AI-RDs: A EuCAIF proposal to structure AI research in Particle Physics

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Abstract: Accelerating the development and application of state-of-the-art AI solutions for high-energy physics calls for a structured effort. The European Coalition for AI in Fundamental Physics (EuCAIF) provides a framework for coordinating AI research in fundamental physics. We propose AI Research and Development Groups (AI-RDs) to enable a long-term, fundamental AI research program. AI-RDs will support the development and maintenance of leading AI tools for experimental and theoretical physics, facilitate knowledge transfer, and provide a structure for the systematic evaluation of AI methods. Additionally, they will create new training and career development opportunities for researchers working at the interface of AI and physics.

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Artifical Intelligence in High Energy Physics

High energy physics (HEP) has a decades-long tradition of exploiting AI concepts to enhance research performance. Starting with the early adoption of neural networks for tracking and jet tagging across the ‘80s and ‘90s, machine learning has played a key role in reaching HEP milestones, such as physics at the B factories, top quark physics at the Tevatron, the discovery of the Higgs boson at the LHC, and the development of the precision LHC program. The use of AI in particle physics was acknowledged as a motivation of the 2024 Nobel Prize in Physics to G. Hinton and J. Hopfield.

Since 2012, AI has accelerated progress in HEP research in an unprecedented way. This progress relies on the exceptional capacity of deep neural networks for pattern recognition and generative modeling, which are also the drivers of the AI revolution that is changing our society. HEP has adopted this new technology to shift the boundaries of what is possible in experimental and theoretical physics. All across data acquisition, object reconstruction and classification, simulation, and inference, cutting-edge AI-solutions are the basis for the success of the LHC program. This includes the establishment of the LHC as the first precision hadron collider.

Transformation through AI

The qualitative and quantitative AI transformation of HEP exploits concepts from image recognition to large language models, most notably including the recent generative AI revolution. Cutting-edge AI is improving the experimental sensitivity in areas where ML has a long tradition, for example jet tagging and parton densities. New avenues are opening in event generation and detector simulation, detector monitoring and operation, quality assessment of sensor production for new detectors, system control for accelerators, end-to-end event reconstruction, fast and accurate inference for real-time data processing and trigger, precision theory computations, optimal simulation-based inference, optimal detector design, or anomaly detection for new physics searches.

The AI-triggered progress in HEP goes far beyond computing aspects, even though it is also transforming, for instance, LHC computing. AI concepts and tools are currently changing every aspect of HEP as a data-intensive and simulation-driven research field. New bridges between HEP and other research fields are opening through data science and AI as a new, interdisciplinary language.

While HEP is benefiting from AI in every possible way, it cannot just rely on tools developed elsewhere. HEP experiments have specific needs in terms of data format and volume, computing environment, and response latency constraints (e.g., for real-time data processing). In addition, the challenge of detecting extremely rare signals against substantial backgrounds demands specialized control over AI tools tailored to high-energy physics, including the direct integration of physical domain knowledge into the models. Finally, the statistical approach underlying the LHC analyses poses a challenge for the treatment of uncertainty in AI concepts and tools. There exist a range of aspects where HEP can and should play a leading role in the development of Scientific AI methods.

A promising avenue for AI-development in HEP are *large physics models*, which bring together the successful aspects of large language models, foundation models, and representation learning. They have the potential to boost performance, scalability, flexibility, and resilience for a wide range of HEP applications, and to transform education and communication. The development and deployment of such large physics models exceeds the resources currently available to the groups driving the AI-transformation of HEP and requires a more coherent program.

Looking into the future, AI-driven discovery methods will increasingly be able to identify subtle patterns and rare phenomena previously inaccessible to traditional analytic methods. Given the current stage, this will affect essentially all leading analyses at the high-luminosity LHC and the next big CERN flagship project, provided the community is able to unlock these opportunities.

HEP-AI program

The AI revolution is transforming HEP as a global scientific program, whereas methodological progress and tool development are still fragmented and driven by individual groups and collaborations. To maintain its scientific leadership, the global HEP community needs to fully embrace the ongoing AI revolution and support it through a structured program. Such a program has to foster collaboration and cooperation on an AI methodology, to shape Scientific AI as a rapidly developing research field. HEP-specific basic research questions and broad training of excellent students and postdocs can ensure mutual benefit across the AI landscape, while sustaining progress in current and future HEP research.

Long-term strategic planning and dedicated funding are the key to establishing fundamental physics as a driver of Scientific AI. A dedicated strategic program needs to include the nuclear physics, astroparticle physics and cosmology communities, and their representative bodies NuPECC and APPEC, sharing concept development as well as training initiatives and computational infrastructures. Beyond fundamental physics, it needs to facilitate interdisciplinary exchange with computer science, applied sciences, and industry. This way, Europe can leverage common AI challenges and accelerate methodological breakthroughs, reinforcing its global leadership in fundamental science.

AI-RDs and EuCAIF

As part of the ongoing discussions and planning initiated by the European Strategy Group, we propose an R&D program on AI concepts and techniques for current and future HEP projects. AI R&D collaborations (AI-RDs) are modeled after the successful Detector R&D (DRD) initiative, a structured and sustainable framework for technological innovation in instrumentation.

The AI-RD Collaborations are carried out within the framework of the AI Research and Development Committee (AI-RDC), which reports to and coordinates with the European Coalition for AI in Fundamental Physics (EuCAIF). The AI-RDC will have members from EuCAIF, CERN and the Laboratory Directors Group (LDG). As the implementing body of the European Strategy for Particle Physics, CERN should take the lead in the implementation. It should align the AI-RDs with its AI strategy, while providing central hardware and software support. This should include access to GPU clusters, a self-contained software stack, and interfaces to high-performance computing (HPC) centers (and AI factories) across Europe. The European AI-RD initiative should be integrated with similar initiatives at the national level. Figure 1 illustrates the roles of AI-RDs, AI-RDC, EuCAIF, and CERN, along with their connections to ECFA, APPEC, and NuPECC.

Like DRDs, these AI-RDs should ensure consistent funding streams, facilitate resource sharing, and accelerate the adoption of AI innovations across the field. The initiative would complement existing project-based funding by supporting sustained development of AI expertise and infrastructure within the physics community. Once such AI-RDs are also recognized as suitable structures in the APPEC and NuPECC communities, the corresponding AI activities can easily be merged into the envisioned HEP framework.

Research program

AI-RDs can define a long-term, fundamental AI research program in fundamental physics. They can also support the development and maintenance of standardized AI tools that serve both experimental and theoretical physics, while enabling knowledge transfer between institutions and experiments. Finally, they will facilitate a systematic evaluation of AI methods and tools and provide training and career development opportunities for the next generation of researchers. Examples of AI-RD groups are:

- **AI for Data Processing:** AI-driven front-end electronics, trigger systems, and real-time event selection. AI enables autonomous data-taking strategies, anomaly detection, and online calibration. A HEP-specific challenge is real-time processing of vast amounts of data, where domain knowledge of the detector will be helpful.

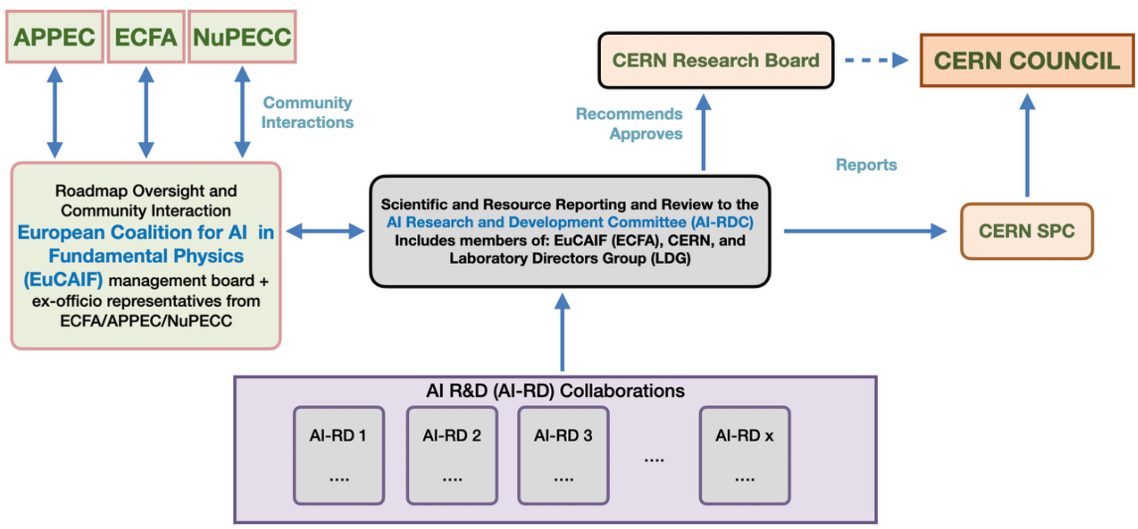

Figure 1. Structure of the AI R&D collaborations (AI-RDs), the AI Research and Development Committee (AI-RDC), and integration with EuCAIF, CERN, ECFA, NuPECC and APPEC.

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- **AI for Detector Optimization:** AI-based workflows to optimize the design of new detectors, exploiting techniques like differentiable programming and reinforcement learning to maximize detector performance while designing AI-friendly detector architectures that would facilitate the use of AI techniques for simulation, reconstruction, and other computing-heavy central tasks.
- **AI for Detector and Accelerator Control:** AI optimizes beam tuning, accelerator performance, experimental design, calibration, predictive maintenance, and system monitoring.
- **AI for Event Reconstruction:** AI-driven reconstruction algorithms, from tracking and calorimetry from detector hits to particle flow, can give sizable improvements to downstream data analysis steps, while improving the real-time processing in trigger systems. Further development in this direction could lead to the development of global-event end-to-end approaches with foundation models.
- **AI for Analysis:** AI-driven applications to data analysis, such as signal-to-background separation, optimal variable definition, and likelihood-free inference approaches improve data interpretation. It leads to optimal parameter estimation with comprehensive uncertainty quantification and a statistical interpretation. A promising direction is representation learning with symmetry-aware architectures and foundation models.
- **AI for Generation and Simulation:** AI accelerates simulations with generative models, surrogate modeling, and AI-enhanced Monte Carlo methods. It enables, for instance, fast and precise evaluation of precise theory predictions, event generation, and detector simulation. Simulation-based inference and generative networks relate this topic to AI for Analysis.
- **AI for Theory:** AI assists in high-dimensional parameter optimization and numerically challenging lattice computations. It helps solve differential equations and allows symbolic regression, related to fundamental physical laws. These applications are focused on theory, but for instance parameter optimization, sampling, and Monte Carlo integration reach much further.
- **AI for HPC Usage:** AI tools will facilitate the exploitation of highly parallelized, large-scale GPU computing. Using the full parallel computing power of GPUs is a challenge for classic simulation methods, for instance Monte Carlo methods. In contrast, AI-methods like surrogates and neural sampling are perfectly suited for highly parallelized architectures.

These efforts can lead to the creation of a flagship program for AI physics at CERN, *e.g.* a world center for Scientific AI with a focus on fundamental physics, to coordinate these research directions. Such a program would serve as a hub for AI innovation in fundamental physics, bringing together researchers from particle physics, astrophysics, cosmology and AI to develop next-generation methods. By providing a shared computing infrastructure, supporting long-term AI-driven research and strengthening partnerships between academia and industry, a flagship initiative based at CERN would consolidate Europe's leadership in AI for Science.

Call for Action

The use of AI and machine learning in high-energy physics has reached an important stage that requires structured and collaborative approaches to maximize the potential of these technologies. We have highlighted the need for AI-driven research in particle physics, ranging from concept development for Scientific AI to field-specific AI-tools. To provide an appropriate framework we propose AI-RDs, organized by EuCAIF, as an important framework to support long-term progress.