# PHD PROGRAM IN TECHNOLOGIES FOR FUNDAMENTAL RESEARCH IN PHYSICS AND ASTROPHYSICS

## CURRICULUM IN COMPUTING & IT

Stefano Giagu
Sapienza Università di Roma

TECH-FPA PhD Retreat 2026 - LNS - 17.2.2026

# WHY COMPUTING IS CENTRAL TO FUNDAMENTAL RESEARCH?

- **Fundamental research today is inseparable from computing:**
  - experiments produce **petabytes of data** ← LHC ~100 PB/year, Square Kilometer Array radio telescope exabyte-scale /day data expected
  - discoveries depend on **advanced algorithms** ← O(ns) latency triggers for collider experiments, tracking in very dense environments, …
  - **supercomputers** simulate physical reality ← cosmological evolution simulations on pre-/hexascale HPCs
  - **AI** enables discoveries impossible with traditional methods ← multidimensional real-time anomaly detection, generative AI, …
  - **Quantum computing** potentially opens new computational paradigms

**computing is no longer a support tool but a core scientific instrument, alongside detectors and telescopes**

# COMPUTING AND IT CURRICULUM OVERVIEW

- Aim of the curriculum is to **train researchers capable of developing the next generation of computational tools** to tackle the most complex challenges in data analysis, modeling, and algorithm development for physics & astronomy

- **Curriculum covers the full computing stack:**
  - computing **infrastructures and networks**
  - High Performance Computing (**HPC**)
  - **Big Data** and distributed computing
  - **Storage** technologies and **data management**
  - **Artificial Intelligence** and Machine Learning
  - **Quantum Computing** and Quantum Technologies

**Curriculum Board Members:**
Carmelo Arcidiacono - INAF
Andrea D'Ambrogio - Roma Tor Vergata
Domenico Elia - INFN
Eva Sciacca - INAF
Pierluigi Bortignon - Università di Cagliari
Stefano Bagnasco - INFN
Stefano Giagu - Roma La Sapienza
Valerio Formato - INFN

# FROM DATA TO DISCOVERY: WHERE AI/QC MAKE THE DIFFERENCE

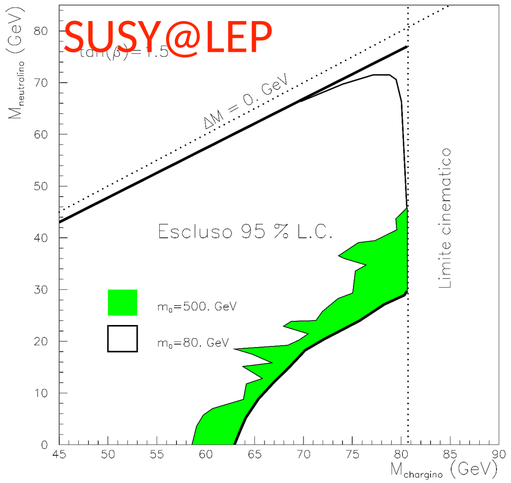
1. **Real-time selection → edge AI / FPGA / compression**
    - detector readout systems, triggering, monitoring, control, fast reconstruction
2. **Offline reconstruction & analysis (high-dimensional)**
    - detector simulations → generative AI models, Quantum sampling (emerging), …
    - Tracks, jets, event interpretation → Deep Learning, QML, …
3. **Inference & exploration (rare signals / anomalies / simulation)**
    - Anomaly detection, fast surrogates, generative models → AI + emerging QC hybrids, …

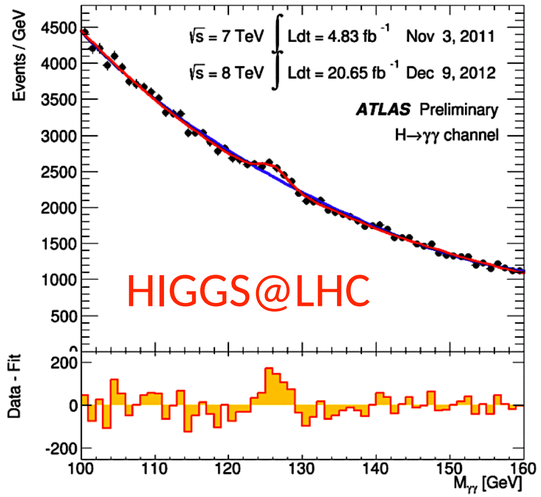
AI/QC are not “extra tools”, they are the enabling layer across the full chain

# EXAMPLE: NEW PHYSICS SEARCHES ENABLED BY AI

## Deep Learning at the LHC

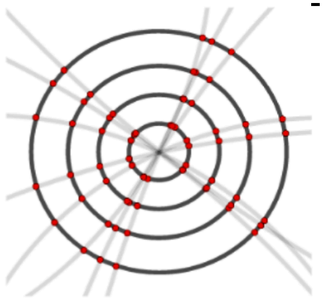
evolution from a simple computational tool to a set of complex systems capable of analyzing data, identifying patterns and hidden structures, and making predictions

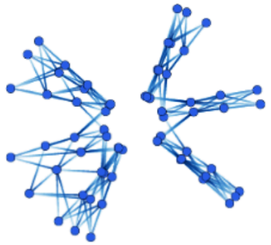



AI pervasive in HEP

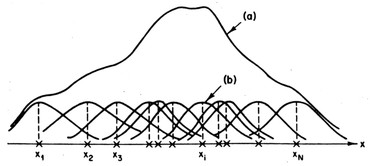
- **ex. GNN & Transformers**
  - track reconstruction
  - Jet tagging
  - event classification





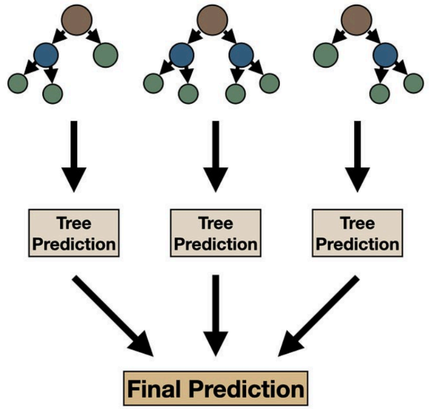
'80-'90 → 2000-12 → today

Classical ML, shallow-ANN

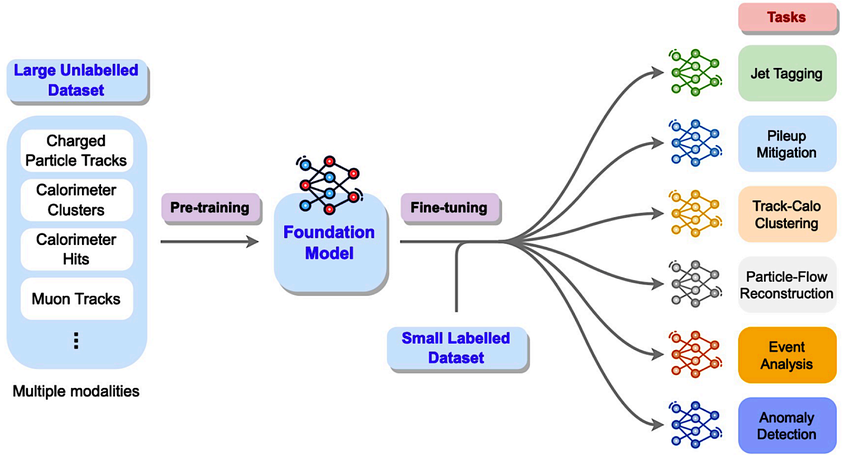



$$\tilde{f}(\mathbf{x}) = \frac{1}{N h_1 \cdots h_d} \sum_{i=1}^{N} \left\{ \prod_{j=1}^{d} K\left( \frac{x_i - x_i j}{h_j} \right) \right\}$$

BDT

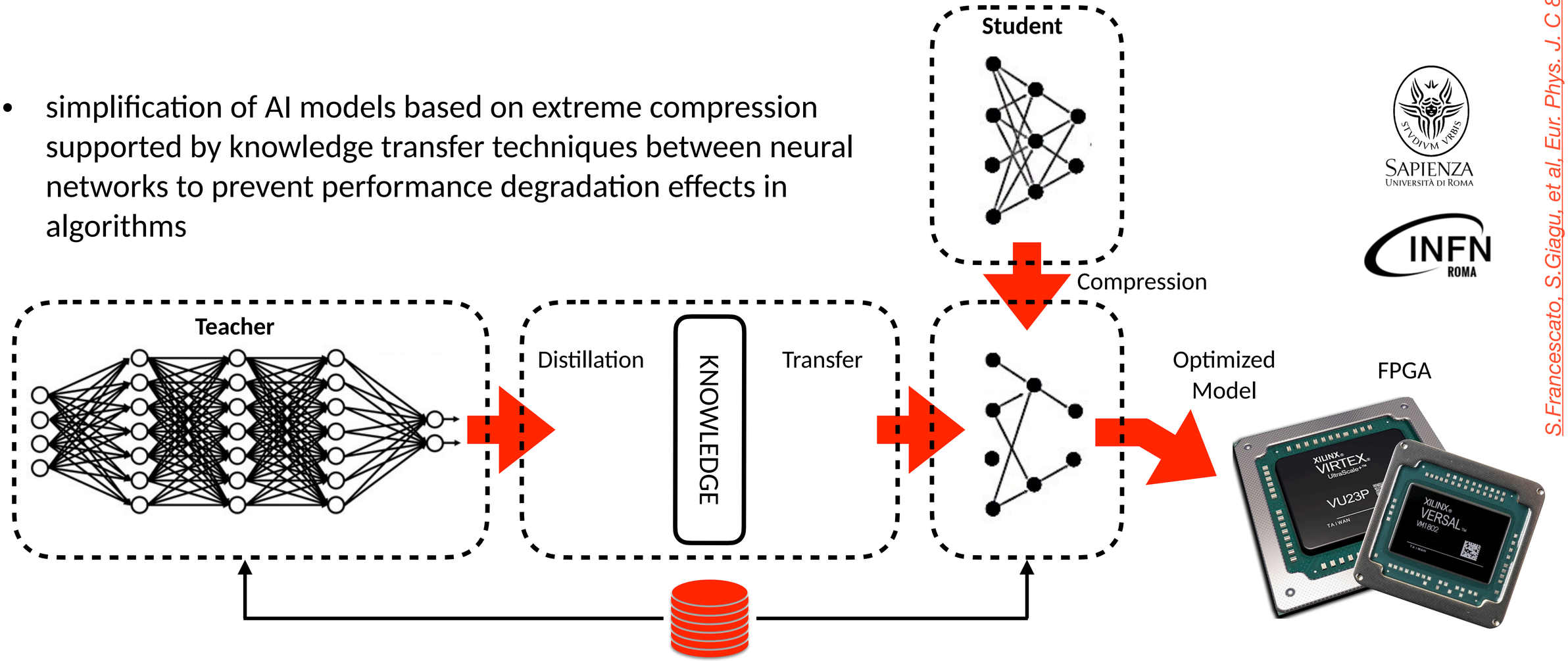



Foundation Models



# ULTRA-FAST AI TO FILTER EXPERIMENTAL DATA

- simplification of AI models based on extreme compression supported by knowledge transfer techniques between neural networks to prevent performance degradation effects in algorithms




- Teacher: CNN 70k weights 32 bits : 5 ms/eventv(Tesla V100 GPU)
- Student: CNN 700 weights 4 bits: 84 ns/event (FPGA Virtex US+)

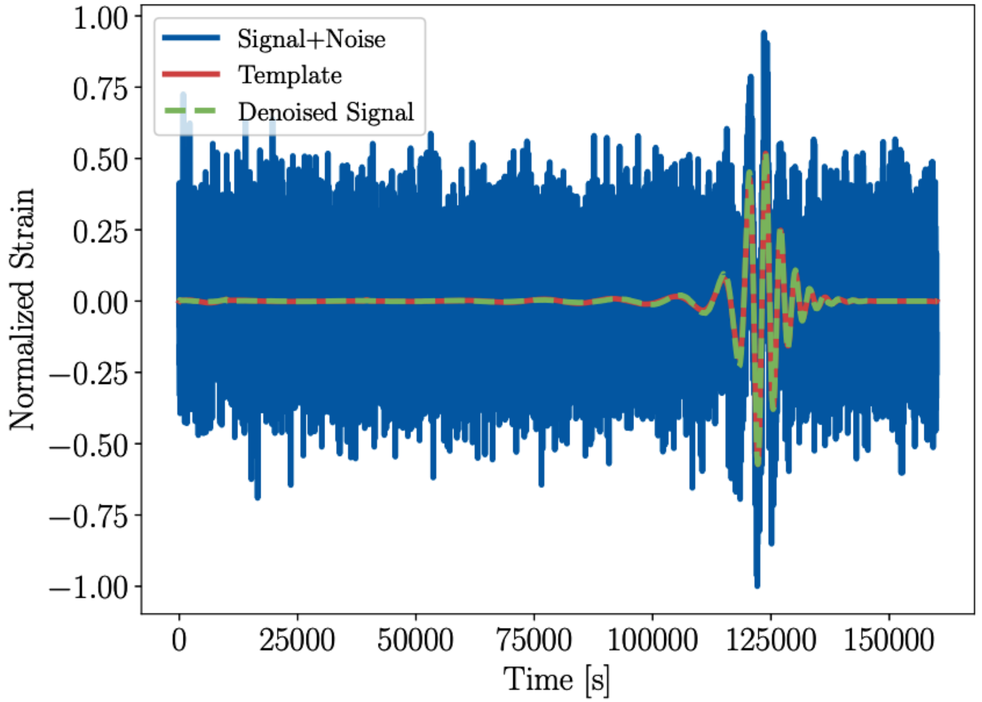
S.Francescato, S.Giagu, et al, Eur. Phys. J. C 81, 969 (2021)

# EXAMPLE: AI IN ASTROPHYSICS AND COSMOLOGY

## DL to detect gravitational waves faster than traditional pipelines

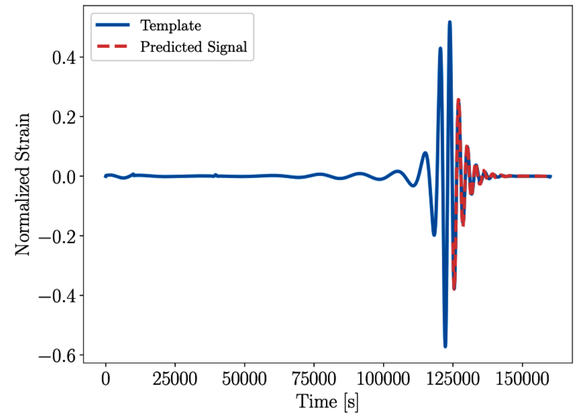
**Applications:**
- gravitational wave detection
- galaxy classification
- dark matter searches
- astronomical image analysis
- …

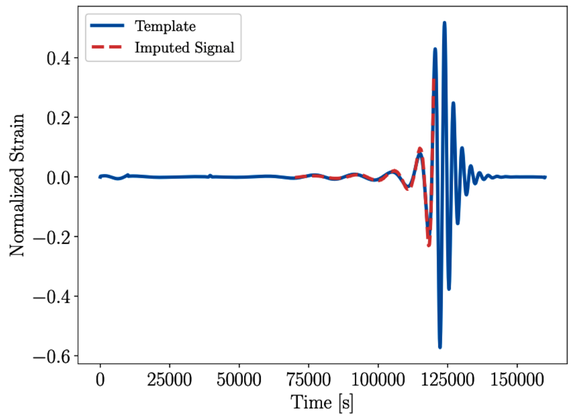
**Impact:**
- real-time detection capability
- increased sensitivity
- faster scientific discovery
- …



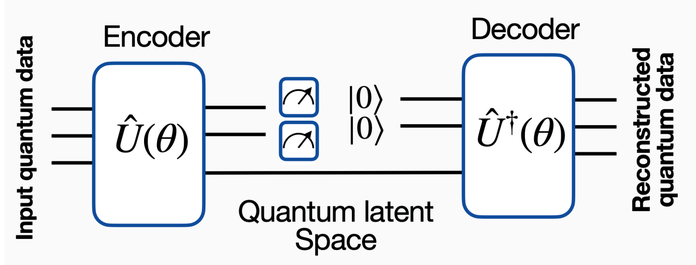

GW denoising via
transformer-based models

GW AI-supported signal
extrapolation and imputation

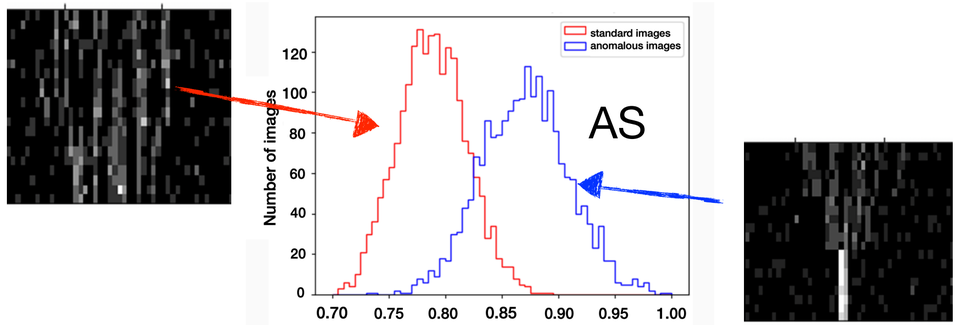


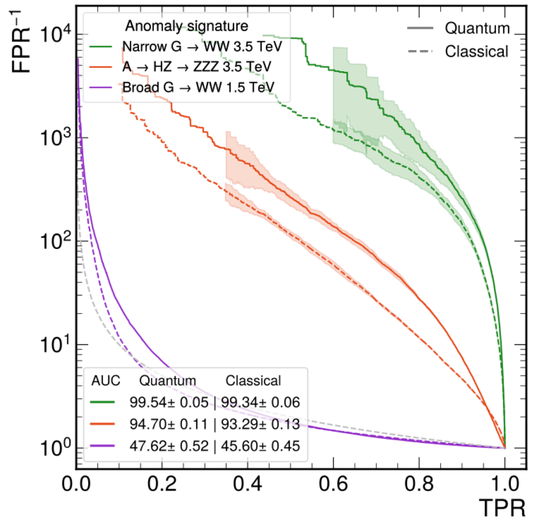
# EXAMPLE: QUANTUM COMPUTING FOR FUNDAMENTAL PHYSICS




- **Applications under development:**
  - simulation of quantum field theories
  - optimization problems in detector design
  - Quantum Machine Learning




- **Example: model agnostic searches for NP based on Quantum Anomaly Detection**
- different hybrid approaches:
  - low-level detector data → Quantum-AE + **quantum hw smart adaptation / approximate amplitude encoding w/ PQC** → Anomaly Score
  - low-level detector data → Classical-AE → **quantum kernel / clustering** → Anomaly Score



# CURRICULUM'S COURSES

- The curriculum provides interdisciplinary training to prepare PhD students for careers in **both academic and industrial research**

- Offer tailored to gain expertise in state-of-the-art computational techniques:
  - Big Data and Scientific Computing
  - Machine Learning and AI for fundamental research
  - High-Performance and Embedded Computing
  - Computational Techniques in Astrophysics and Particle Physics

# SUMMARY OF THE OFFERED COURSES

- **General Courses:**
  - Cloud Computing & Big Data (Tommaso Cucinotta)
  - Cloud Computing & Big Data LAB (Tommaso Cucinotta)
  - Big Data Analysis in Python (Gioacchino Vino)
  - Computing Methods for Experimental Physics and Data Analysis (Andrea Rizzi, Alessandra Retico)
  - Metodologies and techniques for the analysis of experimental data (Alexis Pompili)
  - Machine Learning for Physics (Pierluigi Bortignon)
  - Neural Networks and Deep Learning (Giorgio Carlo Buttazzo)

- **Specialized Topics & Electives:**
  - Advanced Scientific Programming (Matlab (P. Bardella, S. Scialò)
  - Programmable System on Chip (SoC) for Data Acquisition (Andrea Fabbri)
  - Quantum Artificial Intelligence (Filippo Caruso)
  - Introduction to neuromorphic computing (A. Duggento)
  - Maximum-Entropy Methods for Complex Systems I (Diego Garlaschelli)
  - Maximum-Entropy Methods for Complex Systems II (Tiziano Squartini)
  - Adaptive Optics for Astronomy (Carmelo Arcidiacono)
  - Generative Design for smart Additive Manufacturing (Antonio Gloria)
  - Advanced numerical modeling for systems engineering theory and applications (Dalla Vedova Matteo Davide Lorenzo)
  - Advanced FPGA design and design management techniques (Enrico Calore, Nicolò Vladi Biesuz)
  - Statistical Process Monitoring of Complex Engineering Data (Antonio Lepore, Christian Capezza)
  - Simulation of Optical Photon Propagation for Scintillator-Based Detectors (Davide Serini)

# CURRICULUM's ADVERTISED SCHOOLS

- **A non-exhaustive example of known and interesting school & training events …**
  - **ISTODAQ 2026**, July 1-10, 17-26, Bucharest, Romania, https://indico.cern.ch/e/isotdaq2026
  - **DeepLearn 2026,** 13th International School on Deep Learning, Orléans, France · July 20-24, 2026, https://deeplearn.irdta.eu/2026/
  - **INFN School of Statistics 2026**, Caserta, Italy from 14th to 19th of June 2026, https://agenda.infn.it/event/46370/overview
  - **INFN International School on Efficient Scientific Computing ESC2026**, 12-22 october 2026, Bertinoro, Italy, https://esc.infn.it/
  - **CERN School of Computing**: 23 August – 5 September 2026, University of Liverpool, Liverpool, United Kingdom, https://csc.web.cern.ch/csc-2026/
  - **Inverted CERN School of Computing 2026**, 16-19 March 2026, https://home.cern/events/inverted-cern-school-computing-2026
  - **SoBigData Summer School 2026**, 22-28 June 2025 – Baratti (Piombino), https://summerschool2025.sobigdata.eu/
  - **The International Summer School on Generative AI**, June 22-26, 2026, Sapienza Università di Roma, https://intelligent-systems.net/school/
  - **Ellis Summer School 2026 on AI for Research**, 17-21 august 2026, Helsinki (in preparation, see: https://ellis.eu/news/travel-and-study-in-europe-2026-schedule-of-ellis-phd-winter-and-summer-schools)
  - **EQAI 2026 5th European Summer School on Quantum AI**, 31 August – 04 September, 2026, Lignano Sabbiadoro, Italy, https://eqai.eu/eqai-2026/

- **AI_INFN advanced hackathons**: organized yearly, last one in November 2025, https://agenda.infn.it/event/47736/ (covering AI and QML topics with hands-on sessions)
- Training Schools organized by the COST Actions:
  - **EPIGRAPHY CA24153 - Edge Deep Learning for Particle Physics** (https://www.cost.eu/actions/CA24153/, ask me for additional infos)
  - **MLQC4FC CA24146 - Machine Learning and Quantum Computing for Future Colliders** (https://cost-mlqc4fc.github.io/index.html)
  - both actions plan to organize schools and training events in 2026-2028.

# DEDICATED SEMINARS TOMORROW

- **Lucio Anderlini: AI Initiative at INFN (AI_INFN)**
  - Topics:
    - INFN_AI project in CSN5
    - available facilities / knowledge-base
    - opportunities for PhD students

- **Simone Bordoni: Introduction to Quantum Computing and Quantum Sensing**
  - Topics:
    - Quantum Computing basics
    - Parametric Quantum Circuits and QML
    - fundamentals of quantum sensing techniques