Searching for dark matter in final states with low-momentum leptons at the ATLAS experiment

James Frost, Monica D'Onofrio
(james.frost@stfc.ac.uk, monica.d'onofrio@cern.ch)

Science and Technology Facilities Council

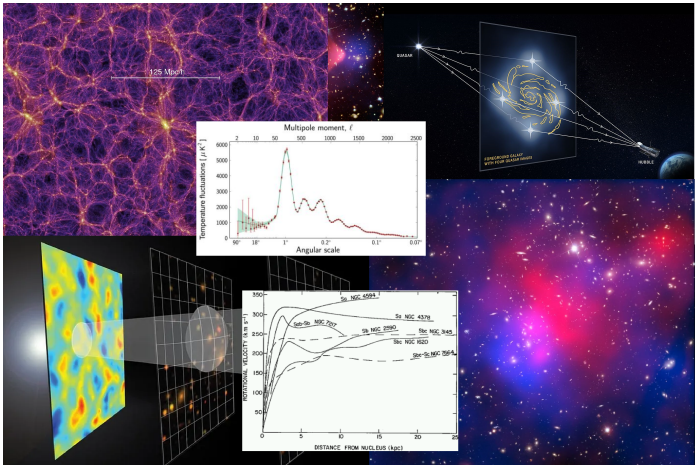
UNIVERSITY OF LIVERPOOL

Friday 27th February 2026

Why search for Dark matter?

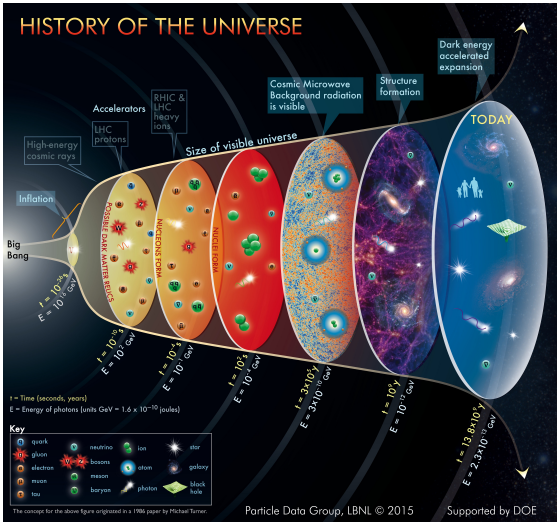
What evidence exists?

- Galactic rotation curves
- Dwarf galaxies
- Large scale structure
- Gravitational lensing
- Cluster collisions
- CMB + Baryogenesis

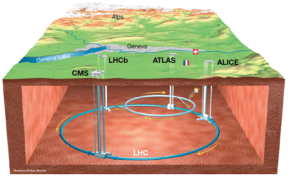


Models of dark matter

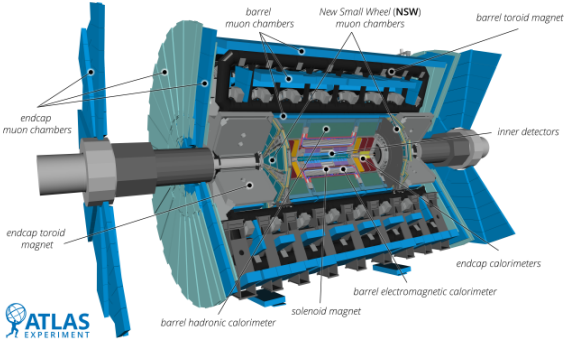
- Dark matter must have very small effective SM couplings
  - Directly to SM particles?
  - Indirectly through new particles?
- Incorporate astrophysical knowledge
  - Relic density
  - Mechanism (freeze out, freeze-in)
  - DM nature (scalar, Dirac fermion, etc...)
- Many candidates: WIMPs, dark γ axion/axion-like particles, dark sectors



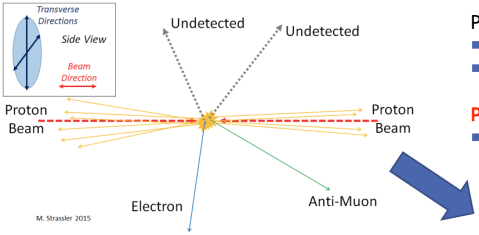
LHC and ATLAS



- CERN's Large Hadron Collider is the world-leading collider - colliding billions of protons, 40 million times a second.
- ATLAS is one of two 'general purpose' detectors.
- Designed to analyse the full range of particle interactions.



From collisions to Dark Matter: ATLAS

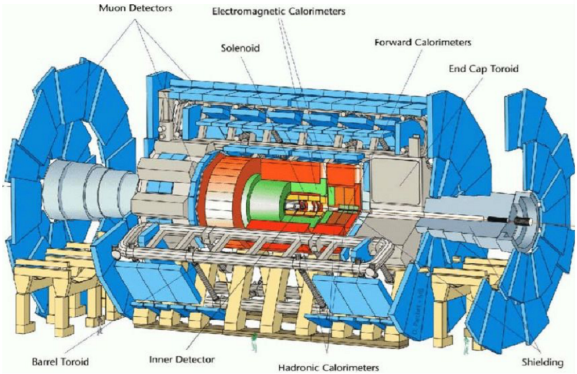


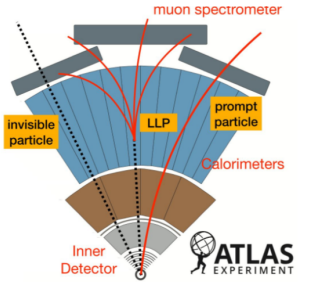
Protons collide at the centre of ATLAS at a huge rate!

- up to 30 million proton-proton collisions/second (MHz)
- BUT Dark Matter signals (or any new particles) are VERY RARE!

Problem is: recording all LHC data takes 400000 PB/year

- ~ 1-1.5 MB/data per collision event, including raw data





Even if we can record DM events, **backgrounds** often look the same and are much more common

Data Challenges

- Too much data produced, lot of uninteresting events → identify where to look and make hard choices from the start: online and offline reconstruction and selections of relevant events are key

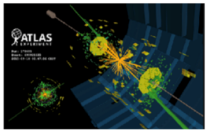
Collision at 30-40 MHz
(~ 1 MB of info each!)

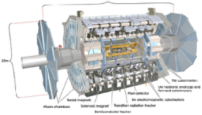
Hardware trigger
Outputs ~ 100 kHz

software trigger
Outputs ~ 1 kHz

Online

Offline

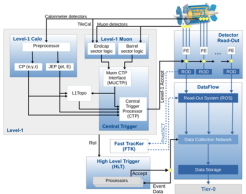


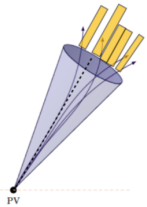


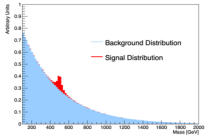
Event selection (trigger)

Object reconstruction and calibration

Data analysis





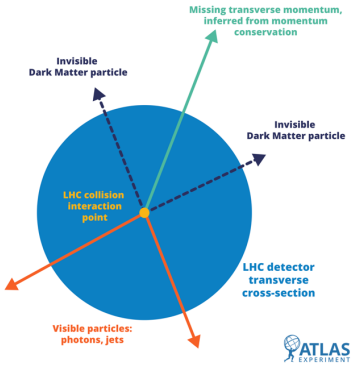


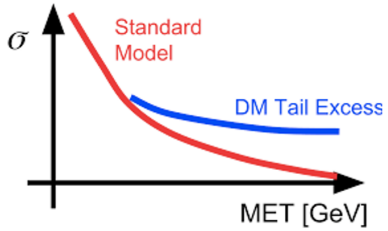
*Complex hardware and software level online selections → **must be fast** (particles are reconstructed on the fly in a simplistic way)*

*Complex software-based offline selections to identify events of interest → **must be precise***

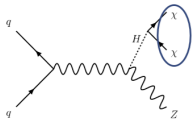
Analysis Challenges - invisible dark matter

- While we want to be as general as possible and look many places at once, we need to make some hypotheses. So: DM can be Weakly Interactive and Massive → **invisible**!
- If the DM candidate does not interact with matter, how do I see it?
- *Reminder:* the total transverse energy in hadron-collision is zero!



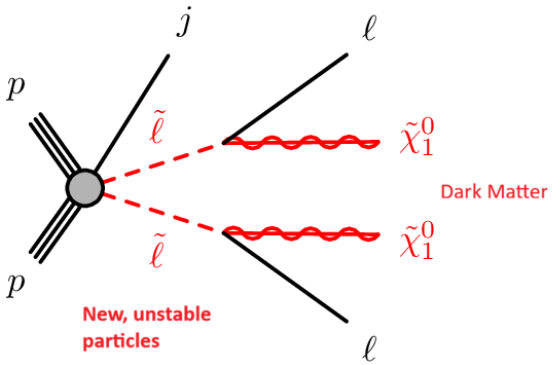


→ part of transverse energy is missing and can measure the 'invisible'!
→ Of course, there must be something else we see, for example:
→ LHC can investigate and characterise the Dark Matter interaction!



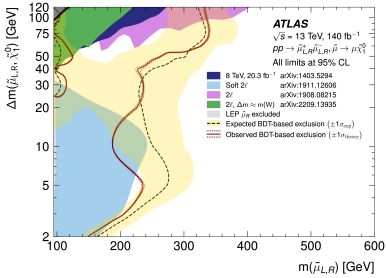
Why soft/low-momentum leptons?

- Huge range of possible dark matter signatures.
- Vital to make sure we do not miss discovering dark matter.
- Low-momentum leptons (electrons, muons, taus) are harder to reconstruct, and their signals hard to distinguish from background processes.
- Not well explored ... need to look harder

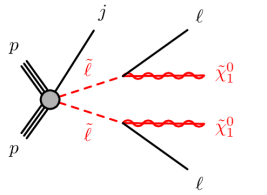


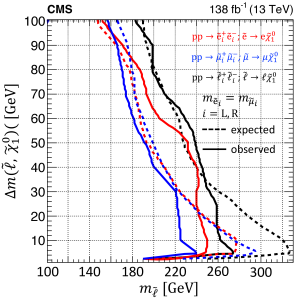
New Physics Strikes Back?

- Current results for small δmass between SUSY partners of electroweak bosons, low p_T signatures.
- Multiple ($\sim 2\sigma$) excesses - Run-3 data needed.
- PhD project aim to confirm/deny with new data!

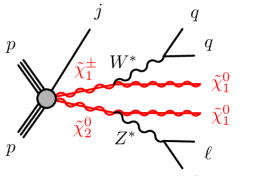


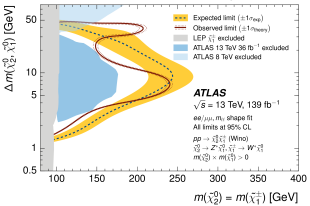
2106.01676





2508.13900



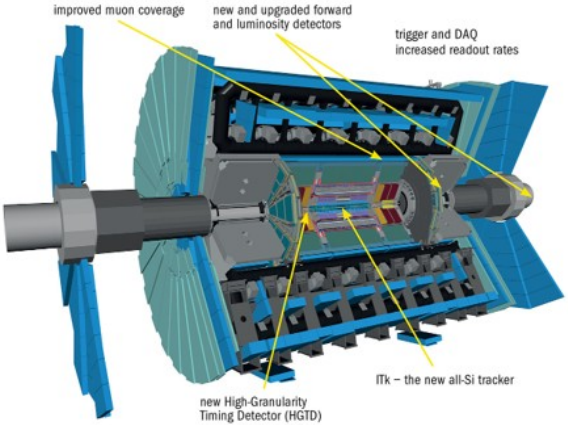


1911.12606

Also CMS: 2111.06296

HL-LHC and Run-4

- From this year, LHC being upgraded to increase collision intensity (luminosity) and provide much more data for analysis: High-luminosity LHC (HL-LHC).
- To record these collision events and their rates, need to upgrade detector.
- Largest upgrade to ATLAS - largely new detector.
- Upgrades designed and under construction now!

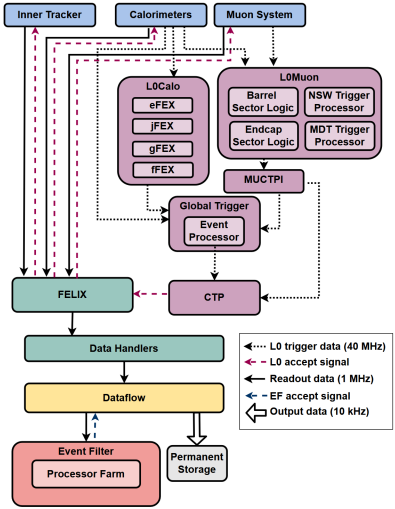


ATLAS TDAQ (Trigger and Data AQuisition)

- ATLAS' trigger system selects interesting events for recording.
- Low-level hardware trigger: high-speed selections
  - Check 40 million collisions a second, select most interesting million, decide within 10 μs
- Higher-level software trigger
  - More complex algorithms, pick 1% from above, within $\sim$ 0.5s

HL-LHC

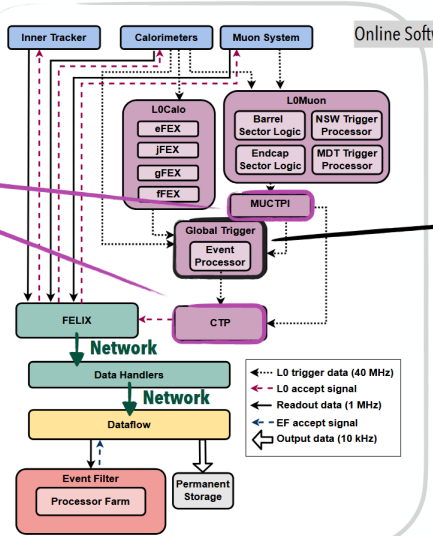
- Upgraded muon and calorimeter triggers.
- New Global Trigger



ATLAS TDAQ (Trigger and Data AQuisition)

L0 Calo
Feature Extractors (FEXs)
FEX Optical Exchange (FOXs)

L0 Central
Central Trigger Processor (CTP)
Muon CTP Interface (MUCTPI)
Local Trigger Interface (LTI)



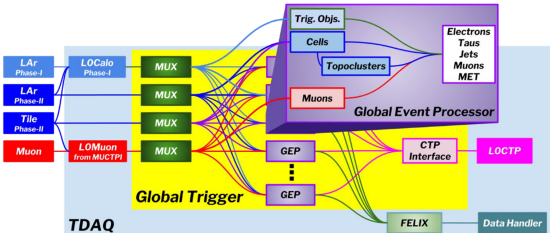
L0 Muon
Barrel + Endcap Sector Logic (SL)
Monitored Drift Tube Trigger Processor (MDT-TP)
New Small Wheel Trigger Processor (NSW-TP)

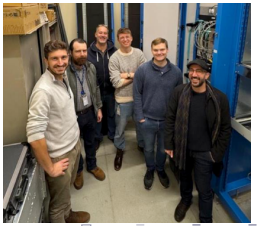
L0 Global
Multiplexer (MUX)
Global Event Processor (GEP)
global CTP Interface (gCTPi)

Key New System
- Advanced selections using full event input
- Better output to SW trigger and analysis

Global Trigger

- Multiplexing - combine all input from each event together on one processing node - previously only possible in software layers.
- Better, more complex decisions (e.g. fast machine learning) - better particle identification.
- Runs on $\sim$ 60 custom boards with 2 FPGAs each - input 50 TB/s!
- Be part of international team delivering state-of-the-art system.
- Develop, install and operate the final system at CERN - access to ATLAS from summer 2027!





Ph.D Project

Prof. Monica D'Onofrio

Experience:

- Deputy Head, Department of Physics (Liverpool).
- STFC Science Board
- ATLAS SUSY Convenor

Dr. James Frost

Experience:

- ATLAS Data Preparation Coordinator
- LHC Dark Matter Working Group Convenor
- Global Trigger

Ph.D Project

Prof. Monica D'Onofrio

Likely Timeline (flexible):

- Ph.D start at Liverpool (visit/access RAL)
- Long-term attachment at CERN
- Work at RAL completing analysis & Global Trigger work
- Return to Liverpool, finish Ph.D, graduate and next opportunity!

Dr. James Frost

Day-to-day:

- Collaborate with experts across Liverpool and RAL/PPD.
- Learn from broad dark matter, data and physics analysis expertise.
- Technical guidance and day-to-day support from senior Liverpool postdoc - other Ph.D students in searches.
- Use the RAL facilities and test-rig, collaborate with engineers and physicists running state-at-the-art technology and data systems.

Summary

You will:

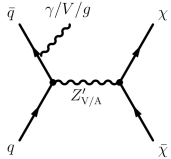
- Have opportunity to take part in **ATLAS**, one of the largest international science projects.
- Look for **evidence of dark matter** in ATLAS collision data - understand challenging signatures and backgrounds, follow up exciting excesses with more powerful datasets.
- Also play a key role in the next phase of LHC and ATLAS.
- Understand, develop and build a truly **state-of-the-art hardware triggering system**, ready for the start of HL-LHC.
- Work with experts in Liverpool, RAL and CERN - learn a great deal!

Backup

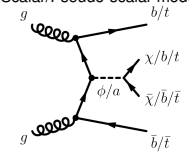
Introduction to Collider DM searches

- Any WIMP DM produced at collider experiments will interact weakly and pass invisibly through detectors.
- Inferred through 'Missing E_T' (E_T^{miss}) when event does not balance in plane transverse to beam.
- Visible radiation (photons, jets, vector bosons) from ISR or associated production can tag DM pair production.
- Consequently, collider searches focus on production of a SM particle(s) (X) with large E_T^{miss}.
- Dark Matter mediators need searches for new resonances. Complementary approaches.
- LHC can investigate and characterise the SM-DM interaction. Use simplified models (with mediator), and specific complete models to explore at ATLAS.

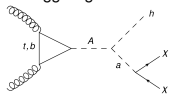
Vector model



Associated production:
Scalar/Pseudo-scalar model

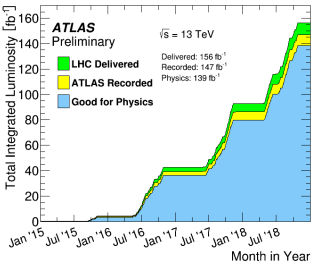


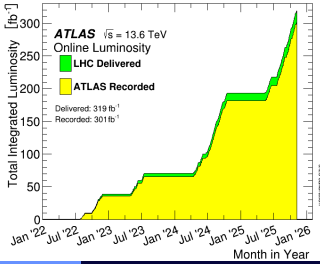
Higgs signatures



LHC Datasets and Luminosity

- LHC Run-2 ended in late 2018.
- An unprecedentedly sensitive dataset.
- And just the beginning...
- LHC Run-3 at 13.6 TeV has been progressing steadily since summer ’22. Run 3 ends this June.
- Ideal time to join ATLAS analysis! Run-3 brought:
  - Greater luminosity and greater collision energy
  - Already tripled our data (> 400 fb^{-1}) and counting - more until mid-2026.





Outline

Spare slide