Physics and Computing with ATLAS and US ATLAS

Peter Onyisi

TIGER Workshop, 9 Apr 2025

The University of Texas at Austin

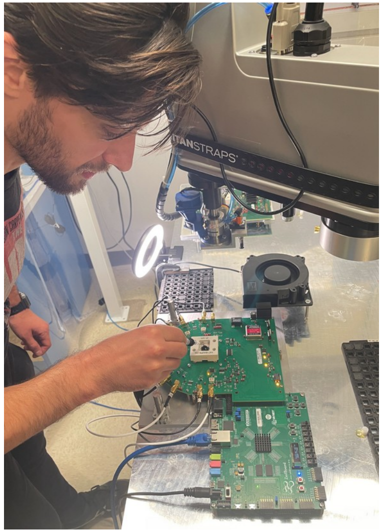
About Myself

- Founder and one of two PIs of the UT-Austin ATLAS group
  - supported by the Department of Energy
- 17 years on ATLAS
  - before then: CLEO-c and CDF experiments
- Deputy US ATLAS Maintenance and Operations manager
- Physics:
  - Higgs discovery
  - observation of top quark-Higgs boson interactions
  - searches for rare top quark decays
  - proton structure (multi-parton interactions)
  - rare bottom quark decays
- Main technical contribution: ATLAS data quality monitoring software
- Started as an “associated institute” with the University of Chicago, became a full member of ATLAS after becoming a two PI group

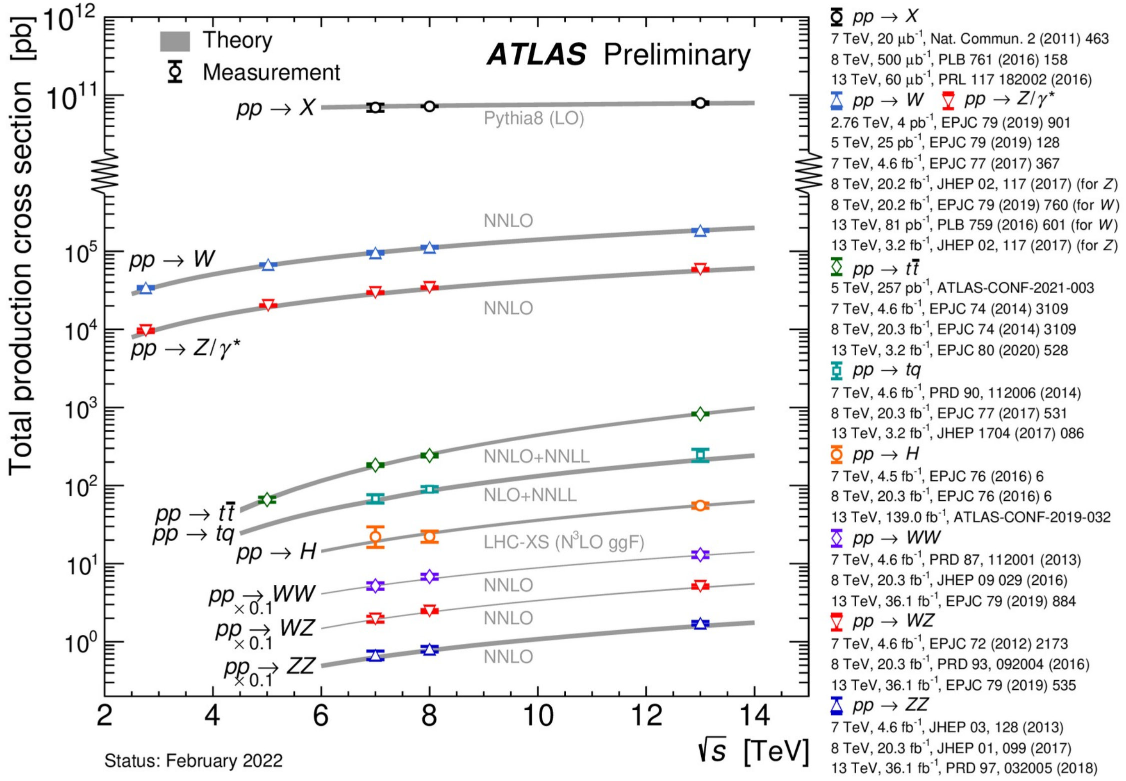
The UT-Austin Group

Physics is more friendly in a group…

- 17 people total – faculty, postdocs, engineers, grad and undergrad students
- I do more software, the other PI – Tim Andeen – is more hardware-oriented (liquid argon calorimeter electronics)
- Complementary physics interests – measurements vs searches



The Standard Model successfully predicts everything within its domain, but …



Electron anomalous magnetic moment:

Exp 0.001 159 652 180 48(18)
Th 0.001 159 652 182 03 2(720)

Incomplete list of problems

No gravity!

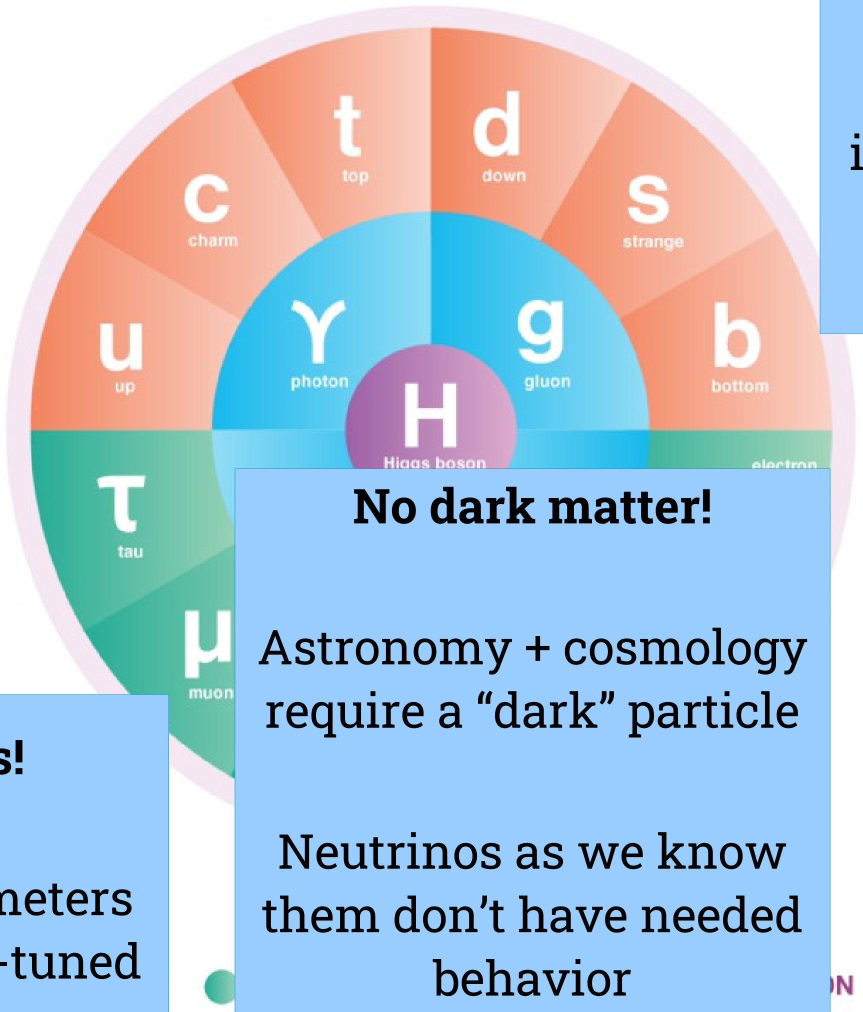
No verified theory of quantum gravity

No neutrino masses!

Neutrino masses require degrees of freedom beyond the SM

Naturalness!

Higgs field parameters seem highly fine-tuned



No dark matter!

Astronomy + cosmology require a “dark” particle

Neutrinos as we know them don’t have needed behavior

No dark energy!

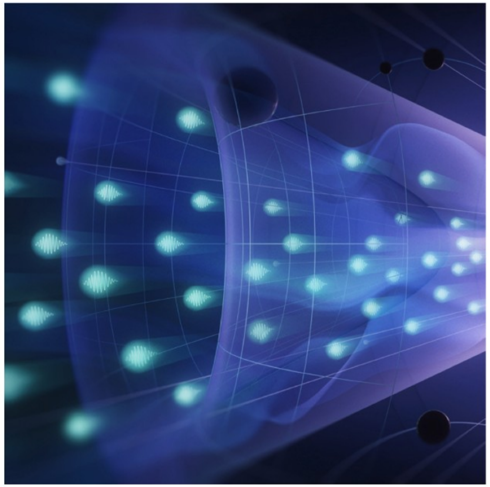
The universe is being inflated by an invisible source of energy – what?

Not enough matter!

Unable to generate enough asymmetry between matter & antimatter in the Big Bang

US Particle Physics Roadmap

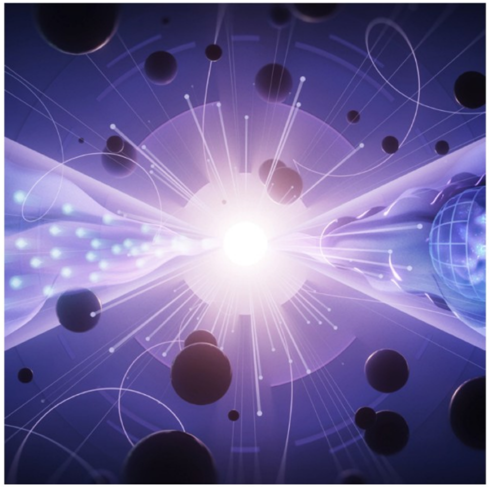
- LHC activities address four of the six science drivers for the next decade+ identified by the 2023 Particle Physics Project Prioritization Panel



Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

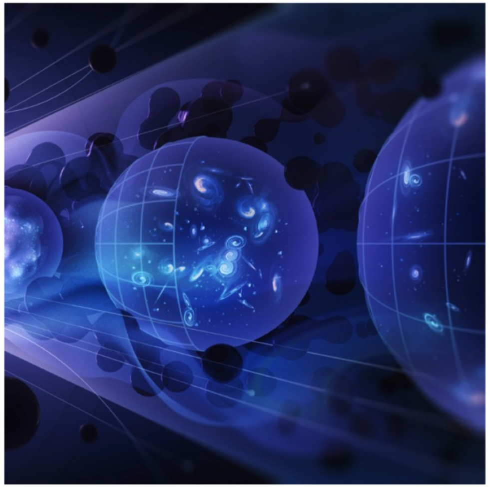
Reveal the Secrets of the Higgs Boson



Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

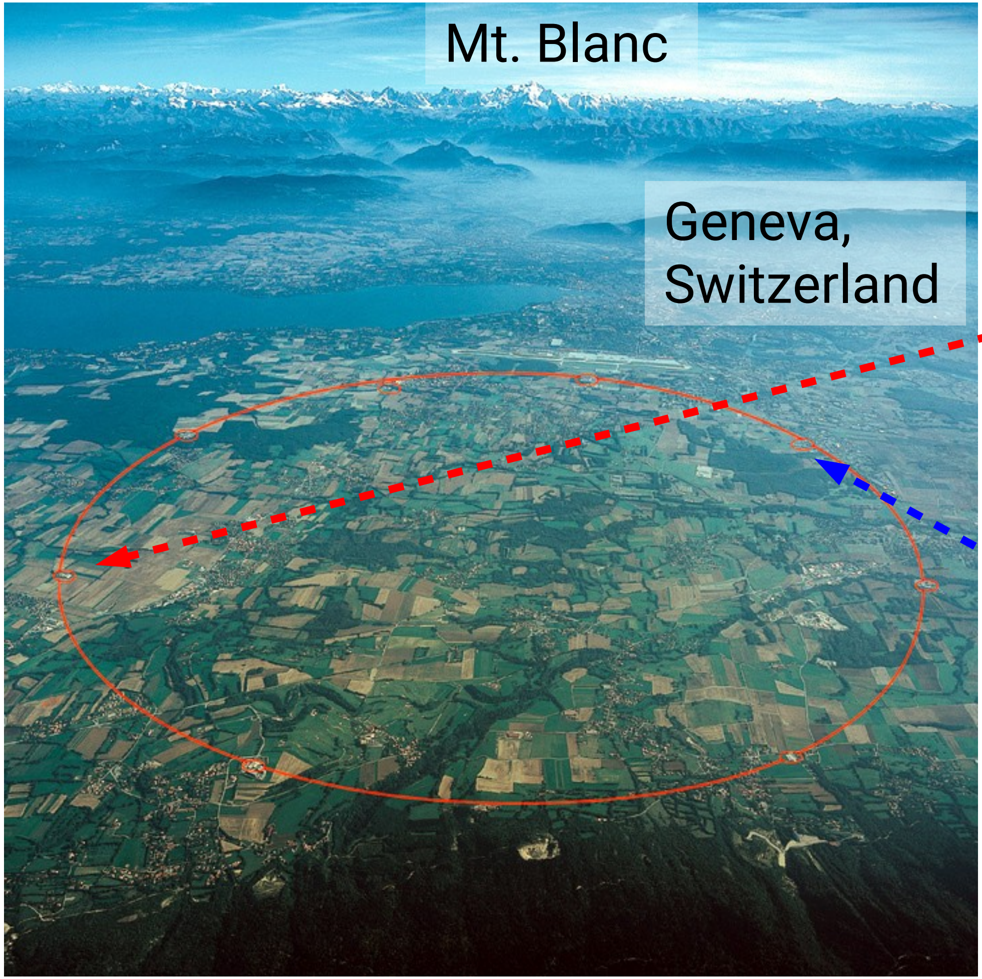
Pursue Quantum Imprints of New Phenomena



Illuminate the Hidden Universe

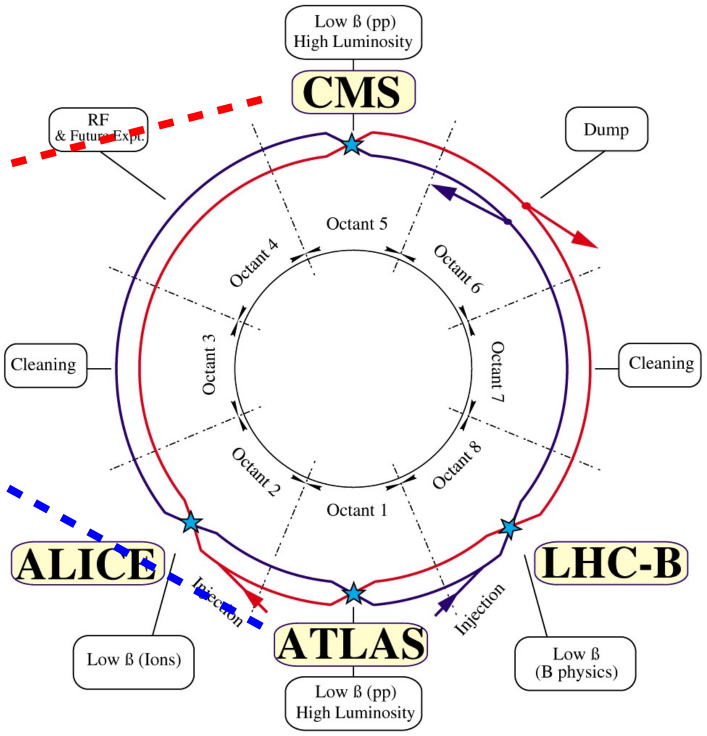
Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution



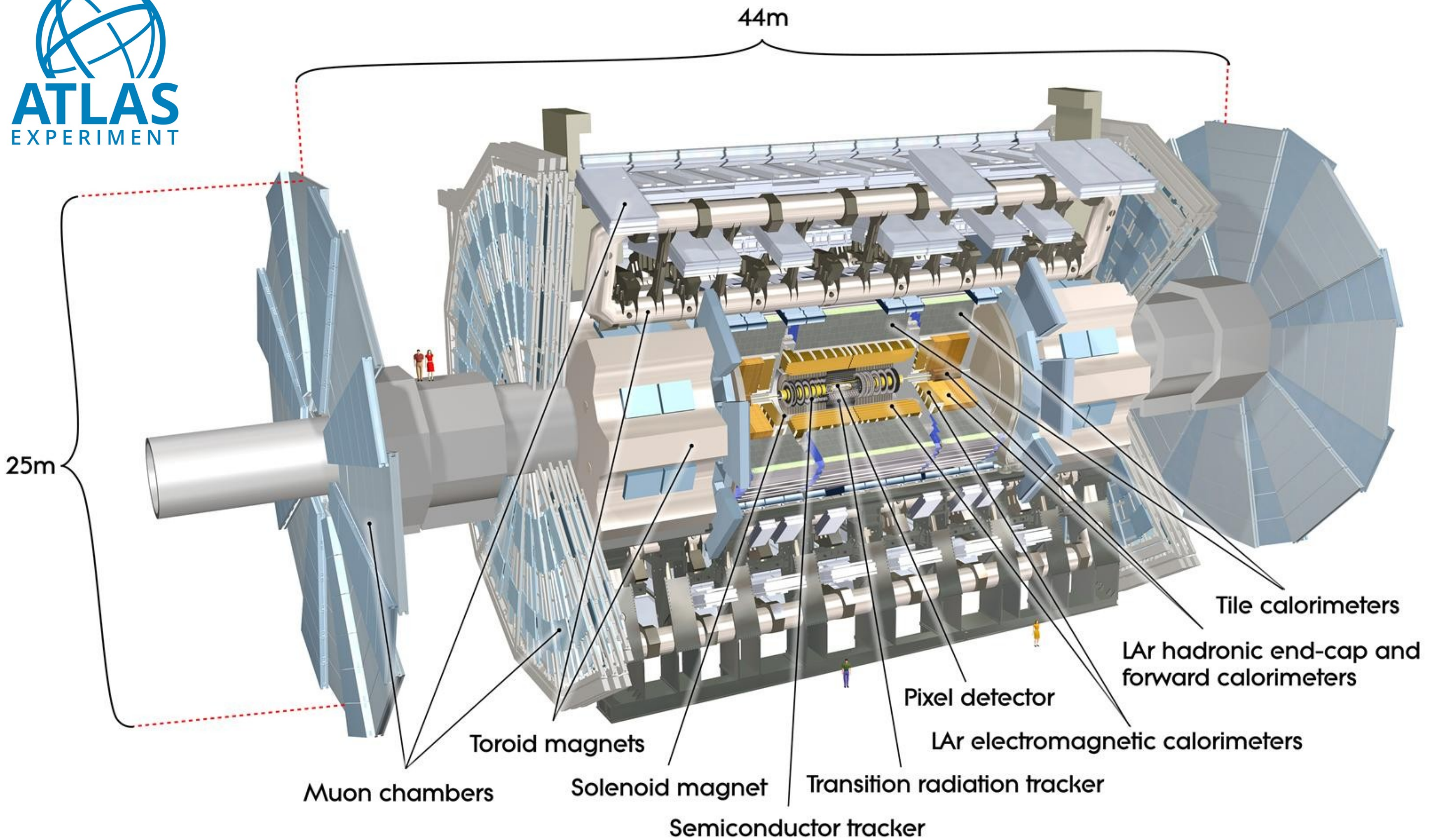
LHC LAYOUT

27 km circumference

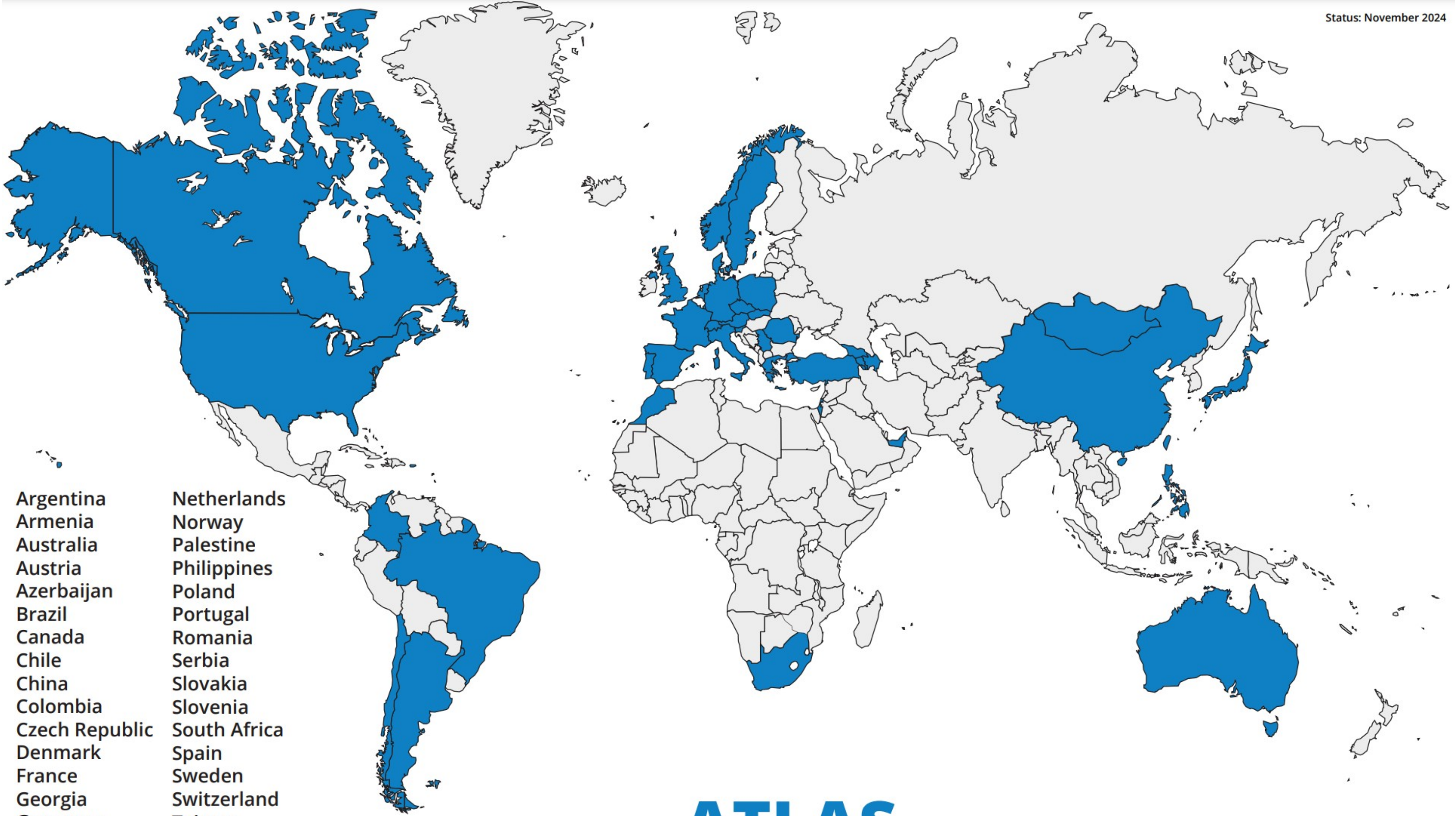


CERN AC _ EI2-4A_ V18/9/1997

ATLAS
EXPERIMENT



Status: November 2024



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Austria
Azerbaijan
Brazil
Canada
Chile
China
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Denmark
France
Georgia
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Italy
Japan
Mongolia
Morocco
Netherlands
Norway
Palestine
Philippines
Poland
Portugal
Romania
Serbia
Slovakia
Slovenia
South Africa
Spain
Sweden
Switzerland
Taiwan
Türkiye
UAE
UK
USA
CERN
JINR

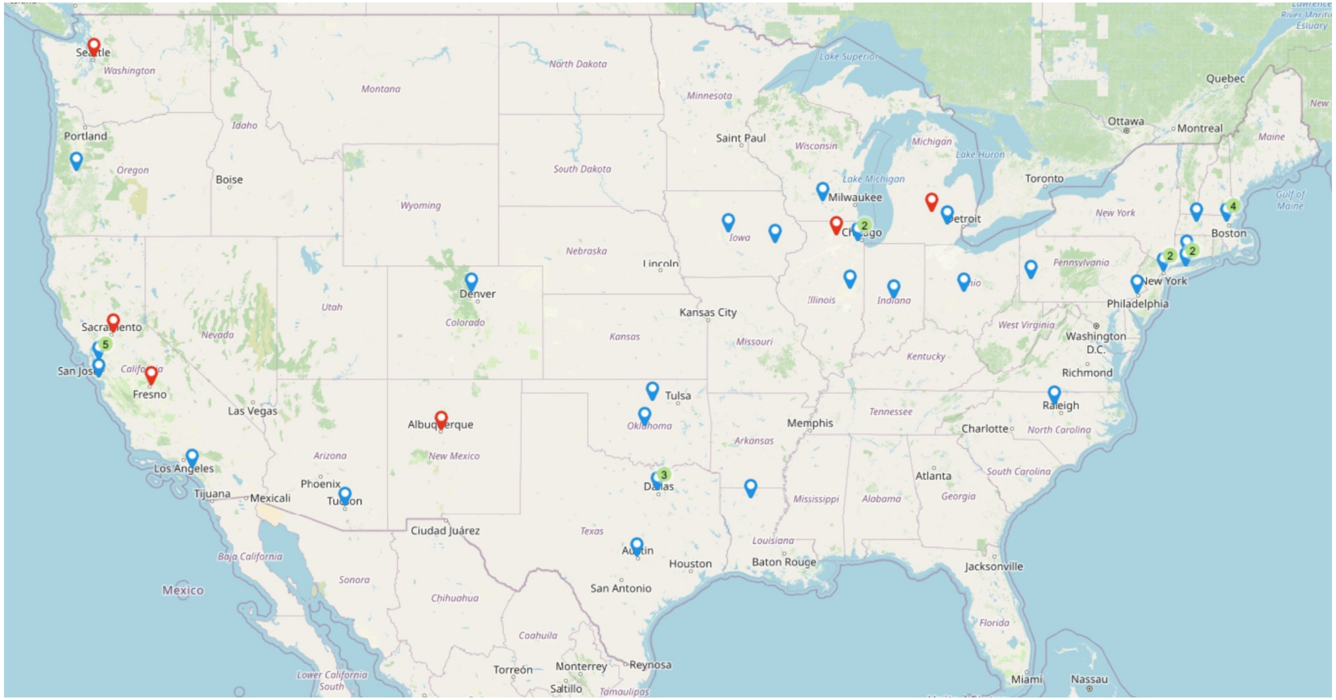
ATLAS Collaboration

177 institutions (243 institutes) from 40 countries

ATLAS EXPERIMENT

The US in ATLAS

- Roughly 20% of the collaborators in ATLAS are from US institutions
  - 5 national laboratories, ≈ 40 university groups
  - largest single country
- Involved in almost every aspect of construction, operation, and physics analysis



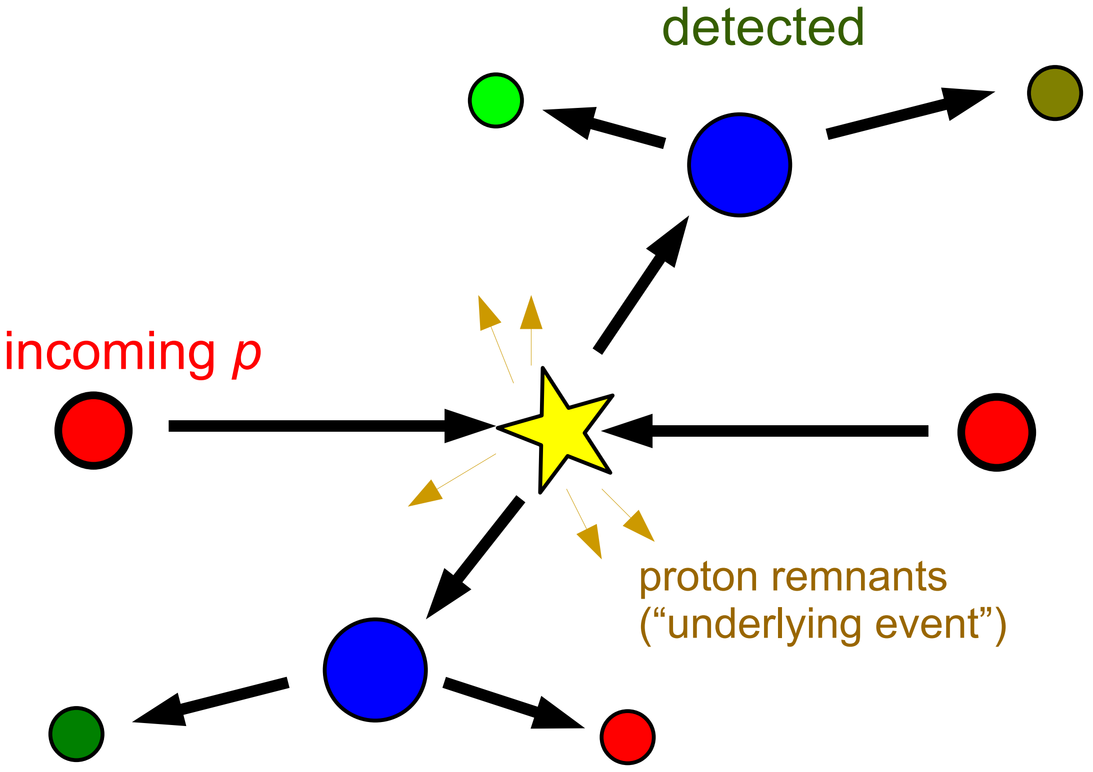
General Principle

convert kinetic energy to mass energy of new particles

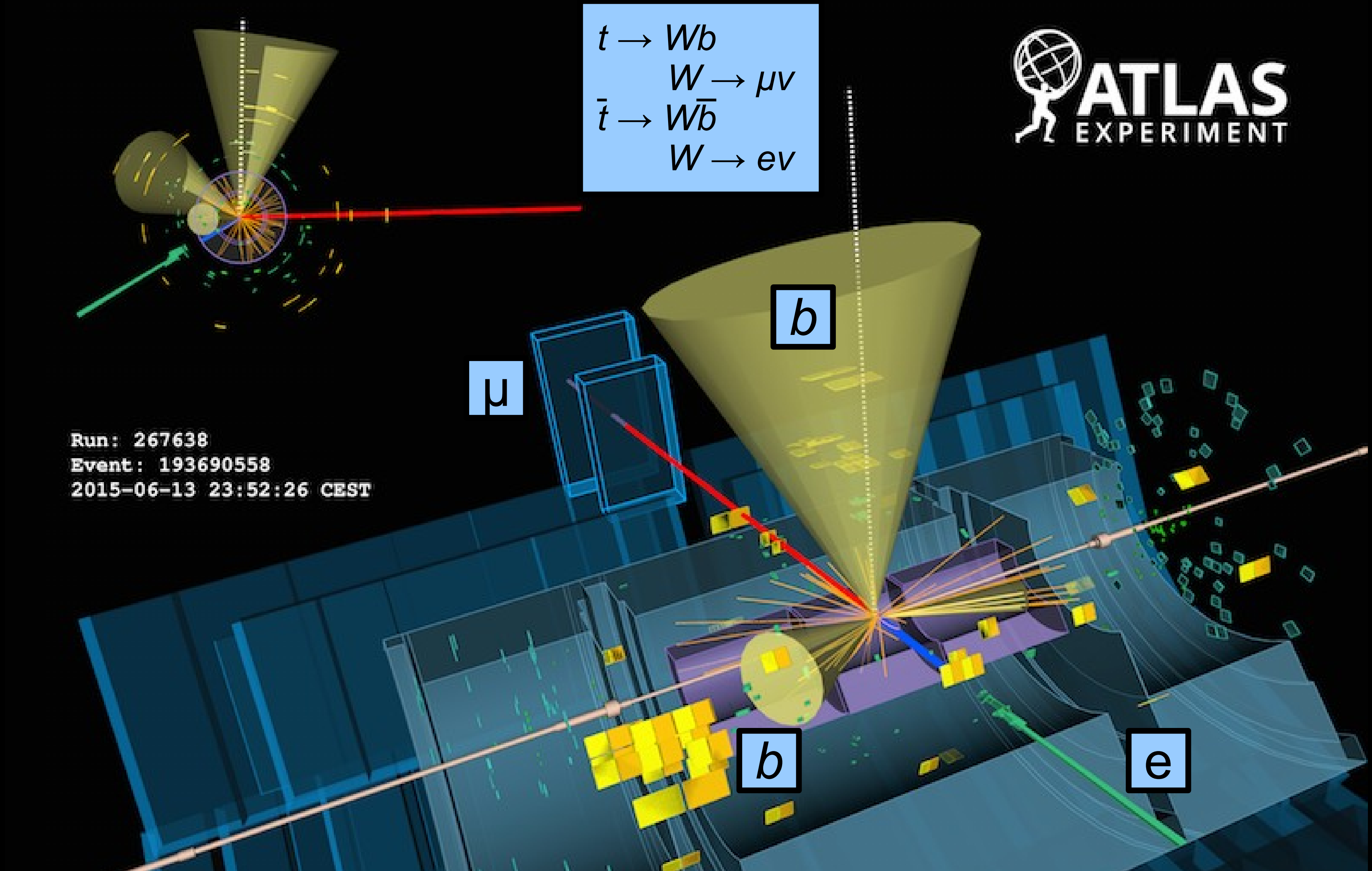
Proton kinetic energy 7250 times proton mass

Protons are messy things, actually collide proton constituents!

Detect long-lived resulting particles in detectors, look for patterns

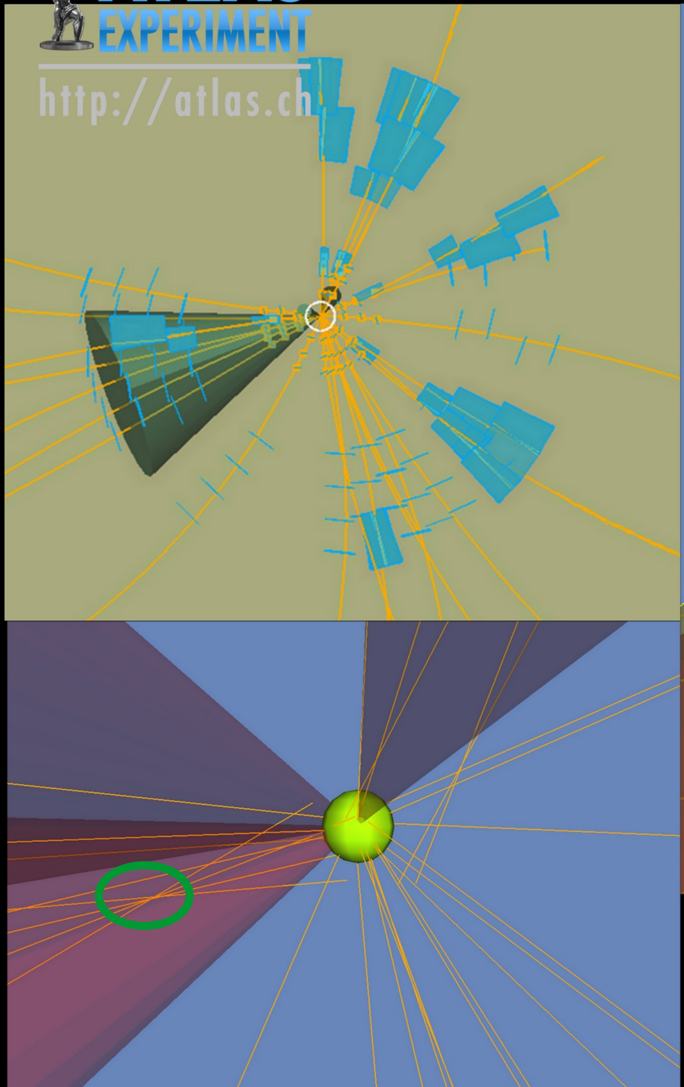


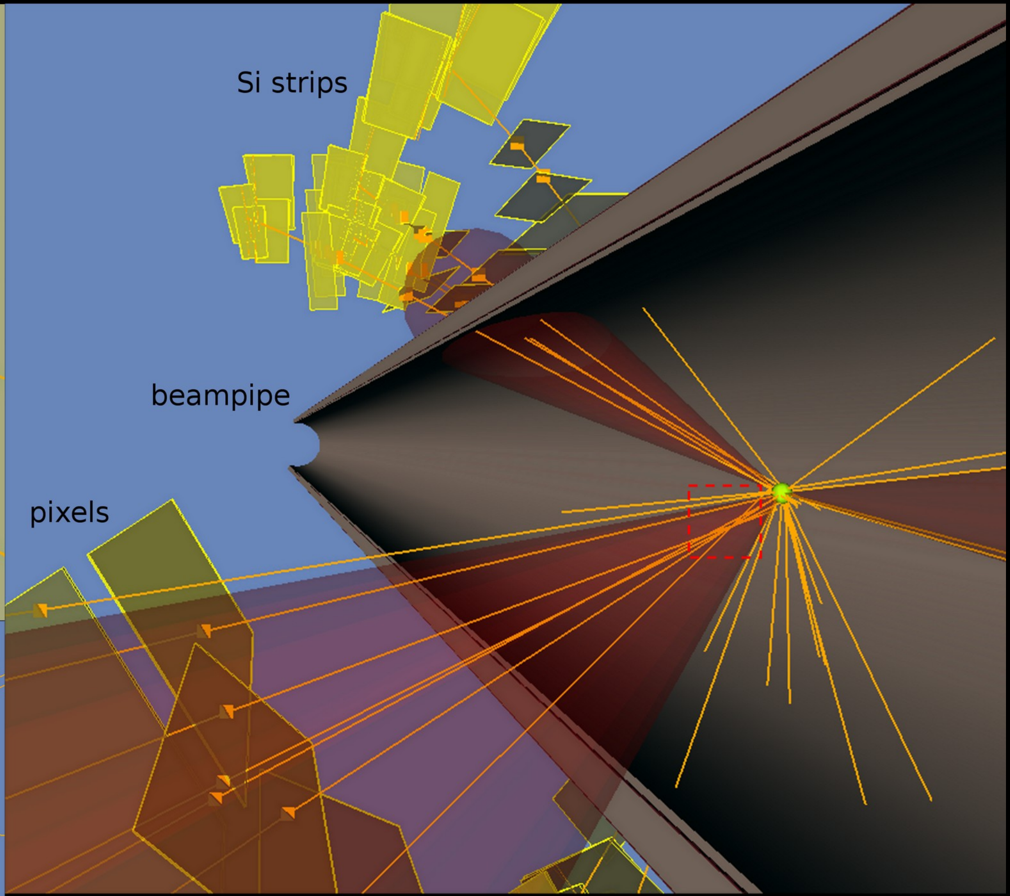
Higgs lifetime ~ 10^{-22} s
top quark lifetime ~ 5×10^{-25} s


$t \to Wb$
$W \to \mu\nu$
$\bar{t} \to W\bar{b}$
$W \to e\nu$
ATLAS
EXPERIMENT
b
μ
Run: 267638
Event: 193690558
2015-06-13 23:52:26 CEST
b
e

Run 152166
Event 817271

b-tagged jet in 7 TeV collisions



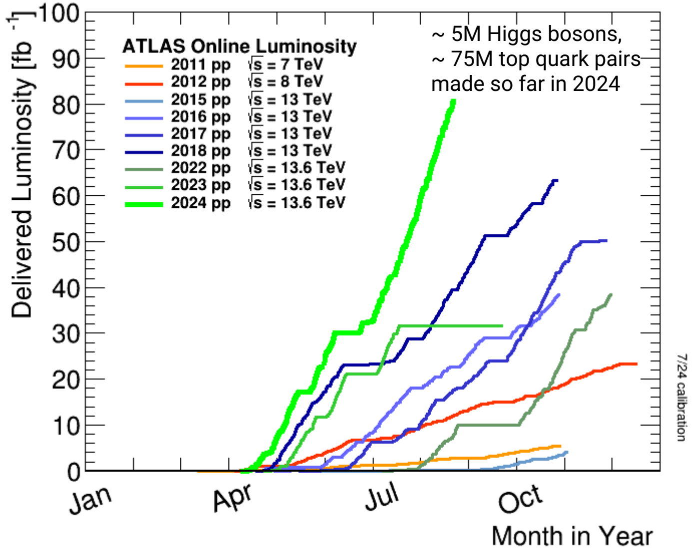


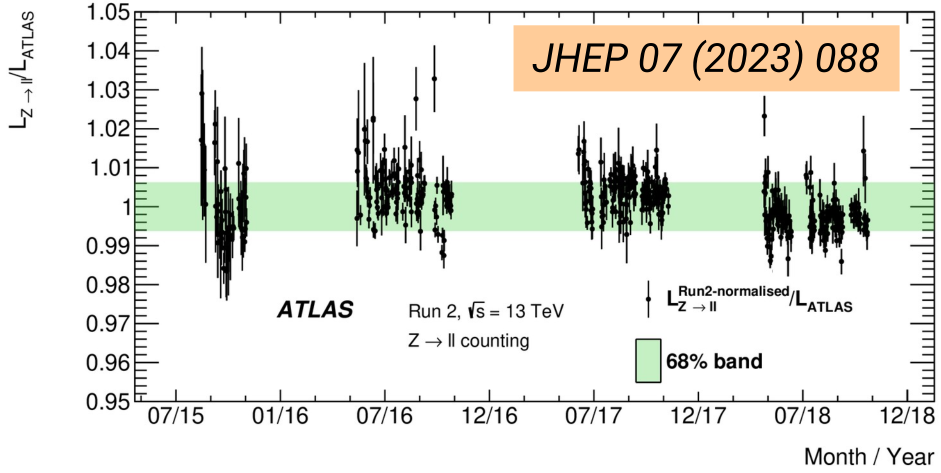
p_T^{jet}=19 GeV (measured at electromagnetic scale)

4 b-tagging quality tracks in the jet

Collecting Data

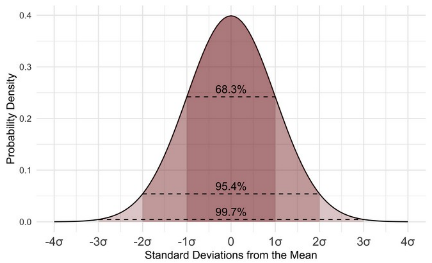
- Run 2 (2015-18) of the LHC was a great success
  - center of mass energy 13 TeV
  - routinely achieved luminosity 2x higher than design
    - design lumi (10^{34} cm^{2} s^{-1}) = 8 top pairs produced per second
  - data still being analyzed
- Started Run 3 in 2022
  - center of mass energy 13.6 TeV
- Need to carefully calibrate the number of recorded collisions
  - One standard candle technique pioneered at UT



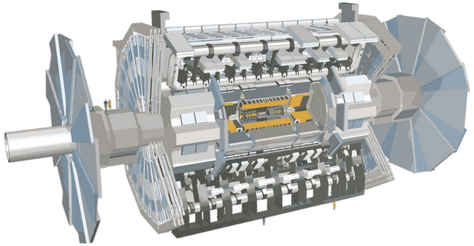


What limits our sensitivity?

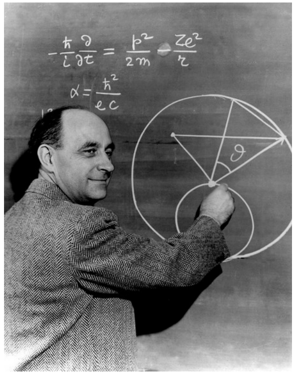
- Statistics
  - some things are just very rare
  - or hard to distinguish from other background processes



- Detector understanding
  - many calibrations need to be done *in situ*
  - simulations of detectors are never perfect

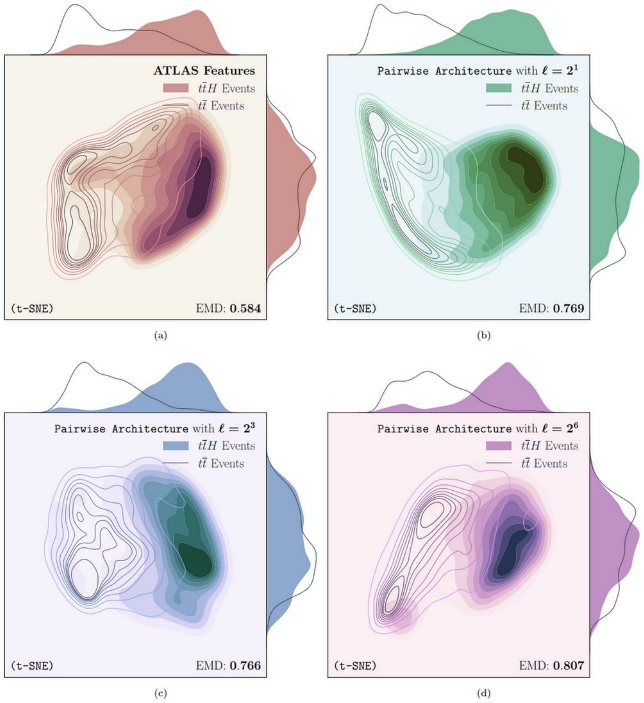


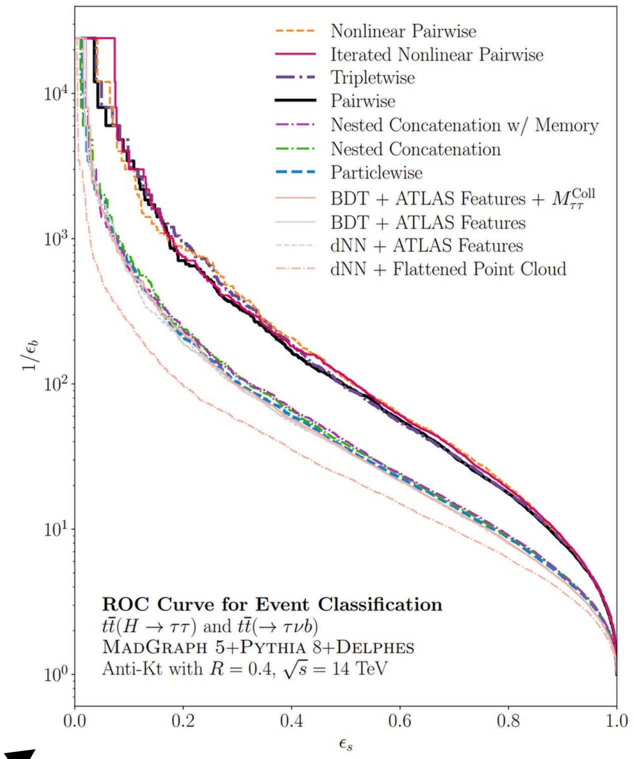
- Theory
  - perturbation theory calculations inherently have truncation uncertainties
  - many nonperturbative effects encapsulated in (imperfect) models



Machine Learning

- AI/ML is a standard part of particle physics workflows
- Our data are kind of weird
  - number & type of particles differs between collisions
  - no natural "order" of particles (unlike language)
- R&D on powerful but practical ML still important
  - can't afford infinite training sets or compute



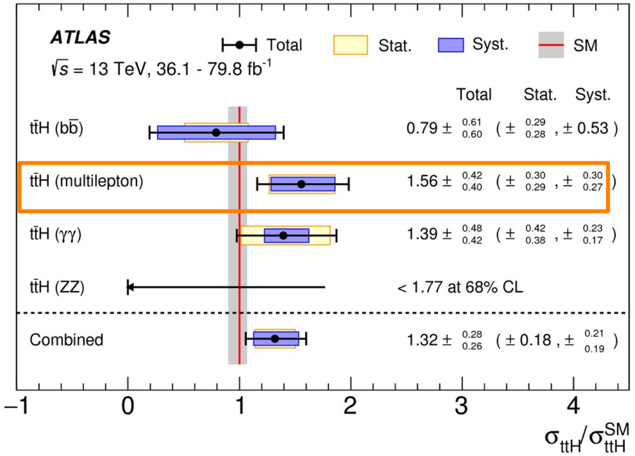


Simple way to include varying particle content in a permutation-invariant way: DeepSets

Onyisi, Thaler, Shen PRD 108, 012001 (2023)

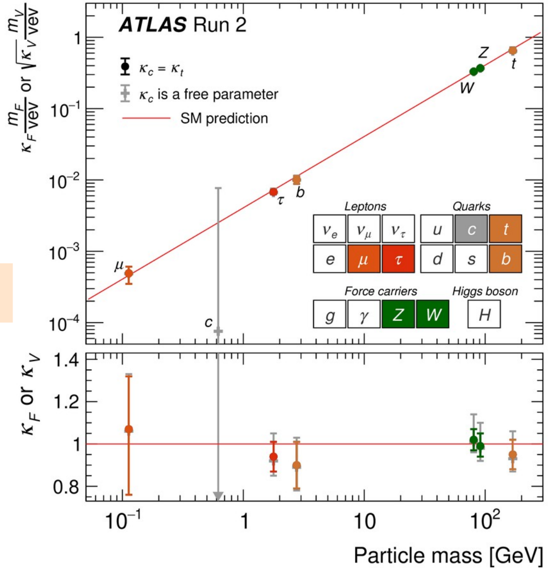
Higgs boson couplings

- First direct observation of the top quark-Higgs boson interaction in 2022



Phys. Lett. B784 173 (2018)

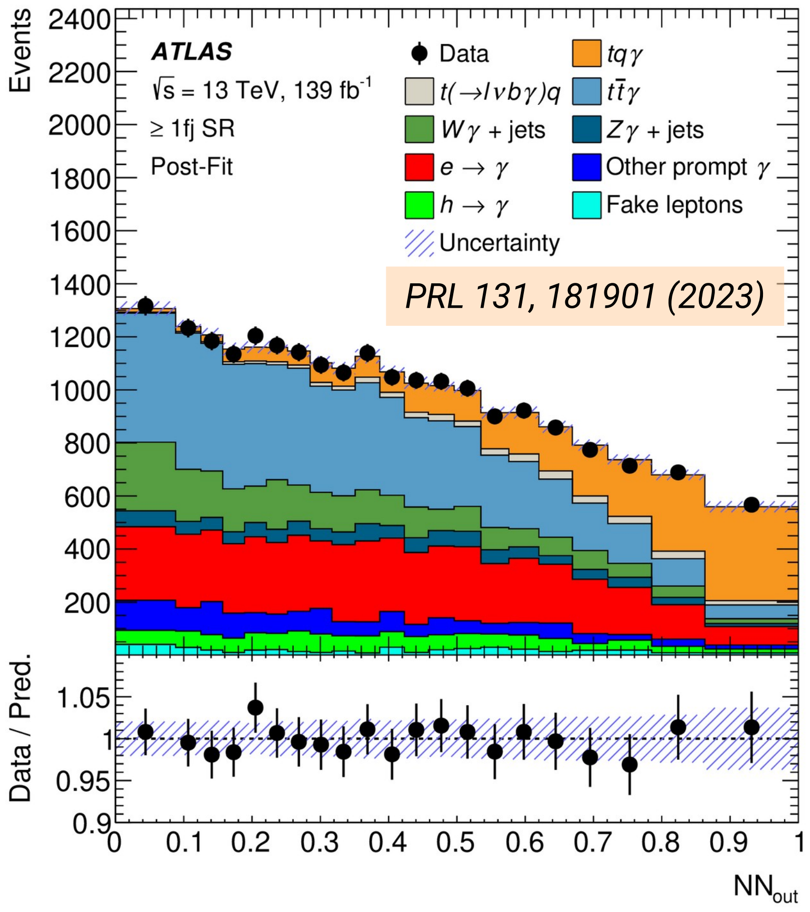
- Part of a comprehensive program of Higgs boson interaction studies
  - Observations are compatible with SM predictions at the 5-10% level



Nature 607, 52 (2022)

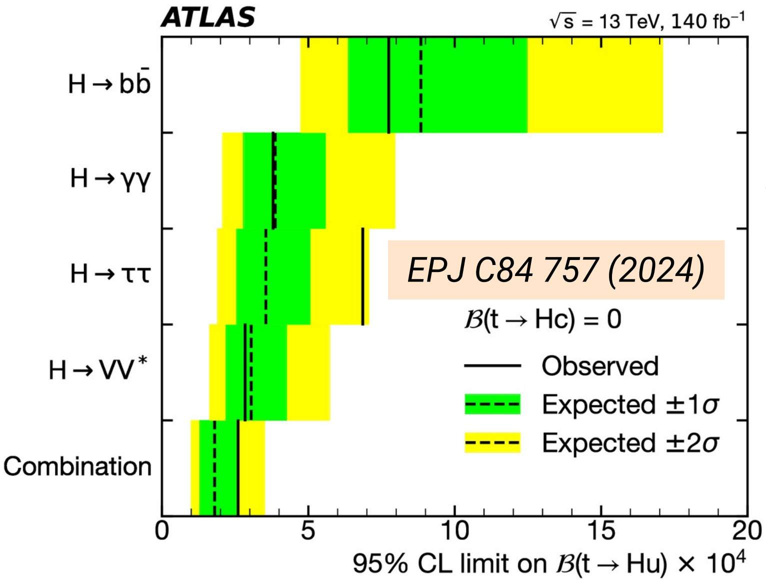
Top-Photon couplings

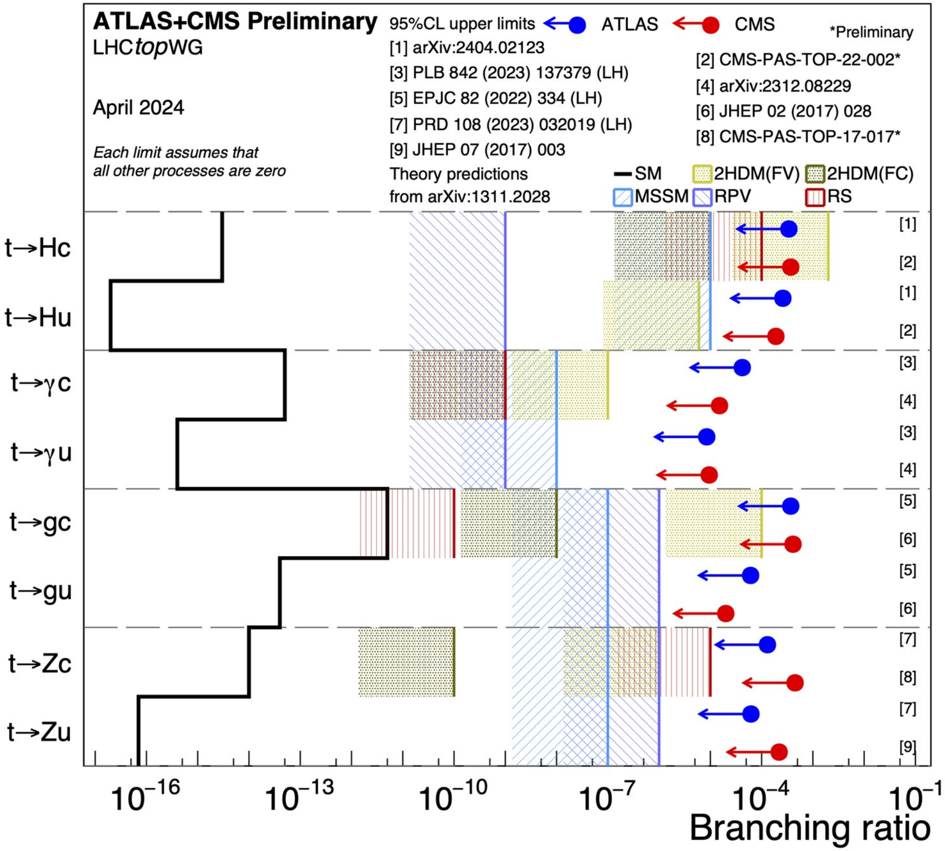
- In the SM, top quark-photon interactions are fully determined by the top quark's electric charge (+2/3 e)
  - heavy charged particles interacting with the top quark could alter this
- Made a first observation of single top quark + photon production
  - in reasonable agreement with SM but a bit higher than expected [(1.34 ± 0.13) × SM)]
  - machine learning critical to signal extraction



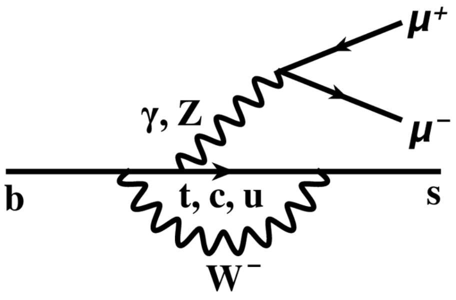
Top Flavor Changing Neutral Currents

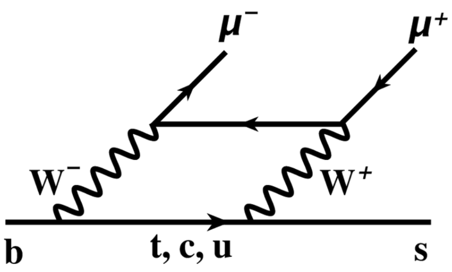
- The decay t → Hq is unobservable in the SM
  - not hard to generate with non-SM particles
- No signal of this so far
  - beginning to exclude certain simple models



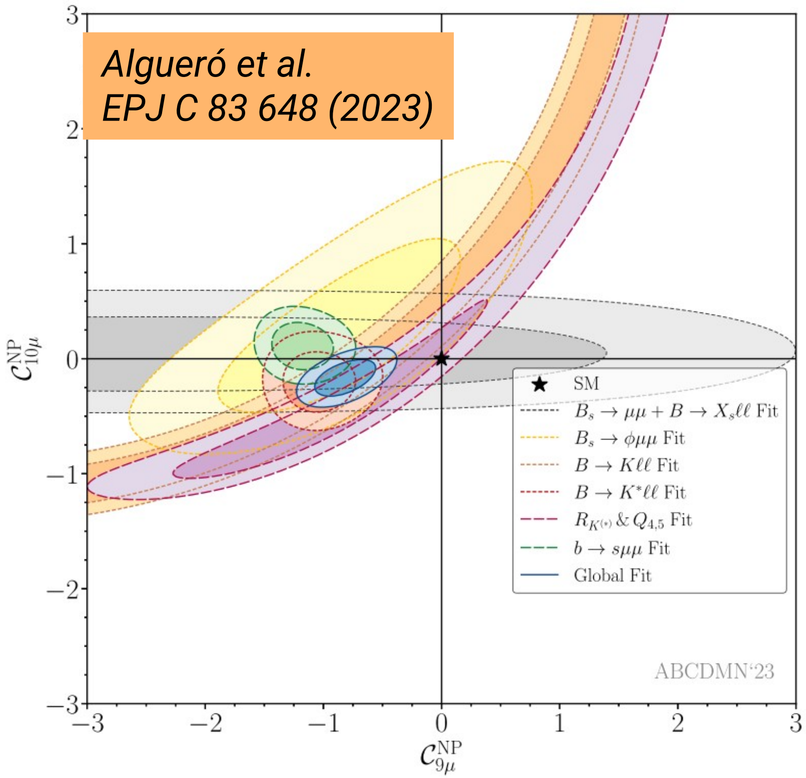


Weak Decays: bsℓℓ





- Interesting vertex with many suggestions of anomalies
  - (in my opinion) biggest theory-experiment discrepancy right now
- Main probes are for bsμμ: $B_s \to \mu\mu$ and $B_d \to K^{(*)}\mu\mu$
- Aiming to confirm with ATLAS data



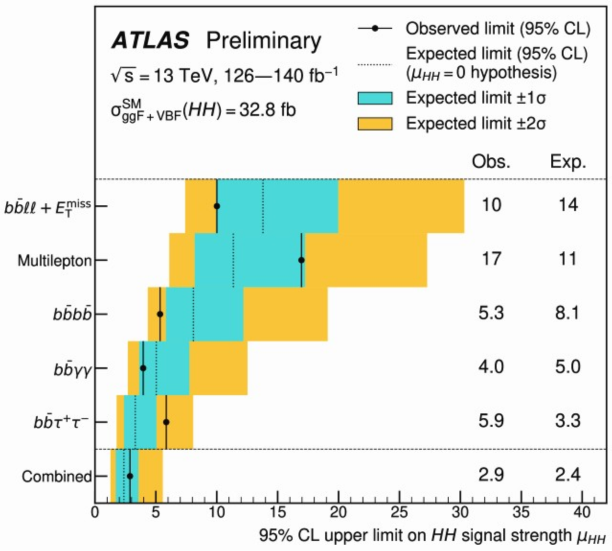
$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

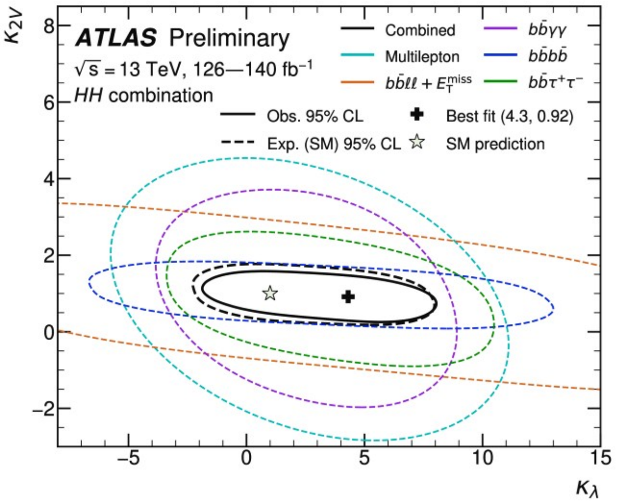
$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$\mathcal{O}_9' = (\bar{s}\gamma_\mu P_R b)(\ell\gamma^\mu \ell)$$

Di-Higgs

- Our most statistics-intensive search: looking for the Higgs boson interacting with itself
  - measure how the Higgs bootstraps its own mass
- Relies on (hampered by) quantum interference
- Combine the results of many searches
  - not near Standard Model sensitivity, but …
  - doing better than we originally expected

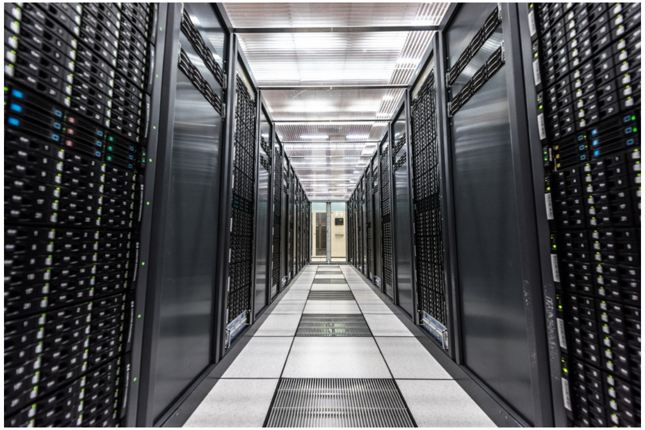




ATLAS-CONF-2024-006

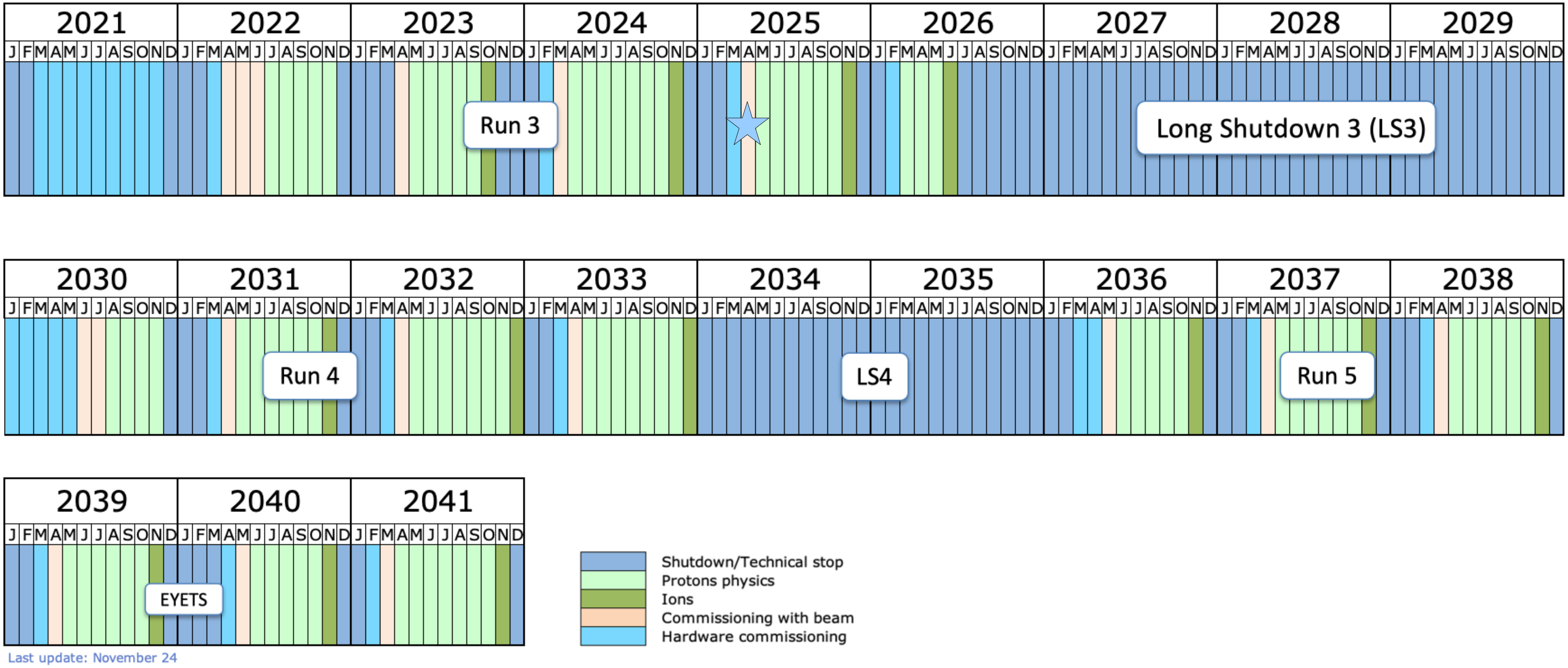
Software & Computing in the US

- ATLAS computing occurs on the Worldwide LHC Computing Grid
  - federation of computing infrastructure from many participating countries
- Many computing centers in the US contribute
  - range from university clusters to DOE/NSF supercomputer centers
  - can be specialized, e.g. supercomputers typically prefer to run simulations
  - scheduling software developed with heavy involvement from UT-Arlington and BNL
- We also have many experts on the reconstruction and analysis software – algorithms, I/O systems, storage formats, evolution to new architectures (GPU? FPGA?), machine learning
- University groups can use common US resources
- Evolution to needs of HL-LHC being studied



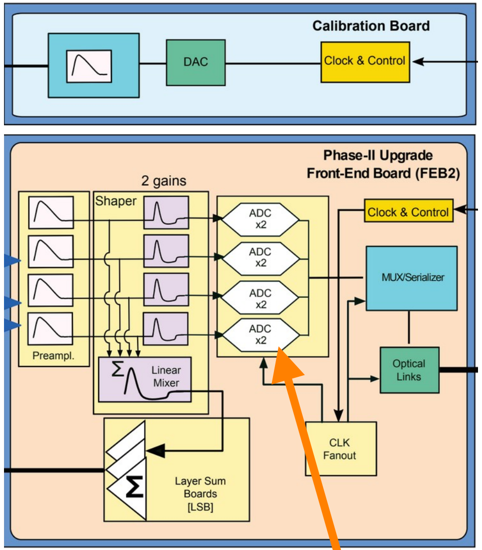
LHC Schedule

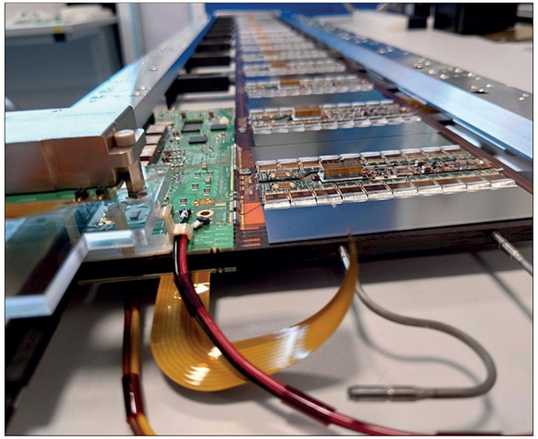
- Long Shutdown 3: major experiment + accelerator upgrades
- 2030 onwards: accumulate x10 existing data set

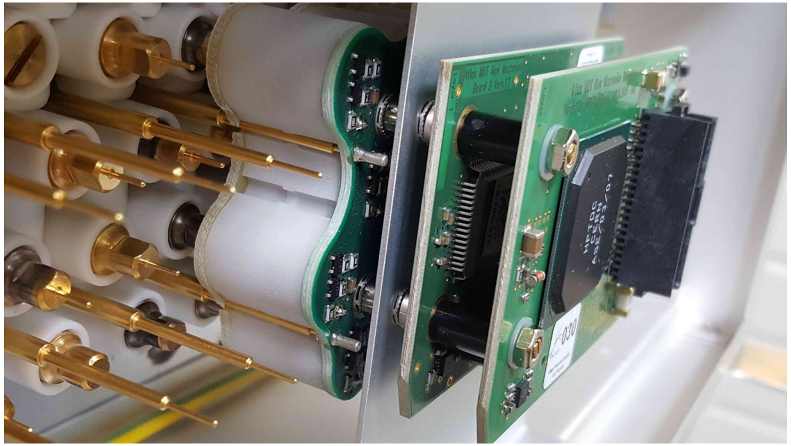


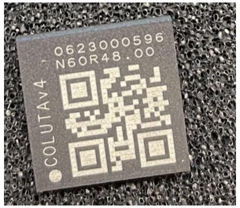
Upgrades

- High-Luminosity LHC experiment upgrades to be installed and commissioned in the next five years
- US is deeply involved in many efforts
  - see next talk for discussion of new inner tracker system
- Not just a matter of installing physical hardware
  - need to design control, readout, and monitoring software and firmware
  - integrate into reconstruction
  - design and perform calibrations





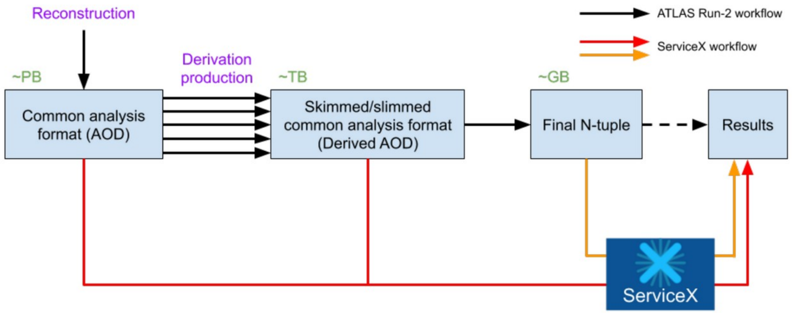


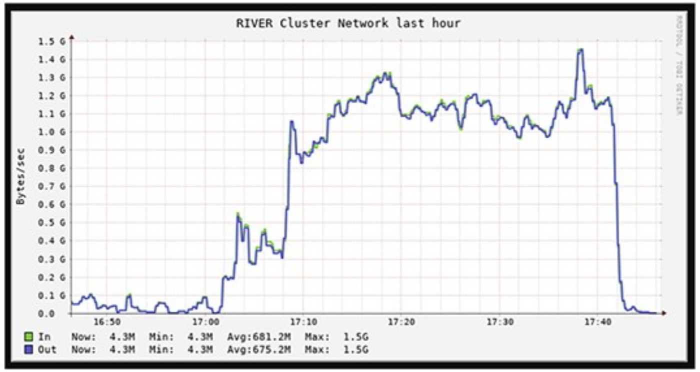


Analyzing Data at the HL-LHC

- Reducing petabytes of data and simulations to a few plots: we have a “big data” problem
- Want to leverage industry tools (Python, etc.) while providing good abstractions
  - physicists are not generally computing professionals!
- ServiceX project: generic data processing and reduction service for particle physics data
  - aim for transformative user experience

https://iris-hep.org/projects/servicex.html

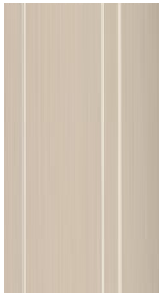




Many thanks to...

Postdocs/Engineers

Rohin Narayan



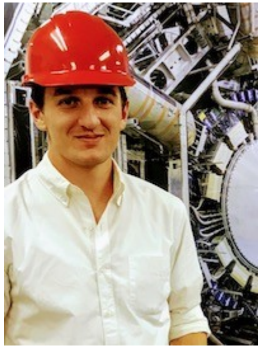
KyungEon Choi

Ketan Mahajan

Grad students

Harish Potti

Aaron Webb



Chuck Burton

Marc Tost

Bryce Holloway

Undergrads

Spencer Stubbs

Delon Shen

Click to add Title

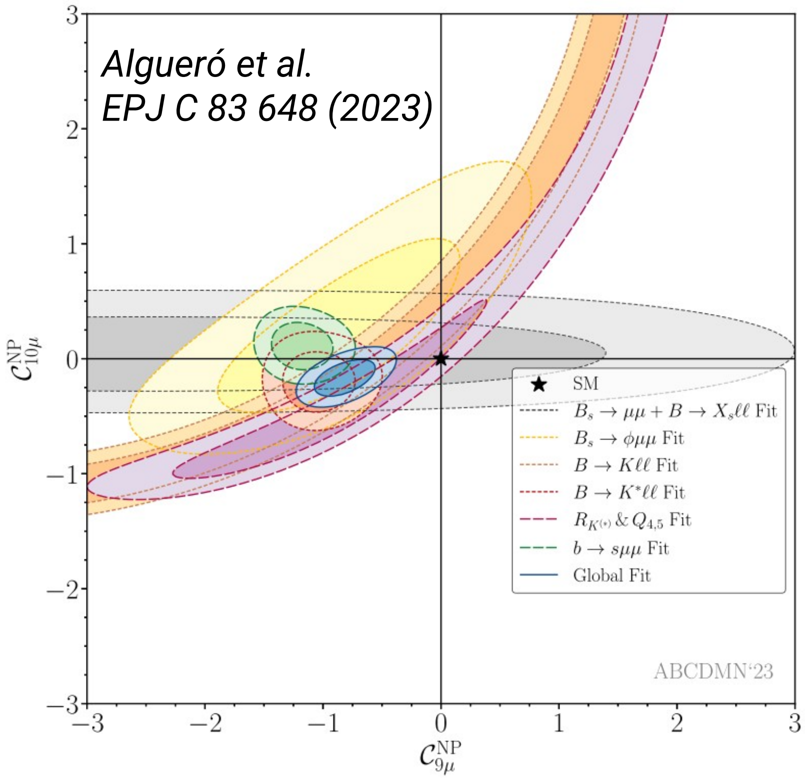
Extra

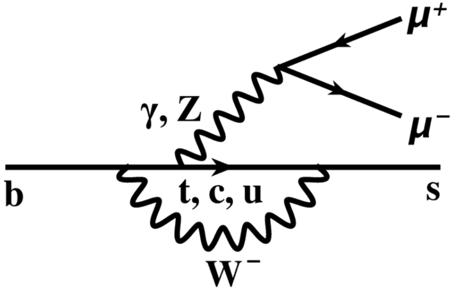
Process for Joining US ATLAS

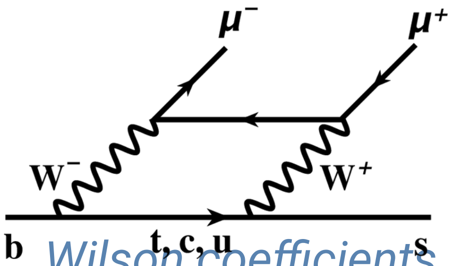
- https://www.usatlas.org/joining-atlas-collaboration-institutions

Weak Decays: $bs\ell\ell$

- Fits significantly favor non-SM interactions
  - remarkably consistent effective field theory picture
- SM can only explain this if hadronic calculations are wrong
  - some of these could be constrained with data
- Aim to confirm with ATLAS data







Wilson coefficients

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum (C_i \mathcal{O}_i + C_i' \mathcal{O}_i') + \text{h.c.}$$

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$
$$\mathcal{O}_9' = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)$$