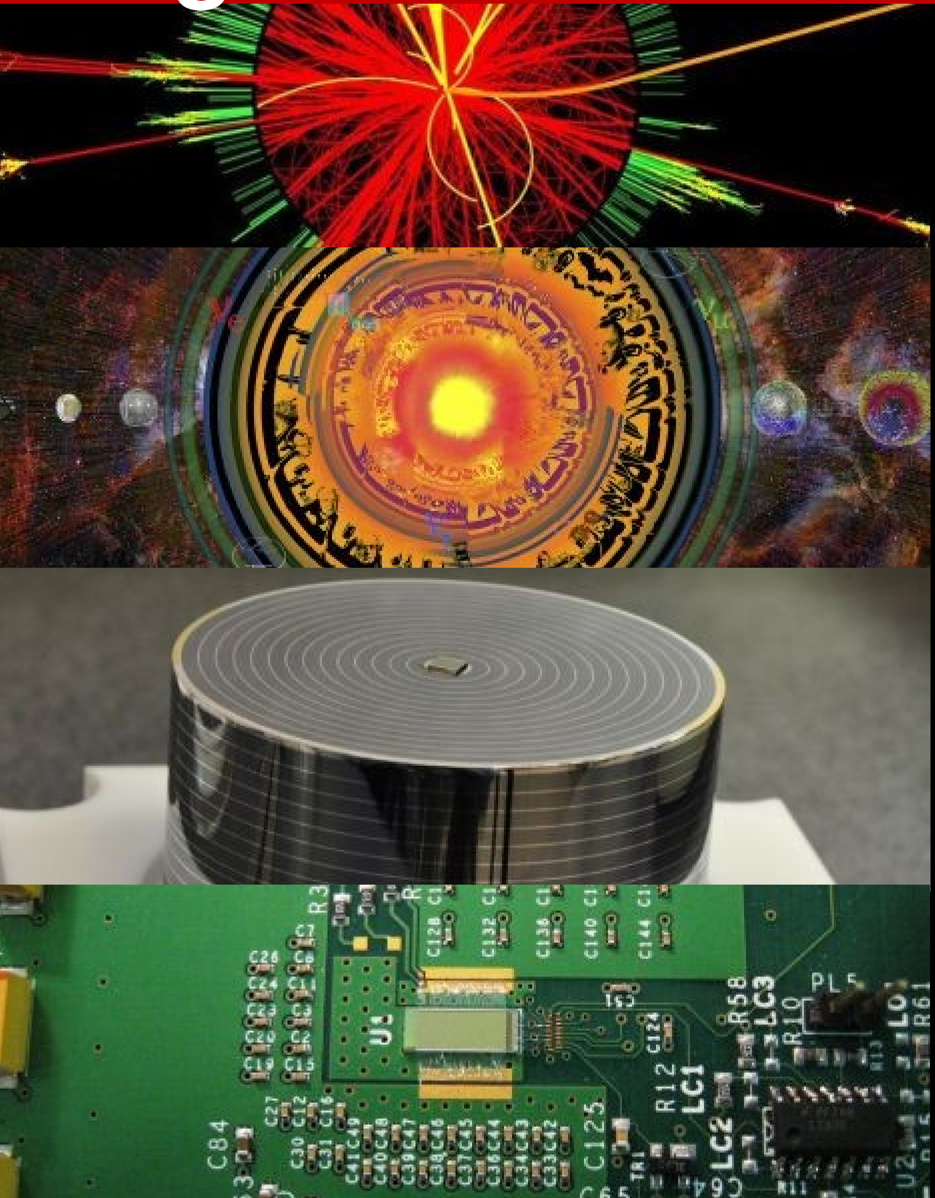
The Oxford Particle Physics Program

UNIVERSITY OF OXFORD

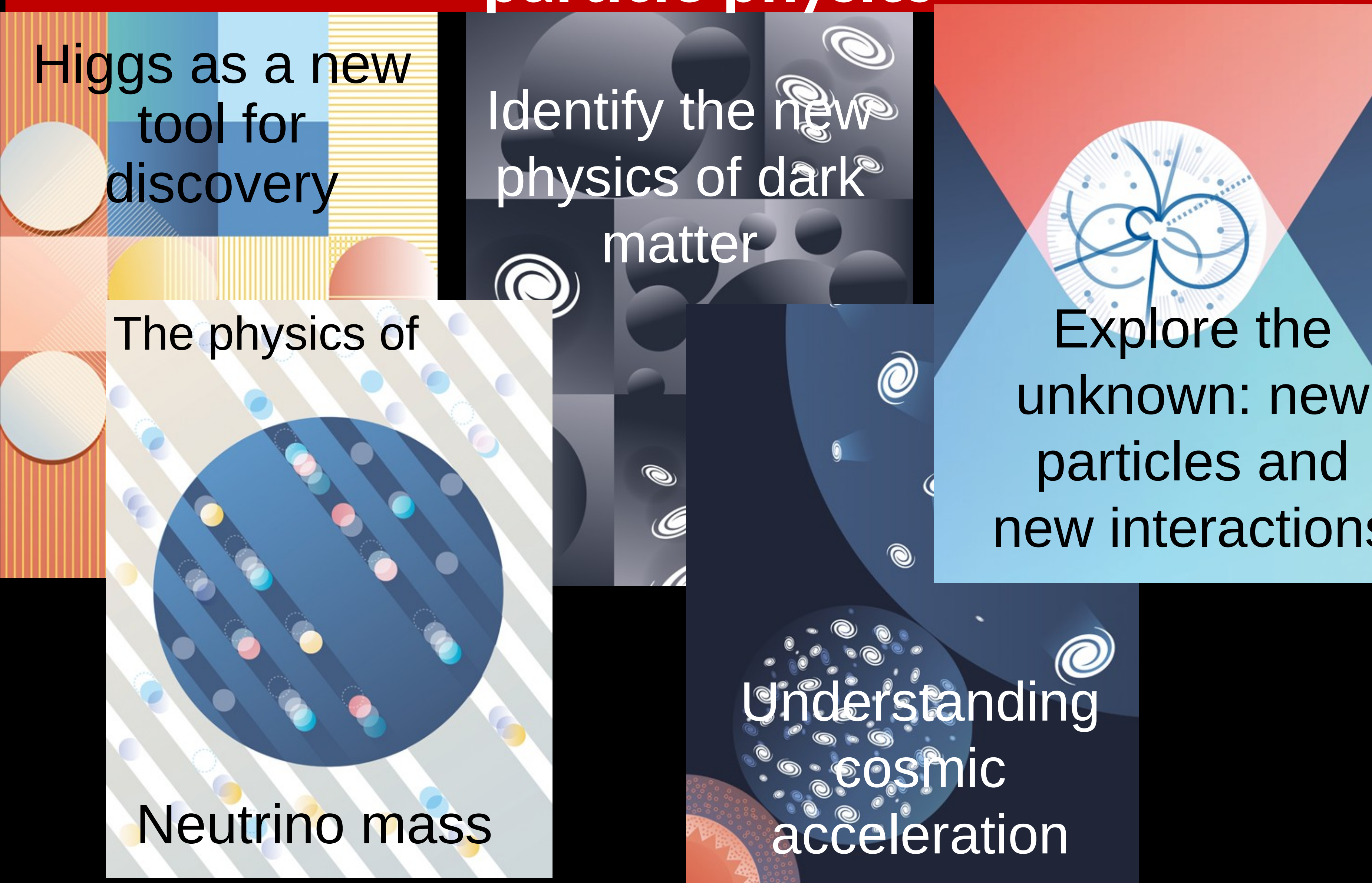


Jeff Tseng

(Director of Graduate Studies for Particle Physics)

(thanks to PP colleagues,
especially Farrukh Azfar,
previous DGS)

Oxford is addressing the science drivers of particle physics



Outline

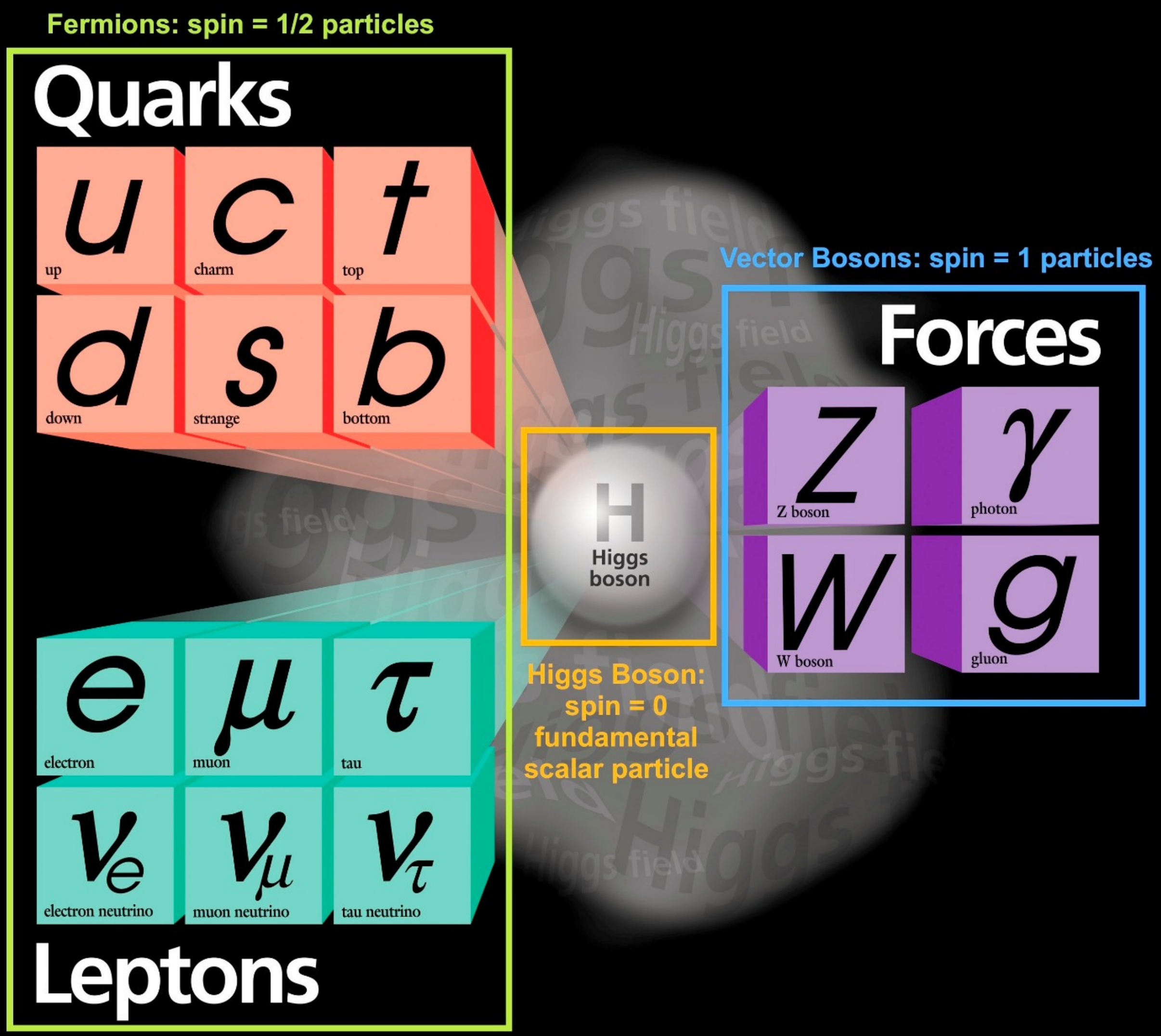
- Why search for new physics?

- Particle physics groups at Oxford
  - ATLAS
  - LHCb
  - Neutrinos
  - Dark matter and dark energy
  - Mu3e

- Along the way: detectors in development

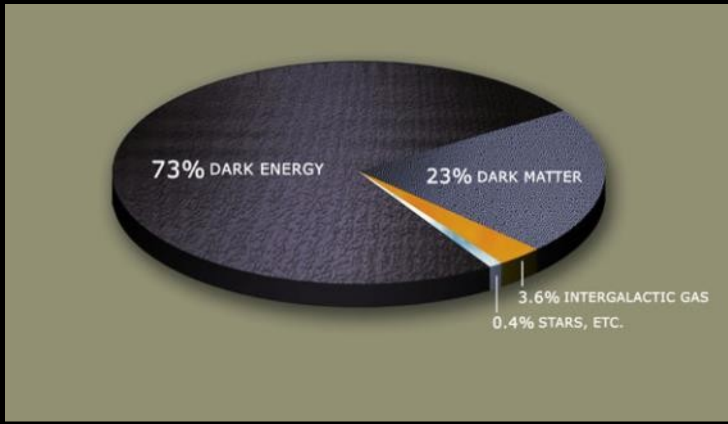
See https://www.physics.ox.ac.uk/study/postgraduates/dphil-particle-physics

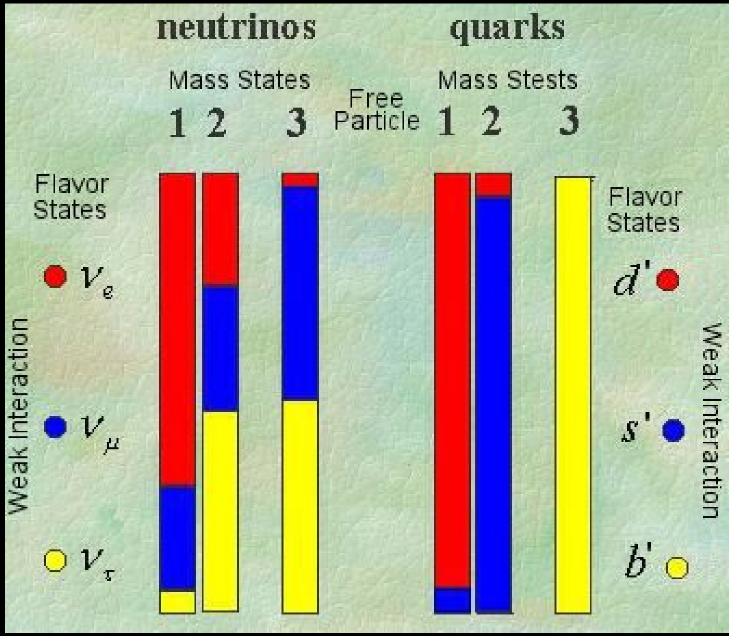
The Standard Model



Why look beyond the Standard Model?

- Experimental Evidence
  - **Non-baryonic dark matter (~23%)**
    - Inferred from gravitational effects
    - Rotational speed of galaxies
    - Orbital velocities of galaxies in clusters
    - Gravitational lensing
    - …..
  - Dark Energy (~73%)
    - Accelerated Expansion of the Universe
  - **Neutrinos have mass and mix**
  - **Baryon asymmetry**
  - **…..**

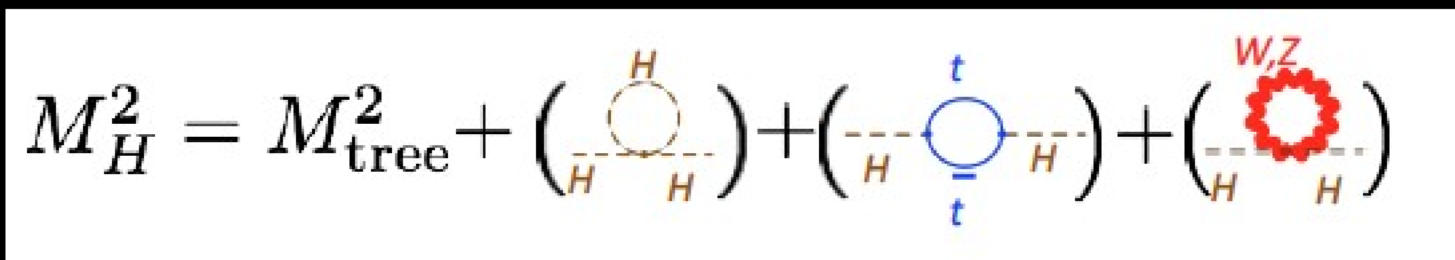


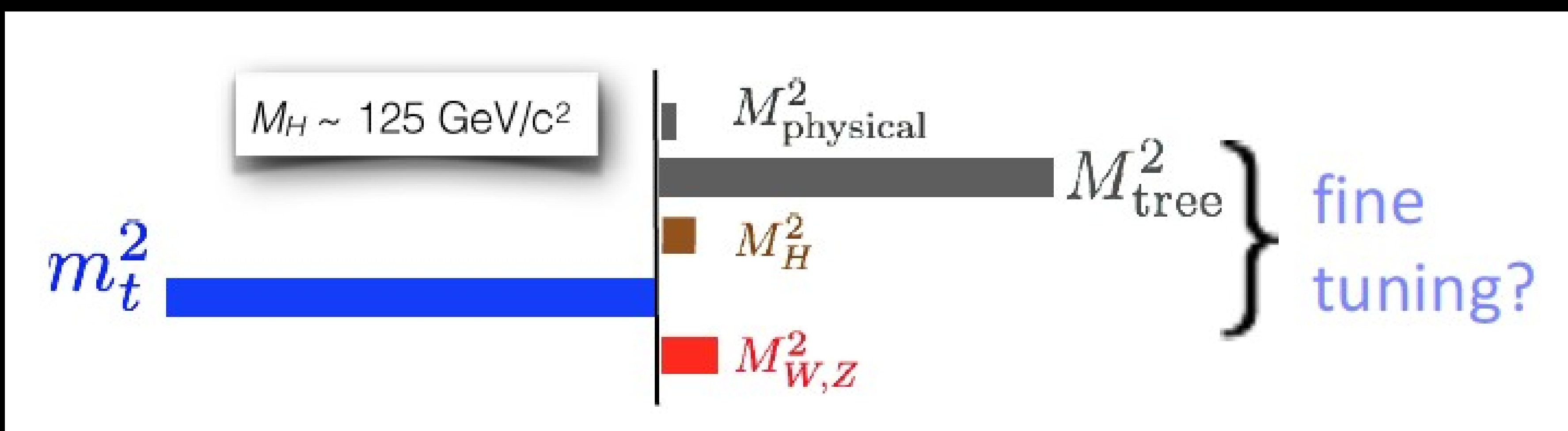


The Higgs boson

- The discovery of the Higgs Boson raises many questions

$$V = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

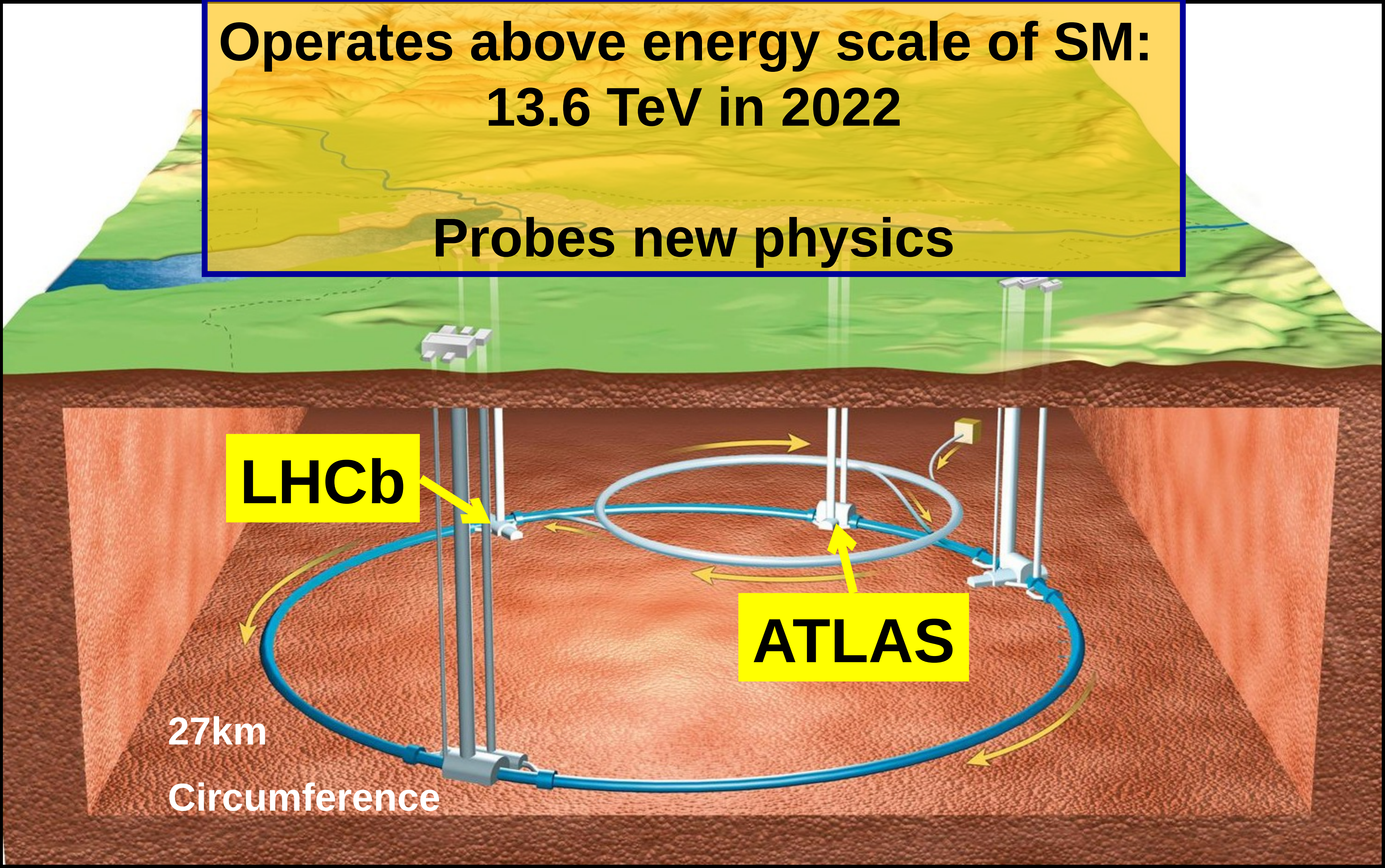




The Large Hadron Collider – A Discovery Machine

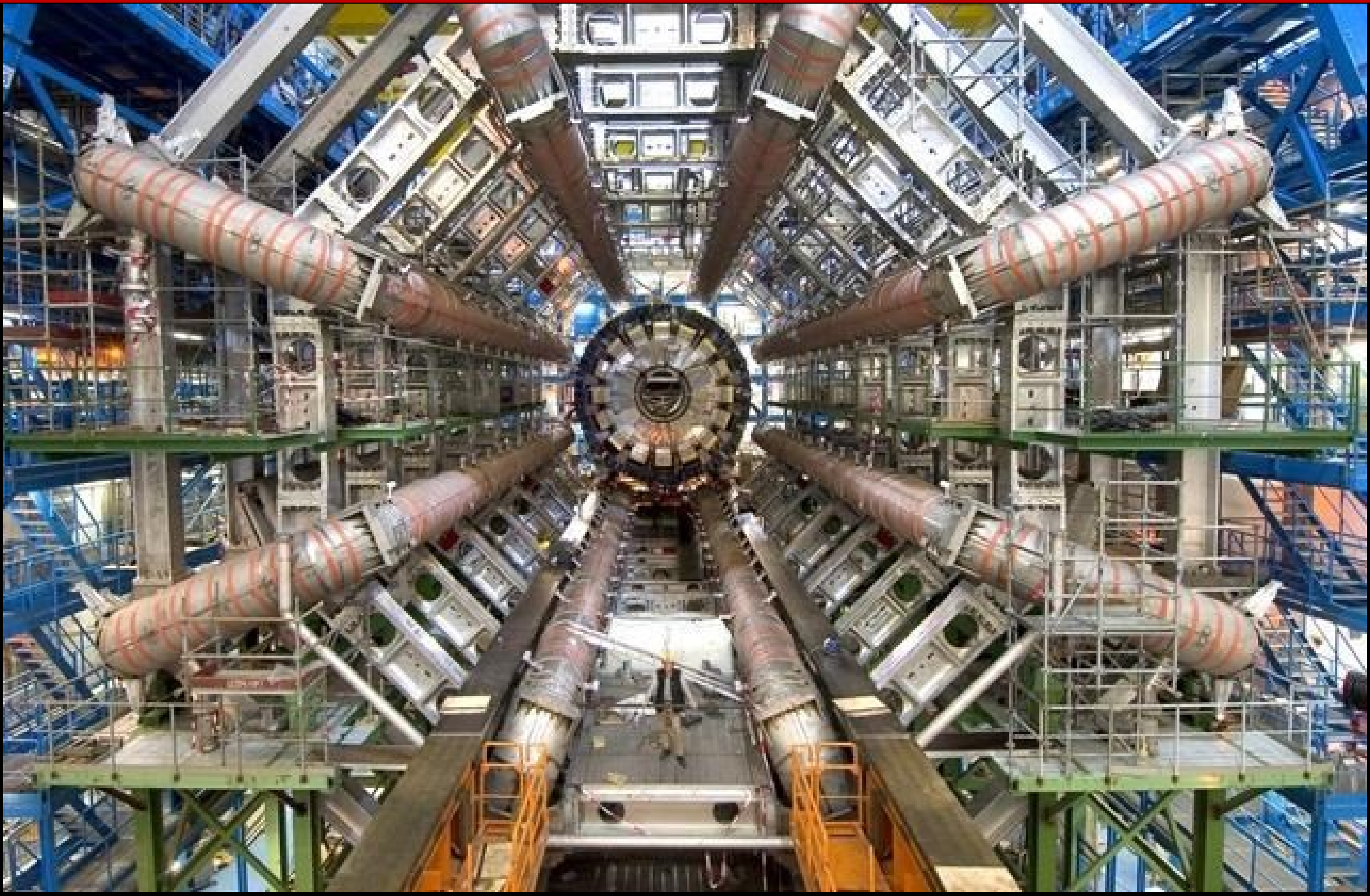
Operates above energy scale of SM:
13.6 TeV in 2022

Probes new physics



ATLAS

Barr, Bortoletto, Cooper–Sarkar, Gwenlan, Hays, Huffman, Nickerson, Shipsey, Viehhauser, Weidberg



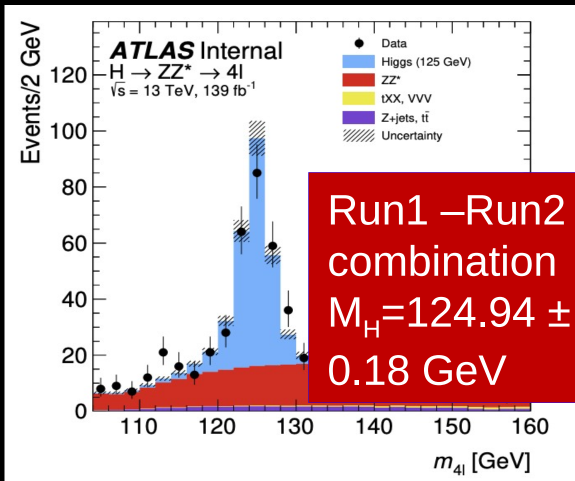
The Oxford ATLAS Group

- Our goals:
  - **Shed light on new Higgs boson**
    - Measure its properties
    - Improve our understanding of SM
  - **Discover new physics beyond SM**
    - Can we make & discover Dark Matter?
    - Are there heavier Higgs bosons?
    - Is nature supersymmetric?
    - Look for more Exotics signatures
  - **Build key parts of next generation LHC detector**

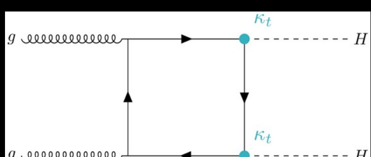
Higgs Group

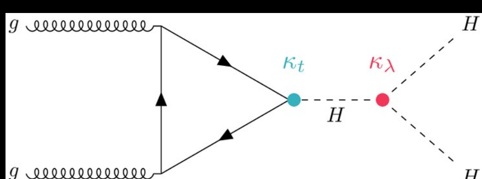
- Two academics: Bortoletto and Shipsey
- 2 Postdocs: Schopf (H→*bb and* H→*cc)* and Rossi (H→*ZZ,* H→$\mu\mu$, diHiggs, combinations)
- Six students in 2022 (two graduated in 2022):
  - Limits on H-muon couplings (Phys. Lett. B 812 (2021))
  - Precision Higgs mass measurments (arXiv:2207.00320)
  - H→*bb* and H→*cc* leading to < at the 95% CL (Eur. Phys. J. C 82 (2022) 717)
- More data will allow us to:
  - Probe coupling to the second generation
  - Test for physics beyond the SM (EFT)
  - Search for di-Higgs production
- Novel contributions to b-tagging and muon performance (ML).
- Contributions to ATLAS pixels possible

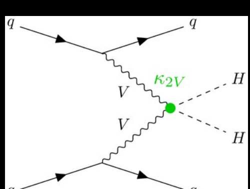
Understanding the Higgs boson

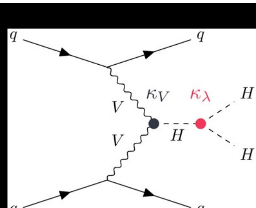


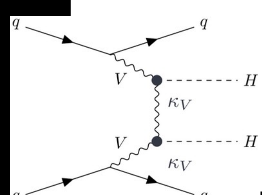
Run1 –Run2 combination
M_H=124.94 ± 0.18 GeV



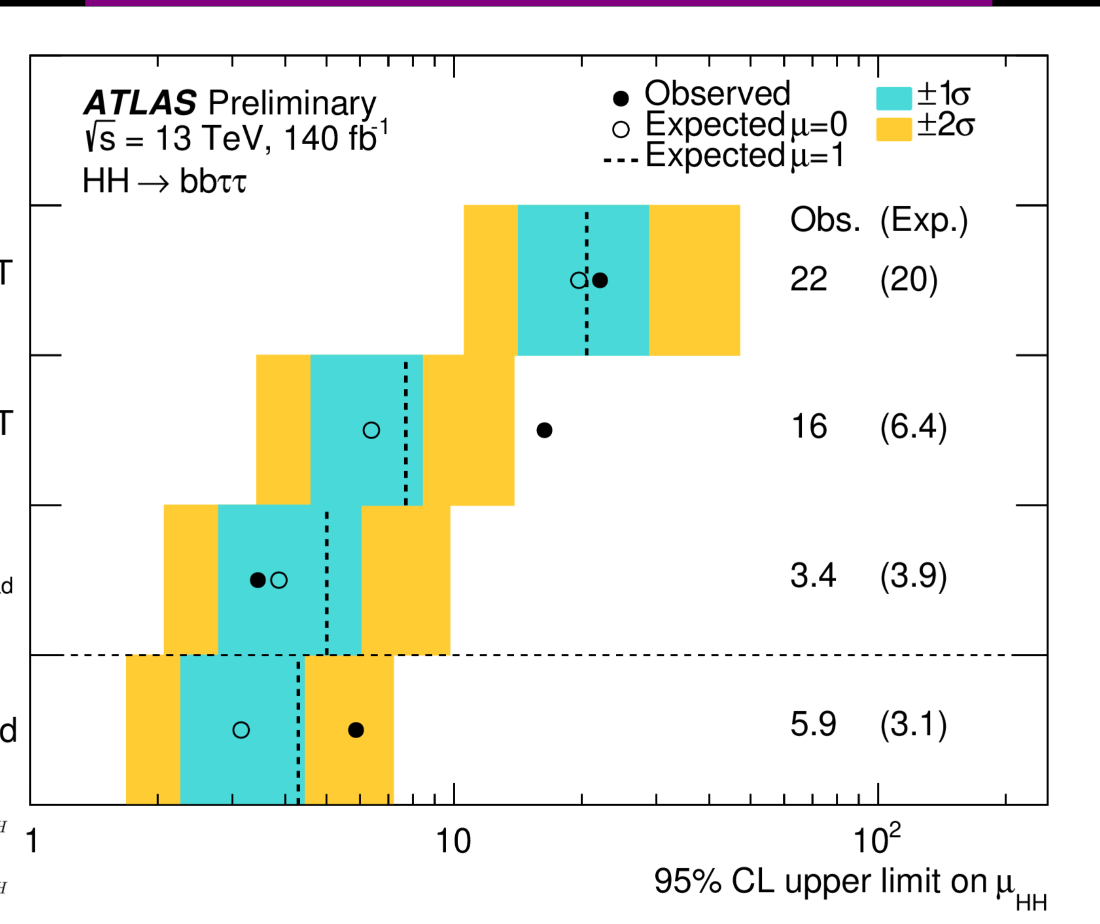






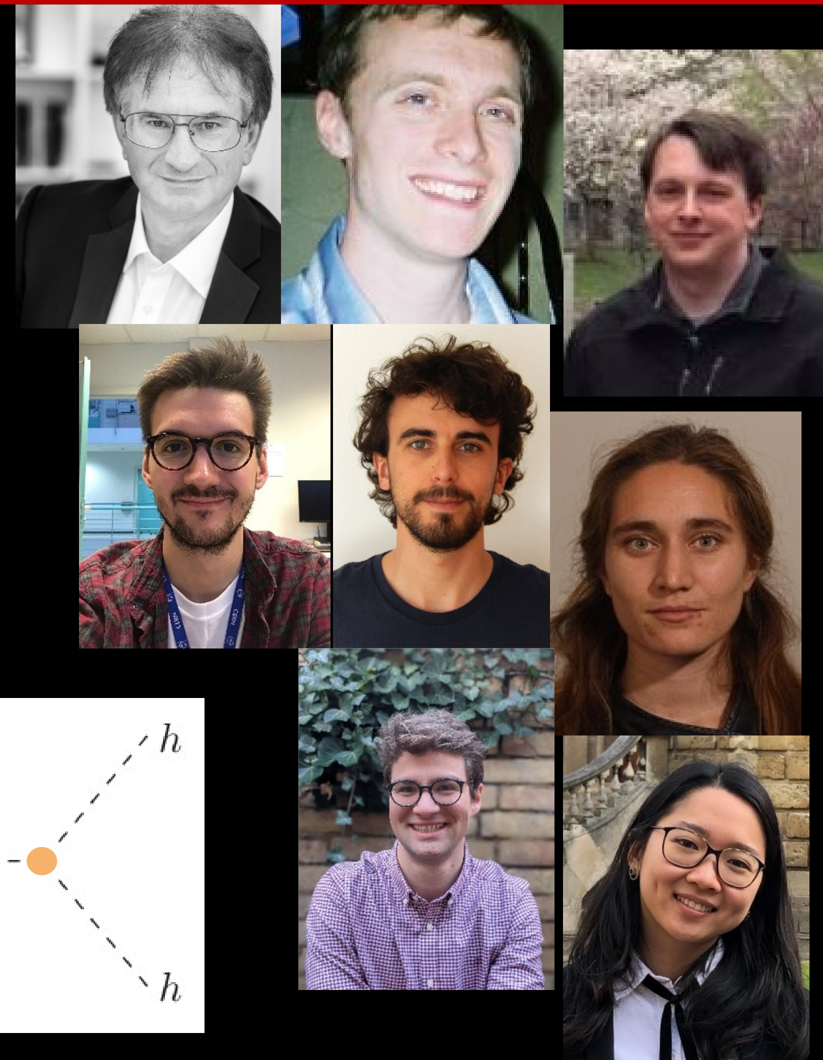


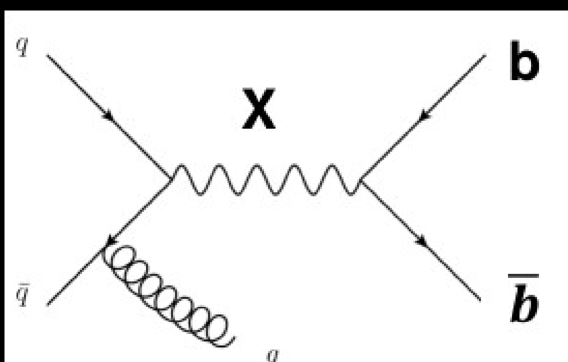
HH to probe the Higgs self-coupling

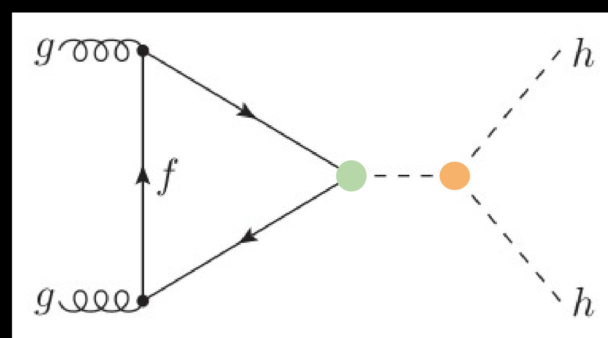


BSM Higgs (Exotics) group

- 2 academics: Huffman, Frost
- 1 (hijacked) postdoc, 5 students
- Searching for unexpected states: produce Higgs bosons
- At high and low energies
  - (X->HH->bbbb)
  - (Dark Matter & Higgs)



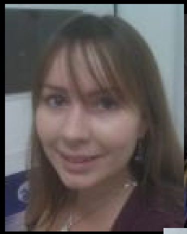
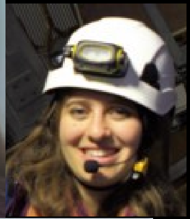




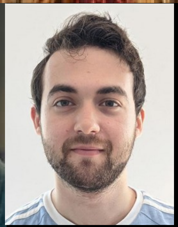
- **Novel experimental techniques, Higgs tagging**
  Neural Nets, Deep sets.
- **Collaboration with Cambridge, Humboldt U., DESY**

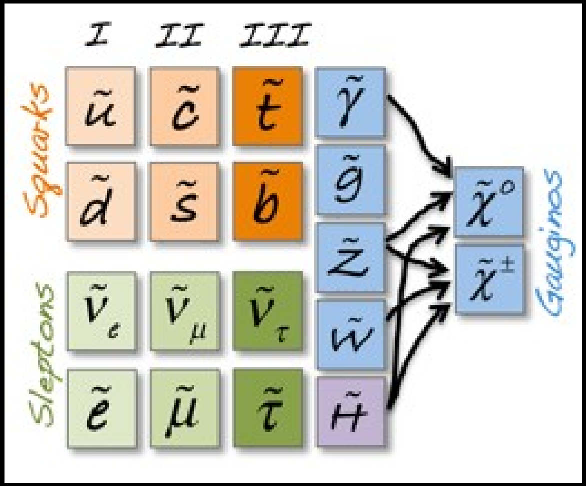
SUSY group

- Supersymmetry, Dark Matter...
  - 2 Academics: Barr, Gwenlan
  - 2 postdocs, 4 students
- Oxford students lead small teams & have many world-first searches @LHC
  - PDF's, W+jets, Sleptons, Higgsinos, Gluinos, Dark Matter, Instantons, Multijets, Bell inequalities, quantum information...
- Also contribute to ATLAS experiment
  - e.g. triggering on events with Dark Matter
  - Reconstructing missing momentum
- Possible to combine with theory studies



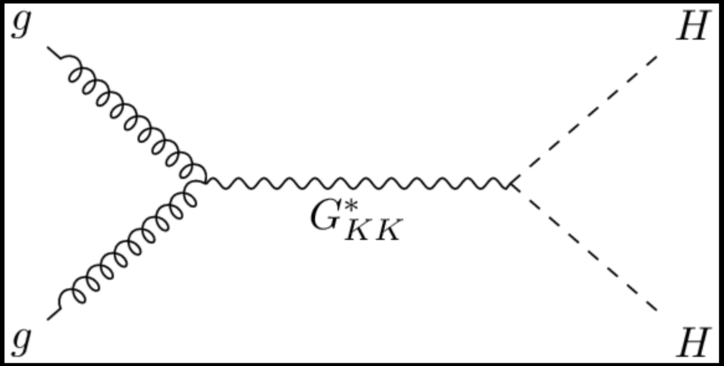



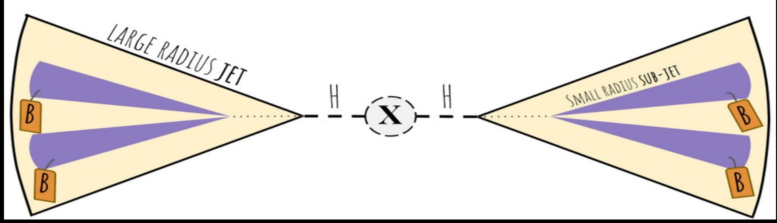


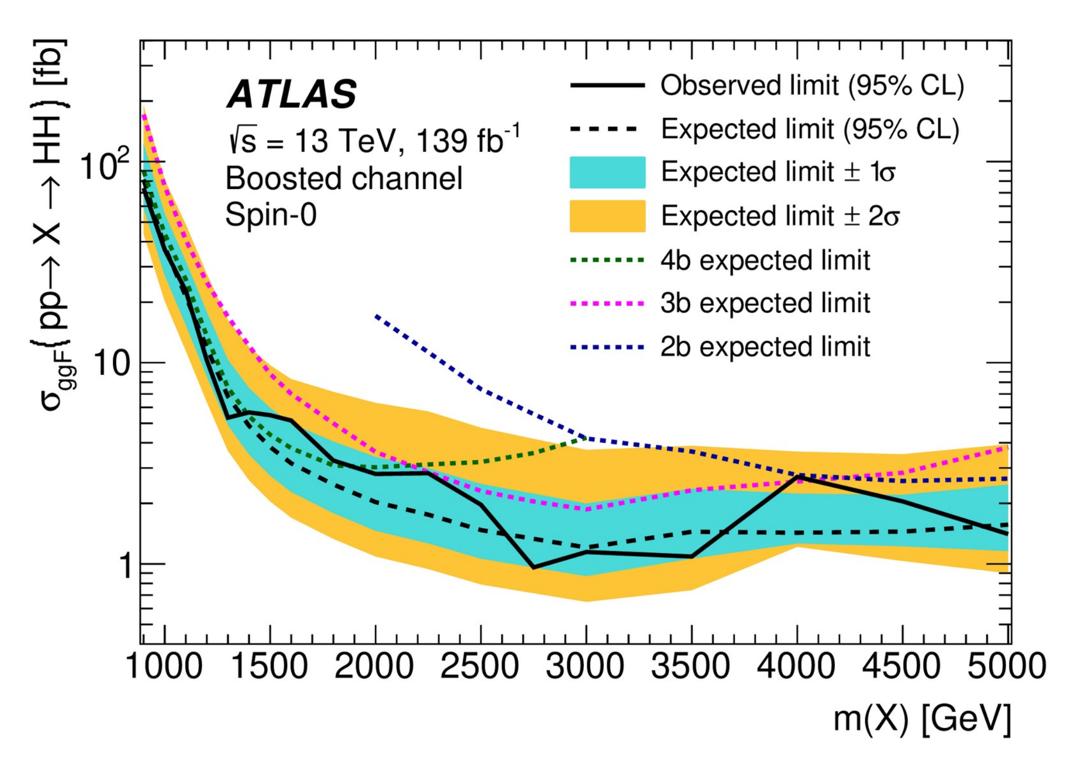
Search for X->HH->bbbb

- BSM particle w penchant for Higgs decays
- Kaluza-Klein gravitons, for example

- Would see them in 4 b-jets



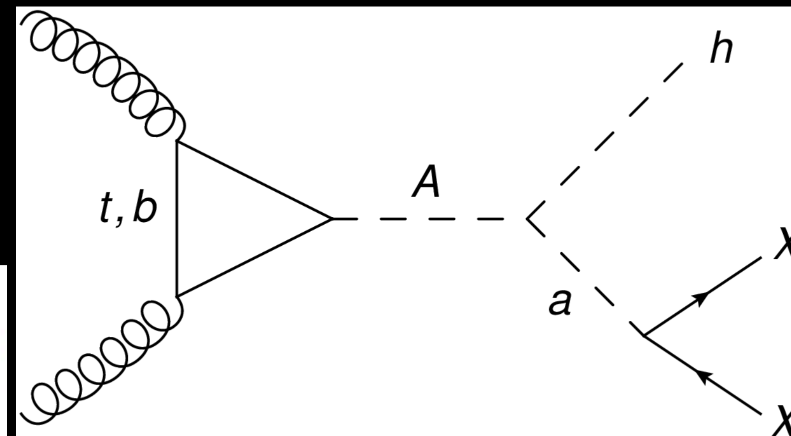




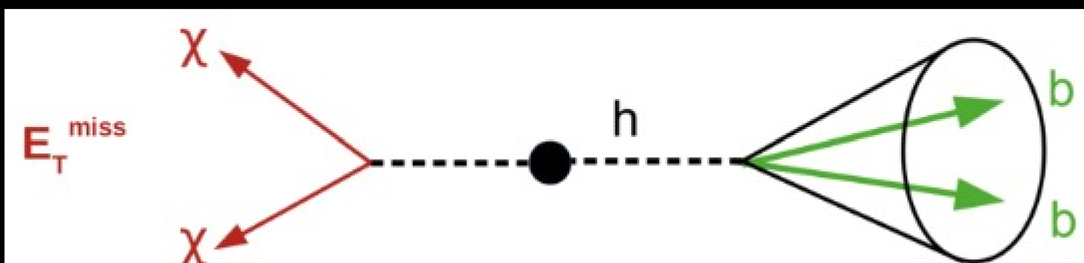
New limit set – PRD 105 (2022) 9, 092002

Searching for dark matter w/ Higgs

- **Higgs is unique – may have unique role in dark matter interactions.**
- **Search for dark matter with a Higgs**

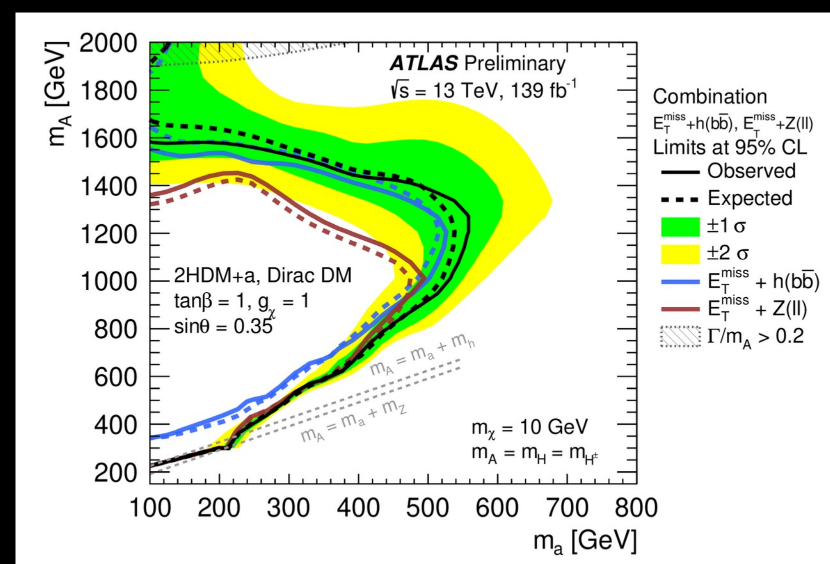


- **Also sensitive to extended Higgs sectors - new Higgs bosons**



- **Most sensitive published search for these types of dark matter!**

Also measuring the highest energy Higgs bosons for evidence of new particles!

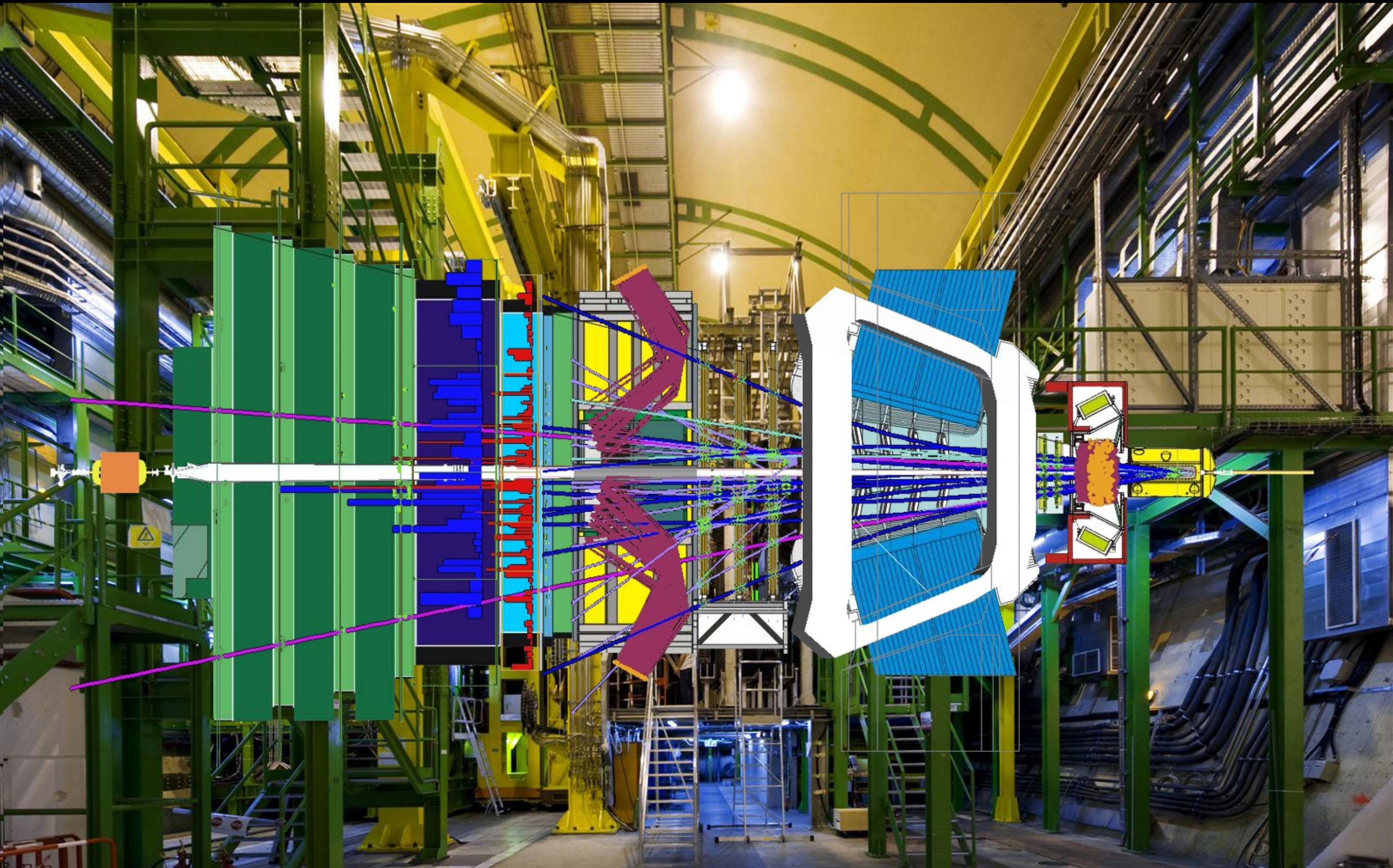


What to expect as a Student in ATLAS

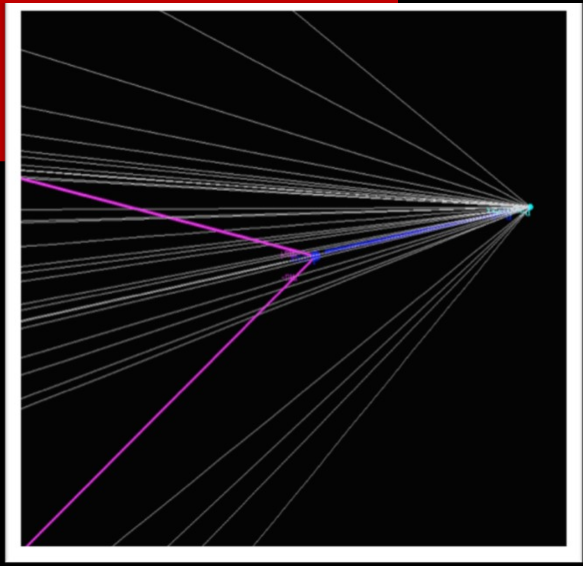
- Students work in small friendly teams
- Have a big impact
- Gain high visibility in ATLAS
- Take responsibility for projects or detectors
- Long term stay at CERN
- Shifts at the detector

ATLAS CONTROL ROOM START OF RUN 2

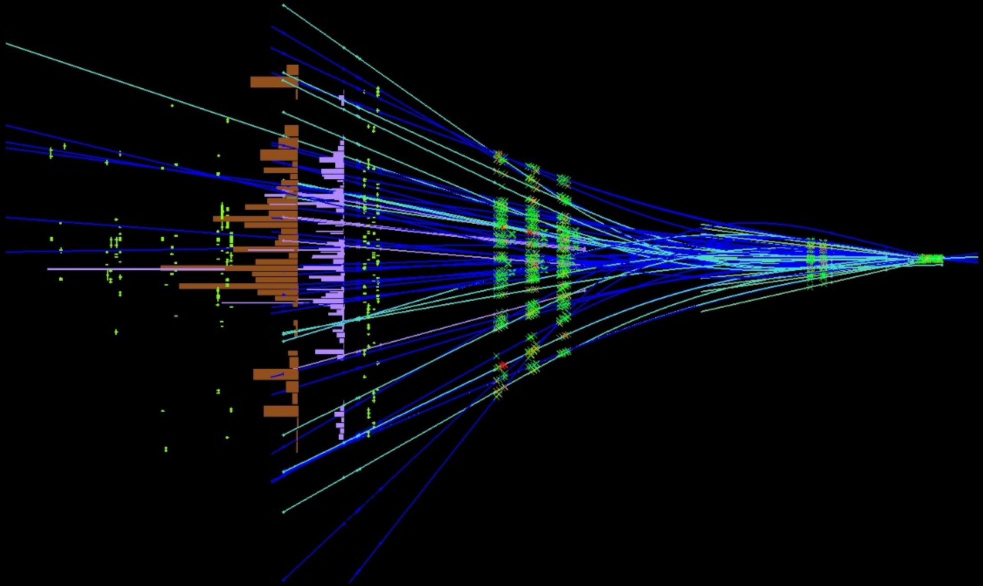
LHCb



The LHCb experiment

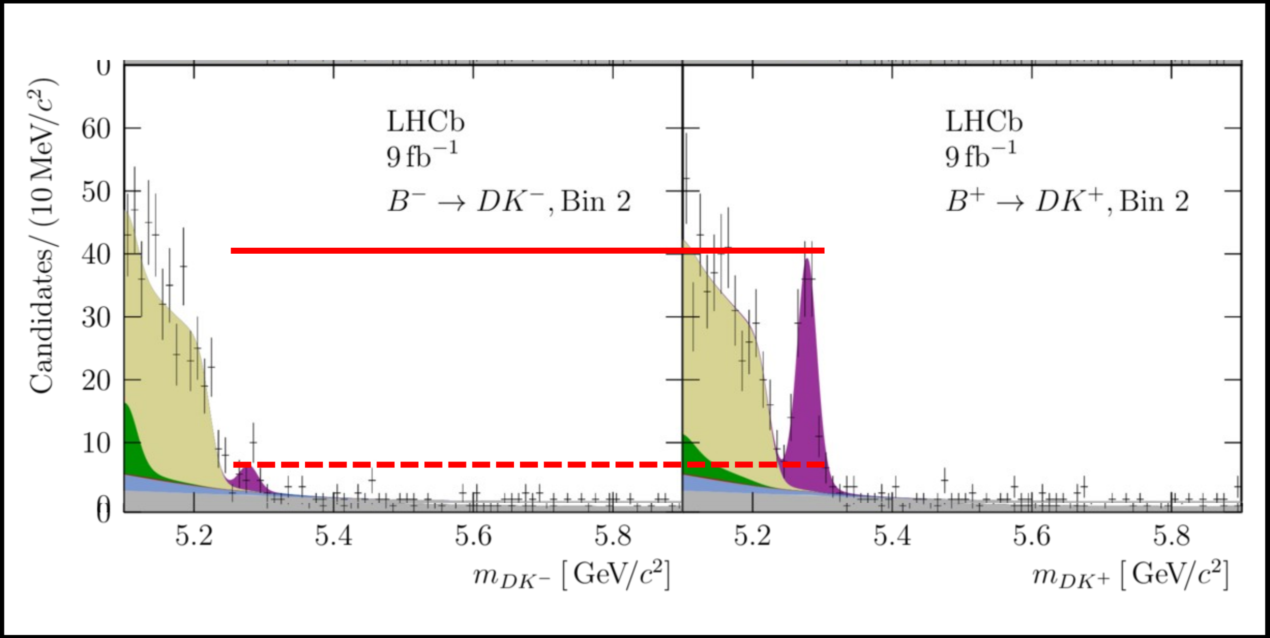


- LHCb is a general purpose experiment for examining the “forward region” of the proton-proton collisions
- Several trillion B hadrons have so far been produced at LHCb.
  - to make precision measurements of CP violation
  - to search for New Physics in rare B decays
- Critical for enabling this physics are particle identification and excellent vertex reconstruction.
  - The RICH detectors were designed and built in Oxford
  - VELO is a major Oxford activity



CP-violation in beauty hadrons

In beauty system, the SM predicts sizable CP-violation.
And this is what we see!



Rate of decay and CP-conjugated process are clearly different !

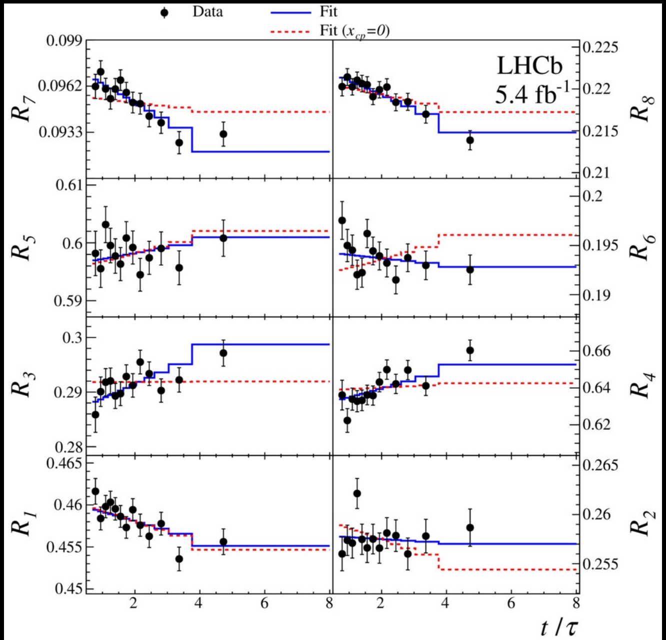
Largest CPV observed to date!

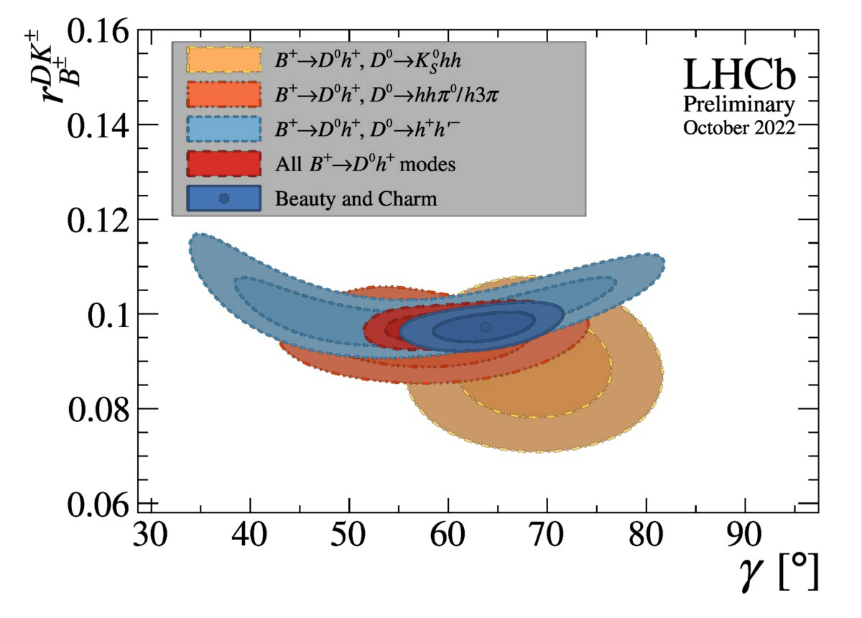
Often, the SM predictions are precise.
The goal then is to make Correspondingly precise measurements.
Any Inconsistencies would indicate New Physics at work !

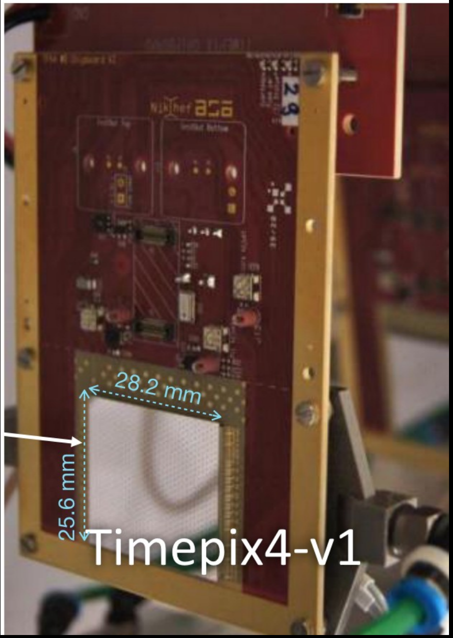
Project topics:

- **Precision Unitarity Triangle measurements**
- **Mixing and CP violation searches in charm decays**
- **Semi tauonic decays**

- **Detector design for LHCb Upgrade II**

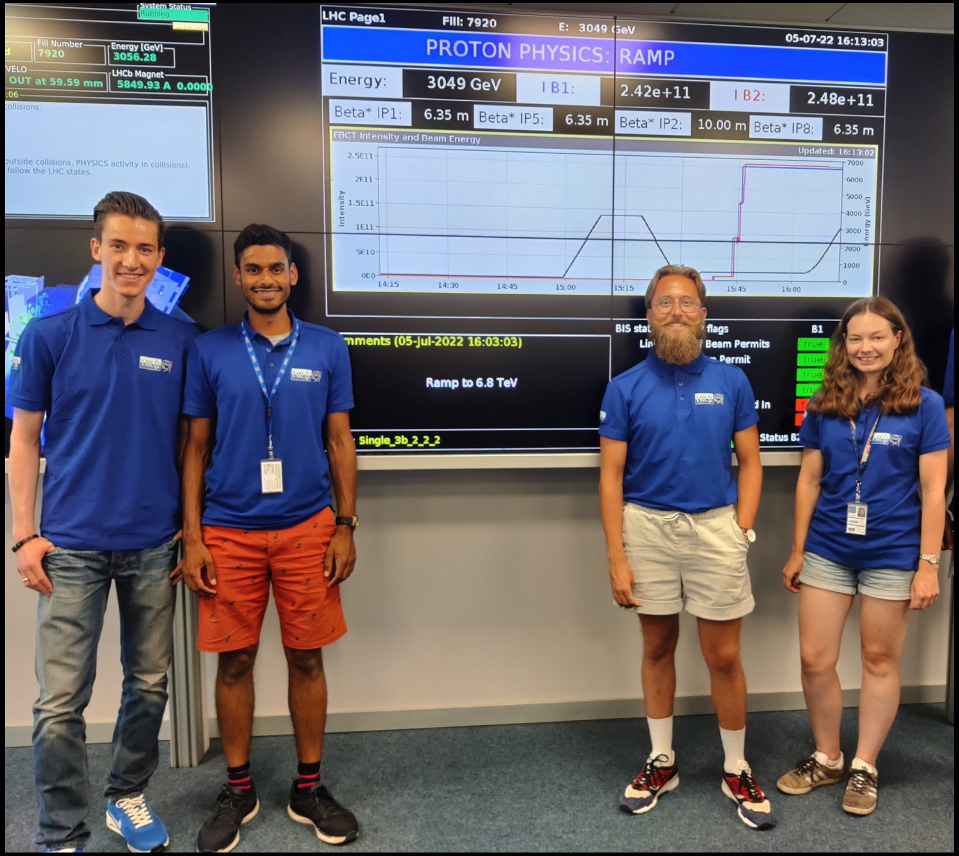






LHCb offers fantastic opportunities for graduate students

- <u>All</u> graduate students are working on **high-profile analyses of LHC data.**
- Graduate students participate fully in the running of the experiment at CERN.
  - Right: Oxford students at the start of Run3



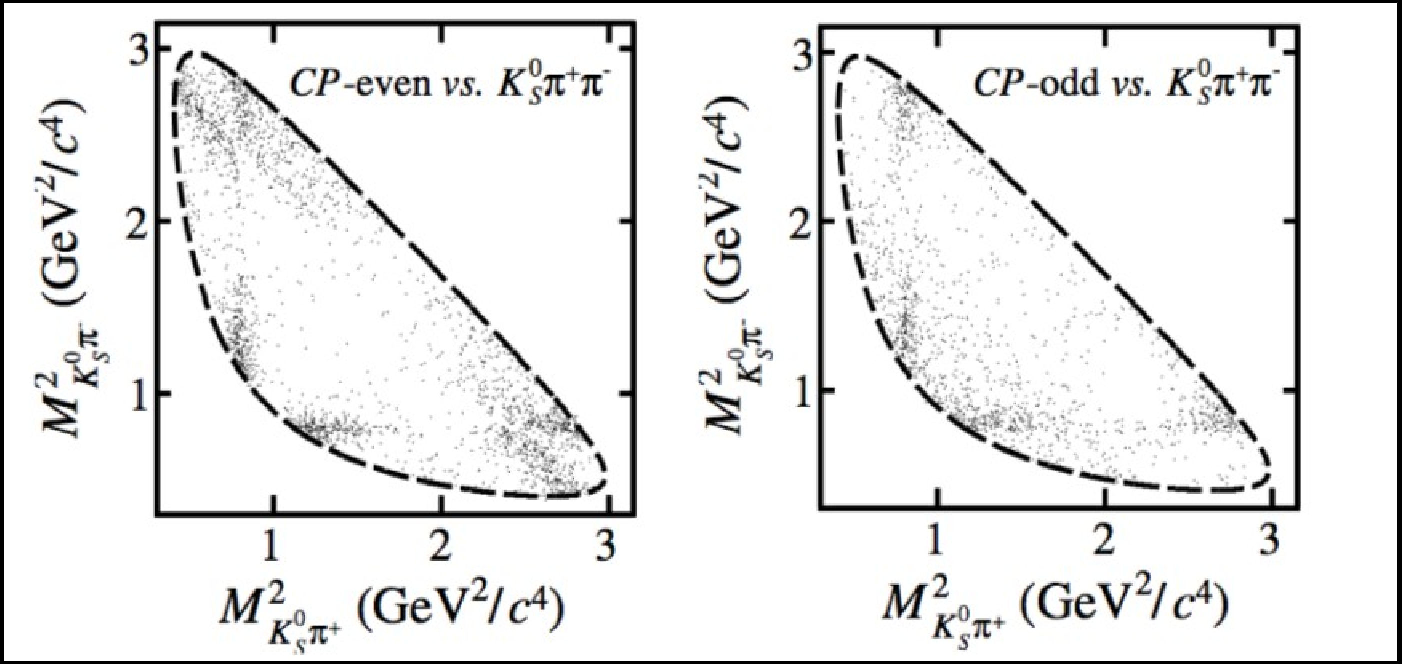
The Oxford LHCb Oxford enjoys an great position in the international collaboration.

4 Academics (Harnew, Wilkinson, John, Malde)

- 4 Post-docs (Cervenkov, Gilman, Pajero, PK)
- 11 Students (Fisher, Mohammed, Scantelbury-Smead, Smallwood, Suljik, Abrantes, Tat, Stanislaus, Mackay, Paton, Bacher)

BES III: e^+e^- to study charm

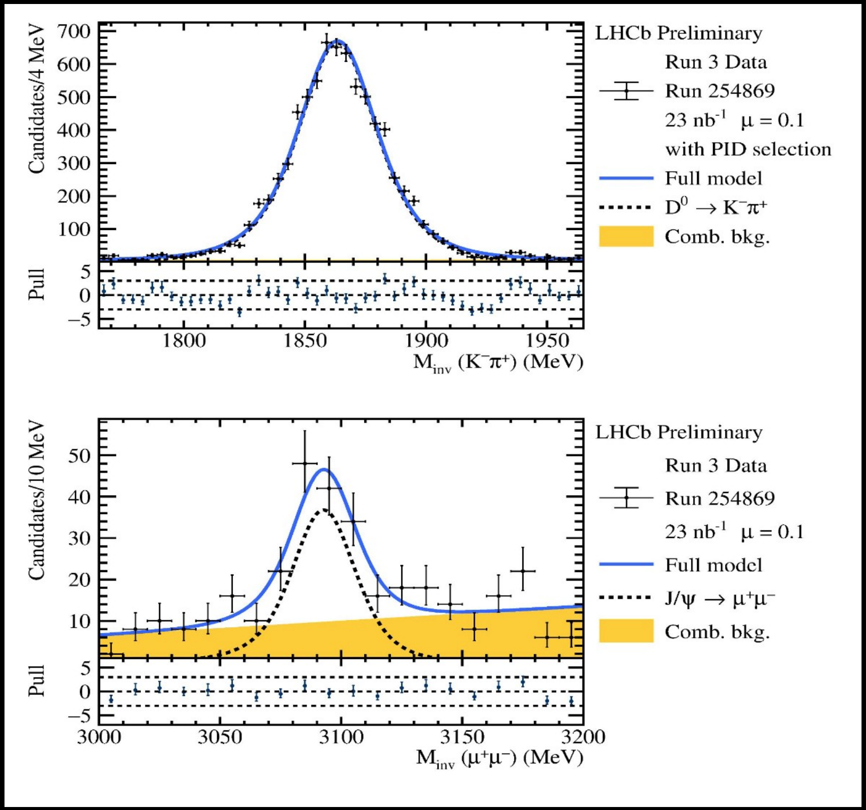
- Experiment located in Beijing
- Unique quantum entangled production of neutral charm meson pairs.
- Gives access to the phases - a vital input for CPV studies at LHCb
- Differences between the plots are proof that quantum correlation is real - rare view of a macroscopic manifestation of this phenonmenon.
- Oxford have made the first measurements using multibody D decays
- **Brand NEW data, vastly larger dataset ready for investigation NOW**



Group members: Malde, Wilkinson, Gilman, Tat

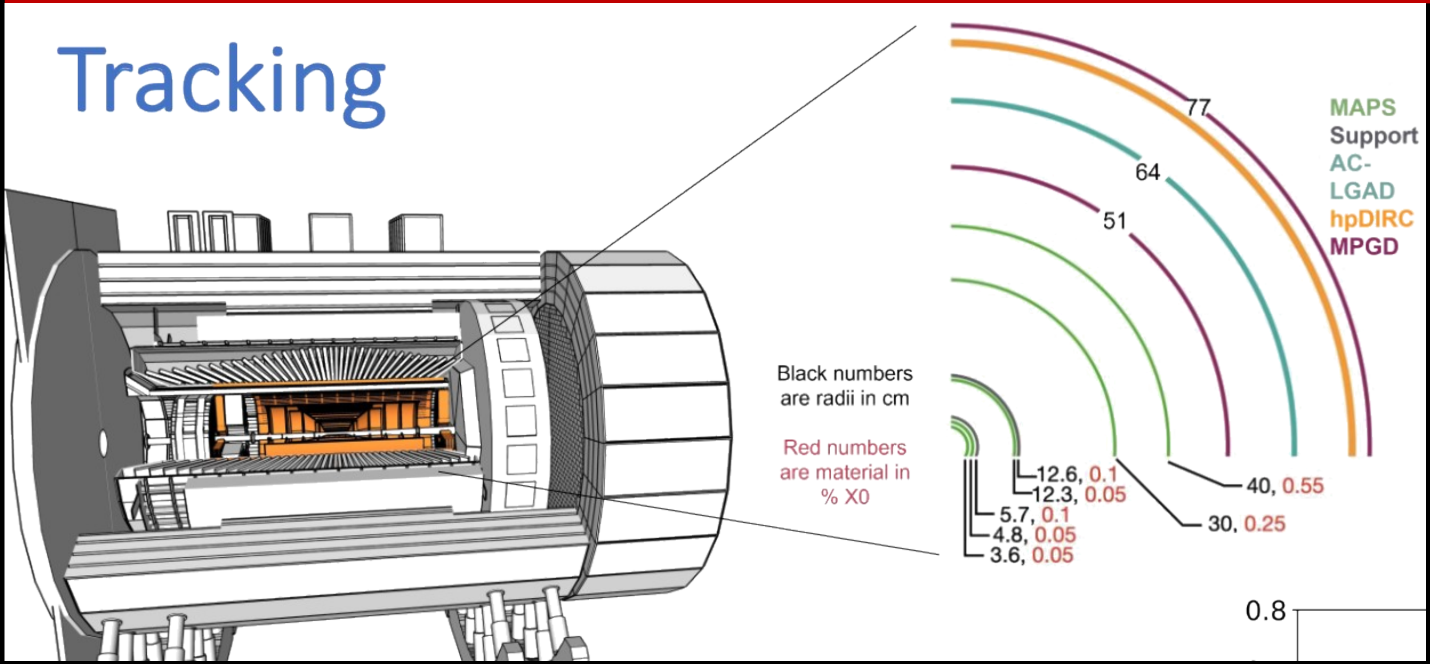
LHCb Upgrade..... is here!!!

- Brand NEW experiment, commissioned in 2022
- Will collect data at an astonishing rate
- Plenty of exciting opportunities to lead new analyses and probe the standard model at a new level of precision!



First D^0 and J/ψ peaks from a small portion of data taken in Nov 2022

ePIC and its silicon tracker



- ePIC will be a *e*-ion collider experiment at the EIC at Brookhaven National Lab
  - Currently under design
  - Construction will start in 2026
  - Collisions from 2031
- At the boundary of particle and nuclear physics
  - Multidimensional imaging of the structure of the proton
  - Study QCD dynamics that can affect the identity of nucleons in a nucleus

- Oxford with UK collaborators will design, build and deliver the outer barrel layers (L3 and L4) of the MAPS tracker
  - This work will encompass all aspects of system: supports, cooling, powering, MAPS sensors
    - PhD projects can span any of these + detector and analysis performance optimisation
  - Extremely low mass, requiring advanced materials and techniques
  - Oxford activities are just starting up
  - Size of collaboration and deliverables is moderate - Your contribution will make a difference!

C Gwenlan, S Henry, T Huffman, G Viehhauser

The physics of neutrinos

- T2K/SK
- HyperK
- ProtoDUNE
- DUNE
- SNO+
- MicroBooNE



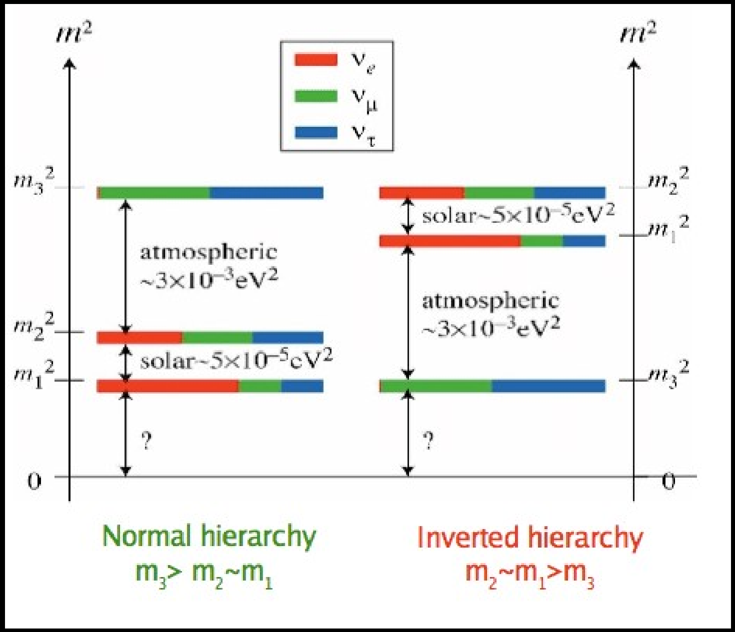








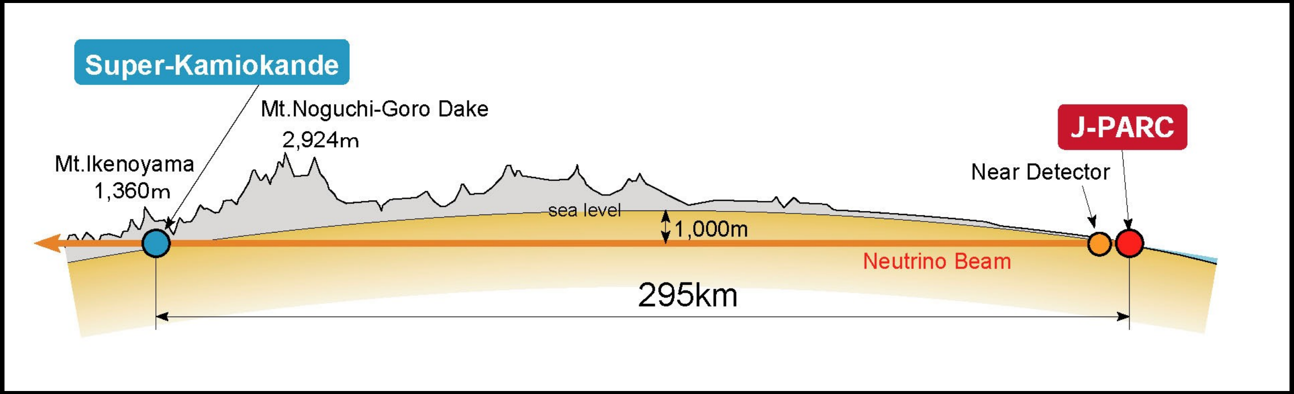
Neutrinos have mass and mix !



Experiments have shown that neutrino weak states are admixtures of neutrino mass states !

- What are the masses of ν's and why are they so small?
- How do ν's get mass in the first place?
- Is helicity the only difference between ν's and anti-ν's?
- To what extent do ν's violate symmetries such as CP?

T2K Neutrino Oscillation experiment

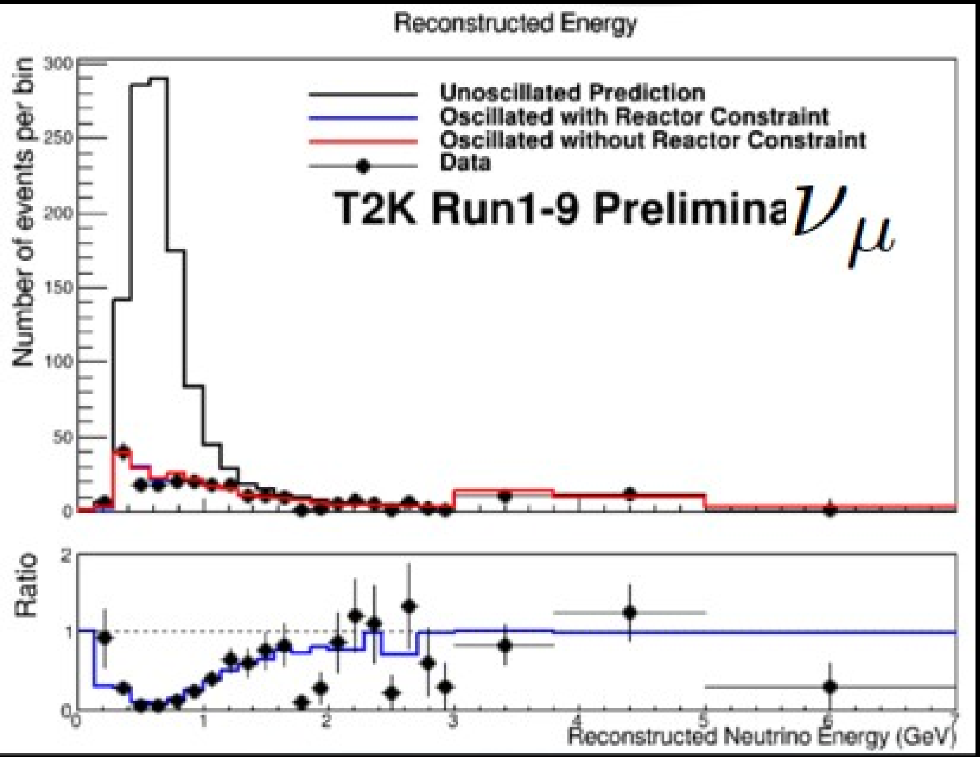


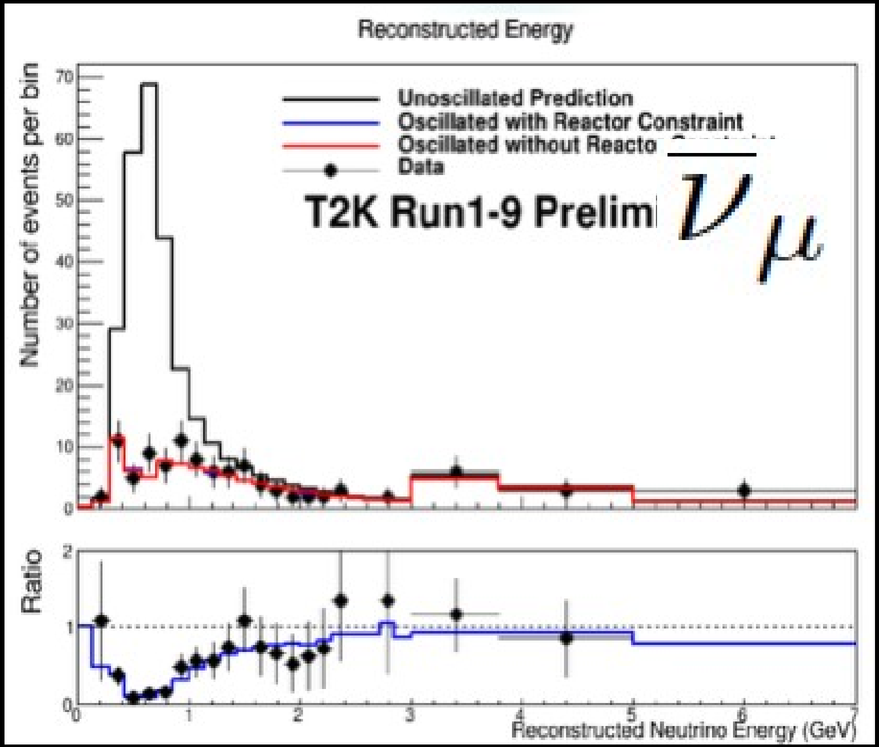
- Measure disappearance of muon neutrinos to determine θ_{23} and Δm^2
- Measure electron neutrino appearance
- Determine if neutrinos and antineutrinos behave the same. In fact, there is a chance to find CP violation in THIS experiment.
- The group is also studying future neutrino experiments for CP violation discovery.

T2K results so far

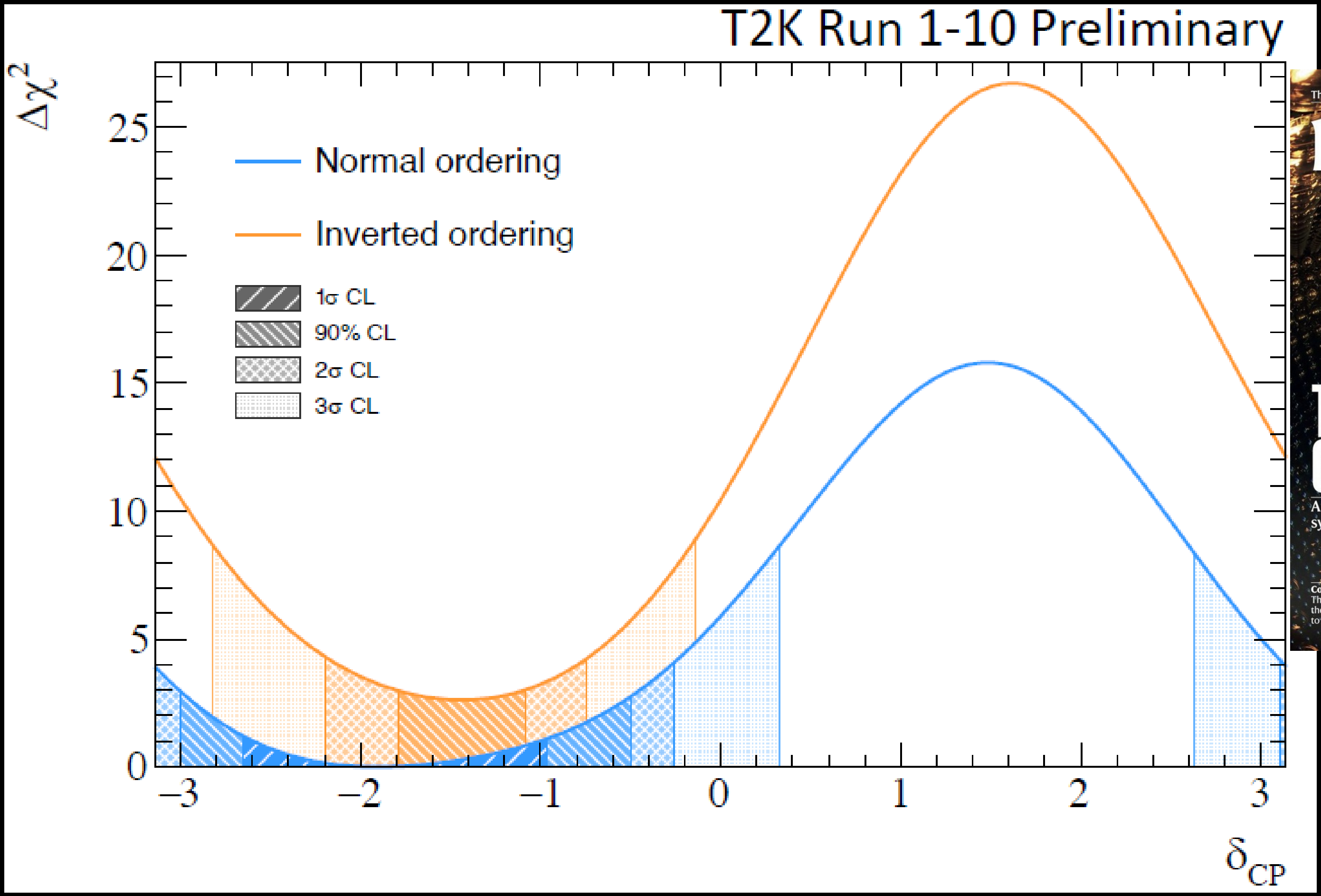
1.49e21 POT

1.12e21 POT



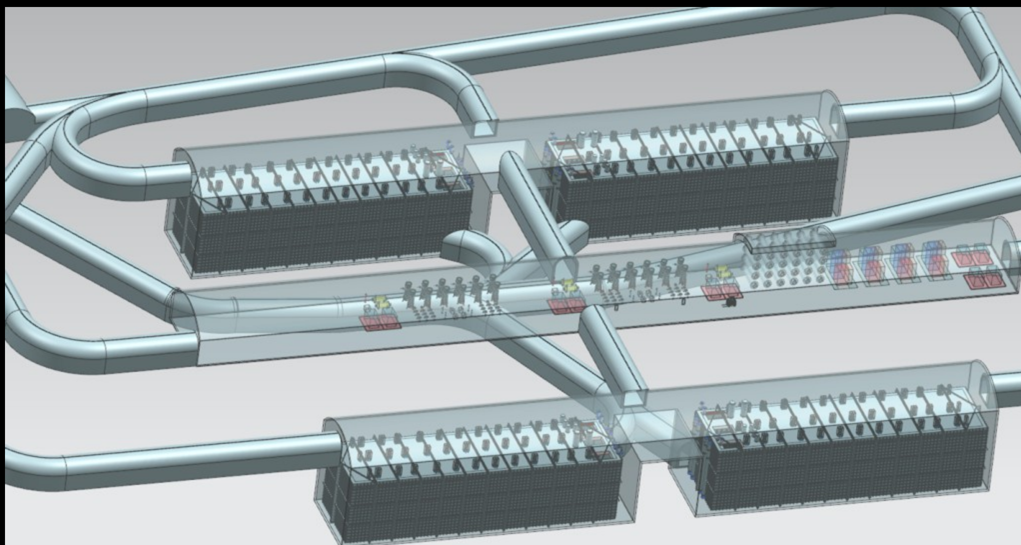


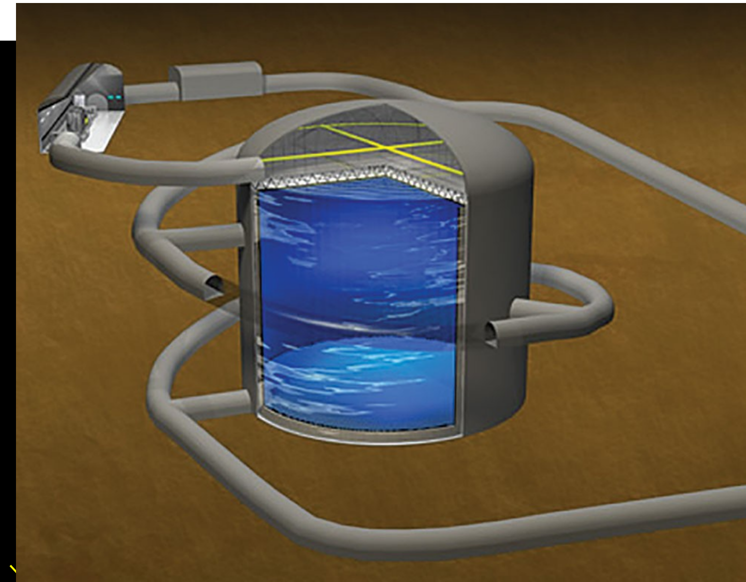
T2K results so far

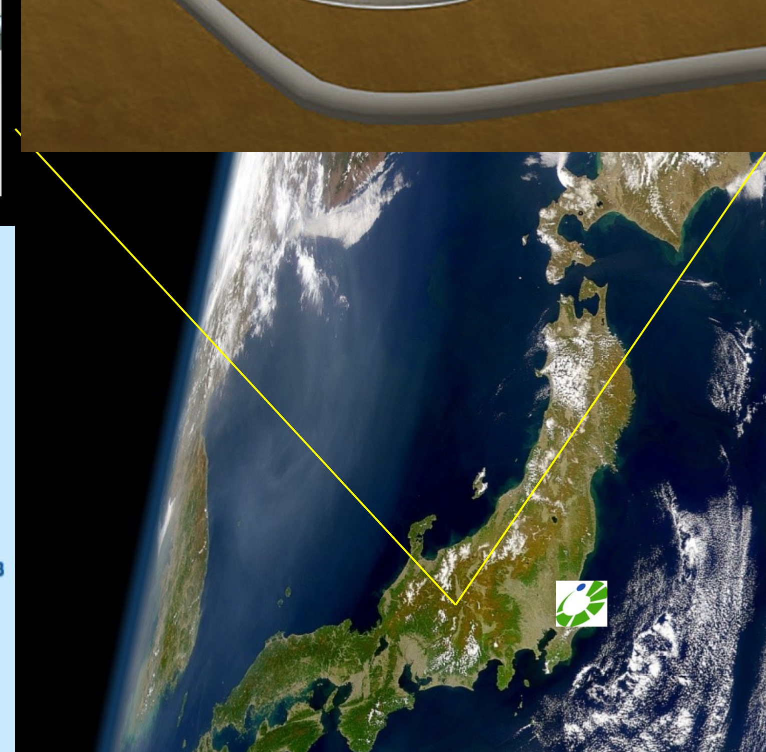


CP conserving values outside of 2σ region for both hierarchies

Future = Liquid Argon in USA and Water Cherenkov in Japan



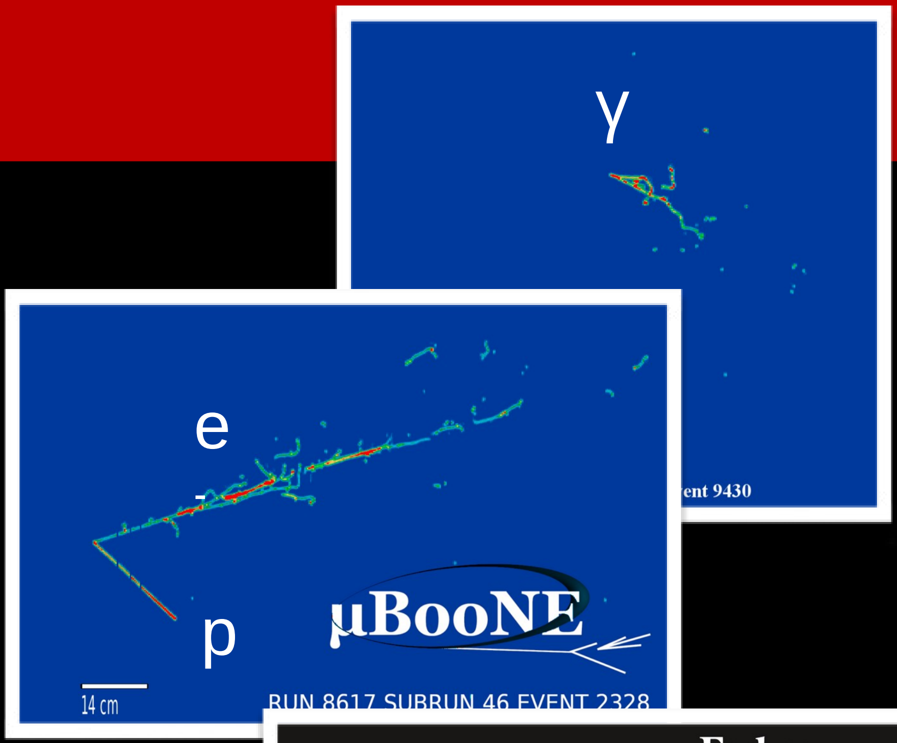


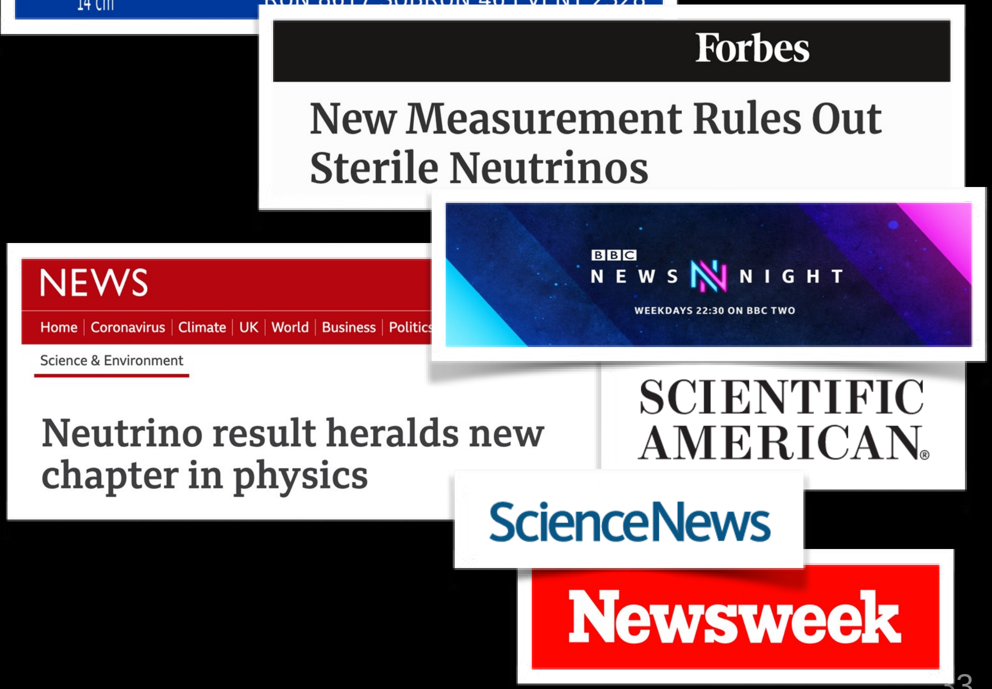


MicroBOONE

- Largest liquid argon data set in the world
- Over 500K ν interactions
- Opportunities to search for new physics, resolve existing “low-energy excess” anomaly, and measure neutrino interactions in argon with fantastic precision
- Huge relevance for DUNE in the future (which will use the same technology)
- First “low-energy excess” results published Oct 2021. Great result with a lot of publicity, but the anomaly remains
- ...and use only half the data set! Huge amount more data will be ready for a PhD analysis starting Oct 2023

Oxford MicroBOONE group:
2 superivsors (including a MicroBOONE physics coordinator), 2 postdocs





SNO+

~100 physicists

Oxford
Lancaster
Liverpool
QMUL
Sussex

Neutrinoless double-β decay

Solar neutrinos
Reactor neutrinos (Δm^2_{12})
Geo-neutrinos
Supernova neutrinos
Invisible nucleon decay
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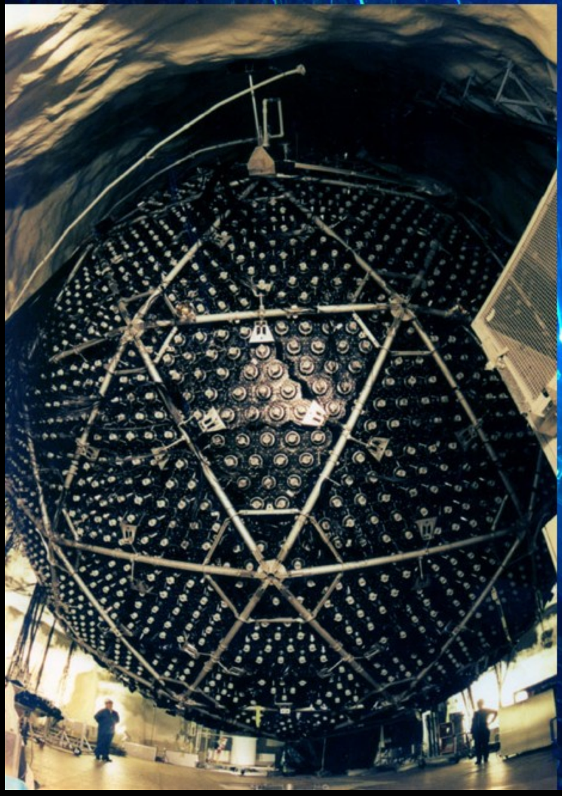
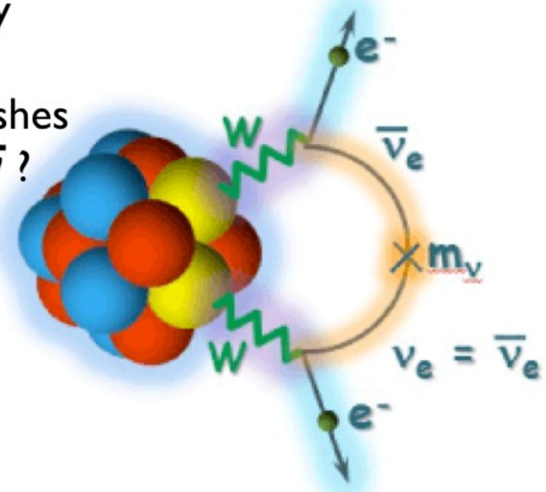


Faculty: Steve Biller, Armin Reichold, Jeff Tseng
Postdocs: Will Parker, Ben Tam, Ana Sofia Inacio
DPhil students: Rafael Hunt-Stokes, Cal Hewitt, Gulliver Milton, Jasmine Simms, Po-Wei Huang

Is helicity all that distinguishes ν from $\bar{\nu}$?



Neutrinoless double beta decay

The origin of neutrino mass: currently the <u>**ONLY**</u> laboratory-accessible physics beyond the SM

(can't be explained by standard Higgs mechanism & left-handed ν's)

- Majorana nature of neutrinos
- Absolute neutrino mass scale
- Lepton number violation
- Potential bridge for GUT
- Crucial for most models of leptogenesis

SNO+ Method: Load large quantity of 130Te into liquid scintillator

Allows for world-leading sensitivity with a easily scalable approach!

Many new techniques (including Te loading) developed at Oxford

Oxford is the lead UK institution on SNO+

(UK comprises ~25% of project manpower)

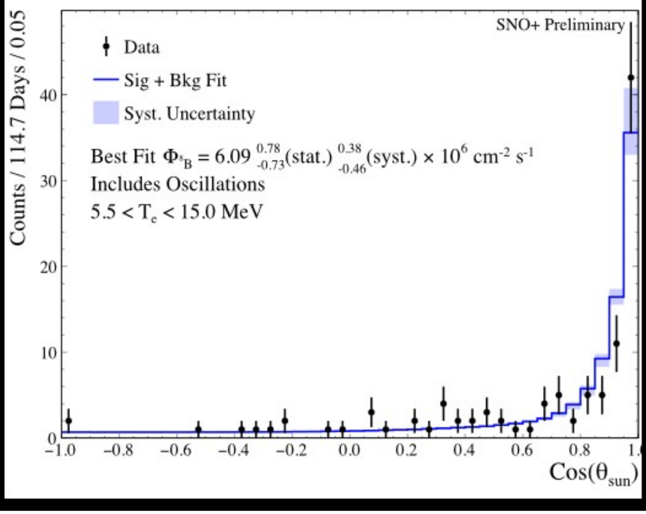
<u>Areas of Oxford Leadership Include:</u>

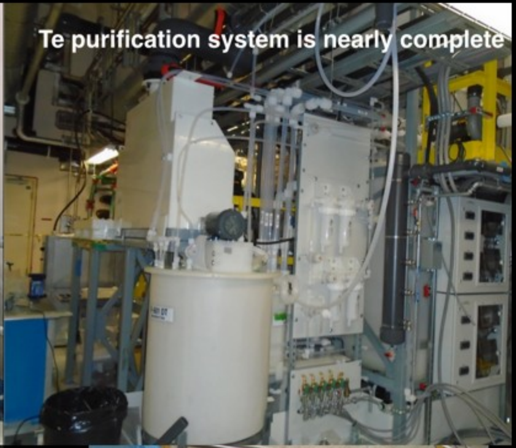
- Te loading and scintillator development
- Laser-based calibration system
- Overall software management
- Signal extraction software
- General simulation & algorithm development
- Future phase development

Operating with water since Spring 2017

Now taking data with full load of scintillator

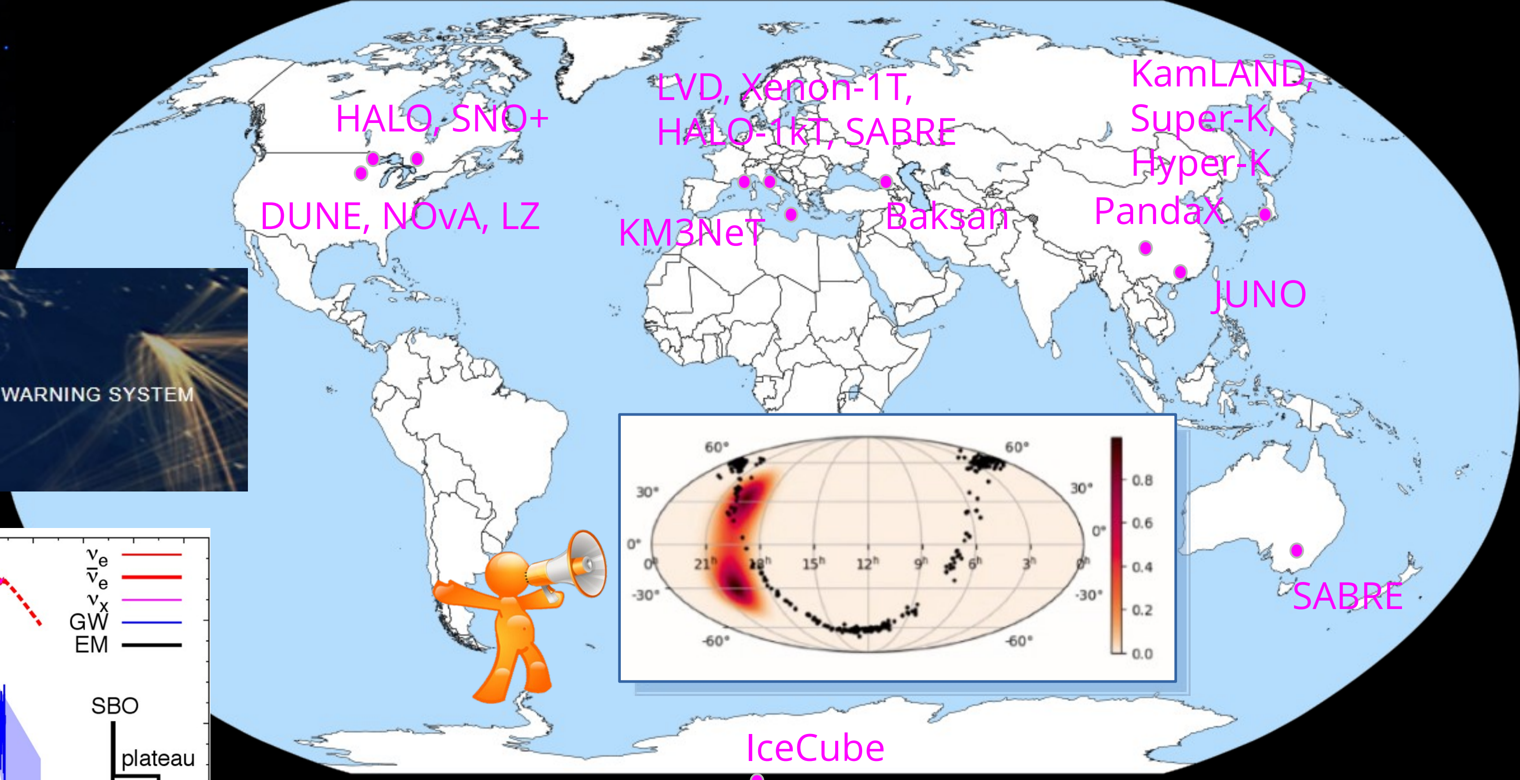
Te loading 0ν double beta decay next year

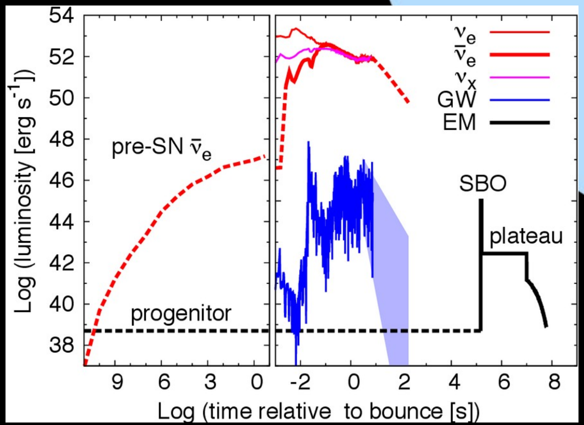




Thesis would involve hardware, software, detector operation, data processing and analysis... the main results would be produced over the course of the next several years!

SNEWS
SUPERNOVA EARLY WARNING SYSTEM





Galactic core-collapse supernovae rare, but rich in astro/nuclear/neutrino physics:

- Mass hierarchy
- Non-standard interactions
- Nucleosynthesis
- Neutron star equation of state
- Black hole formation

Dark Matter Search with Liquid Xenon

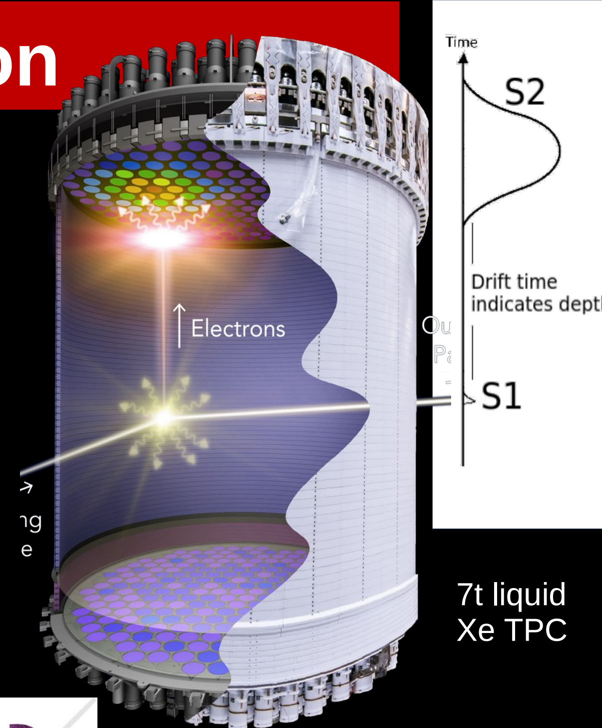
Kimberly Palladino and Hans Kraus
Students: Fearon, Hunt, Dey, Green, Fieldhouse, Swain

- LZ operating in discovery mode
  - Anticipating run through 2028
  - Analysis through 2029
- Many LZ tasks/analyses:
  - Simulations, backgrounds
  - PLR, WIMP's, EFT
  - ^{8}B neutrinos via CevNS
  - S2 only/low threshold
  - Upgrade R&D with HydroX
  - Low-E sensitivity with Migdal

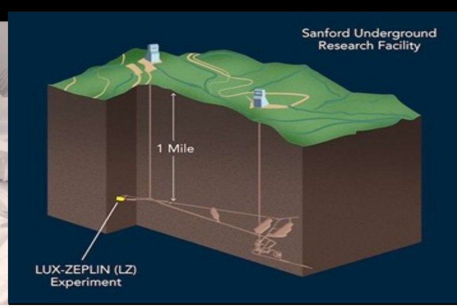
First WIMP result
PRL 131 (2023) 041002

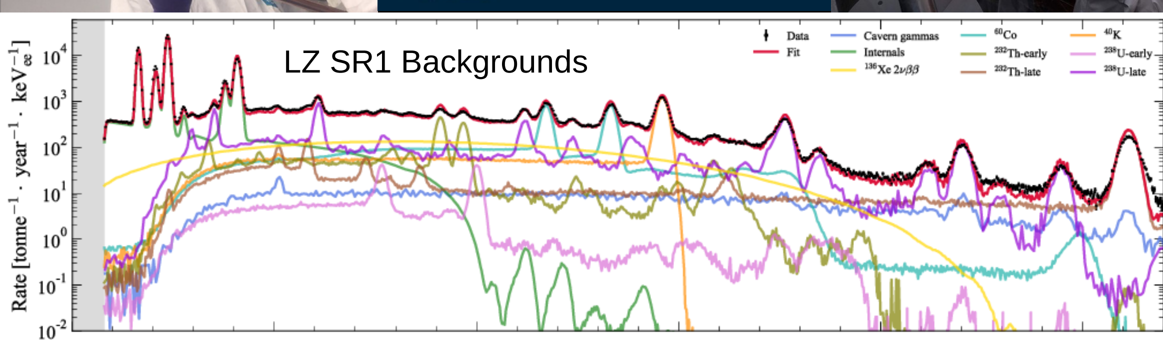
Backgrounds
PRD 108 (2023) 012010

Low E ER
PRD 108 (2023) 072006



7t liquid Xe TPC





XLZD

Dark Matter Search beyond WIMP's: very big & small

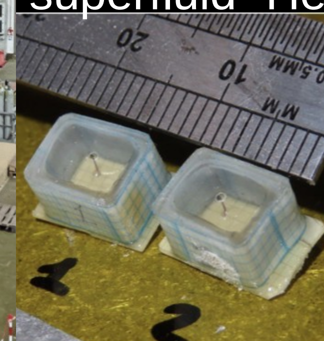
Recent papers:
arXiv:2310.11304, accepted to EPJC;
Phys.Rev.Lett. 130 (2023) 10, 101001;
Phys.Rev.Lett. 130 (2023) 10, 101002

<u>Group members:</u>
George Korga (tech.)

***Fellows*:**
Elizabeth Leason
Ram Jois

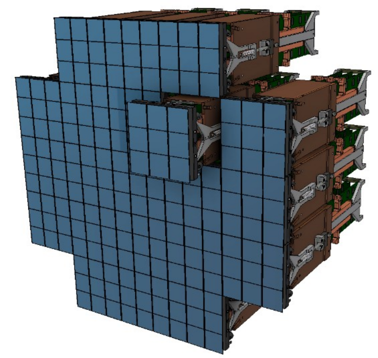
***Postdocs*:**
Daria Santone
Ashlea Kemp
Paolo Franchini (v)
Alice Hamer (v)

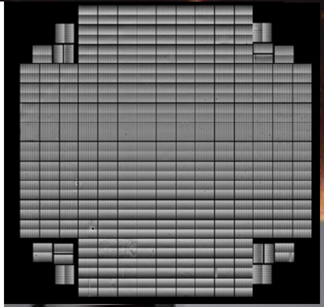
PhD Students:
Zoe Balmforth
Olly Macfadyen
Seraphim Koulosousas
Rob Smith
Angus Thompson
Pritindra Bhowmick
+ You!

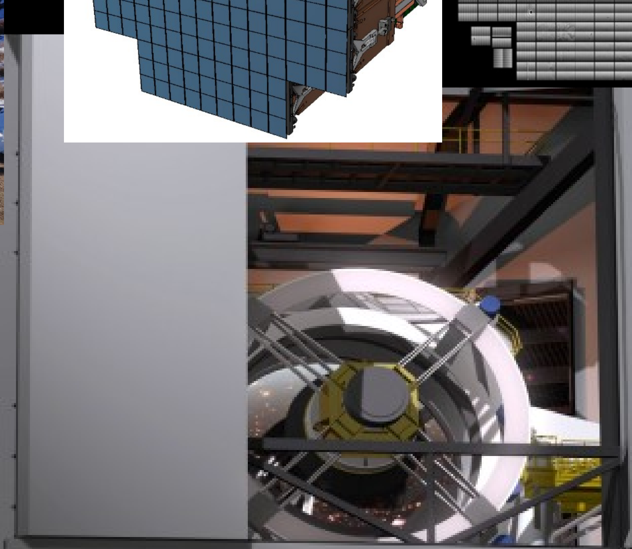


QUEST-DMC:
superfluid ^{3}He

The Large Synoptic Survey Telescope





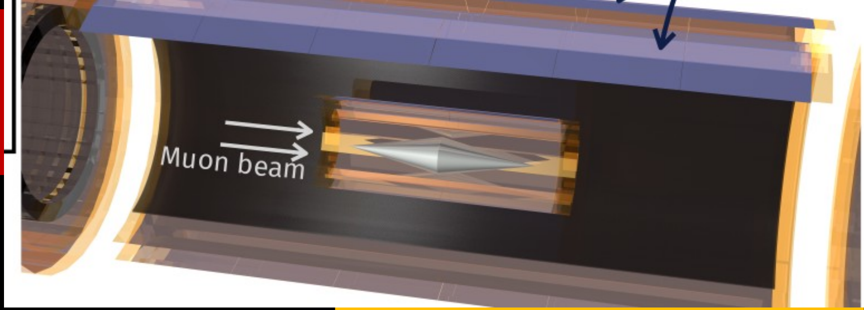


Oxford LSST Camera Test Stand

Particle Astro Synergy

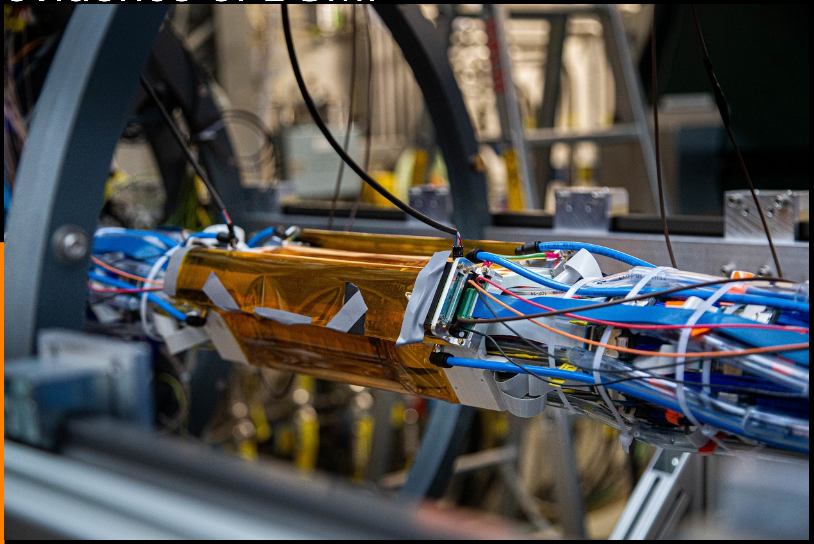
PP: Azfar/Tseng/Shipsey
Astro: Davies/Fender/Ferriera/Jarvis/Lintott/Miller/Smartt

Mu3e

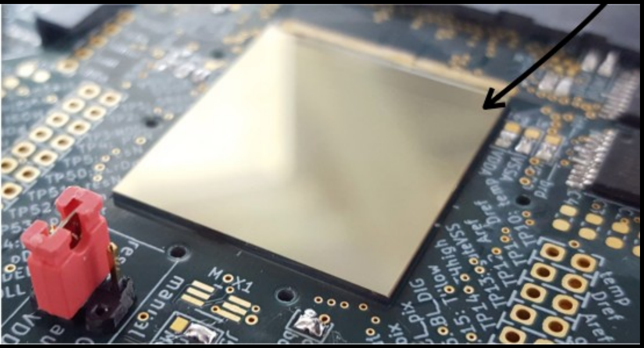


Aim to observe the process μ→eee
- Decay forbidden in SM: predicted BR(μ→eee) ~ 10^{-50}
- BSM models predict BR enhancement
- Observation → direct evidence of BSM!

Detector comprised of pixel tracker + scintillating fibres
- Production of entire outer pixel detector in Oxford
- Full detector expected ~ 2025



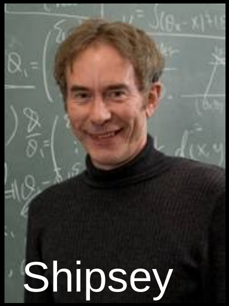
Extremely light-weight detector:
- Ultra-thin silicon monolithic pixel chips
- Gaseous helium cooling
- “Ladder” supports total weight ~ 2g!



Detector production + preparation for data-taking on-going in the next 5 years. DPhil student involvement:
- Silicon pixel sensor testing and detector construction
- Integration and commissioning of the pixel detector @ Paul Scherrer Institute in Switzerland
- Development of analysis procedures + analysis of first dataset to search for rare muon decays

Instrumentation: Oxford Physics Microstructure Detector Laboratory (OPMD)

Bortoletto



Shipsey

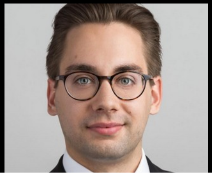
Hynds

Plackett

Weatherill

Wood

- A state-of-the art facility for the development of new sensors for particle physics, photon science, and astrophysics
- Three DPhil students
- Currently focusing on:
  - Construction of ATLAS pixels
  - Construction of ultra light detectors for Mu3e
  - Depleted Monolithic Pixel Detectors
  - Ultra Fast Silicon Detectors
  - CCD for LSST
  - Applications of MEDIPIX

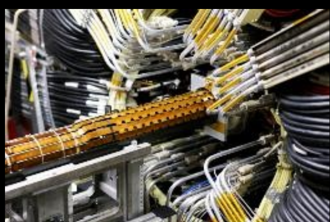


Eberwein

Gazi

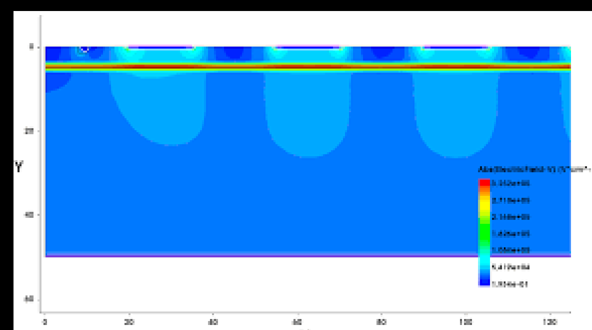
Koch

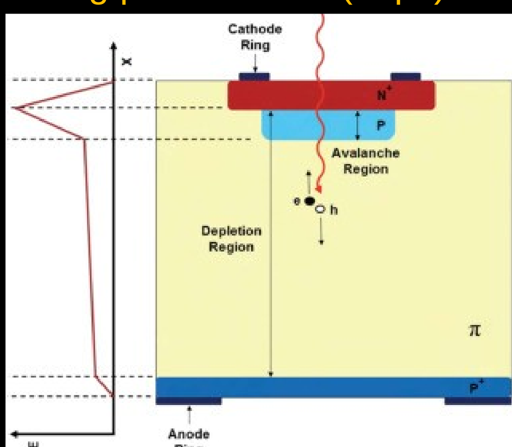
Silicon pixel detectors have revolutionised Particle Physics and Photon Science in the last decades.



Joint DPhil with Diamond Detector Group and Oxford Physics Microstructure Detector (OPMD) Group 50/50 time split

LGADs are a new development of silicon sensor technology LGADs that will increase the x-ray sensitivity (down to 250eV) and timing performance (30ps).





The project will focus on developing operational pixel LGADs, by simulating them, developing calibration algorithms, and testing their performance in the lab and at beam facilities

Pixel LGADs will strongly affect future of both Particle Physics tracking systems, and the study of biological and material properties with soft x-rays.

“Leavers” 2022/23

- James Grundy (ATLAS)
- Jonas Wuerzinger (ATLAS)
- Laurence Cook (Acc Neutrinos)
- Laurence Wroe (JAI)
- Federico Celli (ATLAS)
- Zhiying Li (ATLAS)
- Robert Williamson (JAI)
- Daniel Barrow (Acc Neutrinos)
- Aimee Ross (JAI)
- Luke Scantlebury-Smead (LHCb)
- Iza Veliscek (ATLAS)
- Aiham Al-Musalhi (LZ)
- Kang Yang (Acc Neutrinos)
- Jake Flowerdew (JAI)
- Josie Paton (SNO+)
- Daniel Cookman (SNO+)

Welcome to Oxford Particle Physics

Particle Physics at Oxford

Applications

- Application deadline **12 noon (UK) Friday 5 January 2024**

- Let us know which experiments you're interested in
  - On application form: proposed research area/supervisors
    - Examples: ATLAS, LHCb, AccNeu, SNO+, LZ, DarkSide-20k, LSST, Mu3e, OPMD
    - JAI has other projects (see Phil's talk)
  - We encourage candidates to talk with several groups
  - Feel free to write mostly about just one in your research statement
  - Experiments want to meet you!

- If you're applying for a national scholarship, please indicate so (if form doesn't have a blank, write it in your statement)

- Interviews ~ late January / early February

- See https://www.ox.ac.uk/admissions/graduate/courses/dphil-particle-physics for details on applications, funding, etc

DPhil life

- Year 1: coursework, start research
  – Transfer viva: typically end of Year 1
- Year 2: research (often at lab)
  – Confirmation of status: typically end of Year 2
- Years 3 and 4: research and dissertation
  – 4 years is maximum time
- Wide-ranging support to help you succeed:
  college, training courses, equality & diversity support
  – Plus very helpful and friendly administrators

Further Open Day sessions

- 1430 – 1500: closed Q&A
  - Students only!

- Questions?