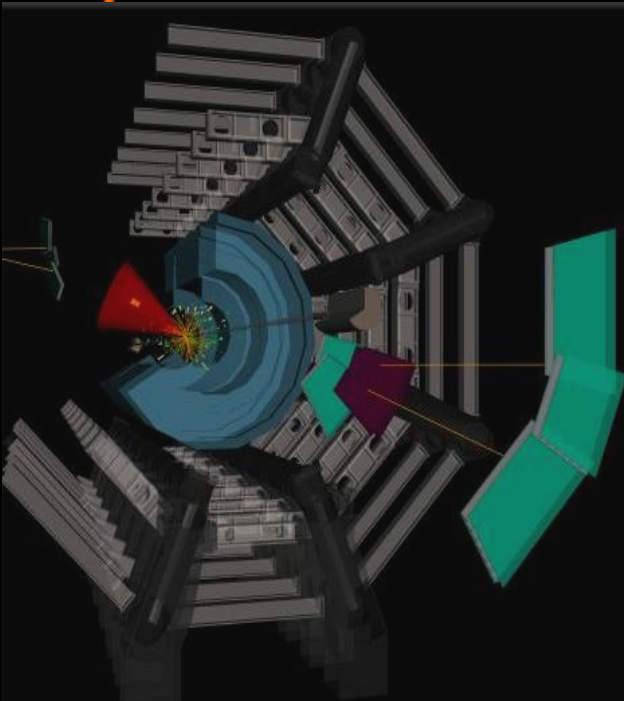


Liverpool Particle Physics

Research programme and facilities

Monica D'Onofrio



Who am I

- Monica D'Onofrio
- Experimental particle physicist and Professor at the UoL Physics Department
- Deputy Head of Department, Head of Research at Liverpool, member of Academic Senate
- Team Leader of the ATLAS and FASER groups at Liverpool, and UK national contact for both experiments

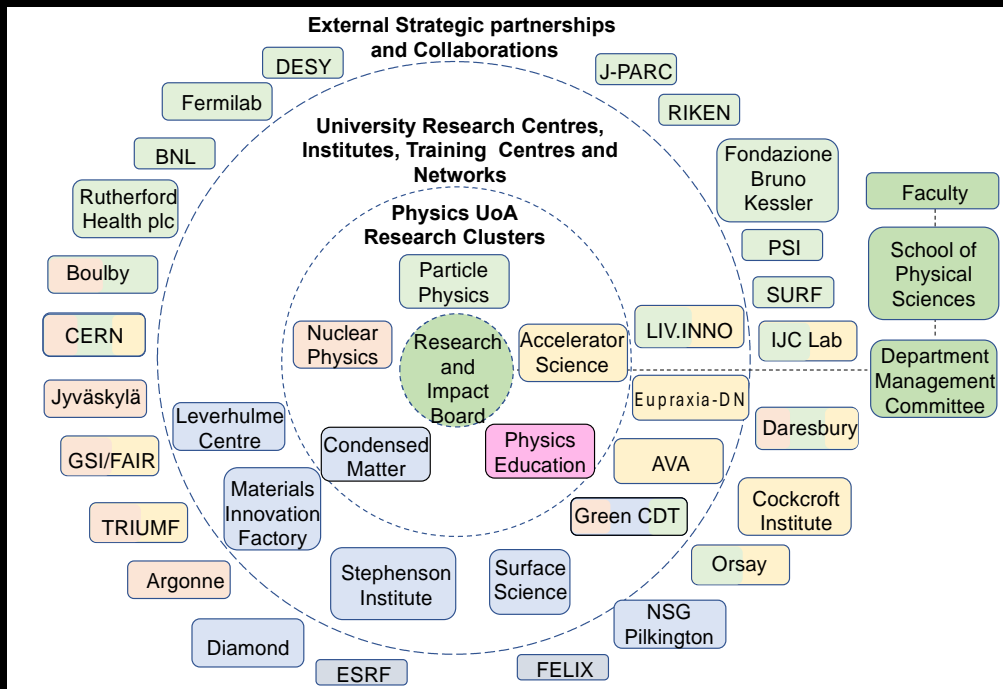
During my career, I have worked mostly on collider experiments (ATLAS, recently also FASER, and CDF at Fermilab in the past). My main interests are on searches for new physics (supersymmetry, dark matter, dark sectors) also using AI tools. I also work on future experiments planned at CERN and beyond and I member of various committees and panels nationally and internationally.



The Department of Physics @ UoL

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PHYSICS
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ENGINEERING
IMPACT
PHENOMENOLOGY
OUTREACH
DARTICLE

- Research activities in our department are distributed in five clusters: **Accelerator Science, Condensed Matter, Nuclear Physics and Particle Physics** and the recently added **Physics Education Research**
- Playing key roles in interdisciplinary institutes and in national and international collaborations.
- Theoretical physics hosted in the Math department → close collaboration!

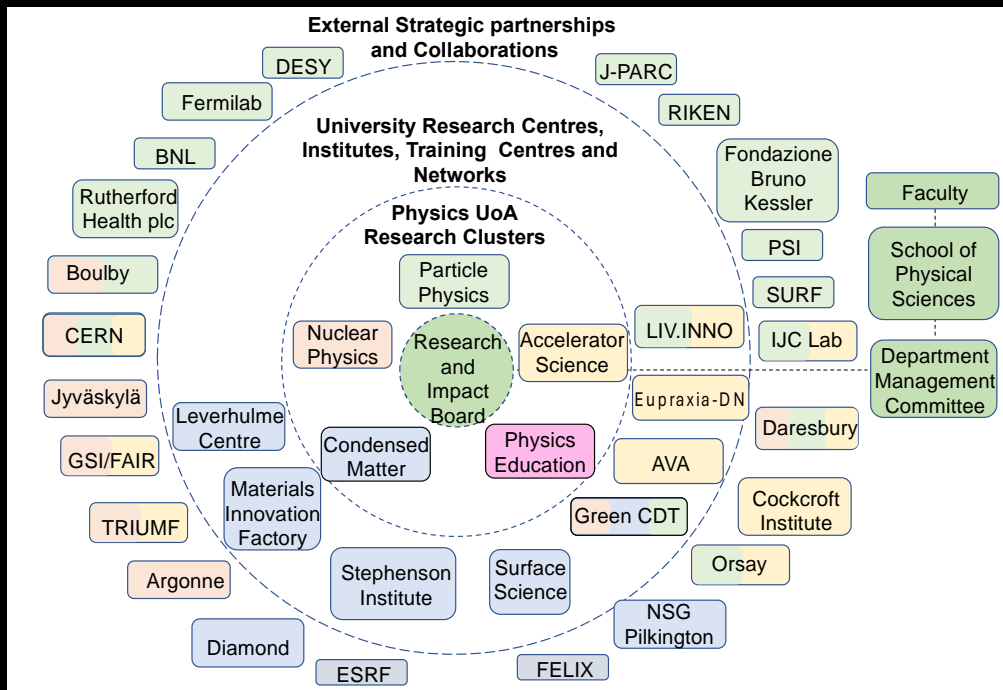


- **~55 academics** (2 joint with other departments)
- more than **50 full time research** and computer physicists, professional, technical and electronic support staff
- About **120 PhD students** enrolled in our programmes (STFC CDT on Big Data Science (LIV.DAT), Innovation in Data Intensive Science (LIV.INNO), EPSRC CDT's on New and Sustainable Photovoltaics and Risk & Uncertainty, and EU ITN on Medical Accelerators and Antimatter Physics).

The Department of Physics @ UoL

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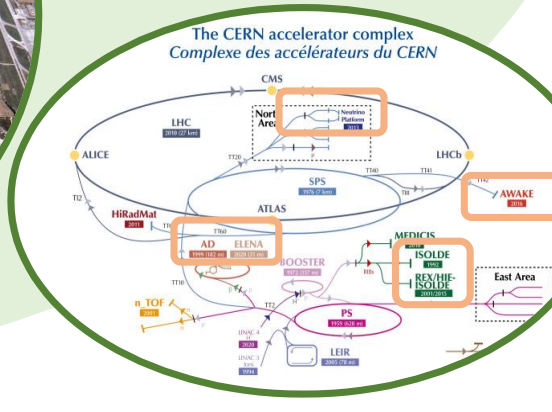
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- Theoretical physics hosted in the Math department → close collaboration!



- Research on **quantum, sustainable technologies, AI/Data science and applications to medical physics/healthcare** underpin all our activities
- **Dedicated groups supporting those activities transversally have been established**

Partnership with CERN

Liverpool @ CERN



- Build, upgrade, maintain, operate and exploit facilities and experiments in particle physics (**ATLAS, FASER, LHCb, neutrino platform DUNE/Ariadne, MUoNE**), nuclear physics (**ALICE, ISOLDE**) and accelerator physics (**AWAKE, AEGiS, ELENA, HL-LHC, FCC**)
- ~75% of academic staff, researchers, engineers and technicians are engaged in CERN-related activities (and **more than 60 PhD students**)

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SCIENCE
ENGINEERING
IMPACT

The Department of Physics is in the **top-25** list of CERN key collaborators, with strong participation in experiments at the Large Hadron Collider (LHC) and beyond.

Liverpool in High Energy Physics: *One of UK's largest particle physics groups*

Approximately 140 staff and students

27 academics; ~38 staff physicists and postdocs; ~26 mechanical and electronic engineers, machinists, cleanroom technicians, computing staff; 1 administration support staff; ~50 PGR students



<https://www.youtube.com/watch?v=rAWbi5YU9rI>

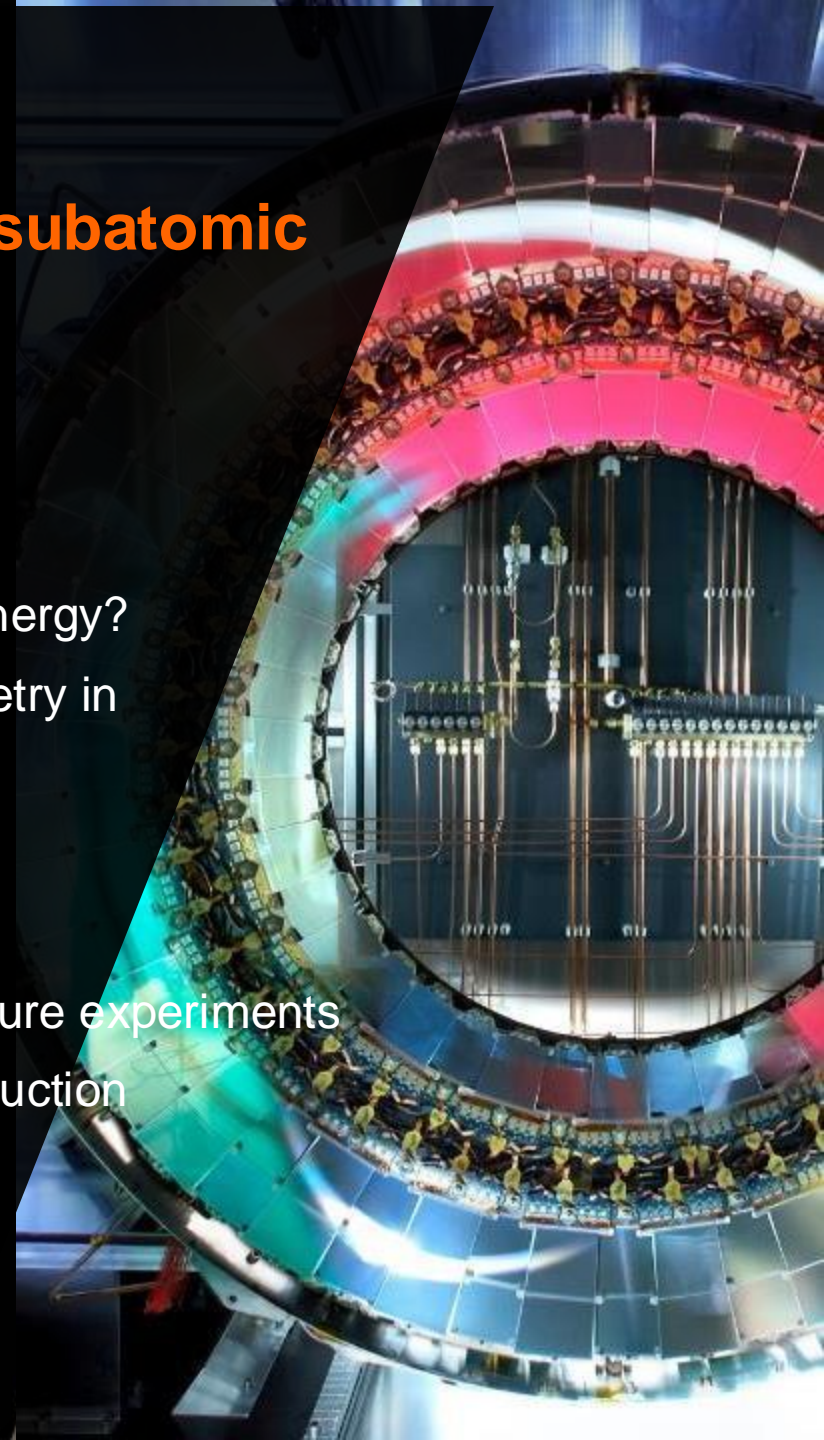
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7 Key fundamental questions in subatomic physics

- What lies beyond the Standard Model?
- What is the origin of neutrino mass?
- What is the nature of dark matter and dark energy?
- What explains the matter anti-matter asymmetry in the universe today?

Liverpool PP activities reflect these priorities:

- Technology Research & Development for future experiments
- Experiment development and detector construction
- Experiment data analysis

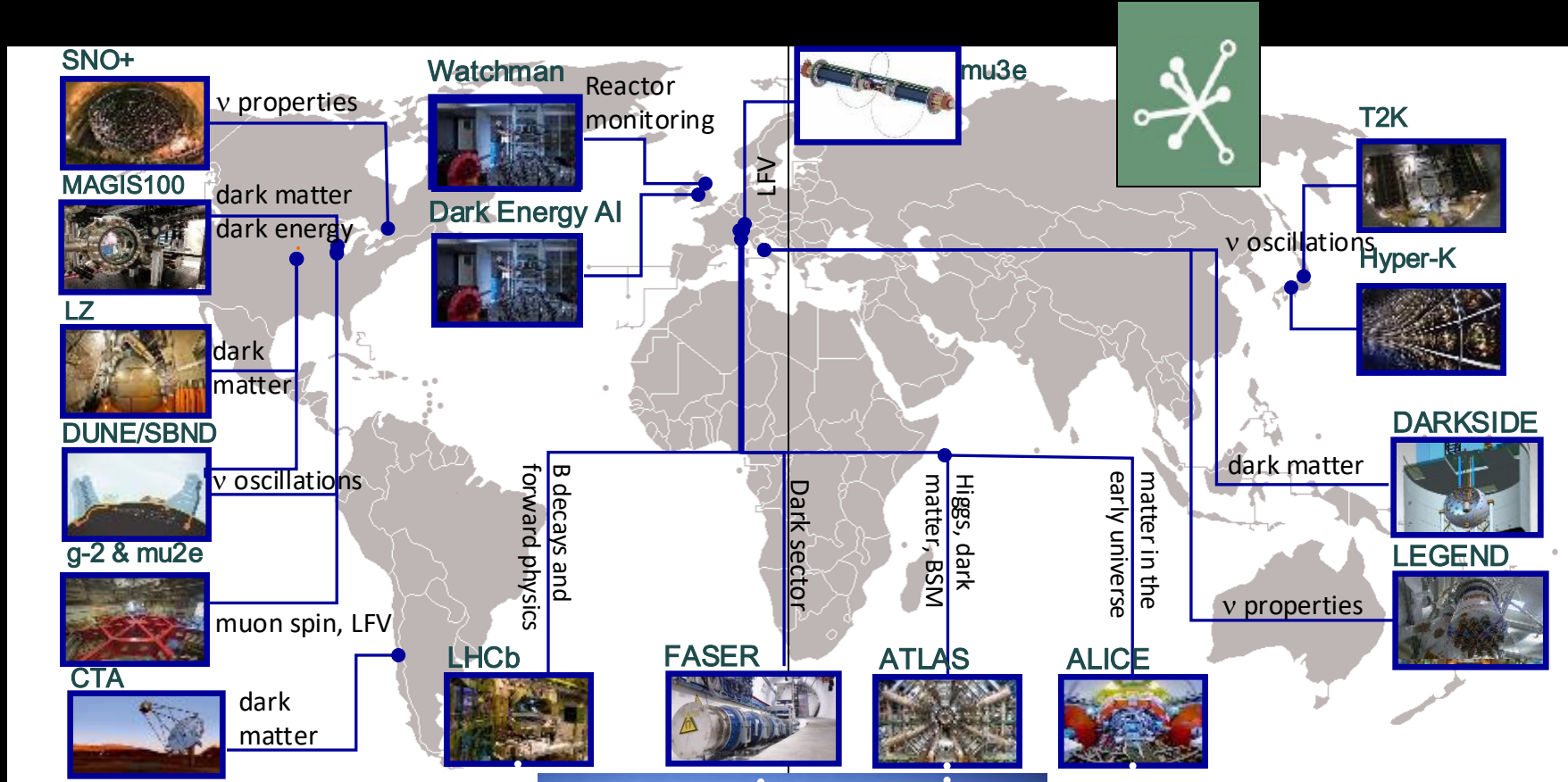


8 Particle Physics research streams

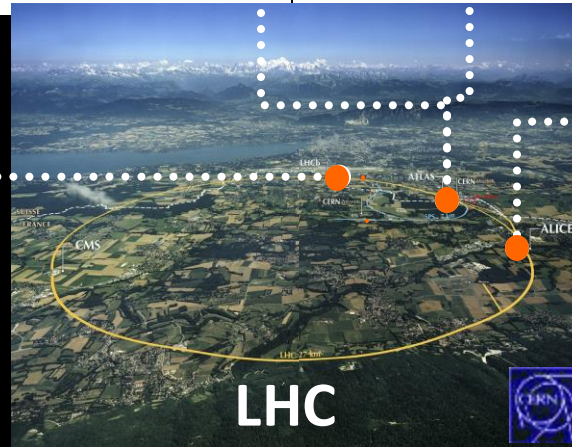
- **Energy frontier experiments** - **ATLAS** and future colliders at CERN
- **Precision, quark and lepton flavour experiments** – LHCb and MUonE at CERN, g-2 and mu2e at FNAL, mu3e and muon-EDM at PSI, proton-EDM and more at Brookhaven NL
- **Neutrino physics** - T2K and Hyper-K in Japan, SBND/DUNE in the US, SNO+ at SNOLAB, Legend at Gran Sasso, Button in Boulby
- **Dark universe** - LZ @ SURF, DarkSide-20k @ Gran Sasso, MAGIS @ FNAL, AION UK, CTA in Chile, FASER @ CERN

Detector R&D and construction - Internationally recognised expertise and infrastructure for detector development: radiation hard and low mass silicon sensors, Argon TPC technology R&D, silicon photonics R&D for cryogenic noble gas experiments, Atom Interferometry and quantum sensors, proton therapy

Advanced computing: development of AI methods to be used for online data-taking and offline analyses, collaborations with Microsoft, CERN and FBK, grant from EPSRC for explainable AI



A worldwide programme:
Experiments at a glance



Experiments at the LHC

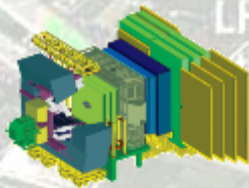


ALICE heavy ion collisions, quark-gluon plasma, early universe (Nuclear Physics group)

ATLAS Higgs boson search and studies, precision measurements and search for new physics.

Higgs discovery: 2013 Nobel Prize in Physics

FASER: new experiment to search for dark sector particles

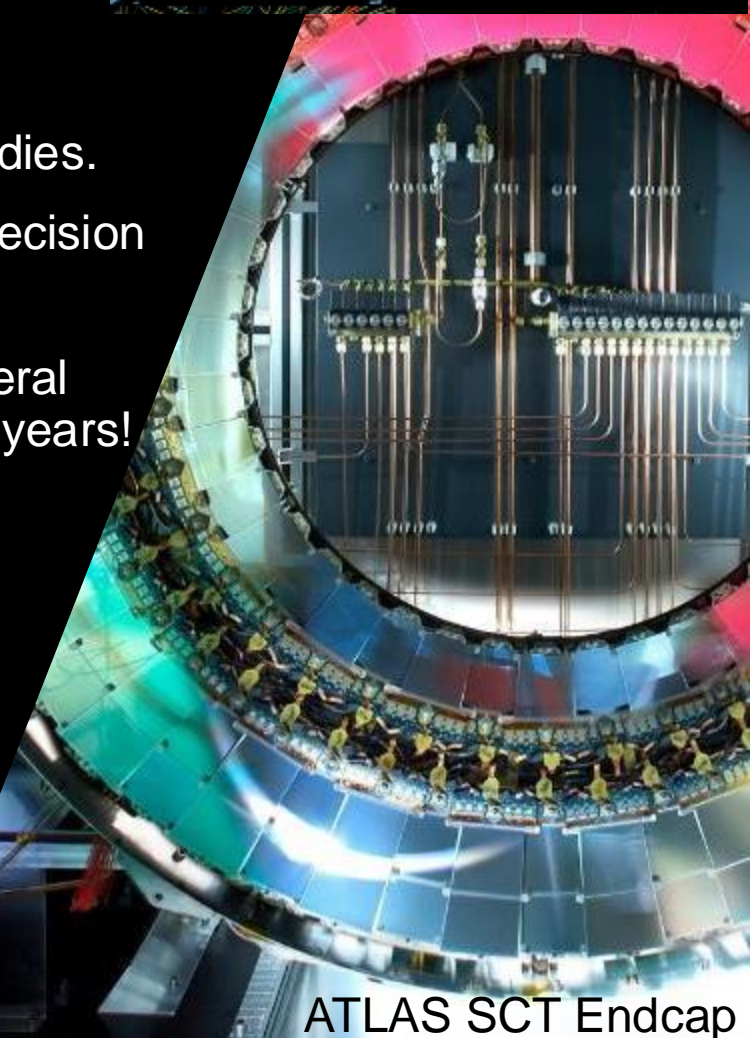
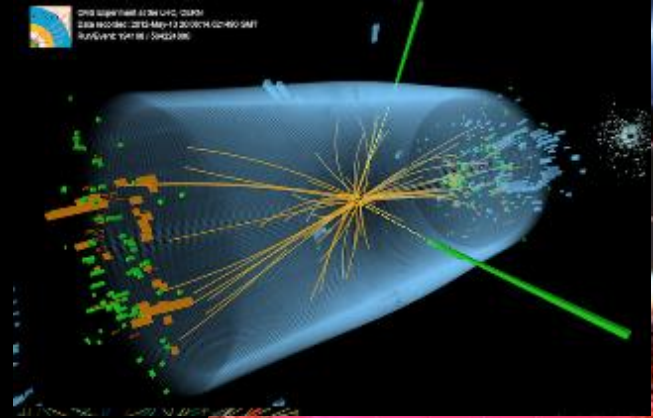


LHCb Study of CP-violation in b-mesons; precision physics in heavy flavour decays; Search for lepton non-universality

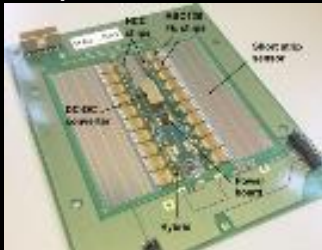
11 ATLAS experiment @ CERN

Strong Liverpool involvement from early conception

- Construction of the semiconductor tracker
- Higgs boson discovery in 2012 and subsequent studies.
- Searches for new physics, including dark matter, precision measurements of Standard model parameters.
 - Liverpool physicists work(ed) and lead/led several data analyses → over 1,200 publications in 13 years!
- Currently building the tracking detector for the High Luminosity LHC upgrades 2029-2030.
- > 30 people - academics, postdocs and students



Strip Barrel module



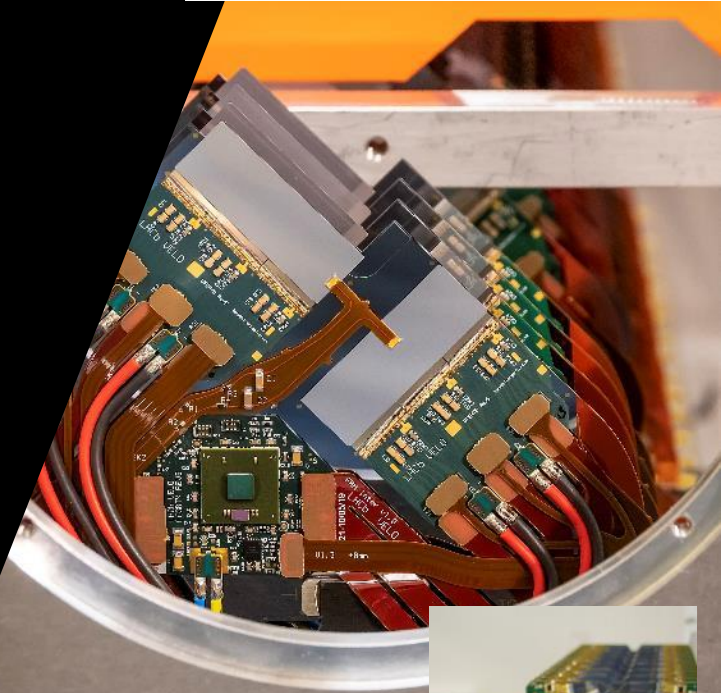
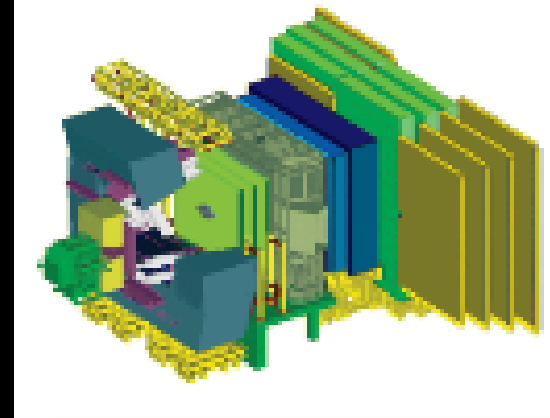
Pixel endcap test stand



ATLAS SCT Endcap

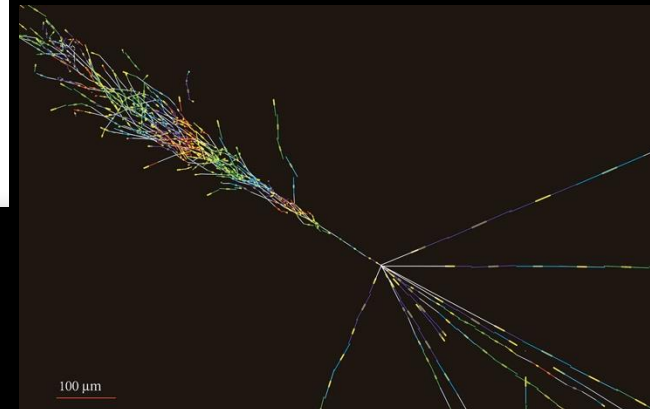
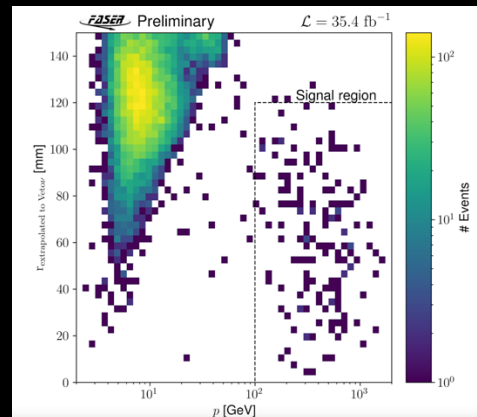
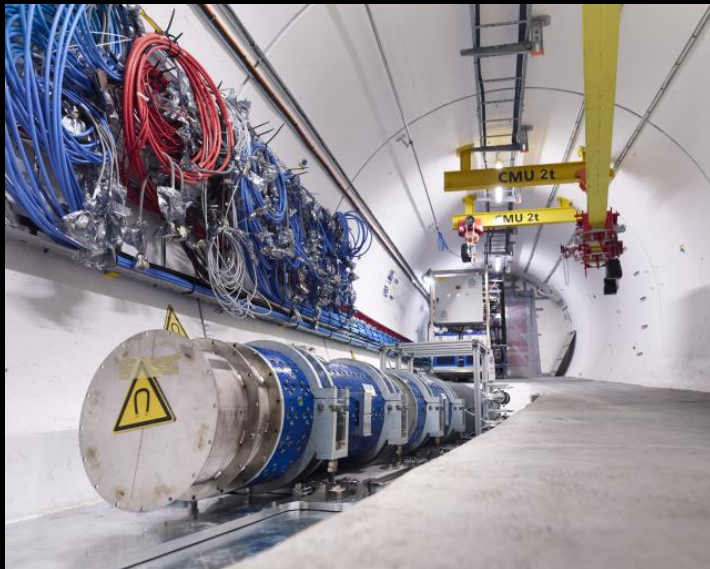
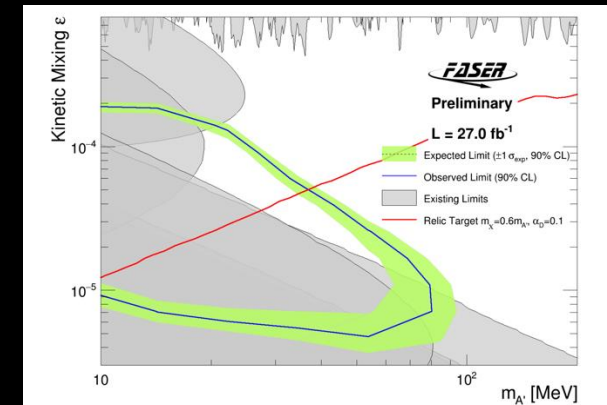
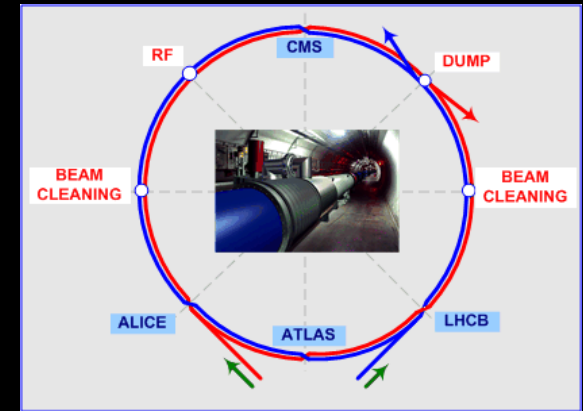
12 LHCb experiment @ CERN

- Second largest single experiment group.
- Development and construction of the silicon sensor modules of the tracking system
- Study of heavy flavour physics, CP violation, SM physics.
 - ~650 papers published since start-up
- coordination of new experiment wide data analysis framework
- Assembly of both halves of the new pixel tracker.



• The **FASER** experiment @ CERN

- FASER is a new (2021) small experiment located at ~ 500 m from ATLAS interaction point
- Dedicated to the search for new particles belonging to a hidden dark sector that could explain dark matter, as well as to the study of highly energetic neutrinos produced by the LHC
- First results released! Constraints on new physics models and first observation of high-energy neutrinos at colliders!

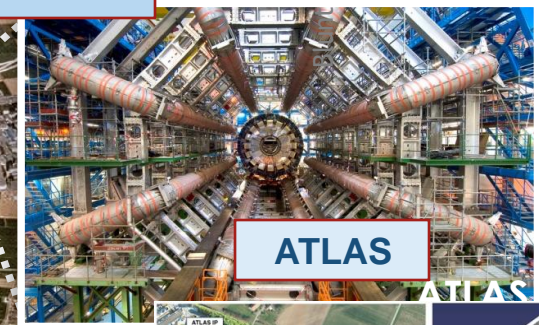


The LHC at CERN

27 km circumference



Run 3 of the LHC mid-way, a very exciting time for all new and old experiments



Monica D'Onofrio, Liverpool Graduate Students

... but there is much more going-on in particle physics at CERN and around the globe, and Liverpool physicists work on many more forefront experiments

Neutrino Programme

Neutrinos are very fascinating – the SM predicts them massless but experimental data tell us that when traveling long distance they can **oscillate** – means they change type, and this can only happen if they have at least a tiny mass...

Many experiments, all based on this idea...

The biggest ones:

Super-Kamiokande programme (Japan)

- Leadership in neutrino oscillation analysis (2016 breakthrough prize in fundamental physics)
- Now operating T2K and building its bigger version, Hyper-Kamiokande or HK (2026)

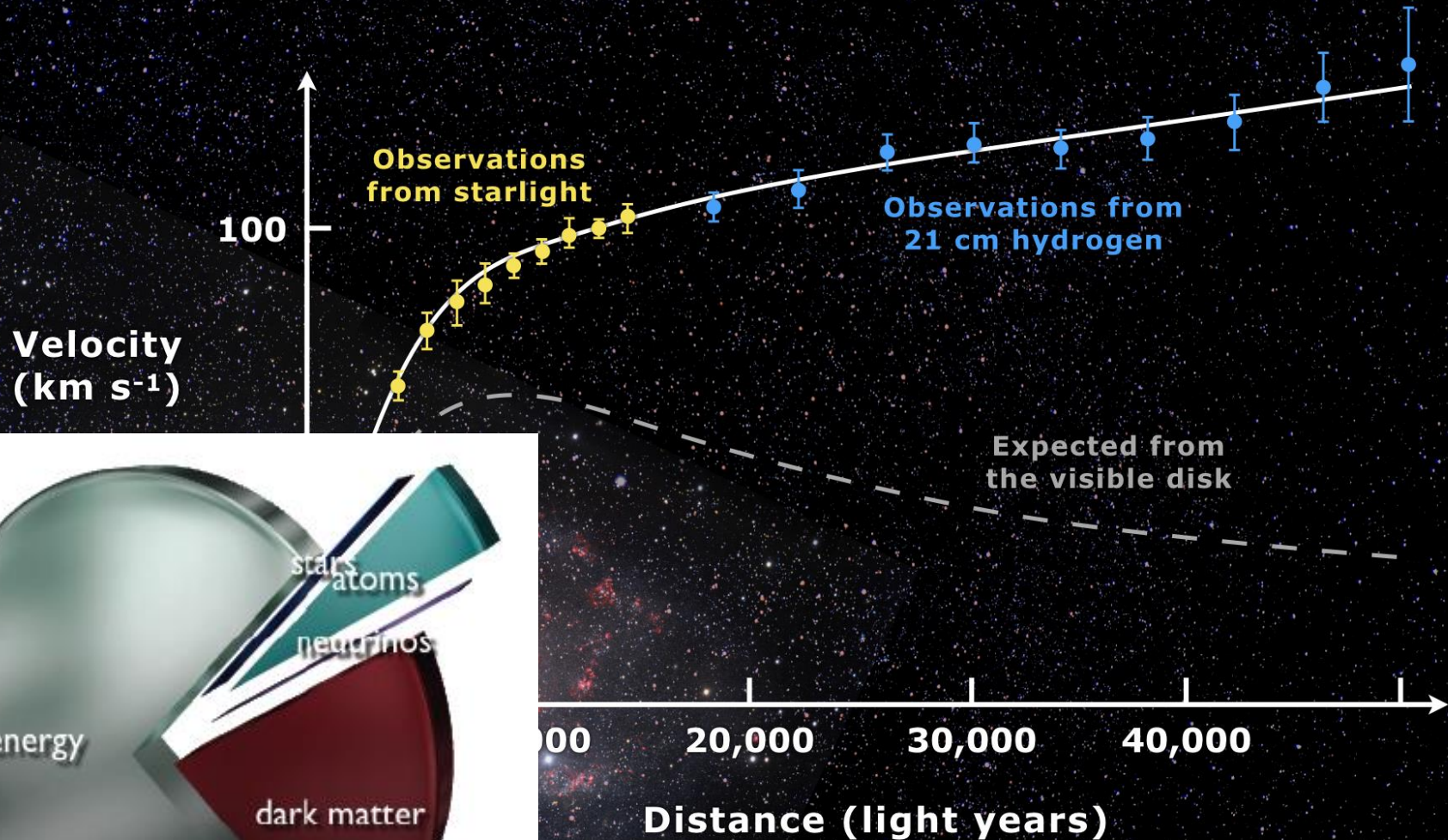
DUNE programme (US)

- Liverpool led prototypes programme at CERN



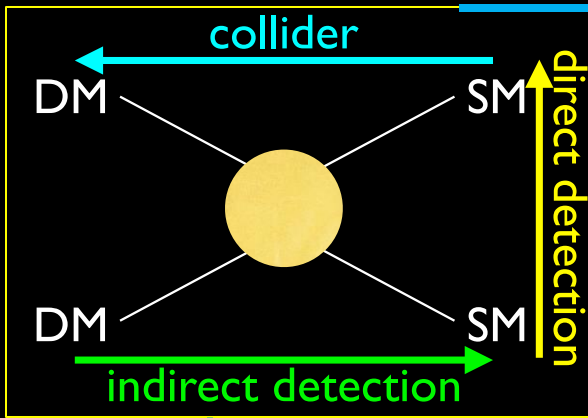
And many more: **SBND**,
SNO+, **LEGEND** etc

DARK MATTER

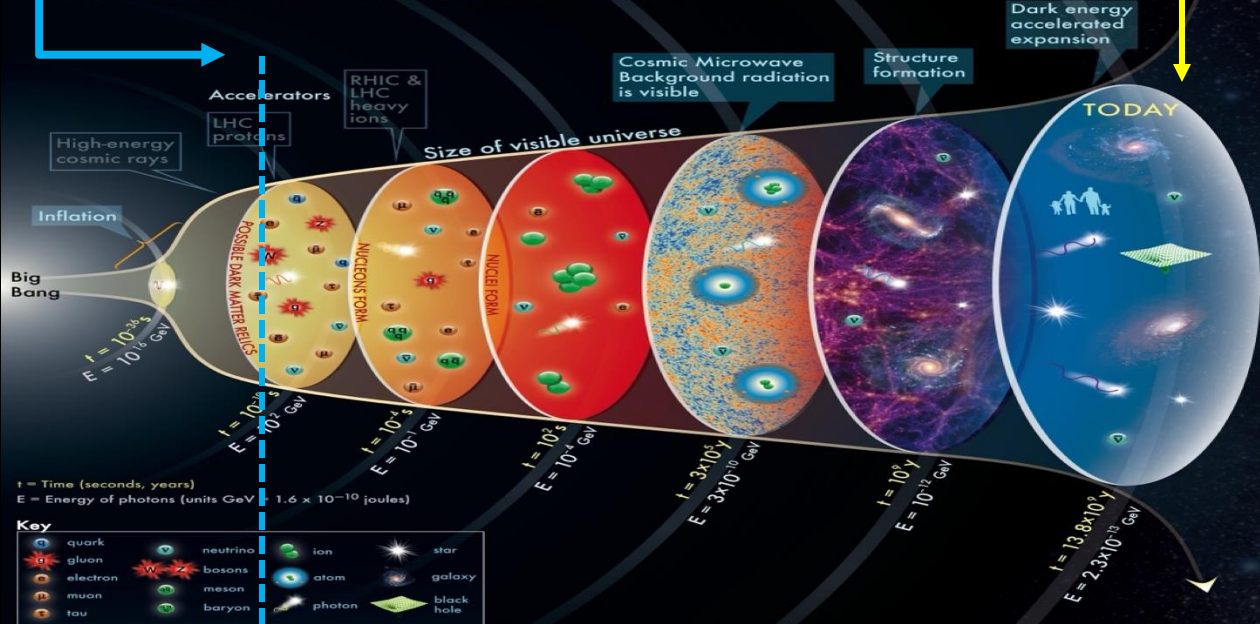


We can search for dark matter at the LHC but we also have dedicated experiments.

Searching for Dark Matter: how



HISTORY OF THE UNIVERSE



DM+matter → DM (+matter)

Colliders reach
p-p → DM particles!

DM+DM → (burst of) matter

Dark Matter Experiments

At the LHC: can study DM if it is a new particle produced in the protons smash

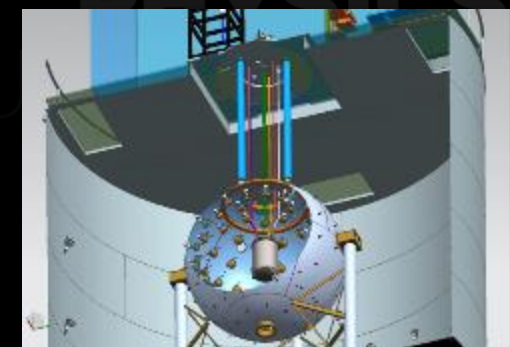
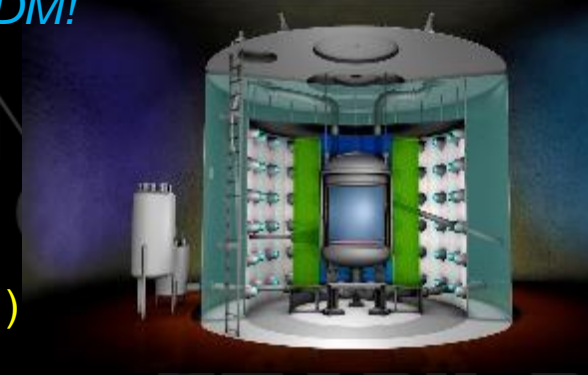
→ Idea behind ATLAS, FASER but also LHCb searches for DM!

At dedicated experiments made of large volume of dense material in the hope that DM particles from space interact:

LuxZepplin: Liquid Xenon detector for dark matter in US (since 2021)

Darkside20k – Liquid Argon detector (start ~2025)

+ number of small experiments based on 'Quantum' principles



With arrays of telescopes:

Cherenkov Telescope Array (CTA) in Chile

Search for gamma rays from DM annihilation in galactic centre using a set of telescopes



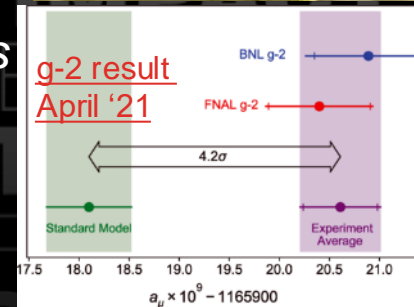
Muon precision programme

Strongly growing area for Liverpool.

The most precise measurements in physics can be made with leptons. In particular muons allow to test for extremely small effects caused by new physics that is otherwise out of reach.

g-2 @ FermiLab: Magnetic moment of the muon

Liverpool built trackers were key to exciting results in 2021.

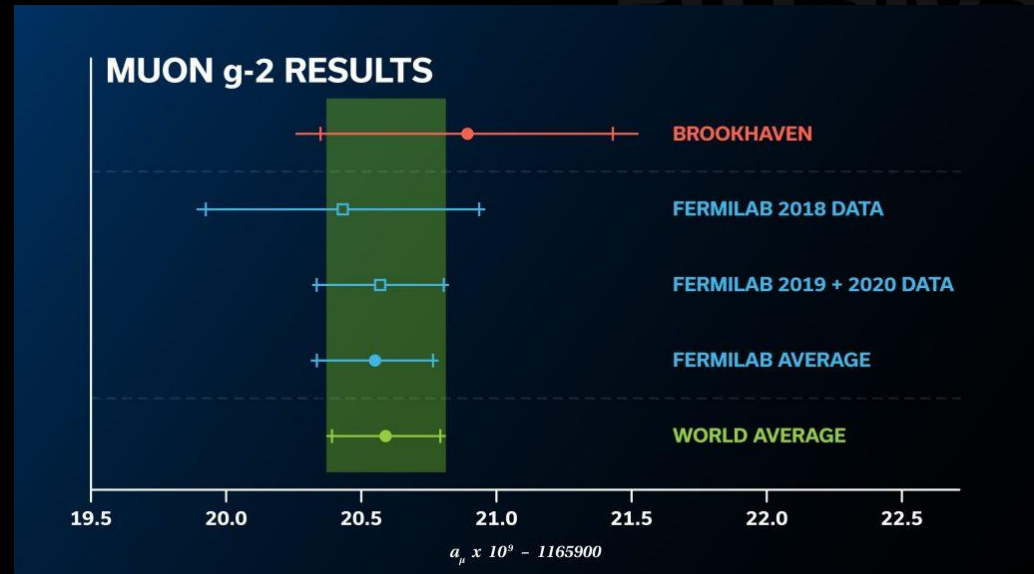


New results released in 2023

result is more than twice as precise as the first result announced in 2021

→ Cornering the Standard Model ?

https://youtu.be/hkHd_wxMfrs



20 Muon precision programme

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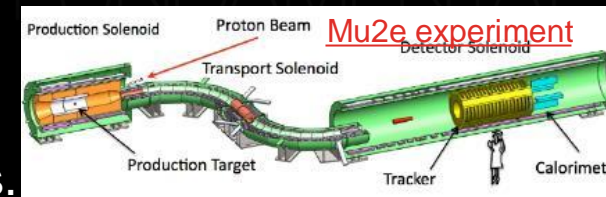
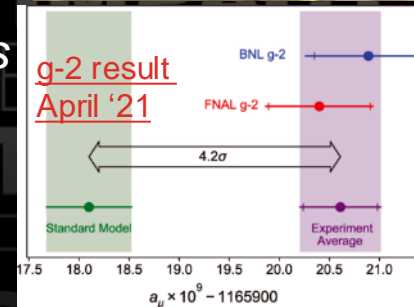
Search for extremely rare lepton flavour violating muon decays (< 1 in 10¹⁶)

Mu2e @ FermiLab

Collaboration PP and NP groups on Germanium detectors.

Mu3e @ PSI, Switzerland

Lowest mass silicon tracker ever built. Liverpool led project.



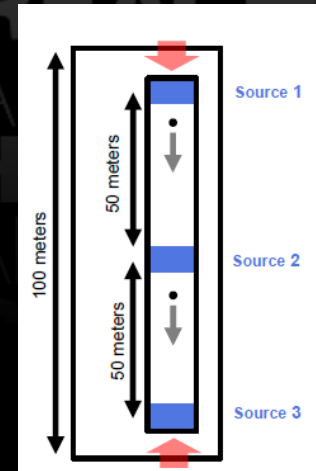
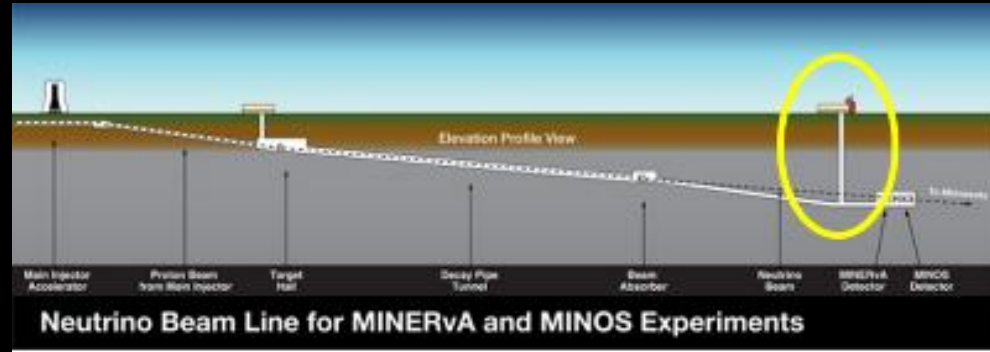
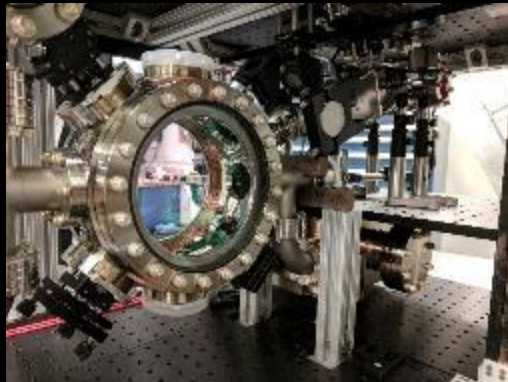
Mu3e HV-CMOS pixel tracker



21 Quantum Technology for Fundamental Physics

New approaches for extreme sensitivity physics measurements

AION / MAGIS-100 project – a 100m dual atomic interferometer at Fermilab, sensitive to ultralight dark matter and to gravitational waves around the 1Hz range, both invisible to current detectors.



To explore aspects of quantum physics, scientists will drop groups of atoms down a vacuum tube, followed by beams of laser light.

Silicon Detector R&D

Long area of expertise for Liverpool

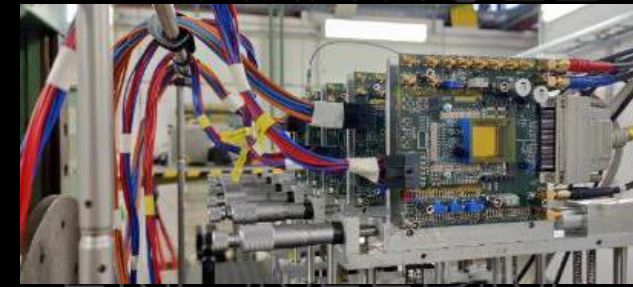
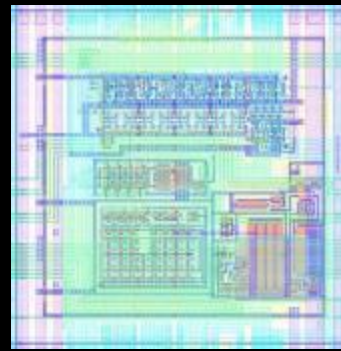
Sensor R&D focussed on high resolution, radiation hard and fast silicon sensors

Supported by excellent R&D and assembly facilities in the LSDC

- Leadership CERN RD50 collaboration
- Silicon sensor technology for LHC experiments
- Established CMOS design group - leading UK group HV-CMOS sensors

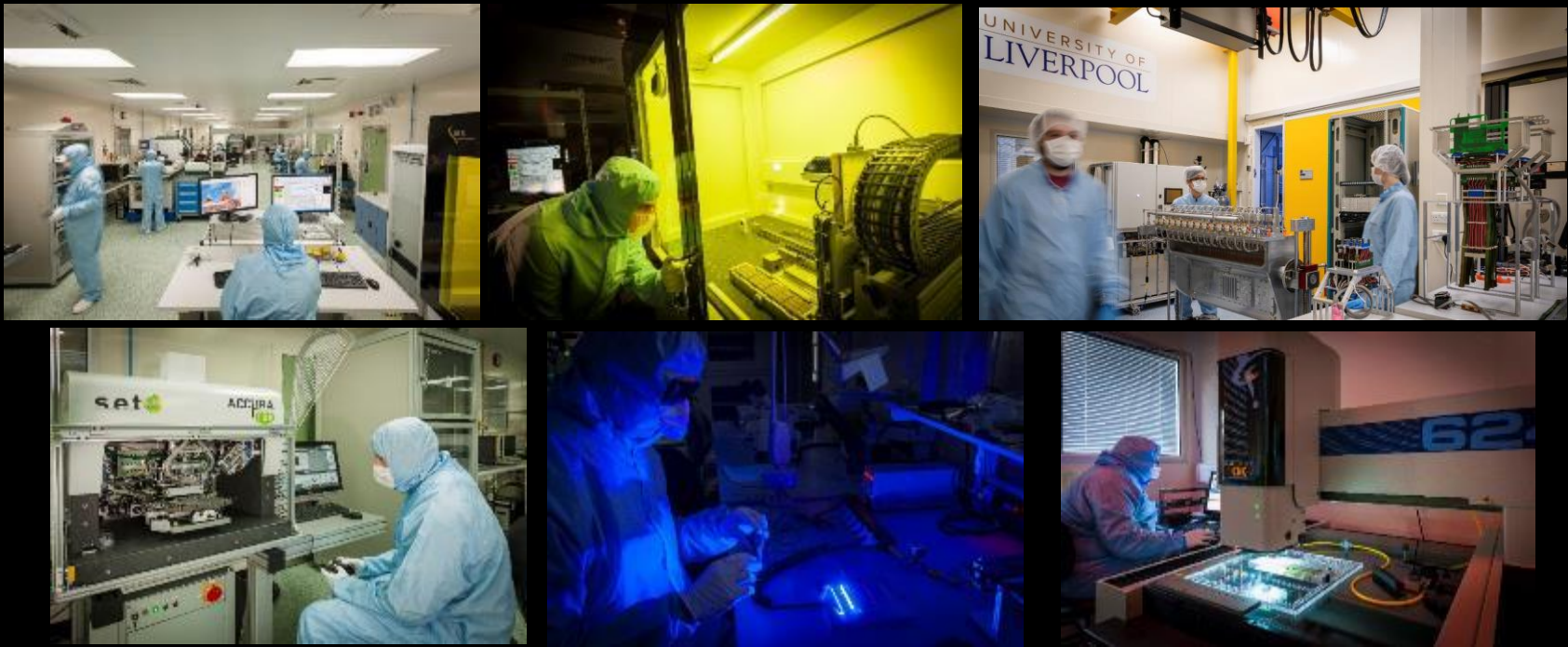
[Some of the] Spin-offs:

- *Applications to medical physics:* Beam diagnostics instrumentation for hadron beam therapy. New HV-CMOS sensor developed with FBK Trento for hadron beam instrument.
- *Commercial products:* patent investigation solutions for increased High Voltage operation with HV-CMOS



23 **LSDC (Liverpool Semiconductor Detector Centre)**

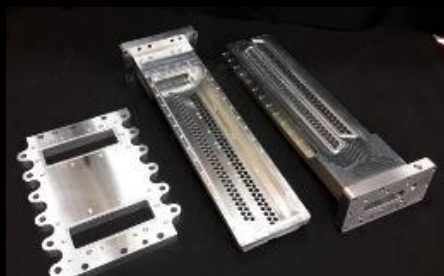
450 m² ISO certified cleanroom facility, initially built for the assembly of the large silicon detectors for the LHC. In operation since 2002. State-of-the-art equipment, infrastructure and expertise on Silicon detector development and construction are unique.



Several major construction projects were (are) hosted in the LSDC
6 detector systems for 3 LHC experiments, T2K ECAL assembly, g-2 tracker, Mu3e pixel tracker, Darkside-20k. Also several Nuclear Physics projects

24 **Detector Fabrication Facility (DFF)**

Equipment and skills build through a long stream of projects and sustained investment by STFC. Advanced equipment and high expertise provide a facility for precision manufacture that is unique in the field.



Manufacture of components for many experiments: *LHC experiments, ARIADNE, DEAI, T2K ECAL, LZ, g-2, Mu3e, NA62, MAGIS, DUNE, ... Also several nuclear physics projects*

25 **Advanced Materials Lab**

Dedicated lab for the development and manufacture of carbon-fibre components.
Large volume autoclave and oven.



Manufacture of components for many experiments: *ATLAS, LHCb, CTA, Mu3e, R3B, ..*
Also collaboration with students Mech. Eng. on formula student car and hand-powered bicycle

26 Computing

Particle Physics has long history in analysing high volume data and requiring high bandwidth readout electronics for experiments.

- A large fraction of the staff and students work on data analysis and on data acquisition technology to collect and analyse the data from our experiments.
 - These analyses are often very sophisticated and use all more model tools including Artificial Intelligence tool, ML and NN. Quantum computing is a recent addition.
- Wide range of work on many experiment requires maintenance of many software packages and computing infrastructure.
- Liverpool is also a major contributing site to GRIDPP computing for LHC and other experiments



Because of the above we host since long an extensive in house computing and networking infrastructure.

Summary and outlook

The Liverpool HEP group is one of the largest in the UK. Members are highly-skilled scientists working hard on many experiments and leading the field to answer the key fundamental questions in subatomic physics

Our unique facilities and the highly expert teams associated with these, are completely critical to delivering the research programme

Academics deliver dedicated and core courses sharing their knowledge with students. Students are also involved in projects since Y2 that allow them to participate and contribute to the experiments we are building and exploiting



Summary and outlook

The Liverpool HEP group is one of the largest in the world in the field of sub-

Our asso-
deliv-

Aca-
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experiments we are building and exploring

For your future: in case you are thinking that particle physics is what you like, Liverpool is a great place to come to 😊

- Undergraduate students can be involved in research activities from Year 2
- Summer studentship programmes at Liverpool but also with CERN, DESY (lab in Germany) and other labs and institutes around the world
- BSc and MPhys projects on working experiments! Recently:
 - FASER and FASER2
 - ATLAS Machine Learning
 - Precision muon physics
 - Future colliders

Get in touch if you wish to have more info!