R&D)		#####	Gabriella Gaudi	
119	The DUNE Phase II Detectors	Michel Sorel														DUNE Phase II detectors		#####	Sergio Bertolucc	
133	A High-Precision, Fast, Robust, and Cost-Effective Muon Detector Concept for the FCC-ee	Jianming Qian														Muon detector for FCC-ee		#####	Fabio Anulli <fal	
142	A Straw Tracker for an FCC-ee experiment	Junjie Zhu														Straw tracker for FCC-ee		#####	Marcos Arias <j	
148	Technology developments for LHCb Upgrade II	Giovanni Punzi														Detector technologies for LHCb Upgrade II		#####	Timothy Gershco	
157	Towards instrumentation for future HEP experiments	Didier Claude Contardo														DRD collaborations for detector R&D		#####	Didier Claude Co	
171	Proposal from the NA61/SHINE Collaboration for the update of the European Strategy of Particle Physics	Seweryn Kowalski														NA61 future programme		#####	Przemyslaw Adr	
204	R&D on quantum sensors for particle physics: the DRD5 collaboration	Michael Doser														DRD5 quatum sensor R&D	30	#####	Marcel Demarte	
211	Expression of Interest for the ALLEGRO Full-Detector Concept for FCC-ee	Martin Aleksa														ALLEGRO detector concept at FCC-ee		#####	Martin Aleksa <	
229	Development of Gaseous Detector Technologies: CERN-DRD1 Collaboration Model	Maksym Titov														DRD1 R&D on gaseous detectors		#####	Anna Colaleo <a	
244	The Importance of Test Beams for Particle Physics worldwide	Marcel Stanitzki														Future of test-beams for HEP		#####	Sven Ackerman	
262	Expression of Interest Toward MCMOS Time of Flight Tracking Layers for a detector	Philippe Schwemling														CMOS time-of-flight for FCC-ee		#####	Roy Aleksan <ro	
269	Novel 3D-Projection Pixelated Detector for Next-Generation High-Energy Physics Experiments	Guang Yang														Pixelated calorimeter R&D for neutrino expt		#####	Guang Yang <g	

FCC-hh main machine parameters

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	84 - 120	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1100 - 4570	7.3	3.6
SR power / length [W/m/ap.]	14 - 58	0.33	0.17
long. emit. damping time [h]	0.77 - 0.26	12.9	
peak luminosity [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.3 - 9.2	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

With FCC-hh after FCC-ee: significantly more time for high-field magnet R&D aiming at highest possible energies

Formidable challenges:

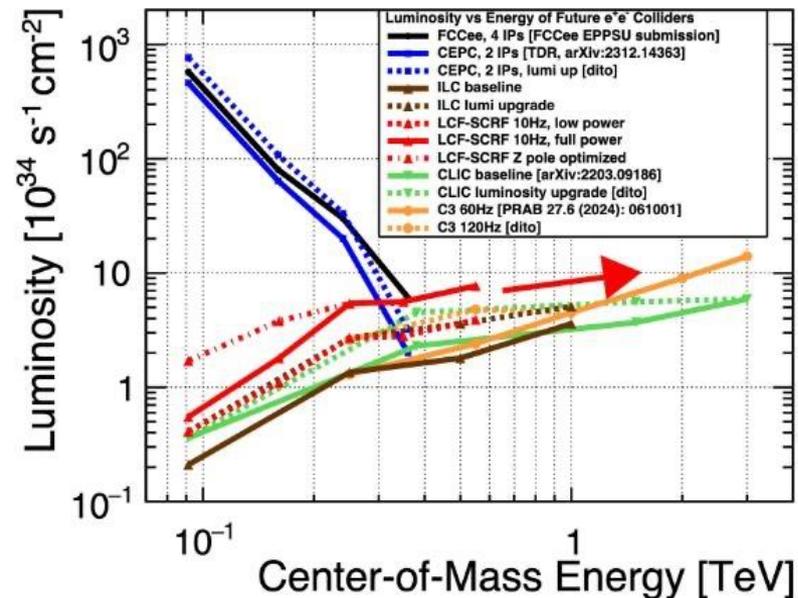
- high-field superconducting magnets: 14 - 20 T
- power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- stored beam energy: ~ 9 GJ → machine protection
- pile-up in the detectors: ~1000 events/xing
- energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, ...

Formidable physics reach, including:

- Direct discovery potential up to ~ 40 TeV
- Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, $Z\gamma$, $\mu\mu$)
- Final word about WIMP dark matter

Considered Projects in Briefing Book

Project	Energies [GeV]
FCC-ee	91 (Z) ✓ 160 (WW) ✓ 240 (HZ) ✓ 365 (ttbar) ✓
LCF-250	91 ✓ 240 ✓
LCF-250+550	91 ✓ 240 ✓ 365 ✓ 550 ✓
CLIC-380	380 ✓
CLIC-380+1500	380 ✓ 1550 ✓
LEP 3	91 ✓ 160 ✓ 230 ✓
LHeC	50 GeV (e ⁻) on 7 TeV (p) ✓



LEP3 to follow (HL-)LHC in same tunnel as LEP2 (1989-2000)

High-Energy Options: **FCC-ee + FCC-hh**,
LCF + 1 TeV, CLIC + 3 TeV, Muon Collider,
LEP3 + FCC-hh, LHeC + FCC-hh

Work Program and Scientific Highlights of the DRD collaborations

Eight densely packed slides

ECFA Detector Panel #157

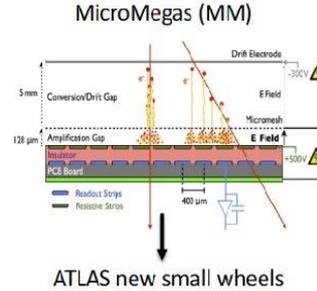


DRD1: Gaseous Detectors

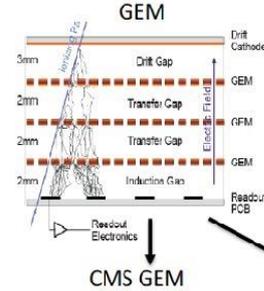
Gaseous Detector Technologies

#229

- **Long road** from MWPC → Drift Chamber → Time Projection Chamber (TPC) → Micro-Pattern Gas Detectors (MPGD)
- Primary choice for large-area coverage with low material budget & dE/dx measurement (TPC, Drift chamber) & ToF functionality (MRPC, PICOSEC)
 - Systems developed for LHC experiments led to unprecedentedly large systems, mostly based on MPGDs
 - Most FCC-ee detector concepts use gas detectors for the main tracker and muon systems



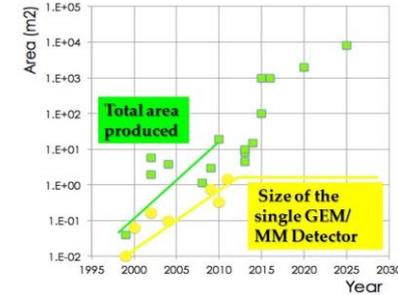
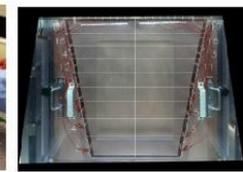
ATLAS new small wheels



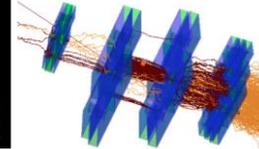
CMS GEM



ALICE TPC upgrade

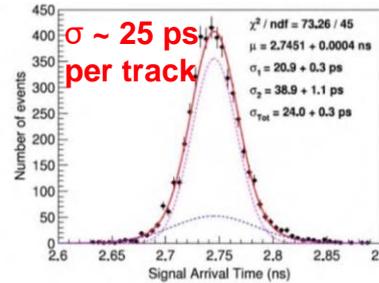


Garfield simulation of 4GEM stack



Working Topics Highlights:

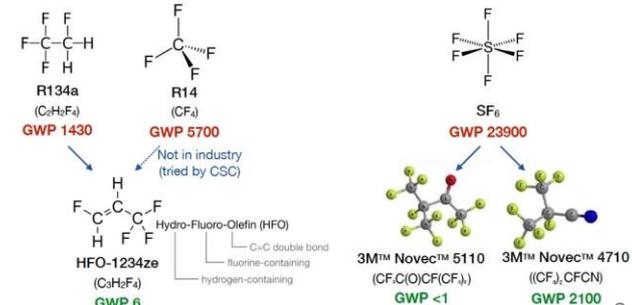
- **High rates:** reduce ion back drift
- **Reduce aging** and radiation hardness
- **Fast Timing:** Multi-Gap RPCs: achieved ~60ps time resolution (ALICE TOF Detector, Z.Liu, NIM A927 (2019) 396), Micromegas with timing (PICOSEC concept): 25ps
- **Eco-friendly gas mixtures:** with lower Global Warming Potential (GWP): 92% of CERN emissions related to LHC experiments
- Common readout system SRS for MPGDs, Beyond HEP



PICOSEC: NIMA903 (2018) 317

Possible alternatives to GHG gases

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

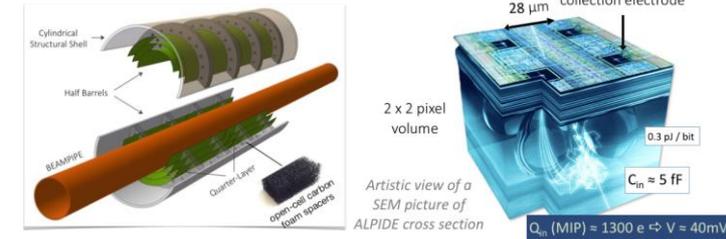
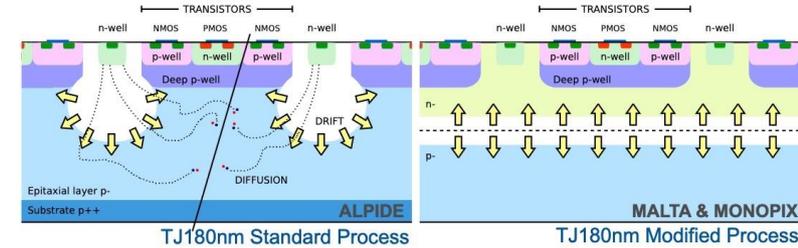


DRD3: Semiconductor Detectors

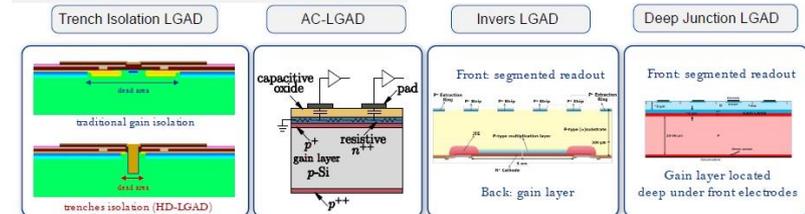
Higgs factory experiments: low mass, high precision **vertex** detectors: ($\sim 0.1\% X_0$)/layer, $3\mu\text{m}$ single-hit resolution; ToF wrappers around tracker for PID: $\sim O(20)\text{ps}$

Research Topics in DRD3:

- **CMOS Monolithic Active Pixel sensors (MAPS):**
 - Sensor development becomes mixed-mode chip development,
 - Challenges: access to foundries, engineering workforce
 - Most advanced developments (ALICE) not strongly involved in DRD3, though
- **4D Tracking/ToF: Timing using Low Gain Avalanche Detectors (LGAD)**
 - Timing performance $\sim 25\text{ ps}$, but radiation hardness limited
- **Extreme Radiation hardness: 3D sensors, wide bandgap sensors, e.g. SiC, GaN and Diamond**
 - Activities from RD50 heritage, and for longer-term R&D towards FCC-hh
- **Interconnection technologies**

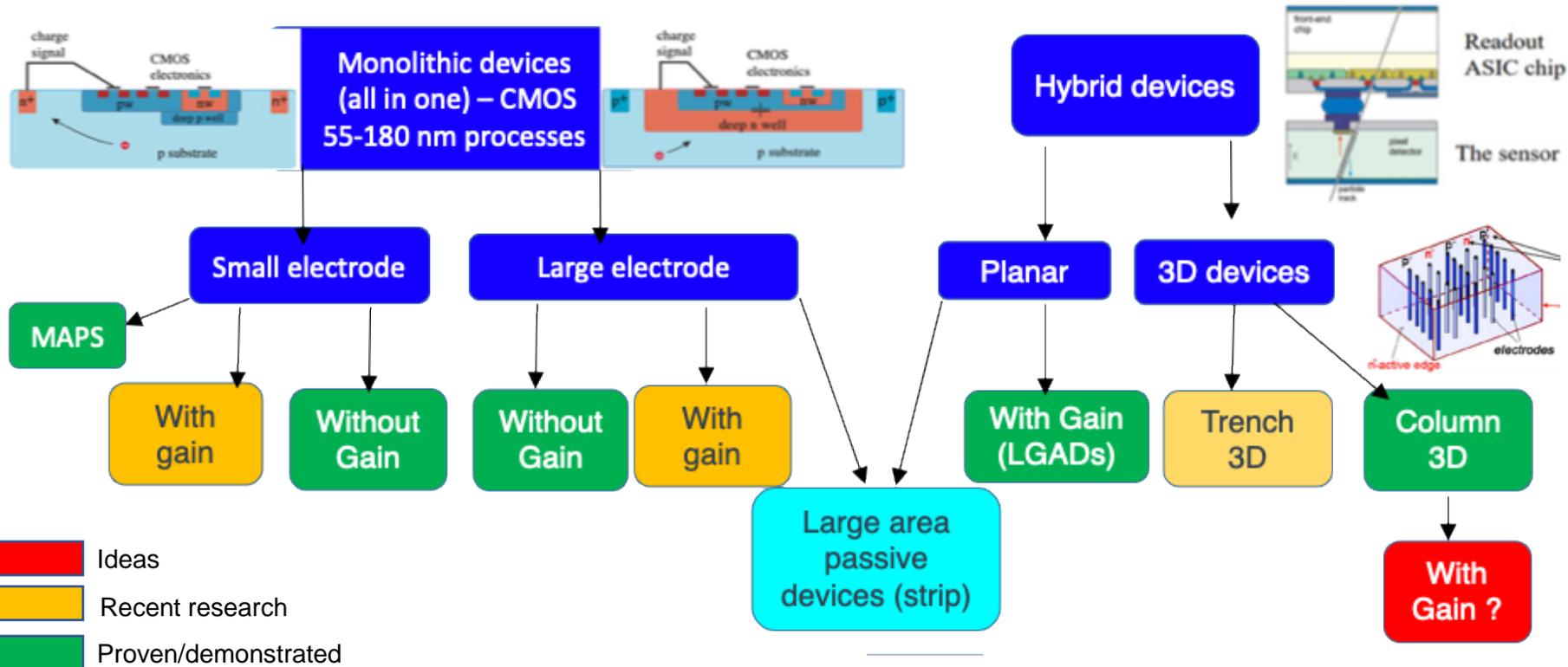


Different LGAD technologies:



R&D Paths for DRD3

Semiconductor Detectors

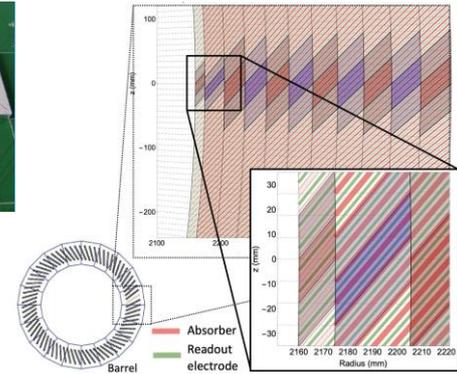


by G. Kramberger

DRD6: Calorimetry #108

Calorimeters need many technologies from other DRDs

- **Sandwich calorimeters** with fully embedded electronics and CMOS MAPS, SiPM or gas-detector readout
- **Liquified Noble Gas:** ALLEGRO detector concept (lAr with lead)
- **Optical calorimeters**, homogeneous EM with scintillators (BGO, LYSO,..) and SiPM or MCP-PMT readout
- Electronics and DAQ: sophisticated FE chip developments

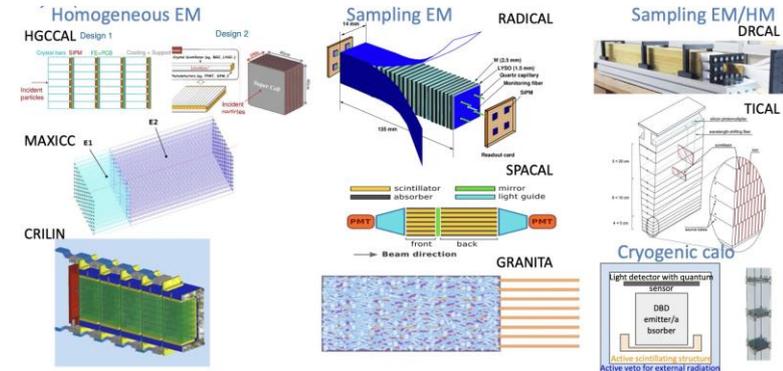


Overarching goals:

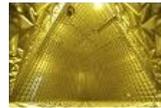
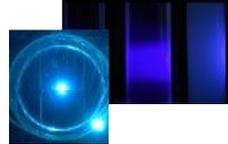
- **Dual Readout Calorimetry** to mitigate different response of EM and hadronic showers
- **Particle Flow** to improve jet energy resolution

Challenges:

- High pixelisation, 4π hermetic \rightarrow little room for services
- Large and challenging prototype setups, even in early stages. What can be done with simulations?

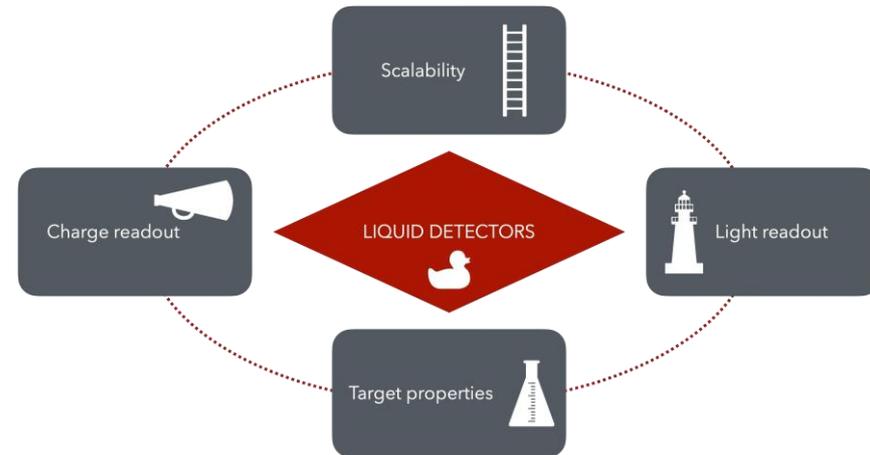
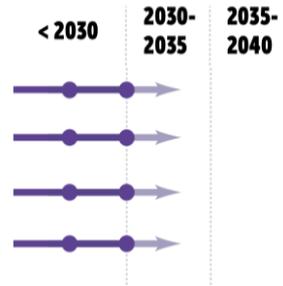


- Covers Dark Matter, Neutrino and $0\nu\beta\beta$ experiments, both accelerator and non-accelerator-based
- Underground Dark Matter Experiments – small and rare signals
- R&D for multi-ton scale noble liquids:
 - Target doping and purification
 - Detector components radiopurity and background mitigation
 - Lower energy thresholds
 - Efficient and fast cryogenic photodetectors → Increase of light yield and background reduction

Noble Elements	Liquid Scintillators	Water Cherenkov
<ul style="list-style-type: none"> • Argon & Xenon • Ionisation charge & transport • VUV Scintillation, light propagation & detection 	<ul style="list-style-type: none"> • Visible Scintillation, light propagation • Scintillator properties • Isotope loading 	<ul style="list-style-type: none"> • Cherenkov light, light propagation • Doping for n-capture 

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





Photodetectors & Particle ID

- **Developments** on PMTs, MCP-PMTs, SiPMs, SciFi
- **Applications** in Ring Imaging Cherenkov Detectors (RICH), Time-of-Flight (ToF), TRD and tracking (SciFi)

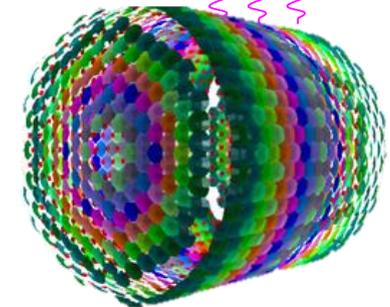
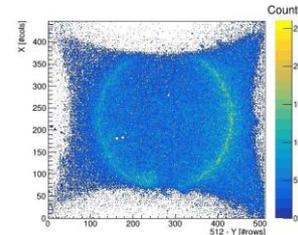
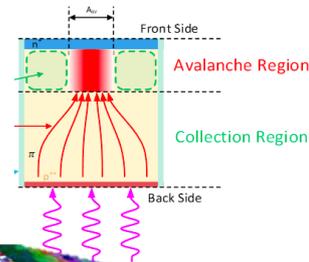
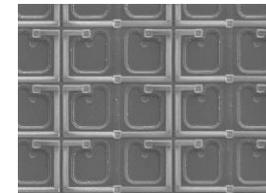
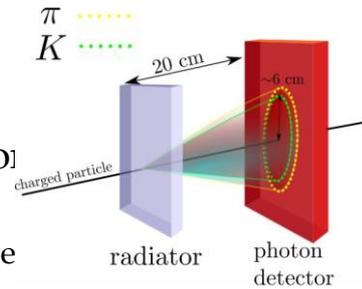
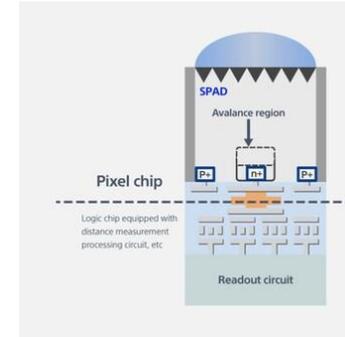
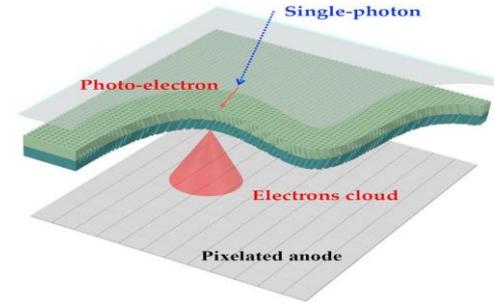
Multi-channel plate PMTs:

- Comsol simulation package
- E.g. Hybrid detector with Medipix4 readout

Silicon Photomultipliers (SiPMs): Array of APD/SPADs

- Many developments, i.e. backside illuminated, integration with CMOS electronics
 - Challenges: improve QE, rad hard, timing, reduce dark count rate
- **Industry interest:** telecommunications, automotive (LIDAR with ToF), with commercial availability (e.g. Broadcom, FBK)

Array of Rich Cells (ARC) concept



Quantum & Emerging Technologies

#204

Quantum Technologies are a **rapidly emerging area** of technology development to study fundamental physics

- Targeting Gravitational Waves, Axion, DM detection on shorter-term
- Development of HEP detectors on the longer term

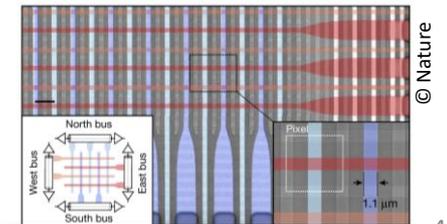
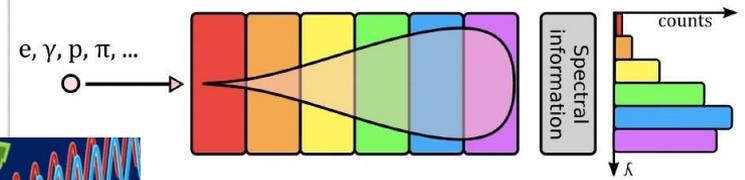
DRD5: different sensors and technologies being investigated:

- Novel materials, kinetic detectors, spin-based, superconducting, optomechanical sensors, atoms/molecules/ions, interferometry, ...
- Scaling up challenge: single → multi channels
- HEP-relevant topics: Superconducting nanowires, Chromatic calorimetry
- Many small-scale setups so far. Now first considerations for common infrastructure

Roadmap topics

Sensor family →	clocks & clock networks	superconducting & spin-based sensors	kinetic detectors	atoms / ions / molecules & atom interferometry	opto-mechanical sensors	nano-engineered / low-dimensional / materials
Work Package ↓						
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

Proposal WP's



DRD7: Electronics

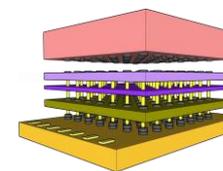
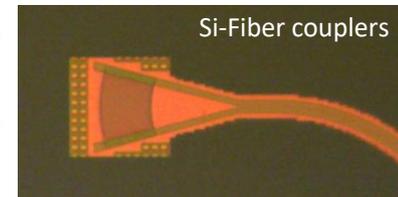
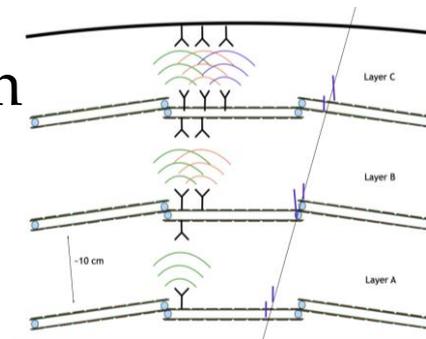
Electronics is vital to any detector system

Modern technologies offer tremendous opportunities:

- Transmission speed @100 Gbit/s and beyond
- Extremely high integration density
- Very high-performance FPGAs
- Advanced packaging technologies
- **But the complexity and cost associated to their use do also increase**

• Work topics in DRD7:

- **Silicon photonics** transceivers, power distribution, **wireless data transmission** and power, interconnections
- **Intelligence on the Front-End: e-FPGA** and RISC-V SoC
- COTS and **no-backend solutions**, i.e. directly from FE to DAQ
- **High Performance ADCs and TDCs** and time distribution
- **Extreme environments:** cryogenic and radiation-hard electronics
- **Shared access and hubs** to selected imaging technologies and 3D integration



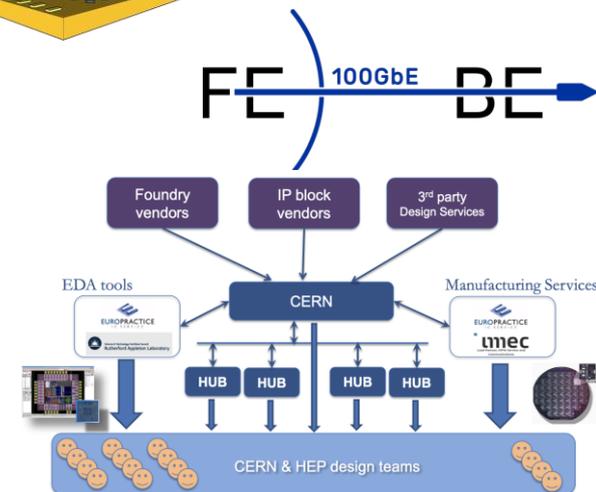
#95

eFPGAs

Fully reconfigurable logic in ASIC design

- The pathway to put ML on-detector!

BDT classifier in 28nm CMOS ASIC

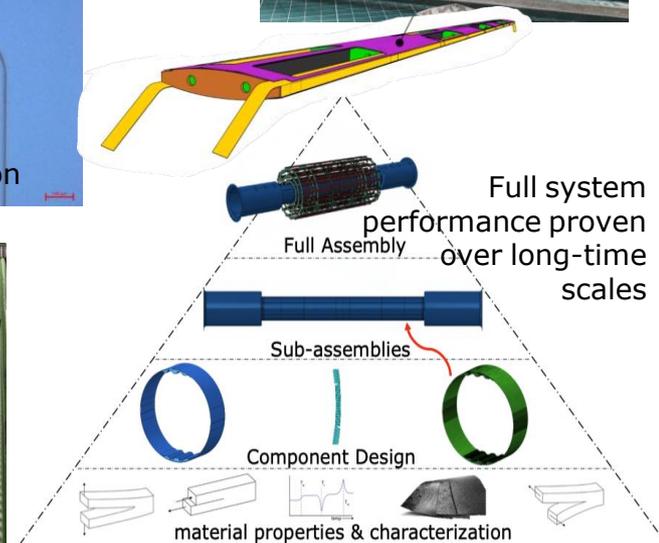
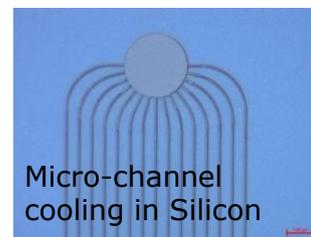


DRD8: Mechanics & Integration

- DRD8 proposal approved by Dec 2024
 - Does not cover all DRDTs, as they are quite diverse
 - Focus on vertex detector mechanics and cooling as emerged from “Forum on Tracker Mechanics” workshop series
- **Advanced materials** and structures for **vertex detectors**:
 - Mechanics for curved sensors, Thin beam pipe, Retractable detectors, MDI, Low-mass hardware, alignment
 - Characterization of Material properties and database
- **Cooling**: Airflow, Evaporative CO₂ and new fluids (Krypton), Microchannel cooling in Si, Cooling tubes welding and material investigations
- **Robots** and **Virtual reality** to simulate/remote control access in restricted areas
- **Software** tools to connect engineering design with physics simulation (e.g. connect GEANT4 with CAD)

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



Establish long-term funding

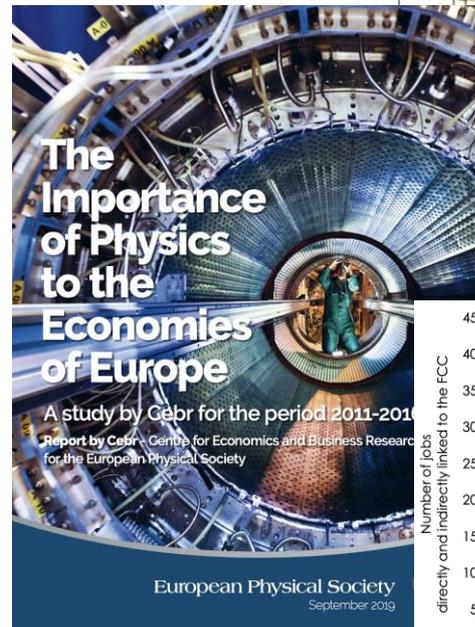
GSR4

DRD collaborations do not bring funding ab initio

- Only resource-loaded projects described in MoUs will be backed up by funding agencies commitments → 2nd phase of setting up DRD collaborations

Funding agencies need to be convinced that detector R&D is a good investment

- Benefit not only for HEP, but also **astroparticle** and **nuclear physics**
- **Society at large:** job creation, education, training, applications and KT to other domains, e.g., medical physics (dosimetry, PET, imaging,..), automotive, environmental,...
- **No metric exists** to quantify socioeconomic impact of instrumentation, but other studies exist
 - Cebr study for EPS (to be updated soon)
 - WIFO report: FCC will generate €50 billion in worldwide value added and create around 26,000 jobs annually



ECFA Detector Roadmap

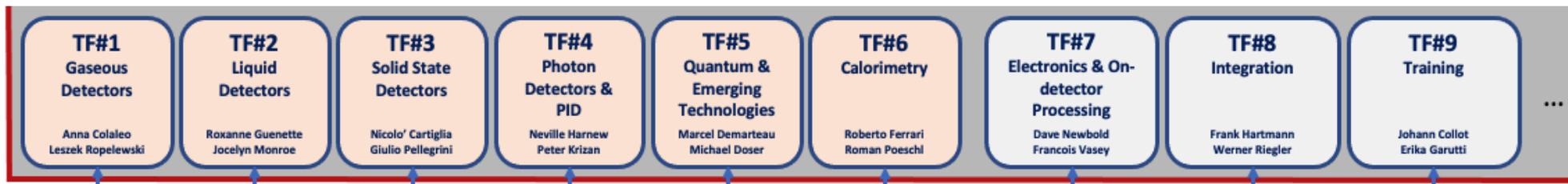
*The community should define a **global detector R&D roadmap** that should be used to **support proposals at the European and national levels.*** **ESPPU 2020**

ECFA detector roadmap released in 2021 with [full document](#) (200 pages) and [synopsis](#) (~10 pages) based on a **community-driven effort** with many community meetings

The full document can be referenced as DOI: 10.17181/CERN.XDPL.W2EX

Document contains:

- Overview of **future facilities** (EIC, ILC, CLIC, FCC-ee/hh, Muon collider) or major **upgrades** (ALICE, Belle-II, LHC-b,...) and their **timelines**
- Ten “**General Strategic Recommendations**” (GSRs) see next slide....
- **Nine Technology domains with Task Forces (TF) areas:**
 - The **most urgent R&D topics** in each domain, identified as **Detector R&D Themes (DRDTs)**



R&D Topics and DRDTs

- The most urgent R&D topics in each Task Force area are identified by **Detector Readiness Matrix**

- Detector R&D Themes (DRDTs)** were formulated as high-level deliverables:

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

Semiconductor Example

- Both were used to define work packages, projects, and deliverables in DRD collaboration proposals

