Exotic particle searches with ATLAS Run 3 data and preparing Tracking software for High Luminosity LHC

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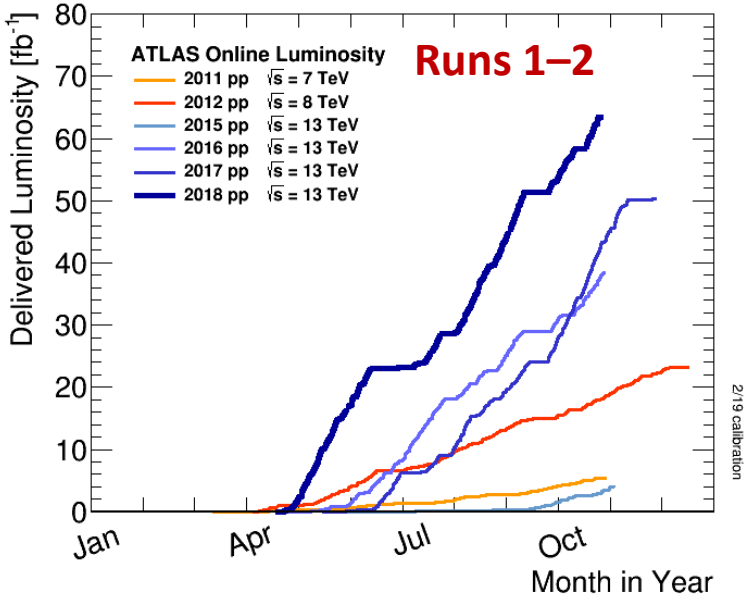
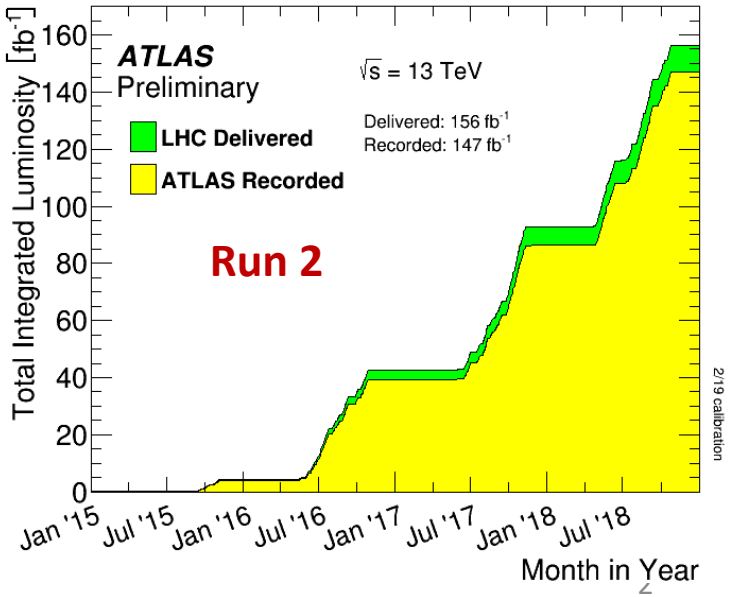
Science and Technology Facilities Council

Large Hadron Collider

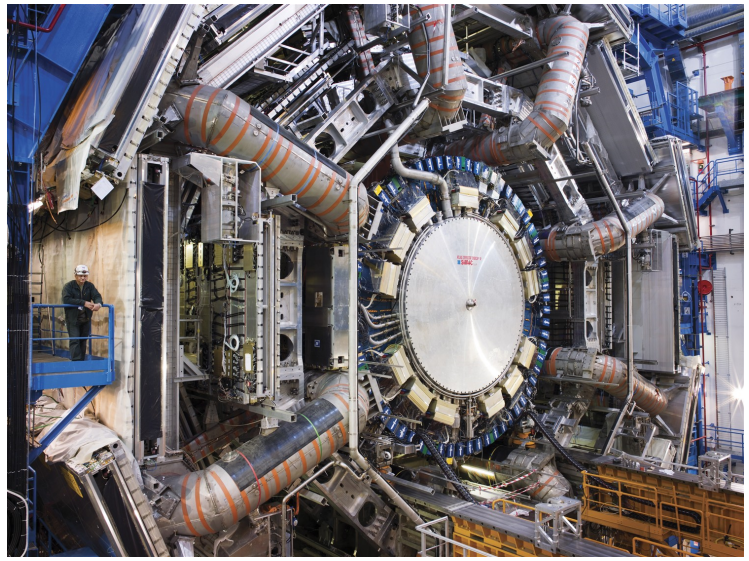
- LHC first started serious data taking in 2011
  - Run 1, ran at up to 75% nominal luminosity, culminated in discovery of Higgs boson
- LHC Run 2 finished at end of 2018
  - Reached 2 times nominal luminosity, delivered over 5 times data of Run 1
- Now completing Long Shutdown 2 for upgrade for Run 3 (2022-2026)
  - Machine consolidation, Phase-I upgrades to ATLAS
- Long Shutdown 3 starting in 2026 for upgrade to HL-LHC
  - Phase-II upgrades to ATLAS for 5–7 times nominal luminosity in Run 4 (from 2028).

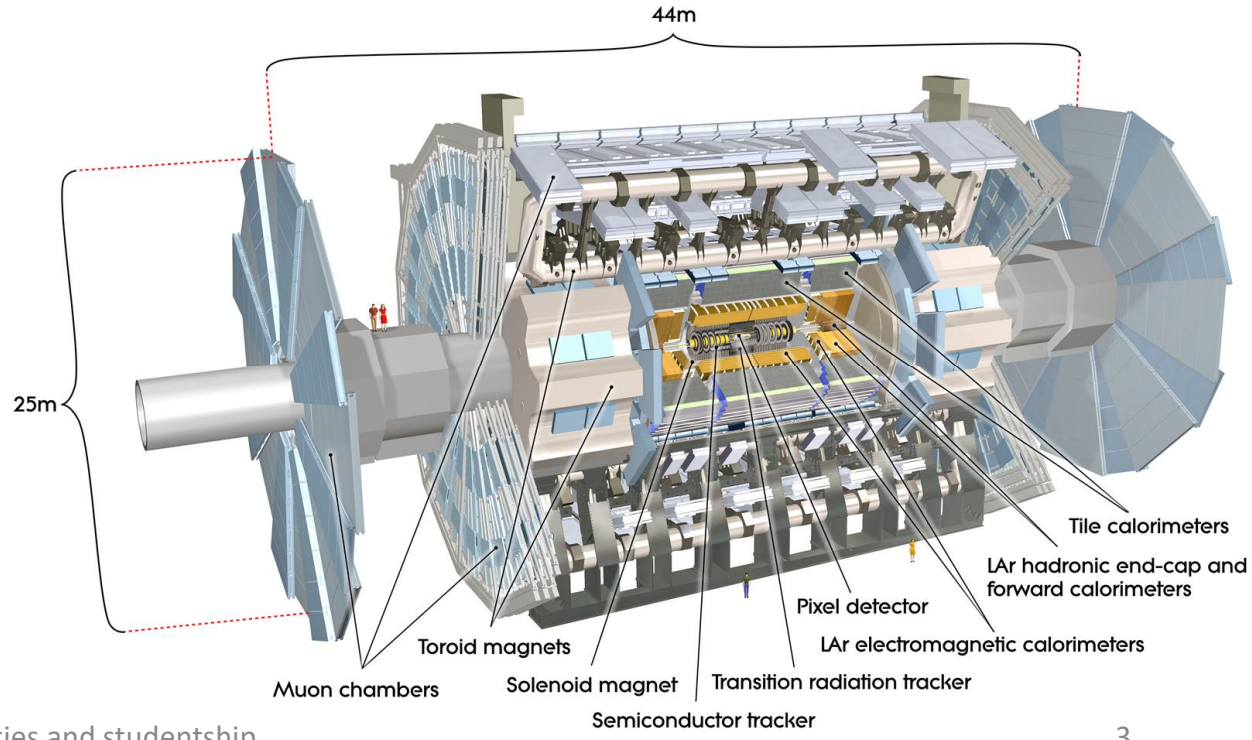




ATLAS

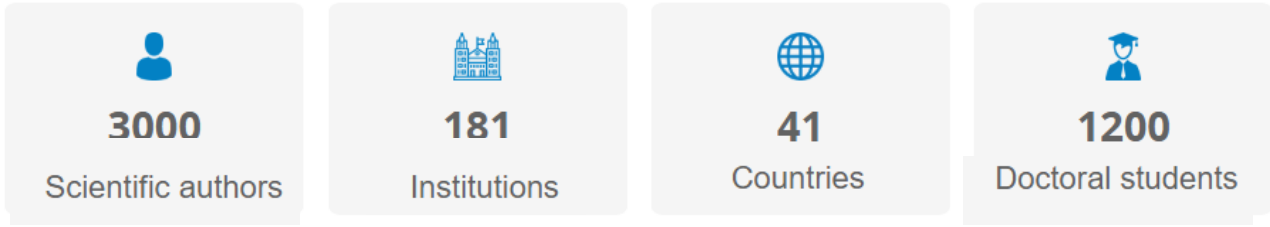
- One of two general purpose detectors at the Large Hadron Collider
- Different subsystems in layers around collision point to record:
  trajectory,
  momentum and
  energy of particles





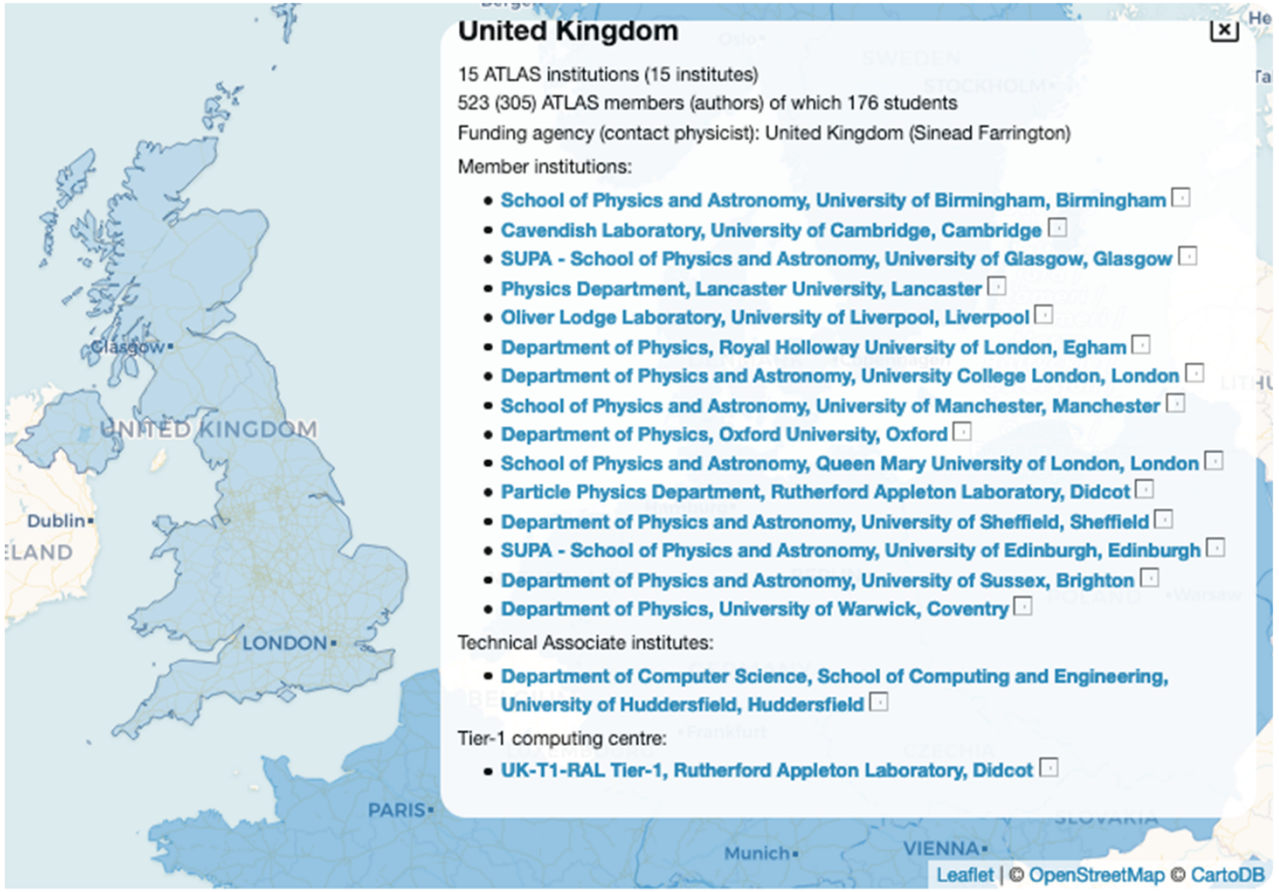
ATLAS Collaboration

- Worldwide effort
  - Beyond the scientific authorship, significant engineering effort: ~1000 people



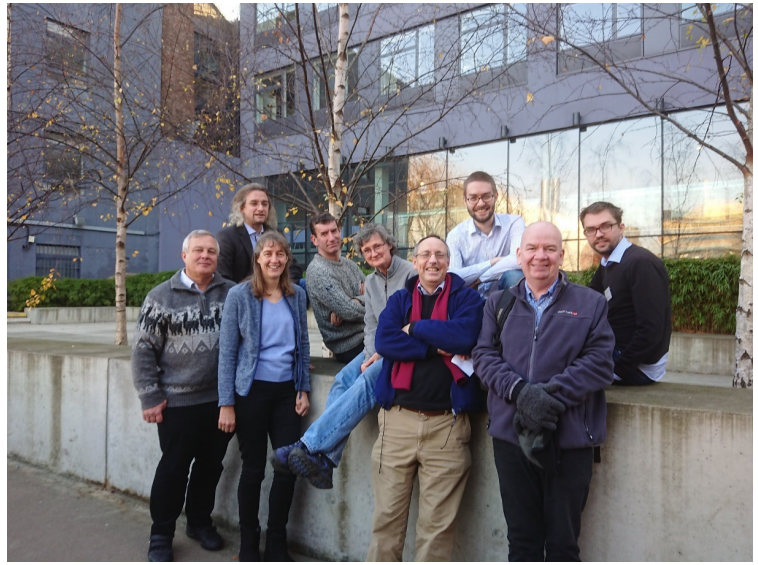
ATLAS UK

- 14 universities + RAL PPD
  - PPD has good links with all ATLAS UK universities
- RAL also hosts the UK Tier-1 computing centre
  - Dedicated internet link to CERN
  - Complete copy of LHC raw data



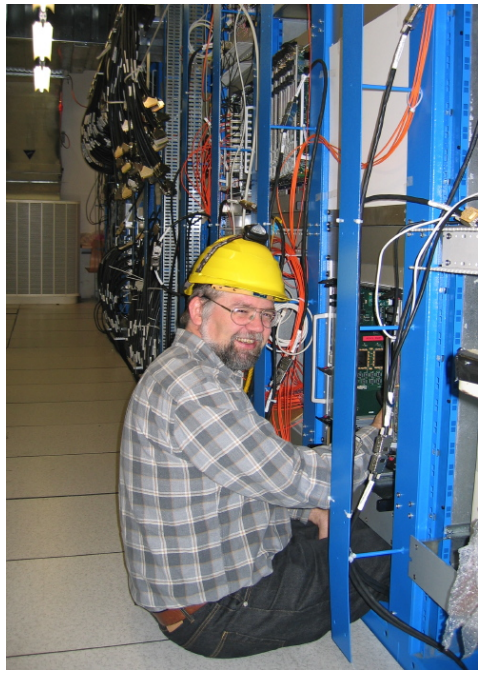
RAL ATLAS group

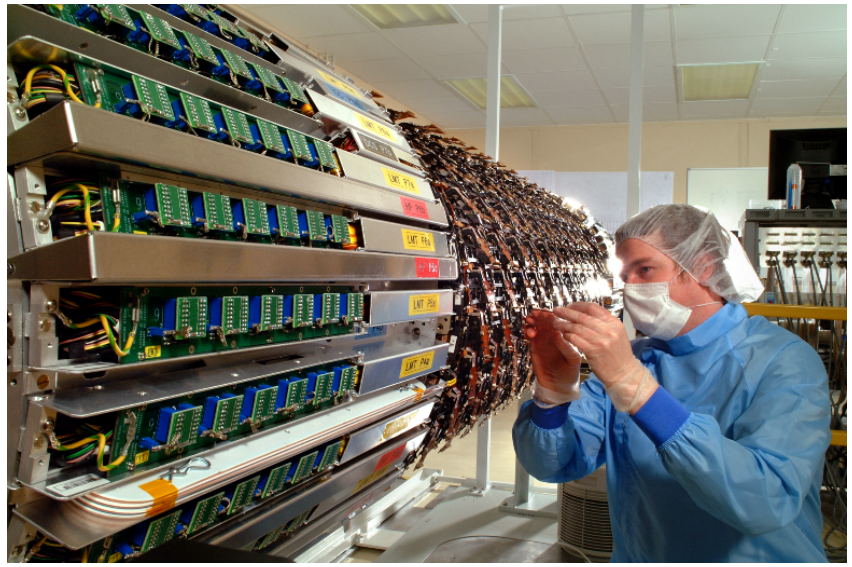
- 21 staff (physicists, engineers)
- 3 PhD students (with Glasgow, Warwick, Birmingham)
  - soon to be 5!
- Photos not comprehensive



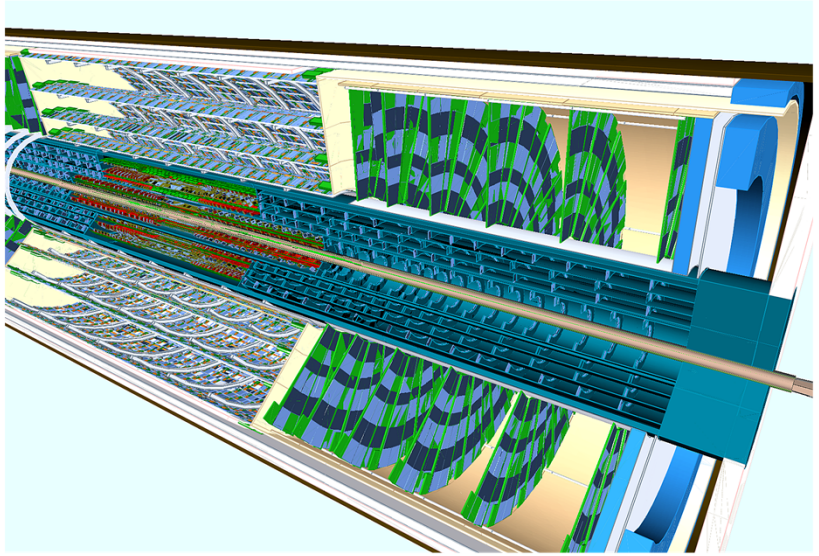
RAL activities

- Built and operated SemiConductor Tracker and trigger systems in Run 1 and 2
- Phase-I upgrades: now being installed for Run 3
  - Level-1 Calorimeter Trigger and High Level Trigger
- Phase-II upgrades: installation in 2026-8 for Run 4
  - Level-0 Global Trigger, Event Filter and new Inner Tracker (ITk)
- Diverse physics involvement:
  - Higgs, searches for new heavy bosons, B-physics

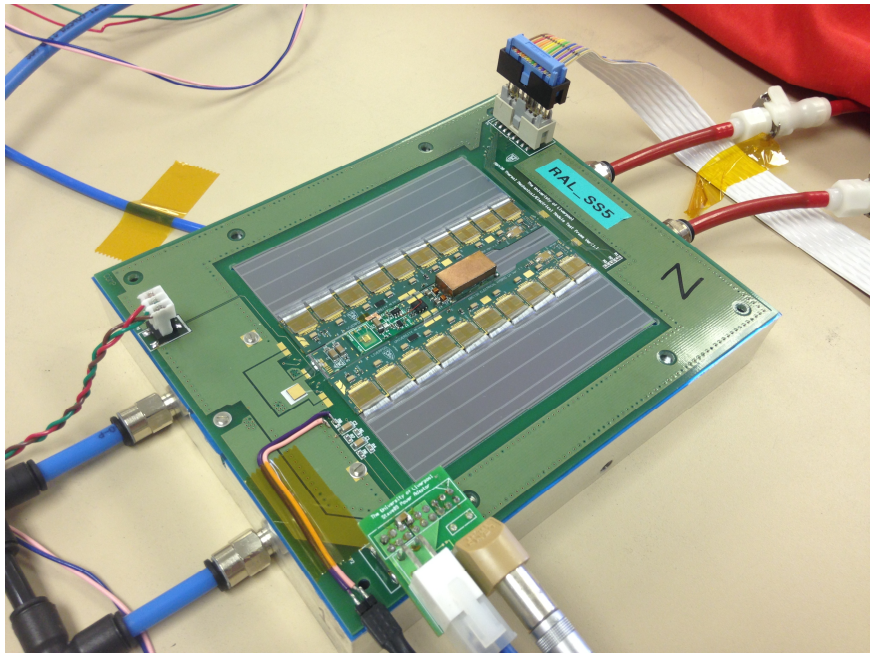




ITk (see Ben's talk)

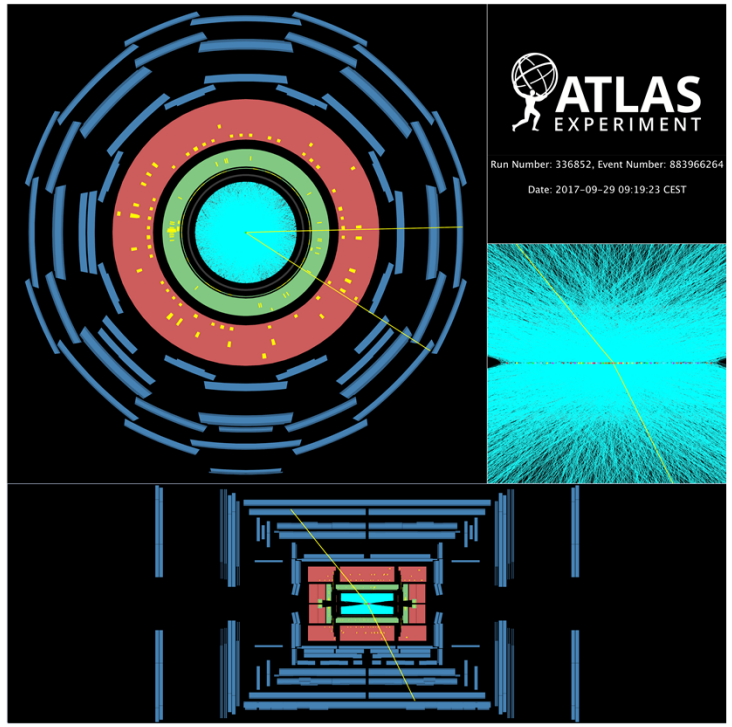


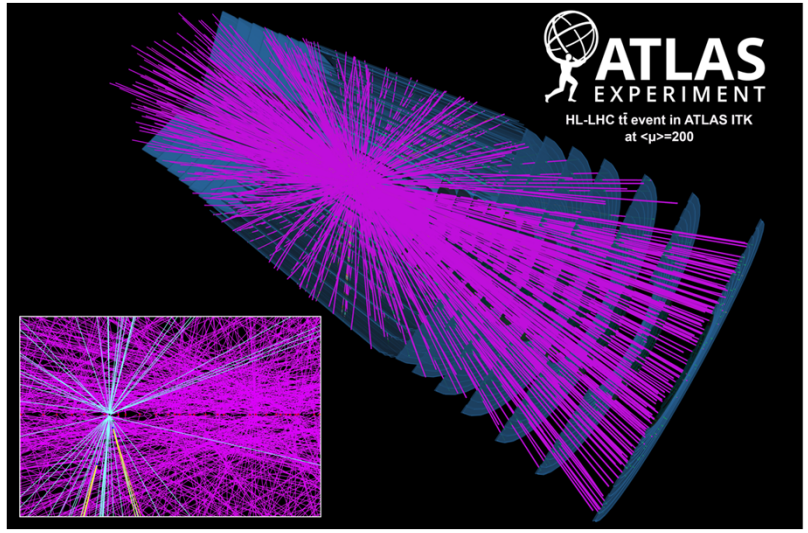
- Inner Tracker is a new all-silicon detector for ATLAS
  - will replace the current Inner Detector, when it reaches its end of life in 2026
- RAL group working on barrel strips, endcap pixels, and overall reconstruction software
  - Design, data acquisition, assembly and eventually operation



Wealth of ATLAS data

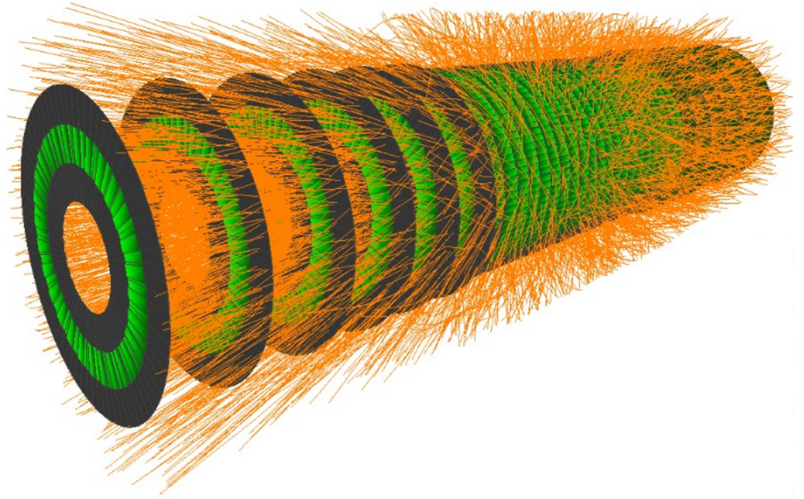
- In Runs 2 and 3, LHC collides bunched beams of protons 40 million times per second
  - Every time the bunches cross, multiple protons collide
  - Typical "pile-up" of 35, but can be much more
    - e.g. real example from 2016 with 85 collisions
- In Run 4, expect an average of 200 collisions each time bunches cross
- Interesting collisions at much much lower rate
  - 1 Higgs boson per 10 billion collisions, some processes only a few collisions per year ($N = \sigma L$)
  - We want just the interesting collisions sitting in a sea of "pileup" collisions

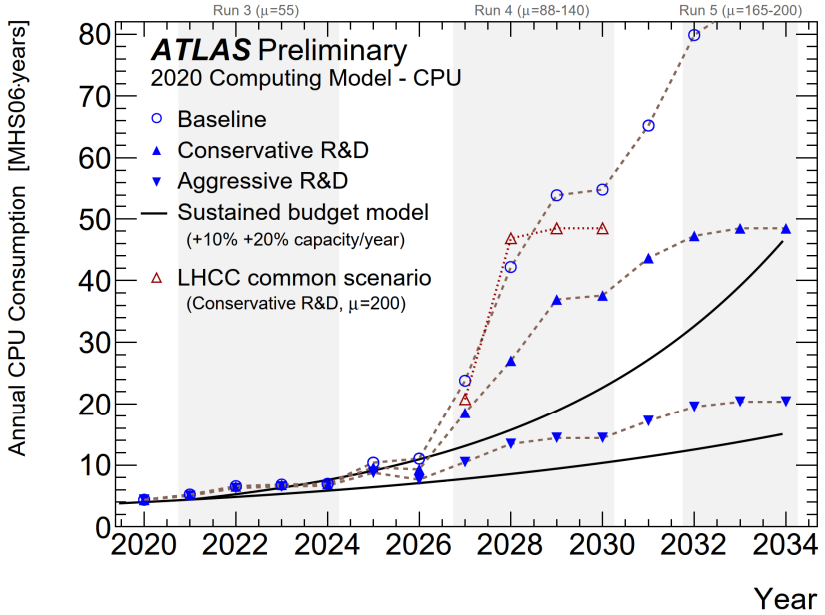




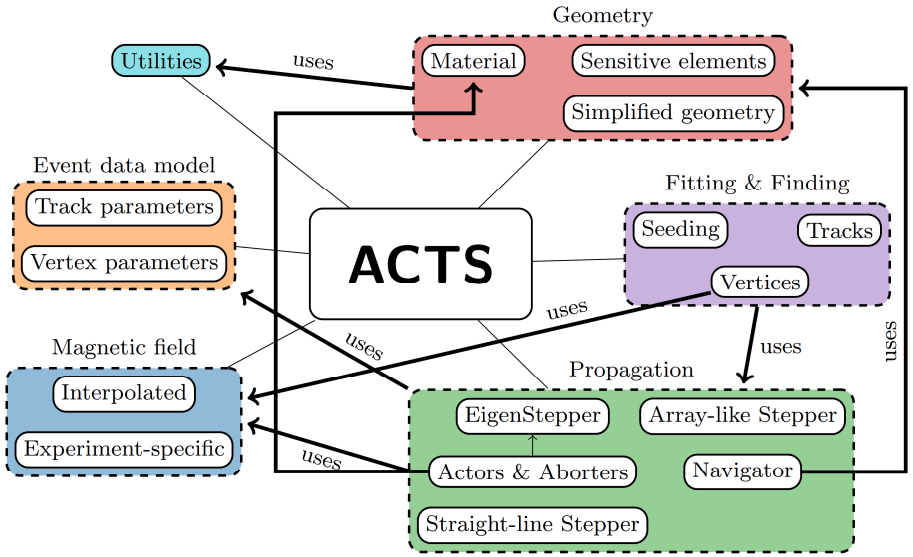
ATLAS Track Reconstruction for the HL-LHC

- Once upgraded, ATLAS will read out ~300,000 measurements for each event
  - Need to identify and reconstruct the trajectories of ~4000 charged particles from this data
- The High-Level Trigger needs to do this at an event rate of 1 MHz to select events of interest, writing them out at 10 kHz
  - Use an online farm, expanded from the current 60,000 CPUs
  - Maybe accelerated with GPUs or FPGAs
- Full/detailed reconstruction performed on the events selected by the Trigger
  - Even with the World-wide LHC Computing Grid, this will be challenging

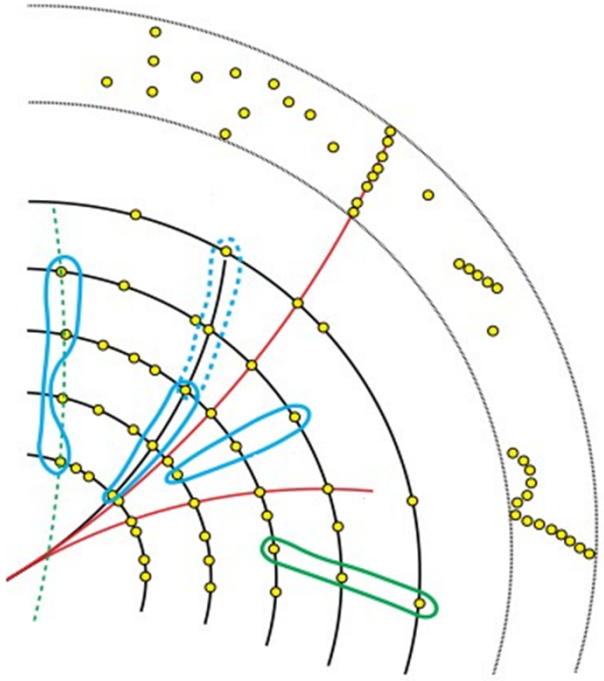




Improved track reconstruction for Run 4



- We need aggressive R&D to handle the data volume from the new ITk detector
- The ATLAS track reconstruction software is being rewritten
  - based on the Open Source ACTS project [1]
  - improved algorithms
  - modern software engineering practices
  - explicitly designed for multi-threaded and GPU applications
  - takes advantage of cross-experiment Machine Learning developments



[1] https://arxiv.org/abs/2106.13593

The RHUL Group

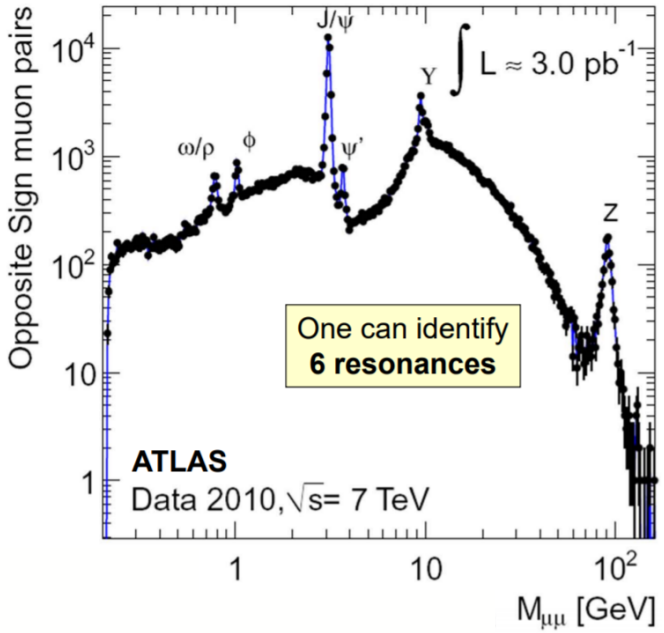
- Group of 12 academics, 5 engineers/technical support staff, 14 postdoctoral researches and 23 postgraduate students

- Active in many of the world-leading particle physics activities:
  - ATLAS on the LHC 5 academics
    (Exotics, Higgs, Statistics, Top)
  - Particle Astrophysics 3 academics
    (DM, neutrino and gravitational waves)
  - Accelerator Science 3 academics
    (John Adams Institute, beams diagnostics for LHC upgrades and future accelerators)
  - Theory 2 academics
    (LHC phenomenology, Dark Matter)

- On ATLAS: Exotics, Higgs, Statistics, Top. Involved in the electronics of the data acquisition system trigger (experiment, upgrade and physics), computing

Why perform (Exotics) Dilepton Searches?

- History of discovery: confirming Standard Model (SM)



- The SM is extremely successful, but it leaves many questions unanswered.

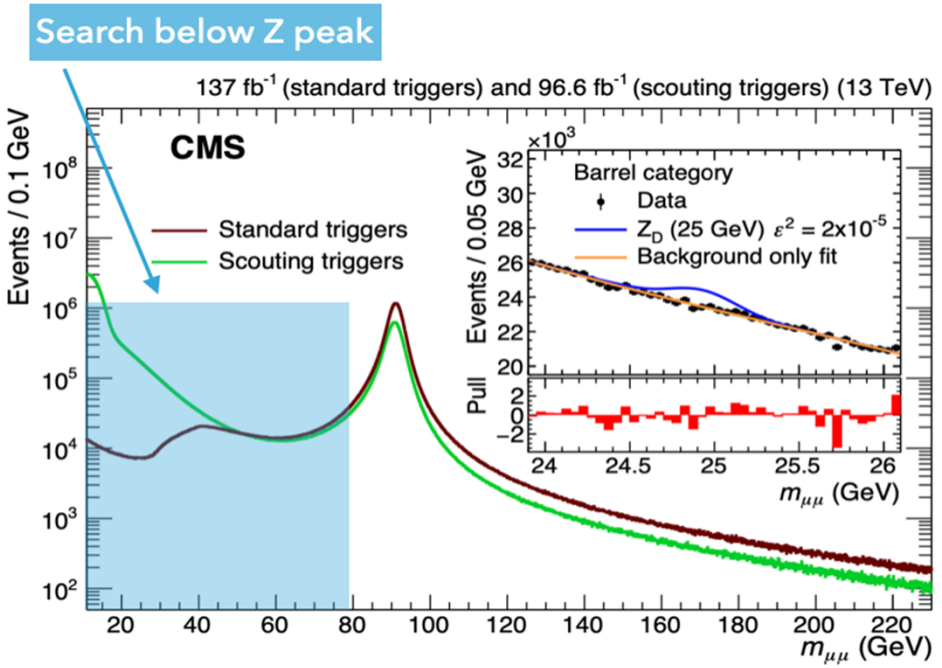
????

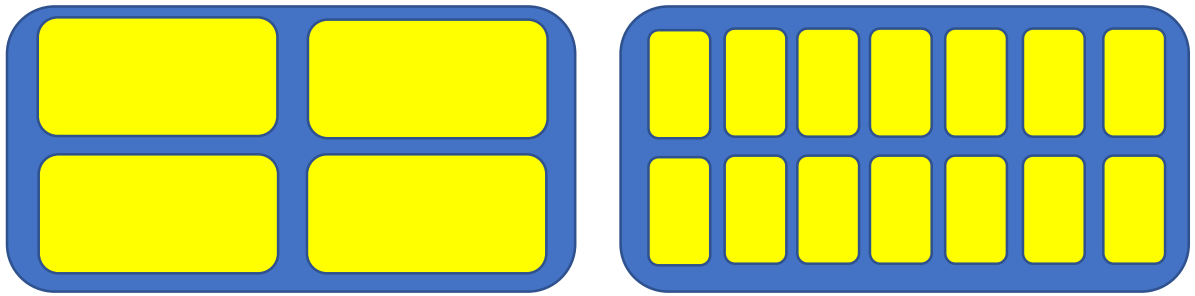
- Hierarchy problem (EW << Planck Scale)
- Gravity is not included
- Are quarks and leptons fundamental particles (contact interactions)?
- Why is only 5 % of matter made of ordinary SM particles? – What is dark matter?

- All can be investigated in the dilepton channels!
  - Resonant bumps
  - Non-resonant excesses
  - Or wiggles!

What is a Trigger Level Analysis (TLA)?

- To search at low invariant mass:
  - Lots of SM backgrounds
  - Can't keep all data on tape
  - Have limited dataset size can store
- TLA:
  - Rather than writing out full data for a few events
  - Keep less data for more events



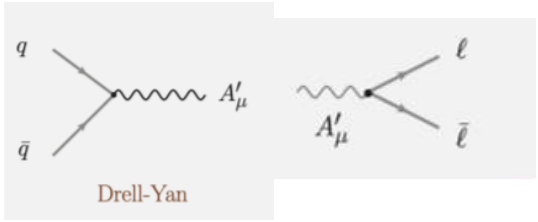


- Run 2 ATLAS dijet TLA search
- No Run 1 or 2 dilepton TLA

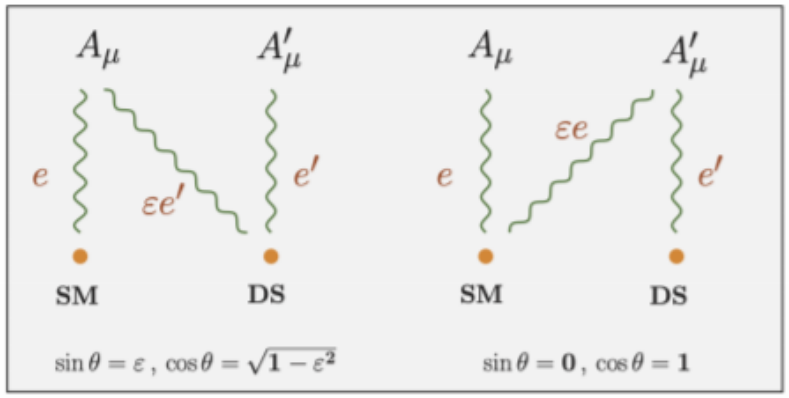
  ** NEW for Run 3!

What can you search for using a TLA?

- Enables search for low mass resonances
  - e.g. dark photons!

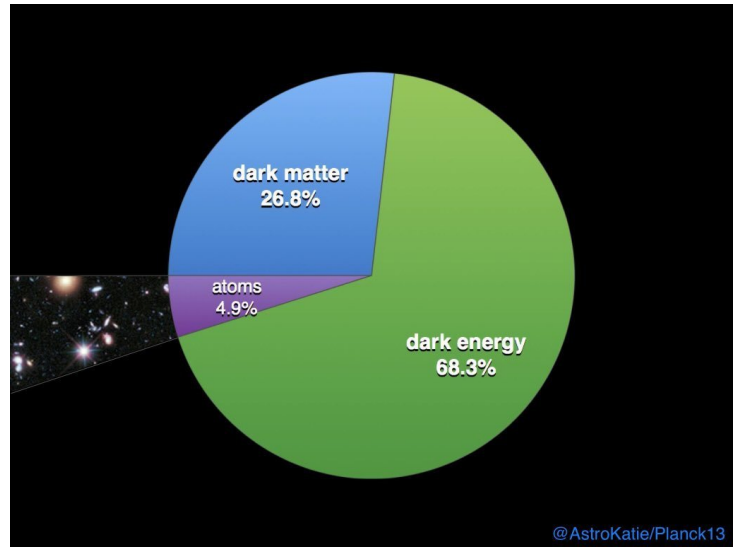


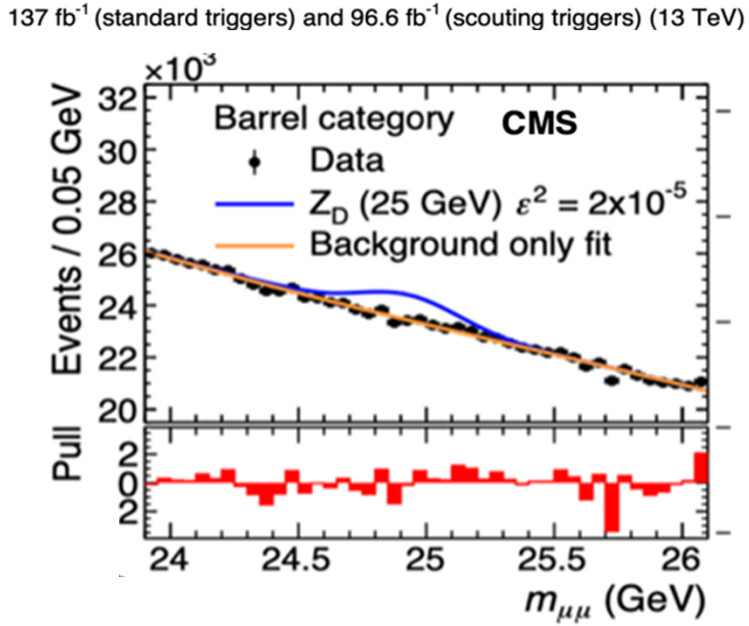
Ordinary Photons: A with coupling e
Dark Photons: A' with coupling e'



Parameters: mixing ε
mass $m_{A'}$ of dark photon

https://arxiv.org/pdf/2005.01515.pdf

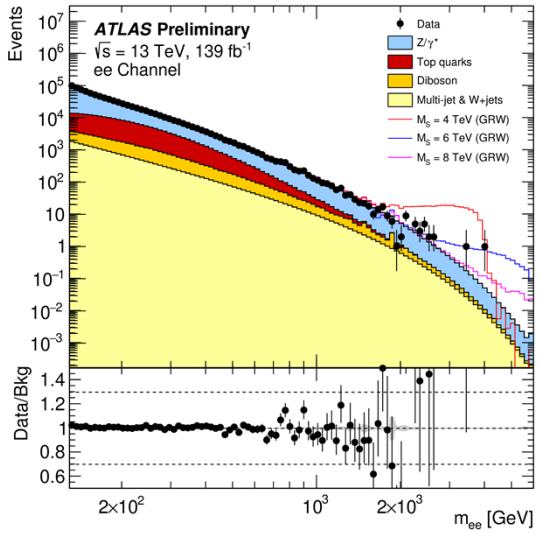




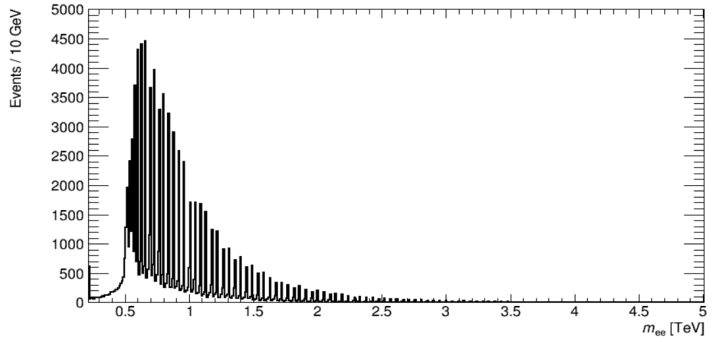
https://arxiv.org/abs/1912.04776

Exotics physics at RHUL

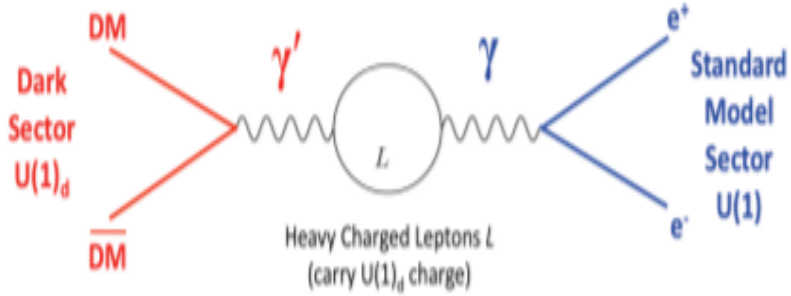
- Nice group of people:
- Exotics (1 academic + 1 post-doc + 1 PhD student + 1 PhD (2022 start))
- Statistics (1 academic + 2 PhD students)



Large
Extra Dimensions



Clockwork Extra
Dimension Search



TLA Dark Matter
Software & Studies

- Precise PhD analysis project flexible at this point
  - also allows to see how LHC schedule develops

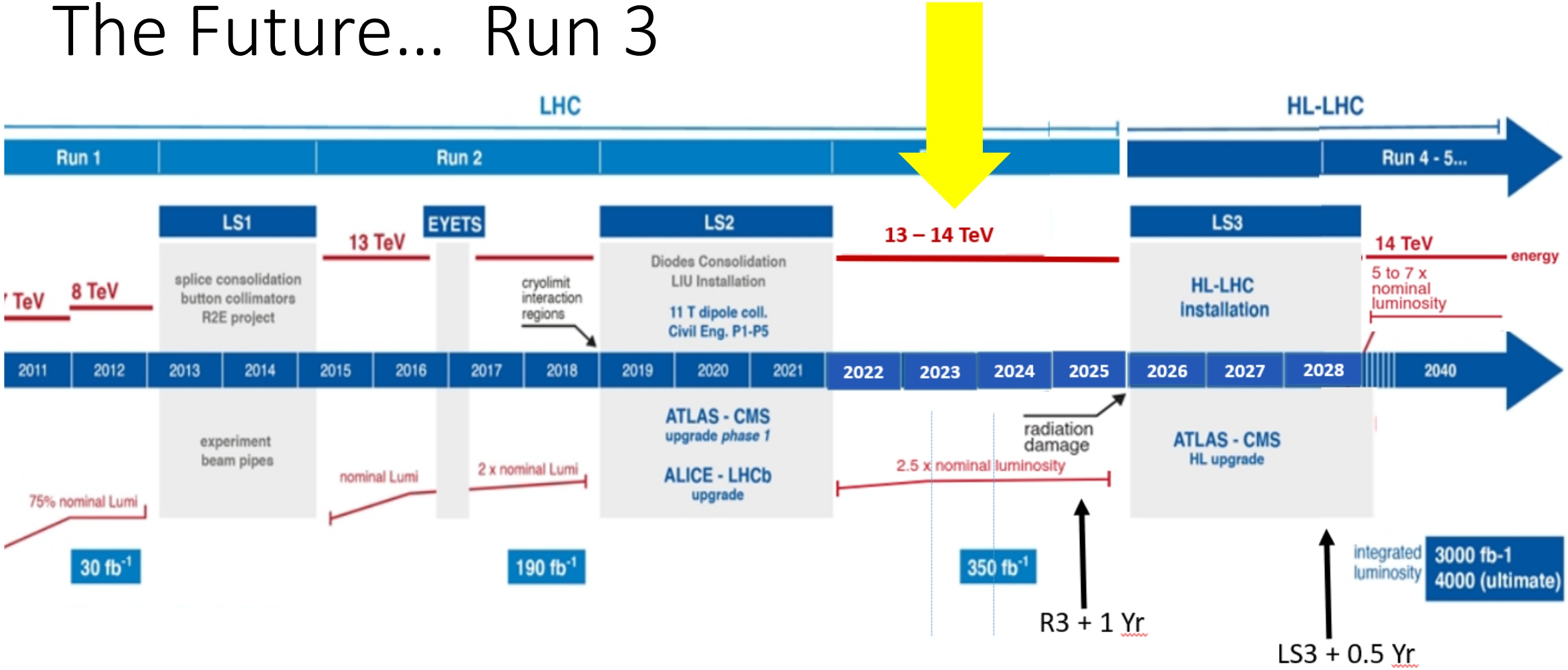
https://www.epj-conferences.org/articles/epjconf/pdf/2016/25/epjconf_meson2016_01005.pdf

Studentship outline

- Start at RHUL (~6 months)
  - Academic lecture and computing courses
  - Start work on HLT/tracking software – gain familiarity with project
- Some time at RAL, then 12 months at CERN
  - Hands-on experience commissioning/operating HLT system during Run 3
    - control room shifts, expert on-call support
  - Join physics analysis group, foundation for physics analysis component of thesis
- Return to RAL/RHUL
  - Finish physics analysis, write thesis


Thanks for listening!
Any Questions?

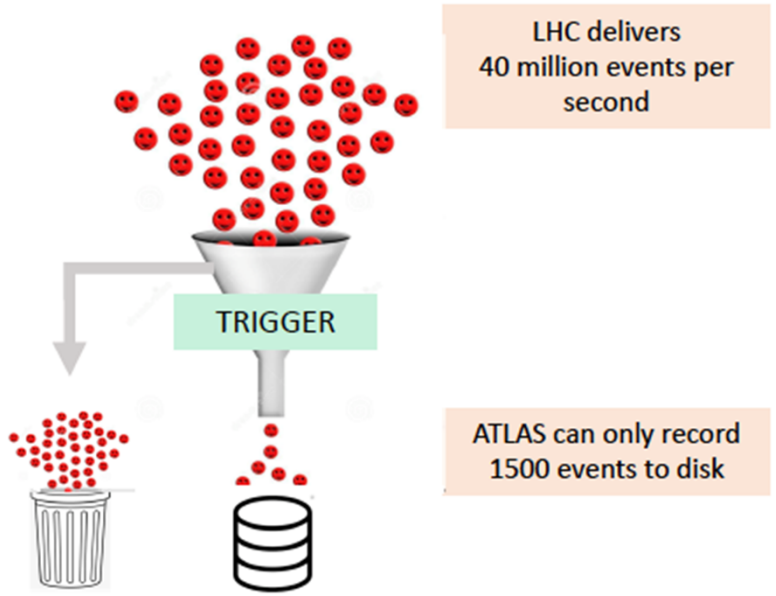
The Future… Run 3

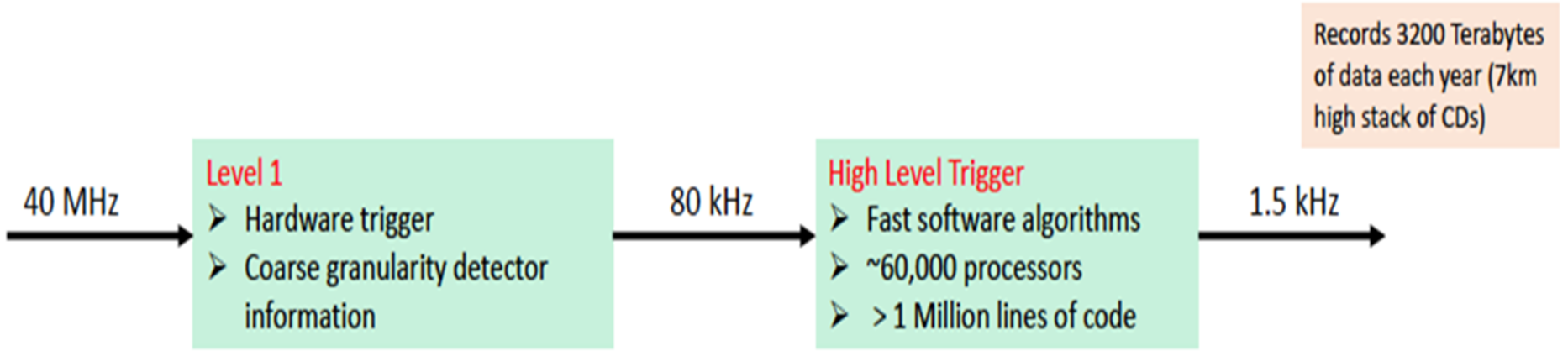


Look forward to more data to come in 2022 with Run 3…

ATLAS Trigger

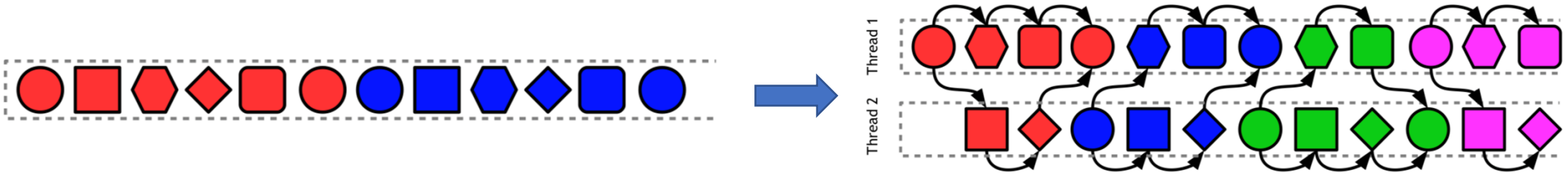
- If we stored all the data that ATLAS generates from collisions, we would use every hard drive in the world within weeks
- Store only the interesting collisions (1500/s)
  - Still record the equivalent of full Netflix catalogue every year
- Use dedicated hardware (Level 1 Trigger) and 60,000 CPUs (High Level Trigger)





ATLAS High Level Trigger

- During LS2 rewrote entire trigger code (nearly 1M lines of C++ and Python) to enable multi-threading and improve the selection algorithms

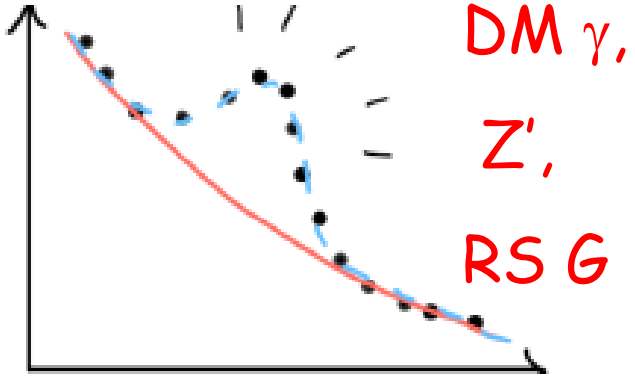


- RAL interests:
  - Tracking – using machine learning techniques to find tracks quickly and efficiently
  - Core trigger software – flow of events/algorithms, control room tools, analysis tools, etc.
  - Validation of trigger software – are we finding the events we want efficiently? Resource usage – memory and CPU time?
  - Beyond CPUs: GPUs and FPGAs for Run 4

Testing the SM of Particle Physics & beyond!

In **ee/μμ** data can look for:

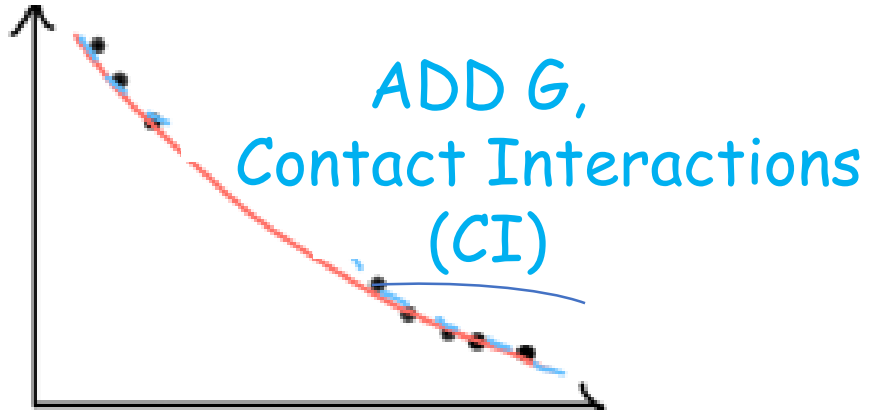
resonances or excesses



DM γ,

Z',

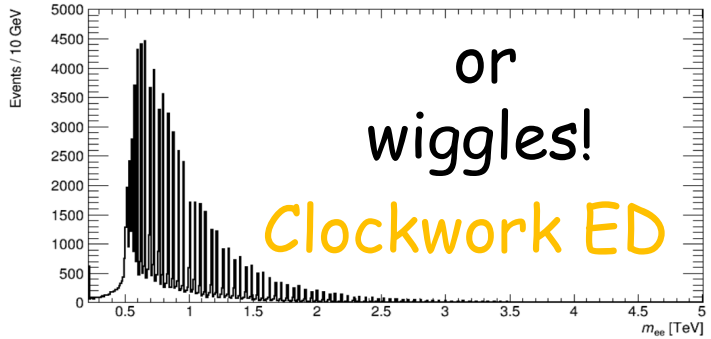
RS G



ADD G,

Contact Interactions

(CI)



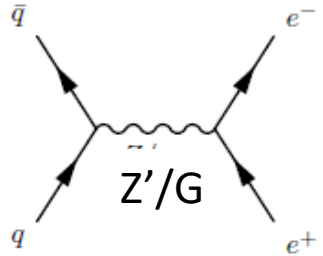
or

wiggles!

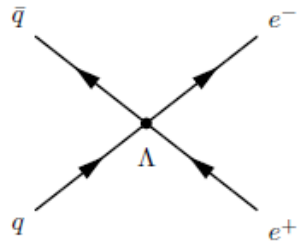
Clockwork ED

RHUL Leadership and Long-term Involvement in High Mass Dilepton Searches

- Run 1 & Run 2 ee/μμ data has been used to search for
- Resonant new physics
  - Spin 1 Z'
  - Spin 2 RS Gravitons



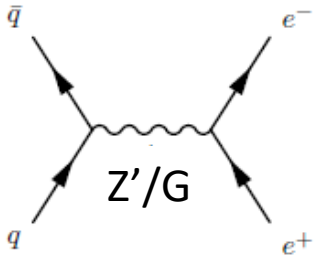
- Non-resonant new physics
  - Contact Interactions
  - ADD (large extra dimensions)



Resonant Dilepton Searches

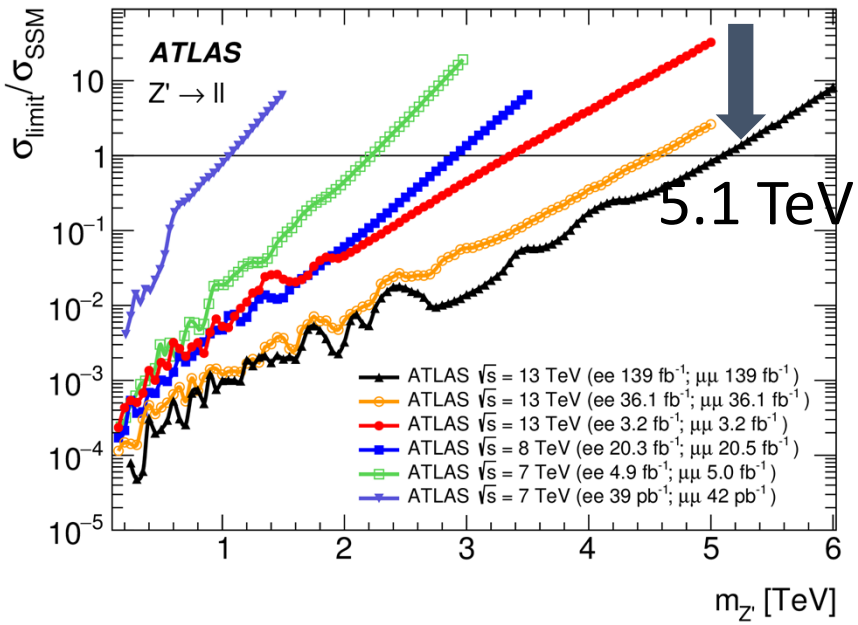
Resonant new physics

Spin 1 Z’

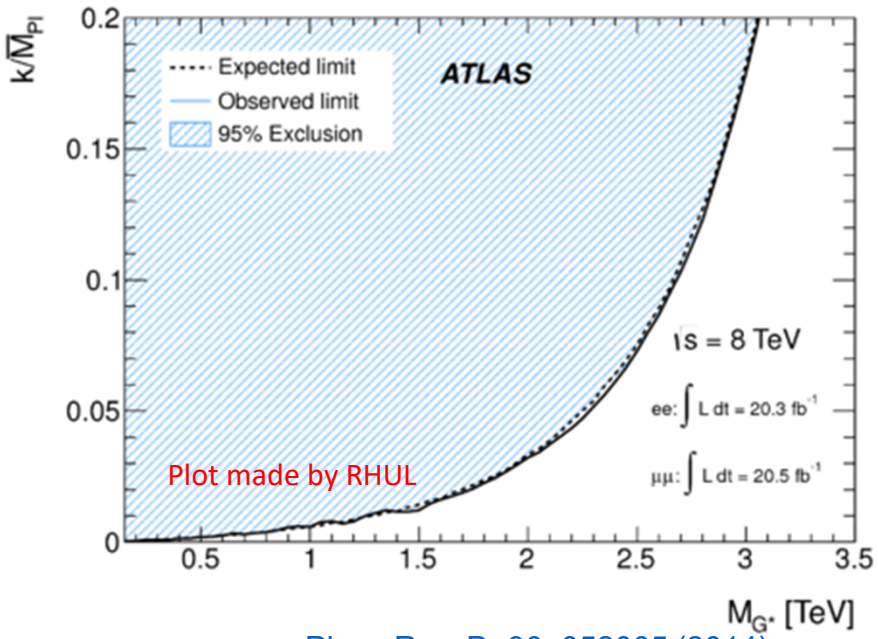


Spin 2 RS Gravitons

extra dimensions



Phys. Lett. B 796 (2019) 68

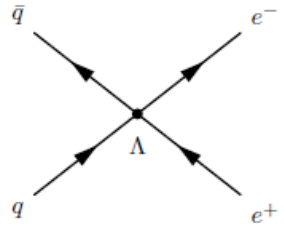


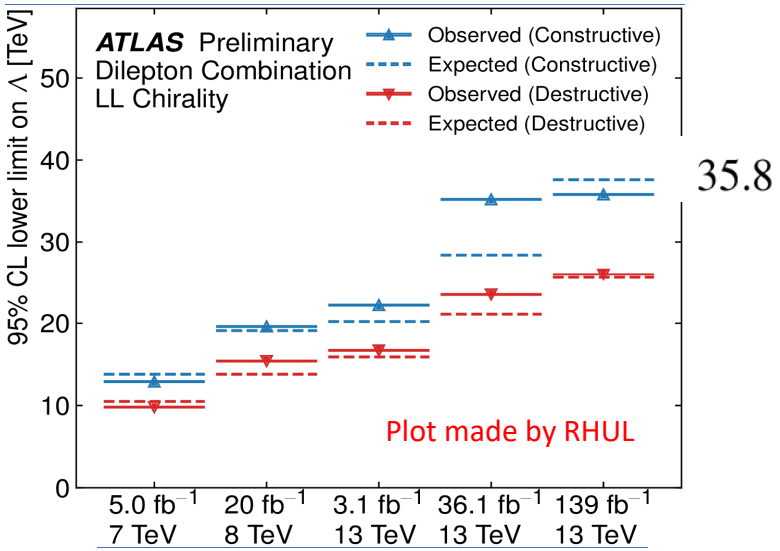
Phys. Rev. D. 90, 052005 (2014)

Non-resonant searches

- Non-resonant new physics

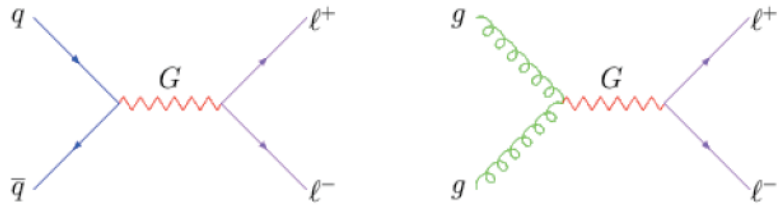
Contact Interactions

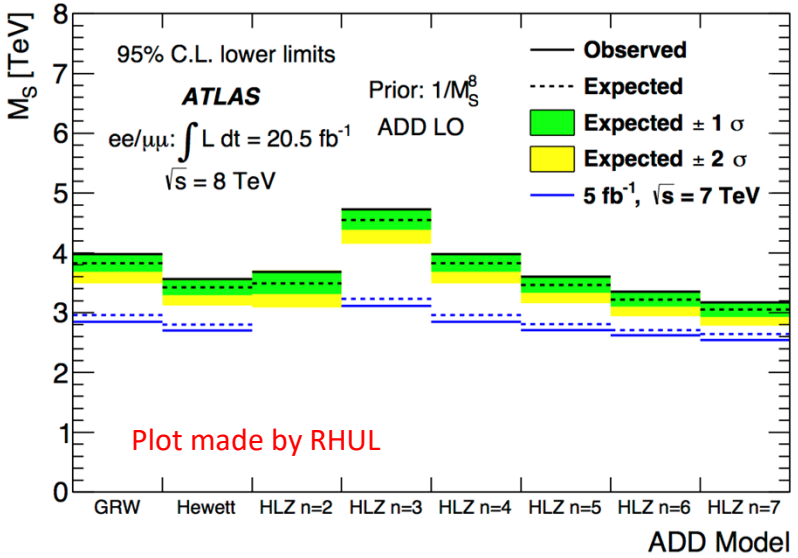




JHEP 11 (2020) 005

ADD (large extra dimensions)





Eur. Phys. J. C (2014) 74:3134

RHUL Publications and Editor (**): Run 2

- Resonant new physics
  - Dilepton Resonance Search 139 fb^{-1}

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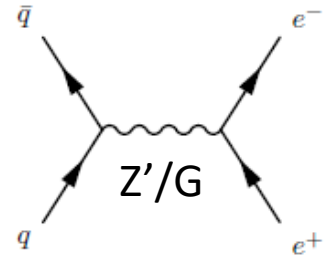
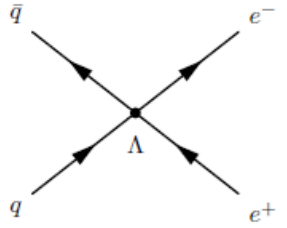


- Both resonant and non-resonant new physics
  - In the dilepton final state 36.1 fb^{-1}

JHEP 10 (2017) 182

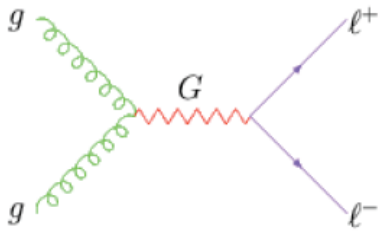
Phys. Lett. B 761 (2016) 372-392



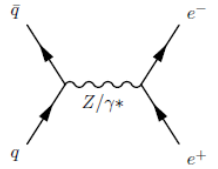
3.2 fb^{-1}

- Non-resonant new physics
  - Non-resonant ADD dilepton search 139 fb^{-1} ** Berry ATL-PHYS-PUB-2021-021
  - Non-resonant dilepton search 139 fb^{-1}

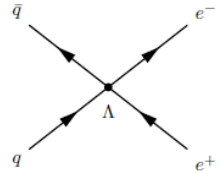
JHEP 11 (2020) 005



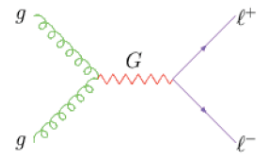
RHUL Publications and Paper Editor (**): Run 1



- **Resonant new physics**
- Dilepton resonances at √s= 7 TeV (~40 pb^{-1}) arXiv:1103.6218, Phys.Lett.B700:163-180 (2011)
- Dilepton resonances at √s= 7 TeV (1 fb^{-1}) arxiv:1108.1582, Phys.Rev.Lett. 107 (2011) 272002
- Dilepton resonances at √s= 7 TeV (4.9 pb^{-1}) arxiv: 1209.2535, JHEP 1211 (2012) 138



- **Non-resonant new physics**
- Non-resonant CI & ADD dilepton search at √s = 7 TeV (~1fb^{-1}) ** Berry
  arXiv:1112.4462, Phys.Lett. B712 (2012) 40-58.
- Non-resonant CI & ADD dilepton search at √s = 7 TeV (~5fb^{-1}) ** Berry
  arXiv:1211.1150, Phys.Rev. D87, 015010 (2013).
- Non-resonant CI & ADD dilepton search at √s = 8 TeV (~1fb^{-1}) ** Berry
  arXiv:1407.2410v3 Eur. Phys. J. C (2014) 74:3134



- Diphoton non-resonant new physics
- Extra Dimensions using diphoton events in 7 TeV (~1fb^{-1} ee + ~ 2fb^{-1} γγ)
  arXiv:1112.2194 Phys.Lett. B710 (2012) 538-556.
- Extra Dimensions using diphoton events in 7 TeV (~5fb^{-1})
  arXiv:1210.8389; NJP 15, 043007 (2013)