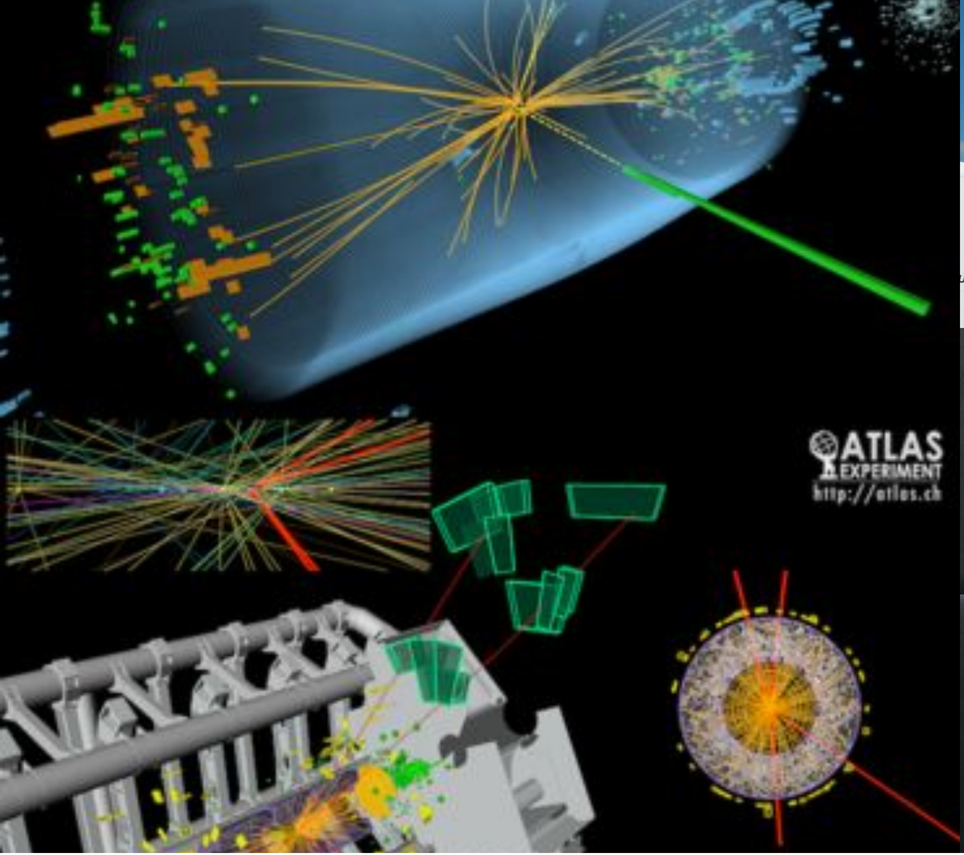
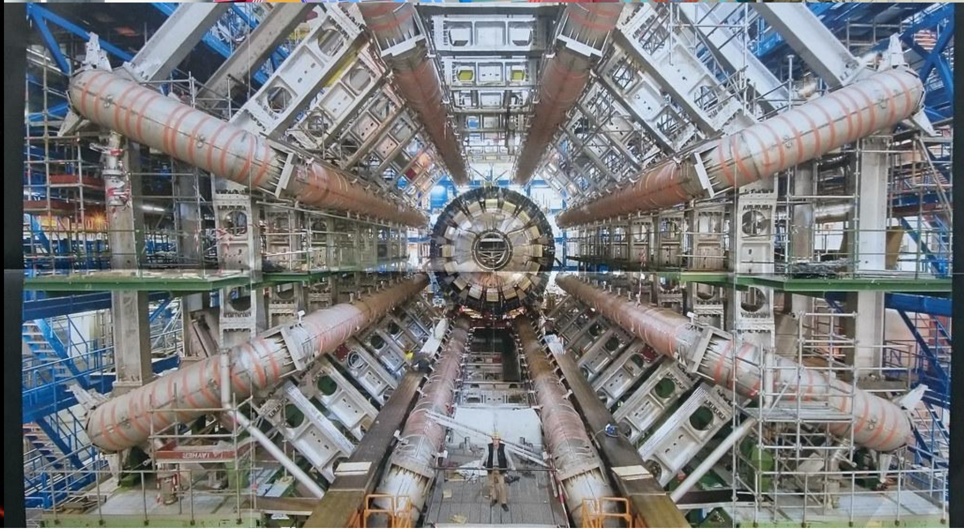
Bachelor & Master Thesis Subjects in ATLAS

Alessandra, Arnau, Craig, Daniel,
Janni, Jørgen, Mogens, and Troels



High Energy Physics @ ATLAS

ATLAS EXPERIMENT

UNIVERSITY OF COPENHAGEN

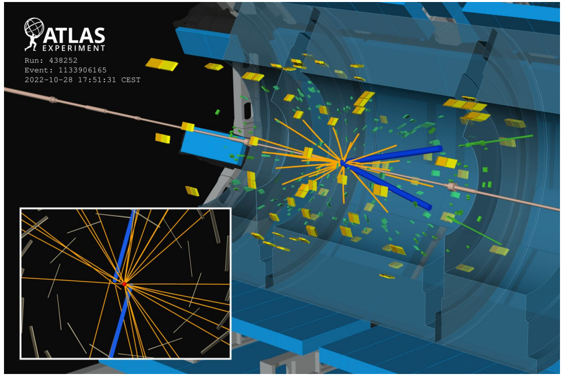
Why High Energy Physics? Why ATLAS?

- Want to probe the basic building blocks of reality
- New particles are either very heavy or very subtle
- We need collisions at high energy (to find heavy particles) and *many* collisions (to find subtle particles)
- The Large Hadron Collider accelerates particles at ten thousand times the energy of everyday life

$$
\begin{aligned}
\mathcal{L}_{\mathrm{SM}} = & -\frac{1}{4}G^{A}_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^{I}_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\
& + \sum_{\psi}\bar{\psi}\, i \not{D}\psi + (D_{\mu}H^{\dagger})(D^{\mu}H) \\
& - \lambda\left(H^{\dagger}H - \frac{1}{2}v^{2}\right)^{2} \\
& - \left[H^{\dagger}\bar{d}Y_{d}q + \tilde{H}^{\dagger}\bar{u}Y_{u}q + H^{\dagger}\bar{e}Y_{e}l + \mathrm{H.c.}\right].
\end{aligned}
$$

Does this…

… match this?



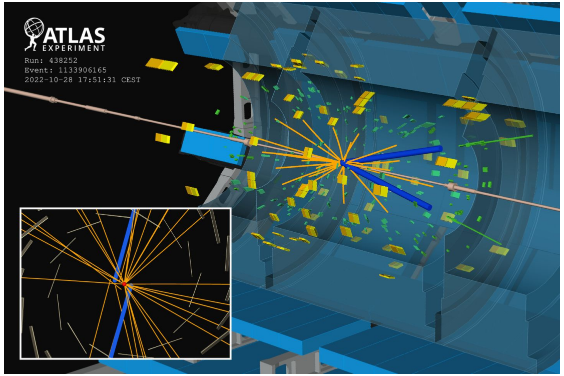
Why High Energy Physics? Why ATLAS?

- By **analyzing** collisions **simulated** according to the Standard Model with collisions **recorded** and **reconstructed** in the real ATLAS detector, we can see if there is a mismatch
- This mismatch might be “New Physics”: extra dimensions, dark matter, extra symmetries (forces), more fundamental particles

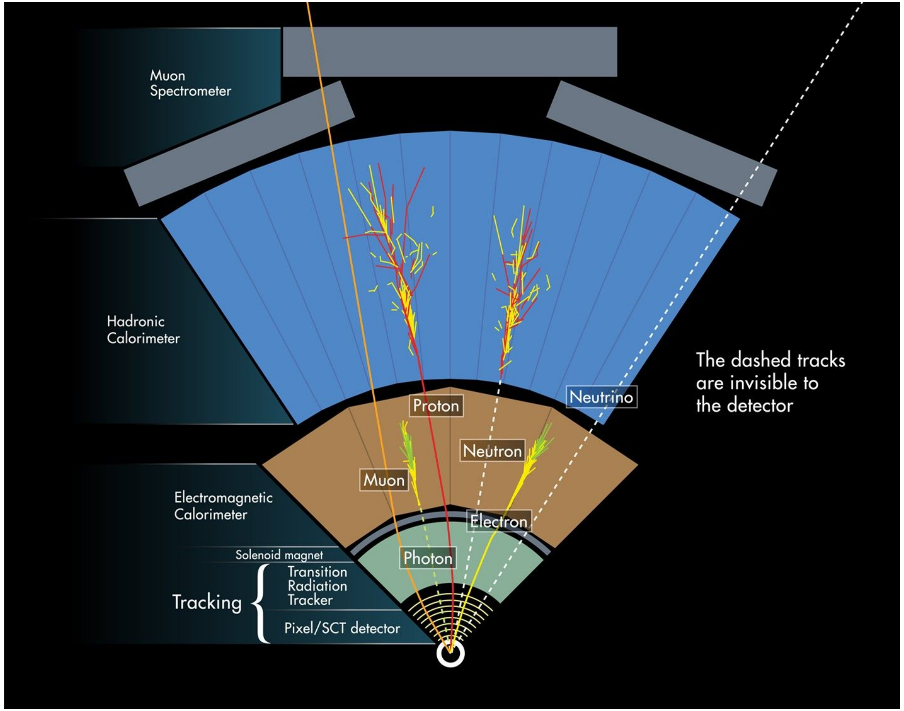
$$
\begin{aligned}
\mathcal{L}_{\mathrm{SM}} = &-\frac{1}{4}G^{A}_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^{I}_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\
&+ \sum_{\psi}\bar{\psi}\, i \not{D}\psi + (D_\mu H^\dagger)(D^\mu H) \\
&- \lambda\left(H^\dagger H - \frac{1}{2}v^2\right)^2 \\
&- \left[H^\dagger \bar{d} Y_d q + \tilde{H}^\dagger \bar{u} Y_u q + H^\dagger \bar{e} Y_e l + \mathrm{H.c.}\right].
\end{aligned}
$$

Does this…

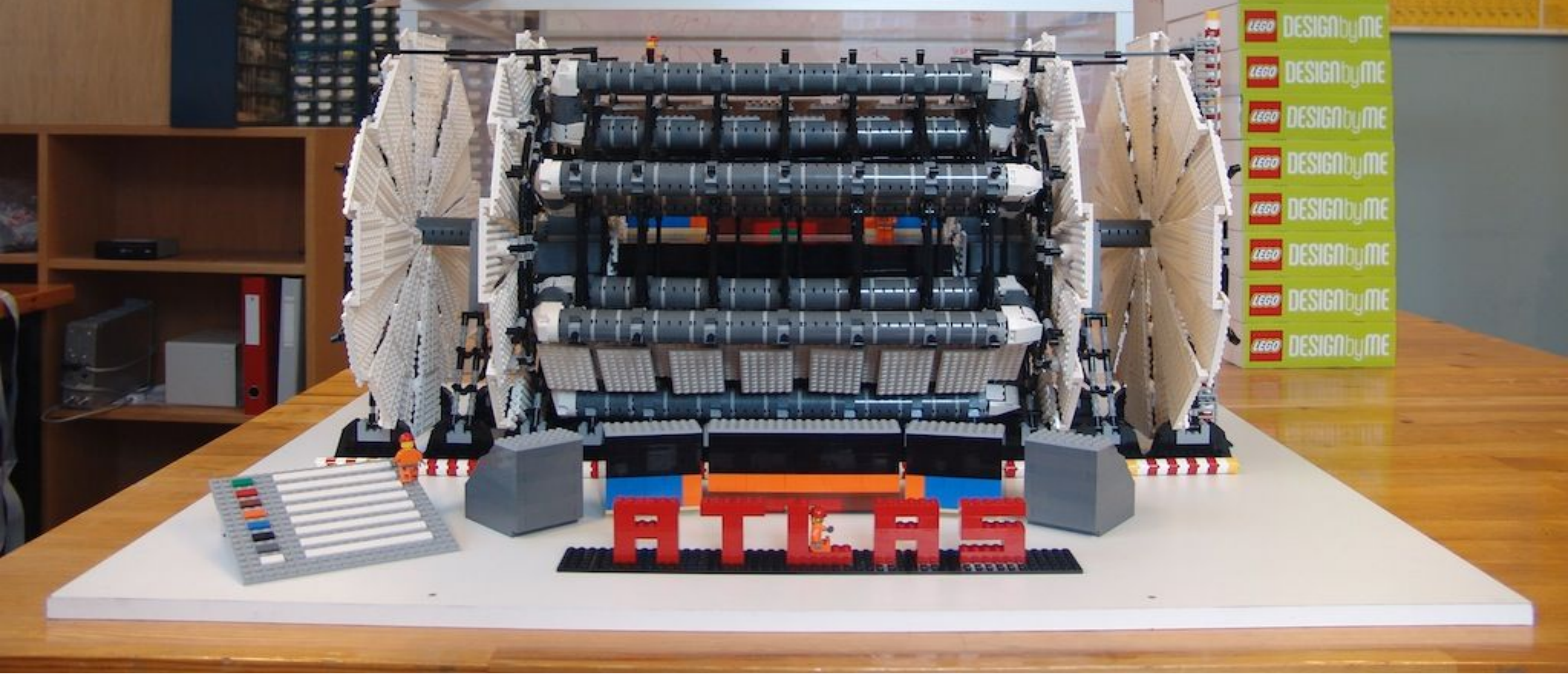
… match this?



What happens in ATLAS hardware, triggering, reconstruction & analysis?



- **Hardware:** The detector needs to be upgraded, already started!
- **Trigger:** Data needs to be stored or discarded.
- **Reconstruction:** All the raw measurements (energy deposits in 4D space) need to be converted to “real physics”
- **Analysis:** Prediction and data are compared, and New Physics discovered (or ruled out)



Research Projects in ATLAS

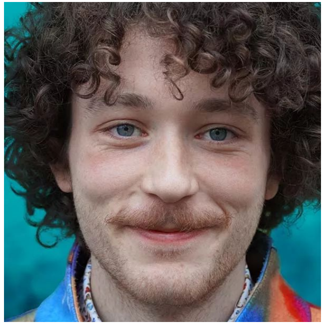
Who are we?

Alessandra
Trigger + Tracking
a.camplani@nbi.ku.dk

Arnau
Analysis

Craig
Hardware
wigleswt@nbi.ku.dk

Daniel
Tracking + ML
daniel.murnane@nbi.ku.dk



Janni
Analysis

Jørgen
FCC
beck@nbi.ku.dk

Mogens
Hardware + FCC
dam@nbi.ku.dk

Troels
Analysis + ML
petersen@nbi.ku.dk

ATLAS Physics Analysis

Troels

- Data analysis in ATLAS is a wide concept: We publish about 100 papers/year across a very varied field. It can broadly be divided into two:
    - **Combined Performance (CP)**: Better performance and understanding of particle identification and reconstruction.
    - **Physics Analysis**: Measurement or Searches based on physics data.
- For CP, our group is working on measuring (and thus optimising) the performance of energy regression on (b-quark) jets. This is a vital input to exploring the Higgs particle (which decays to b-jets 58% of the time).
- For physics, our group is working on a search for the Higgs decay to a Z-boson (decaying to two leptons) and a photon. The decay is rare, which makes it hard. But the final state particles, Z and photon, are not rare, and leaves lots of room for improving the performance (machine learning) and understanding (calibration).

Higgs to jets in ATLAS

Troels

Science Question: Does the Higgs couple to itself?

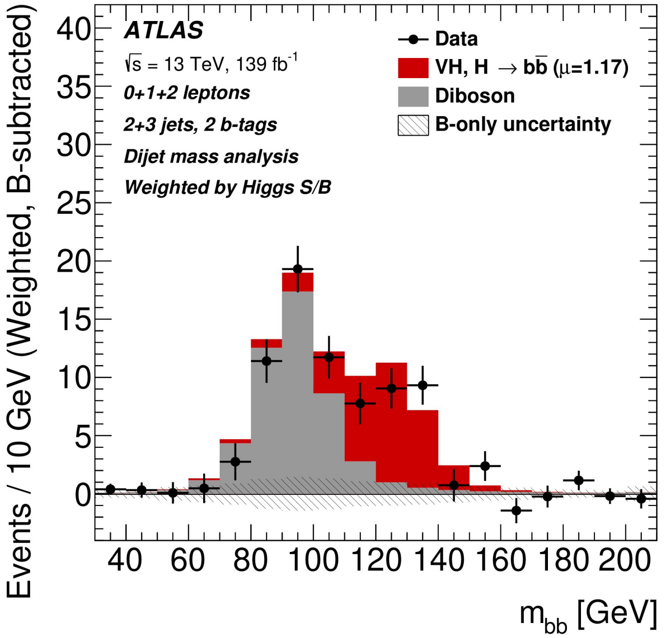
Observation to make: Test if there are events with two Higgs particles.

Challenge: (Di-)Higgs events are very rare (if they exist) and Higgs particles decays most to two b-jets, yielding a very wide mass distribution (below).

Master thesis project:

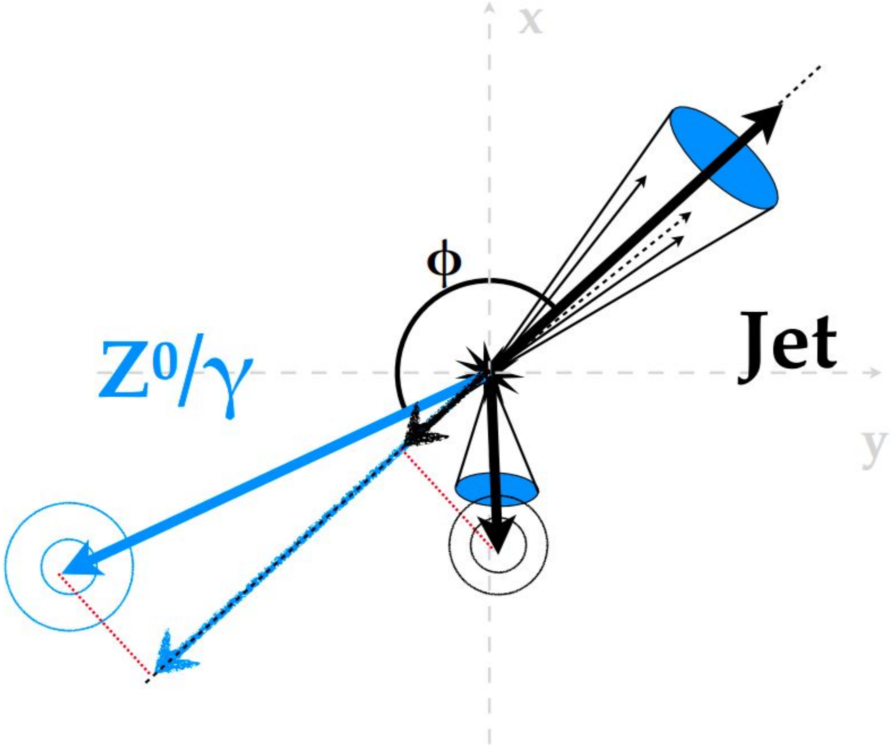
Combine machine learning with good calibration, to minimise the Higgs mass resolution in real data.

Part of the challenge lies in measuring the performance in data.



Jet energy calibration

Troels

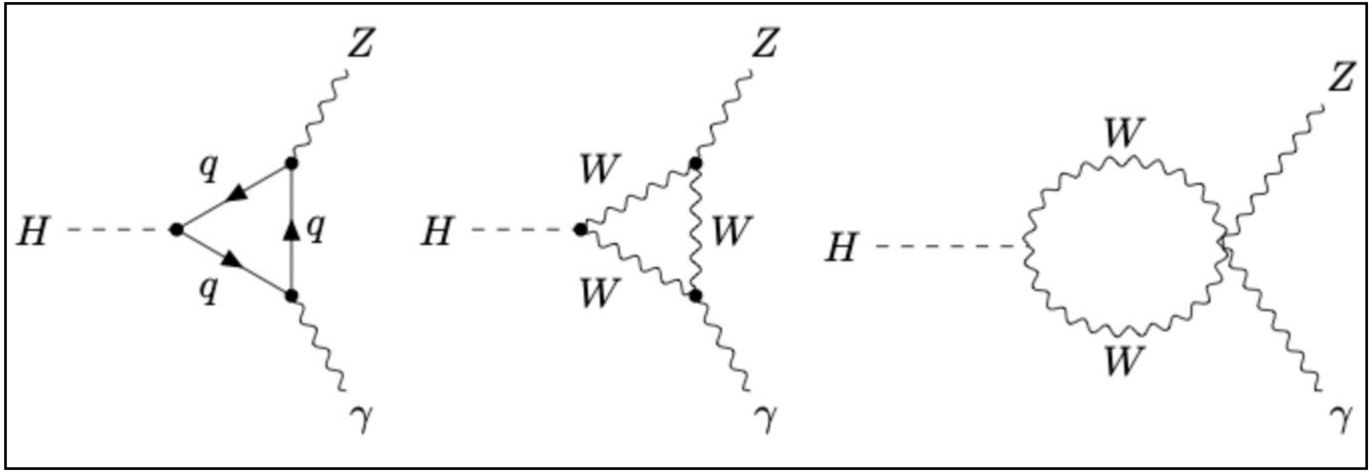


The jet energy calibration can be done based on events like these, or alternatively semi-leptonic ttbar events.

Searching for a Higgs decay

Troels

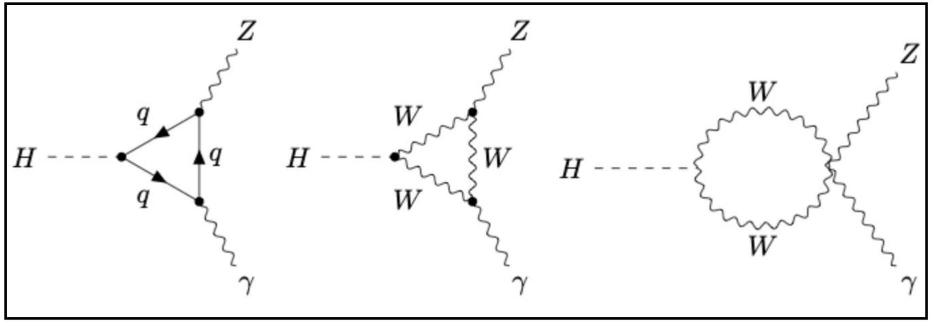
The Higgs decay to a Z and a photon has yet to be observed.

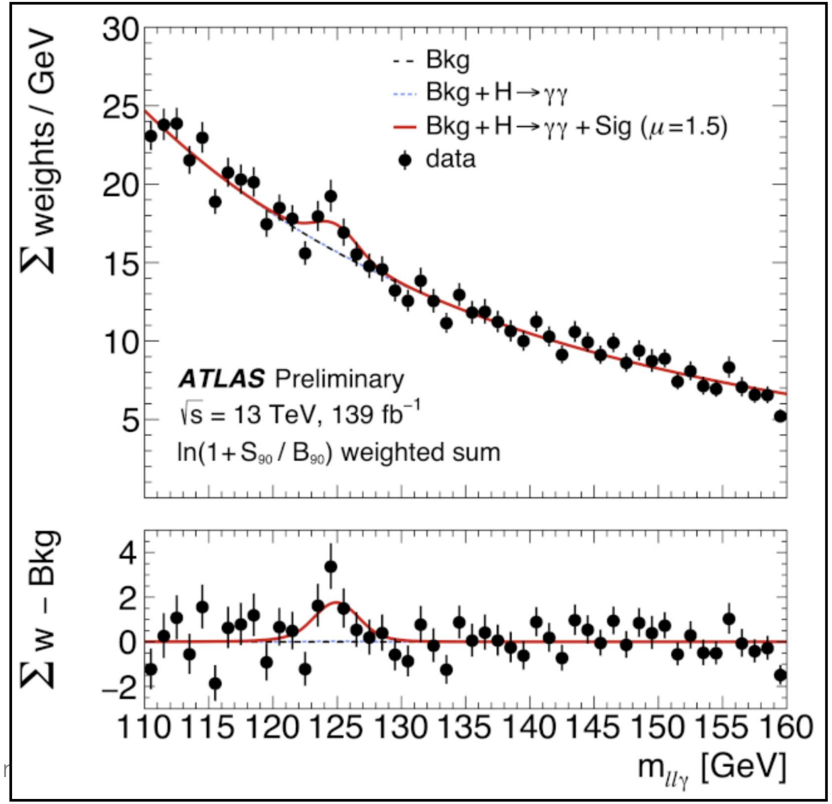


Searching for a Higgs decay

Troels

The Higgs decay to a Z and a photon has yet to be observed.





Generally on ML models

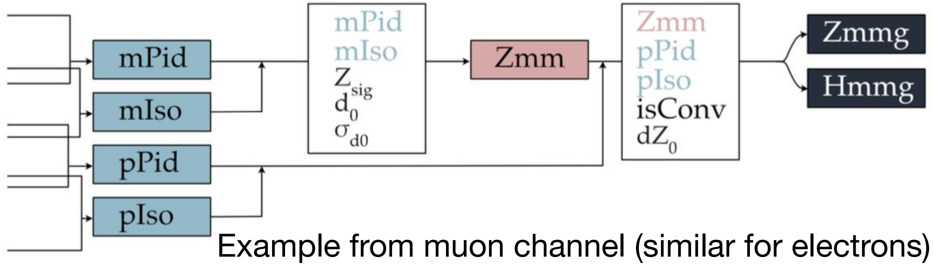
Troels

PID models (Pid): Trained for muons, electrons, and photons.
Note: A separate Pid model was trained for forward electrons.

ISO models (Iso): Trained for muons, electrons, and photons.
Note: The Iso models takes different kinematic variables as input.

Di-lepton models (Zll): Trained for Z → μμ and Z → ee decays.
Combines the Pid and Iso models with track and vertex variables.

Zllg/Hllg: Models for the full Z → llγ and H → Z(→ ll)γ decays.
Combines the di-lepton models with Pid and Iso models for the photon.

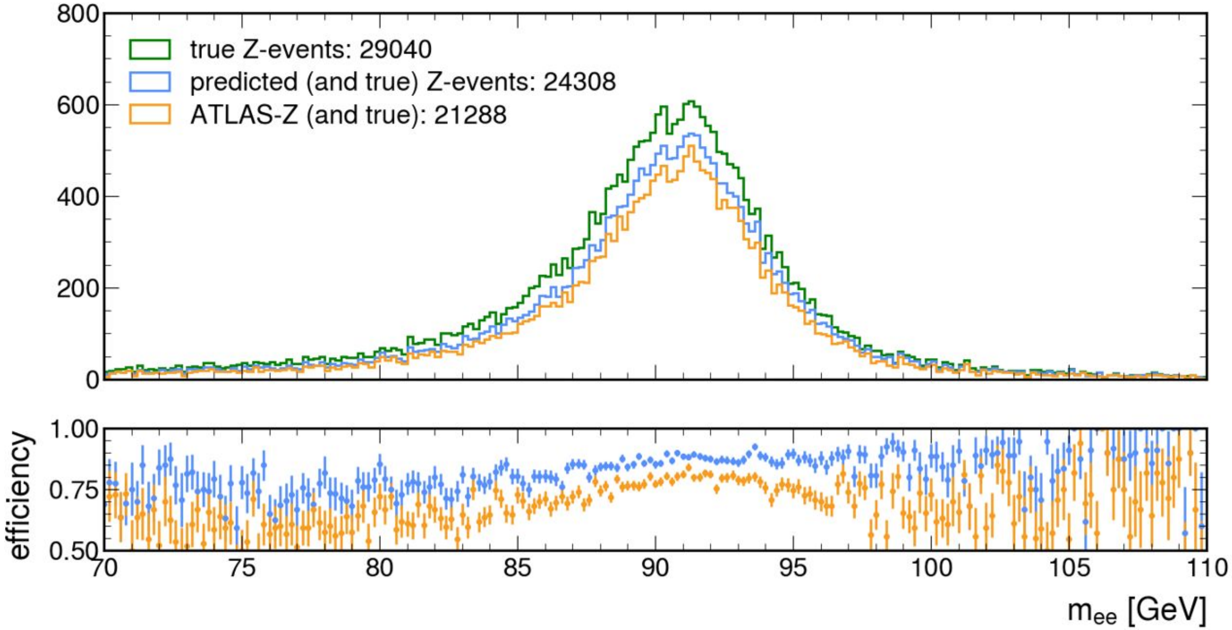


Example from muon channel (similar for electrons)

The Giga-Z^0 project: The motivation

Troels

Using PID and isolation variables for each lepton, along with their distance in z0, we obtain the following selection improvement in (here Zee) signal.



This can be improved further and expanded to include inv. mass estimate.

ATLAS EXPERIMENT

UNIVERSITY OF COPENHAGEN

The Giga-Z^0 project: What will ATLAS gain?

Troels

The gains for ATLAS are:

- Better Z selection (by 10-20%, already proven)
- Better Z mass determination (by 5-15%, partially proven)
- Likely smaller systematic uncertainties
- If this works well, proceed to Z/H → tau tau
- All of the above gains comes with less work for analysis groups, as the systematics will reduce to a single number.

Finally, our field may gain from spurring research into domain shifts:

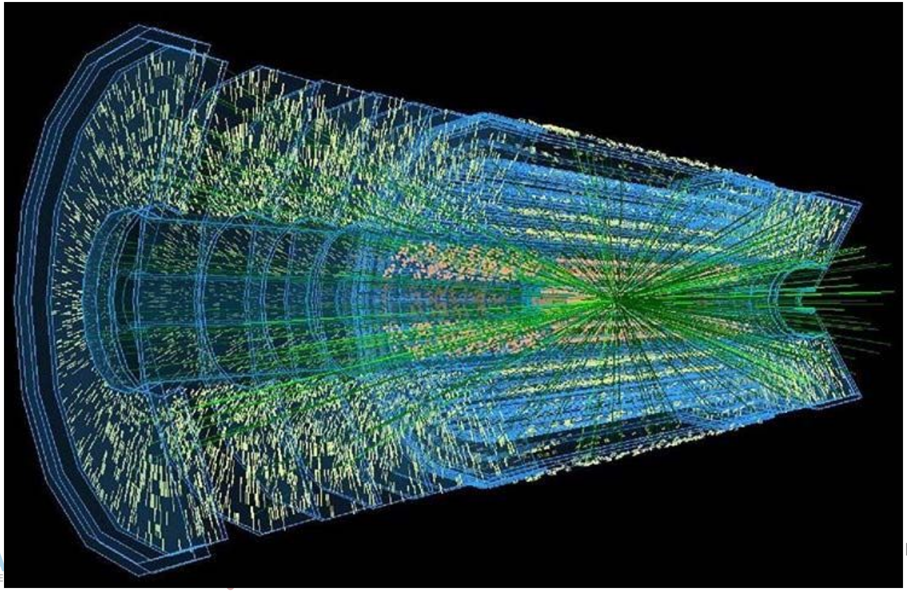
Researchers outside particle physics do not have access to such imminent, huge, complex and (with this QT project) curated data/MC samples, where the central issue is domain shift (differences between data and MC).

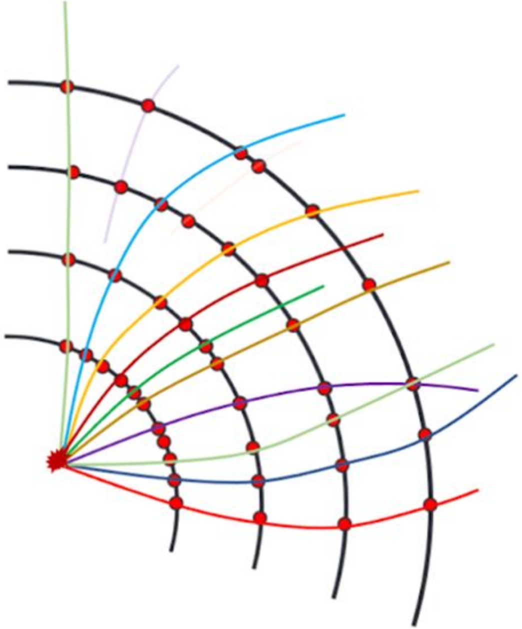
In ATLAS we have about 1/4 billion Z → ll signal events in each channel (e,μ) and source (data, MC) along with background, which could become a (re)known public dataset in both size and quality.

Offline Track Reconstruction

Daniel

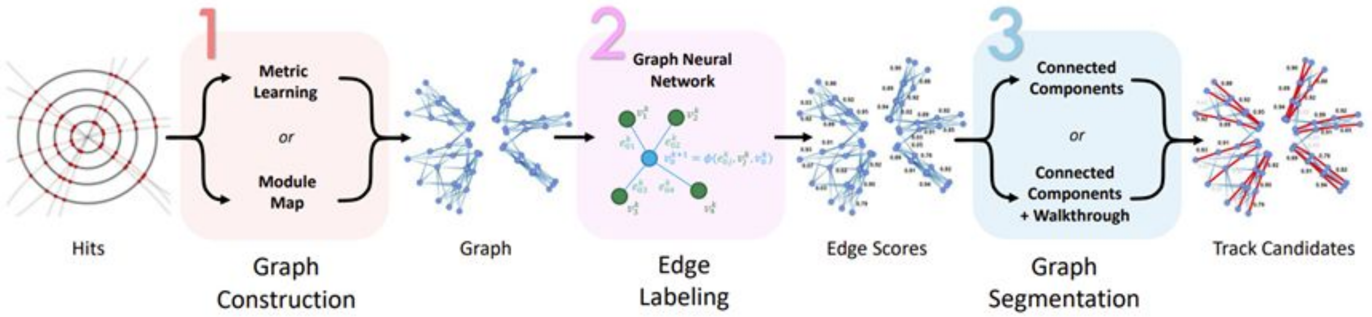
Goal: Take 300,000 points in space, and "connect the dots" to reconstruct the 1,000 interesting particles (and do this 10-100 times per second)





Offline Tracking: Graph Neural Networks & Transformers

Daniel



Many ongoing projects (~12 students across EU + US) to solve tracking with GNNs and transformers: see link. Both bachelor and masters versions of:

Project A: Improved graph construction with *neural module map*

Project B: End-to-end tracking with transformers, object condensation and learned clustering

Project C: Large-scale, distributed training and inference across GPUs

ATLAS EXPERIMENT UNIVERSITY OF COPENHAGEN

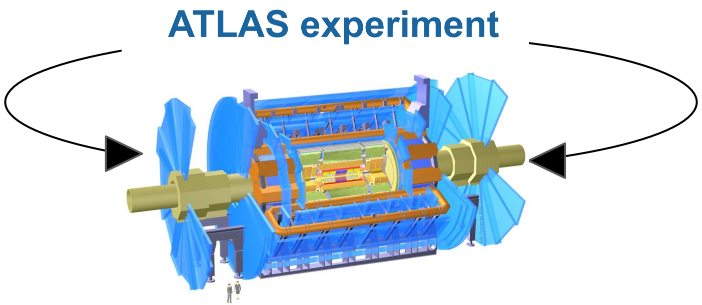
ATLAS Trigger and Data Acquisition system

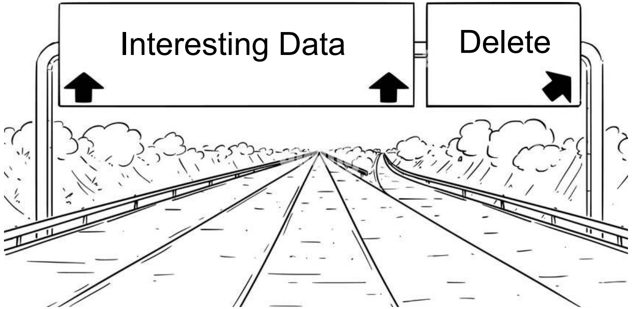
Alessandra

Amount of data produces in ATLAS: **60 TB per second**.

- ➢ Non-feasible and not needed to save everything

- ➢ **Real-time selection system** to **select and save** only the interesting data (Trigger and Data Acquisition - TDAQ)
  - ○ **Critical role**- the saved data are used for (ALL) further physics studies



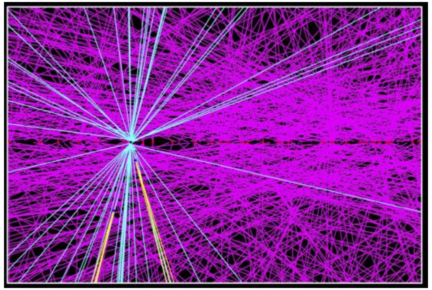


Alessandra's Signal Processing course in Block 3

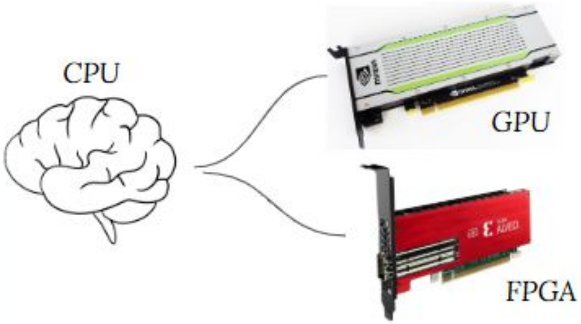
Online Tracking in TDAQ

Alessandra

ATLAS TDAQ - Event Filter Tracking



HL- LHC: ten-fold increase in the amount of data to allow observation of rare processes.



Tracking: **combinatorially complex** task.

Smart algorithms and **heterogeneous hardware** are crucial!

Projects

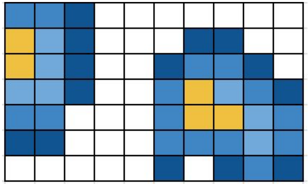
Recent Master Projects:

- GNN for tracking, performance in FPGAs - Sara Schjødt Kjær
- MLP for seeding, performance on GPUs and FPGAs - Mikkel Møller Mødekjær
  Mikkel accepted as PhD student at CERN!!

For the future:

- Clustering algorithms
  Development and performance studies on GPUs and FPGAs

- Performance studies
  On the currently available algorithms



The ATLAS ITk Project

Craig

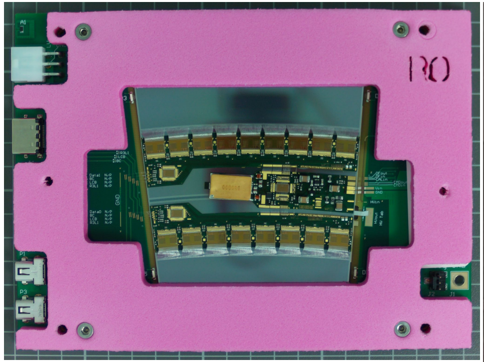
We're also involved in the production of a new particle detector called the Inner Tracker (ITk)

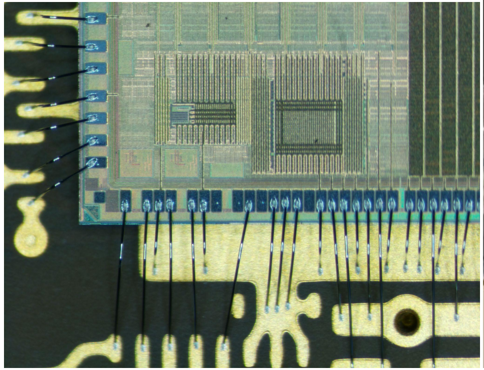
Both BSc and MSc projects are available

Primary task will be to study the performance of these new detector modules with possible mini tasks in parallel, such as developing GUIs, circuit boards, optimising lab

These projects offer a fantastic and rare opportunity to:

- See very first modules installed at CERN
- Work in an international collaboration
- Be recognised as *THE* local expert in DK
- Visit/work at CERN and shadow experts
- Contribute as author to published paper





The ATLAS ITk Project

Craig

Students who have worked with us in the lab tend to do very well

Previous students:

Jonas - PhD in Uppsala - Now works in nuclear power industry

Catherine - MSc Imperial College

Ashley - PhD in Amsterdam - Now a researcher at Oxford

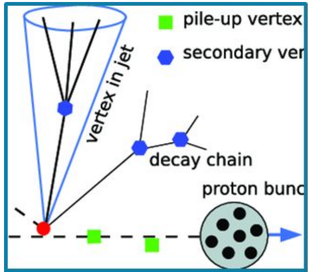
Oliver - Recently finished BSc - Now working with us!

BTW - we can offer lab tours!

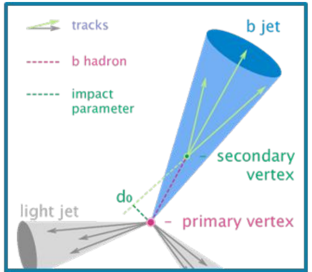
Large A.I. Models for Particle Physics

Daniel

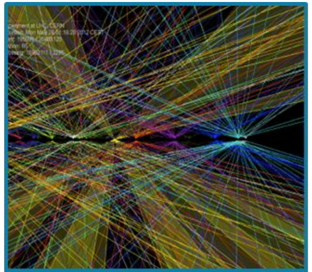
Collaborations with colleagues at CERN, Berkeley, Stanford, Adelaide and Yale, to build self-supervised “foundation models” to perform many HEP tasks:



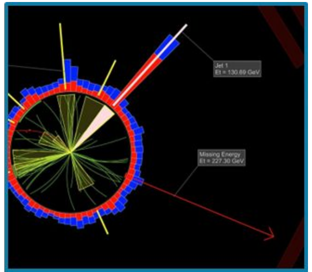
Vertex Reconstruction



Jet Tagging



Pile-up Removal



Missing Energy Reconstruction

Large A.I. Models for Particle Physics

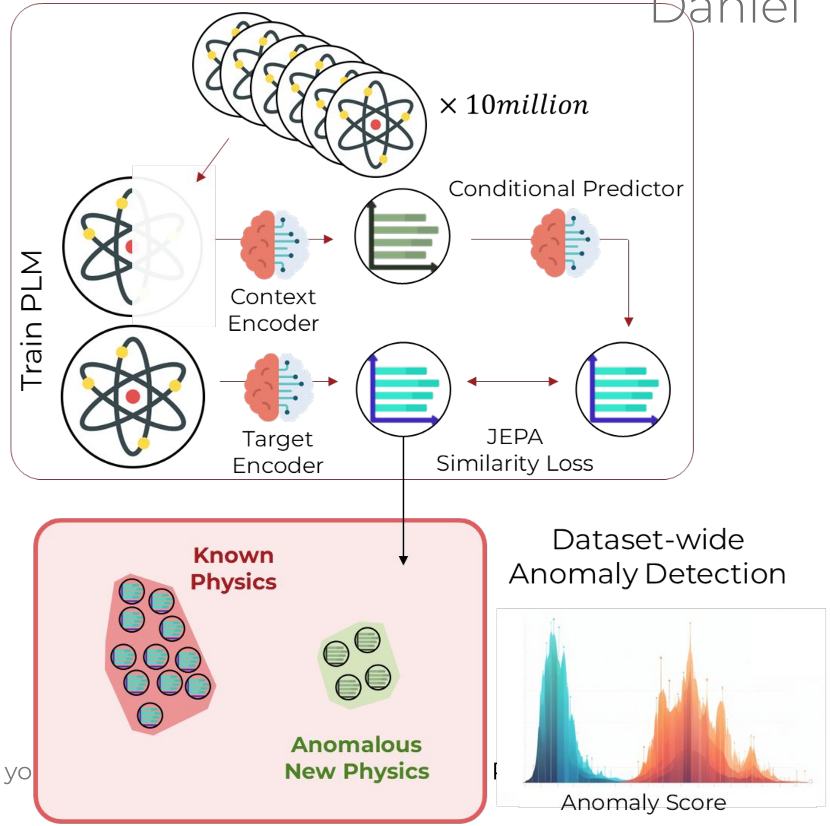
Daniel

Several ambitious projects:

Project A: Study a variety of foundation model training techniques (generative, contrastive, etc.) on a new world-class dataset

Project B: Scaling transformers to million-point collision data

Project C: Anomaly detection on encoded physics - can we directly discover "unusual" physics simply by self-supervised training



Find yo

ATLAS EXPERIMENT

UNIVERSITY OF COPENHAGEN