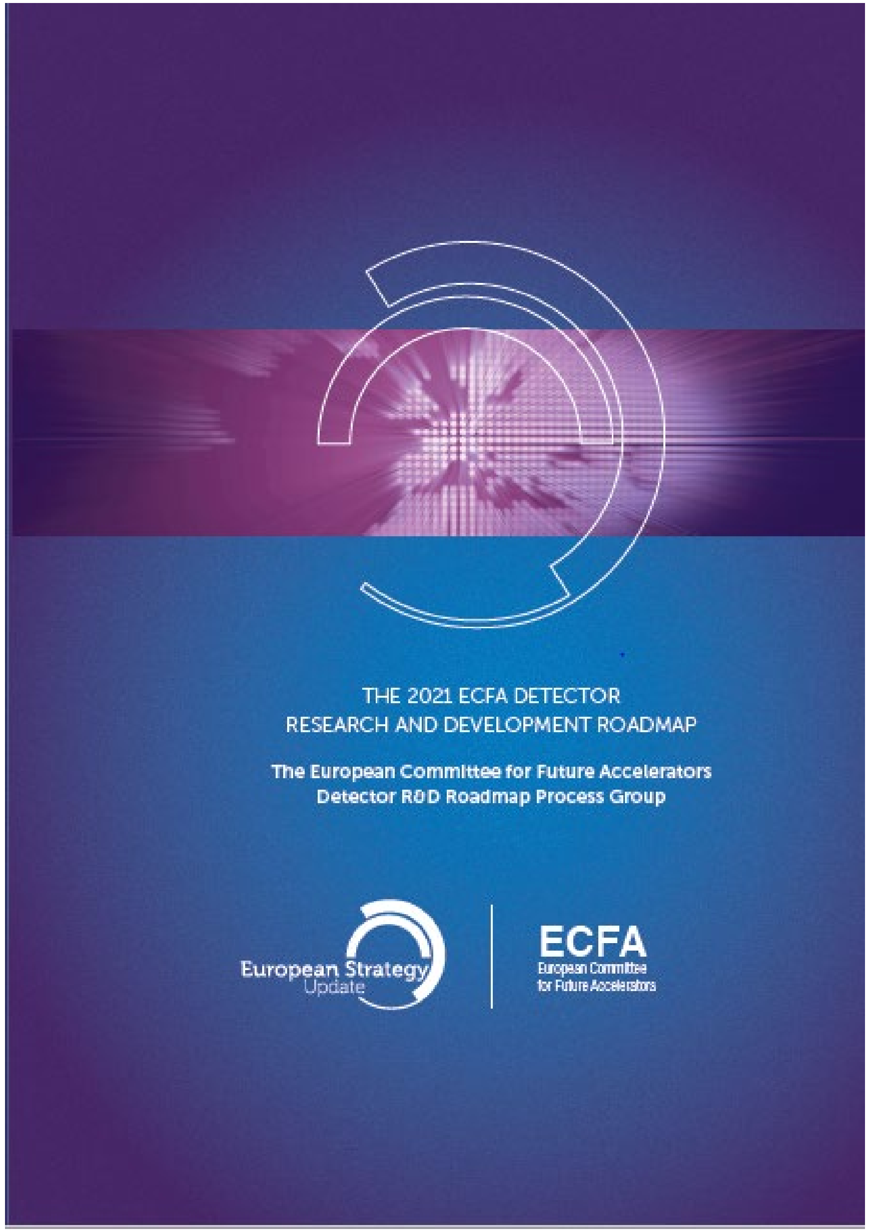
The 2021 ECFA Detector R&D RoadMap



S. Dalla Torre
INFN - Trieste

In my report

- The **scientific context**: the landscape of the RoadMap
- The process of **building up the RoadMap**, shortly recalled
- An introduction to **the conclusive document** of the Roadmap process
  - Relevant aspects and recommendations in the various technology sectors
- Focus on the **Training in the detector sector** and on the **Acknowledgement of the detector relevance and keyrole in HEP**, as resulting from the roadmap process
- **General reccommendations**, transversal to technologies
  - Elements of scientific policy
- RoadMap implementation is starting

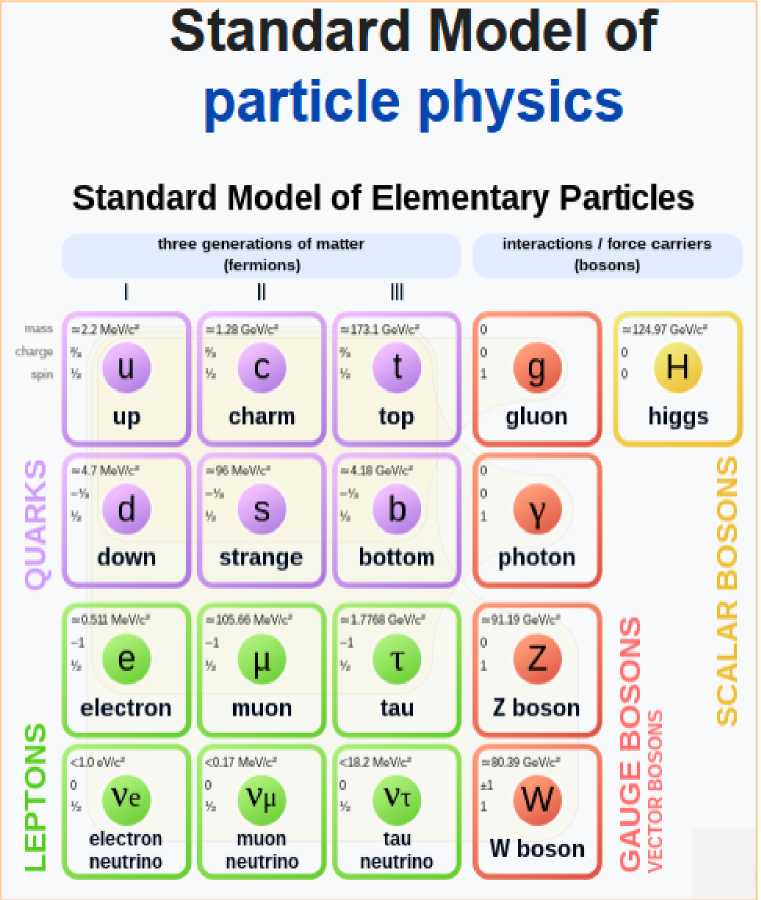
Please, note

- A selection of arguments and examples for these 2h lecture is a must; selected:
    - The **RoadMap process**
    - **EXAMPLES of detector technologies** with focus on frontier studies
        - No space for a comprehensive review !
    - Key aspects of the **scientific policy** messages from the roadmap
        - For the young audience: this choice because this is YOUR future

- Almost always **w/o explicit references**
    - Large majority of the material from the events of the roadmap process
    - Occasionally, also from other sources
    - A global acknowledgement of the Detector R&D community, so active, so creative
        - I am indebted to all the colleagues in this community

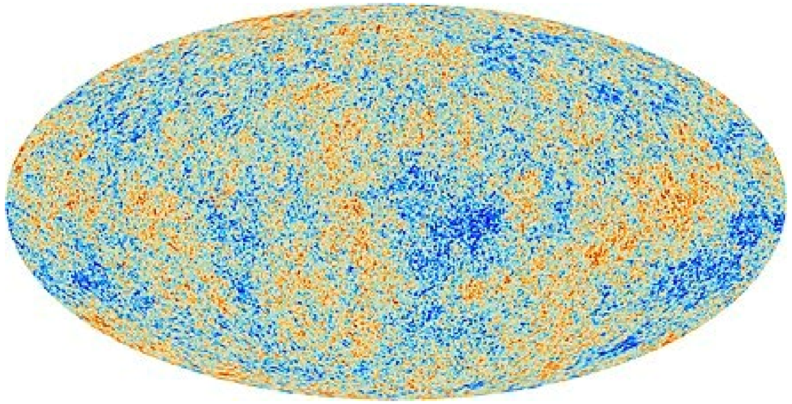
The scientific context: the landscape of the RoadMap

Fundamental science:
present status in a nutshell

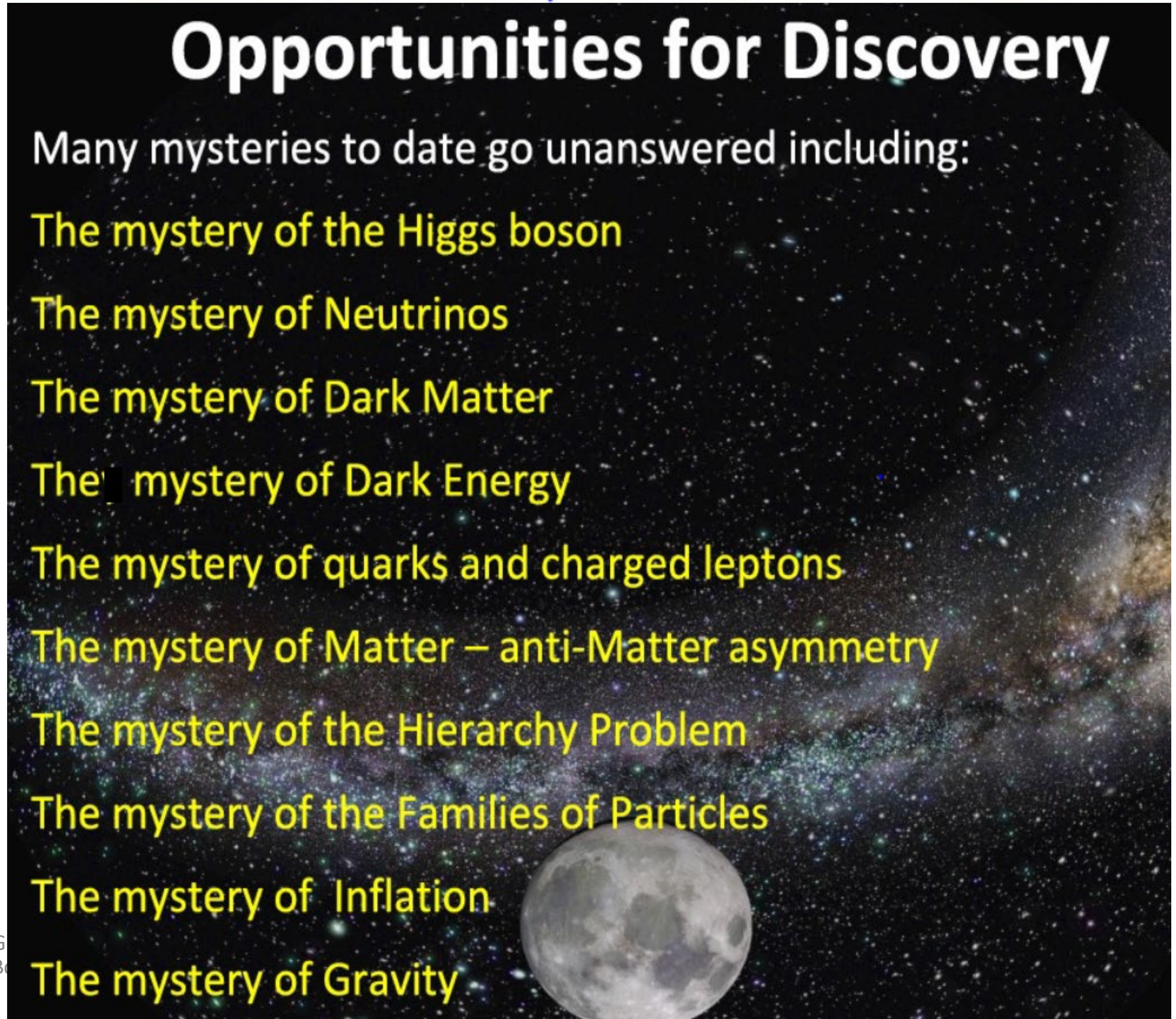


Cosmology Standard Model

Lambda-CDM model

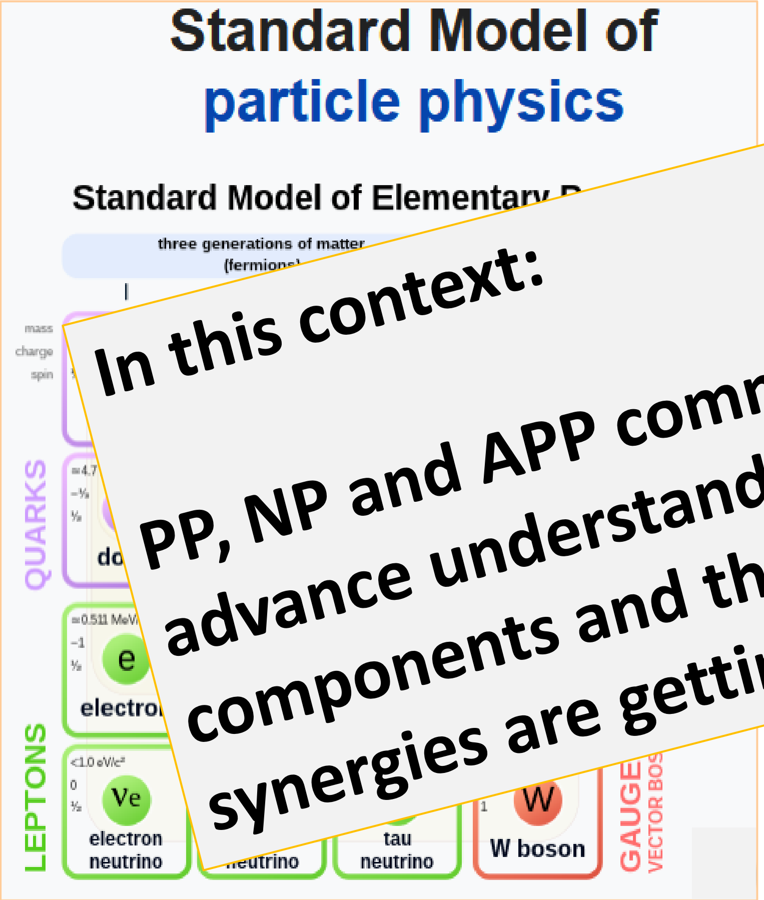


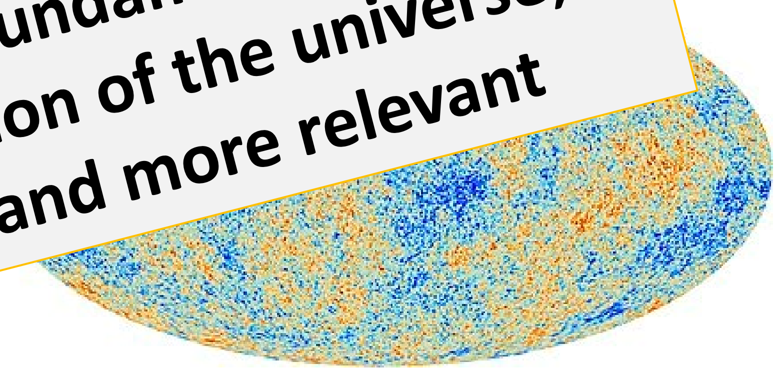
Fundamental science: nevertheless, a number of open questions



From a recent compilation by I. Shipsey, PDM 2022

Fundamental science:
present status in a nutshell

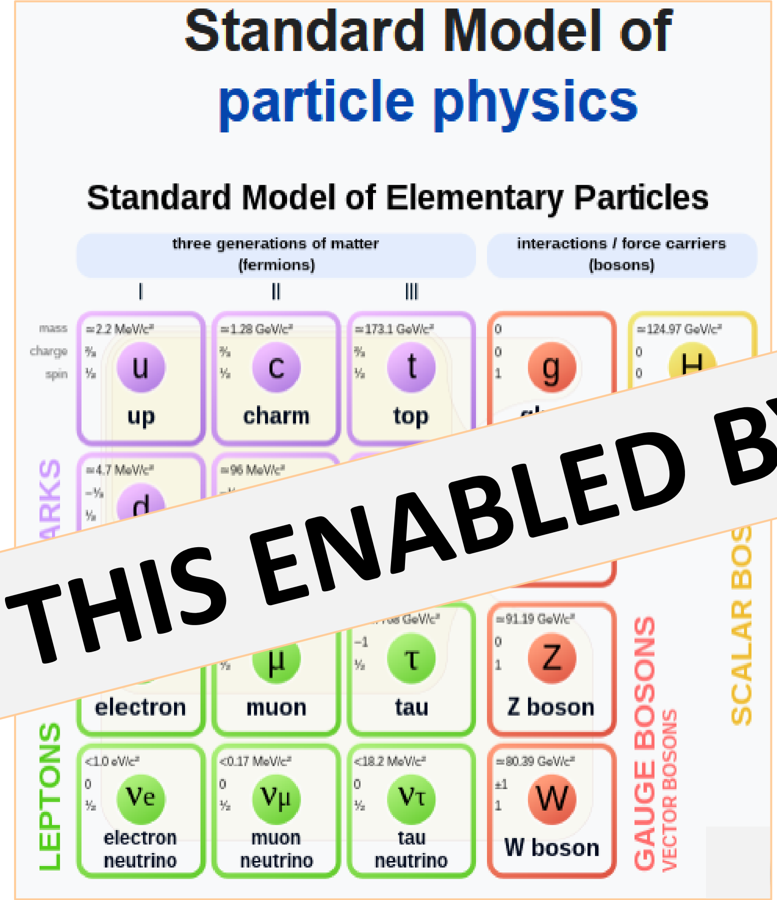




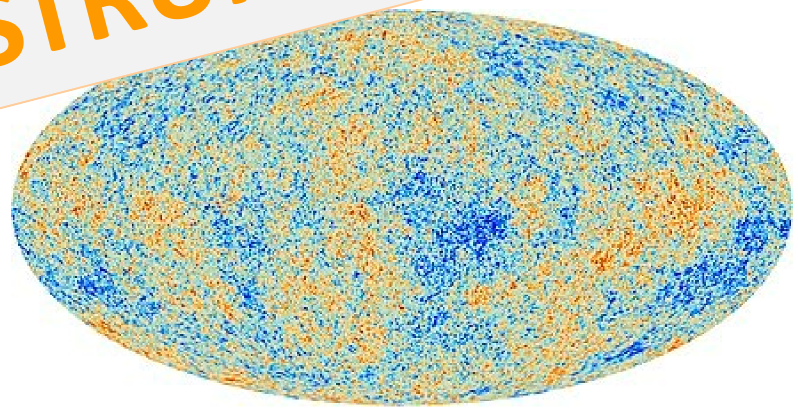
In this context:

PP, NP and APP communities are at work to advance understanding the fundamental components and the evolution of the universe; synergies are getting more and more relevant

Fundamental science: present status in a nutshell



Cosmology Standard M



ALL THIS ENABLED BY INSTRUMENTATION

Instrumentation always key in fundamental physics

- The list of Nobel awards is not a complete and unbiased picture of the progress in physics; nevertheless, it provides important messages

1927: C.T.R. Wilson, Cloud Chamber
1939: E. O. Lawrence, Cyclotron & Discoveries
1948: P.M.S. Blacket, Cloud Chamber & Disccoveries
1950: C. Powell, Photographic Method & Discoveries
1954: Walter Bothe, Coincidence Method & Discoveries
1960: Donald Glaser, Bubble Chamber
1968: Luis Alvarez, Bubble Chamber & Discoveries
1992: Georges Charpak, Multi Wire Proportional Chamber

- More recently, Nobel awards are still strictly related to the instrumentation progress:
  - **2013:** **F. Englert e P. Higgs, Higgs boson theory**
  - **2015:** **T. Kajita e A. B. McDonald, neutrino oscillations**
  - **2017:** **R. Weiss, K. Thorne e B. Barish, observation of the gravitational waves**

The process of building up the RoadMap

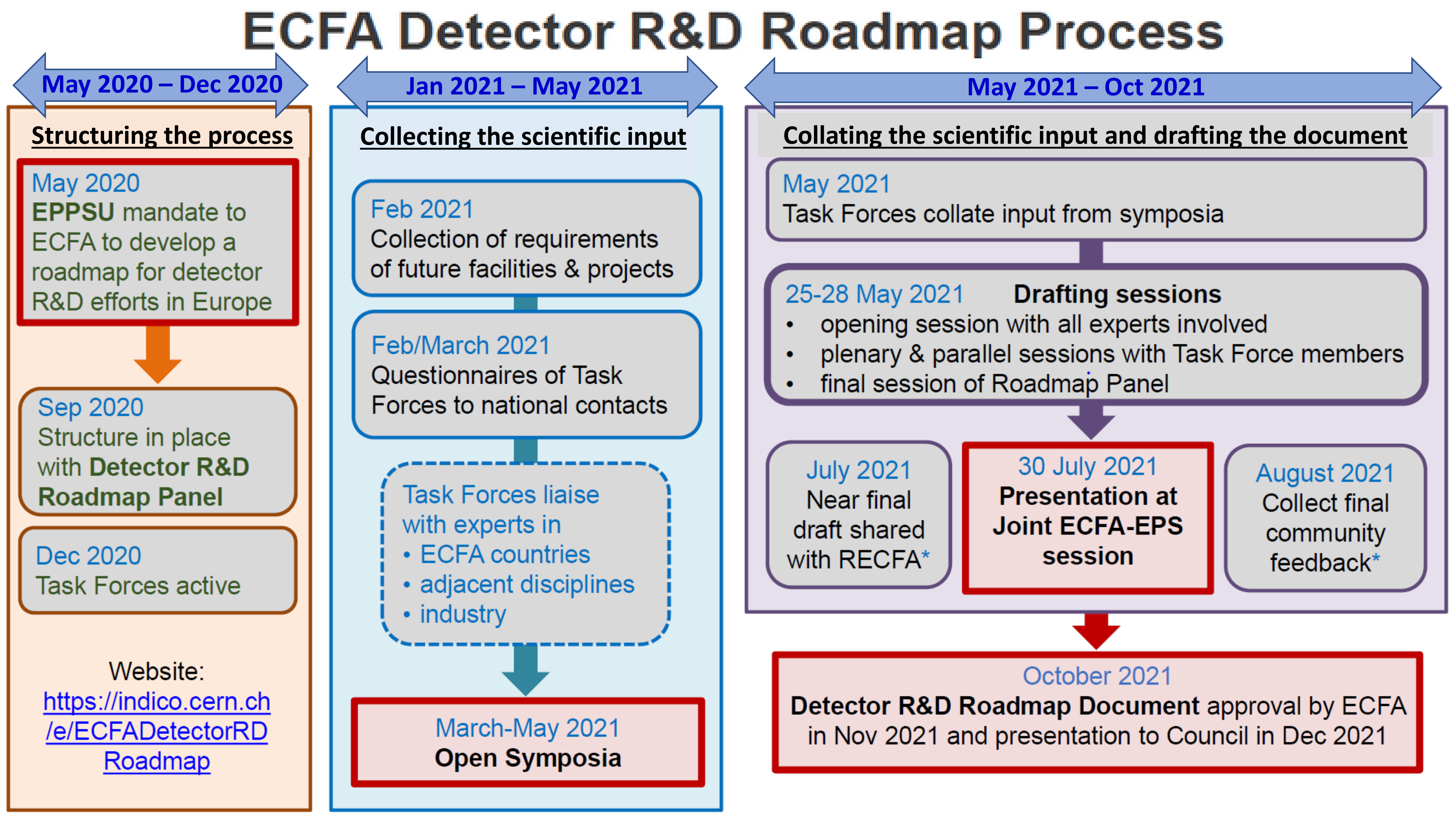
Update of the European Strategy for Particle Physics

4. Other essential scientific activities for particle physics

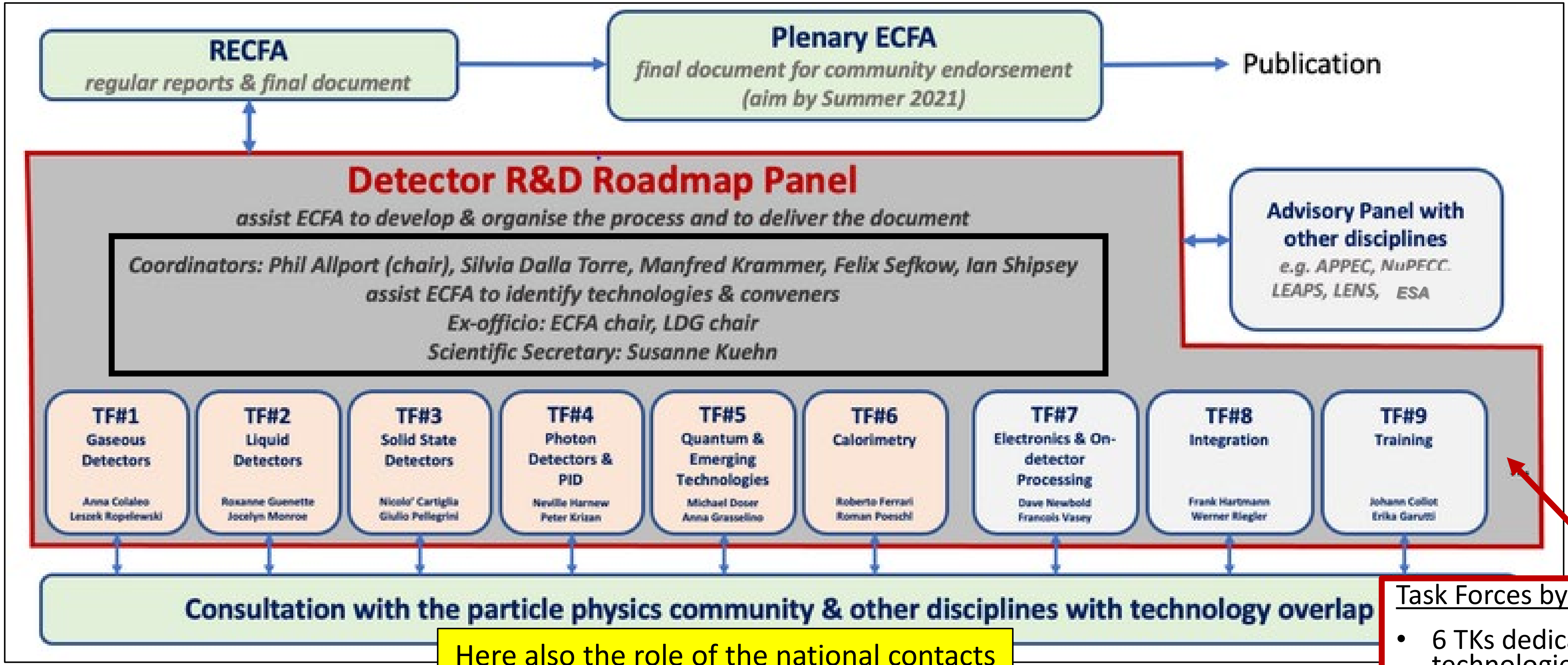
…

*c) The **success of particle physics experiments relies on innovative instrumentation and state-of-the-art infrastructures.** To prepare and realise future experimental research programmes, the community must **maintain a strong focus on instrumentation**. **Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities**. Synergies between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development process and increase opportunities for more technology transfer benefiting society at large. Collaborative platforms and consortia must be adequately supported to provide coherence in these R&D activities. The community should define a **global detector R&D roadmap** that **should be used to support proposals at the European and national levels.***

Organised by ECFA, a roadmap should be developed by the community to balance the detector R&D efforts in Europe, taking into account progress with emerging technologies in adjacent fields. The roadmap should identify and describe a diversified detector R&D portfolio that has the largest potential to enhance the performance of the particle physics programme in the near and long term. …


ECFA Detector R&D Roadmap Process
May 2020 – Dec 2020
Jan 2021 – May 2021
May 2021 – Oct 2021
Structuring the process
May 2020
EPPSU mandate to ECFA to develop a roadmap for detector R&D efforts in Europe
Sep 2020
Structure in place with Detector R&D Roadmap Panel
Dec 2020
Task Forces active
Website:
https://indico.cern.ch/e/ECFADetectorRDRoadmap
Collecting the scientific input
Feb 2021
Collection of requirements of future facilities & projects
Feb/March 2021
Questionnaires of Task Forces to national contacts
Task Forces liaise with experts in
• ECFA countries
• adjacent disciplines
• industry
March-May 2021
Open Symposia
Collating the scientific input and drafting the document
May 2021
Task Forces collate input from symposia
25-28 May 2021
Drafting sessions
• opening session with all experts involved
• plenary & parallel sessions with Task Force members
• final session of Roadmap Panel
July 2021
Near final draft shared with RECFA*
30 July 2021
Presentation at Joint ECFA-EPS session
August 2021
Collect final community feedback*
October 2021
Detector R&D Roadmap Document approval by ECFA in Nov 2021 and presentation to Council in Dec 2021

Structuring the process



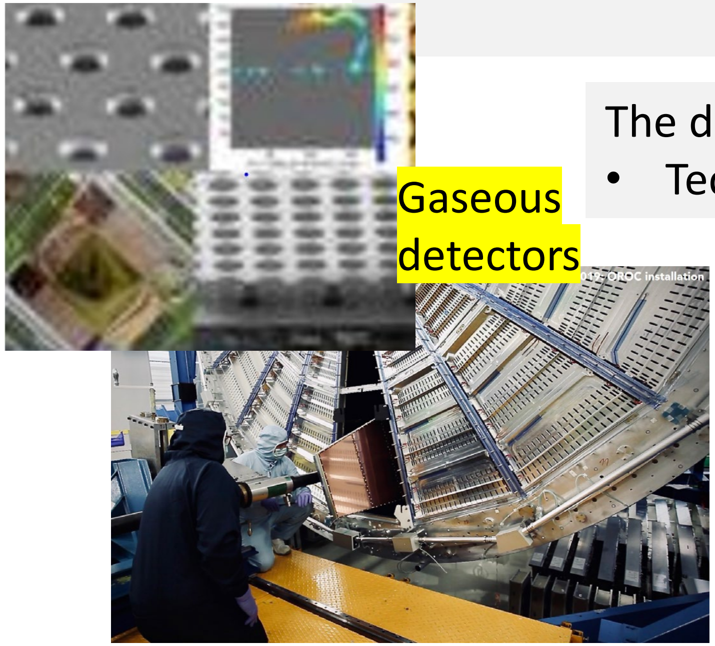
Here also the role of the national contacts
(Italy: Nadia Pastrone)

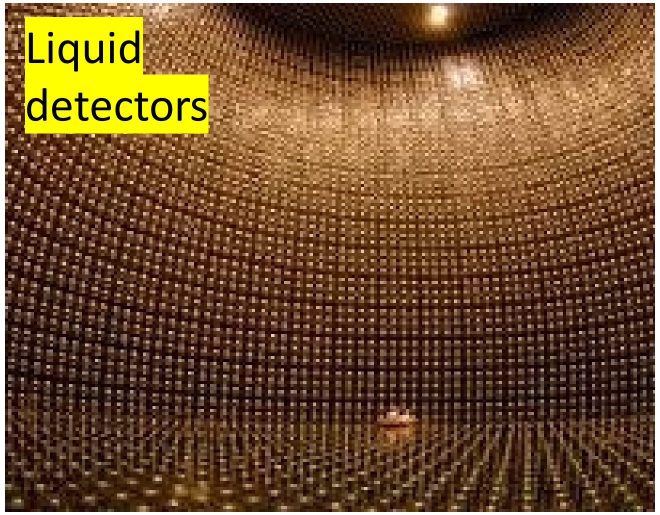
Task Forces by **TECHNOLOGY**

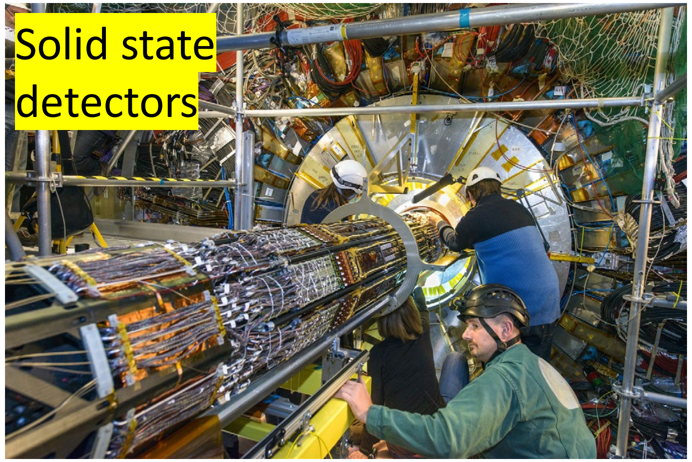
- 6 TKs dedicated to detector technologies
- 3 TKs transversal to the others
  - Please, do not regard TF#9 "Training" as minor

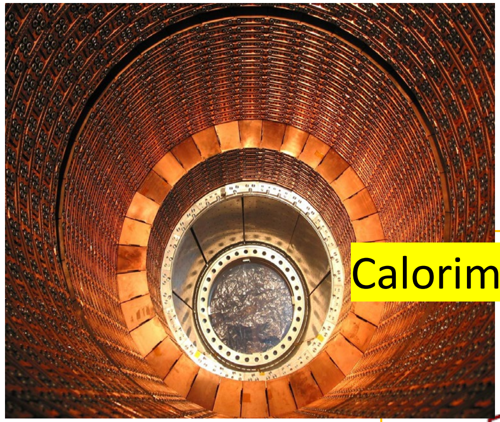
The Task Forces (TF) in a gallery view

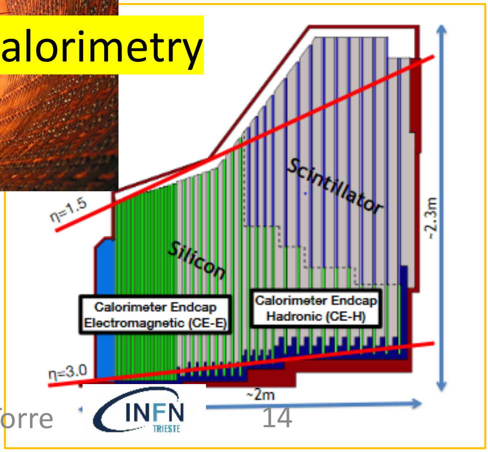
The diagonalization of the subjects is not perfect:
- Technologies & applications w/ technological aspects

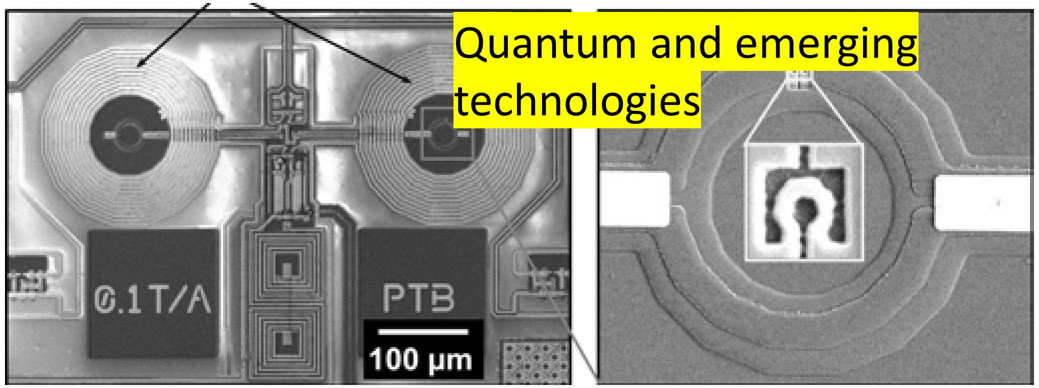




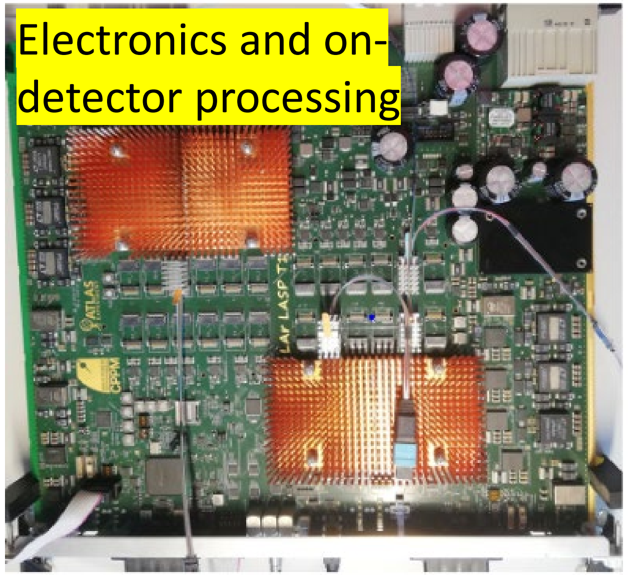


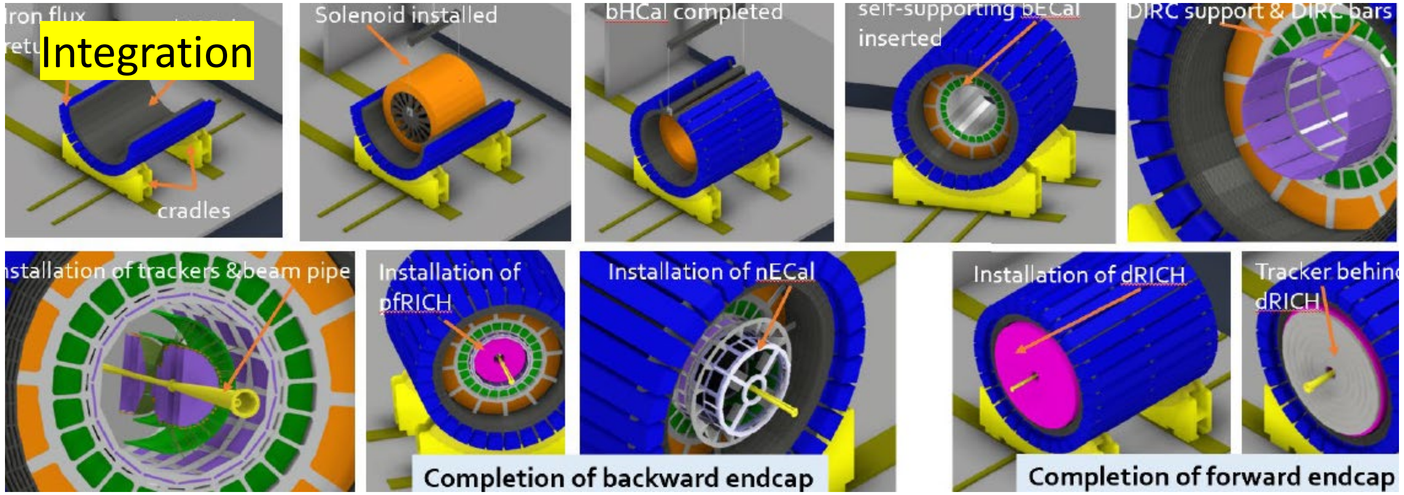






The Task Forces (TF) in a gallery view





Overview of the Panel members and Task Forces

- TF1 Gaseous Detectors
  - Convenors: Anna Colaleo (INFN Bari), Leszek Ropelewski (CERN)
  - Expert members: Klaus Dehmelt (Stonybrook), Laura Fabbietti (TUM Munich), Barbara Liberti (INFN Roma), Joao Veloso (Aveiro)
- TF2 Liquid Detectors
  - Convenors: Roxanne Guenette (Harvard), Jocely Monroe (RHUL)
  - Expert members: Auke-Pieter Colijn (NIKHEF), Antonio Ereditato (Yale/Berne), Ines Gil Botella (CIEMAT), Manfred Lindner (MPI Heidelberg)
- TF3 Solid State Detectors
  - Convenors: Nicolo Cartiglia (INFN Turino), Giulio Pellegrini (IMB-CNM-CSIC)
  - Expert members: Daniela Bortoletto (Oxford), Didier Contardo (IN2P3-IP2I), Ingrid Gregor (DESY and Bonn), Gregor Kramberger (Jozef Stefan Insitute), Heinz Pernegger (CERN)
- TF4 Photon Detectors and Particle Identification Detectors
  - Convenors: Neville Harnew (Oxford), Peter Krizan (Jozef Stefan Insitute)
  - Expert members: Ichiro Adachi (KEK), Christian Joram (CERN), Eugenio Nappi (INFN Bari), Christian Schultz-Coulon (Heidelberg)
- TF5 Quantum and Emerging Technologies
  - Convenors: Michael Doser (CERN), Anna Grasselino (Fermilab)
  - Expert members: Caterina Braggio (Padova), Marcel Demarteau (ORNL), Andy Geraci (NWU), Peter Graham (Stanford), John March Russell (Oxford), Stafford Withington (Cambridge)
- TF6 Calorimetry
  - Convenors: Roberto Ferrari (INFN Pavia), Roman Poeschl (IN2P3-IJCLab)
  - Expert members: Martin Aleksa (CERN), Dave Barney (CERN), Frank Simon (MPP Munich), Tommaso Tabarelli de Fatis (INFN Milano-Bicocca)
- TF7 Electronics and On-detector Processing
  - Convenors: Dave Newbold (RAL), Francois Vasey (CERN)
  - Expert members: Niko Neufeld (CERN), Valerio Re (INFN Pavia), Christophe de la Taille (IN2P3-OMEGA), Marc Weber (KIT)
- TF8 Integration
  - Convenors: Frank Hartmann (KIT), Werner Riegler (CERN)
  - Expert members: Corrado Gargiulo (CERN), Filippo Resnati (CERN), Herman Ten Kate (Twente), Bart Verlaat (CERN), Marcel Vos (IFIC Valencia)
- TF9 Training
  - Convenors: Johann Collot (IN2P3-LPSC), Erika Garutti (DESY and Hamburg)
  - Expert members: Richard Brenner (Uppsala), Niels van Bakel (Nikhef), Claire Gwenlan (Oxford), Jeff Wiener (CERN)

INFN
Conveners: 3 / 18
Members: 5 / 40

In total: 14%

Collecting the scientific input 1/2

- **Input from future facilities**
  - **2 sessions in Feb 2021**

INFN
Speakers: 1/13

Session I (in general collider oriented), afternoon 19 February 2021: Input Session I

- Talk I: HL-LHC (incl. flavour physics)
- Talk II: strong interactions at future colliders
- Talk III: strong interactions at future fixed target facilities
- Talk IV: future linear high energy e+e- machines
- Talk V: future circular high energy e+e- machines
- Talk VI: FCC-hh
- Talk VII: muon collider

Session II (in general non-collider oriented) afternoon 22 February 2021: Input Session II

- Talk I : neutrino short and long baseline
- Talk II: astro-particle neutrinos
- Talk III: DM-like facilities
- Talk IV: decay facilities
- Talk V: low energy facilities

to reach the whole scientific material:
https://indico.cern.ch/e/ECFADetectorRDRoadmap

Collecting the scientific input 2/2

to reach the whole scientific material:
https://indico.cern.ch/e/ECFADetectorRDRoadmap

- **Detector symposia**
  - **9 symposia in Feb-May 2021:**
    Major source of information!

INFN
Speakers: 18/111 (16%)

Task Force 1: Gaseous Detectors

Symposium date: Thursday 29.4.2021
Indico link to agenda

Task Force 2: Liquid Detectors

Symposium date: Friday 9.4.2021
Indico link to agenda

Task Force 3: Solid State Detectors

Symposium date: Friday 23.4.2021
Indico link to agenda

Task Force 4: Photon Detectors and Particle Identification Detectors

Symposium date: Thursday 6.5.2021
Indico link to agenda

Task Force 5: Quantum and Emerging Techologies

Symposium date: Monday 12.4.2021
Indico link to agenda

Task Force 6: Calorimetry

Symposium date: Friday 7.5.2021
Indico link to agenda

Task Force 7: Electronics and On-detector Processing

Symposium date: Thursday 25.3.2021
Indico link to agenda

Task Force 8: Integration

Symposium date: Wednesday 31.3.2021
Indico link to agenda

Task Force 9: Training

Symposium date: Friday 30.4.2021
Indico link to agenda

I make large use of the material
presented at the symposia
I acknowledge all the great speakers !

OTHER DISCIPLINES considered in the process

- **APPEC** – astroparticle physics
- **NuPECC** – nuclear physics
- **LEAPS** – accelerator-based photon source
- **LENS** – advanced neutron sources
- **ESA** – space

Advisory Panel with Other Disciplines

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

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

Named expert contacts		
APPEC	TF1	Jennifer L Raaf (Fermilab)
	TF2	Manfred Lindner (MPI Heidelberg)
	TF3	Fabrice Retiere (TRIUMF)
	TF4	Tina Pollmann (Nikhef)
	TF5	Harald Lück (Hannover)
	TF6	Federica Petricca (MPI Munich)
	TF7	Marc Weber (KIT)
	TF8	Aldo Ianni (LNGS)
	TF9	Katrin Link (APPEC)
NuPECC	TF1	Laura Fabbietti (TUM Munich)
		Bernhard Ketzer
	TF2	
	TF3	Luciano Musa (CERN)
		Michael Deveaux
	TF4	Eugenio Nappi (INFN Bari)
		Jochen Schwiening
	TF5	: Christian Enss (Heidelberg),
	TF6	Thomas Peitzmann (Utrecht)
		Ulrike Thoma (Bonn)
	TF7	David Silvermyr (Lund)
		Christian J. Schmidt
	TF8	Werner Riegler (CERN)
		Lars Schmitt
	TF9	Michael Deveaux,
LEAPS	Bernd Schmitt (PSI)	
	Fabienne Orsini	
	Steve Aplin (European	
	Heinz Graafsma (DESY)	

Named contacts for each TF where appropriate

Many thanks to these experts for their advice and availability

LENS	TF1	Bruno Guerard (ILL)
	TF2	Manfred Lindner (MPI Heidelberg)
	TF3	
	TF4	
	TF5	Helmut Schober (ILL)
	TF6	
	TF7	Bruno Guerard (ILL)
	TF8	
	TF9	
ESA	TF1	Nick Nelms
	TF2	
	TF3	Brian Shortt
		Nick Nelms
		Giovanni Santin
		Alessandra Constantino Mucio
	TF4	Brian Shortt
		Peter Verhoeve
		Sarah Wittig
		Nick Nelms
		Giovanni Santin
	TF5	Peter Verhoeve
		Sarah Wittig
		Nick Nelms
	TF6	Nick Nelms
	TF7	Joerg Ter Haar
		Christophe Honvault
		Nick Nelms
		Alessandra Constantino Mucio
	TF8	Massimo Braghin
	TF9	Christophe Honvault

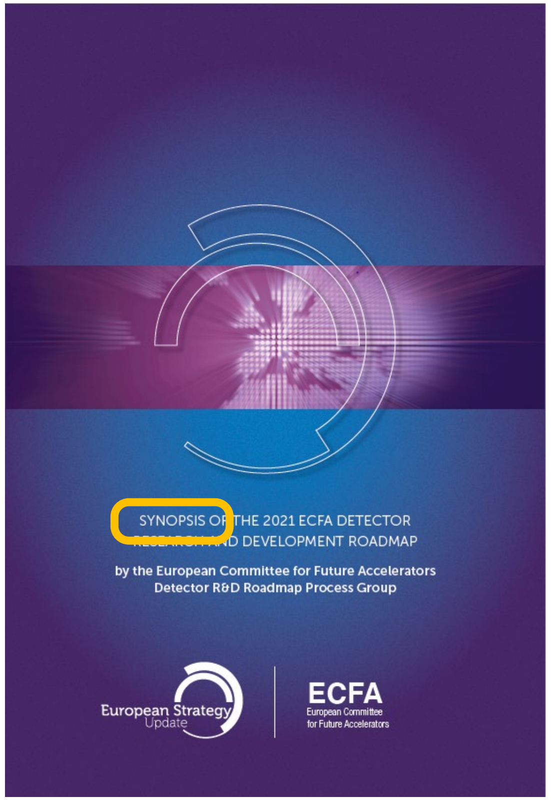
An introduction to the conclusive document: general aspects

Basic information

- ~ 250
- Document structure
  - ➢ Introduction
  - ➢ A chapter per TF (9 FTs)
    - Introduction
    - Main drivers from the facilities
    - Key technologies
    - Observations
    - Recommendations
    - References
  - ➢ General Observations and Considerations
  - ➢ Conclusions

https://indico.cern.ch/event/957057/page/23281-the-roadmap-document

- Available also a synopsis for external readers
  - 8 pages, colourfull
  - Available in printed form



Authors

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

INFN
9 / 68 (13%)

Goals

- Match EPPSU prescriptions:
  - “Identify and describe a **diversified detector R&D portfolio** that has the largest potential **to enhance** the performance of **the particle physics programme in the near and long term**”
  - Considering projects listed in the Deliberation Document of the EPPSU ”**High-priority** future initiatives" or “**Other essential scientific activities** for particle physics"
- Create a **time-ordered technology requirements** driven R&D roadmap
- Other aspects to be considered:
  - Bring out **synergies** and stress **interconnections** between developments of similar technologies needed at different times by **different programmes**
  - **Facilities needed for detector evaluation**, including test beams and different types of irradiation sources, along with the advanced instrumentation required for these;
  - **Infrastructures facilitating detector developments**, including technological workshops and laboratories, as well as tools for the development of software and electronics;
  - **Networking structures** in order to ensure *collaborative environments*, to help in the *education and training, for cross-fertilisation* between different technological communities, and in view of *relations with industry*;
  - **Overlaps with neighbouring fields** and key specifications required for exploitation in other application areas;
  - **Opportunities for industrial partnership** and technical developments needed for potential commercialisation.

Report & timelines

- Reference timelines used in the report, as dictated from CERN, ECFA and other external bodies

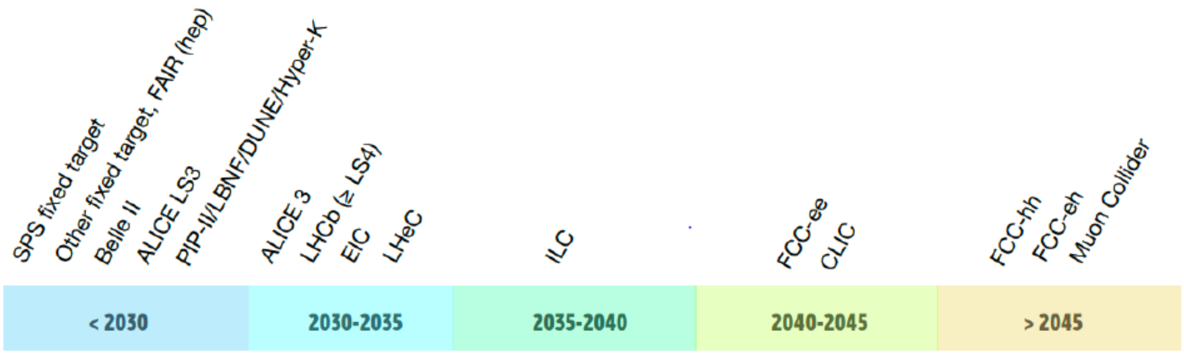


Figure 3: Large Accelerator Based Facility/Experiment Earliest Feasible Start Dates.

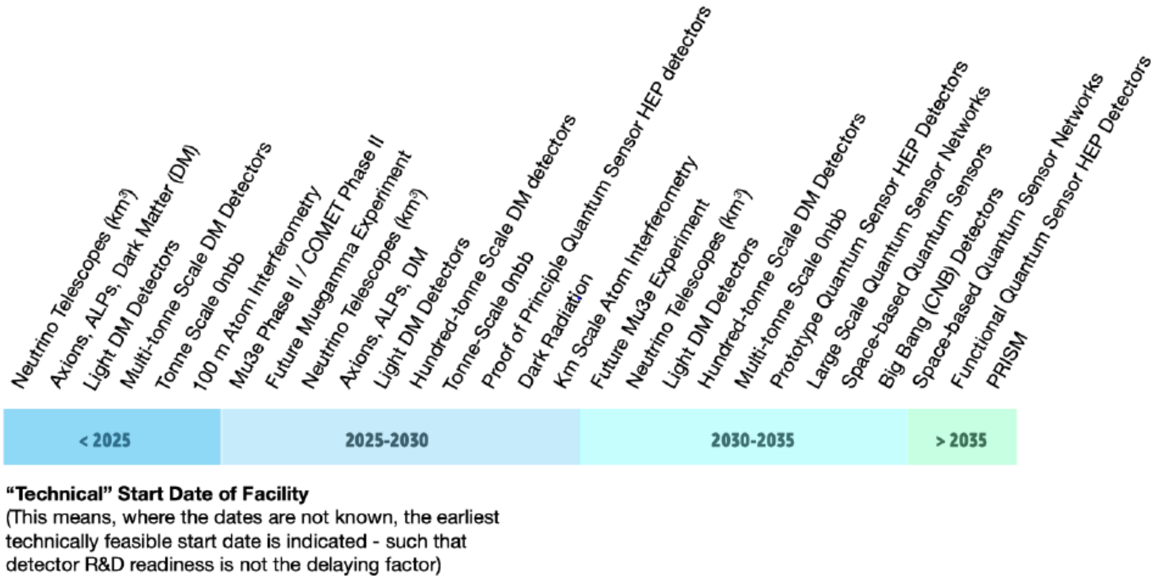


Figure 4: (Representative) Smaller Accelerator and Non-Accelerator Based Experiments Start Dates (*not intended to be at all an exhaustive list*).

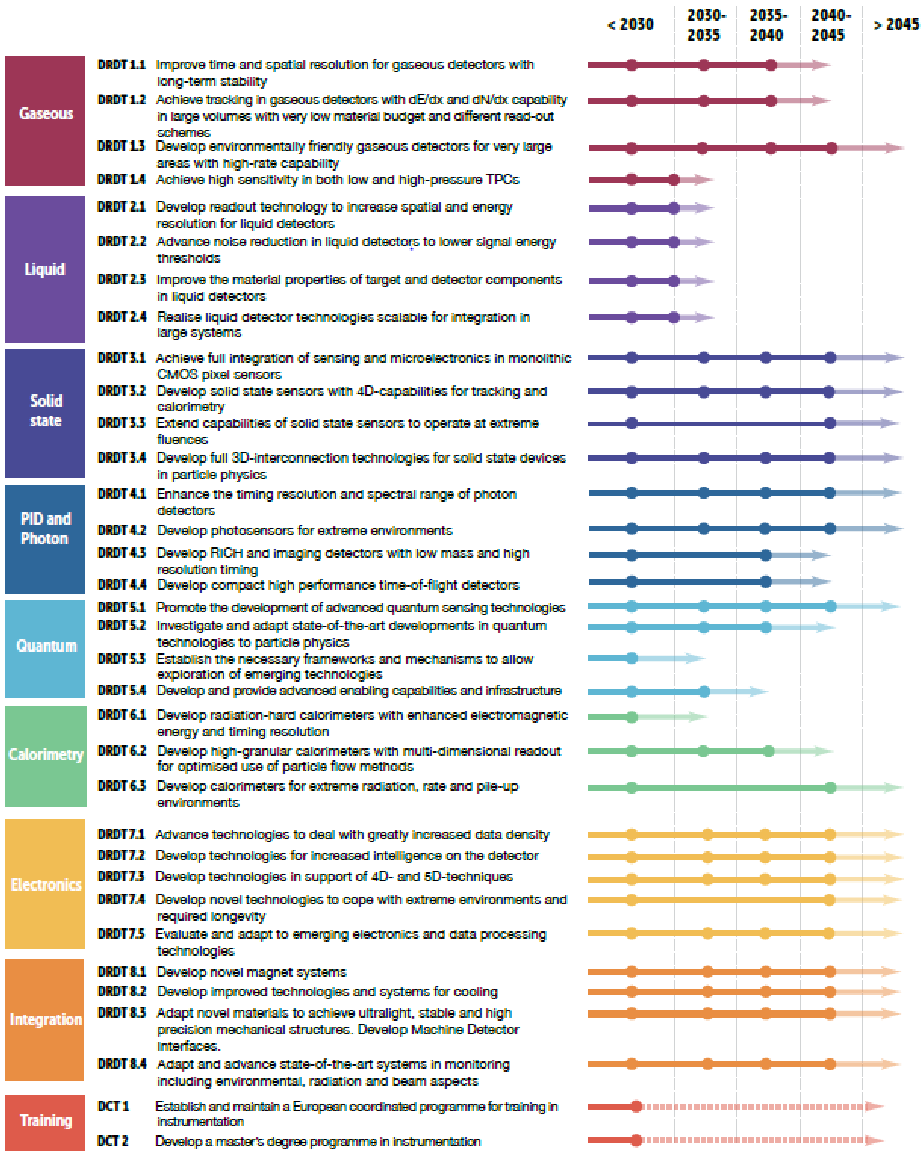
Report & timelines

- How reference timelines are used in the report (e.g.)
  - A similar table for each TF
  - The timelines indicate when a certain technology/technological achievement is needed and the relevance it has for the project
  - These tables are not detector development timelines, as dictated by technical/technological considerations

1) Large ton dual-phase (PandaX-4T, LZ, DarkSide -20k, Argo 200k, ARIADNE, ...)
2) Light dark matter, solar axion, 0nbb, rare nuclei&ions and astro-particle reactions, Ba tagging)
3) R&D for 100-ton scale dual-phase DM/neutrino experiments

Report & timelines

- The summarizing timelines (in “Conclusions”) are also based on the needs of the future facility/experiments
  - Diagonalized respect to
    - Detector R&D Themes (DRDTs), for TFs 1-8
    - Detector Community Themes (DCTs), for TF9
  - “short” timelines mainly correspond to science sectors where long-term planning is not needed/not possible



Much more than facility-functional timelines

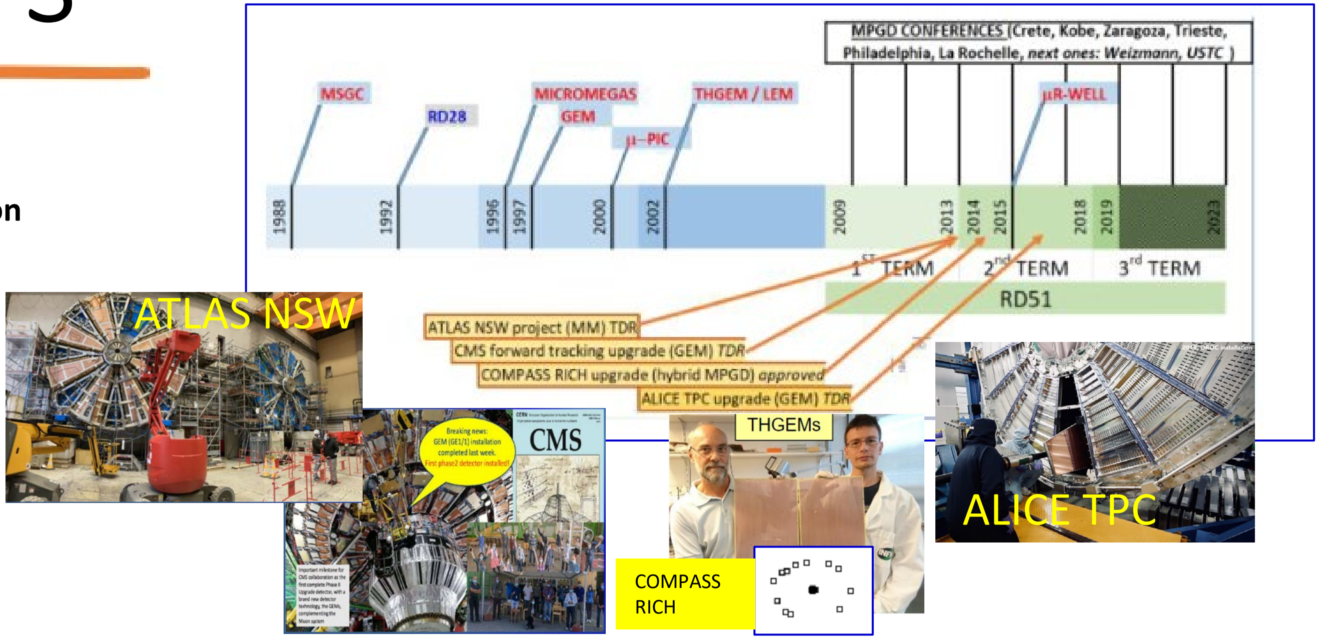
- Deep analysis of
  - Requirements to the detector sector
  - Status and perspectives of detector R&D
    - Including novel ideas
  - Global approaches and requirements to guarantee a successful future to detector R&D
- Resulting in
  - A confirmation of the scientific value of detector R&D studies
  - Underlaying the role that detector novelty has in opening new perspective to science

An introduction to the conclusive document: highlights and examples from the technologies

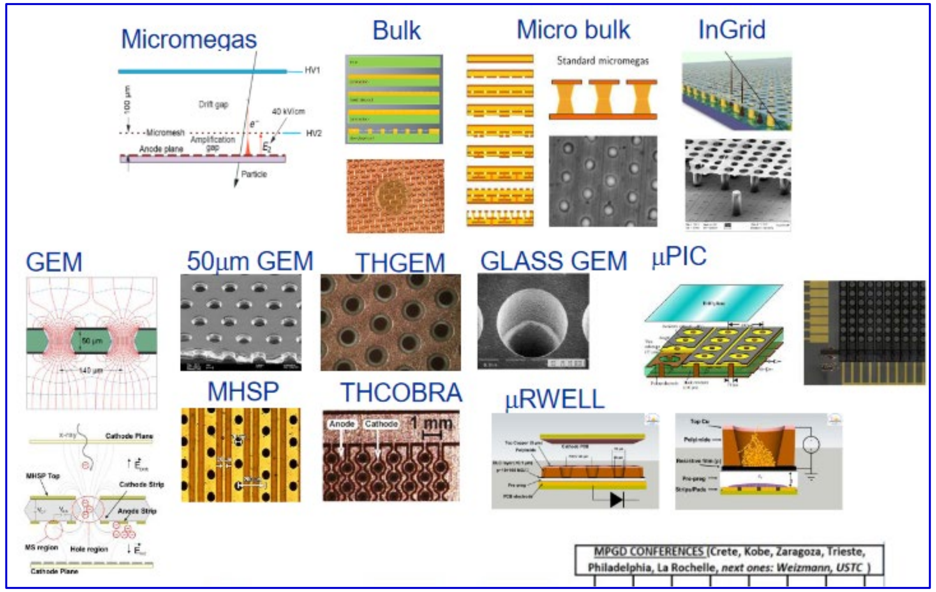
Gaseous Detectors

- A **wide family** of detectors : **MPGDs**
  - **Key role of the RD51 technological Collaboration, CERN-based, world-wide, dedicated to MPGD developments and dissemination**

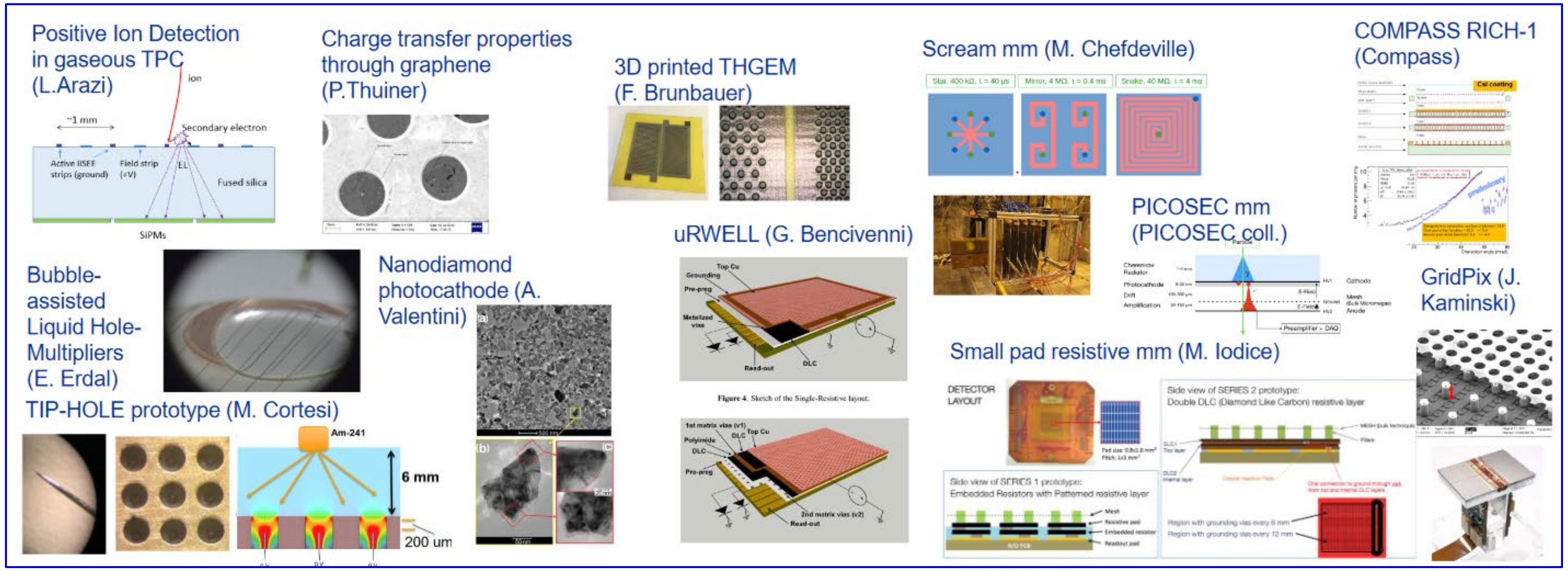
MPGD, the history



MPGD: the present

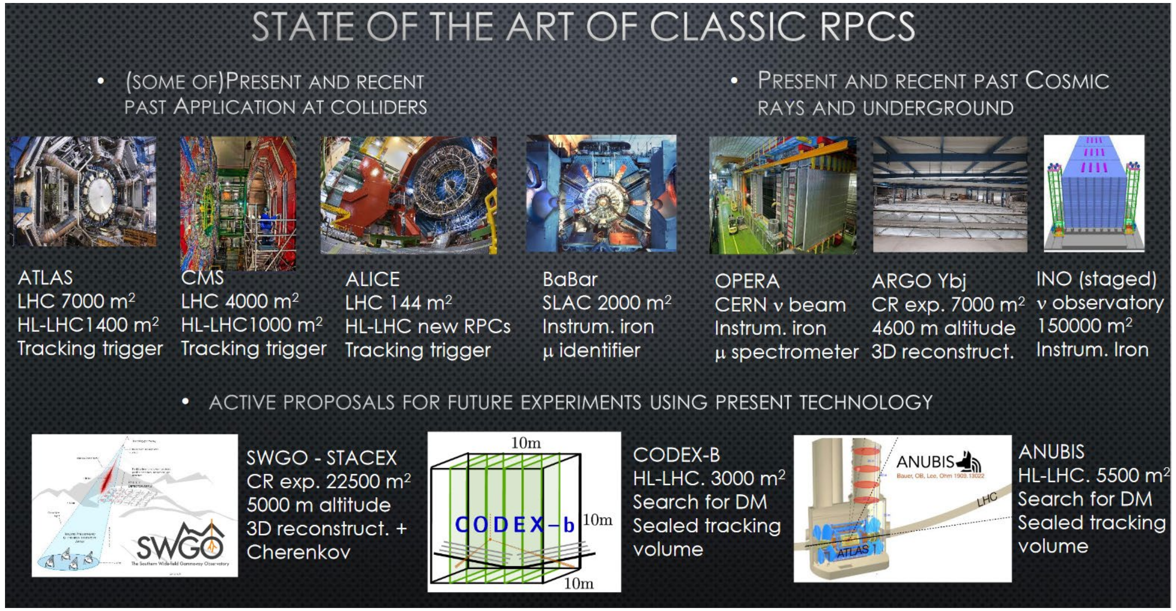


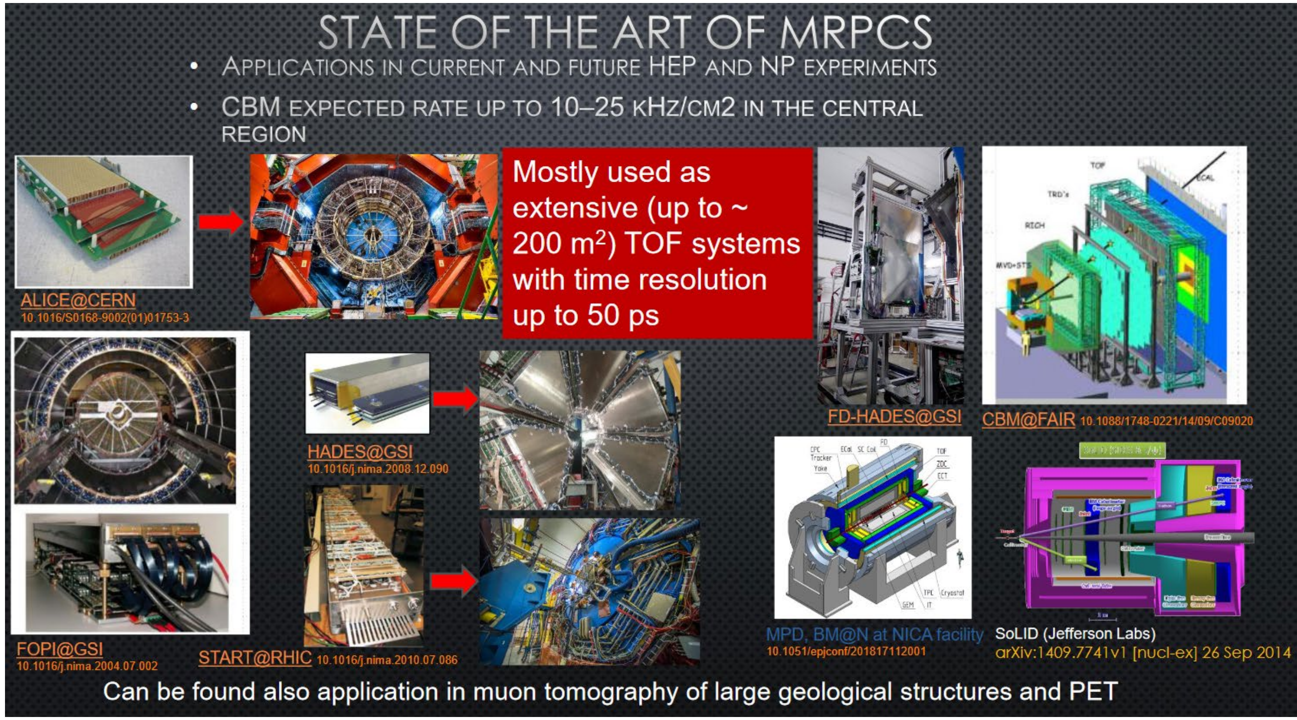
MPGD: New technologies on the way

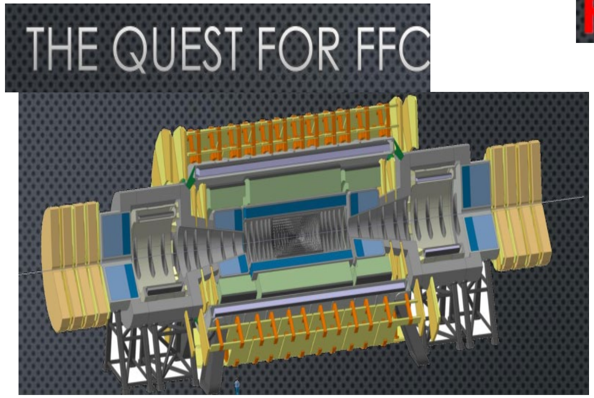


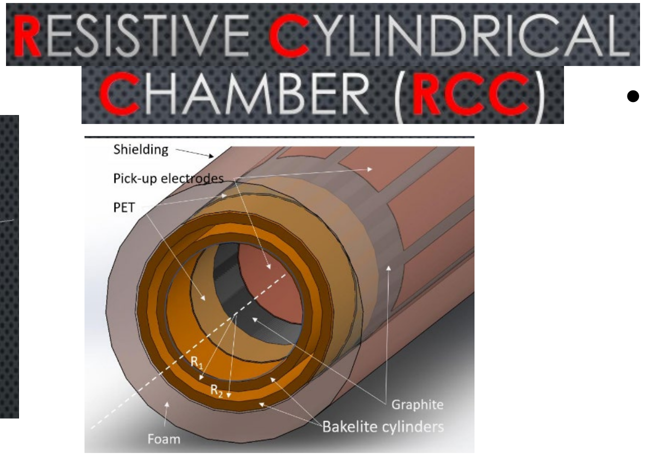
Gaseous Detectors

- A **wide family** of detectors: (m)RPCs







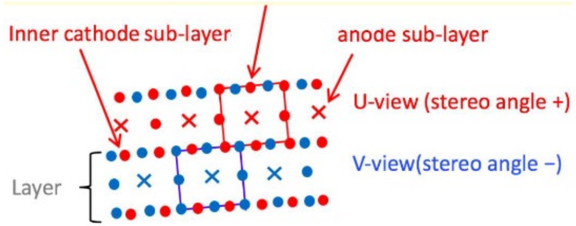


- R&D themes
  - High rates → lower resistance
  - Longevity → lower charge (electronics)
  - Time resolution (~ 50 ps) → thinner mRPCs with increased number of layers
  - 2-D tracking → a new idea: diffusion wave time-walk on graphite electrodes
  - Eco-friendly gasses → smaller gaps, lower gains (electronics)

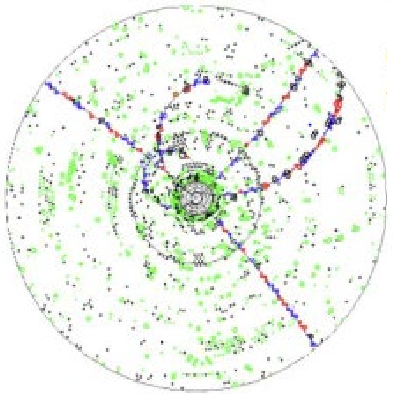
Gaseous Detectors

- A **wide family** of detectors: **large volume drift chambers and TPCs**

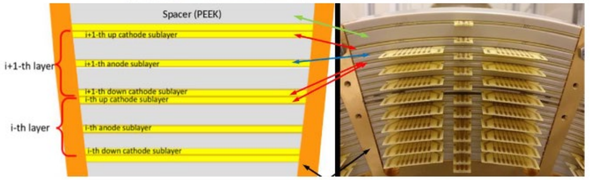
Drift Chambers



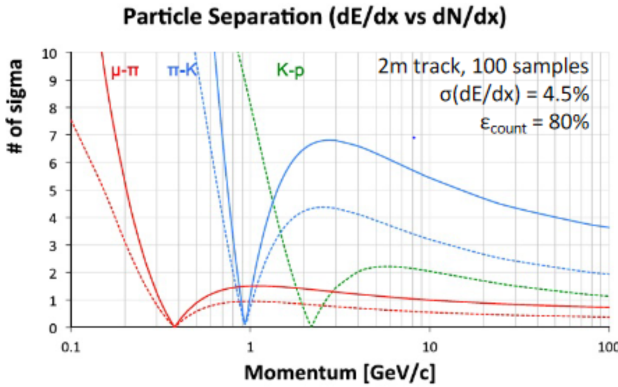
Belle II



MEG-II drift chamber ($\mu \rightarrow e\gamma$ at PSI [11]).

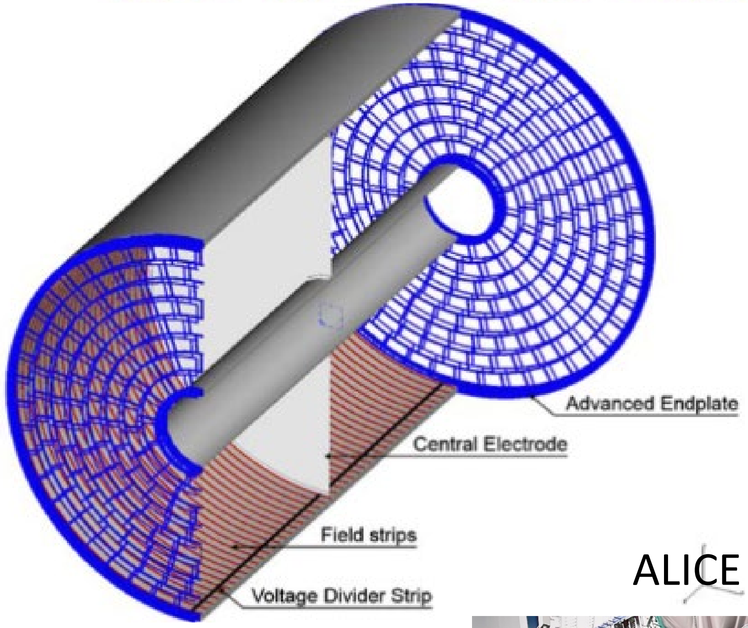


IDEA (Planned) at FCC-ee



Improved dE/dx with cluster counting

MPGD-based TPC with continuous readout



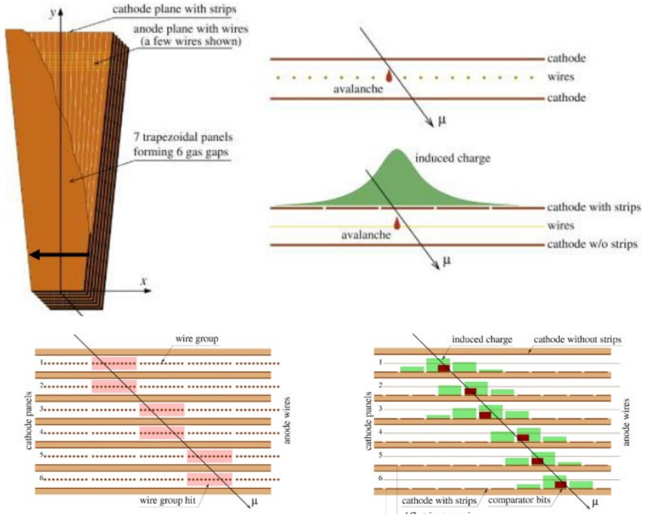
ALICE TPC

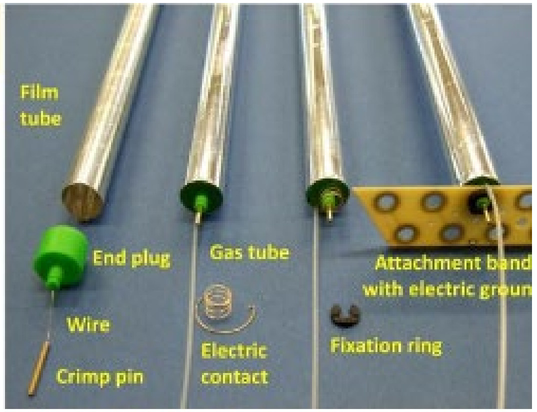
Gaseous Detectors

- A **wide family** of detectors: Straw Tubes, Cathode Strip & Thin Gap Chambers

Cathode Strip Chambers

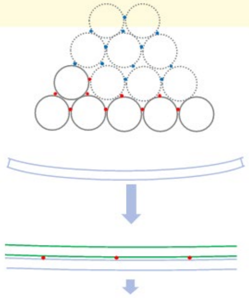
At CMS / ATLAS



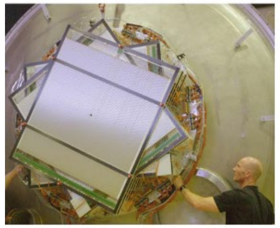


Straw tube components (for PANDA-STT [1])

NA62 Straw station [3].

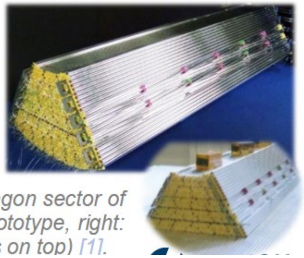


Close-packed glued straw layers sustain wire tension and reduce bending.



COSY-TOF Straw tracker [4]

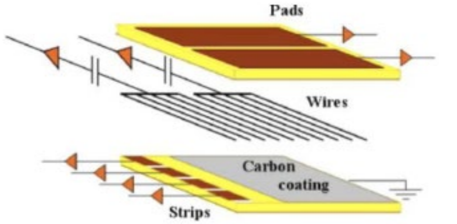
[3], COSY-TOF [5])

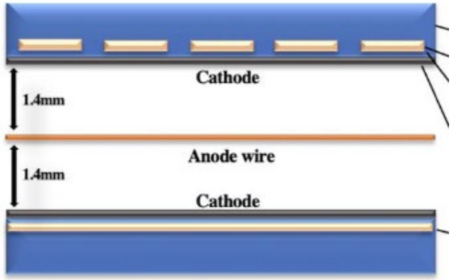


Self-supporting hexagon sector of the PANDA-STT (prototype, right: with 3×3kg Pb bricks on top) [1].

Thin Gap Chamber

ATLAS NSW Upgrade for HL-LHC

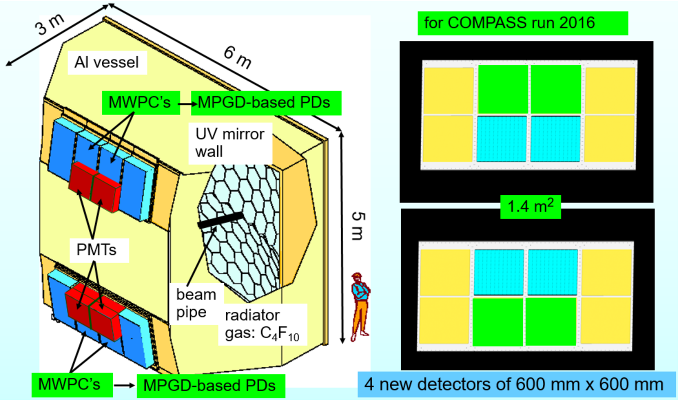


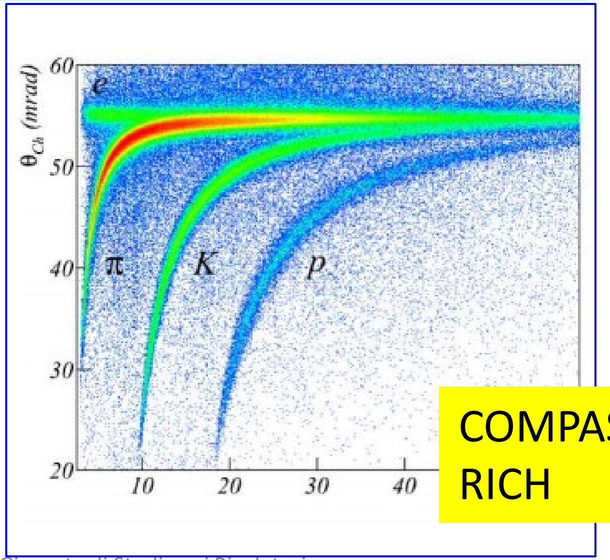


Gaseous Detectors

- A **wide family** of detectors:

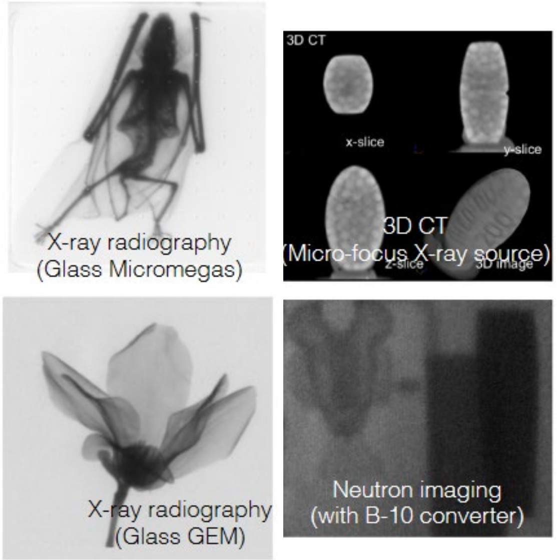
gas also where you would not expect it





COMPASS RICH

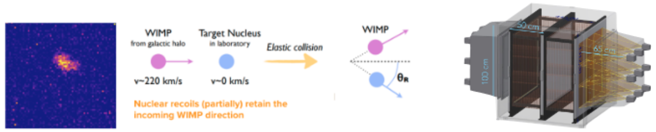
OPTICAL R-O TPCs



Atmospheric pressure Optical TPC

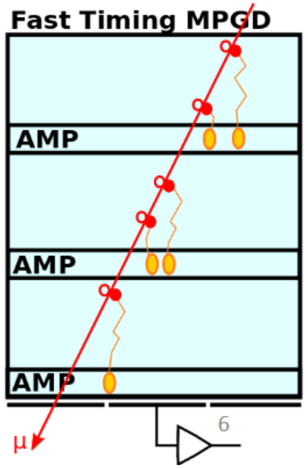
Rare event searches, directional dark matter

Triple GEM with **CMOS + PMT/SiPM** readout requiring low radioactivity background

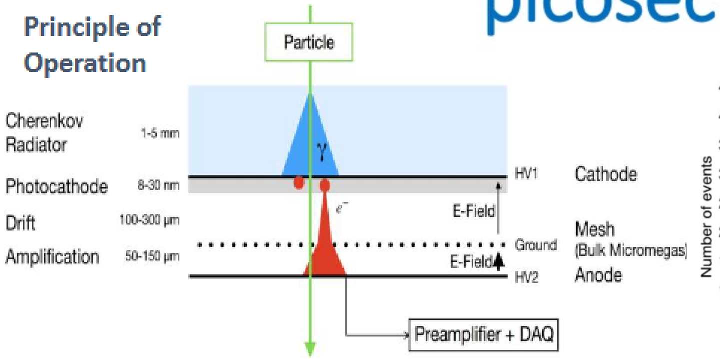


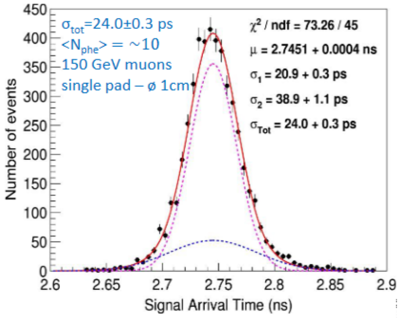
Fast Timing with MPGDs

FTM



picosec

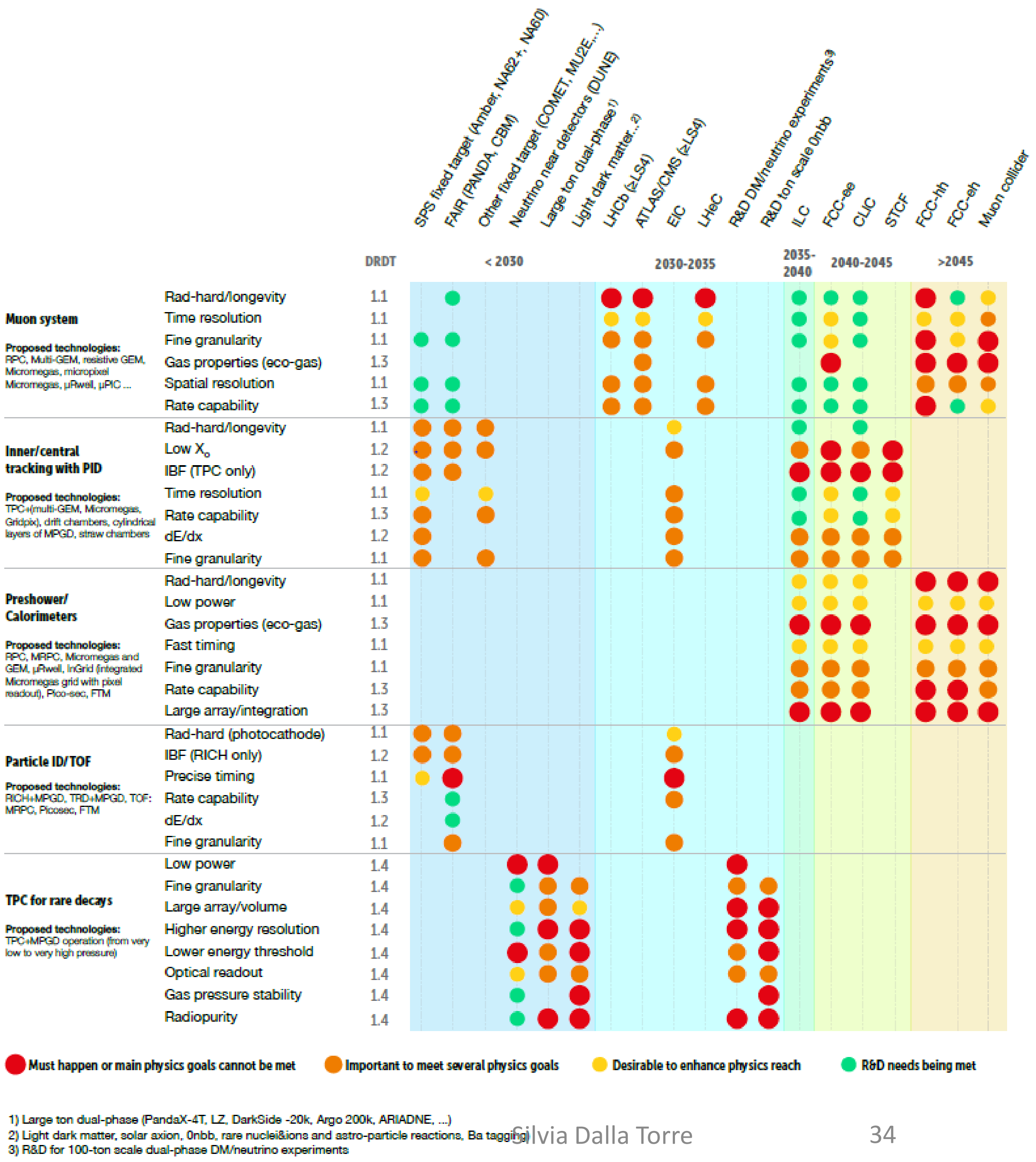




Gaseous Detectors

- Extremely **wide range** of applications **including highest energies and luminosities**, long term projects
  - Largely needed in **fix target**
  - ubiquitous in **collider**
  - key also for **ν-physics** and **dark matter**
  - Even if not included in the Roadmap timelines, also **low energy NP, applications beyond fundamental research**

- **Recommendations**
  - **Discharge understanding and control**, ageing effects (for long-term reliability and high luminosities)
  - **Dedicated FEE** developments
  - **Optical read-out** with imaging sensors
  - **Overcoming the greenhouse gasses** issues (fluorocarbons preferred for fast response, electroluminescence yield)

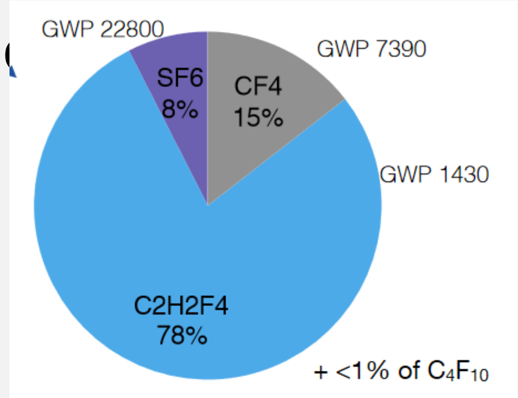


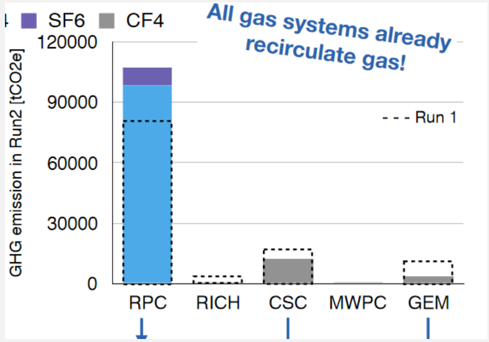
Gaseous Detectors

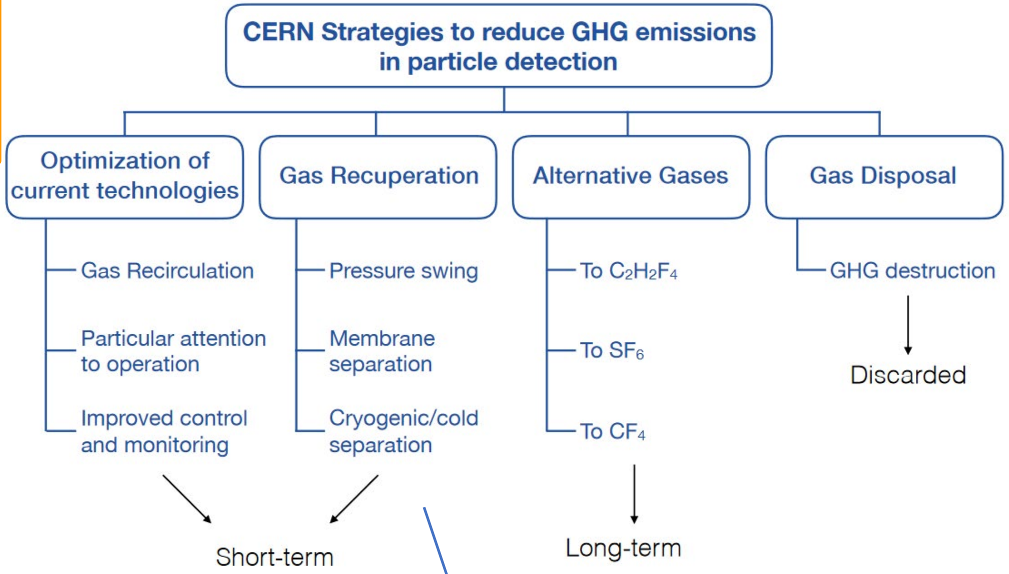
Eco-gas mixtures and mitigation procedures for GreenHouse Gases (GHGs)

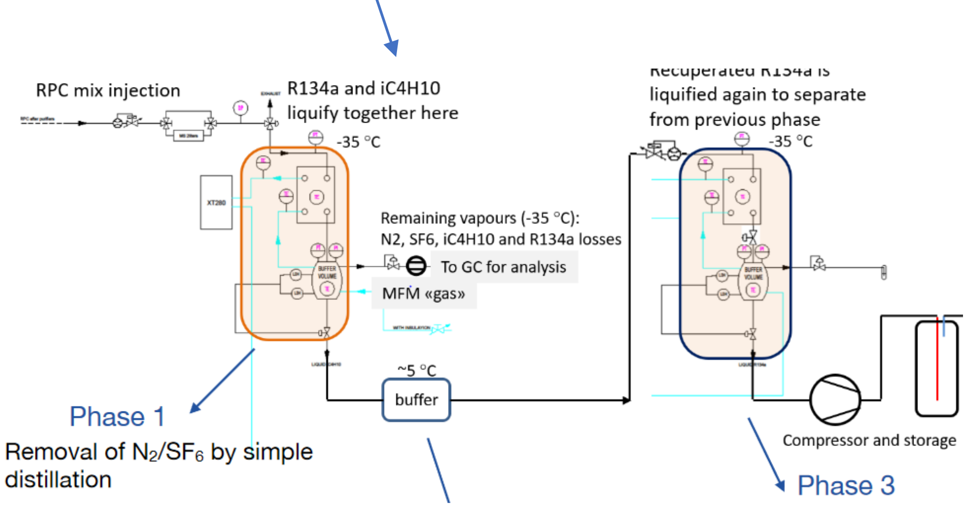
- Why fluorocarbons are key ?
  - **Fast gas**
  - **RPC stability**
  - **Electroluminescence yield**

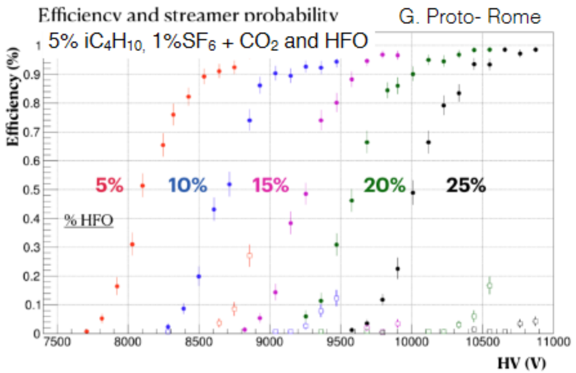
- GreenHouse @ CERN data
- (











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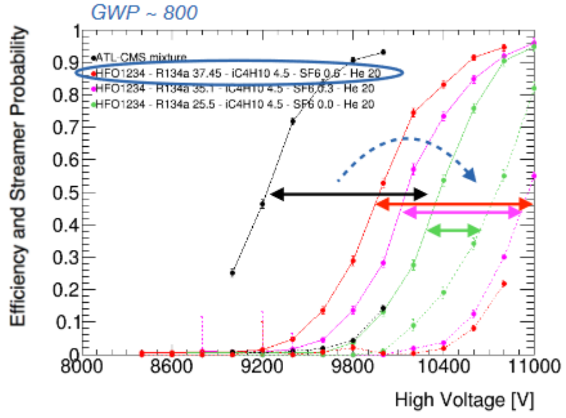
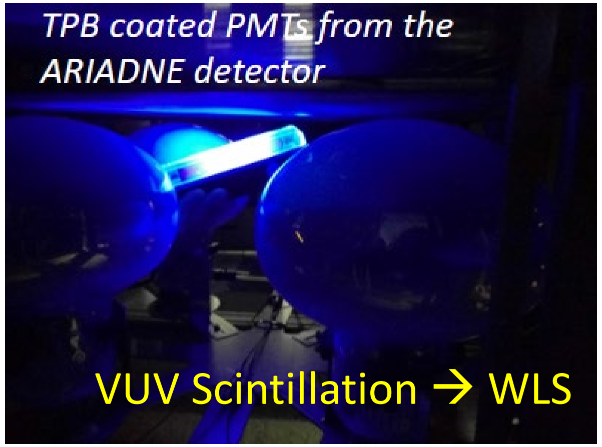
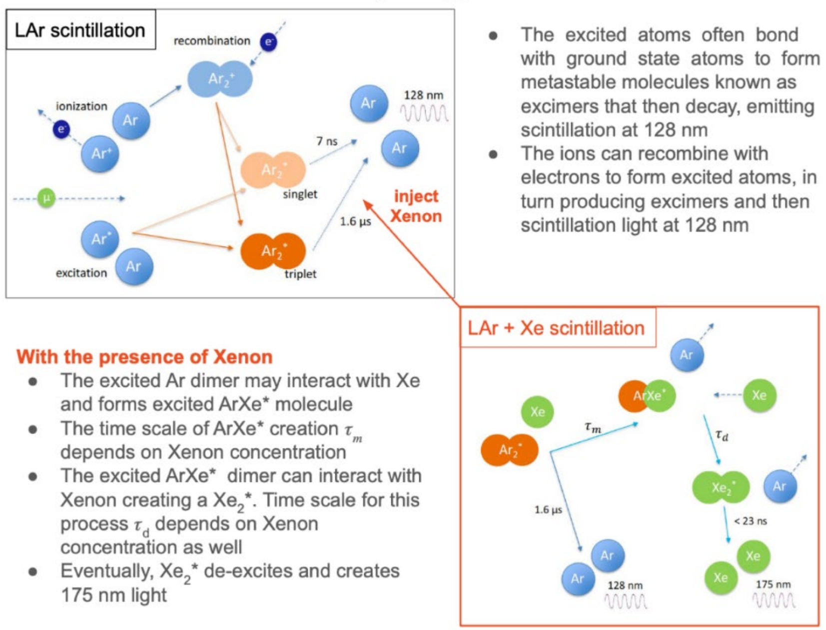


Liquid Detectors

- Which liquids ?
  - **Noble liquids (LAr, LXe)**

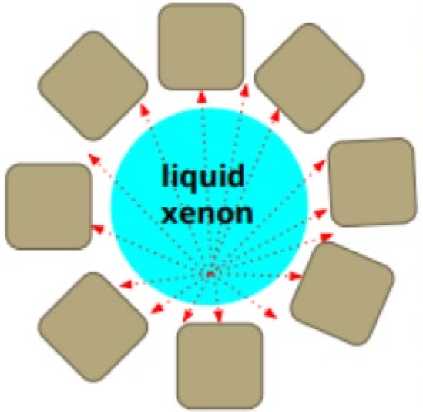




More detected scintillation light with Xe doping:
128 nm → 175 nm

- Liquefied noble gases intrinsic properties are **ideal for ν and DM**
  - Combination of their **scintillation properties**, the **high ionization yield** , where the **ionization electrons released remain free to drift** across long distances
  - Also the possibility of **extracting electrons to the gas phase**, where the ionization signal can be amplified through secondary scintillation or avalanche mechanism → dual phase detectors

Directional and temporal pattern of scintillation from LXe



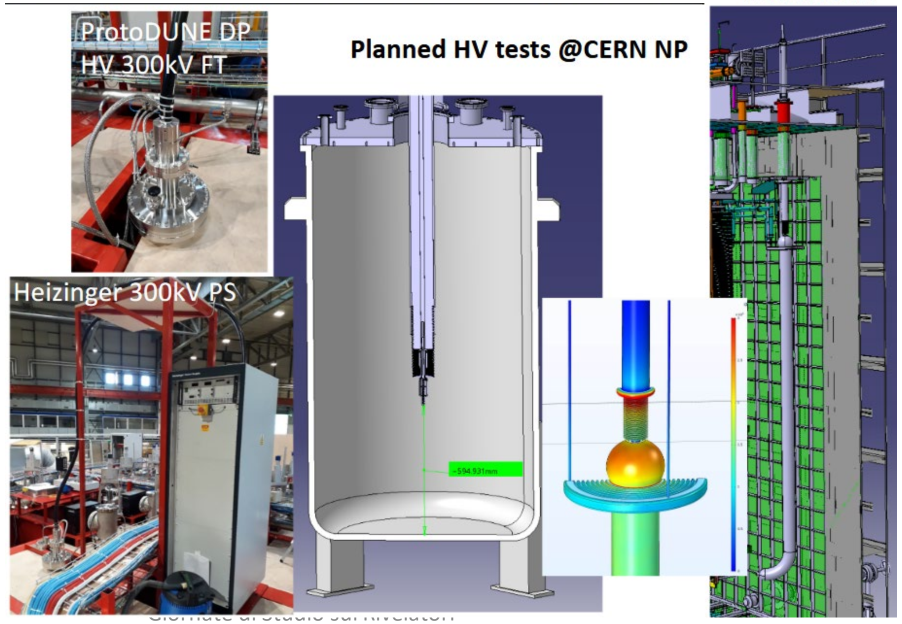
Liquid Detectors

- Which liquids ?
  - **Noble liquids (LAr, LXe), technological aspects**

High Voltage

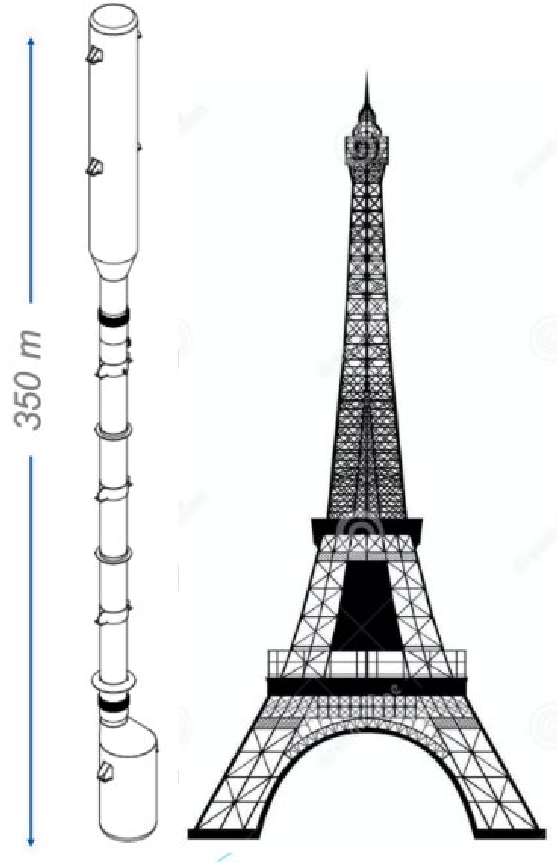
- In order to drift at 0.5kV/cm over 12 m you will need 600kV at the cathode!
- Need to develop new HV FTs
  (For DM an extra challenge is radiopurity)
- Power supplies currently limited to ~350 kV

ProtoDUNE



Radio-Purity

ARIA project (Darkside Collab.), production of depleted argon, below the UAr levels



ARIA -distillation column

Aria is **a 350 m tall cryogenic distillation column**, the tallest distillation column in the world, capable of isotopic enrichment. Operating in a mine shaft on the island of **Sardinia in Italy**, Aria will be able to further reduce the concentration of 39Ar by a factor of 10 per pass and at a rate of several kg/day. Beyond argon isotopic enrichment, the column has **commercial applications in the production of isotopes for nuclear energy and medicine.** For DarkSide-20k, however, Aria will not be used to reduce ^{39}Ar, but rather **to chemically purify the crude UAr** from Urania (99.9% pure) to produce detector-grade UAr. **For this chemical purification Aria will produce on the order of 1000 kg/day of purified UAr.**

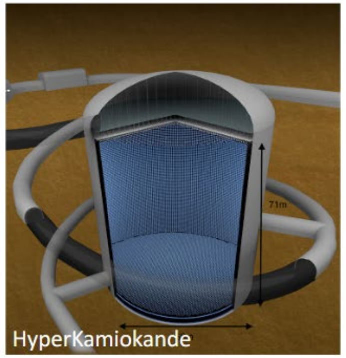
Required purity:
99.9999%

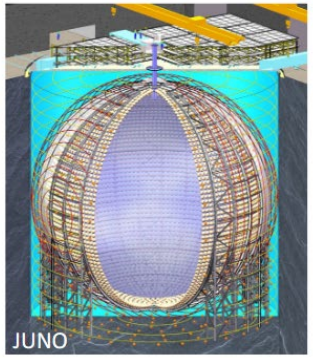
Liquid Detectors

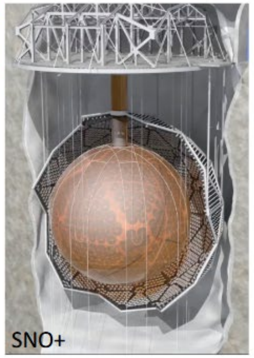
- Which liquids ?
  - **other liquids**
    - Liquid scintillators, Water detectors

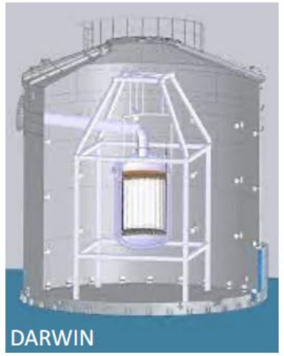
Well-established techniques and projects currently in the development phase

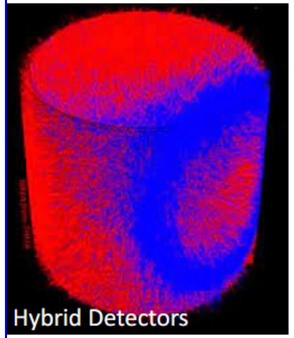
- large-volume water(+Gd!) detectors → HyperK
- ultrapure LS detectors → JUNO
- metal-loaded (Te) LS detectors for $0\nu\beta\beta$ → SNO+
- efficient veto detectors (water, LS, Gd-doped) → Darwin,

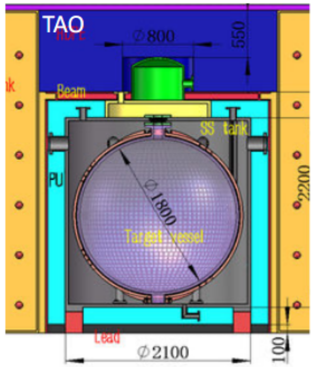


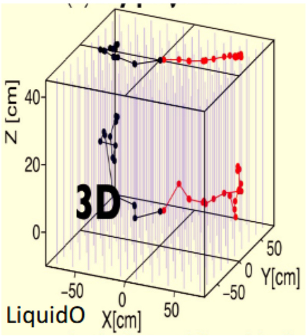


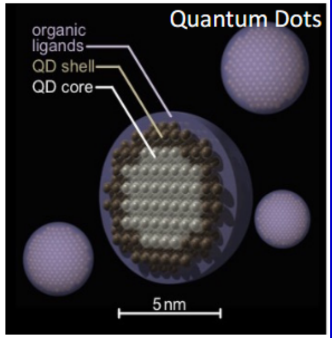












New concepts: New techniques that go beyond the present state-of-the art and are entering demonstration phase

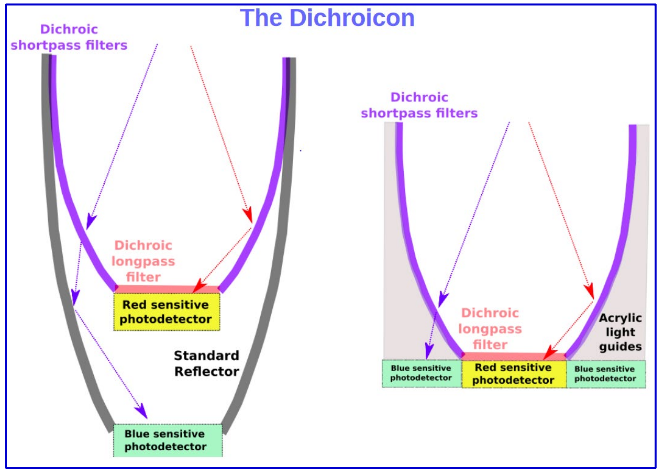
- hybrid Cherenkov/scintillation detectors → Theia
- cold LS with SiPM read-out - 50 °C → TAO
- opaque LS with fiber read-out Better localization → LiquidO
- LS doped with quantum dots for $0\nu\beta\beta$ searches → NuDot

Liquid Detectors

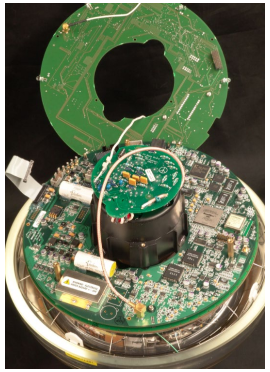
- Photodetectors

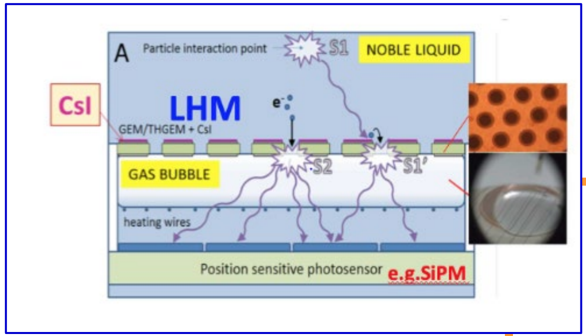
Photosensor	Features
Large-area PMTs (high-QE & MCP-PMT)	Enhanced light collection
M-DOMs, Multi-PMT modules in water	Exploit granularity for reconstruction
LAPPDs in water/WbLS	ps-timing for improved vertex reco and Č/S separation
Dichroicons in WbLS Separate Cherenkov/Scintillation light	Wavelength-separation for hybrid-reconstruction
WOMs in water/LS Wavelength-shifting Optical Modules	Large light collection area optical coupling and emission/absorption spectra
SiPMs in LS	High QE/granularity but cooling for dark noise

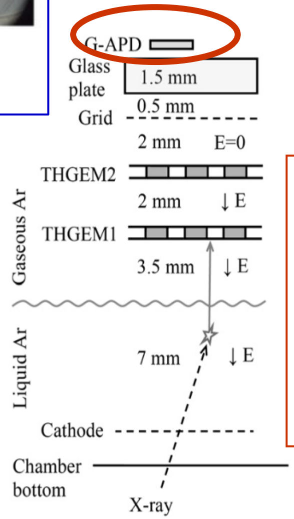
+ enhanced light collection:
mirrors/cones, (active) light guides, fibres, metalenses …



Digital Optical Module







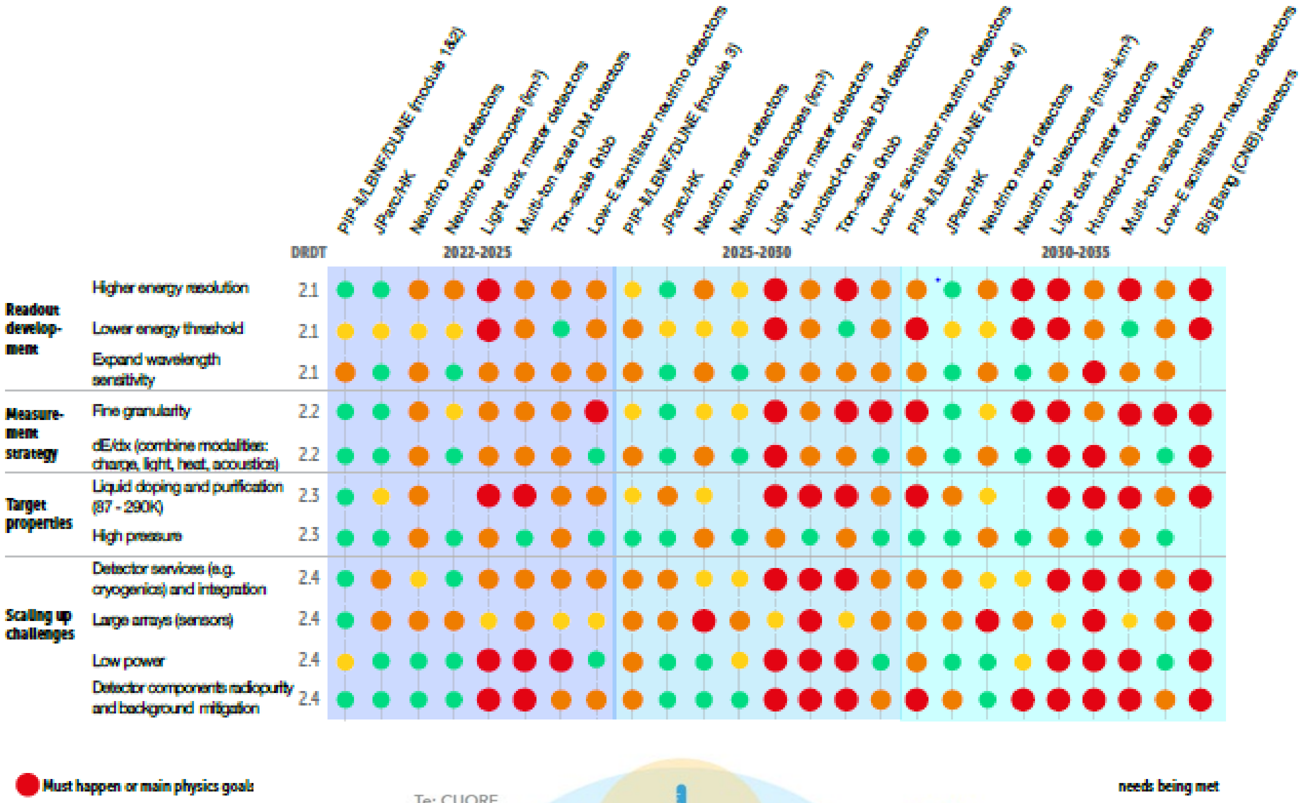
A. Bondaret al., NIMA 628 (2011) 364

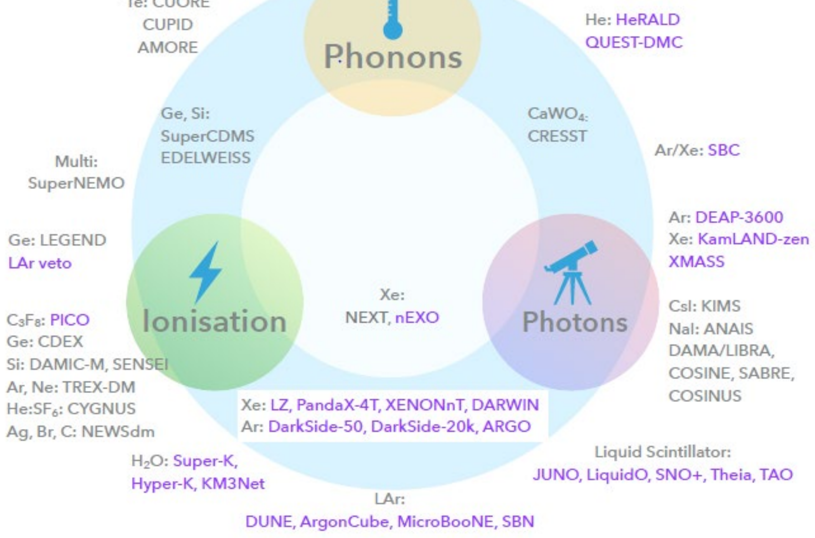
THGEM + G-APD
Detect scintillation light

Liquid Detectors

- Timelines up to 2035
  - corresponding to the present planning in the fields
- Physics field of applications
  - **ν-physics**
  - **Dark matter**
  - **Neutrino-less double beta decay**
- **A wide panorama of projects**

- **Recommendations**
  - facilitate **scalability x O(10)** for mid-term
  - **Multiple read-out** in the same device
    - Scintillation and Cherenkov light
    - Electromagnetic and acoustic
    - Light and charge
  - **Longer term planning**
  - **R&D on material properties**
    - Purification
    - Radiopurity
    - Change isotopic content of materials





Solid State Detectors

Discussed within the Calorimetry TF

Project timescales for new solid sate devices

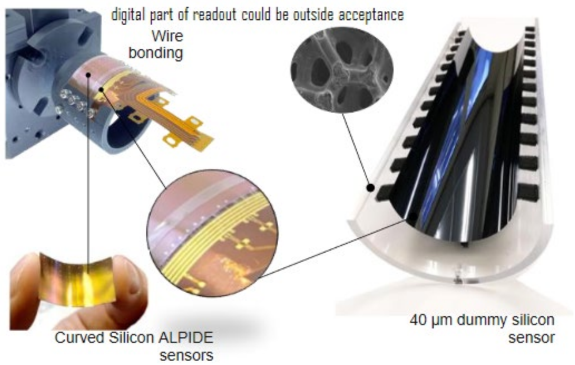
Projects	Timescale	Vertex Det.	Tracker	Calorimeter	Fine time res.
Panda (Fair/GSI)	2025	✓			
CBM (Fair/GSI)	2025	✓			
NA62/KLEVER	2025	✓			
ALICE	2026-27 (LS3) – 2031 (LS4)	✓	✓	✓	✓
Belle-II*	2026	✓			✓
LHCb	2031 (LS4)	✓	✓		
ATLAS-CMS	2031 (LS4) - 2035 (LS5)	✓			✓
EIC	2031	✓	✓	✓	✓
ILC	2035	✓	✓	✓	✓
CLIC	2035	✓	✓	✓	✓
FCC-ee	2040	✓	✓	✓	✓
Muon-collider	> 2045	✓	✓	✓	✓
FCC-hh	> 2050	✓	✓	✓	✓

- R&D completion typically ≃ - 5 years for construction, and including typically ≃ 5 years system engineering on top or in // to technology demonstration***
- Upgrade programs earlier than future colliders provide opportunities to iterate technologies and mature systems in real operation environments

ECFA roadmap detector R&D, TF3 solid state devices symposia
D. Contardo, 23/04/2021

Solid State Detectors – **vertex** requirements

- **high position precision**
  - ALICE, ILC, CLIC, FCC-ee, EIC
  - ALICE ITS2: **ALPIDE** 30 μm pitch, 50 μm thick, $\sigma_{hit} \simeq 5$ μm, X/X0 ≃ 0.3% / layer
  - ALICE ITS3 target: $\sigma_{hit} \simeq 3$ μm, $X/X_0 \simeq 0.05\%$ / layer
    - **MAPs** with stitching process in 65 nm node (TowerJazz)
      - 10-20 μm pixel pitch, thickness down to 20 μm
      - 12” wafers (10 x 28 cm sensors), power ≃ 20 mW/cm^2 for gas flow cooling

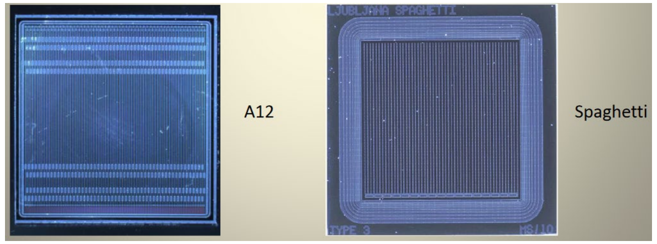


- **medium rate & timing requirements**
  - rates ≲ **100 MHz/cm^2**
    - Achieved in MAPS: ALPIDE ≃ 40 mW/cm^2 at ≃ 10 MHz/cm^2, MIMOSIS (CBM) ≃ 60 mW/cm^2 at ≃ 70 MHz/cm^2
  - ALICE (Run-4), CBM, EIC, ILC, FCC-ee timing precision ≃ **1 – 10 μs**
    - Existing systems, consistent with power consumption of above examples
  - Belle-2, ALICE-run-5 timing precision ≃ **100 ns**, Panda (Fair) ≃ **10 ns**
    - Achieved in MAPS demonstrators, but more challenging for power consumption

Solid State Detectors – **vertex** requirements

- **high rates & medium/high timing requirements**
  - NA62, LHCb, ATLAS, CMS, CLIC rates ≃ **1 to 5 GHz/cm²**, timing precision **25 ns** to resolve BC at LHC, **5 ns** for beam background CLIC, NA62 & LHCb ≲ **50 ps**
  - Challenge to reach GHz with current MAPS node (> 100 nm), also to reduce pitch below 50 μm at these rates in hybrid technology
    - **28 nm node technology** MAPS (for high rates) and ASICs (to reduce hybrid pitch)
    - **3D integration** also an option for both technologies, hybridization at low pitch

- **radiation tolerance**
  - ALICE, CBM, BELLE-2, EIC, ILC, CLIC, FCC-ee: **NIEL**(non-ionizing energy loss) ≲ **10^{15} neq/cm²** and **TID** (total ionizing dose) ≲ **100 MRad**
    - Well within HV-CMOS radiation tolerance
  - LHCb, ATLAS, CMS: **NIEL ≃ 2-5 10^{16}** neq/cm² and **TID ≃ 1 GRad**
    - Marginally compatible with current hybrid technology requiring - *inner layer replacement*(s)
    - Limiting ability for low radius and forward η coverage
  - Challenge to enable MAPs to these levels (to be considered in ATLAS/CMS inner layer replacement)
    - **Lower technology nodes** (65 nm – 28 nm)... process-design developments, Improvements of hybrid technology
    - **Smaller pitch and thinner planar/3D sensors**, improved process and design Lower ASIC node 28 nm
  - **FCC-hh:** Fluence **10^{18} neq/cm²** and **TID 30 GRad** at 2.5 cm

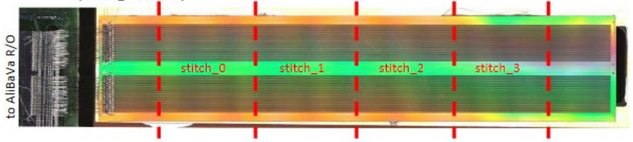


Solid State Detectors – **tracker** requirements

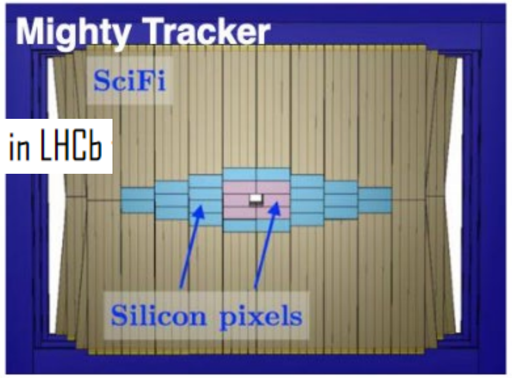
- **high rates & medium/high timing requirements**
  - Most demanding are ILC, CLIC, FCC-ee
    - Initial FCC-ee target: $\sigma(p_T)/p_T^2 \lesssim 5 \times 10^{-5}$ GeV-1 $p_T \gtrsim 100$ GeV (90°)
    - Drivers: **number of measured hits & position precision (σ_{hit}), B-Field and lever arm, multiple scattering (X/X_0)**
      - **Different concepts**
        - Full Si, O(10) hits high σ_{hit}
        - TPC/DC, O(100) hits low σ_{hit} with Si wrap-up layer at r_{out}

- **optimization target**: $\sigma_{hit} \simeq 7$ μm at $\simeq 1\%$ X/X_0 per layer
  - **Longitudinal** granularity and coordinate precision **is not constraining**
    - eg, **strip-sensor** are well suited (so far with hybrid technology)
    - Large area layers require powerful cooling & relatively strong mechanical supports → **X/X_0 (limiting factor to σ_{hit}) is more difficult to minimize than in V**

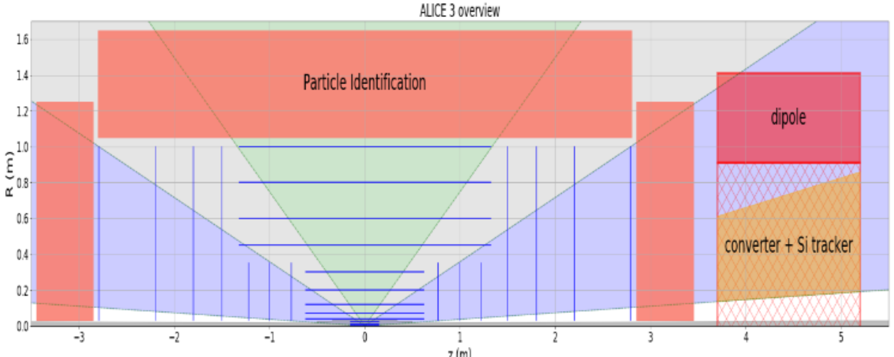
- Strip length > 4 cm → Readout implants across 5 stitches (6 segments)



HV-CMOS is sufficient for inner radii in LHCb



Alice 3 (LS4) – MAPS 20 μm pitch - BC timing 25 ns - 10^{13} neq/cm^2



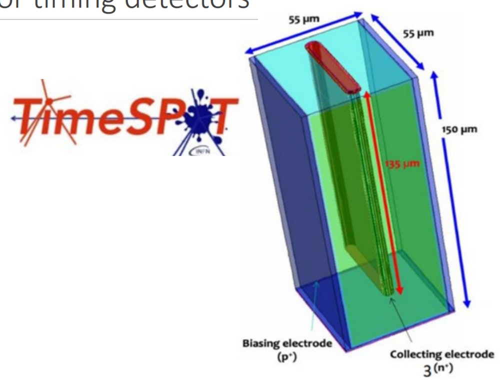
Solid State Detectors – **timing**

- **Particle Identification (PID) dedicated layer(s)**
  - ALICE 3 (post LS4), targeting $\boldsymbol{\sigma_t \simeq}$ **20 ps** for 3σ π/K up to 5 GeV/c
  - Belle-2, FCC-ee similar requirement to cover dE/dx crossing at low p (cluster counting)

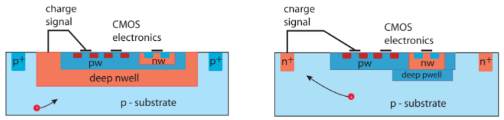
- **4D tracking for track collision time association**
  - Dedicated layer(s) or implementation in VD and/or tracking layers
    - ATLAS/CMS $\boldsymbol{\sigma_t \lesssim}$ **30 ps** (pile-up mitigation)
      - desirable for high η LGADS replacement in LS4-LS5 (for rad. tol.)
    - LHCb pile-up mitigation for vertex precision
      - Options for e-e colliders to reduce beam backgrounds and improve 1st, 2nd, 3rd vertices identification
    - Muon collider: $\boldsymbol{\sigma_t \simeq}$ **10 ps** to eliminate out of time hits
    - FCC-hh pile-up: $\boldsymbol{\sigma_t \simeq}$ **5 ps**
    - FCC-ee at $\boldsymbol{\sigma_t \simeq}$ **6 ps** can allow to correct √s variation within bunches

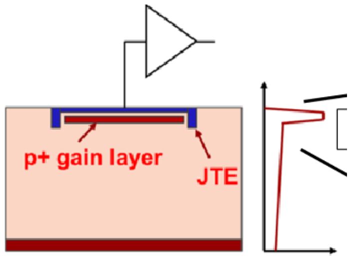
- **R&D**
  - Develop designs with **fast signal collection**, **small stochastic fluctuations**
    - w/o amplification (MAPS, Hybrids 2D/3D)
    - w/ ampl. LGADS, SPADS
    - Related needs of electronics (FE, TDC, clock systems)

3D – for timing detectors



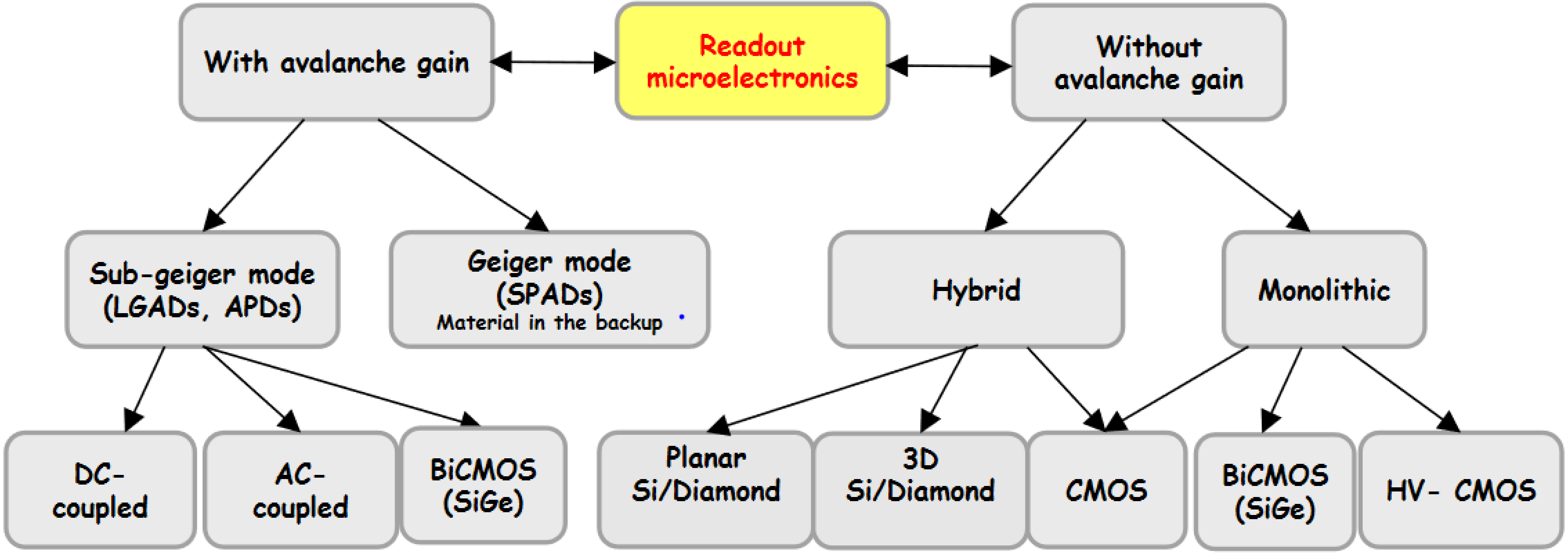
Depleted MAPS - planar





Ultra fast Silicon detector E field

Solid State Detectors – technologies



Also considered:

- silicon carbide (largely improved material quality thank to wide industrial applications)
- innovative 2-D materials (graphene, …)

TF3 – Solid State Detectors

Observations & Recommendations

- Key-need of **irradiation facilities** and test beams
- **Non-silicon materials** particularly promising for high fluence detectors
- **Critical industrial panorama for production**:
  - need of a **sizeable monetary investment** to offset the R&D and production costs
  - the **typical long R&D periods** of the HEP experiments
  - the **uncertainty on the return of the initial investment**
  - → substantial **lack of European producer**
  - Development lines needed by HEP: MAPS, 4-D tracking, high fluence detectors, 3D-vertical stacking
  - **Strategic coordination** for production in Europe (resources needed!)

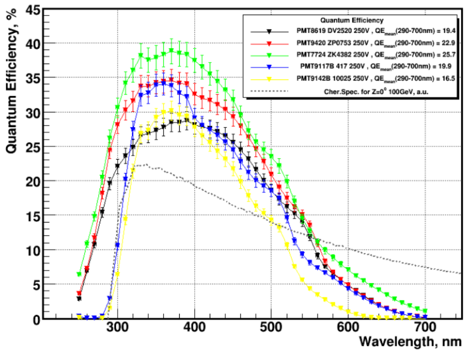
PhotoDetectors

The PD family, something more

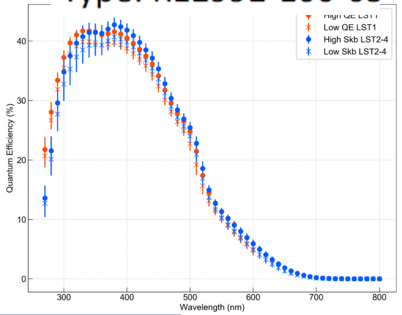
- ***Vacuum-based***
  - PMTs, MAPMTs, MCP-PMTs and large-size LAPPD, Hybrid (HAPD)
- *Solid-state*
  - SiPMs
- *Gaseous*
  - MWPCs, MPGDs
- *Superconducting (all cryogenic)*
  - nano-wire single photon detector (SNSPD), started for quantum information science

PMT

Progress in QE

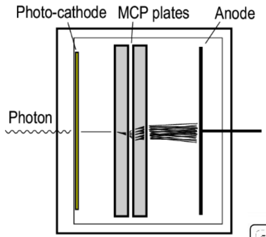


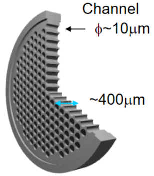
Hamamatsu
Type: R12992-100-05

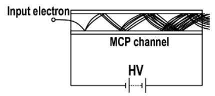


Flat Panel Multi-anode PMT Hamamatsu H9500

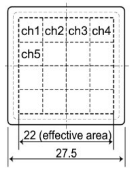
MCP-PMT

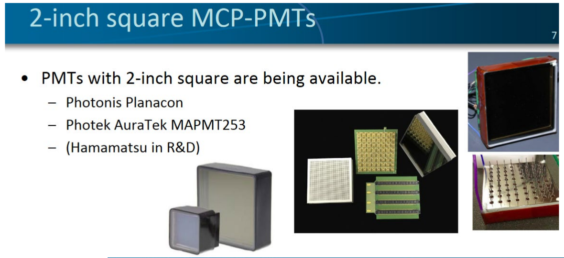




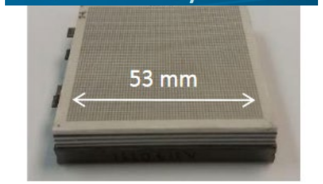


Square-shaped MCP-PMT for Belle II TOP



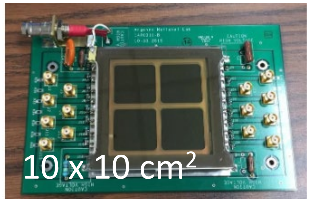


MCP-PMT by Photek

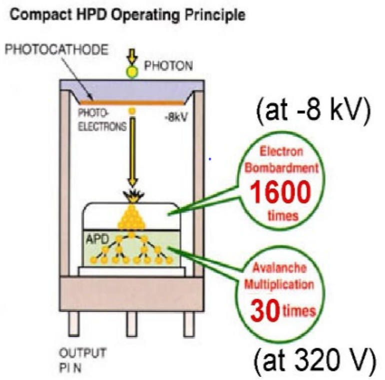


LAPPD (Large Area Picosecond Photodetector)

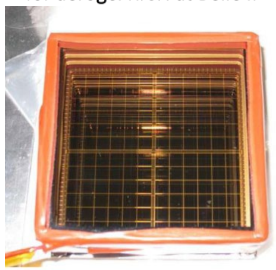
A joint effort of academy and industry

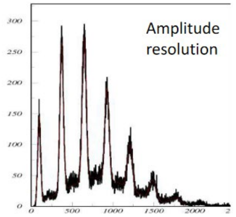


HPD



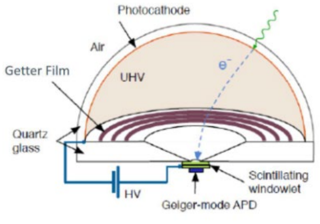
144-channel HAPD for aerogel RICH at Belle II





Abalone

Schematics



10 cm

Prototype for IceCube extention

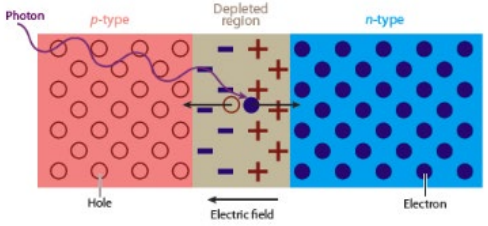
PhotoDetectors

The PD family, something more

- *Vacuum-based*
  - PMTs, MAPMTs, MCP-PMTs and large-size LAPPD, Hybrid (HAPD)
- ***Solid-state***
  - SiPMs
- *Gaseous*
  - MWPCs, MPGDs
- *Superconducting (all cryogenic)*
  - nano-wire single photon detector (SNSPD), started for quantum information science

SiPM

An array of APDs operated in Geiger mode – above APD breakdown voltage (microcells or SPADs – single photon avalanche diodes)

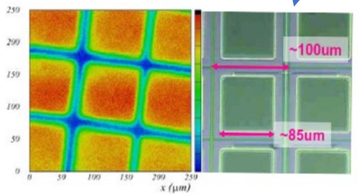


SiPM: PDE

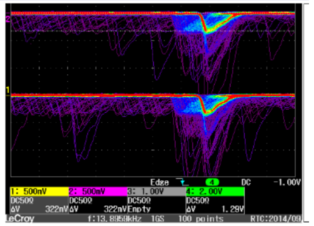
Three main contributions:

$$PDE = QE \times \epsilon_{geo} \times P_{trig}$$

QE depends on surface reflections
→ antireflective coating (ARC)



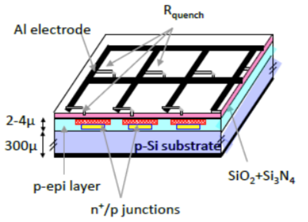
SiPM: noise



- dark counts are produced by thermal generation of carriers, trap assisted tunneling or band gap tunneling
- signal equal to single photon response
- typical rate went from $\approx 1MHz/mm^2$ to below $\approx 100kHz/mm^2$ for more recent devices
- roughly halved for every 8^oC
- increases linearly with fluence
- optical cross-talk produced when photons emitted in avalanche initiate signal in neighboring cell, reduced by screening – tranches
- after-pulses produced by trap-release of carriers or delayed arrival of optically induced carrier in the same cell

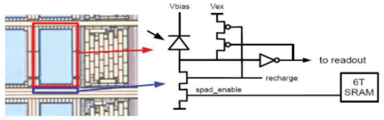
Analoge, digital, 3D

Analoge SiPM:



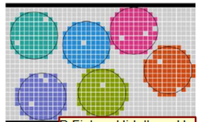
- common output with passive quenching
- custom process with more flexibility in optimization of SiPM parameters
- higher fill factor – higher PDE
- lower DCR

Digital SiPM, SPAD arrays:



Y. Haemisch et al. Phys. Proc. 37(2012)1546

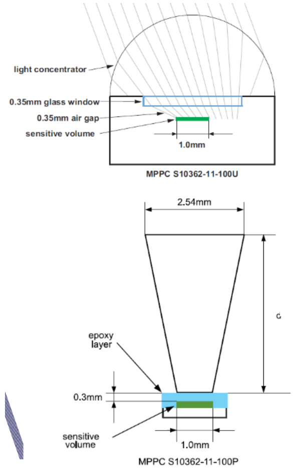
- integration of SPADS into CMOS standard process (p^+ in n-we-l or n^+ in p-well
- allows integration of active quenching and readout electronics (comparator, TDC ...) at micro-cell level
- improved spatial and timing resolution
- higher DCR, possibility to disable noisy channels, enable only used channels (fibre matching)

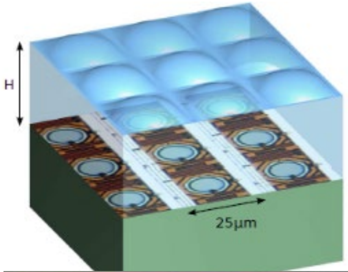


P.Fisher, Hidelberg U.

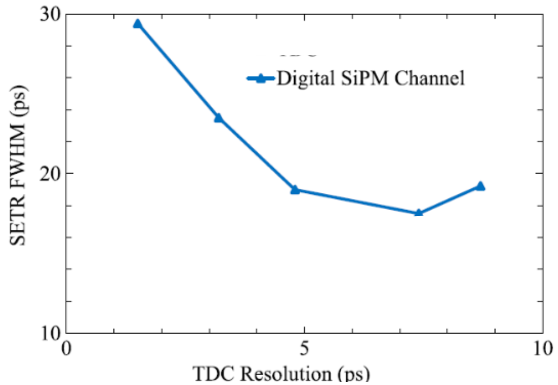
- reduced fill factor - need for compromise between electronics and SPAD area ...

Light concentrators





The best time resolution so far from single SPAD; FWHM ~ 17. 5 ps



PhotoDetectors

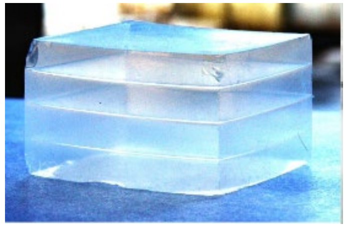
The challenge of the single photon detection (related to Cherenkov Imaging)

The PD family, something more

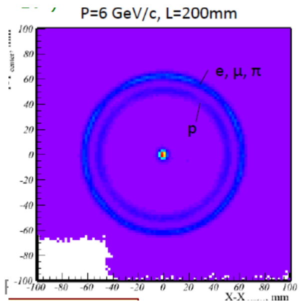
- *Vacuum-based*
  - PMTs, MAPMTs, MCP-PMTs and large-size LAPPD, Hybrid (HAPD)
- ***Solid-state***
  - SiPMs
- *Gaseous*
  - MWPCs, MPGDs
- *Superconducting (all cryogenic)*
  - nano-wire single photon detector (SNSPD), started for quantum information science

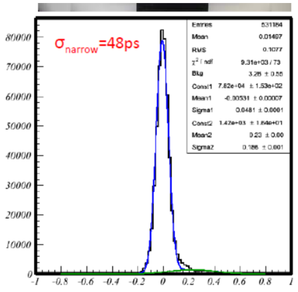
dSiPM RICH

FARICH (Focusing Aerogel RICH) candidate for ALICE, PANDA, Super c-τ, (SuperB):



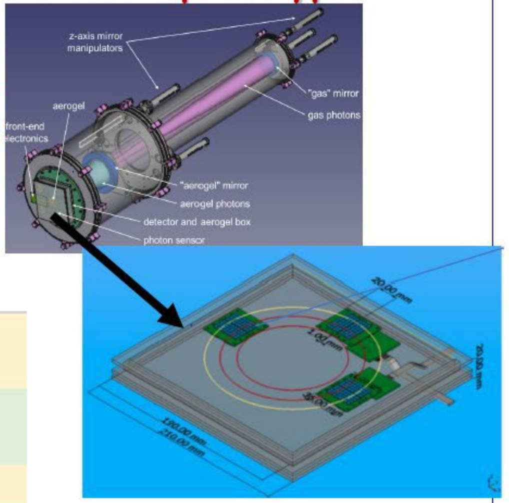
tested at CERN beam line (operated at -20^o)





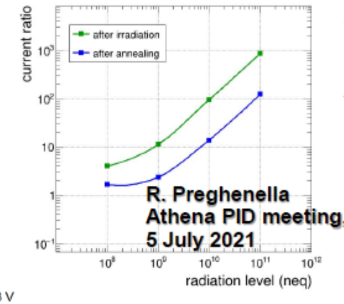
A dedicated effort for application at EIC by a cluster of INFN groups

- **SiPMs from different producers mounted on a RICH prototype**
  - Part as received
  - Part irradiated
  - Part irradiated and thermal annealing cycle
- → **Performance in a test beam**
- **Coupled to specific FE r-o:**
  - ALCOR, developed for DarkSide



MULTIUPLE MANIFACTURES	
SENSEL (OnSemiconductors)	microFJ-30020-TSV
	microFJ-30035-TSV
Broadcom	AFBR-SAN33C013
Hamamatsu Photonics	S13360-3050VS
	S13360-3025VS
	S14160-3015HS
	S14160-3050HS
FBK, Fondazione Bruno Kessler	custom SiPM

[NUV-HD-RH] 1 week of annealing at T = 125 C



annealing reduced dark current by a factor of ~5-10, in line with expectations

SiPM irradiated up to 10¹¹ now behave like if they were irradiated by 10¹⁰

for the time being we stop here with FBK sensors, or perhaps we extend annealing at T = 125 C for another 2 weeks (expecting no improvements)

issue with FBK carriers related to the solder paste used during assembly, unfortunately we have used low-T (138 C) solder paste which does not allow to reach the ultimate annealing temperature of T = 175 → needs reworking of the carriers → will be done after test beam

R. Preghenella Athena PID meeting 5 July 2021

Preliminary !

PhotoDetectors

GASEOUS

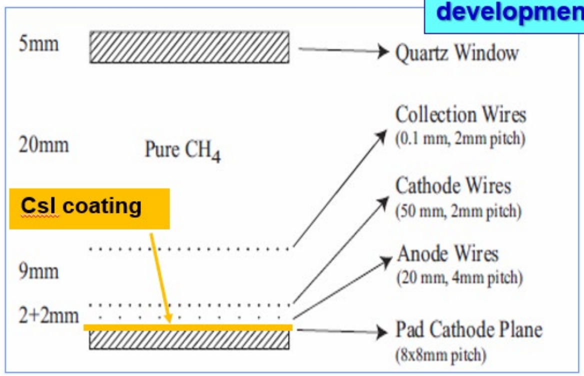
Illustrated by the experience with COMPASS RICH & beyond

The PD family, something more

- *Vacuum-based*
  - PMTs, MAPMTs, MCP-PMTs and large-size LAPPD, Hybrid (HAPD)
- *Solid-state*
  - SiPMs
- ***Gaseous***
  - MWPCs (RD26), MPGDs
- *Superconducting (all cryogenic)*
  - nano-wire single photon detector (SNSPD), started for quantum information science

MWPCs + CsI

RD26 development



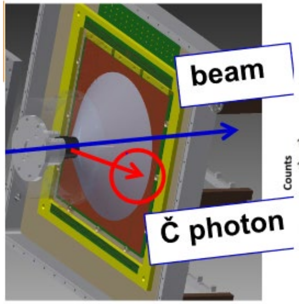
Reduced wire-cathode gap because of :

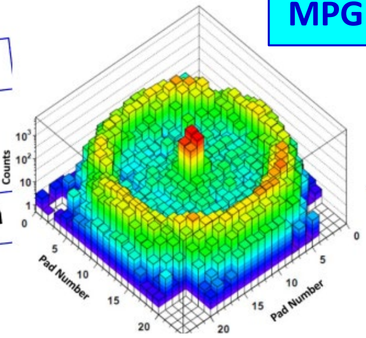
- Fast RICH (fast ion collection)
- **Reduced MIP signal**
- Reduced cluster size
- Control photon feedback spread

To overcome the limitations:

- Less critical architecture
- **suppress the PHOTON & ION feedback**
- **use intrinsically faster detectors**

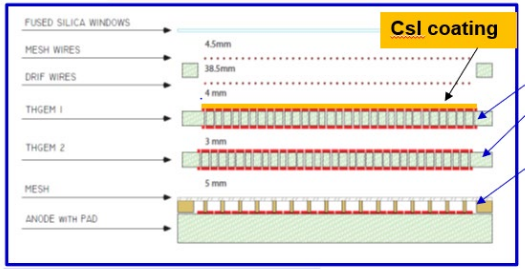
→ MPGDs





MPGD-based PDs

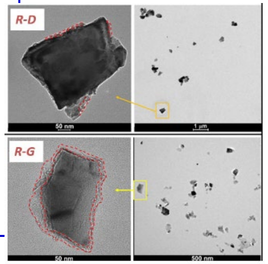
Largely improved electrical stability



Photocathodes by **Hydrogenated NanoDiamonf (H-ND) grains?**

At least 1 order of magnitude more robust for ion backflow bombardment

R&D ongoing

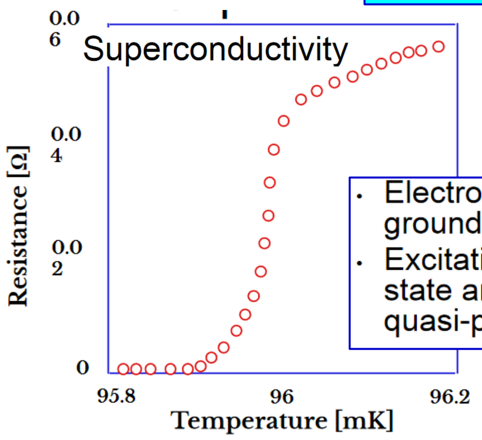


PhotoDetectors

The PD family, something more

- *Vacuum-based*
  - PMTs, MAPMTs, MCP-PMTs and large-size LAPPD, Hybrid (HAPD)
- *Solid-state*
  - SiPMs
- *Gaseous*
  - MWPCs, MPGDs
- ***Superconducting (all cryogenic)***
  - KID, TES, nano-wire single photon detector (SNSPD)

The physics principle

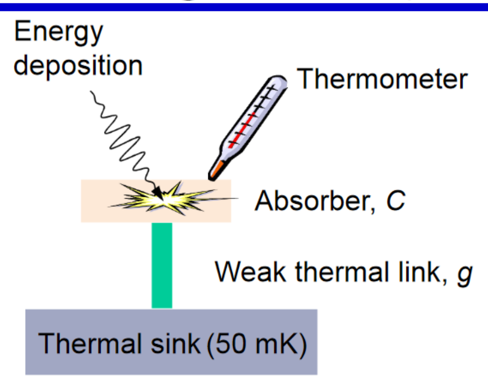


- Electrons in the superconducting ground state form Cooper pairs
- Excitations above the ground state are known as quasi-particles, energy ~ 2Δ

Kinetic Inductance Detector (KID)

- Measure excess exictations, quasiparticles
- Inductance of a superconducting wire (kinetic inductance) rises in the presence of quasiparticles
- Readout by looking at the change in a resonator

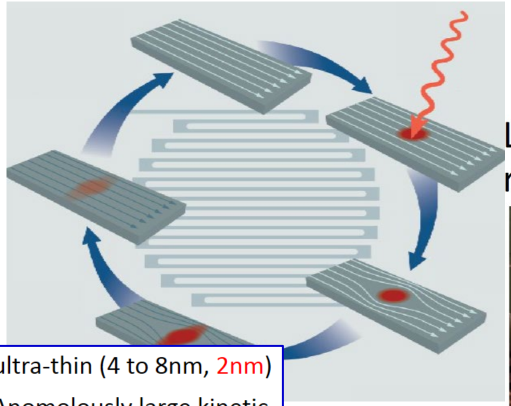
Transition Edge Sensor (TES)



Superconducting-to-normal transition as ultra-sensitive thermometer

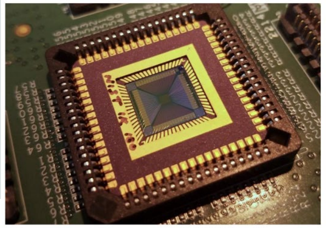
Superconducting Nanowire Single Photon Detectors:

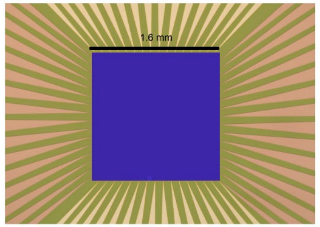
Commercially available, moving towards larger areas



- ultra-thin (4 to 8nm, 2nm)
- Anomolously large kinetic inductance (non-linear)

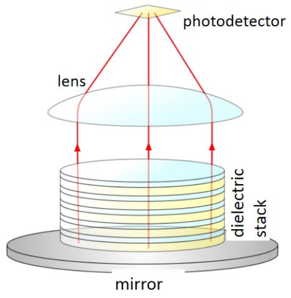
Larger Areas: N^2 pixels with 2N readout





1 kilopixel today, new architectures for 1 Megapixel, 100 Megapixel...

Detecting Dark Photons



PhotoDetectors

Future needs in photodetection

Projects	Timescale	SiPM technology	MCP-PMT technology	Large diameter PMT technology	CCDs & superconducting devices
Panda/CBM (Fair/GSI)	2025	√	√		
NA62/KLEVER/TauFV	2025	√	√		
ALICE	2026-27 (LS3) – 2031 (LS4)	√	√		
Belle-II	2026		√		
Neutrino long baseline	2027	√		√	
LHCb	2031 (LS4)	√	√		
ATLAS-CMS	2031 (LS4) - 2035 (LS5)	√			
Non accelerator & particle astro	--	√		√	√
EIC	2031	√	√		
ILC	2035	√			
CLIC	2035	√			
FCC-ee	2040	√	√		
Muon-collider	> 2045	√			
FCC-hh	> 2050	√			

PID

Future needs in PID

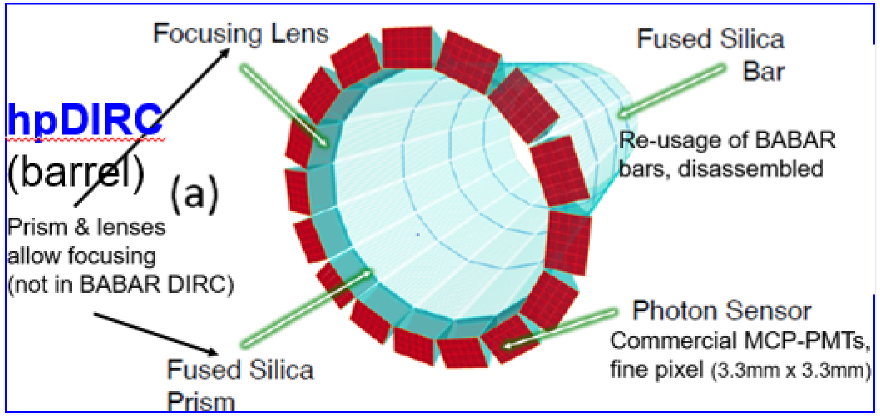
Projects	Timescale	RICH (high and low momentum PID)	Time of flight and DIRC	RPC technologies	TRD & dE/dx
Panda/CBM (Fair/GSI)	2025	✓	✓	✓	
NA62/KLEVER/TauFV	2025	✓	✓		
ALICE	2026-27 (LS3) – 2031 (LS4)	✓	✓	✓	✓
Belle-II	2026	✓	✓		
Neutrino long baseline	2027				
LHCb	2031 (LS4)	✓	✓		
ATLAS-CMS	2031 (LS4) - 2035 (LS5)				
Non accelerator & particle astro	--				
EIC	2031	✓	✓		
ILC	2035				
CLIC	2035				
FCC-ee	2040	✓	✓		✓
Muon-collider	> 2045				
FCC-hh	> 2050				

Summarizing about the fundamental physics domain of application:

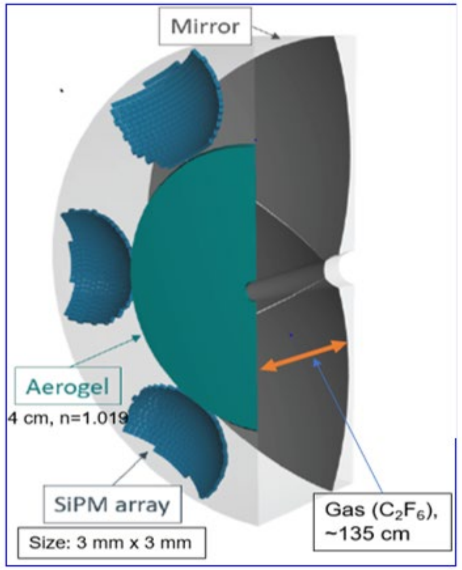
- **Flavour physics**
- **Hadron physics**

PID - future need of RICHes

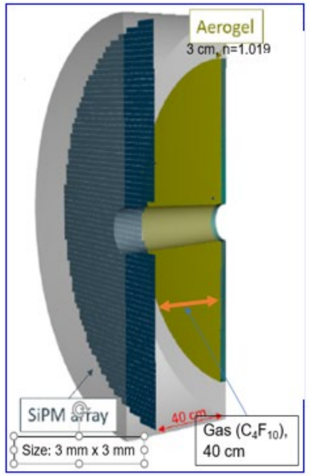
EIC (illustrated via the ATHENA Proposal)



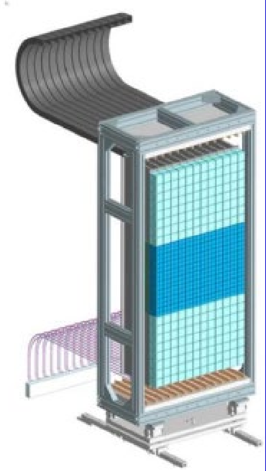
dRICH (forward)



pfRICH (backward)

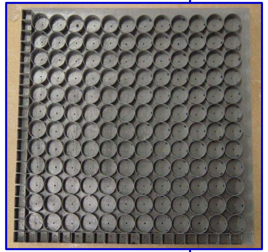


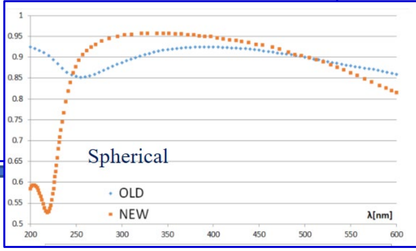
LHCb Upgrade II : RICH



The high-tech approach for improved resolution:

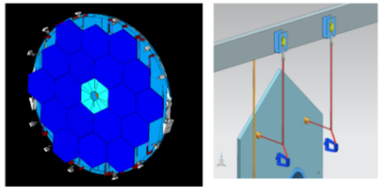
- **Lighter mirrors:**
  - Si-Carbide mirrors (up to 1.5 m and ~5 Kg/m^2)
  - Light composite mirrors
- **Mirror reflectance:**
  - Tuned reflective coatings
- **New approach to PDs (SiPMs ?)**
  - selected wavelength (less chromaticity)
  - fine time information





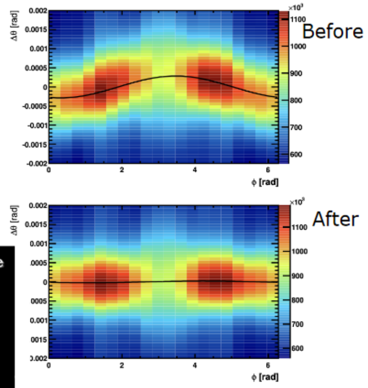
NA62 NIM A952(2020)162005

20 spherical mirrors supported by a dowel.
Piezo motors control their orientation remotely
Alignment in offline analysis



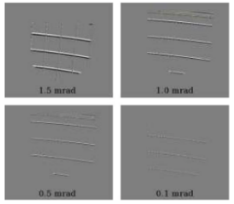
LHCb RICH1 NIM A952(2020)161882

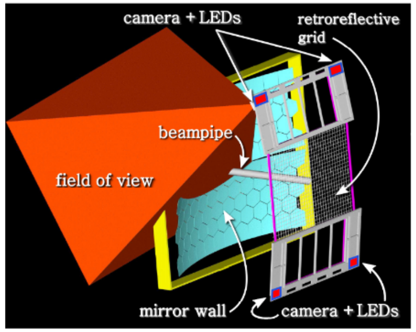
Alignment study in offline data



COMPASS RICH1

CLAM (Continuous line alignment) introduced.





NIM A553(2005)135

Handing mirrors is also a severe alignment issue

PID – radiators for future RICHes

GAS

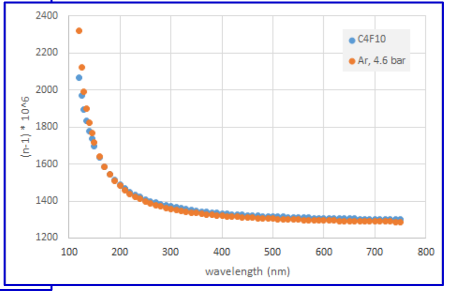
A must for gaseous RICHes: be ecofriendly

Fluorocarbons have high photon yield and low chromaticity, but GWP is high

- **LHCb** : alternative gasses
- **EIC approach:**
  - Pressurising Ar at a few bar you can mimic fluorocarbons both in photon yield and chromaticity

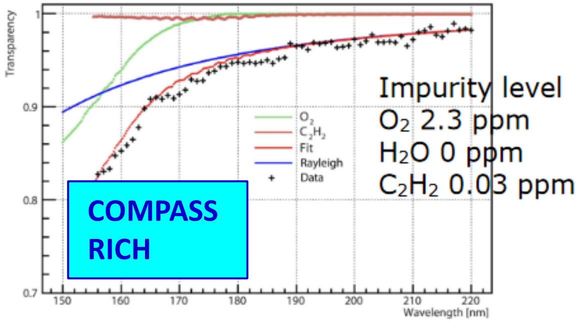
RICH2: RUN3 Preliminary

Nominal single photon resolution (in mrad)	MaPMT; CF_4	MaPMT: CO_2
Chromatic	0.34	0.53
Overall	0.50	0.66
Yield	34	33



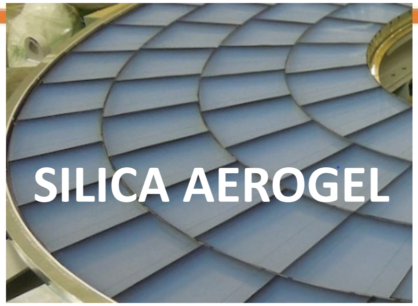
Trasparency

C_4F_{10} transparency monitored



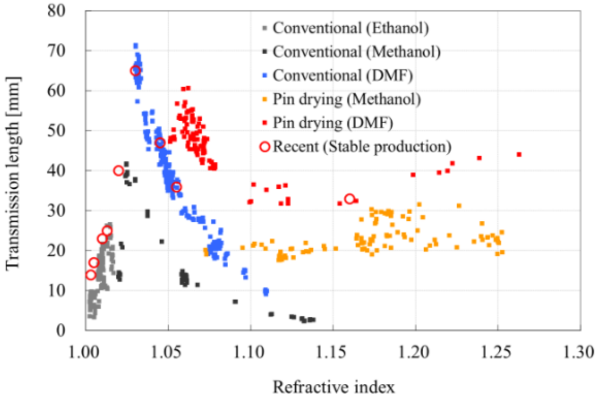
Fine present achievements, nevertheless:

- Watch out new products from industry
  Further better performance
  Compactness..

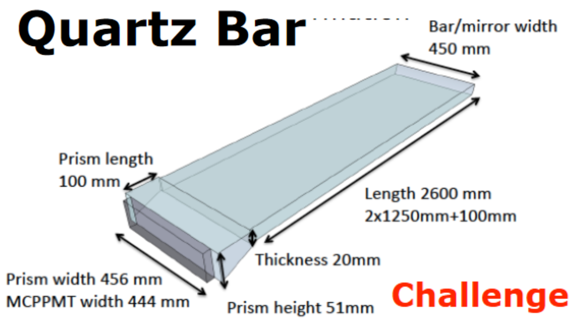


Chiba university in Japan

Hydrophobic sample
Pin-drying (PD) method to get n > 1.1



Quartz Bar

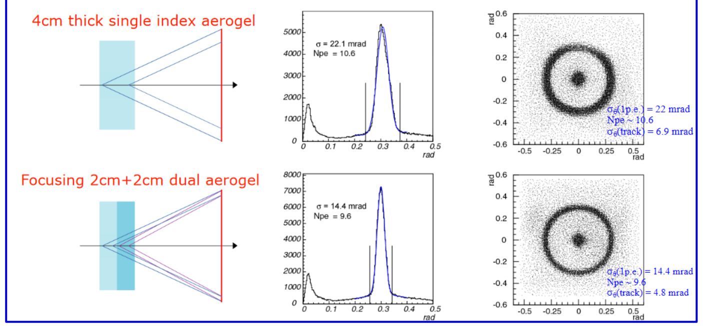


Challenge for ultra-precise machining

Novosibirsk in Russia

No hydrophobic, but recoverable by baking

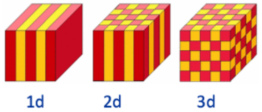
Increase light yield w/ suppressing emission point uncertainty



Can we produce new crystal radiator with refractive index which we want to have ?

Photonic crystals could be one of the candidates.

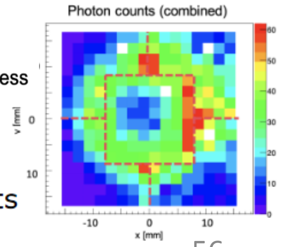
Made from two materials with different n
Layer thickness ~ photon wavelength
Feasible in recent years



1d photonic crystal from industry

- PVDF (n1=1.414) + PET (n2=1.567)
  1024 layers, each with 250 nm thickness

Preliminary results



PID – ToF

TOF
Conceptually easy, but … some major issues:

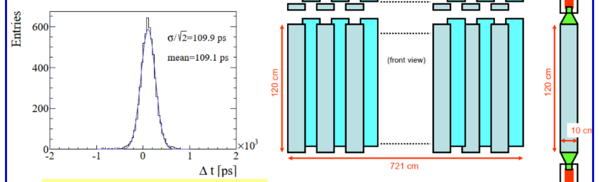
- **Energy loss + multiple scattering** between the IP and TOF detector
- **Start time** (t0) needed
- System issues: **synchronization over a large area** is challenging

Present trend: Timing layers

1. Scintillator
2. Gaseous
3. Silicon
4. Cherenkov

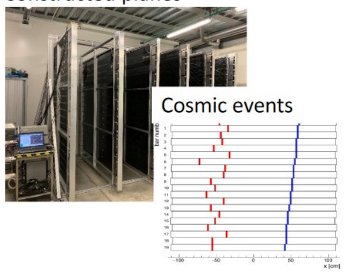
NA61 Fast-Hamamatsu R1828

- TOF resolution ~110 ps



N Abgrall et al 2014 JINST 9 P06005

Constructed planes



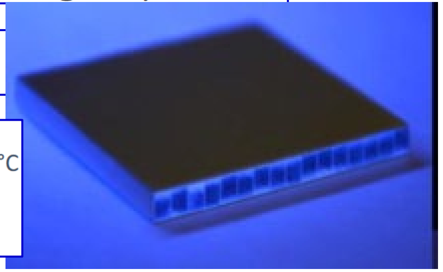
~ 130 ps resolution

T2K near Detector Upgrade
SiPMs (6 × 6 mm2 Hamamatsu S13360-6050PE MPPC)

CMS Barrel Timing Layer

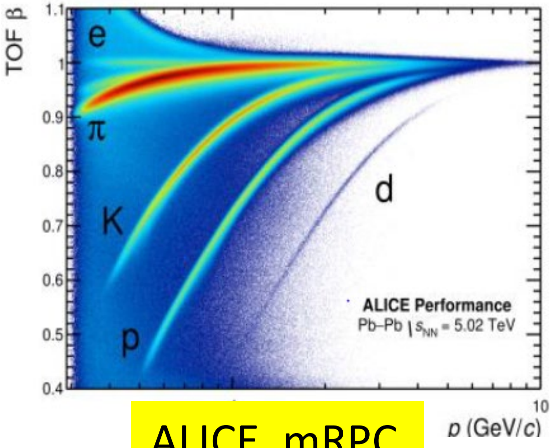
Fast scintillator: LYSO:Ce

- Thermoelectric coolers to improve SiPM radiation tolerance: run at -45°C
- Time resolution: 35 ps at start and 60 ps by the end of HL-LHC



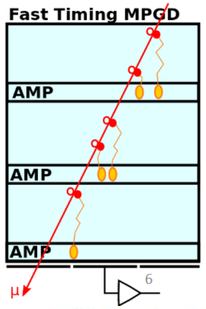
mRPC & MPGD (picosec, FTM)

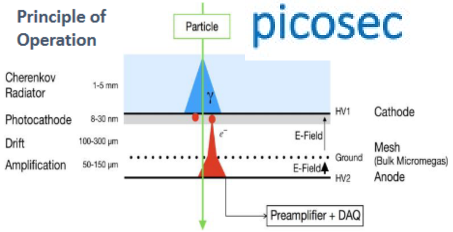
F. Carnesecchi, arXiv:1806.03825



ALICE, mRPC

FTM



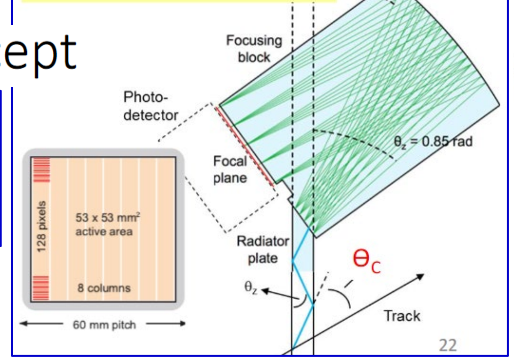


Coupled to MCP-PMTs

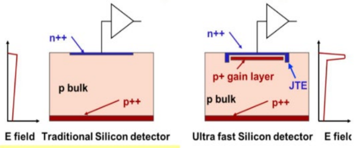
TORCH concept

Target: ~ 50 ps
π/K sep up to 10 Gev/c

M. Charles et al, NIMA 639 (2011) 173

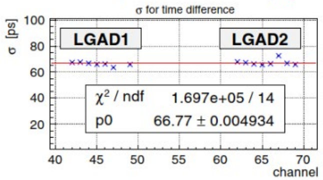


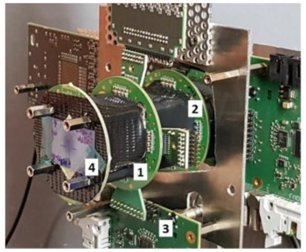
LGADs, low gain avalanche diodes, for end-cap timing, adopted by ATLAS/CMS layers a family of detectors



S. Grinstein, IAS-HEP 2021

Corresponds to 47 ps/hit





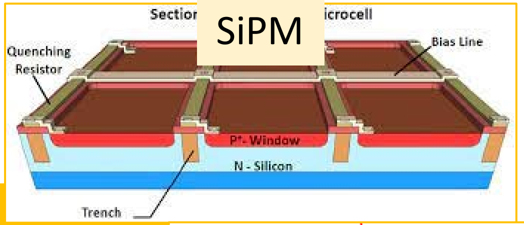
J. Pietraszko et al, Eur. Phys. J. A (2020) 56

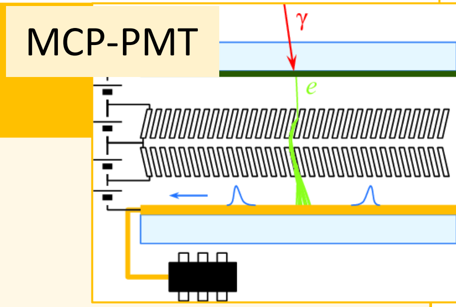
TF4 – PID and Photon Detectors

Observations & Recommendations

- **Compact gaseous RICHes** for collider applications
- Frontiers of **PDs for PID**:
  - Pixel-size → enlarged effectiveness range
  - Precise timing resolution → better S/N ratio (enlarged effectiveness range); chromaticity correction in DIRC devices
  - UV extended → more photons
- **Eco-friendly radiator gasses** preserving photon yield and limited chromaticity: pressurized noble gasses (a few bar)
- **TOF**: detectors (gaseous, solid state) with O(ps) resolution
- **Blue-sky R&D needed**:
  - Meta-materials such as photonic crystals for tunable refractive index radiators

TF4 – PID and Photon Detectors

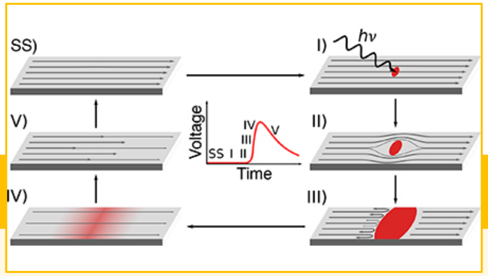




Observations & Recommendations

- Further development of **SiPMs** vital
  - **photon detection efficiencies (PDE)** commonly reach values of up to 60% in the visible range
  - **Noise rates at room temperature**, increasing after radiation damages
  - **Adequate windows UV domain**
- Present **MCP-PMT** frontiers to be overcome:
  - **lifetime** (up to >50 C/cm2)
  - **rate limitation** caused by saturation of the MCP (currently 10^5 cm^{-2})
- **Gaseous PDs** hunting for **innovative photocathodes**
- **Blue-sky R&D needed**:
  - Solid state novel material PDs
  - cryogenic superconducting photosensors for accelerator experiments

QUANTUM AND EMERGING TECHNOLOGIES DETECTORS



Technologies

- Clock
- spin-based sensors, magnons
- superconductive approaches
  - Superconductor Insulator Superconductor (SIS) mixers, Hot Electron Bolometer (HEB) and Cold Electron Bolometer (CEB), Transition Edge Sensors (TES), Kinetic Inductance Detectors (KID), Superconducting Nanowire Single Photon Detectors (SNSPD), Superconducting Quantum Interference Device (SQUID), Josephson Junction Parametric Ampliers (JJPA), Travelling Wave Parametric Amplifiers (TWPA), 3-D microwave cavities
- Optomechanical technologies
- Atoms, molecules, ions and atom-interferometric probes
- Metamaterials, low-dimensional materials, quantum materials

Applications

- particles (CP-violation and Electric Dipole Moments)
- ν-physics
- DM (axions, dark photons, dilatons or string moduli)
- fifth force
- Dark Radiation (DR)
- QM

Observations

- New approaches rapidly evolving → "extrapolation beyond the next 15 years is fraught with risk"

QUANTUM AND EMERGING TECHNOLOGIES DETECTORS

- 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.

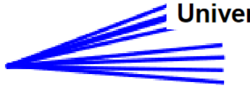
Message from the DRDTs:

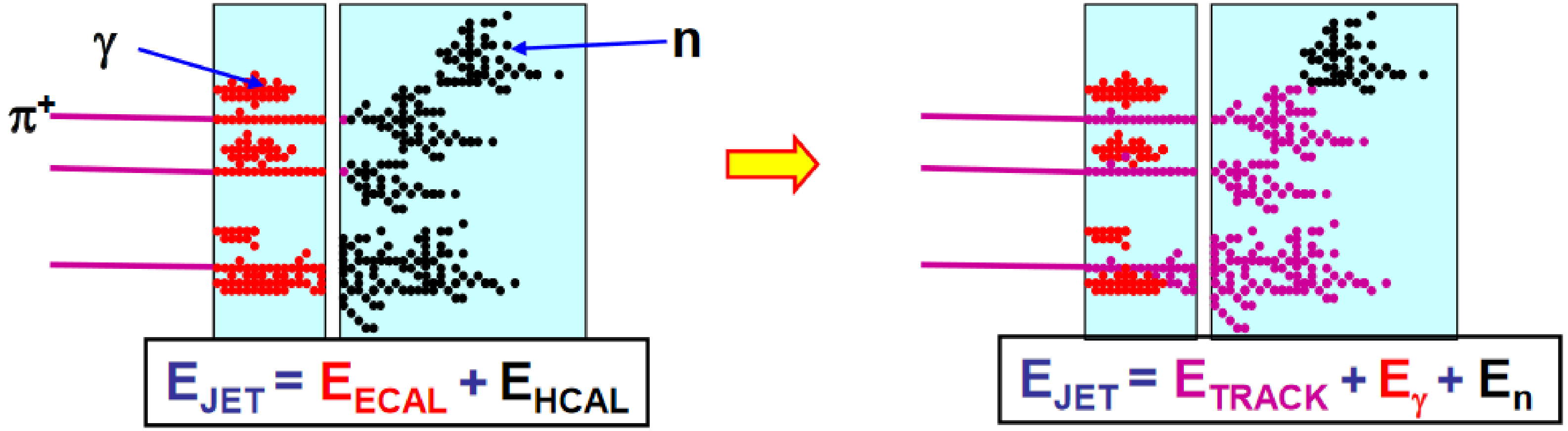
- generic R&D lines because of the novelty: young domain
- need to understand the potentialities/fields of application

CALORIMETRY – a needed introduction

- **In a typical jet :**
  - **60 % of jet energy in charged hadrons**
  - **30 % in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)**
  - **10 % in neutral hadrons (mainly n and K_L)**
- **Traditional calorimetric approach:**
  - **Measure all components of jet energy in ECAL/HCAL !**
  - **~70 % of energy measured in HCAL: $\sigma_E/E \approx 60\,\%/\sqrt{E(\mathrm{GeV})}$**
  - **Intrinsically "poor" HCAL resolution limits jet energy resolution**

Credit:
Mark Thomson
University of Cambridge



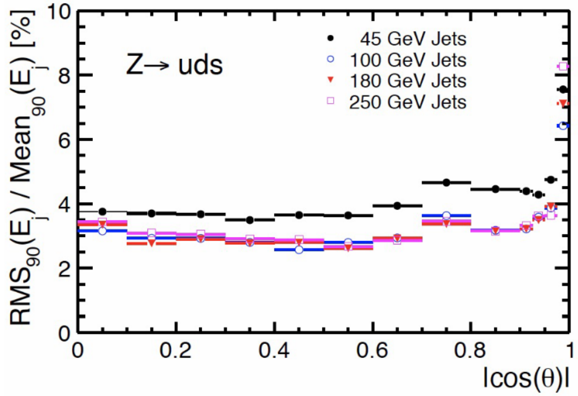


- **Particle Flow Calorimetry paradigm:**
  - **charged particles measured in tracker (essentially perfectly)**
  - **Photons in ECAL: $\sigma_E/E < 20\,\%/\sqrt{E(\mathrm{GeV})}$**
  - **Neutral hadrons (ONLY) in HCAL**
  - **Only 10 % of jet energy from HCAL ⟹ much improved resolution**

PARTICLE FLOW CALORIMETRY:

A modern approach, which requires high granularity
→
We will see a number of approaches to high granularity while presenting the different calorimeter families

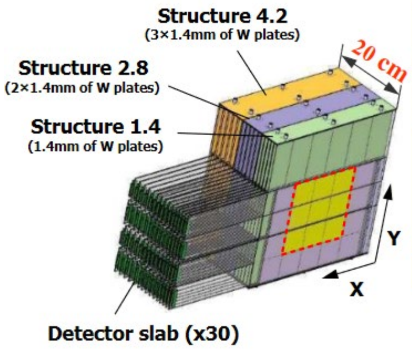
The potential goal



ILCTDR

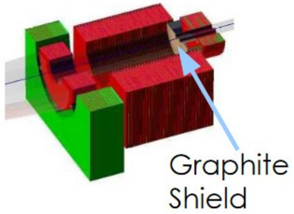
CALORIMETRY – the concepts

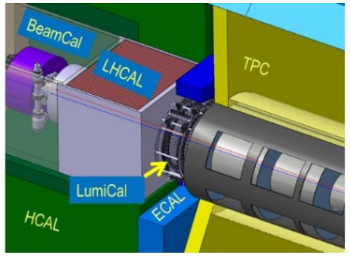
Si-based highly granular calorimeters



CALICE

FCAL Collaboration: LumiCal & BeamCAL with extreme precision for Lin. Colliders



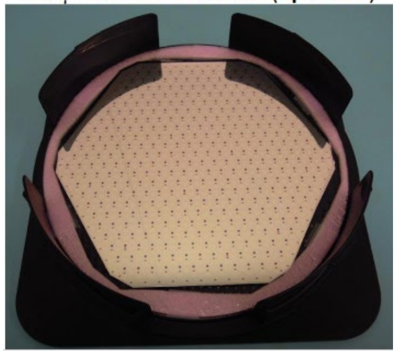


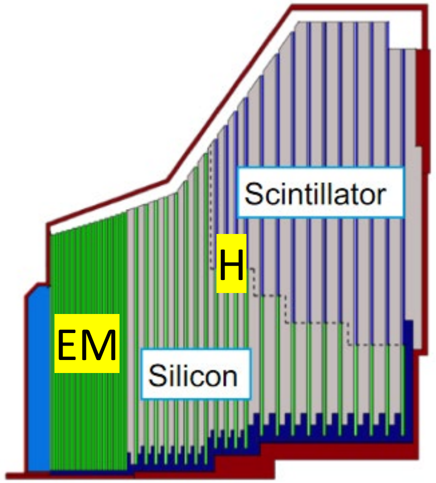
× 2

CMS HGCAL:

8" silicon sensors

High-density 8" sensor
~450 cells of area ~0.5cm²
120μm active thickness (**epitaxial**)

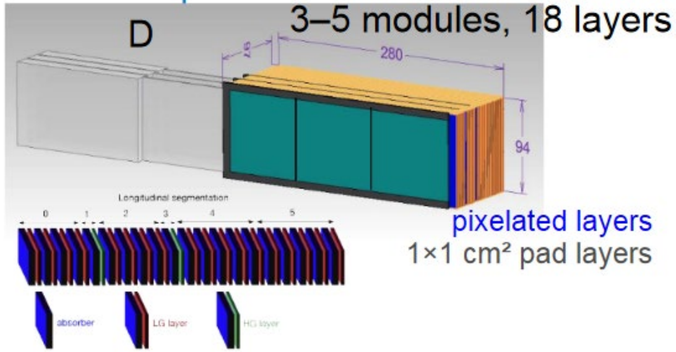


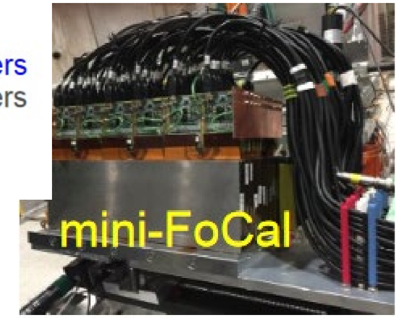


FOCAL-E @ ALICE

Goal: measure of the (n)PDFs at low x_{Bj}

– to be optimized...



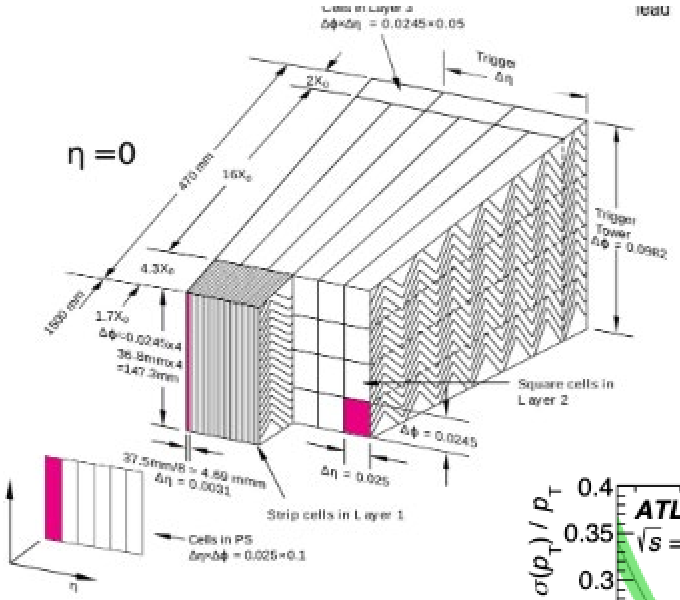


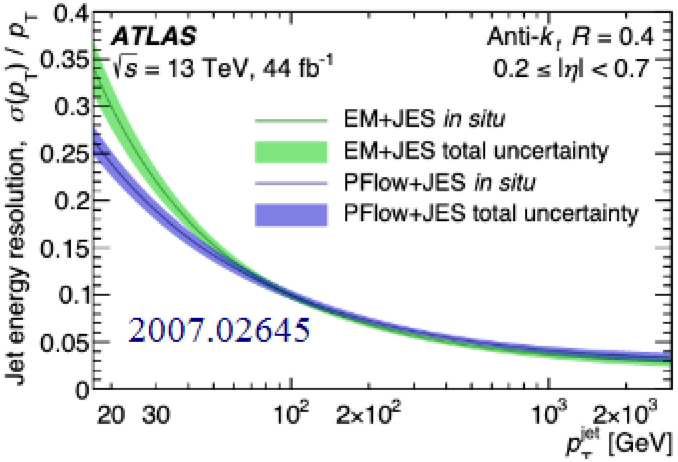
CALORIMETRY – the concepts

Future Noble Liquid Systems

Succesfully operated in D0, H1, NA48/62, ATLAS, ...

ATLAS LAr sampling calorimeter: lead absorbers, LAr active gaps, Kapton electrodes with accordion geometry, everything inside a cryostat bath

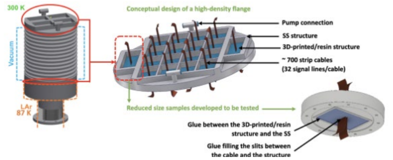




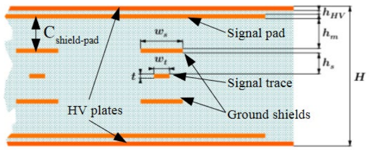
Proposed as
- Baseline for FCC-hh ECAL
- Hadronic Endcap/Forward and LHeC ECAL
- Adapted for FCC-ee

R&D

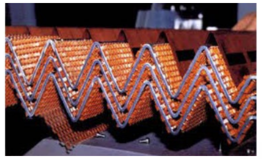
- High-density feedthroughs



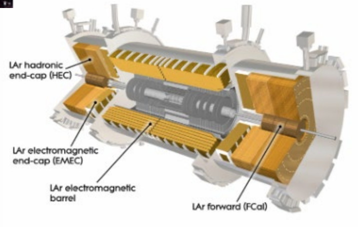
- Increased granularity electrodes

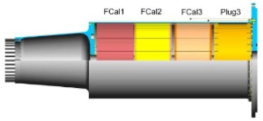


- Detector electrodes



- High-rate mitigation: HiLum/FCalPulse R&D project



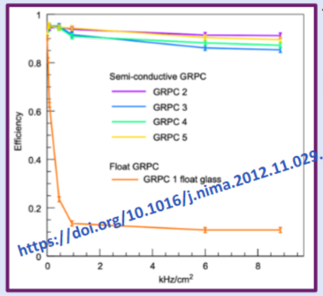


CALORIMETRY – the concepts

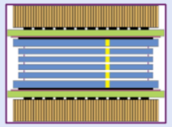
Gaseous calorimeters

Some examples of sub-ns time resolution

A good candidate is the *Multi-gap RPC (MRPC)*

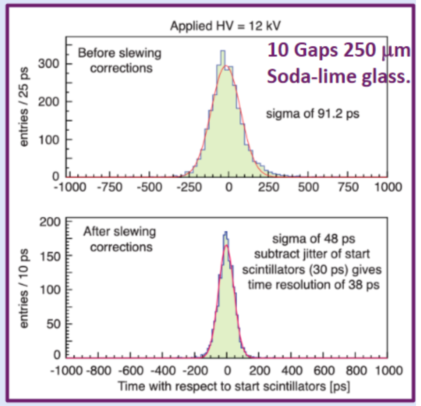


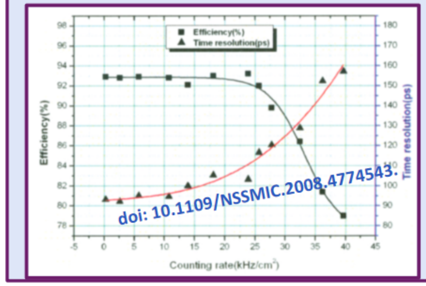
The main limitations is the high rate capability, due to the thin float glass resistivity, but, there are new materials with $\rho \sim 10^{9-10}\ \Omega/cm^2$ as some Semi conductor low resistivity glass.



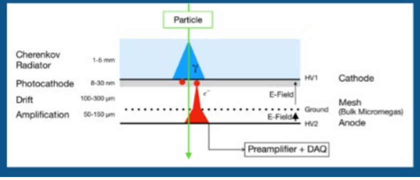
ALICE TOF

MRPC Time distributions





The **PICOSEC Micromegas detector** combines a Cherenkov radiator, a photocathode and a Micromegas-based amplification stage into a high-precision timing detector



Prototypes with gaseous detectors

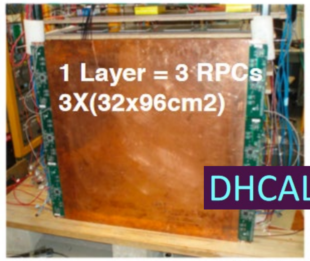
~1.3m^3 prototype at CERN Test Beam

SDHCAL with RPC

SDHCAL - Micromegas

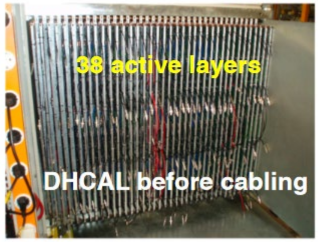
Micromegas prototype of 1x1m2 consisting of six independent Micromegas boards

C. Adams *et al* 2016 *JINST* **11** P07007



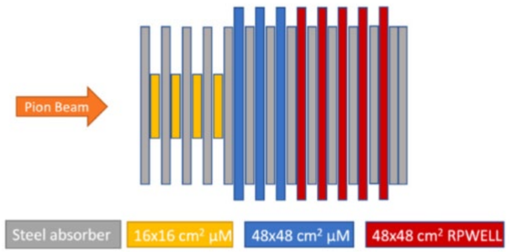
DHCAL – RPC

Readout = 1 bit (digital



The SCREAM project
Sampling Calorimeter with Resistive Anode MPGD

Test beam setup at CERN/PS in Nov 2018



CALORIMETRY – the concepts

Tile and strip calorimeters

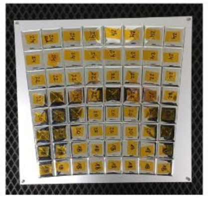
"Classical" scintillator tile calorimeters

ATLAS TileCal
CMS HCAL

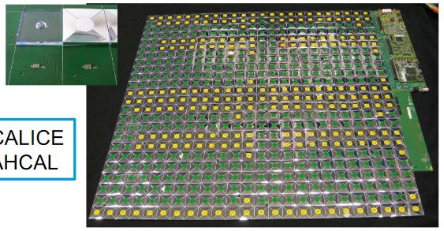
"Integrated" scintillator tile and strip calorimeters

Also photodetector and electronics in radiation area

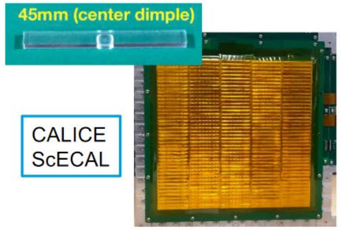
CMS HGCAL



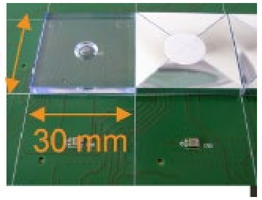
CALICE AHCAL



CALICE ScECAL



Granularity:
2.5 * 2.5 to 5.5 * 5.5 cm²

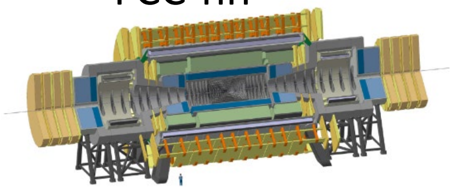


Scintillator and silicon share the same (cold) volume
- Operation at -30º C beneficial for SiPM noise
- Limited possibility to warm up for annealing

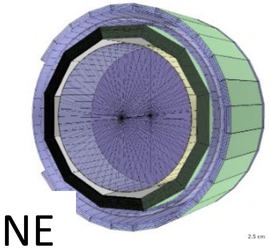
Radiation damage of photodetector (SiPM): neutron fluence
- State of the art: CMS BTL plans use up to 3 * 10^14 neq/cm²
- Effects:
  - Breakdown voltage increases
  - Dark count rate increases
    - Lose ability to see single pixel spectra → implications for calibration
    - Large leakage currents → electronics needs to cope
    - At some point: significant fraction of pixels occupied by noise
  - Effect smaller at lower temperature
  - Effects can be mitigated by annealing (higher T → more annealing)
  - Effects of the package: optical transparency, self-heating

In future projects

FCC-hh

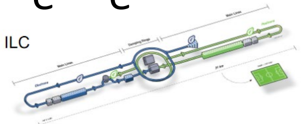


DUNE

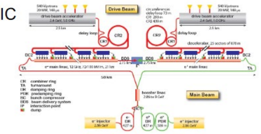


e^+ - e^-

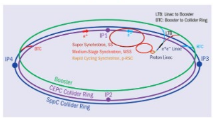
ILC



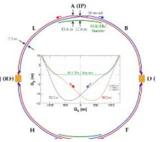
CLIC



CEPC

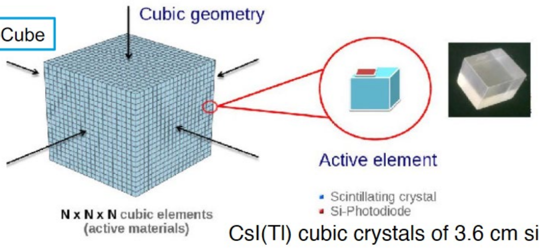


FCCee



Ultimate granularity

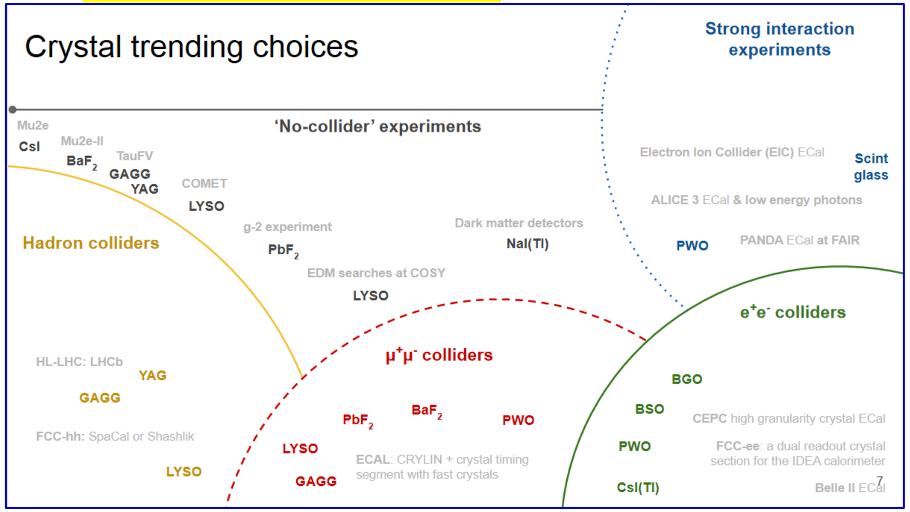
CaloCube

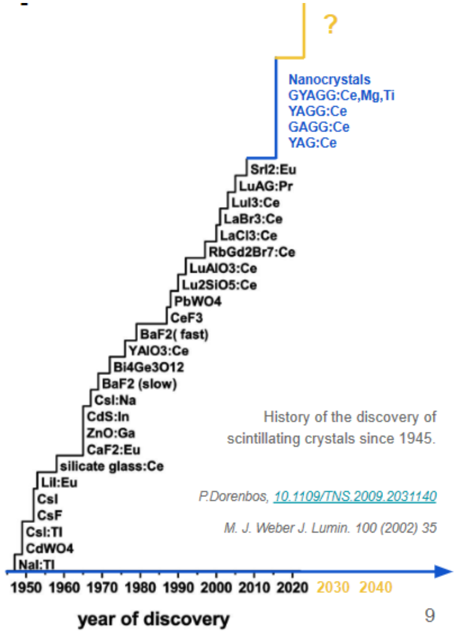


CsI(Tl) cubic crystals of 3.6 cm size

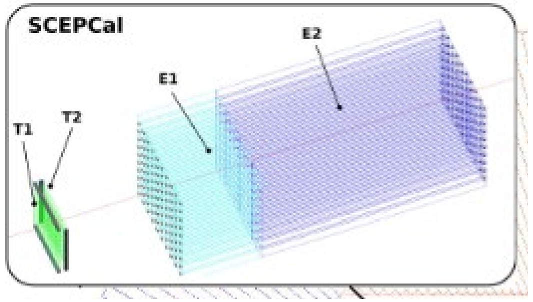
CALORIMETRY – the concepts

Crystal calorimetry

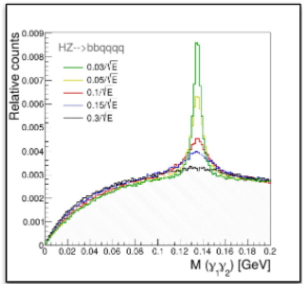




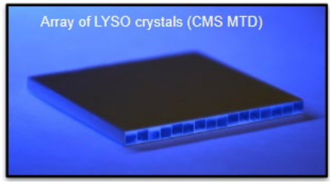
Integration of homogeneous crystals in a **hybrid dual-readout calorimeter**

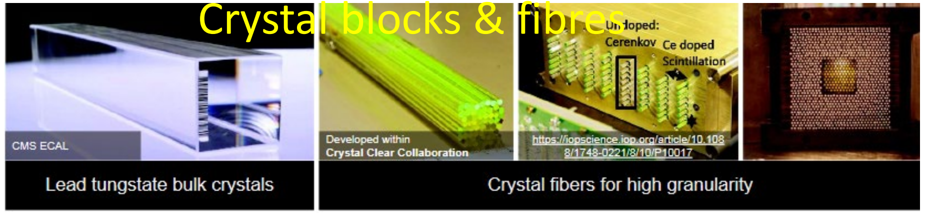


Integration of **precise** energy measurements in **Particle Flow Algorithms**

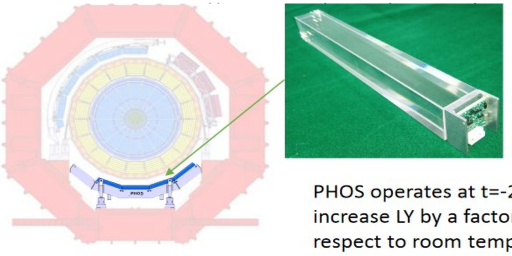


Integration of **precision timing** in crystal calorimeters





$PbWO_4$ crystals intrinsic timing resolution of the order of ~20 ps
In CMS managed to obtain ~70ps at high energy, dominated by front-end



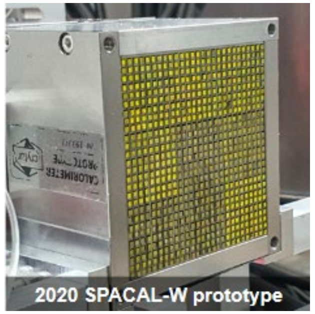
PHOS operates at t=-25°C to increase LY by a factor of 3 with respect to room temperature

Homogeneous crystal calorimeters have the best energy resolution (σ_E/E~1-3%/√E) for low-energy photons/electrons → **will play a role in future colliders**

Towards future calorimeters

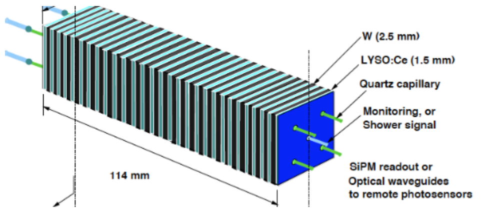
Radiation tolerant sampling crystal calorimeters

Spaghetti calorimeter (



Shashlik calorimeter

RADiCAL



Fast segmented crystals for BIB mitigation

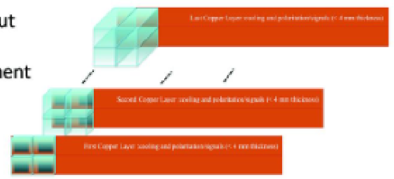
Exploiting crystal timing and longitudinal segmentation for BIB rejection at muon collider

- Calorimeter Layout: the calorimeter can be segmented longitudinally as a function of the energy of the particles and the background level.

Cherenkov light, semi-homogeneous calorimeter: PbF2 + copper + SiPM read-out

Design specific for Muon Collider experiment (Electromagnetic Calorimeter)

CRYLIN: CRYstal calorimeter with Longitudinal Information (idea by Ivano Sarra)



- A reduced first layer used as active pre-shower for timing → PbF2 or LYSO (5+10 mm).

CALORIMETRY – the concepts

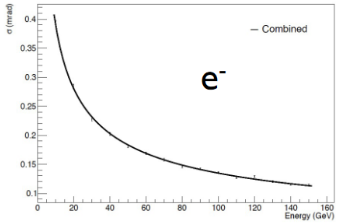
Dual-Readout fibre-sampling calorimetry

Dual-readout in a nutshell

- **f_{em} fluctuations** dominate the hadronic calorimeter resolution
- **Dual Readout:**
  - Scintillation (all particles) and Cherenkov (electrons) signals have **different h/e** $\Longrightarrow$ allow the event-by-event extraction of f_{em}

Dual Readout in IDEA@FCC (CepC)

GEANT4 – IDEA / e⁻ 15-150 GeV

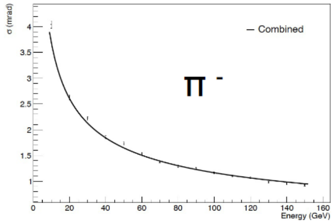


High granularity

good angular resolution

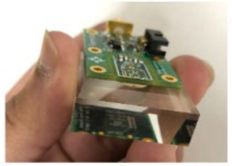
$$\sigma(mrad) = \frac{1.23}{\sqrt{E}} \oplus 0.05$$

GEANT4 – IDEA / π⁻ 15-150 GeV

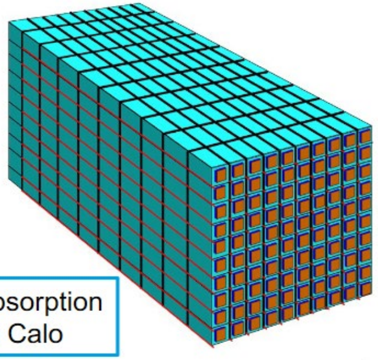


$$\sigma(mrad) = \frac{11.6}{\sqrt{E}}$$

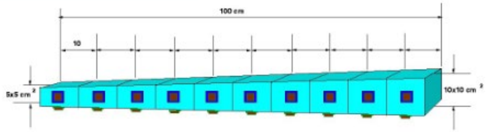
Tiles with Dual Readout



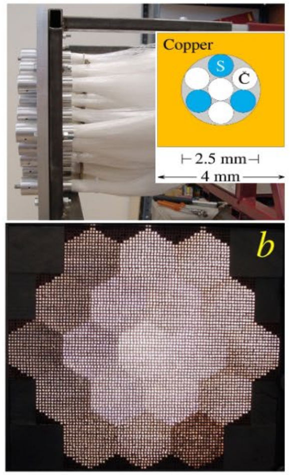
ADRIANO2 Lead-Glass Tile

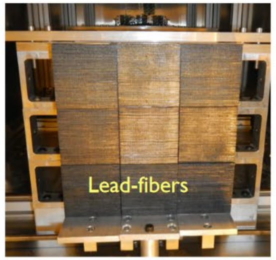


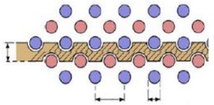
Total absorption Hadron Calo

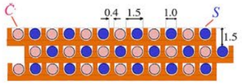


State of the Art – DREAM & RD52 collaboration

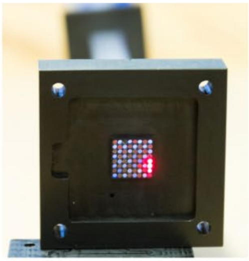


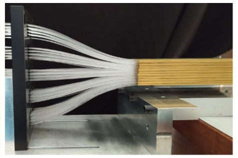


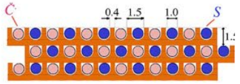




PMT readout







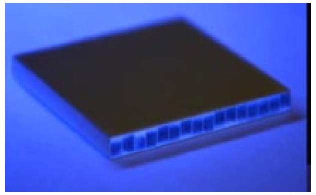
SiPM readout

CALORIMETRY – precise timing

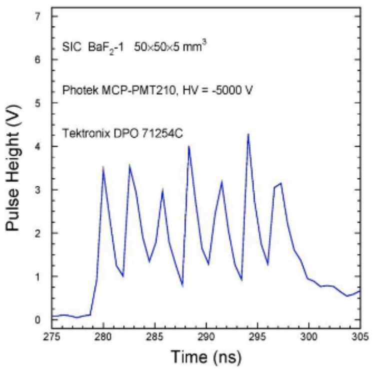
Precision timing, motivated by need for pile-up suppression **and not only**

Move towards HL-LHC adding time layers:

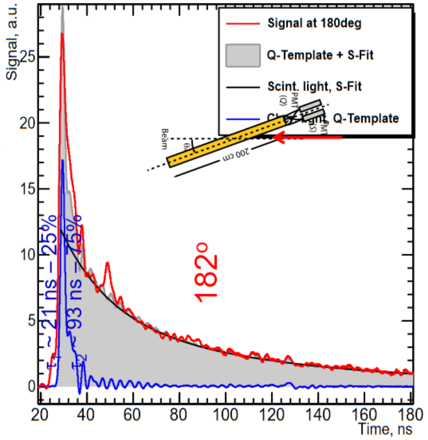
CMS MIP Timing Detector (MTD)



BaF_2: suppress slow luminescence component by dopping → **BaF_2:Y**

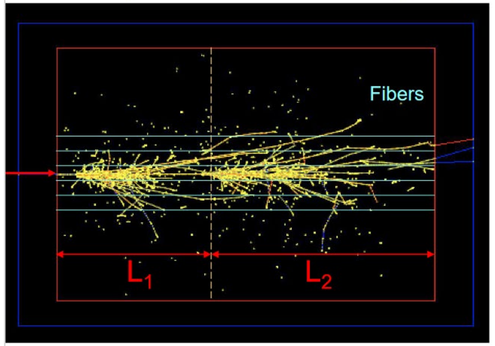


Scintillation/Cherenkov Light in a Single Fiber

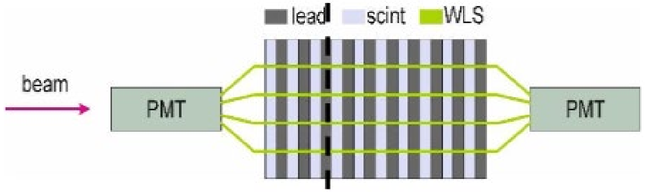


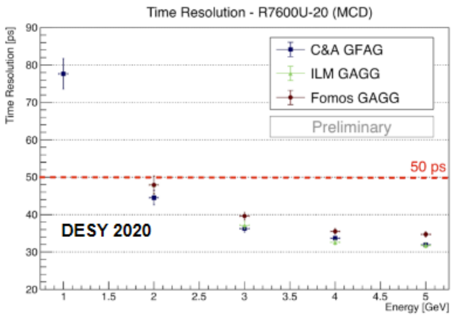
Longitudinal Segmentation with Timing

Fibers in spaghetti calorimeters generate and efficiently transport light. With appropriate timing ("strobing"), it may be possible to effectively segment the calorimeter in depth

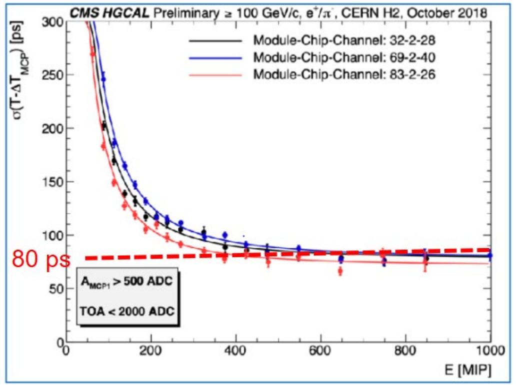


LHCb SPACAL

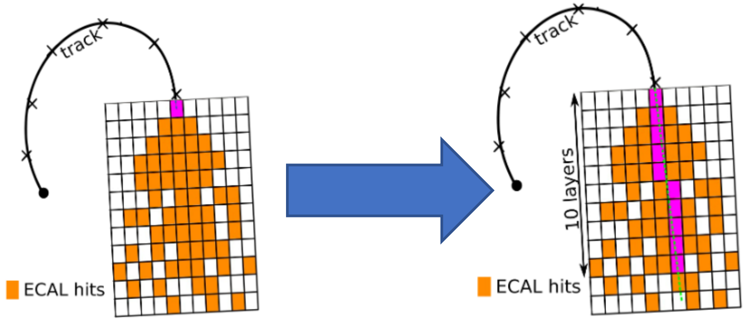




CMS HGCAL:

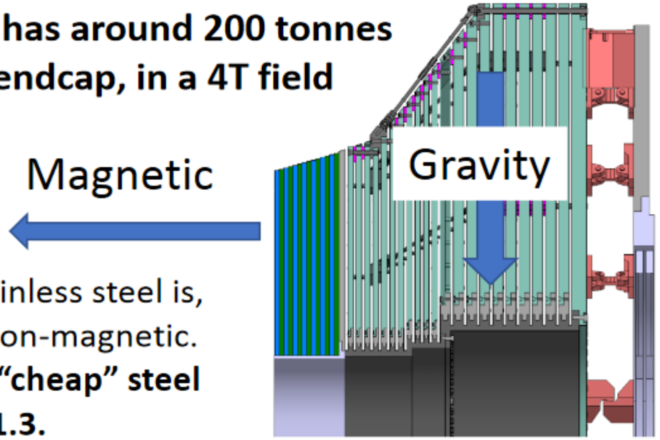


Moving towards a 5-D calormetry !



CALORIMETRY – mechanics & integration

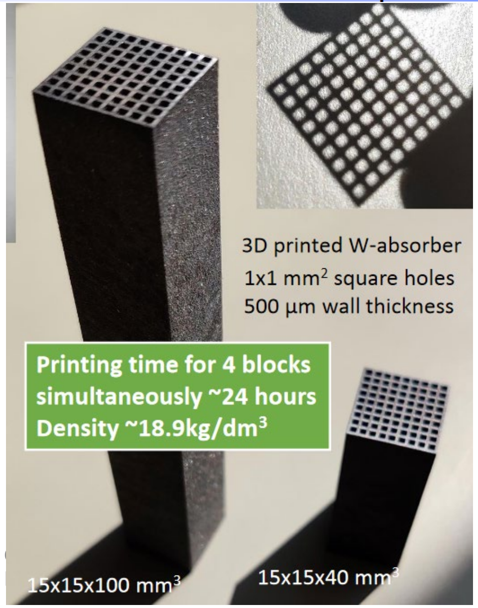
CMS HGCAL has around 200 tonnes of steel per endcap, in a 4T field

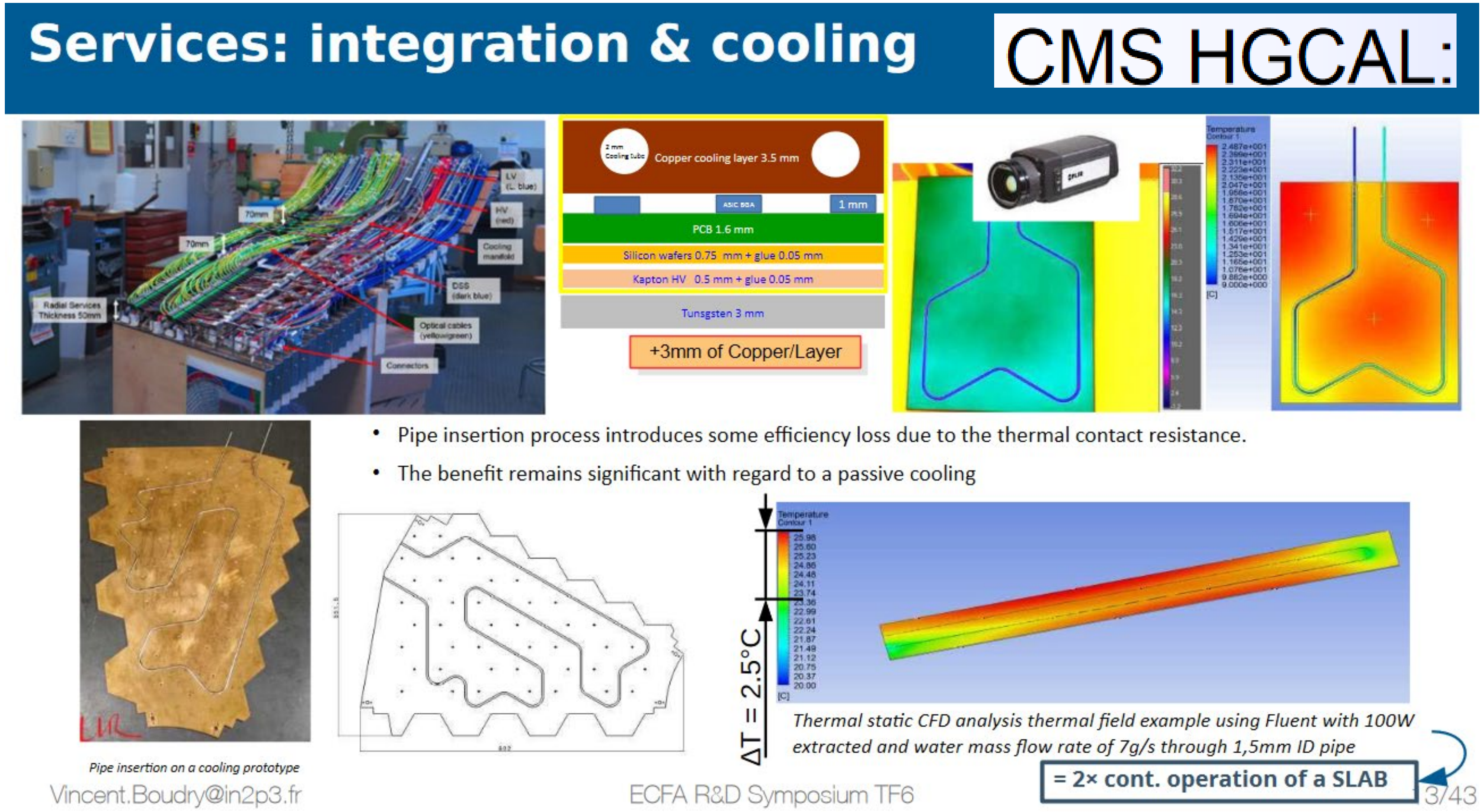


Austenitic Stainless steel is, in principle, non-magnetic. But standard **"cheap" steel may have μ~1.3.**

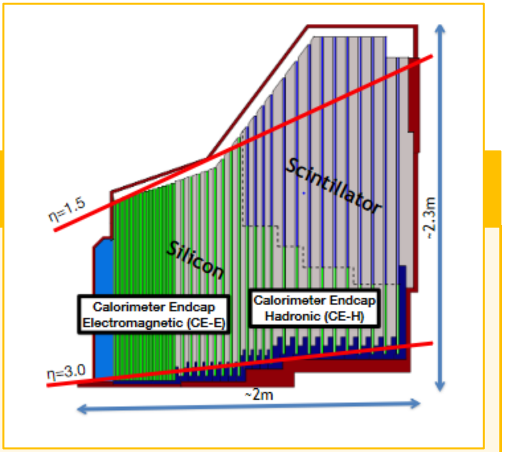
CMS HGCAL support structure designed for $\mathbf{F_{axial}}$ **~100 tonnes**

LHCb SPACAL: excellent recent experience with 3D-printed tungsten absorber for ultra-compact calorimeter





TF6 – Calorimetry



Summarizing about Calorimetry

- Future efforts grouped around **two major approaches**:
  - **Particle Flow**: granularity (also introducing CMOS sensors or SiPMs),
    correlation with tracking,
    sophisticated reconstruction algorithms → **4-D and 5-D imaging**
- **Compensating calorimeters**: dual read-out (scintillation and Cherenkov)
- Major technological needs:
  - progress in crystals
  - radhard SiPMs
  - Cryogenic support for noble liquids

Observations & reccommandations

- Moving toward **5-D calorimetry** allows for global integration of the calorimeters in the experiment detector (**holistic approach**)
- Need of **large-size prototype** for realistic validations: **networking and collaborative efforts**

Training in the detector sector, acknowledging the detector relevance and keyrole in HEP
(TF9)

TF9 – Training

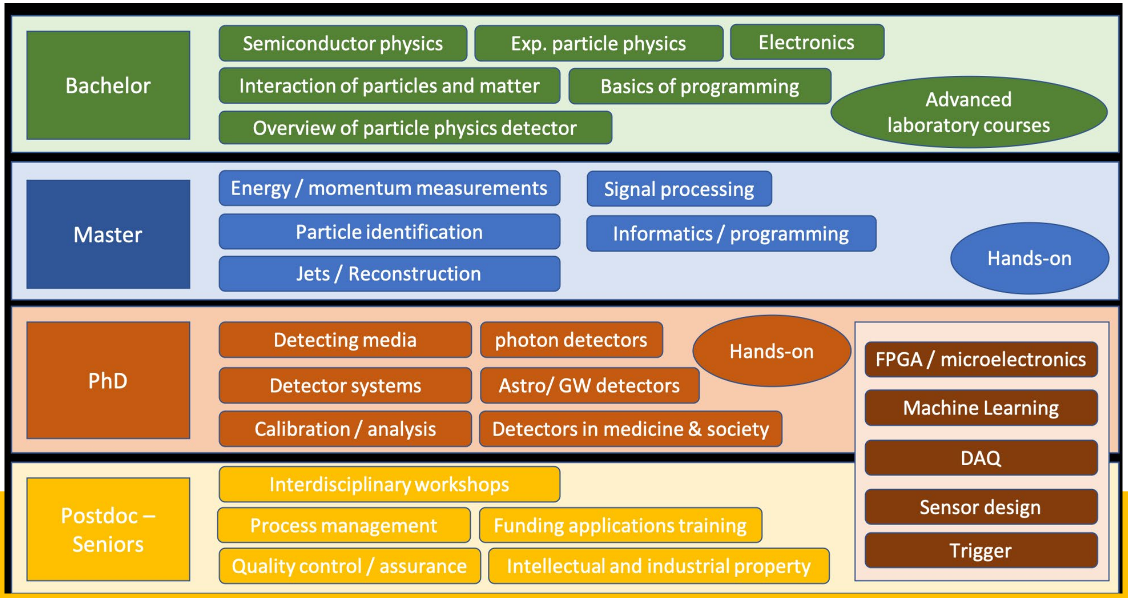
Needs of the community

- **Stimulate** and **recognise the field of instrumentation** in particle physics and specifically the importance of innovation, detector development and operation
  - **Need of training at all levels**, from initial university studies up to continuous update of professionals: **presently, perception of insufficient training opportunities (from ECFA - Early Career Researchers Panel survey)**
  - Role of Universities (bachelor and dedicated masters), Schools, Lab training, Virtual labs, Academia meats Industry
- **Attract and train** outstanding talented individuals in physics and engineering
  - **Recognition** at all stages (dedicated scholarships, stipends, awards)
  - Opportunity for publications **in high-ranked journals** of technology and experimental methods
  - Attractive **career prospects: presently, negative perception (from ECFA - Early Career Researchers Panel survey)**
- Recognise the **diversity of skills needed** in the field
- Find an appropriate **balance between specialisation and breadth**

Observations

- **VITAL for HEP**: w/o implementing a strategic promotion of instrumentation→ missing the continuity of highly qualified detector experts from R&D to construction and to operation of HEP detectors
- Need of a coordinated European training programme

TF9 – Training, DCT



Each point of previous slide can be directly translated into corresponding recommendations, that have been clusterized around the two Detector Community Themes listed here

DCT 1 - Establish and maintain a European coordinated programme for training in instrumentation.

DCT 2 - Develop a master's degree programme in instrumentation.

Recommendations at large

GENERAL STRATEGIC RECOMMENDATIONS

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

- **test beams**
- **large scale** generic **prototyping**
- **irradiation facilities**
- adequate **centralised investment**, maintain a network structure for existing distributed facilities

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

- ever more **integrated detector** concepts, with **holistic** design and **large component**, **scalability** needs
- adequate **mechanical and electronics engineering resources**, to bring in expertise in state-of-the art

GSR 3 - **Specific software for instrumentation**

- specific software **packages must be maintained** and continuously **updated**, **recognizing the expert development**
- **community support** of these needs to be organised at a European level

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

- refresh the **CERN RD programme structure** encouraging **new programmes**, also with **support of national laboratories**
- enhancing the **visibility** of the **detector R&D community**
- easing **communication with neighbouring disciplines**

GENERAL STRATEGIC RECOMMENDATIONS, cont.

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

- a **distributed yet connected** and **supportive tier-ed system** for R&D efforts across Europe
- **focused investment** for those themes where leverage can be reached through **centralisation at large institutions**
- **in parallel**, **distributed resources remain accessible** to researchers across Europe

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

- **short-term funding** for the early **proof of principle** phase
- also **long-term strategic funding** programmes to sustain both research and development of the **multi-decade DRDTs**
- beyond **capital investments** of **single funding agencies**, **international collaboration and support at the EU level** should be established

GSR 7 – **"Blue-sky" R&D**

- **"Fuel** for innovative HEP instrumentation"
- **adequate resources**
- **immense societal benefit** (e.g., WWW, Magnetic Resonance Imaging, PET, X-ray imaging)

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

- *Positions and career perspectives*
- By product: **training in detector** field beneficial to society by acquiring knowledge and skills in high demand by **industries in high-technology** economies

GENERAL STRATEGIC RECOMMENDATIONS, cont.

GSR 9 - **Industrial partnerships**

- recommended **close collaboration between academic and industrial partners**
- **international frameworks** for **exchange on academic and industrial trends**, drivers and needs
- **Dedicated resources** needed on a European scale to intensify the collaboration with industry
  - in particular, for developments in **solid state sensors** and **micro-electronics**

Several possible underlying reasons for failures of industrial productions:

- The lack of monetary investment O(1-10Meuro) to start production in industries
- the typical long R&D periods of the HEP experiments
- the uncertainty on the return of the initial investment

GSR 10 - **Open Science**

- **supported in the context of instrumentation**, taking account of the constraints of commercial confidentiality when needed
- Sponsoring Consortium for Open Access Publishing in Particle Physics (**SCOAP3**) should explore ensuring **similar access is available to instrumentation journals (including for conference proceedings)** as to other particle physics publications

The new phase after 2021:
the implementation process

Some initial elements considered for implementation

PRELIMINAR CONSIDERATIONS

- both **organizational structures** and **adequate resources** are required

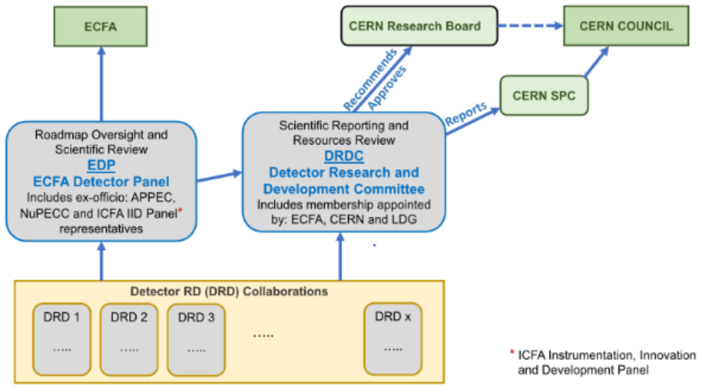
- Establishment of **RD Collaborations** with base at CERN, open to Europe and beyond
  - Tradition: RD50, RD51 , …
  - With also a review/guidance role of the **ECFA Detector Panel (EDP)**
  - **Resources**: from CERN, national agencies, from Europe (joint action of CERN and ECFA ?)
  - A role for the **Main European National Laboratories** in Europe
  - A **dedicated panel review panel ?**

Some initial elements considered for implementation

IMPLEMENTATION STRATEGY CURRENTLY CONSIDERED

Review and Approval Process

K. Jacobs,
RRB Meeting
CERN, 25th April 2022



1. ECFA Detector Panel (EDP): the scope, R&D goals, and milestones should be vetted against the vision encapsulated in the Roadmap. (EDP: http://cds.cern.ch/record/2211641/files/, exists, hosted at DESY)

2. The resources for detector R&D should be reviewed by an independent body, the Detector Research and Development Committee (**DRDC**), which should include members appointed by CERN, ECFA and the LDG.
The DRDC would make recommendations, while the final approval would lie with the CERN Research Board.

GENERAL STRATEGIC RECOMMENDATIONS

GSR 1: Supporting R&D Facilities

GRS 2: Engineering support for detector R&D

GRS 3: Specific software for instrumentation

GRS 4: International coordination and organisation of R&D activities

GRS 5: Distributed R&D activities with centralised facilities

GRS 6: Establish long-term strategic funding programmes ?

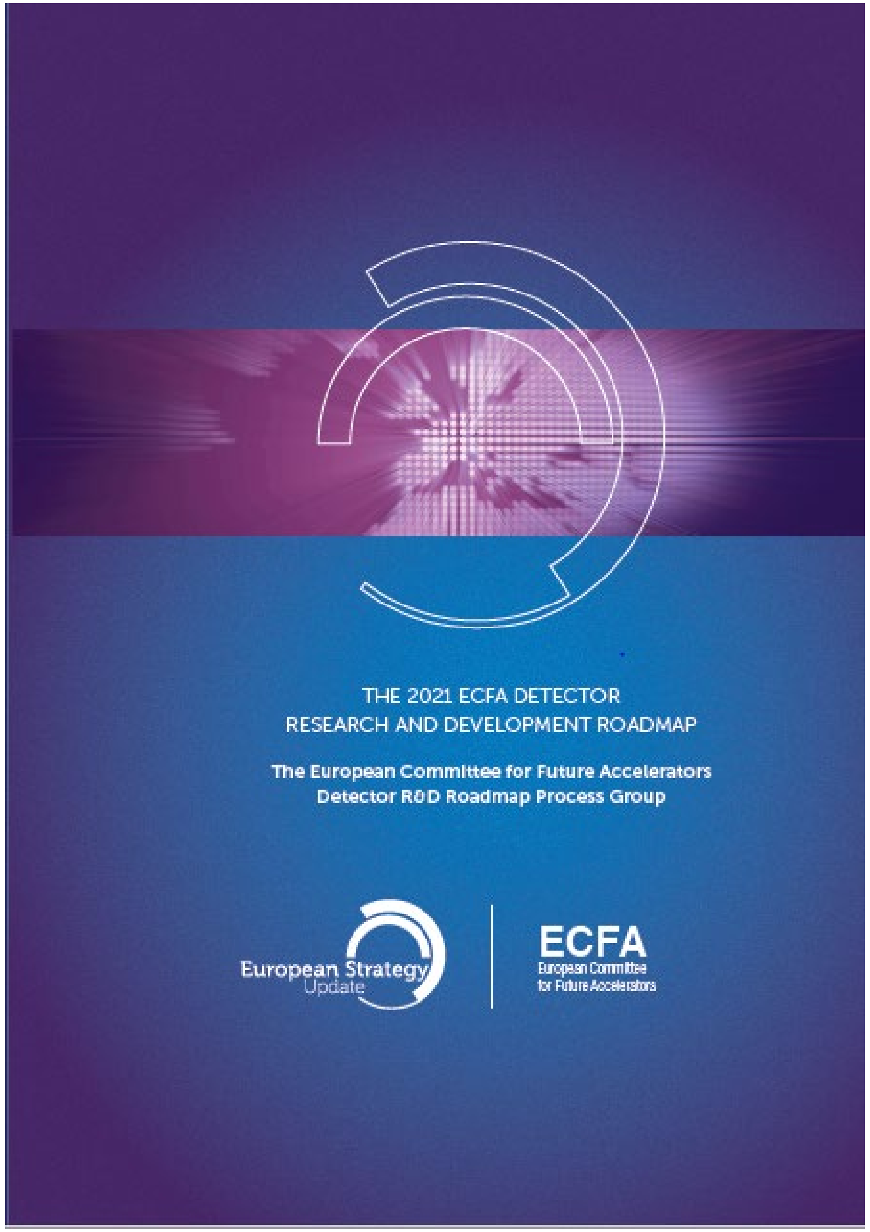
GRS 7: "Blue-sky" R&D"

GRS 8: Attract, nurture, recognise and sustain the careers of R&D experts

GRS 9: Industrial partnerships

GRS 10: Open Science

THANK YOU


THE 2021 ECFA DETECTOR
RESEARCH AND DEVELOPMENT ROADMAP
The European Committee for Future Accelerators
Detector R&D Roadmap Process Group
European Strategy Update
ECFA
European Committee for Future Accelerators