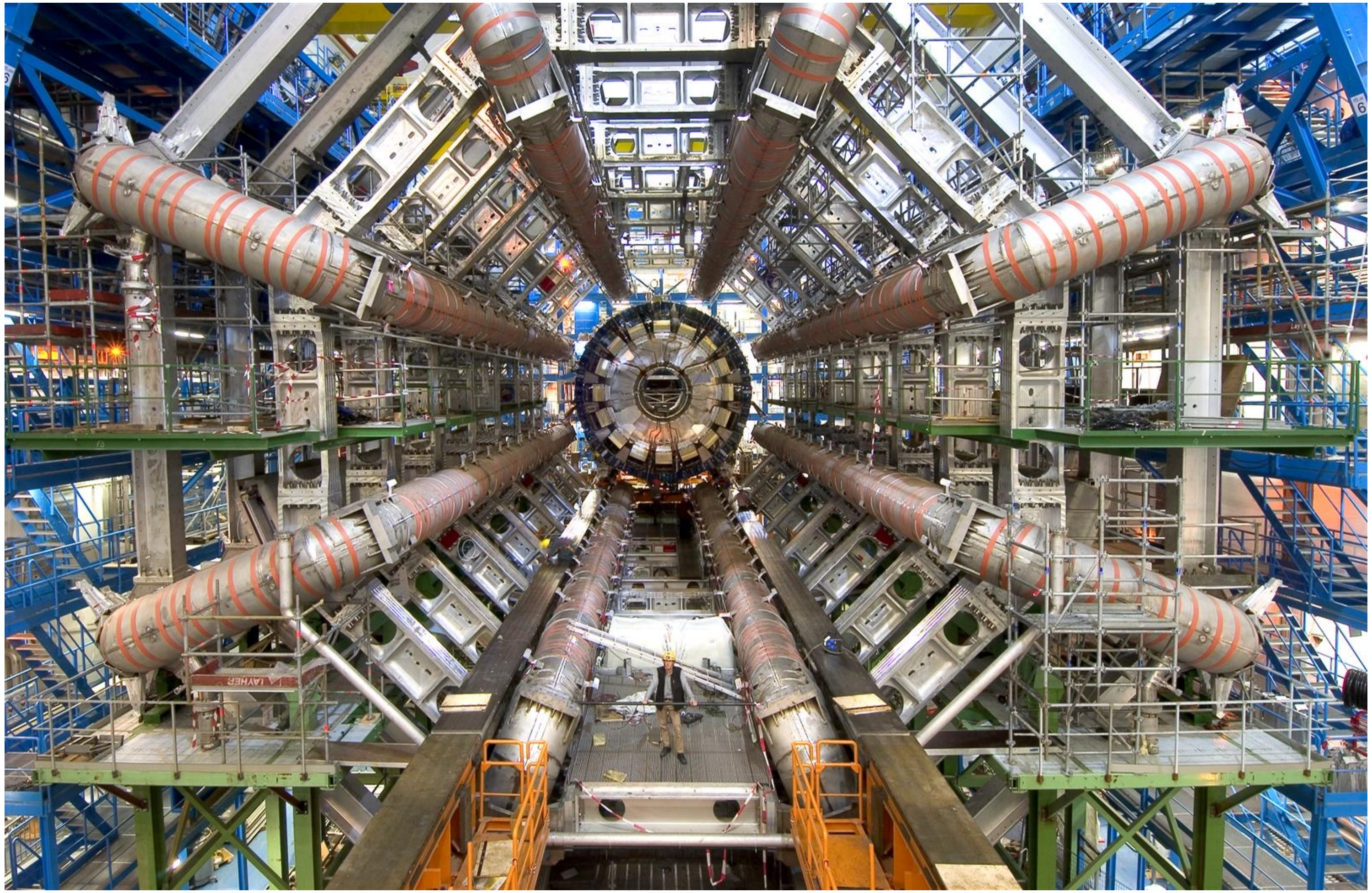
TRIUMF

The ATLAS Detector at the Large Hadron Collider



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University of Victoria Adjunct Prof.

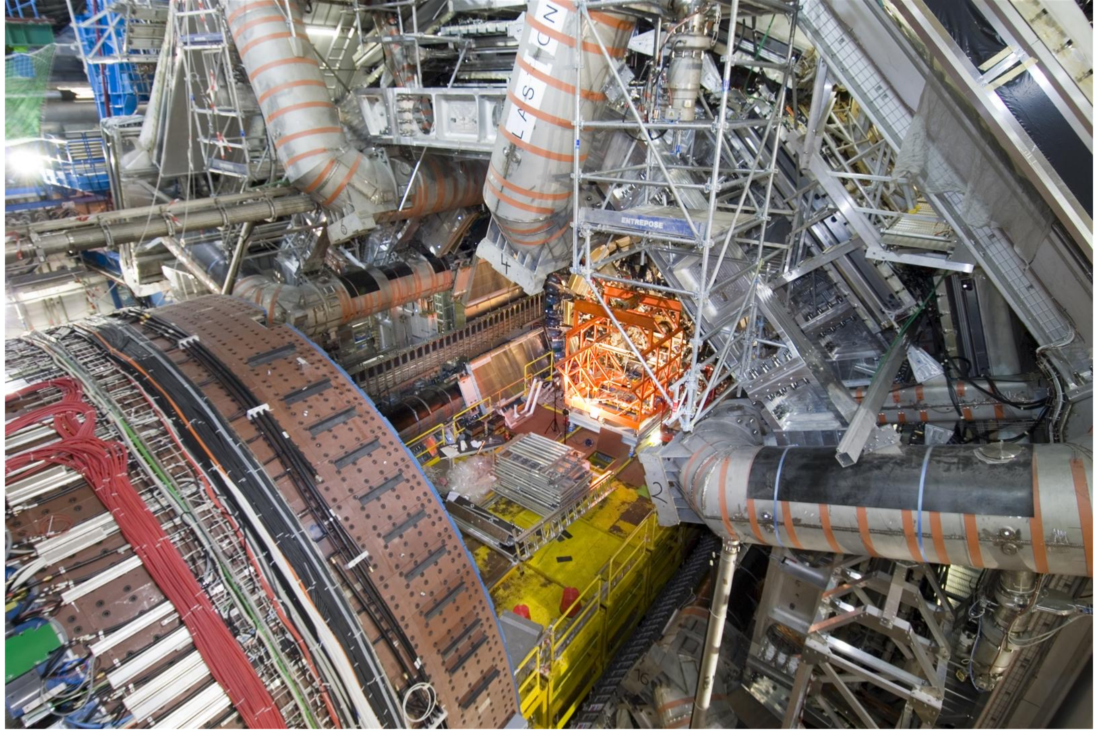
McDonald Institute Summer Particle (Astro)Physics Workshop

May 16, 2024

ATLAS EXPERIMENT

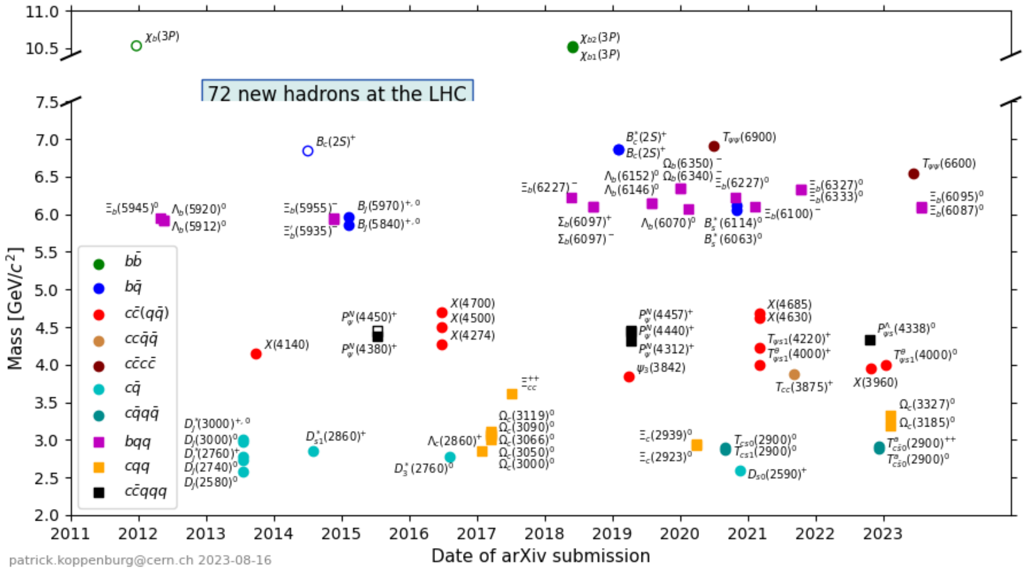
Discovery, accelerated

The Particle Physics of ATLAS



- LHC “creates weird particles by smashing boring ones together”
  - (as Ben Tam once put it in the intro to this workshop)
- Our “boring” particles are mostly protons
  - (protons are actually very interesting: beyond scope of this talk; occasionally we also smash lead and other heavy ions)
- Weird particles LHC makes include:
  - Higgs bosons*, top quarks, W and Z bosons
    - These are all elementary particles
  - Heavy hadrons (made of quarks)
    - Including exotica like tetraquarks and pentaquarks
  - … and *maybe* also charginos, neutralinos (a great DM candidate), Z’, squarks, gluinos…?
    - (But we have not observed those yet)

LHC has [now discovered 72 hadrons and 1 fundamental gauge boson]



Large Hadron Collider – the biggest machine in the world

- Planning started in 1980s
  - First collisions 2009
  - Expected to run until >2040
- For Run 3:
  - E_{beam}=6.8 TeV (E_{cm}=13.6 TeV)
- 120 billion protons/bunch
  - 2808 bunches / beam
  - 11245 circuits / second

Brigitte told you more about accelerators yesterday

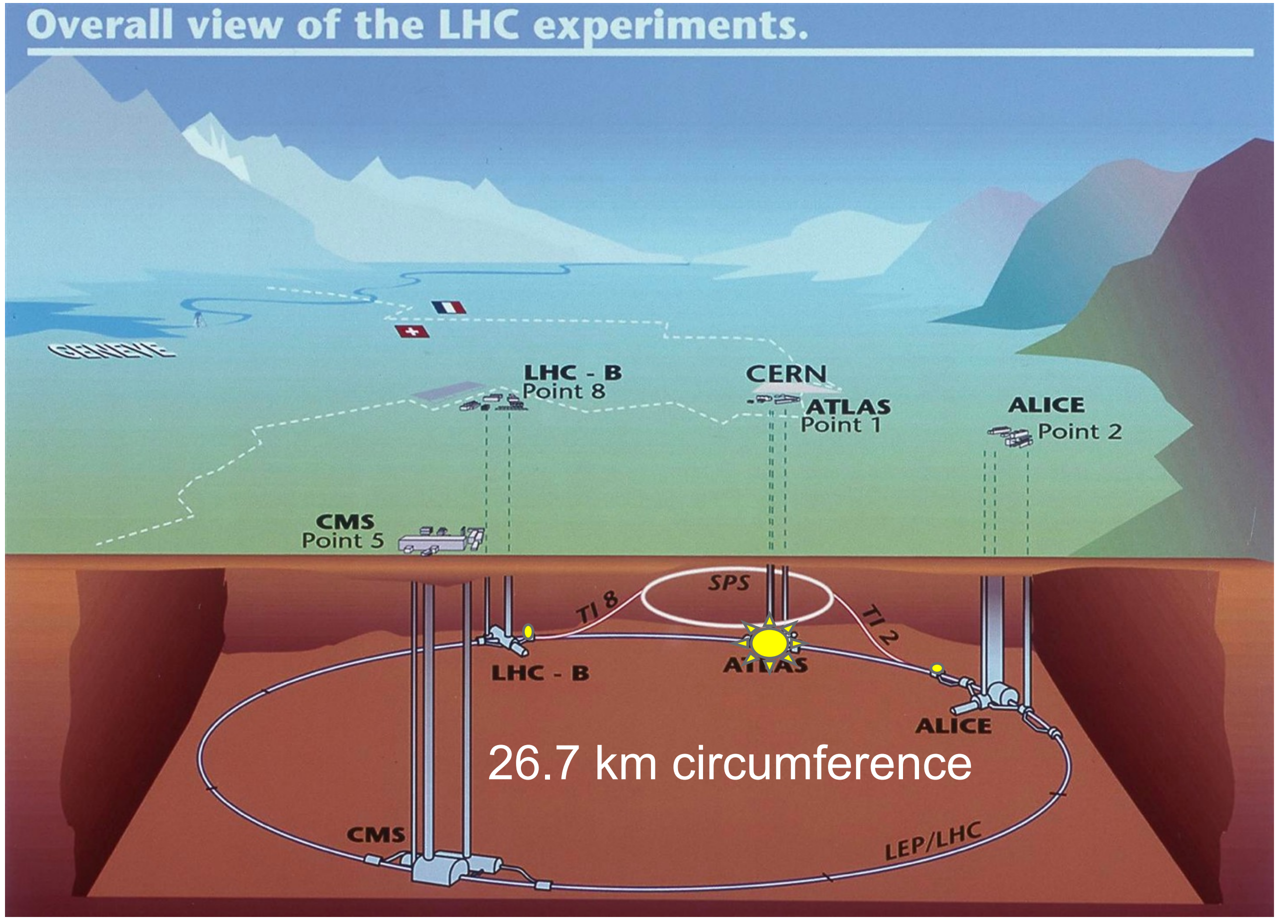
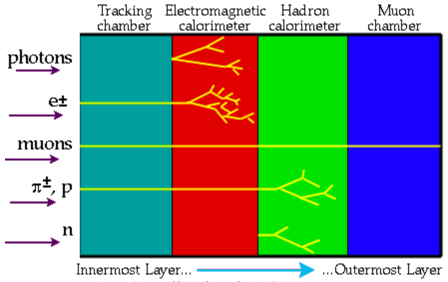
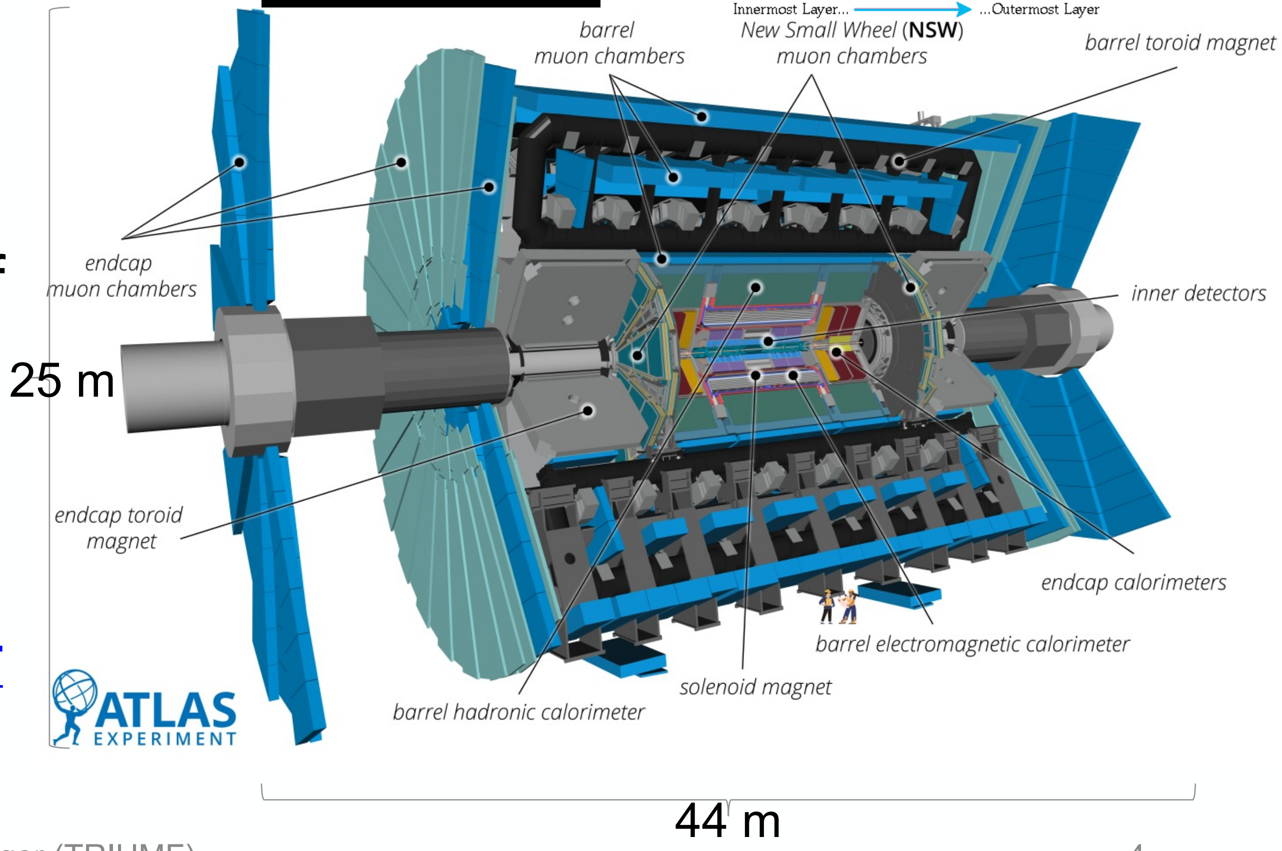


Image: CERN

The ATLAS Detector – our eyes on the subatomic world

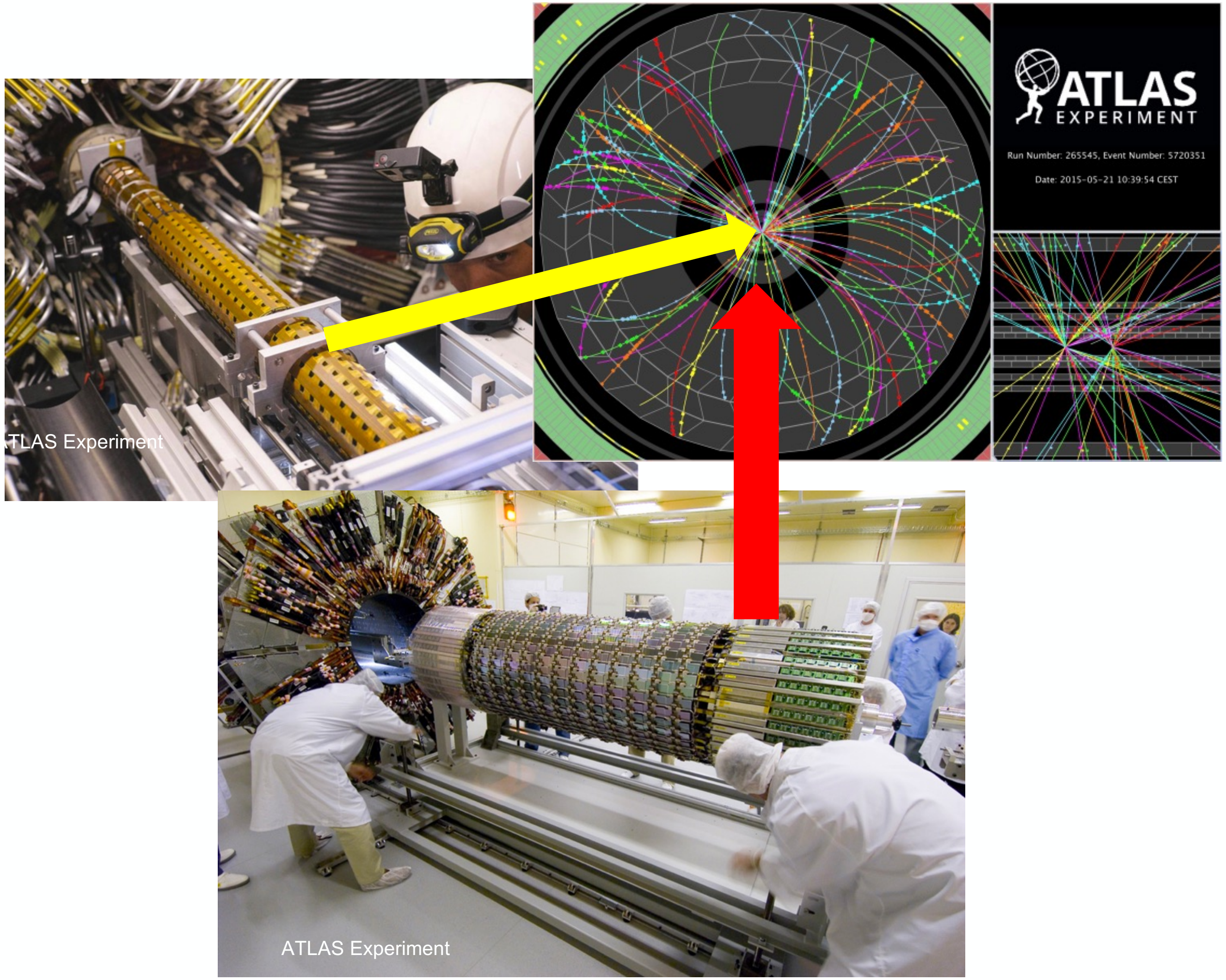
- Most massive new particles are unstable & decay before even leaving beam pipe:
    - NO HIGGS DETECTOR!
    - No top quark, Z or W detector
- We reconstruct *short-lived massive* particles from traces of their (relatively) *stable remnants*: **electrons**, **photons**, **muons**, **protons**, **pions**, so we need…
    - a **General-Purpose** detector!
- http://atlas.cern/discover/detector

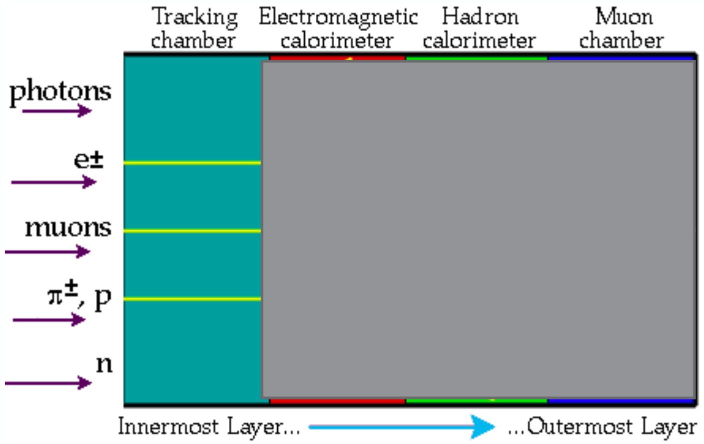




Detecting charged particles – the Inner Detector (Tracker)

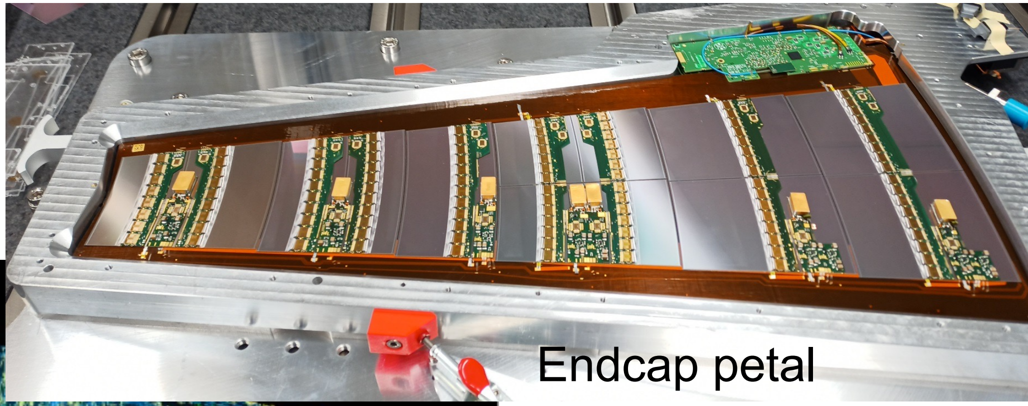
- **Charged particles ionize** material
  - Gas or silicon (tracker material is *low-density*)
  - Leave ionization track of stripped-off electrons
  - Electric field (HV wires in gas, bias on the Si itself for Si) makes charges drift toward readout electrodes
- **Charged particles bend** in a magnetic field
  - Tracker sits in strong solenoid magnet providing axial B-field, so ionization tracks curve in transverse plane
  - Bending *direction* depends on charge
  - Bending *radius* measures momentum
- ATLAS uses
  - silicon pixels and strips for high resolution near beamline
  - straw tubes (with transition radiation detection) farther out, to give many tracking points economically

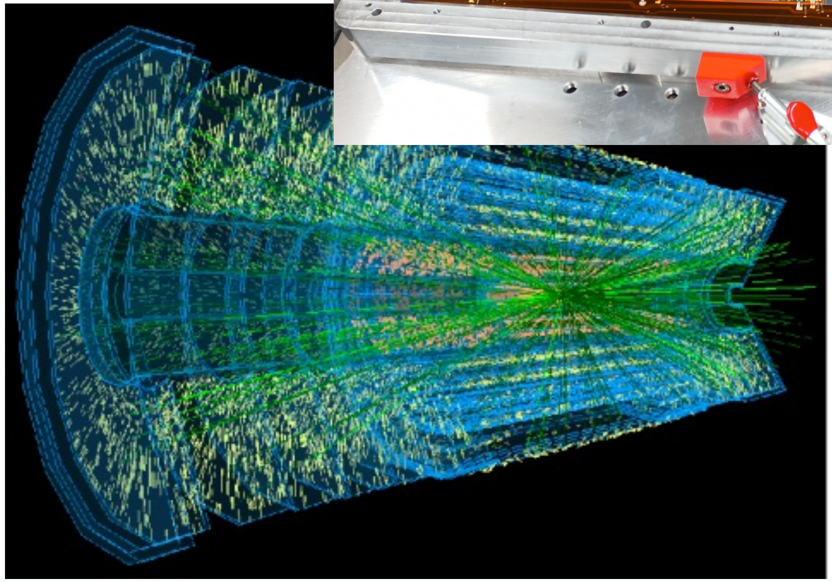


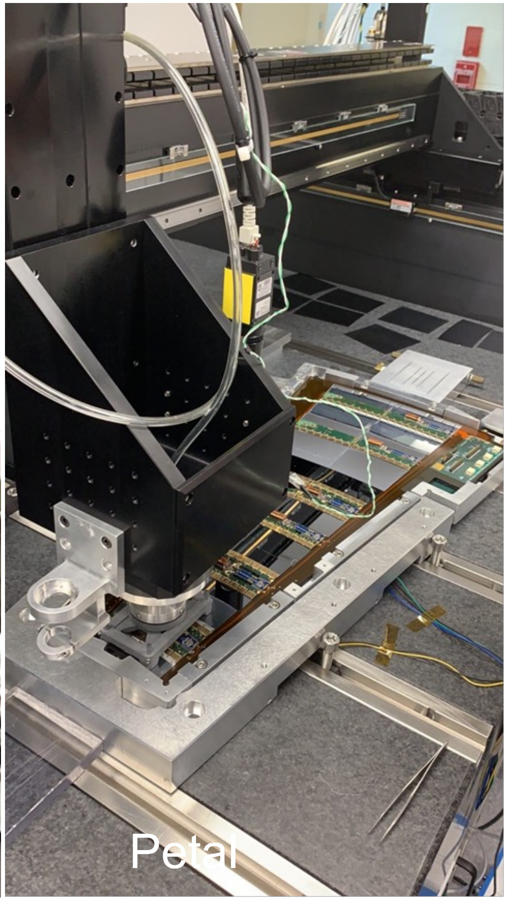


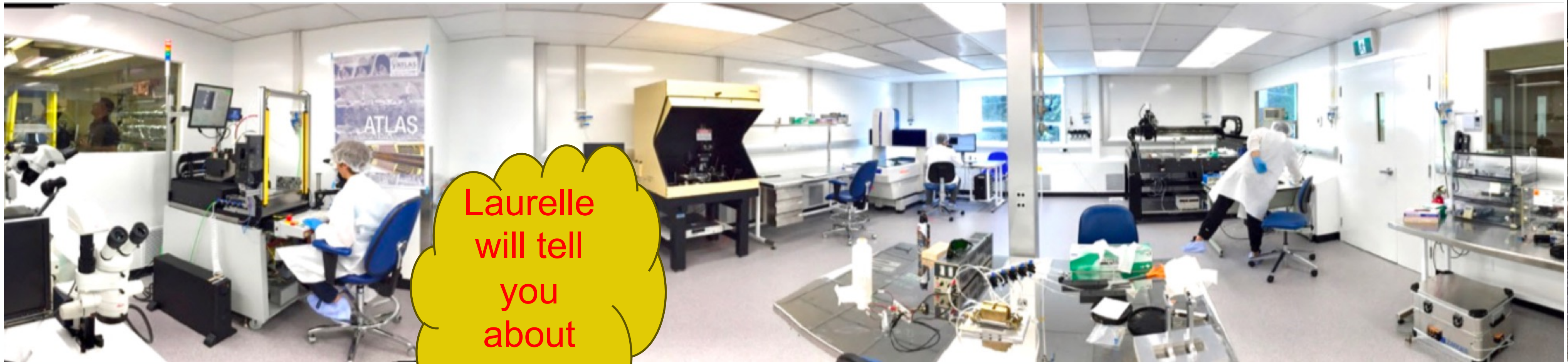
Inner detector upgrades in Canada

- For HL-LHC need to replace entire inner tracker
- All-silicon, same size as old inner detector
  - no more straw tubes, better for high-rate environment
  - MANY more readout channels
- Building 1500 endcap strip modules in Canada





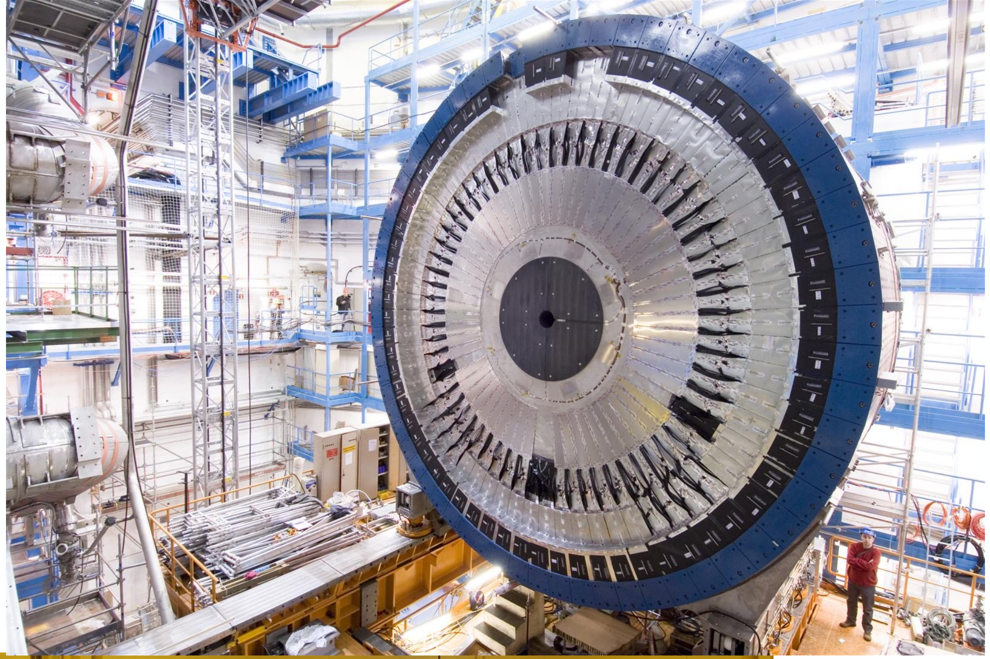


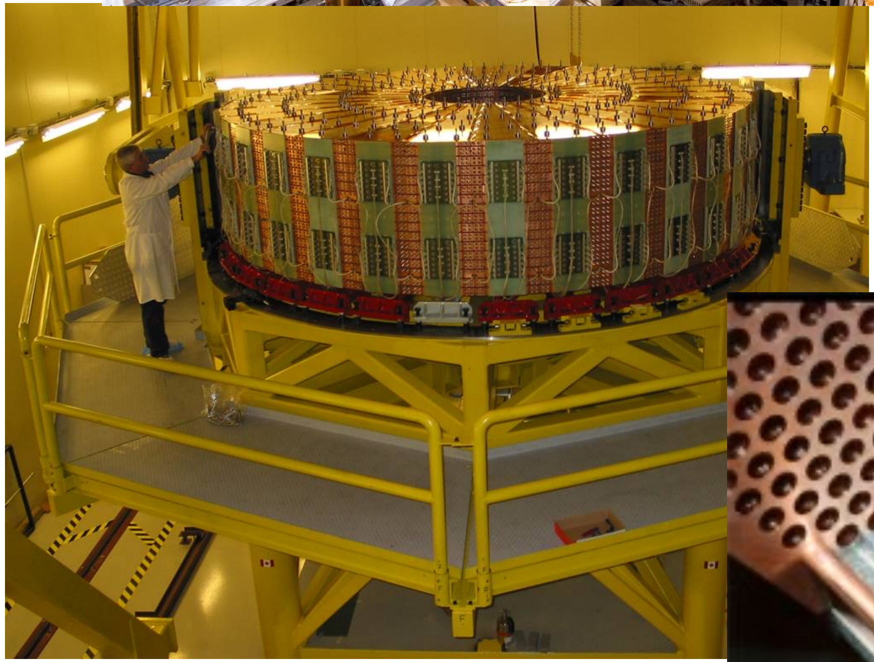


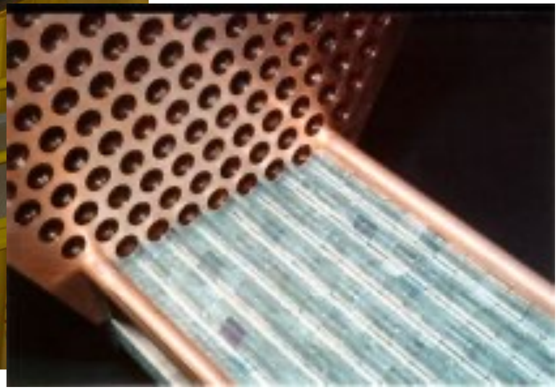
Laurelle will tell you about ITk…

Measuring particle energy in Calorimeters

- Calorimeters measure (or sample) energy deposited as they **stop** particles
- Complementary to tracker momentum measurement for charged particles
- *Only* way to measure *neutral* particles
  - Neutron, $\boldsymbol{\pi}^0$, K^0, photon…
- While trackers are light (non-destructive measurement), calorimeters are dense: goal is to **absorb all energy** of particle!
- ATLAS uses *sampling* calorimeters:
  - Interactions occur mainly in dense **absorber** layers (lead, copper, tungsten)
  - Energy deposits detected in thin **active** layers (either LAr ionization with copper readout pads, or plastic scintillator)

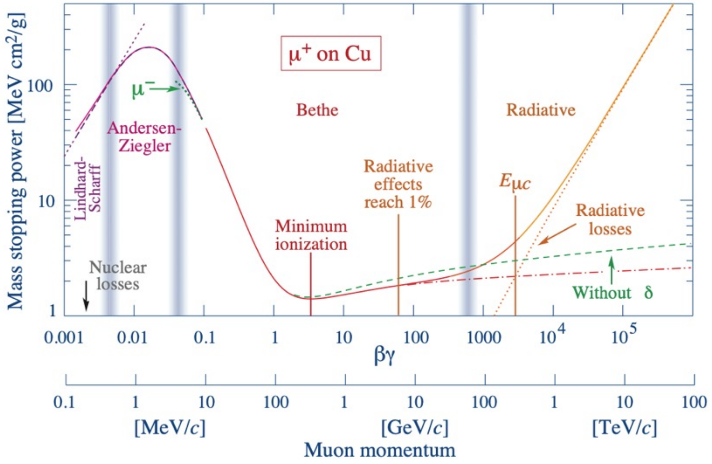


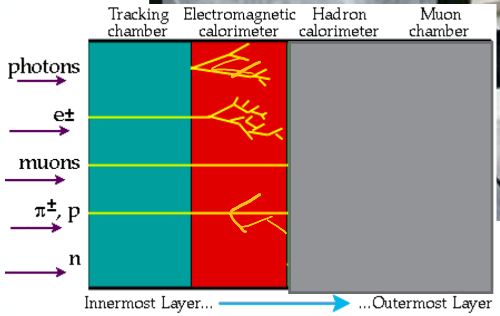




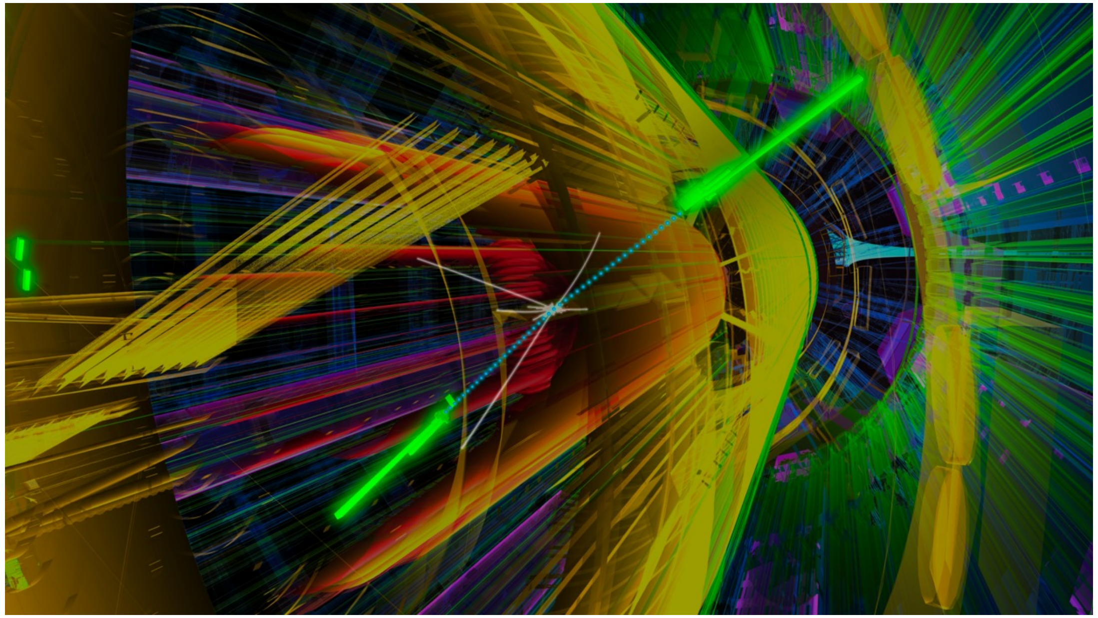
Electromagnetic Calorimeters

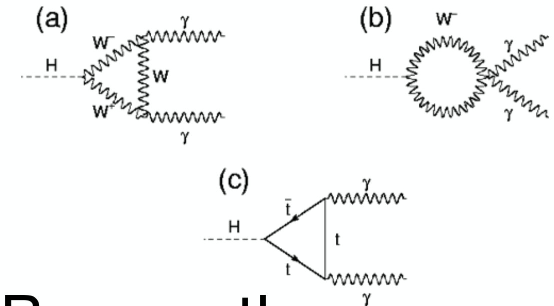
- First stop the light particles
  - Everything charged except e± is minimum-ionizing at LHC energies
- Energy loss via *electromagnetic showers*
  - Distinguishes e± and γ from heavier electromagnetically interacting particles
  - Radiated energy goes into pair production $\gamma \rightarrow e^+e^-$ & bremsstrahlung
    - cascades into increasingly low-energy e^+e^- pairs and photons until not enough energy left for pair-production
  - EM showers are compact, "collimated"
- *Better resolution* than tracking for high-energy electrons
- ATLAS uses lead / LAr accordion calorimeters in both barrel and endcaps; copper / LAr in forward region (around beampipe, outside Inner tracker)

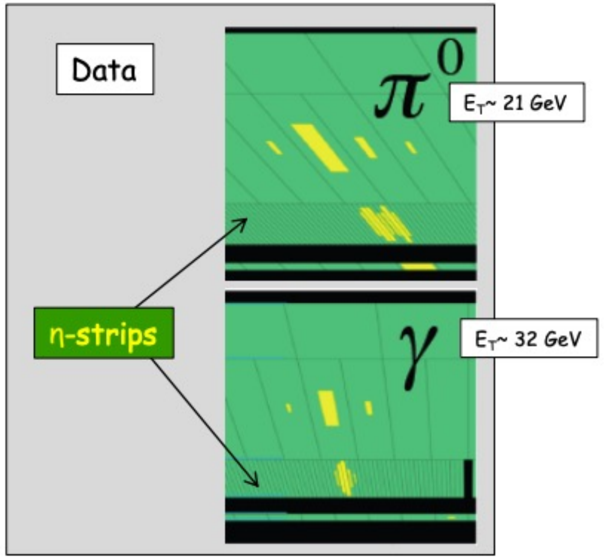




Measuring photons with the EM calorimeter

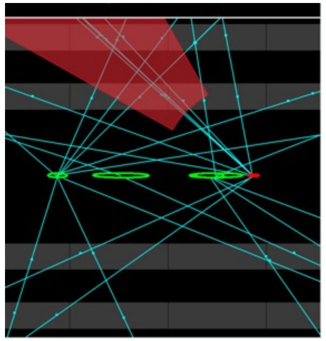






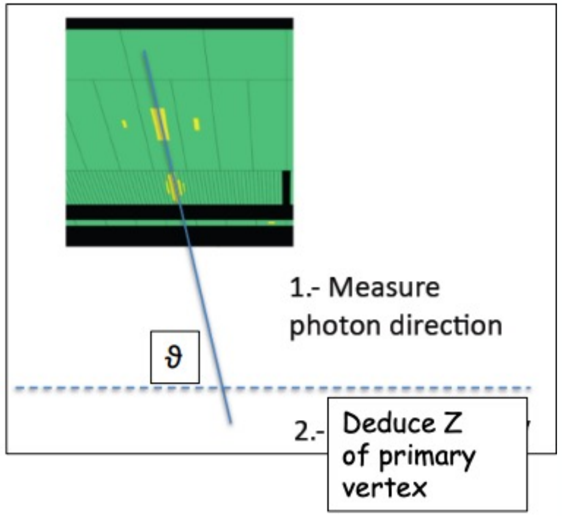
- Be sure they're *prompt* photons, not from π^0 decay
  - Huge background from hard $\pi^0 \rightarrow \gamma\gamma$
- Find vertex of origin
  - Tricky if the only energetic particles produced in interaction are neutral…
- Measure γ energies & angle between them

$$m_H^2 = m^2_{\gamma\gamma} = 2E_1E_2(1-\cos\alpha)$$



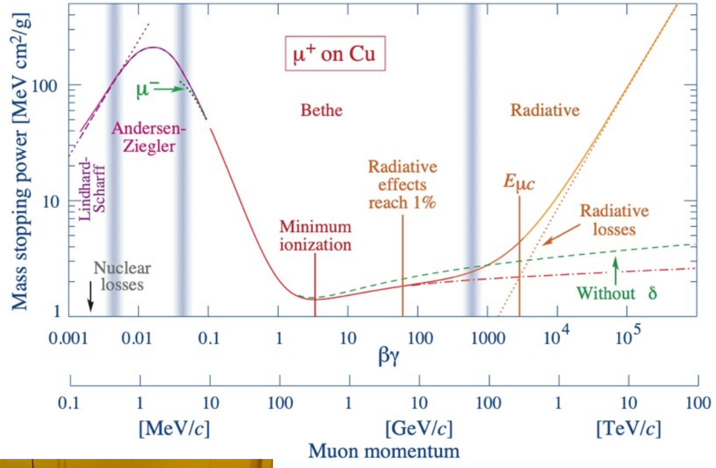
Longitudinal and lateral segmentation of calorimeter help identify vertex, measure angle, determine shower shape

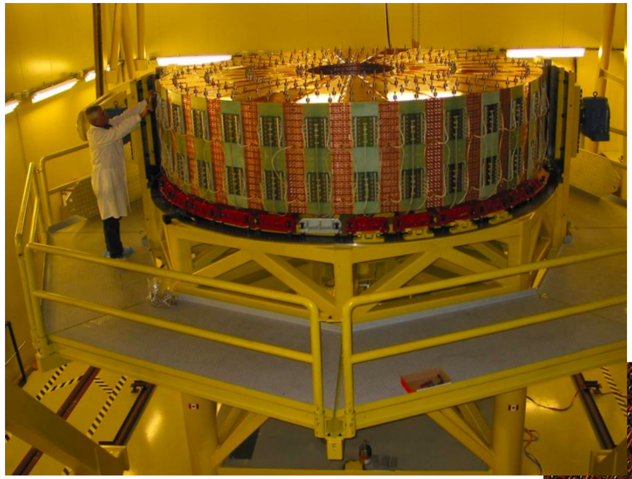
Why 1st layer of EM calorimeter is so finely segmented:

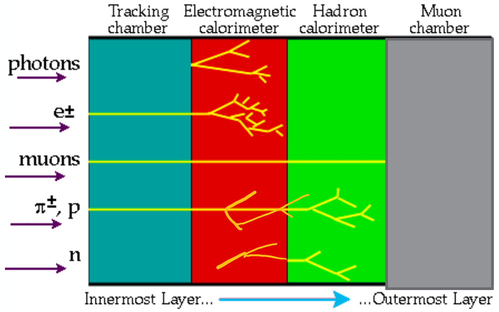


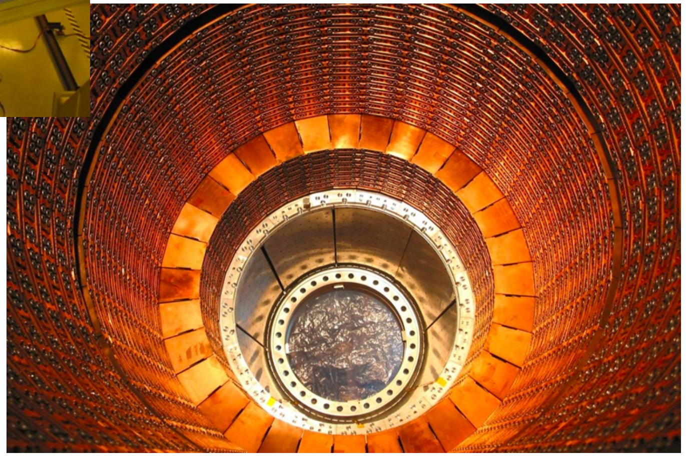
Hadron Calorimeters

- A prompt quark or gluon hadronizes immediately, forming a *jet* of **hadrons** (made of quarks)
  - Typically hadronic showers are not isolated
- Charged hadrons are much heavier than electrons
  - Minimum-ionizing particles (mips)
  - Very little EM shower development
- Neutral hadrons do not ionize at all
  - No track
  - No EM shower development for *long-lived* neutral hadrons
  - (π^0 decays almost instantly to $\gamma\gamma$ which *do* make EM showers…)
- Hadrons interact **strongly** with **nuclei** in detector material
  - *Many* processes, so less precise energy measurement:
    - Production of secondary hadrons
    - Nuclear excitation
    - Charged pion decays to muons and neutrinos
    - Neutral pion decays via EM showers (inside the hadronic showers)
  - Hadronic showers take longer to develop and are more sparse, irregular and spread out than EM showers
- ATLAS hadron calorimeters:
  - *Absorber* with massive nucleus, *active element* to detect energy…
  - iron / scintillating tiles in barrel;
  - copper / LAr in endcaps;
  - tungsten / LAr in forward







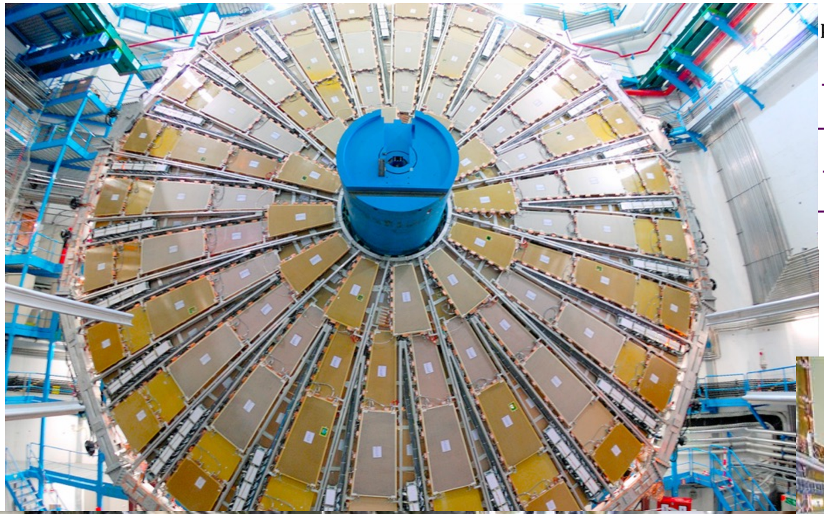


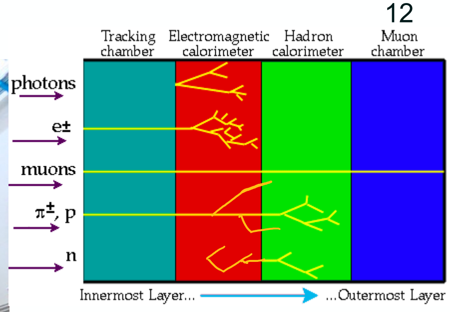
Building Liquid Argon Hadron Calorimeters in Canada

- TRIUMF project lead
- Copper plates machined at U.Alberta on TRIUMF horizontal milling machine
- Readout foils glued, pressed & die-cut at TRIUMF
- Foils, plates & spacers stacked at TRIUMF
- Cryogenic feedthroughs in Victoria
- Electronics in Alberta
- Forward calorimeters at Carleton and Toronto
- TRIUMF engineer designed integration tooling, supervised assembly at CERN
- TRIUMF & UVic built new electronics for trigger upgrade for Run 3, now installed
- Canadians also working on new electronics for readout upgrade for HL-LHC

Tracking Muons – particles that just don't stop

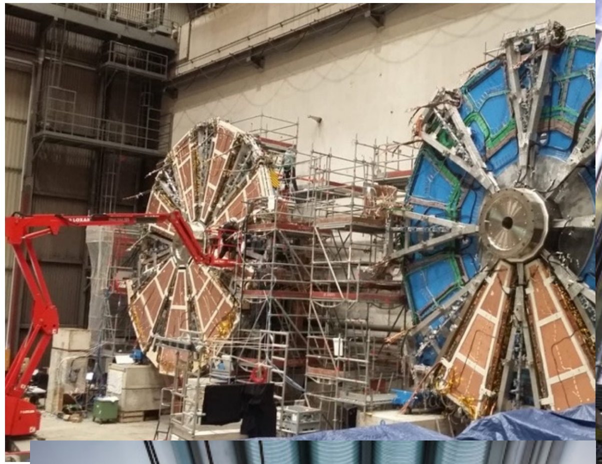
- Lifetime ~ 2μs: muon effectively <u>stable</u> in ATLAS (travel 100s of metres)
- Muon = electron? Not quite:
  - 200 times more massive – relativistic, but not *ultra*relativistic: Minimum ionizing
    - Lose ~3 GeV on average in calorimeters from ionization
  - Lose ~200^2X *less* energy than e by other radiative processes like bremsstrahlung
- Muon = pion? Big difference:
  - *No strong interactions*…
  - Muons emerge from calorimeters with nearly full energy, while pions stop.
    - 2nd **BIG** tracking system outside calorimeter just for muons

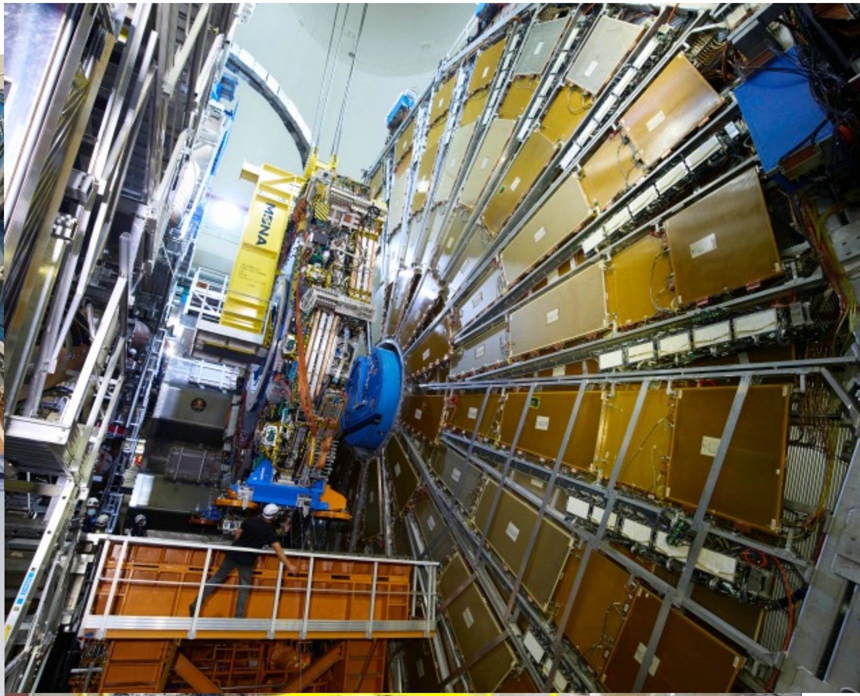


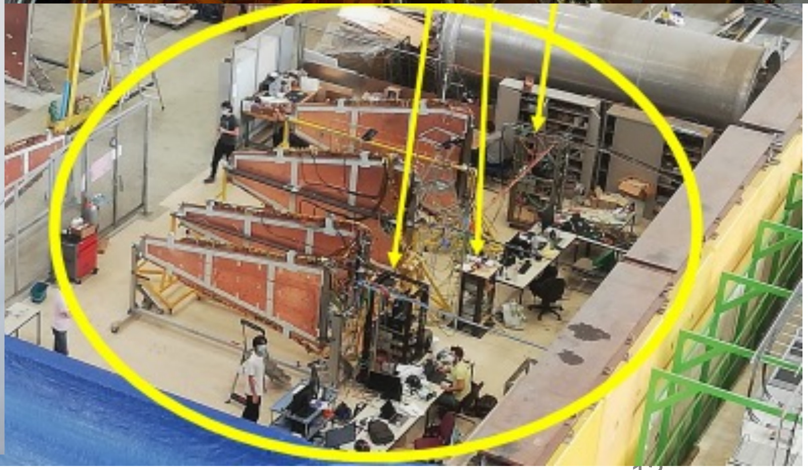


Muon system upgrades (my thing…)

- LHC is a work in progress
  - Collision rate (luminosity) keeps going up, in stages
  - Typically run for ~3-4 years, shutdown for 2 & upgrade LHC
  - Also upgrade ATLAS so it can keep up with the collision rate!
- Canada built 96 thin-gap chamber quadruplets (sTGC) for New “Small” Wheels for Muon system
  - Construction at TRIUMF / Carleton
  - Testing at McGill
  - Integration at CERN
  - Now installed & running
- Much faster than original Small Wheels
  - Allows track-matching in trigger
  - Needed to beat down “fake” muon background

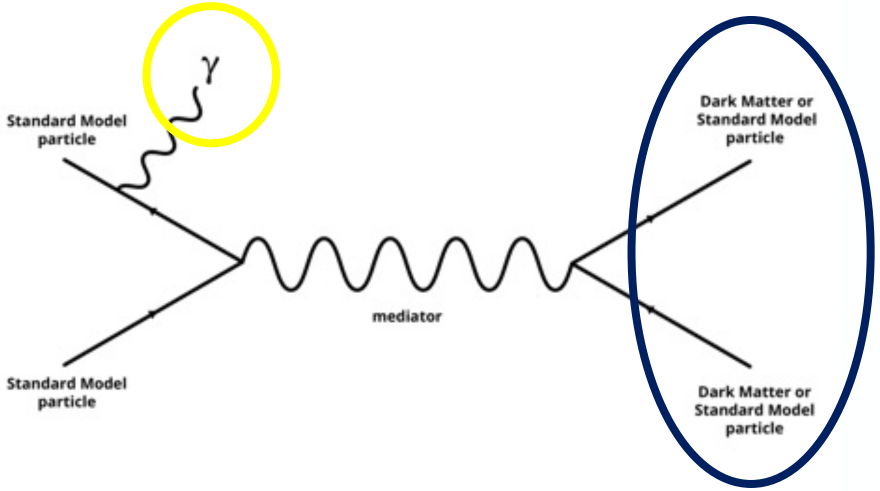


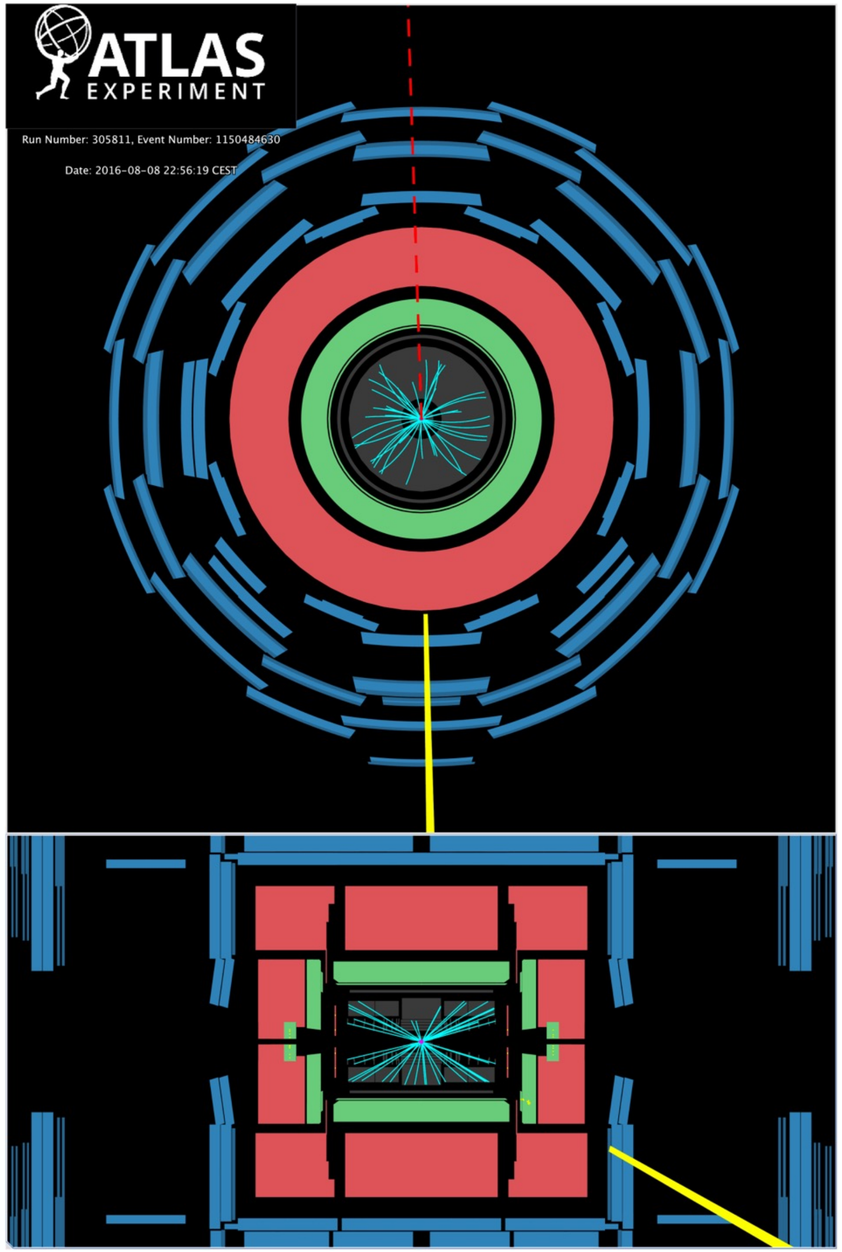




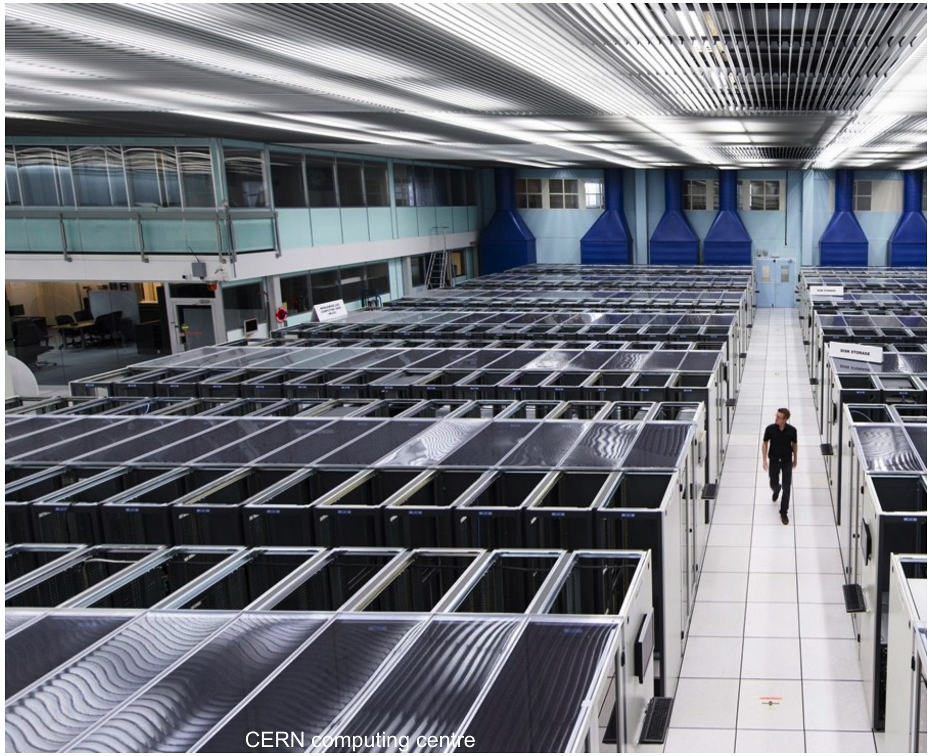
Finding “invisible” particles

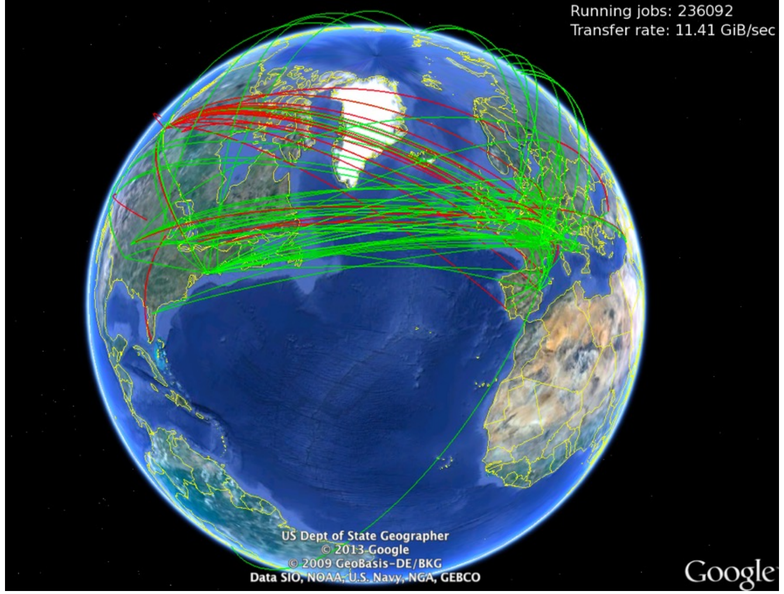
- ATLAS cannot directly detect neutrinos or dark matter, so if final state contains ONLY invisible particles, ATLAS won’t trigger, but…
- Conservation of momentum → momentum transverse to beam sums to zero
    - Detector cannot have any cracks or holes
- If the invisible particle(s) recoil off something you *can* see, you can trigger on the events!

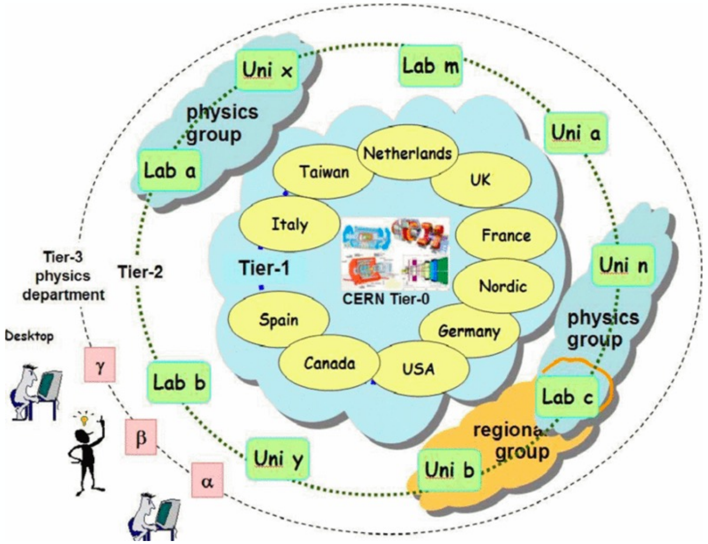




Computing

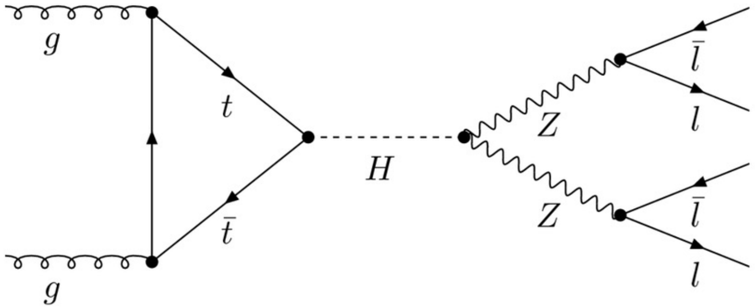


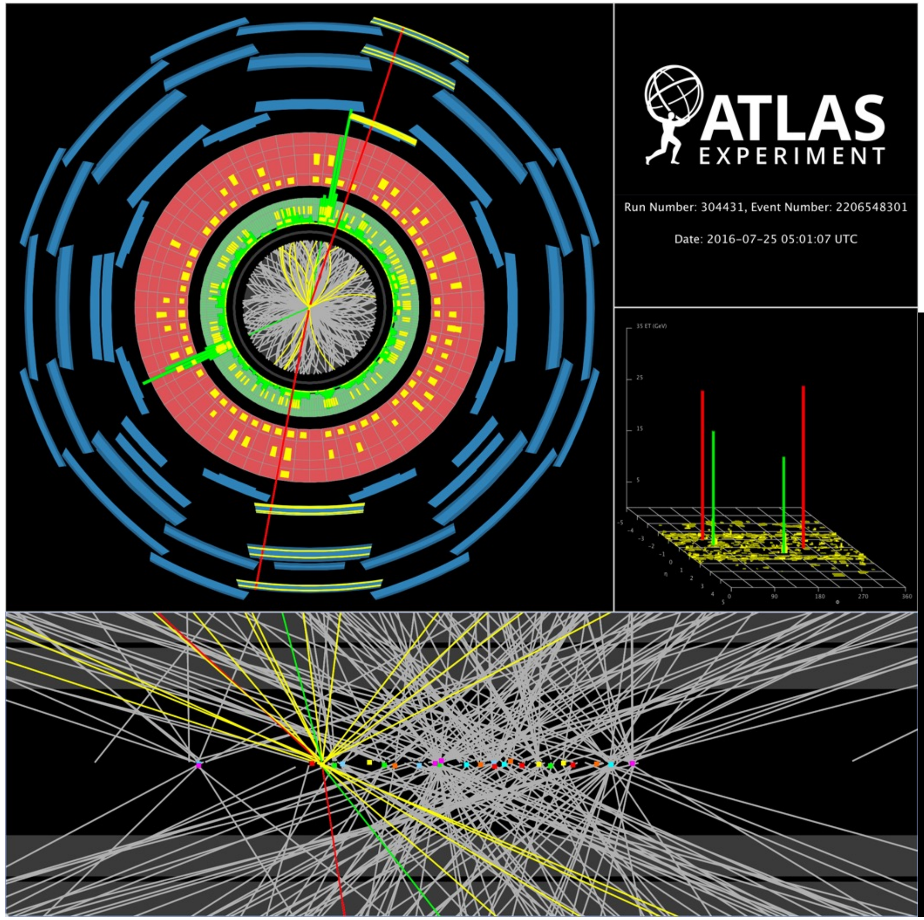




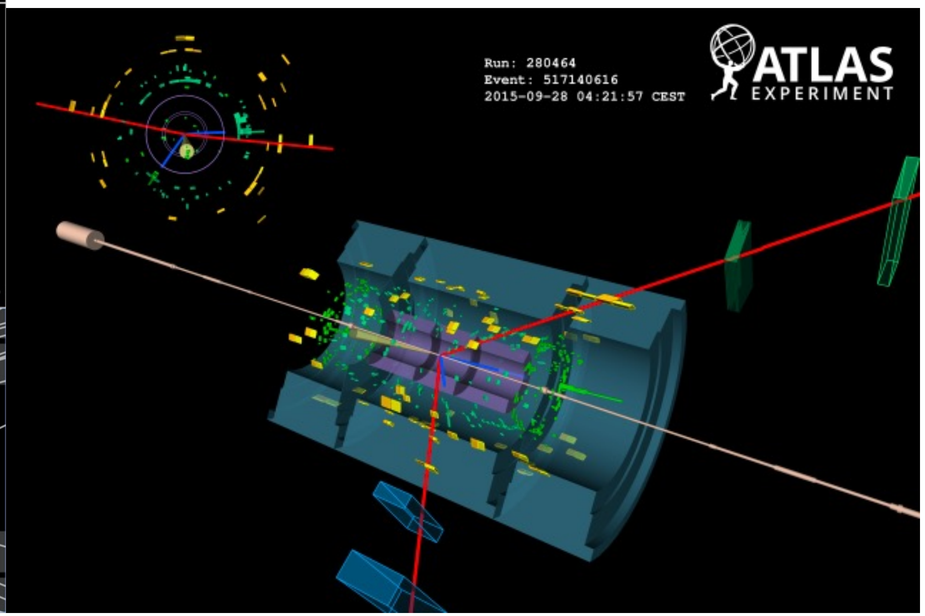
- 40 million colliding bunches / s
  - 10-60 pp collisions / bunch-Xing
- Trigger can keep ~1000 events / s
  - Never see the rest of the 40M collisions/s again - gone
- LHC experiments use over 2100 PB of disk
  - (at CERN, Tier-1 and Tier-2 centres - 170 centres)
- and over 2200 PB of tape storage
  - (at CERN and 14 Tier-1 centres)
- 10% of ATLAS Raw Data are stored at TRIUMF Tier 1 Centre (now located at SFU)

Close-up on “super-clean” $H \rightarrow e^+e^-\mu^+\mu^-$

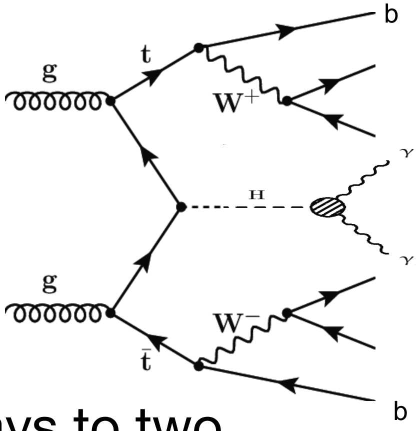


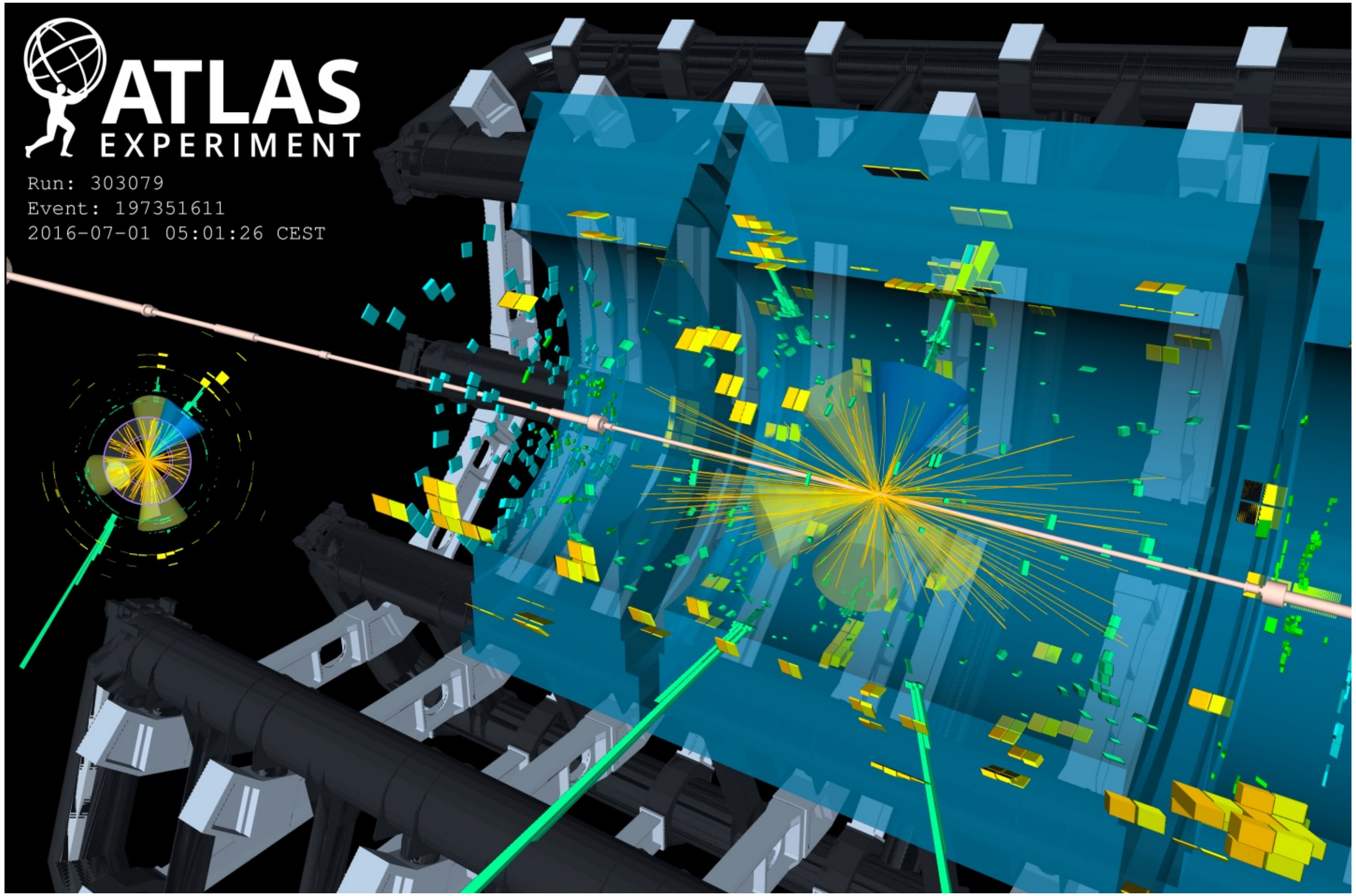


- Calorimeter and inner tracker for electrons
  - Calibration
- Muon spectrometer, tracker for muons
  - Alignment, alignment, alignment



ttH – why you need an omnipurpose detector





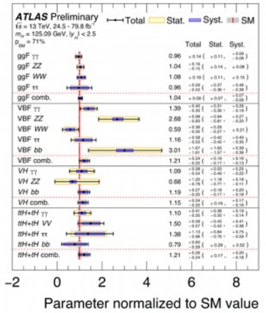
- Higgs decays to two photons in this example
  - EM calorimeter
- Both tops decay to W+b
  - W decay to 2 “light” quarks
  - (but can also decay to lepton plus neutrino)
- All quarks (except top) hadronize to form jets
  - Tracker, EM & hadron calorimeters
- Bottom quark jets contain b-hadron that decays in flight with displaced vertex
  - Silicon pixel vertex tracker

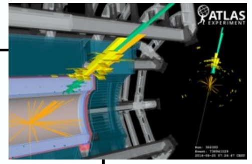
So, what do we do with all these particles?

Discover New Particle!

Measure its properties

Do precision measurements with it





Use it to search for new New Particles

Complain about annoying Higgs boson background in your Dark Matter search

Every ATLAS analysis is the work of a collaboration

- Behind every ATLAS (or CMS) results plot is a list of >2900 authors
  - Designing & building (and constantly upgrading) detector,
  - Keeping it working 24/7,
  - Calibrating it,
  - Reconstructing data,
  - Writing software,
  - Maintaining worldwide computing grid…
  - These tasks are all crucial – and mostly a lot of fun!
- ATLAS (or any detector) will never directly detect Higgs bosons, top quarks, etc.:
  - we detect charge & energy deposits from stable decay products
- Higgs is just one of many particles LHC is uniquely able to study
  - We also have far more top & W than anywhere has ever produced before
- ATLAS story is still just beginning:
  - we have run for ~40% of our projected lifetime and collected <10% of our ultimate dataset
- Discovery is a continuous process; still many previously unmeasured processes to observe and measure, and good chance to find more (totally) new particles