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A Multiple Readout Ultra-High Segmentation Detector Concept For Future Colliders

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The Meadusa (Multiple Readout Ultra-High Segmentation) Detector Concept is an innovative approach to address the unique challenges and opportunities presented by the future lepton colliders and beyond. The Meadusa concept prioritizes ultra-high segmentation and multi-modal data acquisition to achieve ultra-high spatial, timing and event structure precision in particle detection. By combining a diverse array of active materials and readout technologies, Meadusa design is intended to be optimized for specific single particle and jet energy resolution, single particle identification and flavour tagging capabilities.

The Meadusa concept is based on bringing together multiple, highly granular active elements with complementary sensitivities to different particle species in a single detector layer. The Meadusa detector is expected to embed cutting edge technologies and recent findings in optical, solid-state and gaseous detectors. The conceptual development has started as an initial design and is expected to evolve with the advancement of relevant technologies and following the performance estimation and optimization with advanced machine learning and artificial intelligence techniques and experimental validation.

Here we report on the foundations of the concept, the description of the initial design and the preliminary performance parameters using novel machine learning techniques.

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1. Introduction

Future collider facilities will require detectors with levels of granularity and precision well beyond those achieved to date. Meeting the ambitious physics goals of these machines—ranging from precise Higgs and electroweak measurements to sensitivity for new physics phenomena—demands the ability to resolve every particle in complex final states. This, in turn, requires ultra-high spatial and temporal resolution, superior single-particle and jet energy measurements, robust particle identification, and flavour-tagging capabilities that surpass current standards.

The Future Circular Collider electron–positron machine (FCC-ee) [1] is a long-term plan to build a 91-kilometer circular collider at CERN [2]. It is conceived primarily as a precision "Higgs, Electroweak, and Flavor factory." Its program includes the production of a vast amount of Higgs bosons, ultra-precise measurements of the W and Z bosons and the top quark, an intense heavy flavour physics program and critical probes for physics beyond the standard model. The detectors envisioned for FCC-ee take inspiration from previous and current operational detectors as well as the new concepts all adapted to the extreme luminosities of a circular machine. Four general-purpose detectors are currently foreseen: CLD [4], IDEA [5], Allegro [6] and ILD [7]. The detector technologies span silicon, gaseous, crystal, cryogenic and Cerenkov detectors. Highly granular calorimeters are optimized for particle flow algorithms. Precision timing at the level of a few tens of picoseconds is considered essential for both particle identification and background control.

The International Linear Collider (ILC) [8] is a proposed linear electron–positron accelerator with an initial energy of 250 GeV, designed as a Higgs factory with upgrades envisioned up to 500 GeV and 1 TeV. The physics program centers on model-independent precision studies of Higgs couplings, a top quark threshold scan, and searches for new particles in a clean environment that complements the LHC [9]. Two mature detector concepts have been developed: ILD [7] and SiD [10]. ILD combines a large time projection chamber with silicon tracking and ultra-granular calorimetry, while SiD takes a more compact all-silicon approach with a strong solenoid and equally fine calorimeters. Both are optimized for particle flow reconstruction.

The Circular Electron–Positron Collider (CEPC) [11] proposes a 100-kilometer circular ring to operate initially as a Higgs factory at 240 GeV, with the longer-term goal of hosting a 100 TeV proton–proton collider. Its physics program is built on the production of a vast amount of Higgs bosons over a decade, together with high-precision studies of Z and W bosons and indirect searches for physics beyond the Standard Model. The detector concepts feature silicon-based trackers, including monolithic pixel vertex systems and large silicon strip detectors, and calorimeters that combine silicon-tungsten electromagnetic sections with scintillator-SiPM hadronic modules. High granularity and excellent timing are critical features of the detector designs.

The Muon Collider represents a different approach to a high-energy lepton machine, using muon rather than electron beams [12]. Because muons are about 200 times heavier than electrons, synchrotron radiation is dramatically suppressed, making it possible to reach multi-TeV energies in a relatively compact ring. This concept offers both a Higgs factory mode, exploiting the direct s-channel $\mu^+\mu^- \to H$ process, and discovery reach well into the tens of TeV range. The experimental environment, however, is dominated by backgrounds from muon decays. Detector concepts therefore rely on extremely fast silicon tracking with fine timing, high-granularity calorimetry with 10–100 picosecond resolution, and heavy tungsten shielding nozzles close to the interaction point to absorb

out-of-time debris. Particle flow–based calorimetry remains a goal, but its implementation must contend with these harsh backgrounds.

In this context, we introduce the Meadusa (Multiple Readout Ultra-High Segmentation) Detector Concept as a forward-looking approach tailored to the demands of future colliders. Meadusa combines ultra-high segmentation with complementary active materials and readout technologies to deliver unprecedented performance in spatial resolution, timing, and event topology reconstruction. Its modular structure provides a natural testbed for incorporating machine learning and differentiable programming into detector optimization, enabling data-driven tuning of subdetector technologies. By uniting advances in silicon tracking, calorimetry, photodetection, and gaseous detectors under a multi-readout architecture, Meadusa aspires to serve as a cutting-edge demonstrator of AI-assisted detector design for the next generation of high-energy physics experiments.

Section 2 summarizes the state of the art in detector technologies relevant to the development of the Meadusa concept and the advances that motivate the multiple-readout approach. Section 3 introduces the initial design of the Meadusa detector. Section 4 outlines the optimization goals and the role of differentiable programming. Finally, Section 5 presents a summary of the initial design effort and the main conclusions.

2. The State of the Art of Detector Technologies

Silicon detectors have undergone a decisive shift from traditional bump-bonded sensors with separate front-end electronics to monolithic and hybrid designs. Monolithic Active Pixel Sensors (MAPS) integrate sensor and electronics on the same silicon substrate, eliminating the need for bump-bonding and allowing thinning below 100 μm. This reduces the material budget while enabling smaller pixel sizes and lower costs through standard CMOS processes. A prominent example is the ALICE Inner Tracking System (ITS), which implements seven layers of ALPIDE MAPS with a total of 12.5 billion pixels, achieving around 5 μm resolution with power consumption below 40 mW/cm^2 [13]. Such systems demonstrate how monolithic designs can scale to large areas while maintaining the low-mass, high-precision requirements for future colliders.

In calorimetry, the field has moved beyond traditional tower geometries, where energy was integrated into large volumes without resolving individual particles. Instead, the emerging paradigm emphasizes particle flow reconstruction, assigning each particle to the detector component best suited to measure it. This requires electromagnetic and hadronic calorimeters with fine granularity to disentangle electromagnetic and hadronic shower components. Increased segmentation, especially with scintillator tiles and silicon sensors, is a key trend. The development of the Silicon photomultipliers (SiPMs) enables compact and highly scalable optical detector systems. As an example, the CMS High-Granularity Calorimeter will house 240,000 SiPMs [14].

Gaseous detectors remain indispensable for large-area tracking, particle identification, and even calorimetry. Technologies such as PICOSEC-Micromegas [15], μRWELL [16], and hybrid RPCs [17] demonstrate the continuing innovation in gas amplification and readout geometries. The trend is toward functional anodes, more complex structures, and hybridization with other detector types. Hybrid RPCs, for instance, open the possibility of timing layers with neutron sensitivity by employing doped glass electrodes, pointing directly to applications in multi-readout calorimetry.

A particularly important milestone on the path to Meadusa is the ADRIANO3 calorimetric technique, which embodies the principle of triple readout [18]. In ADRIANO3, lead-glass tiles act as Cerenkov radiators, scintillating tiles provide the scintillator component, and resistive plate chambers with Gd-doped glass supply neutron sensitivity. Each component is read out with dedicated SiPMs or pad-based electronics, enabling a triple-readout scheme that separates electromagnetic, hadronic, and neutron components of showers. This architecture demonstrates the feasibility of combining distinct active media in a modular, finely segmented geometry, significantly improving hadronic energy resolution and particle identification.

3. The Meadusa Detector Concept

The Meadusa concept is based on bringing together multiple, highly granular active elements with complementary sensitivities to different particle species in a single detector layer. The Meadusa detector is expected to embed cutting edge technologies and recent findings in optical, solid-state and gaseous detectors. The conceptual development has started as an initial design and is expected to evolve with the advancement of relevant technologies and following the performance estimation and optimization with advanced machine learning and artificial intelligence techniques and experimental validation. Below is the description of the initial design of the Meadusa Detector, which is called Meadusa_v1 hereupon, together with the visuals from the detector geometry constructed with Geant4 [19] for Monte Carlo simulations.

Meadusa_v1 houses a 2T solenoid magnet with an inner diameter of 4.2 m and a length of 6 m. The return yokes in the barrel have 1T field pointing in the opposite direction with respect to the inner field, and the return yokes in the endcaps have radially inward and outward 1T field.

The barrel tracking detector of Meadusa_v1 is entirely based on MAPS. The pixel size envisaged for Meadusa_v1 is 25 μm. The three inner barrel layers are 50 μm and the outer five barrel layers are 100 μm thick. The inner radius of the innermost barrel sensors is 1.3 cm and that of the outermost barrel sensor is 50 cm. The forward tracking detectors are five disks on either side of the interaction point housing 25 μm Si pixels, entirely within the volume defined by the outermost two barrel layers. The simulation models of the tracking system are given in Fig. 1.

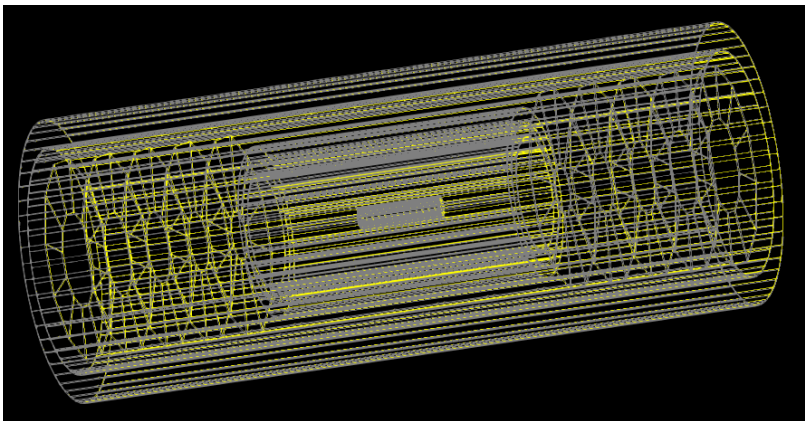

Figure 1: The simulation models of the Meadusa_v1 tracking system.

The Meadusa_v1 barrel and endcap detectors house PbF_2 crystals and Gd-doped plastic scintillators with SiPM readout, and Si active layers. The purpose of the PbF_2 crystals is to provide a fast timing signal for charged particles based on the detection of the fast Cerenkov light and to contribute to the particle identification and energy measurement. The crystals are 1 cm x 1 cm x 1.16 cm in size and are read out by SiPMs coupled to the dimples. The 3 cm x 3 cm x 0.5 cm Gd-doped plastic scintillators are used in the electromagnetic and hadronic energy measurement with enhanced capabilities to measure the neutral component of the hadronic showers. The Si sensors are sensitive to the charged component of electromagnetic and hadronic showers and are 500 μm thick and have granularity of 1 cm x 1 cm. The active elements are placed in cassette structures.

The detector system outside the magnet consists of hybrid resistive plate chambers (RPCs) with Gd-doped glass electrodes as active media, which are attached to the return yokes both in the barrel and in the endcap region. The RPCs provide high efficiency in large areas to measure the muons, the hadron shower tails and also the late neutral component. The barrel outside magnet detectors are shown in Fig. 2. The readout of the RPCs will be with 1 cm x 1 cm pads and 1-bit resolution.

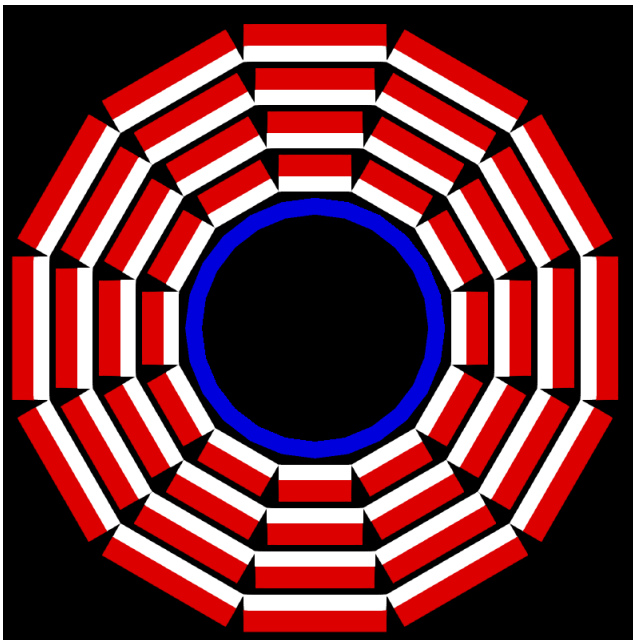

Figure 2: The simulation models of the barrel muon and outer calorimeter system of Meadusa_v1. The magnet is shown in blue, the return yoke in red and the hybrid RPC sectors in white.

Figure 3 shows the display for a ZH event with the Meadusa_v1 partially open for visibility.

4. Optimization of the Meadusa Detectors

The Meadusa detector concept is driven by ambitious optimization targets motivated by the physics program of future colliders. Chief among these is the requirement of achieving a jet energy resolution of the order of 3% at 100 GeV, which is critical for distinguishing hadronic decays of electroweak bosons and probing new physics signatures. Beyond resolution, the detector must

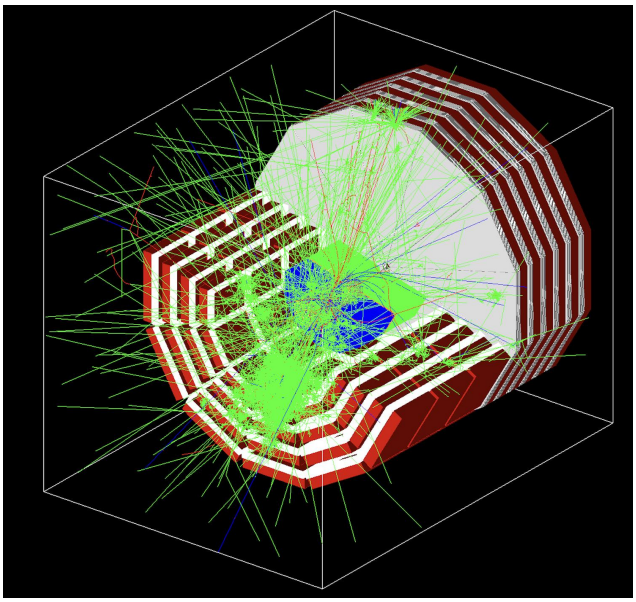

Figure 3: Event display for a ZH event in Meadusa_v1.

also provide robust discrimination between electromagnetic and hadronic components of showers, efficient pattern recognition and tracking in dense environments, and fast timing capabilities for particle identification and jet substructure analysis. Each of these goals translates into a need to carefully balance design parameters such as the choice of materials, the thickness and segmentation of active layers, the spacing of absorbers, and the design of the readout electronics.

Differentiable programming offers a natural framework to meet these challenges by embedding detector design parameters into machine learning models that can be trained with physics-driven objective functions. Segment thickness, pixel or voxel size, and readout specifications can be expressed as learnable parameters, and objective functions such as energy resolution, classification accuracy, or timing resolution can be differentiated with respect to them. In this way, gradient-based optimization can efficiently explore the high-dimensional design space. Applications extend to track reconstruction, where neural networks trained on tracker hits and RPC timing can incorporate trainable noise models and optimize the weighting of spatial versus temporal inputs. For timing layers, the intrinsic resolution of hybrid RPCs or Cerenkov detectors can be treated as tunable within differentiable models, providing direct feedback on the most effective configurations. In calorimetry, multiple-readout shower decomposition can be optimized using differentiable models that learn the best signal combinations to minimize fluctuations between electromagnetic and hadronic response. In the long term, the Meadusa concept envisions full end-to-end differentiable simulations, where detector response and physics reconstruction are optimized jointly.

A first attempt at applying these ideas has been carried out using simulated data from the Meadusa barrel tracker and hybrid RPC system. Preliminary studies focused on muon reconstruction, combining spatial information from the barrel tracker with timing from the RPC stations. Figure 4 presents the efficiency as a function of transverse momentum for the reconstructed muon tracks (left), together with the evolution of the training loss as a function of epoch number (right). The results demonstrated the internal consistency of the simulation framework and the feasibility

of incorporating machine learning tools into reconstruction. While modest in scope, these results validate the simulation and data-handling pipeline and set the stage for more comprehensive applications of differentiable programming in optimizing detector design. In particular, they highlight the potential of integrating timing and tracking information through learnable models that can balance resolution and robustness in a data-driven way.

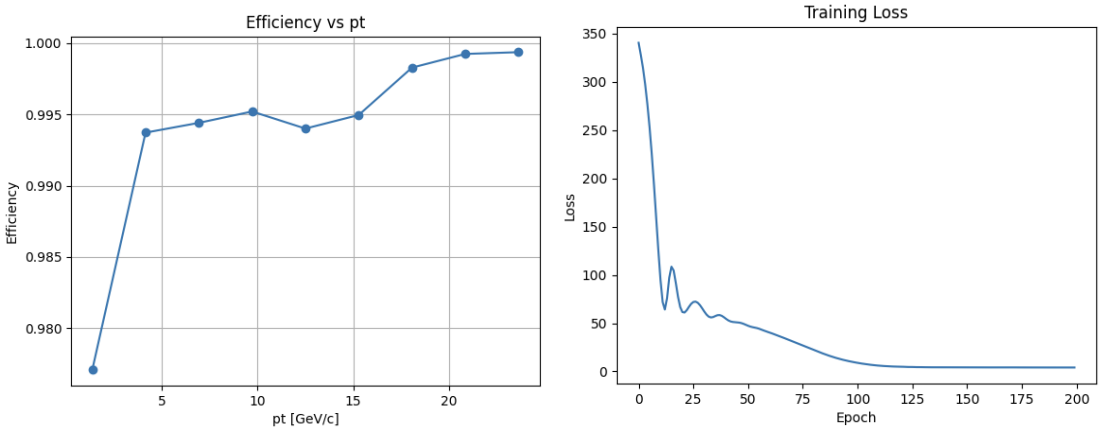

Figure 4: The efficiency vs. transverse momentum for the reconstructed muon tracks (left) and the training loss as a function of the epoch number (right).

5. Conclusions

The Meadusa detector concept represents a novel approach to addressing the challenges of future high-energy collider experiments. By combining ultra-high segmentation with multiple active media and complementary readout technologies, Meadusa is designed to deliver enhanced jet energy resolution, improved single-particle identification, and robust timing performance. The integration of silicon-based tracking, multi-modal calorimetry, and hybrid RPCs provides a versatile platform capable of disentangling electromagnetic, hadronic, and neutron components of showers while maintaining high spatial precision.

The path toward Meadusa builds on the progress of current detector technologies, from monolithic silicon sensors and highly granular calorimeters to advanced photodetectors and functional gaseous detectors. Optimization of such a complex system requires tools beyond traditional design methodologies. Differentiable programming and machine learning offer powerful strategies for embedding detector parameters into trainable models and performing gradient-based optimization with physics-driven objectives. A first attempt using the Meadusa barrel tracker and hybrid RPCs has validated the simulation framework and shown the promise of integrating spatial and timing information through data-driven models.

In summary, Meadusa establishes a foundation for next-generation detectors that combine cutting-edge hardware innovations with artificial intelligence–assisted optimization. As development continues, the concept stands as a strong candidate to meet the demanding requirements of precision measurements and discovery potential at future colliders.

References

[1] https://fcc.web.cern.ch/

[2] https://home.cern/

[3] https://home.cern/science/accelerators/large-electron-positron-collider

[4] N. Bacchetta et al., "CLD – A Detector Concept for the FCC-ee", https://arxiv.org/abs/1911.12230, 2019.

[5] M. Abbrescia et al., "The IDEA detector concept for FCC-ee", https://arxiv.org/abs/2502.21223, 2025.

[6] M. Aleksa et al., "Calorimetry at FCC-ee", https://arxiv.org/abs/2109.00391, 2021.

[7] T. Behnke et al., "The International Linear Collider Technical Design Report - Volume 4: Detectors", https://arxiv.org/abs/1306.6329, 2013.

[8] https://linearcollider.org/

[9] https://home.cern/science/accelerators/large-hadron-collider

[10] https://pages.uoregon.edu/silicondetector/

[11] http://cepc.ihep.ac.cn/intro.html

[12] https://mucol.web.cern.ch/

[13] F. Reidt, "Upgrade of the ALICE ITS detector", https://arxiv.org/pdf/2111.08301, 2022.

[14] C. Amendola, "An overview of the CMS High-Granularity Calorimeter", JINST 20, C01031, 2025.

[15] A. Kallitsopoulou et al., "PICOSEC-Micromegas Detector, an innovative solution for Lepton Time Tagging", Nucl. Instrum. and Meth. A 1069, 169920, 2024.

[16] G. Bencivenni et al., "The micro-RWELL detector for the phase-2 upgrade of the LHCb muon system", Nucl. Instrum. and Meth. A 1049, 168075, 2023.

[17] M. Tosun et al., "Development of hybrid resistive plate chambers", Nucl. Instrum. and Meth. A 1054, 168448, 2023.

[18] https://indico.cern.ch/event/1368231/contributions/5894558/attachments/2834632/4953314/DRD6-CERN20240406_v3.pdf

[19] S. Agostinelli et al., "Geant4 – a simulation toolkit", Nucl. Instr. and Meth. A 506, 250, 2003.