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AI in Particle Physics



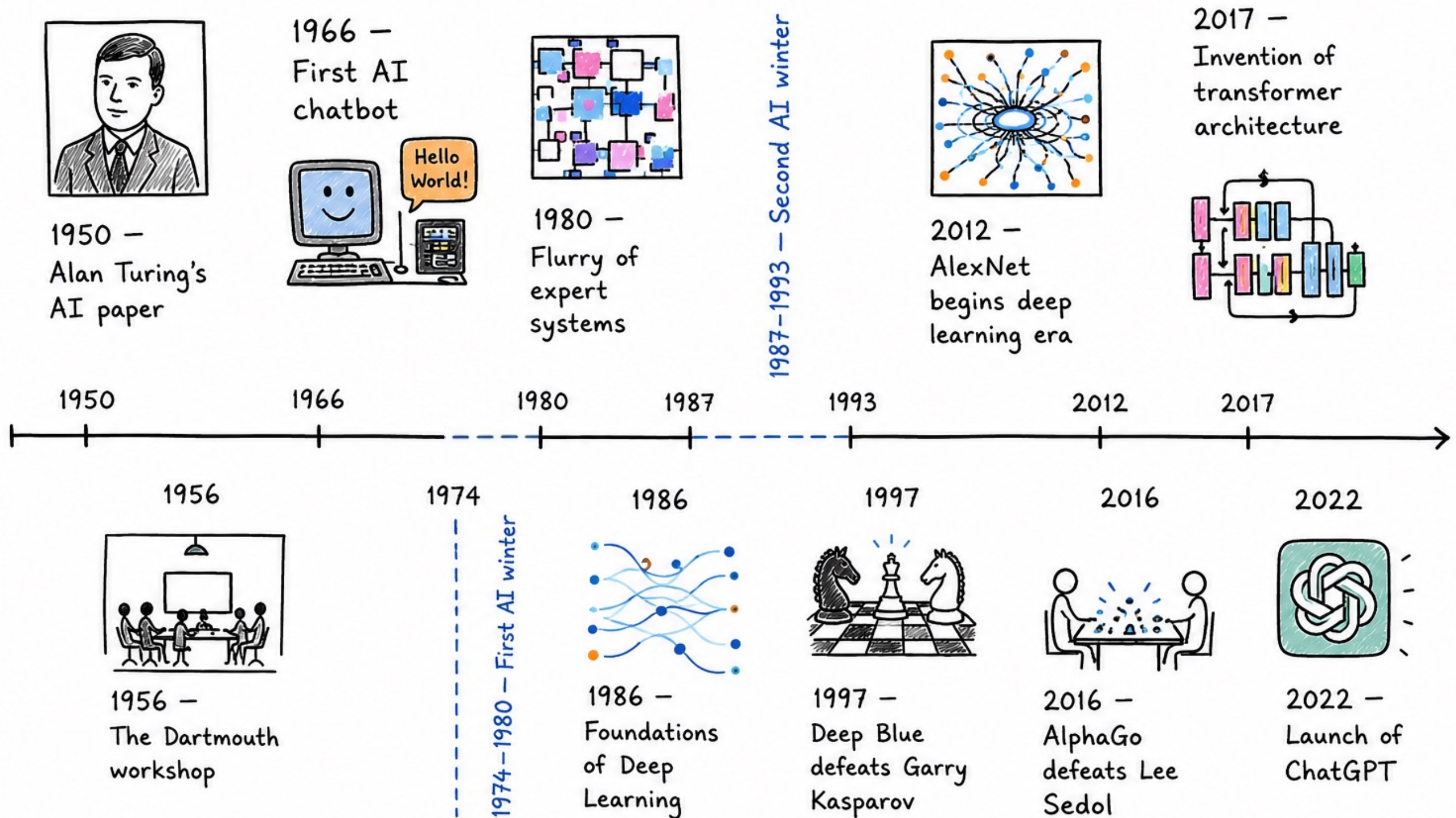


AI and ML

July 22nd, 2026



AI Timeline



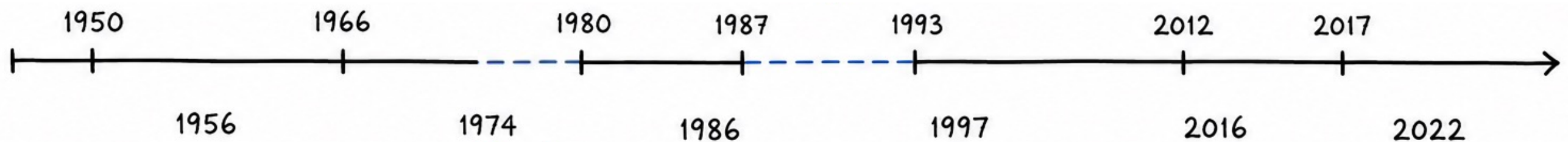
AI Timeline

"In three to eight years, we will get a machine with average human intelligence."

Marvin Minsky, 1970

"I'm increasingly inclined to think that there should be some regulatory oversight, maybe at the national and international level, just to make sure that we don't do something very foolish. I mean with artificial intelligence we're summoning the demon."

Elon Musk, 2014



"I'm still a realist: If we work really hard - and smart - we can have something like a HAL in between four and four hundred years. I suppose if we're lucky, then, we can make it by 2001!"

Marvin Minsky, 1997

"Generative AI is the most powerful tool for creativity ever created. It has the potential to unleash a new era of human innovation."

Elon Musk, 2023

What is AI and Machine Learning?

Artificial Intelligence

The broad field of building systems that can perform tasks that typically require human intelligence.

Machine Learning

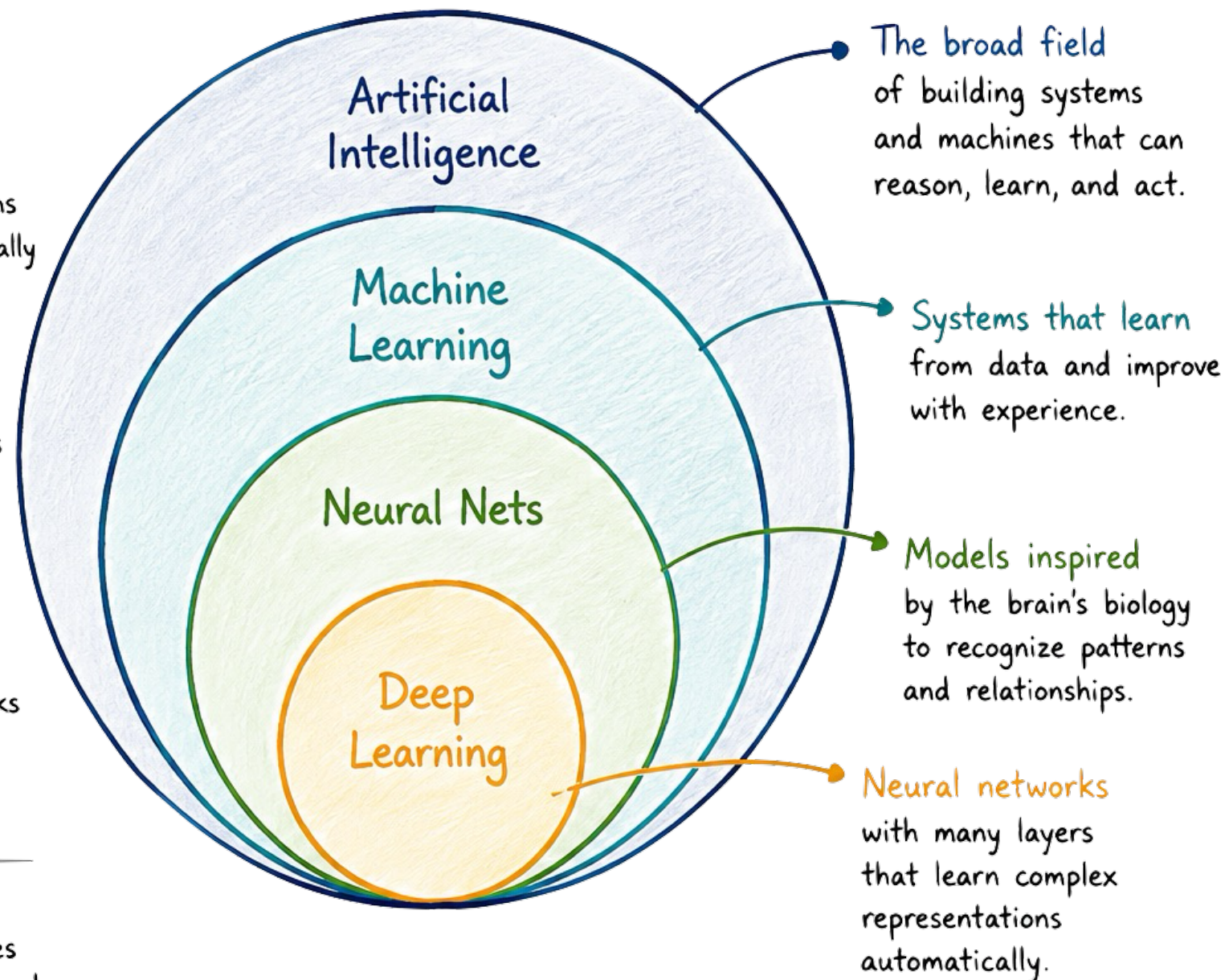
A subset of AI that enables systems to learn from data and improve their performance without being explicitly programmed.

Neural Nets

A subset of ML that uses networks of interconnected nodes (inspired by the brain) to model complex patterns in data.

Deep Learning

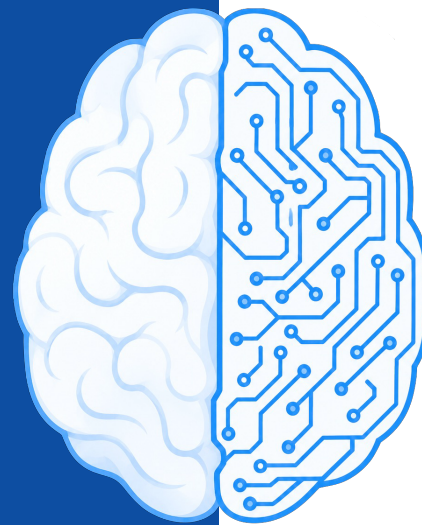
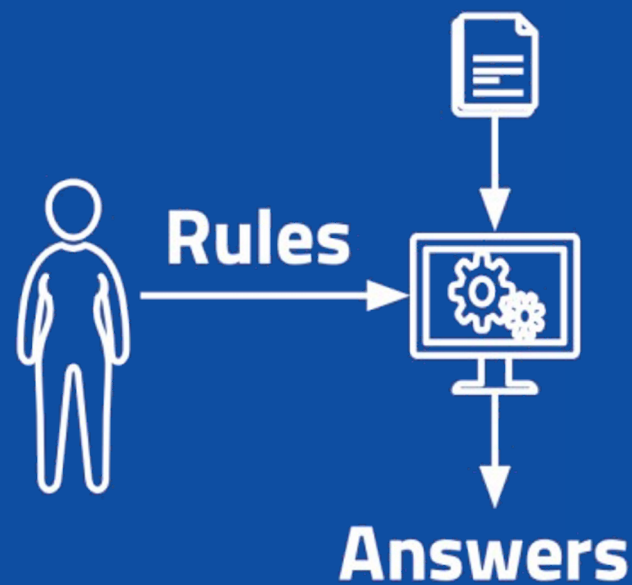
A subset of Neural Nets that uses multiple layers of interconnected nodes (deep neural networks) to learn hierarchical representations from data.



What is Machine Learning?

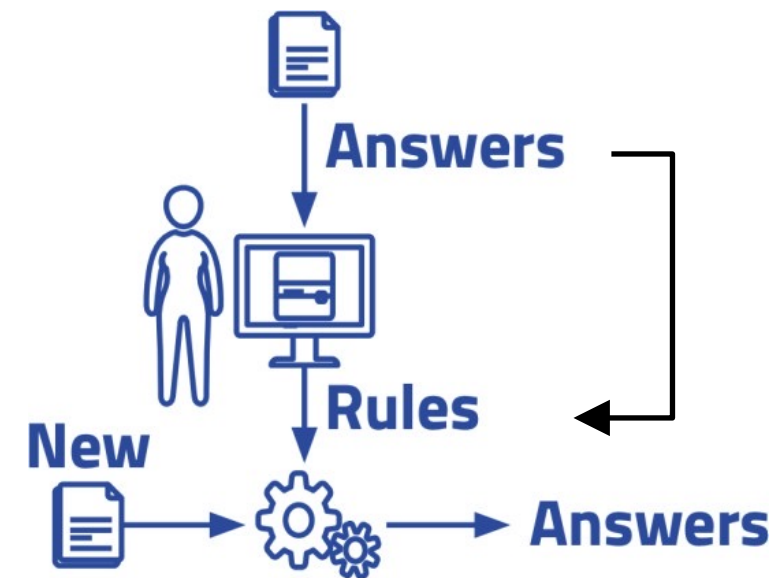
Traditional Computation

The task is programmed by the user as a pre-defined set of rules/algorithms to apply to data



Machine Learning (ML)

The program learns from data what are the necessary rules to execute a task/objective defined by the user: Training

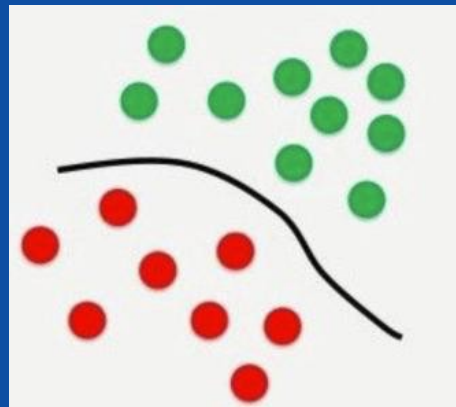


ML tasks and types

ML tasks

Classification

Discrete prediction



Regression

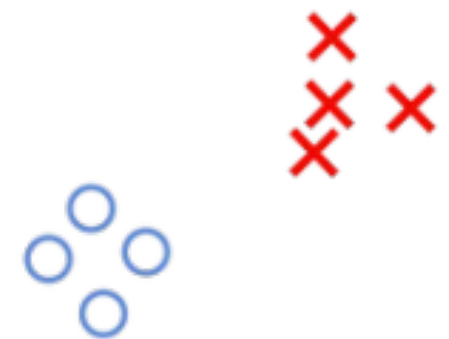
Real-value prediction



Learning types

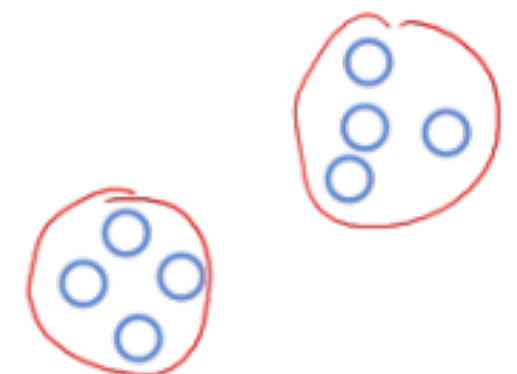
Supervised

(E.g. Simulation in Particle Physics)



Unsupervised

(E.g. clustering)





Why now?

Why now?

BIG DATA



- Larger datasets
- Easy collection and storage

HARDWARE



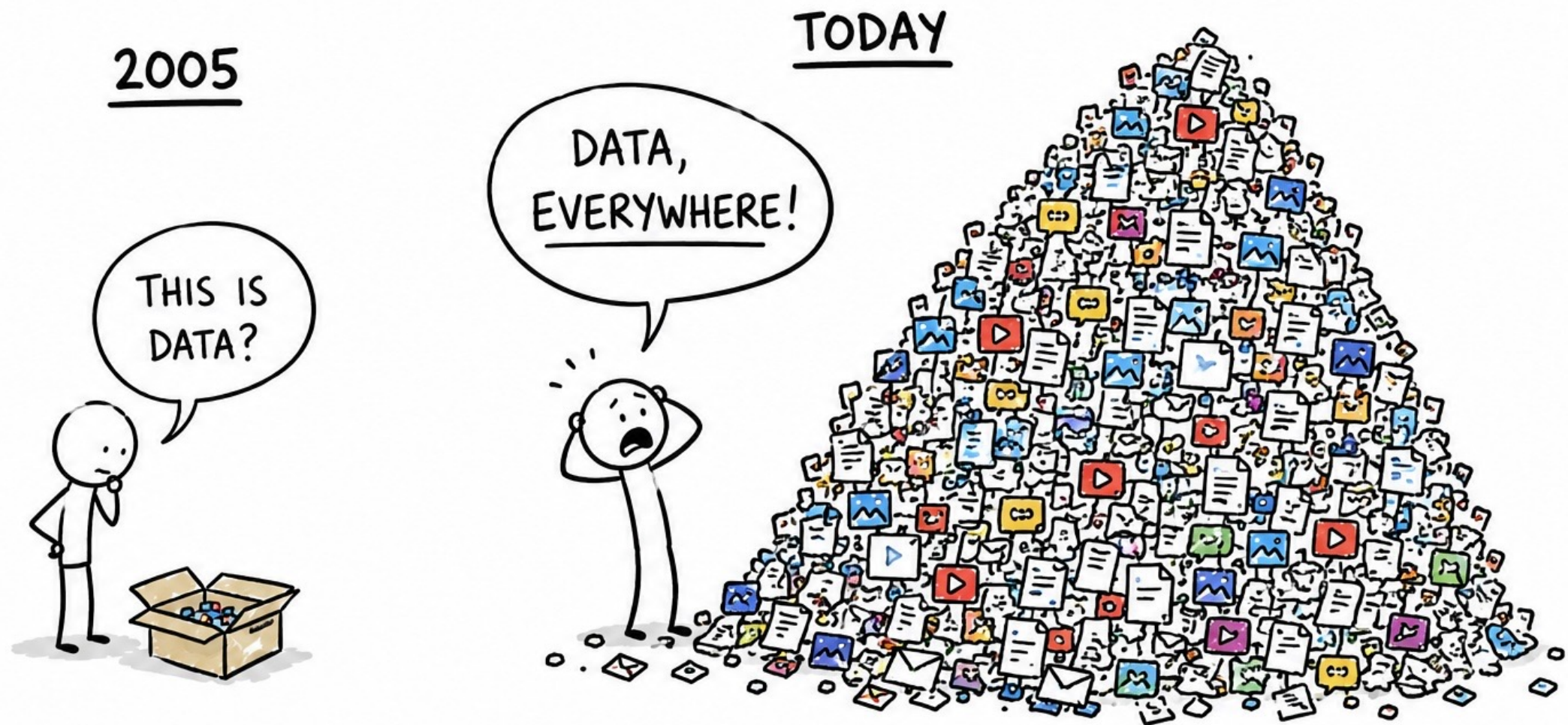
- Graphics Processing Units (GPUs)
- Massively parallelizable

SOFTWARE

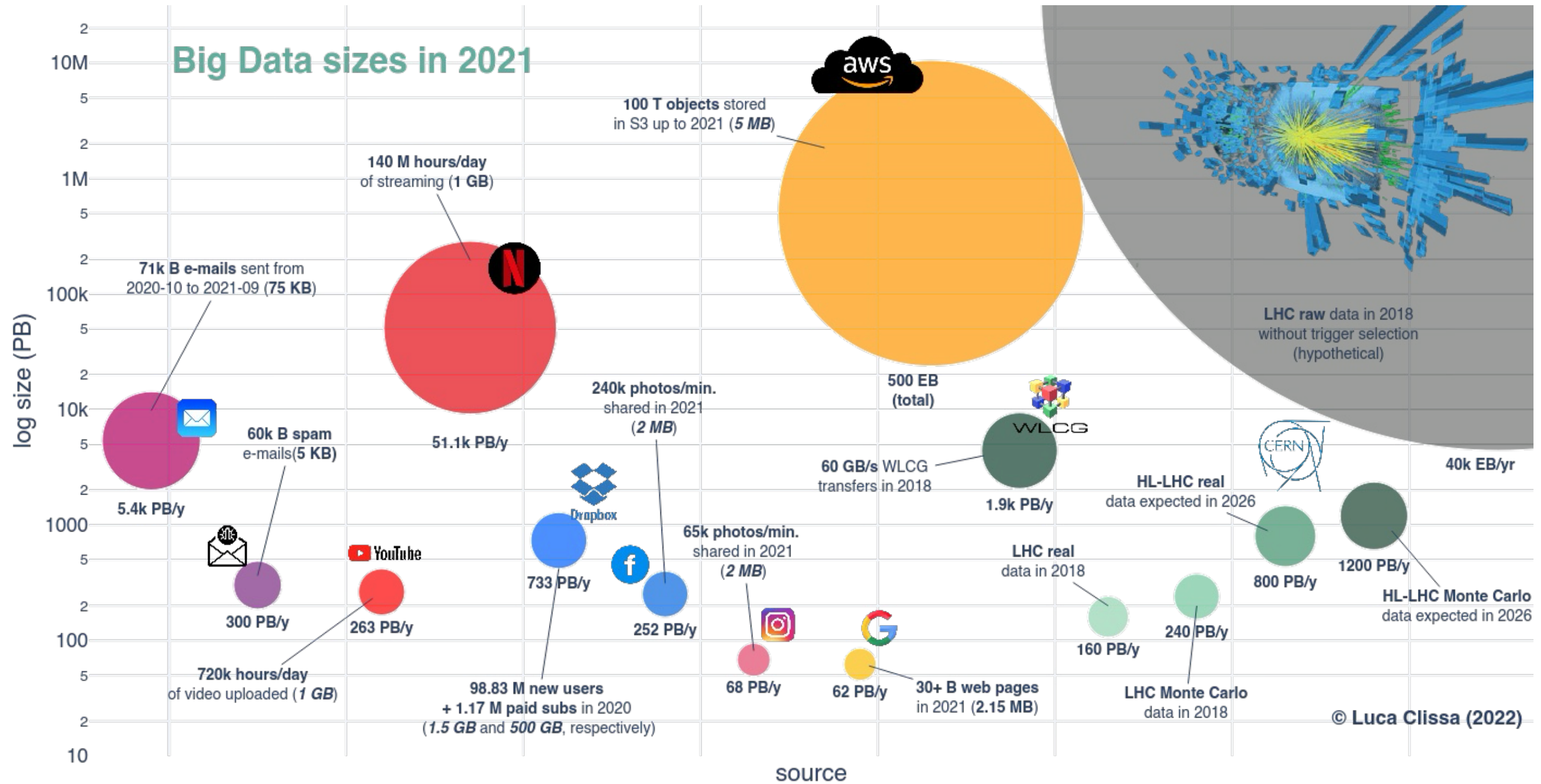


- Improved techniques
- Tools
- New models

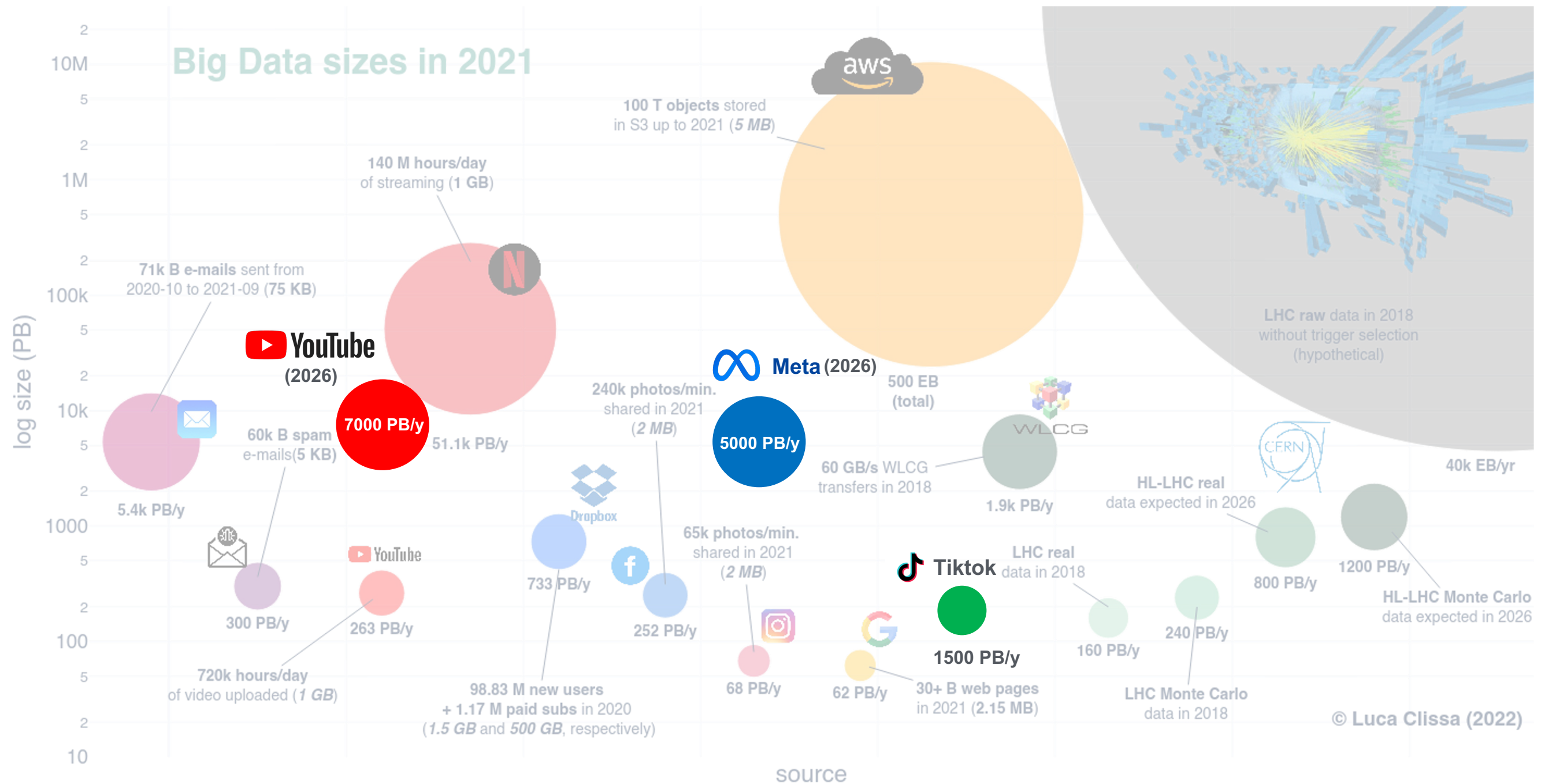
90% OF THE WORLD'S DATA WAS CREATED IN THE LAST 2 YEARS



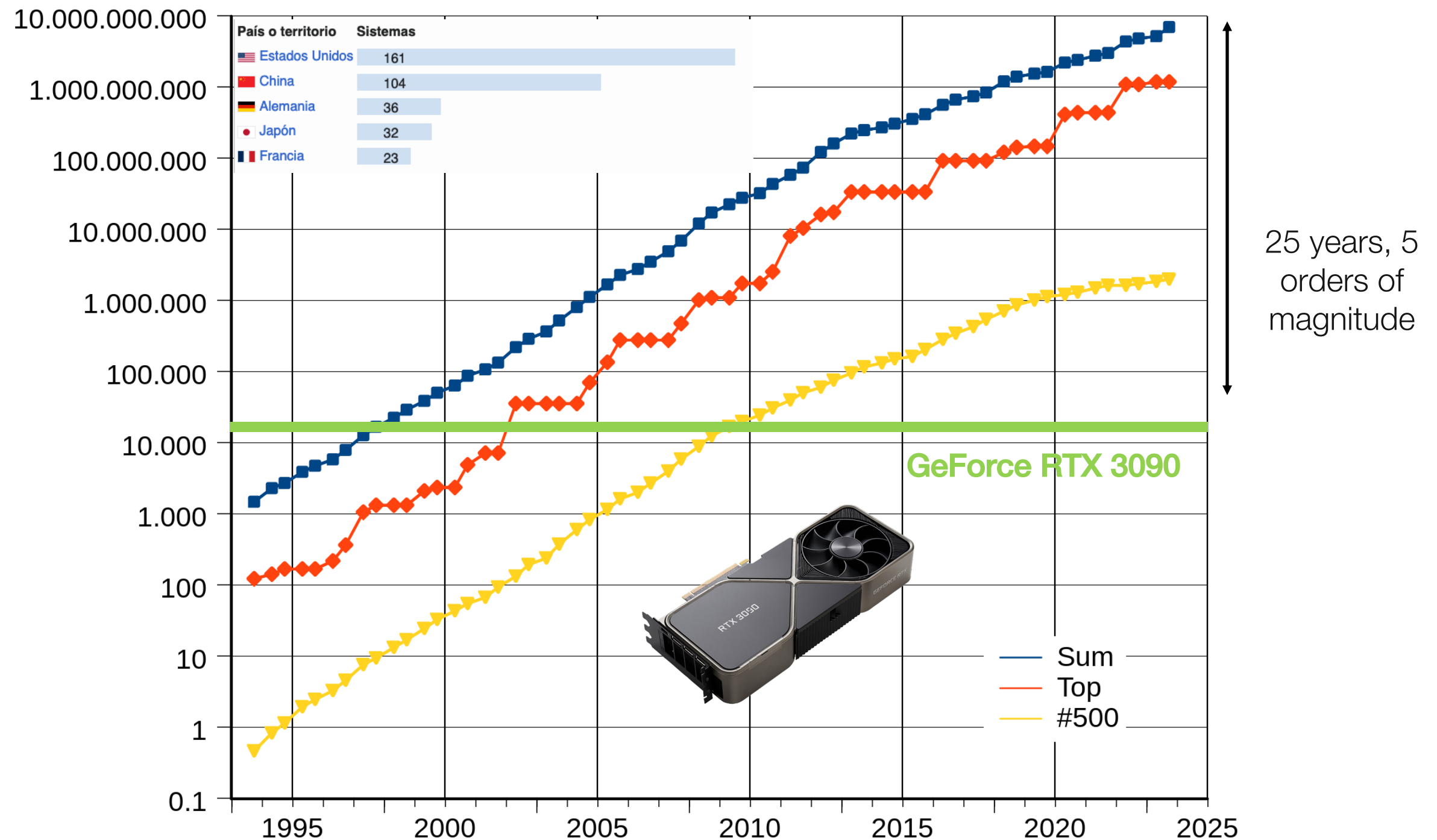
Some Big Data Numbers



Some Big Data Numbers

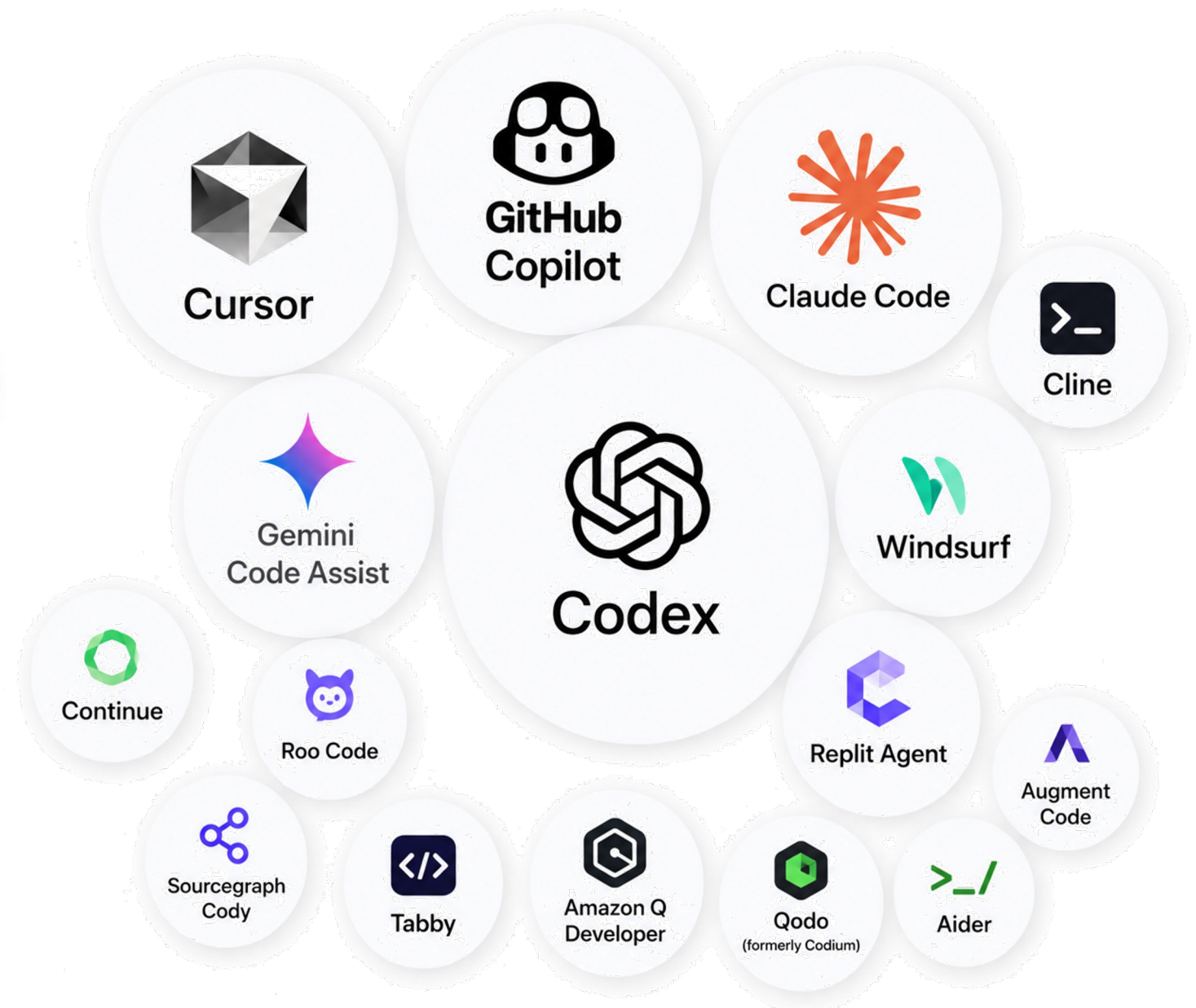


Hardware



*Supercomputer performance, according to data from the top500.org site.
The logarithmic y-axis shows the performance in GFLOPS.*

Software & Tools





r/PhysicsStudents · 7mo ago
Commercial_Ad2801

...

Is a career in research particle physics still worth it with the rise of AI?

As the question says, is it worth it for me to dedicate my life to studying particle physics if human expertise might not be as relevant in 10+ years?

↑ 0 ↓ 22

Many things will be **speed up** and **improved** thanks to **AI**, and it can be used in **many areas**, but...

... there are several tasks that can not be performed by AI (like building your detector).

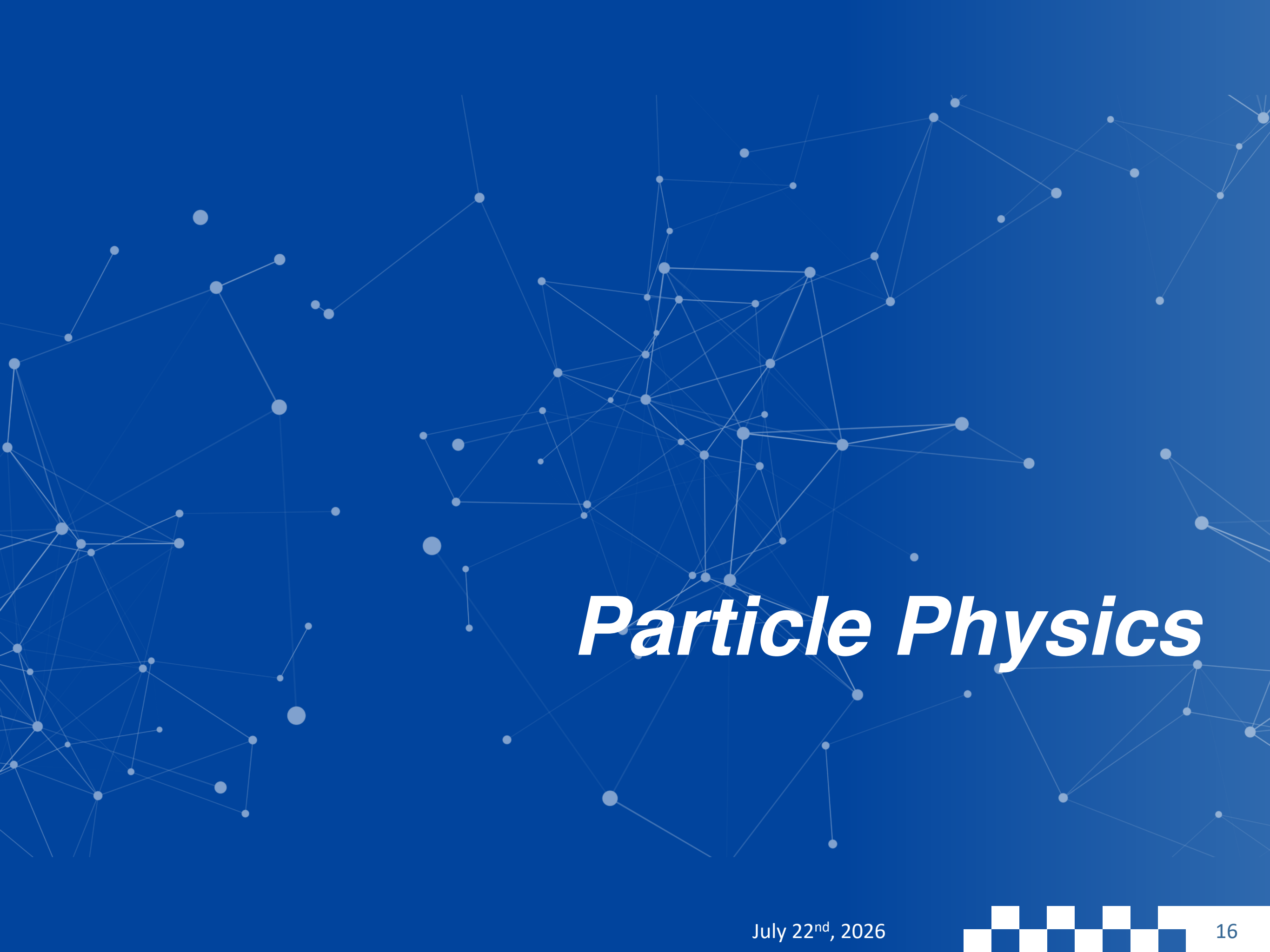
Additionally **AI** has limitations ...



I think we've hit a limitation of the image generator here. It keeps falling back to the same template:

chaos → ML box/person → clean output.

That's not because it's the best idea, it's because it's the most statistically common way these models illustrate ML.

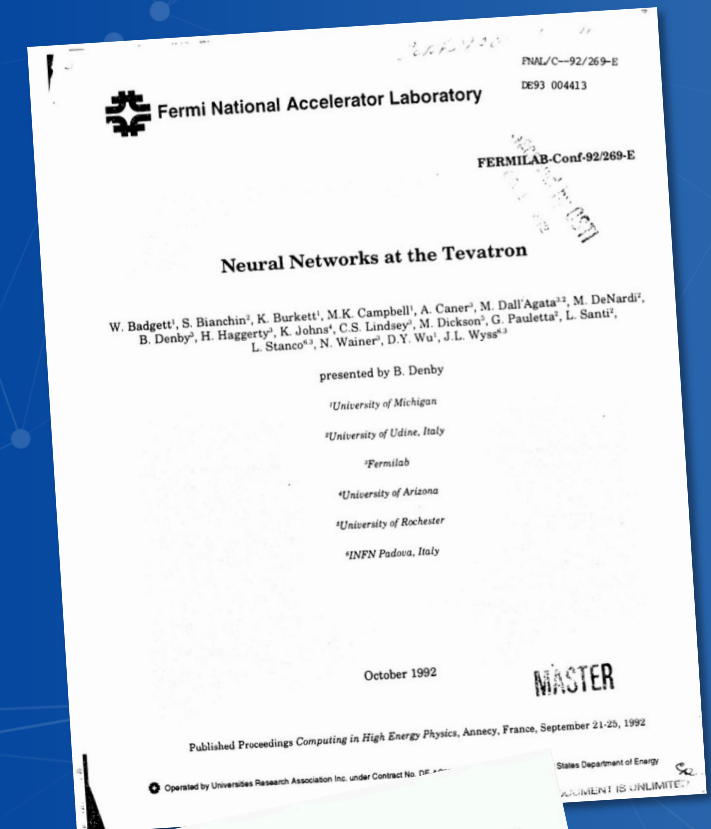


Particle Physics

July 22nd, 2026

Machine Learning in High Energy Physics

- Machine learning has been used in high energy physics for decades, although it was not always referred to as machine learning.
- First adopted in the mid 1990s during the LEP era.
- Played a key role in the discovery of single top quark production by the DØ and CDF collaborations at the Tevatron.
- Shallow Neural Networks have also been employed for specific analyses or Boosted Decision Trees (BDTs) have traditionally been the most widely used algorithms.
- ML models are used to distinguish signal events from background processes.
- Key role in the discovery of the single top quark production at CDF and DØ.
 - DØ: Phys Rev Lett 98, 181802 (2007)
 - DØ: Phys. Rev. D 78, 012005 (2008).
 - CDF: Phys. Rev. Lett. 101, 252001 (2008)

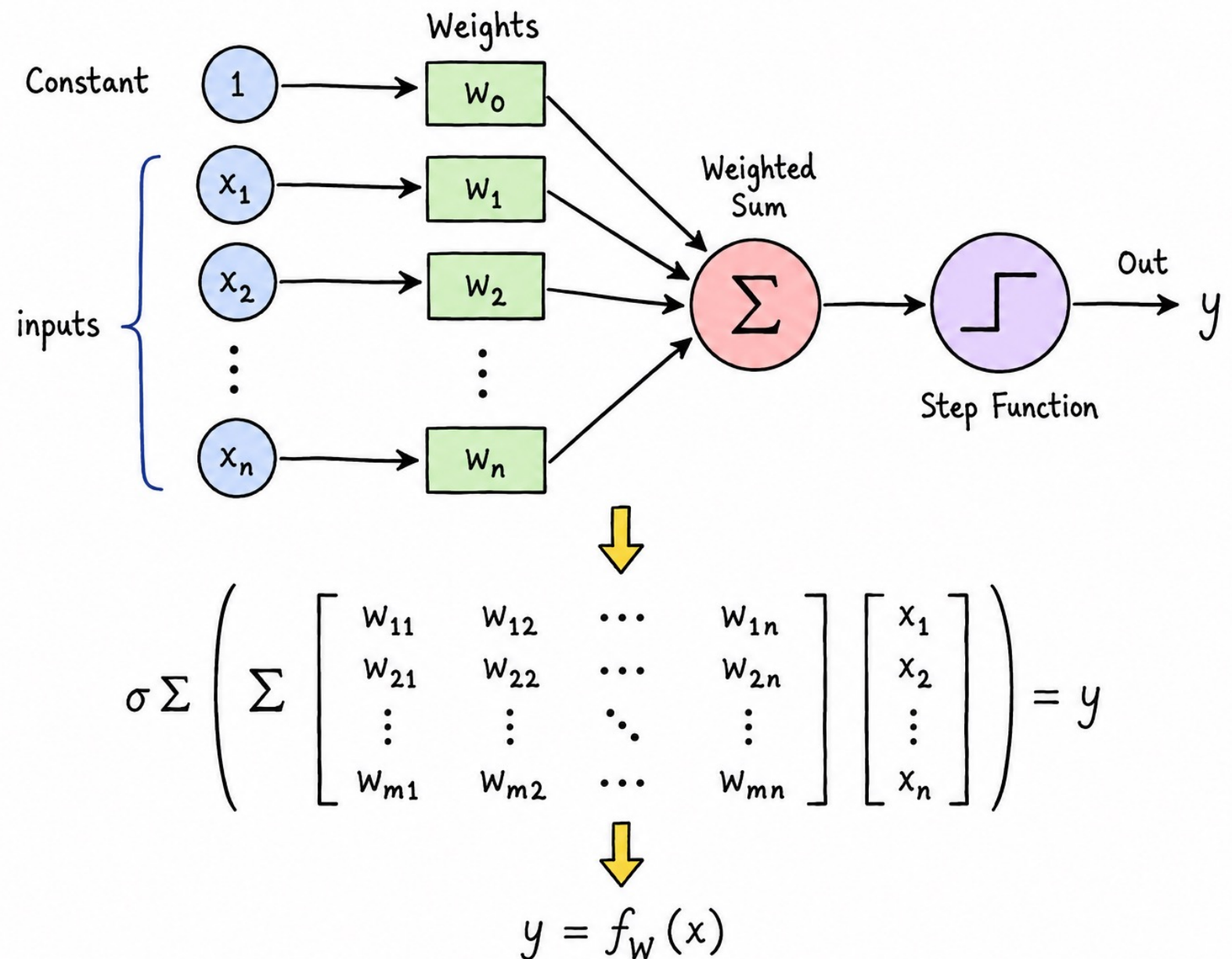


ML is NOT Magic

Perceptron: the foundational building block of artificial neural networks, deep learning relies entirely on simple algebra

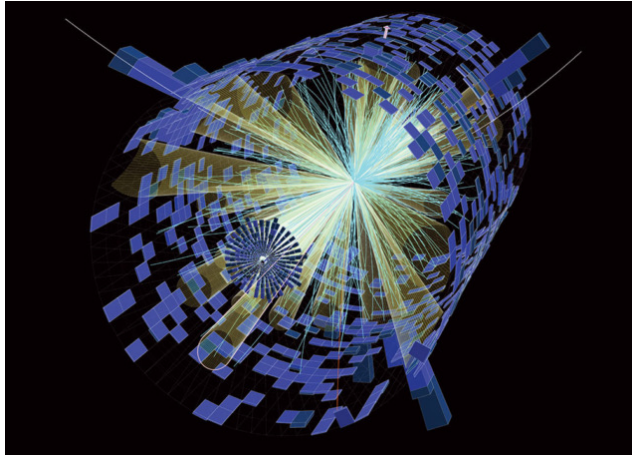
Each individual node as its own linear regression model, consisting of input data, weights, biases (or thresholds), and outputs.

The goal is to get a function that minimizes the difference between y and y_{truth}

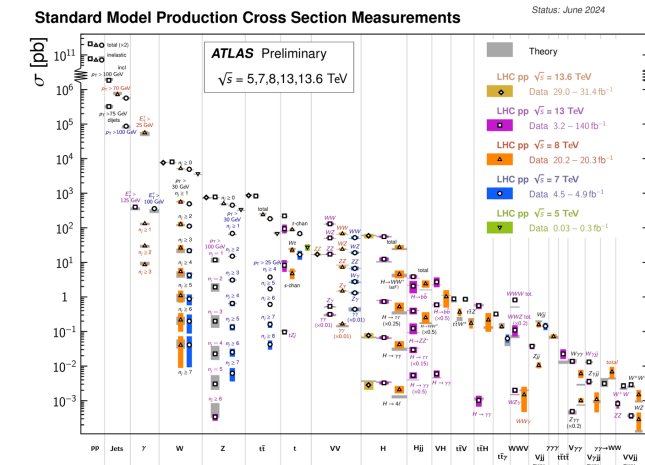


Why ML for High Energy Physics?

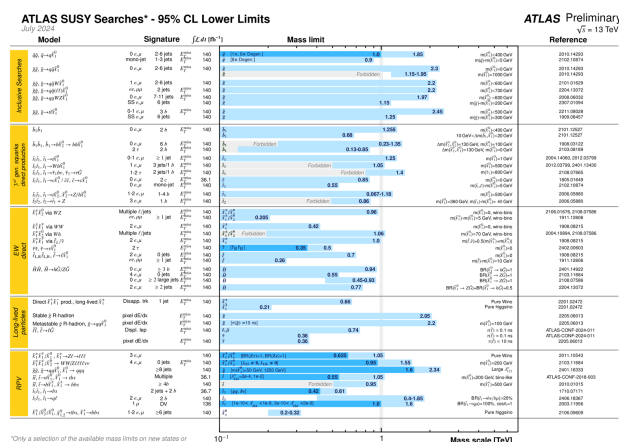
Complex Pattern Recognition



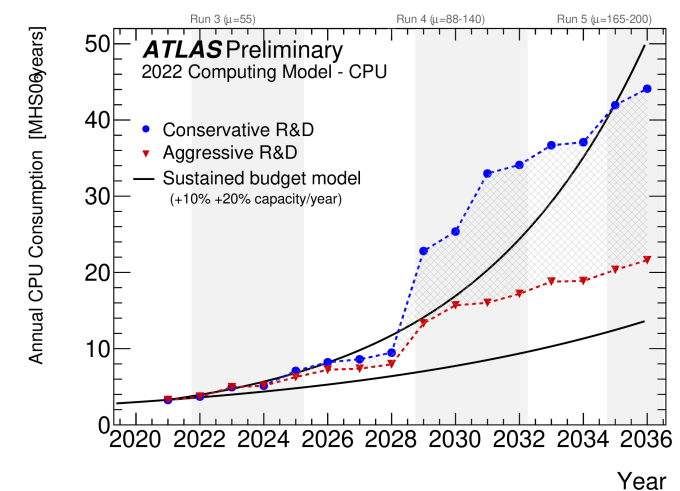
Improve Measurement Precision



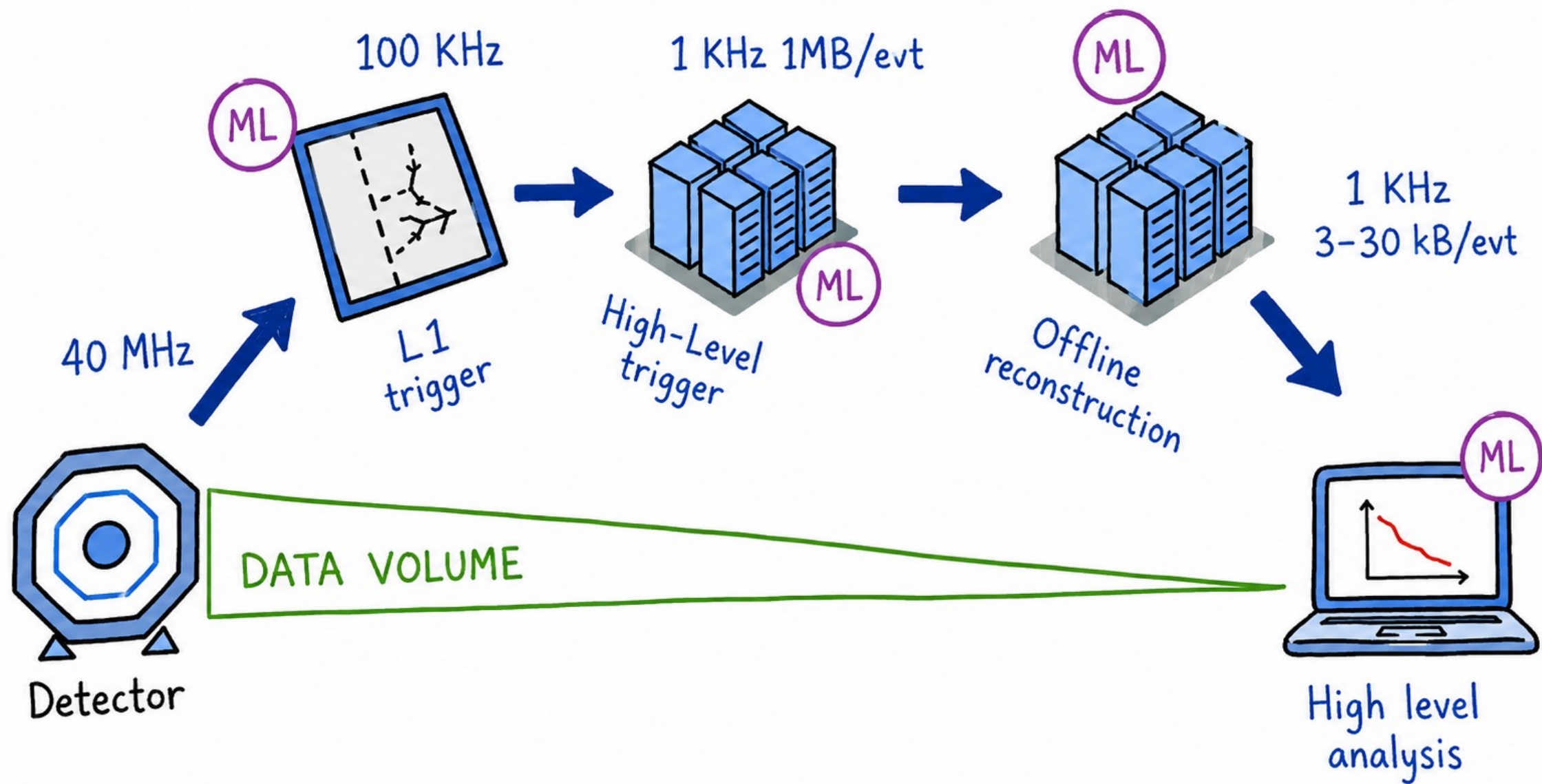
Extend New Physics Searches

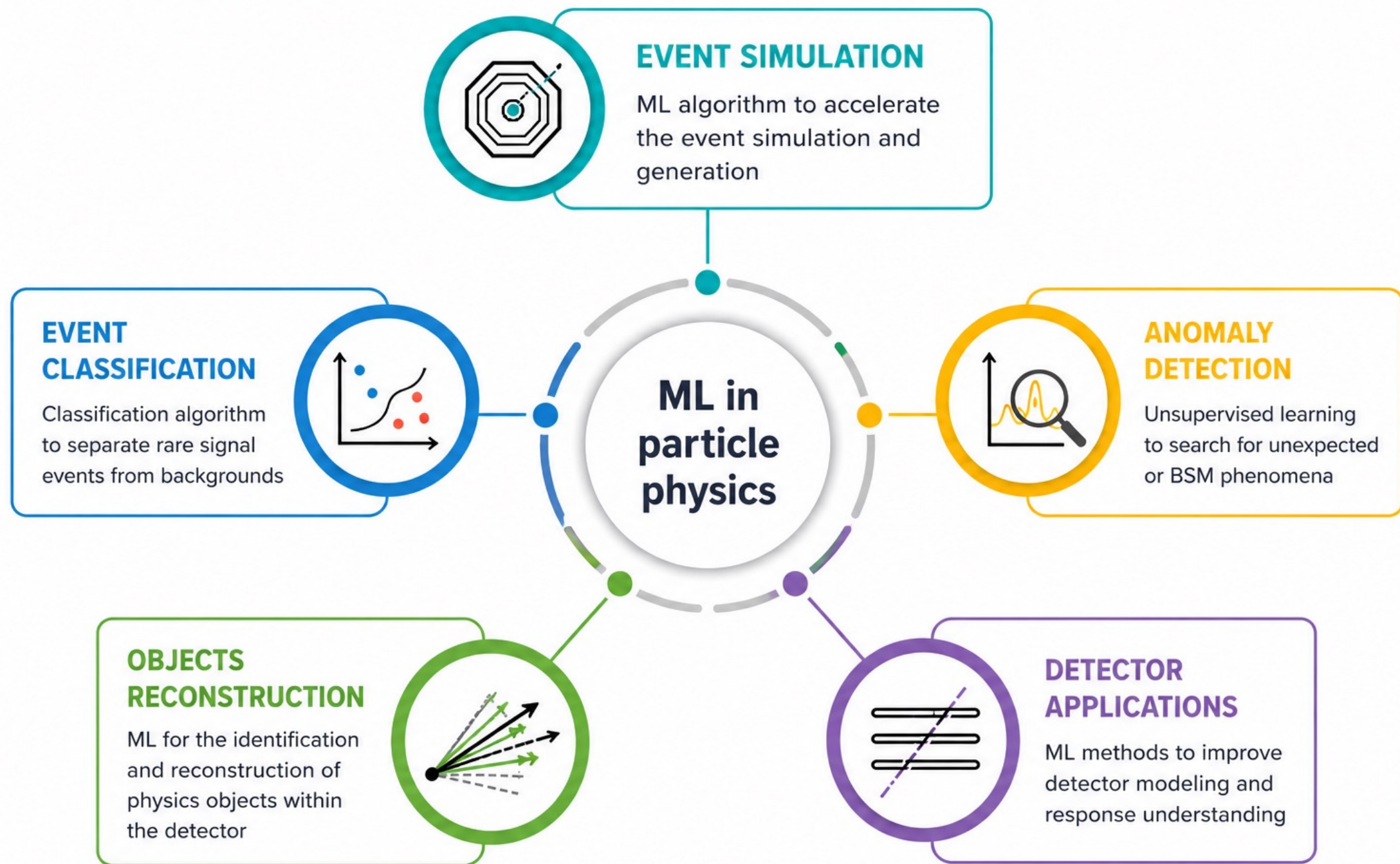


Reduce Resource Demands



Experiment Data Flow



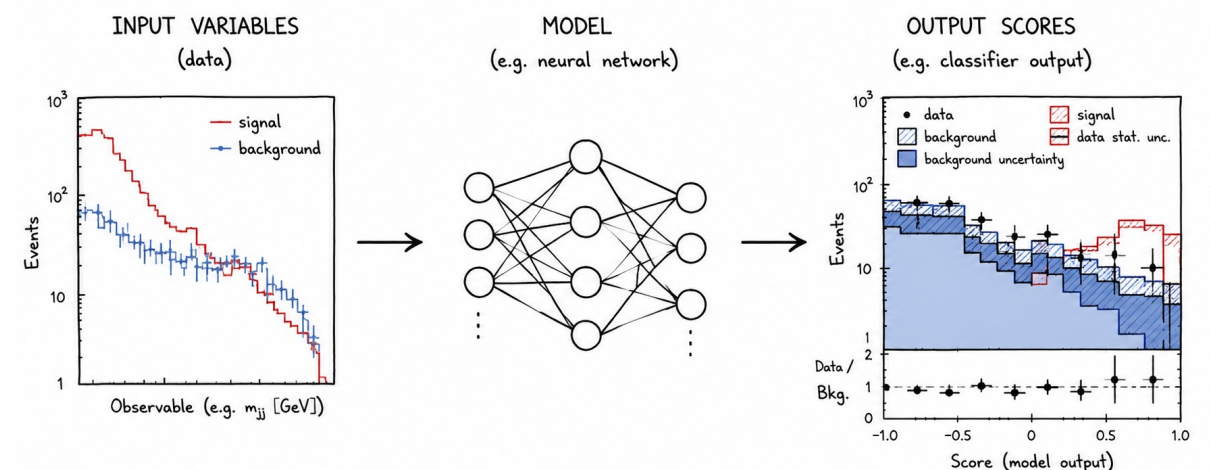
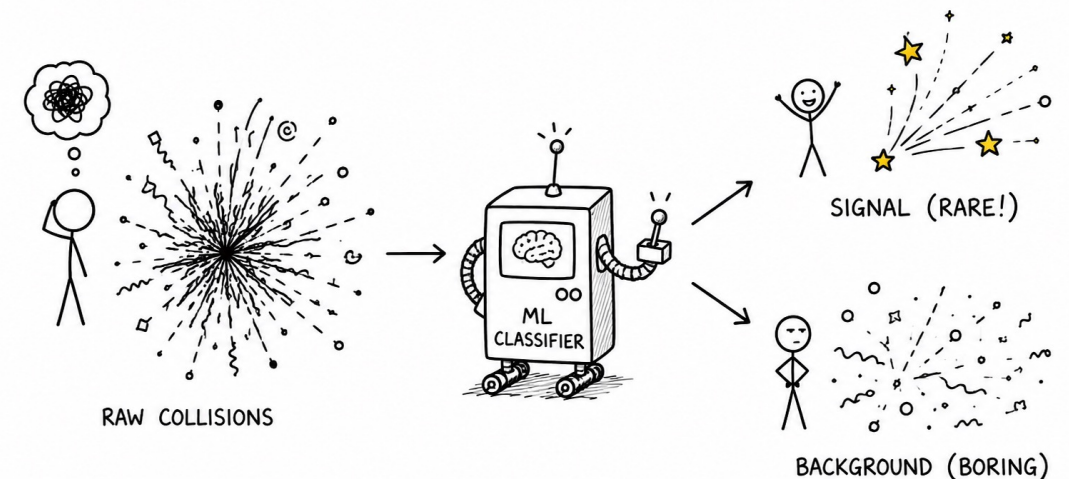




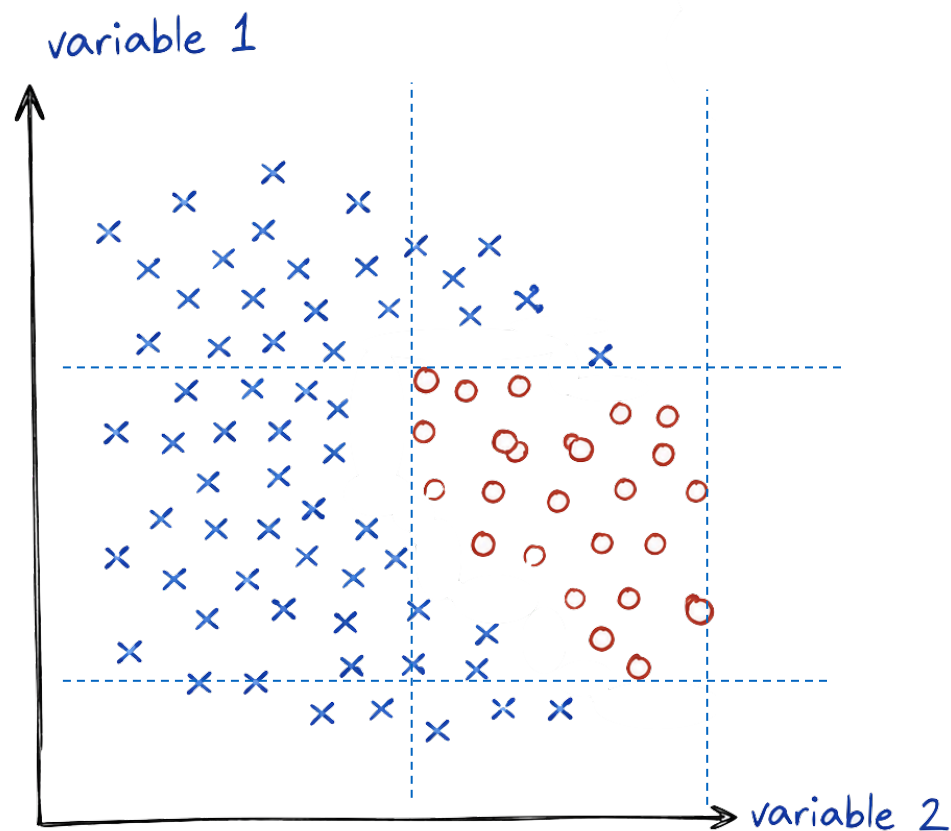
Event Classification

- Two main general use cases:
 - Classification:** Separating different classes of data (e.g. signal vs background), outputs are classification scores
 - Regression:** Compute underlying variables, outputs are estimations of their values
- Different metrics for assessing model's performance:
- Classification:**
 - Most common looking at ROC Curves (Receiver Operating Characteristics)
 - Also, Precision and Recall which can be more useful for imbalanced classes
- Regression:** Mean Absolute error, Root Mean Square error etc

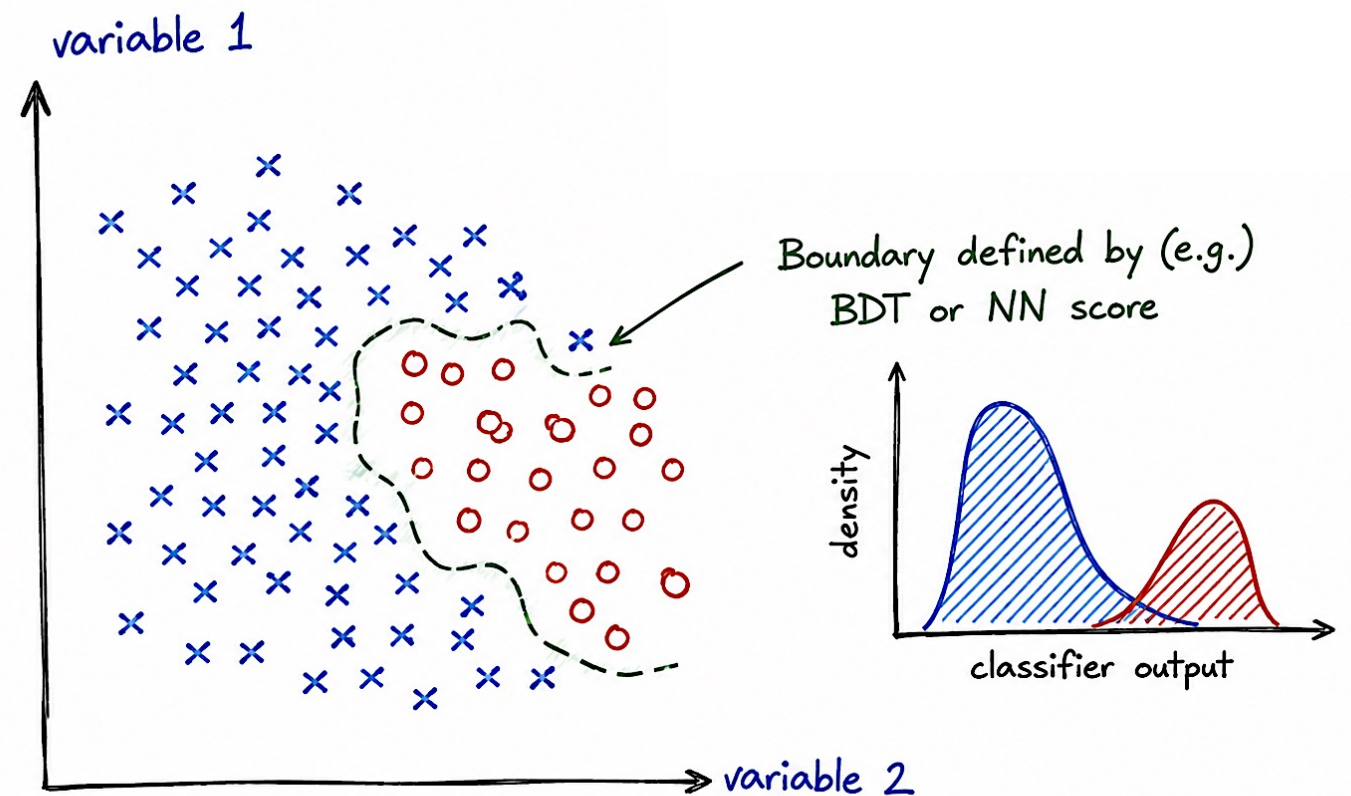
EVENT CLASSIFICATION



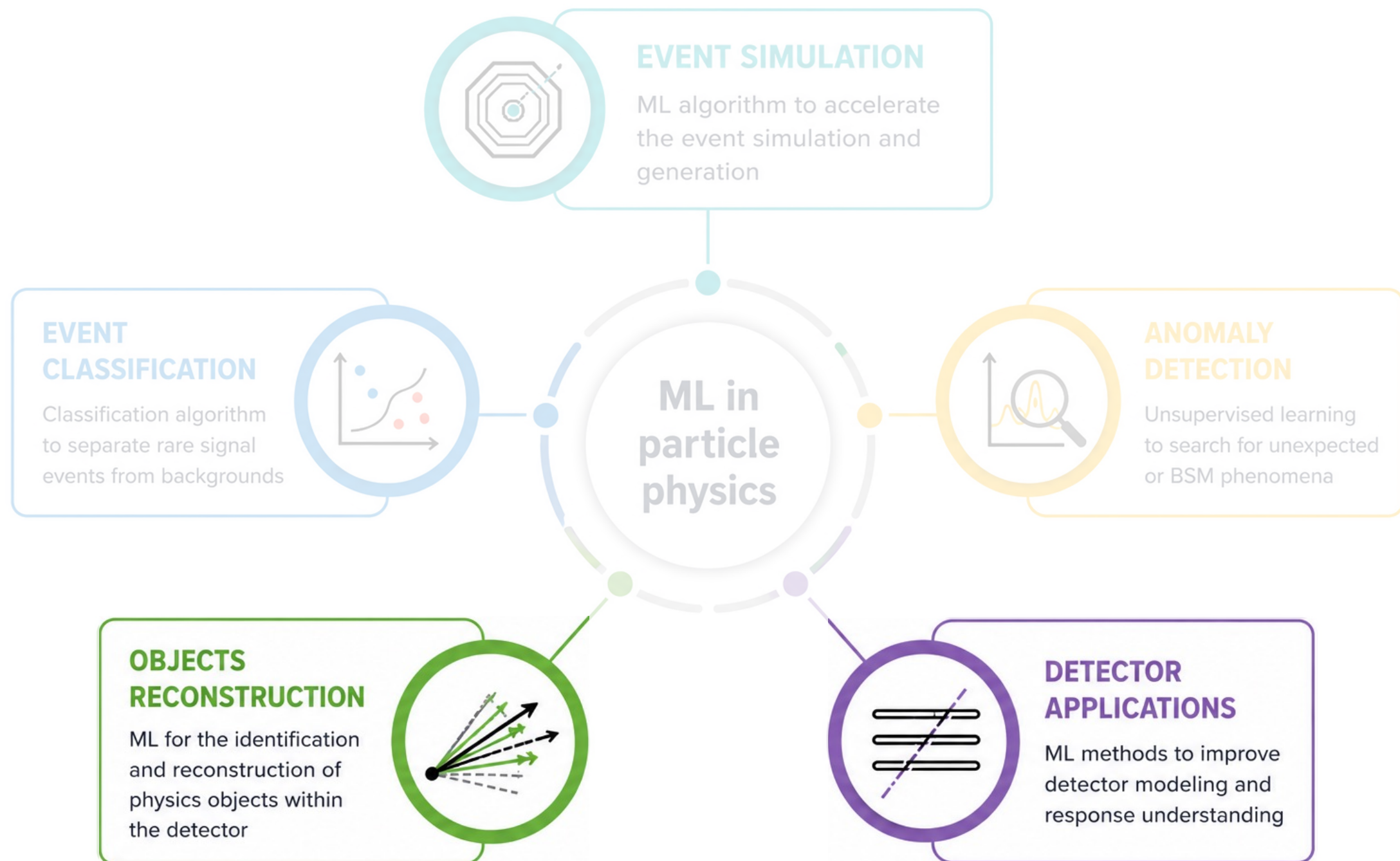
Event Classification



- Traditional way to do analysis: rectangular cuts applied over the variables
- Thresholds tuned using Monte Carlo samples (signal and background) to maximize the signal content



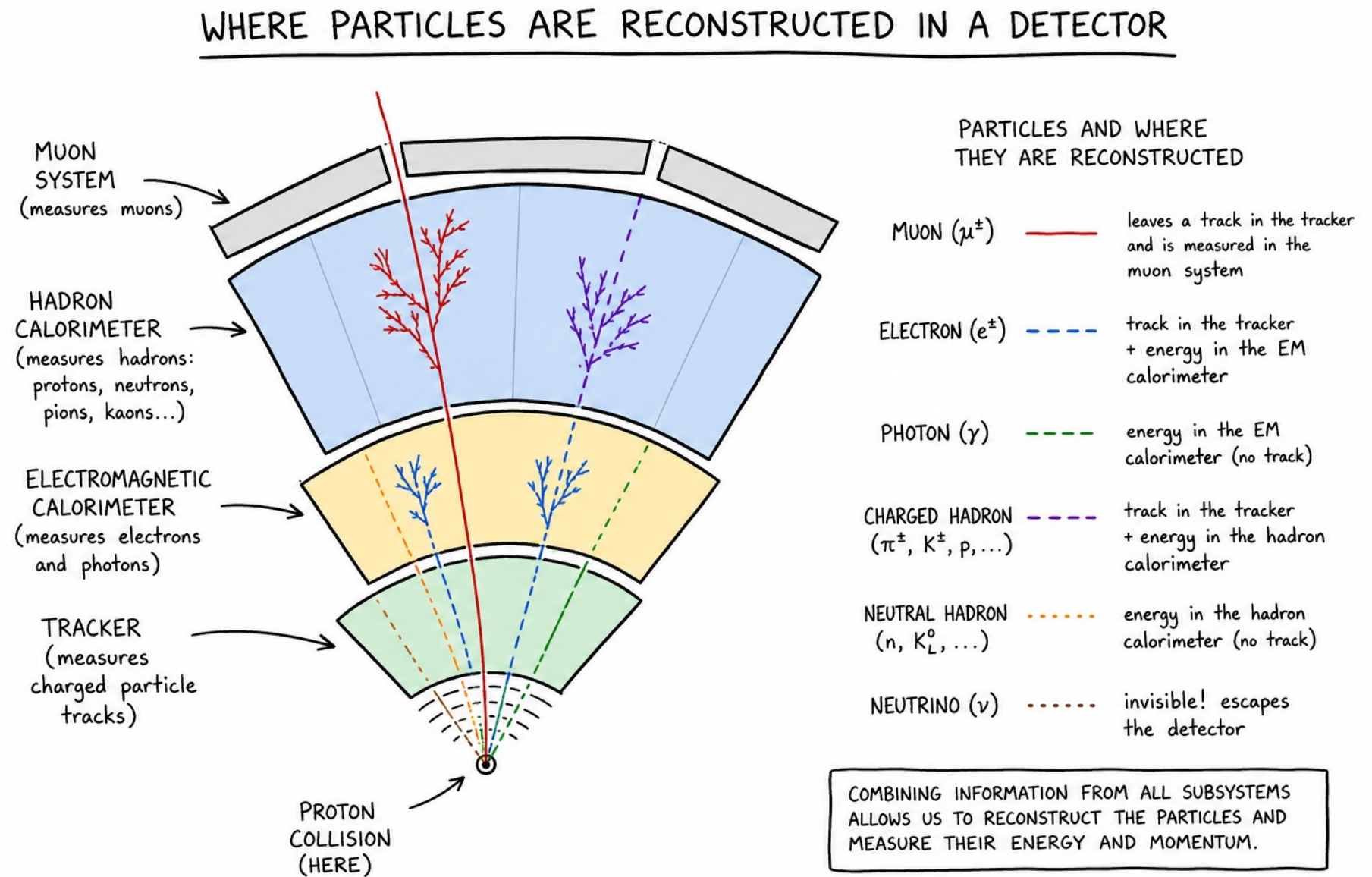
- Multivariate methods using N relevant variables as input
- Training performed maximizing signal vs background.
- The output of the training becomes the selection cut



Event in a Particle Physics Detector

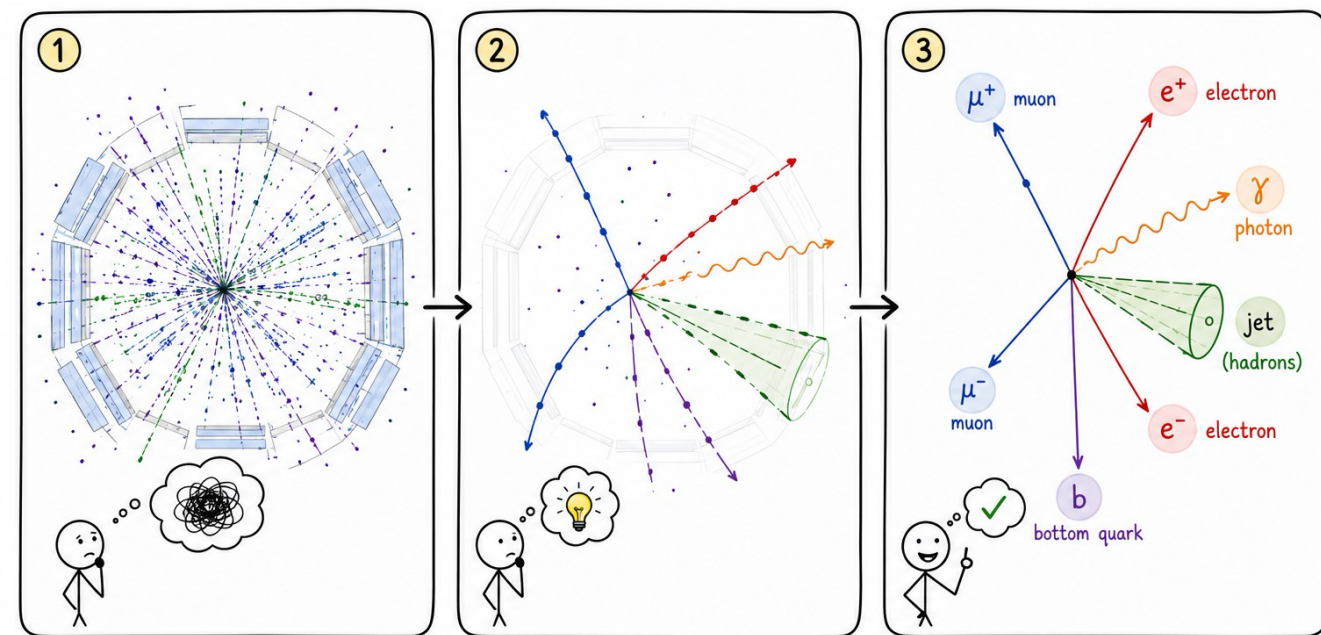
- Identify collision vertices and particles:
- Track-finding
- Electron/jet/muon ID/reconstruction
- Measure energy, momenta, charge
- Jet flavour
- Signal topology

ML is key in many of these tasks



Object Reconstruction and Detector Applications

- Transform detector signals into high level physics objects such as electrons, muons, photons, jets, and missing transverse momentum.
- Improve particle identification by combining information from multiple detector subsystems.
- Enhance detector calibration and alignment for more accurate energy and momentum measurements.
- Accelerate reconstruction algorithms, enabling near real time event processing.
- Optimize trigger decisions, selecting the most interesting collisions within strict latency constraints.
- ...

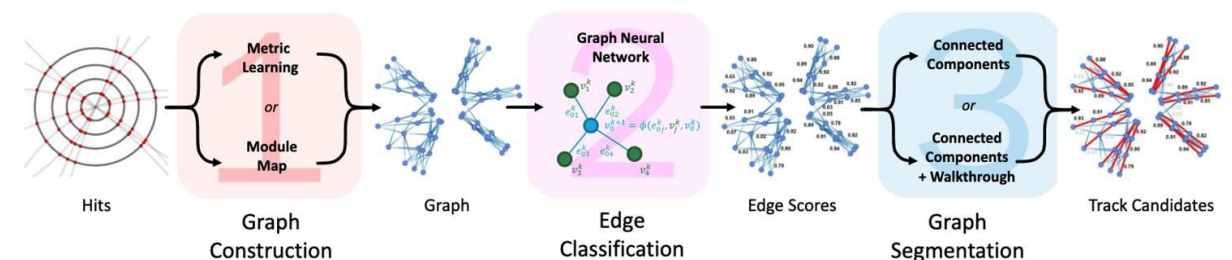


Track Reconstruction

- Track reconstruction is a clustering problem: start with a (large) number of 3D points, identify set of points belonging to a common trajectory
- Combinatorial Kalman Filter considers all combinations of hits:
 - Excellent efficiency & purity
 - CPU performance scales very badly with increasing # of hits
- Solutions for LHC (1k hits per event not applicable later (HL-LHC, FCC))

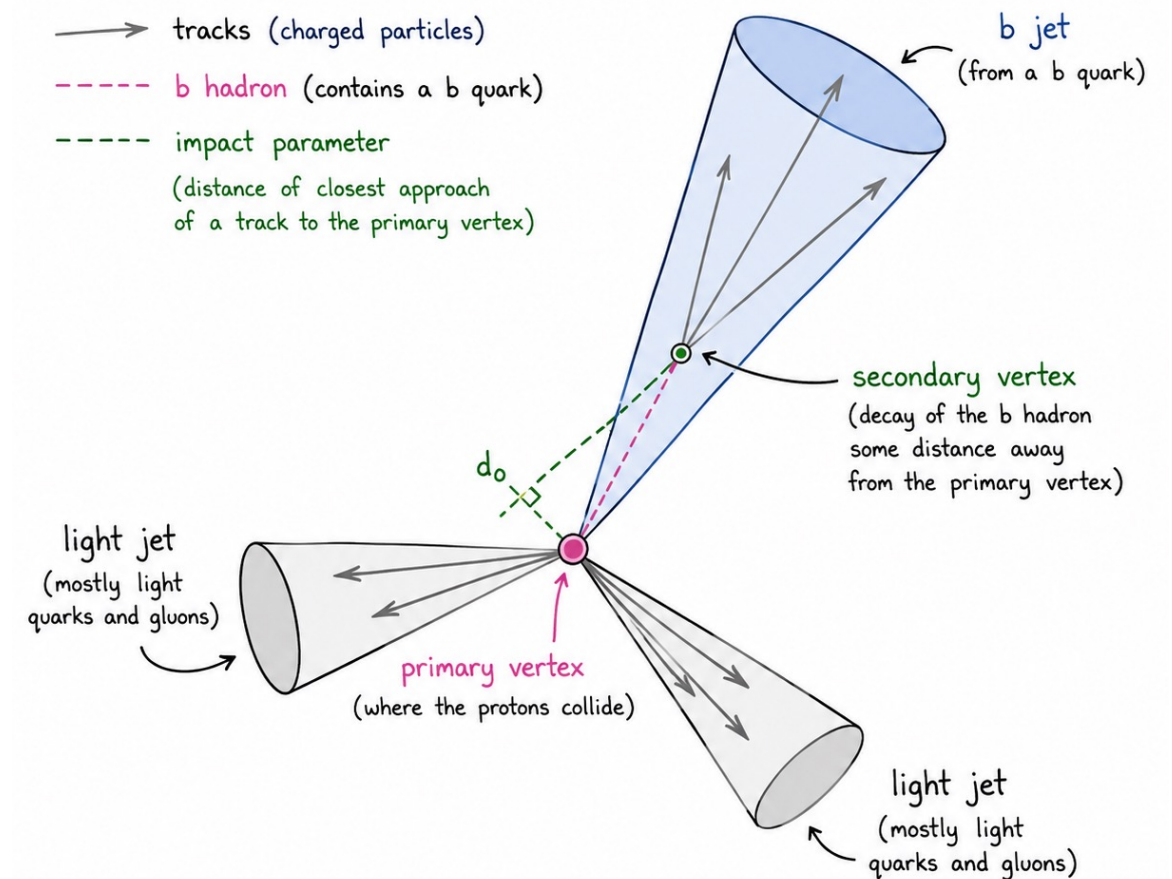
Build a **Graph Neural Networks (GNN)** using k-nearest neighbours to define the graph connectivity

GNN converts collection of hits into a graph: nodes correspond to hits, edges to probability that hits belong to same track



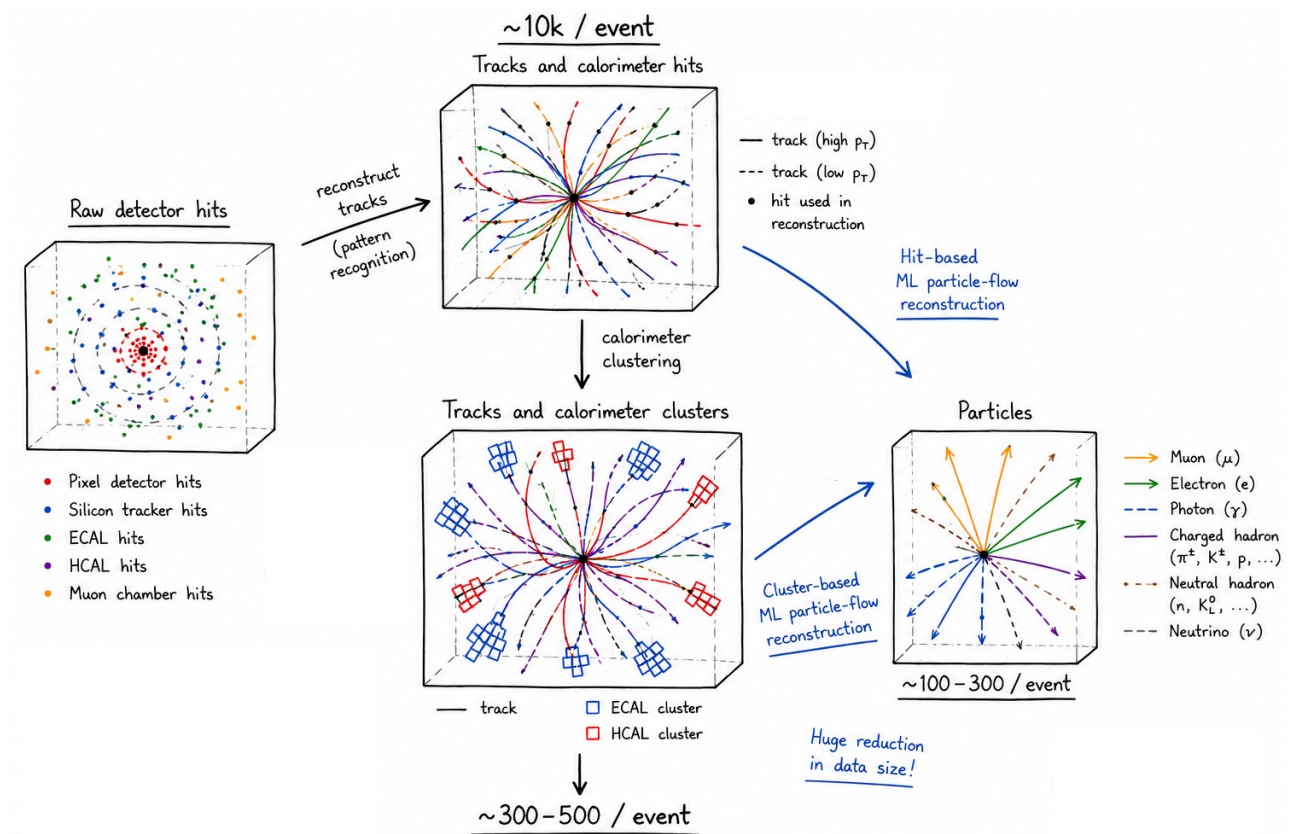
Flavor Tagging

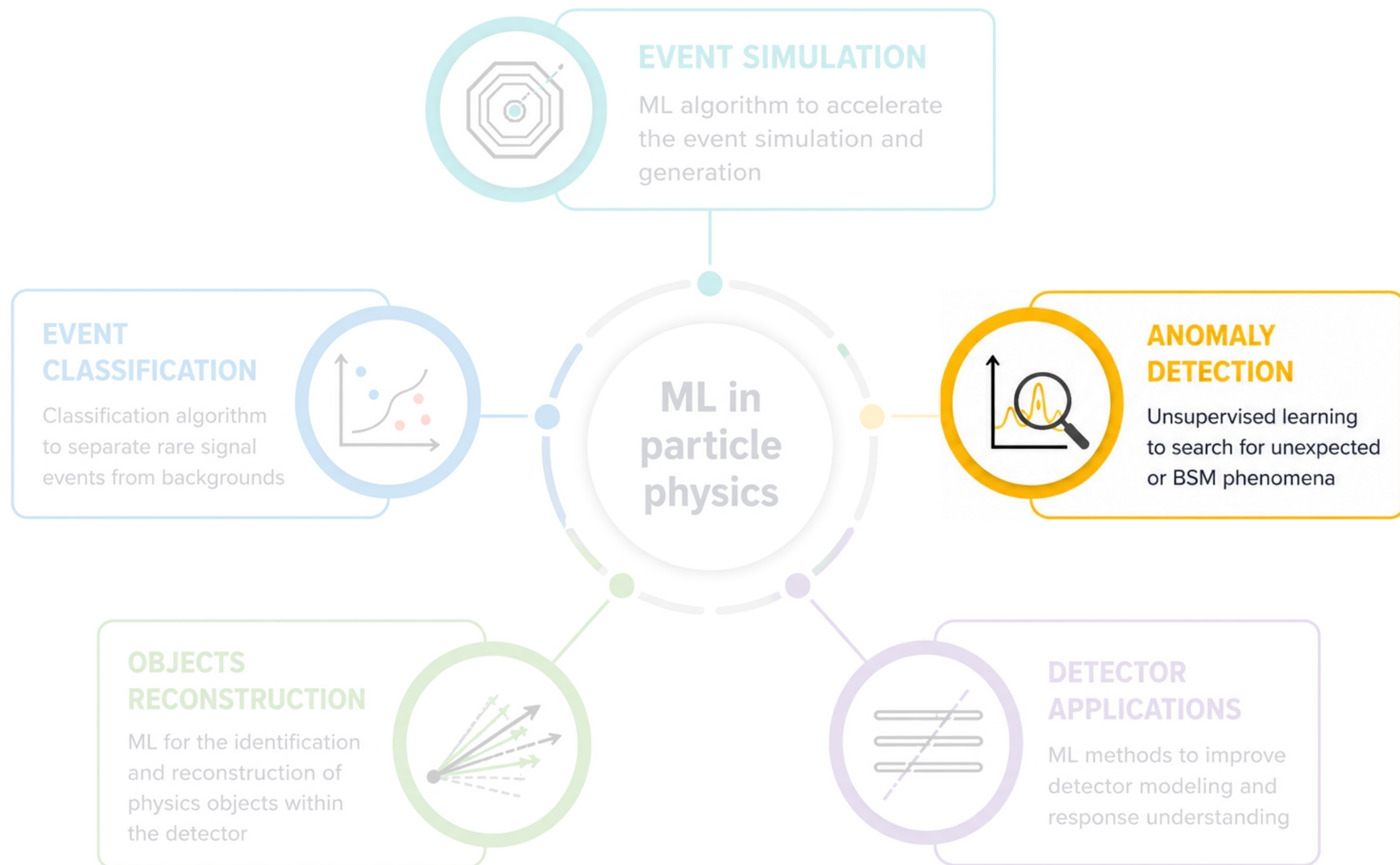
- Essential ingredient for many physics analysis (top, Higgs...)
- Per-jet probability of originating from {b, c, uds} quarks
- Explore unique characteristics of heavy flavour-jets
 - “Large” lifetime of b/c-hadrons ($\sim$ ps)
 - Displaced secondary vertex
 - Soft lepton from b/c hadron decay



Particle Flow

- Combines information from the tracker, calorimeters, and muon system.
- Reconstructs individual particles rather than isolated detector signals.
- Links charged particle tracks to calorimeter energy deposits.
- Produces a complete list of Particle Flow candidates (electrons, muons, photons, charged and neutral hadrons).
- Improves the reconstruction of jets, missing transverse momentum (MET), and event energy resolution.
- Reduces the impact of pile up by exploiting the tracker information.



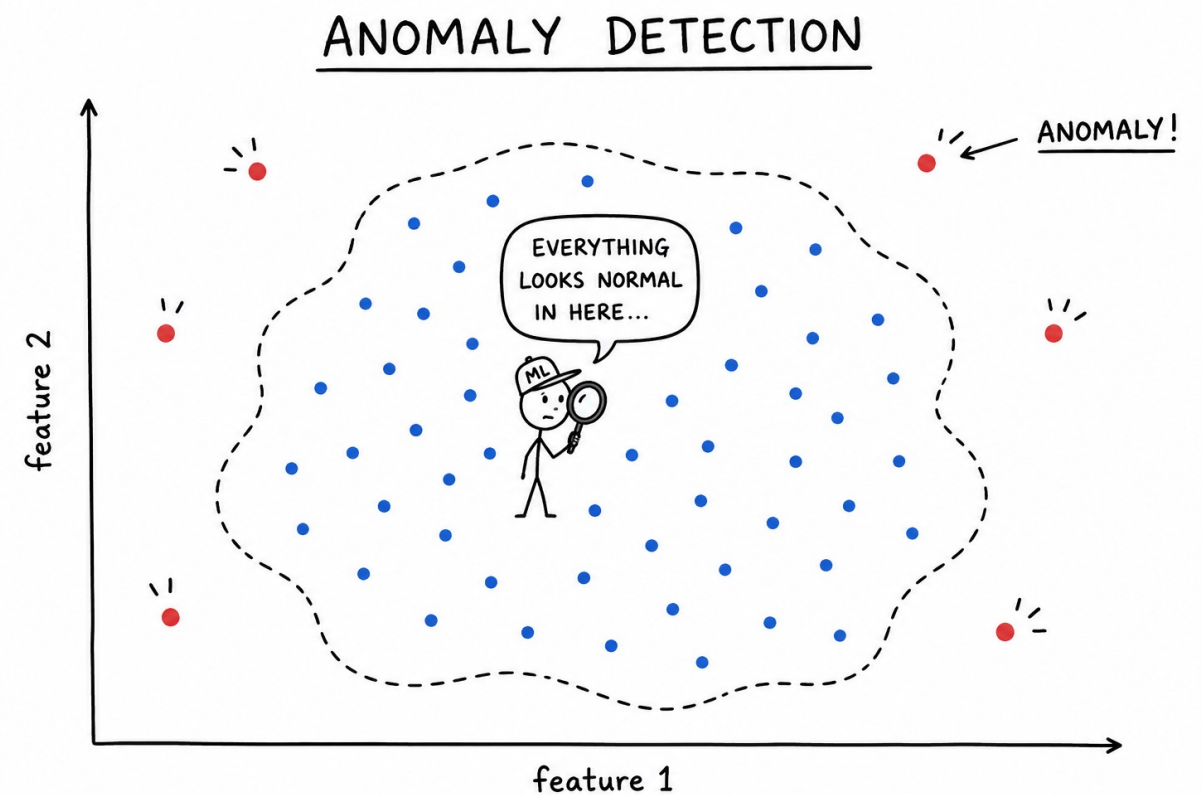


Anomaly detection in the search for New Physics

A primary LHC goal remains to search for new Physics:

no sign of New Physics so far!... ML used in direct searches, classifiers trained to recognise specific signals

Anomaly detection addresses looking for new physics in a different way:



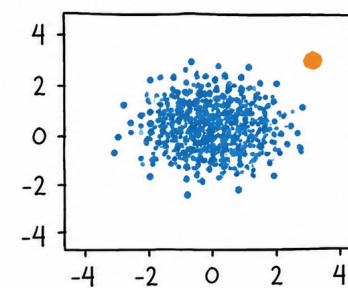
Anomaly detection in the search for New Physics

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no sign of New Physics so far!... ML used in direct searches, classifiers trained to recognise specific signals

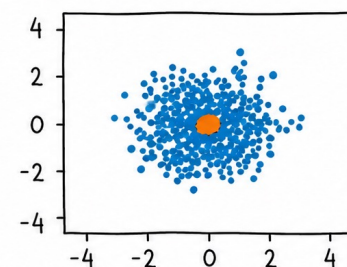
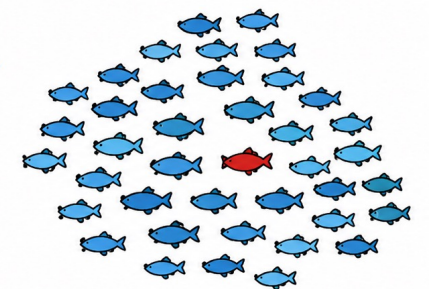
Anomaly detection addresses looking for new physics in a different way:

- Search for unexpected signatures without assuming a specific model of new physics.
- Learn the behavior of Standard Model events and identify collisions that deviate from expectations.
- Explore model independent searches, increasing sensitivity to unknown phenomena.
- Leverage unsupervised and weakly supervised learning to discover potential signals beyond the Standard Model.
- Several initiatives to use AD at Trigger Level: AXOL1TL and CICADA (CMS), and GELATO (ATLAS)



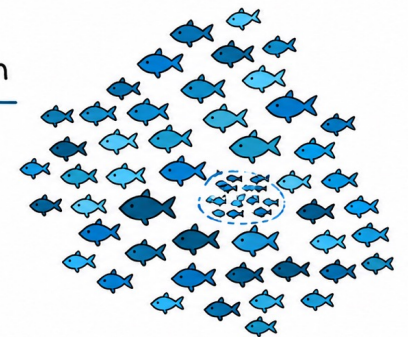
Outlier Detection

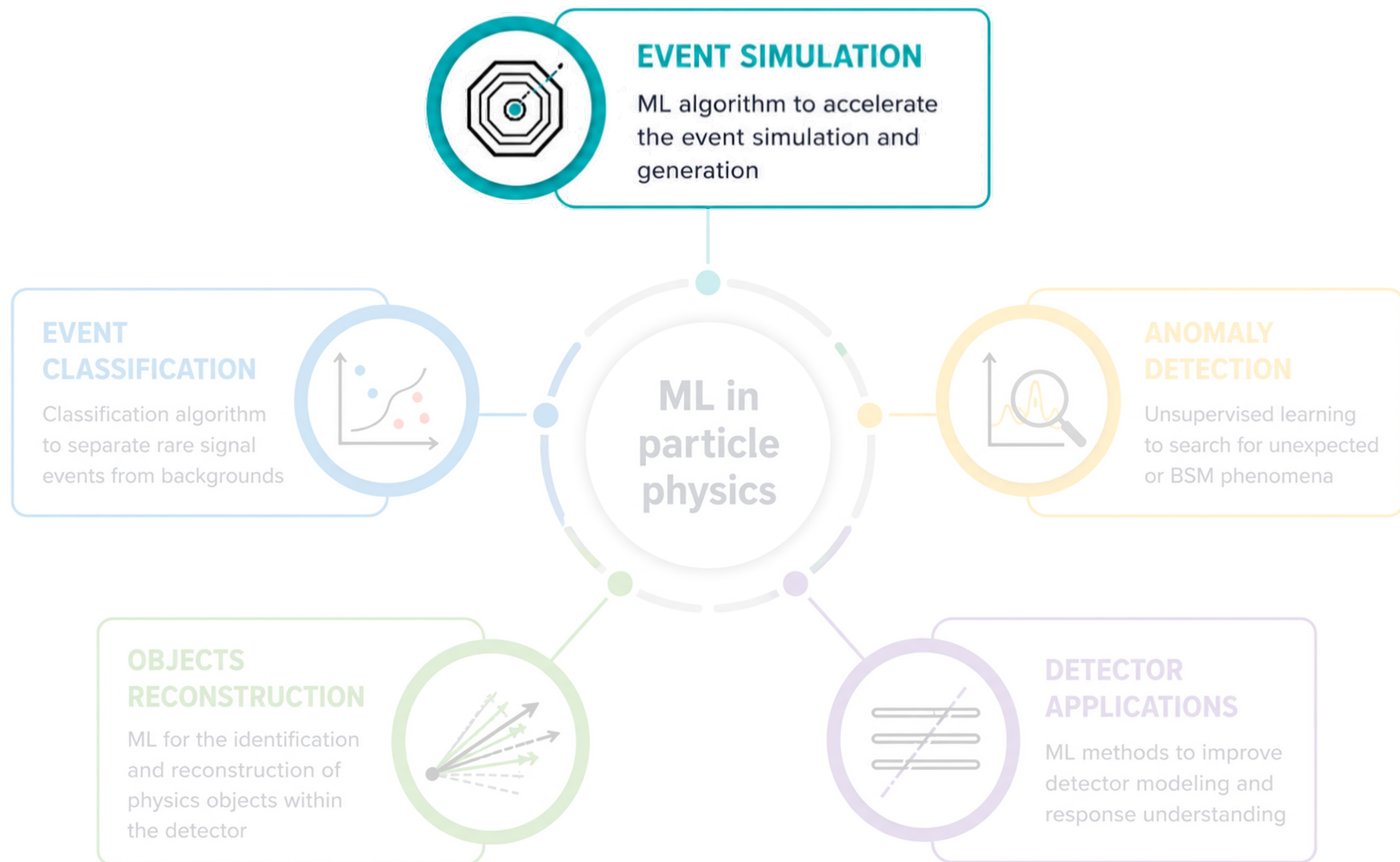
- Searching for unique or unexpected events
- In HEP, this is the tails of distributions or uncharted phase space



Overdensity detection

- Analogous to the traditional bump hunting



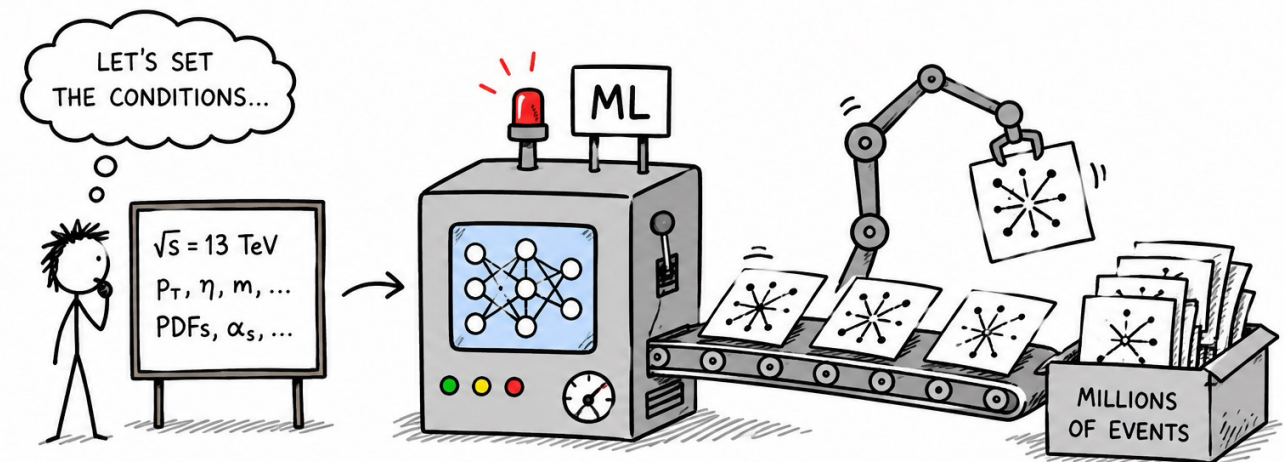


Monte Carlo Simulation

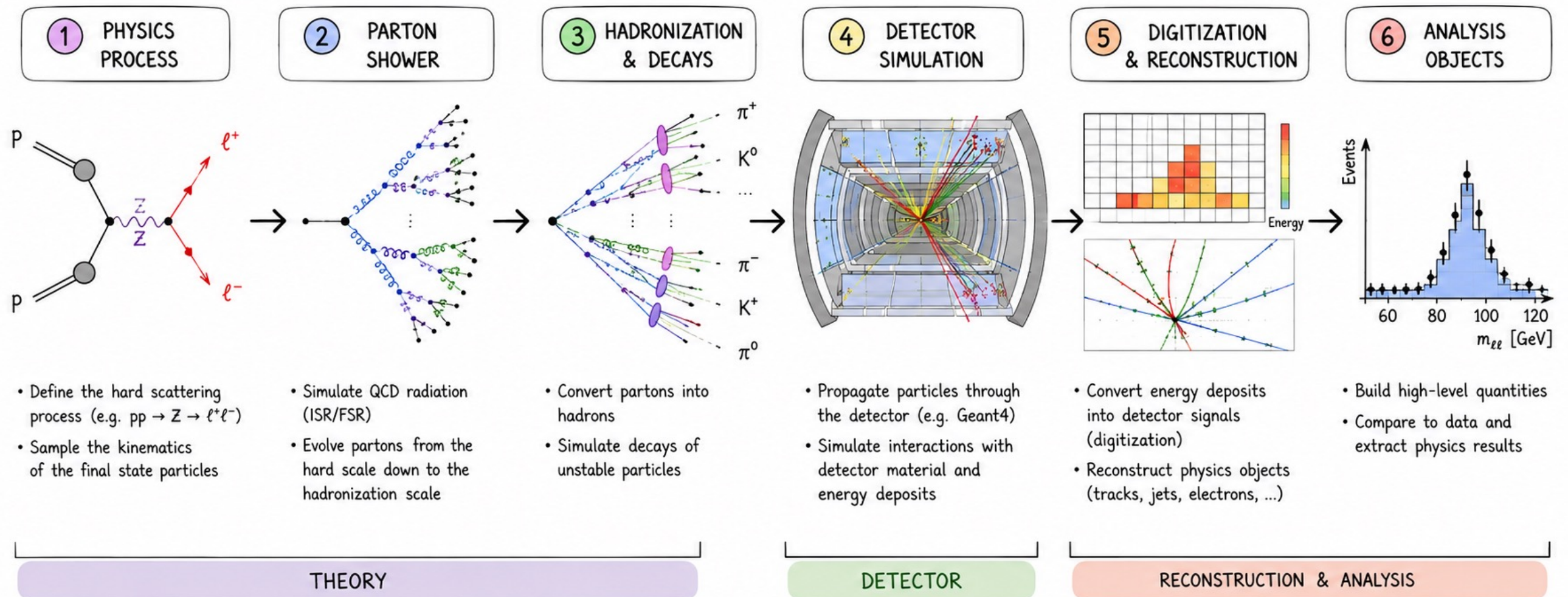
- Fast event generation for signal and background processes.
- Fast detector simulation as a surrogate for detailed Geant4 simulations.
- Large scale Monte Carlo production for detector studies and physics analyses.
- Generative AI models for realistic, high fidelity event simulation.

EVENT SIMULATION

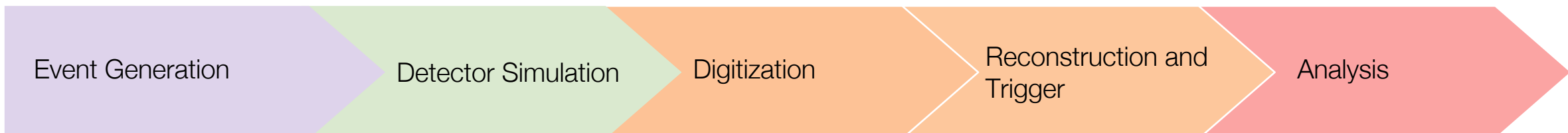
Make (fake) particle collisions ... really, really fast.



Monte Carlo Simulation



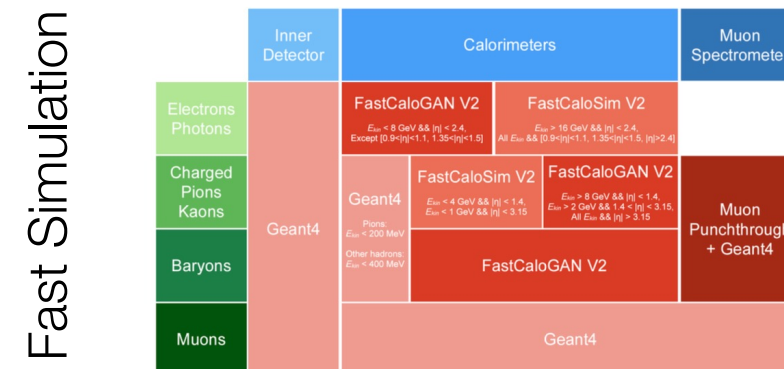
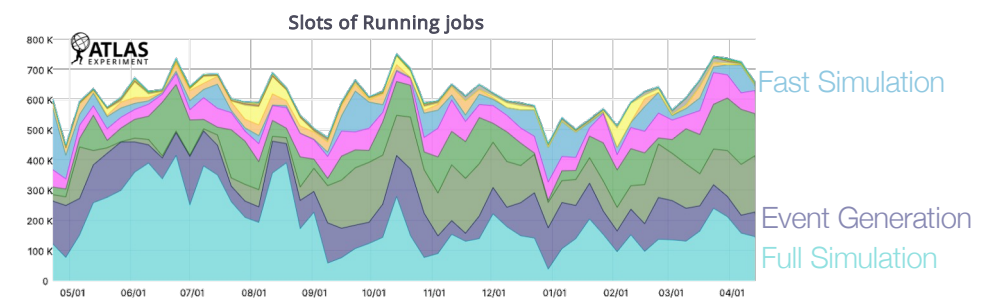
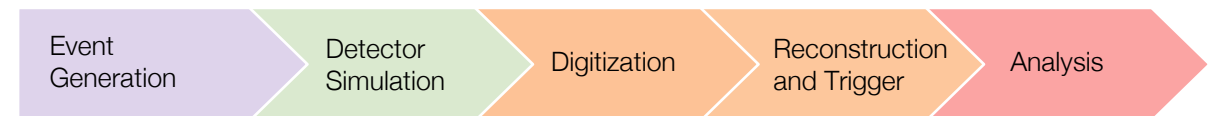
Monte Carlo processing steps



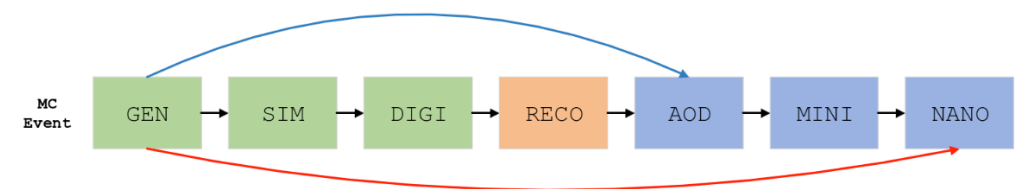
Monte Carlo Simulation

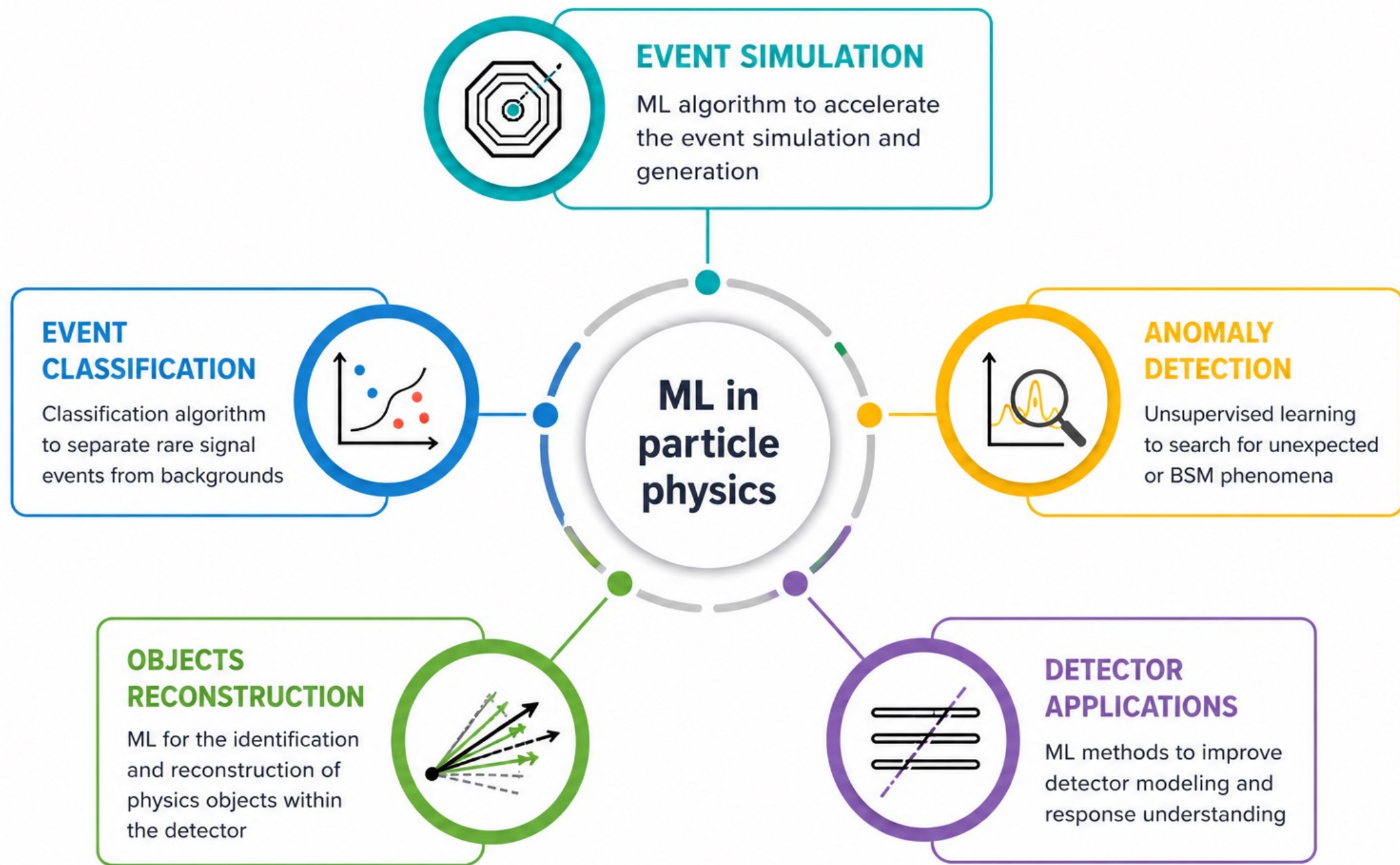
- Event Generators:
 - Increasingly CPU-intensive due to NLO/NNLO and high statistics needs
 - Tools using ML and GPUs like (MadGraph4GPU, PEPPER, ...)
- Detector Simulation:
 - Full Simulation:
 - Performance optimization and focus on GPU-accelerated GEANT4, including projects such as AdePT or Celeritas
 - Fast Simulation:
 - Parametrized or ML (Generative, AutoEncoders) alternatives for time-intensive components
 - Ultra Fast Simulation
 - Parameterization of the high level response of the detector can also enable a fast reconstruction.
 - CMS with Flashsim (normalizing flows), LHCb with Lamarr

Monte Carlo processing steps



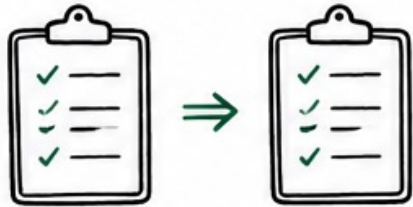
Ultra Fast Simulation





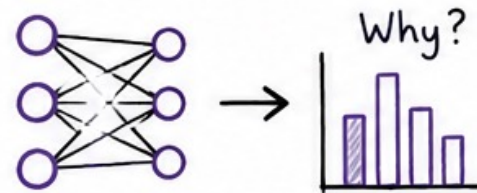
Improvement and performance is not enough ...

REPEATABLE



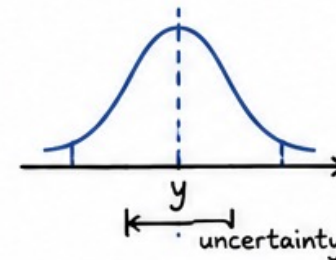
- Results must be reproducible by others, today and in the future.
- Fix seeds, versions, and environments.
- Share code, data, and trained models.

EXPLAINABLE



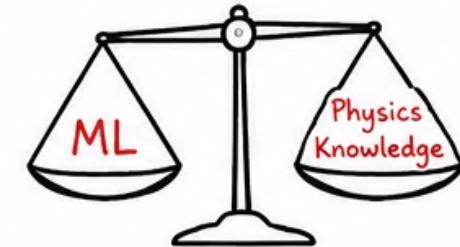
- Understand what the model uses and why.
- Use interpretable models or explainability tools.
- Build trust in the physics conclusions.

UNCERTAINTIES MATTER



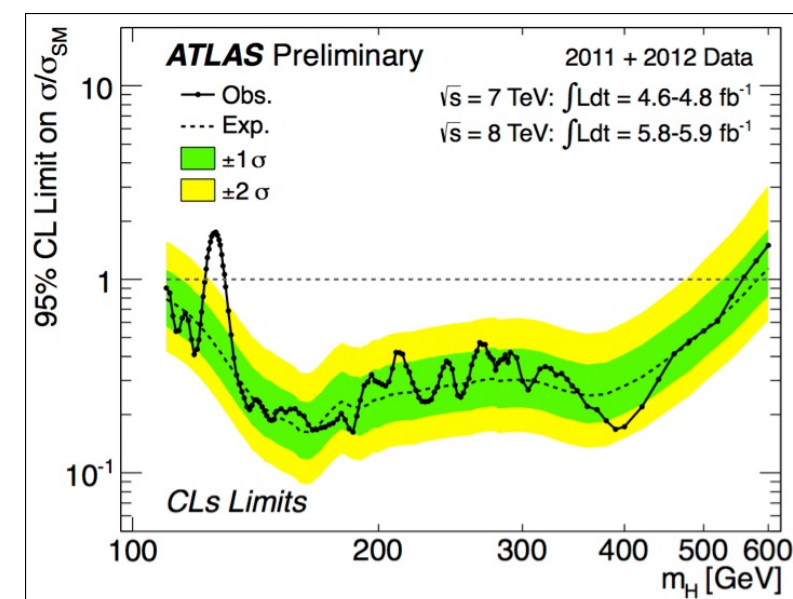
- Predictions must include reliable uncertainties.
- Quantify both statistical and systematic errors.
- Propagate uncertainties to final results.

PHYSICS FIRST



- ML complements, not replaces, physics understanding.
- Validate with control regions and closures.
- Challenge assumptions and check for biases.

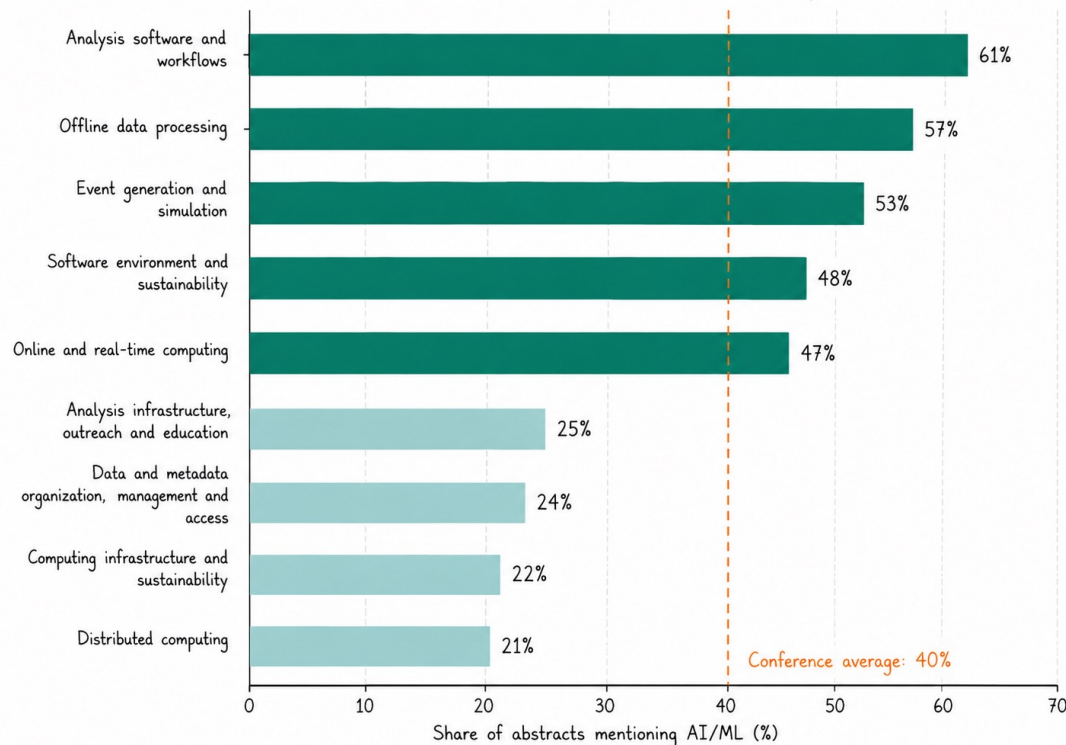
We need this →



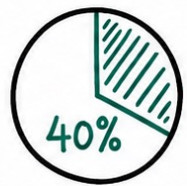
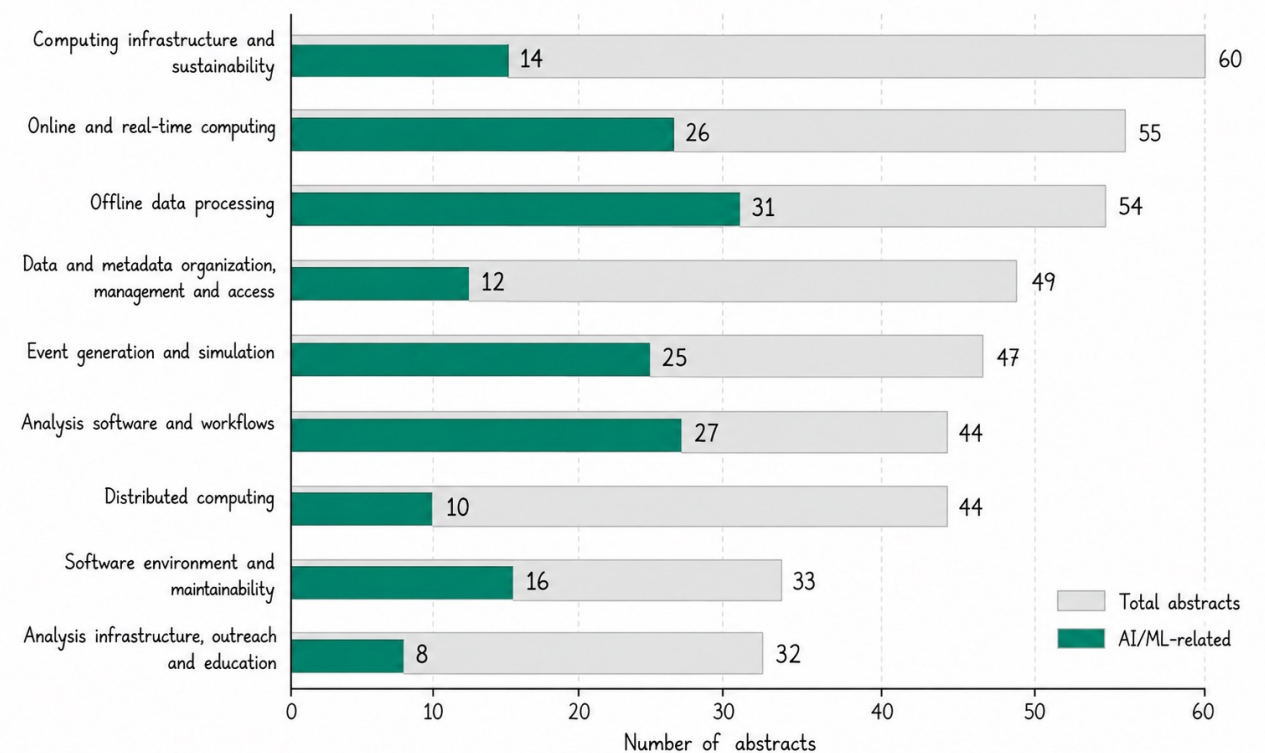
AI/ML is an active topic

Summary of the Conference Computing for High Energy Physics (CHEP 2026)

Share of AI/ML-related abstracts by track



CHEP 2026: Abstracts per track – total vs. AI/ML-related



- 40% of the abstracts had some relation with AI/ML



- All the tracks at the conference had some application of AI/ML



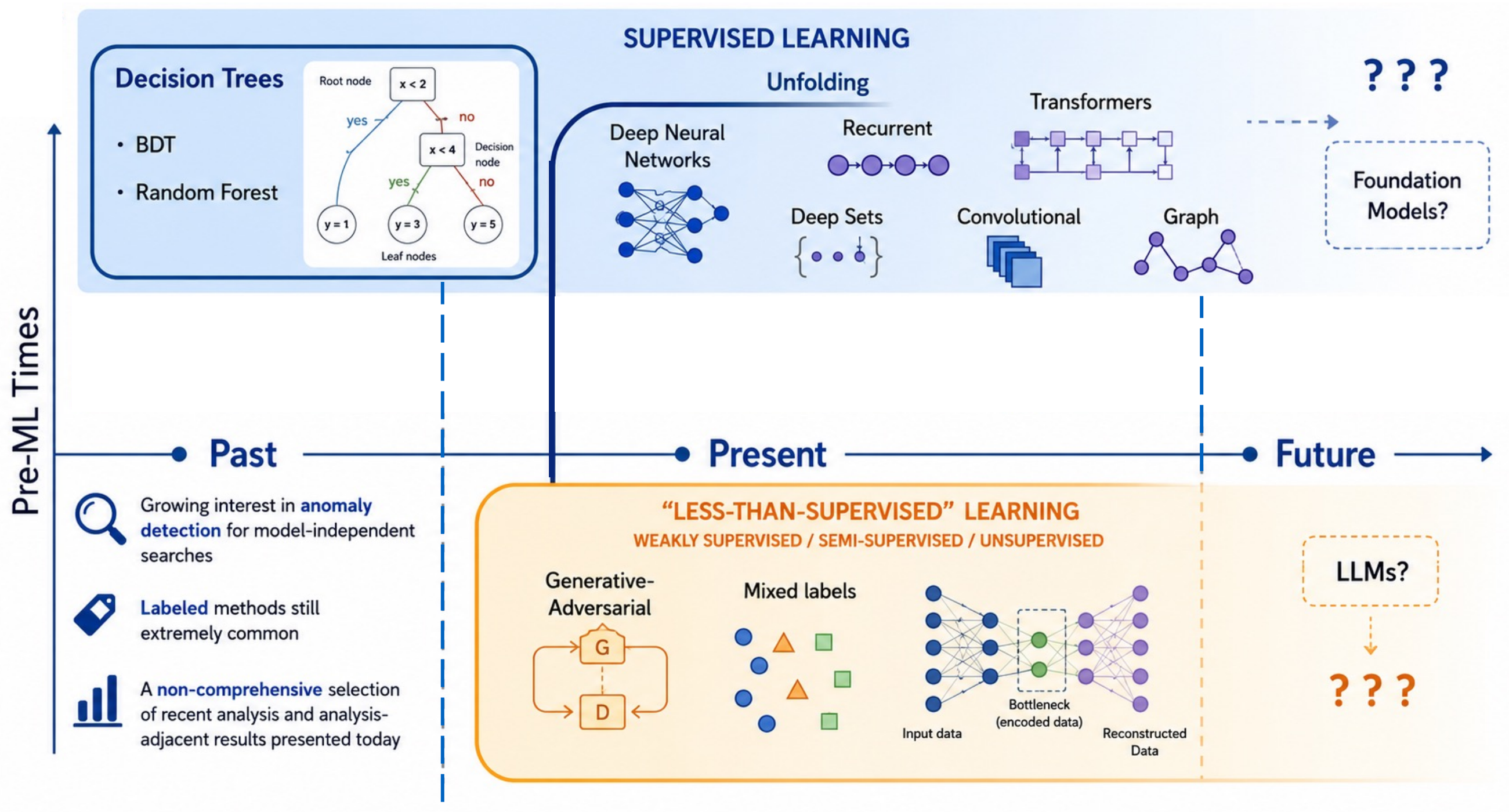
- There are more usages beyond the areas mentioned like:
 - Computing Infrastructure, Online and real time computing, Distributed computing, Metadata organization, ...



Summary ...



Evolution of use of ML in HEP



AI in Particle Physics

Jose Enrique García