Computing and Instrumentation

Tools for Discovery

Ulrich Husemann, Karlsruhe Institute of Technology

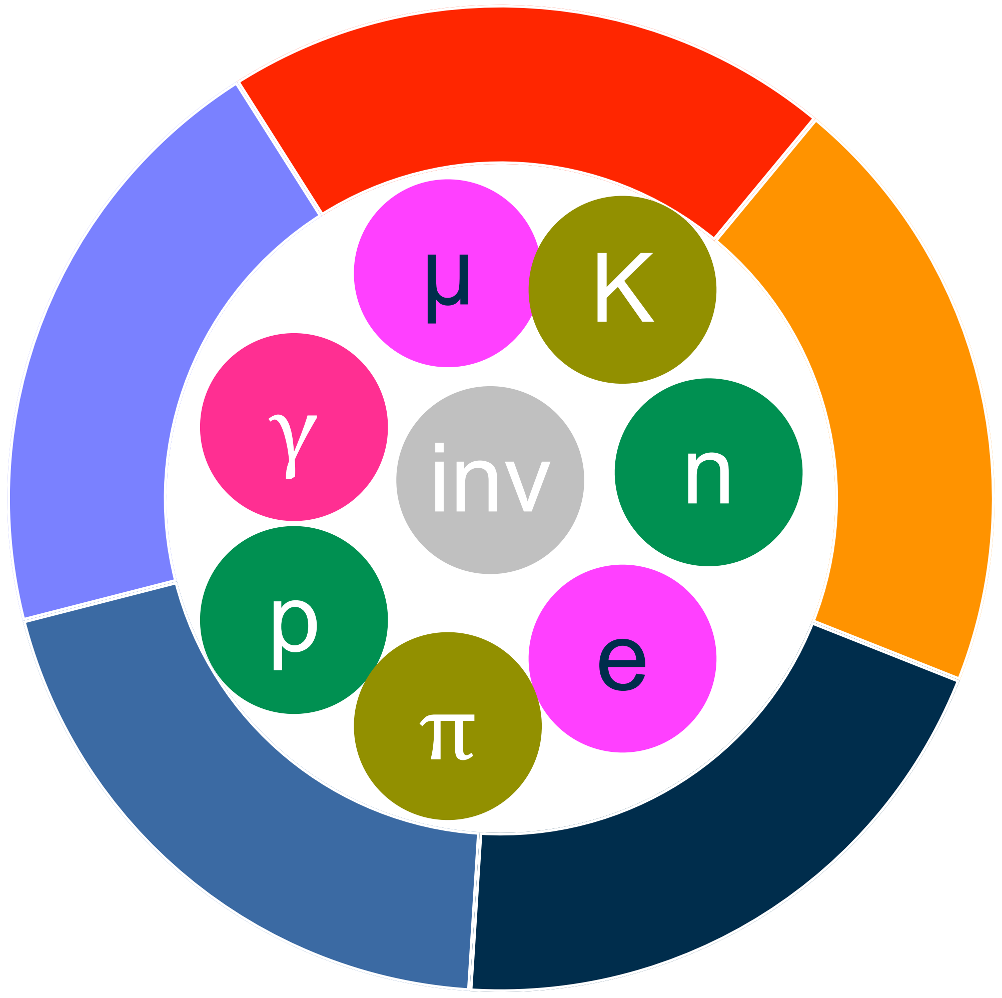
EPS-HEP 2025, Marseille, July 7–11, 2025

Particle Physics – a Tool-Driven Scientific Field

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

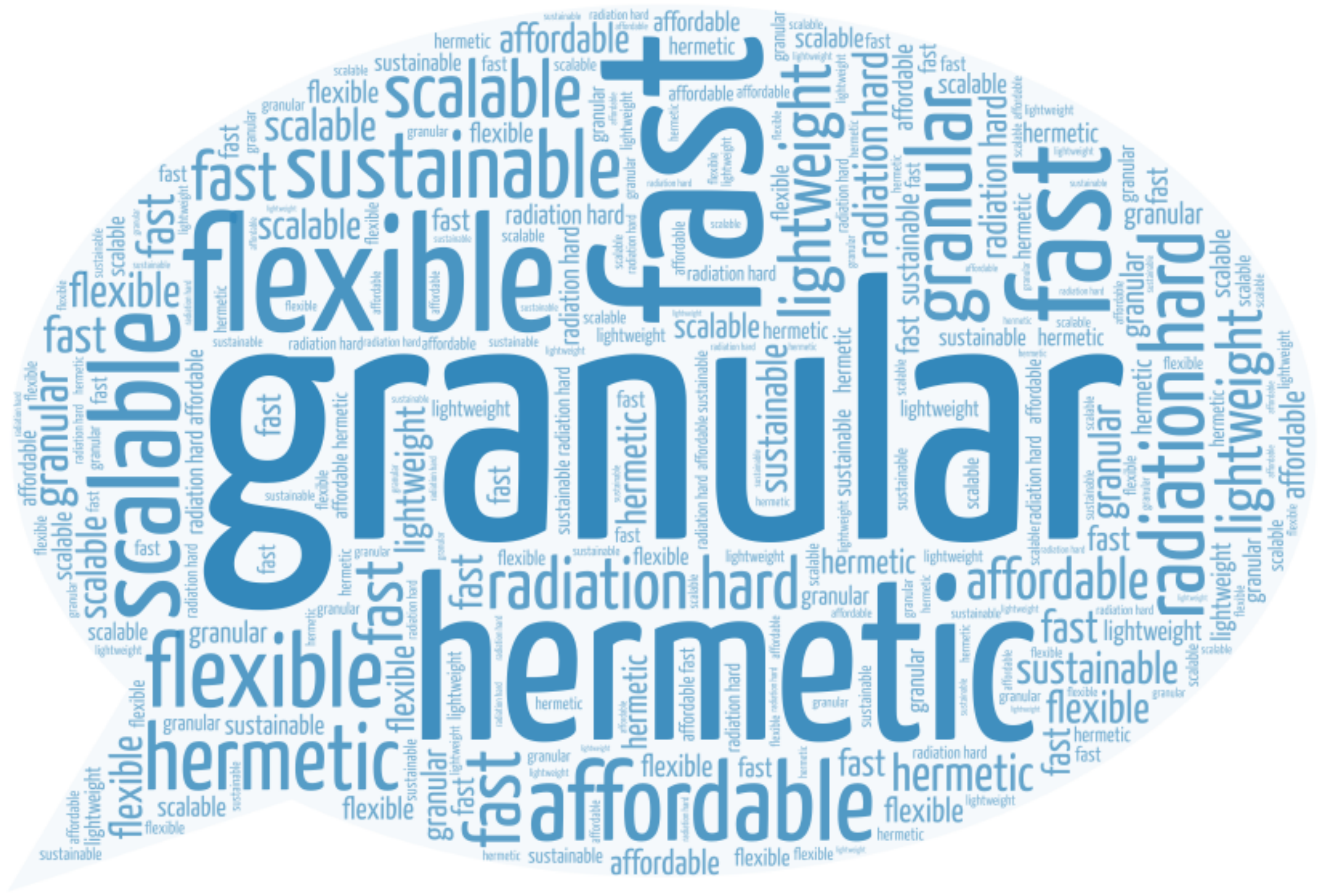
Unraveling the physics of elementary particles and their interactions: **sophisticated tools** required

- Particle **detectors**
- **Electronics** for readout and trigger
- **Computing, Software** and **Artificial Intelligence** (AI)



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

A more detailed look reveals: **wide variety** of requirements, time scales, technological maturity, cost, availability of skilled people and funding, …

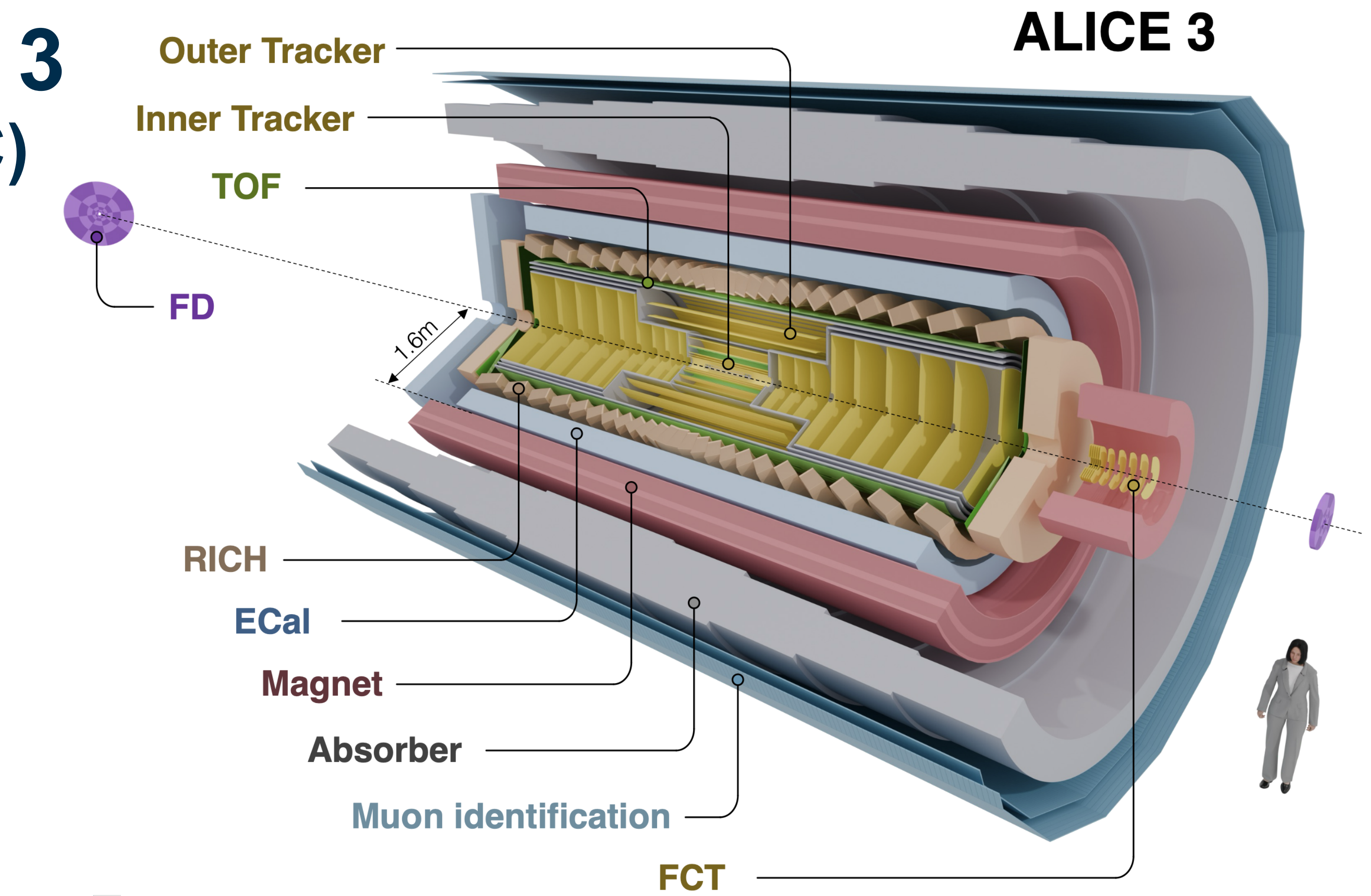


A Simplified Timeline

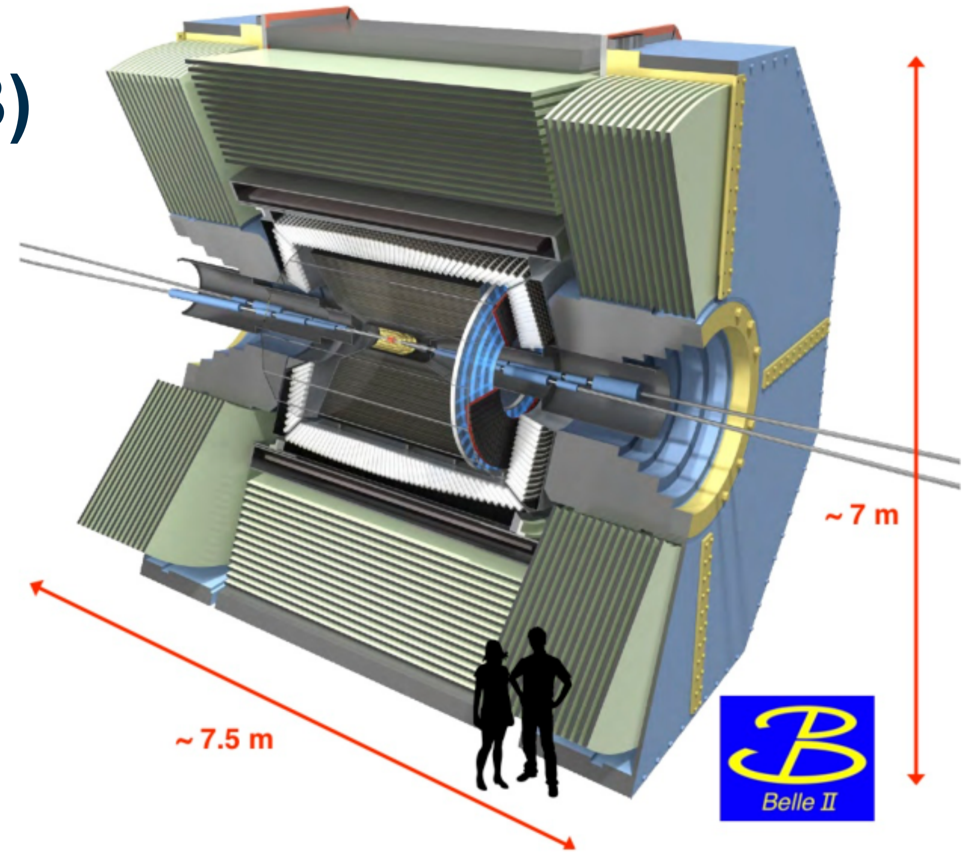
Key Collider Projects

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

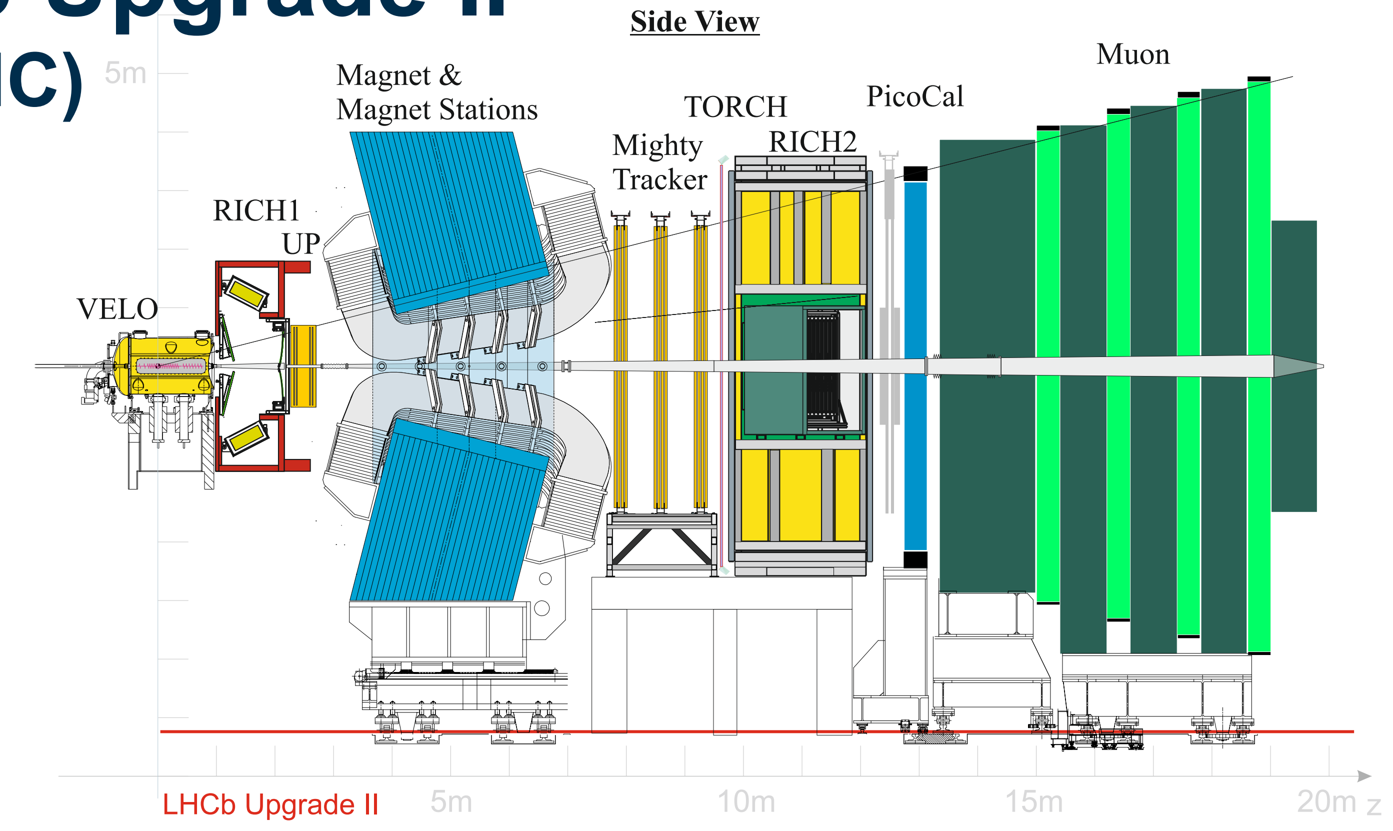
ALICE 3
(HL-LHC)

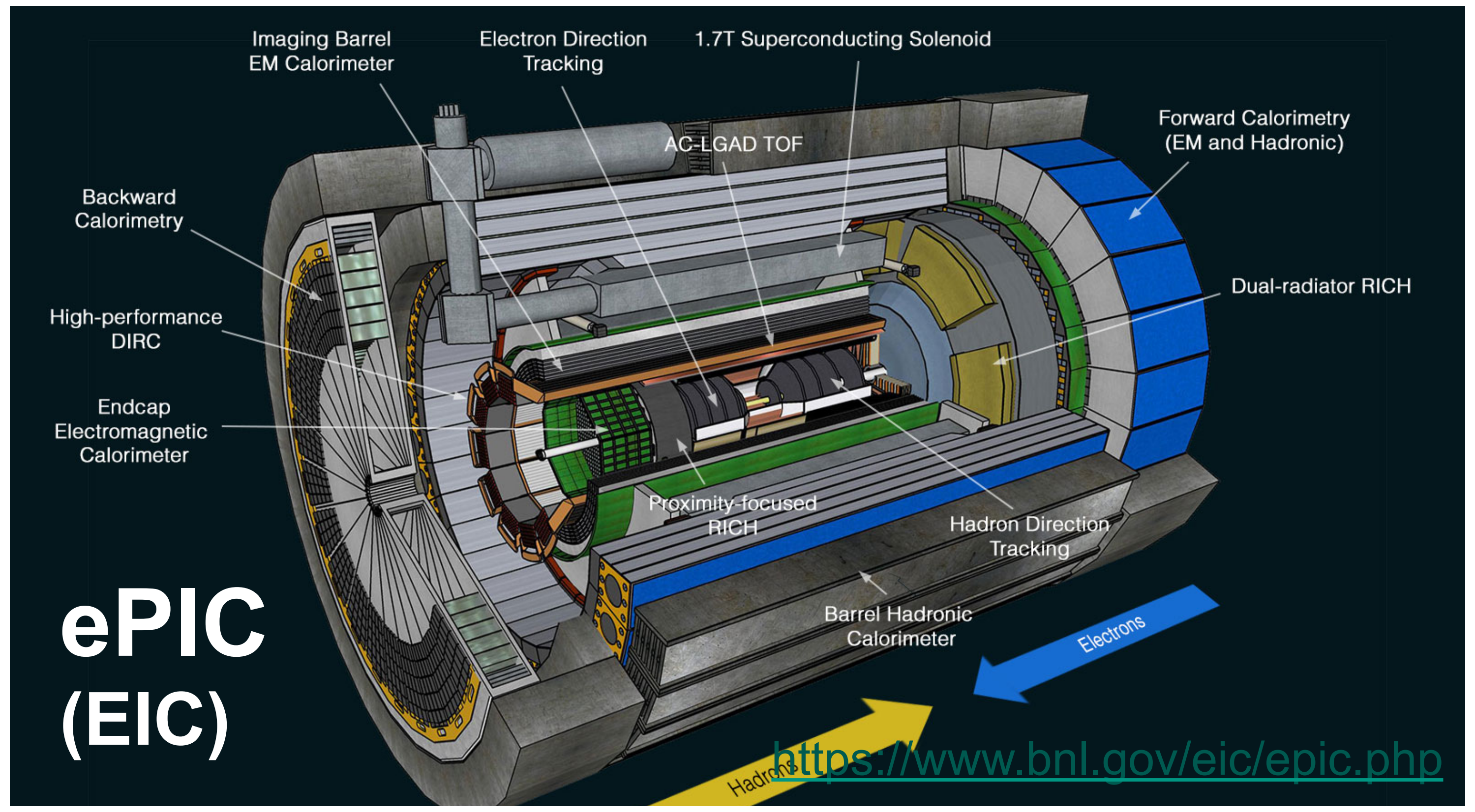


Belle II
(SuperKEKB)



LHCb Upgrade II
(HL-LHC)

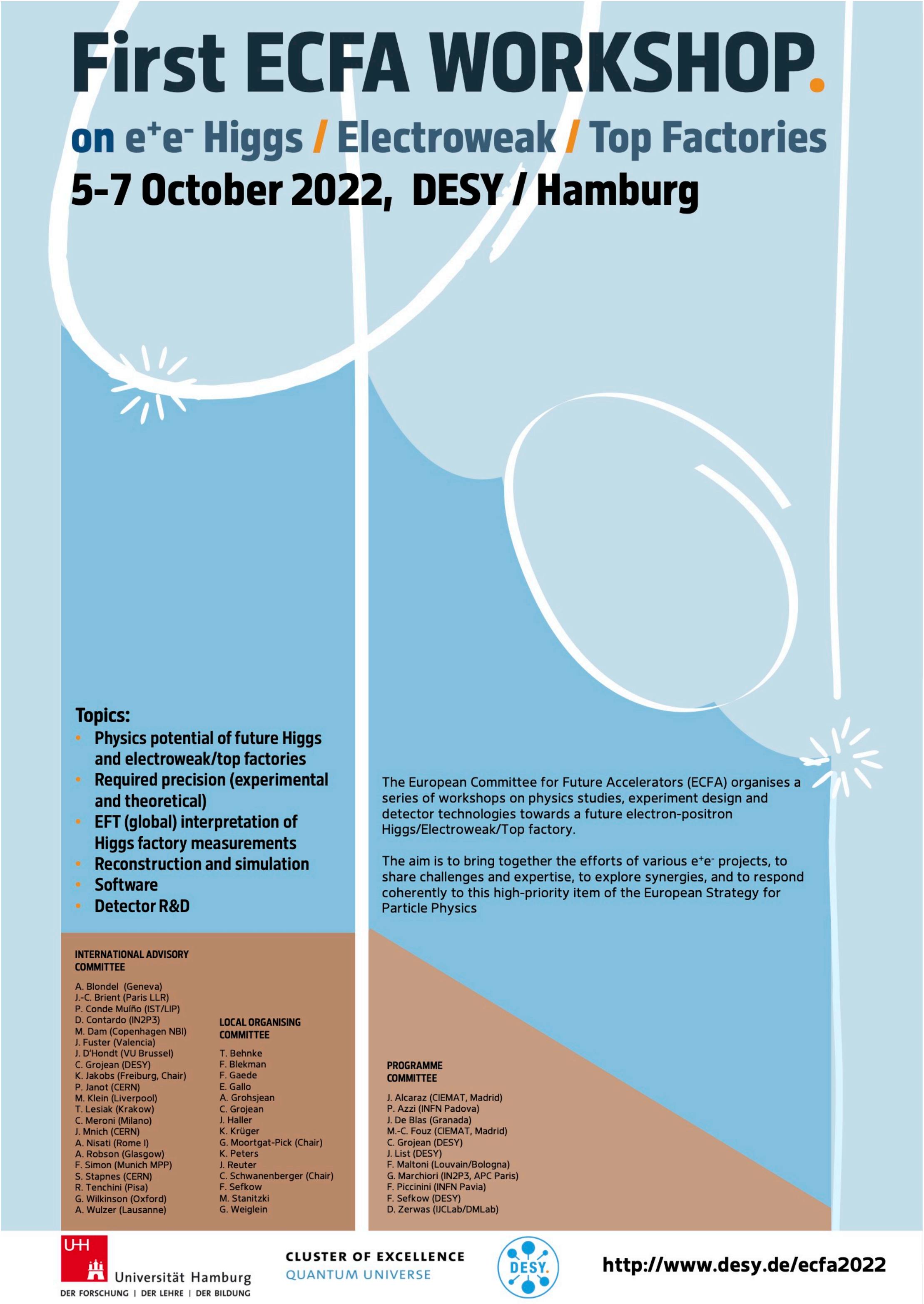


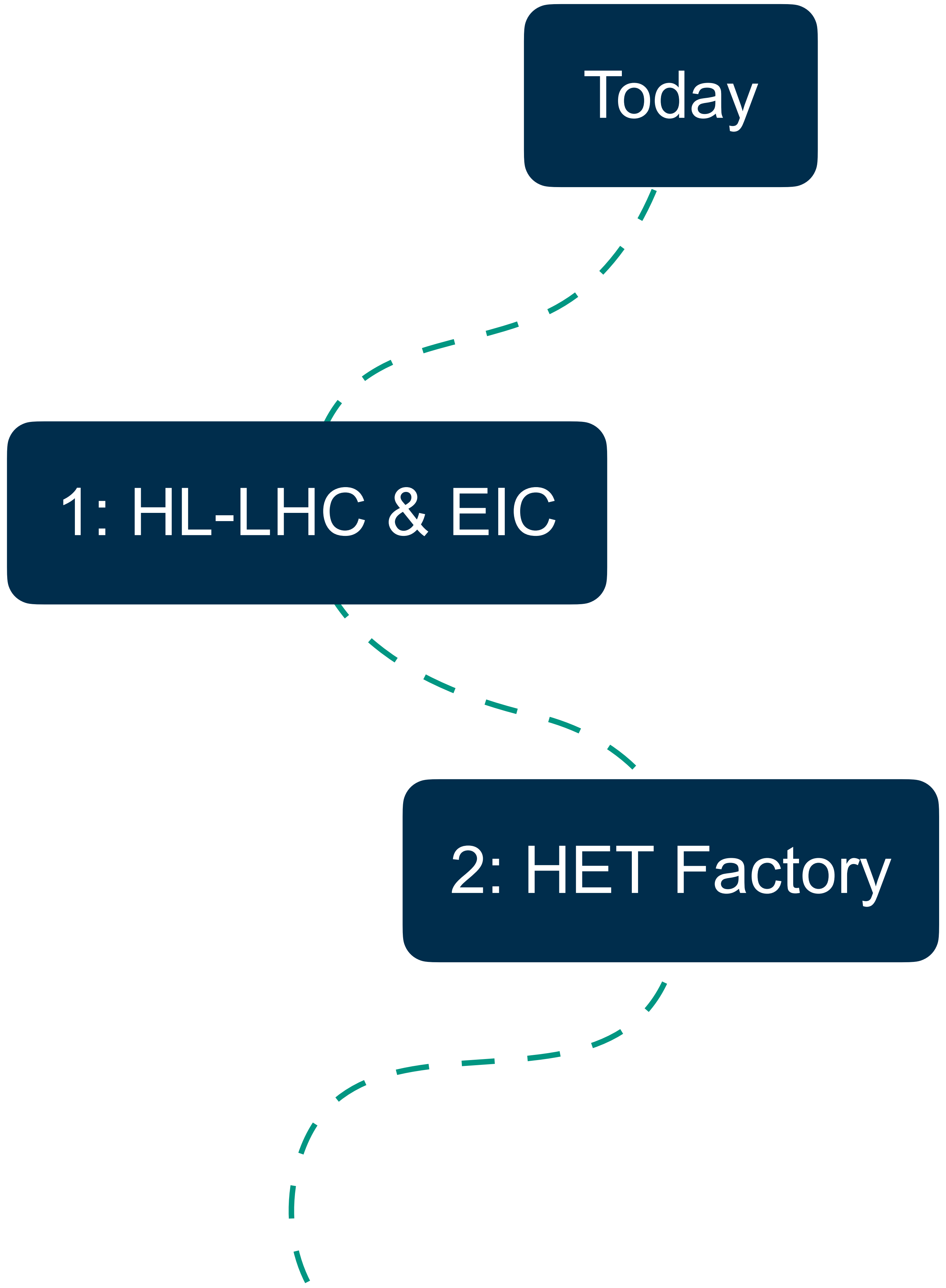


A Simplified Timeline

Key Collider Projects

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

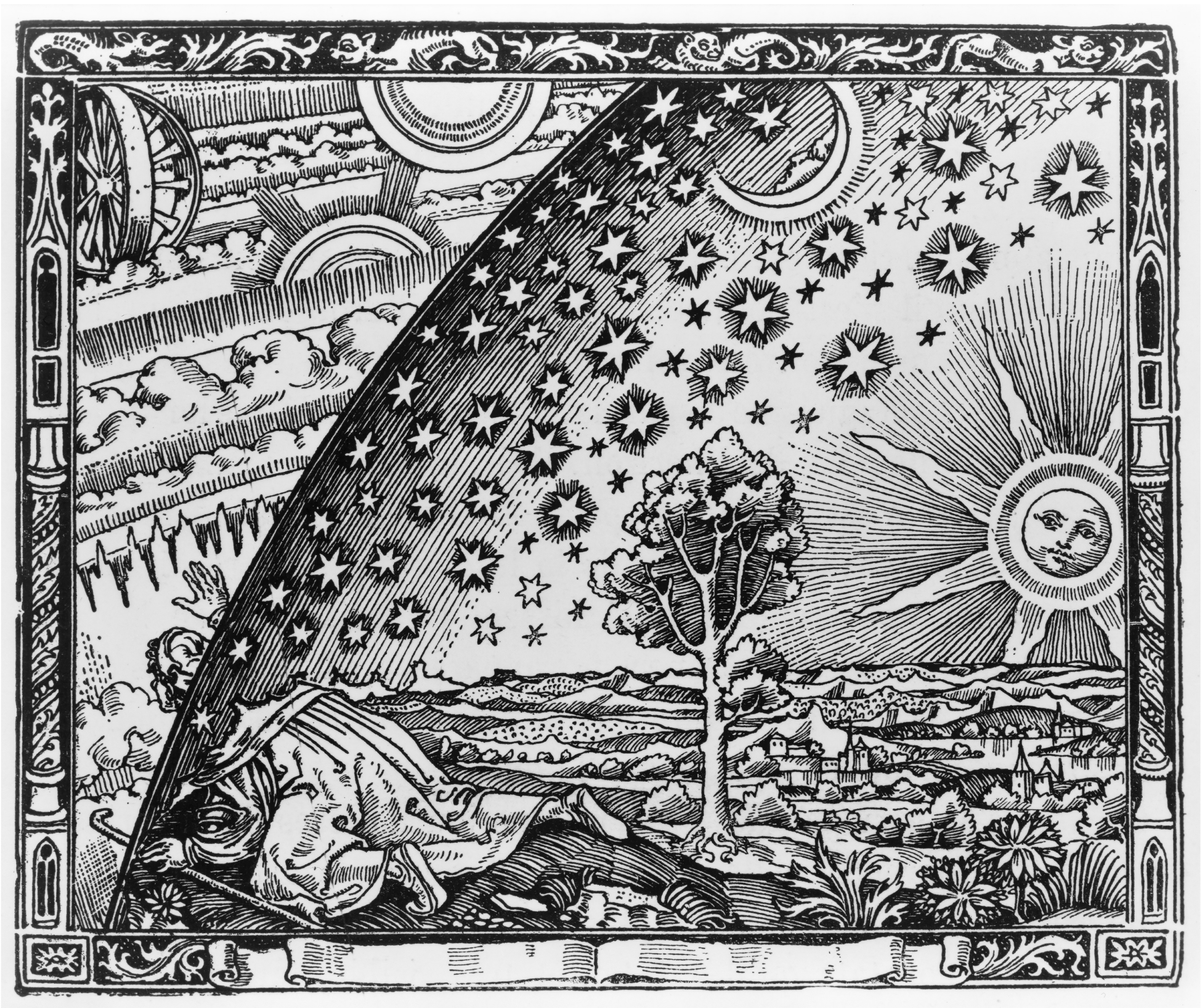




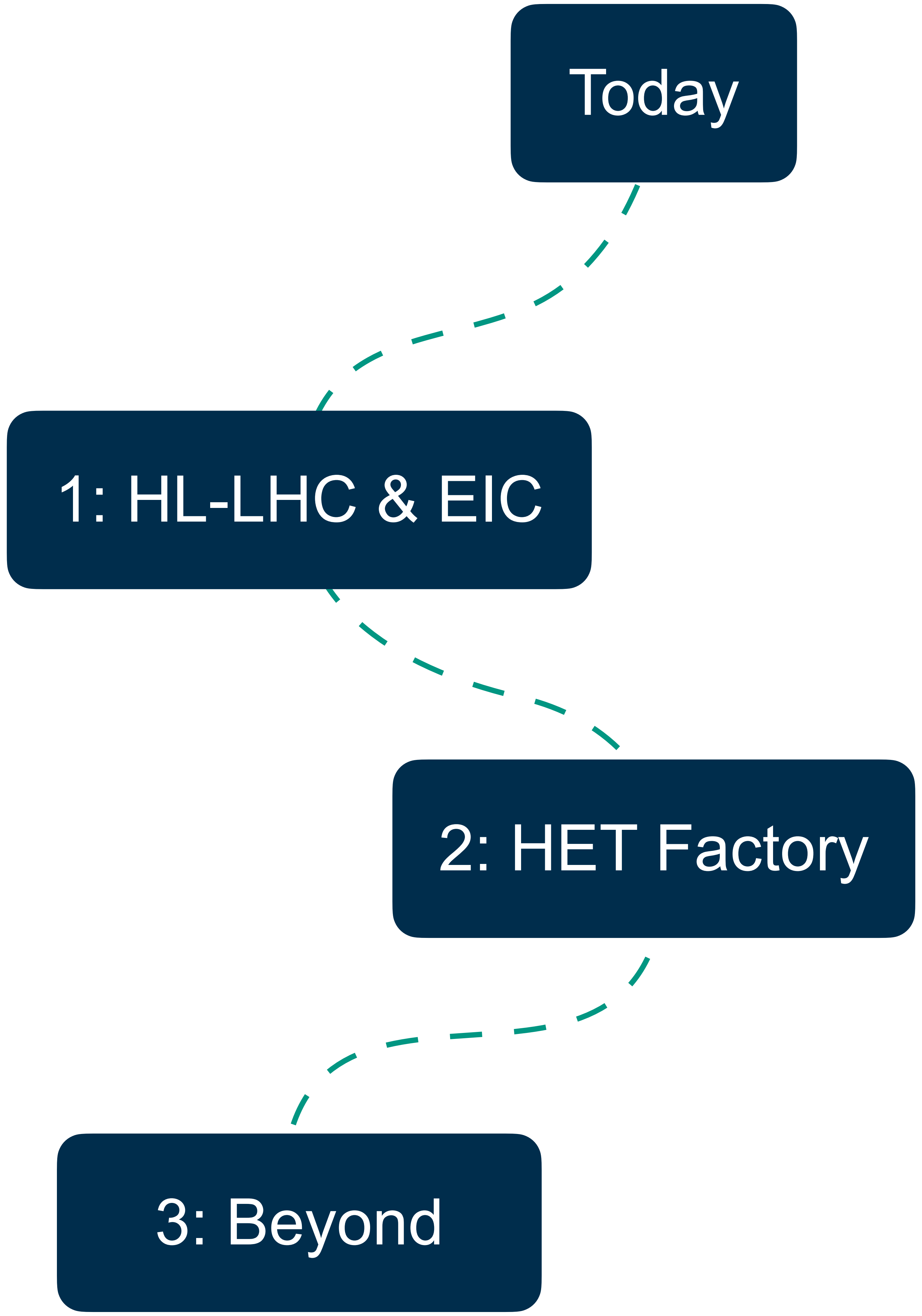
A Simplified Timeline

Key Collider Projects

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

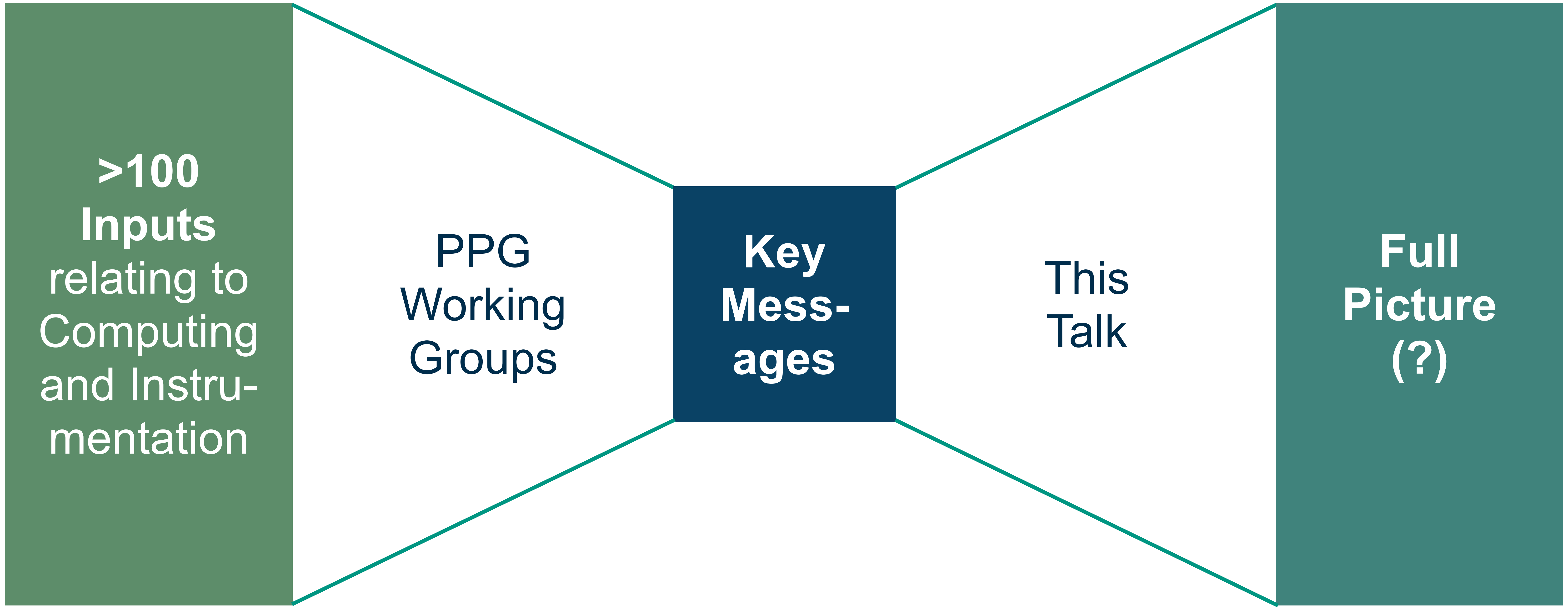


C. Flammarion, *L'atmosphère : météorologie populaire*



Preparing for for the European Strategy for Particle Physics

A Human Autoencoder?



Computing Sessions at Venice Open Symposium

Parallel I: https://agenda.infn.it/event/44943/sessions/33815/

Parallel II: https://agenda.infn.it/event/44943/sessions/33818

Plenary: https://agenda.infn.it/event/44943/sessions/32614/

Instrumentation Sessions at Venice Open Symposium

Parallel I: https://agenda.infn.it/event/44943/sessions/32657/

Parallel II: https://agenda.infn.it/event/44943/sessions/32658/

Plenary: https://agenda.infn.it/event/44943/sessions/32613

Computing

Image: Adobe Stock

Worldwide LHC Computing Grid (WLCG): A Success Story

Computing

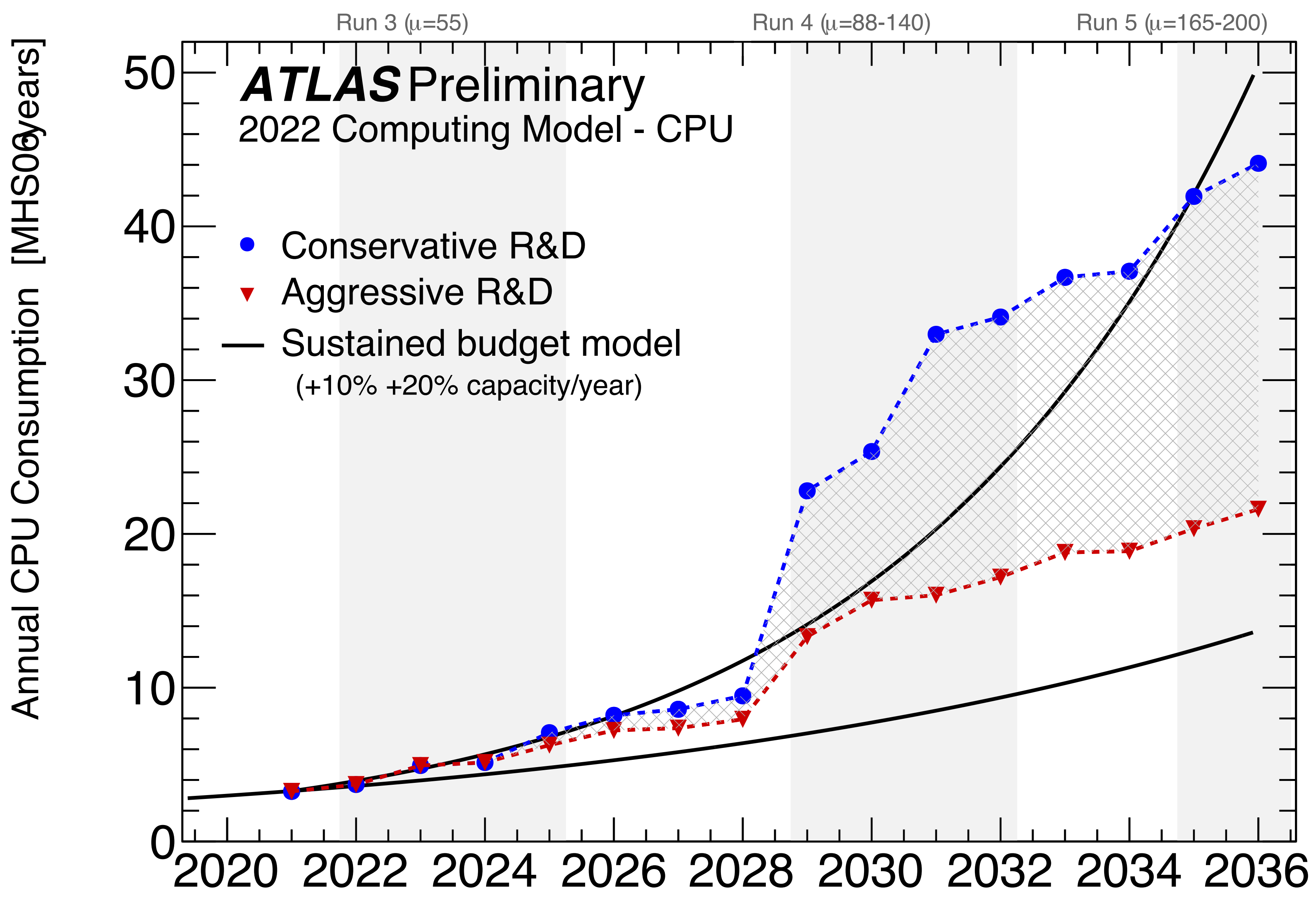
WLCG: Continuously operating since the start of LHC Run 1

- Evolved from “Monarc” design into **system of heterogeneous systems:** CPUs, graphics processing units (GPUs), supercomputers, public/private clouds, **50× as large as in 2010**
- Future direction: **non-LHC experiments** as partners (“beyond the ‘L’ in WLCG”)

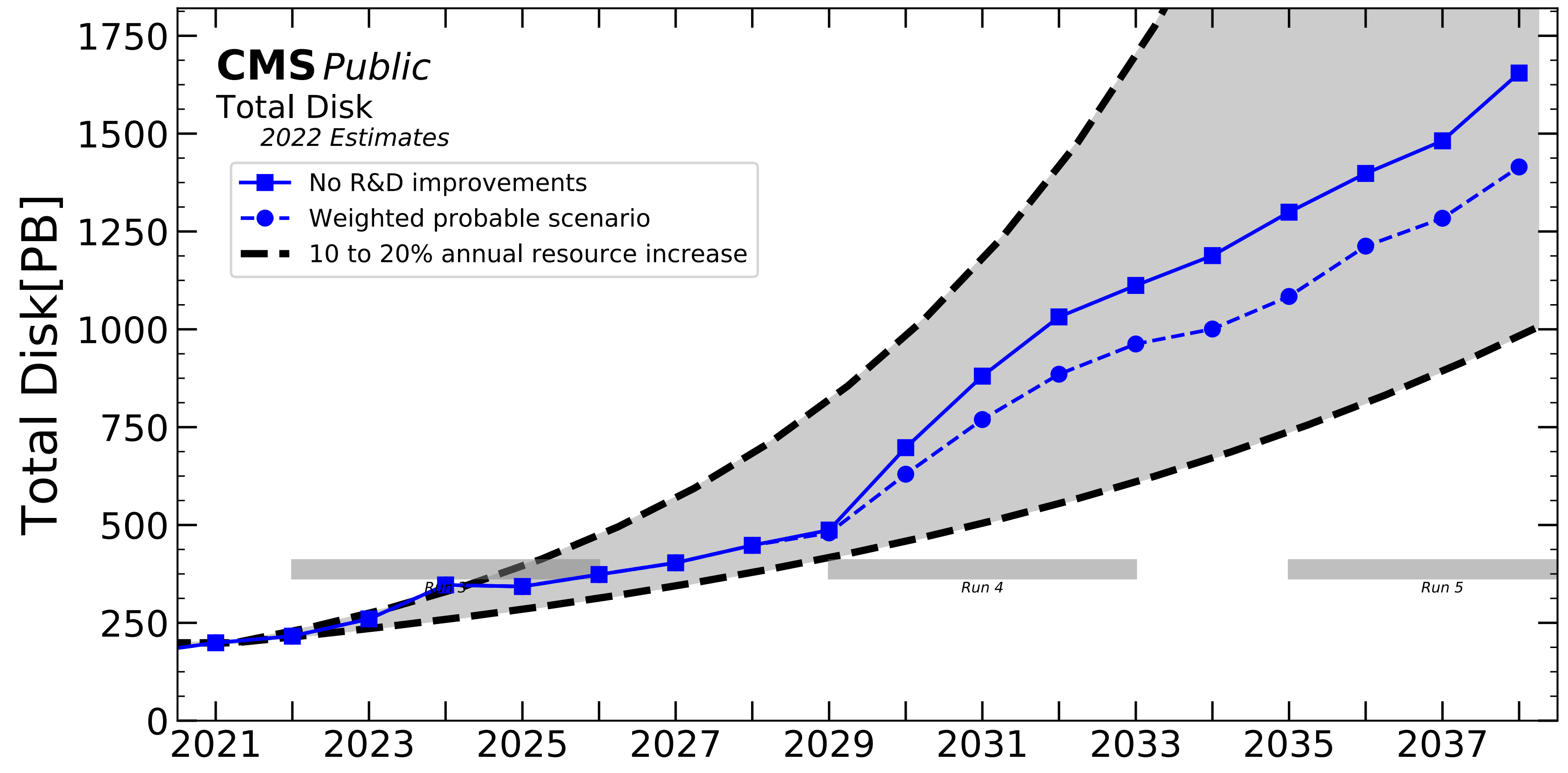
Requirements for Era 1: most recent public **projections**

- Working assumption: “flat budget”
→ annual increase in CPU/disk/tape **slowing down**
- LHCb and ALICE: **“triggerless” operation** for LHC Run 3/4
→ increased data rates at HL-LHC

Bottom line: **CPU/disk/tape requirements ok** for HL-LHC era assuming successful evolutionary R&D



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ComputingandSoftwarePublicResults



https://twiki.cern.ch/twiki/bin/view/CMSPublic/CMSOfflineComputingResults

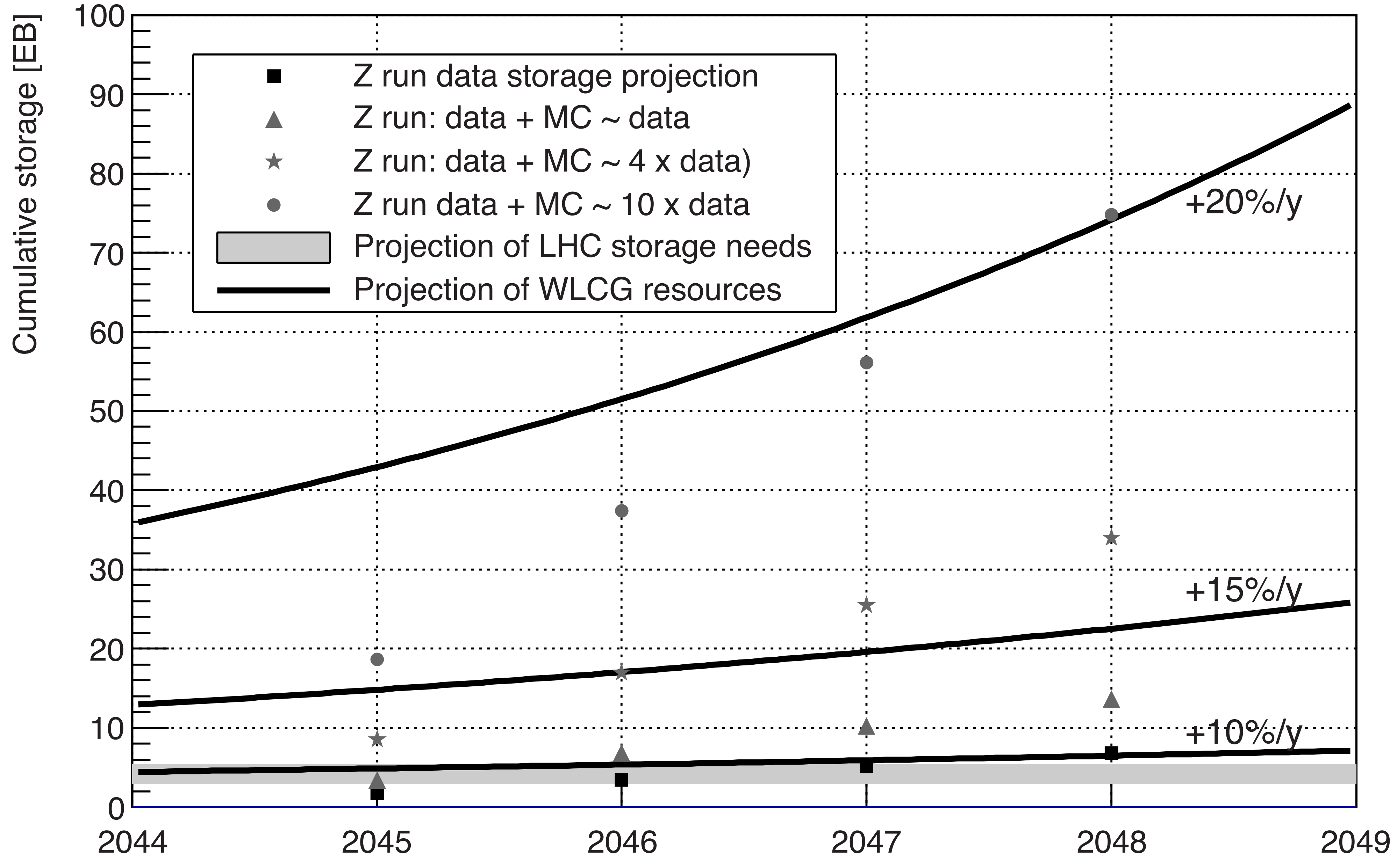
Requirements for Future Collider Projects
Computing

Physics Preparatory Group: compilation for FCC-ee, Linear Colliders, LHeC, LEP3, Muon Collider, FCC-hh

- **Common foundations** for software (e.g. Key4hep software stack), services, operations
- **Conservative planning**, based on LHC experience, not relying on novel “disruptive” technologies (e.g. quantum computing, Large Language Models)
- Projects require **continuing effort** and modest computing resources already now
- Biggest challenge in Era 2: **Z-pole running** (“tera-Z”)

Botton line: **computing will not be a limiting factor** assuming continuing R&D

Storage Requirements for Z-Pole Running



FCC Feasibility Study Report, Vol. 1

Selected Future R&D Directions
Computing

Software stack and **tools**:

- **HEP Software Foundation** (HSF): foster exchange of ideas on event generators, detector simulation, reconstruction and software triggers, data analysis, …
- New **programming languages** (e.g. Julia)
- **External software projects** (e.g. Celeritas/AdePT)

https://celeritas-project.github.io/celeritas/
https://github.com/apt-sim

HEP Software Foundation
https://hepsoftwarefoundation.org/

https://julialang.org/

Hardware and computing **infrastructure**:

- **Heterogeneous computing** on different CPU architectures, GPUs, programmable logic (FPGAs)
- Distributed computing: enable power of **high-performance computing** (HPC) centers for HEP workflows
  → challenge: very different approach (access, standards, …)

CMS HLT Node: CPU + GPU

cms.cern

Selected Future R&D Directions
Computing

Simulation and analysis of exabytes of data (e.g. Tera-Z)

FAIR principles (findable, accessible, interoperable, reusable), e.g., **open data** and **long term data preservation** (LTDP) beyond "bit preservation"

Quantum (and neuromorphic) **computing**:
often considered **national priorities**
→ future particle physics projects **do not rely** on them
(but will be happy to use them eventually)

Contact with **other data and/or compute intensive research fields**, e.g. gravitational waves, astrophysics, genomics

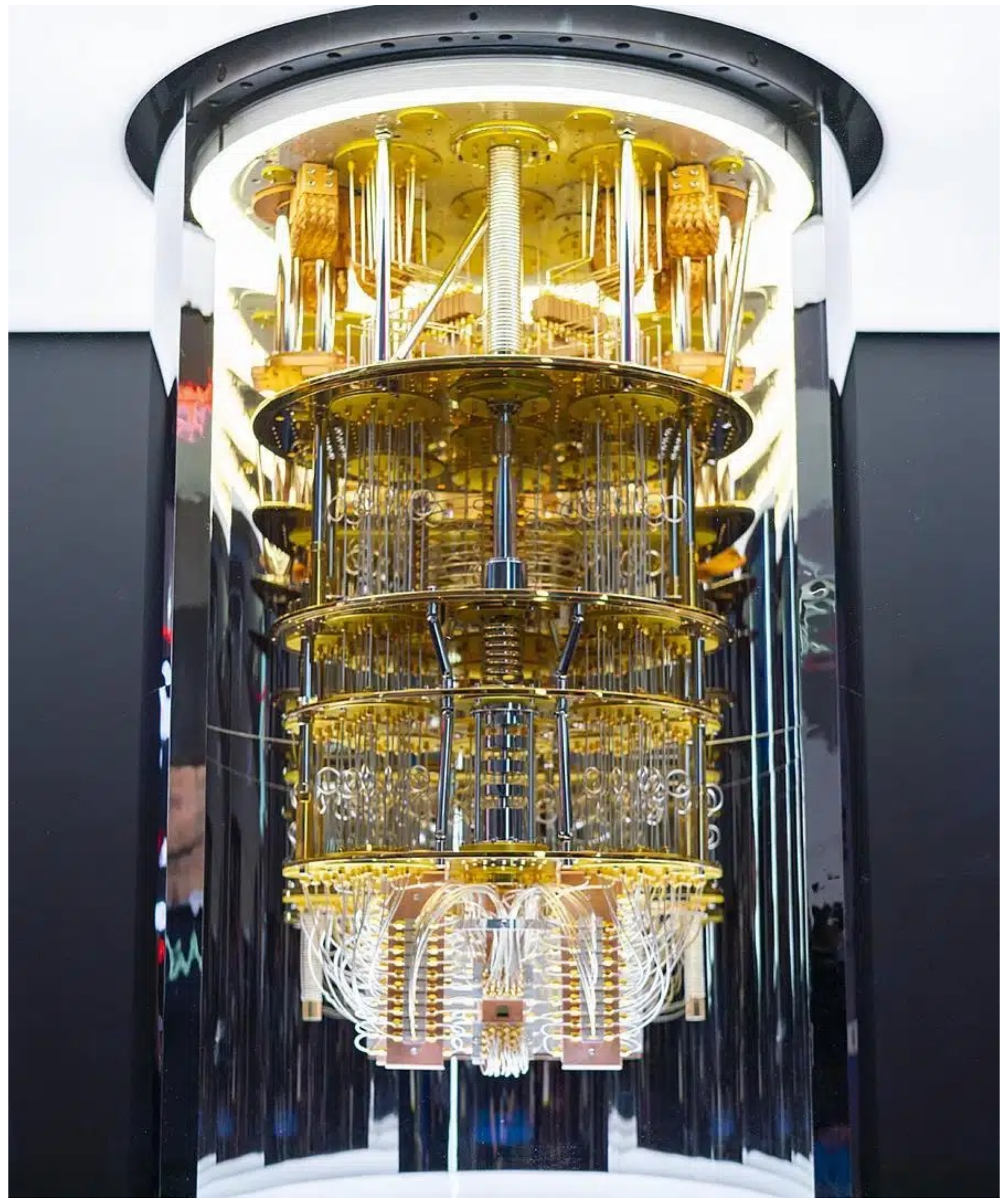
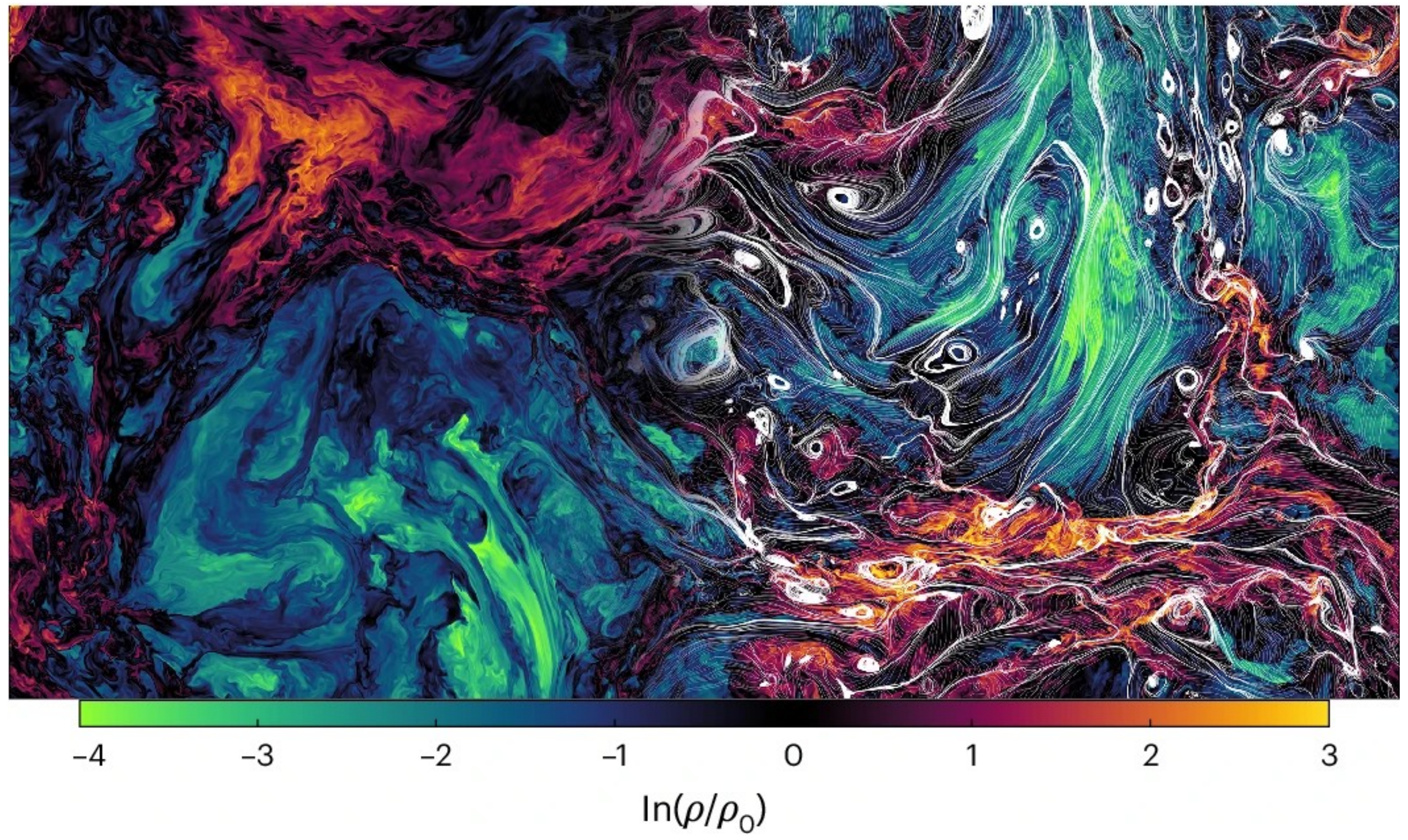


Image: IBM



Nature Astronomy (2025)

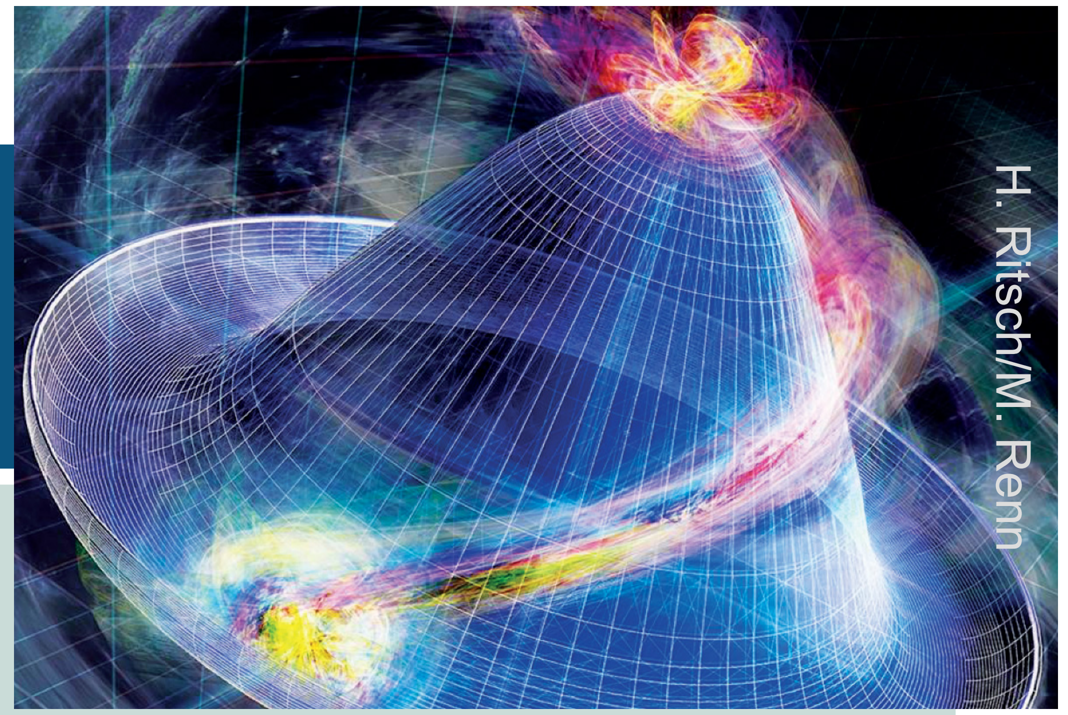
Instrumentation

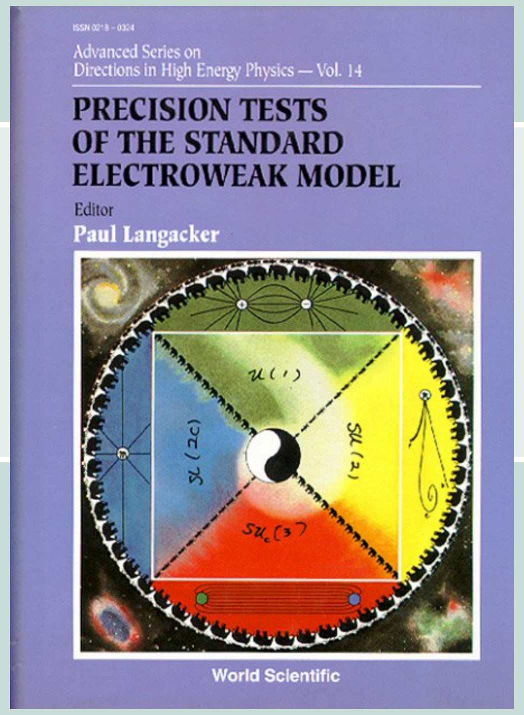
Image: Adobe Stock

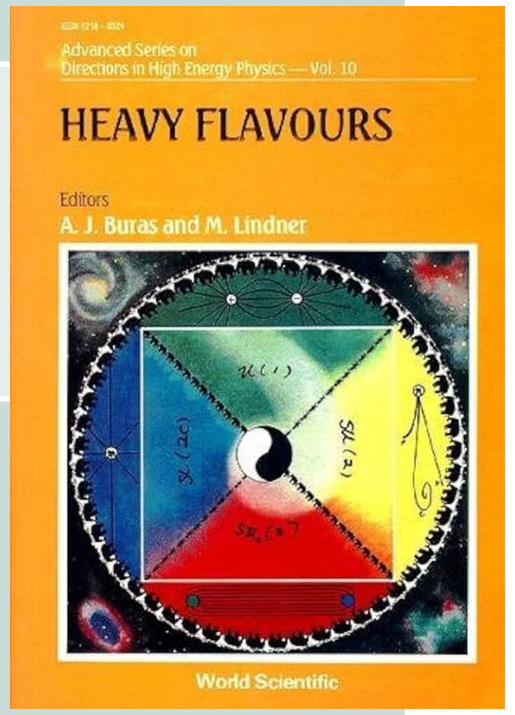
Requirements for a Higgs/Electroweak/Top Factory

Instrumentation

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**







Technologies: Colliders and Beyond
Instrumentation

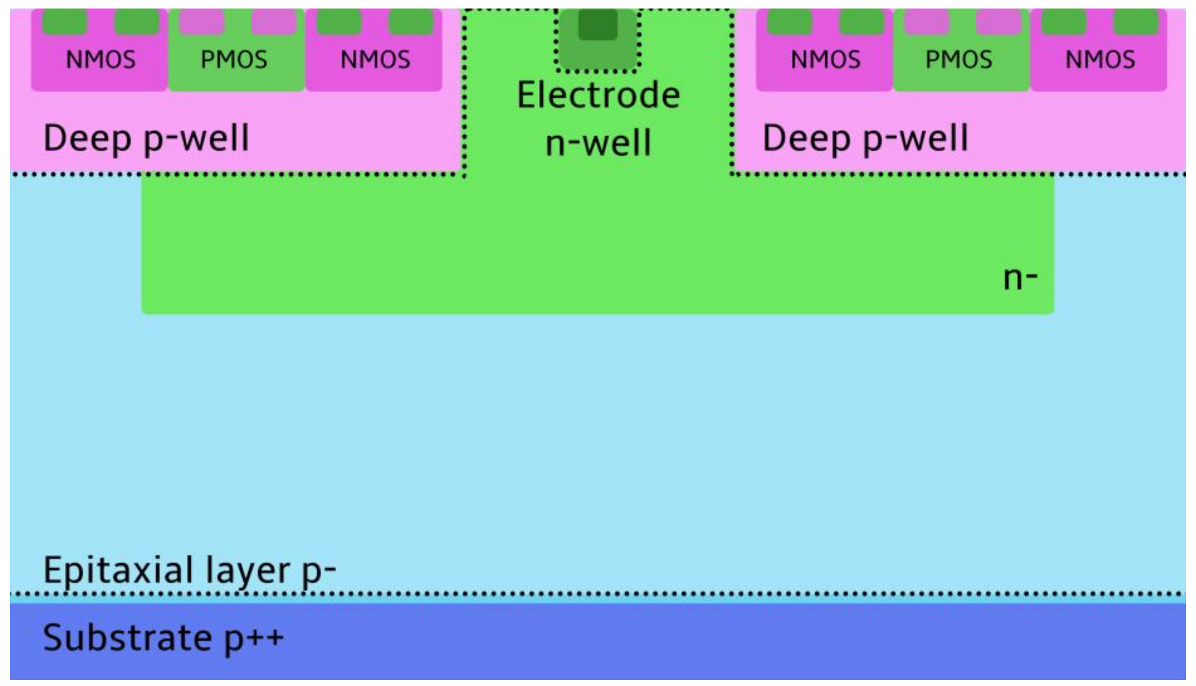
Vertexing and **tracking**:

- Silicon: monolithic active pixel sensors, ultrafast sensors, etc.
- Gaseous detectors: drift chambers, time projection chambers, micro-pattern gaseous detectors, etc.
- New: **4D tracking** (3D position: < 30 μm, time: < 30 ps)

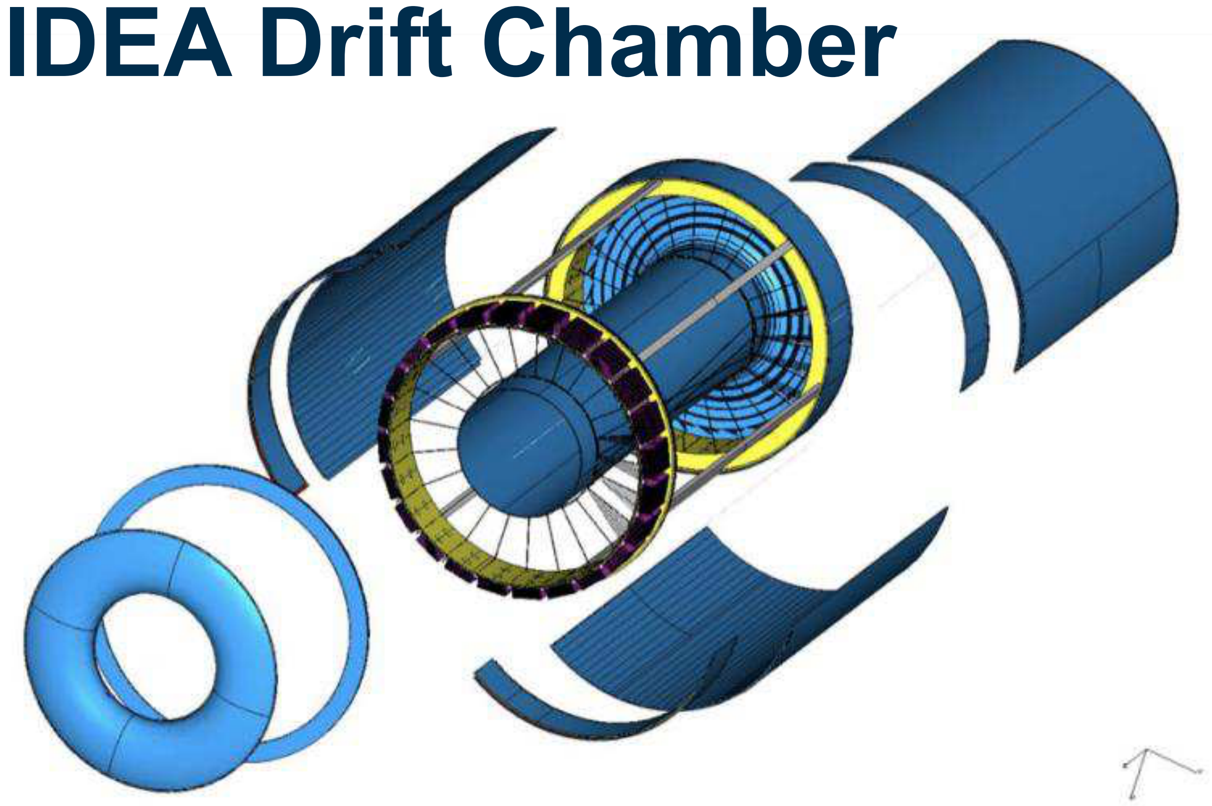
Calorimetry:

- High granularity **imaging** calorimeters
- **Dual-readout** (scintillation & Cherenkov) calorimeters
- Suited for **modern reconstruction algorithms**: particle flow, machine learning
- New: **5D calorimetry** (energy, 3D position, time)

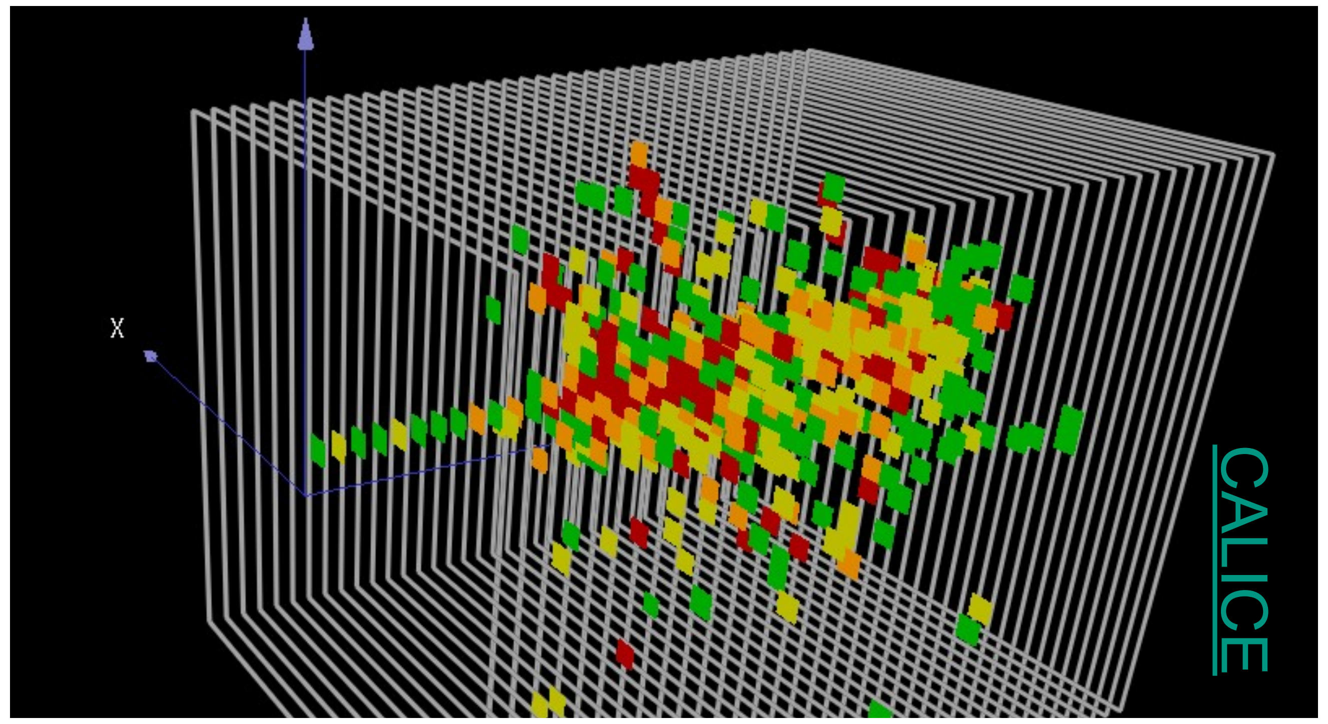
OCTOPUS MAPS Layout



IDEA Drift Chamber



Event in SiPM-on Tile AHCAL



Technologies: Colliders and Beyond

Instrumentation

Photon detection: high quantum efficiency, single-photon detection, high speed, low dark rate, cryogenic readout …

→ key technology: **silicon photomultipliers** (SiPMs)

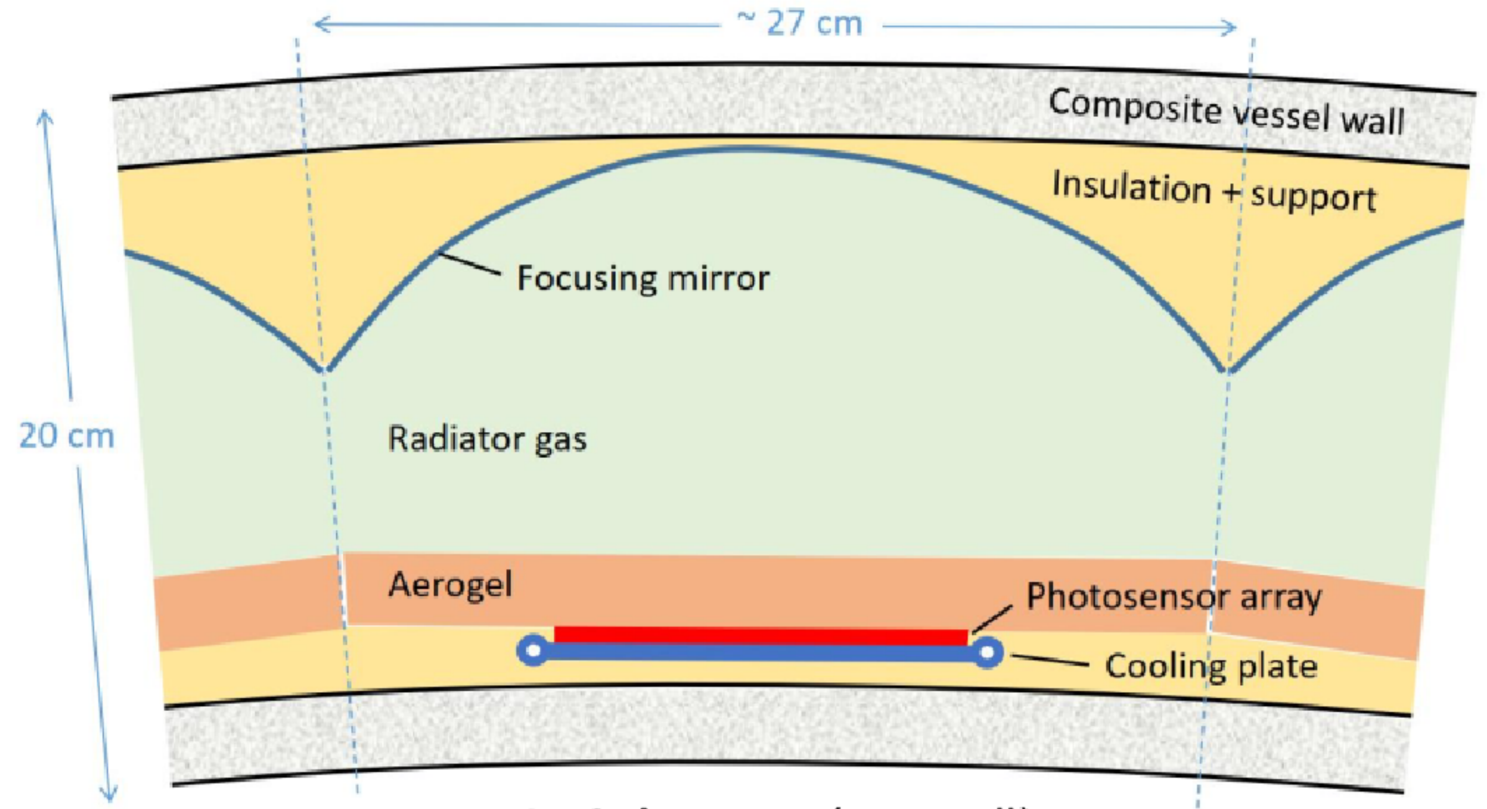
Particle identification (PID): pion/photon and hadron separation over various relevant momentum ranges, muon ID

→ key technologies: **RICH** (ring-imaging Cherenkov) counters, **TOF** (time-of-flight) detectors, **d*E*/dx** and **d*N*/dx** in gaseous tracking detectors, gaseous/scintillating **muon detectors**

Detectors for **neutrino** physics and **rare event** searches: diverse set of physics objectives and requirements

→ **broad range** of technologies: (noble) liquids, semiconductors, **quantum sensors**, microwave resonators, and more

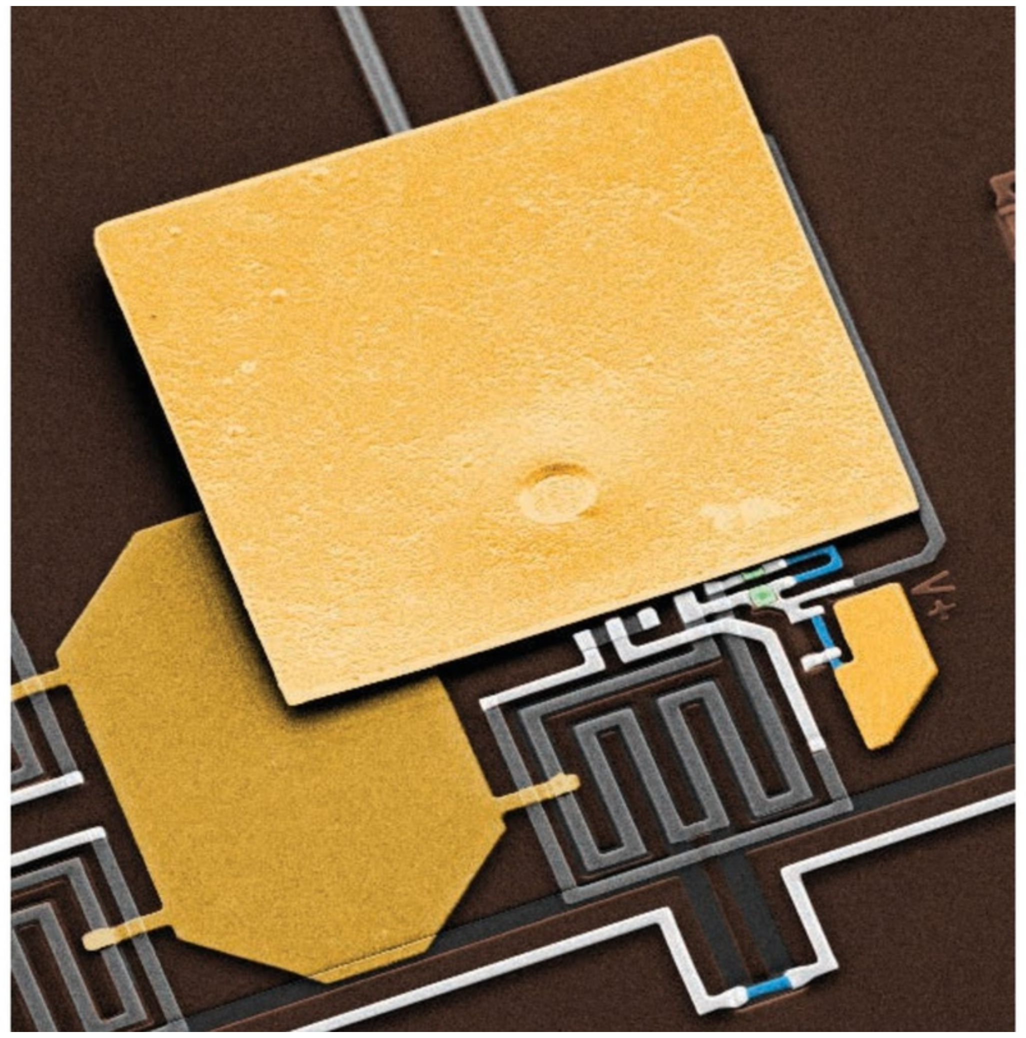
ARC: Array of RICH Cells



ARC detector (one cell)

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

Magnetic Microcalorimeter



App.Phys.Lett. 124 (2024) 032601

ECFA Detector R&D Roadmap 2021

Instrumentation

2020 ESPP Update: **ECFA Detector R&D Roadmap**

- Series of **bottom-up workshops** to identify requirements, technologies, time scales, expert training, …
- Comprehensive **roadmap document**
- New **DRD** (Detector R&D) **collaborations** → **strategic R&D**

CERN-ESU-017

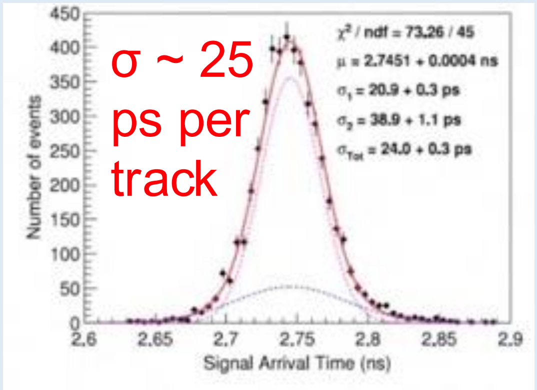
ECFA Detector R&D Roadmap 2021: DRD Collaborations

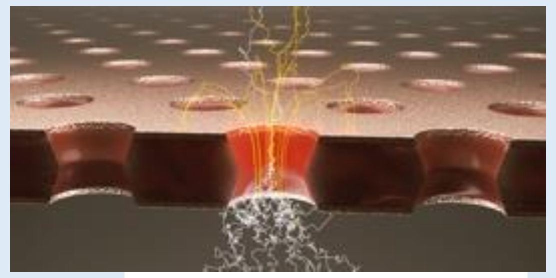
Instrumentation

+ close collaboration and efforts in the US, Japan, and China

DRD1: Gaseous Detectors

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

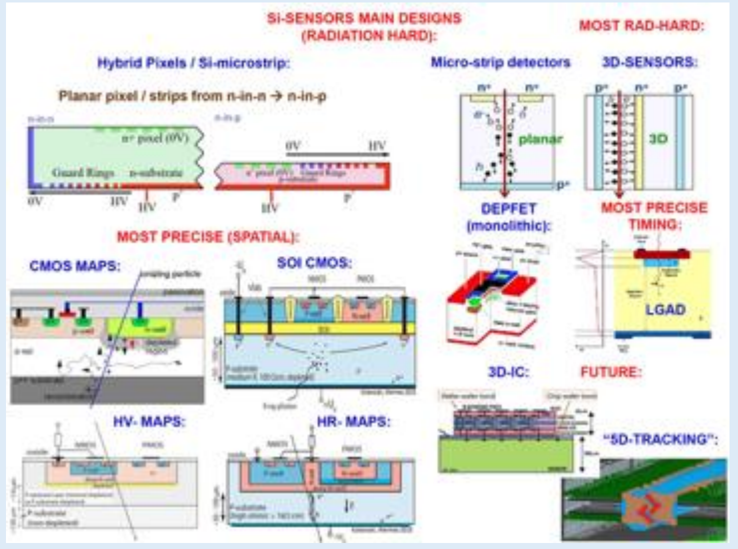




PICOSEC: NIMA903 (2018) 317

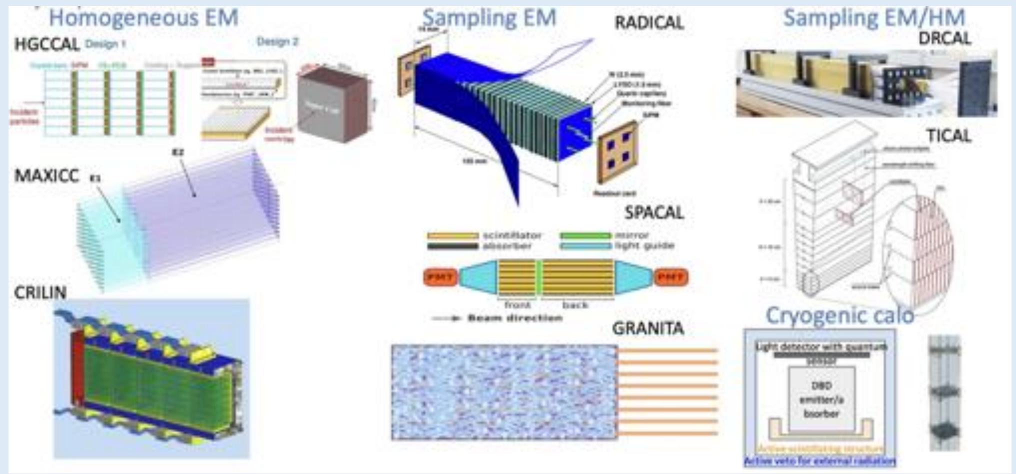
DRD3: Semiconductor Det.

Monolithic CMOS · LGADs · radiation hardness · interconns.



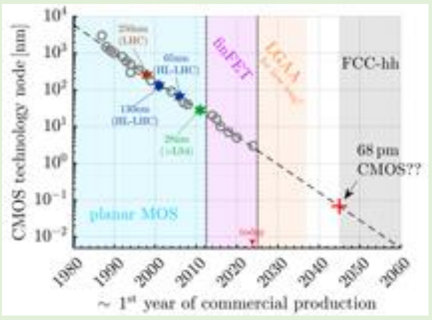
DRD6: Calorimetry

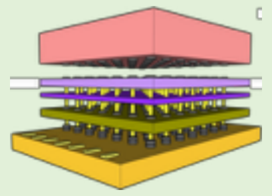
Energy resolution · High granularity · dual readout · particle flow · sandwich · optical

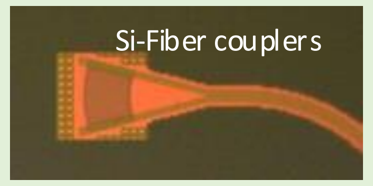


DRD7: Electronics

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





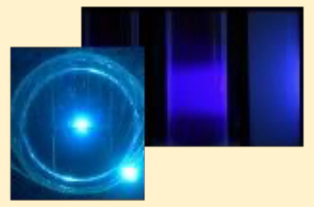


DRD2: Liquid Detectors

for Neutrinos · Dark Matter · 0vbb

Noble Elements
- Argon & Xenon
- Ionisation charge & transport
- VUV Scintillation, light propagation & detection

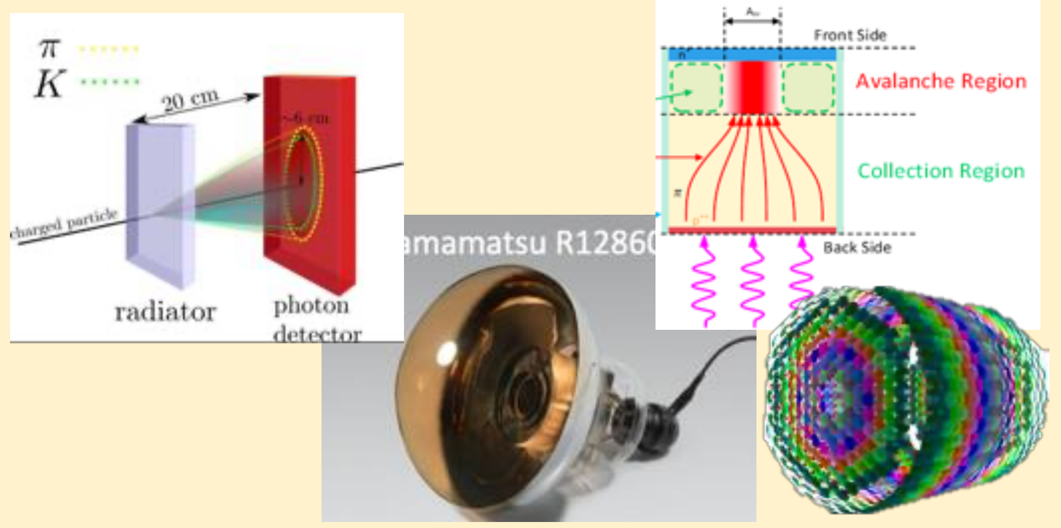
Liquid Scintillators
- Visible Scintillation, light propagation
- Scintillator properties
- Isotope loading



Water Cherenkov
- Cherenkov light, light propagation
- Doping for n-capture

DRD4: Photon detectors

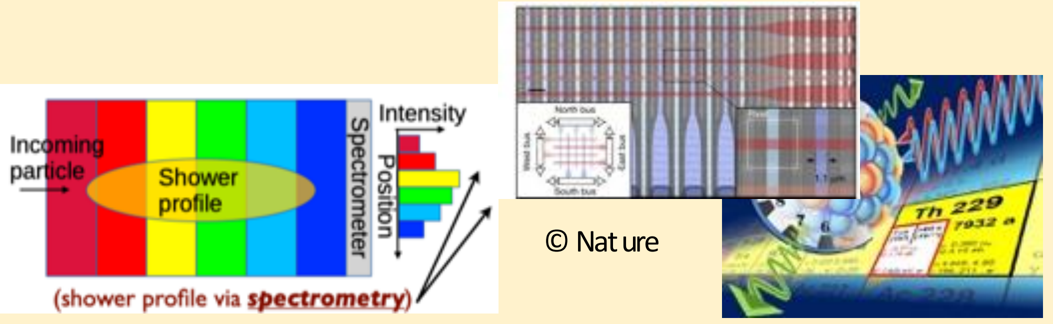
vacuum, solid-state (SiPM), hybrid single-photon and SciFi detectors · applications in PID, RICH, tracking



DRD5: Quantum Sensors

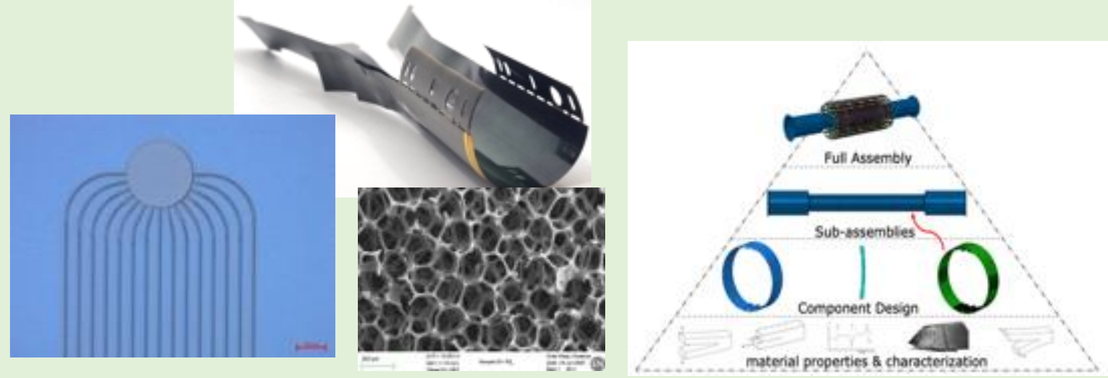
Quantum dots · superconduct. nanowires · bolometers · TES · MMC · nuclear clocks

Applications in LEPP, first projects in HEPP happening



DRD8: Mechanics

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



T. Bergauer

ECFA Detector R&D Roadmap 2021

Instrumentation

2020 ESPP Update: **ECFA Detector R&D Roadmap**

- Series of **bottom-up workshops** to identify requirements, technologies, time scales, expert training, …
- Comprehensive **roadmap document**
- New **DRD** (Detector R&D) **collaborations** → **strategic R&D**

2026 ESPP Update:

- **New/updated requirements** and **recent developments**
- Not (yet fully) considered: detector **magnets**, **quantum** detectors for rare event searches, **“intelligent”** trigger and data acquisition – electronics and software tools
- New **R&D collaborations for AI**? (“AI-RD collaborations”)

CERN-ESU-017

Transversal Topics

Transversal Topics: Machine Learning & AI

Computing & Instrumentation

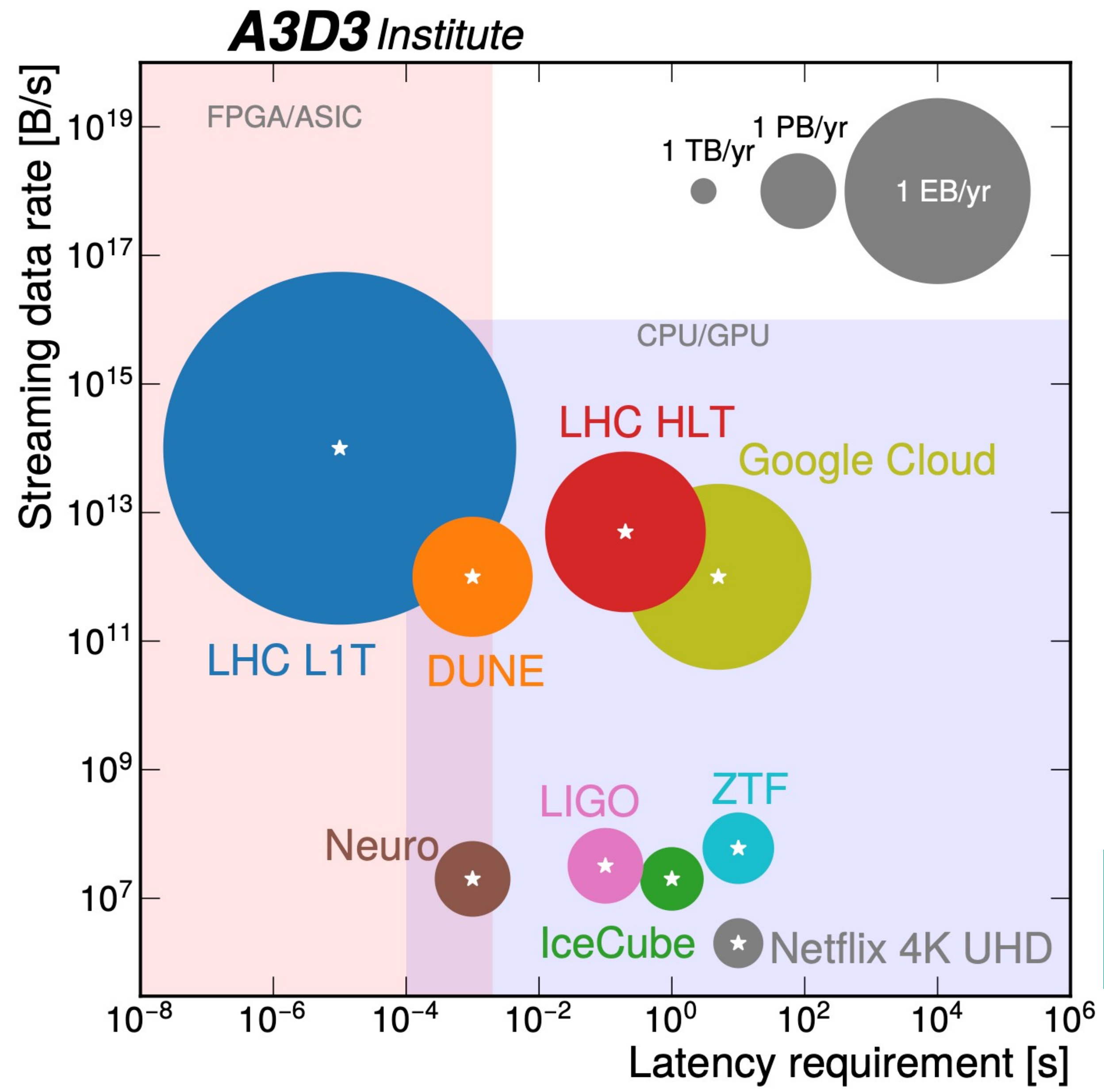
Data challenges: rate **bottlenecks**, vendor **lock-in** (e.g. GPUs, FPGAs), long-term **maintenance** of large code base (10s of millions lines of code)

Machine learning ubiquitous in particle physics: detector design, detector frontend ("edge AI") and backend, trigger, simulation, data analysis

Artificial intelligence: potential for **disruption**, but **no reliance** on, e.g., large language models, foundation models

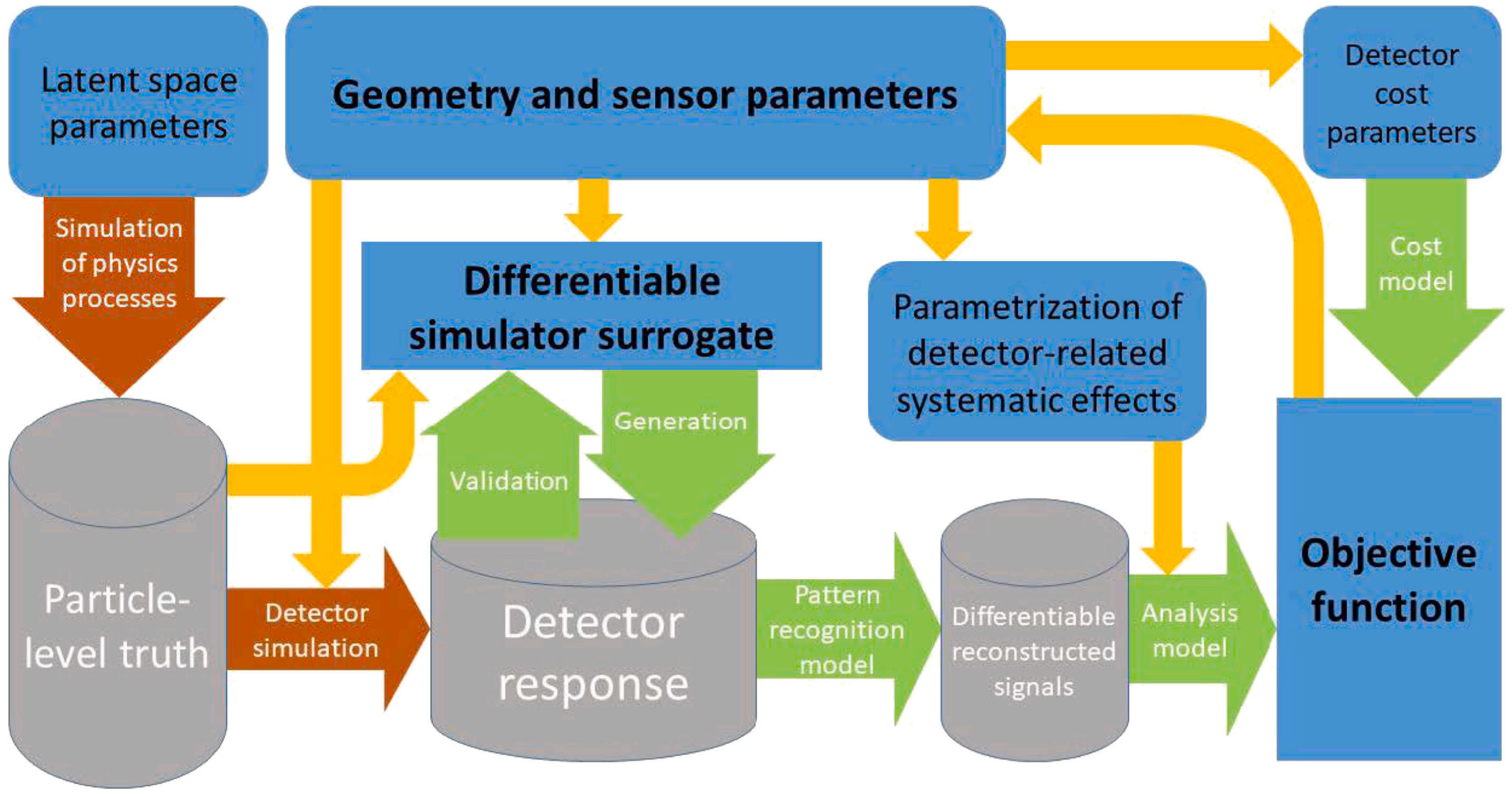
Need to **bridge gaps** to computer science and industry (over decades-long projects)

Rate/Latency Requirements



a3d3.ai

AI Detector Optimization



Review in Physics 10 (2023) 100085

Infrastructures and Relations

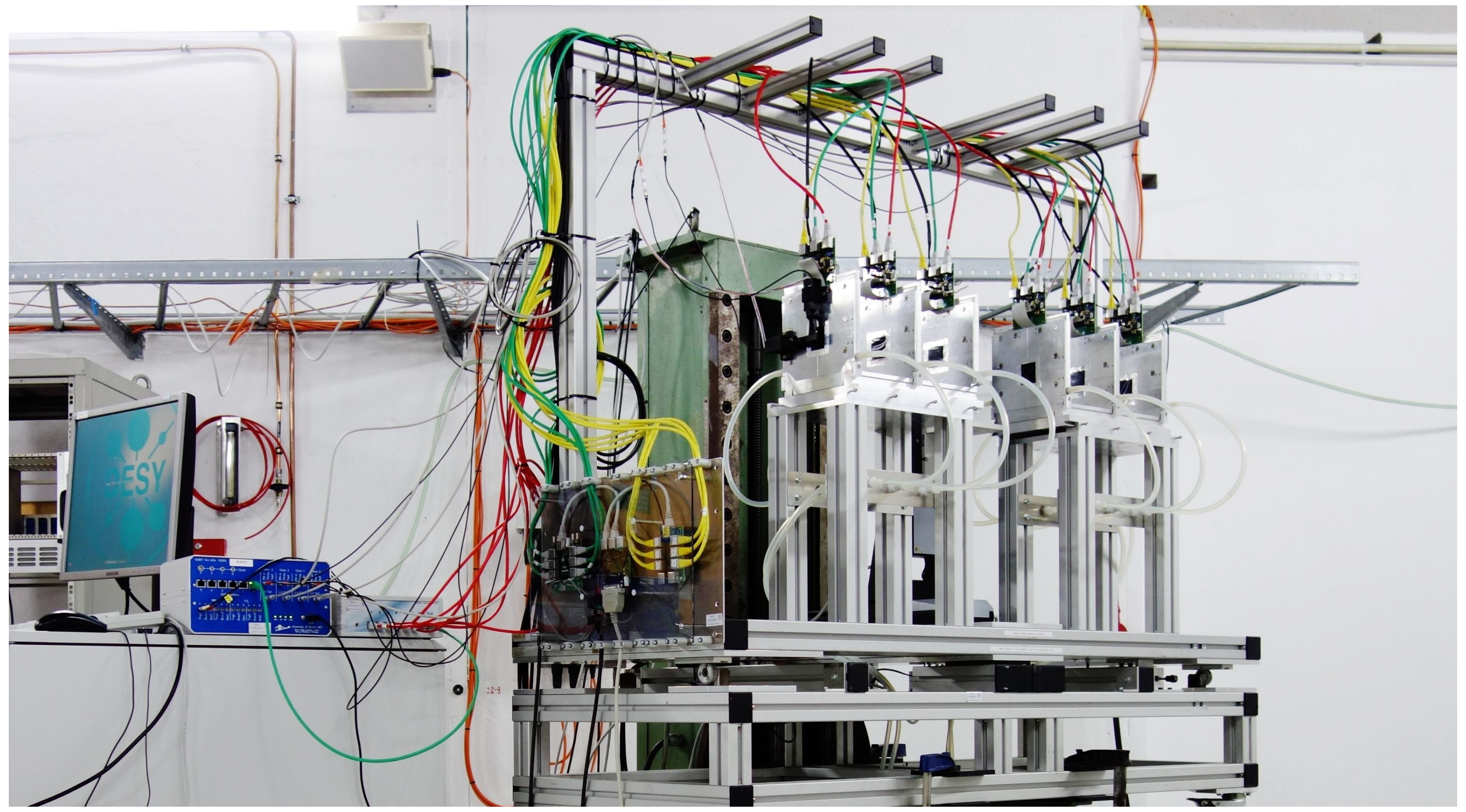
Computing & Instrumentation

Key infrastructures for detector R&D: irradiation and beam test facilities, CERN Neutrino Platform

Relations to the “world outside particle physics”:

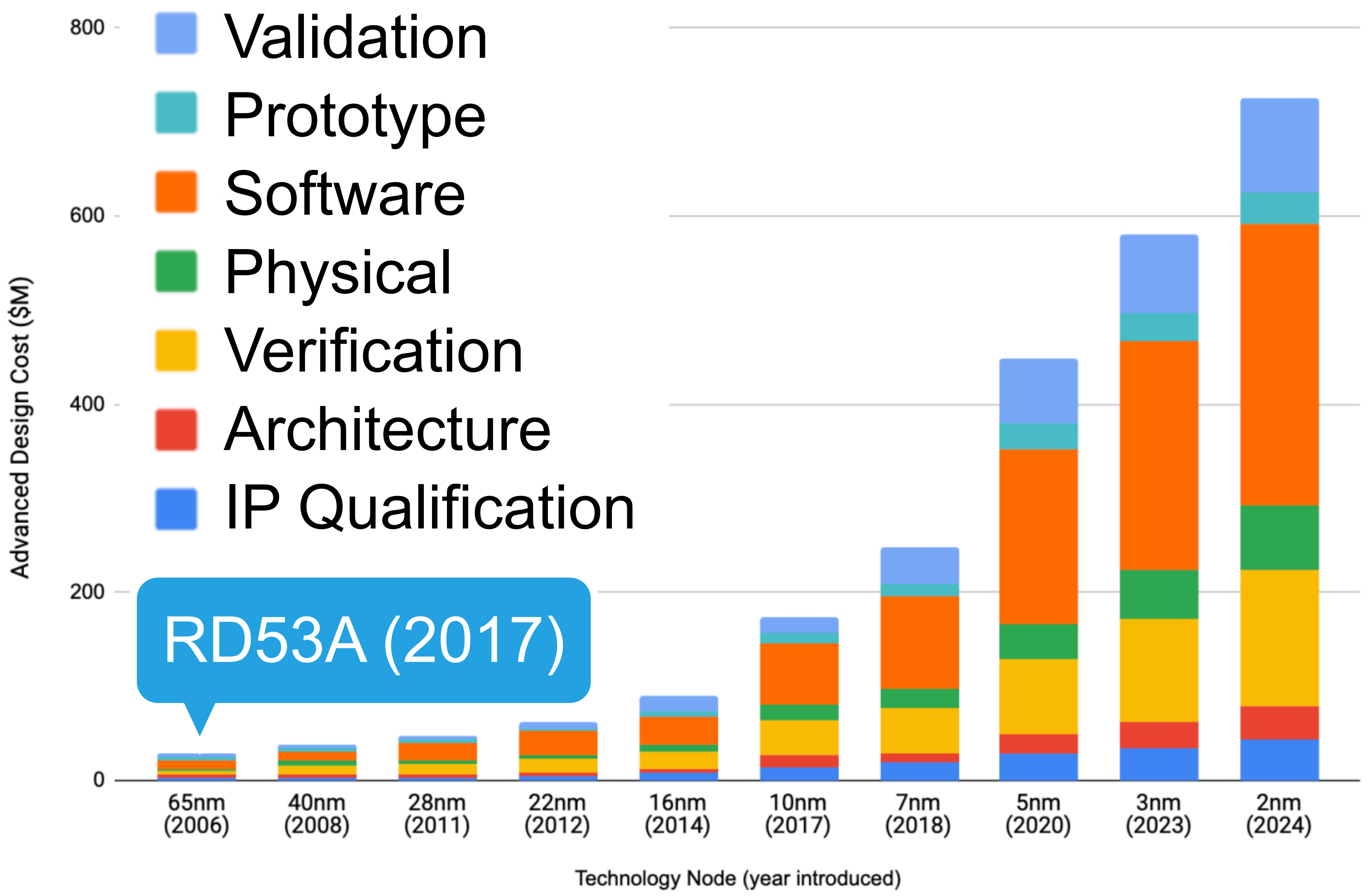
- **Engineering** and **disruptive new technologies**: software, quantum materials and sensing, manufacturing
- **Microelectronics challenge**: much increased complexity and cost, particle physics lagging behind
- **Partnerships with industry** for latest developments, joint research, commercial interest (e.g. knowledge transfer, licensing), careers in science and industry

Beam Hodoscope at DESY Test Beam



https://particle-physics.desy.de

Cost of Advanced ASIC Designs

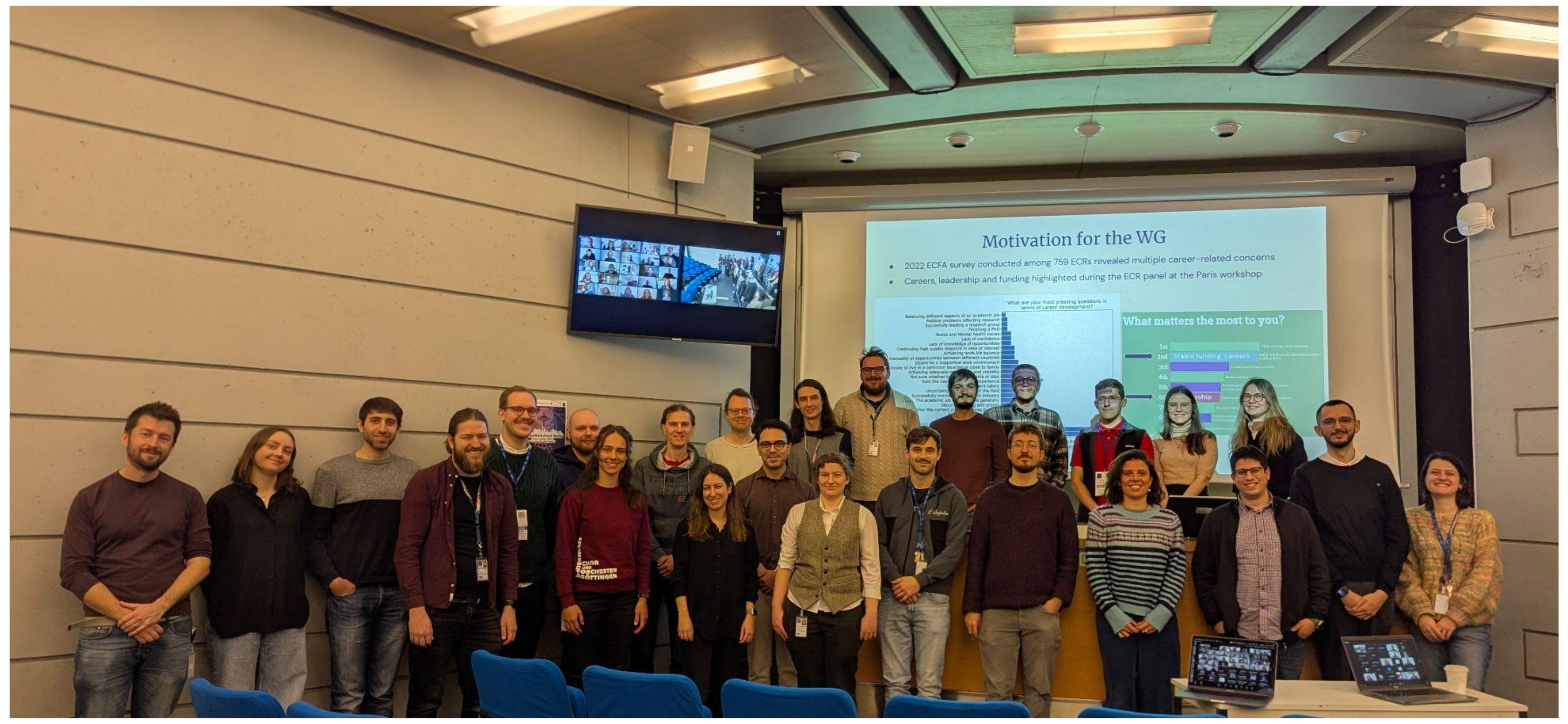


Dario Soatto (Data source: International Business Strategies)

Transversal Topics: Workforce and Sustainability

Computing and Instrumentation

ECR Open Symposium 2025

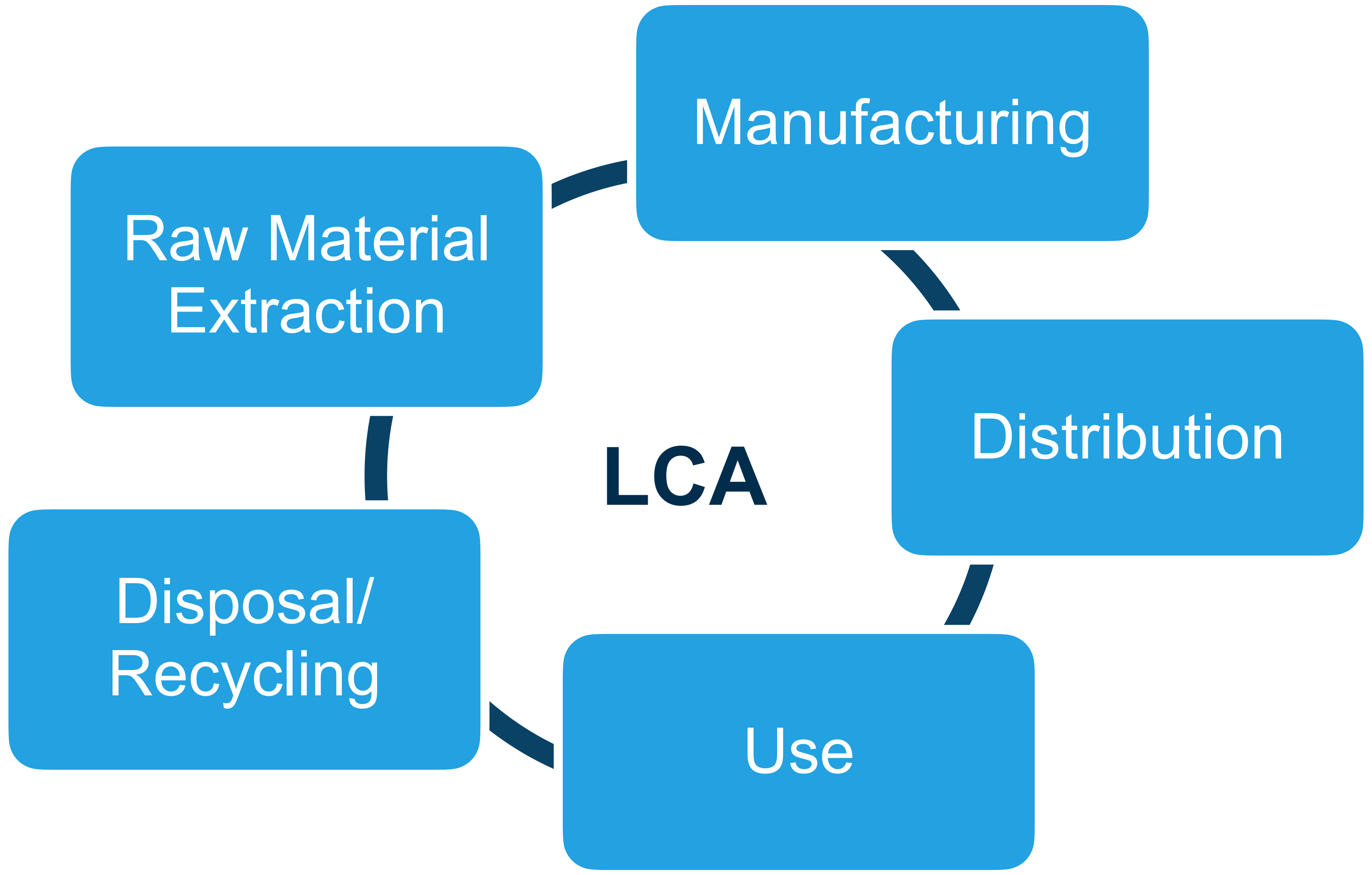


Maintaining expertise:

- Attract and train **early career researchers** (ECRs)
  → ambitious projects, **recognition**,
  transparent career paths
- Attract and retain **highly specialized experts** (AI, chip design, …), foster mobility in and out of particle physics

Making computing and instrumentation **sustainable**:

- Computing: **energy efficiency** of devices and facilities, efficient algorithms
- Detectors: full **life cycle assessment** (LCA), new **eco-friendly** materials



Summary & Conclusion

The **future** of particle physics is **bright**: vivid field, broad range of experiments

Computing and instrumentation in particle physics: **tools for discovery**

- Significant **technological limitations and challenges** → continuing R&D required
- **New ideas**, may turn out as potential **game changers** (AI, second quantum revolution)
- Community **willing and able to transform** → to be further developed