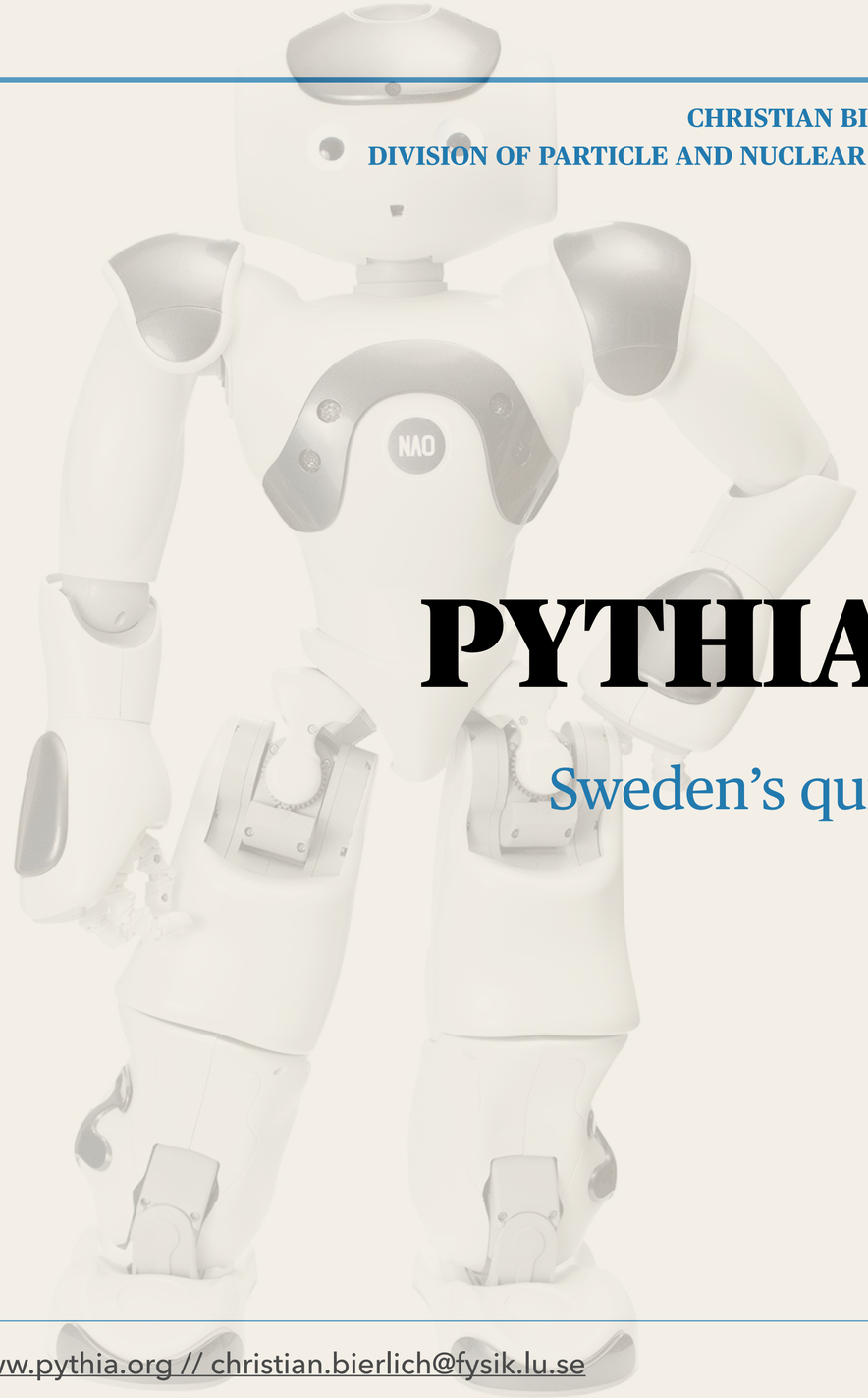
CHRISTIAN BIERLICH, PARTIKELDAGARNA NOV 25 2025, GÖTEBORG
DIVISION OF PARTICLE AND NUCLEAR PHYSICS DEPARTMENT OF PHYSICS, FACULTY OF SCIENCE, LUND UNIVERSITY



PYTHIA in the age of AI

Sweden's quiet particle physics infrastructure

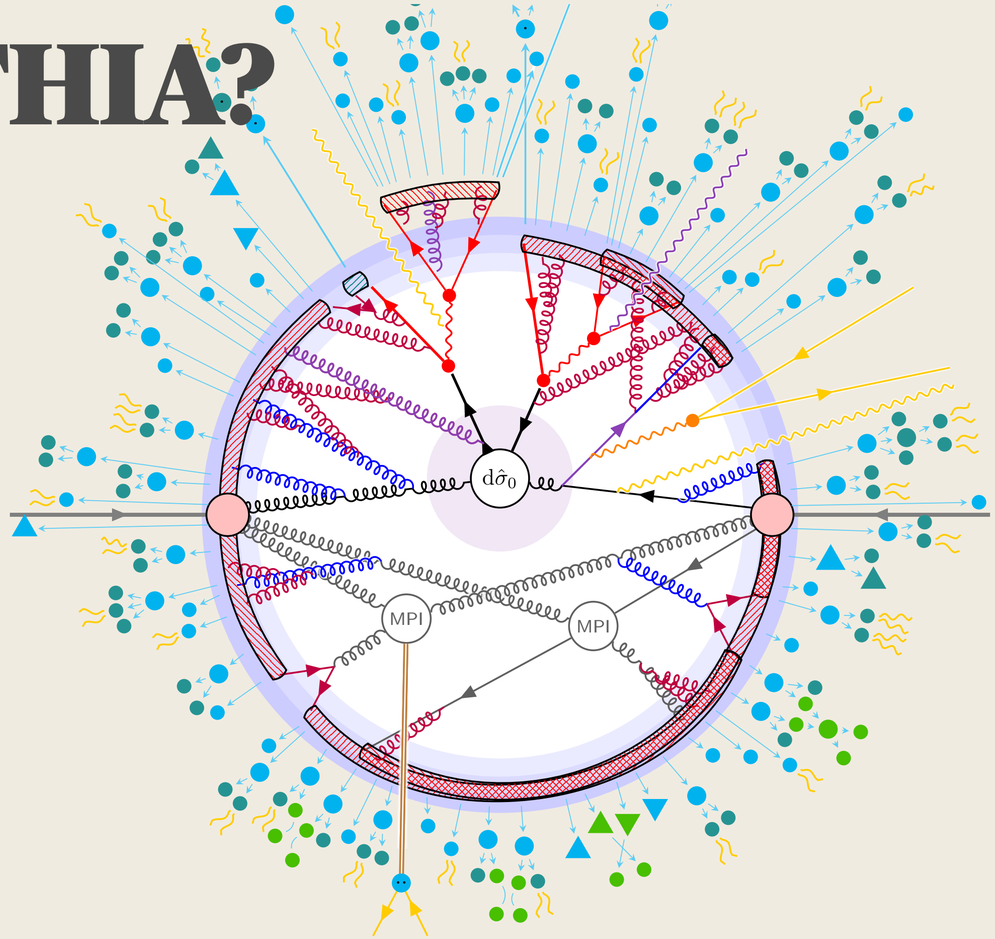
www.pythia.org // christian.bierlich@fysik.lu.se

What is PYTHIA?

- **General Purpose** Monte Carlo event generator.
  - All collision system from e^+e^- to PbPb.
  - Encodes SM & BSM physics + many phenomenological variants.
- Two main **modes of use** (15-20k global users):
  - **Experimental tool**: underlies most* LHC results, used by ALL collider experiments, several non-collider experiments.

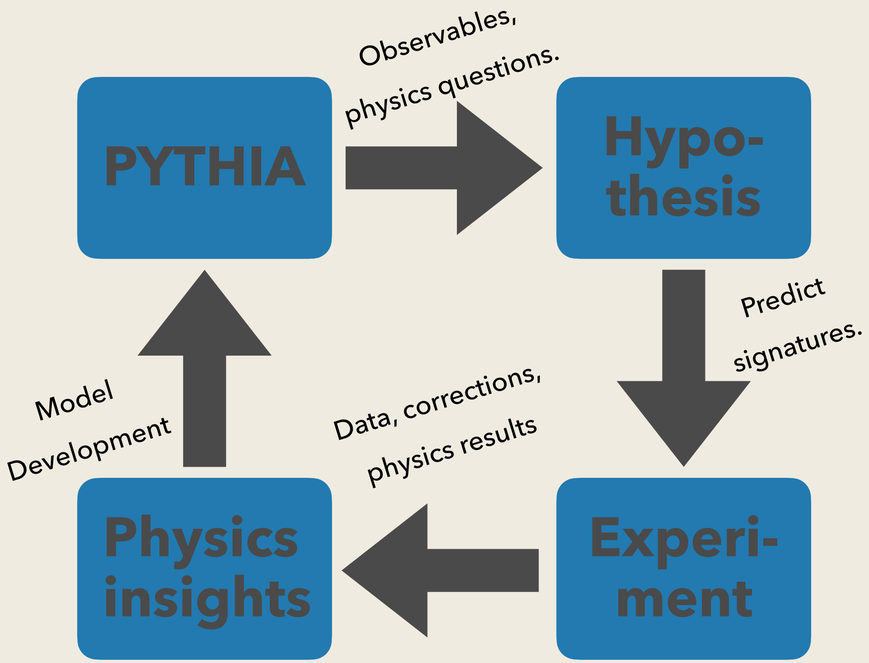
    * 73% of all ATLAS papers use PYTHIA (CMS: 72%, ALICE: 42%, LHCb: 75%).

  - **Theory tool**: Theory collaborations interface to PYTHIA, PYTHIA is used as framework for implementing models.

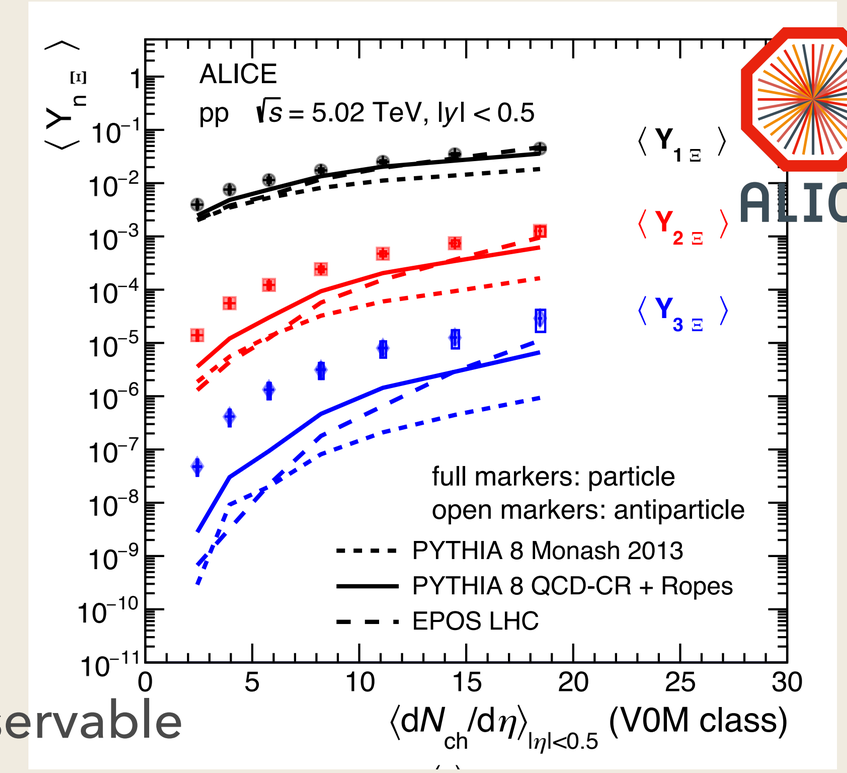


- PYTHIA is **essential** for detector design, analysis strategies, backgrounds and systematics.

PYTHIA as a physics laboratory



- New **ALICE observable:** event-by-event strange multiplet yields.
- Access to **extreme strangeness** configurations.
- Much stronger **discriminatory power** for hadronization models



- PYTHIA acts **both** as physics and infrastructure: motivates the observable and enables the analysis.
- Study enabled by **community interaction**: user questions, summer school discussions.
- PYTHIA as infrastructure is **more than just the code**

ALICE COLLABORATION: 2511.10413

PYTHIA as infrastructure (2024 → 2025)

Last year:

- *"Should VR consider PYTHIA as Research infrastructure of national interest?"*

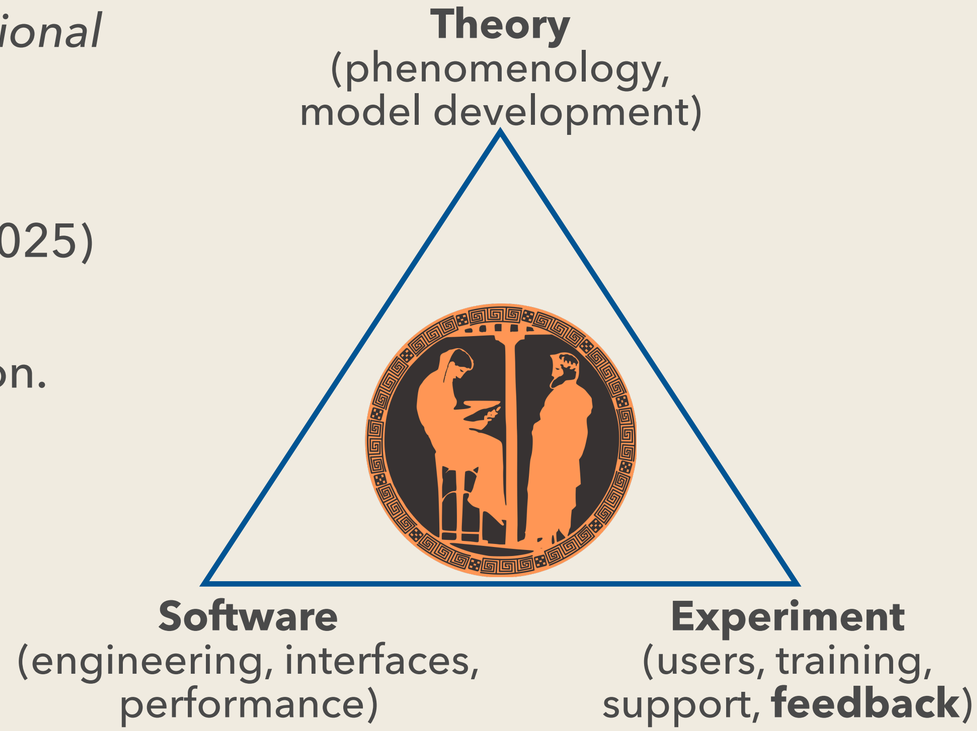
Where are we now?

- First-ever infrastructure application (VR needs-assessment, 2025) submitted.
- Anchored in input to ESPPU, supported by the Particle Section.

Why this matters?

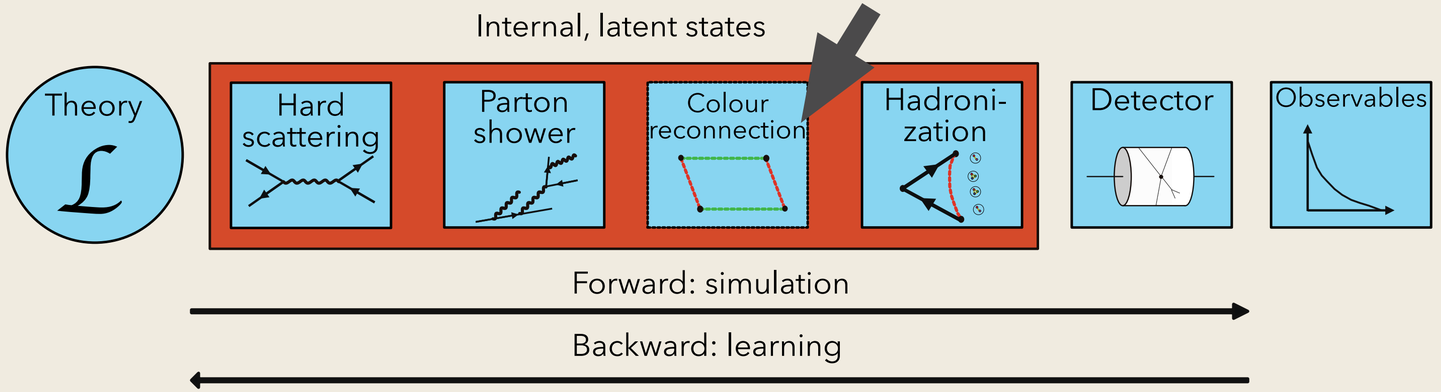
- MCEG development is *not* a short-term project.
- PYTHIA is part of *every* analysis chain.
- Simulation needs are exploding:
  HL-LHC, FCC, EIC, LDMX, IceCube, …

The field is changing: AI as **user** (truth simulation); AI as **developer** (coding assistant); AI as **surrogate model.**



PYTHIA & AI: a new class of model is entering

- **Zooming in on ML surrogates:** Can ML *enhance* or even *replace* parts of a physics simulator?
  - *Black-box replacements:* Fast but with no **explainability** or **interpretability**.
  - *Module-level swaps:* Replace on physics step with a learned, explainable, surrogate.



Intepretability:
Can I understand how it works?
Explainability:
Can I relate it to physics?

Key challenge: the *"latent space mismatch":*

You cannot train a surrogate if its output lives in a latent representation that your classical simulator never exposes.

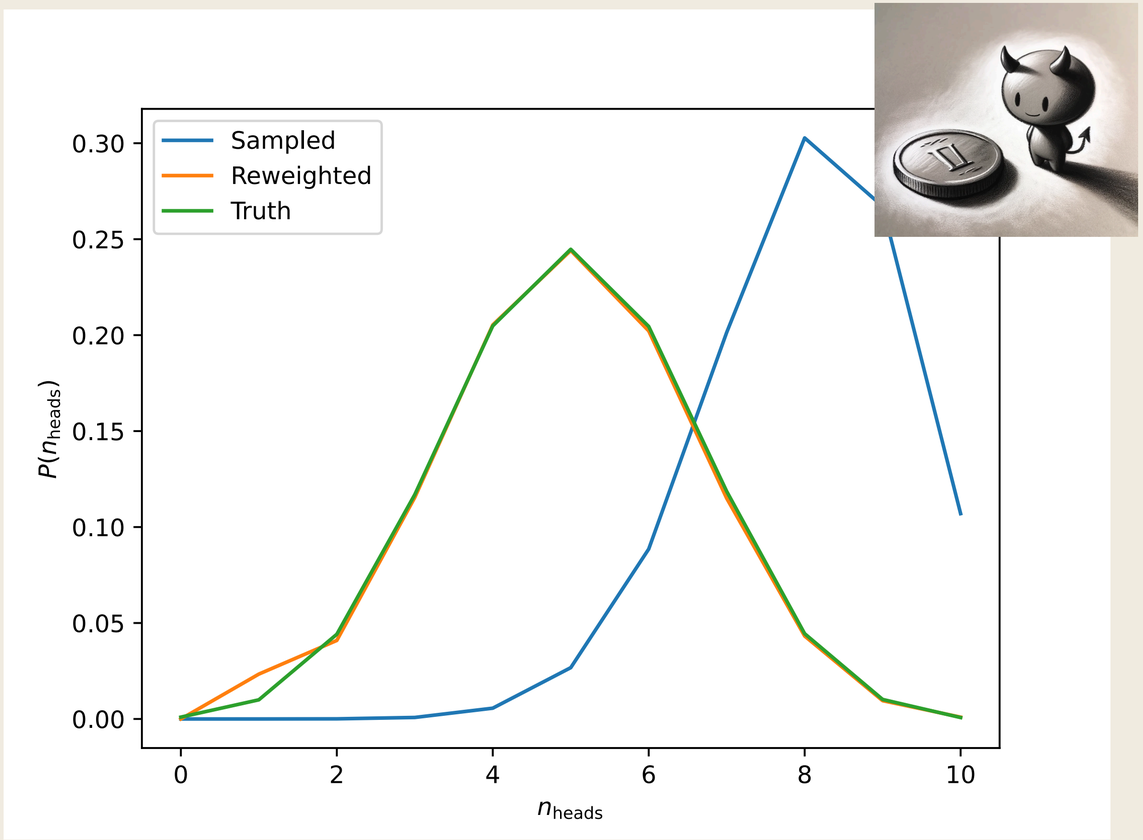
Consequence: You can only train on Monte Carlo truth, your surrogate becomes a toy which never learns from real data.

- **Our goal:** Enable researchers to do this *correctly* by making the pipeline differentiable when needed.

"Loss" (χ^2) is calculated on observables

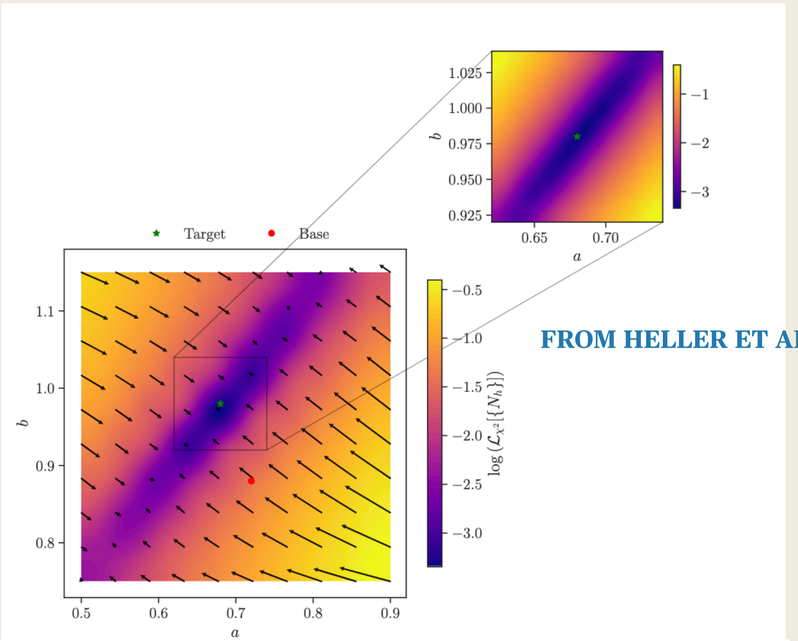
- Training an embedded surrogate → pipeline must be differentiable.
- We cannot do traditional differentiable programming: but we can **reweight observables.**
- Example: coin tosses: one **event** is 10 tosses, **observable** is $P(n_{heads})$.
- Technique well-known since 1990s. Novelty:
  - *Post-hoc* (after simulation) reweighting, general sampling algos.
  - Reweight through computational graph breaks

- **Reweighted samples, example:**

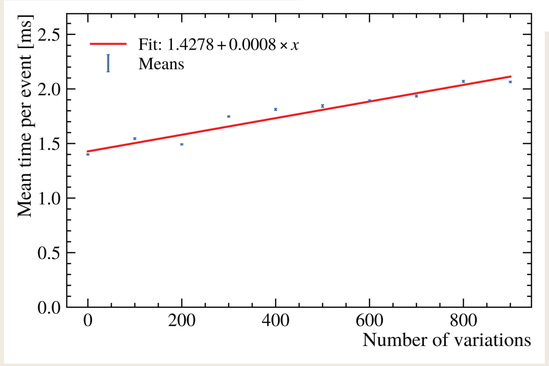


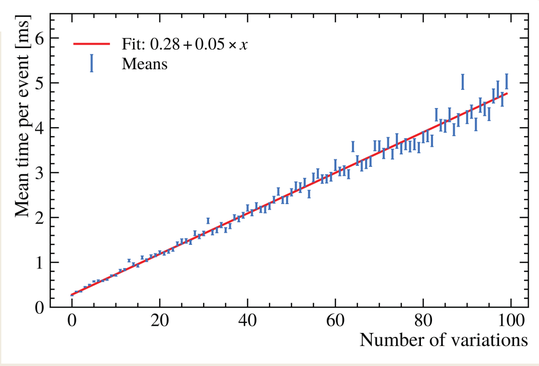
1000-fold timing improvement and gradients

- And it works!
- First no-ML use case: retuning parameters.
  - Fast physics tunes. From 0.5-1k CPU hours (**HPC**) to minutes (**Laptop**).
  - Uncertainty estimates.
- Coming: **true hybrid** ML+MC models, trainable on real data.
- **Note:** gradients can be propagated through e.g. detector simulation.
- There are certainly more use cases!
- **This is where you enter the picture!**



FROM HELLER ET AL: 2411.02194

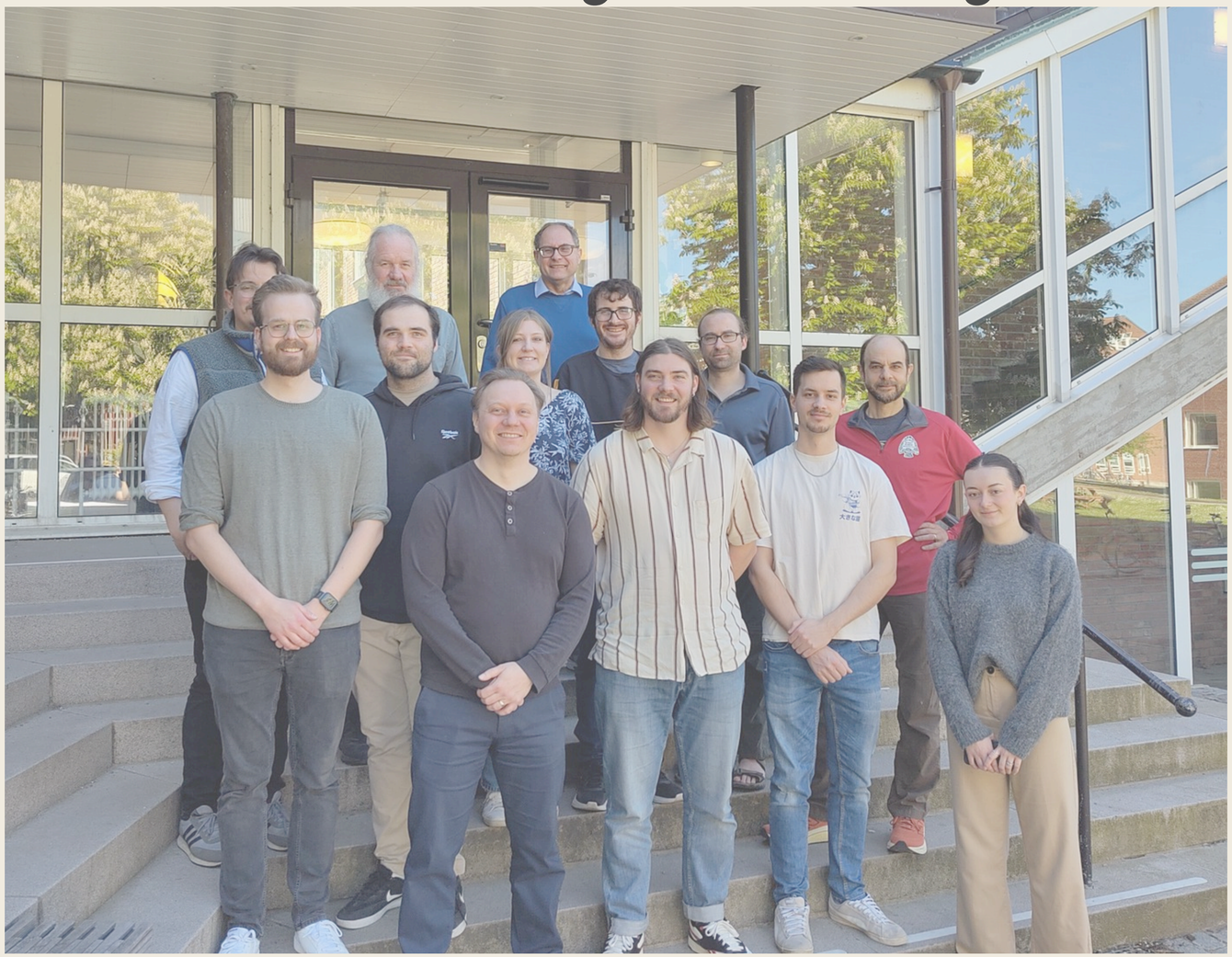




Summary

- Measured on number of users, **PYTHIA is the largest Swedish particle physics infrastructure.**
- Physics development for **all collider physics** and **physics beyond colliders.**
- Support for ML driven modules in development.
- PYTHIA is nothing without **you, our users!**
- If you use PYTHIA directly or indirectly, feel free to take advantage.
- We can answer questions, point to new developments (what can **you** do with fast gradients?), host tutorials etc.
- We are looking forward to continue to provide our contribution to particle physics, together with you.

Thank you for your attention!



https://www.pythia.org/