European Strategy for Particle Physics

PLENARY / **DETECTOR TECHNOLOGIES**

Tools for Discovery

Instrumentation Requirements for Future Projects

Ulrich Husemann (KIT)

23-27 JUNE 2025 Lido di Venezia

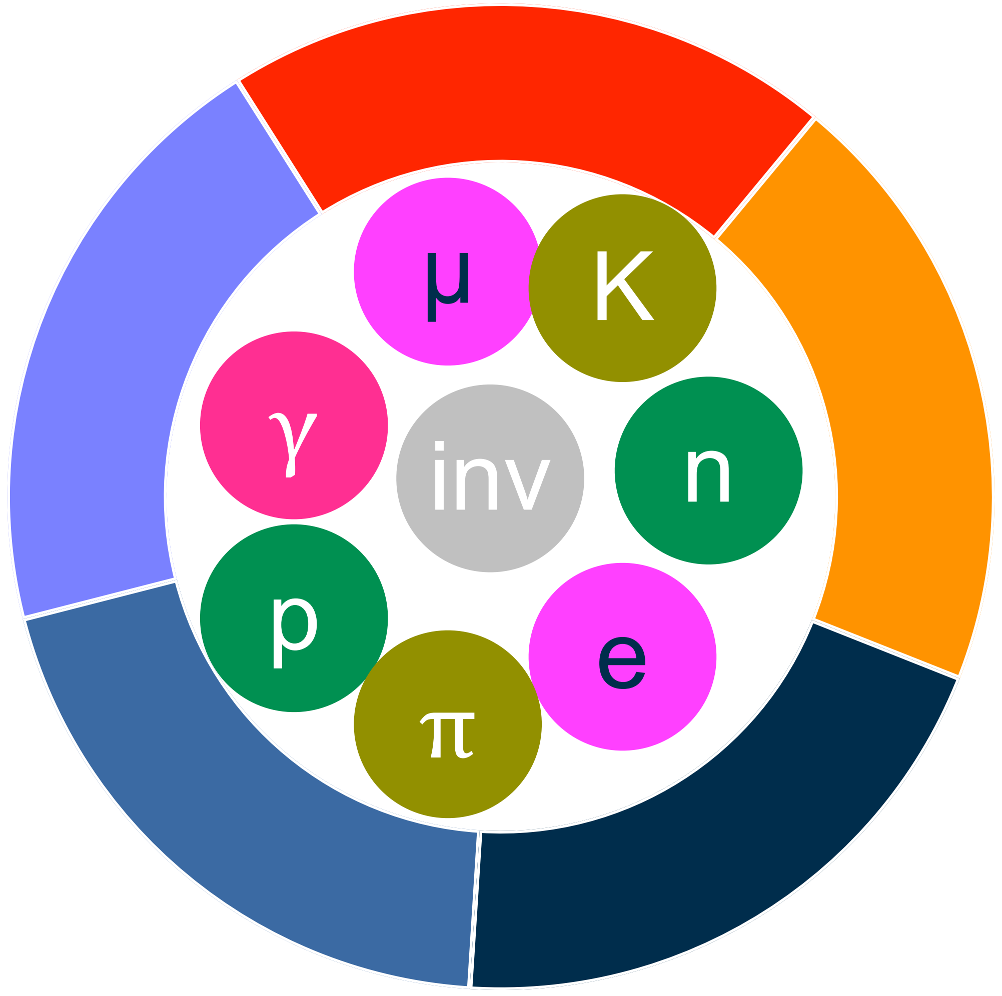
Setting the scene

European Strategy
for Particle Physics

KIT

Particle Physics – a Tool-Driven Scientific Field

(See e.g. Galison: *Image and Logic*)

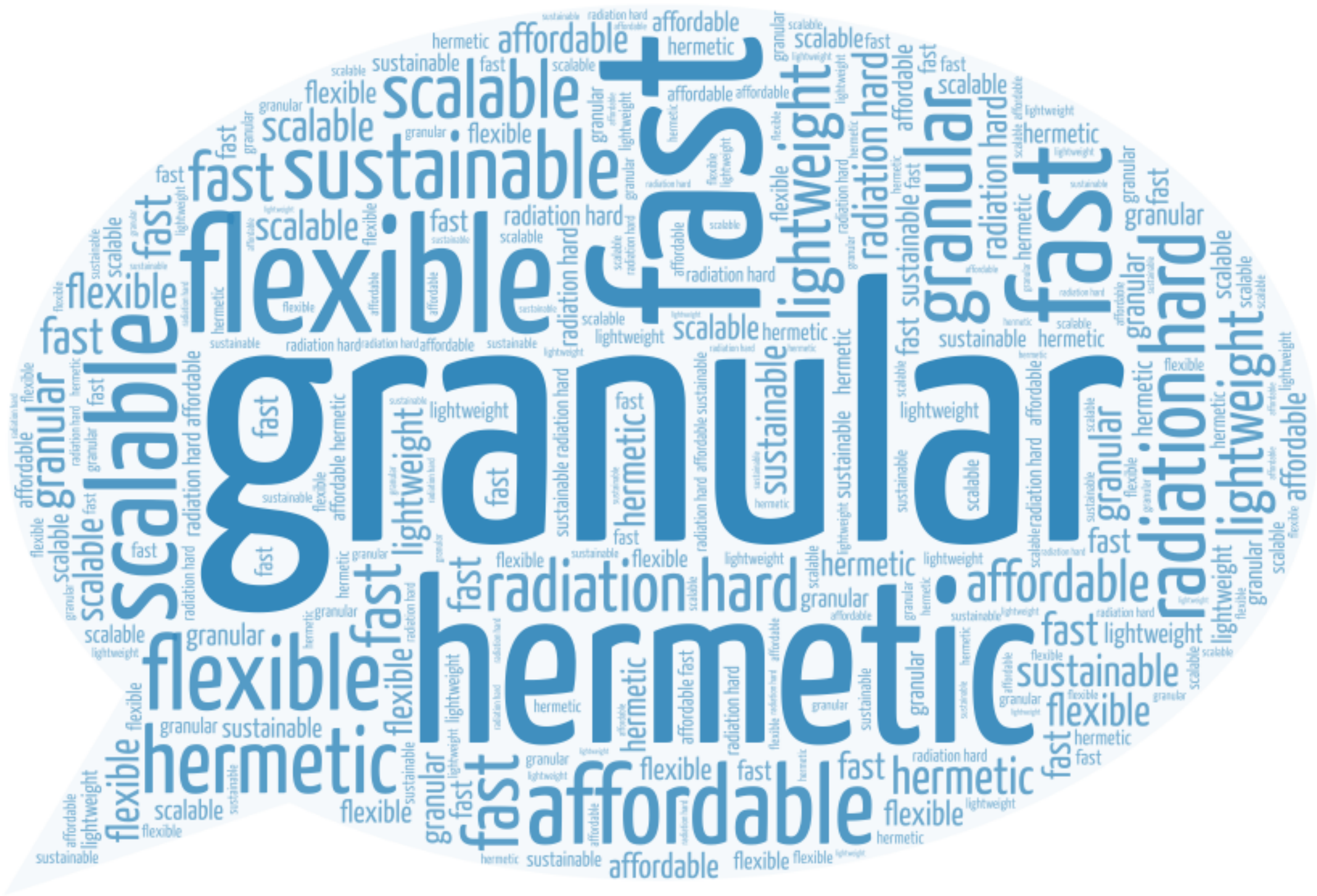


Unraveling the physics of elementary particles and their interactions: **sophisticated tools** required
→ **particle detectors, electronics** and **software/AI**

Basic detection task (seemingly) simple:
collect **full information** of **all** final state particles

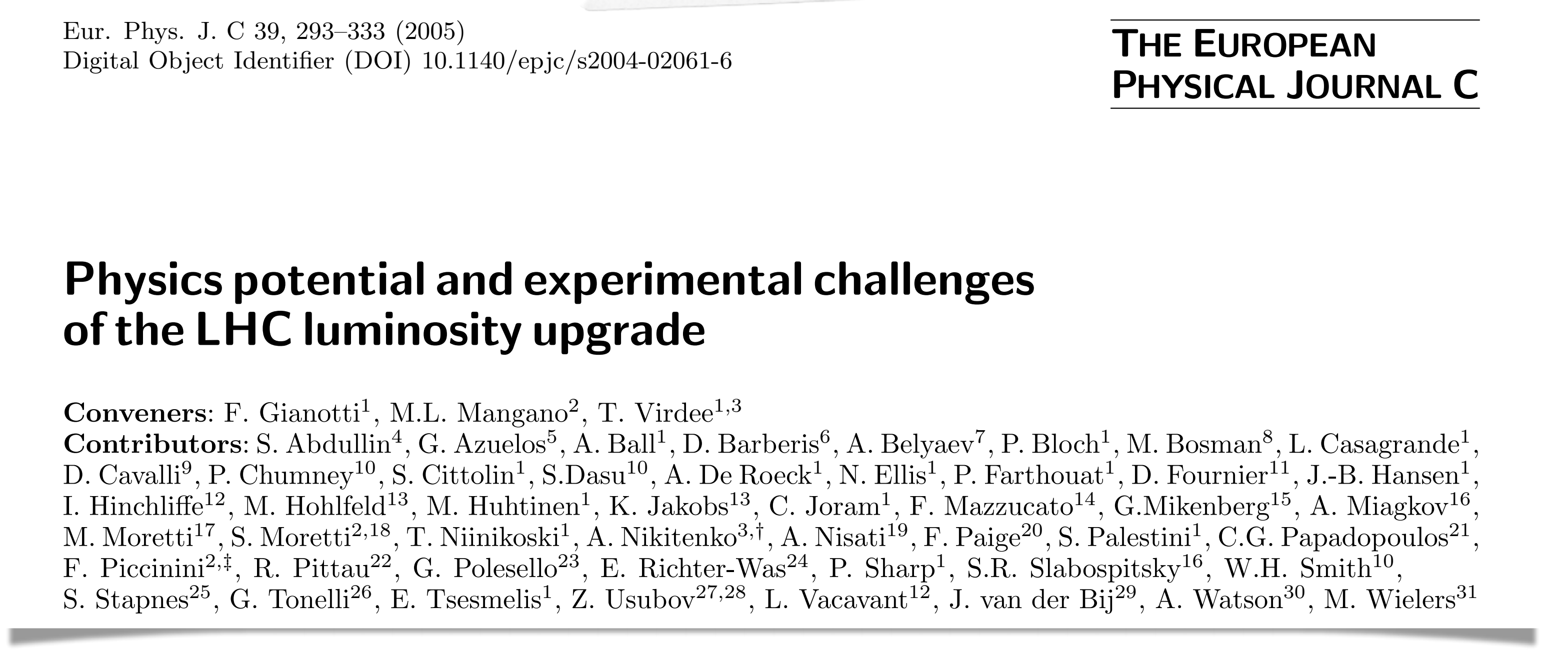
A more detailed look reveals:

- Wide variety of technology **requirements**
- Very different **time scales** and technological **maturity**
- Widely varying **cost** and technology **dependencies**
- Very different availability of **skilled people** and **funding**



From R&D to Large Detectors

Typical Development Cycles: 20–30 Years


Eur. Phys. J. C 39, 293–333 (2005)
Digital Object Identifier (DOI) 10.1140/epjc/s2004-02061-6

THE EUROPEAN PHYSICAL JOURNAL C

Physics potential and experimental challenges of the LHC luminosity upgrade

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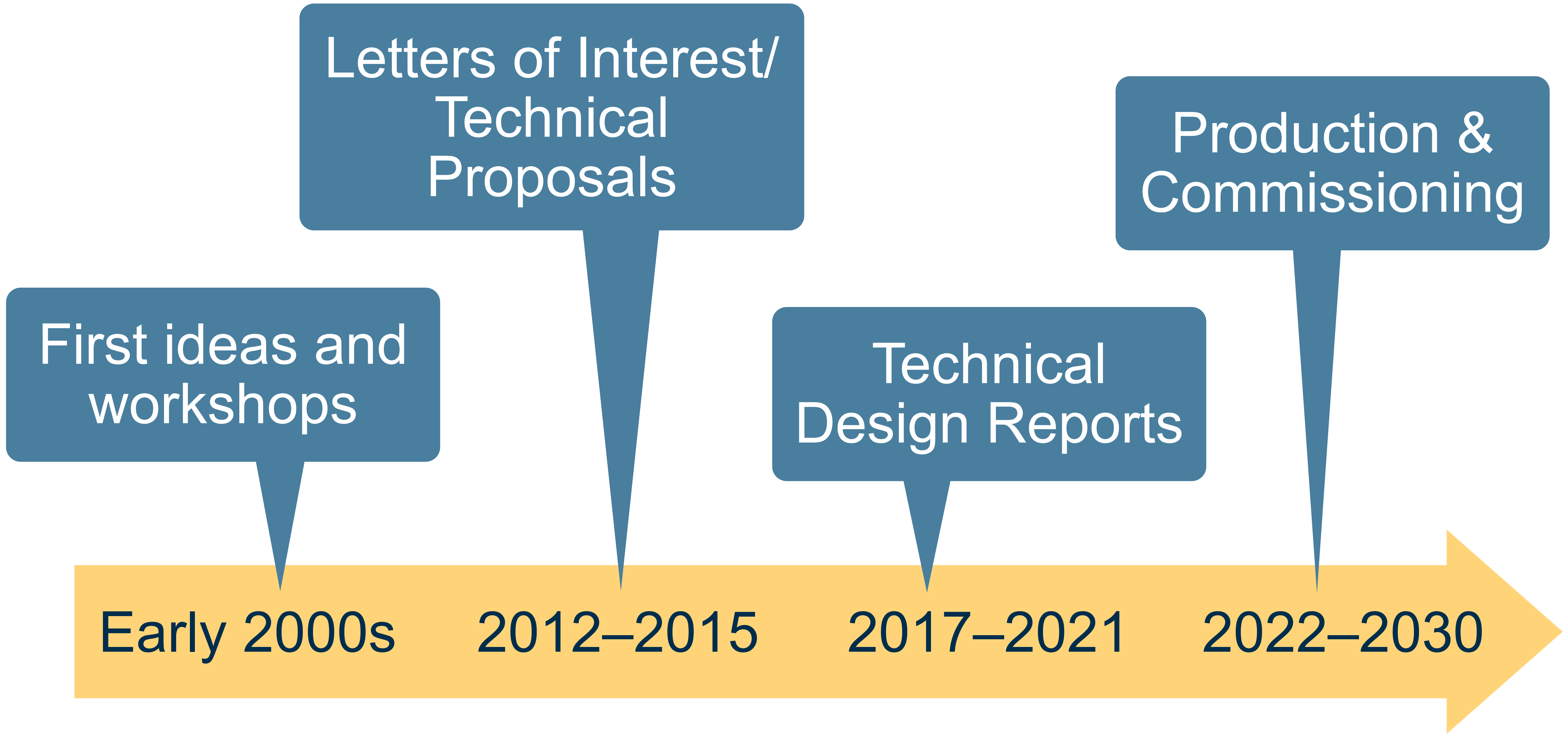
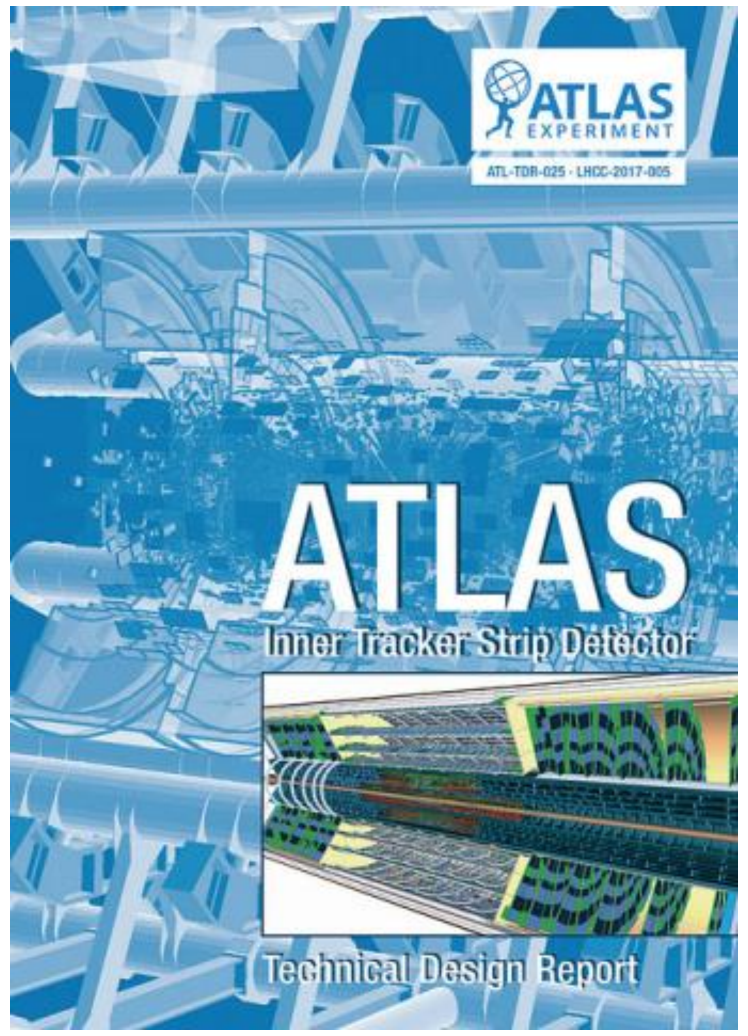
Contributors: S. Abdullin[4], G. Azuelos[5], A. Ball[1], D. Barberis[6], A. Belyaev[7], P. Bloch[1], M. Bosman[8], L. Casagrande[1], D. Cavalli[9], P. Chumney[10], S. Cittolin[1], S.Dasu[10], A. De Roeck[1], N. Ellis[1], P. Farthouat[1], D. Fournier[11], J.-B. Hansen[1], I. Hinchliffe[12], M. Hohlfeld[13], M. Huhtinen[1], K. Jakobs[13], C. Joram[1], F. Mazzucato[14], G.Mikenberg[15], A. Miagkov[16], M. Moretti[17], S. Moretti[2,18], T. Niinikoski[1], A. Nikitenko[3,†], A. Nisati[19], F. Paige[20], S. Palestini[1], C.G. Papadopoulos[21], F. Piccinini[2,‡], R. Pittau[22], G. Polesello[23], E. Richter-Was[24], P. Sharp[1], S.R. Slabospitsky[16], W.H. Smith[10], S. Stapnes[25], G. Tonelli[26], E. Tsesmelis[1], Z. Usubov[27,28], L. Vacavant[12], J. van der Bij[29], A. Watson[30], M. Wielers[31]

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





Smaller-scale experiments: **shorter** development cycles, more **agile**

The world is **changing fast** around us new, e.g. materials science, quantum technologies, AI

Outline of the Presentation

Metrics and Guiding Questions

Useful **metrics** to evaluate instrumentation projects in detail: **key performance indicators** (KPIs) and **technology readiness levels** (TRLs)

This presentation: less quantitative
→ attempt to answer **three guiding questions**:

- Which **future projects drive** instrumentation development?
- Which **technologies** are **required** on which **timescale**?
- **Who will work** on instrumentation?

Source: Shutterstock

Which future projects drive instrumentation development?

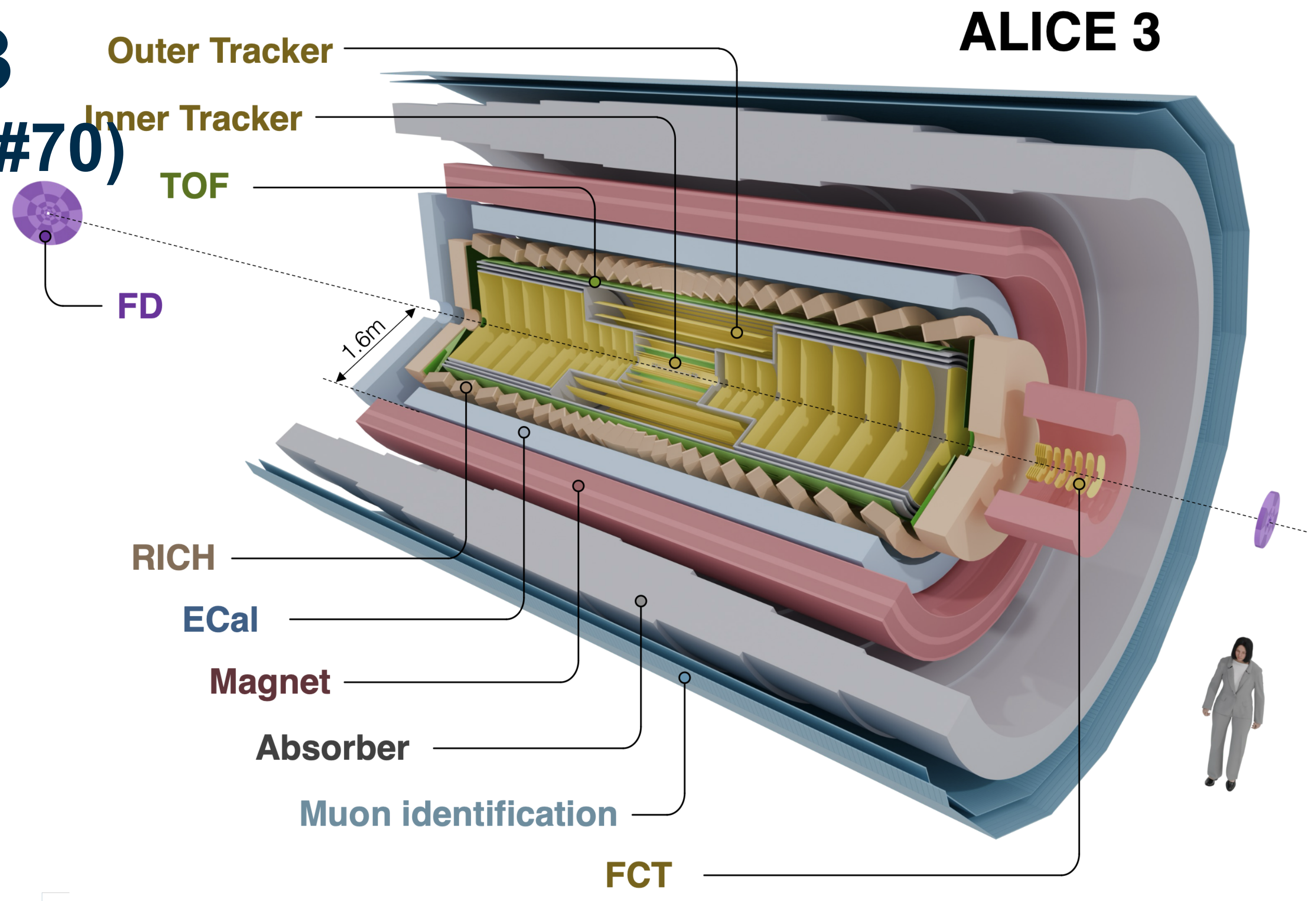
European Strategy
for Particle Physics

A Simplified Timeline

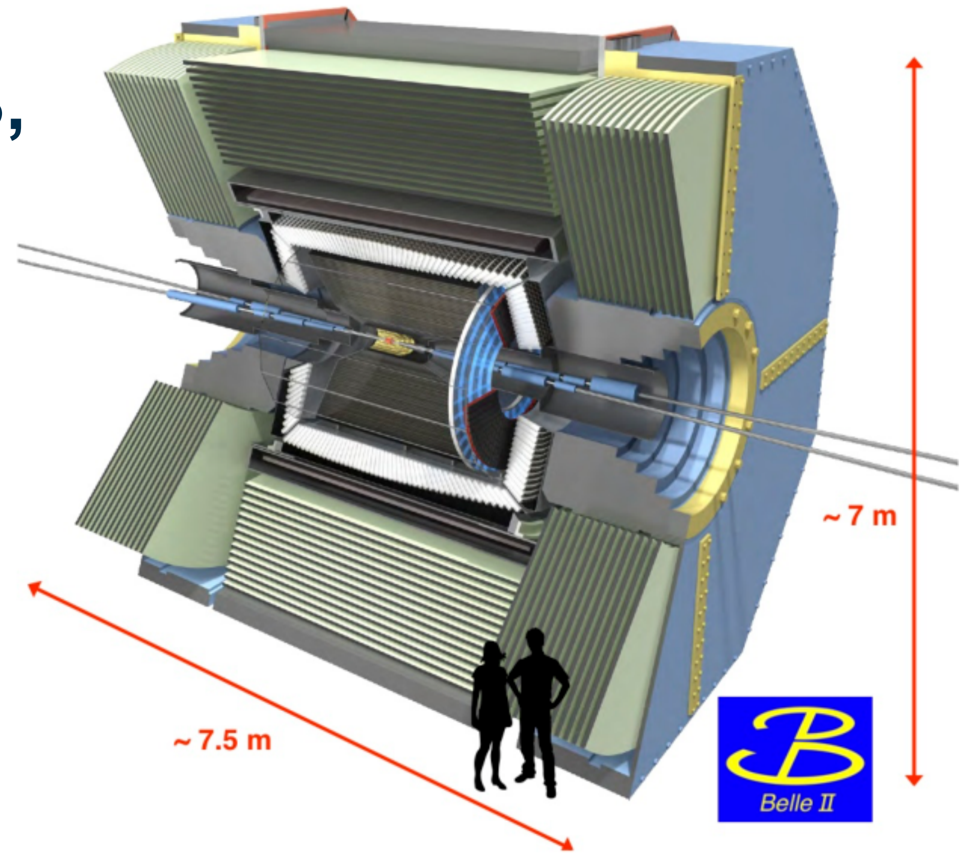
Key Collider Projects

- **Era 1: ALICE 3, LHCb Upgrade II, Belle II, ePIC**

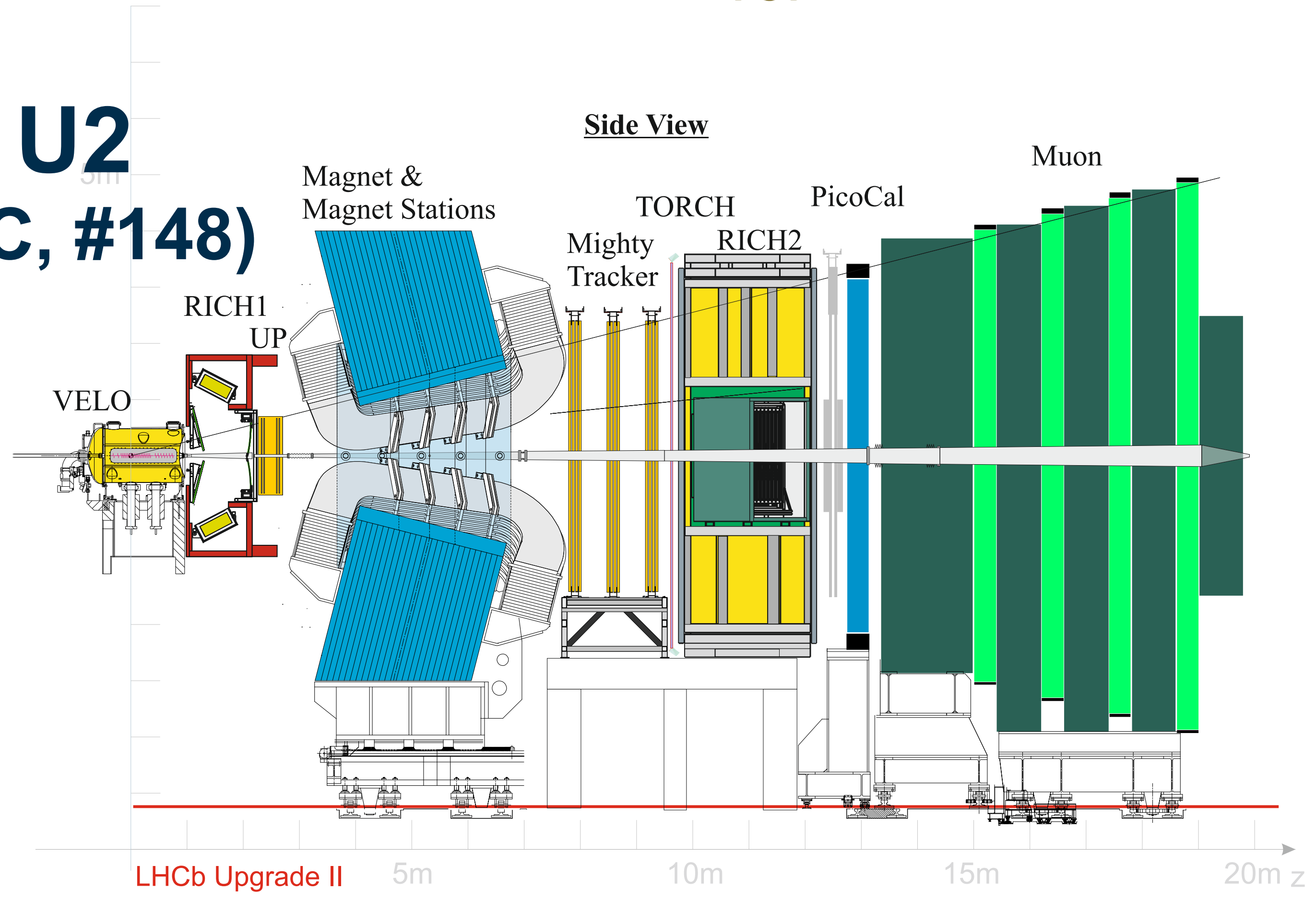
ALICE 3
(HL-LHC, #70)

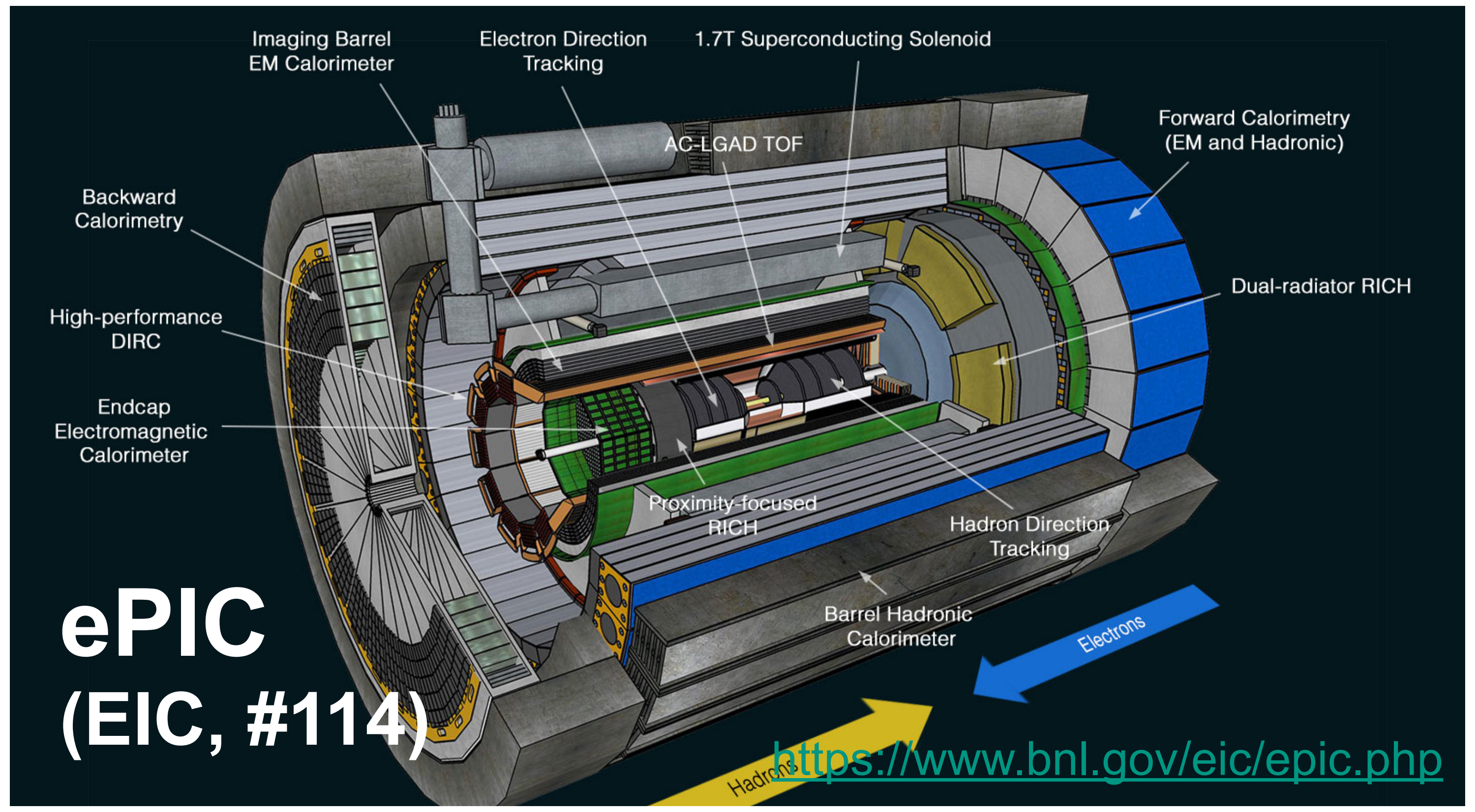


Belle II
(SuperKEKB, #205)



LHCb U2
(HL-LHC, #148)

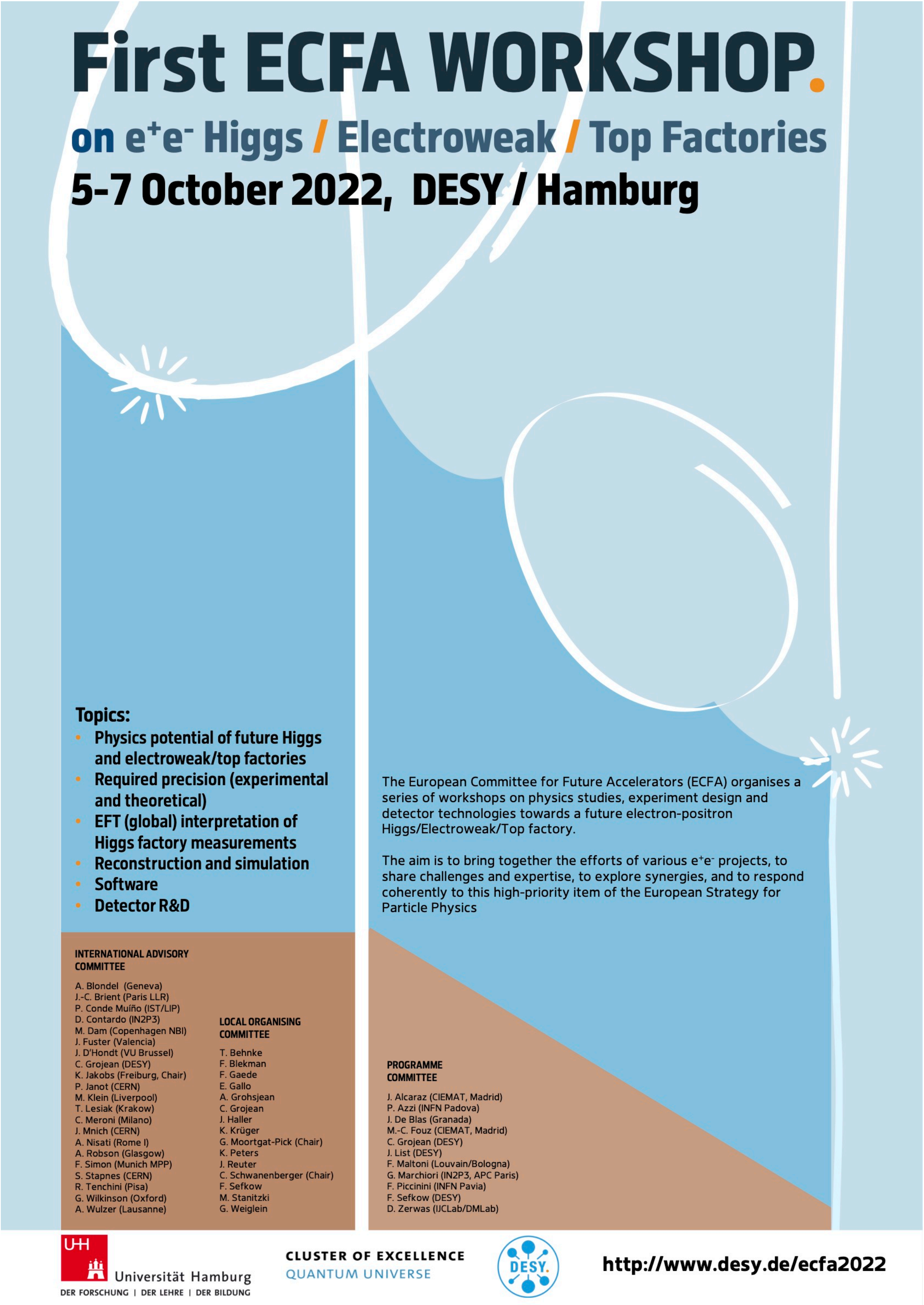


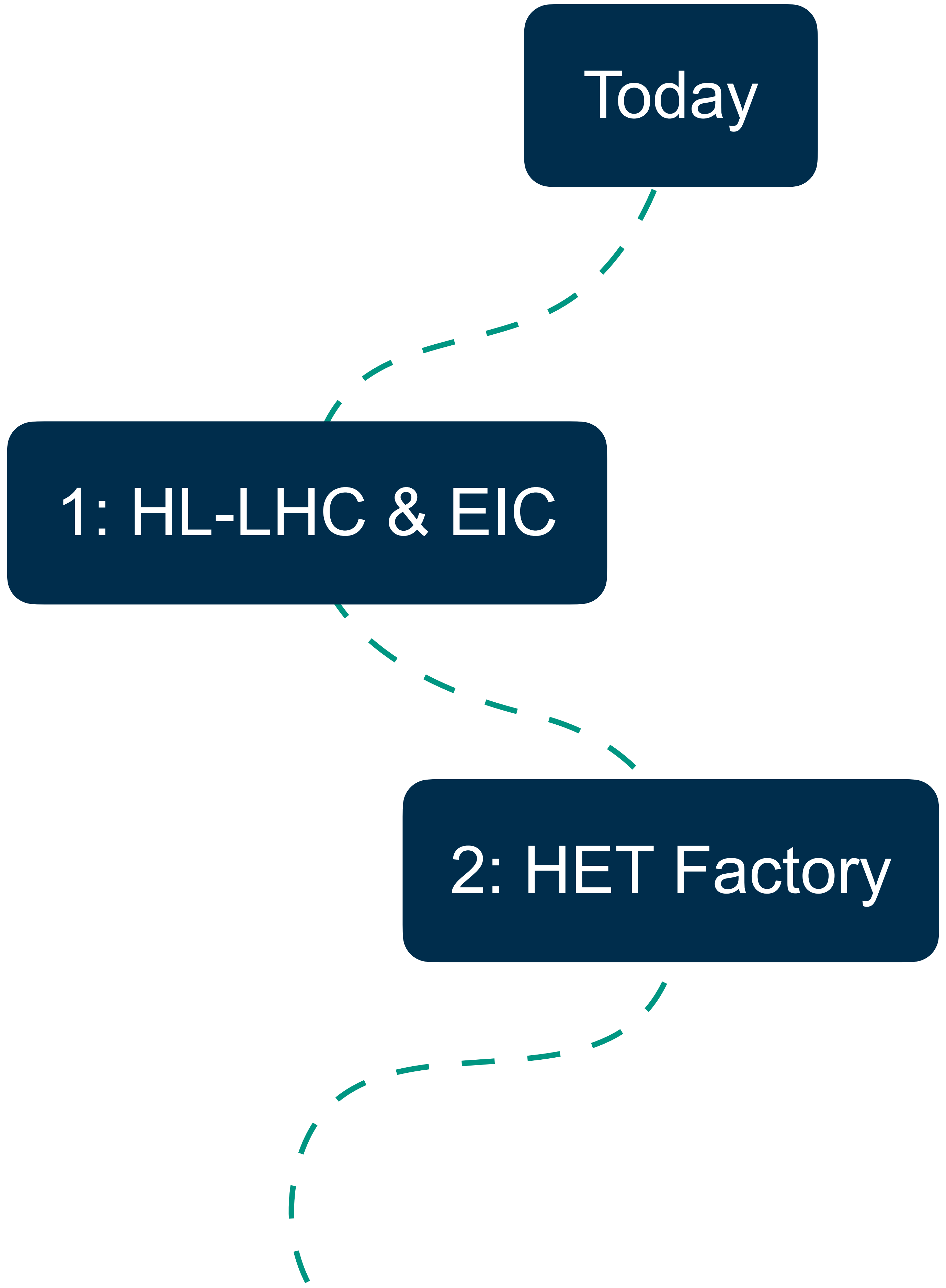


A Simplified Timeline

Key Collider Projects

- Era 1: ALICE 3, LHCb Upgrade II, Belle II, ePIC
- **Era 2: Higgs/Electroweak/Top (HET) factory**

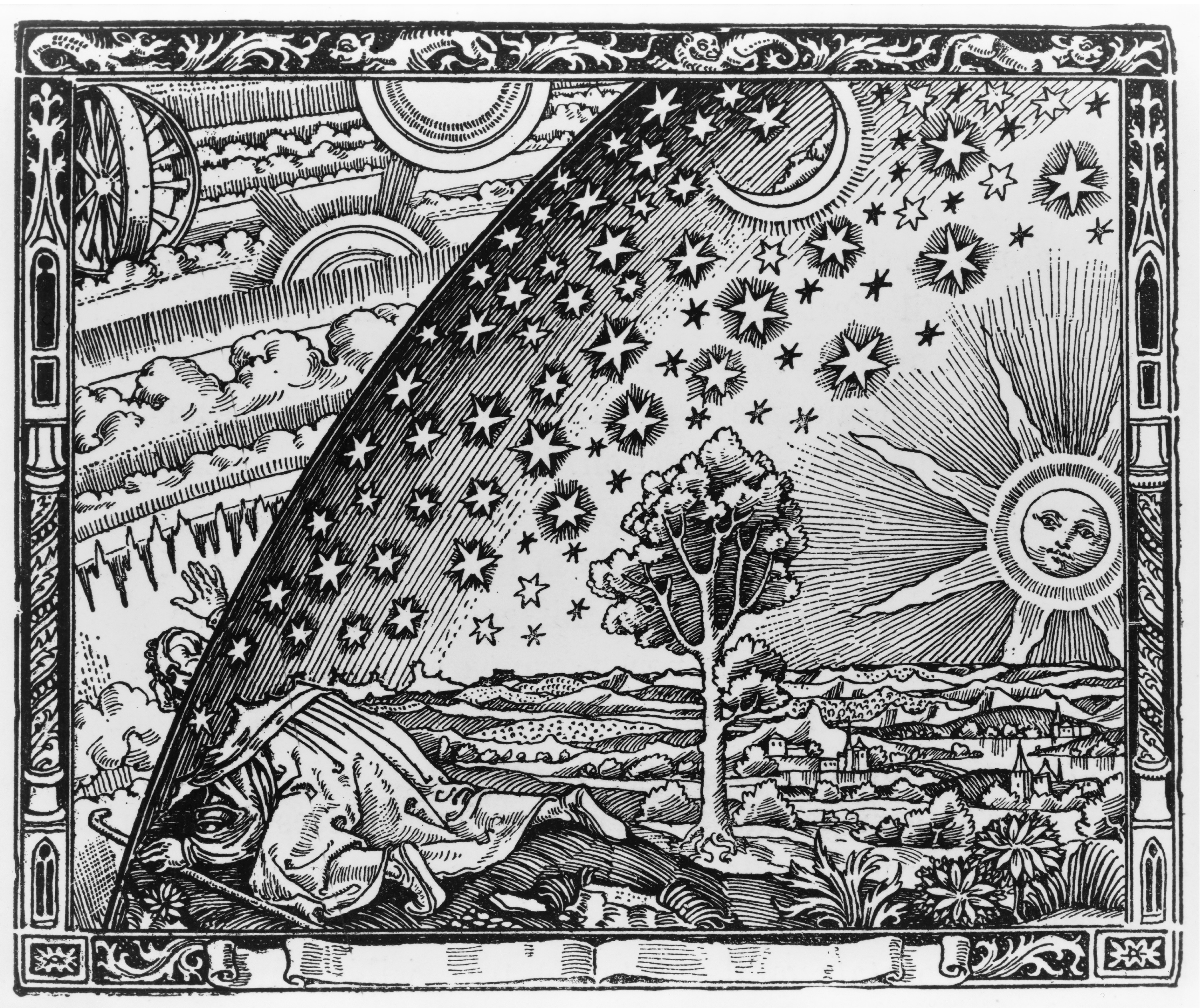




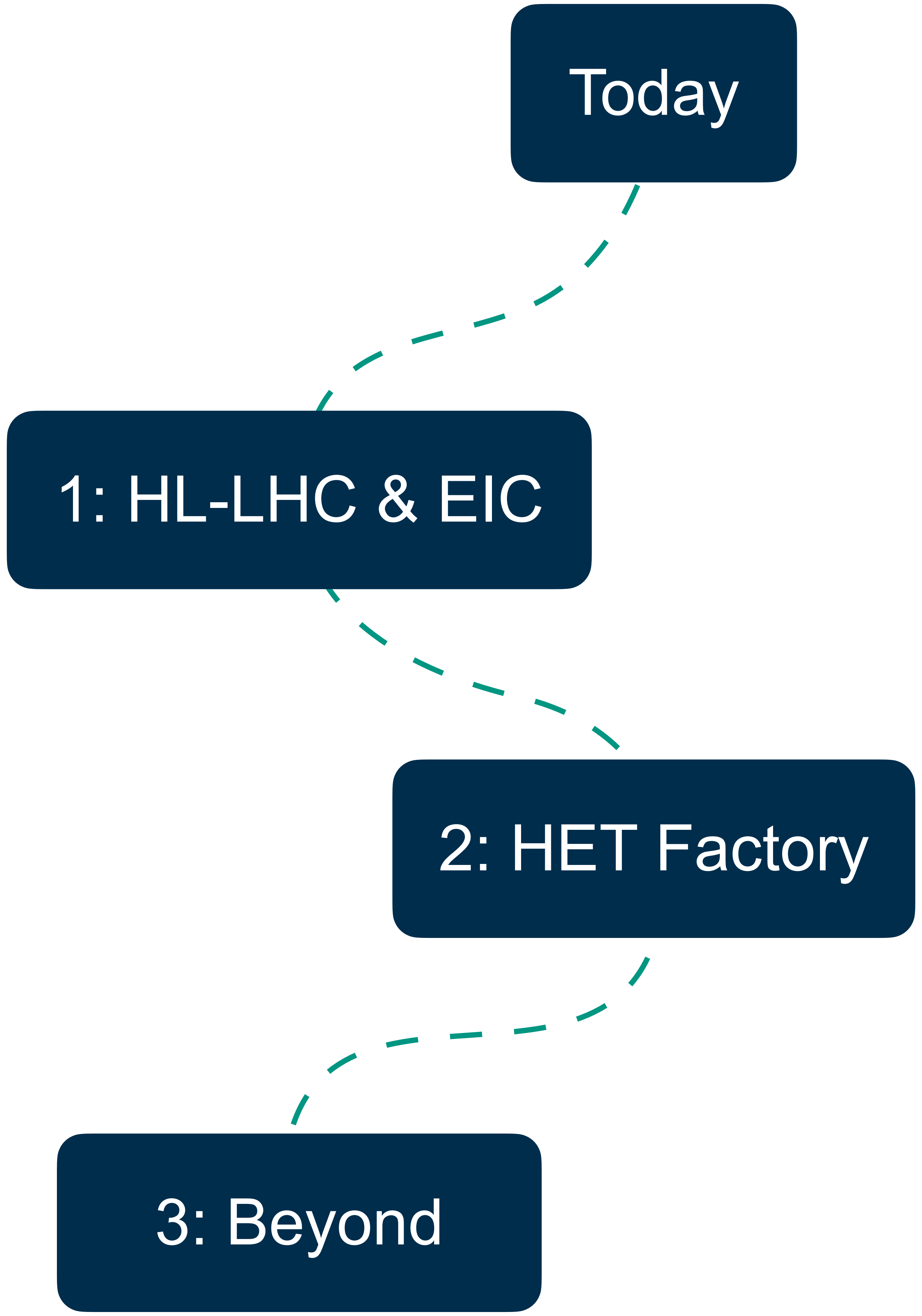
A Simplified Timeline

Key Collider Projects

- Era 1: ALICE 3, LHCb Upgrade II, Belle II, ePIC
- Era 2: Higgs/Electroweak/Top (HET) factory
- **Era 3: Beyond**



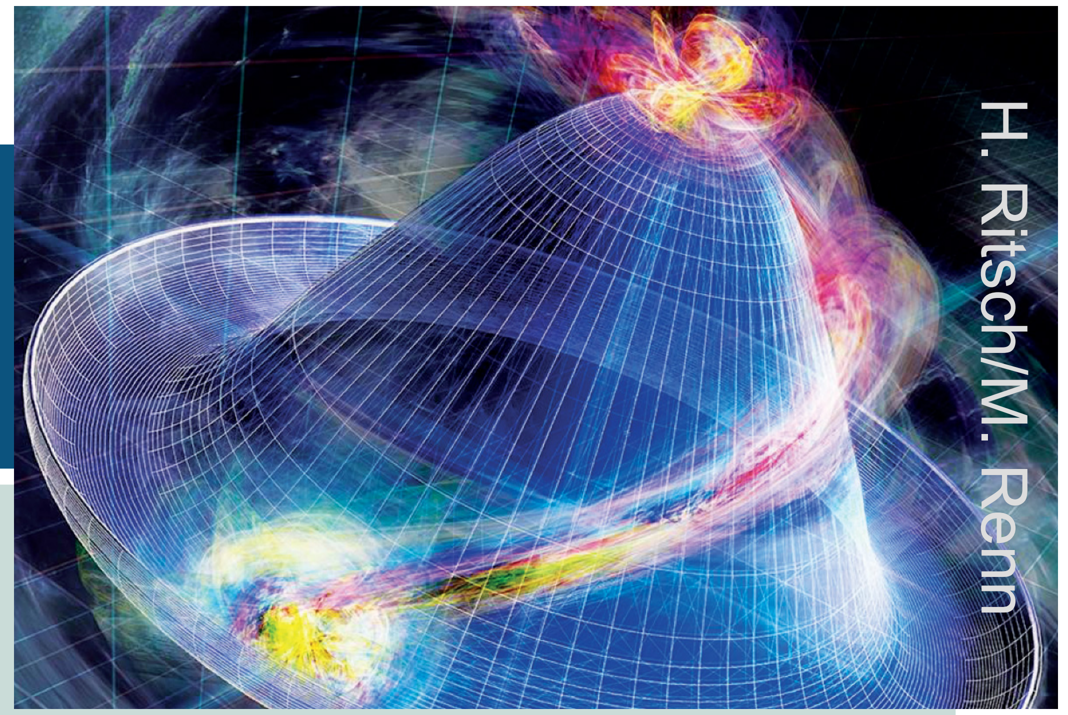
C. Flammarion, *L'atmosphère : météorologie populaire*

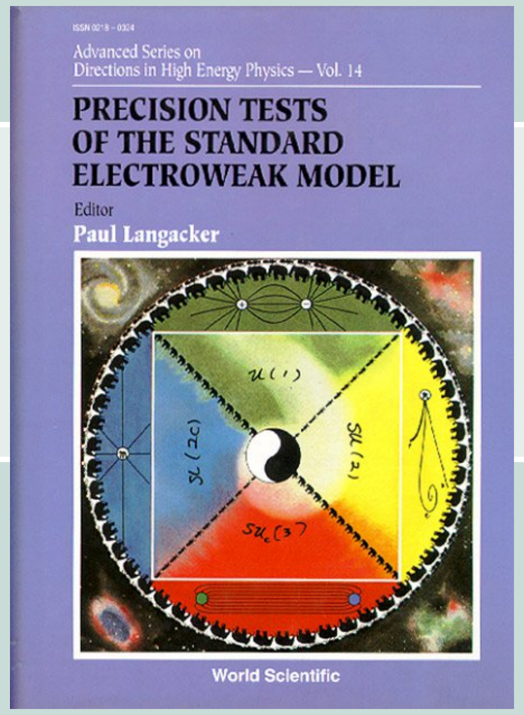


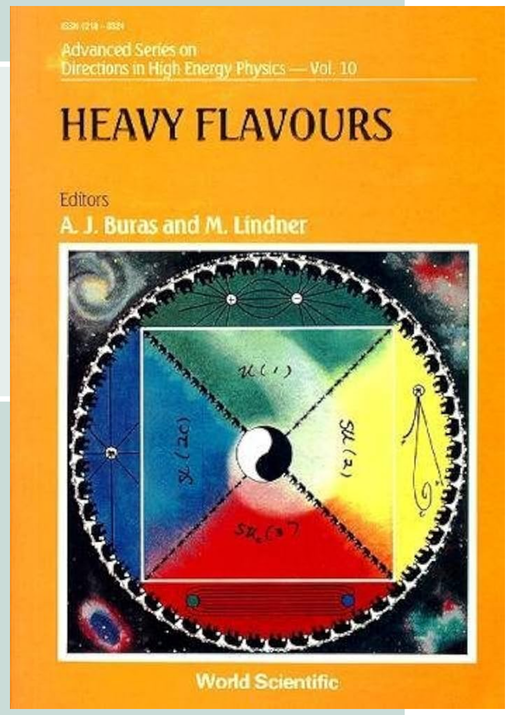
Requirements for Era 2: Higgs/Electroweak/Top Factory

From Physics Goals to Instrumentation Challenges, #141
Parallel Session: F. Palla

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**







Example: HET Detector Concepts

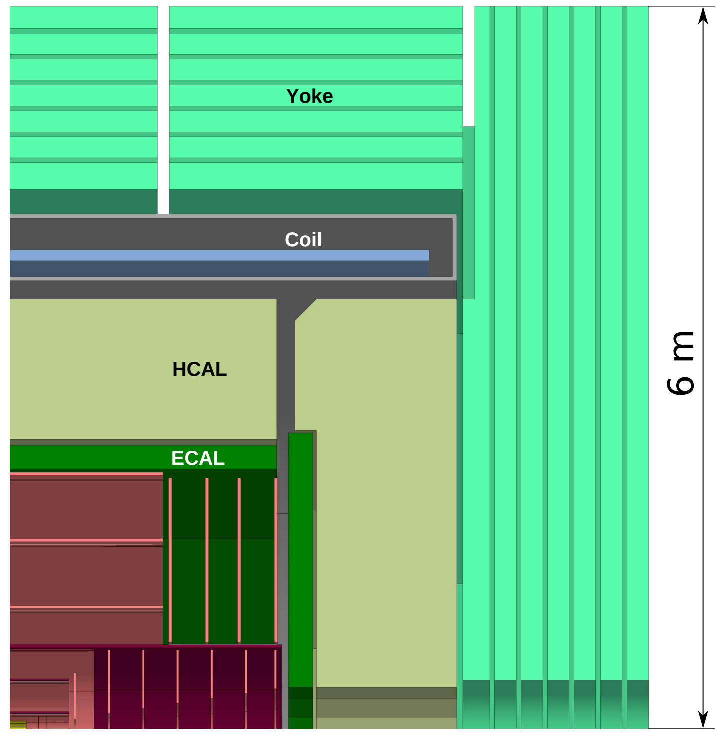
A Link between Requirements and Technology, #94, #95, #102, #211
Parallel Session: F. Palla

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

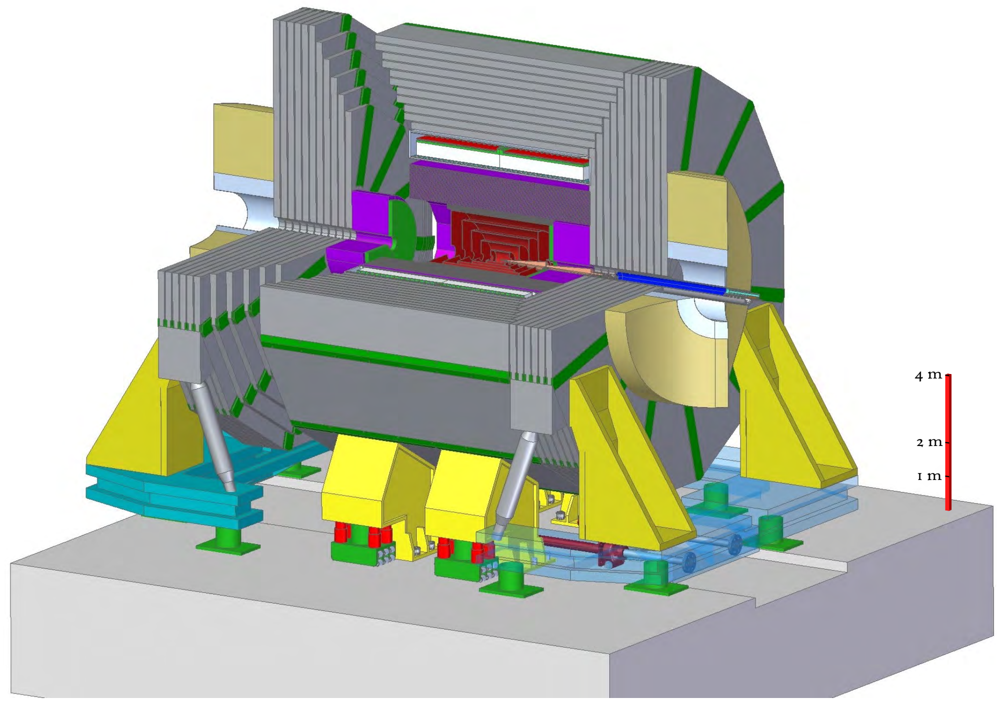
*evolutions from detector concepts for CLIC (#78) and ILC

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

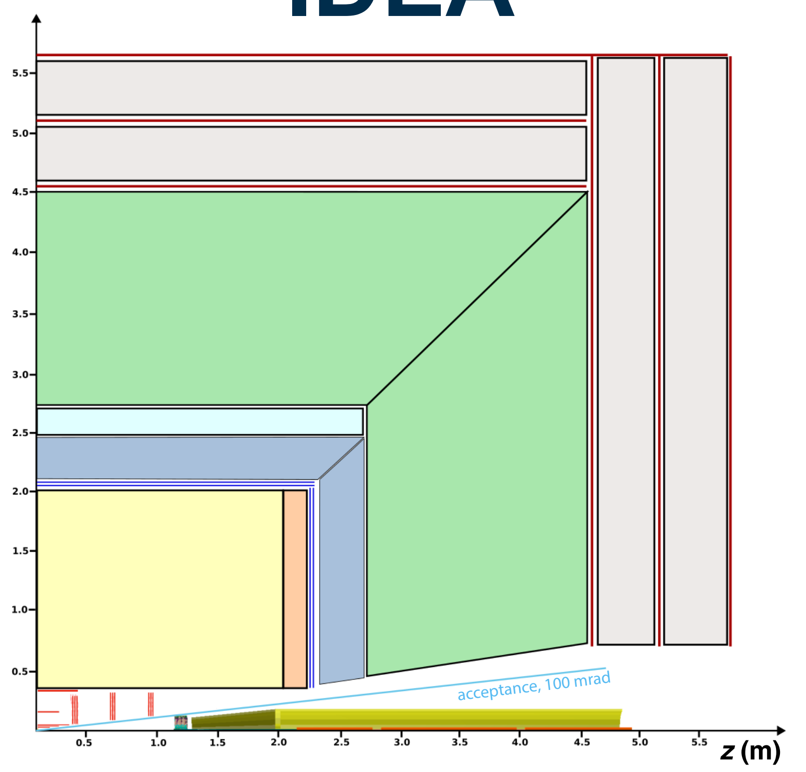
CLD



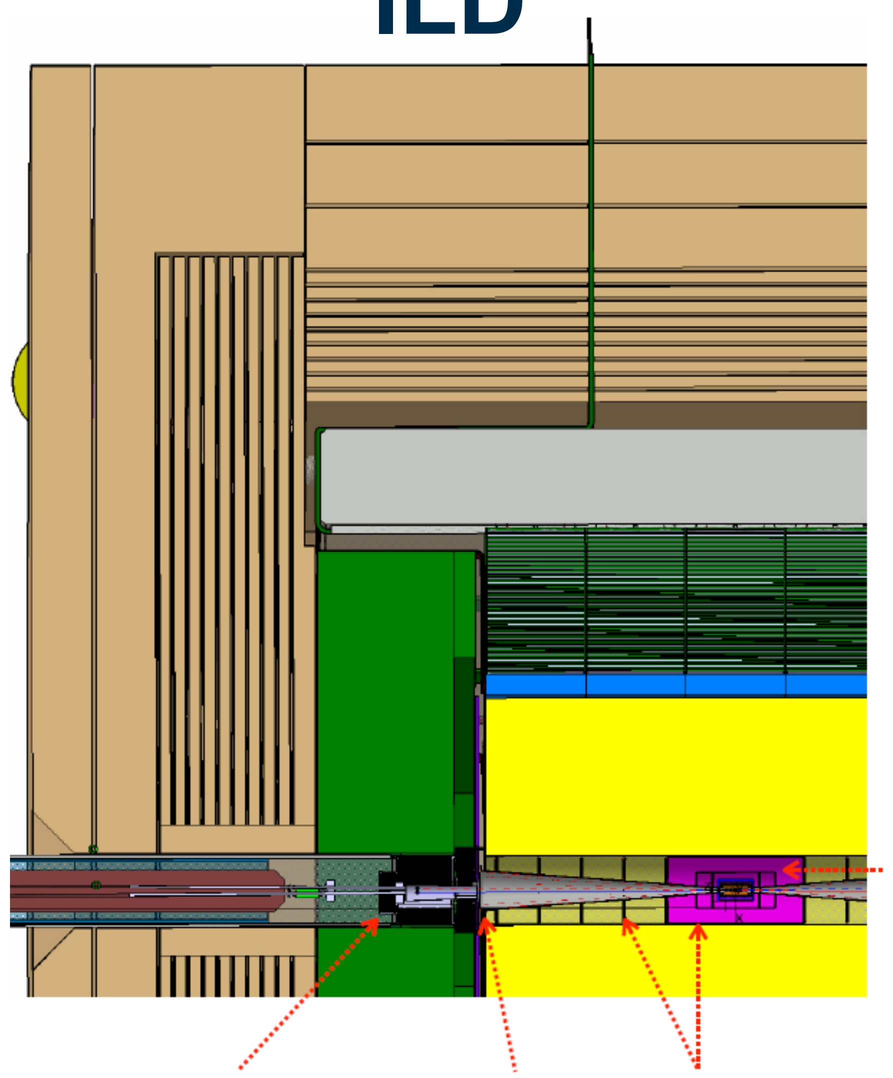
SiD



IDEA



ILD



ALLEGRO

Which technologies are required on which time scale?

European Strategy
for Particle Physics

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The ESPP Input Documents

Lots of Excellent Material for us to Read…

More than **80 submissions** related to instrumentation → shows **great interest** and **innovation capability** of our community

Wide range of inputs received
(more details in parallel session presentations)

- Single technologies, small and large experiments, trigger, data acquisition, electronics, software, AI
- Collider and beyond, e.g. dark sector, neutrinos
- Summaries of DRD Collaborations
- National inputs highlighting importance of instrumentation

PPG Instrumentation Group Spreadsheet

PPG Instrumentation Group … and Parallel Session Speakers

Thank you all very much for your commitment!


T. Årrestad


T. Bergauer


S. Bressler


M. Doser


I. Gil-Botella


A. Giuliani


D. Bortoletto


M. Demarteau


U. Husemann


F. Palla


R. Pestotnik


F. Sefkow


D. vom Bruch


G. Gaudio


F. Simon


M. Titov

Colliders and Beyond: Vertexing

#17, #32, #68, #70, #75, #78, #94, #95, #101, #102, #131, #145, #148, #157, #211, #245
Parallel Session: D. Bortoletto

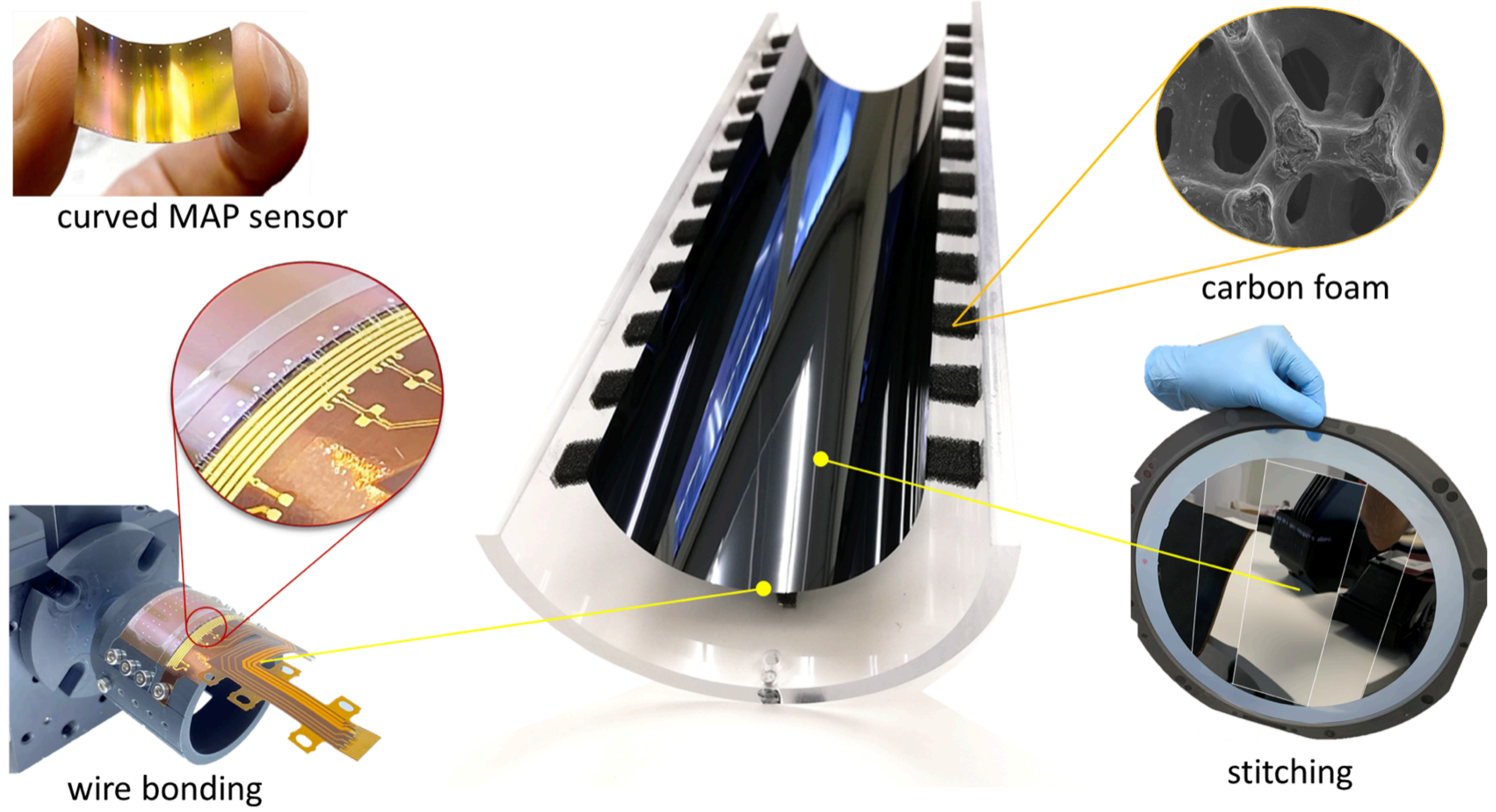
Key requirements (Eras 1 and 2, #70):

	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

Key technology: **MAPS** – monolithic active pixel sensors

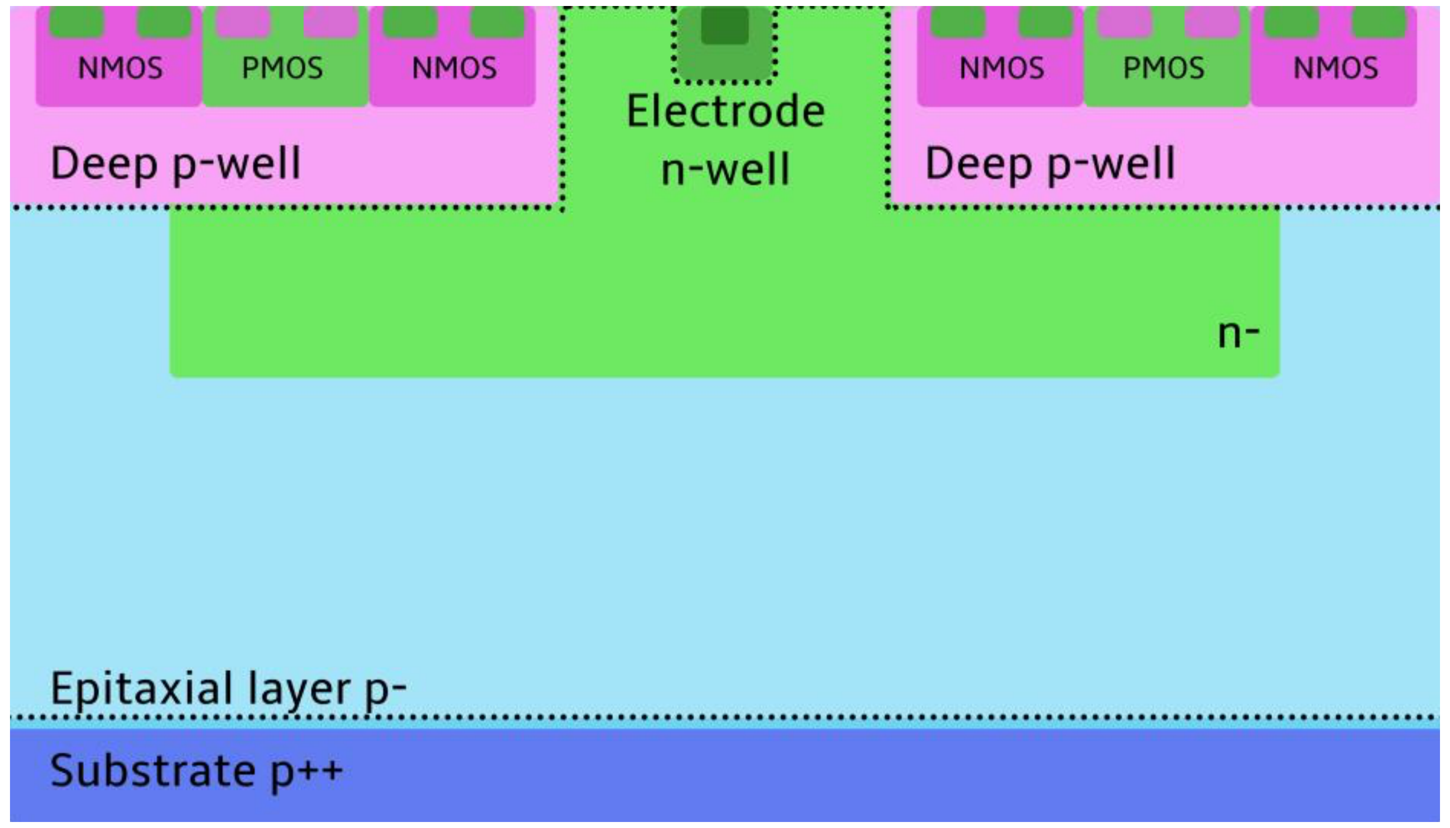
- **Integration** of sensitive elements and logic on a **single chip**
- Leveraging industry **standard CMOS** processes, modified for particle physics (e.g. LFoundry 110 nm, TPSCo 65 nm)

ALICE ITS3



CERN EP News

OCTOPUS MAPS Layout



Colliders and Beyond: Tracking & Muon Detection

#19, #32, #44, #61, #74, #89, #94, #95, #100, #101, #109, #133, #141, #142, #145, #149, #157, #189, #202, #205, #211, #218, #229, #231, #245
Parallel Session: D. Bortoletto, M. Titov/S. Bressler

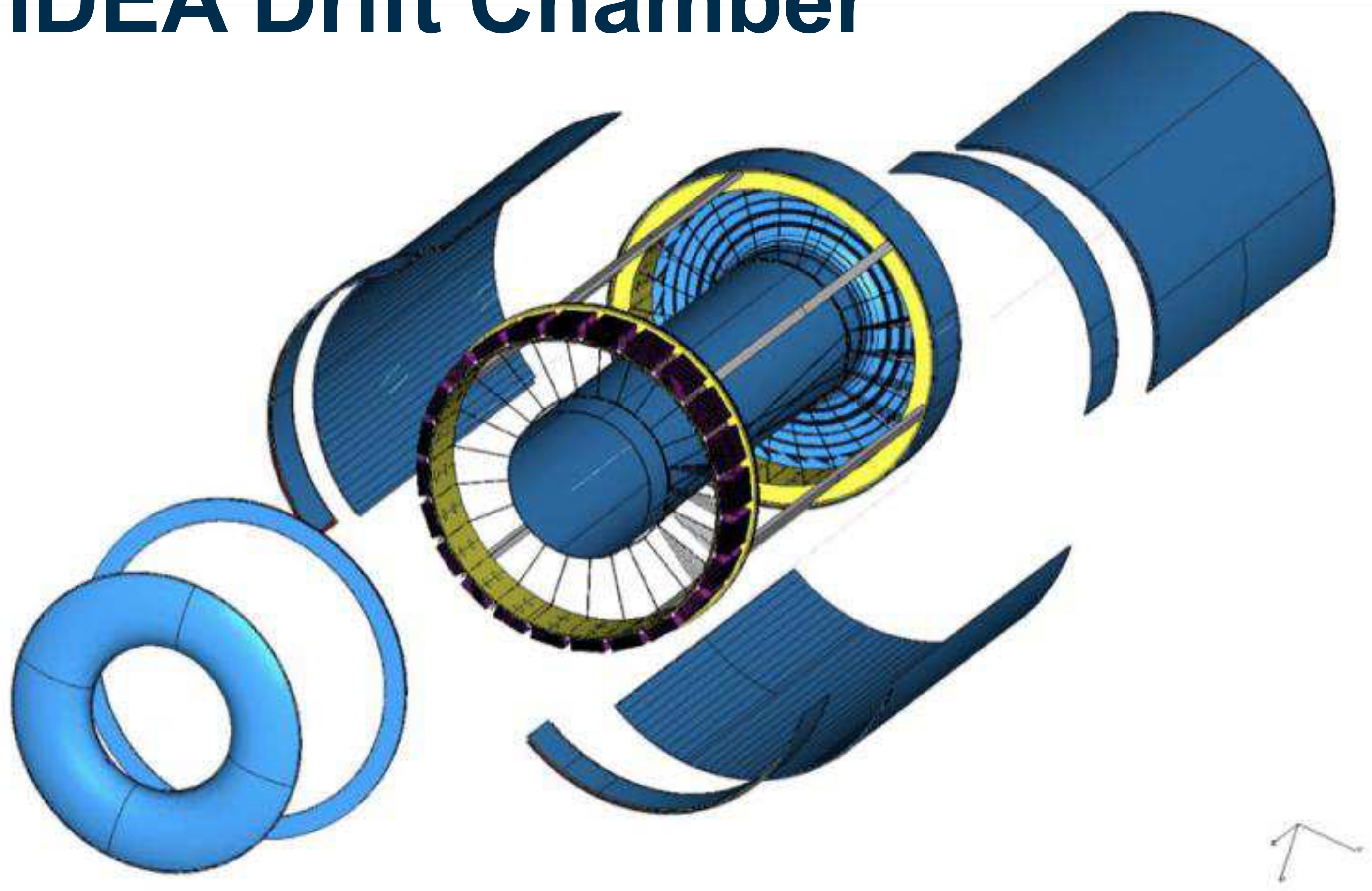
Key requirements (example figures for Era 2, FCC-ee):

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

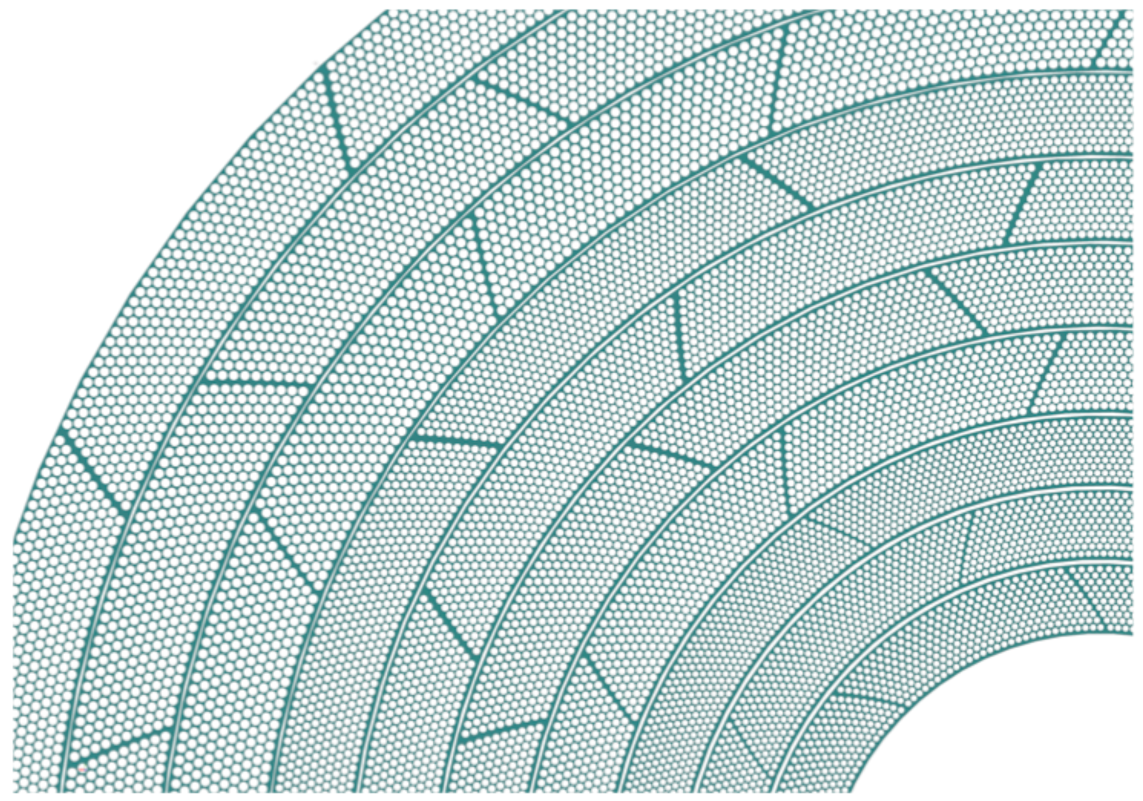
Key technologies:

- **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



Colliders and Beyond: Calorimetry

#32, #44, #46, #50, #63, #78, #94, #95, #102, #108, #141, #145, #157, #211, #266
Parallel Session: G. Gaudi

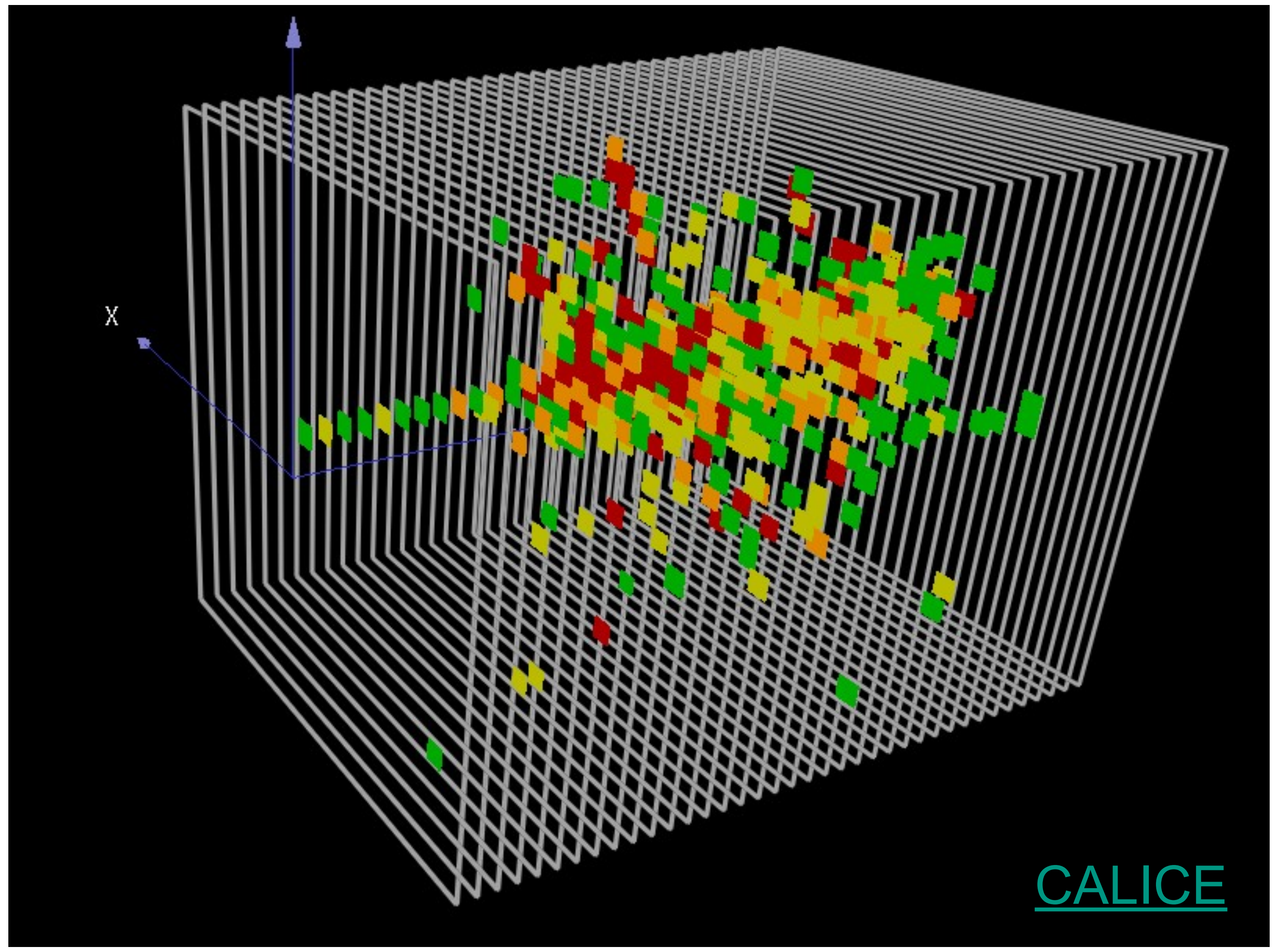
Key requirements (example figures for Era 2, FCC-ee):

- **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)

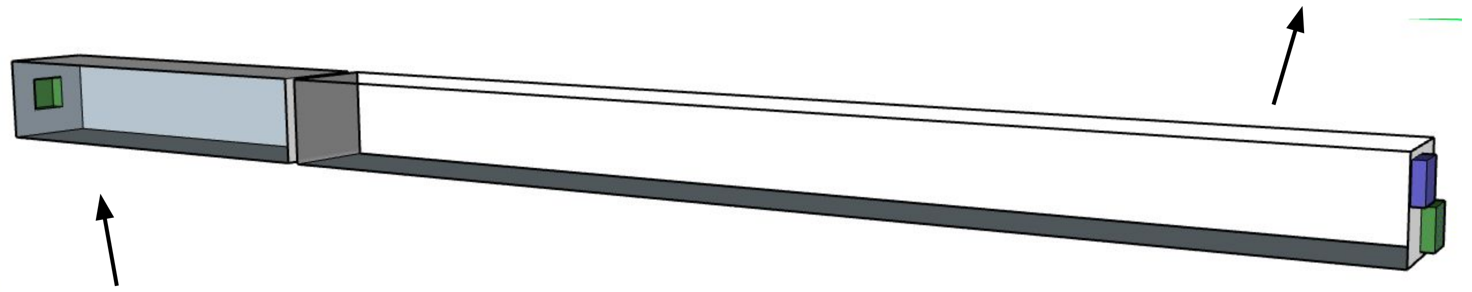
Key technologies:

- 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 (→ later)

Event in SiPM-on Tile Analog HCAL



Dual Readout Crystal ECAL



Neutrino Physics and Rare Event Searches

#27, #36, #54, #63, #87, #116, #119, #125, #132, #151, #171, #175, #181, #182, #197, #225, #232, #238, #253, #260, #263, #264, #266, #268, #272

Parallel Session: I. Gil-Botella/A. Giuliani

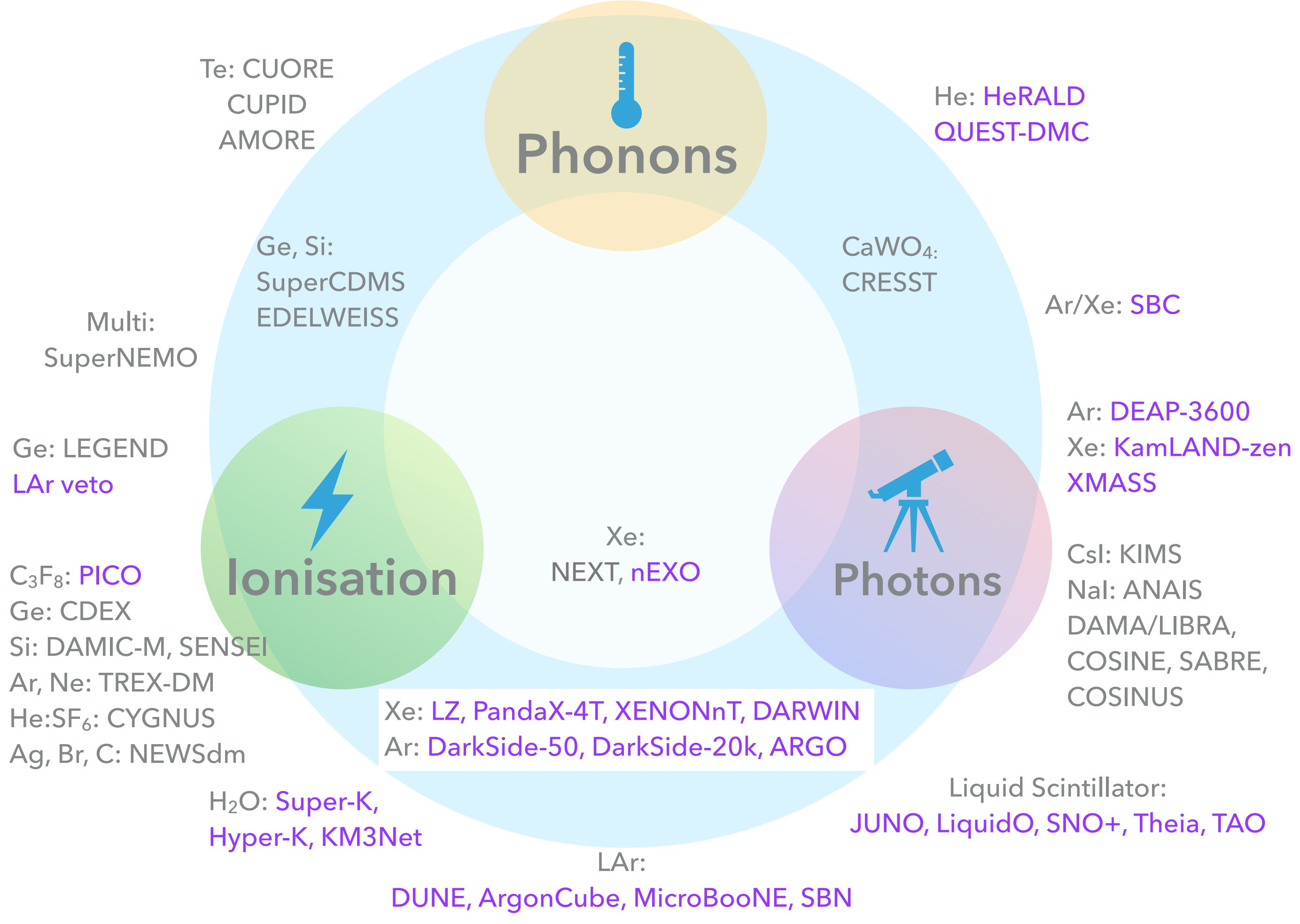
Diverse set of physics **objectives**:

- Neutrino oscillation, CP violation, mass ordering
- Direct neutrino mass measurement
- Neutrinoless double beta decay ($0\nu\beta\beta$)
- Coherent elastic neutrino-nucleus scattering (CEνNS)
- Direct Dark Matter detection

Diverse set of detector **requirements**:

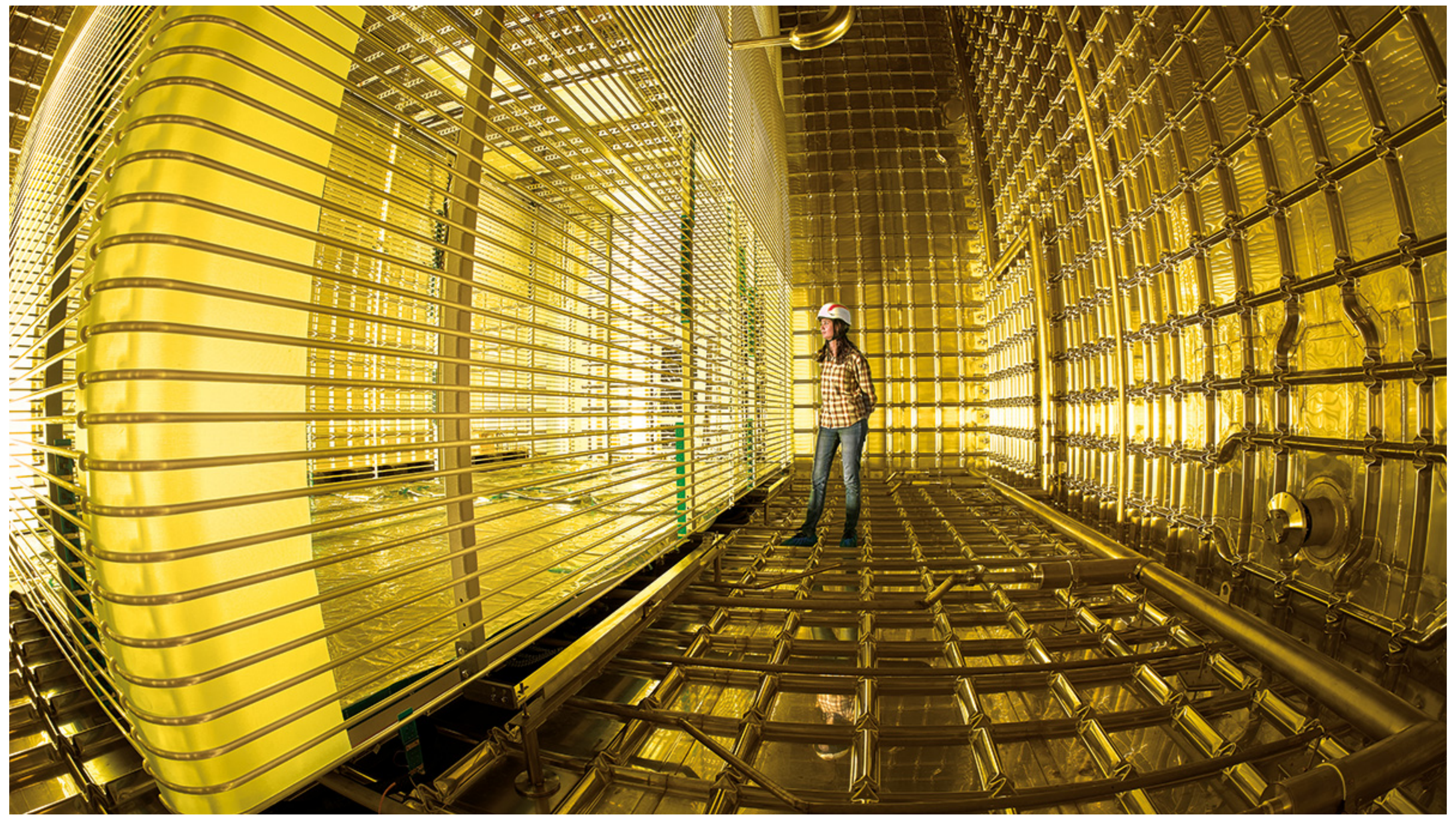
- **Combinations** of signals from photons/phonons/ionization
- Outstanding (recoil) **energy resolution**
- Outstanding **background control** and **mitigation**
- **Scalability** of technologies (e.g. with target volume)

Dark Matter Detection Modalities



modified from L. Baudis

protoDUNE Vertical Drift module0



Photograph: M. Cavazza

Neutrino Physics and Rare Event Searches

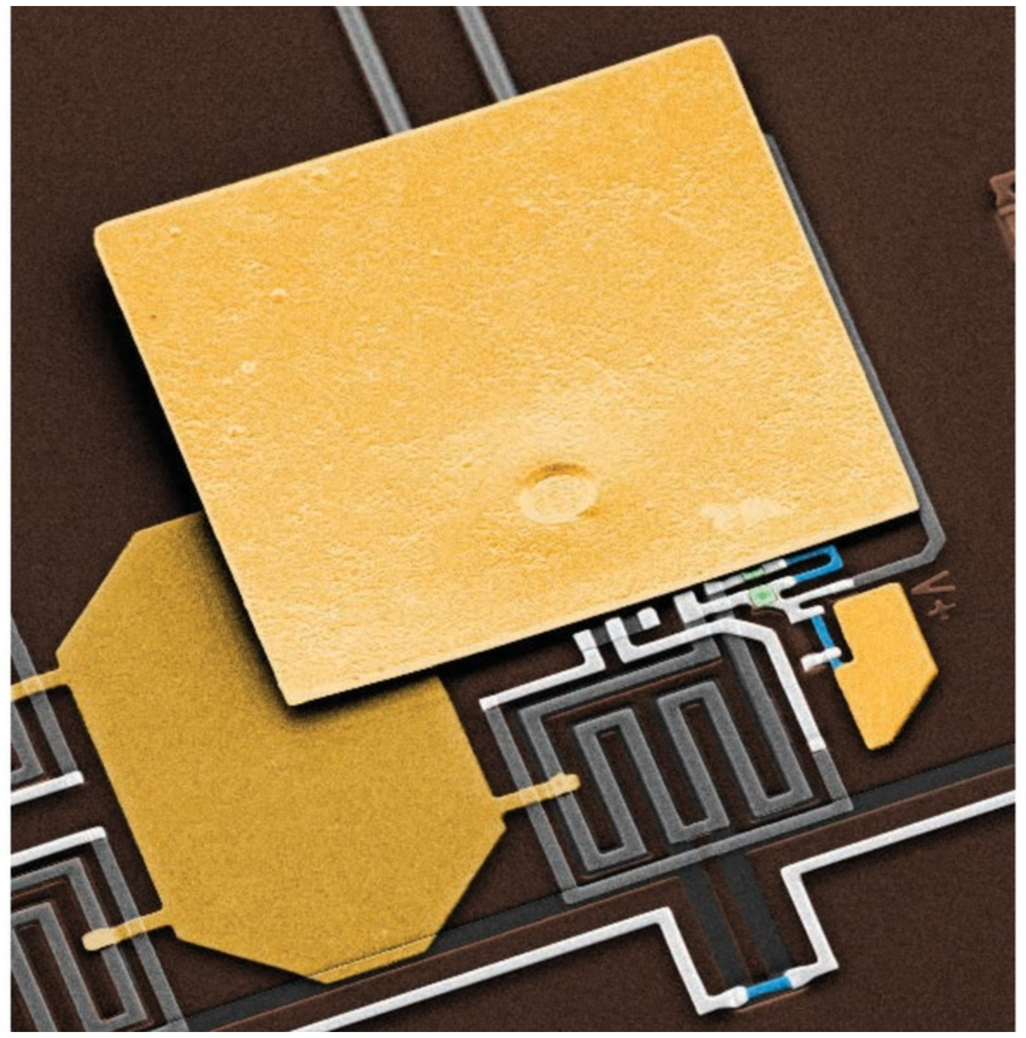
Detector Technologies Beyond Colliders
Parallel Session: I. Gil-Botella/A. Giuliani

Broad range of key **technologies**:

- **Liquid** detectors: water Cherenkov, scintillators, noble liquids, including **photon detectors** (→ later)
- **Semiconductor** detectors: (skipper) CCDs, silicon and germanium detectors
- **Quantum sensors**: transition edge sensors (TES), magnetic microcalorimeters (MMCs), superconducting quantum interference devices (SQUIDs), nuclear magnetic resonance (NMR) devices, atomic magnetometers, …
- And **more**: microwave cavities, bolometers, emulsions, noble gases, …

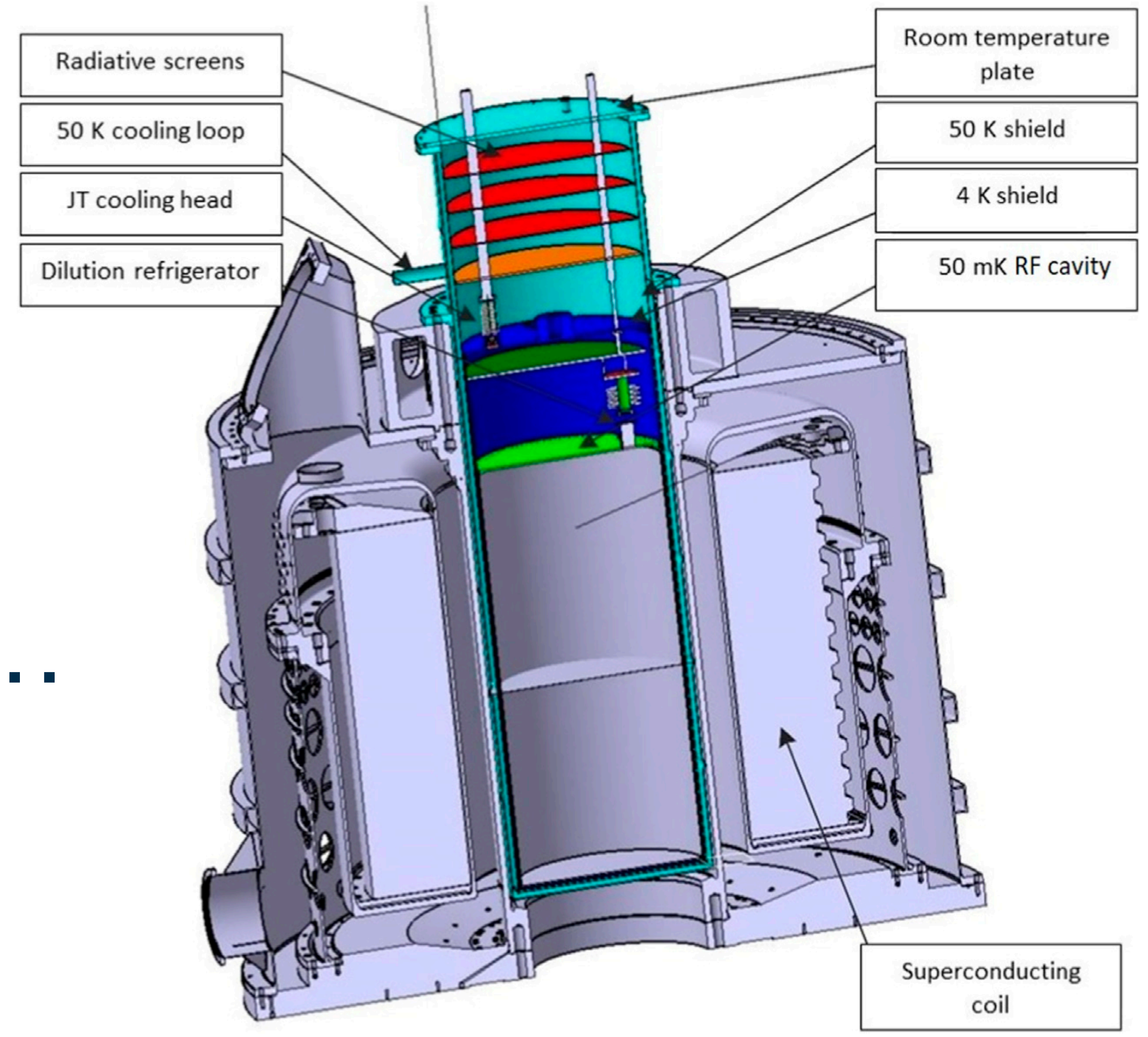
Dedicated infrastructures important: CERN Neutrino Platform, underground laboratories, etc.

Magnetic Microcalorimeter



App.Phys.Lett. 124 (2024) 032601

GrAHal-DMAG Cryostat



Frontiers in Physics 12 (2024) 1358810

Photon Detection & Particle Identification

#17, #32, #89, #93, #94, #95, #102, #140, #141, #148, #211
Parallel Session: G. Gaudi

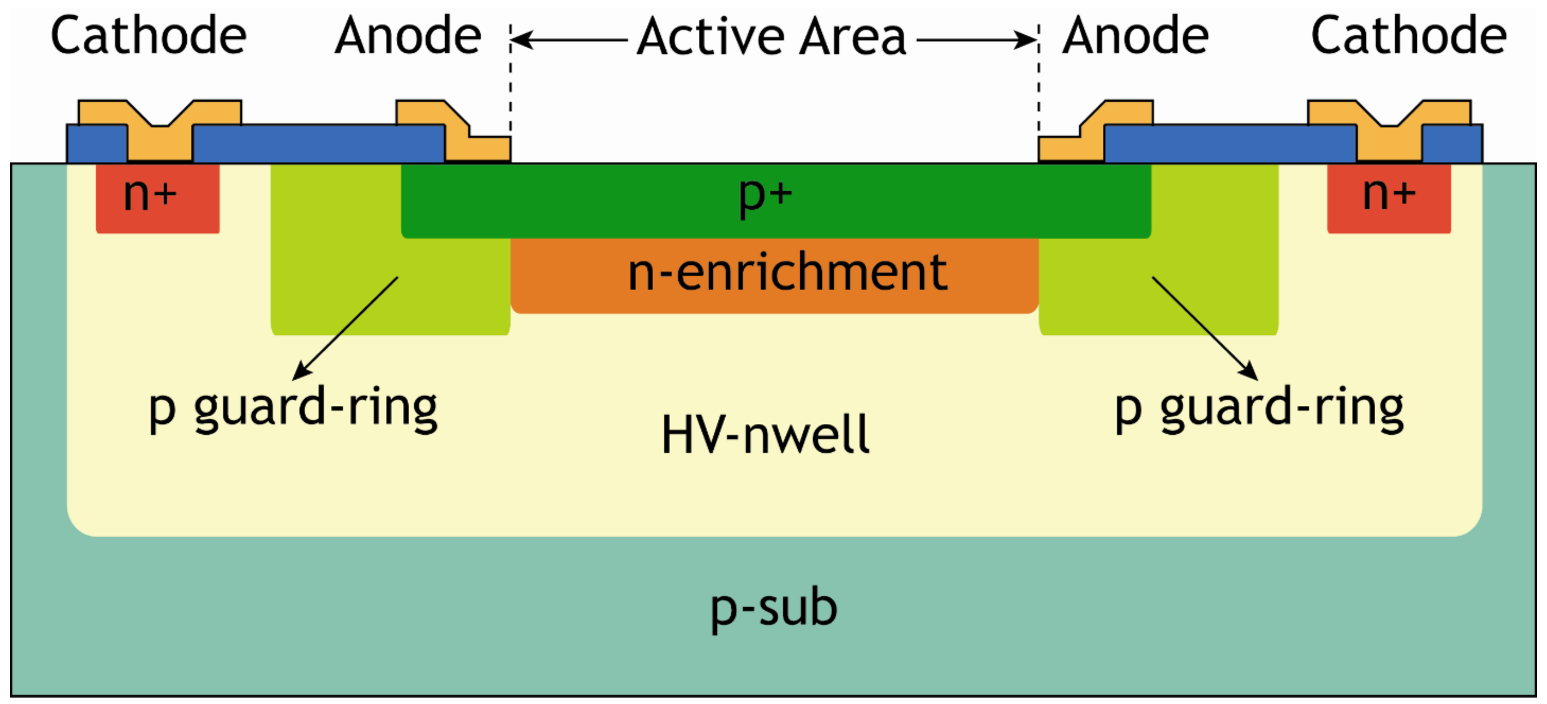
Photon detection:

- 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

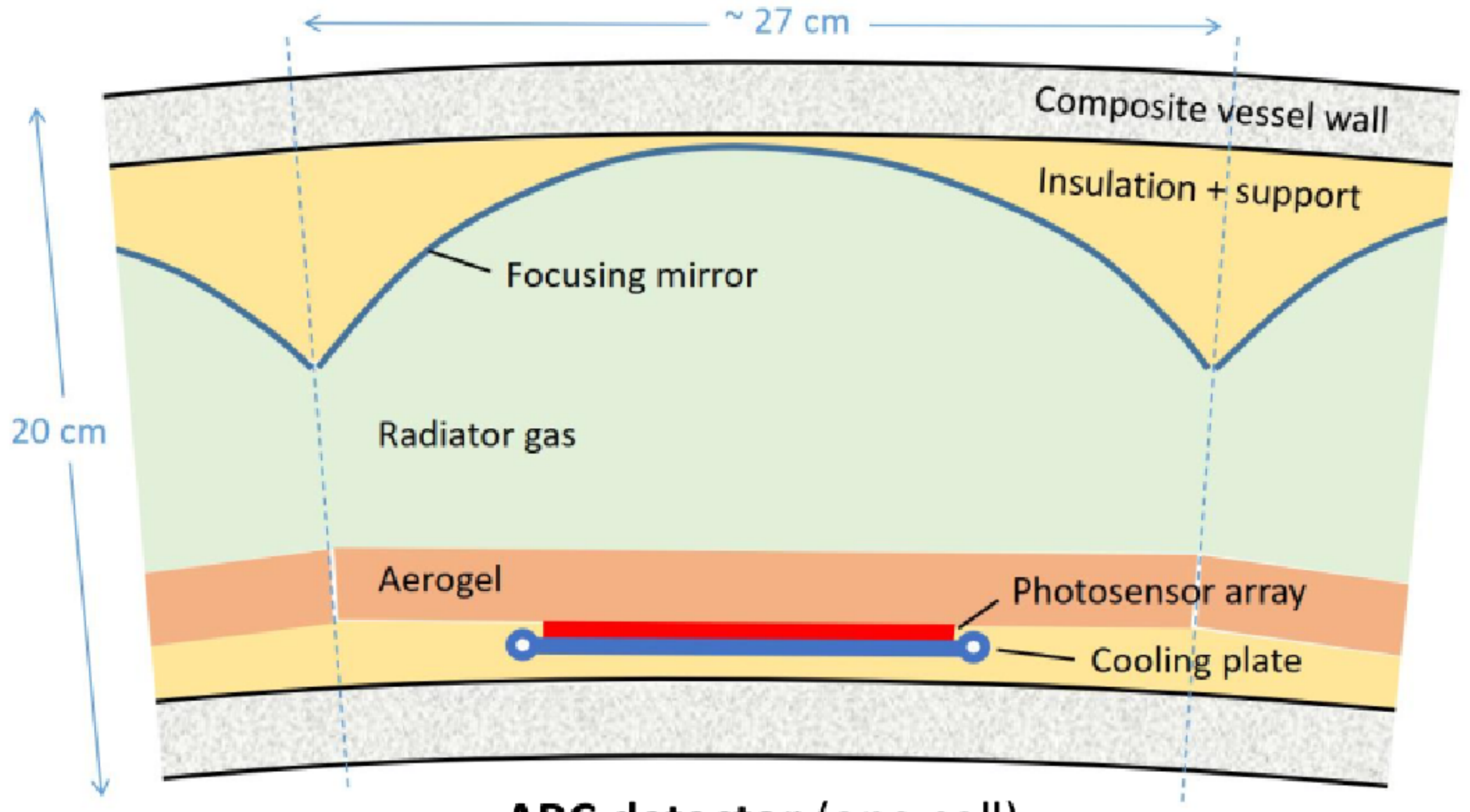
- Key **requirements**: pion/photon and hadron separation over various relevant momentum ranges
- Key **technologies**: ring-imaging Cherenkov (RICH) counters and time-of-flight (TOF) detectors, e.g. using ultrafast silicon detectors (e.g. low-gain avalanche detectors, LGADs)

CMOS Single Photon Avalanche Diode (SPAD)



Fraunhofer IMS

ARC: Array of RICH Cells



ARC detector (one cell)

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

Transversal Topics: Electronics

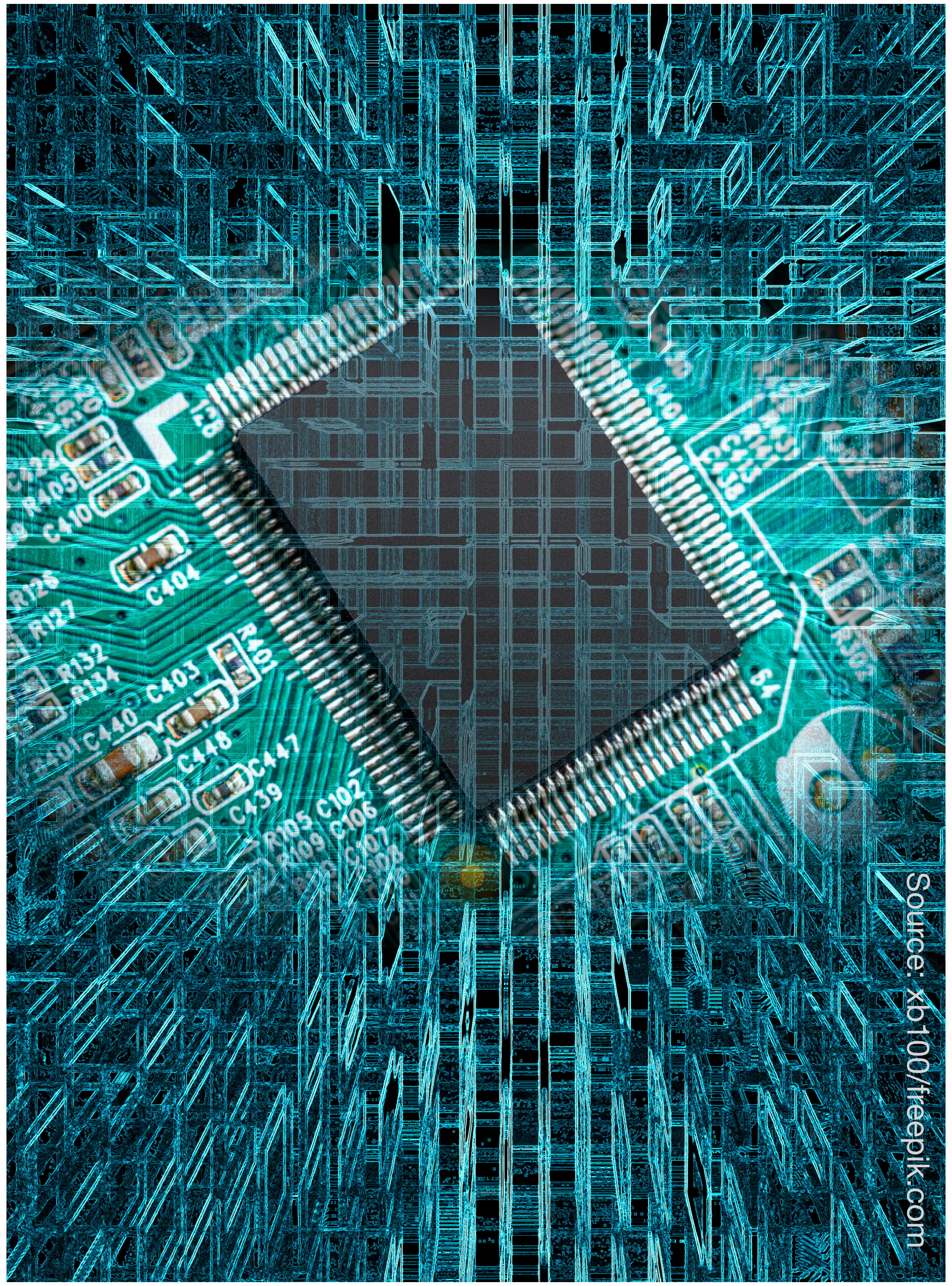
Custom-made or Off-the-shelf, Increasingly “Intelligent”
Parallel Session: F. Simon, M. Demarteau

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)



Source: xb100/freepik.com

Transversal Topics: Trigger and Data Acquisition (TDAQ)

#17, #42, #67, #93, #94, #95, #109, #127, #131, #189, #199, #205
Parallel Session: T. Årrestad/D. vom Bruch

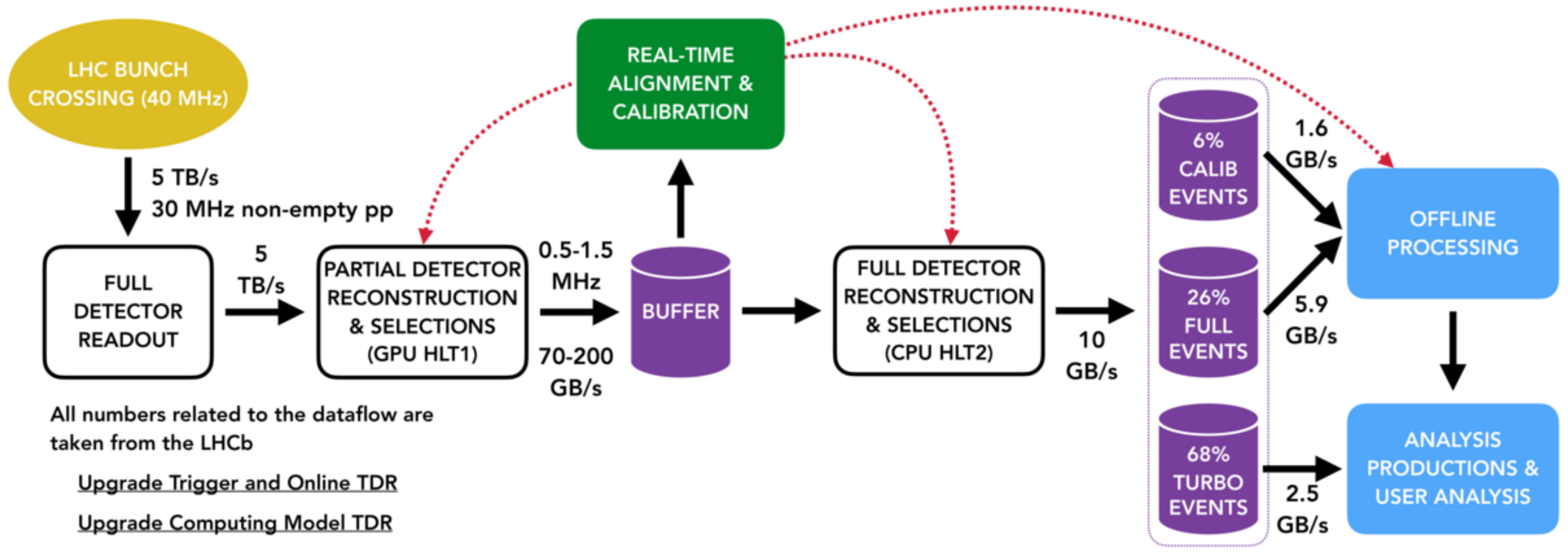
Requirements:

- 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

Status and challenges:

- Era-1 experiments (LHCb Upgrade II, ALICE3, Belle II, ePIC): all TDAQ requirements for next flagship likely fulfilled
- Challenges: maintain versatile heterogeneous frameworks (no vendor lock-in), avoid bottlenecks between ASIC and DAQ

LHCb Run 3 Trigger System



LHCb Starter Kit

CMS HLT Node: CPU + GPU

cms.cern

Transversal Topics: Quantum, Software, AI

#37, #53, #93, #95, #132, #167, #204, #228, #258, #260
Parallel Session: M. Doser, T. Årrestad/D. vom Bruch

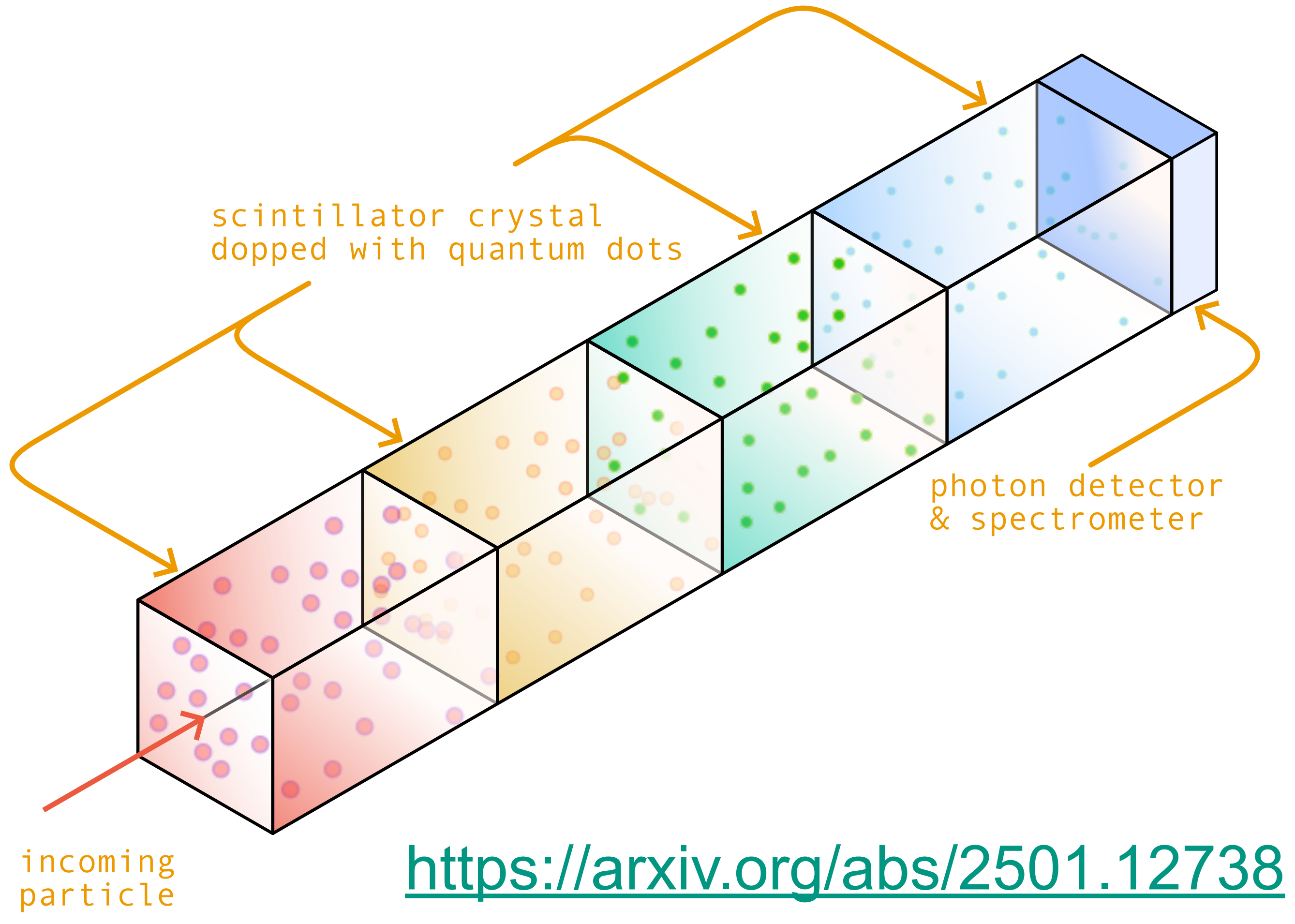
Quantum sensing:

- **Potential** seen in the community (→ national inputs)
- 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):

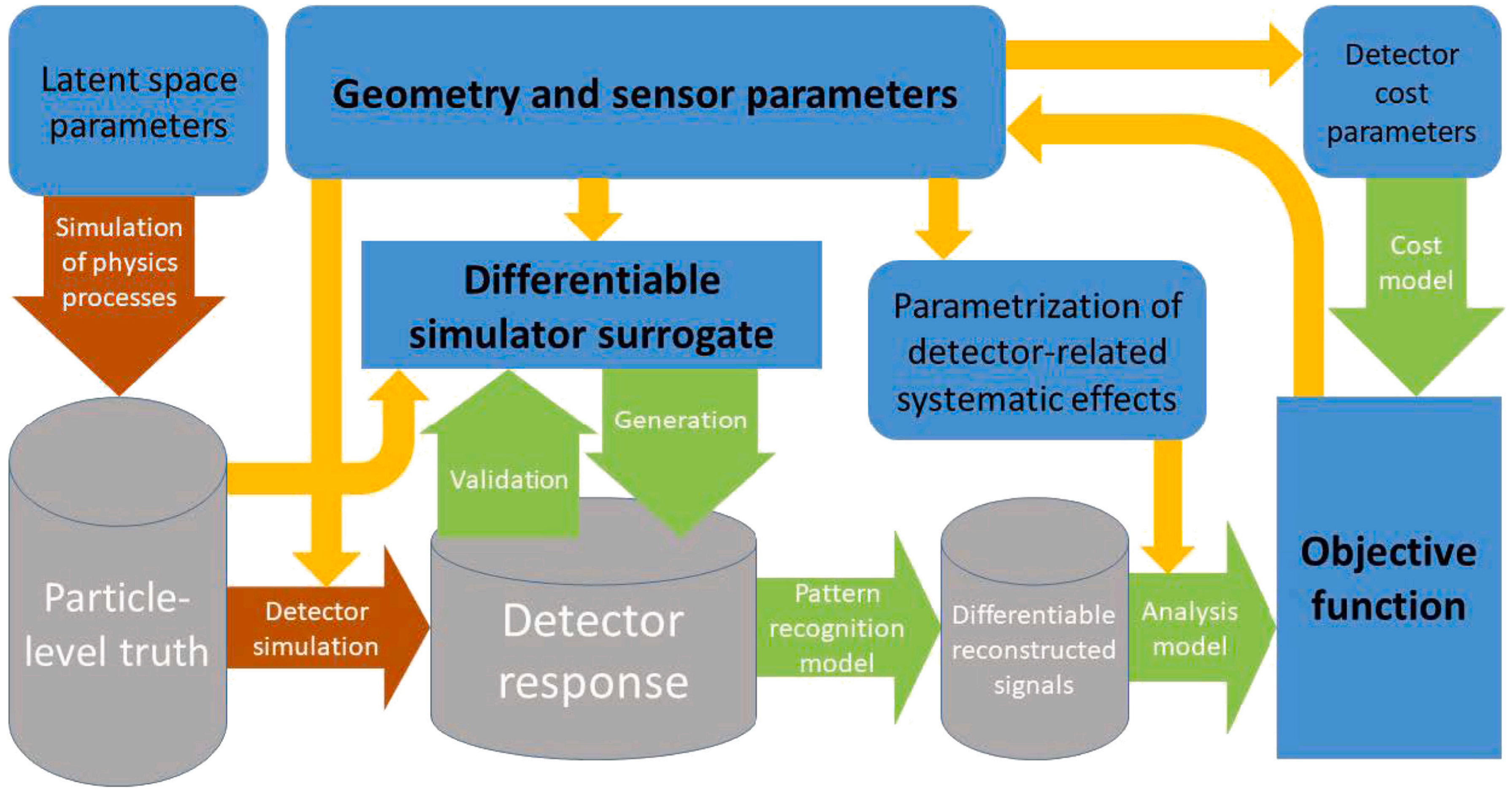
- Tighter **integration** of hardware and full software stack (simulation, pattern recognition, reconstruction, …)
- **Edge AI**: integration of real-time AI in frontend and trigger
- **Detector optimization with AI** (e.g. surrogate models, differentiable simulation code)

Chromatic Calorimeter



https://arxiv.org/abs/2501.12738

AI Detector Optimization



Review in Physics 10 (2023) 100085

Transversal Topics: Mechanics, Sustainability

#17, #70, #93, #95, #162, #265, #281
Parallel Session: F. Palla, M. Demarteau

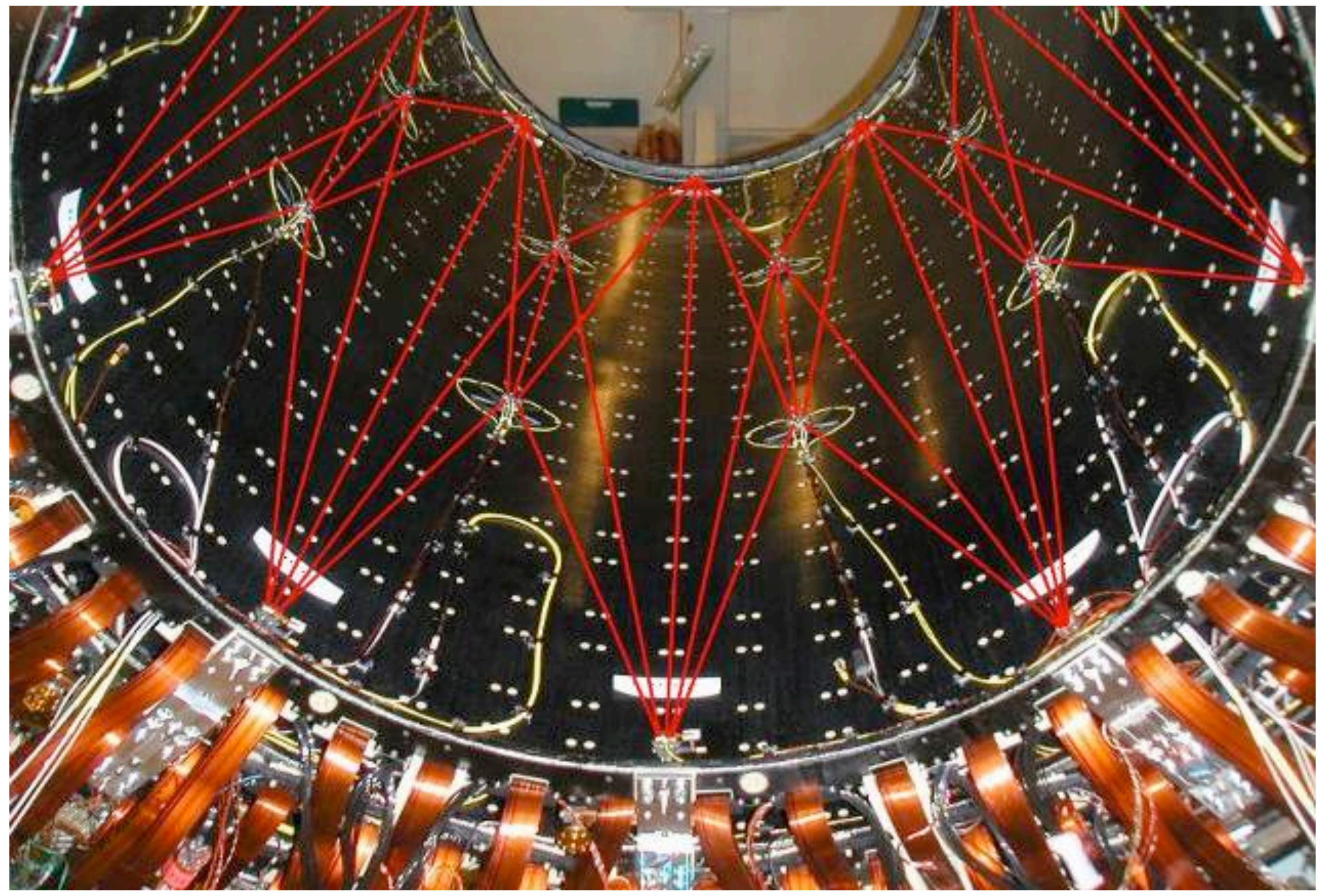
New challenges for **mechanics** and **cooling**:

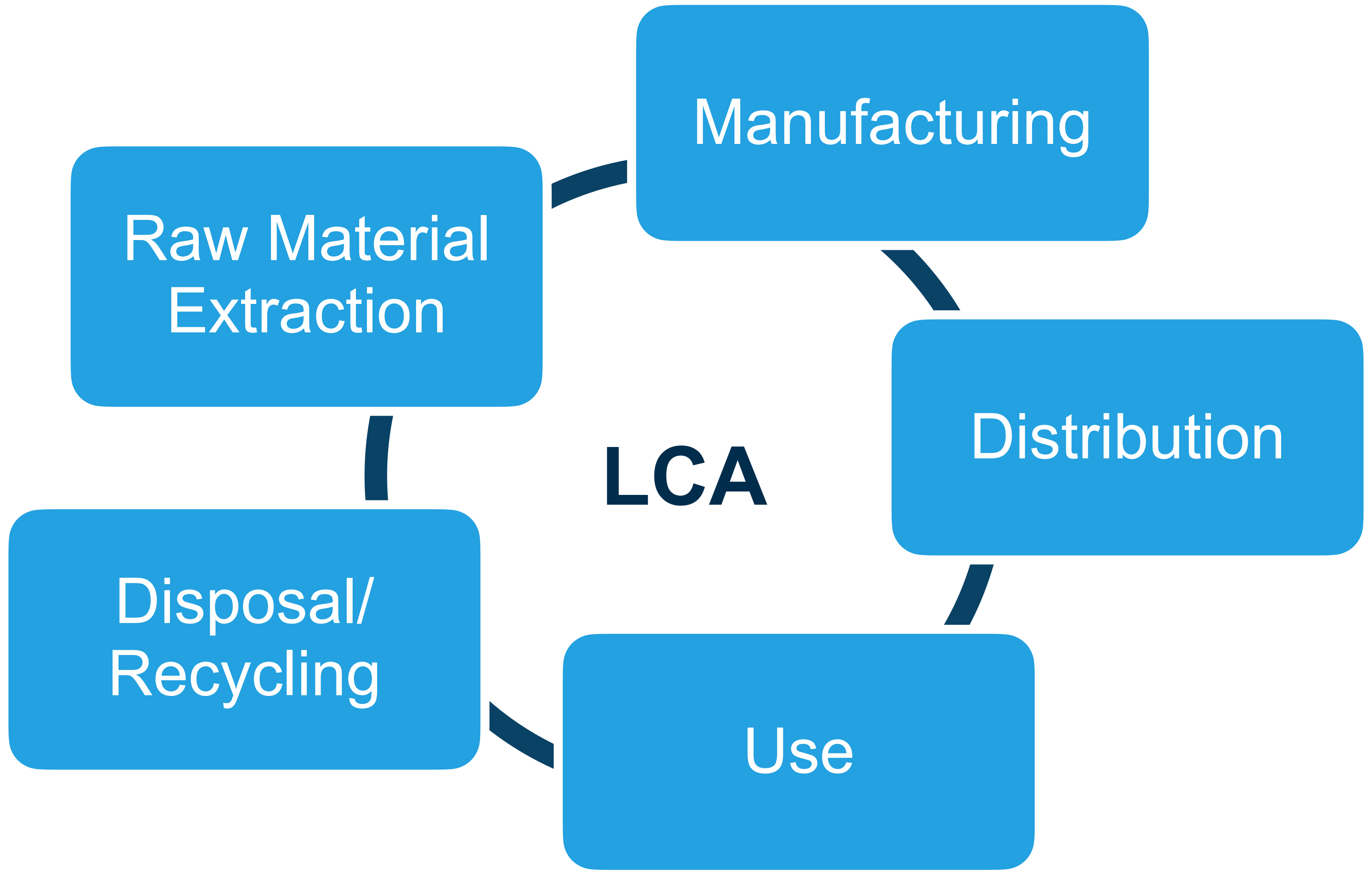
- Requirements: high granularity and power density, ultra-low material budget for tracking
- Technologies: curved/titled sensors, retractable detectors, air cooling, new coolants, low-mass alignment systems, novel materials and manufacturing techniques

Tomorrow's detectors will be **sustainable**:

- All technologies: full **life cycle assessment** (LCA)
- Individual technologies: e.g. **eco-friendly gases**, reduction of hazardous substances (RoHS) in electronics

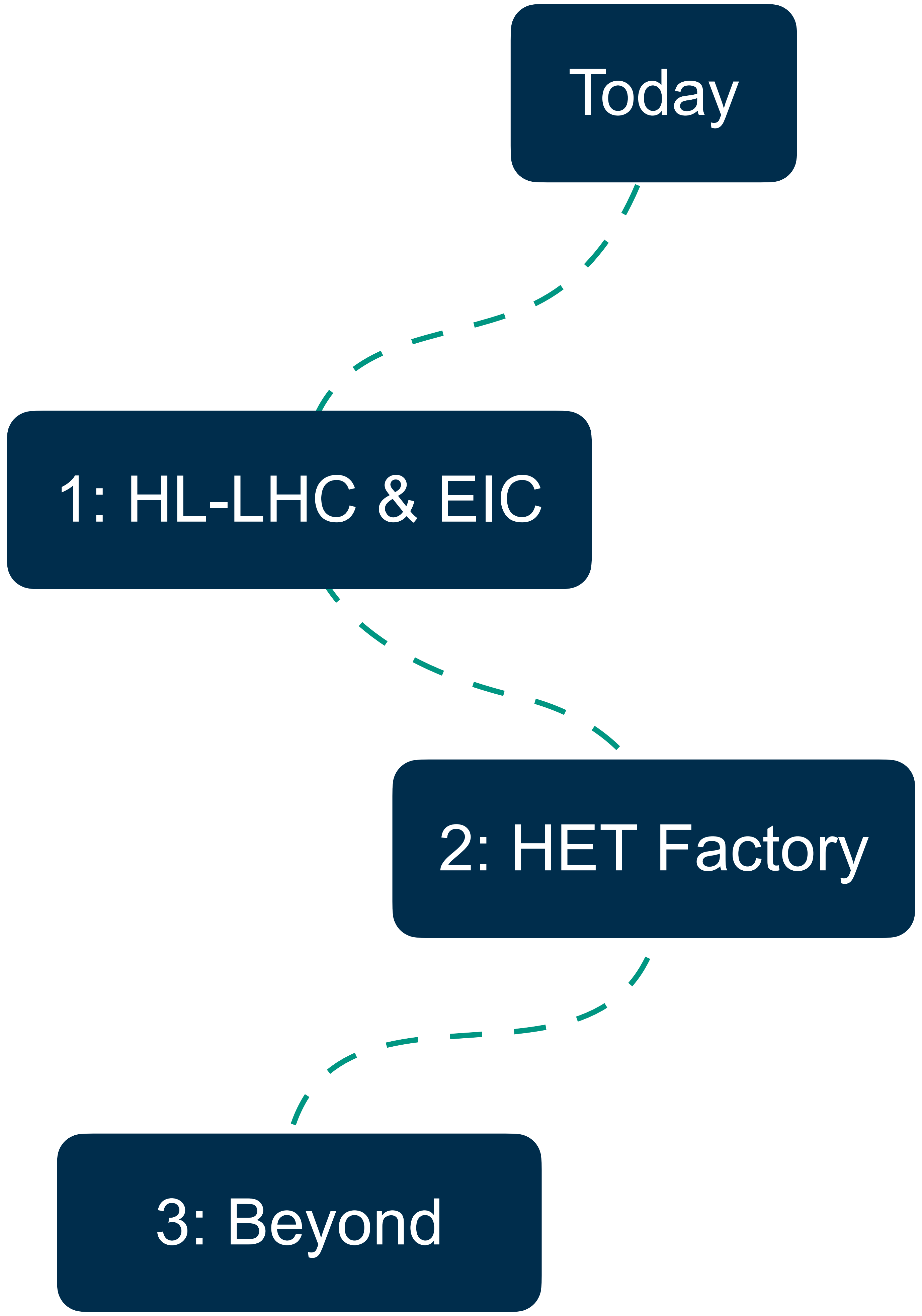
Low-mass Laser Alignment System





A Simplified Timeline

Future Requirements in Today's or Tomorrow's Experiments?



Small-scale experiments:

- **Individual requirements** similar to future flagships ("technology benchmarks"), see e.g. #46, #92, #115
- But: future flagships require **full detector systems** → non-trivial **combinations** of requirements

Era-1 experiments and upgrades as a **showcase**:

- ALICE 3 and LHCb Upgrade II at the HL-LHC, ePIC at the EIC, Belle II + Upgrade at SuperKEK
- **Similar** requirements: vertexing with low material budget (MAPS), tracking with gaseous/silicon detectors, triggerless high-rate readout, new superconducting solenoids → exploit **synergies**

Image credit: Adobe Stock

Who will work on instrumentation?

European Strategy
for Particle Physics

Instrumentation Workforce

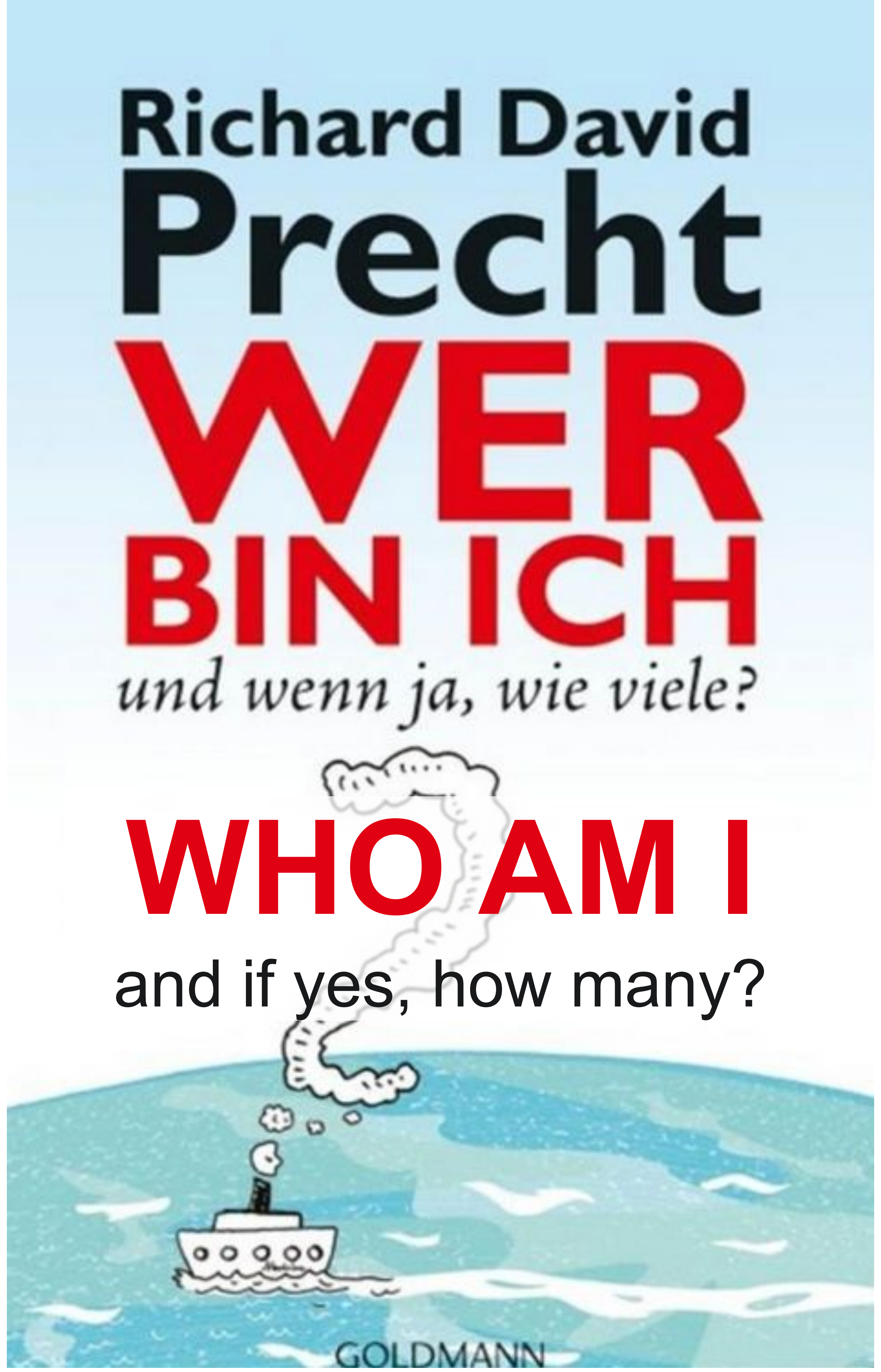
Who are we? And if “yes”: How many? – #30, #42, #90, #93
Parallel Session: M. Demarteau

Key **questions**:

- How **large** will instrumentation workforce be in *n* years from now?
- How can we establish/maintain a working **talent pipeline**?
- Is instrumentation **attractive** for early-career researchers?
  → ambitious projects, recognition, transparent career paths
- How do we **attract experts** and **keep them** in the field (including highly specialized experts, e.g., in chip design or electronics)?

Action items for the community (non-exhaustive list):

- **Prioritize** the most ambitious projects
- Foster **mobility**: internationally, in and out of particle physics
- **Coordinate** expert training: from university education to deep tech expertise (ECFA Training Panel, #30)



WHO AM I
and if yes, how many?

European Strategy for Particle Physics

KIT

Tools for Discovery

Instrumentation Requirements for Particle Physics

The **future** of particle physics is **bright**:

- Vivid field, broad range of physics objectives and experimental techniques
- Broad range of future experiments, requirements, and challenges

Future of instrumentation in particle physics:

- Significant **technological limitations and challenges** to overcome for future projects
- **New ideas**, may turn out as potential **game changers** (AI, second quantum revolution)
- Community showed **willingness and ability for transformation** → to be further developed