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LAWRENCE BERKELEY NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

The Higgs Boson and Beyond
Explore the Unknown

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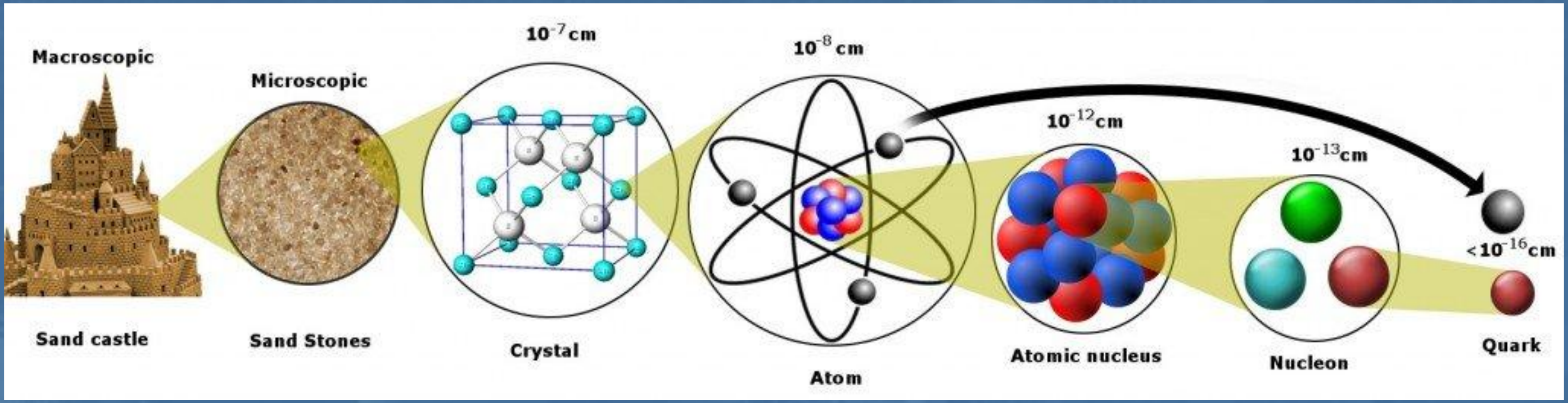
Particle Physics

Particle physics studies elementary particles and their interactions

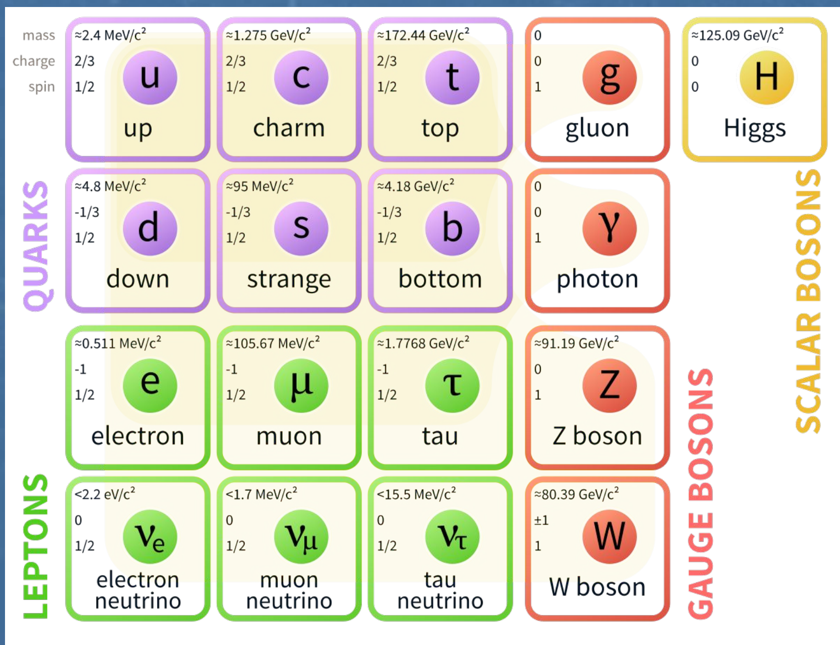
Elementary particles are at the smallest scale that humans can possibly perceive



Particle physics is discovery-driven science. We want to discover new particles and new interactions

The Standard Model

A theory of elementary particles and fundamental forces



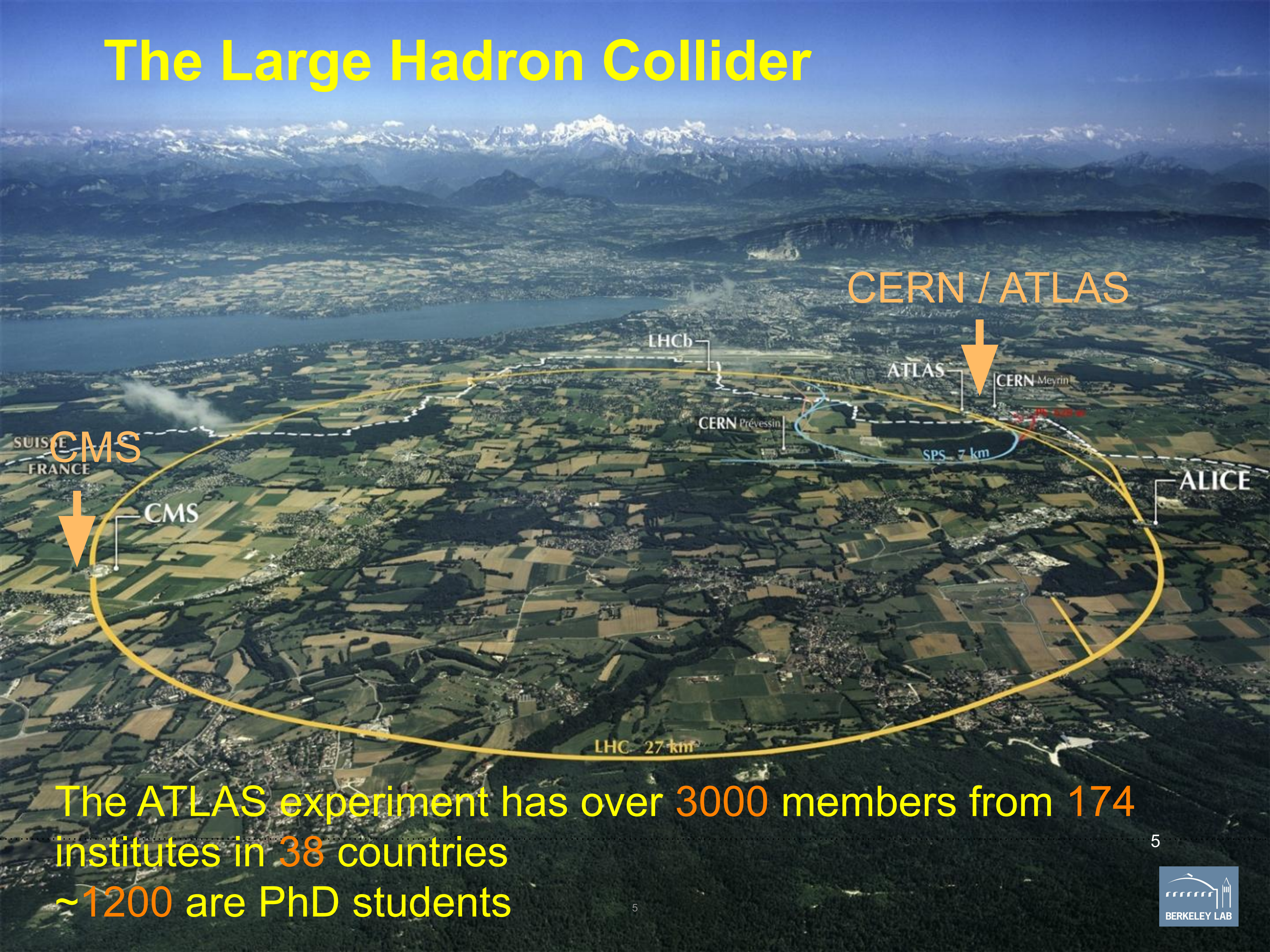
$$
\begin{aligned}
\mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} \\
&+ i\bar{\psi} \not{D} \psi + h.c. \\
&+ \psi_i y_{ij} \psi_j \phi + h.c. \\
&+ |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

Quarks and leptons – fermions – building blocks of the universe

Gluon, photon, W and Z – bosons – carriers of fundamental forces

Higgs boson is responsible for giving masses to other elementary particles

The Large Hadron Collider



The ATLAS experiment has over 3000 members from 174 institutes in 38 countries

~1200 are PhD students

The Berkeley LBNL group

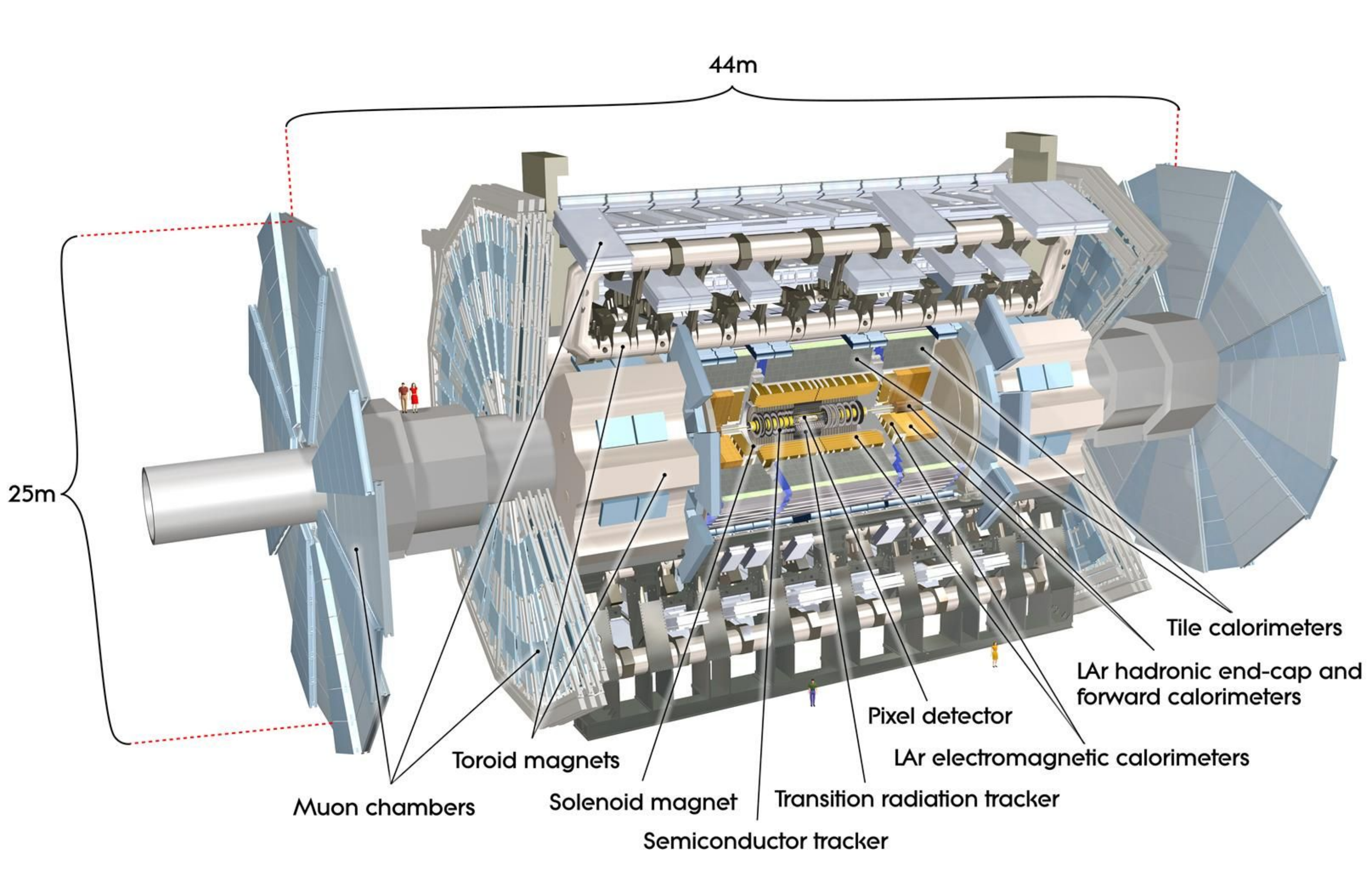
In the ATLAS experiment, UC Berkeley and LBNL operate as a single group

12 staff scientists from Lab's Physics Division + several more from Computing Sciences and Engineering Divisions + 3 faculty members (1 current + 2 incoming) from the physics department + ~ 7 – 8 postdocs (the best postdocs in ATLAS)

- ~ 6 – 7 graduate students
- Many undergrad., visitors from other US and international institutes

We are the largest US ATLAS group with students

ATLAS detector



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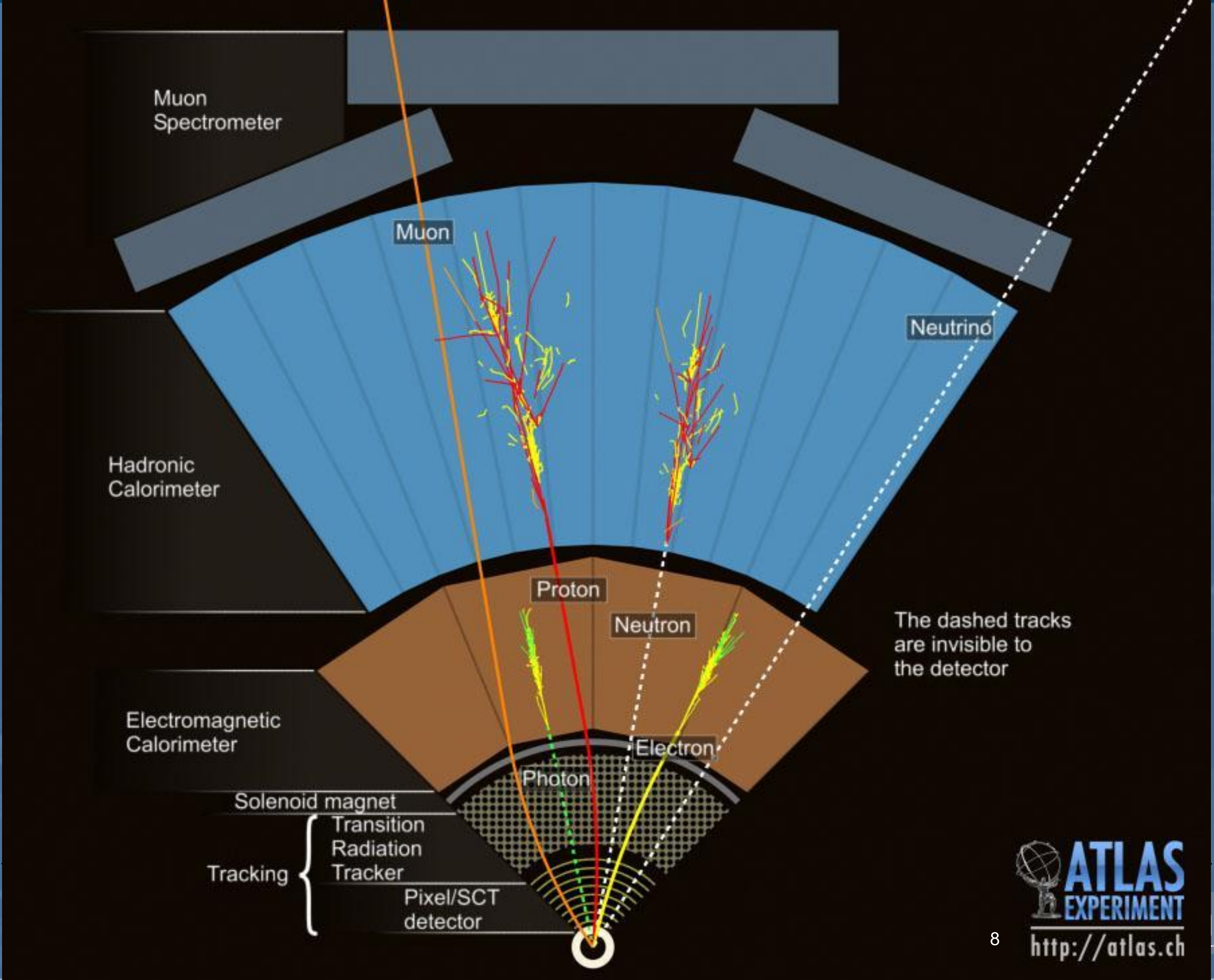
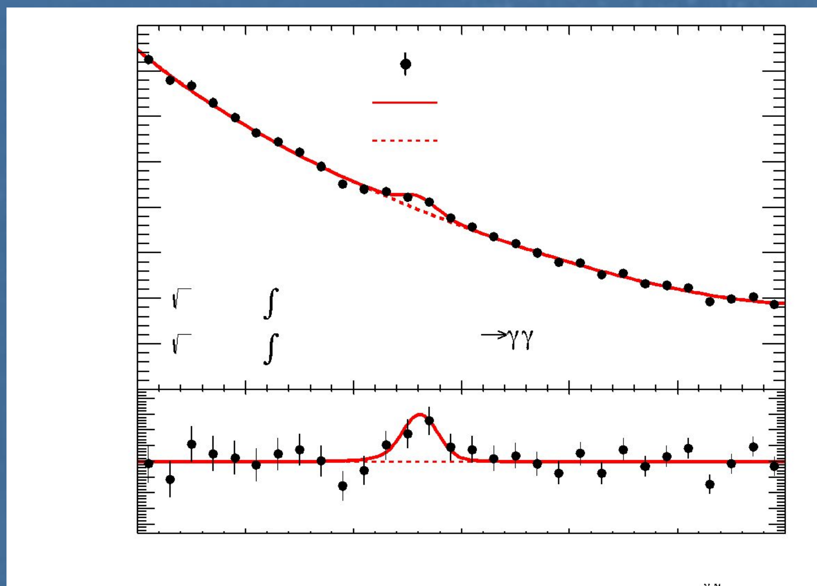
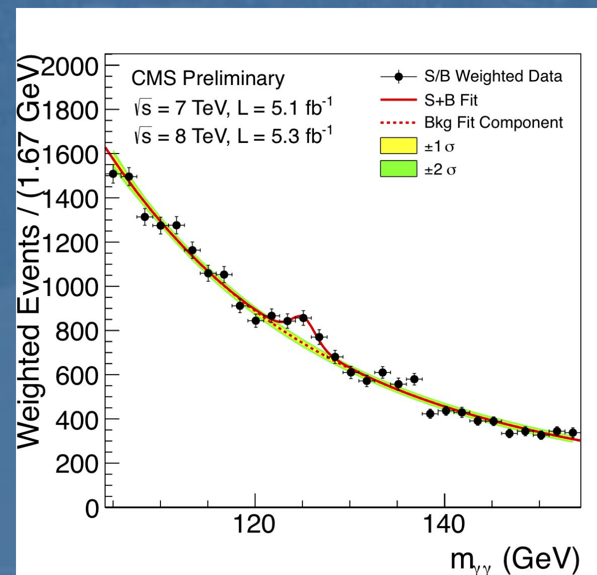


Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Muon
Neutrino
Proton
Neutron
Electron
Photon
The dashed tracks are invisible to the detector
ATLAS EXPERIMENT
http://atlas.ch

The discovery of a Higgs boson

On July 4th, 2012, the ATLAS and CMS experiments at the LHC announced the discovery of a new particle





The decay of the Higgs boson was observed in the diphoton channel and four-lepton channel, independently by ATLAS and CMS

The Nobel Prize in 2013

The Nobel Prize in Physics 2013

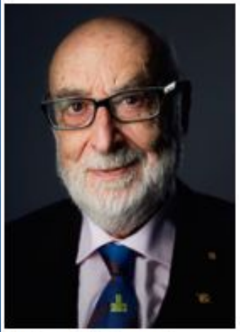


Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Big, open questions

- Why is the electroweak force so much stronger than gravity?
  - Often presented as the “hierarchy problem”
  - Supersymmetry, extra dimensions, composite Higgs, etc., are motivated for this

- What is the particle nature of dark matter?
  - dark matter is the majority of matter in the Universe
  - Can dark matter particle be produced at the LHC?
  - How does the Higgs boson interact with the dark matter?

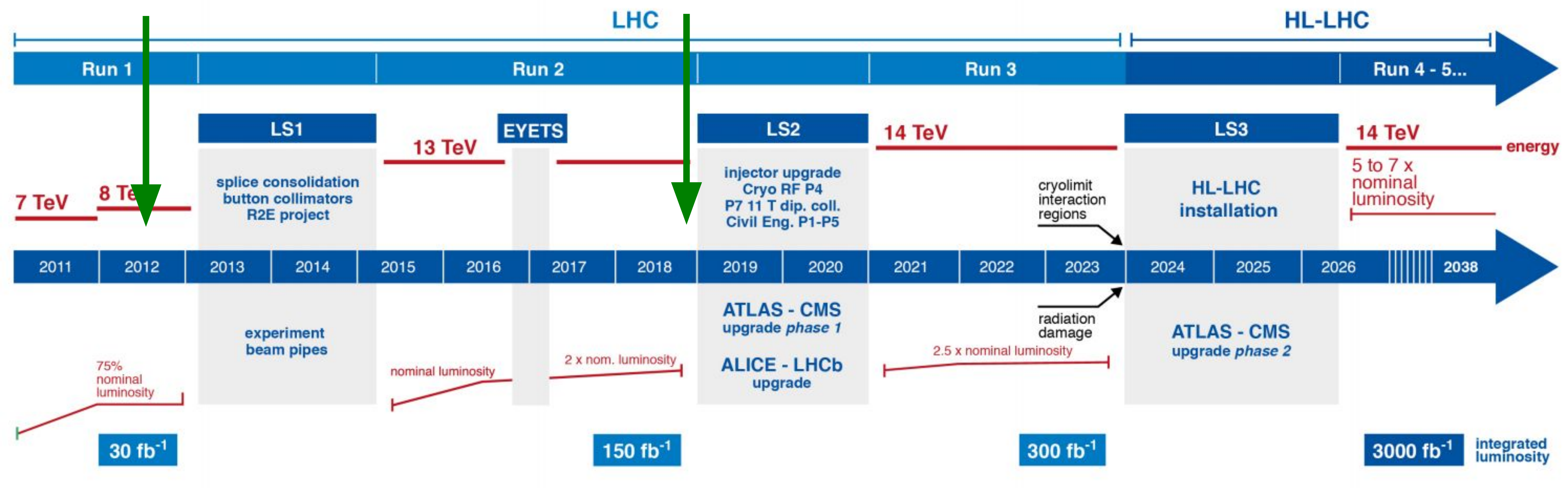
- Why is there an imbalance between matter and anti-matter?
  - CP-violation and new physics?
- The origin of neutrino mass?

Many of the proposed solutions to these questions predict new physics at the TeV scale

The LHC timeline

Higgs discovery

Now



- We are at the end of the LHC “Run-2”, 150 fb^{-1}, ~ 15 times more data than the Higgs discovery, at higher energy
- Long Shutdown 2019 – 2020, detector upgrade and data analysis
- Run-3 2021-2023, will double the data sample we have now
- Long shutdown 2024 – 2026 shutdown for the high luminosity LHC upgrade
- 2026 – high luminosity LHC, 20 times more data by 2035

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The Higgs Boson as a Tool for Discovery

Now that we discovered the Higgs boson, we will use it as a tool for discovery

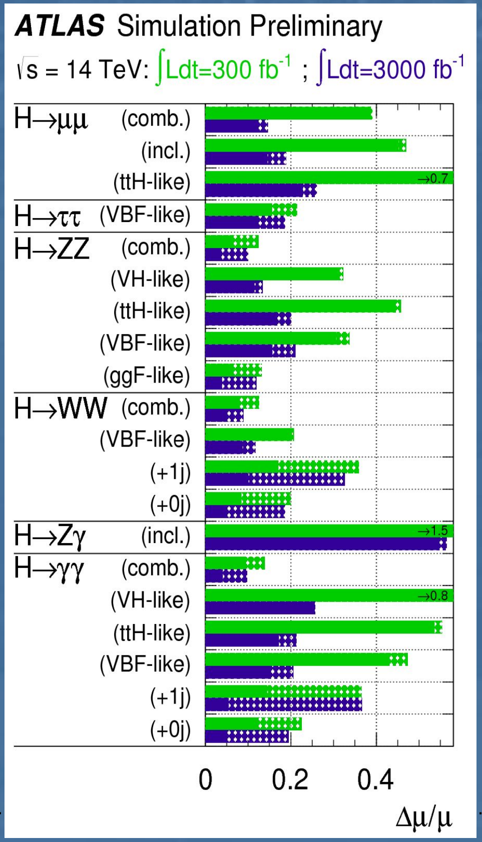
- Are there additional Higgs bosons?
    - Many extensions to the Standard Model predict more than one Higgs boson
- Does the Higgs boson interact with unknown particles?
    - Higgs decays to new particles
    - Higgs boson produced from new particle decays
    - Does the Higgs boson interact with dark matter?

There are many theoretical models behind these questions, and they predict new signatures in collision data that involve the Higgs boson. Direct searches for such signatures are a priority

Precision Higgs Boson Measurements

New physics, new particles, may also alter rates of the known Higgs boson production processes and its decay to other Standard Model particles

- Observe the SM Higgs production and decay processes, as much as possible
  - Some are inaccessible at the LHC because of background
- Improve the precision of the measurements so that we can see subtle effects due to new physics
  - ~10% precision by the end of HL-LHC (2035)



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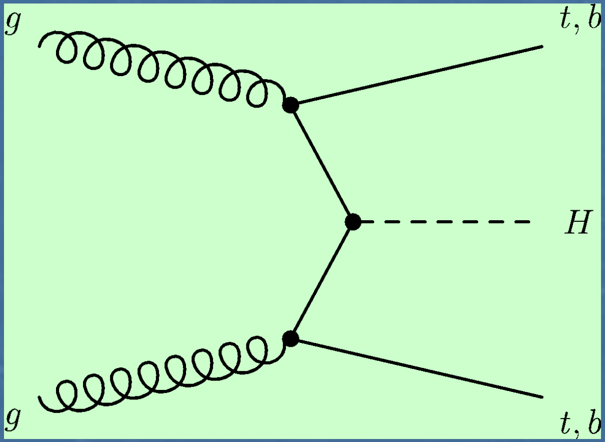
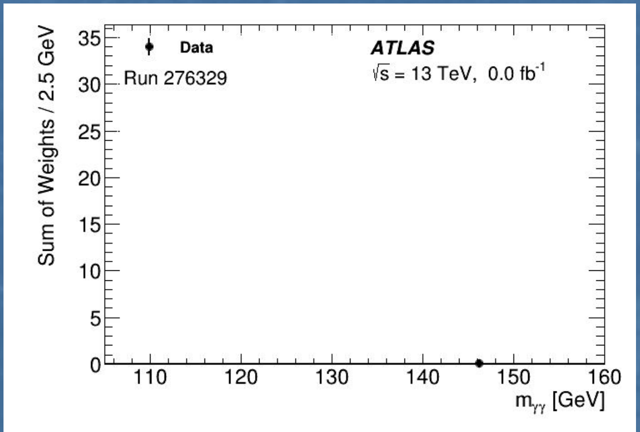
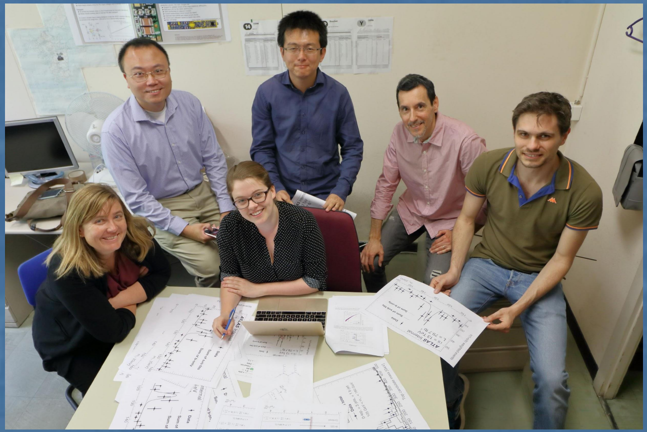
A Recent Highlight – ttH observation







The process where the Higgs boson is produced in association with two top quarks was observed this year

The first direct evidence that the Higgs boson interacts with the heaviest SM particle – the top quark

Graduate student Jennet Dickinson was a driving force in the observation

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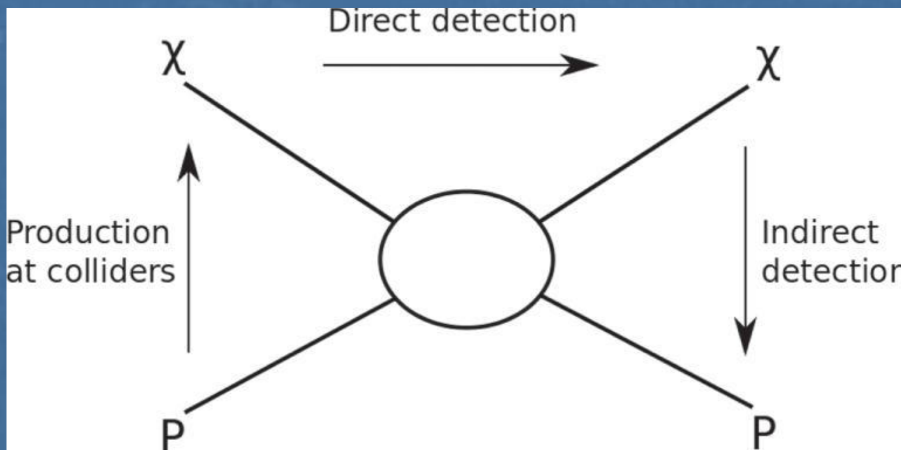
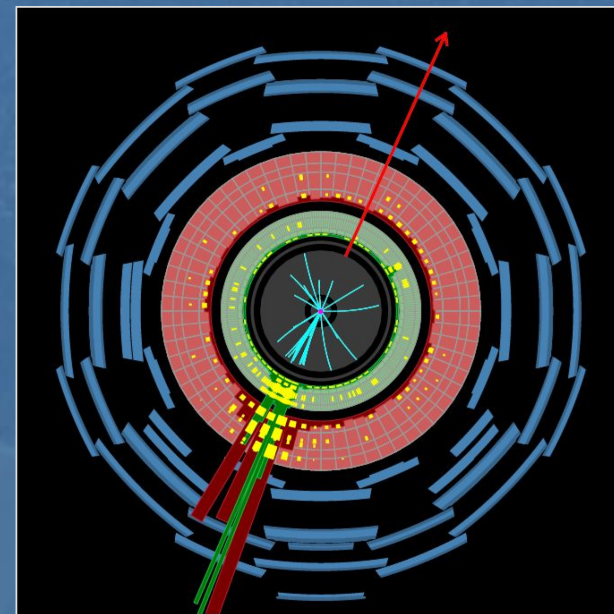
Dark Matter

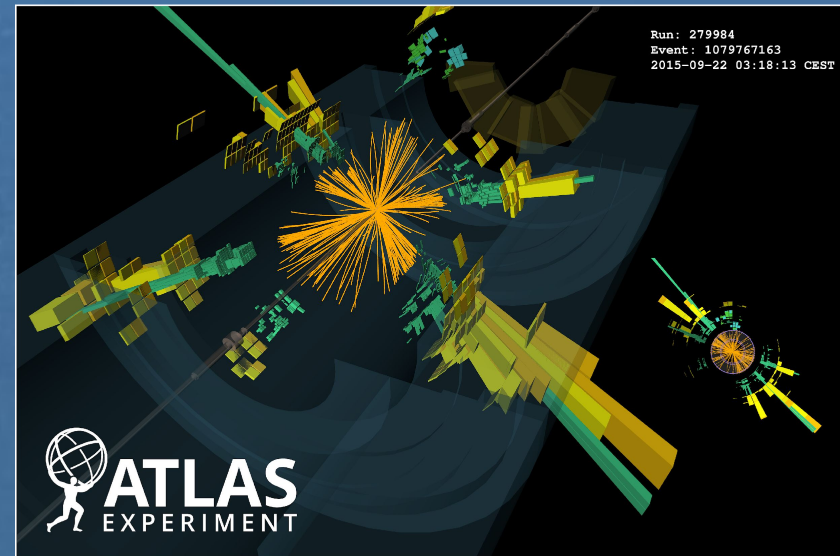


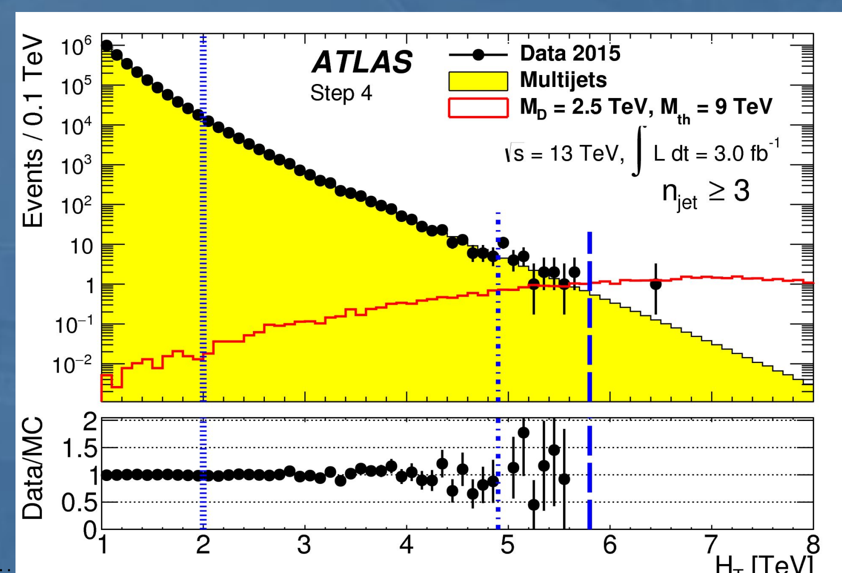


- It is possible that dark matter particles can be produced at the LHC, as predicted in many models of supersymmetry and other theories
- The produced DM particles will escape detection, leaving "Missing Transverse Energy" – imbalance in momentum of all observed particles
- These searches are complementary to direct detection experiments

Extra Dimensions

- Extra spatial dimensions, in addition to the 3 dimensions known to us
- Possible solutions to the Hierarchy Problem
- Fascinating phenomena at the LHC - Graviton, Black Holes





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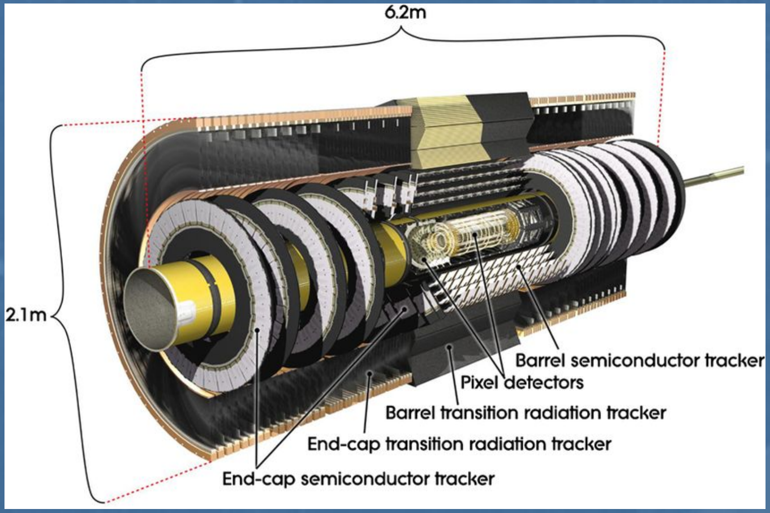
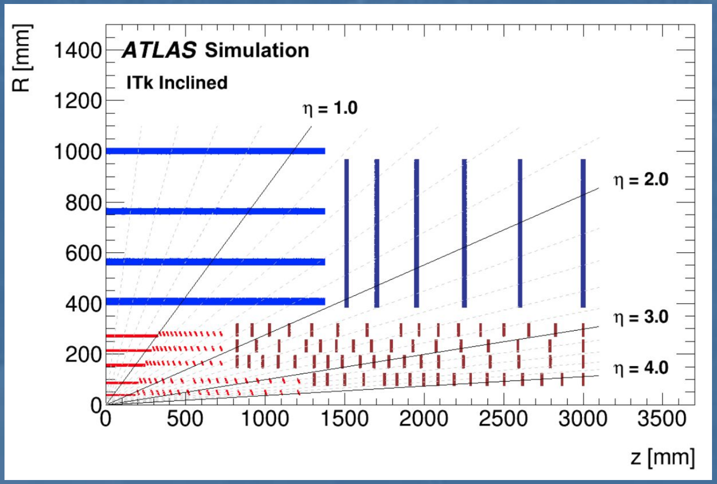
Detector upgrade

The high luminosity upgrade is a major upgrade for the LHC and the detectors. It will take place in the long shutdown 3 (2024-2026)



Current tracker



New tracker layout

- The largest project is the ATLAS inner tracker upgrade. It needs to be replaced due to radiation damage, much higher event rate in the high luminosity Run (2026+)
- Berkeley has many leading roles in the development of the new tracker
  - Detector layout, performance with simulation, readout electronics, powering, mechanical support structures, etc.
- We will build a large fraction of the new tracker here

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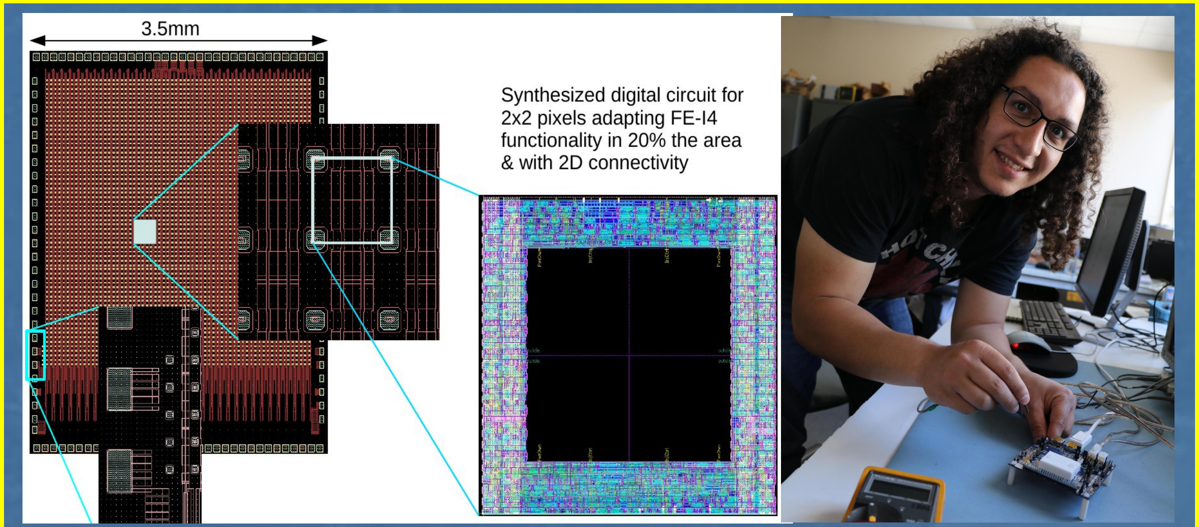
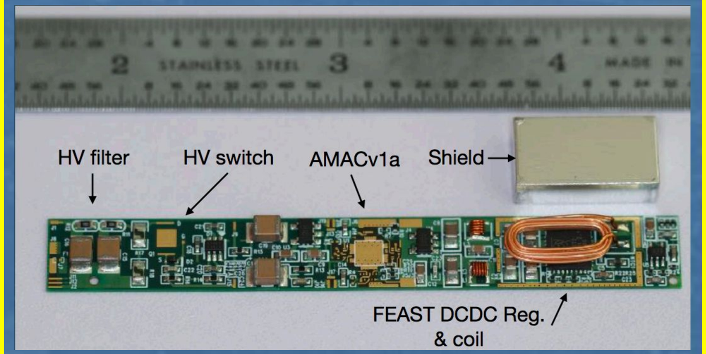
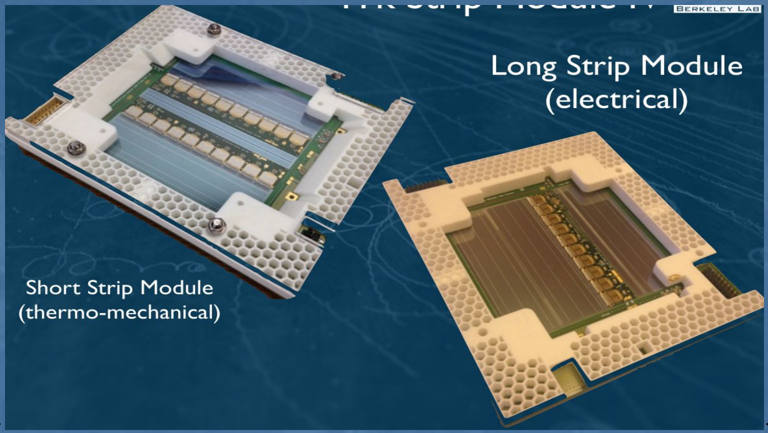
Some Examples of Recent R&D



Design and test of pixel front end readout chip



Power control board for Strip tracker

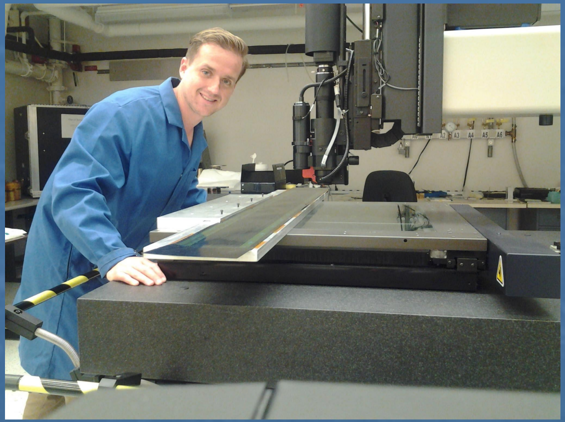


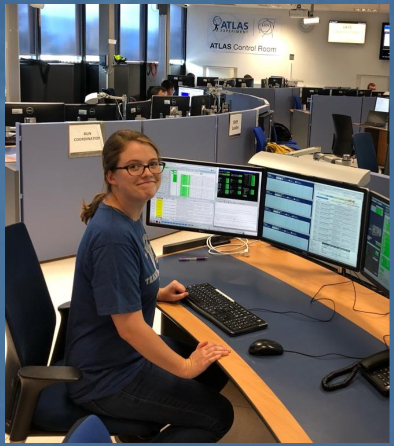
Strip detector module

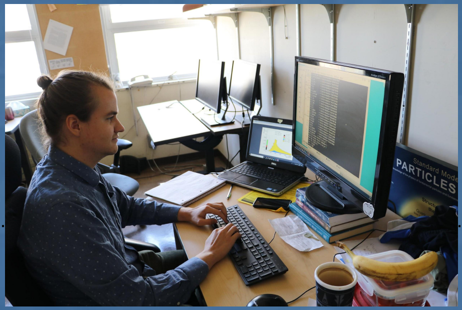
Advanced carbon composite for mechanical support

Where can you fit in

- Berkeley students are fully integrated into the experiment
  - Contributions to future upgrades through hardware studies at Berkeley
  - ~1 year living at CERN helping to make ATLAS run (depends on shutdown schedule)
  - Can (if desired) contribute to incorporation of latest software techniques (machine learning, data mining) into data collection and analysis
  - Wide choice of world-class thesis topics







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UC Berkeley ATLAS PhD Theses since 2011

Lauren Tompkins (Assistant Professor, Stanford U) A Measurement of the proton-proton inelastic scattering cross-section at √s=7 TeV with the ATLAS detector at the LHC

Michael Leyton (postdoc Berlin HU) Minimum Bias Measurements with the ATLAS Detector at the CERN Large Hadron Collider

Maxwell Scherzer (Goldman Sachs) Measurement of the Y(1S) Production Cross Section in Proton-Proton Collisions at Center of Mass Energy 7 TeV

Seth Zenz (faculty at Queen Mary) Properties of Jets Measured with Charged Particles with the ATLAS Detector at the Large Hadron Collider

Andre Bach (Uber) Search for Pair Production of a New b' Quark that decays into a Boson and a Bottom Quark with the ATLAS Detector at the LHC

Joe Virzi (Amphor Security) A Measurement of the Underlying Event Distributions in Proton-Proton Collisions at √s=7 TeV in Charged-Particle Jet Events using the ATLAS Detector at the Large Hadron Collider

Loiuse Skinnarl (assistant professor at Northeastern) A Search for Physics Beyond the Standard Model using Like-Sign Muon Pairs in pp Collisions at √s=7 TeV with the ATLAS Detector

Peter Loscutoff (Clover Health) Search for resonant WZ to lvll production using 13 fb-1 in √s=8 TeV p-p collisions with the ATLAS detector

fb-1 √s=8 TeV dataset collected with the ATLAS detector

UC Berkeley ATLAS PhD Theses since 2011

Ana Ovcharova (postdoc UCSB) Measurement of the top quark pair differential cross-section at high top quark transverse momentum in $\sqrt{s}$ = 8 TeV proton-proton collision data collected with the ATLAS detector at the LHC

Alexander Sood Evidence for the production of two W bosons with the same electric charge and two jets in 20.3 fb^{-1} of pp collisions at $\sqrt{s}$=8 TeV using the ATLAS detector

David Yu (postdoc Brown U) Searches for new phenomena using events with three or more charged leptons in pp collisions at $\sqrt{s}$=8 TeV with the ATLAS detector at the LHC

Jackie Brosamer (Square) Measuerment of jets produced in top quark events using the em final state with two b-tagged jets in pp collisions at $\sqrt{s}$=8 TeV with the ATLAS detector

Robert Clarke (US Navy) A Search for Lepton-Flavor-Violating Decays of the Higgs Boson with hadronically decaying tau lepsons in the 20.3 fb-1 $\sqrt{s}$=8 TeV dataset collected with the ATLAS detector

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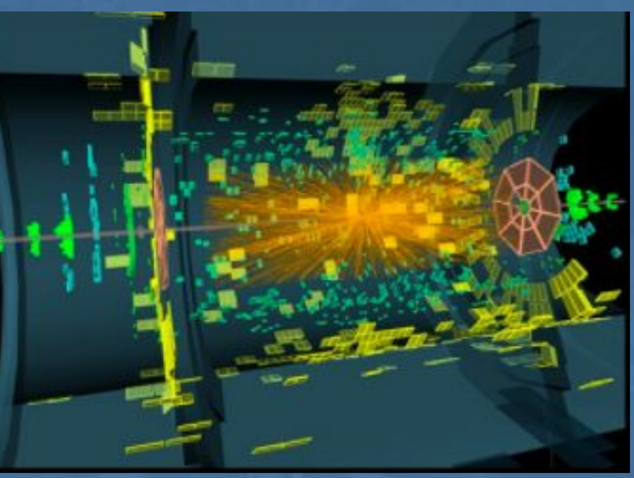
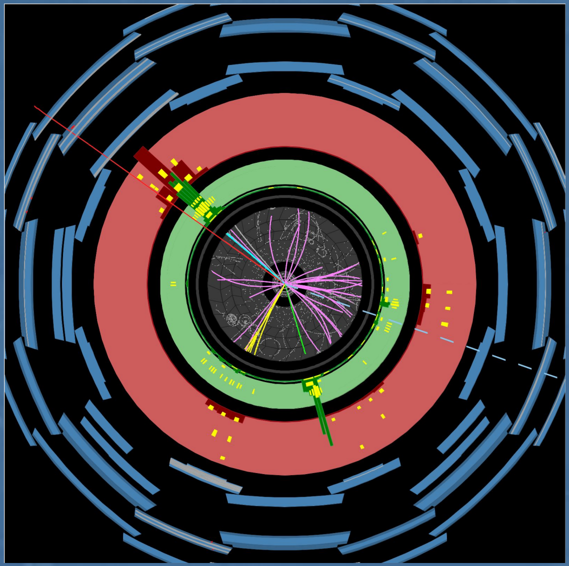
Advanced machine learning application

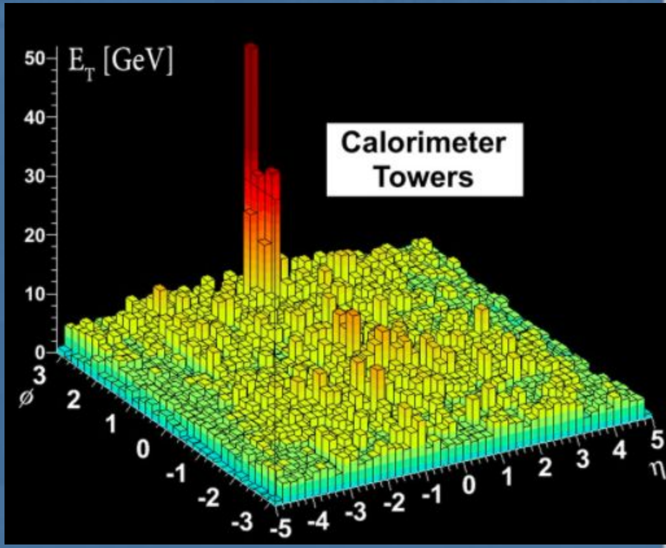
Machine learning algorithms are known to be powerful in extracting features from images

We can consider the top-quark as a feature

How do we present data as an image?







If we can extract top-quark, we can use the same principle to extract any particle we want

Supersymmetry

- SUSY is a popular theory that postulates that there is a symmetry between bosons and fermions
- It solves the Hierarchy problem because SM contribution to the dmh2 and their SUSY counterparts contributions cancel out each other
- In the most popular implementation of the SUSY, minimal SUSY SM, the lightest susy particles do not decay, and are a perfect candidate for dark matter particles
- Practically, SUSY gives a lot interesting signatures to look at. These signatures may also arise from other new physics.