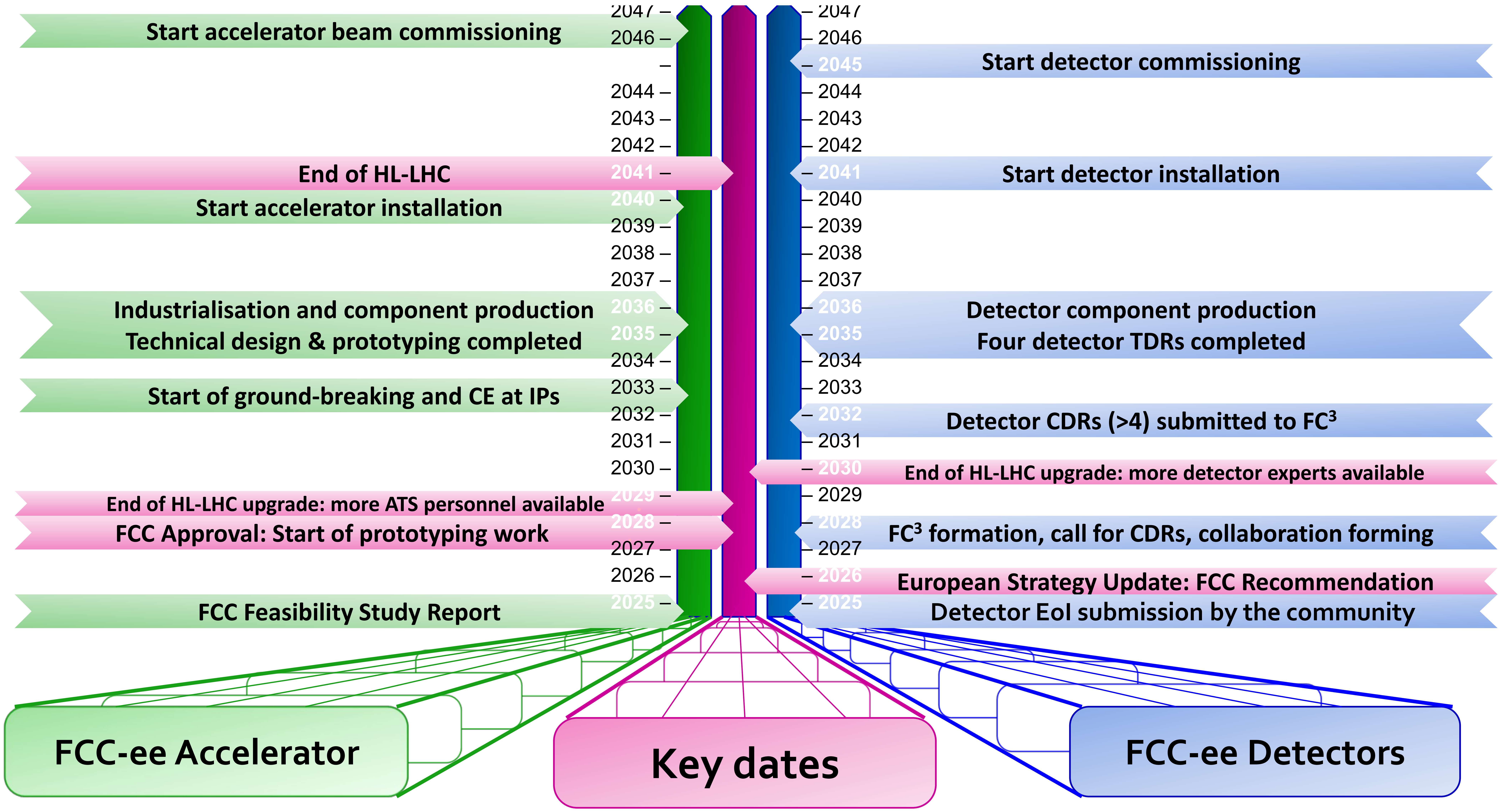
Paradigm Changing Technologies for Future Colliders

The Software Perspective 21.11.2025

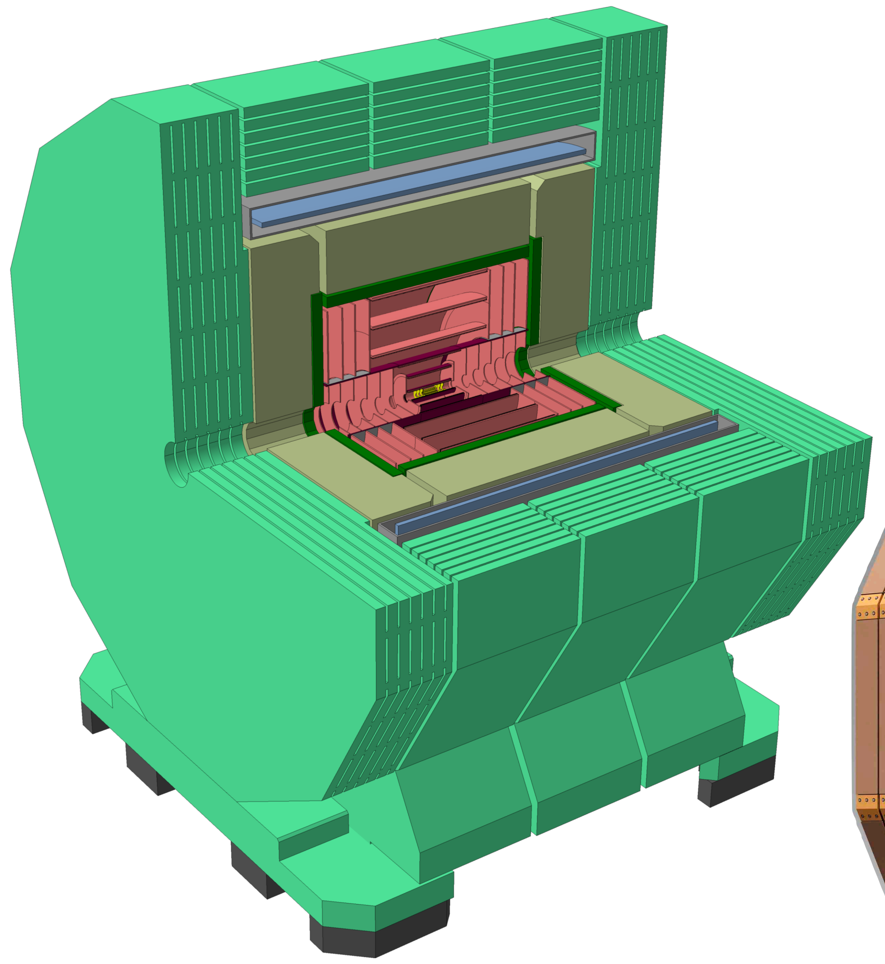
Jan Kieseler, Florian Bernlochner, Torben Ferber, Frank Gaede, Christian Grefe, Lukas Heinrich, Gregor Kasieczka, Thomas Kuhr, Felix Sefkov, Frank Simon

DESY. LMU TUM KIT Karlsruher Institut für Technologie UHH UNI BONN

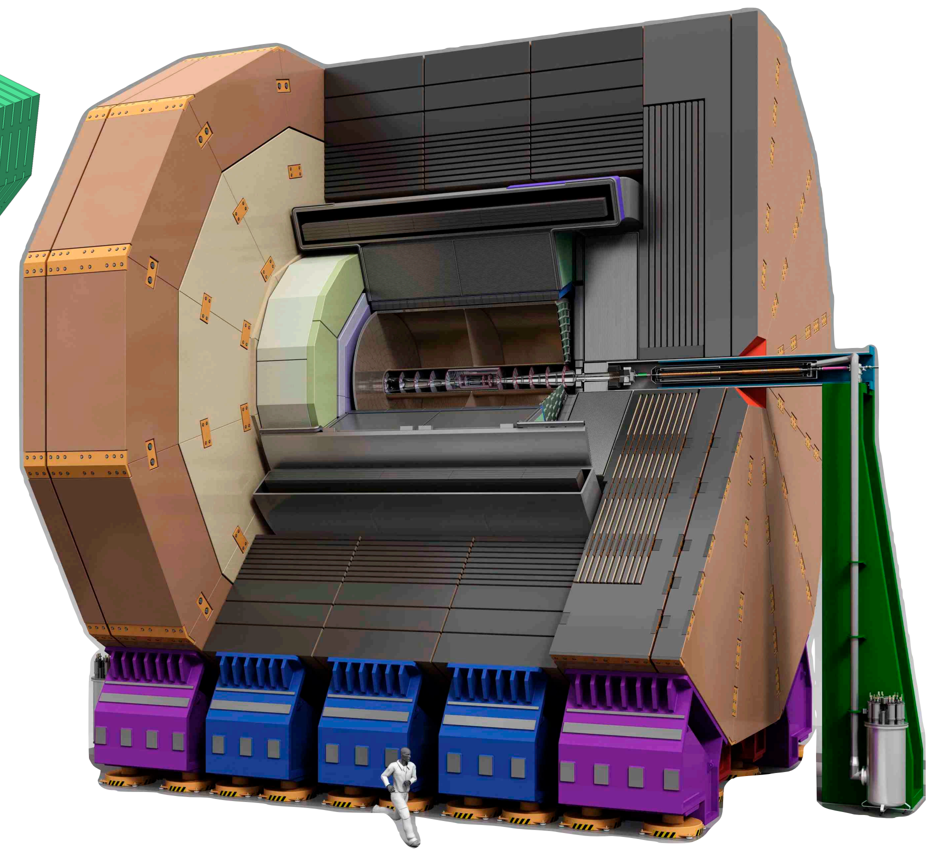
Detectors on a Challenging Timeline: e.g. FCC-ee



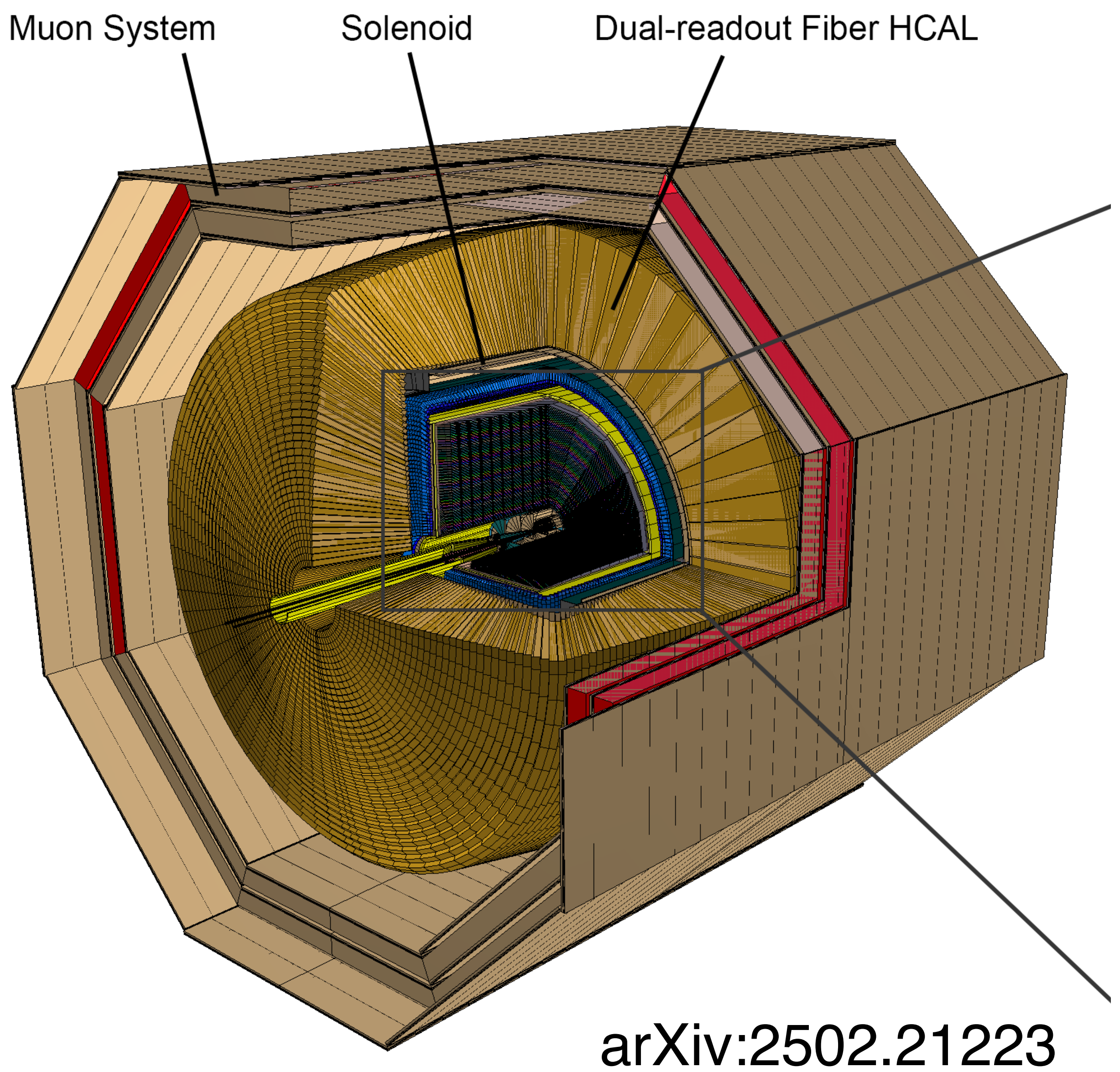
Full Simulation Chains for Current Concepts



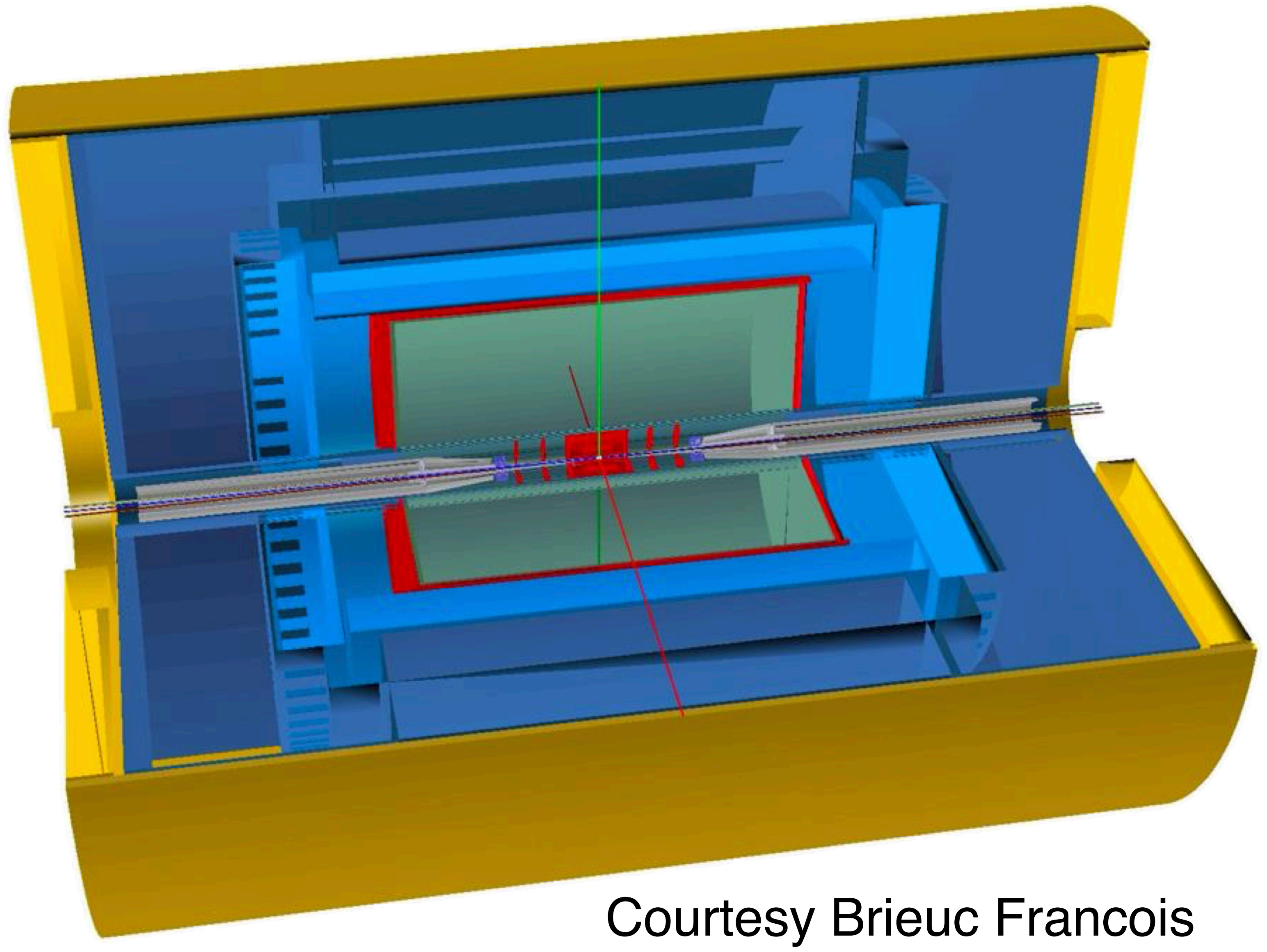
LCD-Note-2019-001



arXiv:2506.06030



arXiv:2502.21223



Courtesy Brieuc Francois

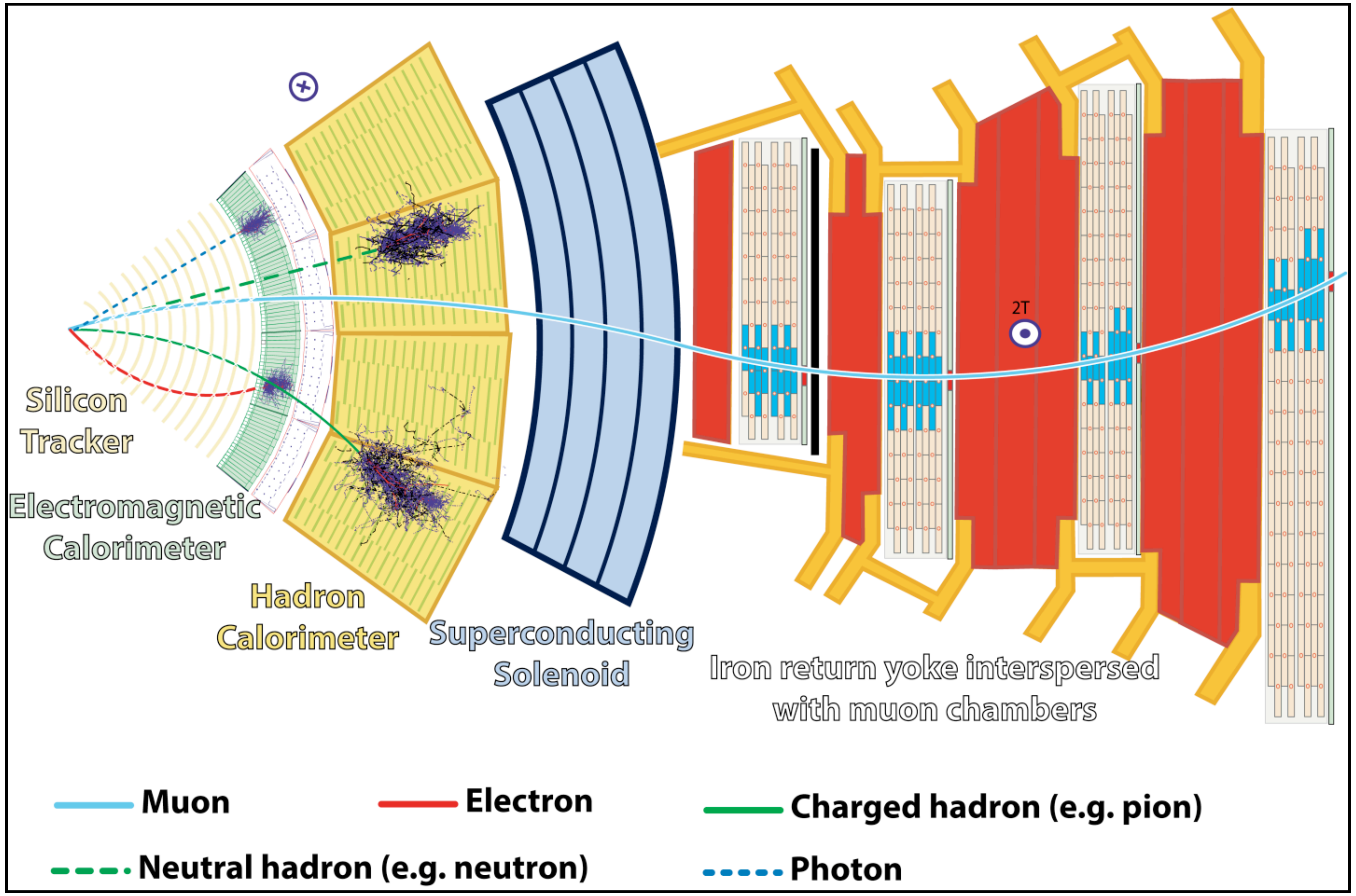
CLD / ILD
Full Simulation
Reconstruction

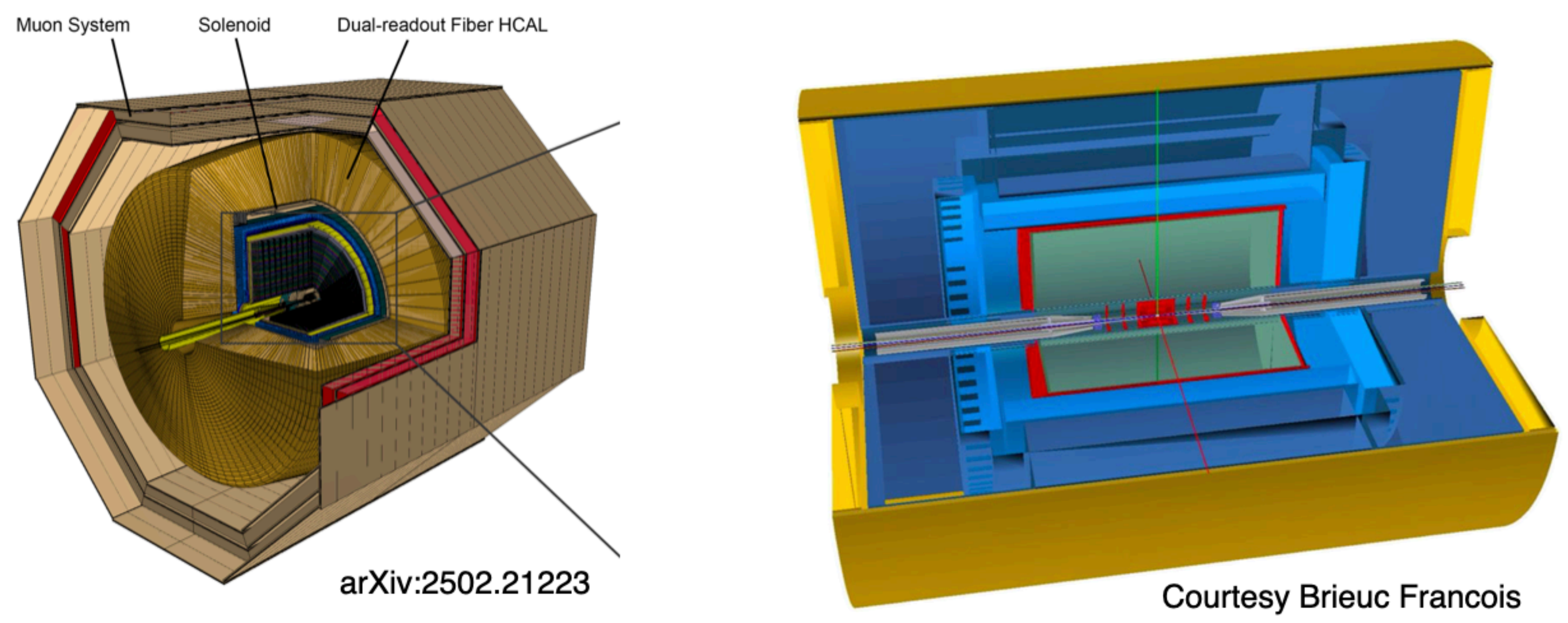
IDEA
Full Simulation
Reconstruction partially available

ALLEGRO
Full Simulation mostly available
Reconstruction incomplete

➡All concepts centred around the particle flow idea as guiding principle

Algorithms are Crucial to Assess and Optimise Global Performance





IDEA
Full Simulation
Reconstruction partially available

ALLEGRO
Full Simulation mostly available
Reconstruction incomplete

Without full simulation of the entire detector we cannot reliably assess the performance

➡Overall physics performance does not factorise between components, in particular in presence of constraints
➡Surrogate metrics can only bring us so far; algorithms finally connect the pieces

ML algorithms provide high performance and fast turn-around time

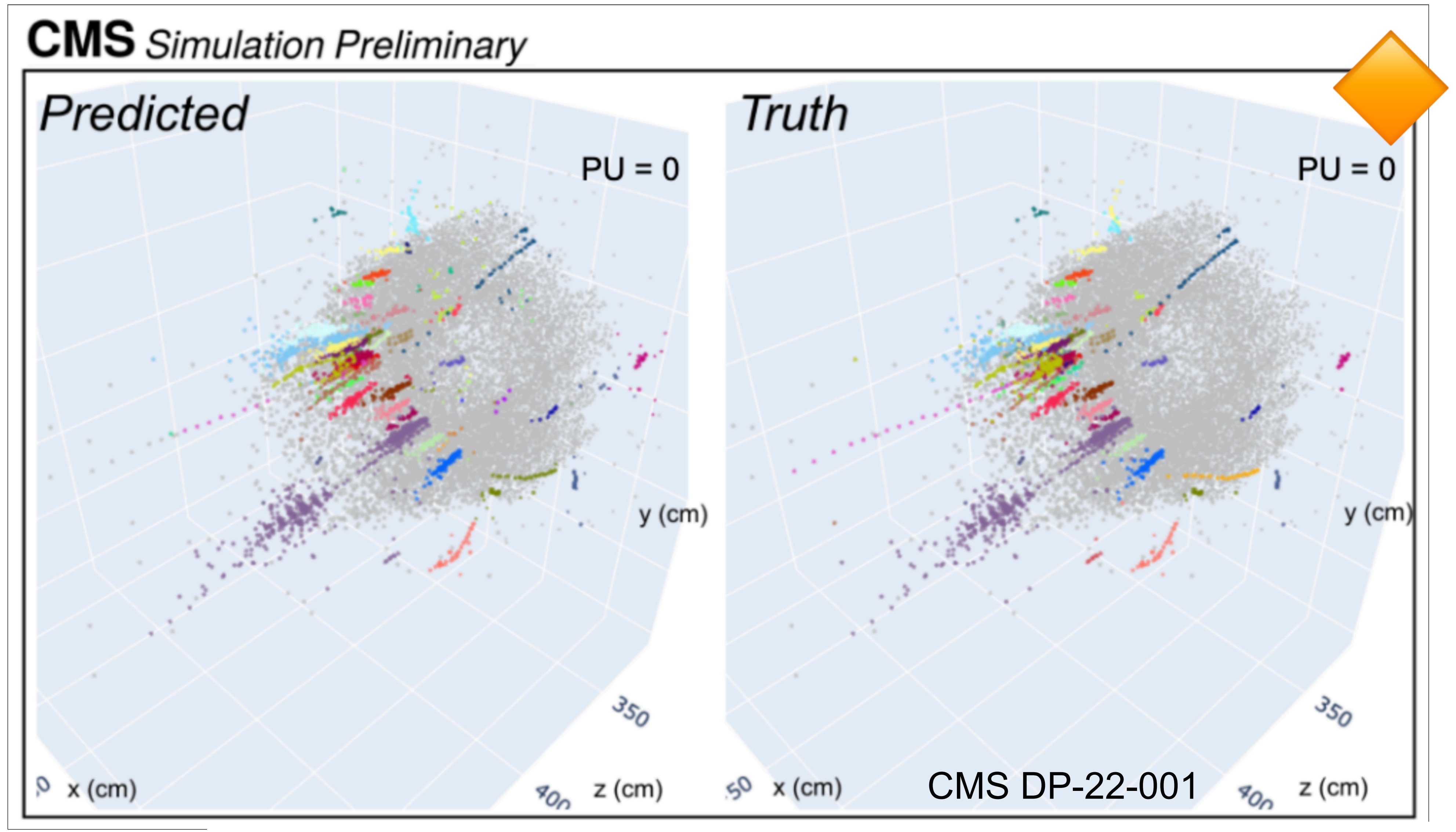
Default classical algorithm: Pandora [arXiv:0907.3577]
Tuned for CLD, by-hand tuning needed for other (and new) concepts, experts missing

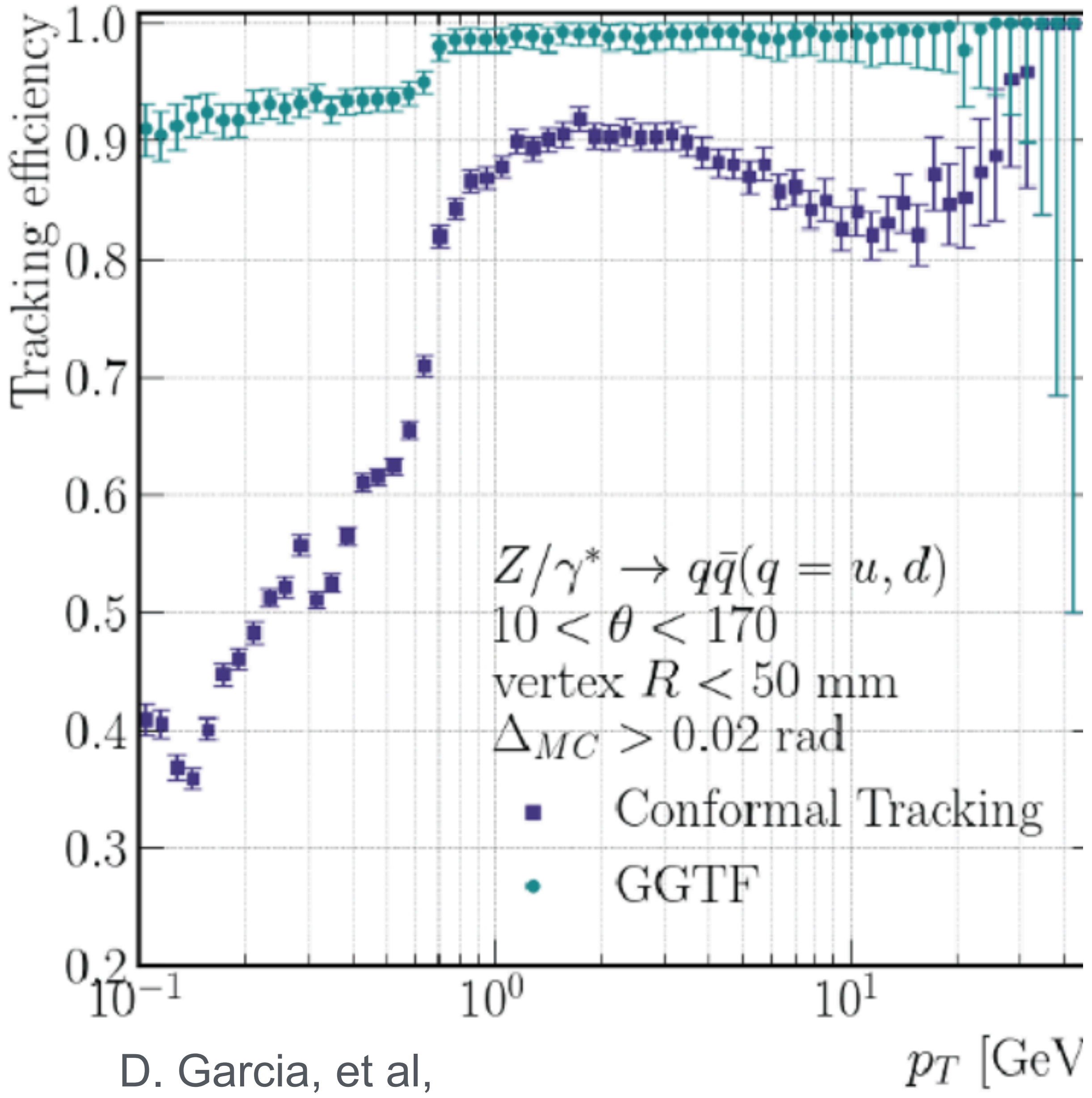
Vast majority of sub detectors will support precision timing

A lot of developments on ML reconstruction methods and applications in the community with many success stories

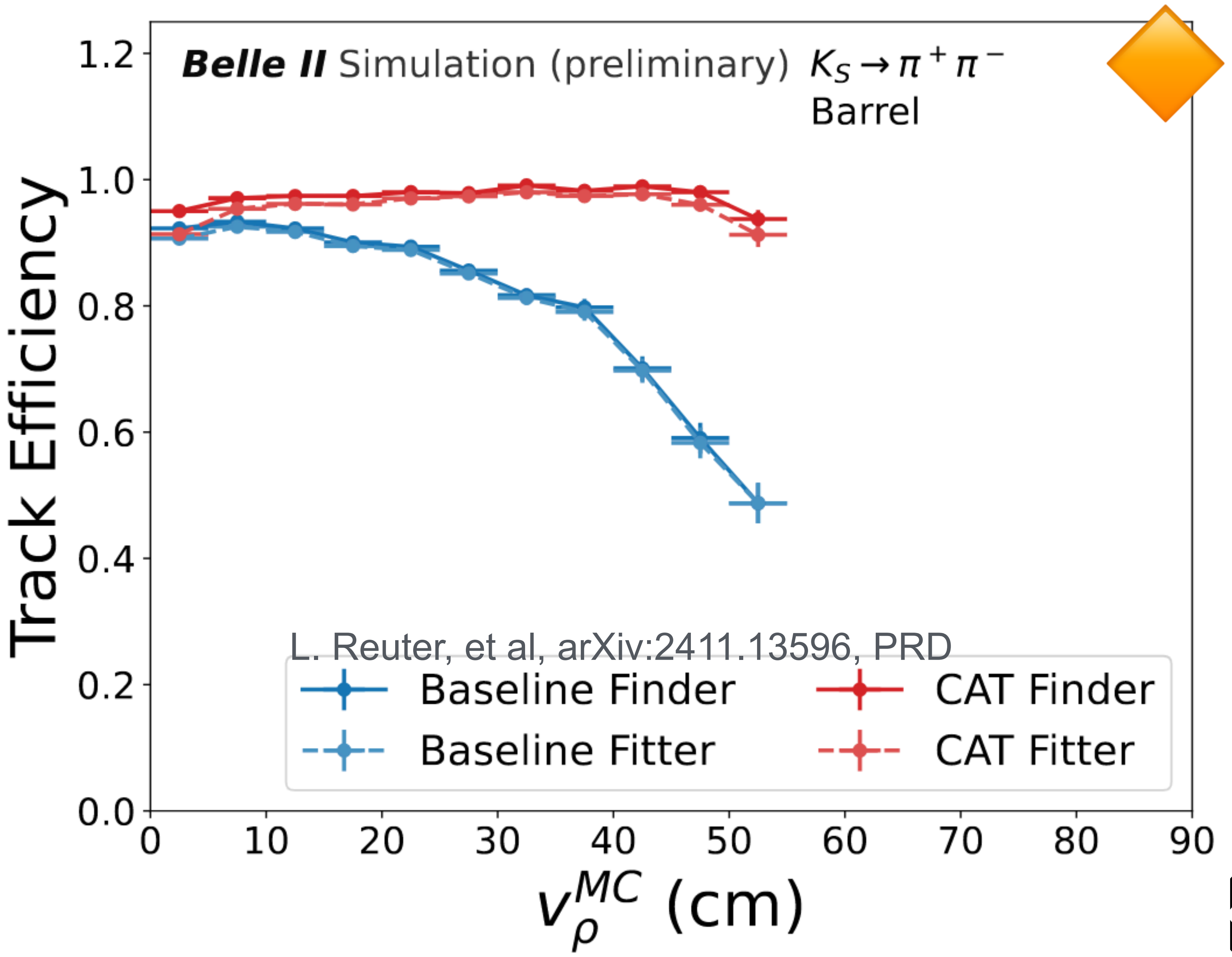
ML particle flow / reconstruction can be fine tuned to different geometries [e.g. arXiv:2503.00131]

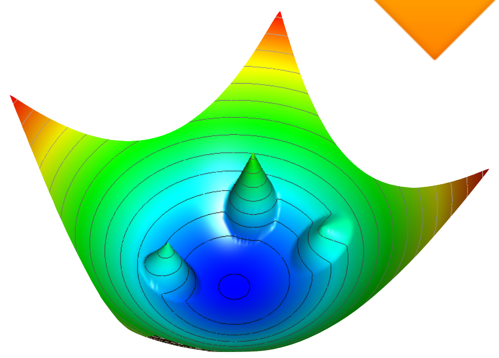
Holistic ML event interpretation methods "ML Analysis"



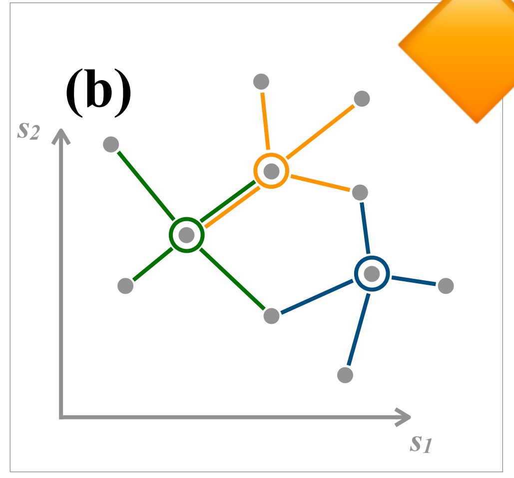


D. Garcia, et al, 10.1051/epjconf/202533701125





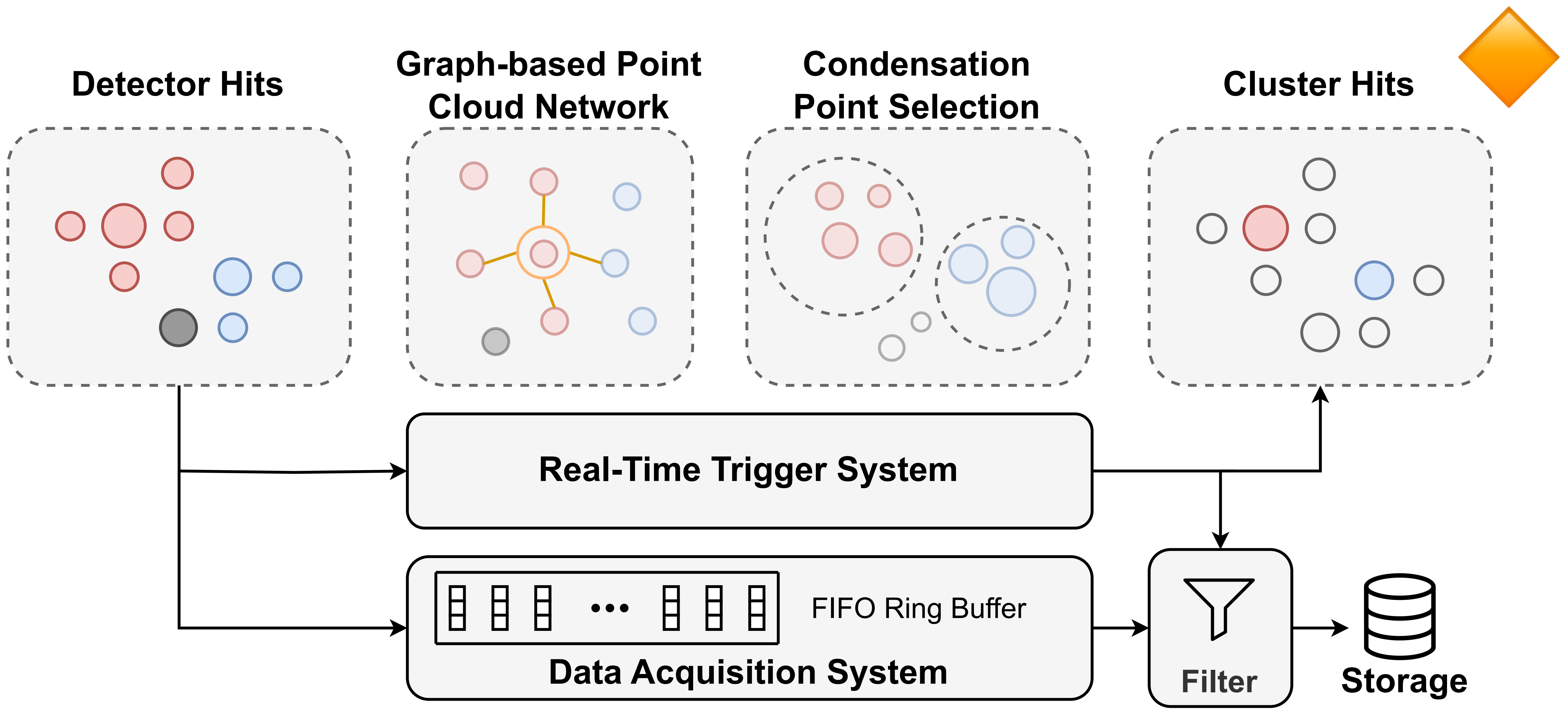
arXiv:2002.03605



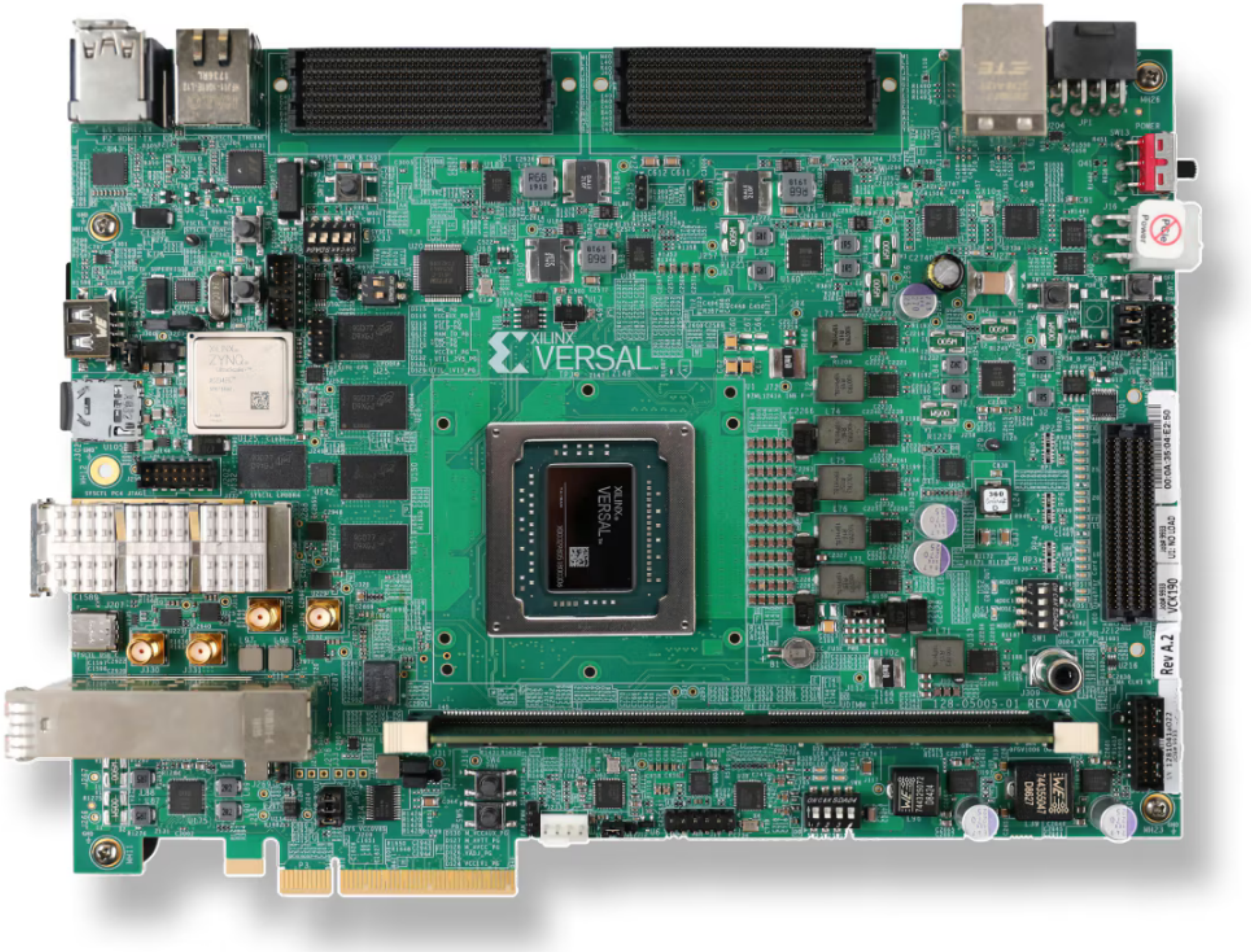
arXiv:1902.07987

Online Algorithms: intelligence closer to the beam

- **Trigger-less** readout to **exploit full potential**, online calibration procedures becoming more prominent



arXiv:2507.05099



- Algorithms & intelligence move closer to the sensors

➡**Build and maintain expertise towards TDRs**

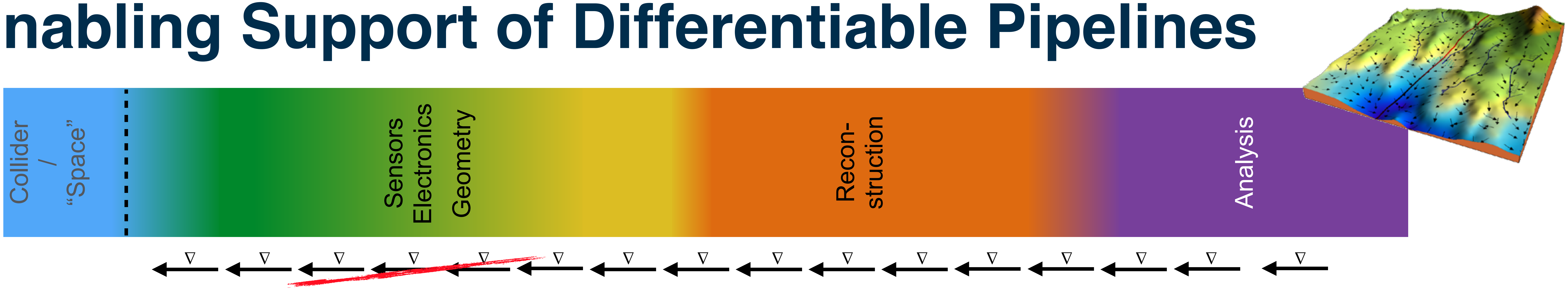
The next Generation of Detectors will be a Hardware+Software Co-Design Problem

From Wikipedia, the free encyclopedia

In radio communications, an **evolved antenna** is an antenna designed fully or substantially by an automatic computer design program that uses an evolutionary algorithm that mimics Darwinian evolution. This

- New ML reconstruction can be paradigm changing
- **The optimal design *might* be unexpected and maybe further from the starting conditions than we think**
- ML reconstruction allows to adapt to it and evaluate a new design efficiently

Enabling Support of Differentiable Pipelines

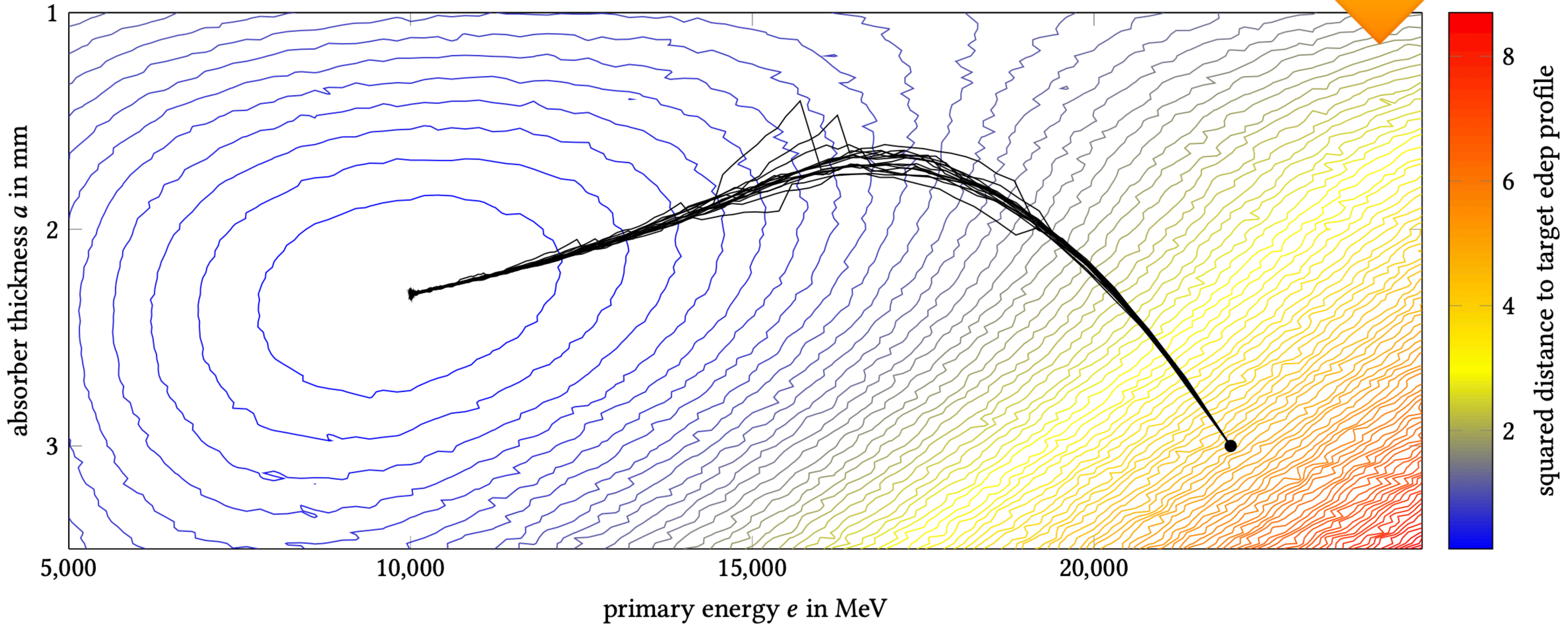


Work ongoing

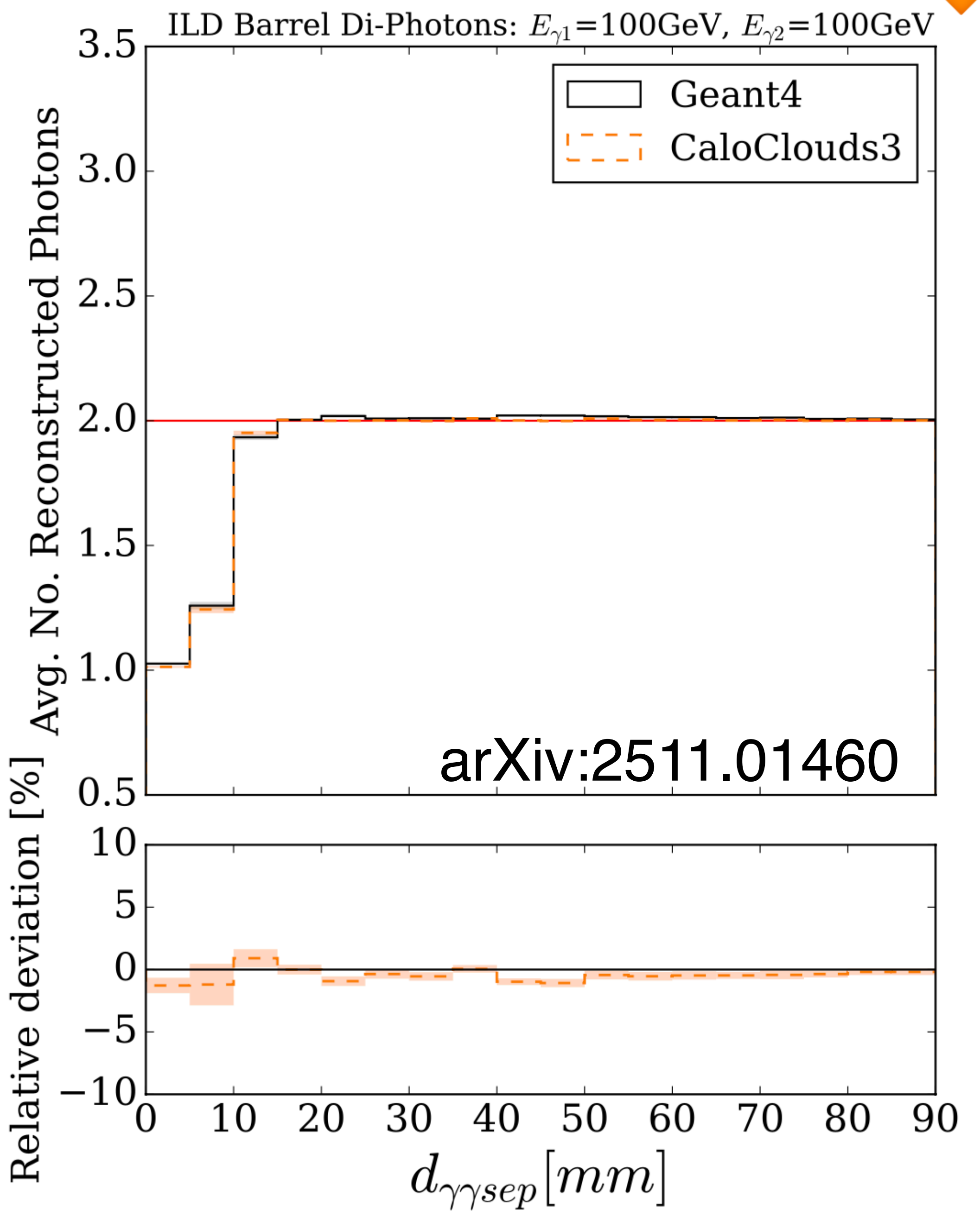
Conceptually ✓ Conceptually ✓

G4 EM* differentiable

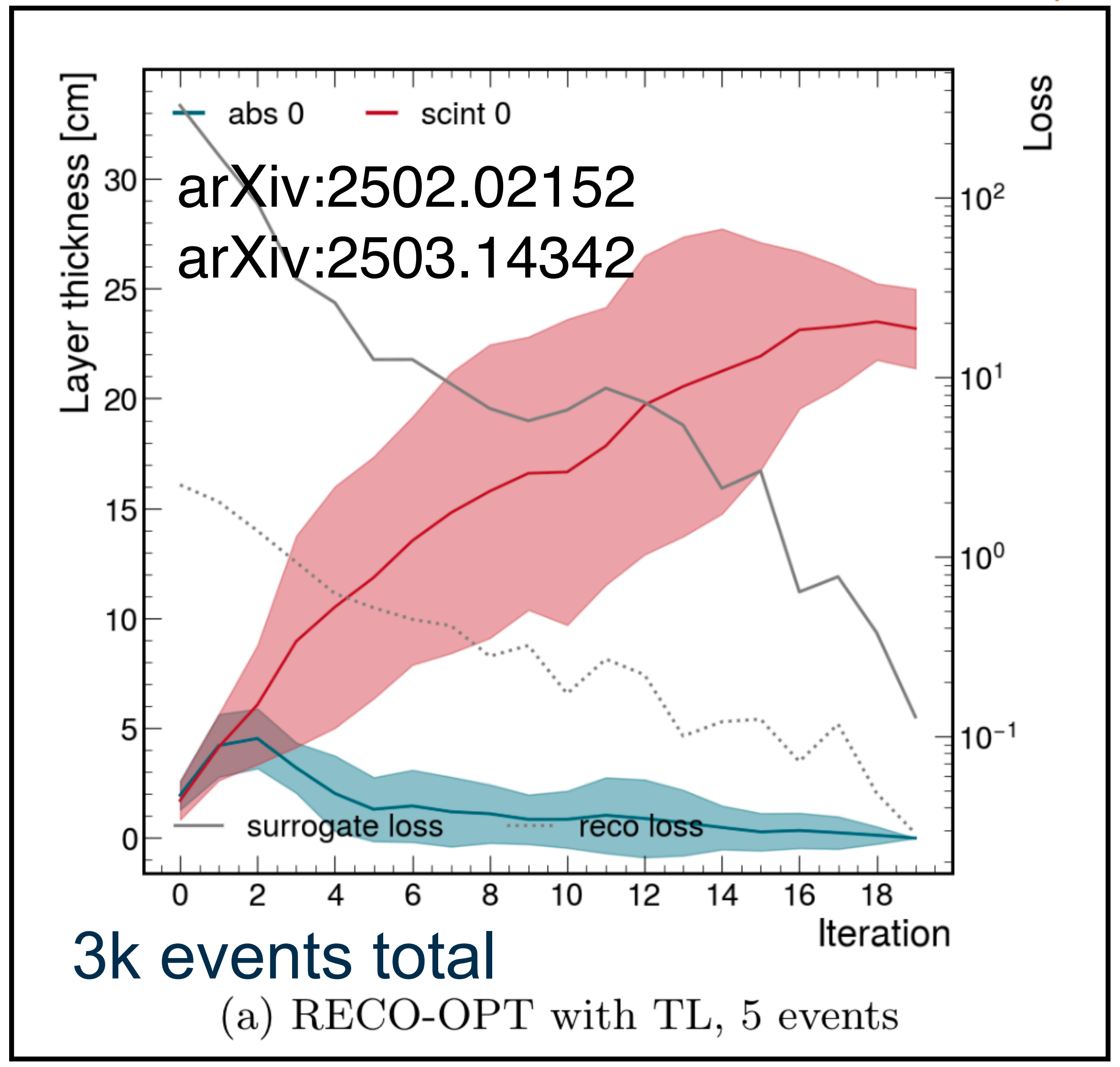
arXiv:2405.07944



Simulation surrogates



End-to-end surrogates

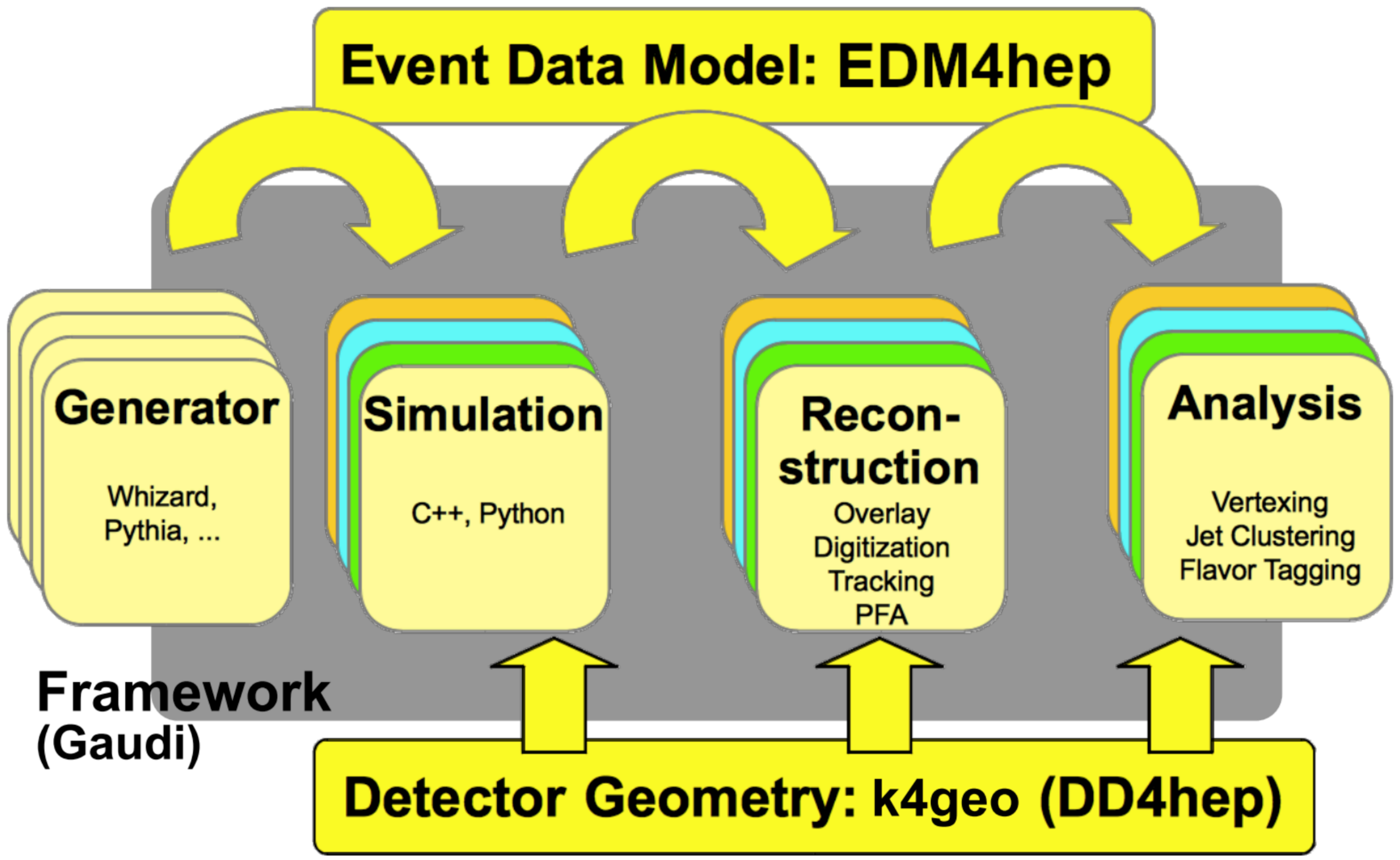


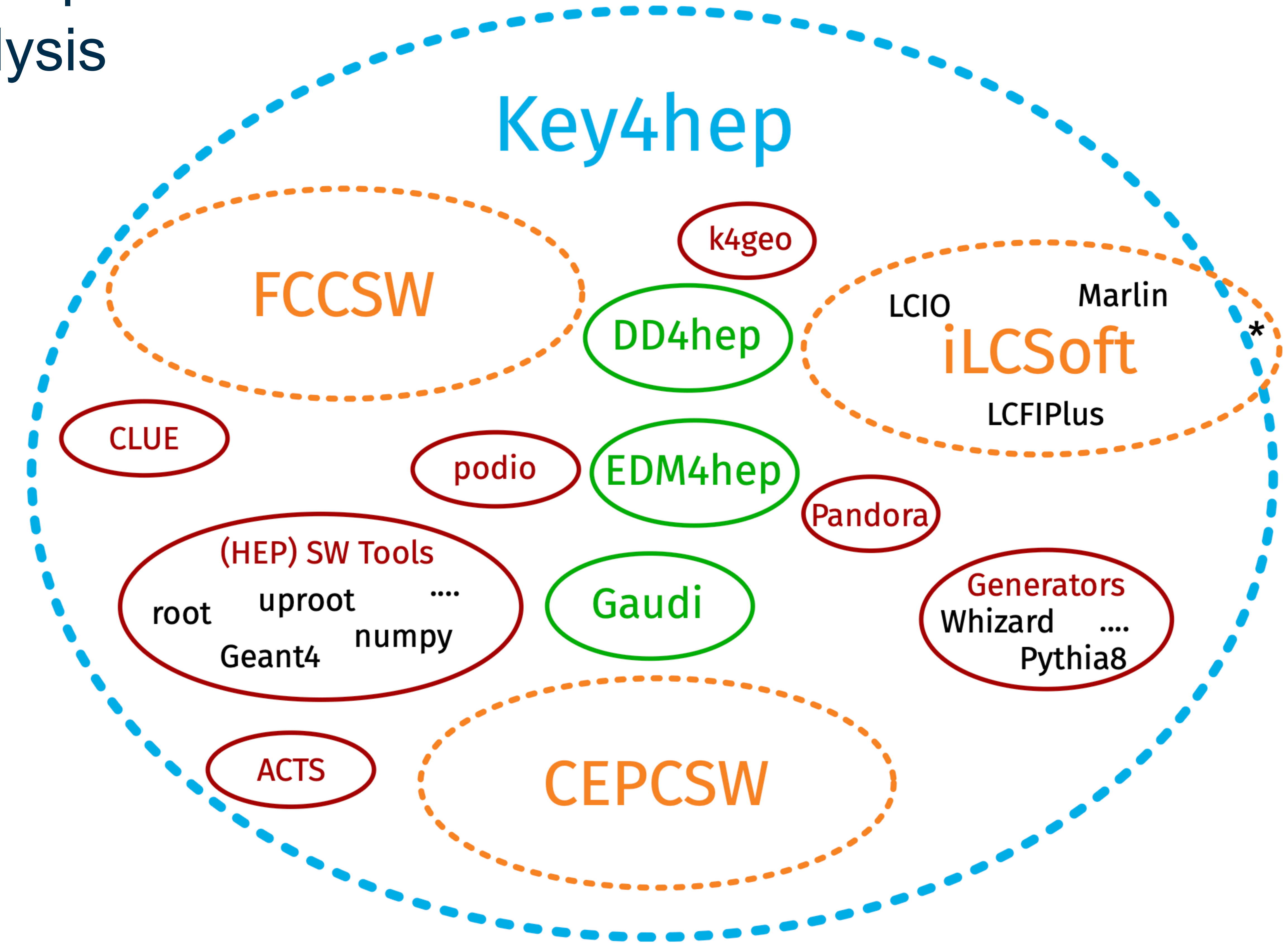
- Powerful and paradigm changing tool for detector optimisation

➡Ensure methods and pipelines integrate smoothly into workflows

A Central Platform: Key4hep

- Complete data processing framework from generation to data analysis
- De-facto common turnkey software for future colliders
- Shared components to reduce maintenance and development cost
- New developments should push for synergy with analysis facility efforts for (HL)-LHC

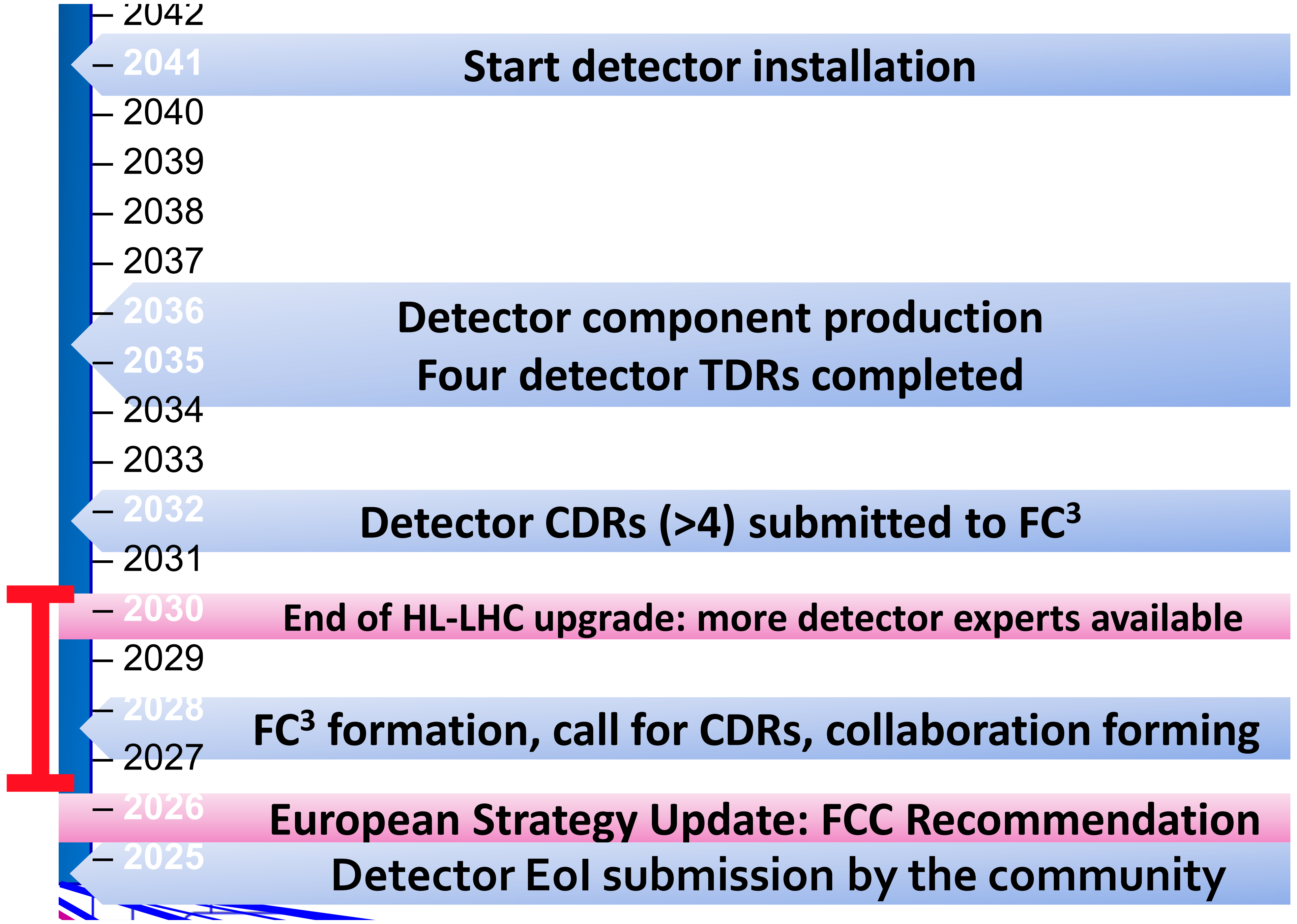




A coordinated effort for co-design, complementing and supporting hardware developments horizontally

2027–2030:

- **Full and flexible detector simulation** for all relevant design proposals with easy to change parameters
- **Particle-flow ML reconstruction** and event interpretation models usable across changing geometries, natively include timing
- **key4hep** as offline backbone; require **stable interfaces** to ML+ (classic) ACTS
- **Enable** surrogate and differentiable pipelines linking detector parameters → reconstruction → physics sensitivity for gradient/search-based optimisation
- Parallel development of **online/real-time ML interfaces** to hardware R&D (FPGA ML, multi-stage real-time ML, ML on ASICs/readout, HLT beyond CPU/GPU, continuous alignment/calibration)
- **Open pathways** to quantum computing



➡ Not limited to one particular detector concept, keeps decision open

Embedding in long-term Effort

2030–2033:

- Scale to full concepts: offline and online
- Involve detector experts (even) more closely
- Produce design recommendations (reach vs cost/power/latency)
- Analysis automation (LLM/agent-assisted analysis design/execution)
- Integrate quantum optimisation pipelines if input dimensionalities reach necessary order of magnitudes

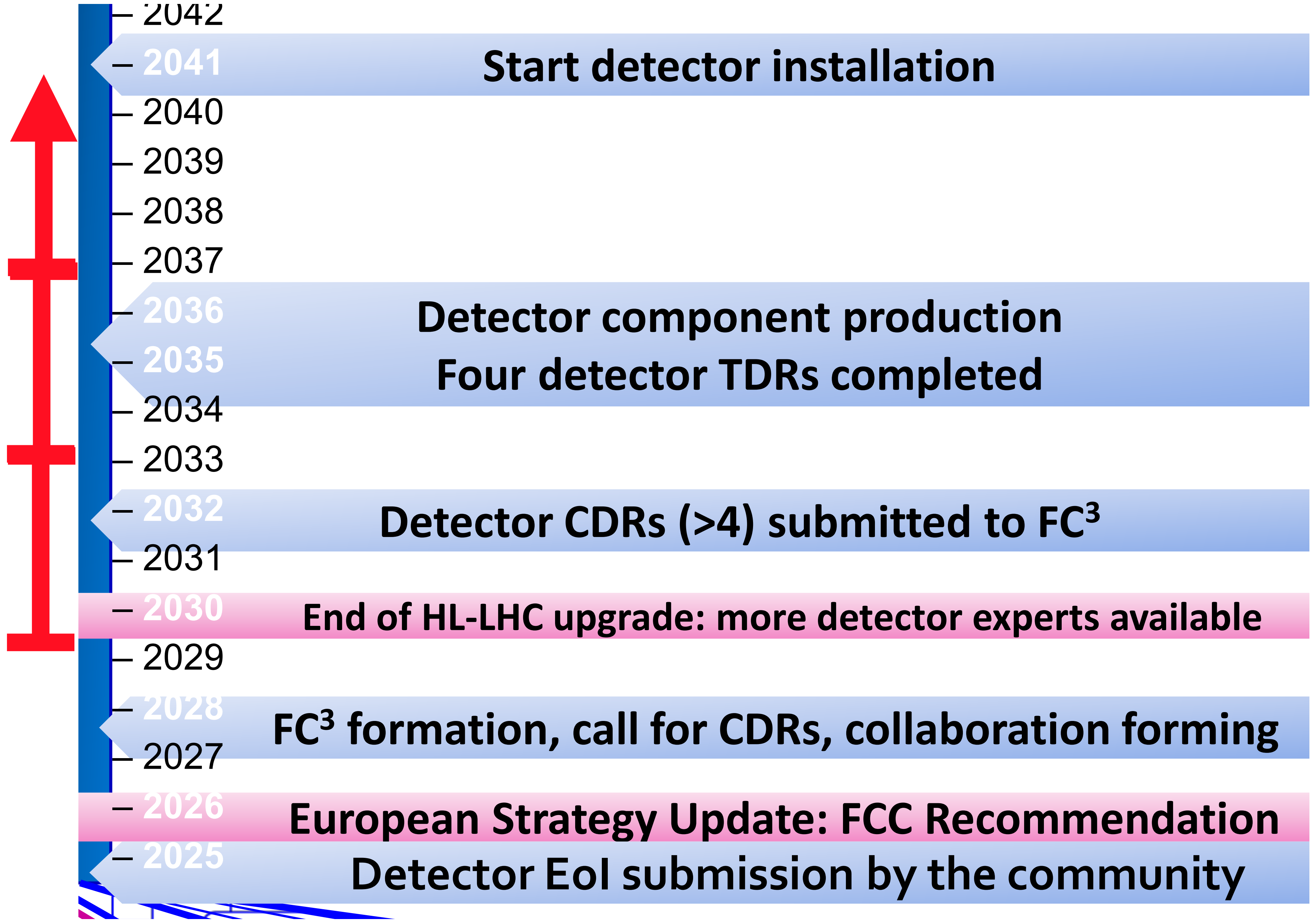
With collaborations forming, software might split

2033–2035/36:

- Consolidate optimised layouts and pipelines
- Deliver TDR results
- Address review requests

After

- Support hardware developments **towards production**, refine **and maintain** algorithms in parallel



Groups and Boundary Conditions

Groups (so far): KIT-ETP, KIT-IPE, Bonn, LMU, UHH, TUM, DESY, …
→ a lot of expertise 🔶

Boundary conditions / constraints

- Software requires both **development and long-term maintenance** effort (FTE)
- **Vendor/toolchain lock-in risks** needs mitigation (GPU, FPGA ecosystems)
- **key4hep manpower fragile**; partial ARM builds, generic ACTS integration non-trivial
- **DESY** as the central hub for evolving key4hep can only be **associated partner** for BMFTR funding
- **Field spread thin**: Run 3 exploitation, HL-LHC preparations and commissioning
- **Start in 2027 required** to match TDR cadence (mid-2030s)
- Developments will need (heterogenous) **computing resources** → Thomas Kuhr's talk

Strong national and international synergies with Belle II / ATLAS&CMS / LHCb w.r.t concepts (offline, real-time, alignment/calibration), **but clearly separable target**

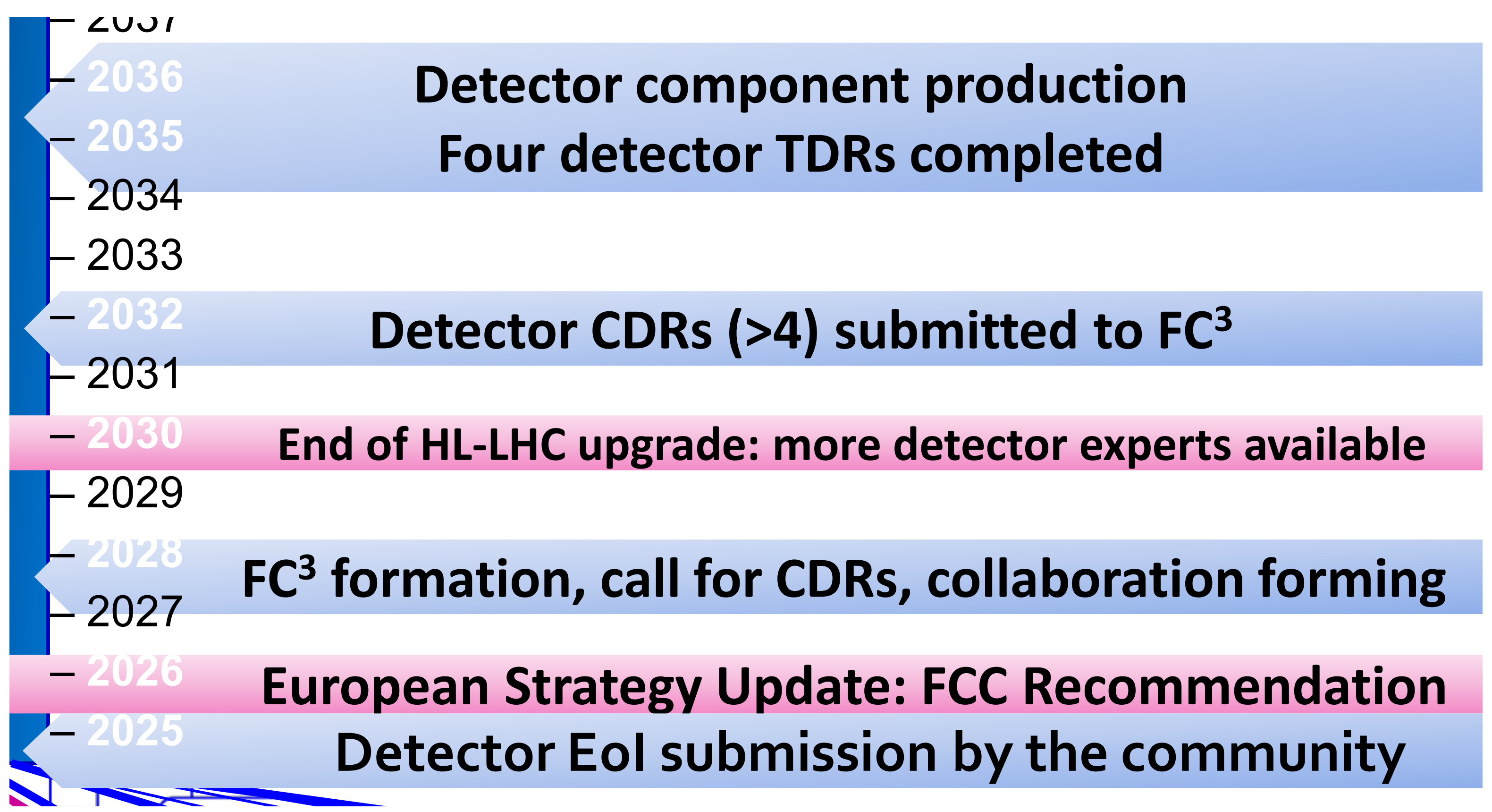
Critical mass would significantly **strengthen German role in the future flagship project**

Sustainability & Technology Transfer & Urgency

- **Strengthen sustainable software foundations: shared core SW infrastructure** — maintainers, CI/packaging, ARM-ready, efficient and portable tools with reusable, well-documented pipelines.

- **Advance detector and algorithm co-design** — more efficient use of final design resources (hardware and computing), including real-time.

- **Leverage cross-domain innovation** — medical imaging (e.g. p/ion CT) and real-world object detection as transferable testbeds.



Now is the time:

- The necessary methods must exist during 2027–2030 to **influence detector choices**.
- **Investment** in shared core software, PF co-design, and real-time interfaces is an area where we could **establish a leading German participation** in a CERN flagship project.

Possible Funding Scheme

KIT-ETP, KIT-IPE, Bonn, LMU, UHH, TUM, DESY, …

A dedicated software-focused Verbundprojekt could ensure critical mass & address chronic underfunding in software

- **Risk of cuts in ErUM-Pro** due to tight budgets and overlap with ErUM-Data
- **Possible overlap with ErUM-Data + HEP-CS** initiatives that could instead pursue **DFG** funding

- Could be made clearly distinct from ErUM-Data / DFG by focusing on **contributions to a concrete CERN flagship** rather than **overarching** data-science **developments**
- Is different from the “dedicated Verbünde” since it **spans multiple experimental designs** and provides **overarching** software foundations, rather than supporting a single technology

Summary

- **We have a chance** to establish a coordinated, reproducible workflow for co-design, complementing and supporting hardware developments horizontally
- **This software support for the detector developments is crucial** already at an early stage for the success of the next flagship project
- **A strong German effort with critical mass would be highly visible** given the general lack of funding for core software development
- The optimal integration into the funding structures is still open.
- **The effort is necessary**