INFN
Istituto Nazionale di Fisica Nucleare

From Requirements to Construction: R&D for Detectors at Future Colliders

Lorenzo Sestini
INFN-Firenze

"Physics At The Highest Energies With Colliders" GGI Conference - 31/7/2025

Introduction

- **Physics at the highest energy with colliders: it will will be possibile if adequate detectors will exists**

- An intense R&D activity for **cutting-edge detector technologies** is necessary in the next year to match our ambitious plans

- This R&D is mainly driven by physics goals, but also collider conditions (backgrounds, radiation etc.) poses important challenges

- **In this talk you have a broad overview of the detector R&D, and how the work is organized in Europe through the DRD collaborations**

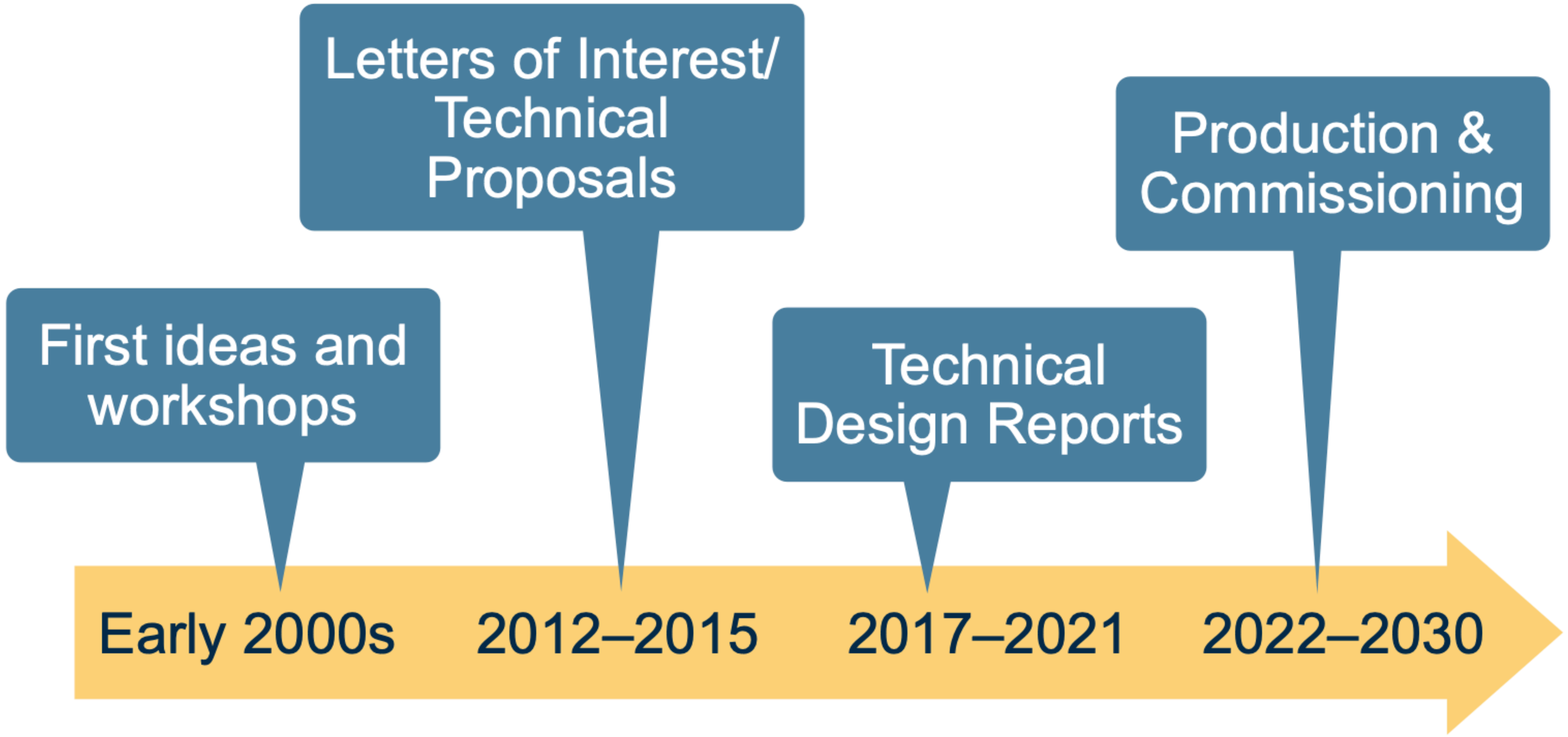
- The material is mainly taken by the talks presented at the Open Symposium on the European Strategy for Particle Physics in Venice

Timeline: from R&D to large detector

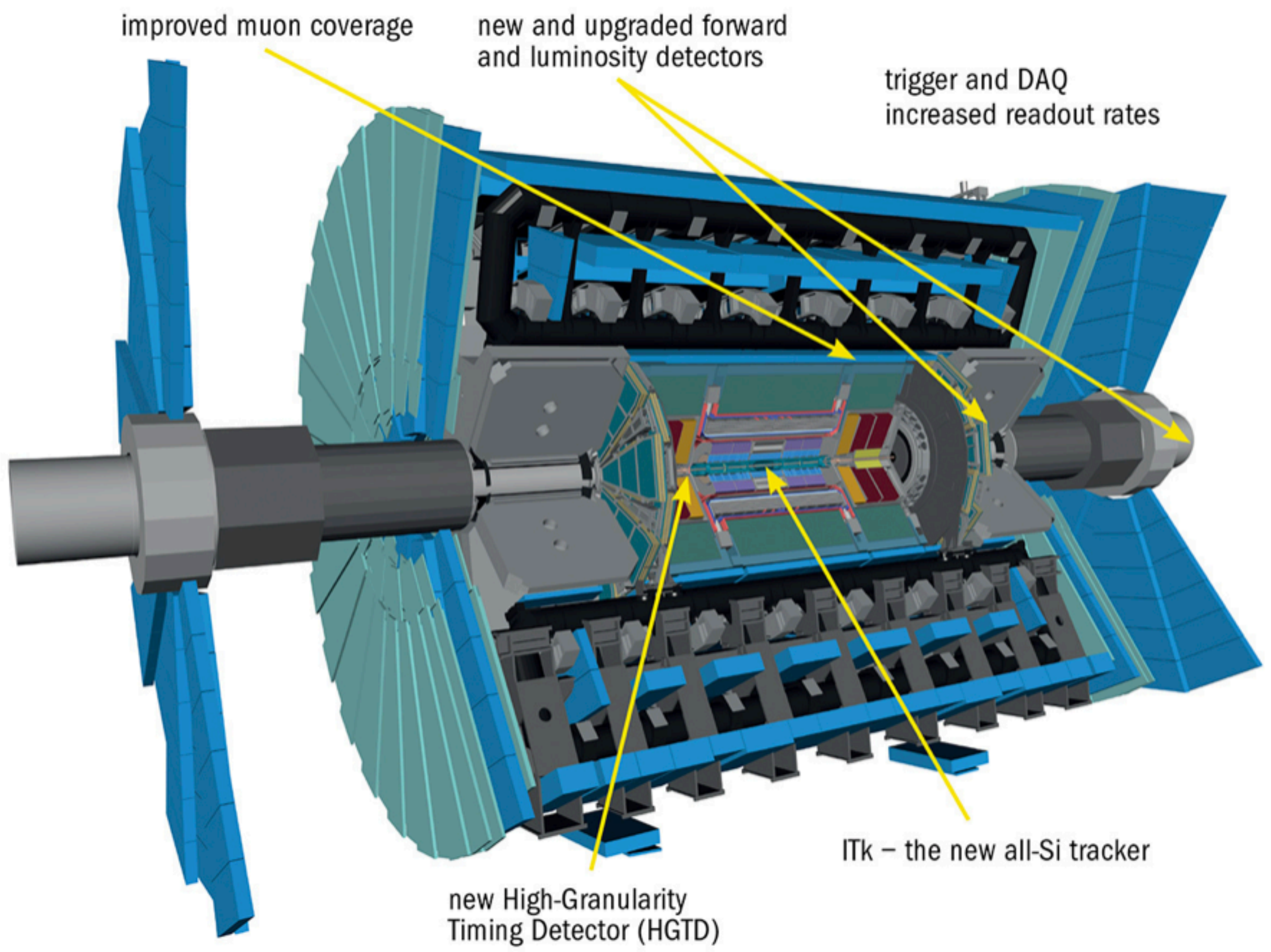
Typical Development Cycles: 20–30 Years

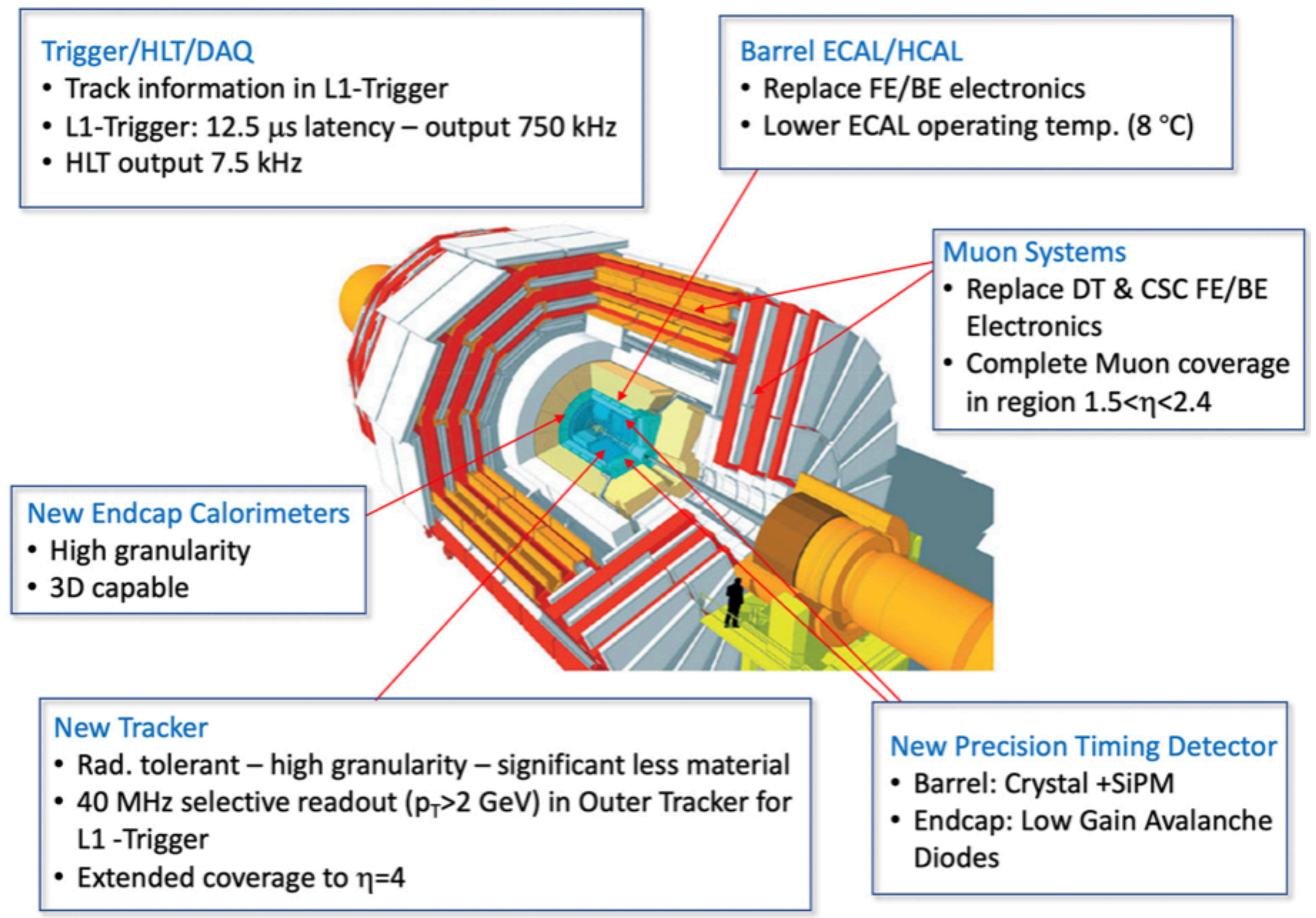
Example: Phase-2 upgrades of the ATLAS and CMS detectors for the high-luminosity phase of the LHC

U. Husemann, Open Symposium of the ESPP



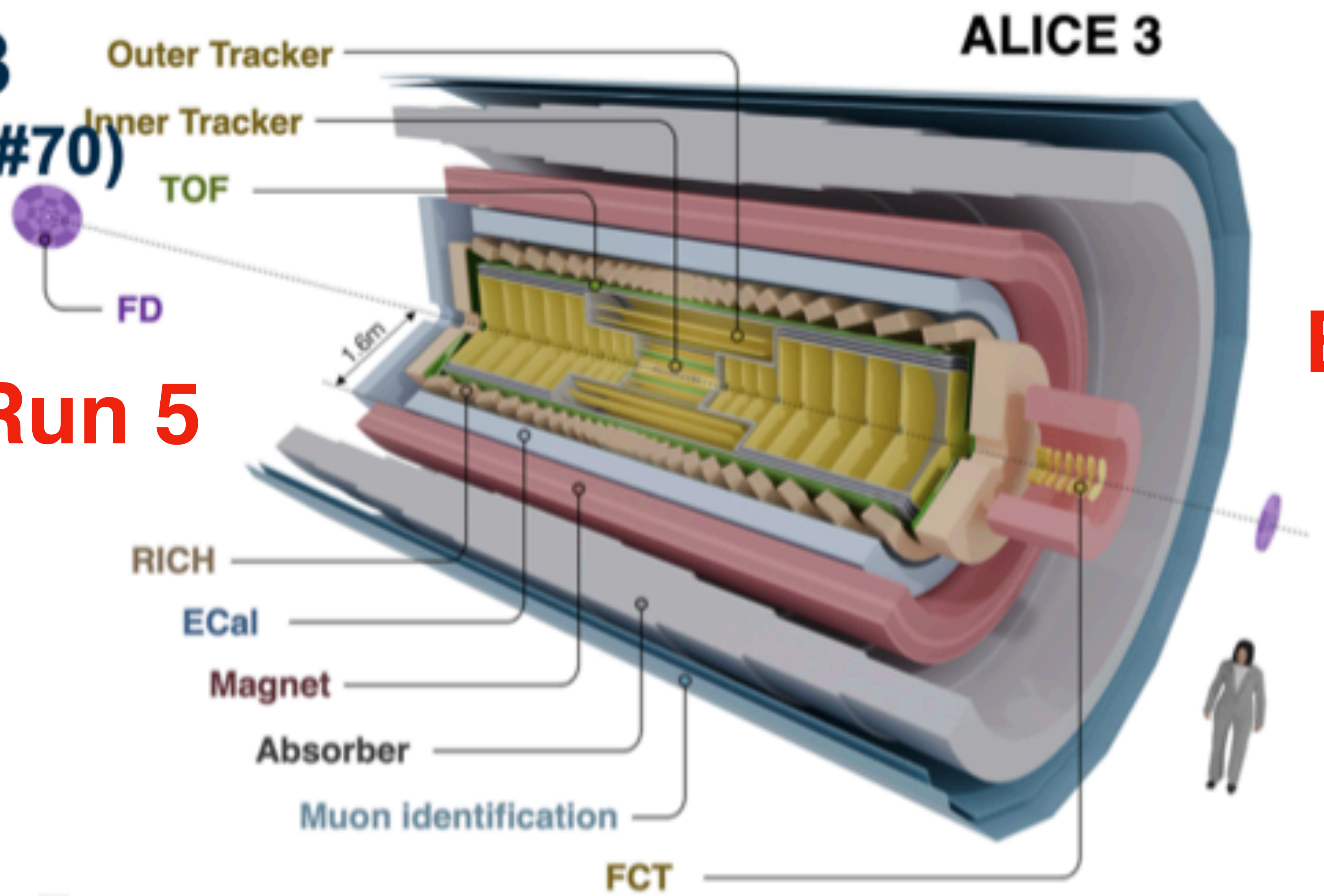
Smaller-scale experiments: *shorter* development cycles





Next generation detectors

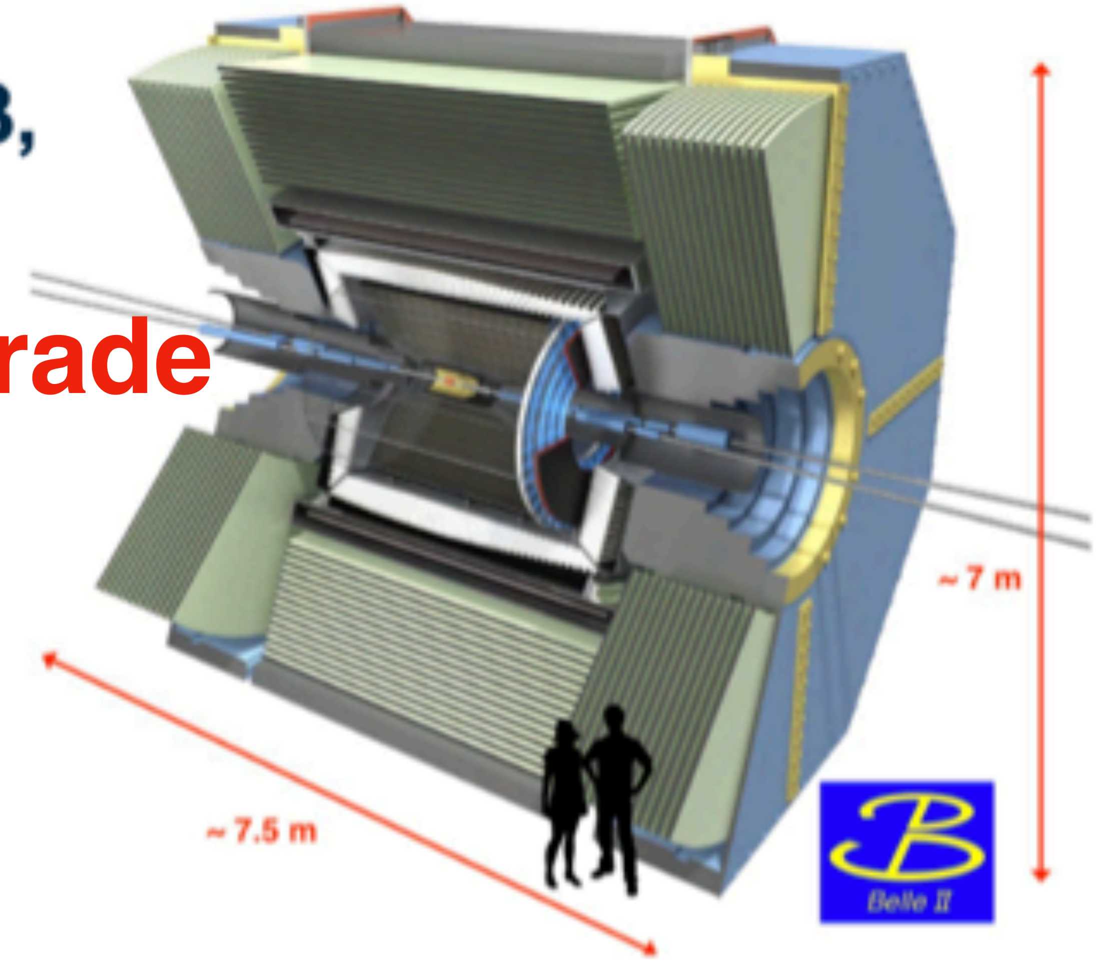
ALICE 3
(HL-LHC, #70)



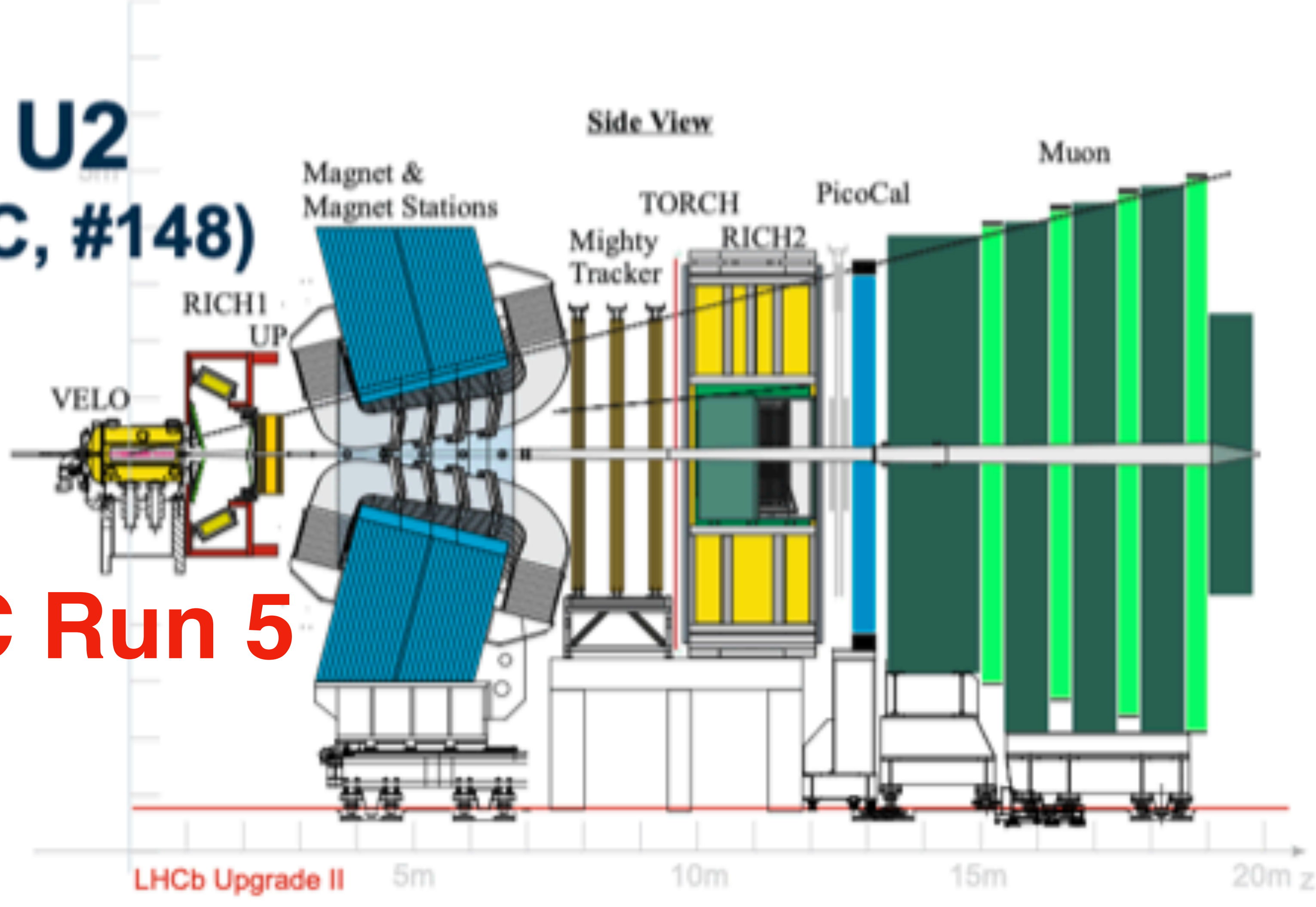
HL-LHC Run 5

Belle II
(SuperKEKB, #205)

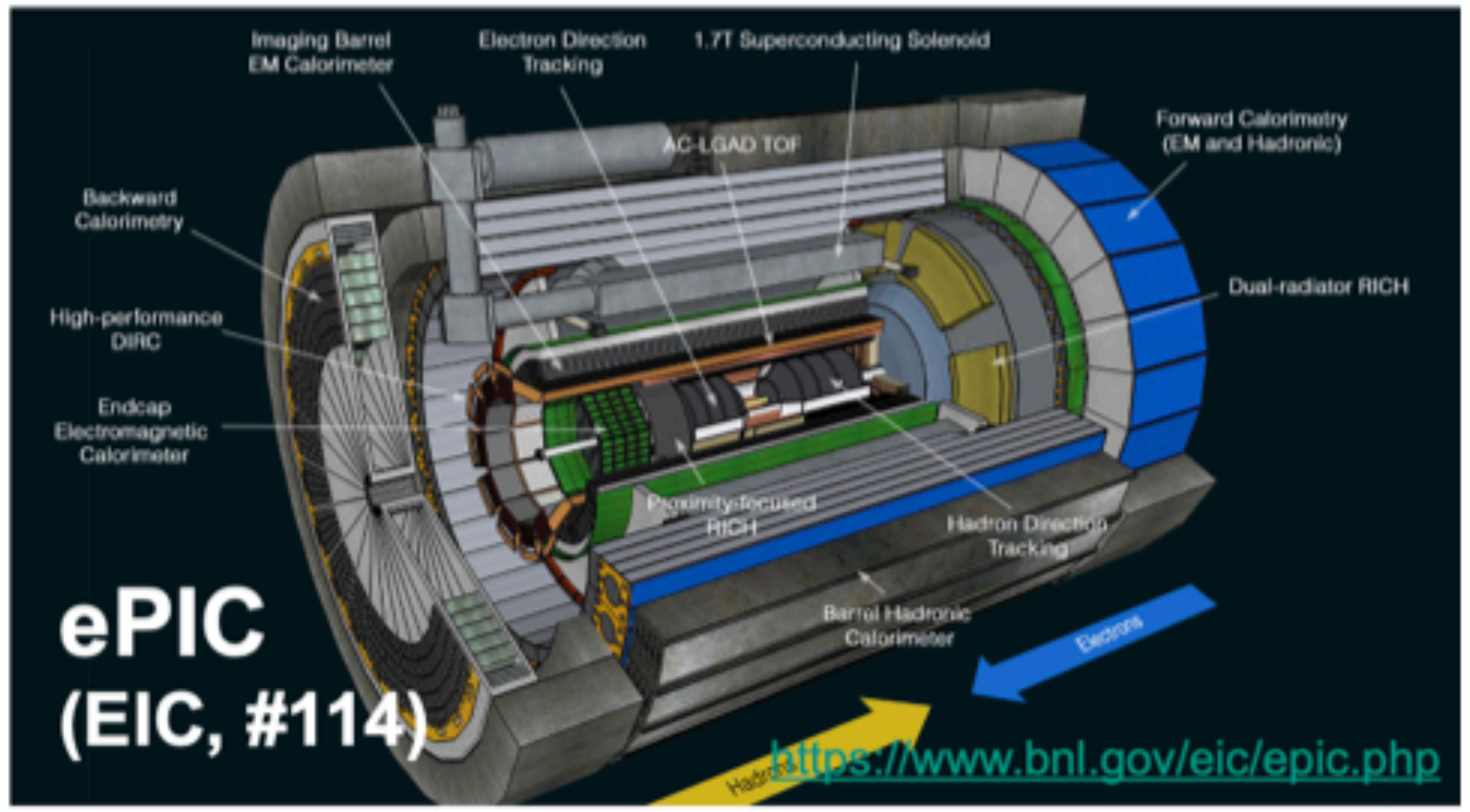
Belle 2 upgrade



LHCb U2
(HL-LHC, #148)



HL-LHC Run 5



U. Husemann: Computing and Instrumentation

Higgs/EW/Top factory detectors

INFN
Istituto Nazionale di Fisica Nucleare

IDEA detector (FCCee)

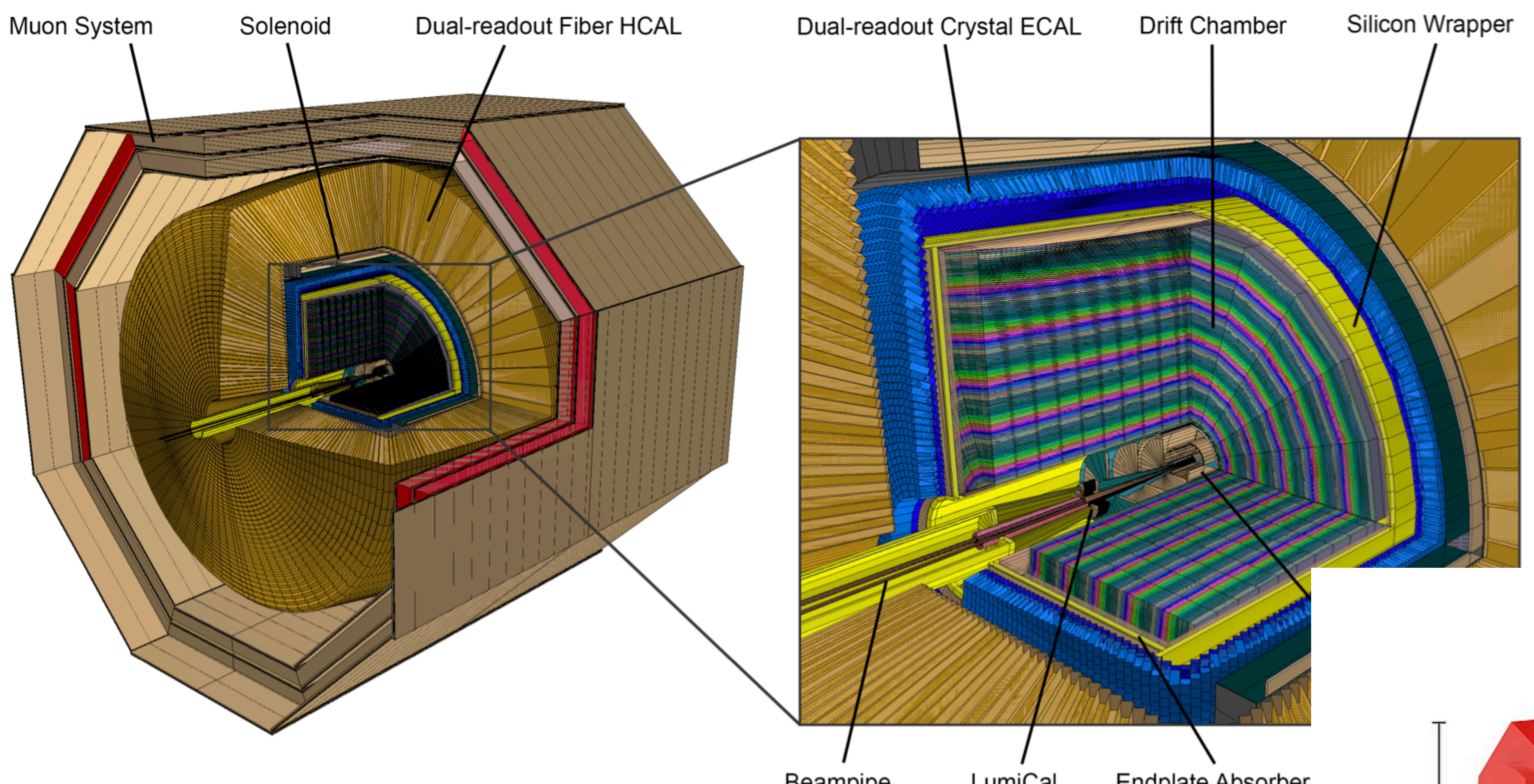
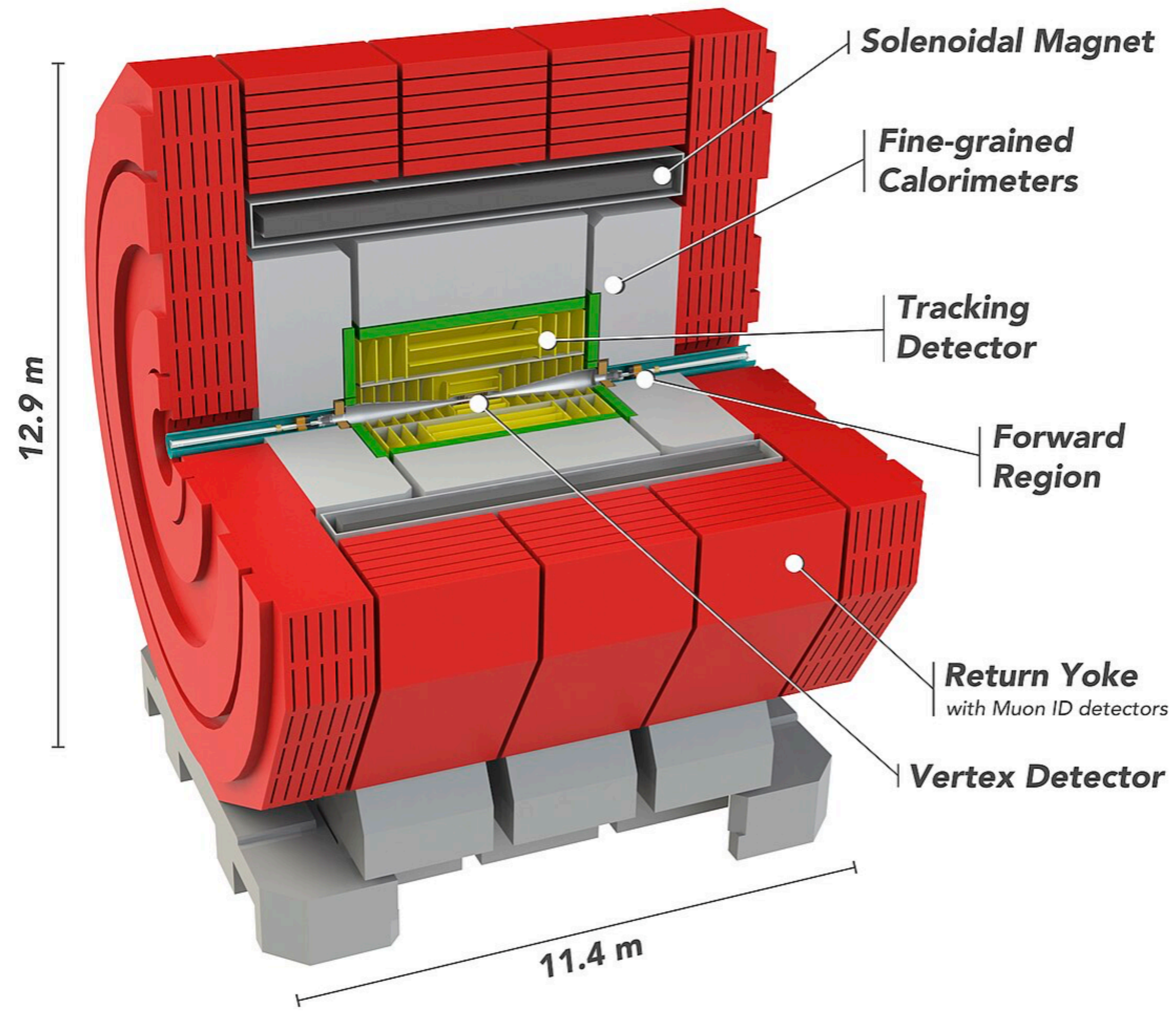


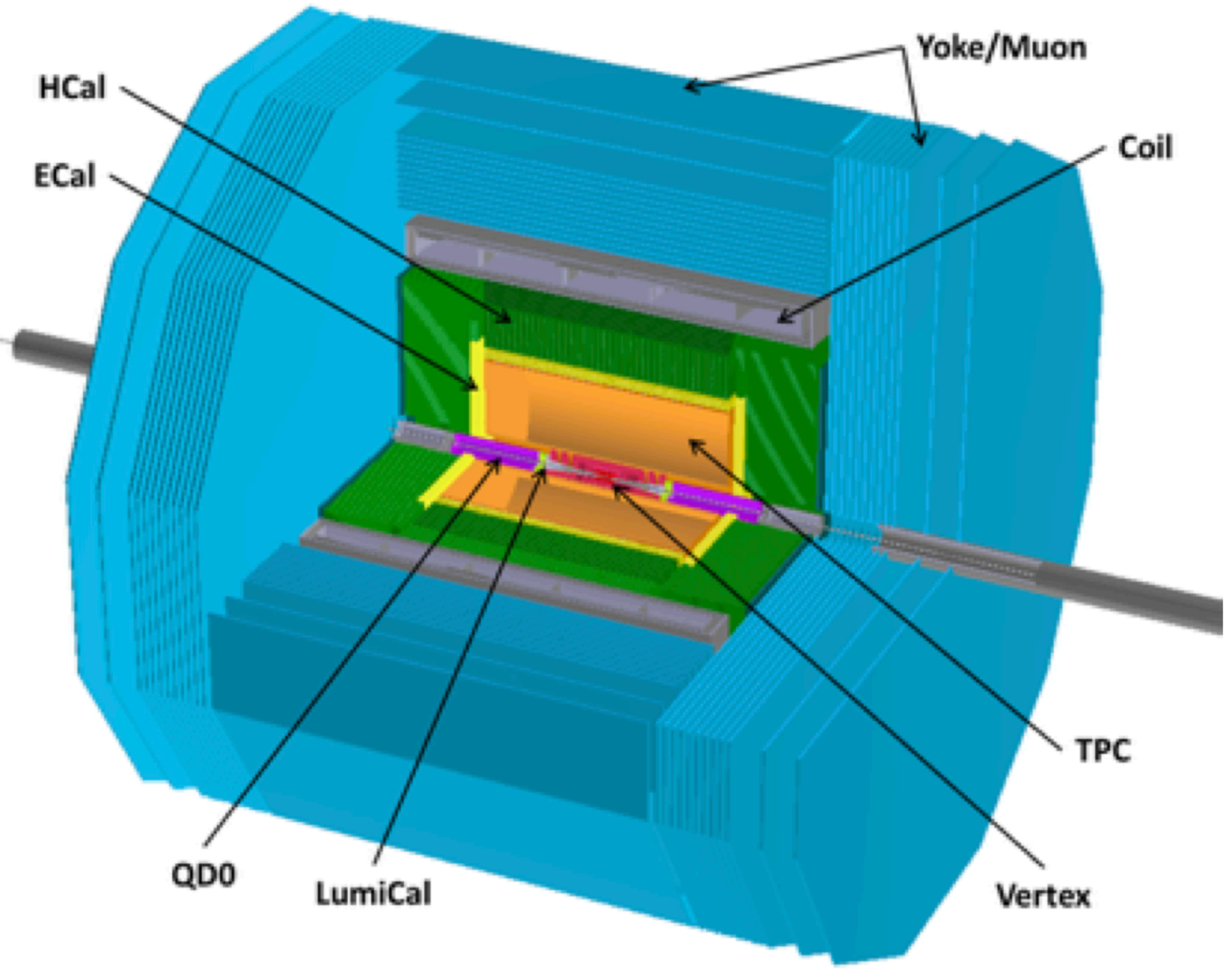
Figure 1: 3D cutout view of the IDEA baseline detector design wit labels.

Expected by the late 2040s or in the 2050s

With the 20-30 years cycle the time for R&D is now!

CLIC detector





CEPC detector

Just few examples of detectors proposed for ee colliders

Beyond ee colliders

INFN
Istituto Nazionale di Fisica Nucleare

Muon Collider detector

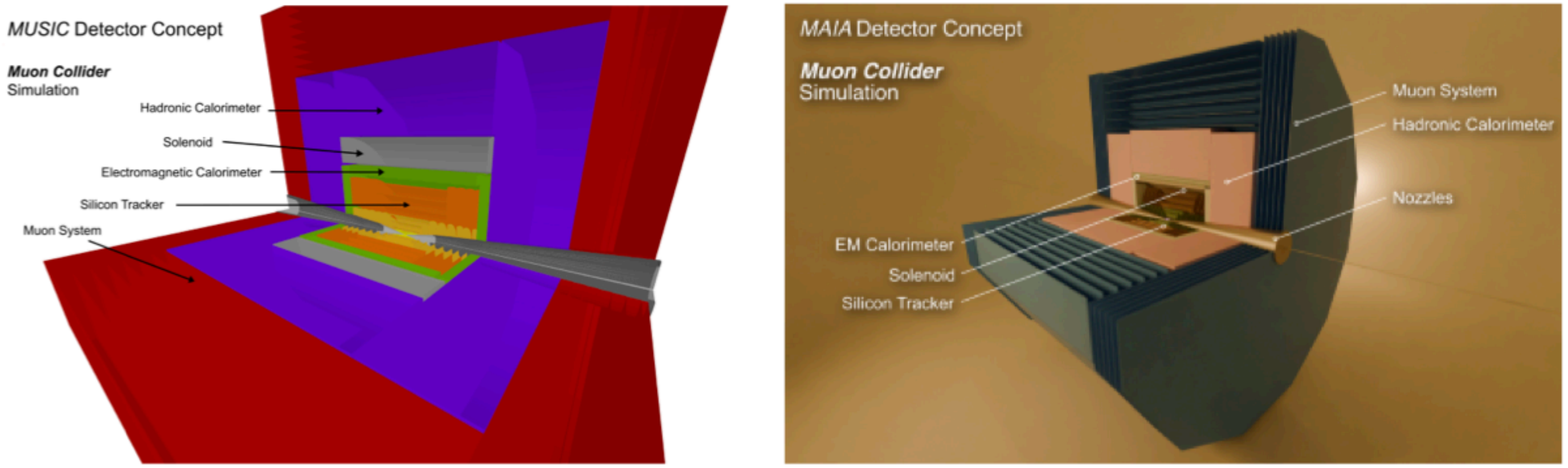
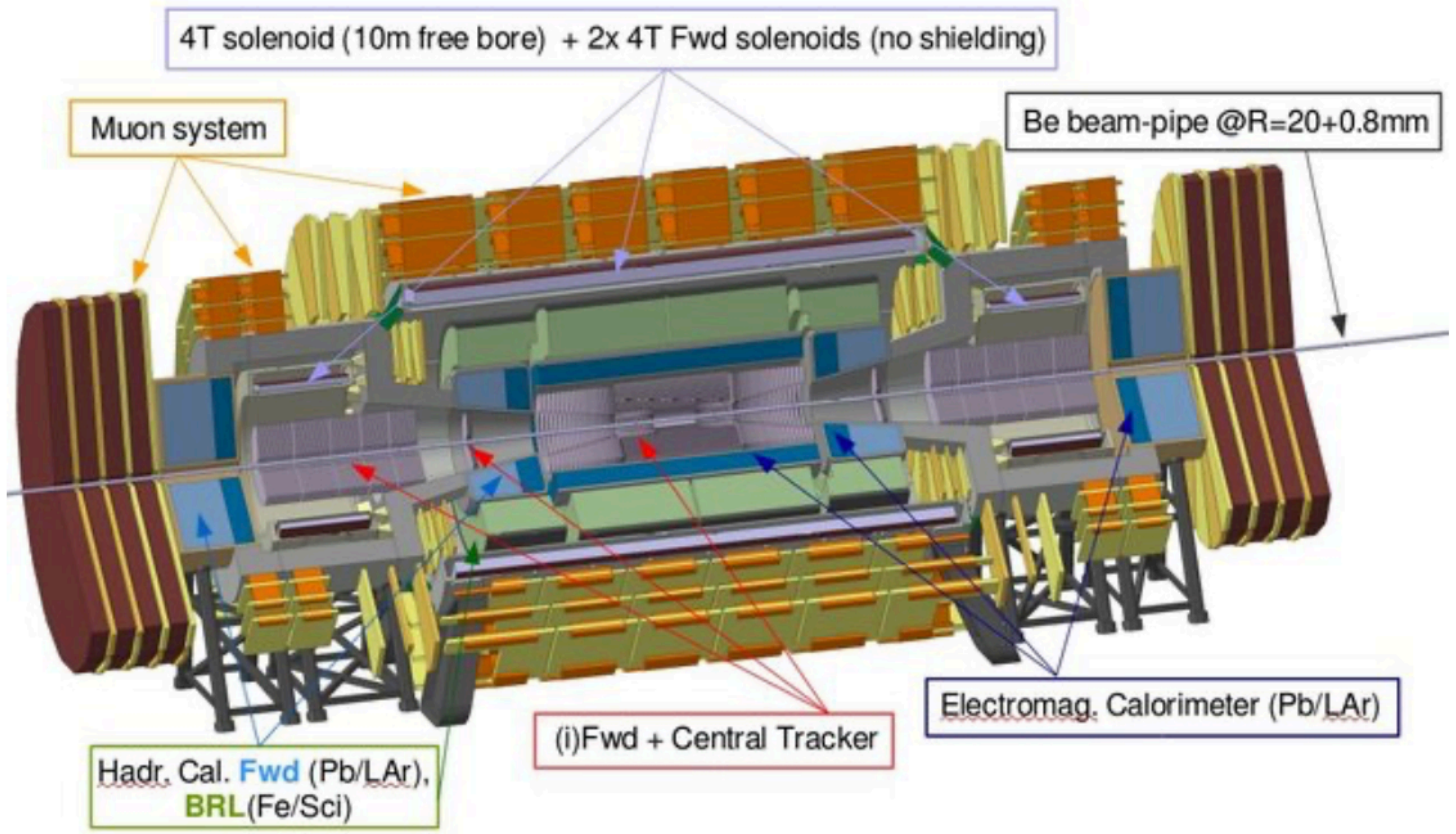


Figure 1.3.1: Layout of the MUSIC (left) and MAIA (right) detector concepts

With technically limited timeline proposed by the International Muon Collider Collaborations, a Muon Collider is expected in the 2050s

FCChh detector



Optimistically the FCChh could be expected in the 2070s.

A very complex detector is necessary

We have much time to work on these, but the first ideas/concepts should be developed in the next years!

Requirements

U. Husemann, Open Symposium of the ESPP

Physics Program	Instrumentation Challenges
Higgs Factory	Outstanding **momentum/impact parameter** resolution **W/Z/H boson separation** in multijet events Hadron **identification**
Precision Electroweak & QCD Physics	Outstanding absolute and relative **luminosity** accuracy Bias-free **tracking** with outstanding **angular resolution**
Heavy Flavor Physics	Excellent **impact parameter** and **secondary vertex** resolution Excellent **ECAL energy** resolution **Particle ID:** π^0/γ and π/K separation
Physics of Feebly Interacting Particles	Excellent sensitivity to **detached vertices** (up to meters) **Hermetic** detectors Precision **timing**

Detector requirements are driven by

- **physics goals**
- **backgrounds (e.g. beam-induced backgrounds)**
- **Radiation**

FCCee detector concepts

INFN Istituto Nazionale di Fisica Nucleare

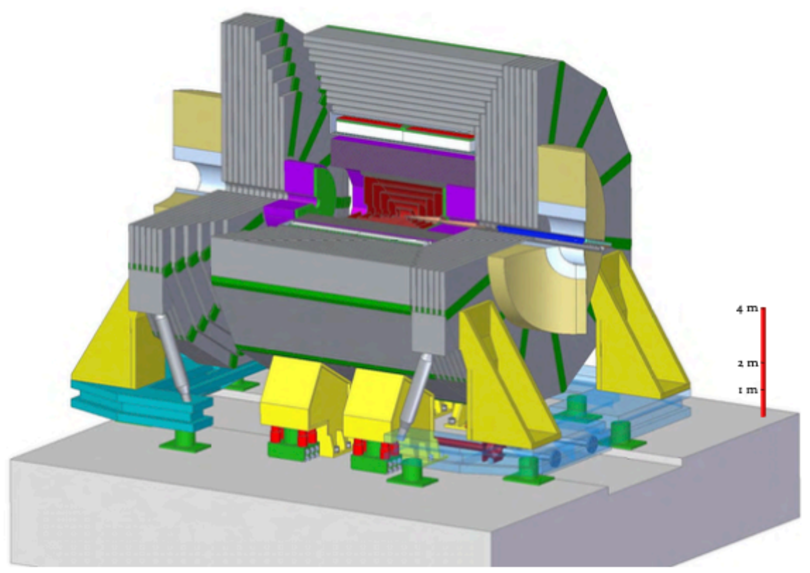
U. Husemann, Open Symposium of the ESPP

Concept	*#94* SiD	*#102* ILD'*	*in #95* CLD*	*#211* IDEA	*in #95* ALLEGRO
Vertexing	Silicon MAPS	Silicon MAPS	Silicon MAPS	Silicon MAPS	Silicon MAPS
Tracking/ PID	Silicon Strips	Time Projection Ch.	Silicon, RICH option	Gaseous	Gaseous, Silicon+ RICH
Calorimetry	Silicon/ Scintillator	Silicon/ Scintillator, Gaseous	Silicon	Dual Readout	Noble Liquids
Muon System	Scintillator	Scintillator	Gaseous	Gaseous	Gaseous
Magnet	5 T	3.5 T	2 T	2 T	2 T

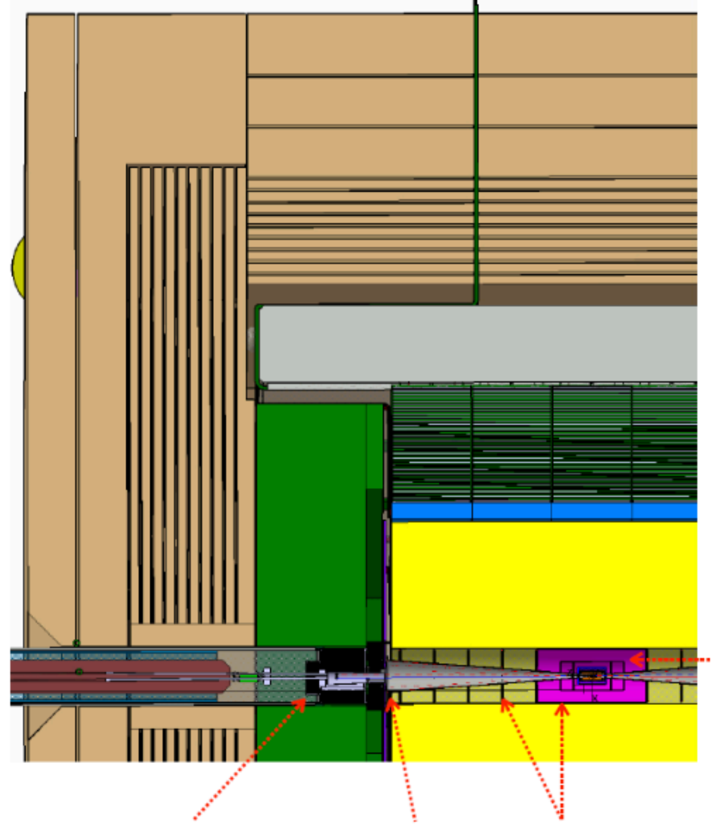
*evolutions from detector concepts for CLIC (#78) and ILC

→ **guide R&D**, maintain **freedom to combine** technologies later

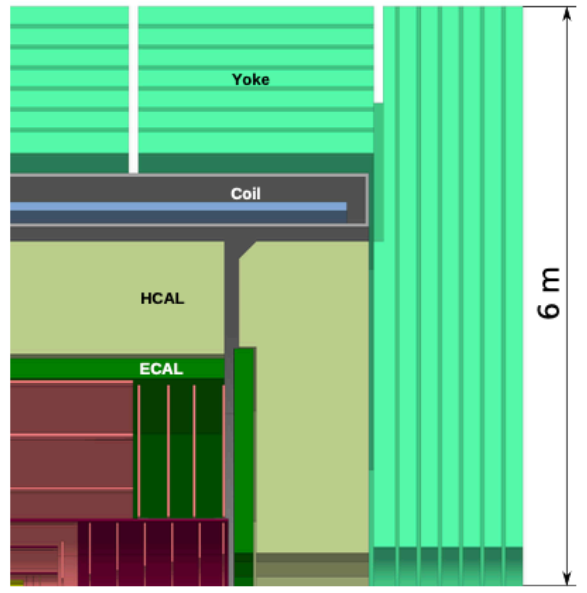
SiD



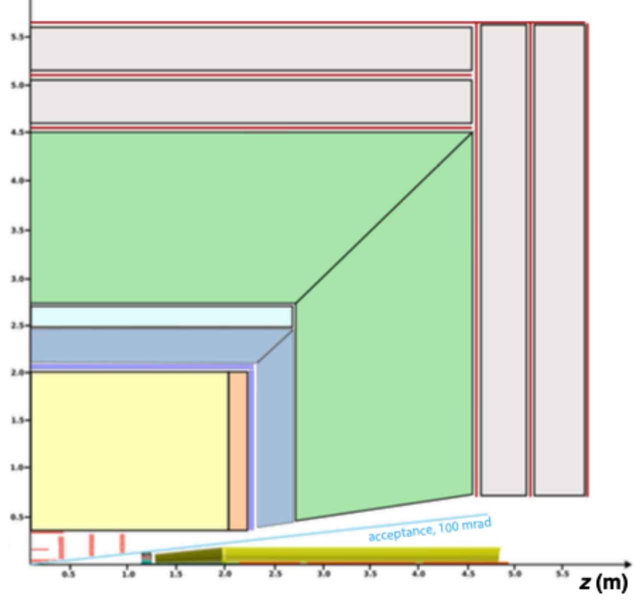
ILD



CLD



IDEA



ALLEGRO

European Strategy KIT

Requirements: MuC and FCChh

INFN
Istituto Nazionale di Fisica Nucleare

Muon Collider detector requirements

Table 1.3.1: Preliminary summary of the "baseline" and "aspirational" targets for selected key metrics for a 10 TeV muon collider.

Requirement	**Baseline**	**Aspirational**
Angular acceptance $\eta = -\log(\tan(\theta/2))$	$\|\eta\| < 2.5$	$\|\eta\| < 4$
Minimum tracking distance [cm]	~ 3	< 3
Forward muons ($\eta > 5$)	tag	$\sigma_p/p \sim 10\%$
Track σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	1×10^{-5}
Photon energy resolution	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
Neutral hadron energy resolution	$0.4/\sqrt{E}$	$0.2/\sqrt{E}$
Timing resolution (tracker) [ps]	$\sim 30 - 60$	$\sim 10 - 30$
Timing resolution (calorimeters) [ps]	100	10
Timing resolution (muon system) [ps]	~ 50 for $\|\eta\| > 2.5$	< 50 for $\|\eta\| > 2.5$
Flavour tagging	b vs c	b vs c, s-tagging
Boosted hadronic resonance identification	h vs W/Z	W vs Z

Muon collider physics requirements

- Performance in the middle between HL-LHC and ee colliders
- Also radiation levels are similar to HL-LHC
- Sinergy with HL-LHC and FCCee detector R&D

Comparison between hadron colliders

Table 7.1: Key numbers relating the detector challenges at the different accelerators.

Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
Total number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm, est.(FLUKA)	GHz cm^{-2}	0.1	0.7	2.7	8.4 (10)
1 MeV-neq fluence at 2.5 cm, est.(FLUKA)	10^{16} cm^{-2}	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm, est.(FLUKA)	MGy	1.3	13	54	270 (300)
$dE/d\eta\|_{\eta=5}$ [331]	GeV	316	316	427	765
$dP/d\eta\|_{\eta=5}$	kW	0.04	0.2	1.0	4.0
90% $b\bar{b}$ $p_T^b > 30$ GeV/c [332]	$\|\eta\|<$	3	3	3.3	4.5
VBF jet peak [332]	$\|\eta\|$	3.4	3.4	3.7	4.4
90% VBF jets [332]	$\|\eta\|<$	4.5	4.5	5.0	6.0
90% $H \to 4l$ [332]	$\|\eta\|<$	3.8	3.8	4.1	4.8

- The FCChh will have to deal with a flux of particles 10 times more than HL-LHC
- Ionizing dose >20 times higher than HL-LHC
- These extreme conditions will require groundbreaking technologies that does not exists now

Which are today the general R&D directions for each sub-system?

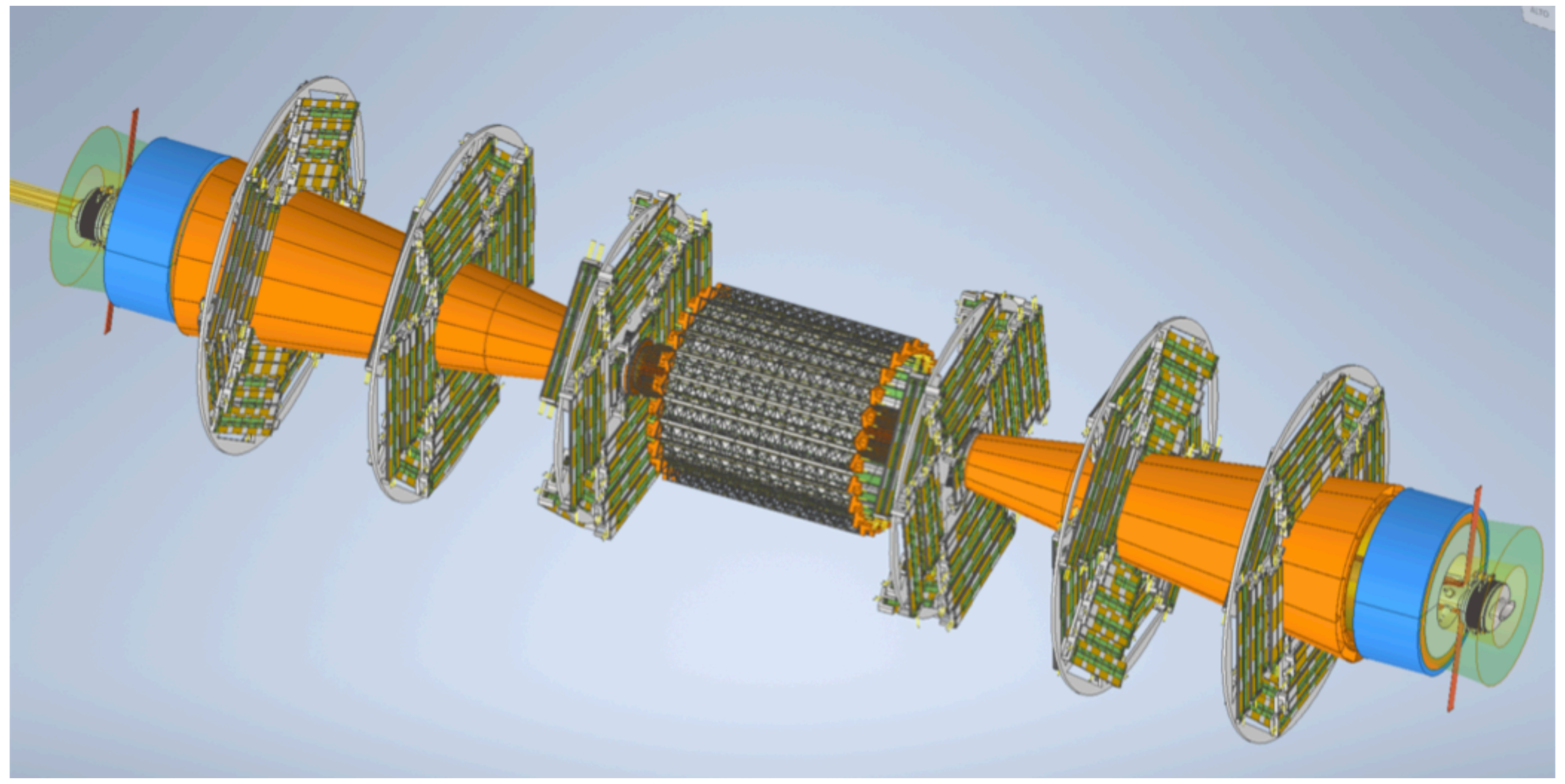
From U. Husemann talk, Open Symposium of the ESPP

Vertexing

U. Husemann, Open Symposium of the ESPP

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

Vertex detector of the IDEA detector



Key technology: MAPS – monolithic active pixel sensors

- Integration of sensitive elements and logic on a **single chip**
- Leveraging industry **standard CMOS** processes, modified for particle physics

Tracking and Muon Detection

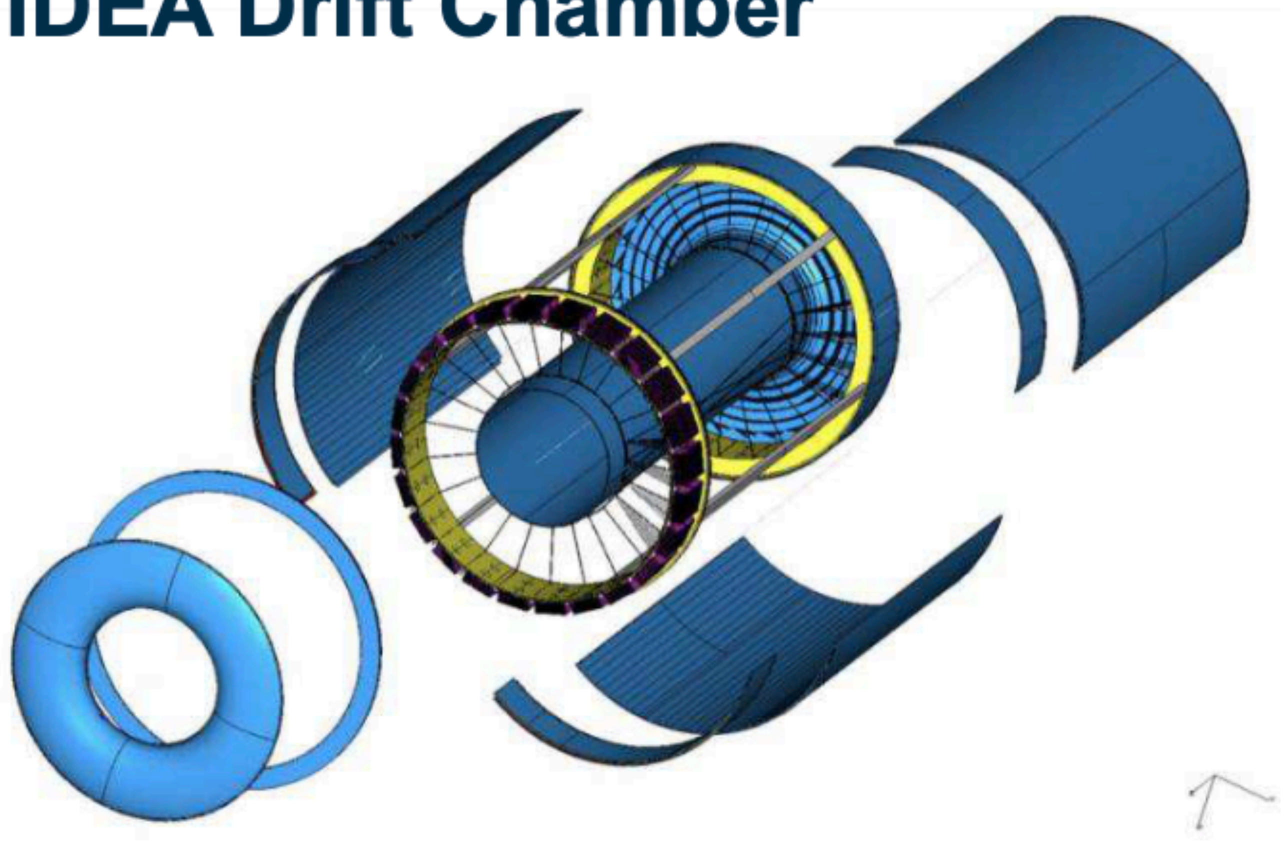
Key requirements

- **Resolution** (momentum: 0.1% at 45 GeV, time)
- **Particle identification** (dE/dx or dN/dx in gaseous detectors: π/K separation up to 100 GeV; muon ID)
- **New: 4D tracking** (3D position: $< 30\ \mu$m, time: < 30 ps)

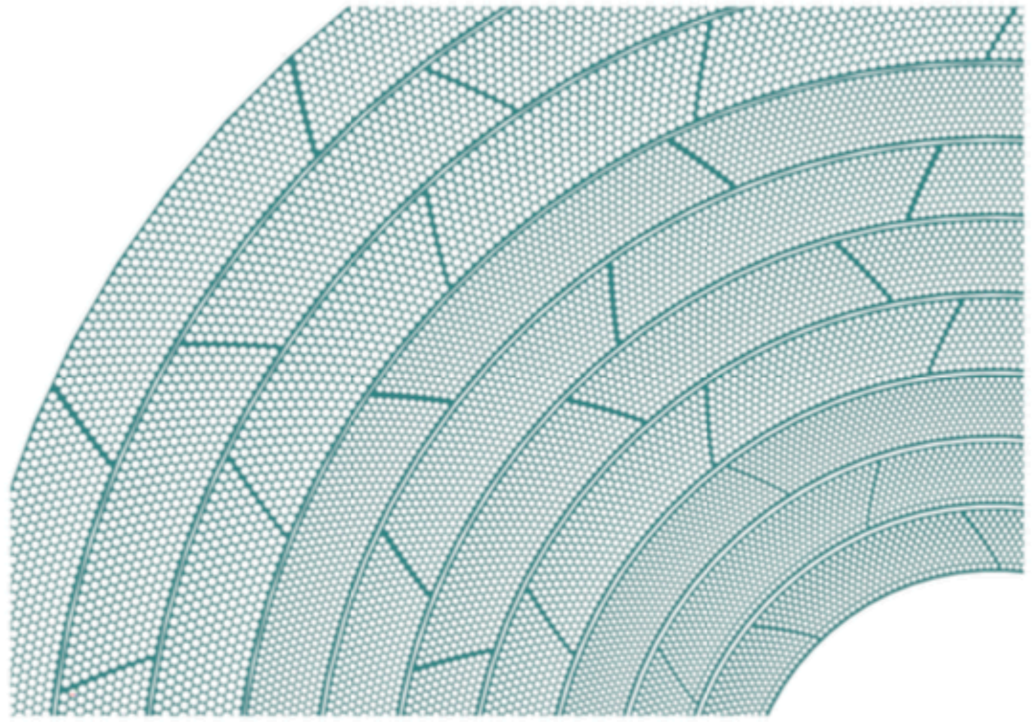
Key technologies

- **Gaseous** detectors:
  parallel plates, wire chambers, micro-pattern detectors, drift chambers, time projection chambers
- **Silicon** detectors:
  hybrid and monolithic pixels, ultrafast timing, strips
  (FCC-ee: gaseous tracker enclosed with silicon "wrapper")
- **Scintillating (fiber)** detectors

IDEA Drift Chamber



FCC-ee Straw Tracker



Calorimeters

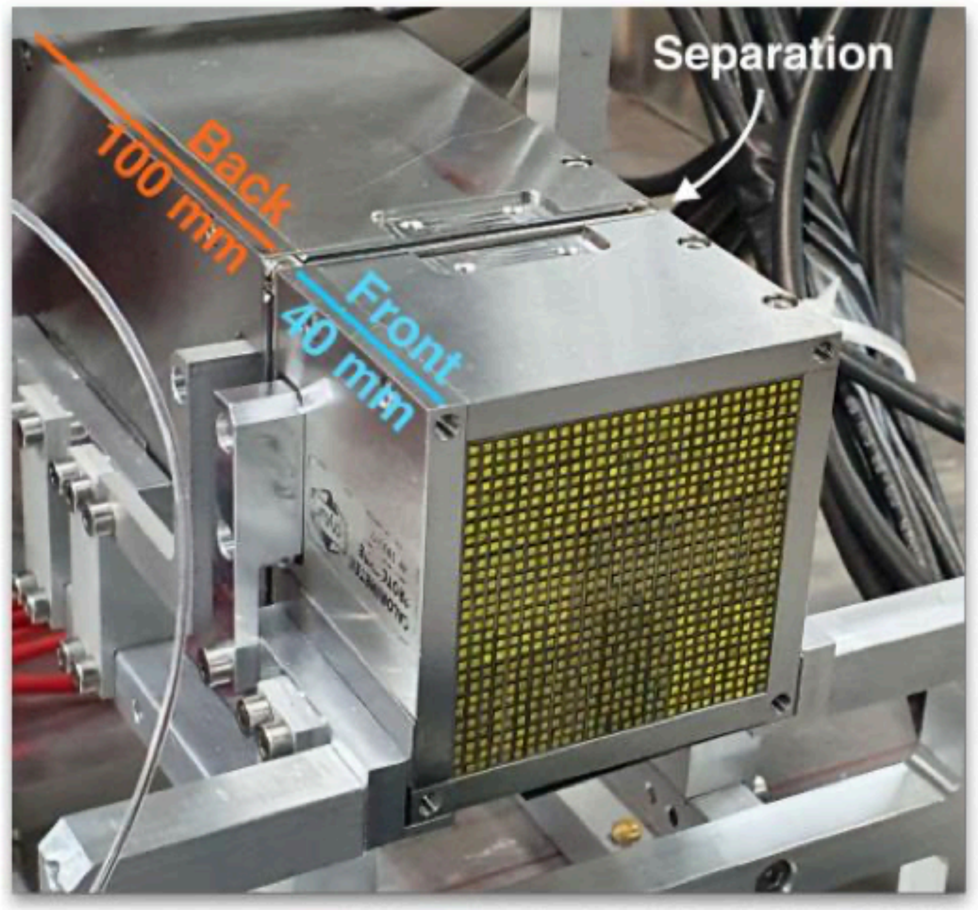
Key requirements:

- **Energy resolution (3-4% at 100 GeV)** and compensation of different response to electrons and hadrons
- Suited for modern algorithms: **particle flow, machine learning**
- New: **5D calorimetry** (energy, 3D position, time)

Key technologies:

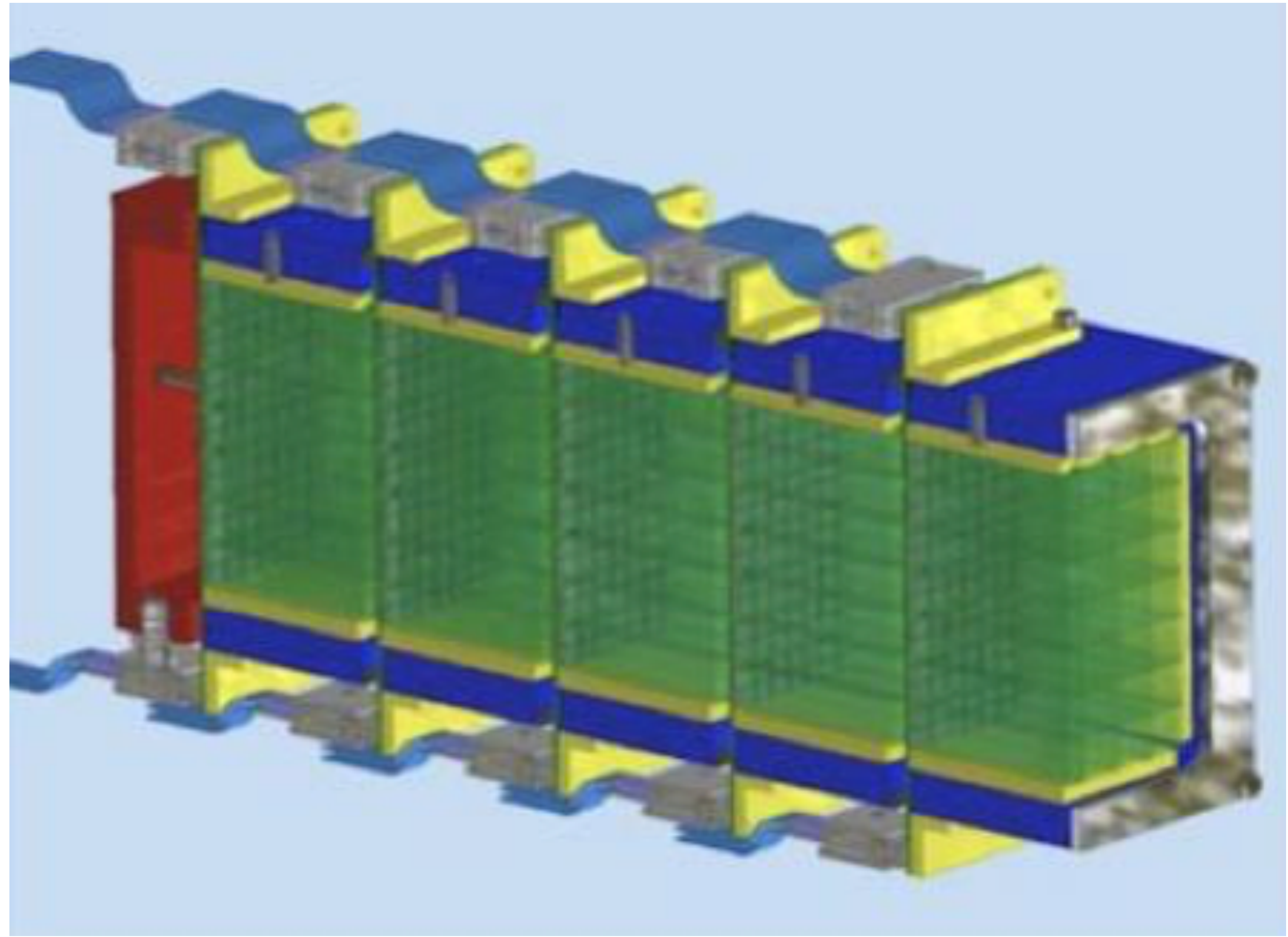
- Main types: sandwich, optical (crystal, fiber), noble liquids
- High granularity imaging calorimeters high lateral and longitudinal segmentation
- Dual-readout calorimeters: scintillation and Cherenkov effects
- Optical calorimeters: efficient photon detectors

SPACAL (LHCb U2)



NIM A 1045, 167629 (2022)

CRILIN (MUSIC, Muon Collider)



Photon detection and particle ID

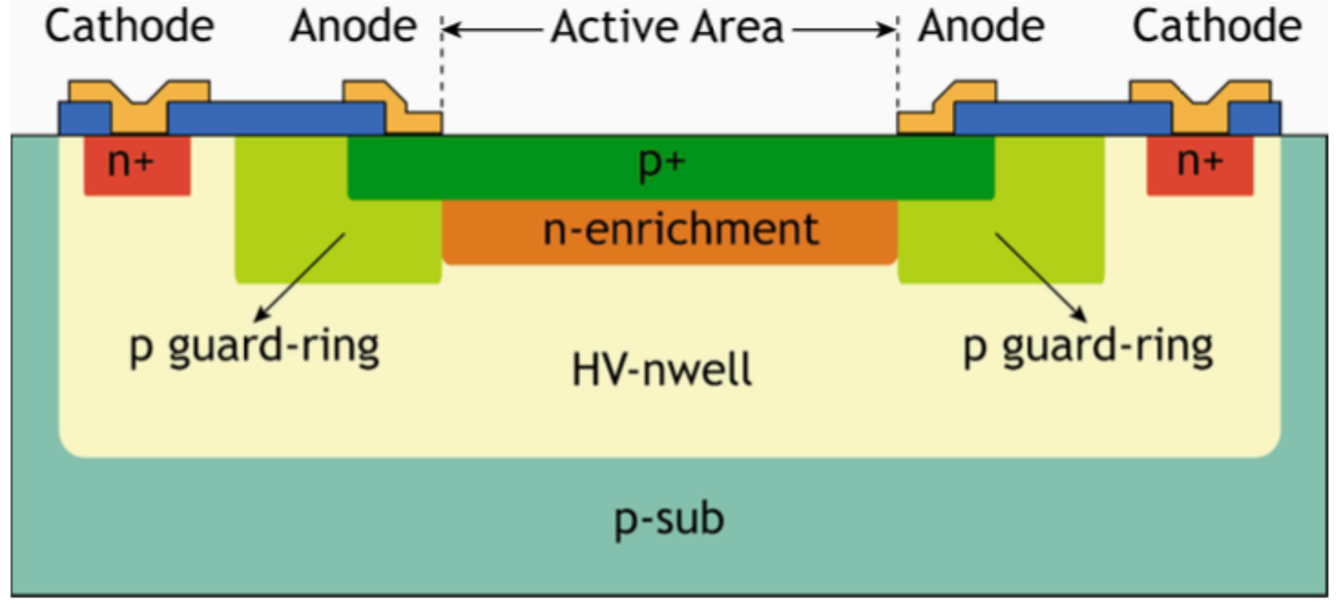
Photon detection:

- **Key requirements:** high quantum efficiency, single-photon detection, high speed, low dark rate, radiation hardness, temperature-stabilized and/or cryogenic environment
- **Key technologies:** **silicon photomultipliers** (SiPMs), **traditional PMTs** (including microchannel plates, MCPs)

Particle identification (PID): dedicated detectors

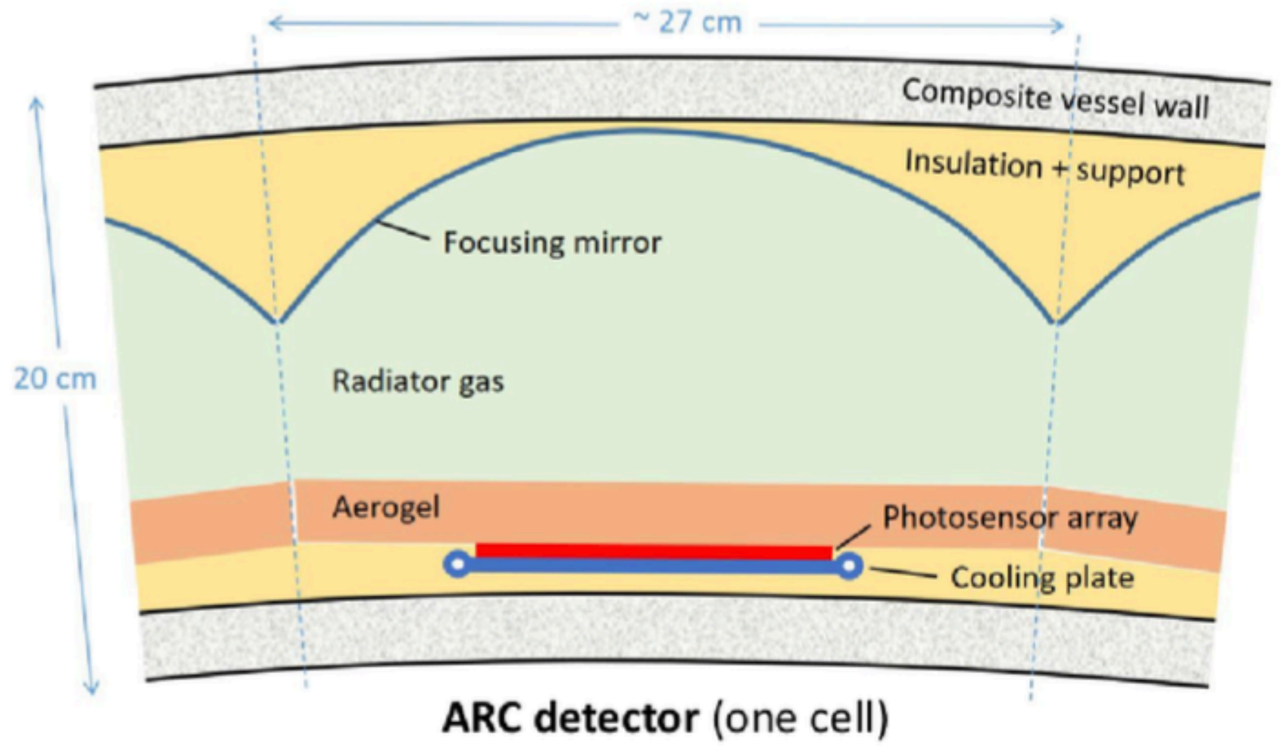
- **Key requirements: pion/photon and hadron separation over various relevant momentum ranges**
- **Key technologies:** **ring-imaging Cherenkov** (RICH) counters and **time-of-flight** (TOF) detectors, e.g. using ultrafast silicon detectors (e.g. low-gain avalanche detectors, LGADs)

CMOS Single Photon Avalanche Diode (SPAD)



Fraunhofer IMS

ARC: Array of RICH Cells



https://doi.org/10.17181/6enti-pmm10

Trigger and data acquisition

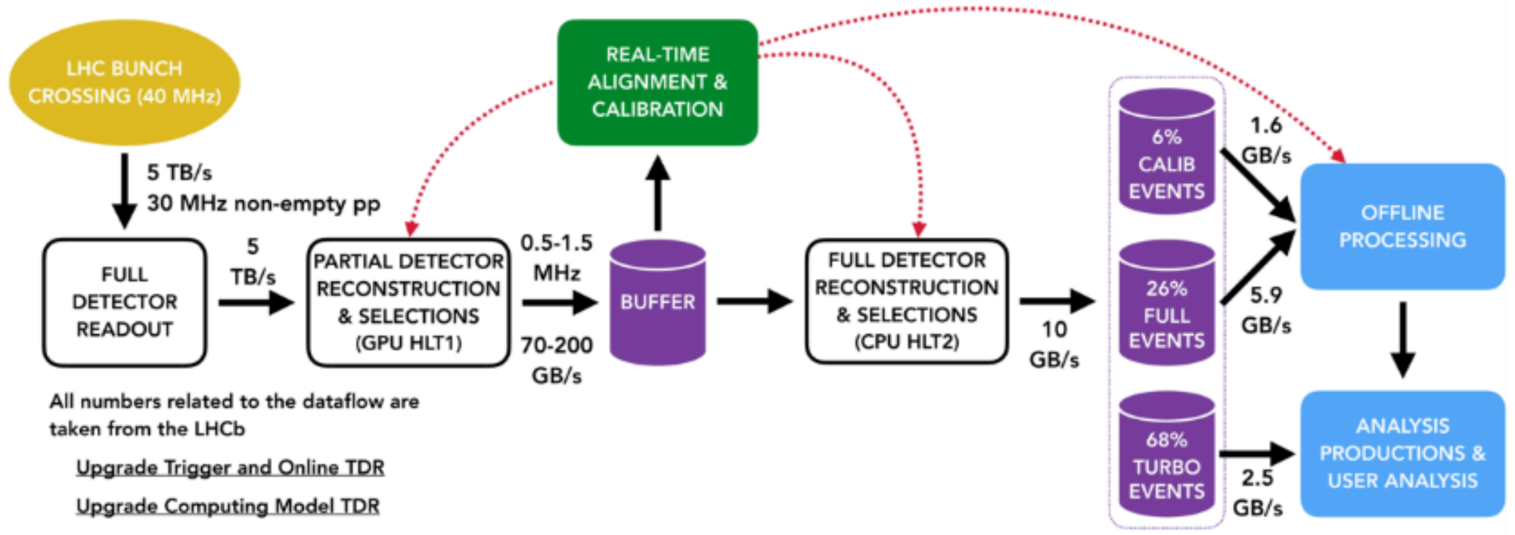
Requirements:

- High-rate electrical/optical data transmission, photonics
- Traditional approach: triggered readout
- **New trend: triggerless/streaming readout with (ML-enabled) "intelligent" backend processing**
- Heterogeneous trigger farms: **CPU/GPU/FPGA**

Challenges:

- maintain versatile heterogeneous frameworks (no vendor lock-in)
- avoid bottlenecks between ASIC and DAQ

LHCb Run 3 Trigger System



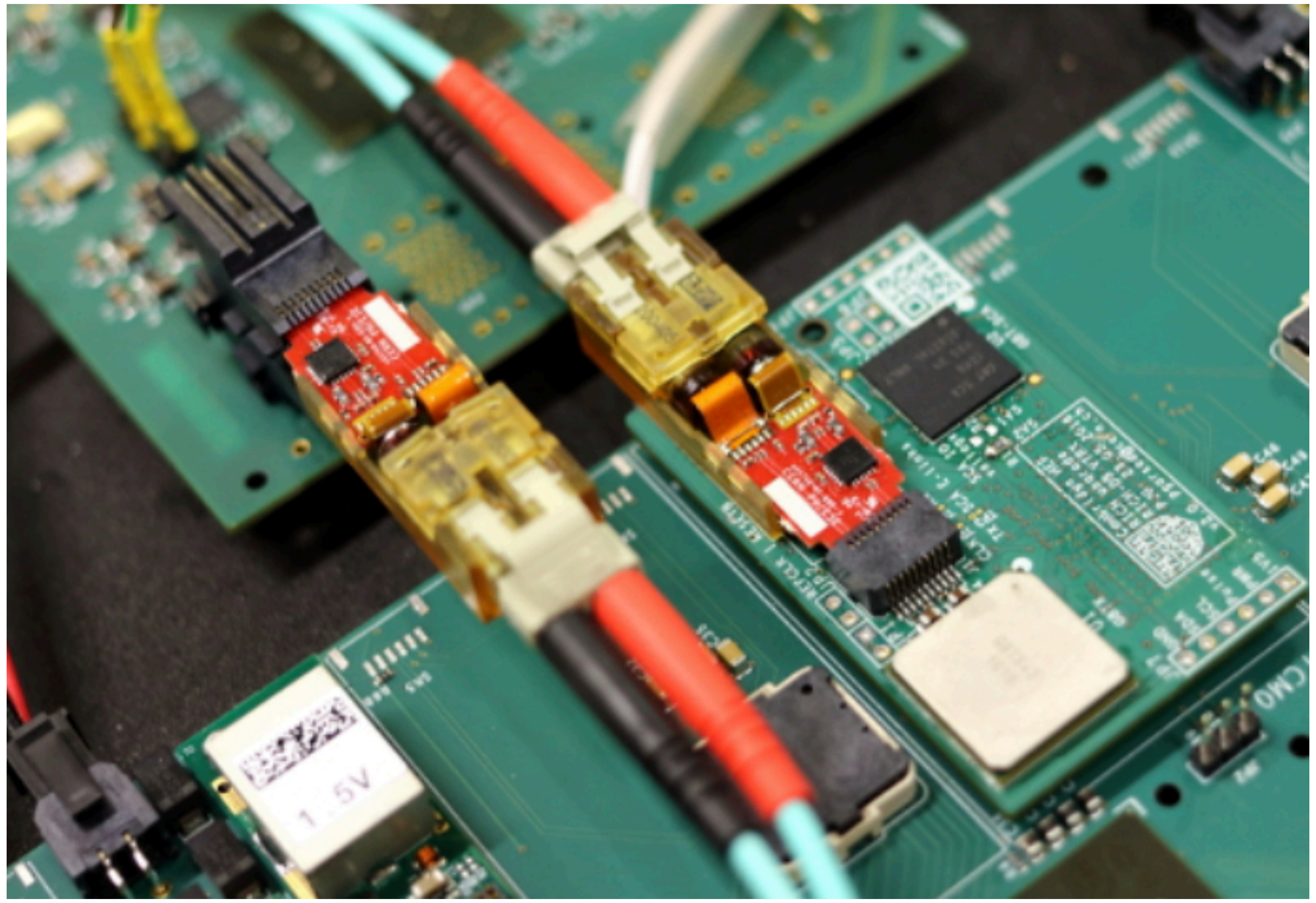
LHCb Starter Kit

LHCb trigger farm

Electronics

Requirements:

- **Dedicated chips (ASICs) and programmable logic (FPGAs)** at the detector frontend and in the "counting room"
- New development: **"intelligent" frontends smart pixels**, embedded FPGAs
- Low-noise, cryogenic, superconducting electronics (e.g. SQUIDs, parametric amplifiers, ...) ▪
- Packaging, interconnects, system integration



Challenges:

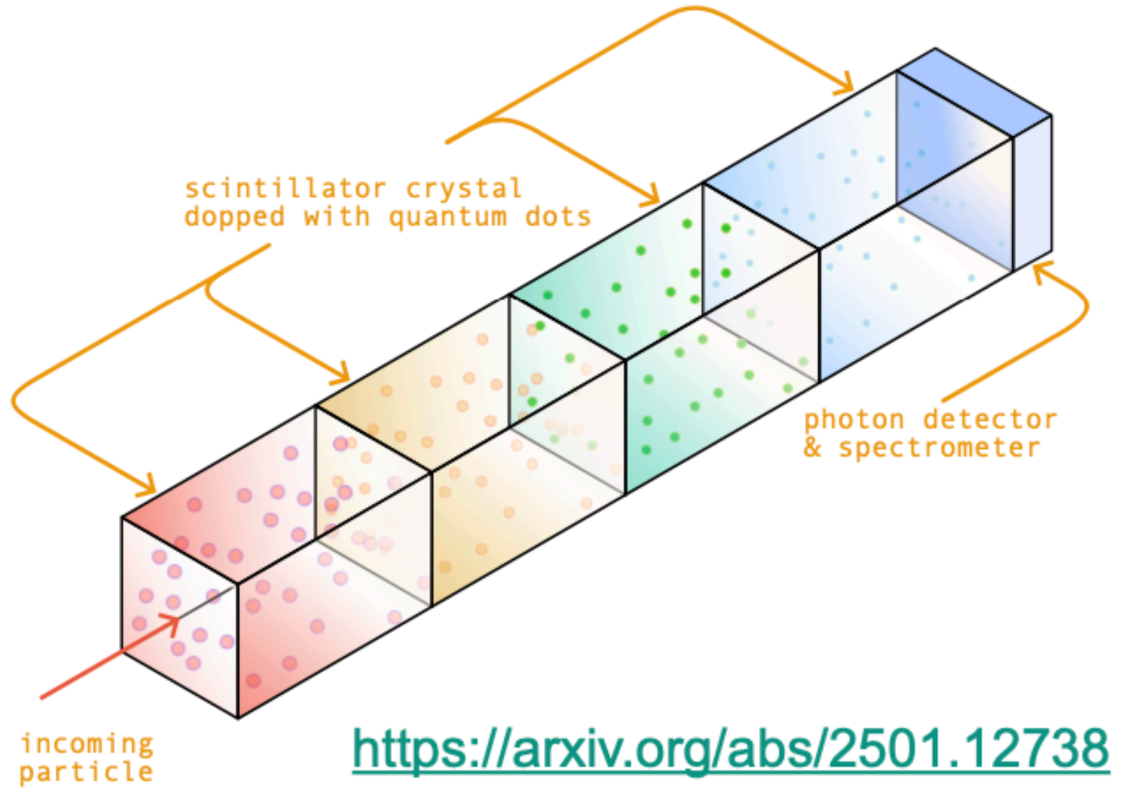
- Special requirements compared to industry —> high costs
- Increasing gap to industry state of the art (e.g. feature size)

AI, emerging technologies

Quantum sensing:
• Potential seen in the community
• **Particle physics applications driven by non-accelerator experiments** (e.g. axion and DM searches, neutrinos)
• Some ideas for colliders (e.g. quantum dots in "chromatic" calorimeters, nanowires in luminometers)

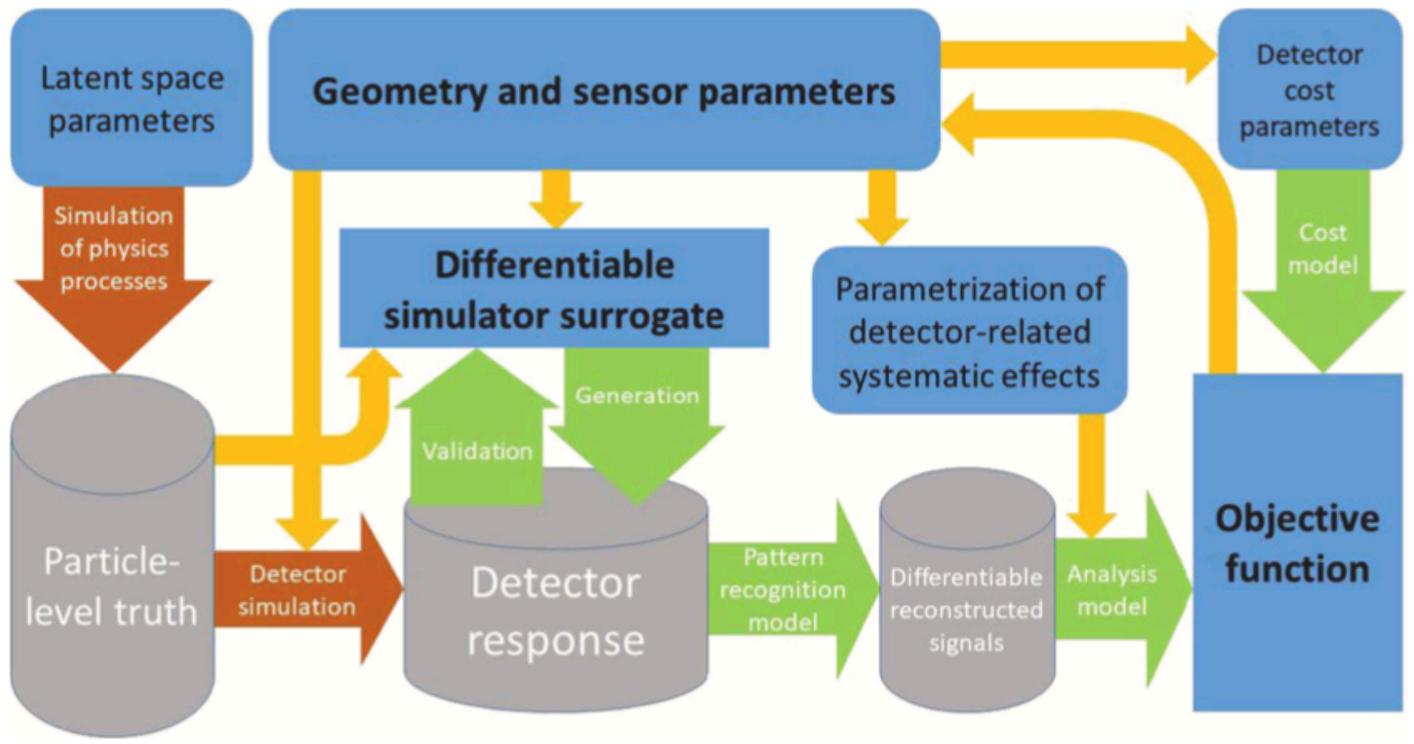
Software and Artificial Intelligence (AI):
• Tighter integration of hardware and full software stack (simulation, pattern recognition, reconstruction,
• Edge AI: **integration of real-time AI in frontend and trigger**
• **Detector optimization with AI**
(e.g. surrogate models, differentiable simulation code)

Chromatic Calorimeter



https://arxiv.org/abs/2501.12738

AI Detector Optimization



Review in Physics 10 (2023) 100085

What is the framework in which this R&D will be developed in Europe?

ECFA roadmap

INFN
Istituto Nazionale di Fisica Nucleare

T. Bergauer,Open Symposium of the ESPP

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

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

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

Document contains:

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

TF#1	Gaseous Detectors	Anna Colaleo, Leszek Ropelewski
TF#2	Liquid Detectors	Roxanne Guenette, Jocelyn Monroe
TF#3	Solid State Detectors	Nicolo' Cartiglia, Giulio Pellegrini
TF#4	Photon Detectors & PID	Neville Harnew, Peter Krizan
TF#5	Quantum & Emerging Technologies	Marcel Demarteau, Michael Doser
TF#6	Calorimetry	Roberto Ferrari, Roman Poeschl
TF#7	Electronics & On-detector Processing	Dave Newbold, Francois Vasey
TF#8	Integration	Frank Hartmann, Werner Riegler
TF#9	Training	Johann Collot, Erika Garutti

…

- **2021**: ECFA Detector Roadmap
- **2022**: Roadmap implementation plan
- **2023**: Q1/Q2: Community input by open meetings; Q3/Q4: Submission and review of proposals
- **2024**: Approval, then: Collaborations started

Detectors R&D collaborations (DRD)

INFN
Istituto Nazionale di Fisica Nucleare

T. Bergauer, Open Symposium of the ESPP

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

- Based on previous R&D collaborations:
  - **DRD1: Gaseous detectors** (based on RD51): *161 institutes, 700++ people*
  - **DRD3: Semiconductor Detectors** (previously RD42, RD50): *145 institutions / 700++ people*
  - **DRD6: Calorimetry** (CALICE, other proto-experiment collabs.): *135 institutes*

- Completely new: (community building, building trust, and finding benefit of being "CERN hosted")
  - **DRD2: Liquid Detectors:** *86 institutes, 205 members*
  - **DRD4: Photodetectors & PID:** *74 institutes*
  - **DRD5: Quantum Sensors and emerging technologies:** *112 involved groups*

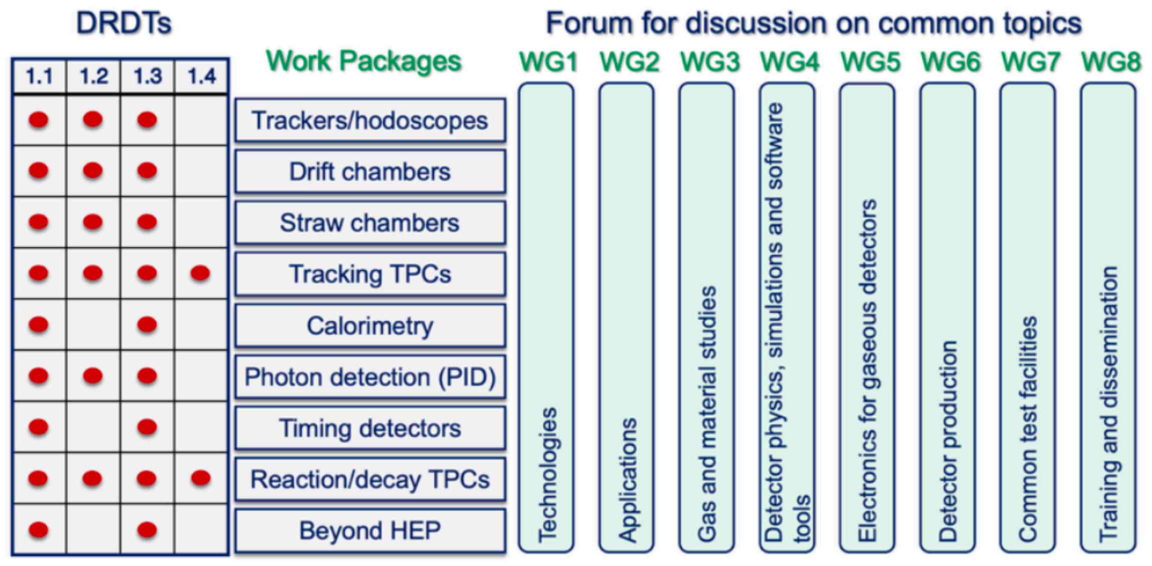
- Transversal activities: no service provider, but with genuine R&D interest (TF9 → ECFA Training Panel)
  - **DRD7: Electronics:** *67 Institutes*
  - **DRD8: Mechanics & Integration:** *38 institutes*

DRD goals and status

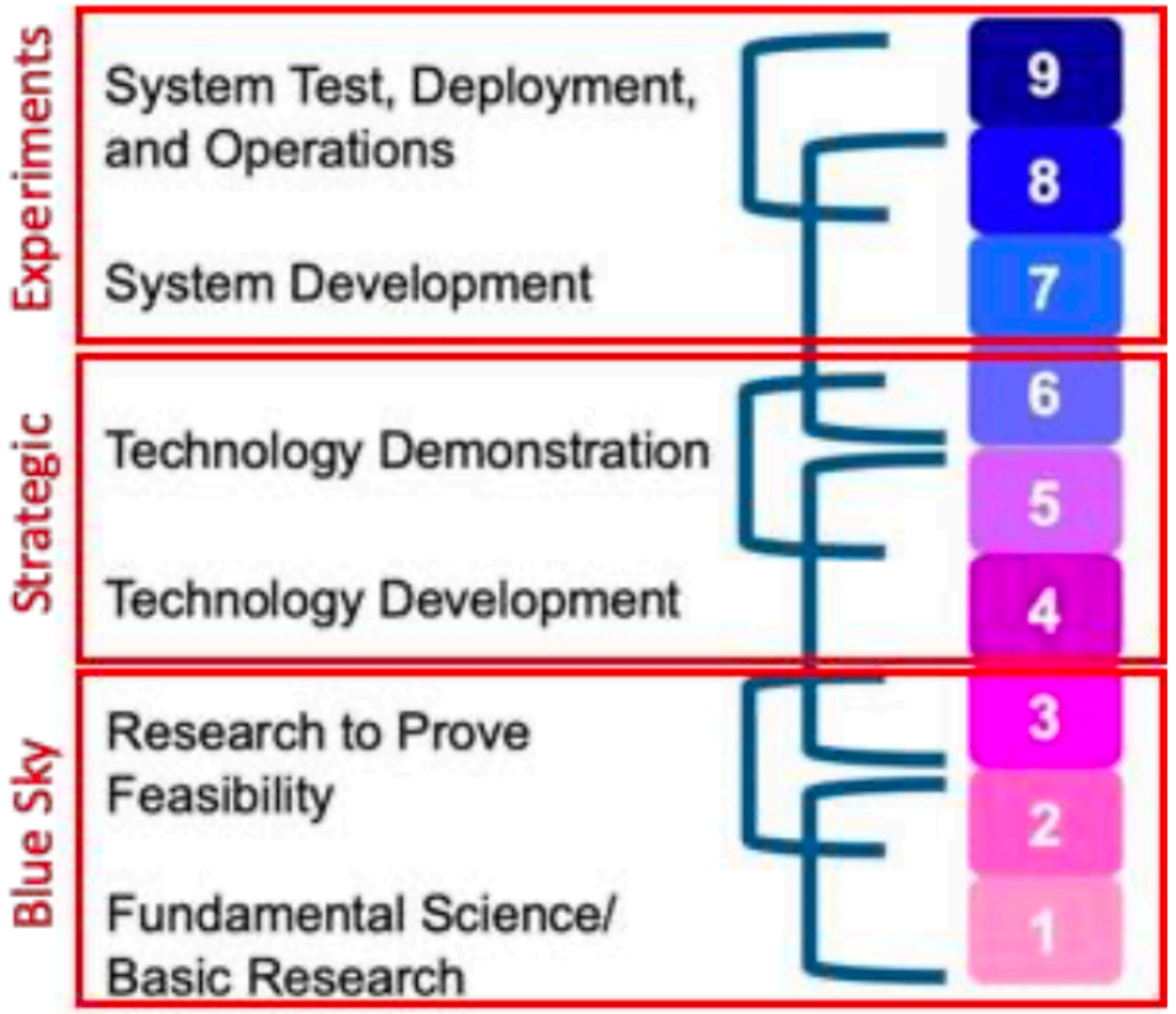
INFN
Istituto Nazionale di Fisica Nucleare

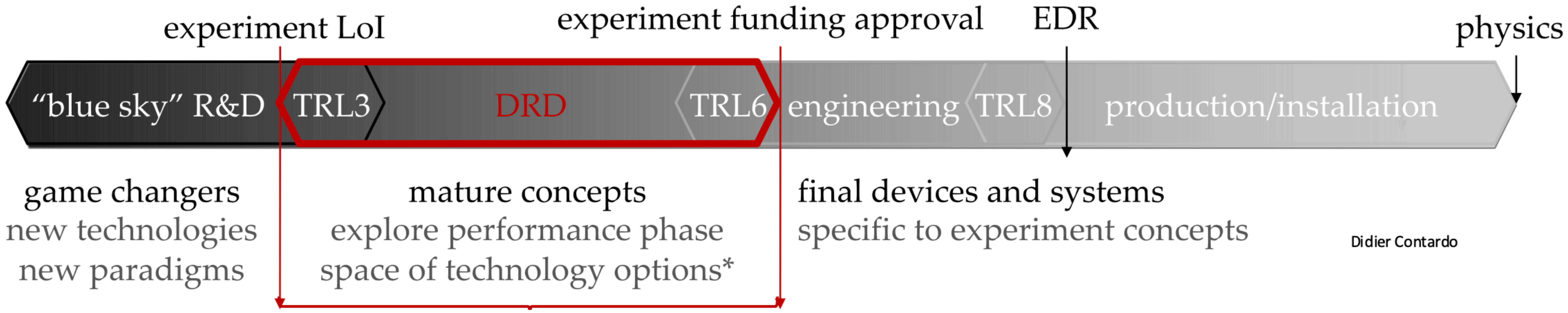
T. Bergauer, Open Symposium of the ESPP

- Approved for an **initial period of three years** based on work programs in the proposals
  - Annual review by the DRDC committee
- Collaborations are organized in
  - **Working Groups**: (WG) serving as the backbone of R&D
  - **Work Packages**: resource-loaded; will reflect the DRDTs
- All administrative positions (WP/WG convenors) filled, but most work started in working groups so far
- CERN Greybook entries exist; Users can be registered to DRD collaborations
- Websites for all (but DRD6) exist following the schema https://drd1.web.cern.ch
- Certain DRD collaborations ask for a fixed **yearly membership fee** (Common Fund), targeting common projects, but also blue-sky R&D projects (GSR 7)
  - However, DRD collaborations are not funding proposals!
  - MoU's with resource requests to be signed by funding agencies → ongoing (GSR 6)



DRD1 input proposal #229





Didier Contardo

Highlights from DRD activities

DRD1: gaseous detectors

DRD1 Gaseous Detector Technologies

INFN Istituto Nazionale di Fisica Nucleare

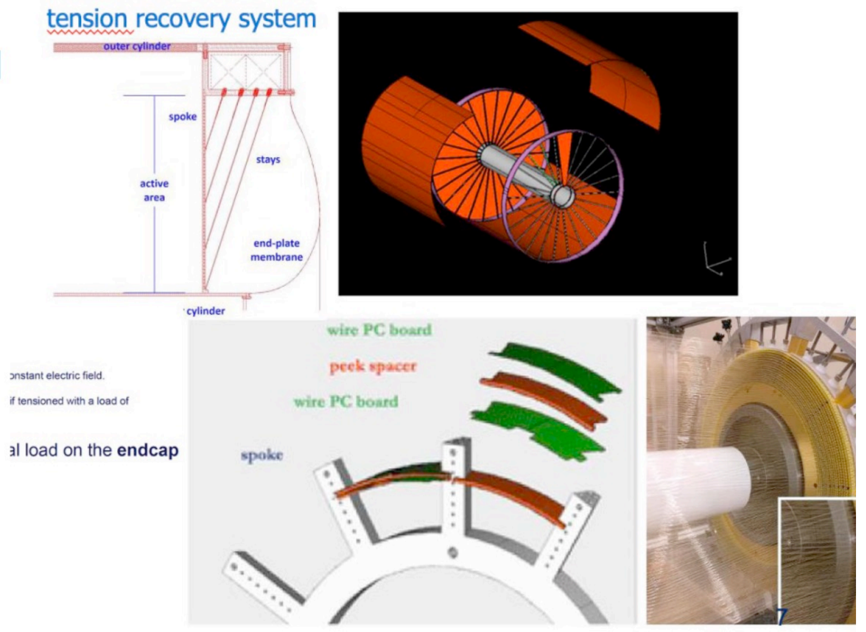
M. Titov

Drift chamber for IDEA@FCC: hardware and detector simulation

INFN Bari and Lecce

Hardware:

- studies about mechanical design of a drift chamber for the IDEA proposal at FCC-ee

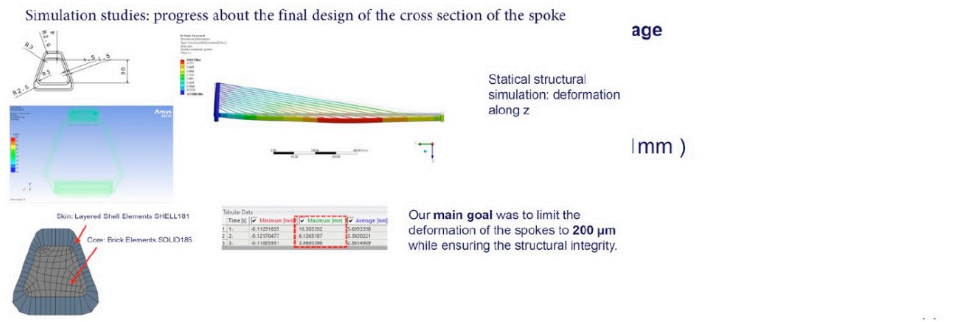


- DCH is a unique-volume, high granularity, fully stereo, low-mass cylindrical
- gas: He 90% - iC_4H_{10} 10%
- inner radius R_{in} = 0.35m, outer radius R_{out} = 2m
- length L = 4m, drift length ~1 cm, drift time up to 400ns
- σ_{xy} < 100 μm, σ_z < 1 mm
- 12÷14.5 mm wide square cells, 5 : 1 field to sense wires ratio
- 112 co-axial layers, at alternating-sign stereo angles, arranged in 24 identical azimuthal sectors, with frontend electronics
- 343968 wires in total:

Big Problems to manage!

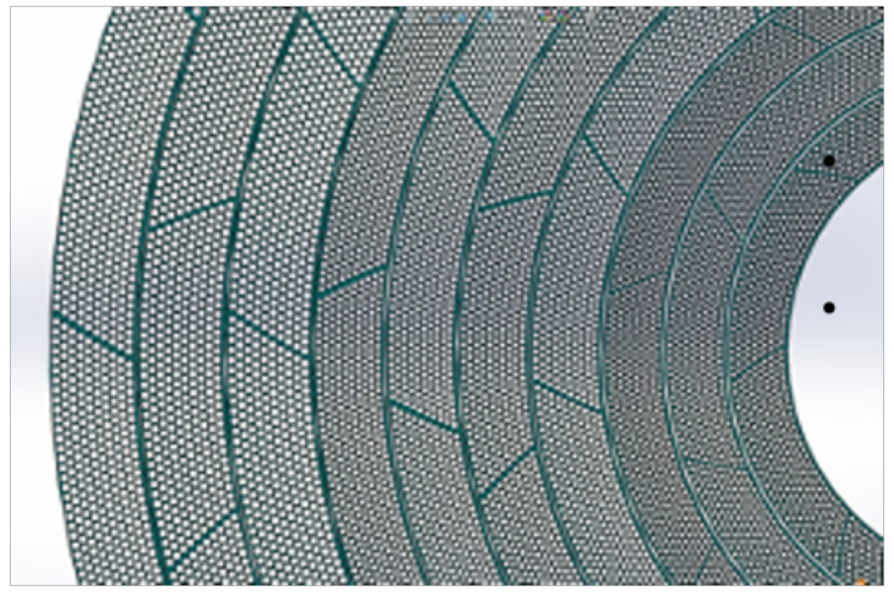
- σ_{xy} < **100 μm** → accuracy on the position of the anodic wires < **50 μm**.
- The anodic and cathodic wires should be parallel in space to preserve the constant electric field.
- A 20 μm tungsten wire, 4 m long, will bow about 400 μm at its middle point, if tensioned with a load of approximately 30 grams.

30 gr tension for each wire → **10 tonnes** of total load on the **endcap**



A realistic complete model ready:

- mechanically accurate
- precise definition of the connections of the cables on the structure
- connections of the wires on the PCB
- location of the necessary spacers
- connection between wire cage and gas containment structure



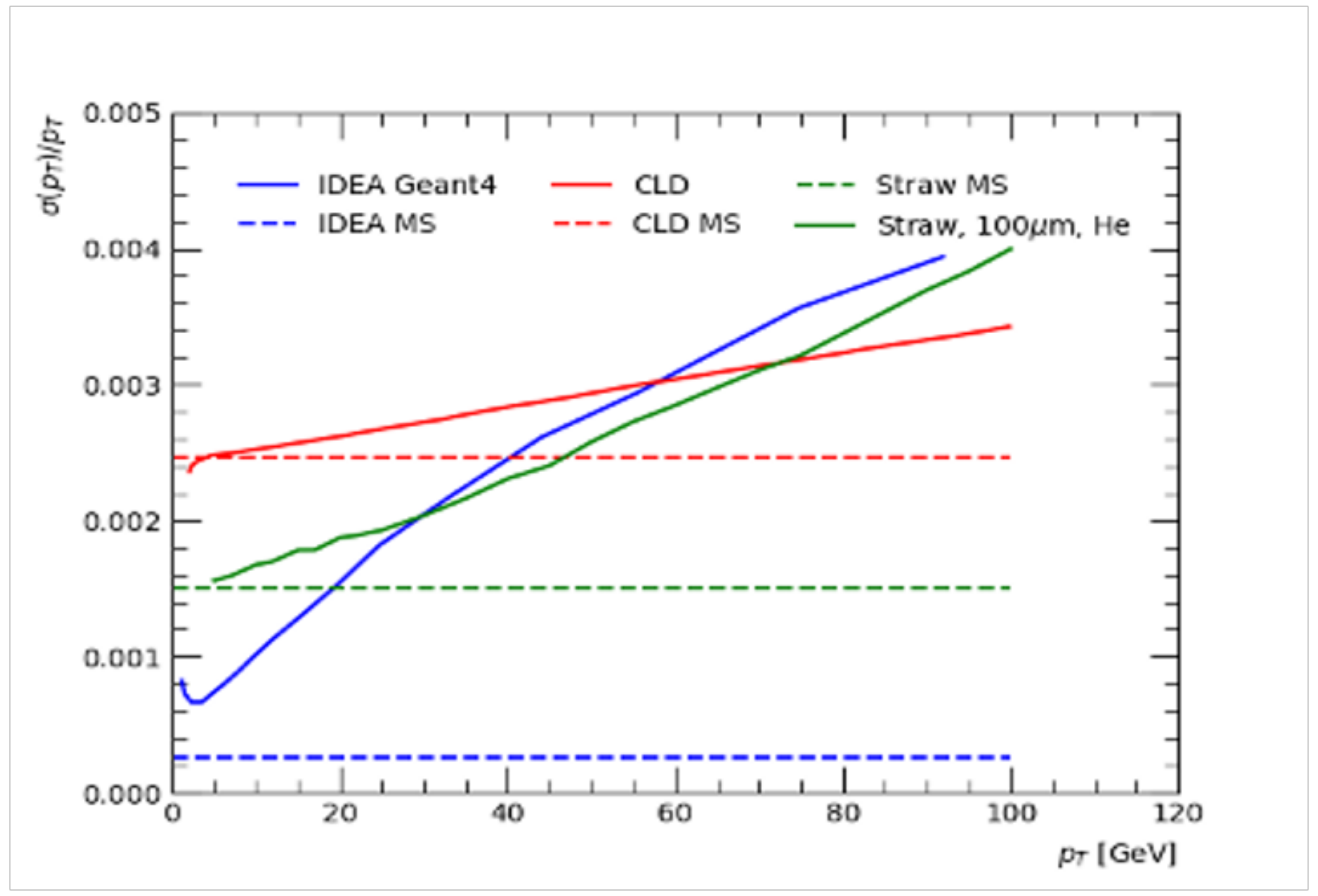
J. Zhu, O. Kortner, P. Wintz, D. Bick, R. Petti

Straw tracker proposal

- *Build a thin-wall straw inner tracker for FCC-ee*

Implemented a geometry inside the FCC-ee simulation framework, ~1.2% X_0 for 100 layers of straws with a wall thickness of 12-20 μm

Example layout: O(60k) straws, coverage: R between 0.3-1.8 m and a length of 4-5 m Diameters 1.0 - 1.5 cm, single hit resolution: ~100 μm 10 superlayers (each 10 layers), Stereo angle: 2-5 degrees



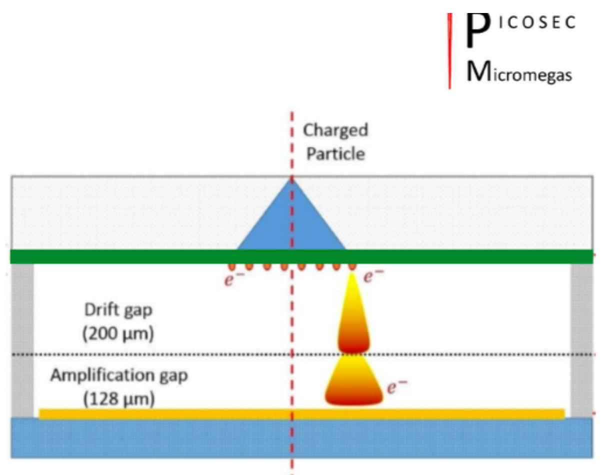
DRD1: gaseous detectors

M. Titov

Precise timing with PICOSEC Micromegas

Primary charge production is localised in space and time by coupling Cherenkov radiator with photocathode and Micromegas amplification stage for precise timing.

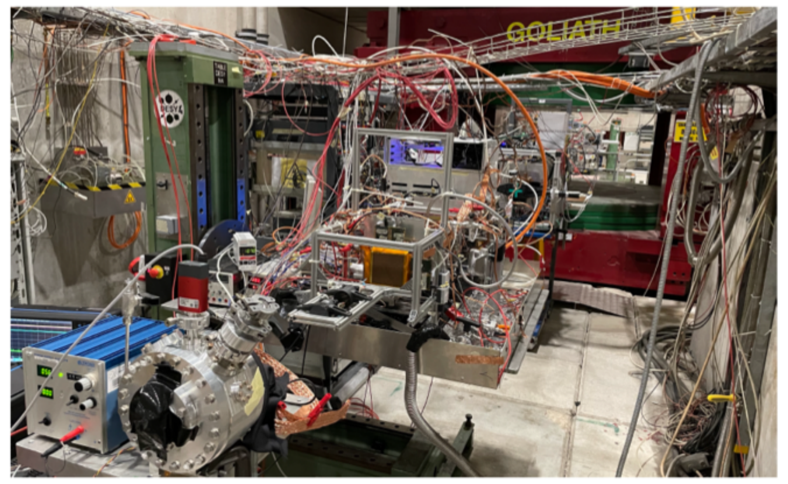
Proof of concept started as **RD51 Common Project** in 2015 and initiated large collaborative effect addressing all aspects of detector optimisation and scaling: amplification stage improvement, robust photocathodes, readout electronics chain.



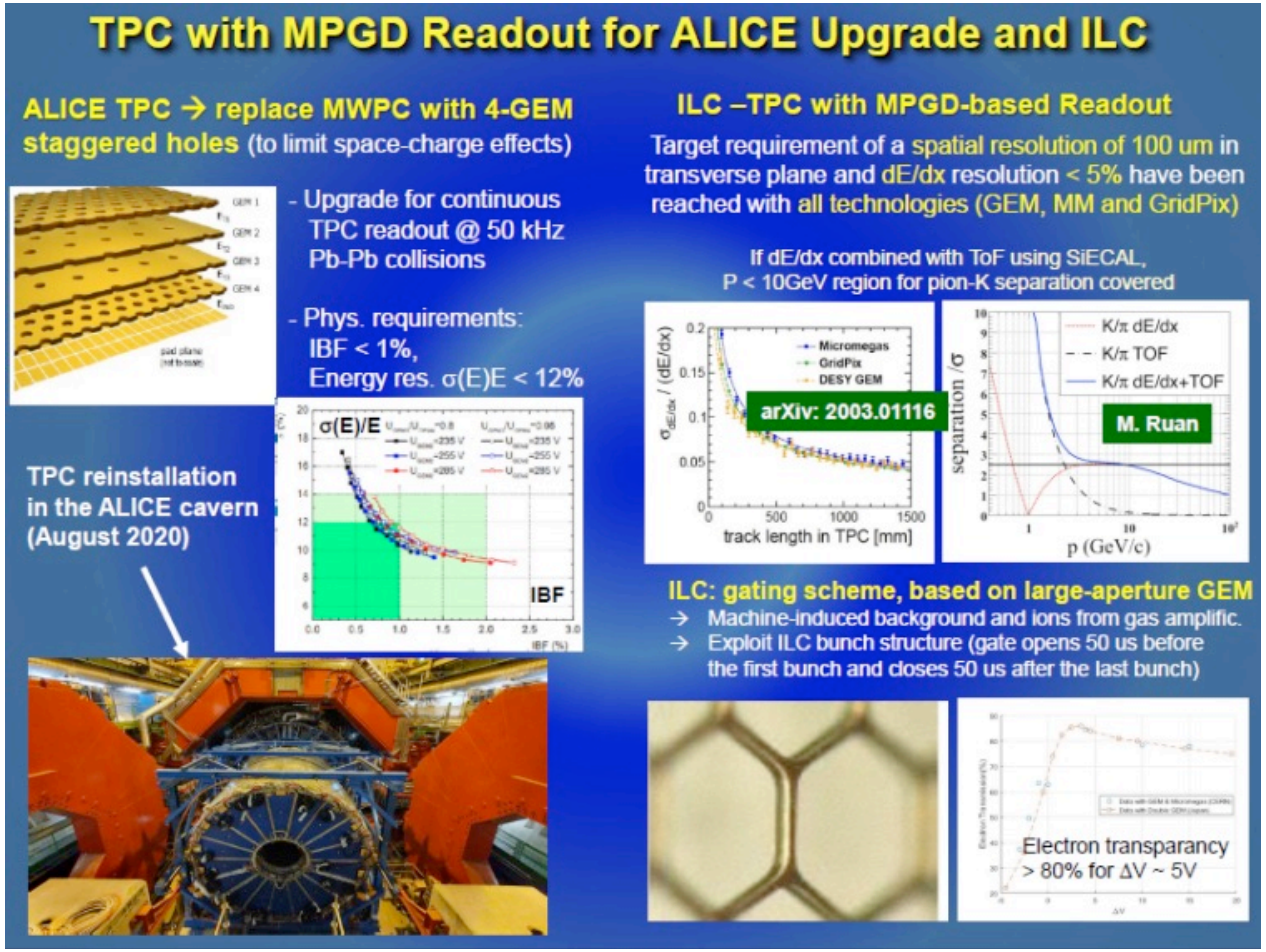
Picosec detection concept

Proof of concept with small prototypes

Regular shared SPS H4 test beams



M. Titov, Open Symposium of the ESPP



DRD2: liquid detectors

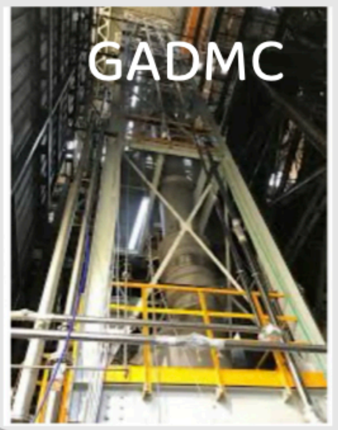
DRD2 LIQUID DETECTORS

INFN Istituto Nazionale di Fisica Nucleare

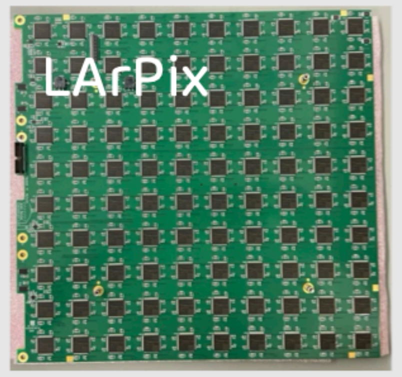
I. Gil-Botella & A. Giuliani

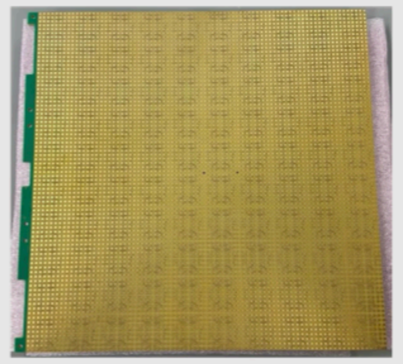
European Strategy for Particle Physics

Liquid detector challenges

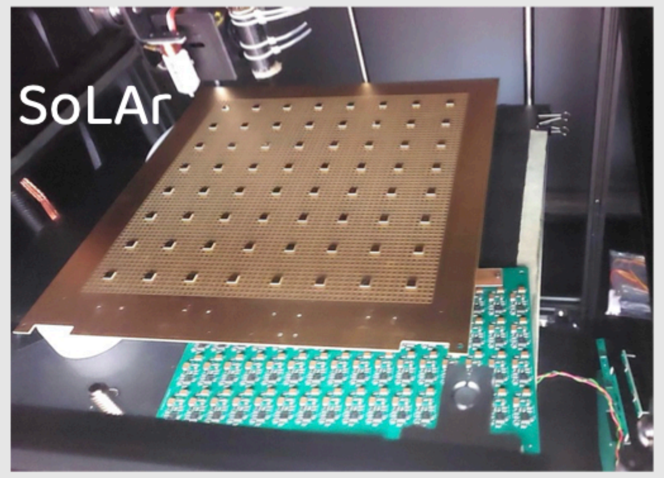


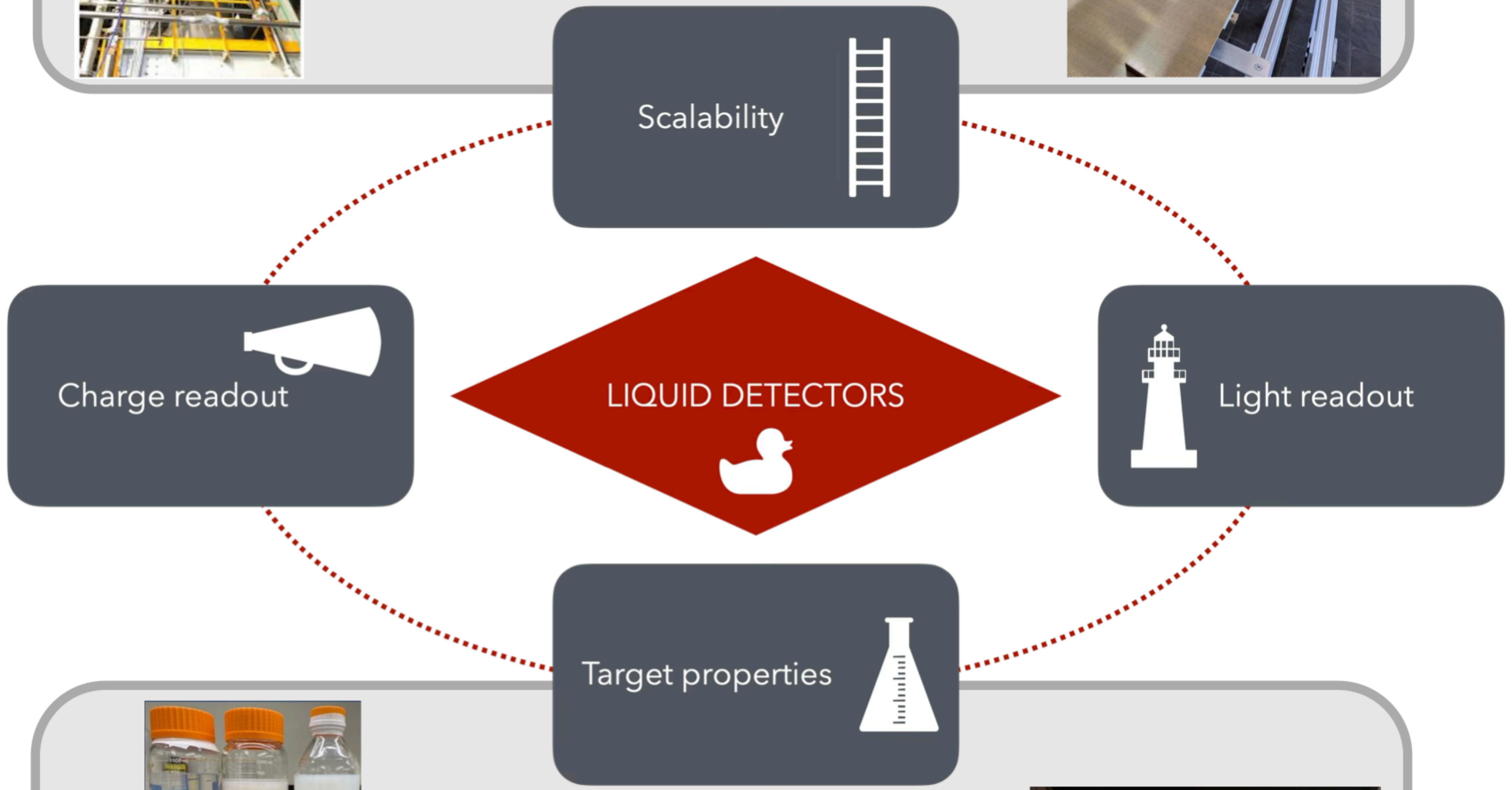
- Very large mass
- Radiopurity & backg mitigation (radioassay, novel materials, Rn fac)
- Target production and purification
- Large-area readouts

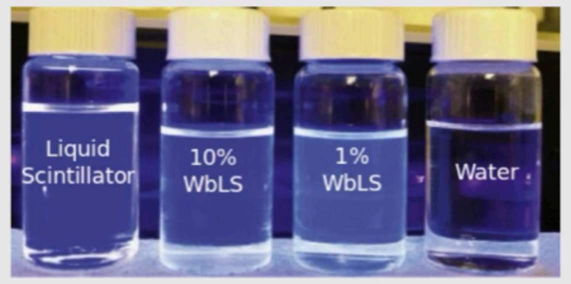




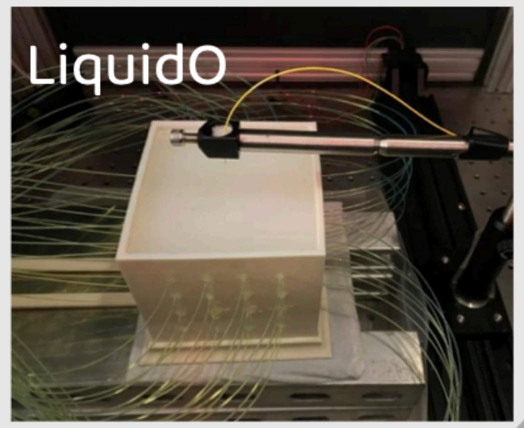
- Amplification of charge in liquid TPCs
- 3D imaging, lower power, lower pixel thresholds
- Multiple modality pixels
- Dual-phase optical TPCs

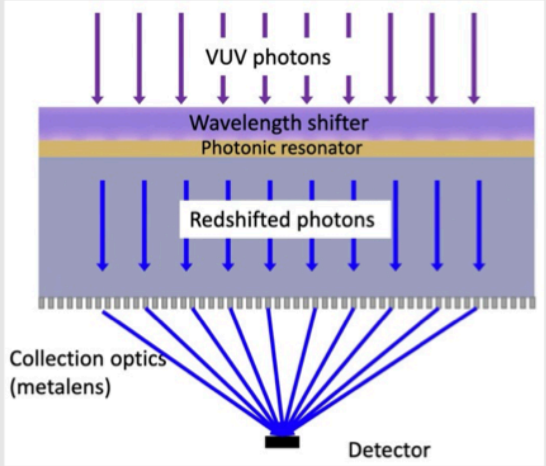






- Isotope loading of LS and WC (Te-loading, WbLS)
- Opaque LS
- Loading of noble liquids (Xe doping of LAr)





- Increase photodetection efficiency and collection
- WLS, reflectors, metalens
- Digital cryogenic SiPMs
- Power-over-fiber, Signal-over-fiber
- Cryogenic facilities for VUV sensor characterization

DRD2: liquid detectors

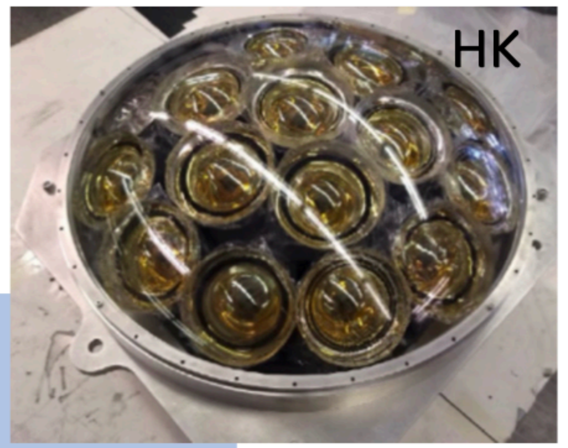
DRD2 LIQUID DETECTORS

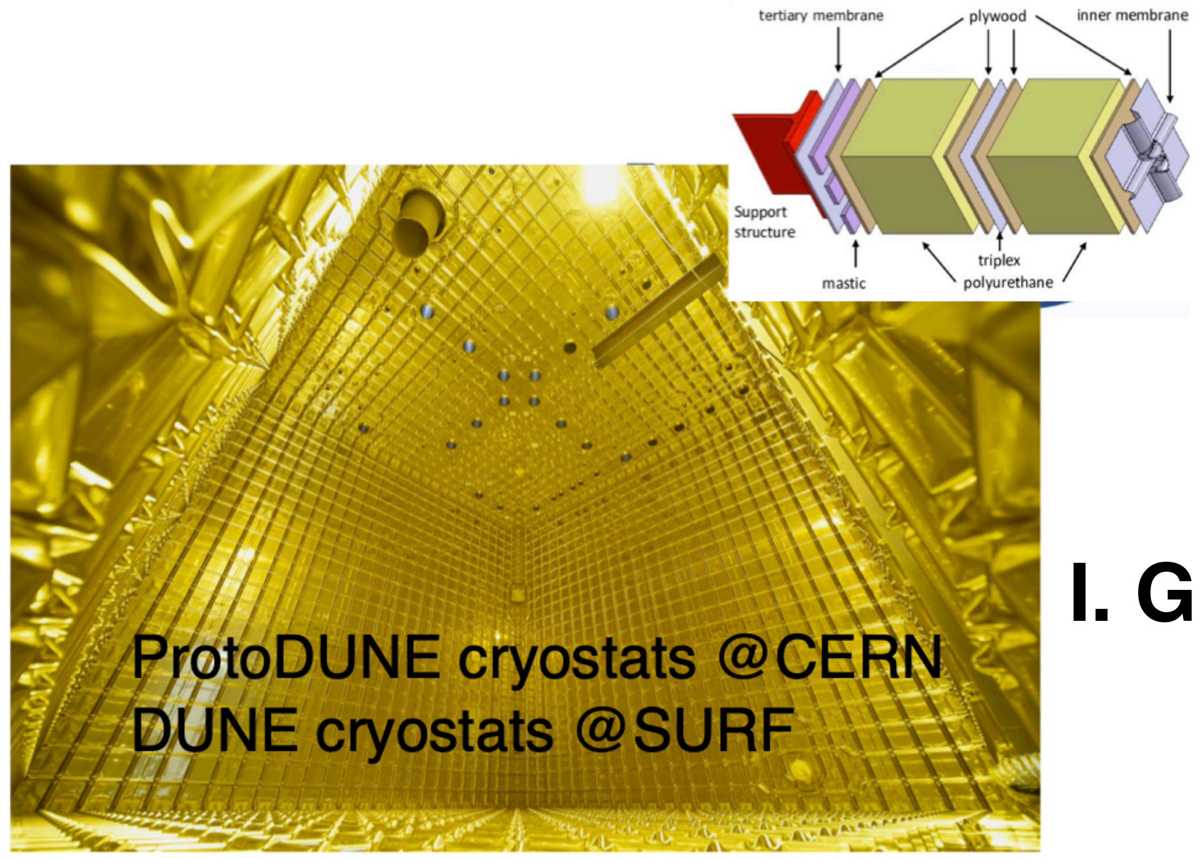
Liquid detectors

- **State of the art** (running or under construction)

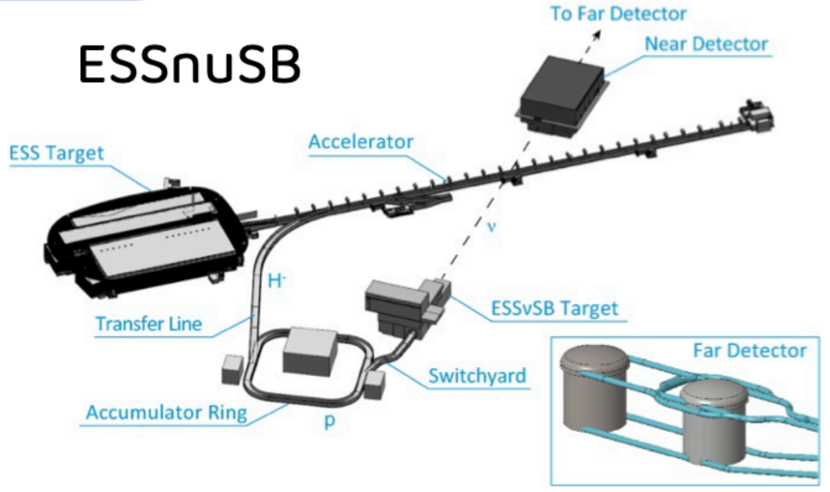
  SK, HK, JUNO, DarkSide, XENON, SBN, DUNE Phase I, KamLAND-Zen, SNO+, …
  - Intense R&D on photodetection (high QE and time resolution)
  - Gd-loaded WC to enhance neutron tagging
  - Large cryostats: Technological breakthrough from naval industry led by CERN
  - Pixelated readout, cold-electronics developments
- **Challenges/Detector R&D needs**

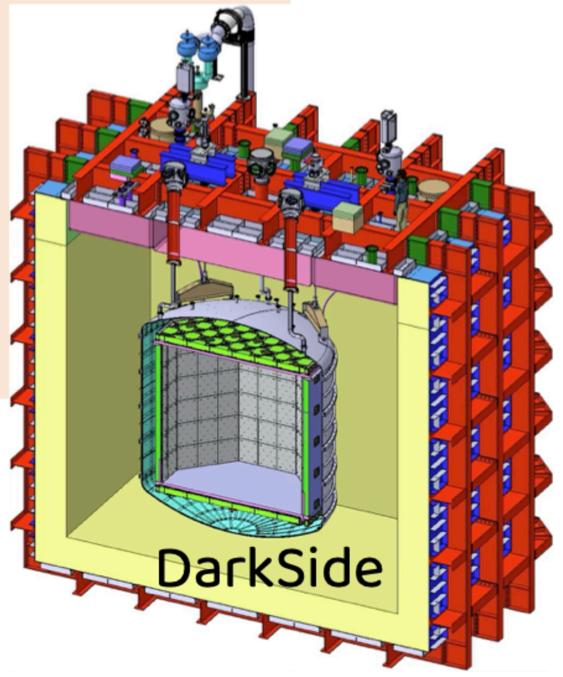
  (acc νs+astro) DUNE Phase II, ESSnuSB, THEIA, P-ONE, (DM) ARGO, XLZD
  - Very large mass (~kton)
  - Scalability of readout
  - Efficient and fast photodetectors
  - Increase of light yield and backg reduction
  - Metal loaded LS, opaque LS, hybrid WbLS
  - Liquid purification techniques
- **DRDs**:
  - DRD2: Strategic R&D on future liquid detectors identified
    - 86 institutions, 17 countries, 205 members, 4 WPs and 3 WGs
  - DRD4: R&D on non-cryo photosensors

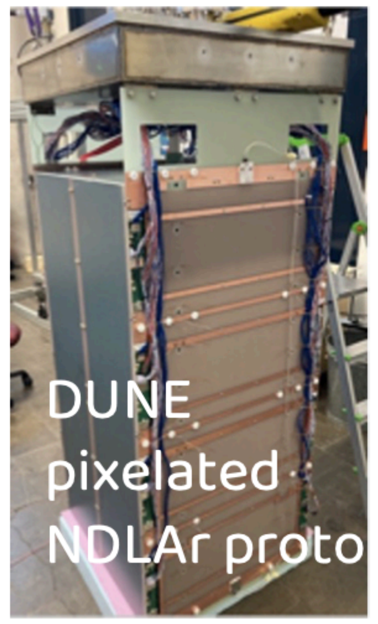


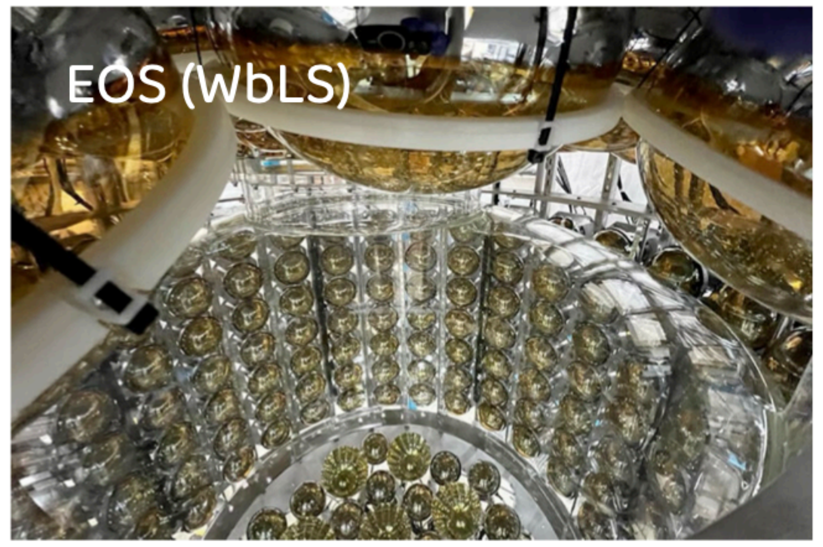


I. Gil-Botella & A. Giuliani









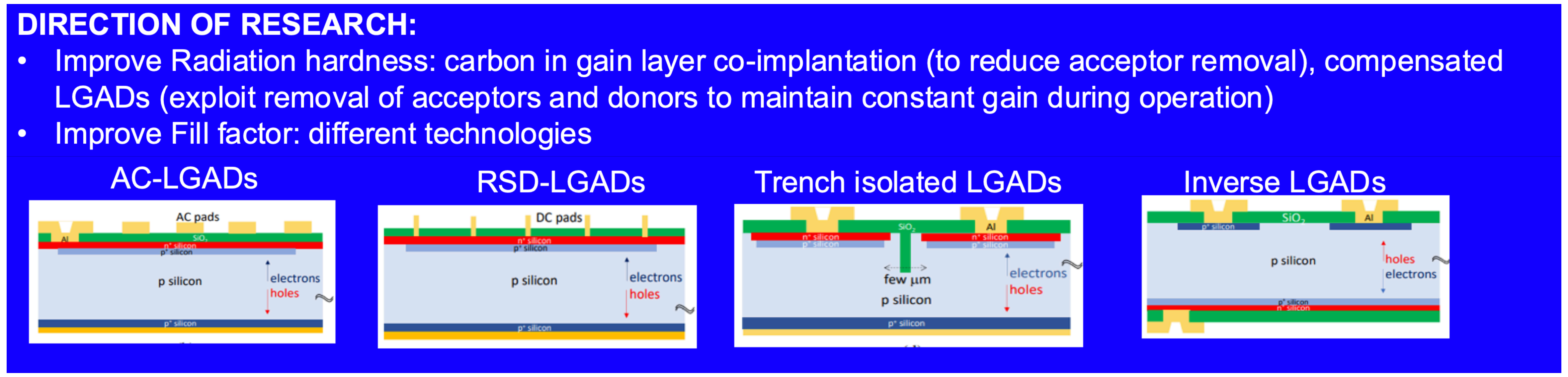
DRD3: semiconductor detectors

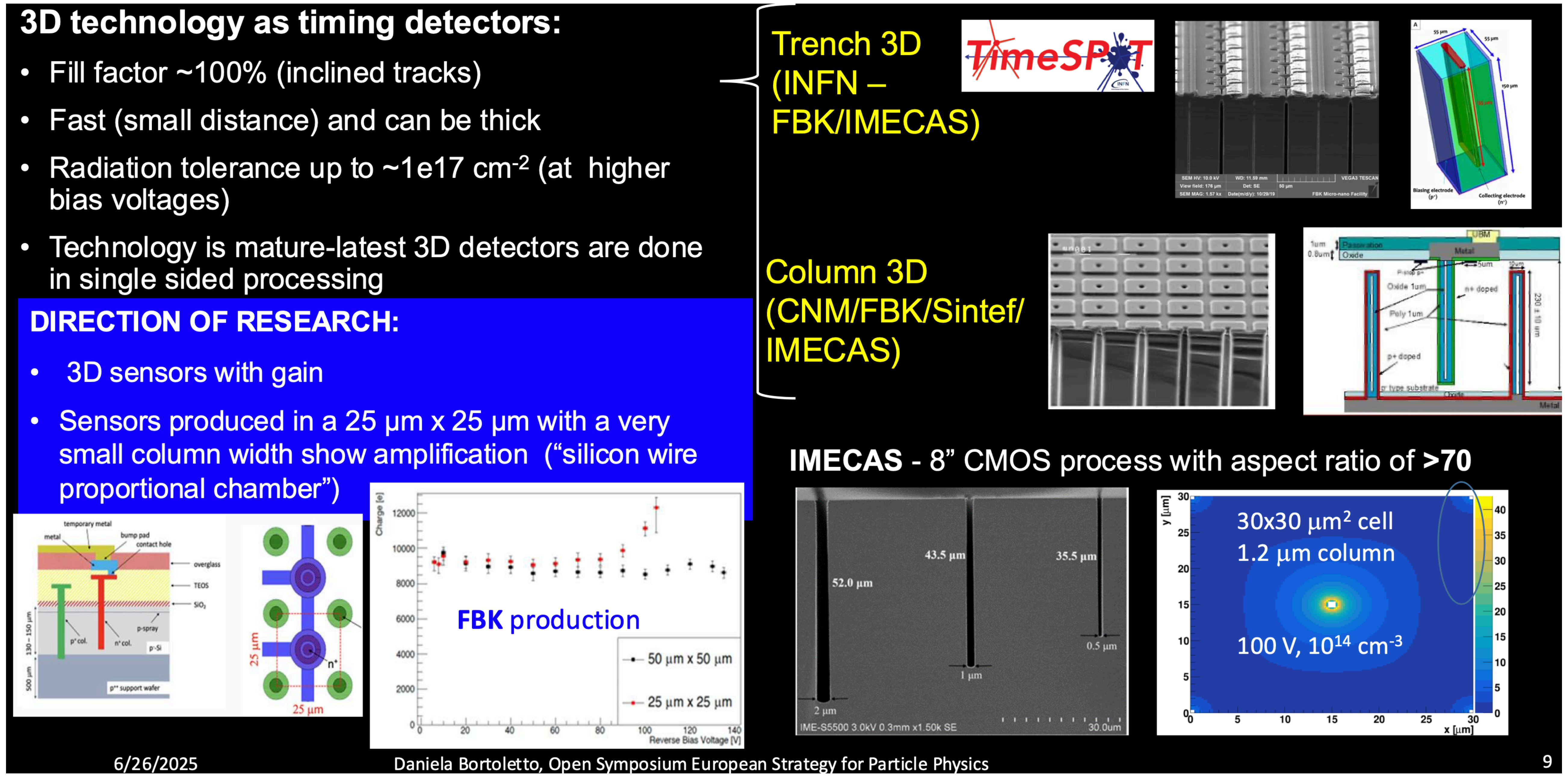
D. Bortoletto

Higgs factory experiments: low mass, high precision **vertex** detectors: (~0.1% X_0)/layer, 3μm single-hit resolution; ToF wrappers around tracker for PID: ~O(20)ps

Research Topics in DRD3:

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

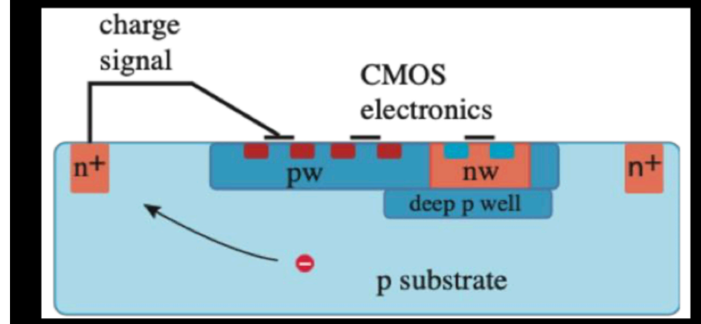




DRD3 semiconductor detectors

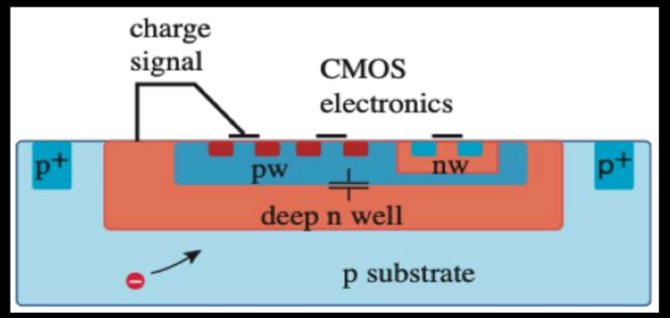
D. Bortoletto

SMALL ELECTRODE



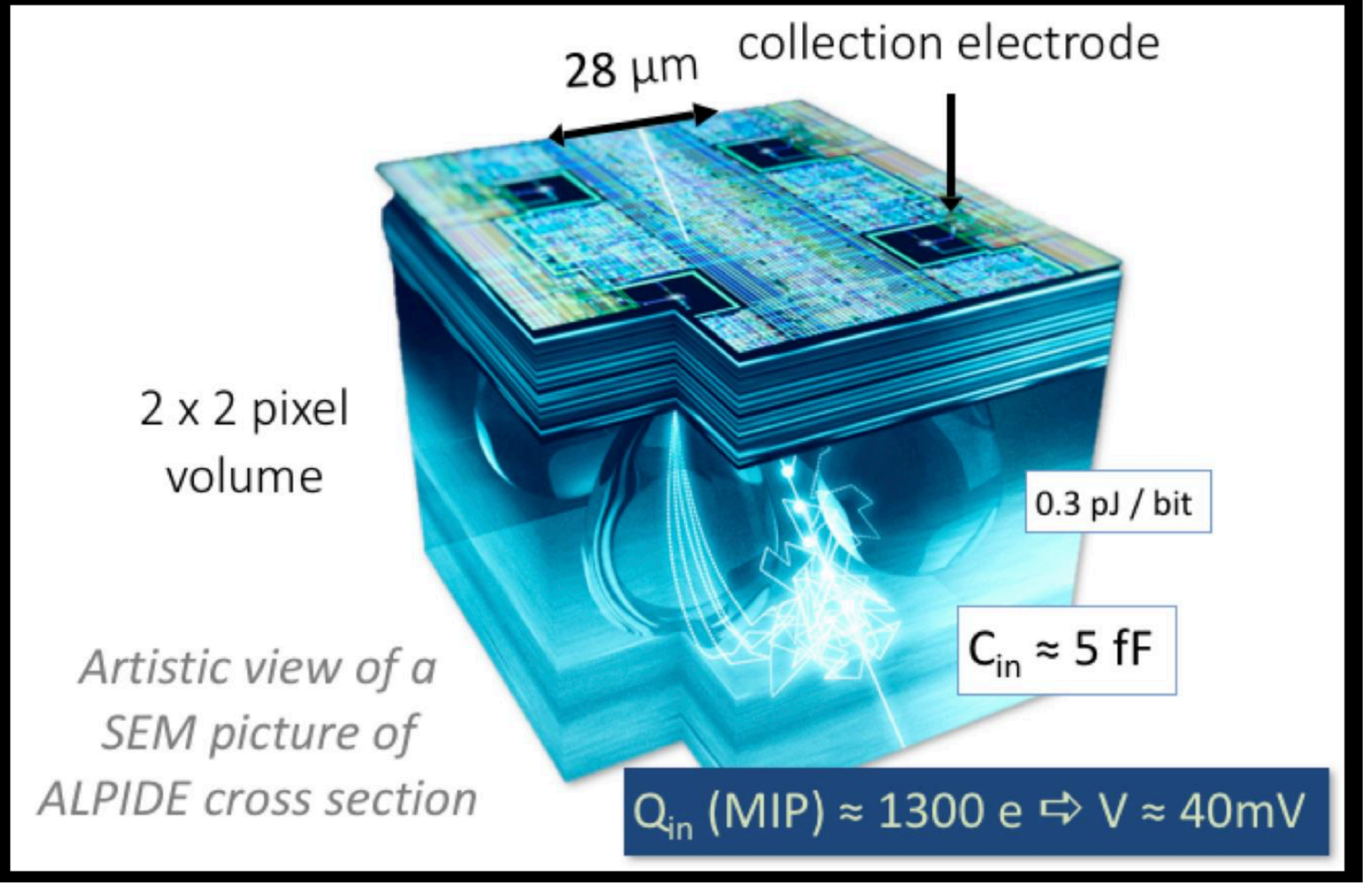
- C ≈ 3 fF
- Low analogue power
- Difficult lateral depletion, requiring process modification of radiation hardness
- Threshold ≈ 100 e-

LARGE ELECTRODE



- C ≈ 300 fF
- Strong drift fields, short drift path, large depletion depth
- Higher power, slower
- Threshold ≈ 500-1000 e-

Operational experience from ALICE ITS2 (SMALL ELECTRODE)



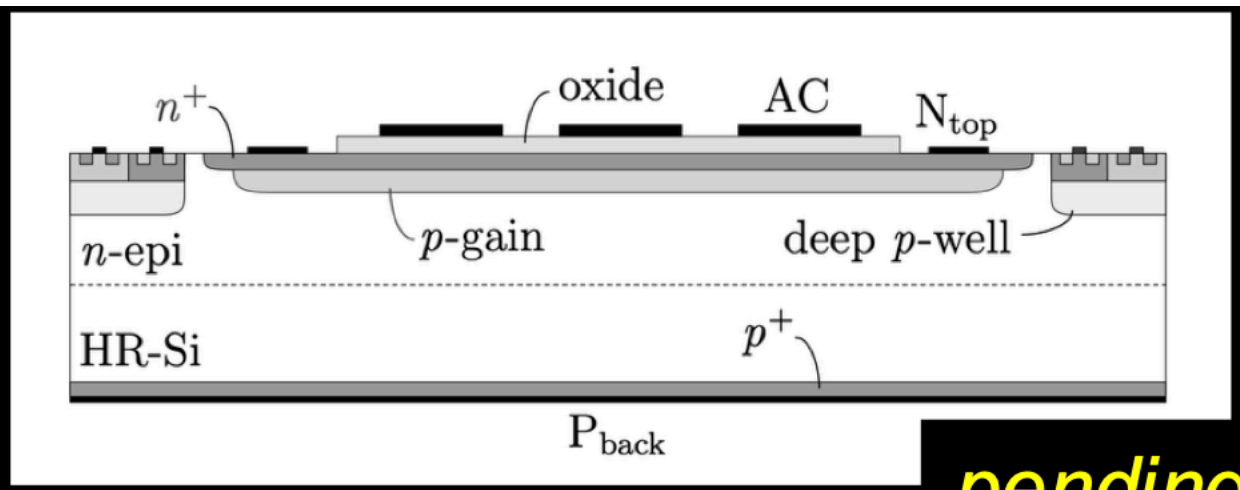
Directions of research:

- Achieve very high spatial resolution (3 μm – easier for SMALL ELECTRODE)
- Achieve excellent time resolution (CMOS with gain)
- Support high data rates
- Improve radiation tolerance
- Minimize power consumption
- Maintain low material budget
- Enable coverage of large detector areas
- Control and reduce costs

Integrate all requirements

- Advanced Readout CMOS Architectures with Depleted Integrated sensor Arrays (LF11is technology)

ALICE 3 time of Flight system
σ(t) ~ 20 ps

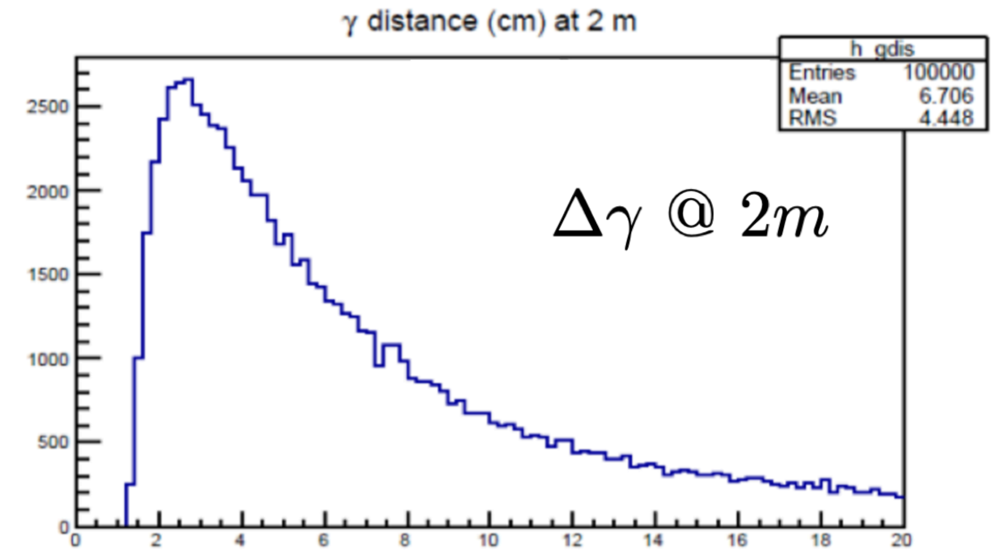


pending patent

Monolithic AC LGAD for IDEA silicon wrapper

DRD6: calorimeters

“Higgs Factories” (in particular FCC-ee) among the main drivers for current calorimeter development

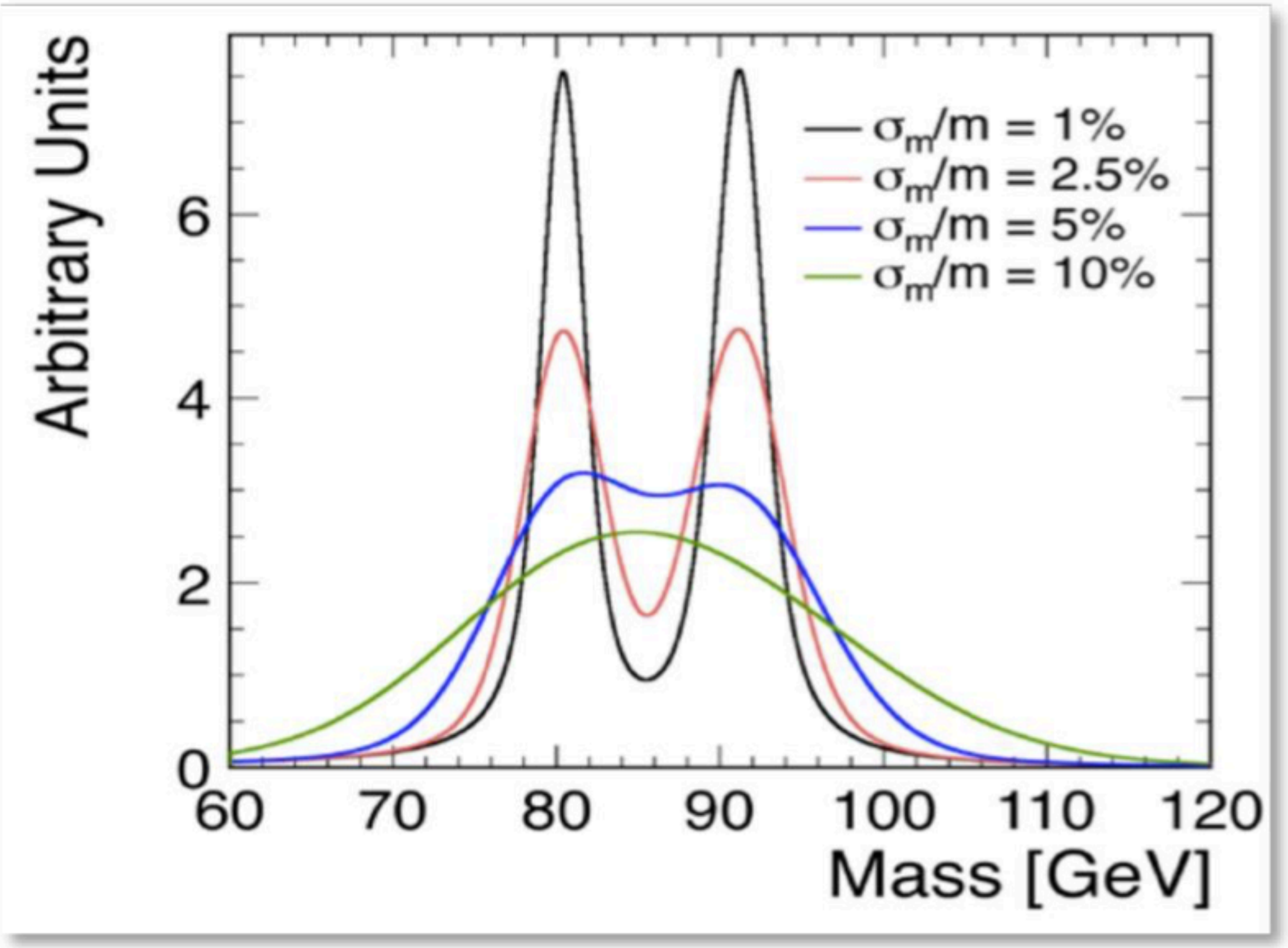


e^+e^- HZ physics constraints
$H \rightarrow \gamma\gamma \Rightarrow$ ECAL resolution
As good as possible – at least $20\%/\sqrt{E}$ + 1%

For HF physics $3\%/\sqrt{E}$ is required

High granularity / Pre-shower is needed for π^0 identifications

$Z \rightarrow \tau^+\tau^-$
$\tau^+ \rightarrow \rho^+\nu \rightarrow \pi^+\pi^0\nu$



G. Gaudio

5D-calorimeter paradigm

Energy	Position(3D)	Timing

High Energy Resolution
- Reduce fluctuations by construction
- Improved by algorithm (e.g. Particle Flow approach) and Machine Learning approach

High granularity
- mechanical integration
- cooling for embedded electronics
- increased number of channels

Fast timing information
- fast detector
- fast electronics
- larger data size

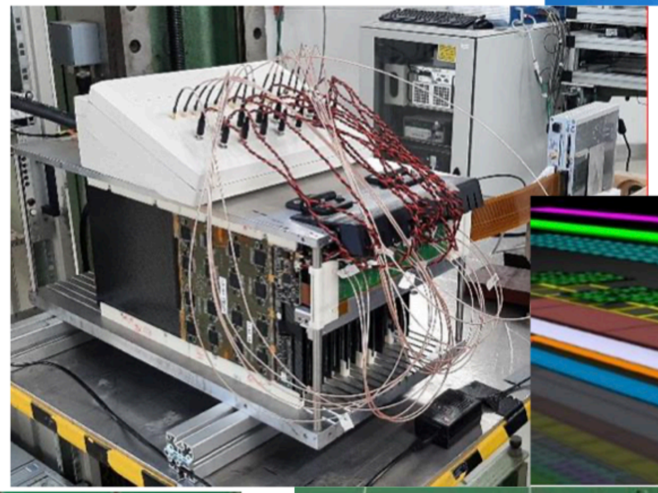
DRD6: calorimeters

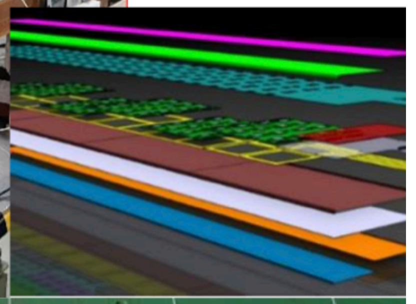
G. Gaudio

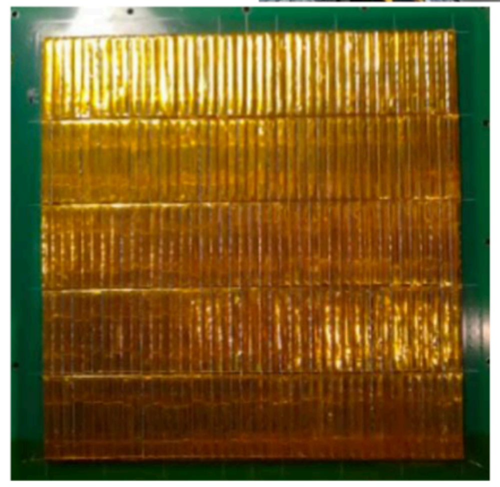
Sandwich calo with fully embedded elx

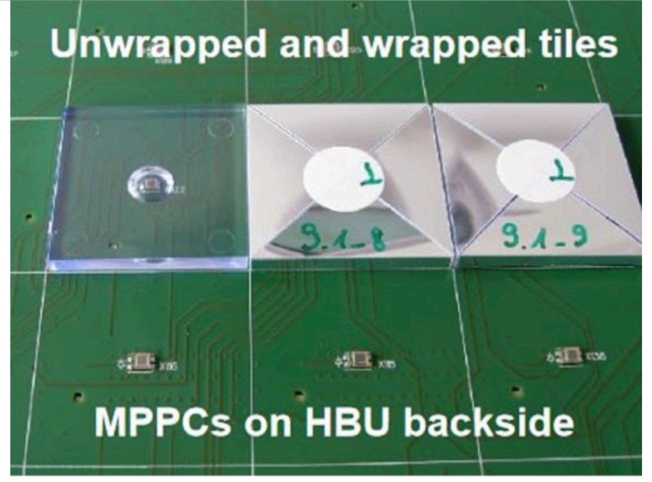
Strong connection with DRD7 (electronics)

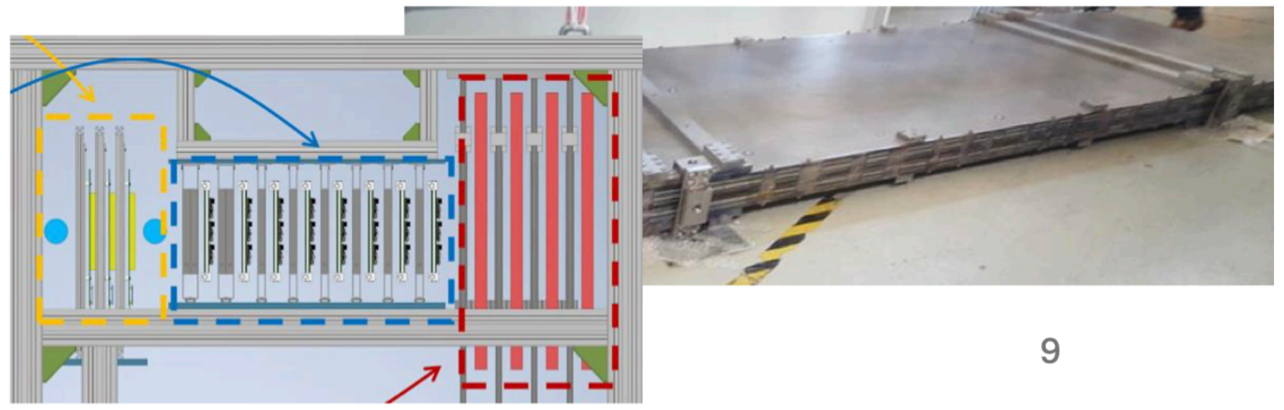
Solid State	
Silicon or GaAs Detectors MAPS	Solid State sensors (see Daniela's talk for more details) connection with DRD3
Optical	
Scintillator Strips Scintillator Tiles Glass Scintillator Tiles Lead Glass (Cherenkov)	R&D on optical material Connection with DRD4 for photodetectors
Gaseous	
RPC (semi-digital with Timing) MPGD	Connection with DRD1 for gaseous detector (see Maksym's talk for more details)







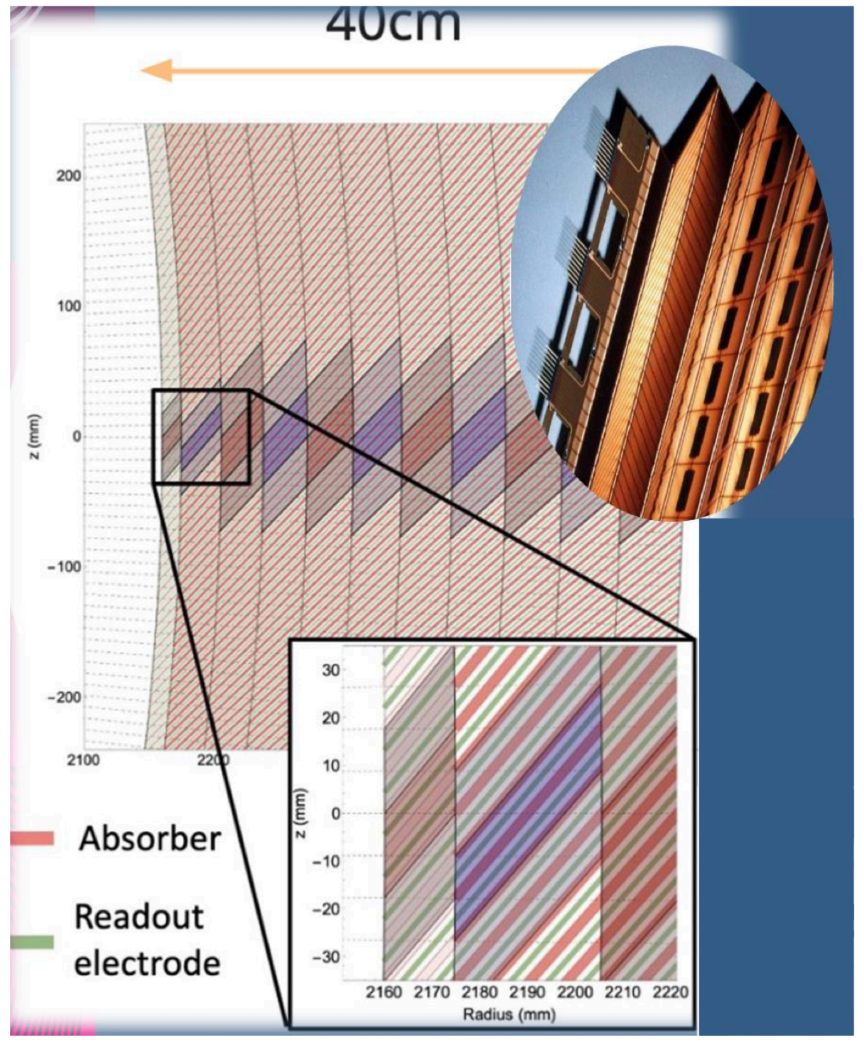




9

Liquified Noble Gas calorimeters

- Long and successful tradition in HEP
- Low systematics
- High granularity achievable => can be optimized for particle flow
- Cold electronics option under study
- Mechanical design optimization for energy resolution

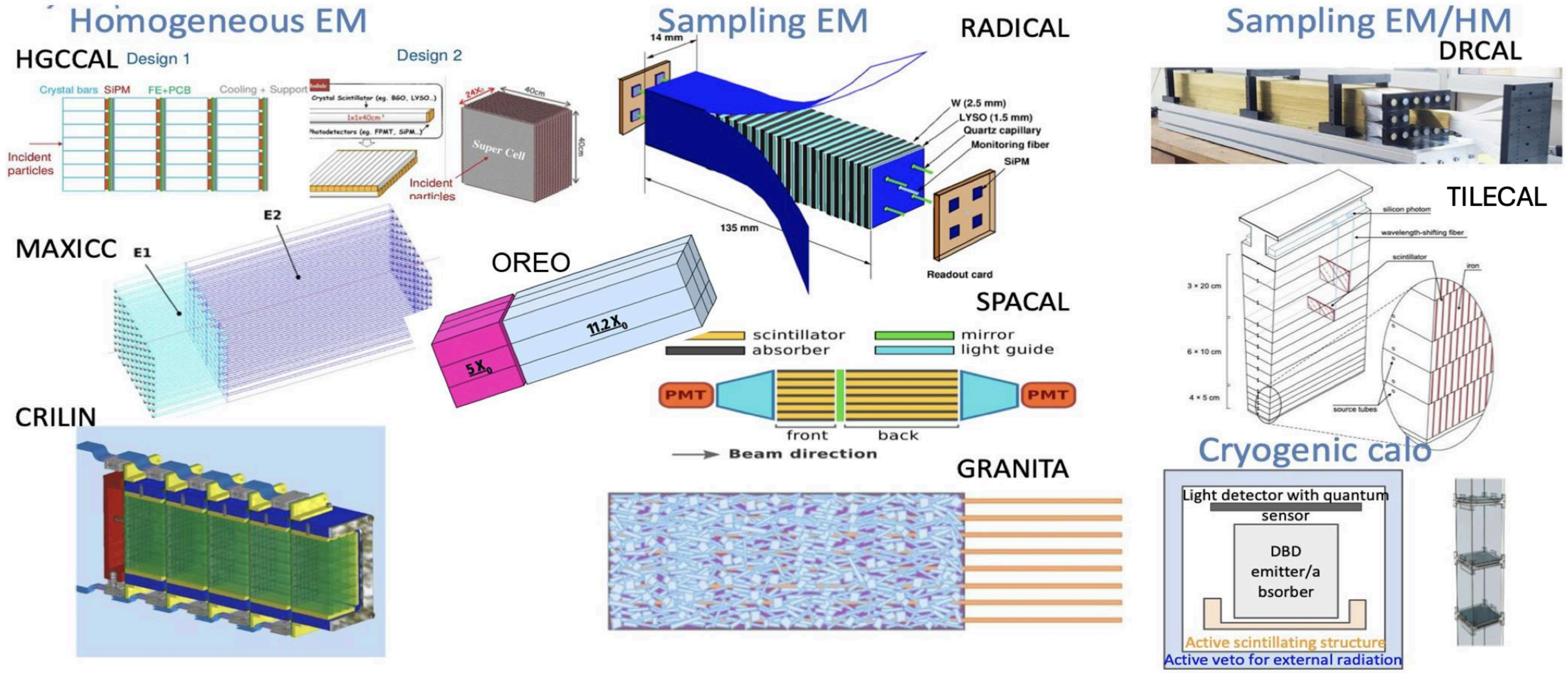


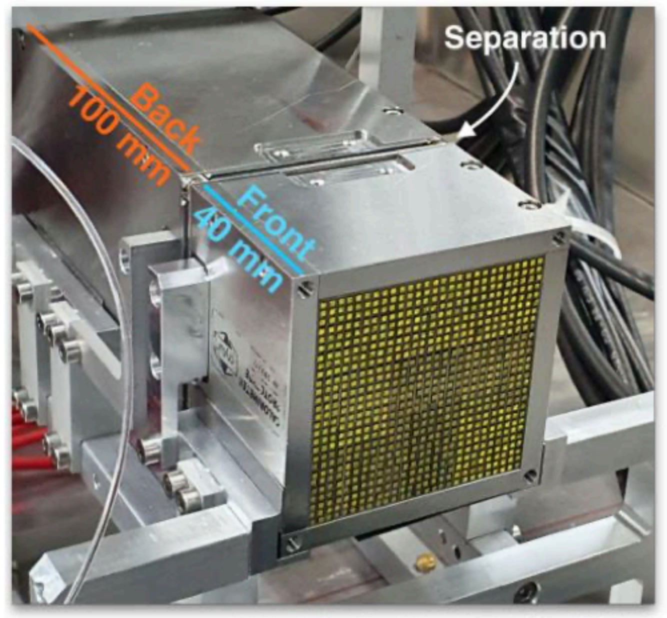
DRD6: calorimeters

Optical calorimeters

G. Gaudio

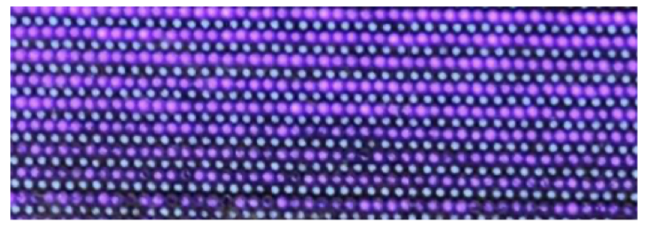
Homogeneous ECAL	Sampling ECAL	Sampling HCAL
• High granular crystal optimized for PF • Dual Readout segmented crystals • Rad-hard segmented crystals • Oriented crystals	• SpaCal with rad-hard scintillating fibres • Shashlik rad-hard with shower max measurement • Crystal grain innovative calo	• Hadron tile calorimeter • Dual-Readout fibre calorimeter

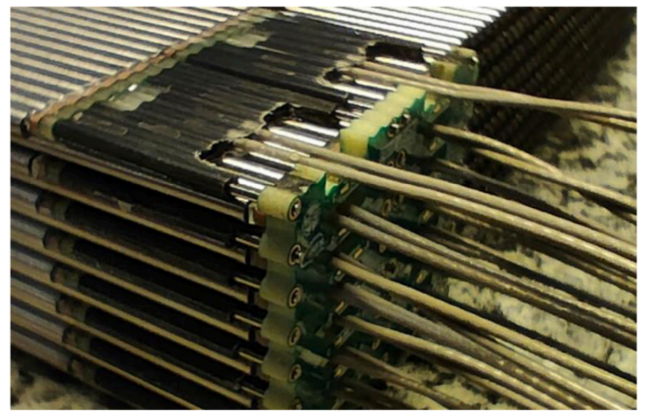




NIM A 1045, 167629 (2022)

W-GAGG crystal fiber R&D synergic to LHCb ECAL upgrade





- Dual readout technique aiming at reducing the fluctuation of electromagnetic fraction (Cherenkov and scintillating light)
- Both fibre based (2 different media) or separating within the same crystal (e.g BGO/PWO-UF)
- Timing information for longitudinal "segmentation"
- Toward high granularity (PF-friendly) with SiPM (or MCP-PMT)

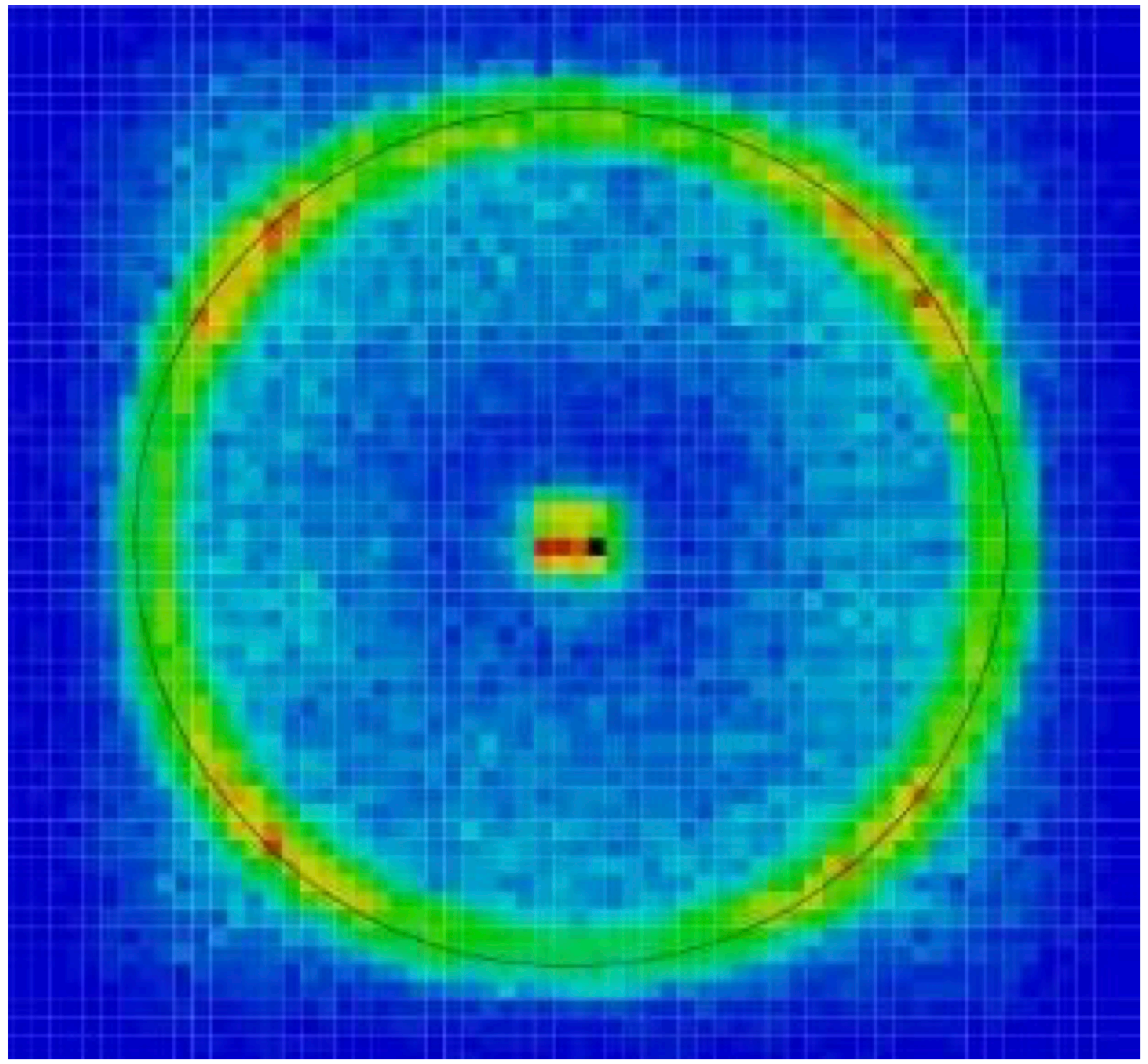
DRD4: photodetectors and PID

Experimental drivers:

- **HL-LHC** (e.g. LHCb and ALICE3) **and future hadron colliders**
  - Operation at higher luminosities, increased background rates, and stricter integration.
  - Upgrades needed for enhanced robustness, rate capability, and precision.
- **FCC-ee experiments**: PID is essential for precision studies of heavy-flavour physics and Z, Higgs, W, and top decays.

G. Gaudio

RICH development main drivers

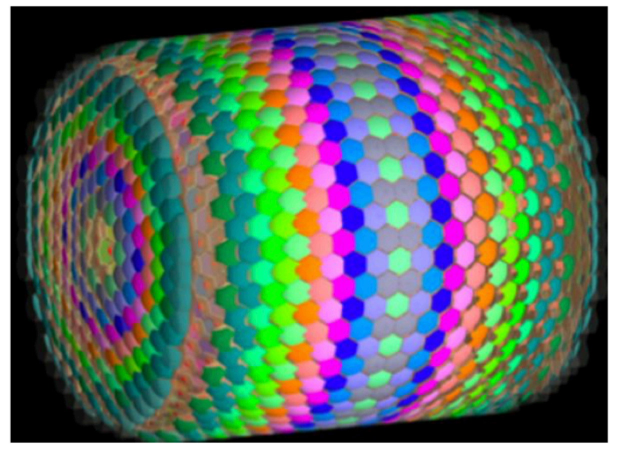


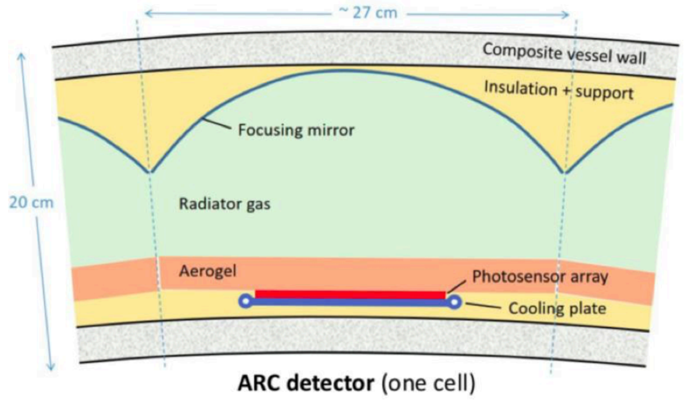
- High Particle Rate:
  - Resolving multiple, overlapping Cherenkov rings (pile-up).
  - Need to handle particle fluxes exceeding (10^5 - 10^6) tracks/cm²/s, avoid signal saturation, and ensure fast recovery.
- Spatial & Time Resolution:
  - Fine pixelation in photon detectors for accurate ring reconstruction.
  - Precision timing (<100 ps) to suppress background (from pile-up and noise).
  - Breakthroughs in pixel density (sub-mm), time resolution (down to 20–50 ps), and minimising optical system aberrations
- Radiation Hardness:
  - Materials and sensors must retain properties/stability under radiation.
  - Anticipated rates increase by x5–x10 (expected fluence > 10^{11}); require more radiation-durable materials, sensor lifetimes >10 years, and rate tolerance beyond MHz/cm² without significant loss/aging

DRD4 photodetectors and PID

G. Gaudio

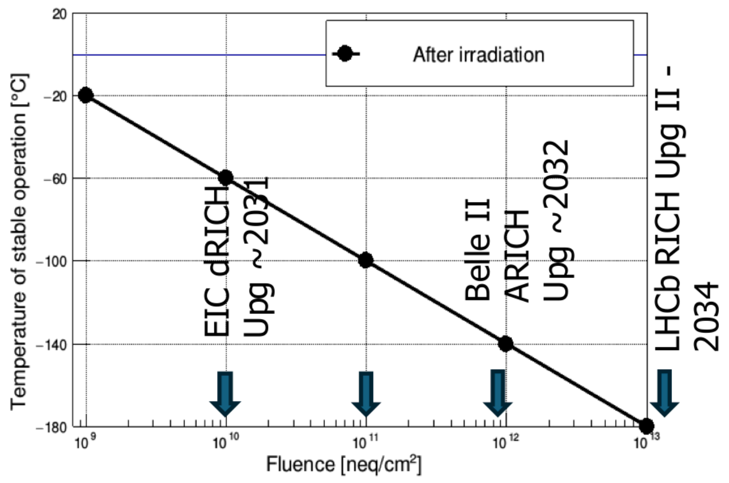
Solid State Single Photon Detectors

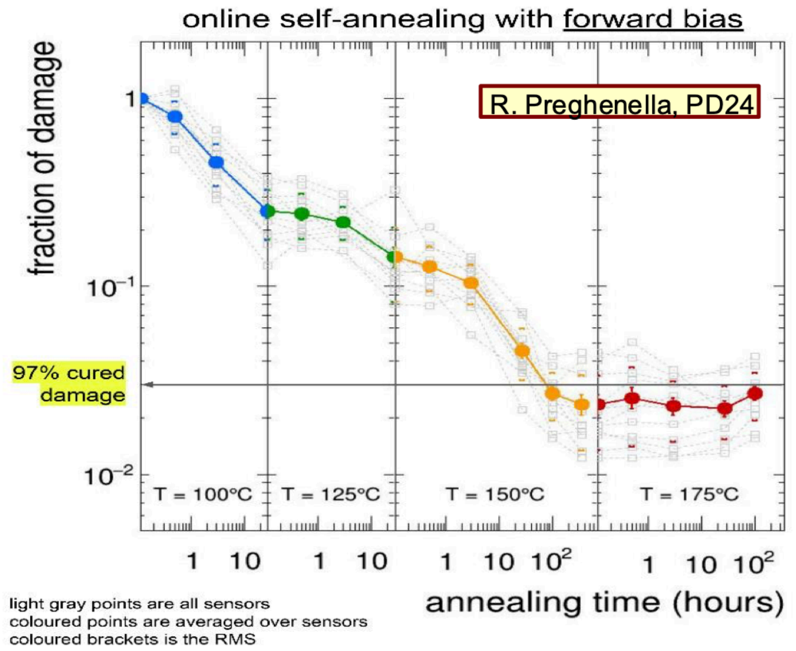




ALICE3 and FCC development based on mix gas and aerogel radiator and SiPM modules with integrated cooling

Current Status: SiPMs offer QE 50%, operation in magnetic fields, fast timing (100 ps), but dark noise and crosstalk remain challenges, especially after irradiation

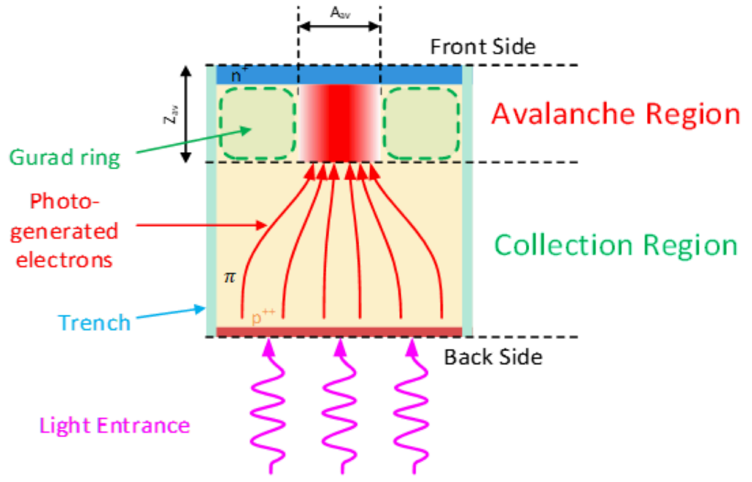


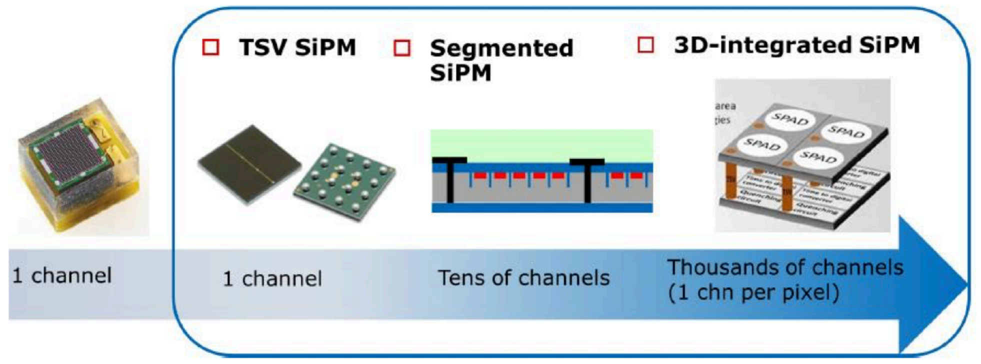


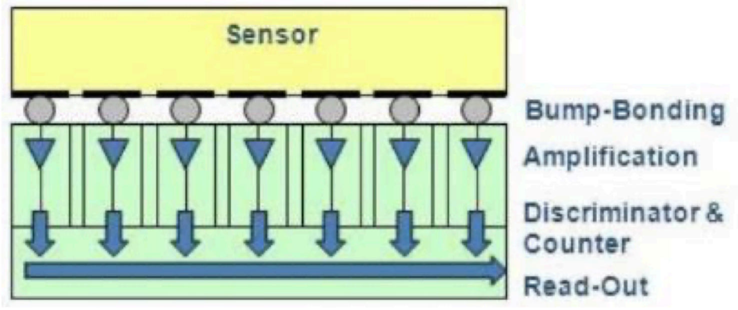
Future Expectations:

- lower dark count rates (<100 kHz/mm²),
- higher tolerance to radiation 10^{12}-10^{13} n/cm²,
- reduced crosstalk (<1%),
- improved QE in deep UV;
- stable operation in strong magnetic fields;
- scalable to larger areas

- Developments:
  - BSI (Backside Illumination) technology for enhanced PDE and radiation tolerance;
  - ultra-granular SiPMs with 2.5D/3D integration (SiPM+integrate RO elx); CMOS-SPAD sensors;
  - blue sky research - alternative materials (SiC, GeC, InGaAs).







DRD5: quantum sensors and emerging technologies

Istituto Nazionale di Fisica Nucleare

Parallel Talk:
M. Doser

Quantum & Emerging Technologies

European Strategy for Particle Physics

#204

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

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

DRD5: different sensors and technologies being investigated:

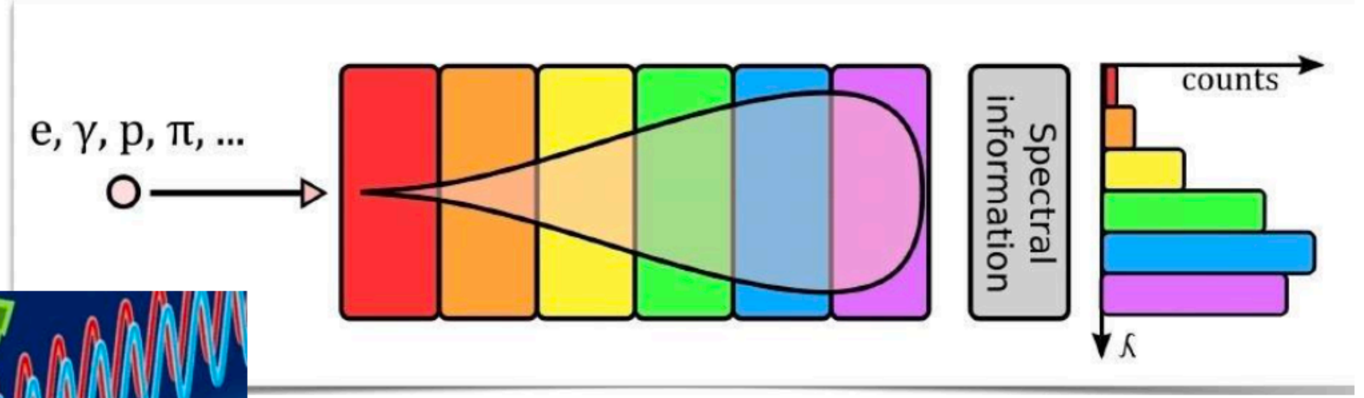
- Novel materials, kinetic detectors, spin-based, superconducting, optomechanical sensors, atoms/molecules/ions, interferometry, …
- Scaling up challenge: single → multi channels
- HEP-relevant topics: Superconducting nanowires, Chromatic calorimetry

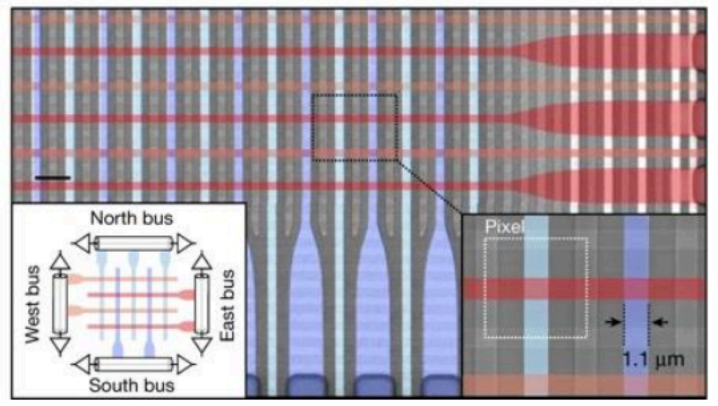
- Many small-scale setups so far. Now first considerations for common infrastructure

Roadmap topics

Proposal WP's

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





© Nature

DRD7: electronics

T. Bergauer

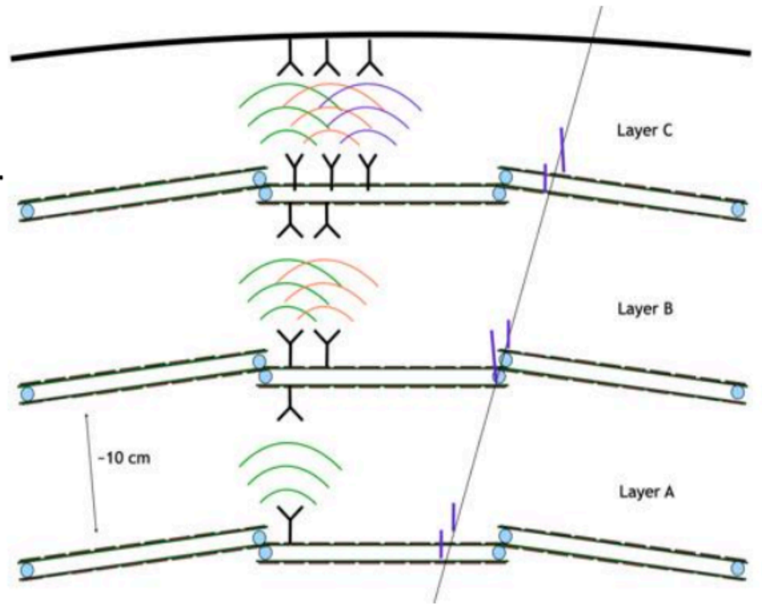
DRD7: Electronics

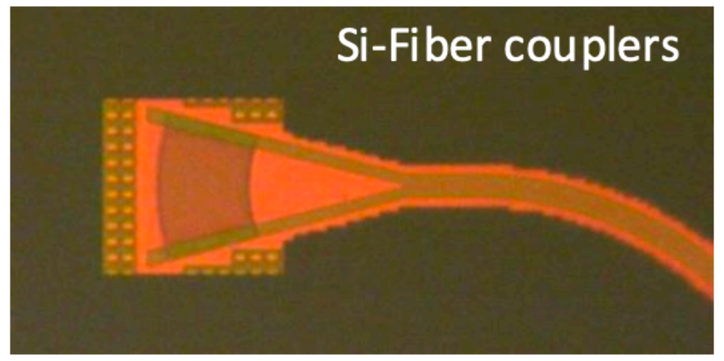
European Strategy for Particle Physics

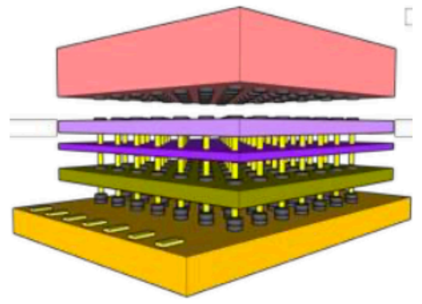
Electronics is vital to any detector system

Modern technologies offer tremendous opportunities:

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





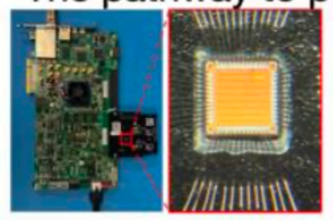


#95

eFPGAs

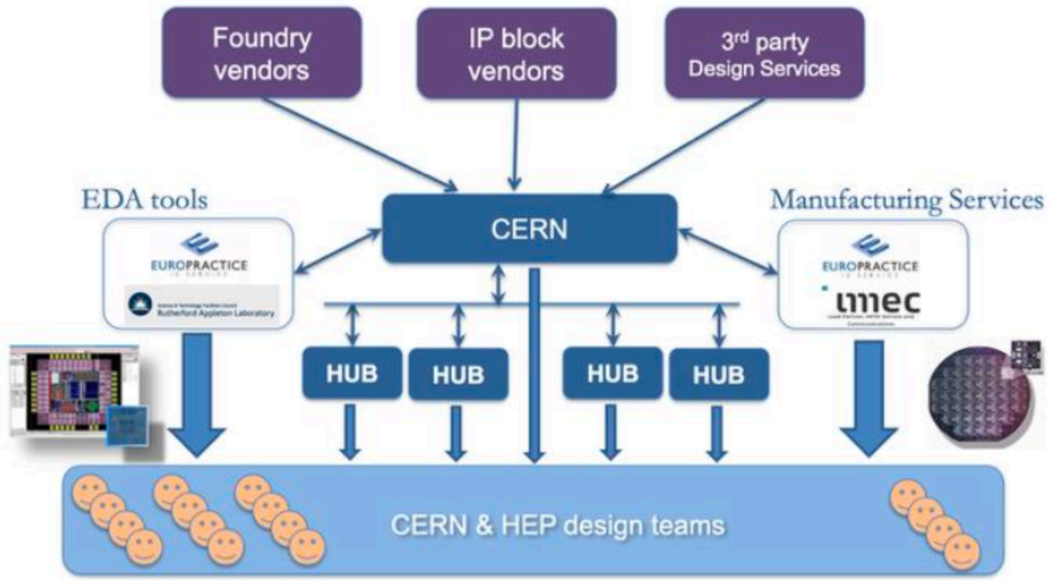
Fully **reconfigurable logic** in ASIC design

- The pathway to put ML on-detector!



BDT classifier in 28nm CMOS ASIC

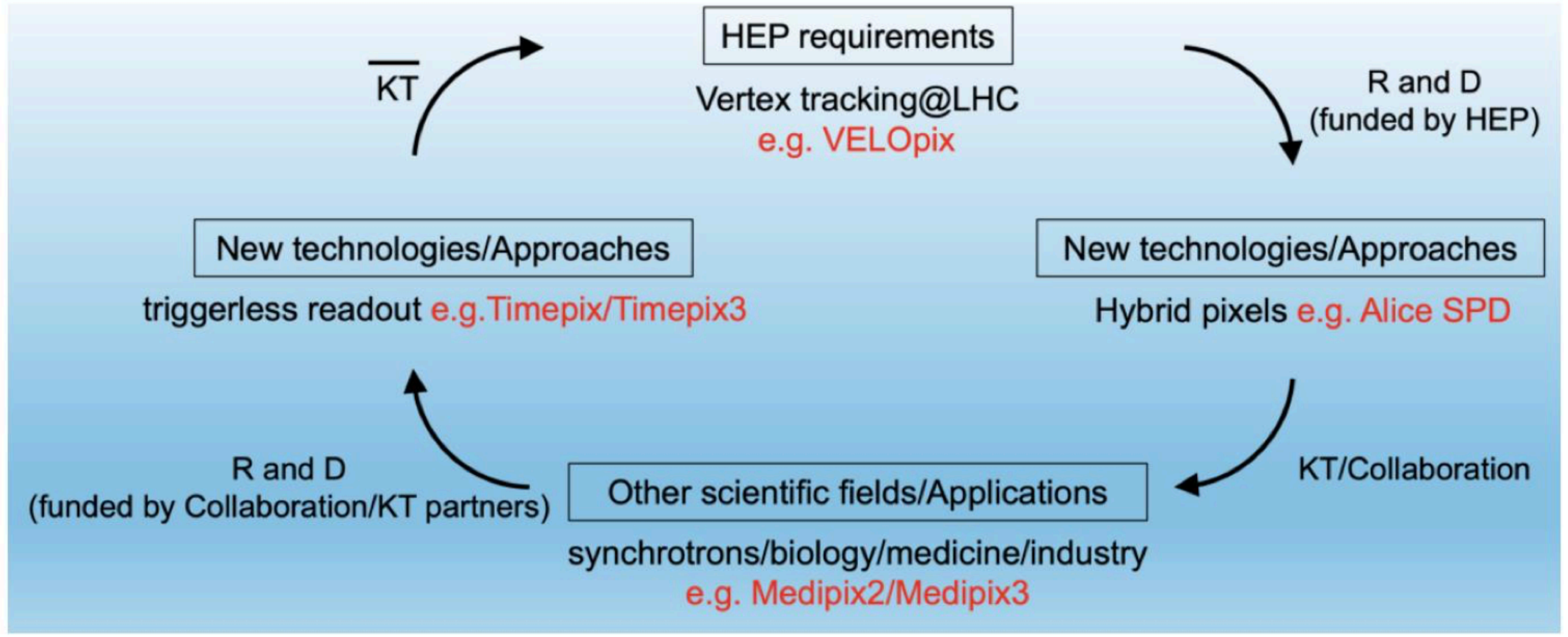
- Work topics in DRD7:
  - **Silicon photonics** transceivers, power distribution, **wireless data transmission** and power, interconnections
  - **Intelligence on the Front-End**: **e-FPGA** and RISC-V SoC
  - COTS and **no-backend solutions**, i.e. directly from FE to DAQ
  - **High Performance ADCs and TDCs** and time distribution
  - **Extreme environments**: cryogenic and radiation-hard electronics
  - **Shared access and hubs** to selected imaging technologies and 3D integration



MediPix/TimePix
A Model for Experiment-Agnostic Development

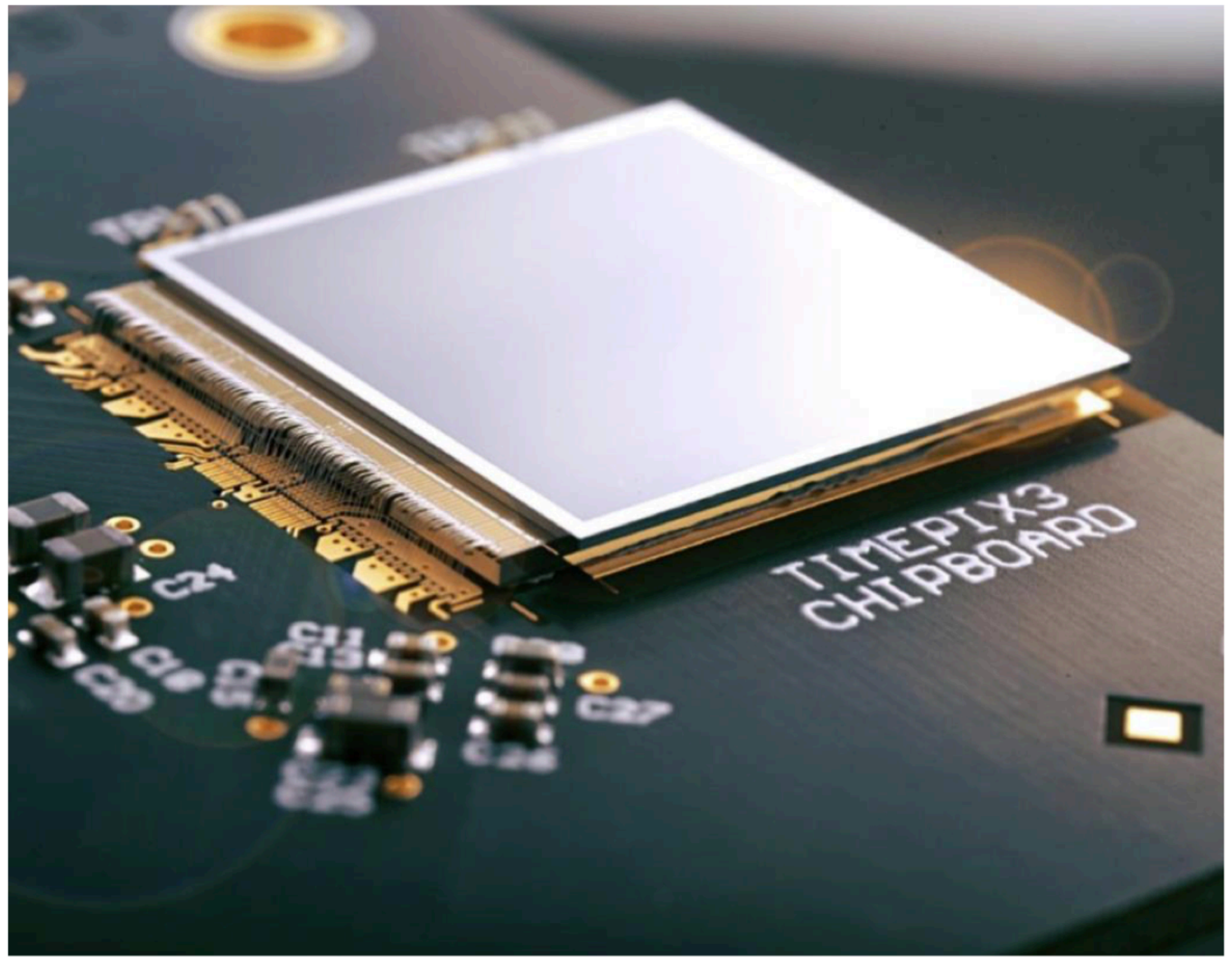
F. Simon

An example of an HEP-driven development that evolved into much broader applications



- Further generalizing activities can add additional dynamics, new ways of funding developments: Fewer developments with higher volumes – involving communities well outside of HEP.

ESPPU input #161: "Call for a new approach to detector developments involving microelectronics"



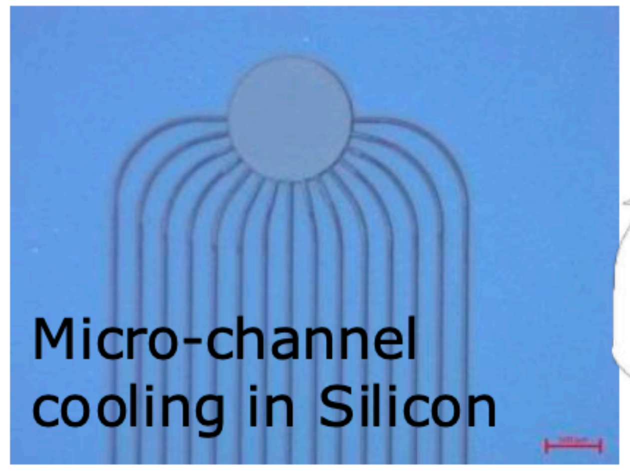
DRD8: mechanics and integration

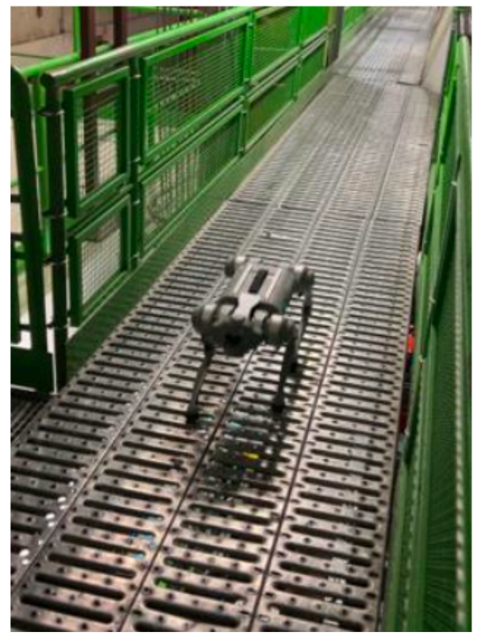
T. Bergauer

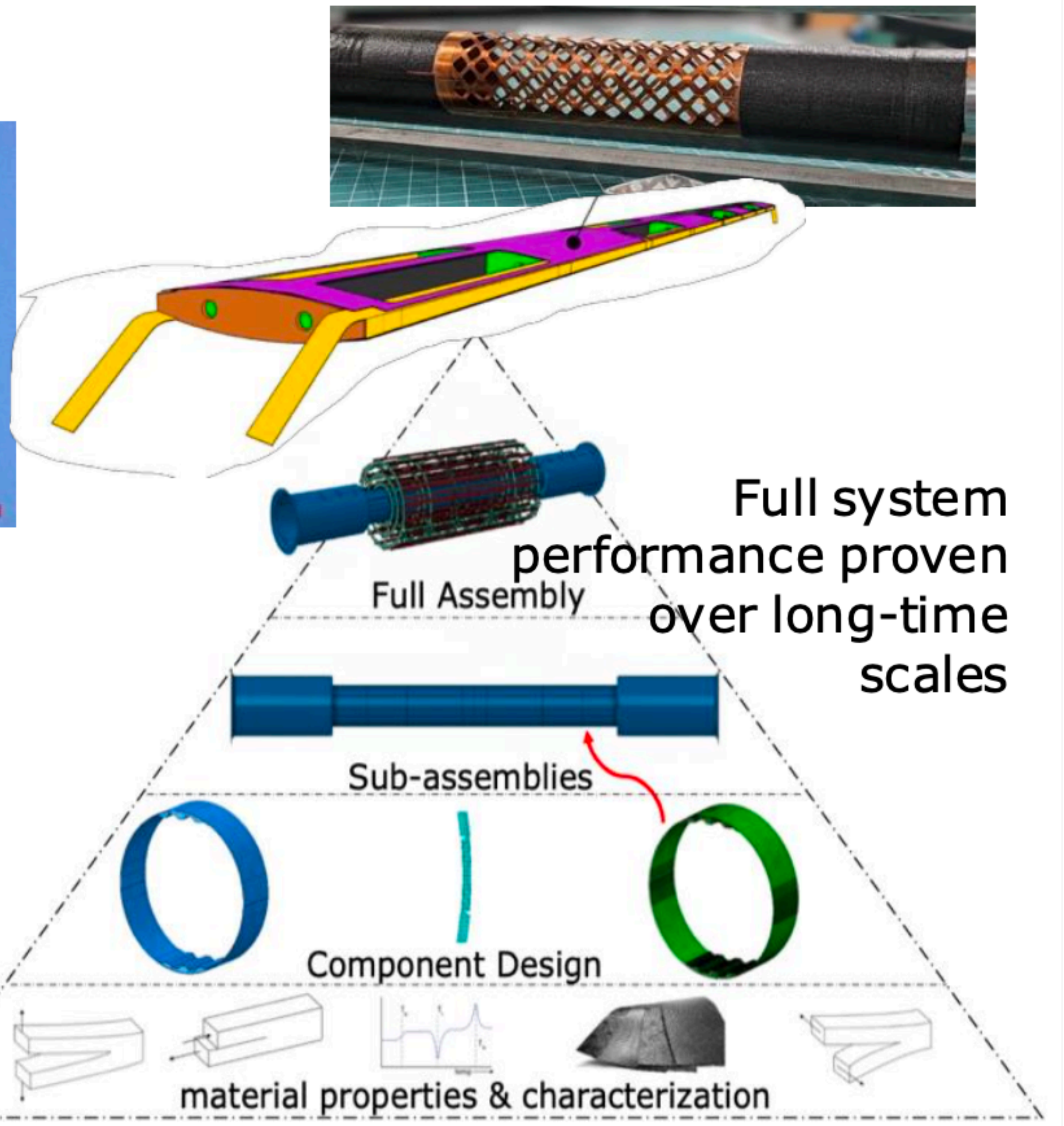
- DRD8 proposal approved by Dec 2024
  - Does not cover all DRDTs, as they are quite diverse
  - Focus on vertex detector mechanics and cooling as emerged from “Forum on Tracker Mechanics” workshop series

- **Advanced materials** and structures for **vertex detectors:**
  - Mechanics for curved sensors, Thin beam pipe, Retractable detectors, MDI, Low-mass hardware, alignment
  - Characterization of Material properties and database
- **Cooling**: Airflow, Evaporative CO_2 and new fluids (Krypton), Microchannel cooling in Si, Cooling tubes welding and material investigations
- **Robots** and **Virtual reality** to simulate/remote control access in restricted areas
- **Software** tools to connect engineering design with physics simulation (e.g. connect GEANT4 with CAD)

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







Summary and conclusions

Istituto Nazionale di Fisica Nucleare

- As you have seen there is a very long lists of R&D activities for detector technologies
- **Next generation of detectors (LHCb Upgrade 2, ALICE 3, ePIC etc.) is approaching the TDR phase**
- **Concepts for detectors at ee colliders are already at a mature level, technologies developments proceed at full pace**
- **Convincing concepts for Muon Collider detectors already exist, and they are going through significative developments. Technologies R&D in sinergy with HL-LHC and ee colliders**
- **The FCChh detector is the most challenging system ever thought, but we have time to develop it**
- **The DRD collaborations have taken these challenges and will bring us to the future of HEP measurements!**

Thanks for your attention!