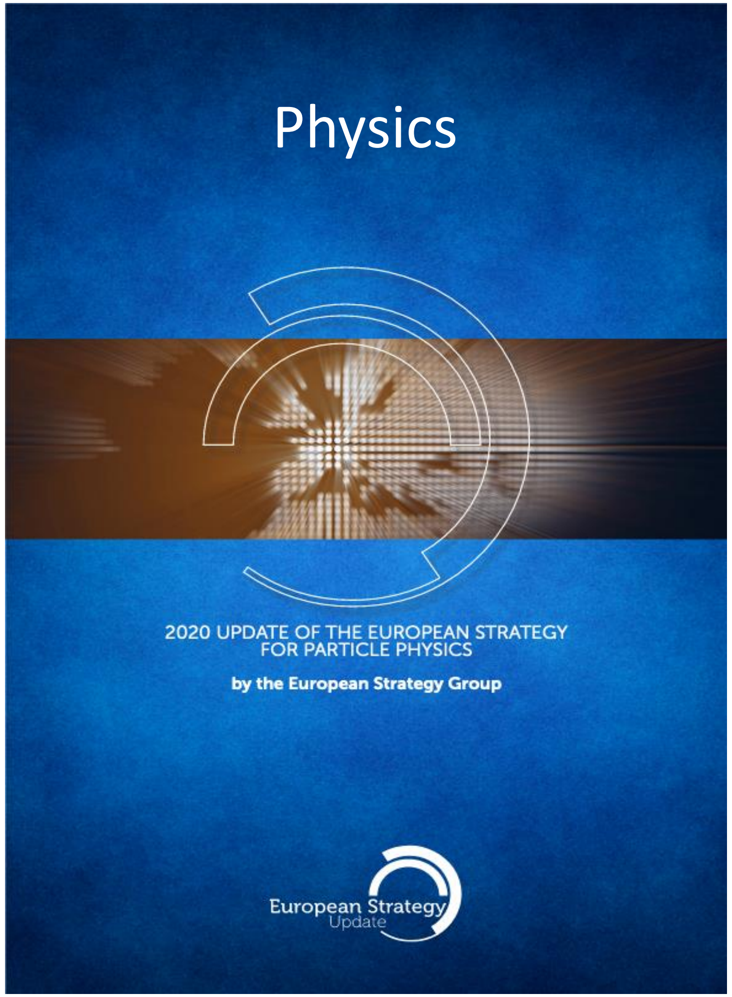
Nordic Conference on High Energy Physics, 4-7 January 2022

Future experimental programs and detector R&D

D. Contardo, CNRS-IN2P3 IP2I

European Strategy for Particle Physics update in 2020



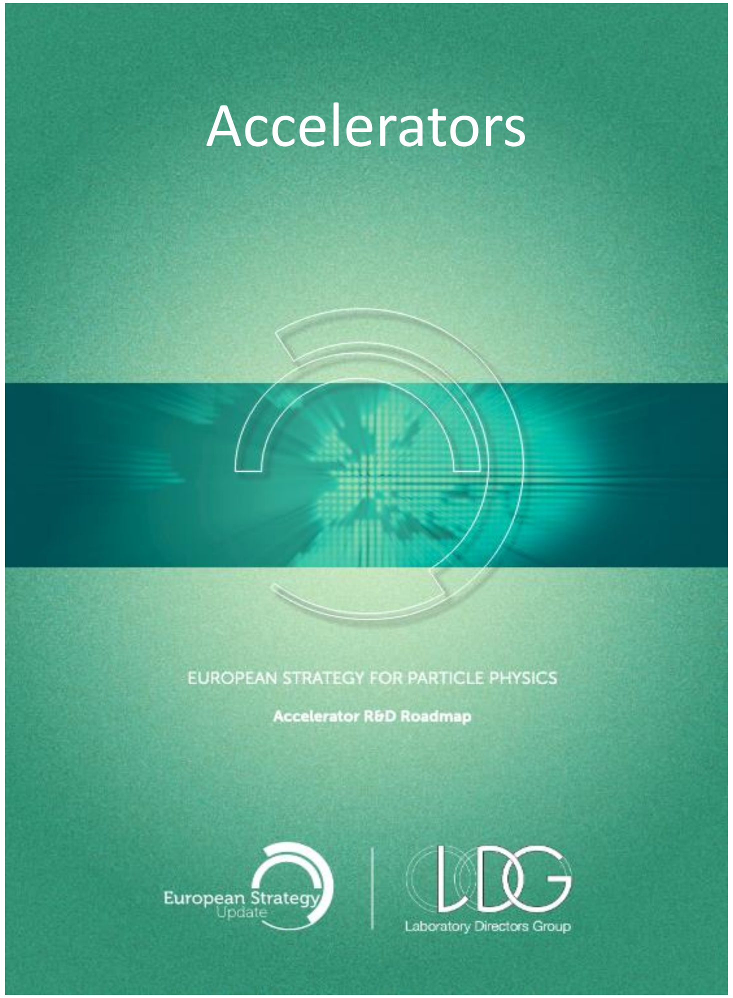
Physics

2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

European Strategy Update

https://cds.cern.ch/record/2721370
https://cds.cern.ch/record/2691414/files/1910.11775.pdf



Accelerators

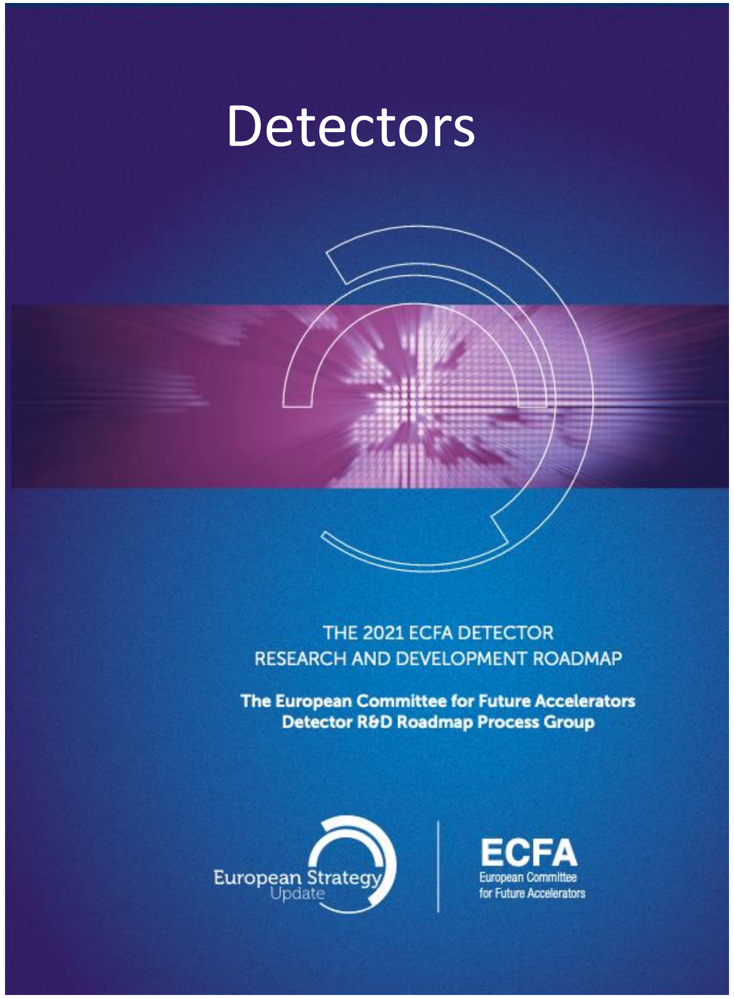
EUROPEAN STRATEGY FOR PARTICLE PHYSICS

Accelerator R&D Roadmap

European Strategy Update

LDG Laboratory Directors Group

https://cds.cern.ch/record/2800190



Detectors

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

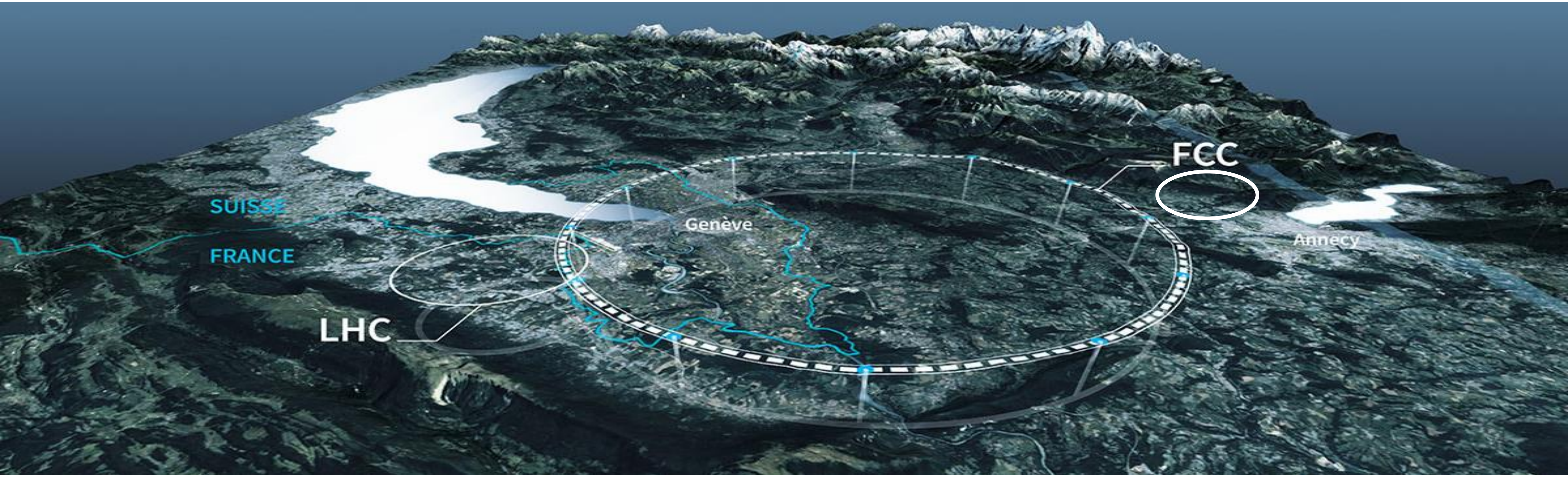
https://cds.cern.ch/record/2784893

Snowmass strategy process in US https://arxiv.org/pdf/2211.11084.pdf 2022, P5 recommendation beginning of 2023

“ An electron-positron Higgs factory is the highest-priority next collider…”

“Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage”

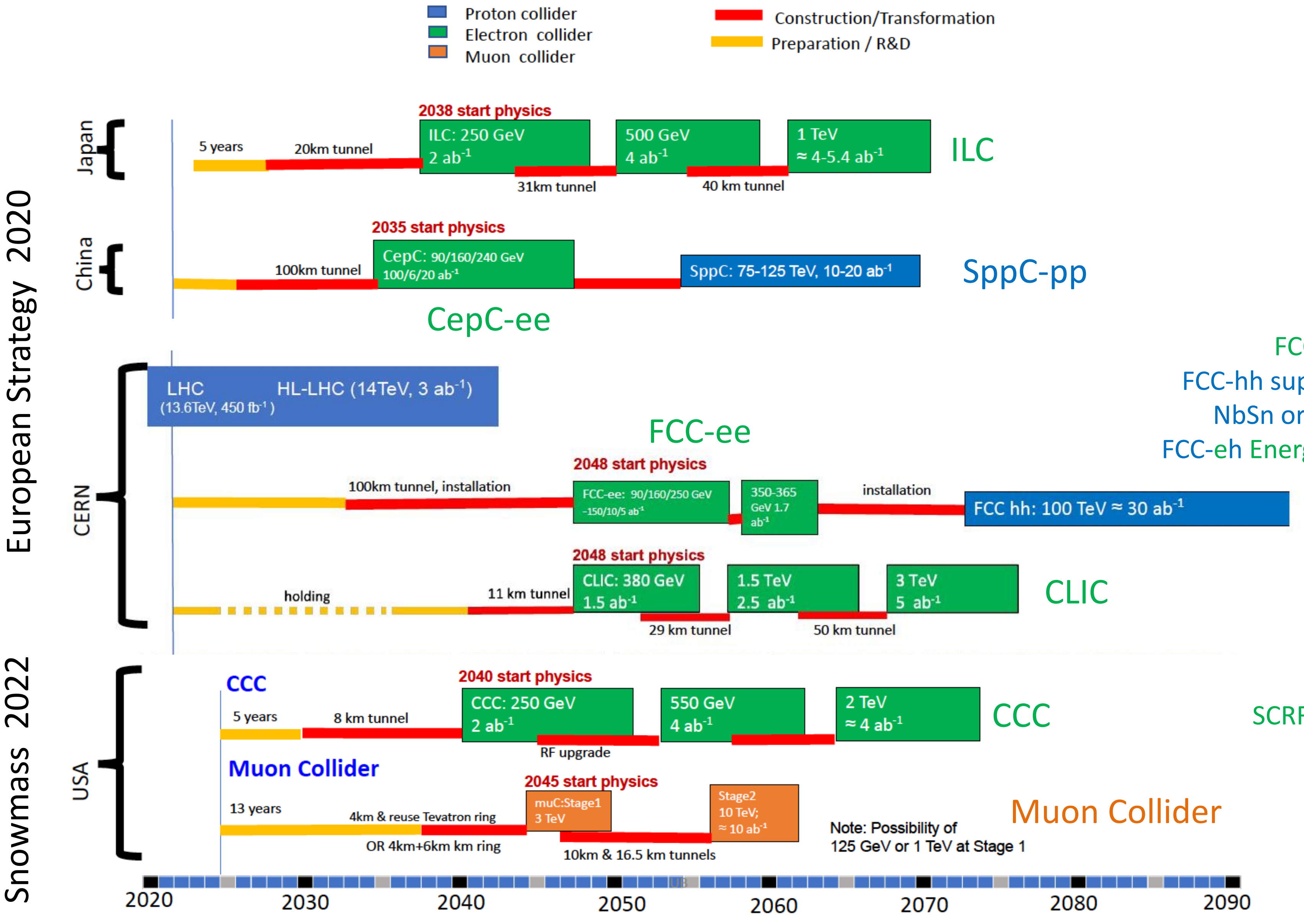
(European Strategy for Particle Physics https://cds.cern.ch/record/2721370)



Future Circular Collider is an integrated physics program with e-e, h-h, e-h, Pb-Pb and e-Pb collisions

a feasibility study report is expected end-2025 for the next ESPP update and possibly a decision

Physics planning proposals for future colliders



🟦 Proton collider
🟩 Electron collider
🟧 Muon collider
🟥 Construction/Transformation
🟨 Preparation / R&D

European Strategy 2020

Japan
5 years
20km tunnel
2038 start physics
ILC: 250 GeV
2 ab^{-1}
31km tunnel
500 GeV
4 ab^{-1}
40 km tunnel
1 TeV
≈ 4-5.4 ab^{-1}
ILC

China
100km tunnel
2035 start physics
CepC: 90/160/240 GeV
100/6/20 ab^{-1}
CepC-ee
SppC: 75-125 TeV, 10-20 ab^{-1}
SppC-pp

CERN
LHC
(13.6TeV, 450 fb^{-1})
HL-LHC (14TeV, 3 ab^{-1})
FCC-ee
100km tunnel, installation
2048 start physics
FCC-ee: 90/160/250 GeV
~150/10/5 ab^{-1}
350-365 GeV 1.7 ab^{-1}
installation
FCC hh: 100 TeV ≈ 30 ab^{-1}
FCC-hh (eh-PbPb-ePb)

holding
11 km tunnel
2048 start physics
CLIC: 380 GeV
1.5 ab^{-1}
29 km tunnel
1.5 TeV
2.5 ab^{-1}
50 km tunnel
3 TeV
5 ab^{-1}
CLIC

Snowmass 2022

USA
CCC
5 years
8 km tunnel
2040 start physics
CCC: 250 GeV
2 ab^{-1}
RF upgrade
550 GeV
4 ab^{-1}
2 TeV
≈ 4 ab^{-1}
CCC

Muon Collider
13 years
4km & reuse Tevatron ring
OR 4km+6km km ring
2045 start physics
muC:Stage1
3 TeV
10km & 16.5 km tunnels
Stage2
10 TeV;
≈ 10 ab^{-1}
Note: Possibility of
125 GeV or 1 TeV at Stage 1
Muon Collider

2020 2030 2040 2050 2060 2070 2080 2090

technology readiness and R&D

XFEL based SCRF cavities

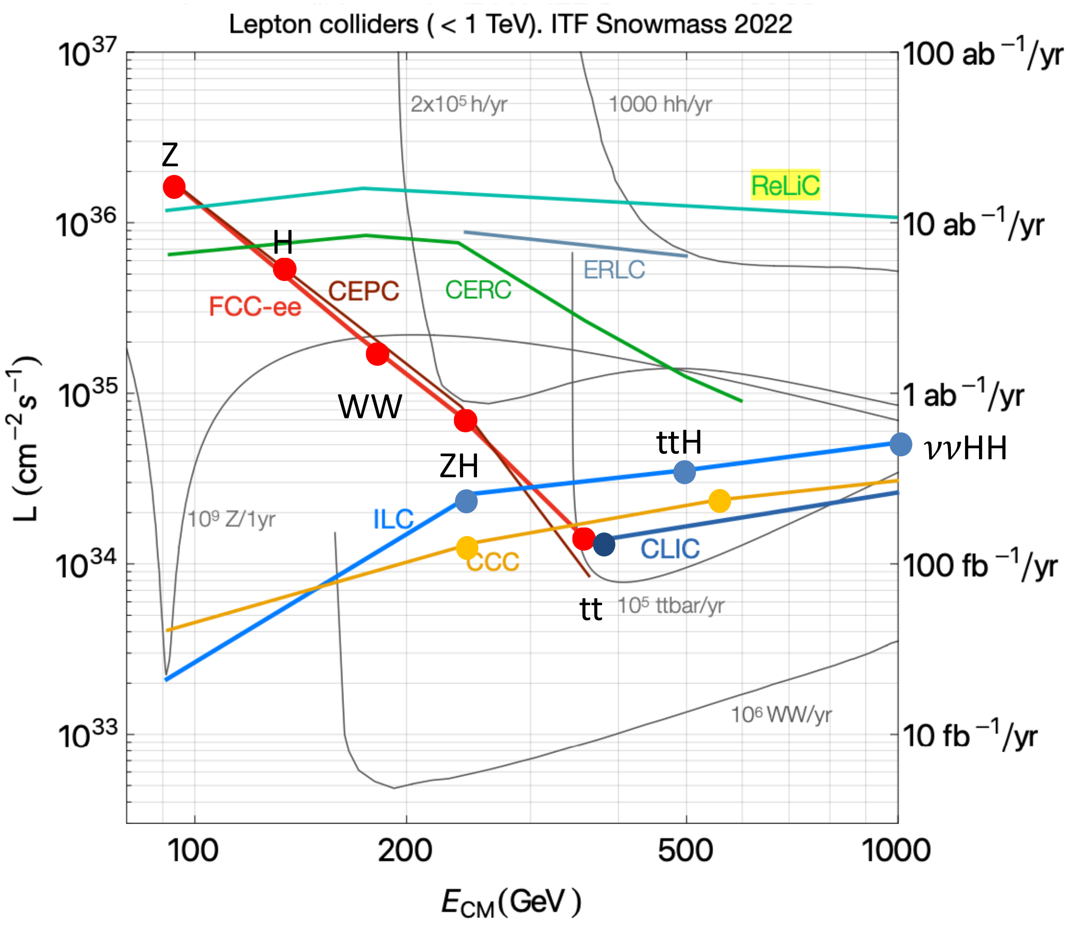
FCC-ee CERN JLab based SCRF cavities
FCC-hh superconducting magnets ≳ 16 T with
NbSn or High Temperature Superconductor
FCC-eh Energy Recovery for e-beam accelerator

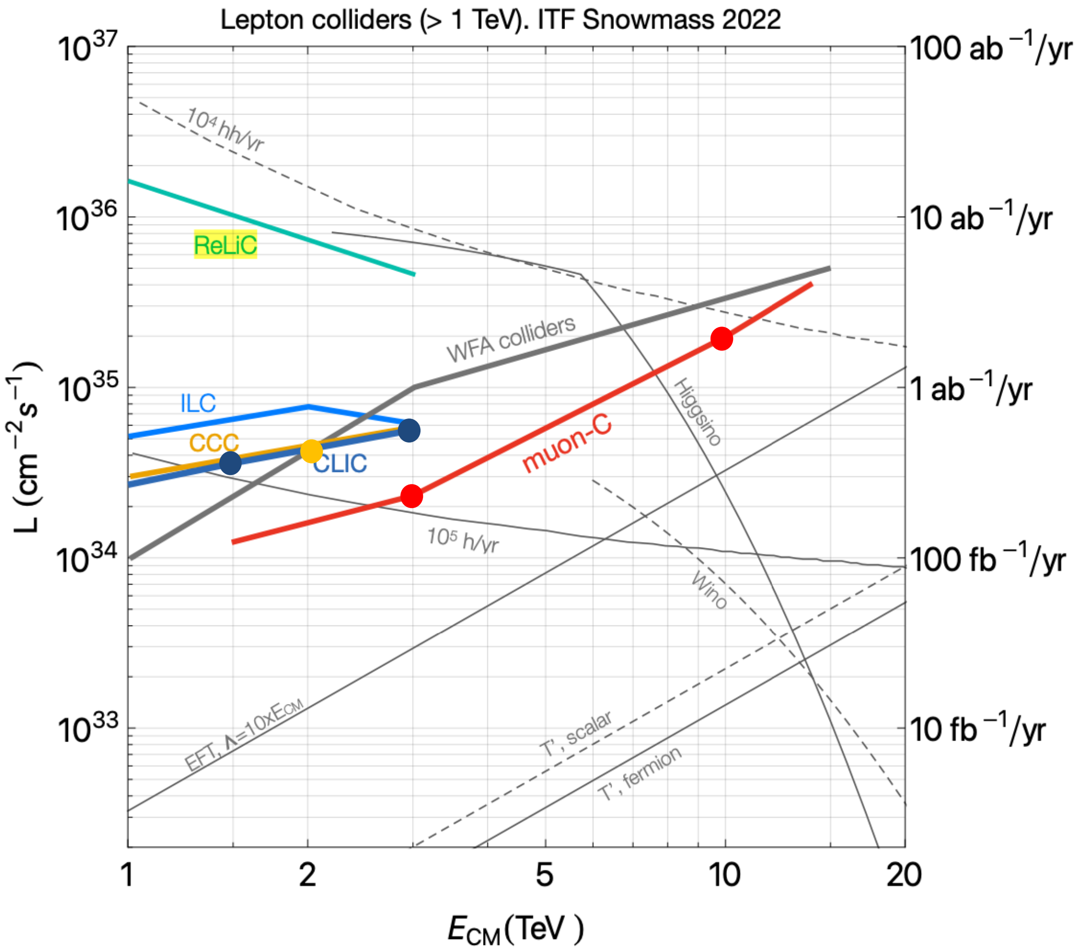
CERN based NCRF cavities e-drive

SCRF cavities high acceleration gradient

μ-cooling technology

Lepton colliders luminosity and energy program*



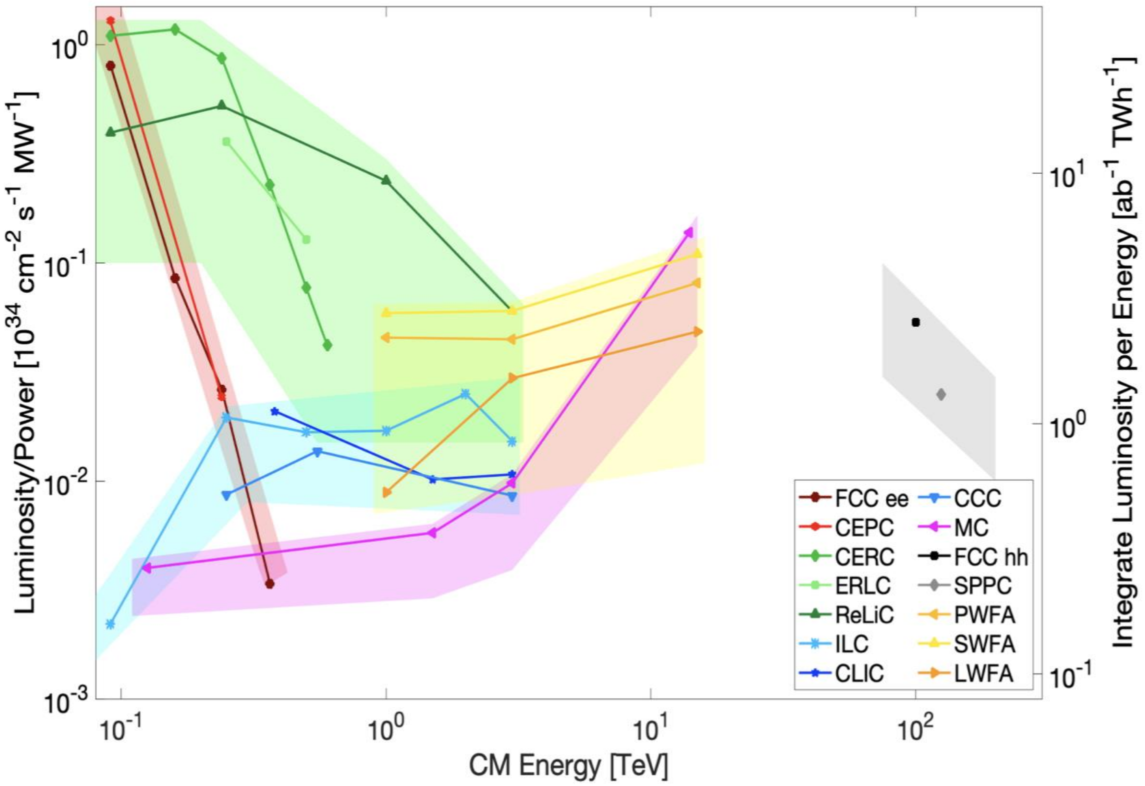


Energy recovery (CERC, ERLC, ReLIC), Wake Field (plasma) accelerators are at early R&D stage

** Luminosities per IP, assuming 10^7 s/ year for integrated luminosity Snowmass strategy process in US https://arxiv.org/abs/2208.06030*

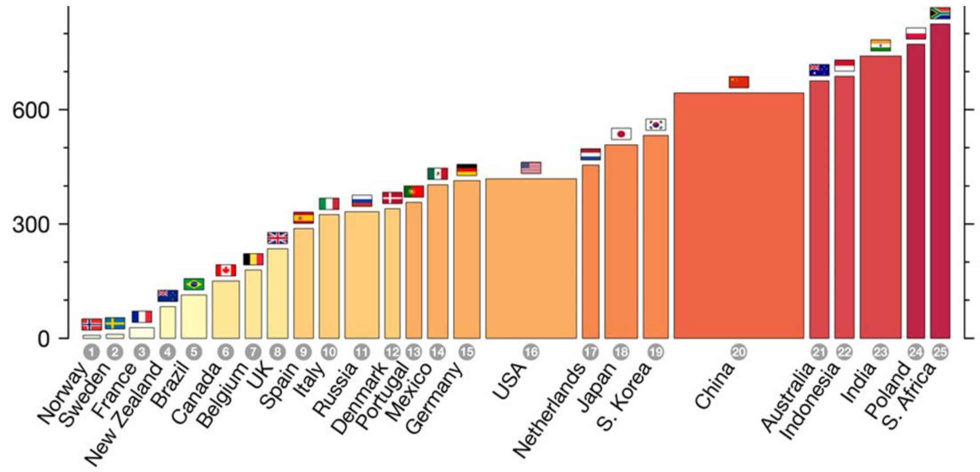
Sustainability

luminosity per electrical power figure of merit



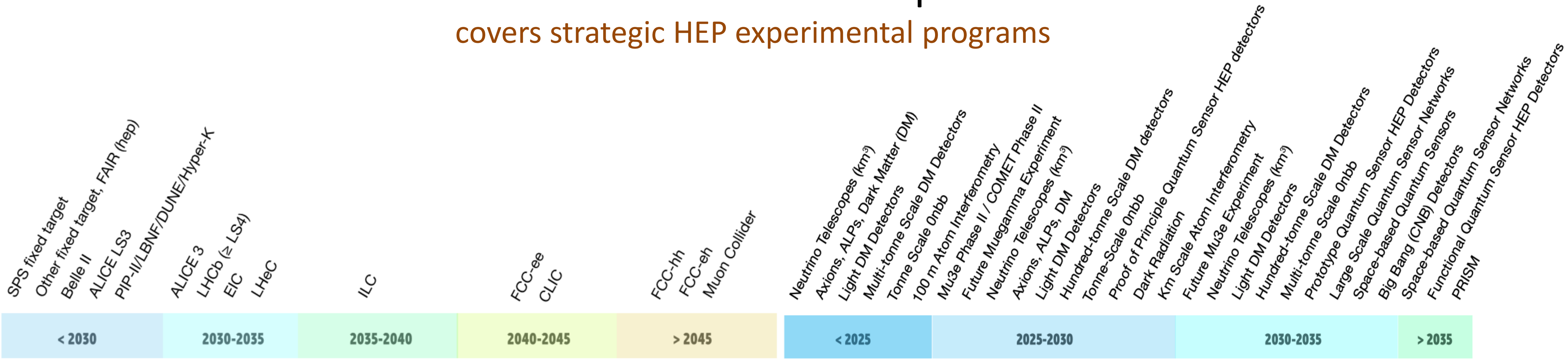
France & Switzerland ~ lowest electricity C content

https://www.weforum.org/agenda/2018/12/ten-charts-show-how-the-world-is-progressing-on-clean-energy



ECFA R&D roadmap

covers strategic HEP experimental programs



Future experiments (including upgrades)
at large accelerator facilities

Future experiments 1st , 2nd, 3rd phases
at small accelerators, nuclear reactors, with cosmic rays

Gaseous - Solid State - Photon and PID - Calorimeter

Liquid – Quantum sensors

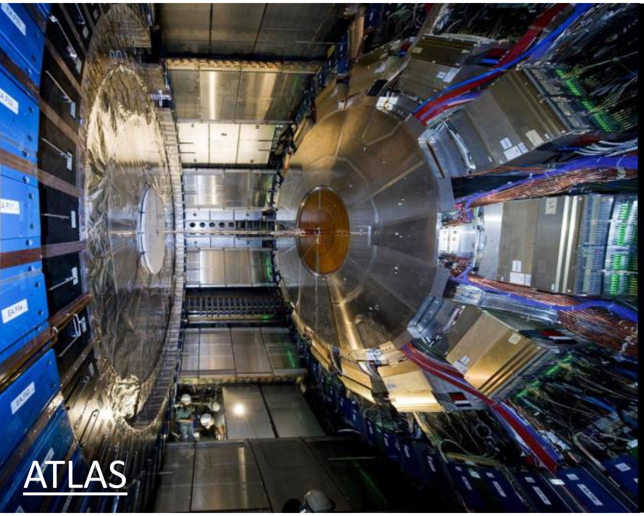
Electronics and on-detector processing - Integration

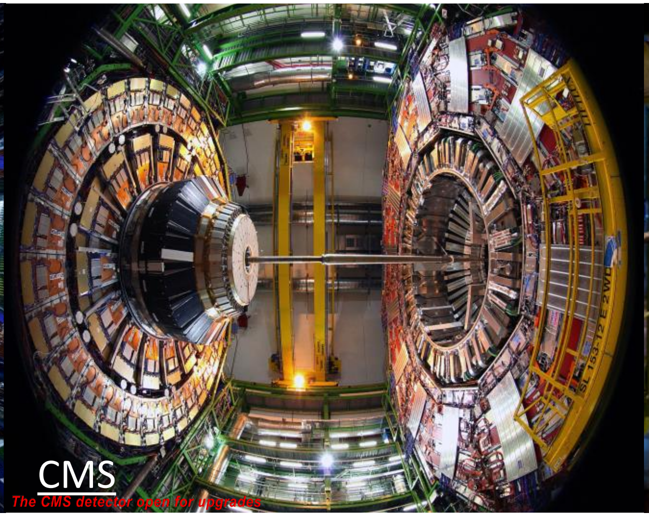
Test facilities and Infrastructures – Industrial partnerships – Networking and Training

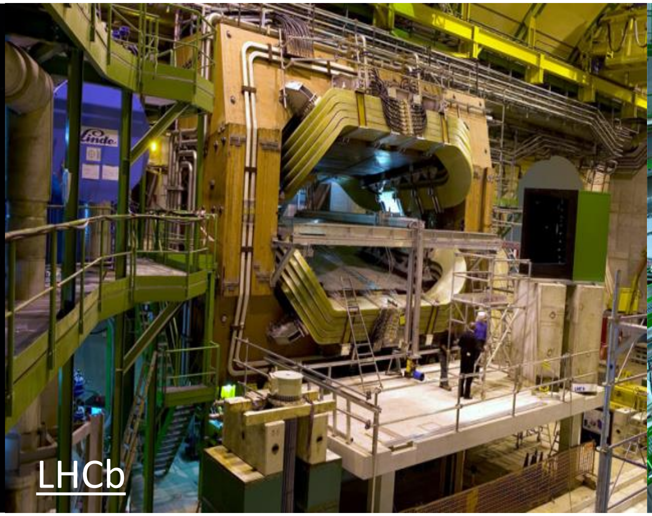
Nuclear Physics, AstroParticle (including Gravitational Wave) not considered, but NuPPEC and ApPEC invited to the process
also joint ECFA - NuPPEC - ApPEC seminars in 2019 - 2022 to develop common instrumental projects

Future Collider Detectors

most constraining applications with R&D representative for several other projects





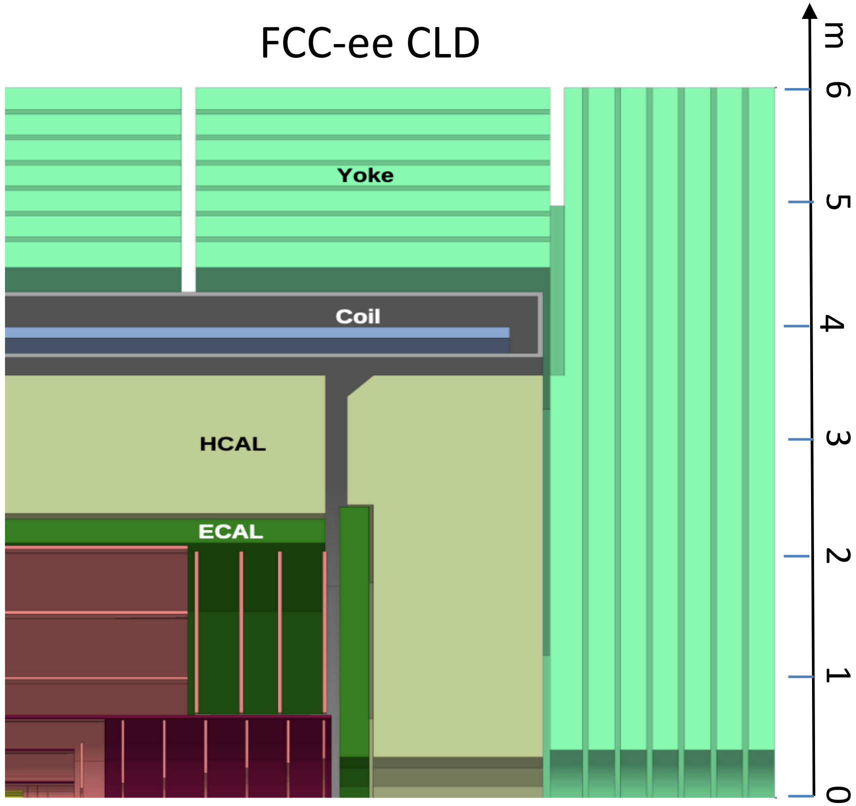


illustrations in the following mostly taken from LHC detectors above and/or State of the Art R&D

Original detector concepts for e^+e^- Higgs factory

ILD - SiD @ ILC, scaled to beam conditions @ CLICdet, then CEPC-BL/FST and FCC-ee CLD

unprecedented tracking and hadron calorimetry precision



Solenoid superconducting magnet 2 to 4 T*

High Granularity PFlow calorimeter
to resolve Z/W jet decays

Central Tracker Full Silicon (here) or TPC

Vertex Detector Silicon

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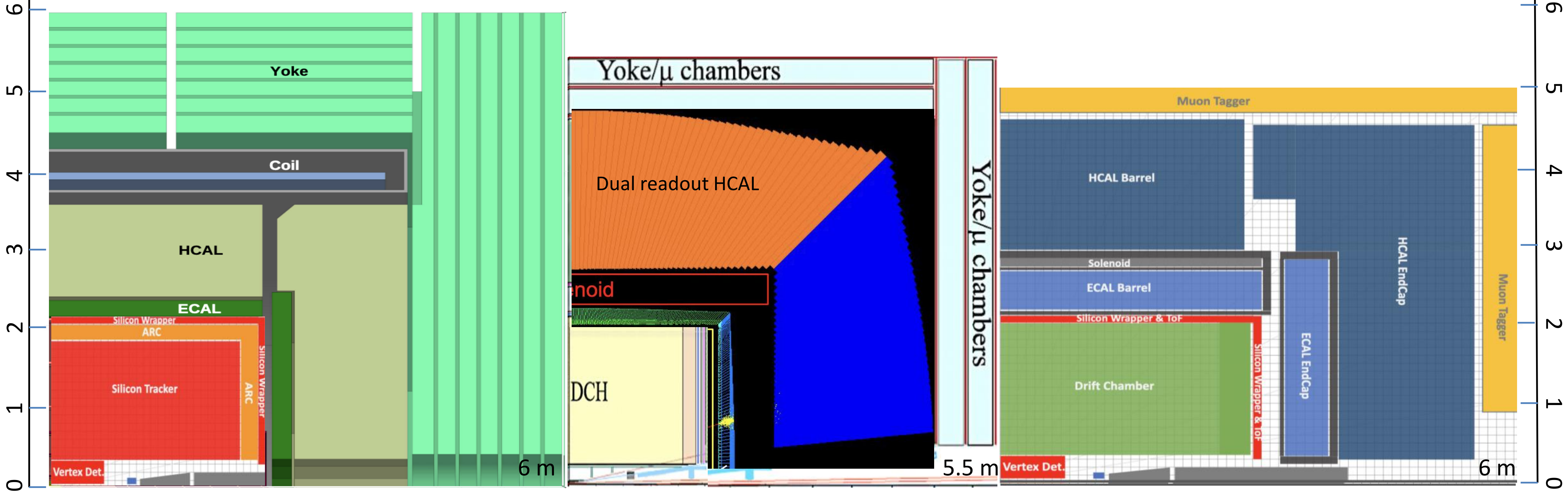
* *At FCC-ee the Z-pole B-field is limited to 2T (for high lumi.), also somehow setting tracker radius at 2m,* calorimeters are 22 X/X_0 and 7 λ with depth driven by absorbers

FCC-ee and CepC at Z-pole are also electroweak and flavor factories

new detector concepts include Particle ID, and high γ-energy resolution

systematics < statistical errors require precision on: √s O(10^{-6}), lumi. O(10^{-4}), accep. O(10^{-5}), B-field O(10^{-6})

Colliders can feature 4 detectors, 3 examples below
driven by calorimeters inside and/or outside solenoid, with tracking options exchangeable



ex. CLD with FST plus
PID RICH and ToF

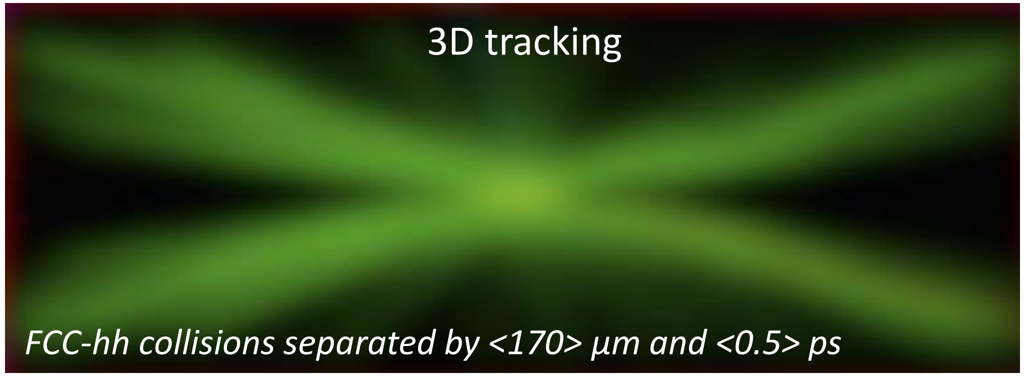
ex. IDEA with DCH PID
crystal ECAL inside solenoid

ex. Noble Liquid ECAL inside solenoid
with DCH

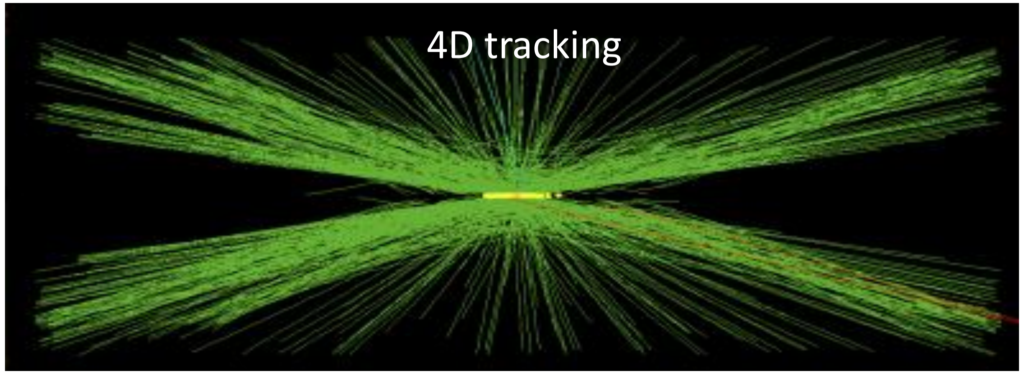
FCC-hh collider detector challenges and concept

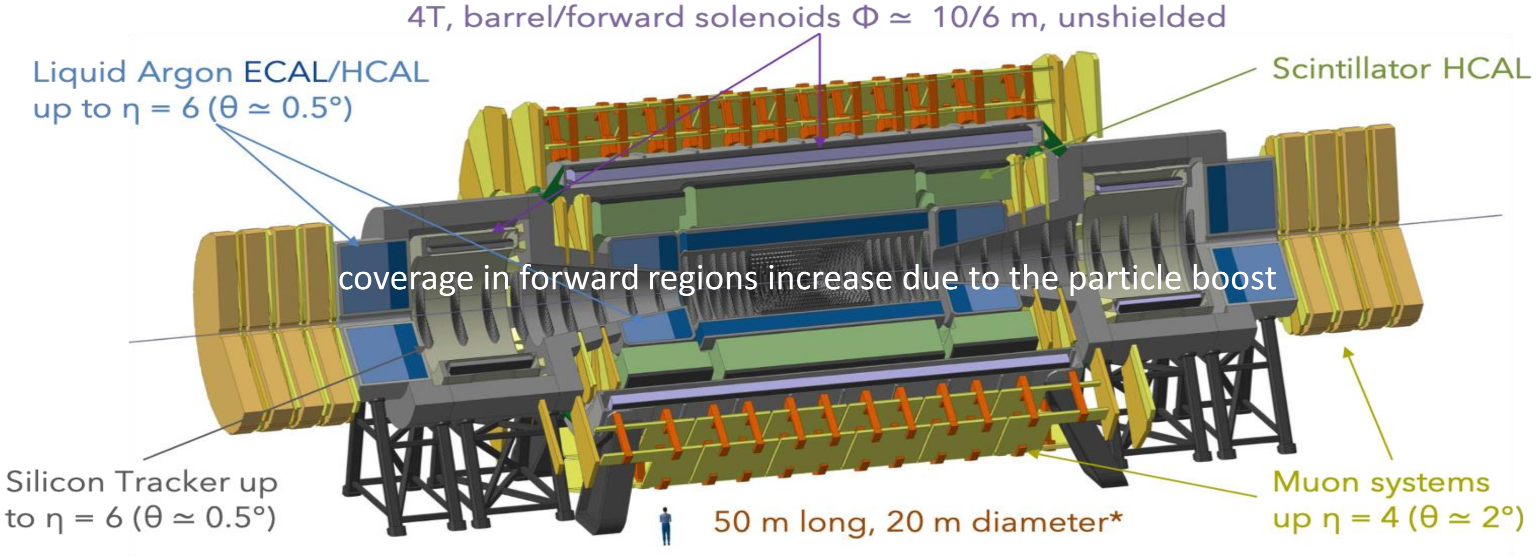
collision rate 30 GHz - <1000> collisions/BC every 25 ns, O(10^2) x LHC irradiation

4D measurements with time precision O(5) ps, on-detector data reduction,
new data transfer technologies, new material for radiation tolerance


3D tracking

FCC-hh collisions separated by <170> µm and <0.5> ps


4D tracking



coverage in forward regions increase due to the particle boost

https://cds.cern.ch/record/2842569/files/CERN-2022-002.pdf

ECFA R&D roadmap Solid State

Semi-conductor sensors highly granular, fast, transparent and radiation tolerant

Solid state

DRDT 3.1	Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors
DRDT 3.2	Develop solid state sensors with 4D-capabilities for tracking and calorimetry
DRDT 3.3	Extend capabilities of solid state sensors to operate at extreme fluences
DRDT 3.4	Develop full 3D-interconnection technologies for solid state devices in particle physics

		DRDT	< 2030					2030-2035					2035-2040	2040-2045		>2045		
			Panda 2025	CBM 2025	NA62/Klever 2025	Belle II 2026	ALICE LS3 1)	ALICE 3	LHCb (≥ LS4 1))	ATLAS & CMS (≥ LS4 1))	EIC	LHeC	ILC	FCC-ee	CLIC	FCC-hh	FCC-eh	Muon collider
Vertex detector 2)	Position precision	3.1,3.4		🟢		🟡	🔴	🔴	🔴	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	Low X/X_0	3.1,3.4	🟠	🟢	🟡	🟠	🔴	🔴	🟠	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	Low power	3.1,3.4		🟢	🟡	🟡	🔴	🔴	🟡	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	High rates	3.1,3.4		🟢	🔴	🟢		🟢	🟢		🟢	🟢	🟢	🟢	🔴	🔴	🟢	🟢
	Large area wafers 3)	3.1,3.4	🟡	🟡	🟡	🟡	🔴	🔴			🔴	🟡	🟠	🔴	🟠	🟡	🟡	🔴
	Ultrafast timing 4)	3.2			🔴				🔴	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴
	Radiation tolerance NIEL	3.3							🟢	🟡						🔴		
	Radiation tolerance TID	3.3							🟢	🟡						🔴		
Tracker 5)	Position precision	3.1,3.4						🔴	🟡		🔴	🟢	🟠	🔴	🟠	🟠	🟢	🟠
	Low X/X_0	3.1,3.4						🔴	🔴		🔴	🟢	🟠	🔴	🟠	🟠	🟢	🟠
	Low power	3.1,3.4						🔴	🔴		🔴	🟢	🟠	🔴	🟠	🟠	🟢	🟠
	High rates	3.1,3.4							🟢			🟢				🔴	🟢	
	Large area wafers 3)	3.1,3.4						🟡	🟡		🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡
	Ultrafast timing 4)	3.2							🟡		🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴
	Radiation tolerance NIEL	3.3							🟢							🟢		
	Radiation tolerance TID	3.3							🟢							🟢		
Calorimeter 6)	Position precision	3.1,3.4																
	Low X/X_0	3.1,3.4																
	Low power	3.1,3.4					🟡				🟡	🟠	🟠	🟠	🟠	🟠	🟠	🟠
	High rates	3.1,3.4														🔴		
	Large area wafers 3)	3.1,3.4					🟡				🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴
	Ultrafast timing 4)	3.2										🟡	🟡	🟡	🟡	🔴	🟡	🔴
	Radiation tolerance NIEL	3.3														🔴		
	Radiation tolerance TID	3.3														🔴		
Time of flight 7)	Position precision	3.1,3.4				🟡		🟡		🟡	🟡	🟡		🟡			🟡	
	Low X/X_0	3.1,3.4				🟡		🟡		🟡	🟡	🟡		🟡			🟡	
	Low power	3.1,3.4				🟡		🟡		🟡	🟡	🟡		🟡			🟡	
	High rates	3.1,3.4																
	Large area wafers 3)	3.1,3.4				🟡		🟡		🟡	🟡			🟡				
	Ultrafast timing 4)	3.2				🔴		🔴		🟡	🔴	🔴		🟠			🔴	
	Radiation tolerance NIEL	3.3								🟡								
	Radiation tolerance TID	3.3								🟡								

🔴 **Must happen or main physics goals cannot be met** 🟠 **Important to meet several physics goals** 🟡 **Desirable to enhance physics reach** 🟢 **R&D needs being met**

Tow configurations of Si-sensors

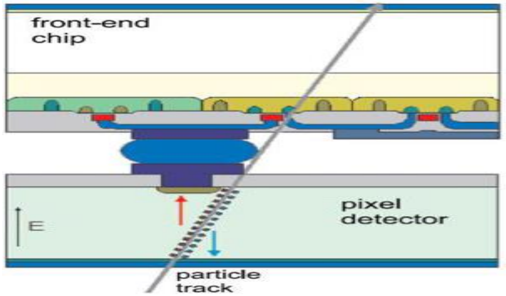
Hybrid design

electronics bumped or wire bonded to Si-sensor
highest rates & radiation tolerance

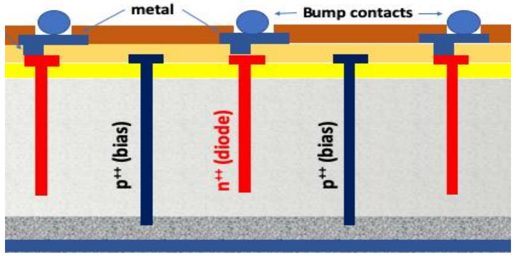
Monolithic Active Pixels

single CMOS imaging process
thinnest, highest granularity

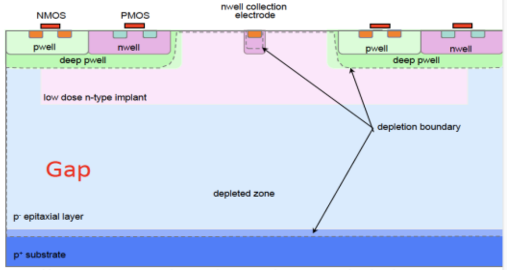
planar sensors



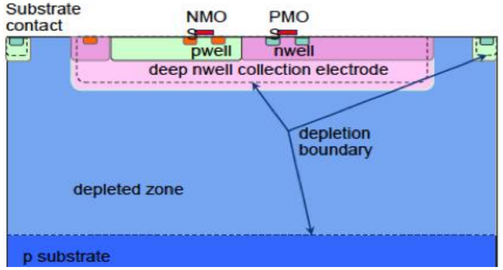
3D sensors



small electrode



large electrode



Several design variants, often driven by process available at the fabrication foundry

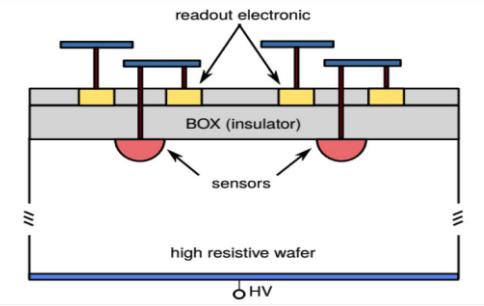
R&D hit resolution, transparency and high rates

Hybrid design

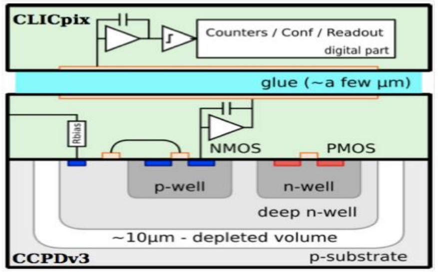
pixel pitch < 50 µm at rate capabilities O >1 GHz/cm^2

- Finer granularity (cheaper) connection technology
- 28 nm ASIC technology

SoI technology Through Silicon Via



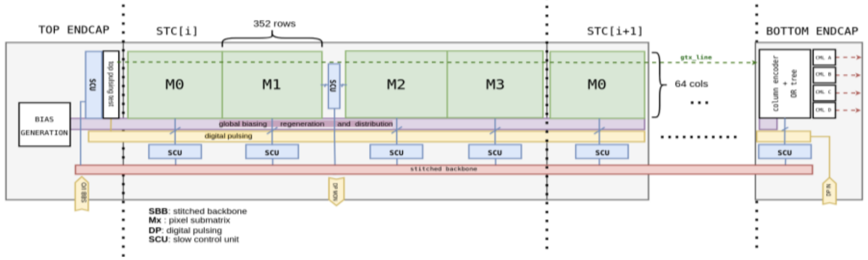
Conductive glue*



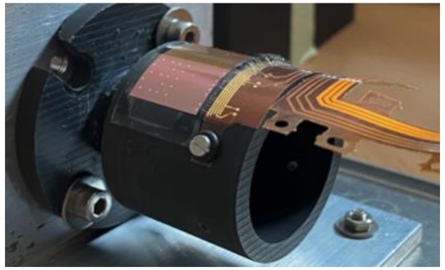
Monolithic Active Pixels

pixel pitch <20 µm

- 65 nm technology pitch
- 12’’ sensors thinned to < 50 µm
- Low power redout architecture



ex. ALICE ITS3 (LS3) 10 x 28 cm^2 sensors, thinned to < 50 µm for bending, σ_{hit} O(3) µm at X/X_0 O(<0.1)% , power O(20) mW /cm^2 for gas flow cooling



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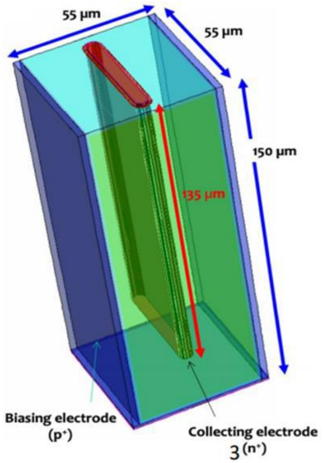
* *Here applied to build a two-tier analog and digital functionality on MAPS design*

R&D high precision timing

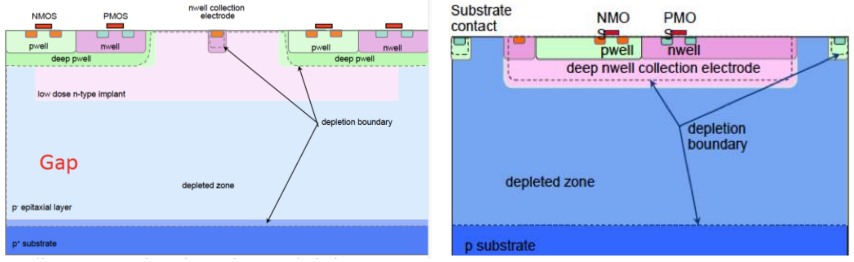
O(10-20) ps for PID layer at FCC-ee and O(5) ps for 4D tracking at FCC-hh

Designs without gain

Hybrid 3D electrodes
O(20) ps SoA



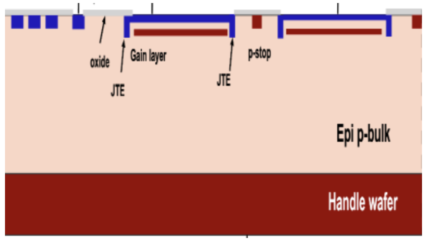
MAPS small/large electrodes
O(100/50) ps expected



adding low gain amplification

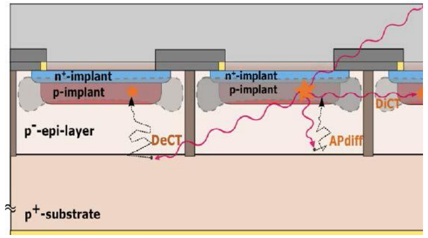
Designs with gain

Hybrid Low Gain (pad)
Avalanche Diode O(25) ps SoA



Increase granularity

Single Photon Avalanche Diode
O(20) ps SoA



Reduce Dark
Current Rates

- ➢ Process tuning for speed and collection efficiency
- ➢ New faster process ex. SiGe BICMOS and materials ex. SIC/GaN
- ➢ Fast <1 ns risetime and low power electronics

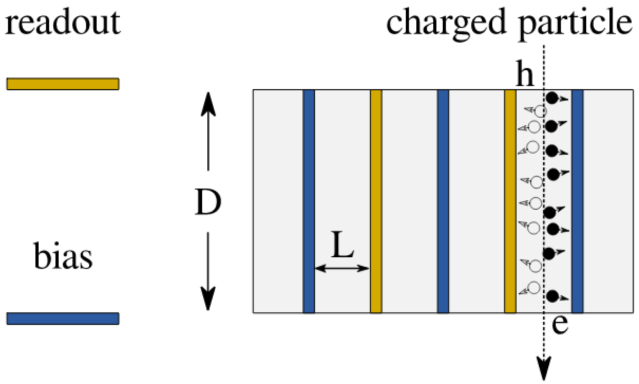
R&D radiation tolerance

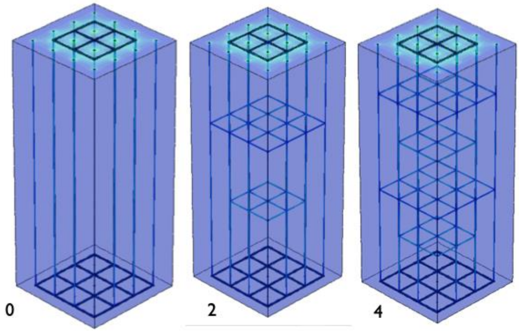
no current technologies would survive below 30 cm at FCC-hh

- Si-sensor sensitive to Non Ionizing Energy Loss, tolerance beyond $10^{17}/cm^2$ neq unknown
- ASIC sensitive to Total Integrated Dose, tolerance up to 1 GRad

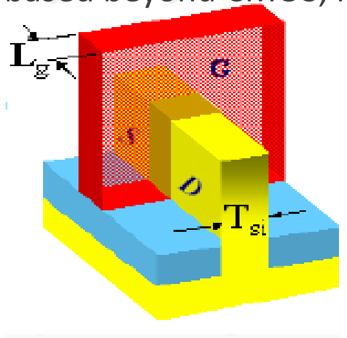
➢ For both new materials and 3D process to be evaluated (now of commercial interest)
  - WBG semiconductors Diamond, GaInP, GaAs, GaN, SiC
  - Graphene, Carbon-based metamaterials, nanotubes…

ex. CVD-diamond semiconductor pixel sensors
  - 3D design with laser graphitization for thin low ρ electrodes





ex. ASICs
  - Higher dielectric thick oxide (multiple) gates
  - Carbon based beyond CMOS, nanotube, graphene



FinFET 3D transistors

ECFA R&D roadmap Particle ID and photon

Ring Imaging CHerenkov, Time of Flight, Sensitive materials and photosensors

PID and Photon

- **DRDT 4.1** Enhance the timing resolution and spectral range of photon detectors
- **DRDT 4.2** Develop photosensors for extreme environments
- **DRDT 4.3** Develop RICH and imaging detectors with low mass and high resolution timing
- **DRDT 4.4** Develop compact high performance time-of-flight detectors

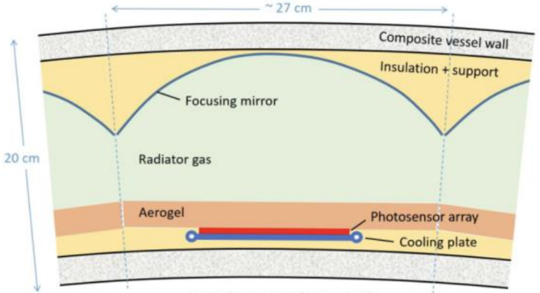
		DRDT	SPS fixed target	FAIR (hep)	PIP-II/LBNF/DUNE	Dark matter, noble liquids	ALICE 3	LHCb (≥LS4)	ATLAS/CMS (≥LS4)	EIC	LHeC	Belle II Upgrade	ILC	FCC-ee	CLIC	FCC-hh	FCC-eh	Muon collider
			< 2030				2030-2035						2035-2040	2040-2045		>2045		
RICH and DIRC technologies	Rad-hard	4.2	🟠	🟢			🟡	🔴		🔴		🔴		🟡				
	Rate capability	4.2	🟠	🟢			🟡	🔴		🔴		🔴		🟠				
	Fast timing	4.3	🟠	🟢			🟠	🔴		🟠		🟠		🟠				
	Spectral range and PDE	4.1	🟡	🟢			🟠	🟠		🟠		🟠		🟠				
	Radiator materials	4.3	🟠	🟢			🟠	🟠		🟠		🟡		🟠				
	Compactness, low X_0	4.3	🟡	🟢			🟠	🟠		🔴		🟠		🟠				
Time of flight	Rad-hard	4.2	🟡	🟢			🟠	🟠		🟠		🟡		🟡				
	Low X	4.3	🟡	🟢			🟠	🟠		🟠		🟡		🟡				
	Fast timing to <10ps level & clock distribution	4.3	🟠		🟠		🟠	🟠		🟠		🟡		🟡				
Other	TRD	4.3		🟢						🟠								
	dE/dx	4.3			🟠					🟠			🟡	🟠	🟡			
	Scintillating fibres (light yield, rad-hard & timing)	-						🟠					🟡		🟡			
Silicon photomultipliers	Rad-hard	4.2	🟠	🟢			🟡	🔴	🟡	🟠	🔴	🟠	🔴	🔴	🔴	🔴	🔴	🔴
	Low noise	4.1	🟠	🟢	🟠	🔴	🟠	🔴	🟡	🟠	🔴	🟠	🔴	🔴	🔴	🔴	🔴	🔴
	Fast timing	4.1	🟠	🟢	🟠	🔴	🟠	🔴	🟡	🟠	🔴	🟠	🔴	🔴	🔴	🔴	🔴	🔴
	Radio purity	4.2				🔴												
	VUV / cryogenic det op	4.2			🔴	🔴												
Vacuum photon detectors	Photocathode ageing & rate capability	4.2	🟠	🟢				🟠		🟠		🟠		🟡				
	Fast timing	4.1	🟠	🟢				🔴		🔴		🔴		🟡				
	Fine granularity / large area	4.1	🟡	🟢	🟠	🟠		🟠		🟠		🟠		🟡				
	Spectral range and PDE	4.1	🟡	🟢	🟠	🟠		🟠		🟠		🟠		🟡				
	Magnetic field immunity	4.2		🟢				🟡		🔴		🔴		🟡				
Gaseous photon detectors	Photocathode ageing & rate capability	4.2	🟠							🟡								
	Fine granularity / large area	4.1	🟡							🟡								
	Spectral range, PDE and fast timing	4.1	🟠							🟡								

🔴 **Must happen or main physics goals cannot be met** 🟠 **Important to meet several physics goals** 🟡 **Desirable to enhance physics reach** 🟢 **R&D needs being met**

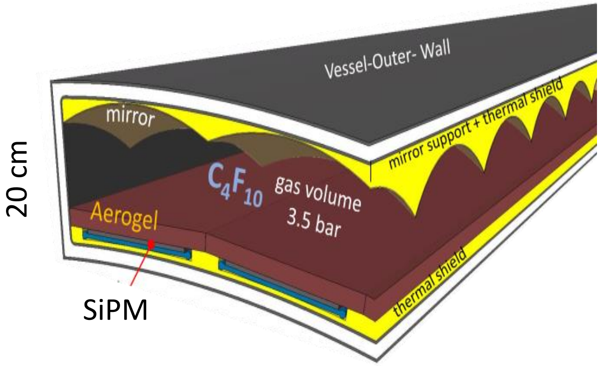
R&D Particle Identification with RICH

Challenge to reach ≳ 3σ π/K separation up to O(50) GeV

new concept ex. Thin Array of RICH Cells (X/X_0 <10%) for FCC-ee
coupling aerogel and gas radiator with single SiPMs readout



ARC detector (one cell)

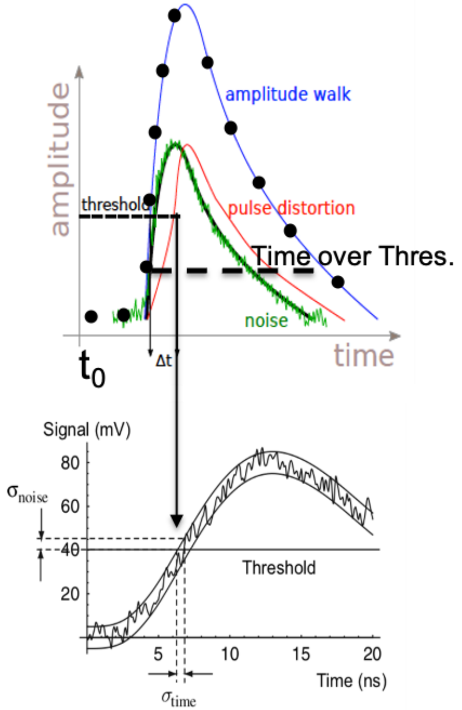


- ➢ New materials for tunable refractive index
- ➢ Improved optics ex. lens, mirror coating

R&D Time of Flight precision

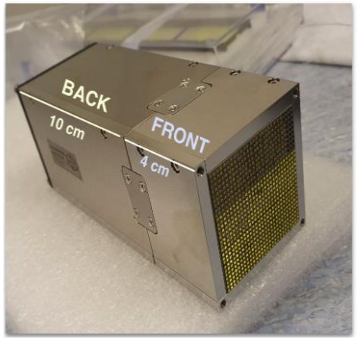
SoA is at O(20) ps target for FCC-ee O(10) ps for PID, and ≲ 5ps at FCC-hh

- Pulse fluctuations and electronics jitter are the limitation
  - increased speed and S/N
- Resolution also depends on number of measurements
  - hits in tracking, photons in RICH, showers particles in calorimeters, single Time of Amplitude at threshold or Waveform Sampling*

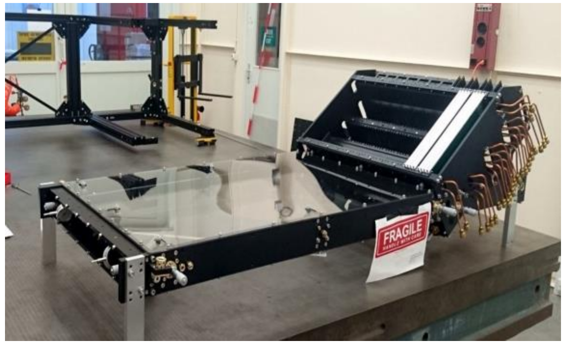


ALICE
Fast Interaction Trigger
Cherenkov radiator
+ MCP-PMT
≃ 30 ps

LHCb
Spaghetti Calo.
crystal/scint. + MCP PMT
waveform sampling
≃ 20 ps

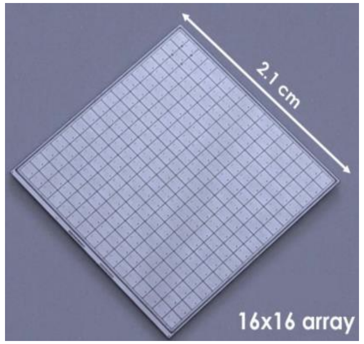


LHCb
TORCH RICH
Cerenkov radiator
+ MCP-PMT
SPTR ≃ 70 ps



CMS
Timing Layer (pile-up)
LYSO crystal + 2 SiPM
ToA and ToT
≃ 20 ps

ATLAS - CMS
Timing Layer
LGAD Si-sensors
ToA and ToT
≃ 25 ps

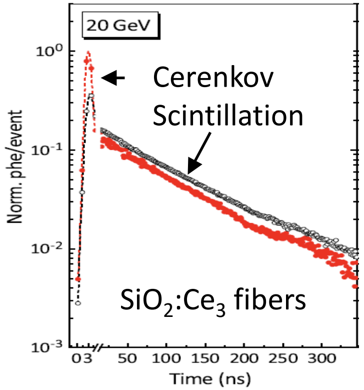


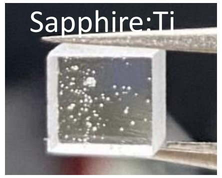
** Time-walk correction can be provided by ToT, waveform sampling or ADC amplitude depending on system*

R&D Scintillator and Cherenkov materials

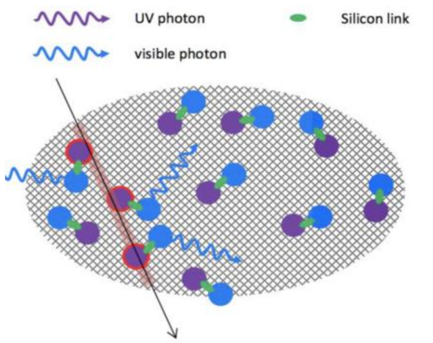
- ex. new crystals (fibers) providing both Cherenkov and scintillating light (doping)
- ex. new nano-materials, luminophore WLS, quantum dots tuning of WL with size
- 3D printing for unconventional shapes, ex. square fibers for Dual Readout calorimeters

Separate sources
with waveform sampling

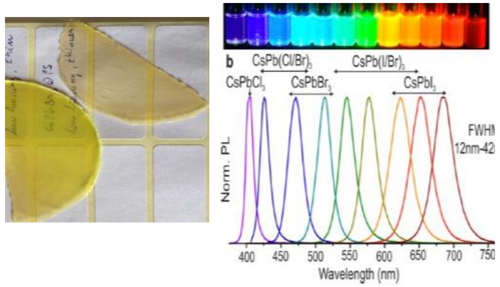




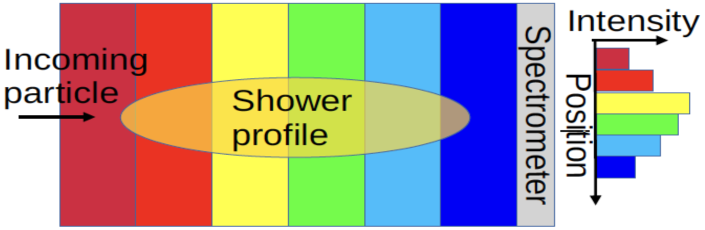
luminophore

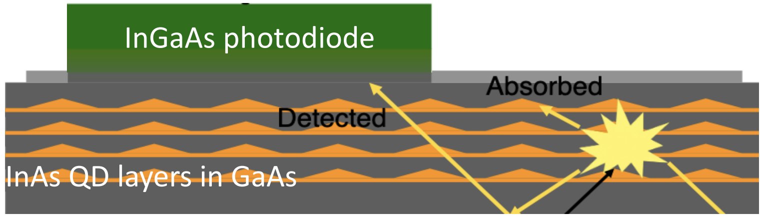


Quantum Dot ex. perovskite
embedded in polymer



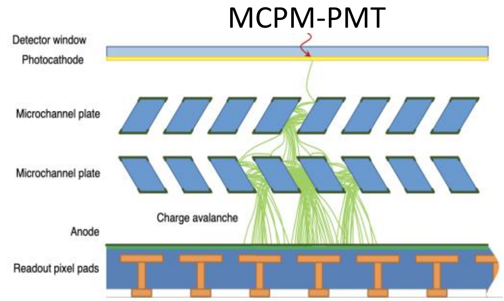
Quantum Dots could allow new cutting edge concepts for depth segmentation in homogenous calorimetry (left) and 4D scintillating tracking in monolithic scintillating photodiode sensors (right)

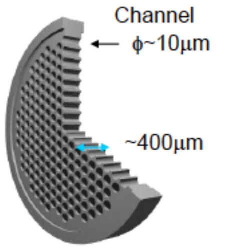


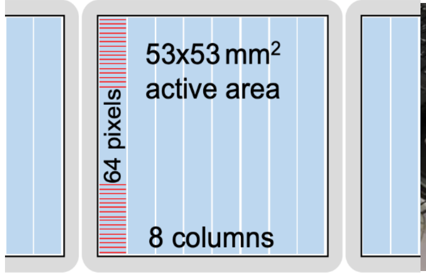


R&D Photosensors

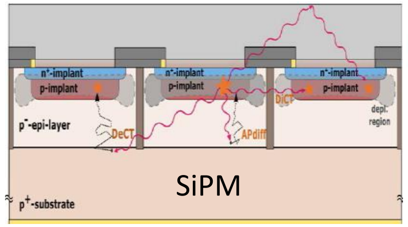
- MCP-PMT
  - ex. Large Area Picosecond PhotoDetectors (20 cm^2), O(1) mm^2, SPTR O(30) ps
  - ➢ Improved photocathode efficiency for radiation tolerance
  - ➢ Hybrid design with pixel ASIC integration in vacuum tube
  - ➢ Nanopore channels for ultra high granularity
  - ➢ Design for MIP (with Cerenkov Radiator or from secondary emission)

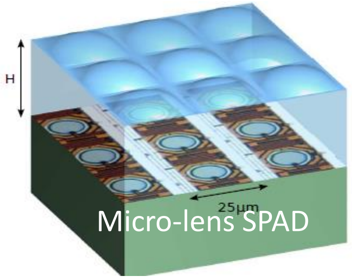






- SiPM hybrid analog design, 1(3x3) mm^2, 30(80) ps
- SPAD monolithic digital pixel counting, 50 µm pitch, SPTR O(20) ps
  - ➢ Reduce Dark Current Rates (new materials ex. WBG GaInP, GaAs, SiC, GaN)
  - ➢ Improve QE, particularly in UV and NIR
  - ➢ Micro-lens array design to compensate fill factor
  - ➢ Lower pitch





ECFA R&D roadmap Calorimeters

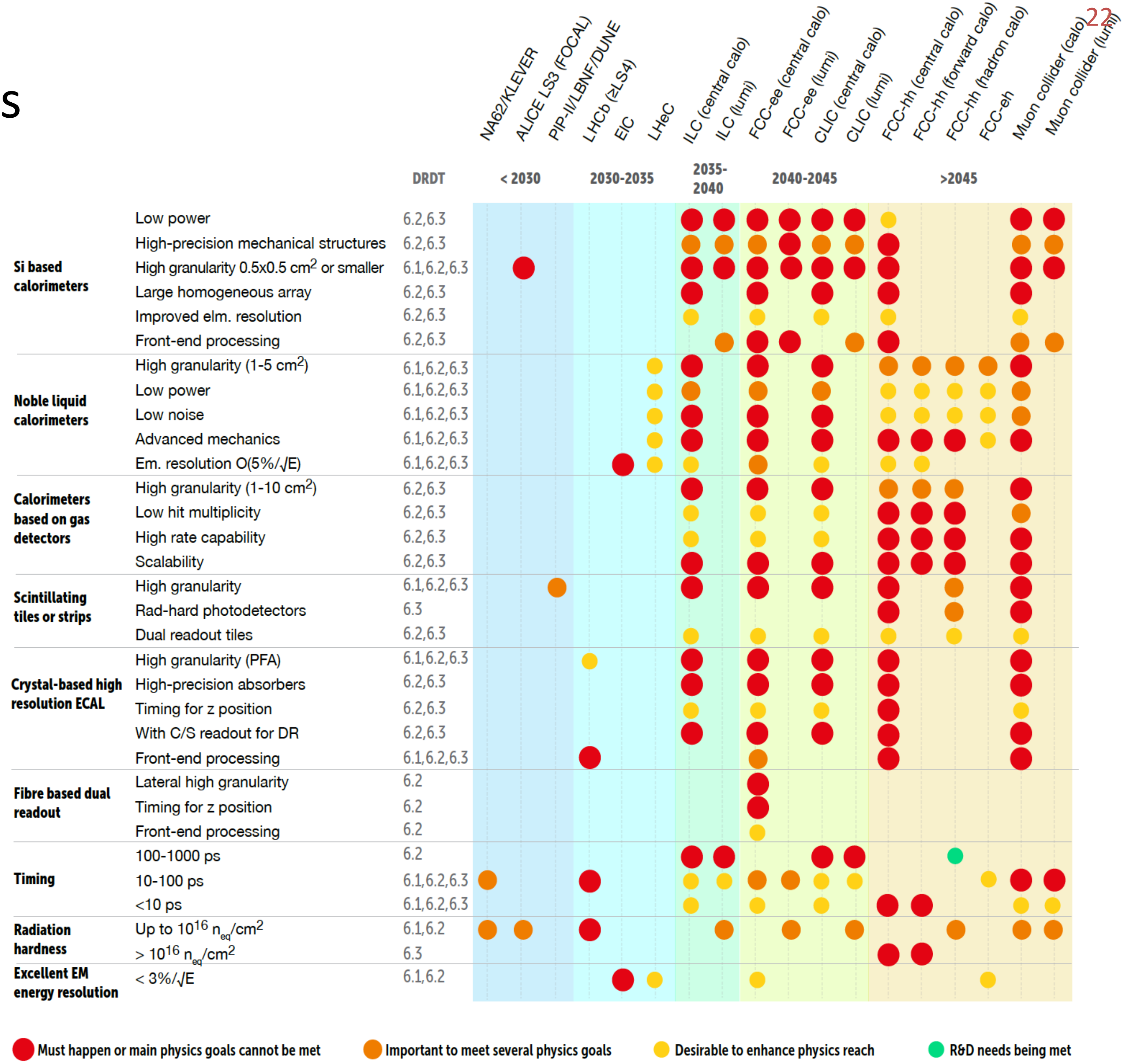
Several concepts with specific performance several sensor technology options

Calorimetry

DRDT 6.1 Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution

DRDT 6.2 Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods

DRDT 6.3 Develop calorimeters for extreme radiation, rate and pile-up environments

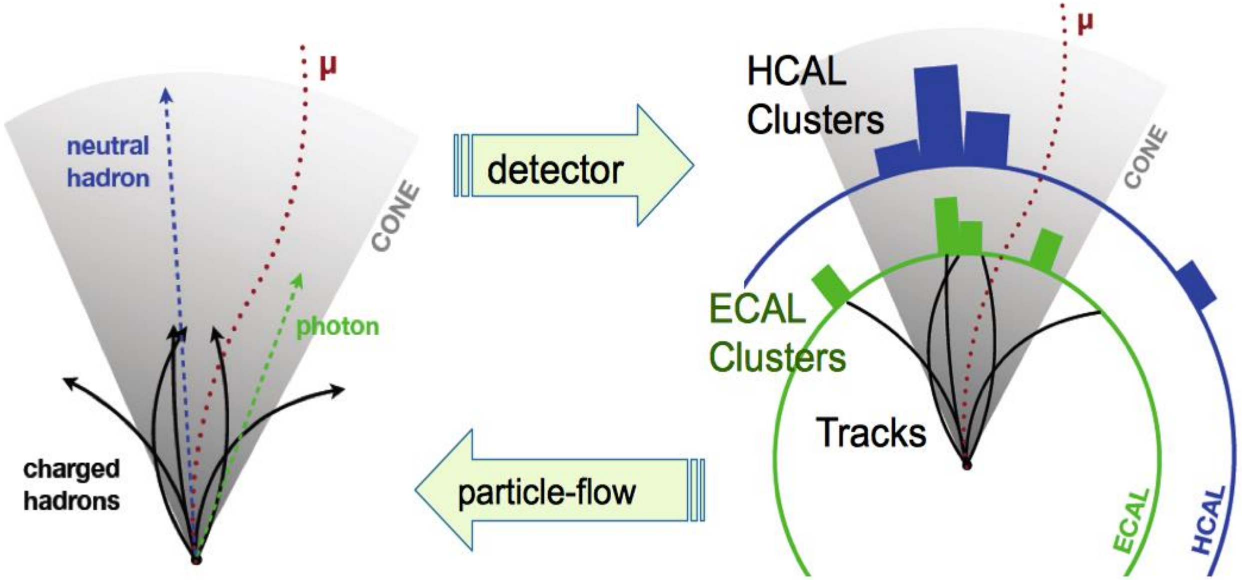


		DRDT	< 2030			2030-2035			2035-2040		2040-2045				>2045					
			NA62/KLEVER	ALICE LS3 (FOCAL)	PIP-II/LBNF/DUNE	LHCb (≥LS4)	EIC	LHeC	ILC (central calo)	ILC (lumi)	FCC-ee (central calo)	FCC-ee (lumi)	CLIC (central calo)	CLIC (lumi)	FCC-hh (central calo)	FCC-hh (forward calo)	FCC-hh (hadron calo)	FCC-eh	Muon collider (calo)	Muon collider (lumi)
Si based calorimeters	Low power	6.2,6.3							🔴	🔴	🔴	🔴	🔴	🔴	🟡				🔴	🔴
	High-precision mechanical structures	6.2,6.3							🟠	🟠	🟠	🔴	🟠	🟠	🔴				🟠	🟠
	High granularity 0.5x0.5 cm^2 or smaller	6.1,6.2,6.3		🔴					🔴	🔴	🔴	🔴	🔴	🔴	🔴				🔴	🔴
	Large homogeneous array	6.2,6.3							🔴		🔴		🔴		🔴				🔴	
	Improved elm. resolution	6.2,6.3							🟡		🟡		🟡		🟡				🟡	
	Front-end processing	6.2,6.3								🟠	🔴	🔴		🟠	🔴				🟠	🟠
Noble liquid calorimeters	High granularity (1-5 cm^2)	6.1,6.2,6.3						🟡	🔴		🔴		🔴		🟠	🟠	🟠	🟠	🔴	
	Low power	6.1,6.2,6.3						🟡	🟠		🟠		🟠		🟡	🟡	🟡	🟡	🟠	
	Low noise	6.1,6.2,6.3						🟡	🔴		🔴		🔴		🟡	🟡	🟡	🟡	🟠	
	Advanced mechanics	6.1,6.2,6.3						🟡	🔴		🔴		🔴		🔴	🔴	🔴	🟡	🔴	
	Em. resolution O(5%/√E)	6.1,6.2,6.3					🔴	🟡	🟡		🟠		🟡		🟡	🟡				
Calorimeters based on gas detectors	High granularity (1-10 cm^2)	6.2,6.3							🔴		🔴		🔴		🟠	🟠	🟠		🔴	
	Low hit multiplicity	6.2,6.3							🟡		🟡		🟡		🔴	🔴	🔴		🟠	
	High rate capability	6.2,6.3							🟡		🟡		🟡		🔴	🔴	🔴		🔴	
	Scalability	6.2,6.3							🔴		🔴		🔴		🔴	🔴	🔴		🔴	
Scintillating tiles or strips	High granularity	6.1,6.2,6.3			🟠				🔴		🔴		🔴		🔴		🟠		🔴	
	Rad-hard photodetectors	6.3													🔴		🟠		🔴	
	Dual readout tiles	6.2,6.3							🟡		🟡		🟡		🟡		🟡		🟡	
Crystal-based high resolution ECAL	High granularity (PFA)	6.1,6.2,6.3				🟡			🔴		🔴		🔴		🔴				🔴	
	High-precision absorbers	6.2,6.3							🔴		🔴		🔴		🔴				🔴	
	Timing for z position	6.2,6.3							🟡		🟡		🟡		🔴				🟡	
	With C/S readout for DR	6.2,6.3							🔴		🔴		🔴		🔴				🔴	
	Front-end processing	6.1,6.2,6.3				🔴					🟠				🔴				🔴	
Fibre based dual readout	Lateral high granularity	6.2									🔴									
	Timing for z position	6.2									🔴									
	Front-end processing	6.2									🟡									
Timing	100-1000 ps	6.2							🔴	🔴			🔴	🔴			🟢			
	10-100 ps	6.1,6.2,6.3	🟠			🔴			🟡	🟡	🟠	🟠	🟡	🟡				🟡	🔴	🔴
	<10 ps	6.1,6.2,6.3							🟡		🟡		🟡		🔴	🔴			🟡	🟡
Radiation hardness	Up to 10^{16} n_{eq}/cm^2	6.1,6.2	🟠	🟠		🔴				🟠		🟠		🟠			🟠		🟠	🟠
	> 10^{16} n_{eq}/cm^2	6.3													🔴	🔴				
Excellent EM energy resolution	< 3%/√E	6.1,6.2					🔴	🟡			🟡							🟡		

🔴 Must happen or main physics goals cannot be met 🟠 Important to meet several physics goals 🟡 Desirable to enhance physics reach 🟢 R&D needs being met

Calorimeter concepts

e-γ electromagnetic showers develop in front segment
hadronic interaction develop deeper in back segment
homogenous calorimeters provide best e-γ $\sigma(E)/\sqrt{E}$ O(3)%
so far only sampling calorimeters for hadrons, current target is $\sigma(E_{Jet})$ O(30)%/$\sqrt{E}$



E_{jet} (PFlow)
=
E_{h0} ($\simeq$ 10%)
+
$E\gamma$ ($\simeq$ 15%)
+
E_{track} ($\simeq$ 75 %)

High transverse granularity for charged track shower association (PFlow technique)
Hadron shower energy compensation (calibration) with “dual readout” measuring both em and had. shower components or from depth segmentation providing the shower shape

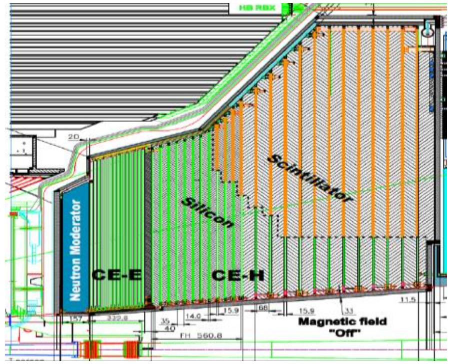
Calorimeter configurations

Sampling

absorber (W/Pb/Cu/Fe/Brass)

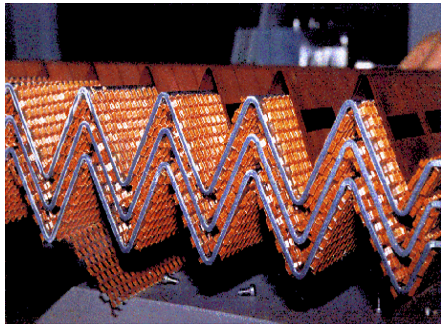
Solid State, Scint. tiles, fibers, Gas, Noble Liquid

High Granularity
Si-pads and scint tiles/MPGDs

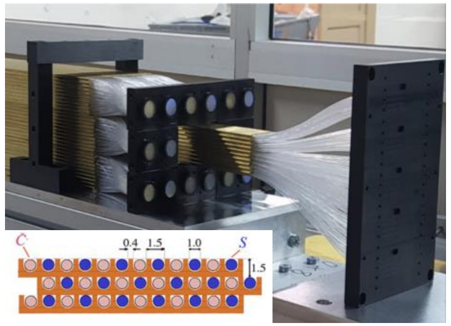


Shashlik EM concept
Scintillator + WLS

Noble Liquid (LAr)



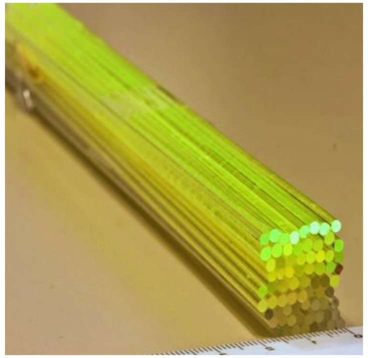
Spaghetti Dual Readout
Scint. & Cherenkov fibers



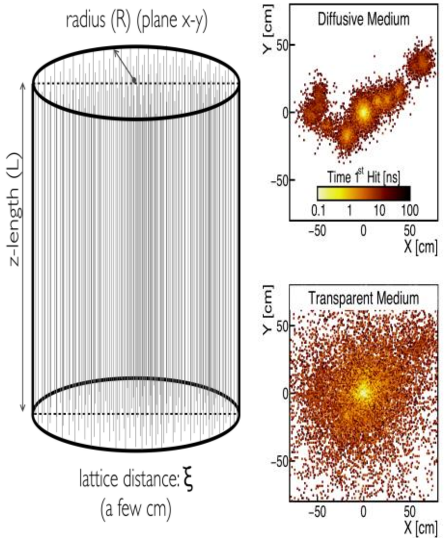
Homogenous

new concepts

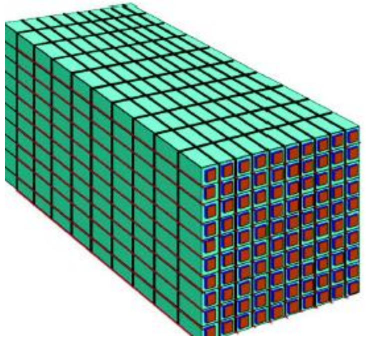
ECAL
crystal fibers



Opaque scintillator
crystal grains



HCAL with
⊥ & // granularity



R&D different concepts

sensitive elements and photosensors R&D are covered in other technology areas

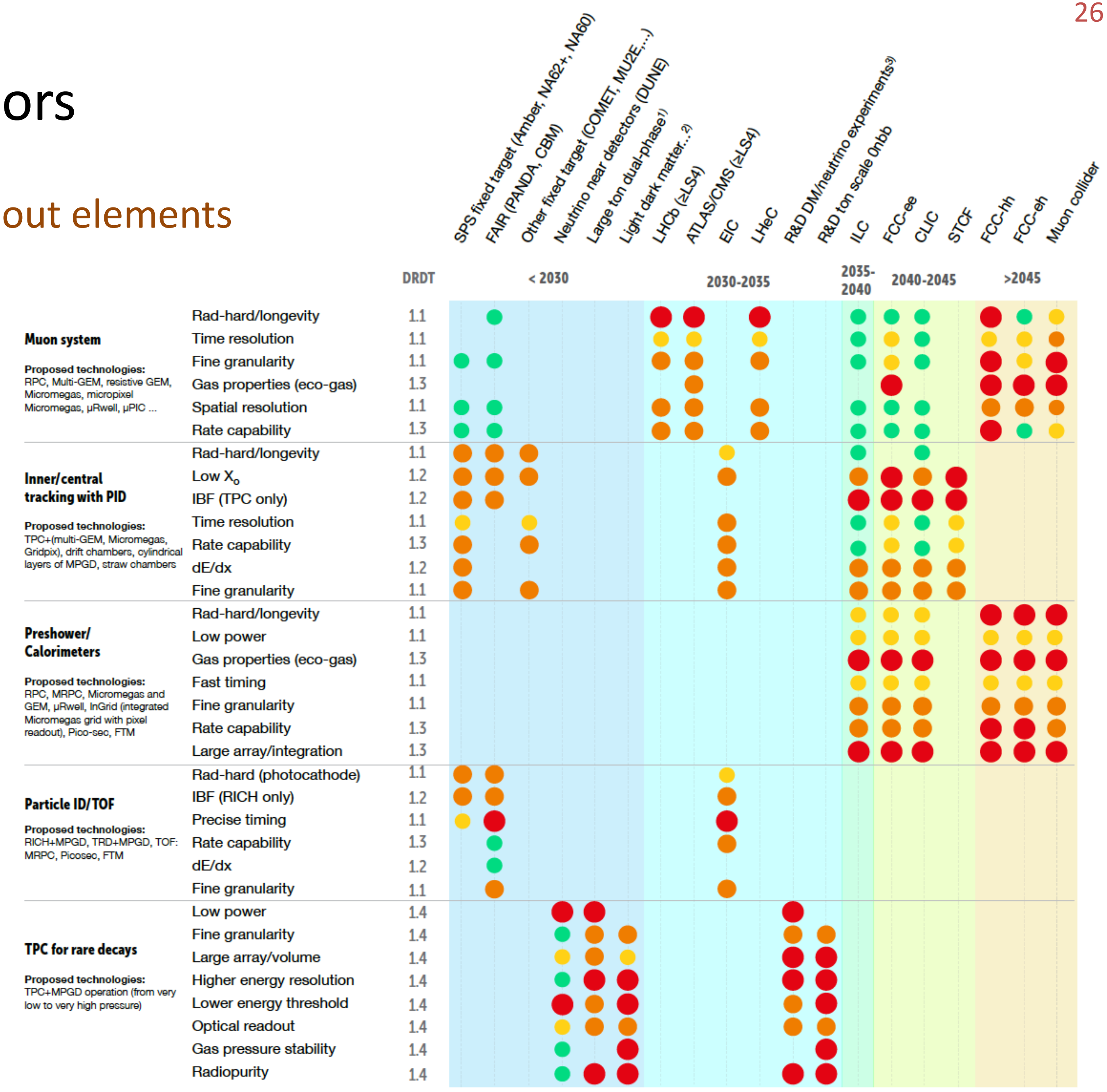
- High Granularity Calorimeter
    - Improved sampling fraction for e-γ energy, ex monolithic Si-sensors w/ low power electronics
    - Ultimate pixel digital counting with <10 ps for full 5D shower profiles
- Dual Readout calorimeter
    - Single dual readout fibers providing both scintillating and Cherenkov light
    - Waveform sampling for shower ToF (depth in calorimeter)
- Noble Liquid Calorimeter
    - Improve transverse and depth segmentation with large size multiple layer PCBs
    - Light cryostat vessel, cold electronics, high density feedthrough*
- Homogenous calorimeters
    - Implement dual readout, ex. wavelength filtering w/ two photosensors, waveform sampling or physical depth segmentation

** common problematics NL TPCs and magnets*

ECFA R&D roadmap Gaseous detectors

Versatile (cheap) systems in large areas
wide range of application as sensitive and/or readout elements

Gaseous		
	DRDT 1.1	Improve time and spatial resolution for gaseous detectors with long-term stability
	DRDT 1.2	Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes
	DRDT 1.3	Develop environmentally friendly gaseous detectors for very large areas with high-rate capability
	DRDT 1.4	Achieve high sensitivity in both low and high-pressure TPCs



		DRDT	< 2030						2030-2035						2035-2040	2040-2045			>2045		
			SPS fixed target (Amber, NA62+, NA60)	FAIR (PANDA, CBM)	Other fixed target (COMET, MU2E...)	Neutrino near detectors (DUNE)	Large ton dual-phase[1]	Light dark matter...[2]	LHCb (≥LS4)	ATLAS/CMS (≥LS4)	EIC	LHeC	R&D DM/neutrino experiments[3]	R&D ton scale 0nbb	ILC	FCC-ee	CLIC	STCF	FCC-hh	FCC-eh	Muon collider
Muon system **Proposed technologies:** RPC, Multi-GEM, resistive GEM, Micromegas, micropixel Micromegas, μRwell, μPIC ...	Rad-hard/longevity	1.1		🟢					🔴	🔴		🔴			🟢	🟢	🟢		🔴	🟢	🟡
	Time resolution	1.1							🟡	🟡		🟡			🟢	🟡	🟢		🟡	🟡	🟠
	Fine granularity	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟡	🟢		🔴	🟡	🔴
	Gas properties (eco-gas)	1.3								🟠						🔴			🔴	🔴	🔴
	Spatial resolution	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🟠	🟠	🟠
	Rate capability	1.3	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🔴	🟢	🟡
Inner/central tracking with PID **Proposed technologies:** TPC+(multi-GEM, Micromegas, Gridpix), drift chambers, cylindrical layers of MPGD, straw chambers	Rad-hard/longevity	1.1	🟠	🟠	🟠						🟡				🟢		🟢				
	Low X_o	1.2	🟠	🟠	🟠						🟠				🟠	🔴	🟠	🔴			
	IBF (TPC only)	1.2	🟠	🟠											🔴	🔴	🔴	🔴			
	Time resolution	1.1	🟡		🟡						🟠				🟢	🟡	🟢	🟡			
	Rate capability	1.3	🟠		🟠						🟠				🟢	🟡	🟢	🟡			
	dE/dx	1.2	🟠								🟠				🟠	🟠	🟠	🟠			
	Fine granularity	1.1	🟠		🟠						🟠				🟠	🟠	🟠	🟠			
Preshower/ Calorimeters **Proposed technologies:** RPC, MRPC, Micromegas and GEM, μRwell, InGrid (integrated Micromegas grid with pixel readout), Pico-sec, FTM	Rad-hard/longevity	1.1													🟡	🟡	🟡		🔴	🔴	🔴
	Low power	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Gas properties (eco-gas)	1.3													🔴	🔴	🔴		🔴	🔴	🔴
	Fast timing	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Fine granularity	1.1													🟠	🟠	🟠		🟠	🟠	🟠
	Rate capability	1.3													🟠	🟠	🟠		🔴	🔴	🟠
	Large array/integration	1.3													🔴	🔴	🔴		🔴	🔴	🔴
Particle ID/TOF **Proposed technologies:** RICH+MPGD, TRD+MPGD, TOF: MRPC, Picosec, FTM	Rad-hard (photocathode)	1.1	🟠	🟠							🟡										
	IBF (RICH only)	1.2	🟠	🟠							🟠										
	Precise timing	1.1	🟡	🔴							🔴										
	Rate capability	1.3		🟢							🟠										
	dE/dx	1.2		🟢																	
	Fine granularity	1.1		🟠							🟠										
TPC for rare decays **Proposed technologies:** TPC+MPGD operation (from very low to very high pressure)	Low power	1.4				🔴	🔴						🔴								
	Fine granularity	1.4				🟢	🟠	🟠					🟠	🟠							
	Large array/volume	1.4				🟡	🟠	🟡					🔴	🔴							
	Higher energy resolution	1.4				🟢	🔴	🔴					🔴	🔴							
	Lower energy threshold	1.4				🔴	🟠	🔴					🟠	🔴							
	Optical readout	1.4				🟡	🟠	🟠					🟠	🟠							
	Gas pressure stability	1.4				🟢		🔴						🔴							
	Radiopurity	1.4				🟢	🔴	🔴					🔴	🔴							

🔴 **Must happen or main physics goals cannot be met** 🟠 **Important to meet several physics goals** 🟡 **Desirable to enhance physics reach** 🟢 **R&D needs being met**

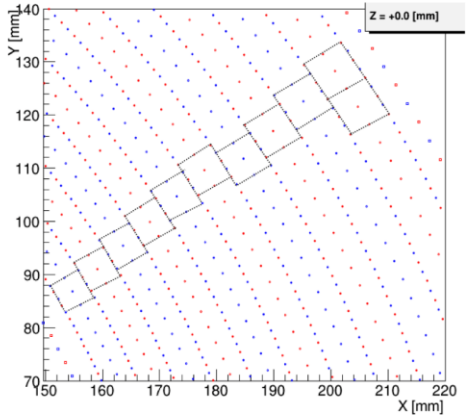
Central Tracking and Particle IDentification with DCH or TPC

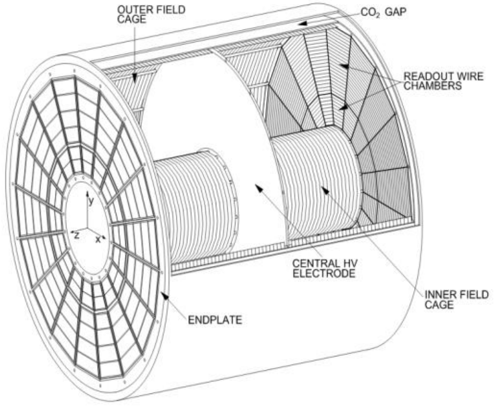
enabling at the same time best momentum resolution and PID up to 50 GeV for FCC-ee

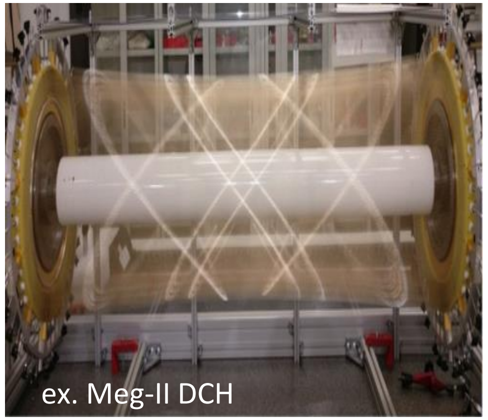
Central Tracking

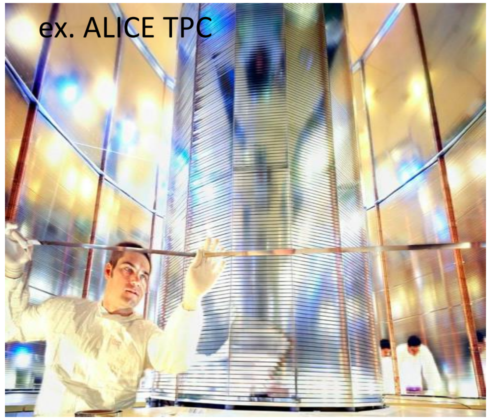
O(100) points with O(100) μm precision

O(1/5) % X/X_0 barrel/endcap






ex. Meg-II DCH

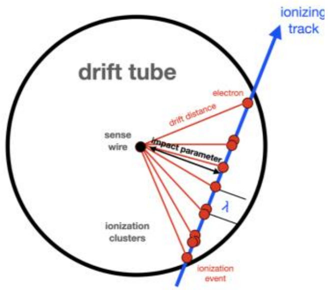

ex. ALICE TPC

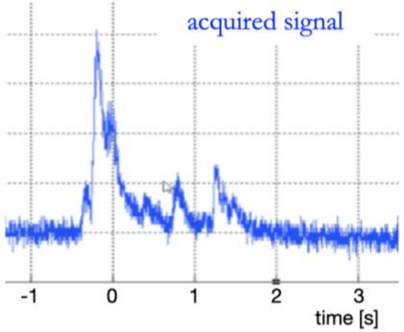
PID

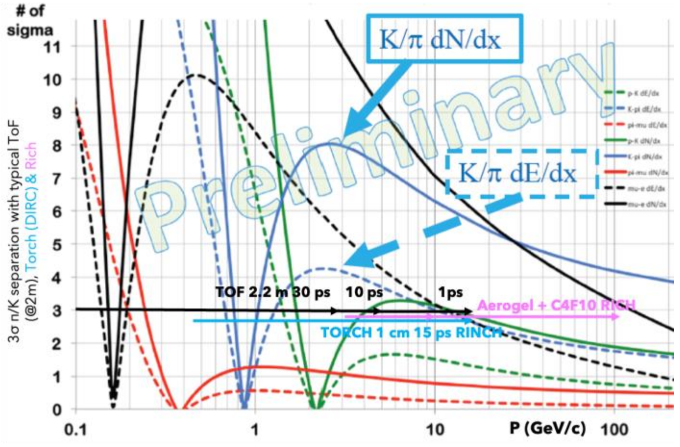
new concept of waveform sampling O(1) GHz*

to count e-clusters for O(<3%) energy resolution

ex. FCC-ee IDEA DCH







10 – 20 ps ToF to cover dE/dx crossing

---

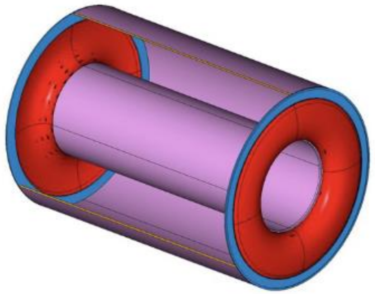
* *also expected to improve position resolution from 100 μm to ≲80 μm*

R&D Drift CHamber and Time Projection Chamber

DCH mostly engineering

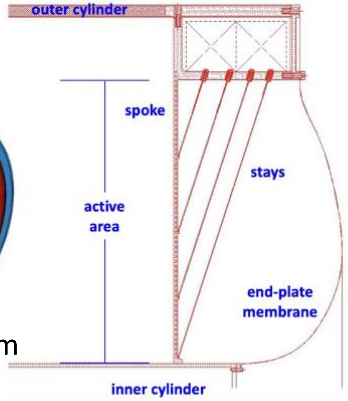
- ➢ Large size design structure and production
- ➢ Light and thin wires ex. 40 µm Al/C/Ti (field), 20 µm Mo/W (sense)
- ➢ dN/dx measured through waveform sampling electronics O(1) GHz

ex. FCC-ee IDEA DCH



gas vessel free to deform

DCH wire tension compensation

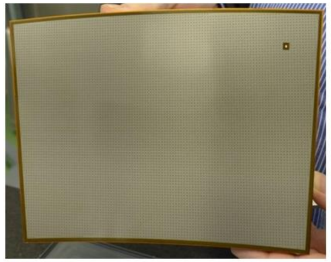


TPC main challenge to reduce ion backflow

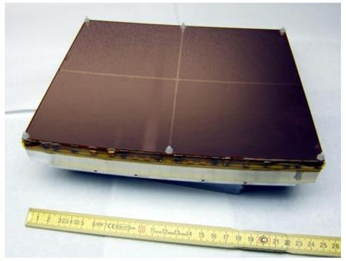
- ➢ Operating conditions (gas, voltages, pressure)
- ➢ Highly sensitive and granular readout MPGD
  - dN/dx measured through cluster counting

ex. MPGD readout ILD TPC

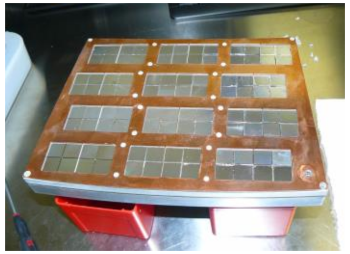
Micromegas



GEM



Gridpix

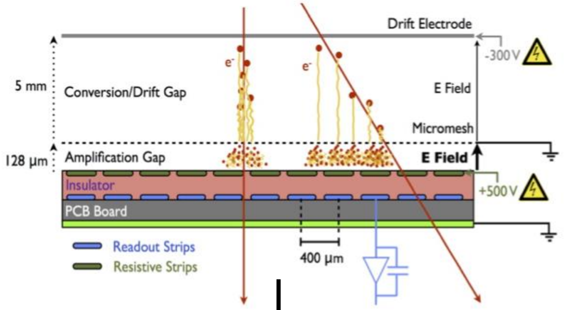


MicroPattern Gas Detectors

precision down to O(50) μm at rates O(1) MHz/cm^2

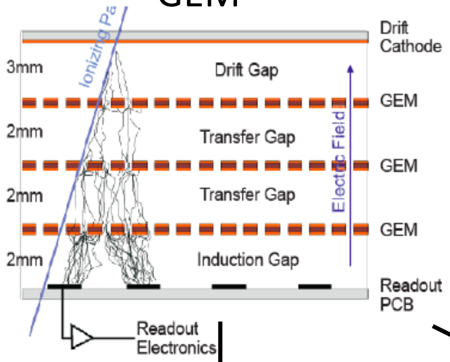
Muon chambers, calorimeter preshower or hadronic segment, readout system elements

MicroMegas (MM)

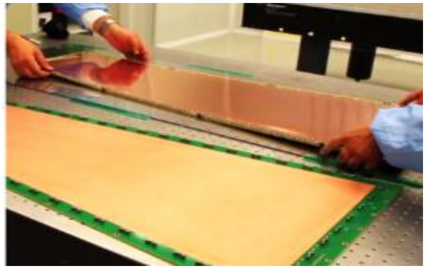


ATLAS new small wheels

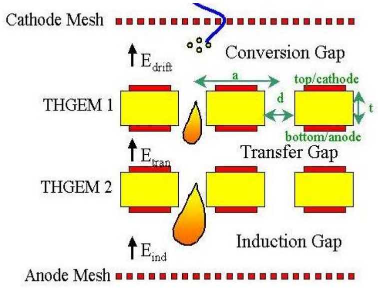
GEM



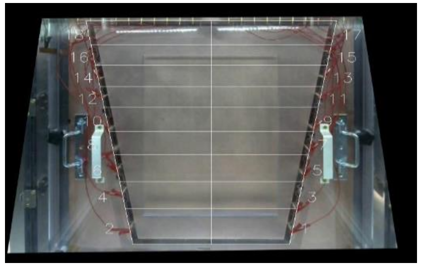
CMS



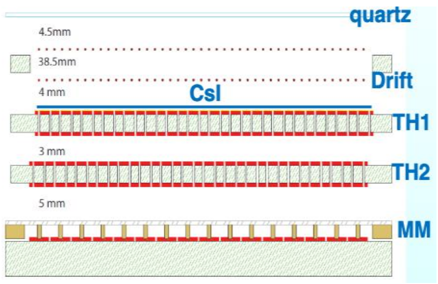
THGEM



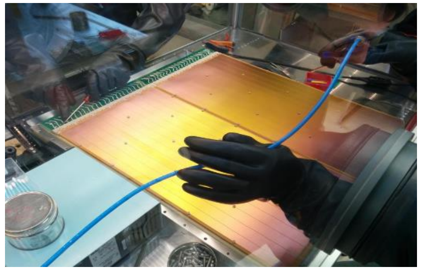
ALICE TPC



Hybrid design THGEM + MM



COMPASS RICH



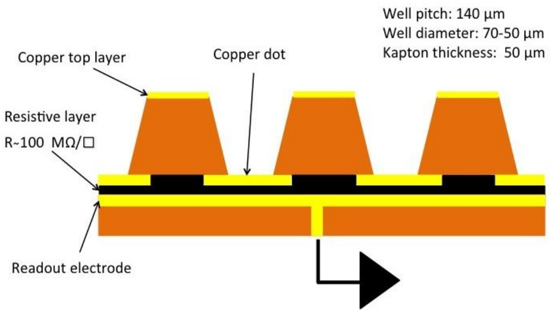
ex. muon tracking systems

ex. readout systems ionization (left) light (right)

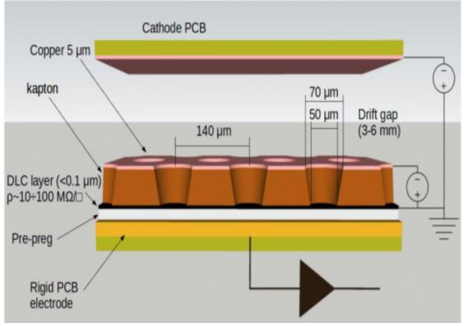
R&D MicroPattern Gas Detectors precision and rates

approach performance of Solid State in printed board technology or CMOS monolithic designs

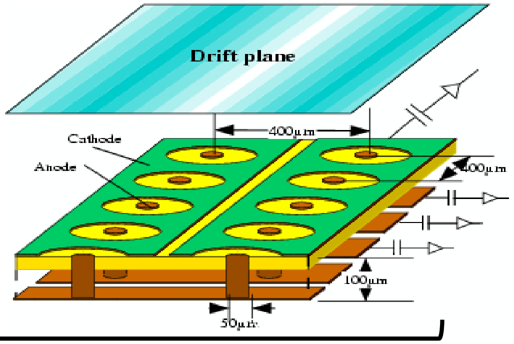
μ -Resistive-Well



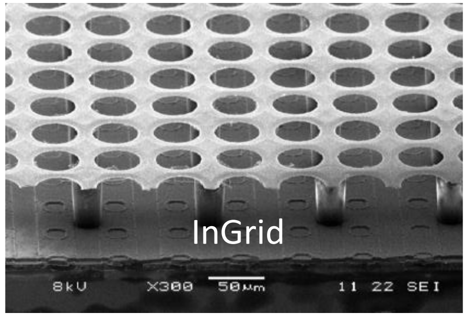
Resistive-Plate-Well



μPIC



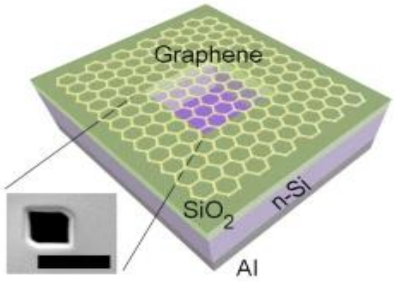
CMOS MicroMegas
mesh grown on pixel ASIC

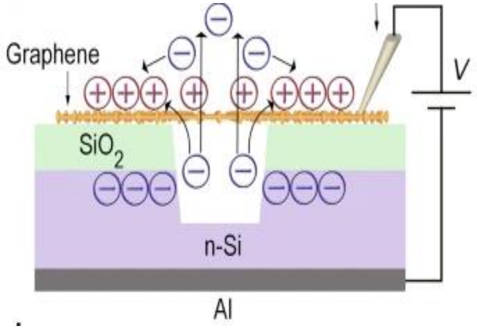


New GEM-like single amplification stage with fine pitch strips (left) or pixels (right)

Monolithic design

- Improve rate capability O($\gtrsim$ 100) MHz/cm^2
  - AC coupling through DLC coating resistive layer
- 3D printing, dry plasma ink jet printing
  - developed for flexible PCB devices
- New material concept ex. Graphene grid

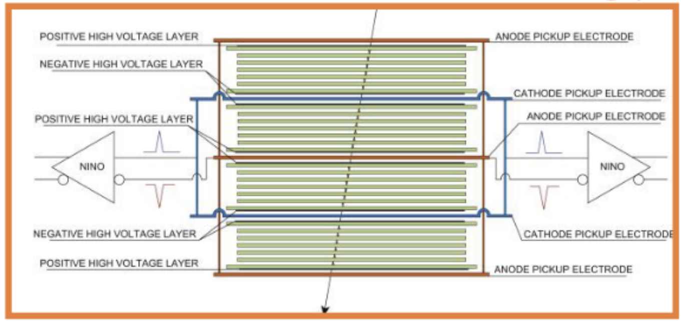




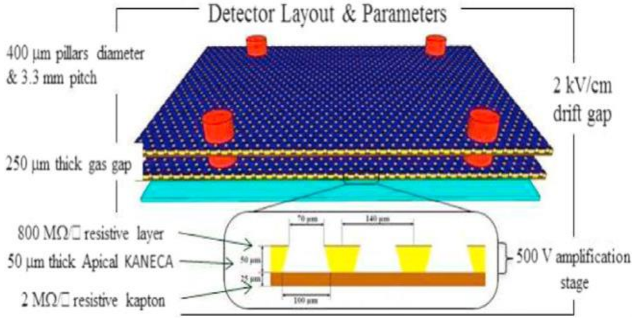
R&D timing precision

- Multigap RPCs
  - ➢ low ρ material and thin gaps O(100) µm
- Fast Timing MPGD
  - ➢ Thin gaps multiple GEM amplification stages on top of µ-rwell
- MicroMegas with Cherenkov radiator and photocathode
  - ➢ Improve photocathode QE and radiation tolerance
    - New materials ex. hydrogenated diamond spray, nano-diamond (gold) grains (UV-sensitive)

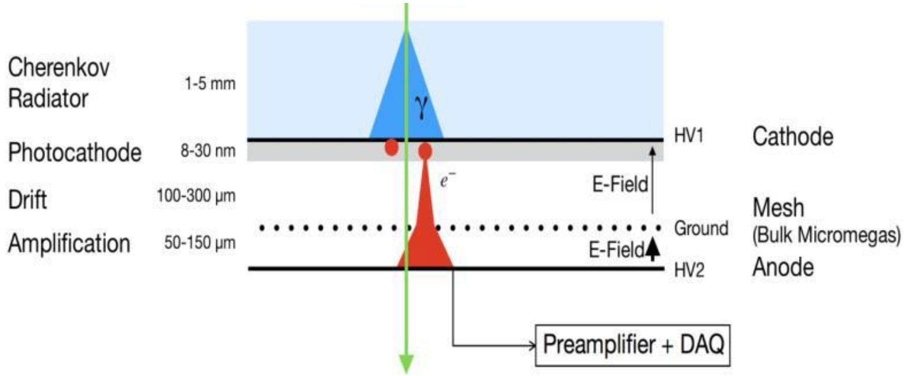
Multigap RPCs
24 x 160 µm gaps O(20) ps



Fast Timing MPGD



Picosec MM (1 MIP ≃ 10 pe) O(25) ps



R&D Eco-friendly gas mixtures

- Reduced discharge of currently used GHG ($C_2H_2F_4$, CF_4, SF_6, C_4F_{10})
  - Recirculation/recuperation/abatement should fulfil current regulation
- Alternative mixtures
  - HydroFluoroOlefin (ex. $C_3H_2F_4$) commercial refrigerant replacements
    - do not yet provide full performance without some (relatively small) fraction of CF4
  - New design and operation conditions to compensate possible performance loss

ECFA roadmap Liquid detectors

Water Cerenkov, Noble Liquid, Liquid Scintillator

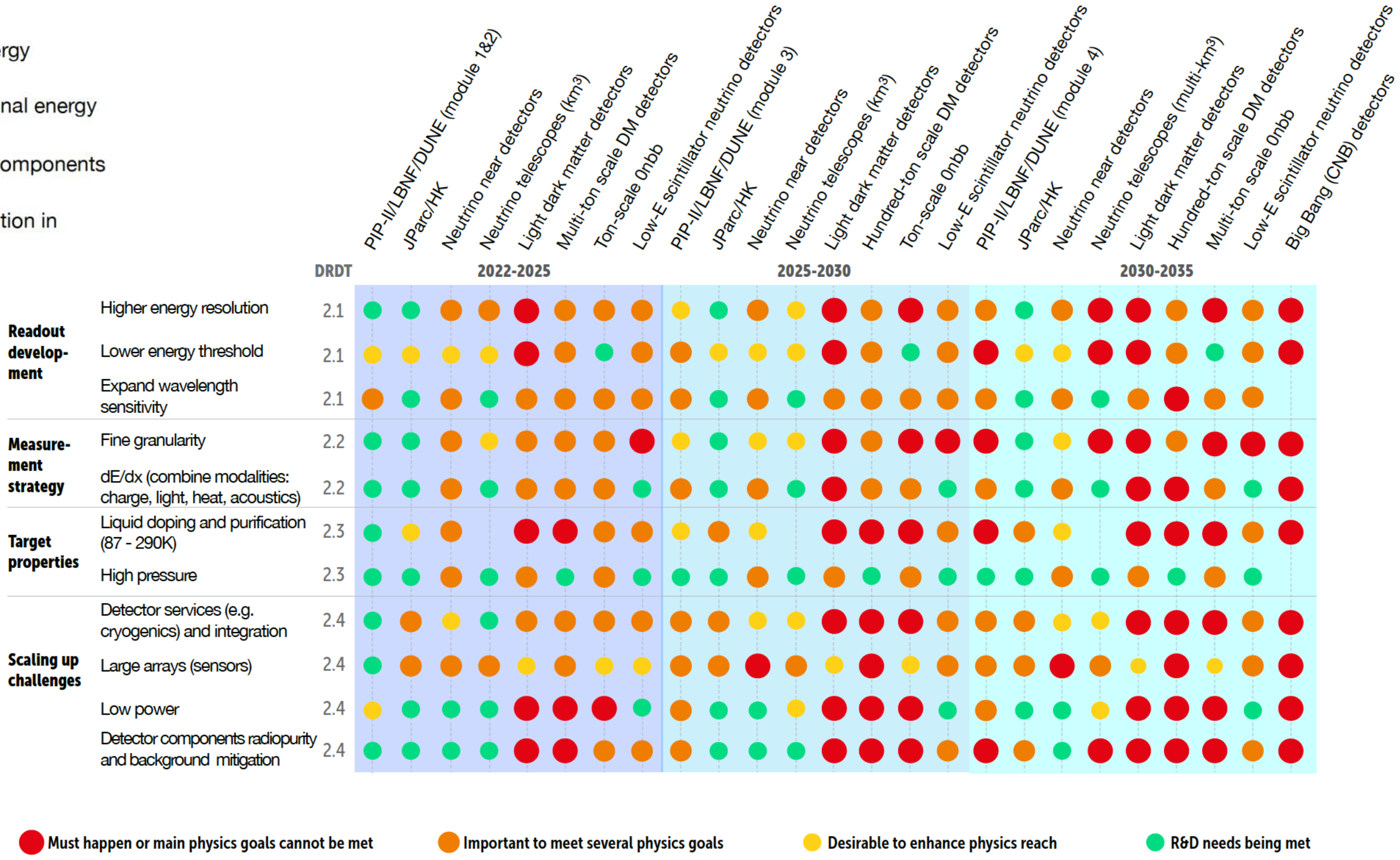
Liquid

DRDT 2.1 Develop readout technology to increase spatial and energy resolution for liquid detectors

DRDT 2.2 Advance noise reduction in liquid detectors to lower signal energy thresholds

DRDT 2.3 Improve the material properties of target and detector components in liquid detectors

DRDT 2.4 Realise liquid detector technologies scalable for integration in large systems



		DRDT	2022-2025								2025-2030								2030-2035								
			PIP-II/LBNF/DUNE (module 1&2)	JParc/HK	Neutrino near detectors	Neutrino telescopes (km³)	Light dark matter detectors	Multi-ton scale DM detectors	Ton-scale 0nbb	Low-E scintillator neutrino detectors	PIP-II/LBNF/DUNE (module 3)	JParc/HK	Neutrino near detectors	Neutrino telescopes (km³)	Light dark matter detectors	Hundred-ton scale DM detectors	Ton-scale 0nbb	Low-E scintillator neutrino detectors	PIP-II/LBNF/DUNE (module 4)	JParc/HK	Neutrino near detectors	Neutrino telescopes (multi-km³)	Light dark matter detectors	Hundred-ton scale DM detectors	Multi-ton scale 0nbb	Low-E scintillator neutrino detectors	Big Bang (CNB) detectors
Readout develop-ment	Higher energy resolution	2.1	🟢	🟢	🟠	🟠	🔴	🟠	🟠	🟠	🟡	🟢	🟠	🟡	🔴	🟠	🔴	🟠	🟠	🟢	🟠	🔴	🔴	🟠	🔴	🟠	🔴
	Lower energy threshold	2.1	🟡	🟡	🟡	🟡	🔴	🟠	🟢	🟠	🟠	🟡	🟡	🟡	🔴	🟠	🟢	🟠	🔴	🟡	🟡	🔴	🔴	🟠	🟢	🟠	🔴
	Expand wavelength sensitivity	2.1	🟠	🟢	🟠	🟢	🟠	🟠	🟠	🟠	🟠	🟢	🟠	🟢	🟠	🟠	🟠	🟠	🟠	🟢	🟠	🟢	🟠	🔴	🟠	🟠	
Measure-ment strategy	Fine granularity	2.2	🟢	🟢	🟠	🟡	🟠	🟠	🟠	🔴	🟡	🟢	🟡	🟡	🔴	🟠	🔴	🔴	🔴	🟢	🟡	🔴	🔴	🟠	🔴	🔴	🔴
	dE/dx (combine modalities: charge, light, heat, acoustics)	2.2	🟢	🟢	🟠	🟢	🟠	🟠	🟠	🟢	🟠	🟢	🟠	🟢	🔴	🟠	🟠	🟢	🟠	🟢	🟠	🟢	🔴	🔴	🟠	🟢	🔴
Target properties	Liquid doping and purification (87 - 290K)	2.3	🟢	🟡	🟠		🔴	🔴	🟠	🟠	🟡	🟠	🟡		🔴	🔴	🔴	🟠	🔴	🟠	🟡		🔴	🔴	🔴	🟠	🔴
	High pressure	2.3	🟢	🟢	🟠	🟢	🟠	🟢	🟠	🟢	🟢	🟢	🟠	🟢	🟠	🟢	🟠	🟢	🟢	🟢	🟠	🟢	🟠	🟢	🟠	🟢	
Scaling up challenges	Detector services (e.g. cryogenics) and integration	2.4	🟢	🟠	🟡	🟢	🟠	🟠	🟠	🟠	🟠	🟠	🟡	🟡	🔴	🔴	🔴	🟠	🟠	🟠	🟡	🟡	🔴	🔴	🔴	🟠	🔴
	Large arrays (sensors)	2.4	🟢	🟠	🟠	🟠	🟡	🟠	🟡	🟡	🟠	🟠	🔴	🟠	🟡	🔴	🟡	🟠	🟠	🟠	🔴	🟠	🟡	🔴	🟡	🟠	🔴
	Low power	2.4	🟡	🟢	🟢	🟢	🔴	🔴	🔴	🟢	🟠	🟢	🟢	🟡	🔴	🔴	🔴	🟢	🟠	🟢	🟢	🟡	🔴	🔴	🔴	🟢	🔴
	Detector components radiopurity and background mitigation	2.4	🟢	🟢	🟢	🟢	🔴	🔴	🟠	🟠	🟠	🟢	🟢	🟢	🔴	🔴	🔴	🟠	🔴	🟠	🟢	🔴	🔴	🔴	🔴	🟠	🔴

🔴 Must happen or main physics goals cannot be met 🟠 Important to meet several physics goals 🟡 Desirable to enhance physics reach 🟢 R&D needs being met

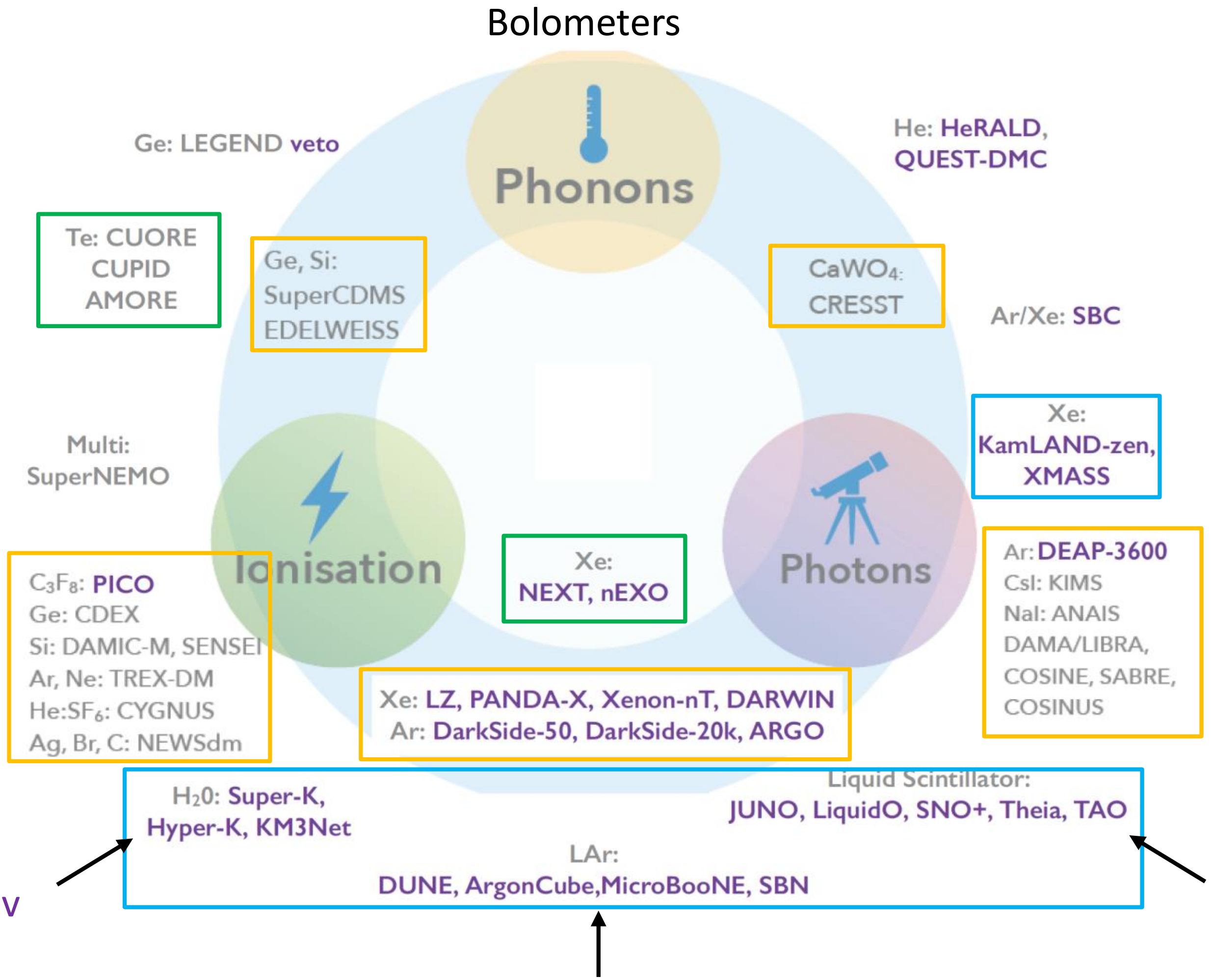
Neutrino, Dark Matter, $0\nu\beta\beta$ decay detectors

Strategy driven by energy sensitivity

goal to measure the different signals in same multi-purpose detectors of increasing volumes

Low energy thresholds
small detectors crystals
with quantum sensors

Neutrino
$0\nu\beta\beta$
Dark Matter



Large detector volumes,
different readout schemes

Water Cherenkov
$O(10^2)\ \gamma$/MeV
visible range

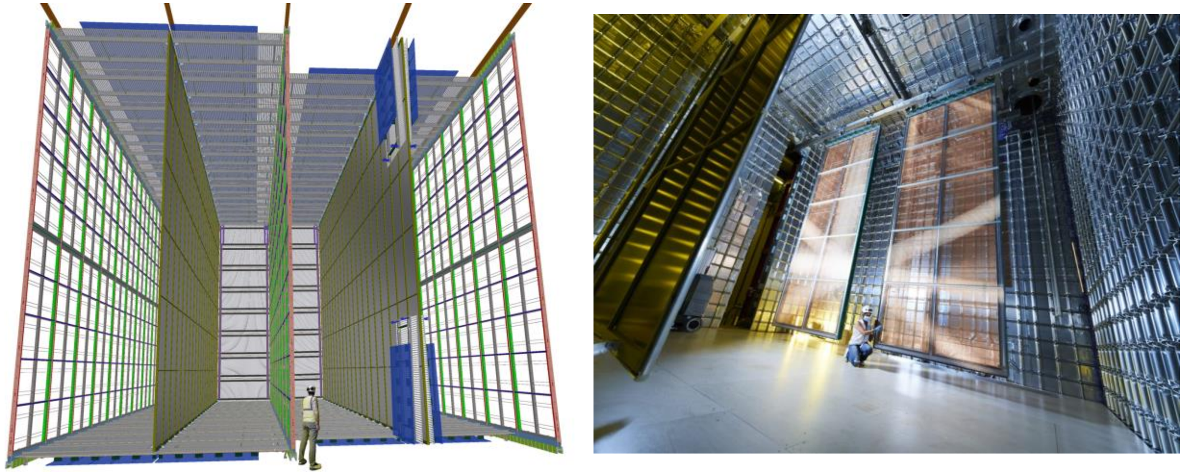
Liquid Scintillators
$O(10^4)\ \gamma$/MeV
visible range

Noble Liquid TPC
Ionization and $O(4\text{x}10^4)\ \gamma$/MeV VUV 128(178) nm for LAr(Xe)

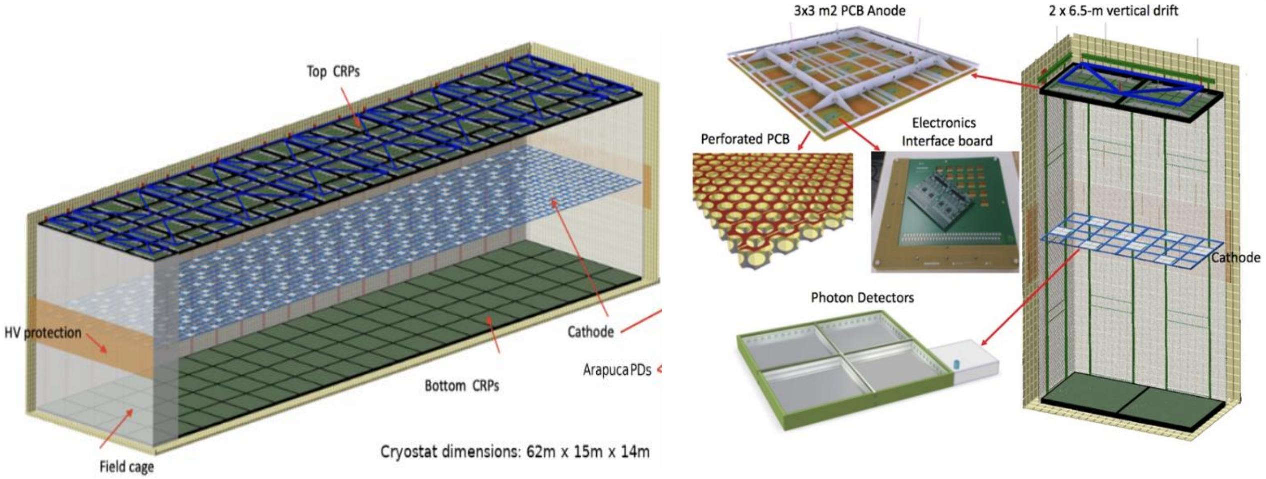
Noble liquid TPC Neutrino

DUNE at Stanford Underground Research Facility 1.5km deep and 1300 km from Fermilab 2026-28 Far Detector 1 and 2 Single Phase LAr TPCs 17 kt 68(l) x 14(w) x 12(h) m^3 1.5 km undeground

- Next step FD3 and FD4 technologies to be decided ex. Theia Liquid Scintillator module 60(r) m x 60(h) m



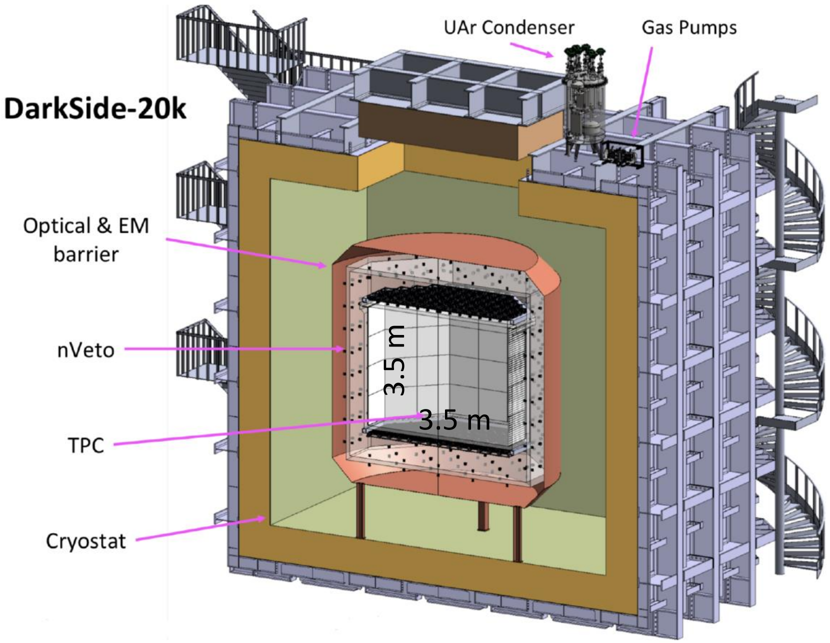
FD1 horizontal anode drift wire readout and SiPMs

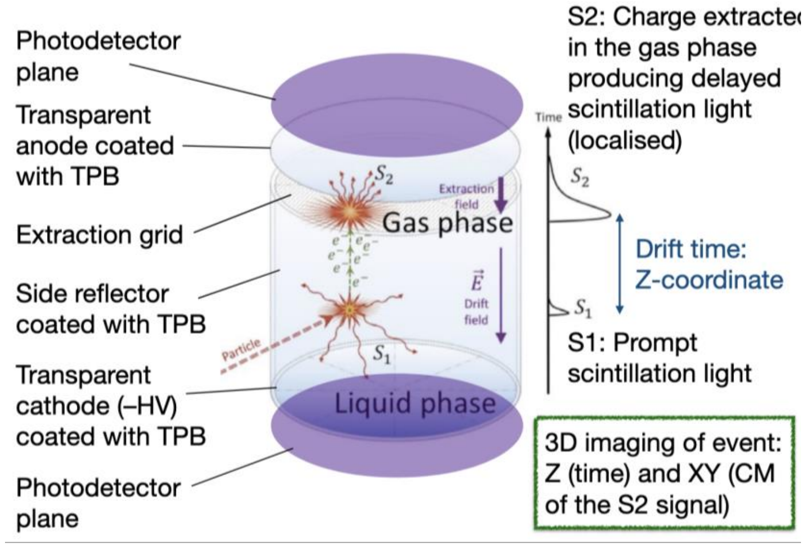


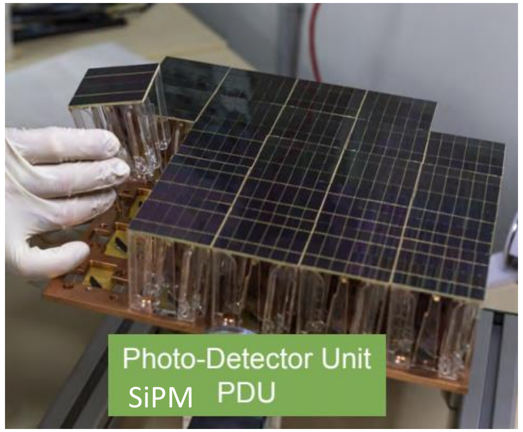
FD2 vertical drift PCB anode readout and SiPMs in cathod plane

Noble liquid TPC Dark Matter

- DarkSide-20k 20t (30 m^3) double phase LUAr* TPC at Lab. Nat. Grand Sasso, 2025
  - readout both scintillation and ionisation proportionale electroluminescence
- ➢ Next step ARGO at SNOLAB (Canada) 300t





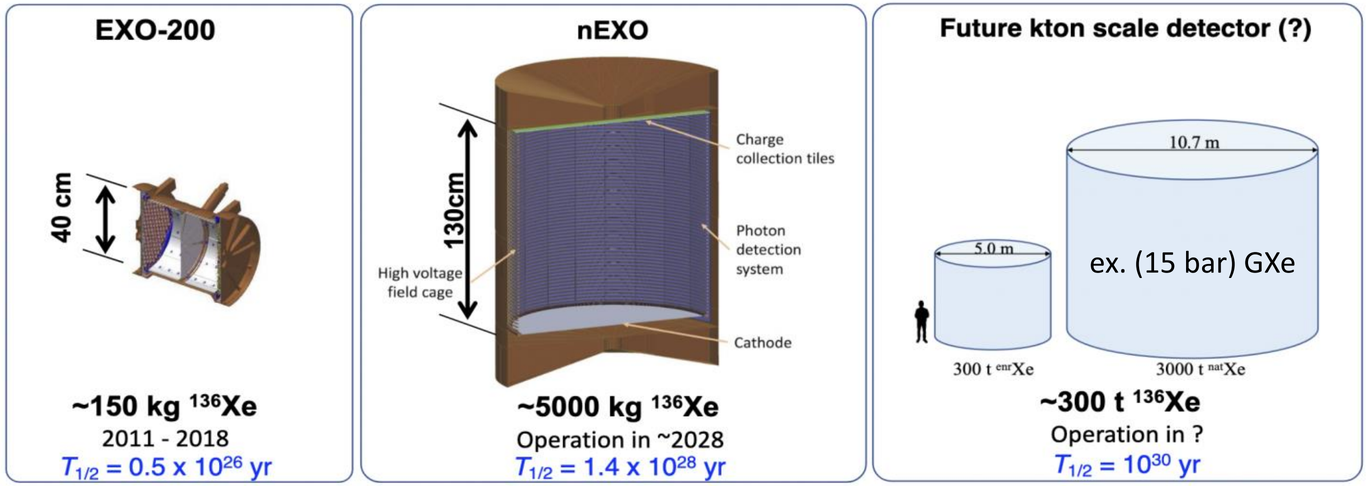


- DARWIN 50t 2.6 x 2.6 m double phase LXe TPC $\lesssim$ 2030?
  - Also using water Cherenkov and Liquid Scintillator to shield TPC

** Underground extracted, free of ^{39}Ar radoactive isotope*

Noble liquid TPC $0\nu\beta\beta$

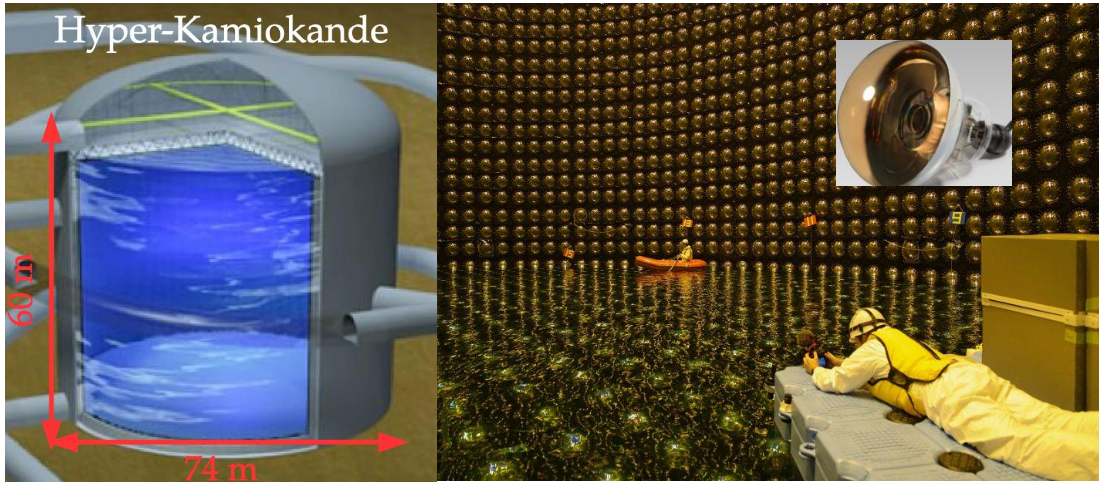
- nEXO 5t single phase LXe single phase TPC (2028)
  ^{136}Xe decay source and the sensitive medium – readout anode tiles and SiPMs
  - ➢ Next generation 300t
    - Supply of Xe is a major challenge
    - High Pressure (15 bar) GXe versus LXe is a compromise between energy resolution and backgroung



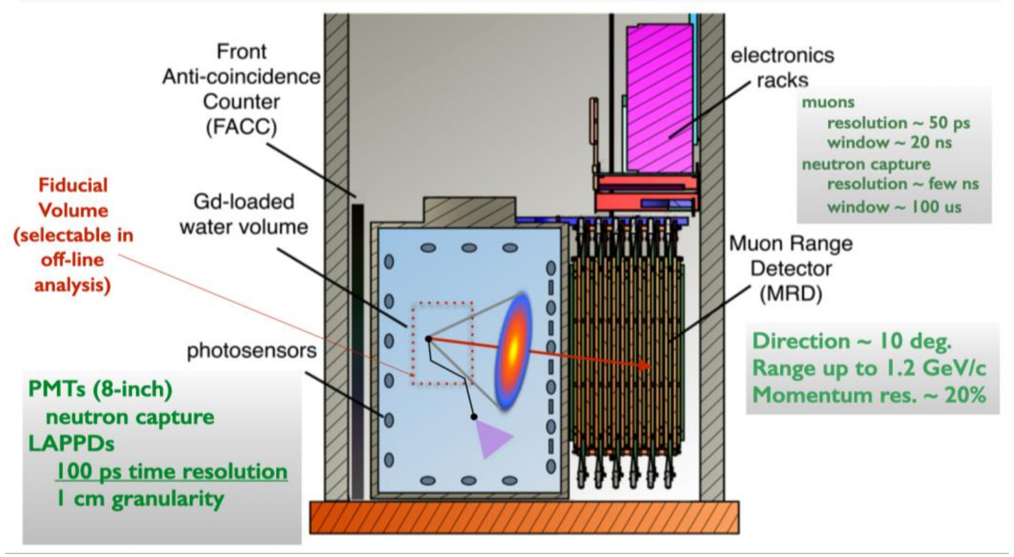
D. Moore, Yale CPAD – Nov 29, 2022

- NEXT High Pressure Xenon TPC (2028) with double phase like readout
  - ➢ Study daughter Ba^{++} combination with fluorescence molecules to tag signal for background rejection

Water Cherenkov Neutrino



Hyper-Kamiokande 2027
300 km from JPARC (Tokai, Japan)
650 m underground 260 ktons ultra pure water Cherenkov, readout 40 000 PMT Φ = 50 cm, PDE ≃ 30%, 2.6 ns time resolution inner tank and 67000 PMT Φ = 20 cm outer tank



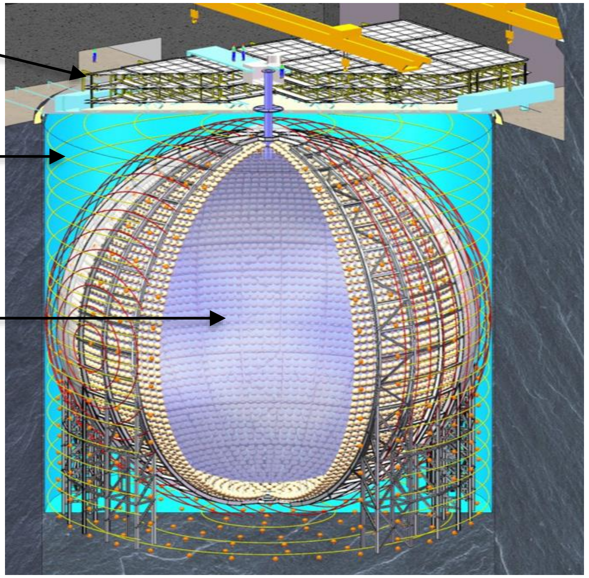
Accelerator Neutrino Neutron Interaction Experiment at FNAL Booster Neutrino Beam
26 t Gadolinium loaded water Cherenkov*
(measure neutrons), Large Area Picosecond PhotoDetectors 20x20 cm^2, 60 ps 1 cm position resolution

Gd loaded Liquid Scintillator also used in TAO at (JUNO) and LZ for veto

Liquide scintillator Neutrino

Jiangmen Underground Neutrino Observatory China (2023)

53 km from 2 nuclear power plants, 700 m underground
20 kt of liquid scintillator, 35 m (d) sphere



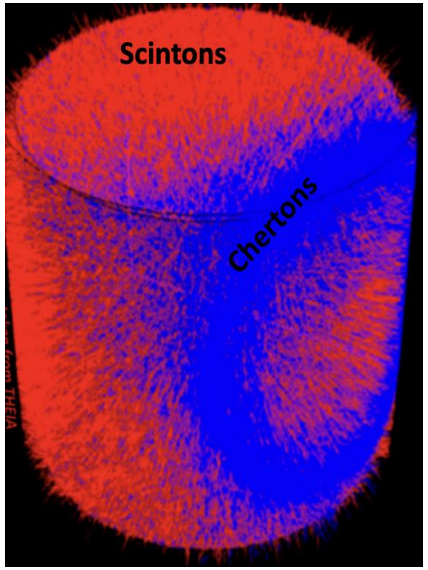
Tracking veto, 3 layers of plastic scintillators

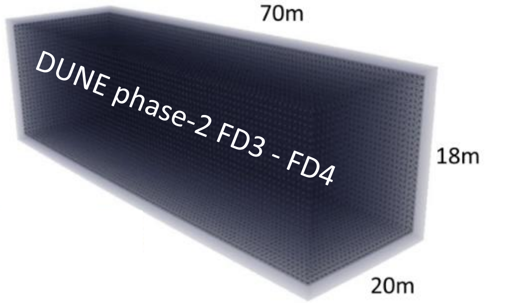
35 kt Water Cherenkov veto
5000 PMT Φ 50 cm

Liquid scintillator
75% coverage
- 15000 PMT Φ 50 cm
  - MCP and Dynode
- 26000 PMT Φ 7.5 cm

DUNE Phase2 new concept Theia

25kt Water Based Liquid Scintillator
Scintillation high light yield & Cherenkov ring directionality, dychroic filters to separate WL on 2 photosensors or waveform sampling with LAPPD

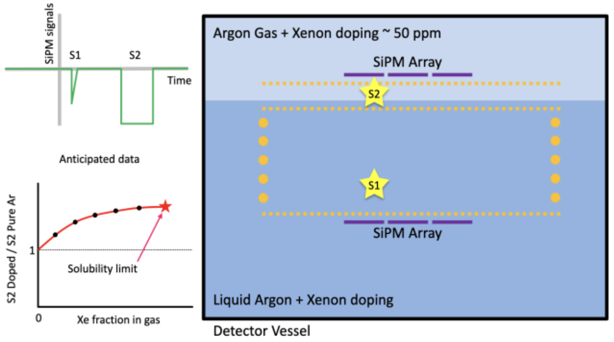


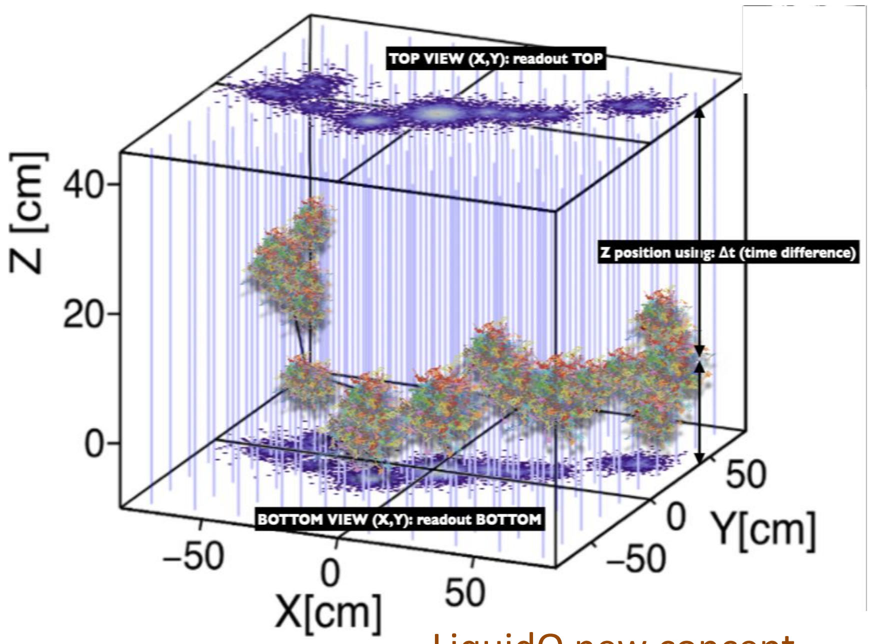


R&D Liquid

Increased signal and reduced background

- Noble Liquid (TPC)
  - ➢ Xe doping in LAr to increase electro-luminescence in DP
- Liquid Scintillator
  - ➢ Develop liquid scintillators with luminophore/quantum dots
  - ➢ Develop water-based LS for both scintillation and Cherenkov
    - ex. (Theia DUNE Phase-2 module)
  - ➢ Develop opaque liquid scintillator (LiquidO)
- Improve purity of liquid by O(10) to reduce signal absorption
- Improve radiopurity by O(10) to 1000 all materials
  - ➢ ex. new concept of crystal/vapor Xe dual phase to eliminate Radon



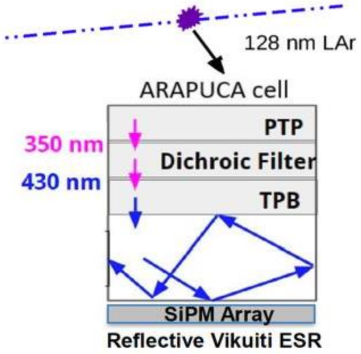


LiquidO new concept

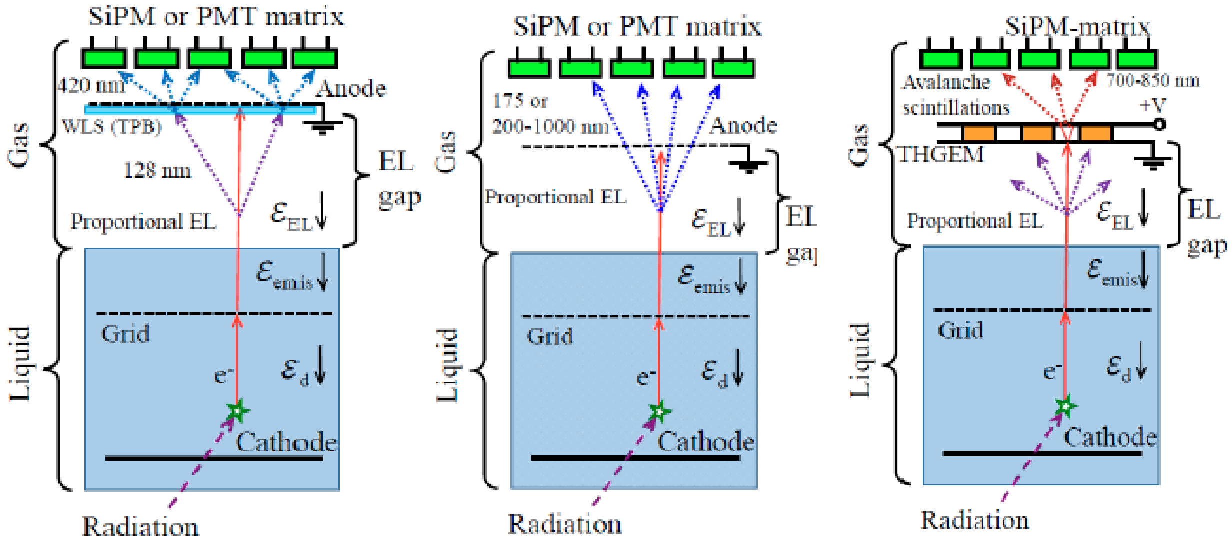
R&D readout

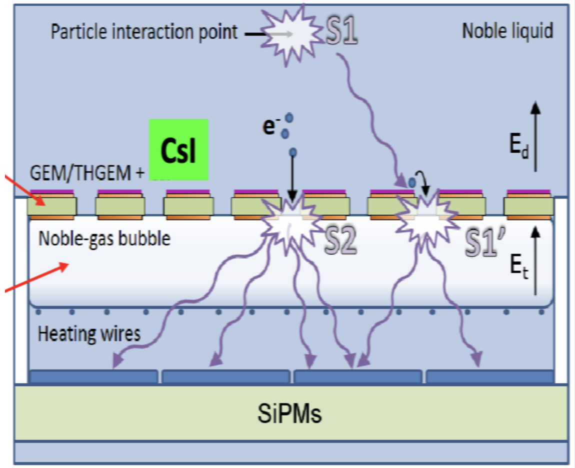
Improved photon/ionisation sensitivity and higher granularity

- Photosensors (PMT, LAPPD, SiPM/SPADs, CCD)
  - ➢ Improve Wave Length Shifting and/or VUV – NIR Quantum Efficiency
  - ➢ Design devices with both ionisation and light sensitivity
- Readout schemes
  - ➢ Improved amplification scheme in DP TPC
  - ➢ Increase granularity ex CCD with TimePix ASIC for spatial NEXT)

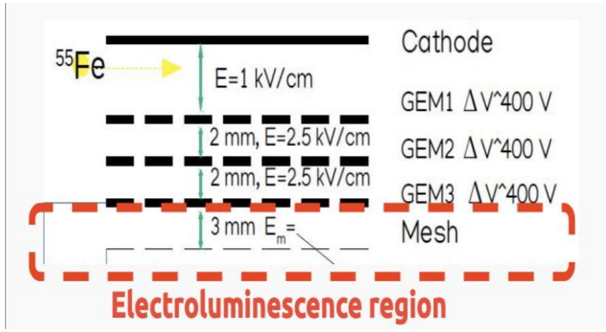


Dune Arapuca SiPM



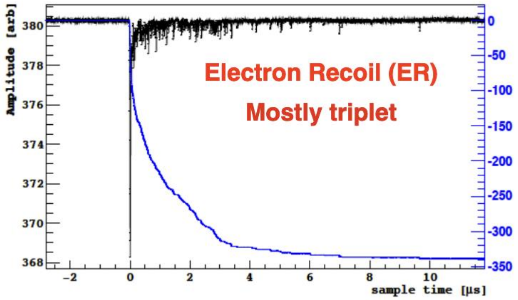


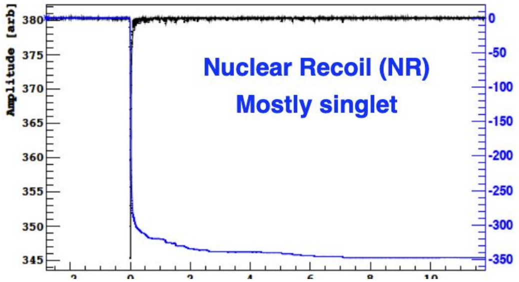
CYGNO directional DM 30 m^3 TPC low density $HeCF_4$



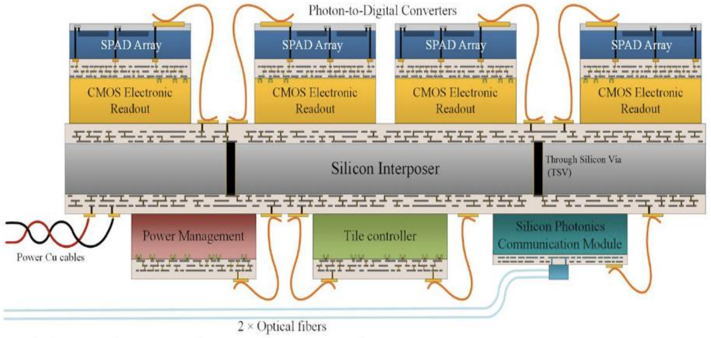
R&D Electronics

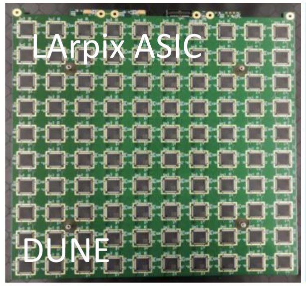
- Electronics
  - Waveform sampling to reject background (potentially to separate Cherenkov/Scintillation)
  - 3D integrated readout operated at cryogenic temperature (including optical transmission)
- Other engineering challenges for volume scaling
  - Cryostat vessels, cryogeny systems, feedthrough, power supplies, monitoring and calibration

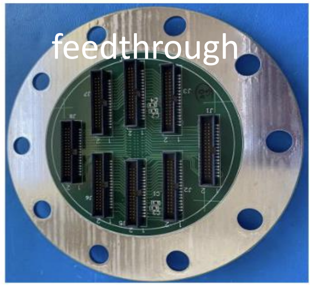


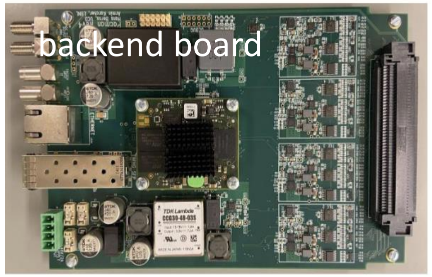


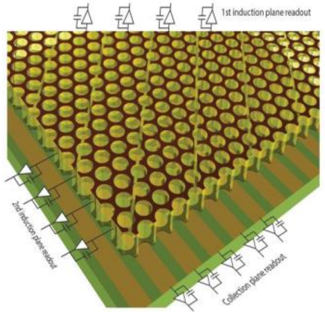
ARGO integrated readout with SPADs





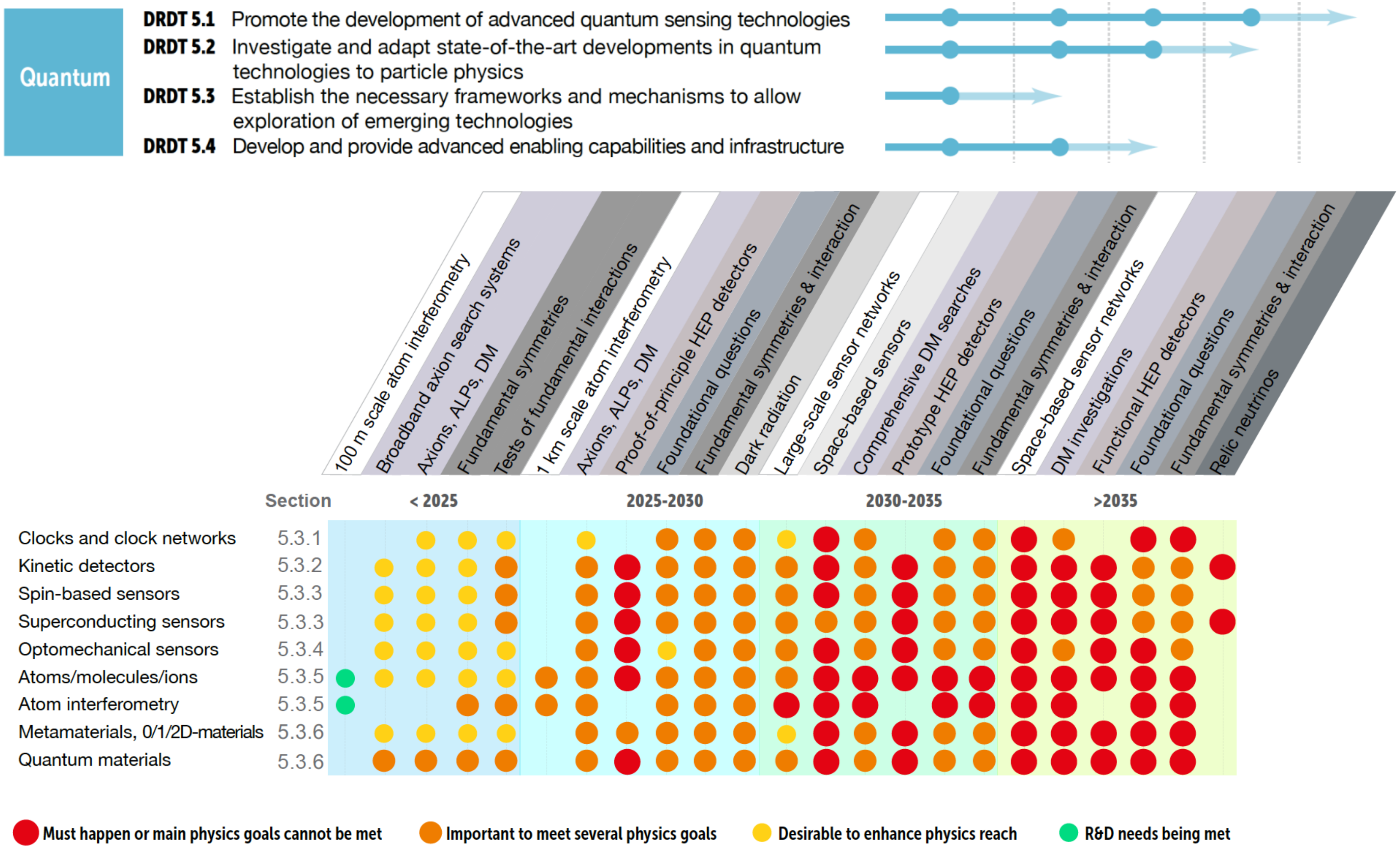






ECFA roadmap Quantum Sensors and emerging technologies

Sensors to measure very small signals with high resolution



Quantum

DRDT 5.1 Promote the development of advanced quantum sensing technologies

DRDT 5.2 Investigate and adapt state-of-the-art developments in quantum technologies to particle physics

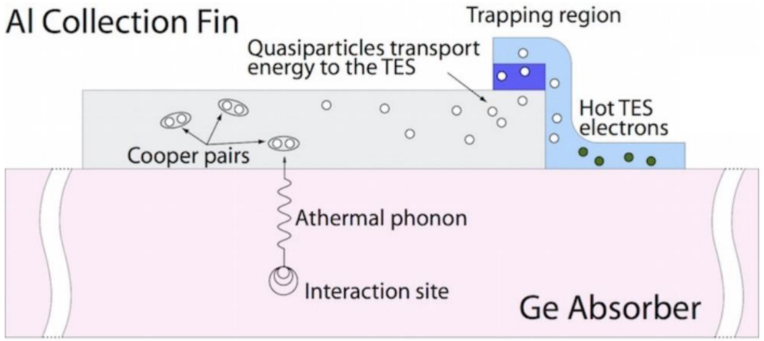
DRDT 5.3 Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies

DRDT 5.4 Develop and provide advanced enabling capabilities and infrastructure

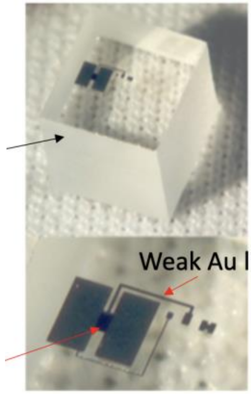
	Section	< 2025					2025-2030						2030-2035						>2035					
		100 m scale atom interferometry	Broadband axion search systems	Axions, ALPs, DM	Fundamental symmetries	Tests of fundamental interactions	1 km scale atom interferometry	Axions, ALPs, DM	Proof-of-principle HEP detectors	Foundational questions	Fundamental symmetries & interaction	Dark radiation	Large-scale sensor networks	Space-based sensors	Comprehensive DM searches	Prototype HEP detectors	Foundational questions	Fundamental symmetries & interaction	Space-based sensor networks	DM investigations	Functional HEP detectors	Foundational questions	Fundamental symmetries & interaction	Relic neutrinos
Clocks and clock networks	5.3.1			🟡	🟡	🟡		🟡		🟠	🟠	🟠	🟡	🔴	🟠		🟠	🟠	🔴	🟠		🔴	🔴	
Kinetic detectors	5.3.2		🟡	🟡	🟡	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🟠	🟠	🔴
Spin-based sensors	5.3.3		🟡	🟡	🟡	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🟠	🟠	
Superconducting sensors	5.3.3		🟡	🟡	🟡	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🟠	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🟠	🟠	🔴
Optomechanical sensors	5.3.4		🟡	🟡	🟡	🟡		🟠	🔴	🟡	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🟠	🔴	🔴	🟠	
Atoms/molecules/ions	5.3.5	🟢	🟡	🟡	🟡	🟡	🟠	🟠	🔴	🟠	🟠	🟠	🟠	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	
Atom interferometry	5.3.5	🟢			🟠	🟠	🟠	🟠		🟠	🟠	🟠	🔴	🔴	🔴		🔴	🔴	🔴	🔴		🔴	🔴	
Metamaterials, 0/1/2D-materials	5.3.6		🟡	🟡	🟡	🟡		🟠	🟠	🟠	🟠	🟠	🟡	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🔴	🔴	
Quantum materials	5.3.6		🟠	🟠	🟠	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🔴	🔴	

🔴 **Must happen or main physics goals cannot be met** 🟠 **Important to meet several physics goals** 🟡 **Desirable to enhance physics reach** 🟢 **R&D needs being met**

Phonon detection



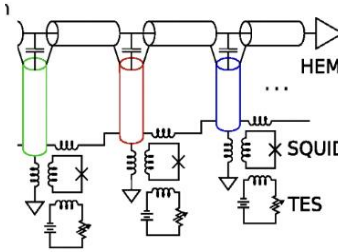
$CaWO_4$
or Al_2O_3
or Ge
or Si…



TES
W thin film
T_C 20 mk

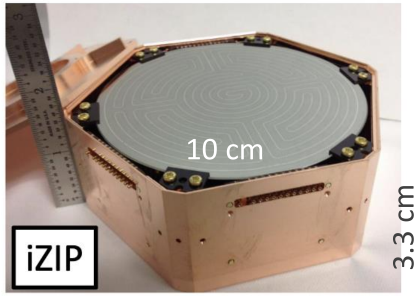
J. Rothe, PhD thesis, TUM 2020

Squid
multiplexed readout

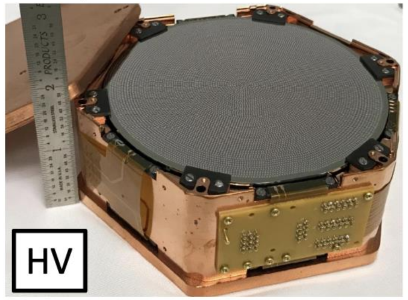


Super CDMS DMS 1.39(0.61) kg kgr

12 phonon, 4 charge channels
sensitive to ≥5GeV/c^2 DM
Ge(Si) σ_{ph}=50(25) eV σ_{ch}= 160(180) eV

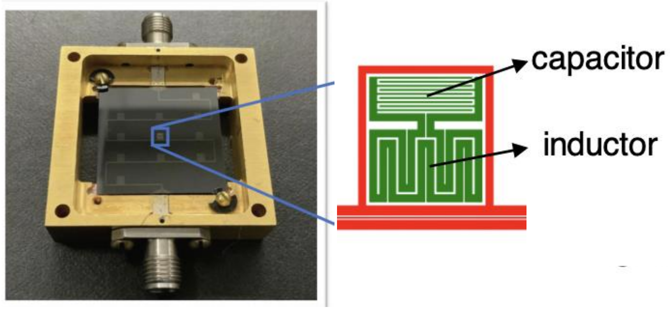


12 phonon channels
sensitive to sub-GeV DM
Ge(Si) σ_{ph}=10(5) eV

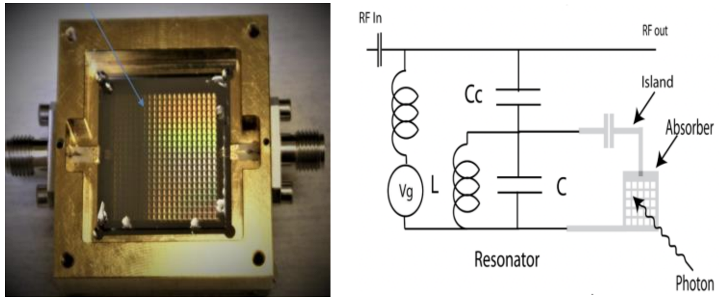


- Transition Edge Sensors loss of superconductivity
  - Kinetic Inductance Detector transmission in a LC resonator
    - Quantum Capacitance Detector shift of resonator frequency with change of capacity in a tunnel junction

Single KID 2 cm CRESST 1-10gr



Quantum Capacitance Detector



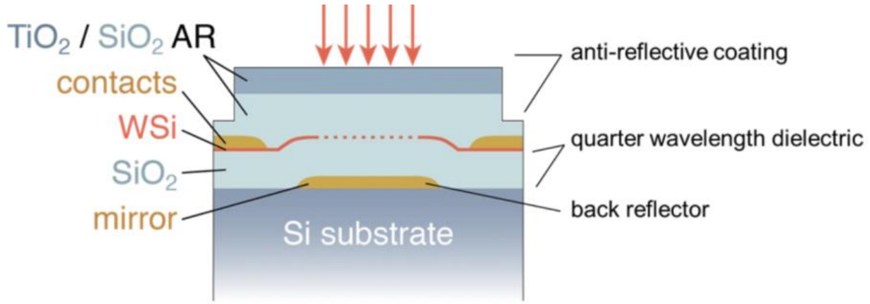
R&D to reach sub-ev sensitivity, with larger scale systems

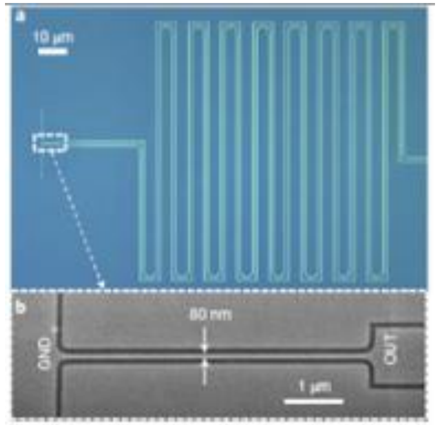
- ➢ Superconducting film material (Al, W, TiNx, Nb)
- ➢ Configuration of signal measurement structures
- ➢ Production process and readout

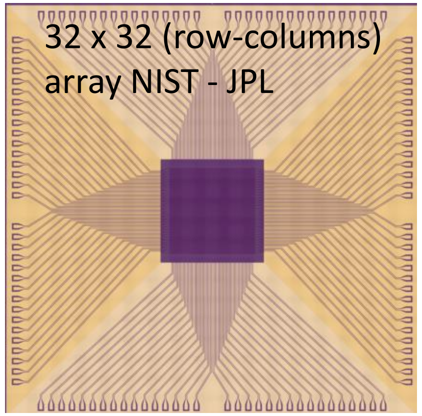
Superconducting Nanowire Single Photon Detector

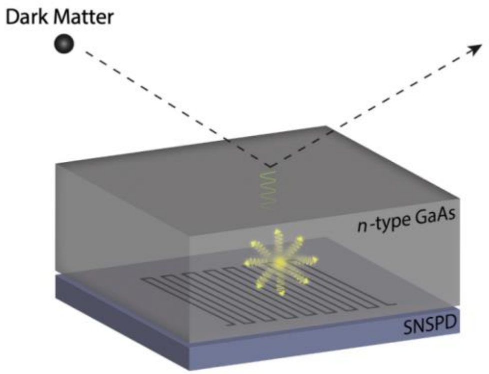
Measure resistance variation of nanowires (< 1 µm) at 1–4 K

- Very high QE 10 nm to 10 µm WL, ultralow DCR < 10^{-5} cps, timing $\simeq$ 3 ps, rate capability O(1) GHz/mm^2
  - ➢ Configuration for further improved sensitivity for threshold below 70 meV
  - ➢ Larger size sensors accompanied by electronics for channel multiplexing






32 x 32 (row-columns) array NIST - JPL

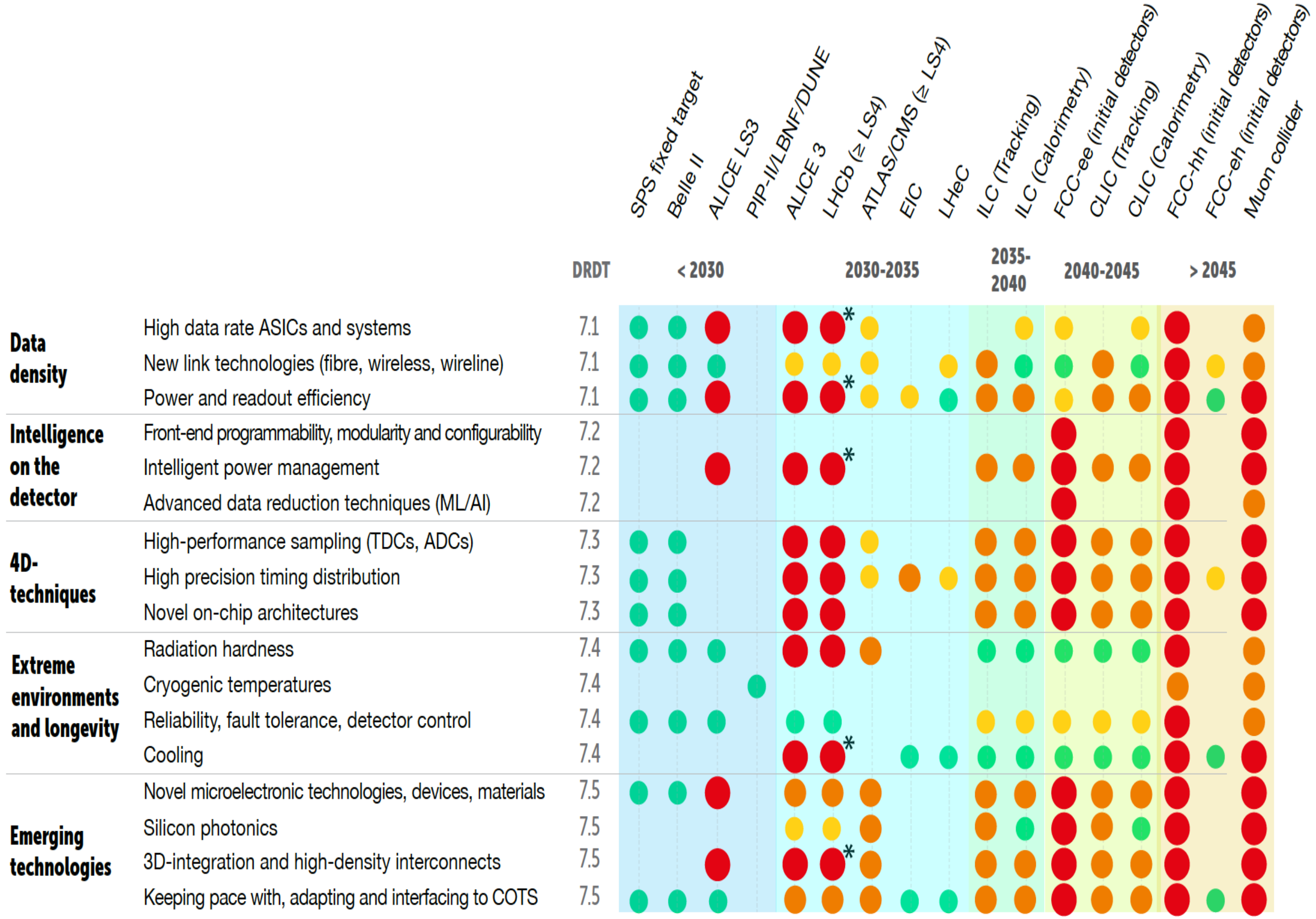


ECFA R&D roadmap: Electronics

Provide high data density readout and processing in extreme environments,
Organise access to technologies, training, help shared developments of complex ASICs
Ensure new technology watch

Electronics

DRDT 7.1 Advance technologies to deal with greatly increased data density
DRDT 7.2 Develop technologies for increased intelligence on the detector
DRDT 7.3 Develop technologies in support of 4D- and 5D-techniques
DRDT 7.4 Develop novel technologies to cope with extreme environments and required longevity
DRDT 7.5 Evaluate and adapt to emerging electronics and data processing technologies



		DRDT	< 2030				2030-2035					2035-2040		2040-2045			> 2045		
			SPS fixed target	Belle II	ALICE LS3	PIP-II/LBNF/DUNE	ALICE 3	LHCb (≥ LS4)	ATLAS/CMS (≥ LS4)	EIC	LHeC	ILC (Tracking)	ILC (Calorimetry)	FCC-ee (initial detectors)	CLIC (Tracking)	CLIC (Calorimetry)	FCC-hh (initial detectors)	FCC-eh (initial detectors)	Muon collider
Data density	High data rate ASICs and systems	7.1	🟢	🟢	🔴		🔴	🔴*	🟡				🟡	🟡		🟡	🔴		🟠
	New link technologies (fibre, wireless, wireline)	7.1	🟢	🟢	🟢		🟡	🟡	🟡		🟡	🟠	🟢	🟢	🟠	🟢	🔴	🟡	🟠
	Power and readout efficiency	7.1	🟢	🟢	🔴		🔴	🔴*	🟡	🟡	🟢	🟠	🟠	🟡	🟠	🟠	🔴	🟢	🔴
Intelligence on the detector	Front-end programmability, modularity and configurability	7.2												🔴			🔴		🔴
	Intelligent power management	7.2			🔴		🔴	🔴*				🟠	🟠	🔴	🟠	🟠	🔴		🔴
	Advanced data reduction techniques (ML/AI)	7.2												🔴			🔴		🟠
4D-techniques	High-performance sampling (TDCs, ADCs)	7.3	🟢	🟢			🔴	🔴	🟡			🟠	🟠	🔴	🟠	🟠	🔴		🔴
	High precision timing distribution	7.3	🟢	🟢			🔴	🔴	🟡	🟠	🟡	🟠	🟠	🔴	🟠	🟠	🔴	🟡	🔴
	Novel on-chip architectures	7.3	🟢	🟢			🔴	🔴				🟠	🟠	🔴	🟠	🟠	🔴		🔴
Extreme environments and longevity	Radiation hardness	7.4	🟢	🟢	🟢		🔴	🔴	🟠			🟢	🟢	🟢	🟢	🟢	🔴		🟠
	Cryogenic temperatures	7.4				🟢											🟠		🟠
	Reliability, fault tolerance, detector control	7.4	🟢	🟢	🟢		🟢	🟢				🟡	🟡	🟡	🟡	🟡	🔴		🟠
	Cooling	7.4					🔴	🔴*		🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🔴
Emerging technologies	Novel microelectronic technologies, devices, materials	7.5	🟢	🟢	🔴		🟠	🟠	🟠			🟠	🟠	🔴	🟠	🟠	🔴		🔴
	Silicon photonics	7.5					🟡	🟡	🟠			🟠	🟢	🔴	🟠	🟢	🔴		🔴
	3D-integration and high-density interconnects	7.5			🔴		🔴	🔴*	🟠			🟠	🟠	🔴	🟠	🟠	🔴		🔴
	Keeping pace with, adapting and interfacing to COTS	7.5	🟢	🟢	🟢		🟠	🟠	🟠	🟢	🟢	🟠	🟠	🔴	🟠	🟠	🔴	🟢	🔴

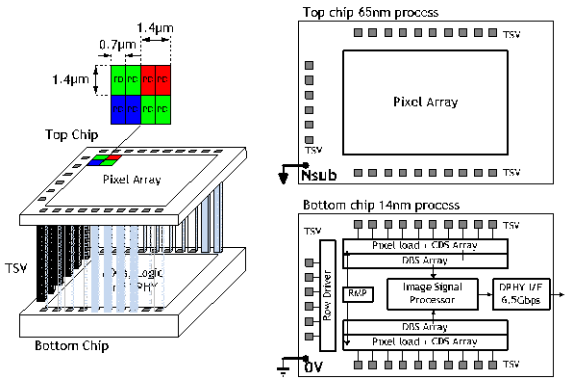
🔴 Must happen or main physics goals cannot be met
🟠 Important to meet several physics goals
🟡 Desirable to enhance physics reach
🟢 R&D needs being met

R&D Electronics

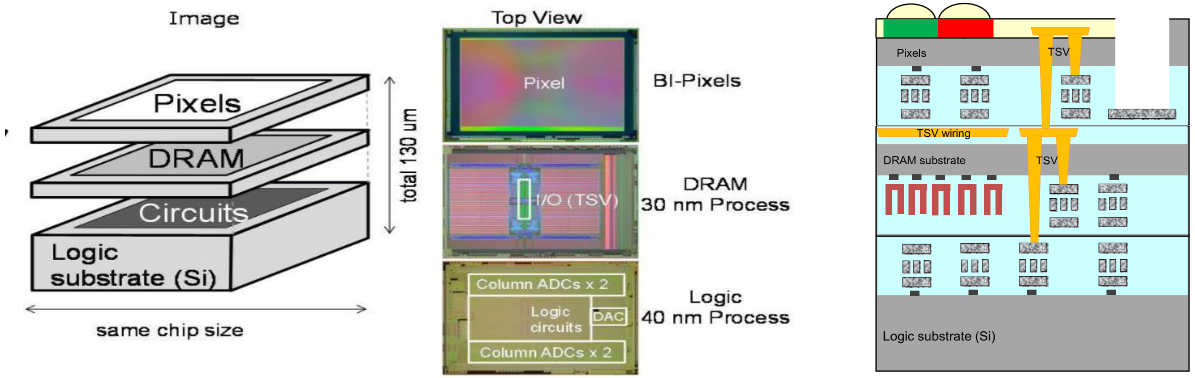
- Transition to deeper ASIC nodes (28 nm R&D started)
- New readout architectures
  - low power, timing precision, on-detector processing implementing Machin Learning
  - operation at cryogenic temperature

➢ Develop 3D integrated devices, sensitive element + analogic + digital readout features

- ex. commercial imagers could be an ultimate tracking solution if made radiation hard



Samsung: 1.4 μm pixels in 65 nm & 14 nm Fin-FET (3D transistors) readout , wafer level stacking



Sony (left) 3D layer thinned to 3 μm design for 960 fps
Samsung (right) 1.2 μm pixels, 2.5 μm TSV 6.3 μm pitch, 20 nm DRAM, 28 nm logic

➢ Technology watch

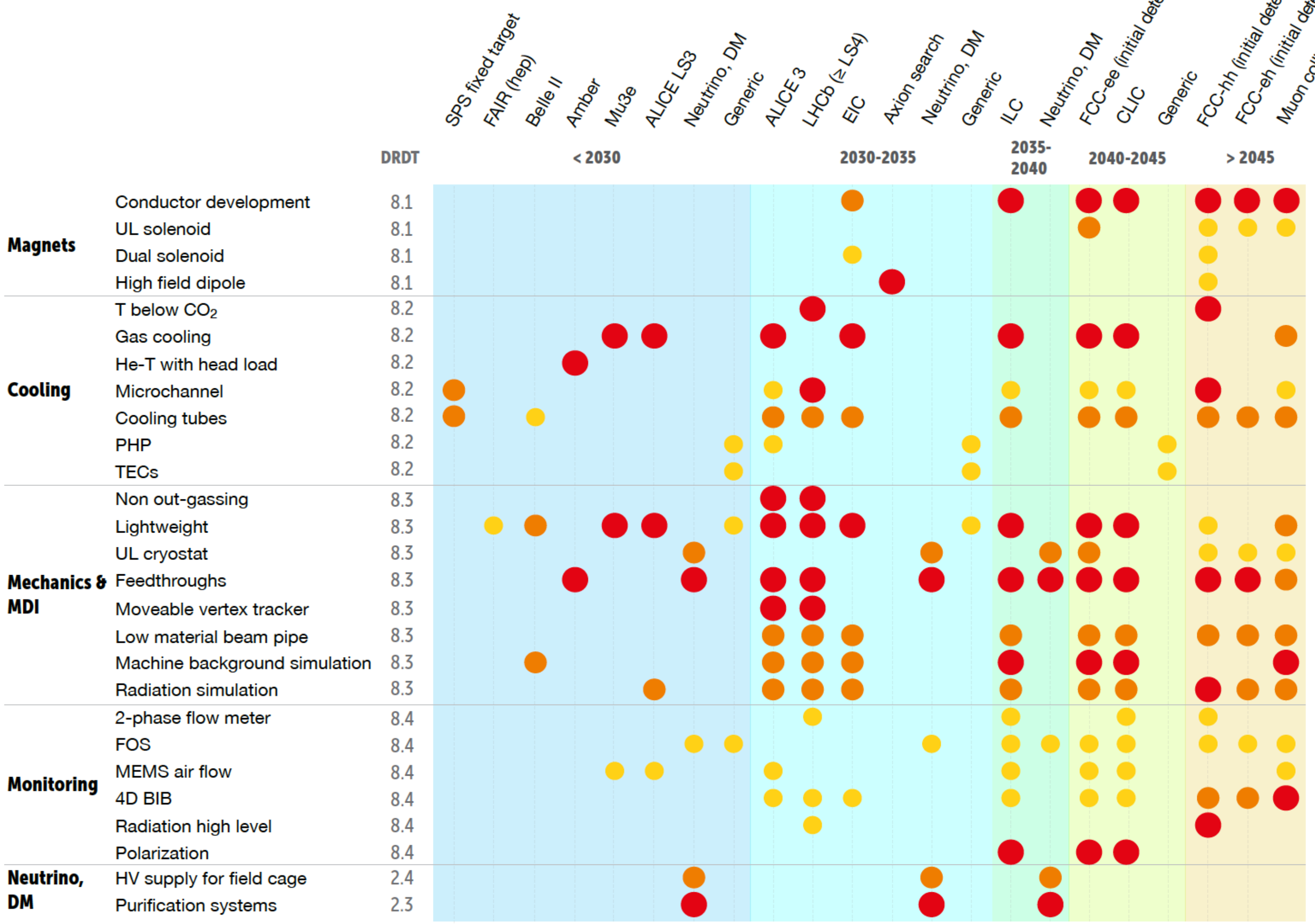
- Photonics data transfer, wireless communication (R&D advancing in WADAPT project)
- New semiconductor materials use in microelectronics industry

ECFA R&D roadmap: Integration

Magnets, cooling, mechanical support and structures, management of radiation environment

Integration

- **DRDT 8.1** Develop novel magnet systems
- **DRDT 8.2** Develop improved technologies and systems for cooling
- **DRDT 8.3** Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces.
- **DRDT 8.4** Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects



		DRDT	< 2030								2030-2035						2035-2040		2040-2045			> 2045		
			SPS fixed target	FAIR (hep)	Belle II	Amber	Mu3e	ALICE LS3	Neutrino, DM	Generic	ALICE 3	LHCb (≥ LS4)	EIC	Axion search	Neutrino, DM	Generic	ILC	Neutrino, DM	FCC-ee (initial detectors)	CLIC	Generic	FCC-hh (initial detectors)	FCC-eh (initial detectors)	Muon collider
Magnets	Conductor development	8.1											🟠				🔴		🔴	🔴		🔴	🔴	🔴
	UL solenoid	8.1																	🟠			🟡	🟡	🟡
	Dual solenoid	8.1											🟡									🟡		
	High field dipole	8.1												🔴								🟡		
Cooling	T below CO_2	8.2										🔴										🔴		
	Gas cooling	8.2					🔴	🔴			🔴		🔴				🔴		🔴	🔴				🟠
	He-T with head load	8.2				🔴																		
	Microchannel	8.2	🟠								🟡	🔴					🟡		🟡	🟡		🔴		🟡
	Cooling tubes	8.2	🟠		🟡						🟠	🟠	🟠				🟠		🟠	🟠		🟠	🟠	🟠
	PHP	8.2								🟡	🟡					🟡					🟡			
	TECs	8.2								🟡						🟡					🟡			
Mechanics & MDI	Non out-gassing	8.3									🔴	🔴												
	Lightweight	8.3		🟡	🟠		🔴	🔴		🟡	🔴	🔴	🔴			🟡	🔴		🔴	🔴		🟡		🟠
	UL cryostat	8.3							🟠						🟠			🟠	🟠			🟡	🟡	🟡
	Feedthroughs	8.3				🔴			🔴		🔴	🔴			🔴		🔴	🔴	🔴	🔴		🔴	🔴	🟠
	Moveable vertex tracker	8.3									🔴	🔴												
	Low material beam pipe	8.3									🟠	🟠	🟠				🟠		🟠	🟠		🟠	🟠	🟠
	Machine background simulation	8.3			🟠						🟠	🟠	🟠				🔴		🔴	🔴				🔴
	Radiation simulation	8.3						🟠			🟠	🟠	🟠				🟠		🟠	🟠		🔴	🟠	🟠
Monitoring	2-phase flow meter	8.4										🟡					🟡			🟡		🟡		
	FOS	8.4							🟡	🟡					🟡		🟡	🟡	🟡	🟡		🟡	🟡	🟡
	MEMS air flow	8.4					🟡	🟡			🟡						🟡		🟡	🟡				🟡
	4D BIB	8.4									🟡	🟡	🟡				🟡		🟡	🟡		🟠	🟠	🔴
	Radiation high level	8.4										🟡										🔴		
	Polarization	8.4															🔴		🔴	🔴				
Neutrino, DM	HV supply for field cage	2.4							🟠						🟠			🟠						
	Purification systems	2.3							🔴						🔴			🔴						

🔴 Must happen or main physics goals cannot be met

🟠 Important to meet several physics goals

🟡 Desirable to enhance physics reach

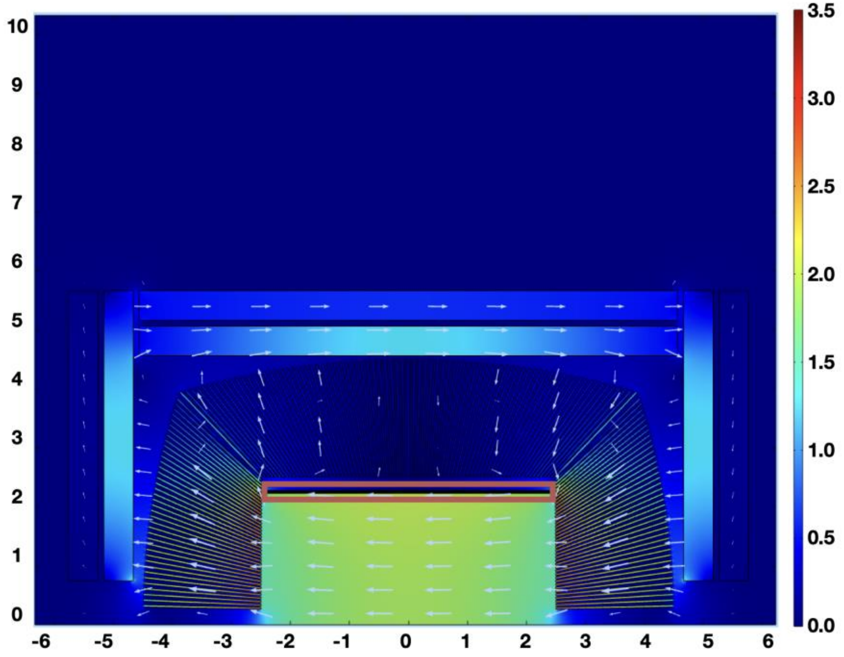
🟢 R&D needs being met

Integration R&D solenoid magnets

2T thin solenoid for outside calorimetry concepts

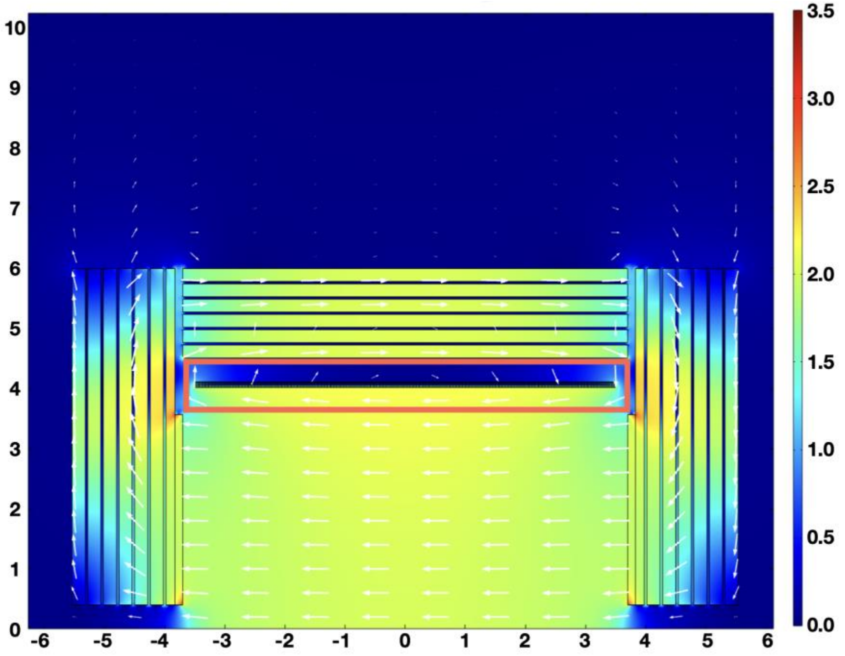
R&D to develop high-strength Al-stabilized NbTi superconducting cable and light vacuum vessel

< 0.5-1X_0 and ≃ 0.1 λ



CMS-like solenoid, calorimetry inside

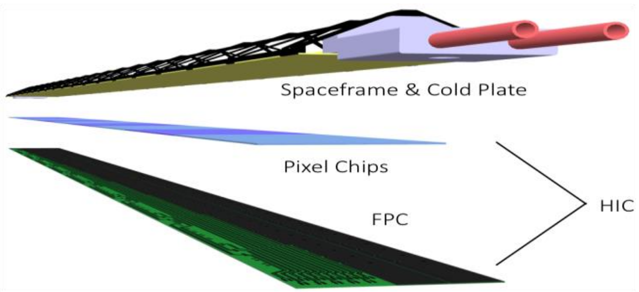
B up to 4T above Z-peak energy



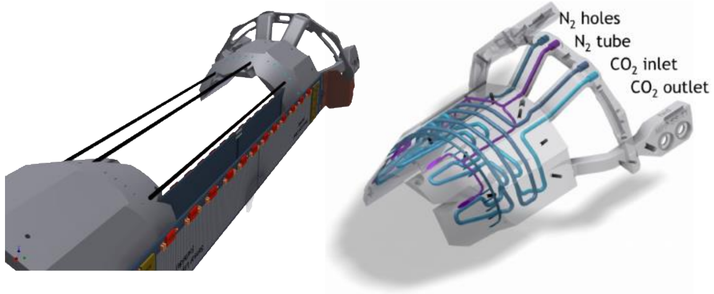
Integration R&D light stable structures

x 10 reduction in X/X_0 in Vertex Detectors

ALICE ITS2 0.36% X_0 /layer
Sensor 15%, PCB 50%
Cooling 20% Support 15%

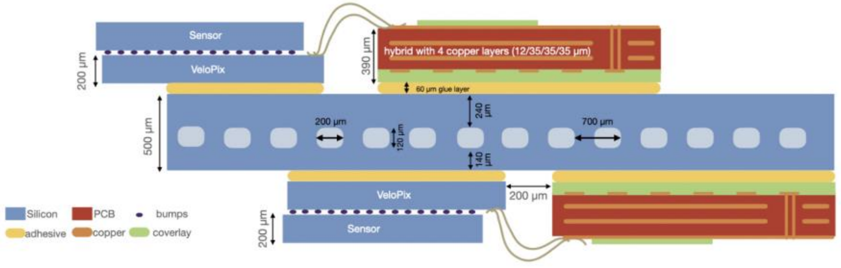


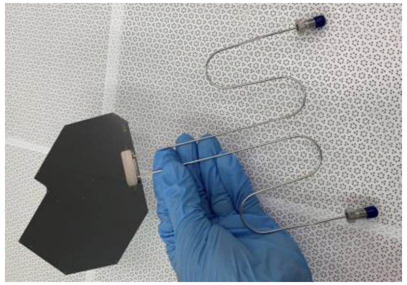
BELLE-II 0.2% X_0 / layer mixed cooling
N_2 with carbon tubes flow and CO_2



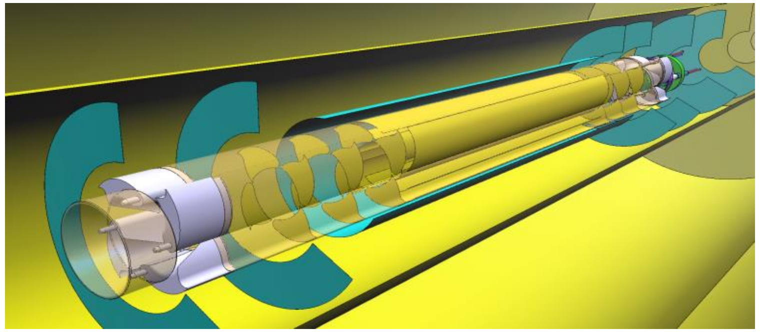
Mu3e average 0.12 % X_0 /layer
He cooling, Sensor 0.064 % X_0,
PCB 0.049 % X_0 Polyimide 0.012 X/X_0

LHCb microchannel cooling embedded in Si-sensors



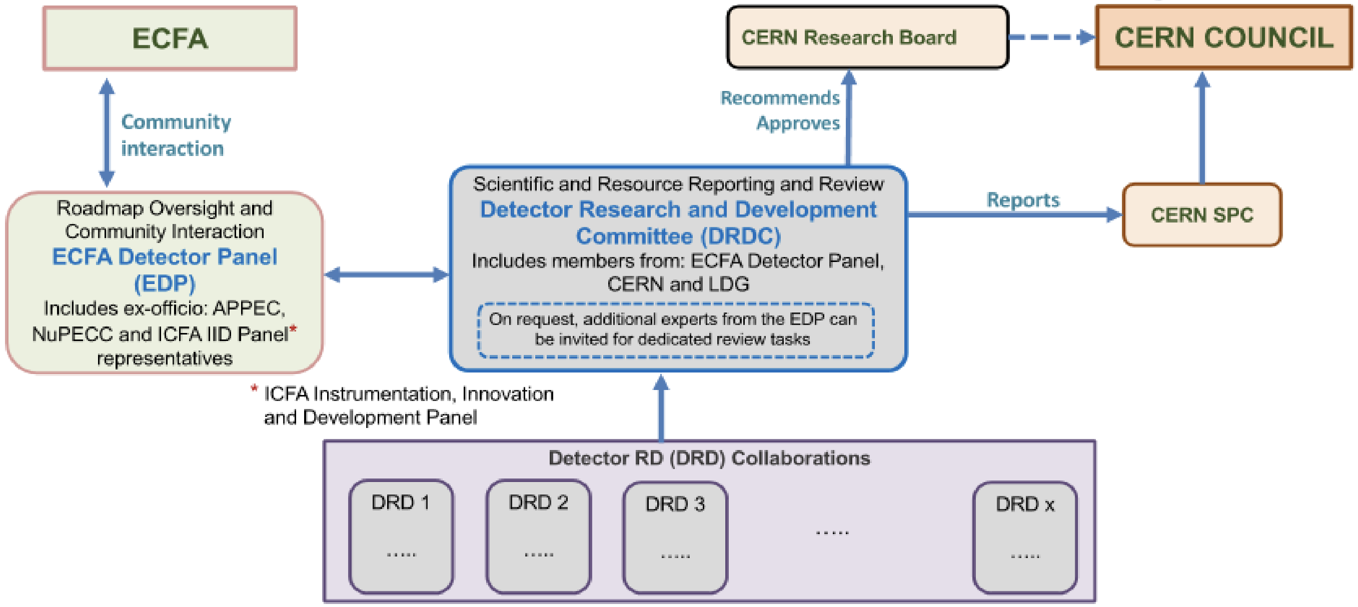


ALICE-3 study retractable layer concept
to approach beam at 5 mm inside Beam Pipe



ECFA R&D roadmap implementation

organize R&D effort in new DRD collaborations (for each areas of the roadmap)
engage Funding Agencies through MoUs and a dedicated Resources Review Board



DRD proposal prepared for reviewing by DRDC by July 2023 community consultation process https://indico.cern.ch/event/957057/page/27294-implementation-of-the-ecfa-detector-rd-roadmap

New collaborations start to be active beginning of 2024

Funding Agencies sign MoUs in 2024

A propitious time to join instrumentation efforts
in the new DRD collaborations