PHD PROGRAM IN TECHNOLOGIES FOR FUNDAMENTAL RESEARCH IN PHYSICS AND ASTROPHYSICS

CURRICULUM IN COMPUTING

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TECH-FPA PhD Retreat 2025 - LNGS - 18.2.2025

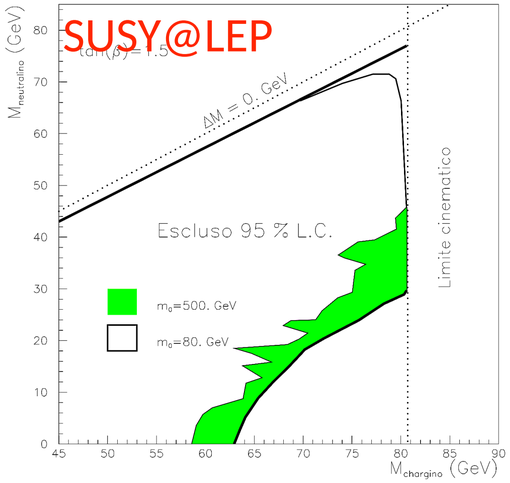
THE COMPUTING AND INFORMATION TECHNOLOGY CURRICULUM

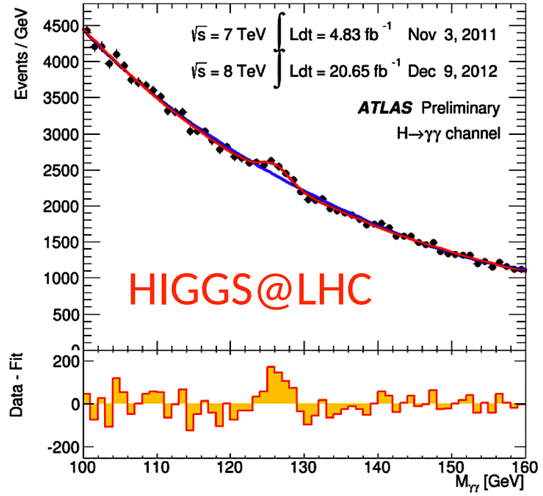
- Computing is at the heart of modern fundamental research
- Cutting-edge computational methods crucial in all fields of physics and astrophysics

- Aim of the curriculum is to train experts with advanced computational skills to tackle the most complex challenges in data analysis, modeling, and algorithm development:
  - processing enormous amounts of data (**Big Data**) from experiments and simulations
  - utilizing **HPC** for complex simulations and advanced data analysis
  - implementing **AI algorithms** for pattern recognition and generative tasks
  - learn efficient **management and storage** of scientific data

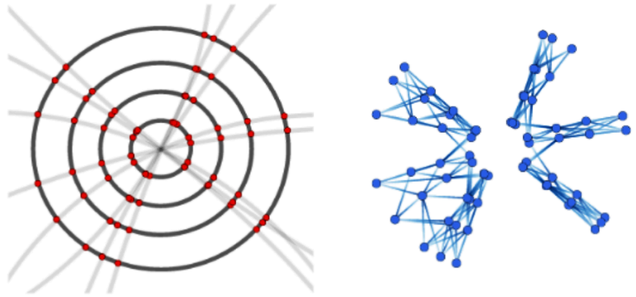
AN EXAMPLE: AI IN FOUNDAMENTAL SCIENCES

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



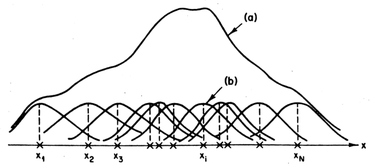


AI pervasive in HEP



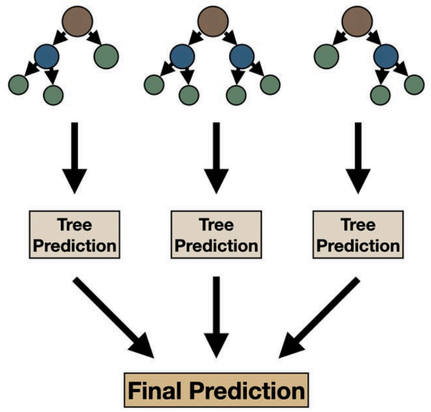
’80-’90 — 2000-12 — today

Classical ML, shallow-ANN

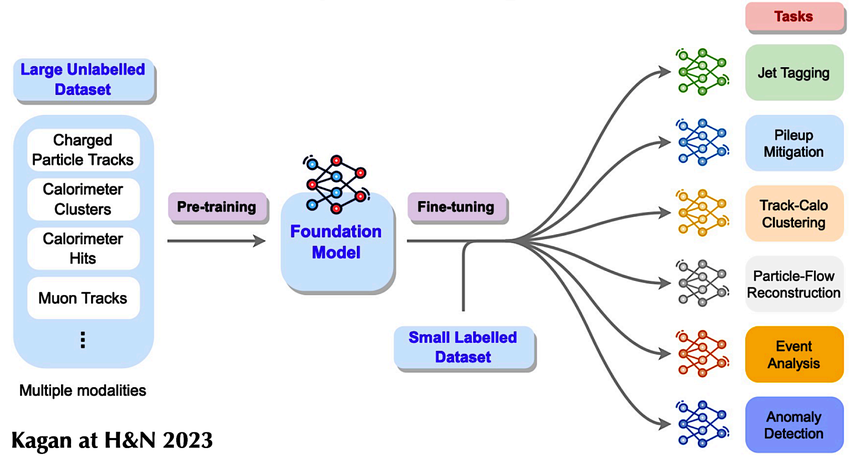


$$\tilde{f}(\mathbf{x}) = \frac{1}{Nh_1 \cdots h_d} \sum_{i=1}^{N} \left\{ \prod_{j=1}^{d} K\left(\frac{x_i - x_i j}{h_j} \right) \right\}$$

BDT

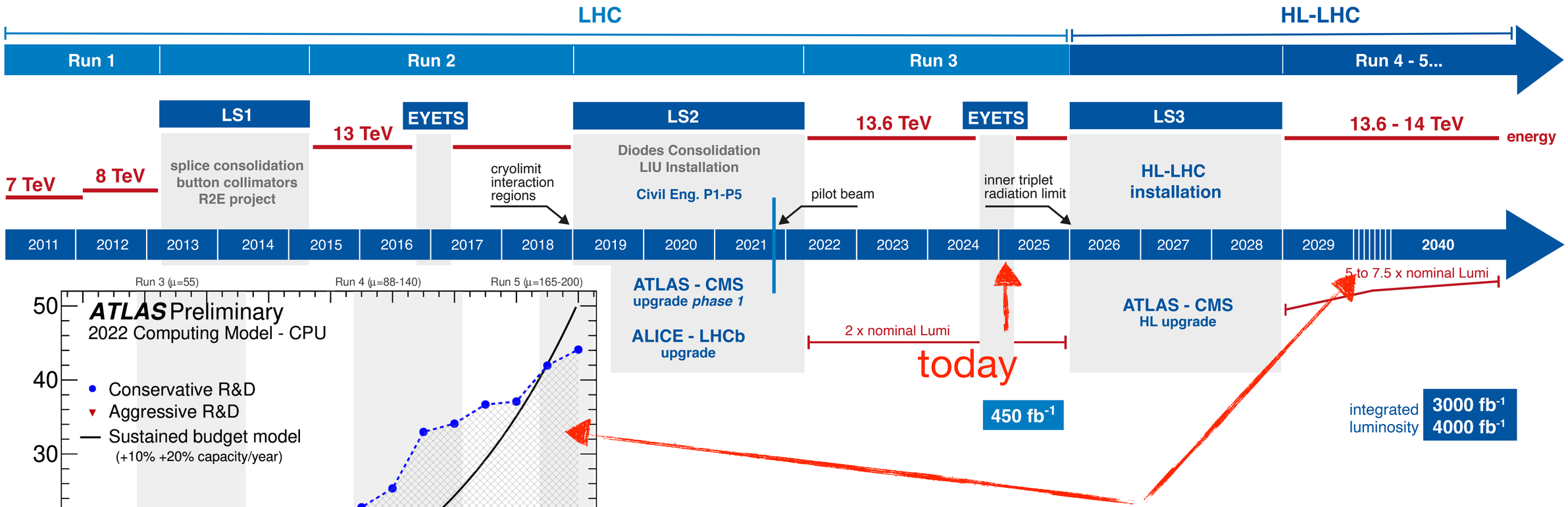


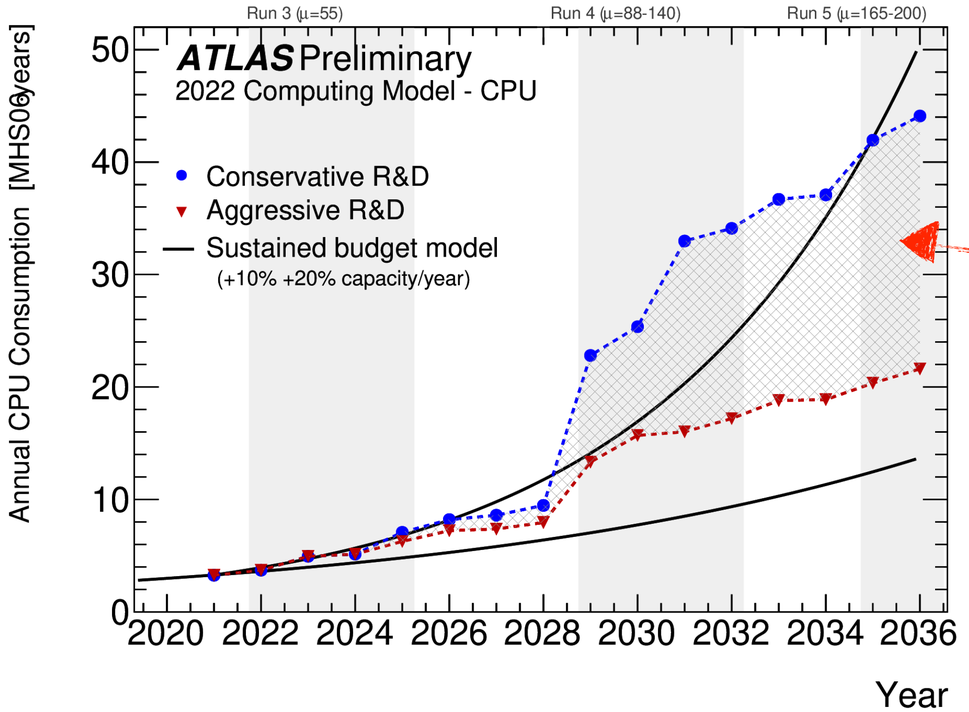
Deep Learning/LLM



Kagan at H&N 2023

BIG DATA AT HADRON COLLIDERS





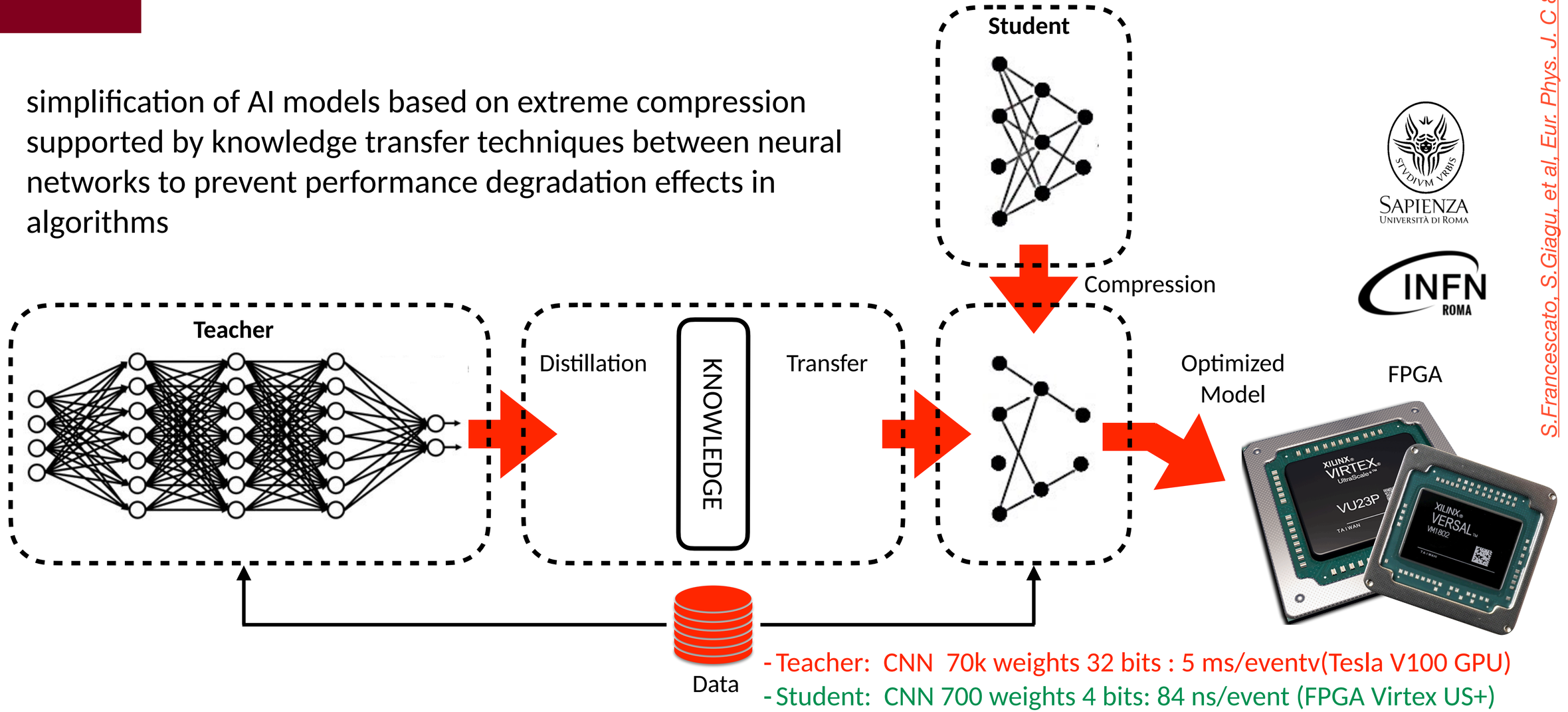
Experimental challenge at the High-Luminosity Large Hadron Collider

for example in the ATLAS experiment:

- **computing power needed**: x10 wrt today
- **data volume to be analized and stored**: ~2.5 exaByte by the end of Run-4 in 2033

LEVERAGE 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



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

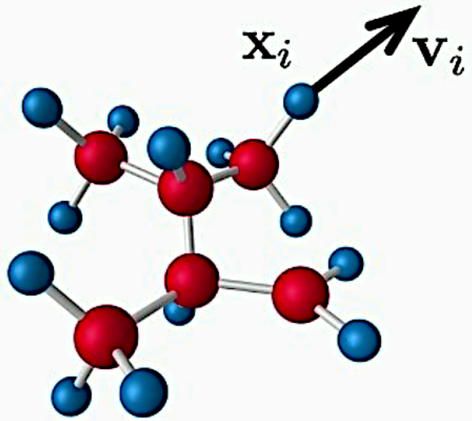
onging spinoff (PRIN 2022 PNRR - Recentre): real-time AI-based motion correction and denoising in Magnetic Resonance

LEVERAGE AI FOR FASTER EVENT SIMULATION

- first principle Monte Carlo simulation of complex processes at collider detectors extremely costly
- statistical uncertainty on simulated events soon will become one of the limiting factor on many measurements / searches at HL-LHC

- **a viable solution:** generative-AI

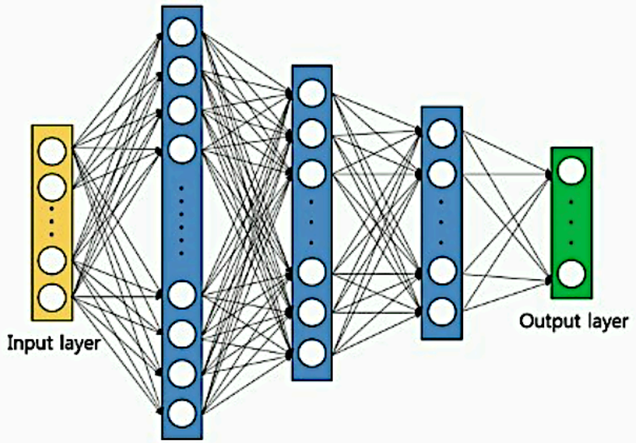
numerical simulator based on first principles (**SLOW**)



artificial data

emulated data

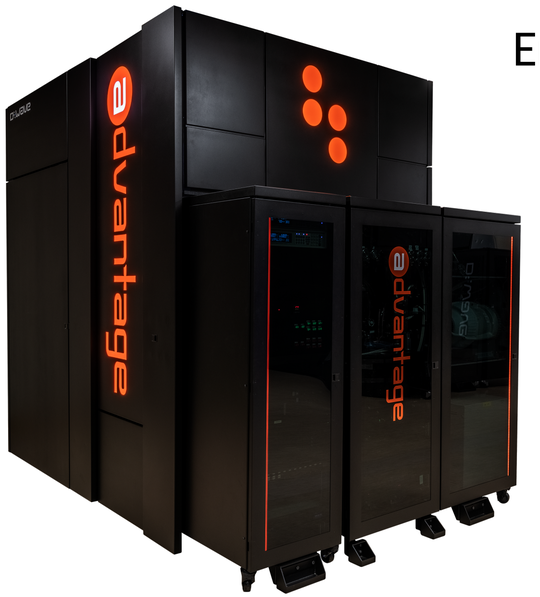
Emulator based on AI (**FAST**)

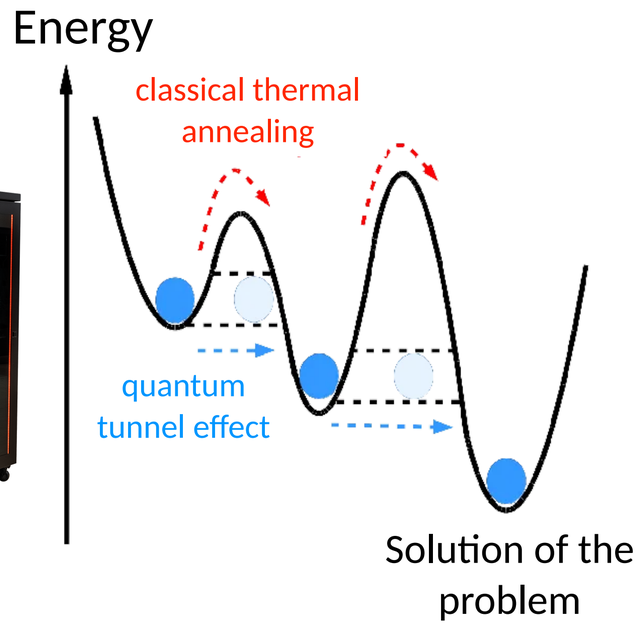


An **extremely effective approach** when:
- classical numerical simulations are slow and expensive
- the mechanism underlying the analyzed phenomenon is known

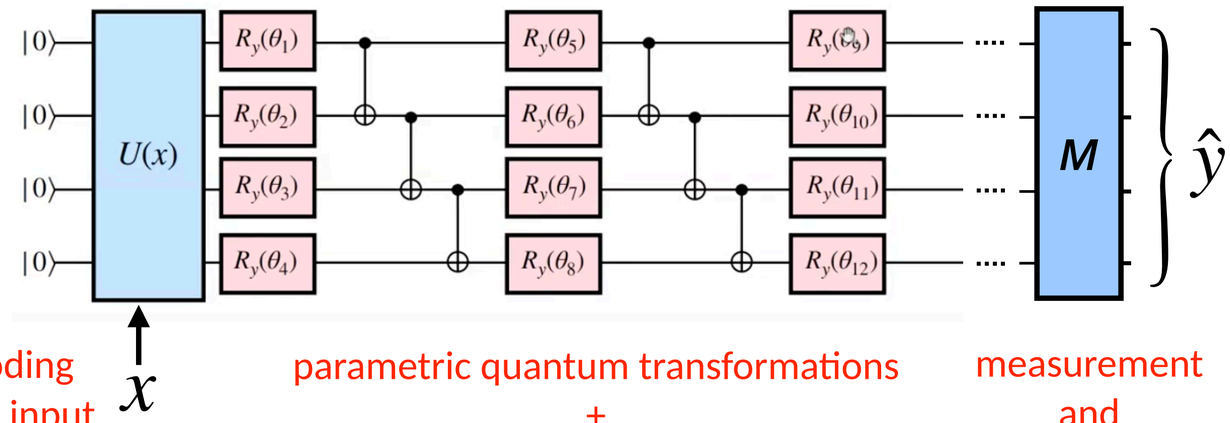
ENHANCE CLASSICAL AI WITH QUANTUM COMPUTERS

- quantum computers allow for a more efficient and faster finding of energy minima in highly complex systems: **classical AI algorithms assisted by quantum computers**
- quantum circuits enable a more efficient representation of the solution space of a problem and the identification of complex correlations in high-dimensional and highly complex data: **hybrid Quantum Machine Learning algorithms**





Quantum-NN

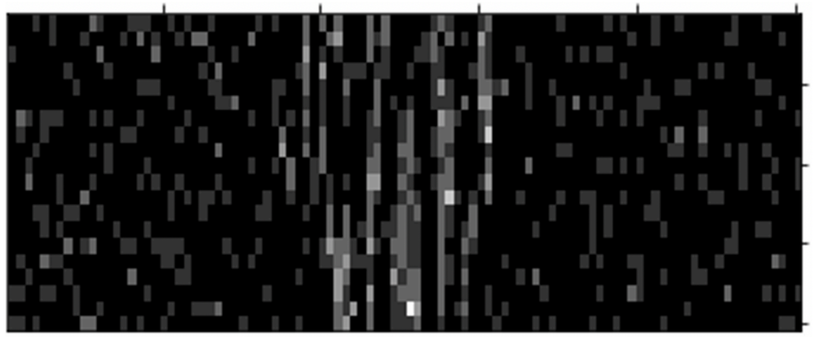


QUANTUM ANOMALY DETECTION FOR LONG LIVED PARTICLES

- Design and train a Quantum-AE able to identify highly displaced decays using the ATLAS muon spectrometer information

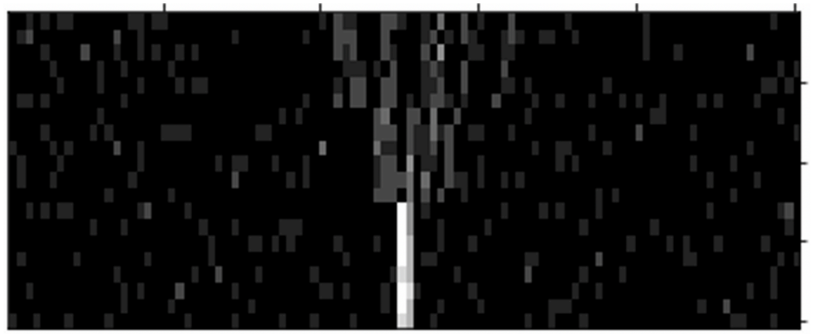
NORMAL event

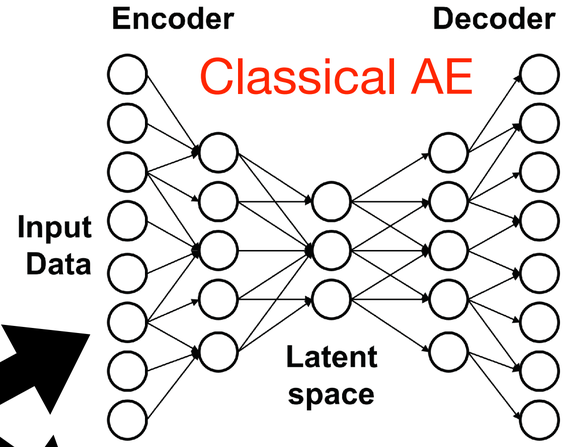
"image" representation of a prompt decay in multi-muons

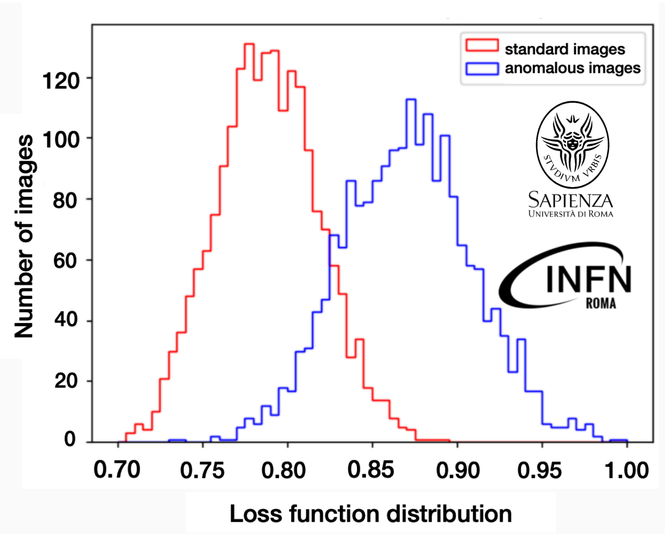


ANOMALOUS event

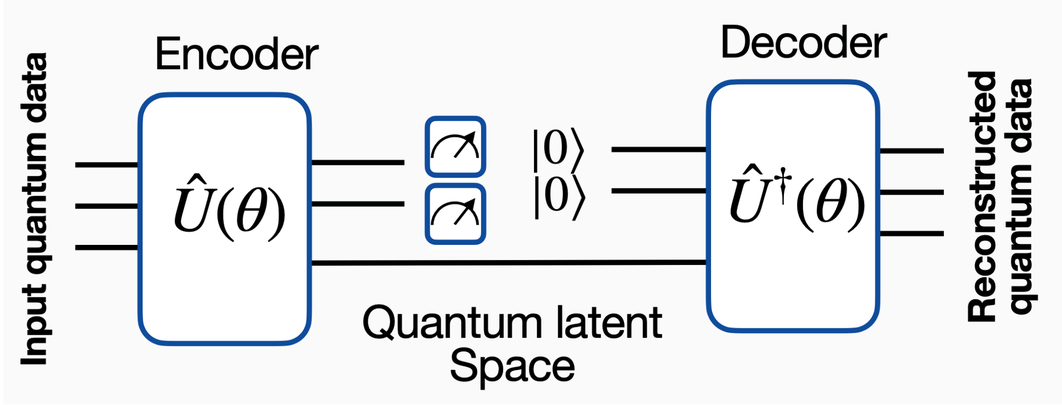
"image" representation of a highly displaced decay in multi-muons







Quantum-AE



S.Bordoni et al, Particles 2023, 1, 1–15

onging spinoff (Innovation Grant PNRR - Fraud Detection): fraud detection in financial transactions with Banca Intesa

CURRICULUM'S ACADEMIC OFFER

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

- Academic offer tailored to gain expertise in state-of-the-art computational techniques:
  - **Big Data and Scientific Computing:**
    - Advanced scientific programming for physics applications
    - Big data modeling, cloud computing, and distributed systems
    - Maximum-entropy methods for complex systems
  - **Machine Learning and AI for Fundamental Research:**
    - Machine learning and numerical techniques for physics applications
    - Deep learning and neural networks for data analysis
    - Quantum artificial intelligence and neuromorphic computing
  - **High-Performance and Embedded Computing:**
    - Programmable Systems on Chip (SoC) for real-time data acquisition
    - Computing methods for experimental physics and data analysis
  - **Computational Techniques in Astrophysics and Particle Physics:**
    - Simulation techniques for optical photon propagation
    - Adaptive optics for astronomy
    - Machine learning applications in high-energy physics
    - Advanced numerical methods for inverse problems

SUMMARY OF THE OFFERED COURSES

- a diverse set of core courses, hands-on training, and research-oriented projects

- **Core Courses:**
  - Big Data & Cloud Computing (Tommaso Cucinotta)
  - Big Data modeling and learning (Ester Pantaleo)
  - Machine Learning for Physics (Pierluigi Bortignon)
  - Computing Methods for Experimental Physics and Data Analysis (Andrea Rizzi, Alessandra Retico)
  - Neural Networks and Deep Learning (Giorgio Carlo Buttazzo)
  - Advanced Scientific Programming (Matlab (P. Bardella, S. Scialò) and Python-focused (G. Vino) courses)
- **Specialized Topics & Electives:**
  - Programmable System on Chip (SoC) for Data Acquisition (Andrea Fabbri)
  - Quantum Artificial Intelligence (Filippo Caruso)
  - Maximum-Entropy Methods for Complex Systems (Diego Garlaschelli, Tiziano Squartini)
  - Adaptive Optics for Astronomy (Carmelo Arcidiacono)
  - Introduction to neuromorfic computing (A. Duggento)
- **Hands-on Training & Research Applications:**
  - Big Data Analysis in Python (Gioacchino Vino)
  - Cloud Computing & Big Data th & lab (Tommaso Cucinotta)
  - Simulation of Optical Photon Propagation for Scintillator-Based Detectors (Davide Serini)
  - System Engineering & Project Management for Big Experiments (Marco Xompero, Runa Briguglio)

CURRICULUM's ADVERTISED SCHOOLS

- **ML&AI&Quantum:**
  - DeepLearn 2025: International School on Deep Learning, 21-25 july, Porto, Portugal, https://deeplearn.irdta.eu/2025/
  - ML4PHYSICS, june 26-july 2, Ljubljana, Slovenia, https://indico.cern.ch/event/1488532/
  - 4th Sumer School on Artificial Intelligence in Health and Life Sciences. 8-12 September 2025, Campus Biomedico Roma, Italy, web site in preparation (2024 version: https://sites.google.com/view/summer-school-aihls/home)
  - Advanced Course and Symposium on Artificial Intelligence & Neuroscience 2025 (ACAIN) , september 21-24, Castiglione della Pescaia, Italy, https://acain2025.icas.events/
  - Advanced Course on Data Science & Machine Learning 2025 (ACDL), 9-13 june, Castiglione della Pescaia, Italy, https://acdl2025.icas.events
  - AI_INFN hackathons: organized yearly at starting and advanced levels, last one in November 2024 https://agenda.infn.it/event/43129/overview (typically 2 per year, covers AI and QML topics)
- **TDAQ:**
  - ISTODAQ, june 17-26, Vilnius, Lithuania, https://indico.cern.ch/event/1477462/
  - FPGA programming school organized by CN1 - Spoke 1 - WG2 (two in 2025, introductory + advanced), first one will be announced soon (contact me if interested)

CURRICULUM's ADVERTISED SCHOOLS [2]

- **Computing & BigData:**
  - INFN International School on Efficient Scientific Computing ESC25, september 28-october 9, Bertinoro, Italy, https://esc.infn.it/ and https://agenda.infn.it/event/45177/ (in preparation)
  - CERN School of Computing: 6-19 july, Lund Sweden, https://indico.cern.ch/event/1512761/
  - CERN inverted School of Computing, 24-27 march, https://indico.cern.ch/event/1468713/
  - SoBigData Summer School 2025, Baratti, Italy, http://sobigdata.eu/events/sobigdata-summer-school-data-social-innovation
- **Other:**
  - Lipari Summer School 2025 on Computational Complex and Social Systems, 20-26 july, Lipari, Italy, https://complex25.liparischool.it/
  - INFN School of Statistics 2025 - to be announced (2024 version: https://agenda.infn.it/event/36980/)