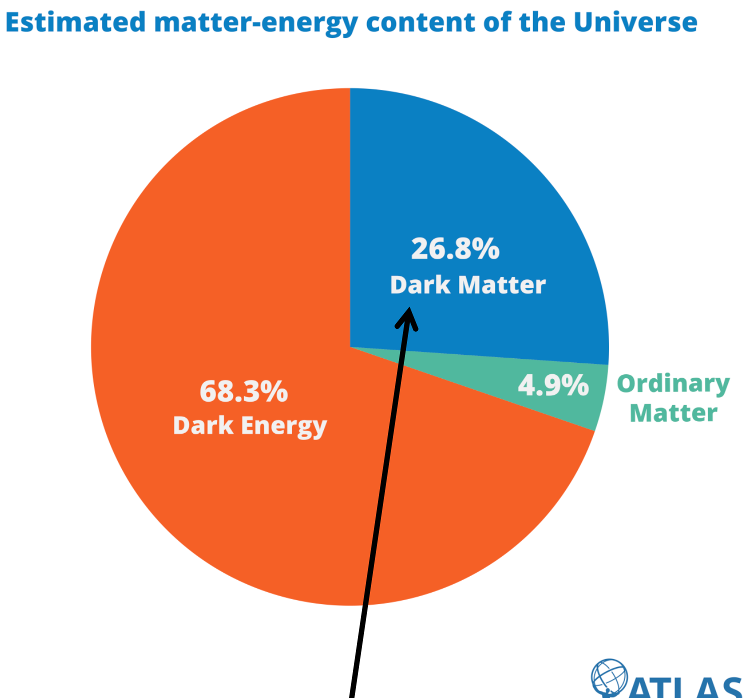
LHC Theme: Dark Matter @ ATLAS

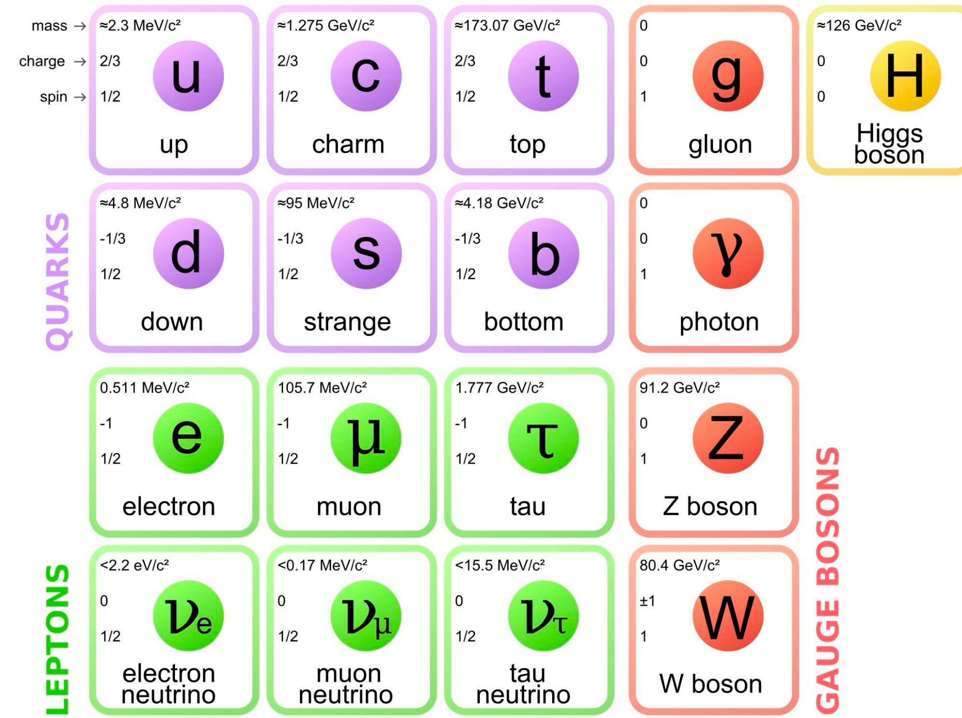
Paul Jackson, University of Adelaide

CDMPP Annual Workshop, Glenelg SA.

November 29th, 2023

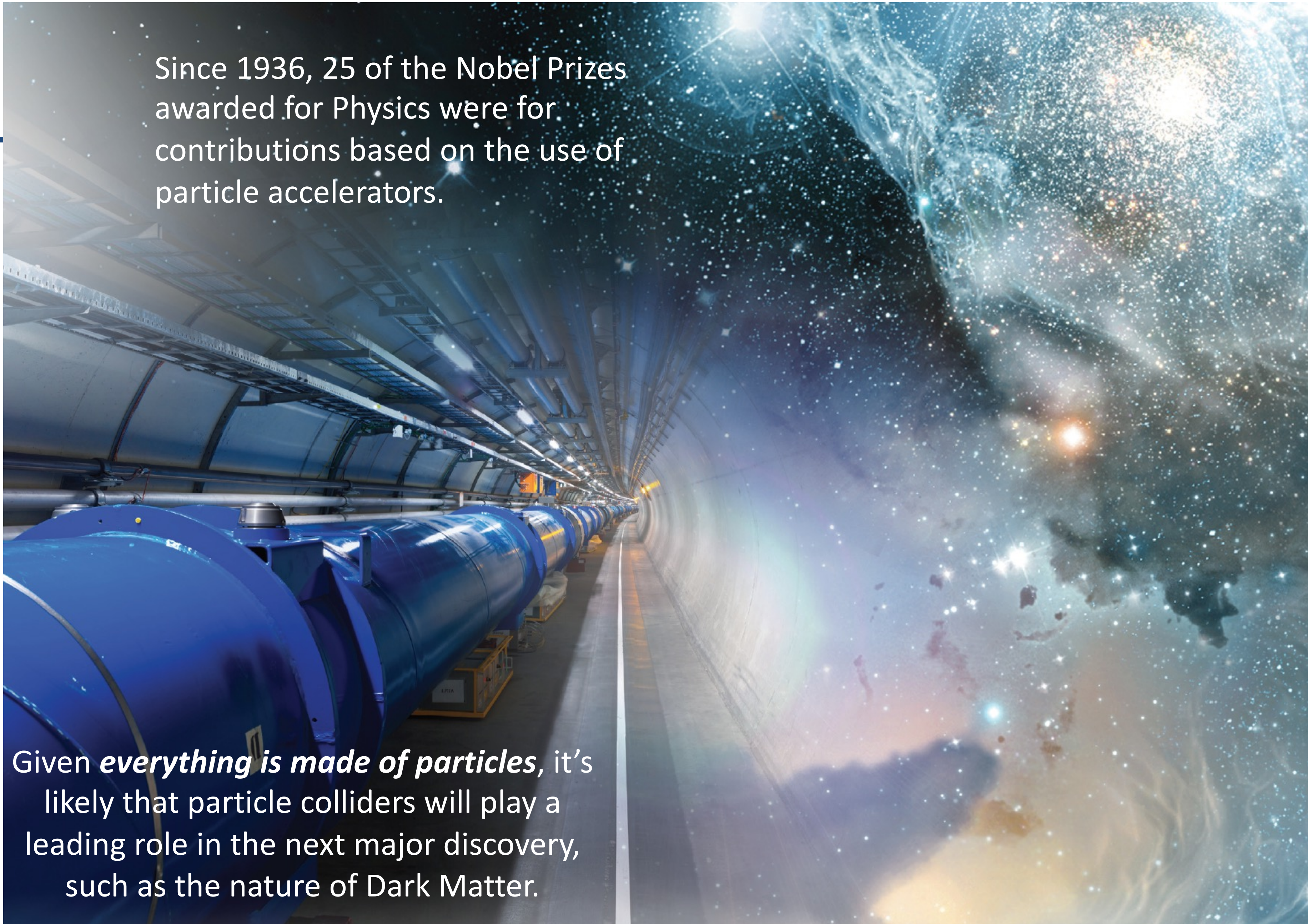
Everything is made of Particles!





We know this exists but don't know what it is yet. ***One of the biggest challenges in fundamental physics.***

As everything is made of particles, we assume Dark Matter is made of one or more particles

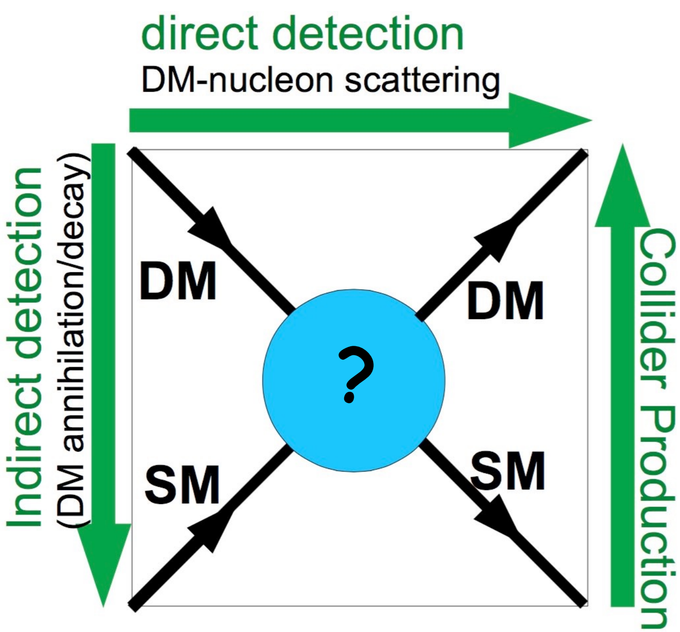


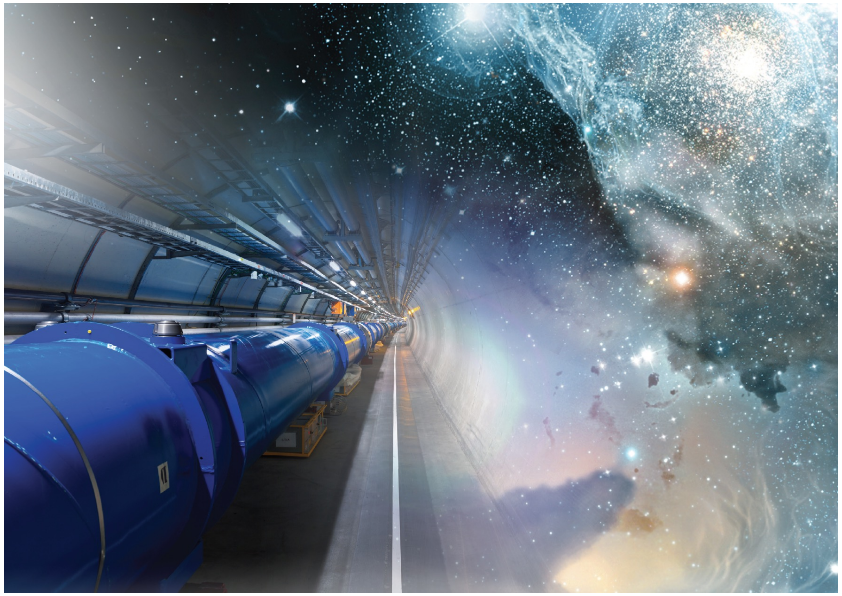
Since 1936, 25 of the Nobel Prizes awarded for Physics were for contributions based on the use of particle accelerators.

Given ***everything is made of particles***, it's likely that particle colliders will play a leading role in the next major discovery, such as the nature of Dark Matter.

A Dark Matter Search Strategy

- ✓ Unknown dark/SM coupling -> dark particles mediators could have a range of properties
- ✓ Unknown dark/SM mediators -> probe unexplored mass scales (multi-TeV)
- ✓ A weakly interacting massive particle (WIMP) produced in thermal equilibrium could produce observed relic density -> probe weak scale masses (100s GeV)
- ✓ …..but actually, we have no idea what we're looking for! -> look for the unexpected





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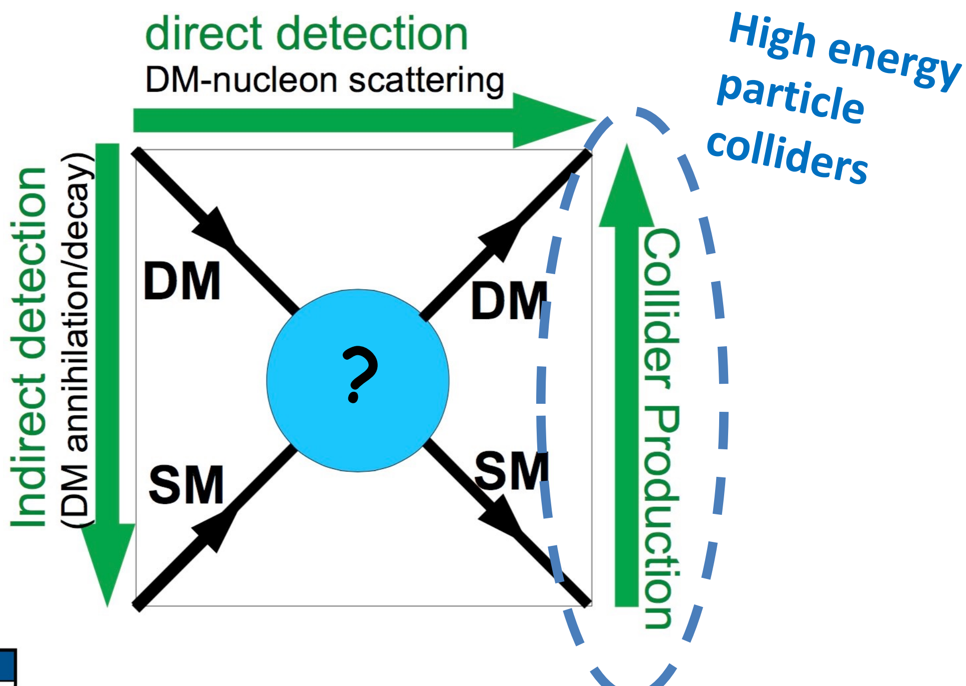
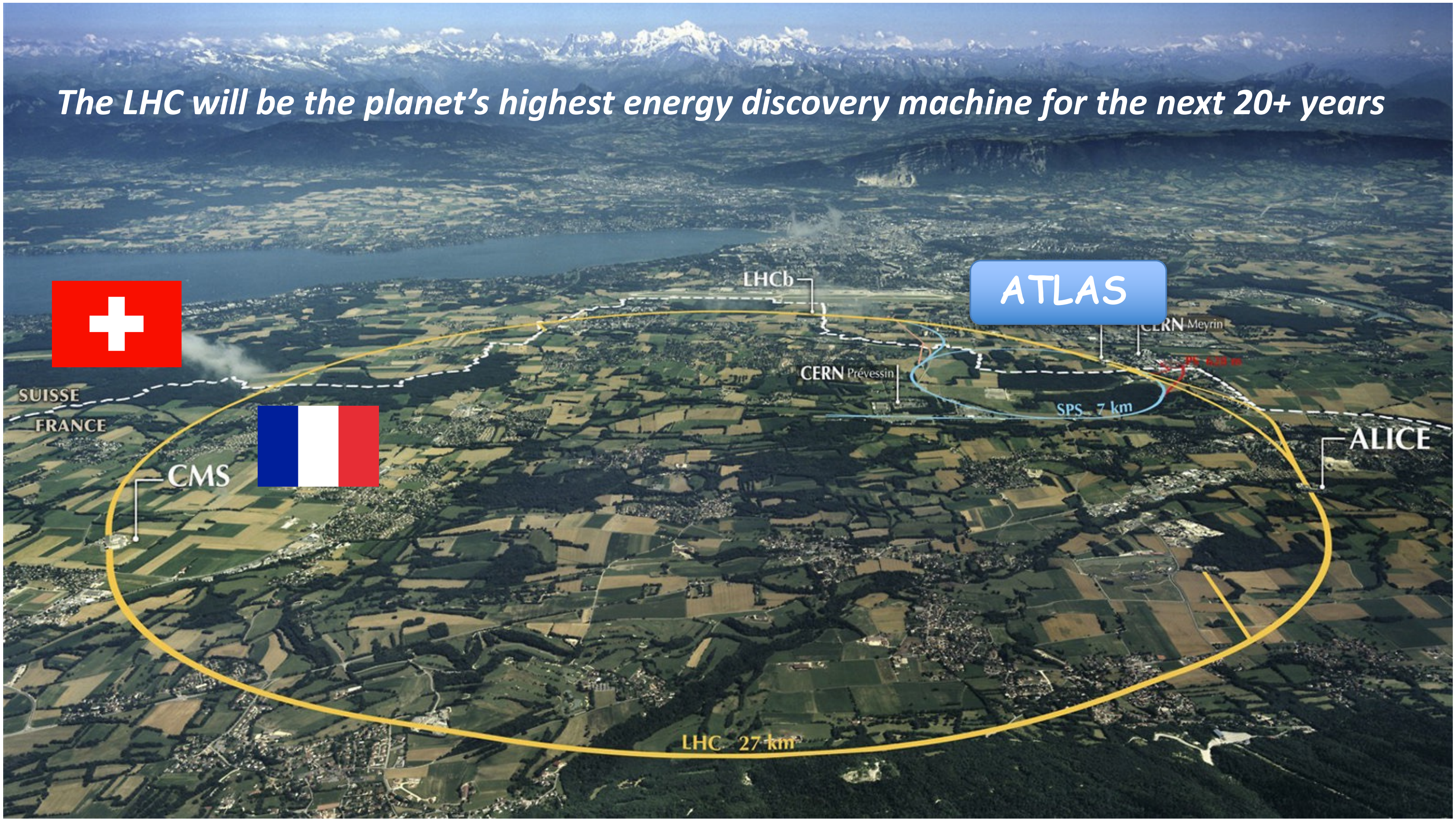


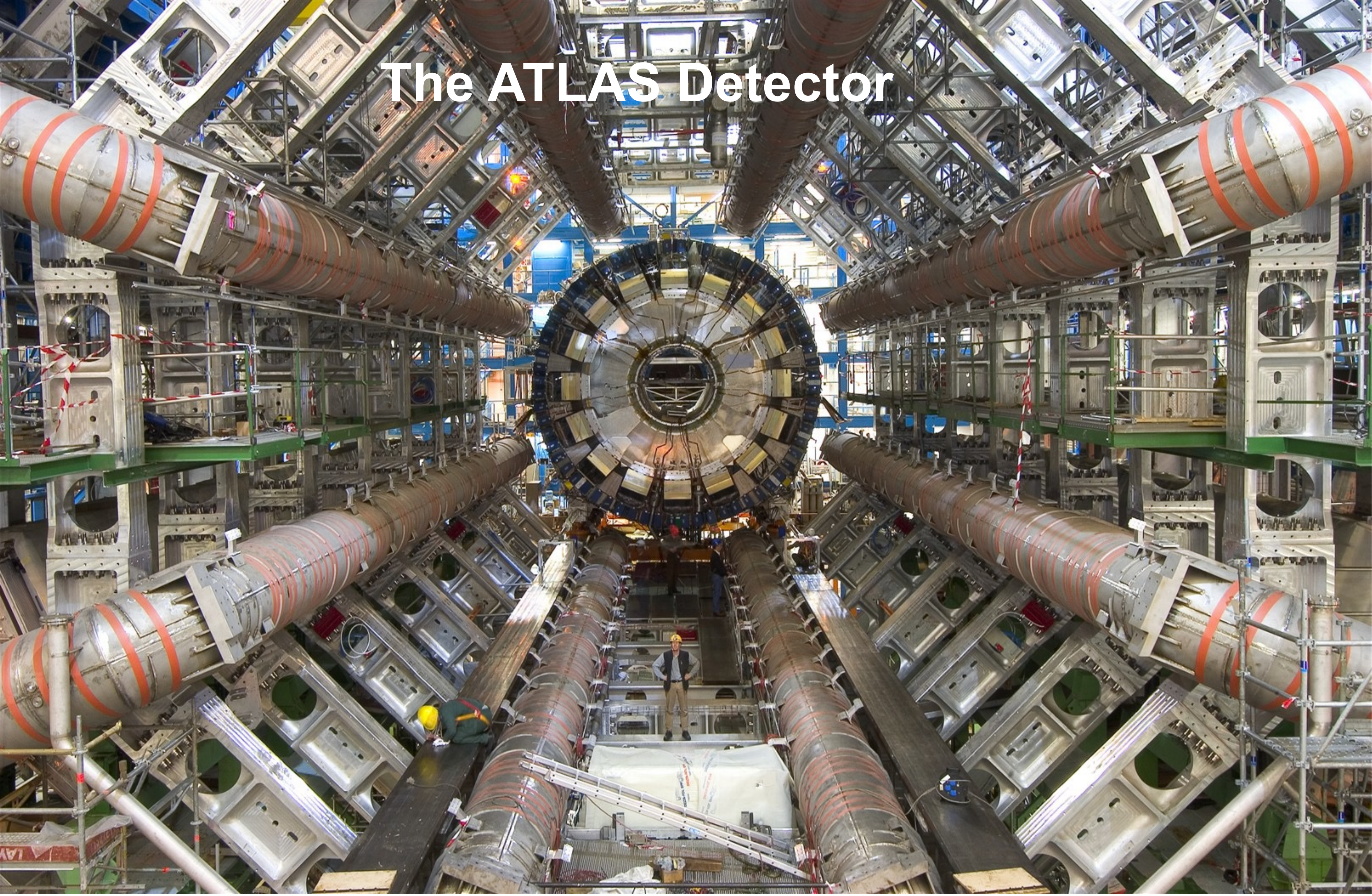
The Large Hadron Collider

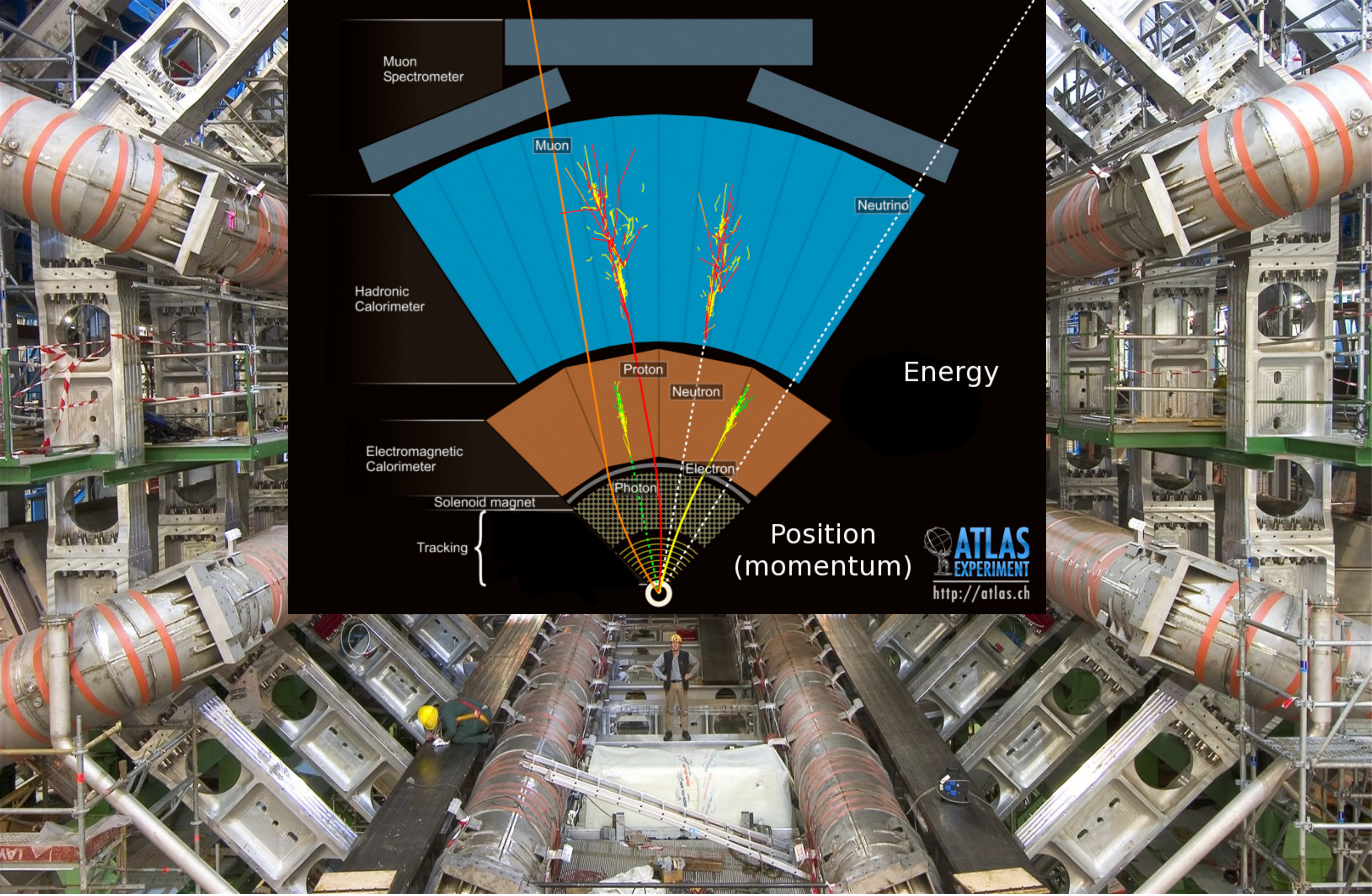
ATLAS EXPERIMENT



A 27 km synchrotron at CERN colliding protons at $\sqrt{s} \geq 13$ TeV

The ATLAS Detector




Muon
Spectrometer
Muon
Neutrino
Hadronic
Calorimeter
Proton
Neutron
Energy
Electromagnetic
Calorimeter
Electron
Photon
Solenoid magnet
Tracking
Position
(momentum)
ATLAS
EXPERIMENT
http://atlas.ch

ATLAS in the news

ATLAS EXPERIMENT

CERN DG Fabiola Gianotti welcomed President of the French Republic Emmanuel Macron and the President of the Swiss Confederation Alain Berset for an official visit from our host states to the Laboratory.

They had a lengthy visit to ATLAS and the new visitor centre. Positive feedback from both French and Swiss sides.

CDMPP ATLAS at this workshop

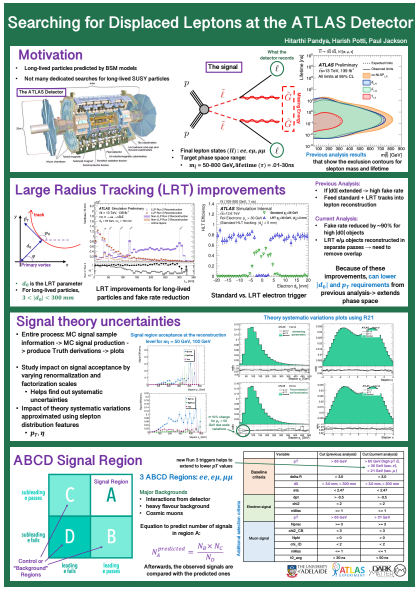
Talks

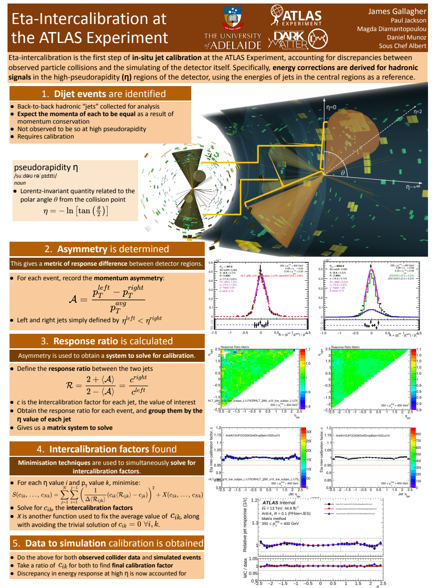
- **Albert Kong** (Wednesday 16:15-16:30) – "Improving ATLAS Hadronic Object Performance with ML/AI Algorithms"
- **Emily Filmer** (Thursday 14:45 – 15:00) – "Hide and Super-Seek: Searching for Displaced Vertices with Missing Transverse Energy at the ATLAS Detector"
- **Tristan Ruggeri** (Thursday 16:45 – 17:00) – "Search for new physics in final states with objects originating from a top-quark, a charm-quark and large EmissT in pp collisions at $\sqrt{s}$=13TeV"

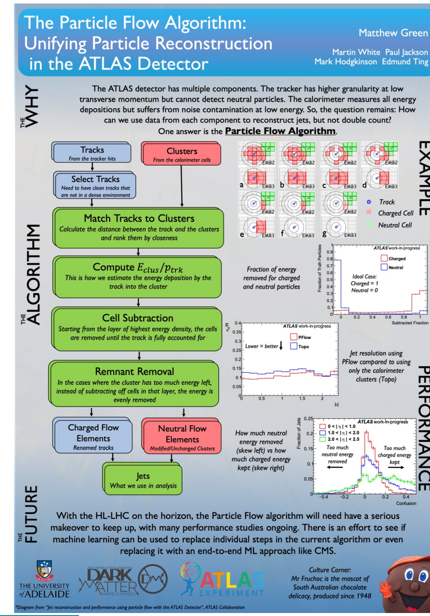
Posters

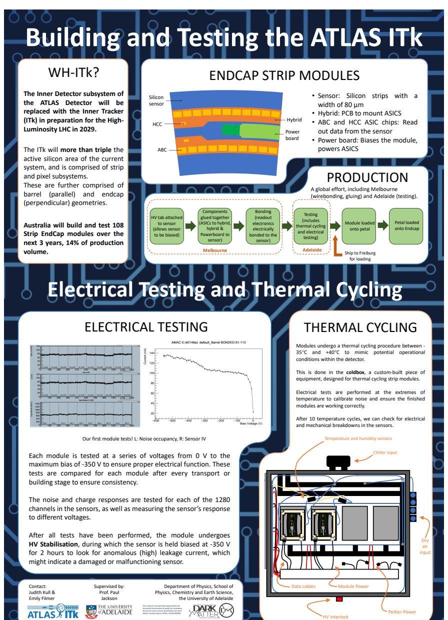
Hitarthi Pandya - Searching for Displaced Leptons at the ATLAS Detector
Judith Kull – Building and Testing the ATLAS Inner Tracker
Emily Filmer - Using Missing Energy to search for Missing Matter
Edmund Ting - Reuse, Repurpose, Reinterpret: Making the Most of LHC Results
Matthew Green - ParticleFlow Algorithm for LHC Physics
James Gallagher - Eta-Intercalibration at the ATLAS Detector
Matthew Fewell - Towards Improved Photon Isolation in the ATLAS Detector at CERN
Harish Potti - Run-3 operations of the ATLAS experiment

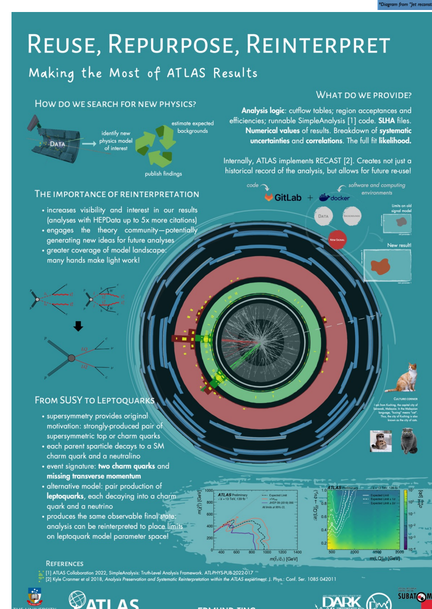
CDMPP ATLAS at this workshop









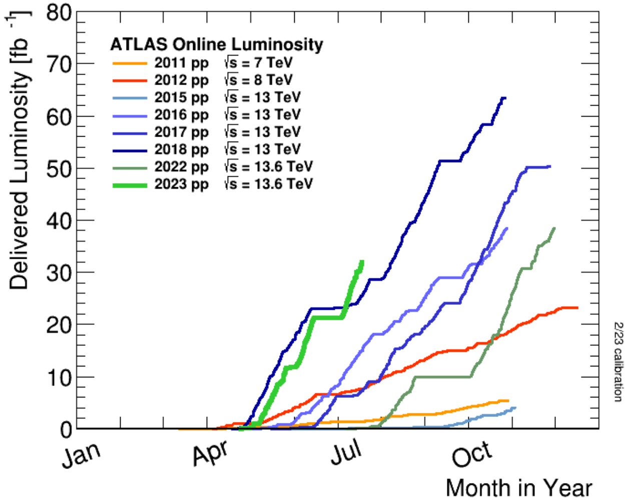


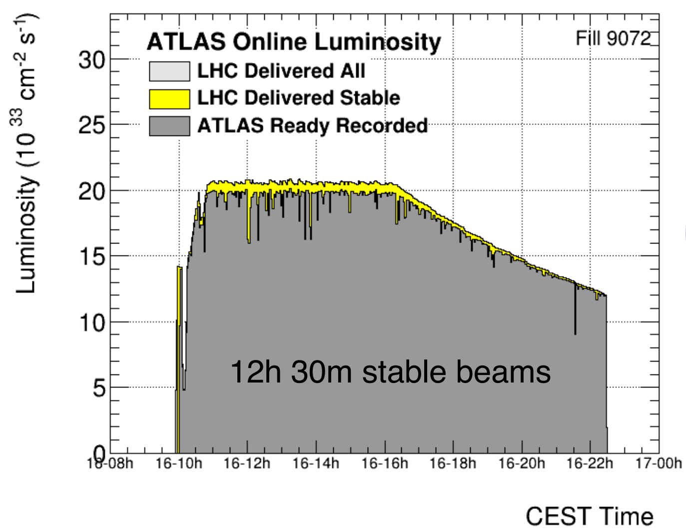
People

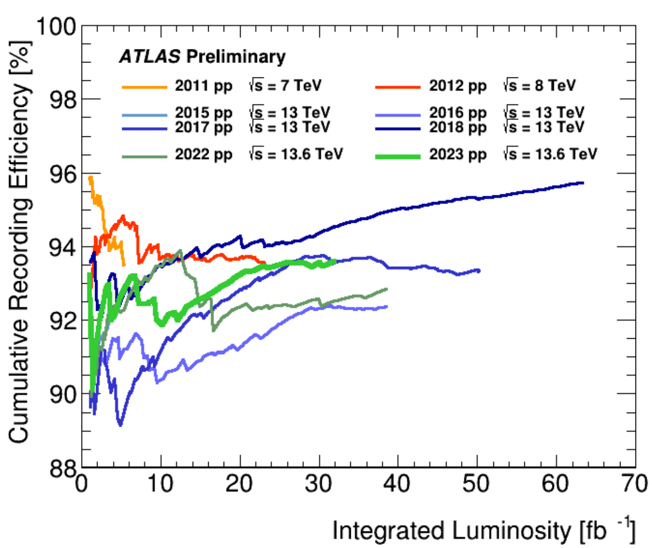
Former: Abhishek, Anna.
Current: Joni, Harish, Emily, Steve, Paul, Albert, Charles, Frederic

See Harish Potti's poster for more details

LHC/ATLAS data taking







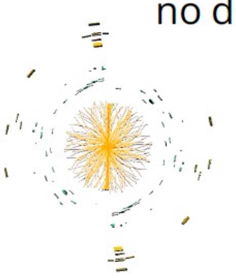
Excellent data taking efficiency throughout Run 3.

Highest energy collisions ever recorded!

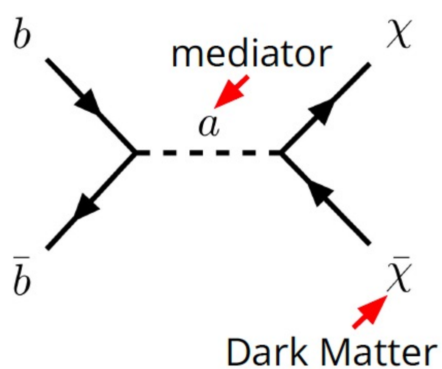
CDMPP researchers involved in trigger/DAQ shifts, inner detector, luminosity, computing and Jet/MET and photon performance group

DM at Colliders

- Small interaction cross section of Dark Matter with detectors at colliders



no detectable signal

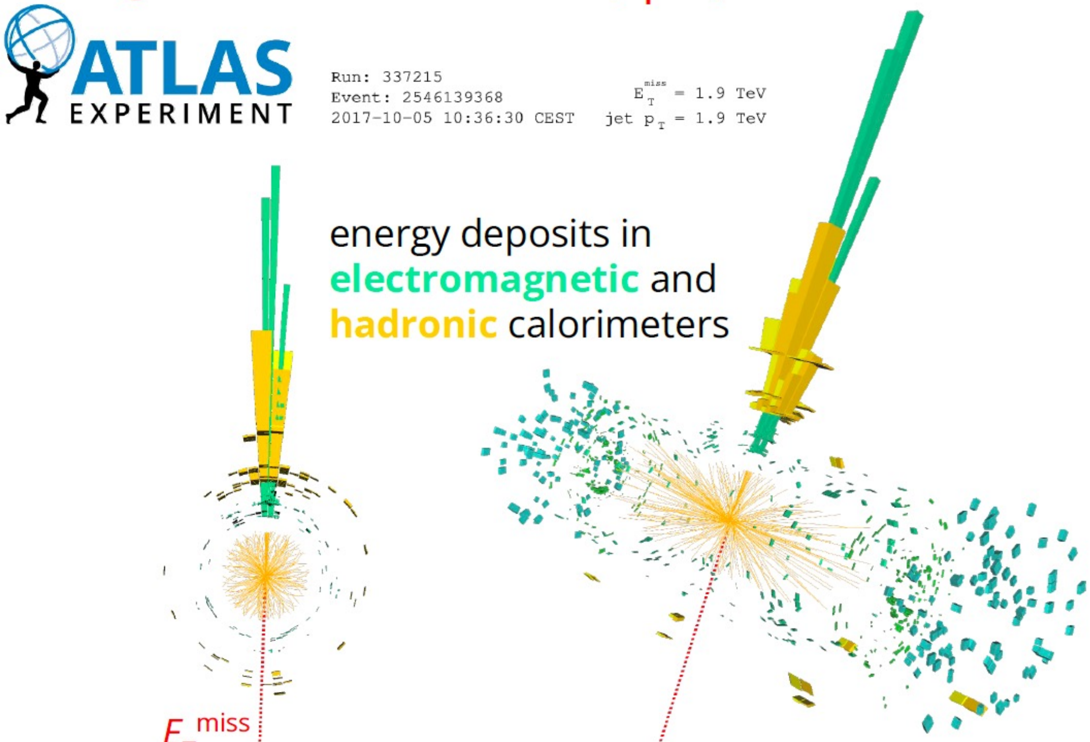


DM at Colliders

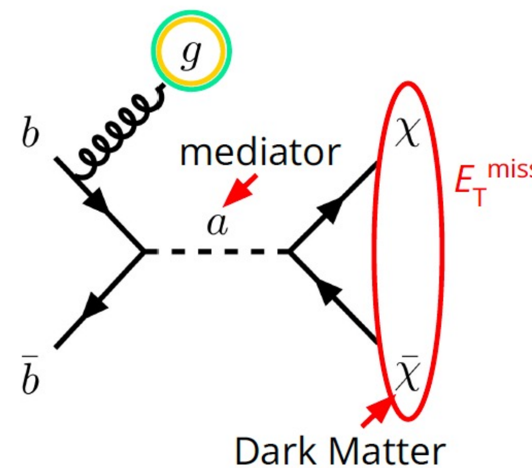
- Small interaction cross section of Dark Matter with detectors at colliders

➔ Need recoil against **detector-visible object**

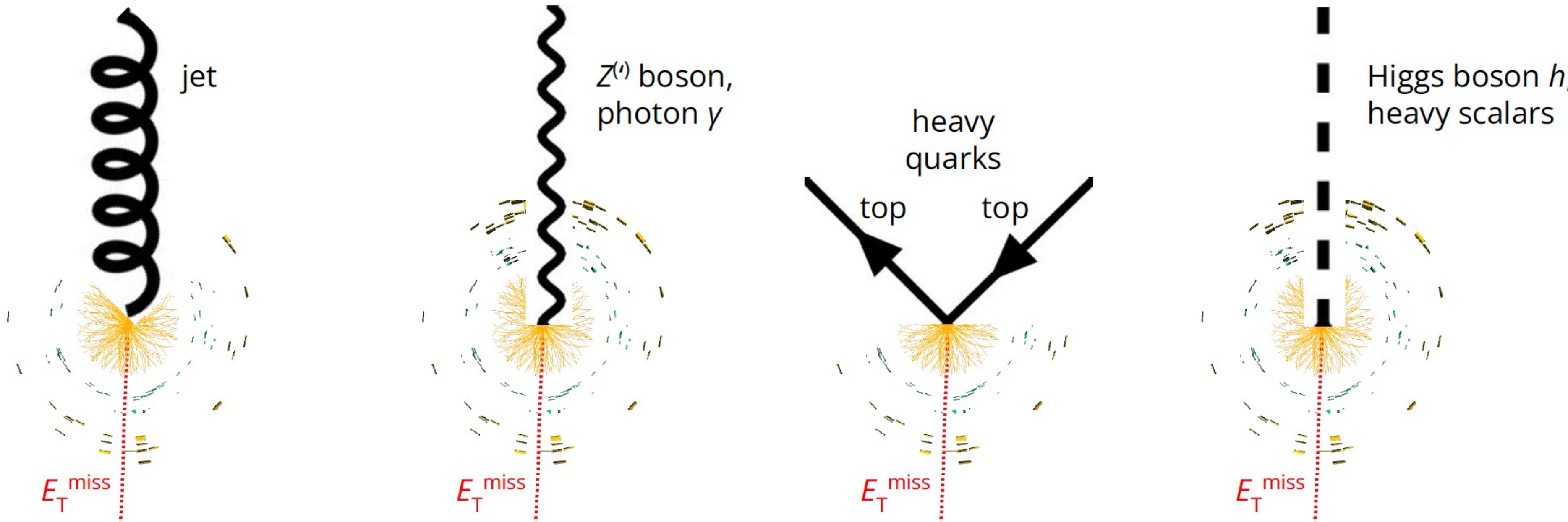
➔ **Missing transverse momentum (E_T^{miss})**



→ATLAS event display of a jet recoiling against E_T^{miss}



DM signatures @ Colliders



jet+E_T^{miss}: →2102.10874

$Z(\to\ell\ell)$+E_T^{miss}: →2111.08372
γ+E_T^{miss}: →2011.05259
$Z'(\to\ell\ell)$+E_T^{miss}: →EPS last week

tW+E_T^{miss}: →2211.13138
tt+E_T^{miss}: →2211.05426

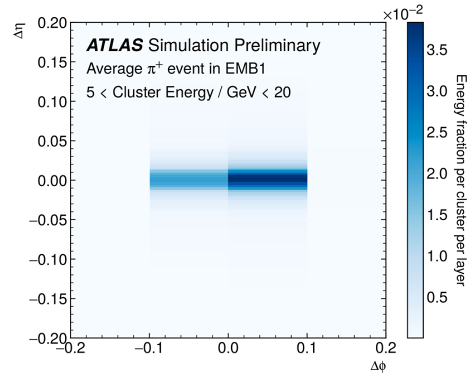
$h(\to\tau\tau)$+E_T^{miss}: →2305.12938
$h(\to bb)$+E_T^{miss}: →2108.13391
$h(\to\gamma\gamma)$+E_T^{miss}: →2104.13240
$s(\to WW)$+E_T^{miss}: →2211.07175

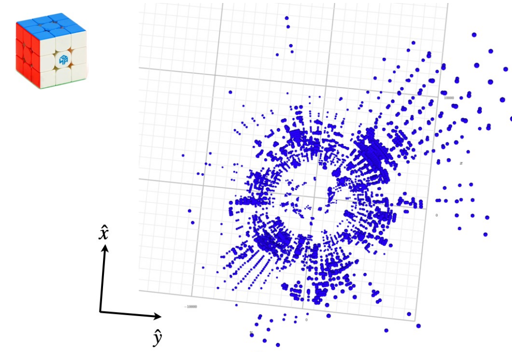
... and many more!

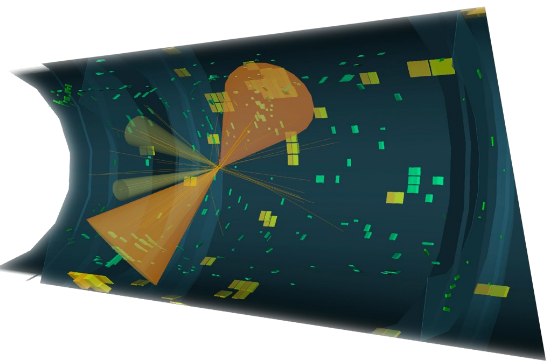
A vast array of results with increasingly sophisticated methods used!

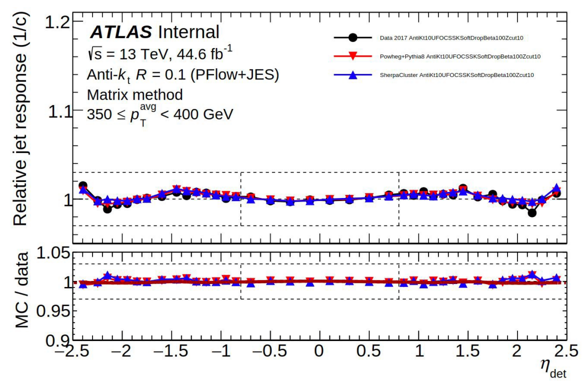
DM signatures need jets and missing ET

Albert Kong is exploring deep learning techniques using different types of data, image-based (left) and point cloud (right)

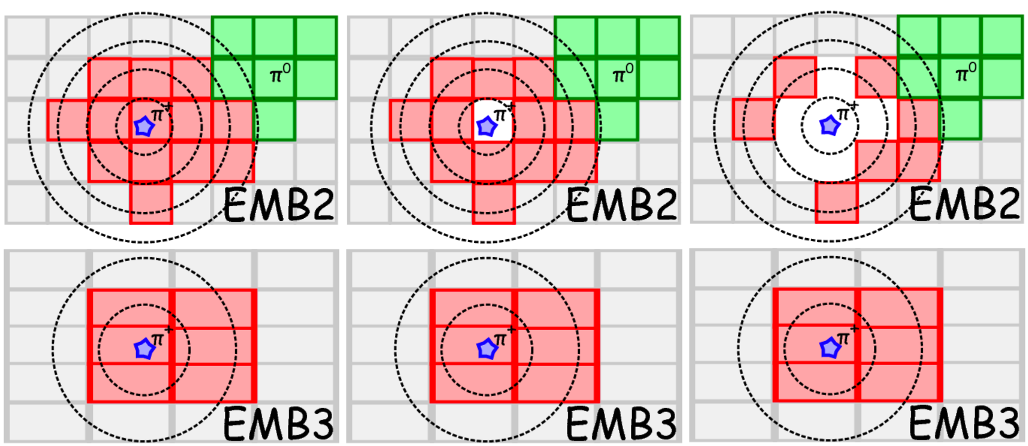








James Gallagher is looking at the eta inter-calibration of large radius jets. This is the first step of the ATLAS in-situ jet-calibration.



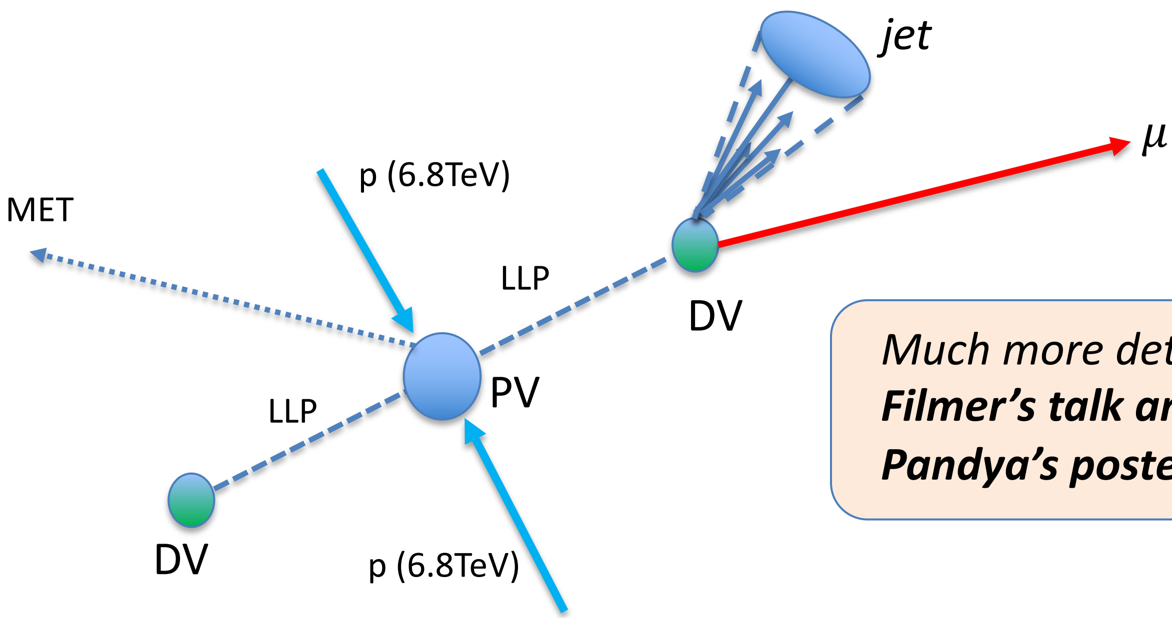
Matthew Green is studying a particle flow algorithm to leverage the high granularity of low pT tracks in jets while ensuring to not double-count the energy of clusters in the calorimeter.

Displaced Vertices

Non-SM particles with long-lifetimes compared to SM, give rise to long-lived particles.

If these objects decay in the detector volume there will be a displaced vertex signature.

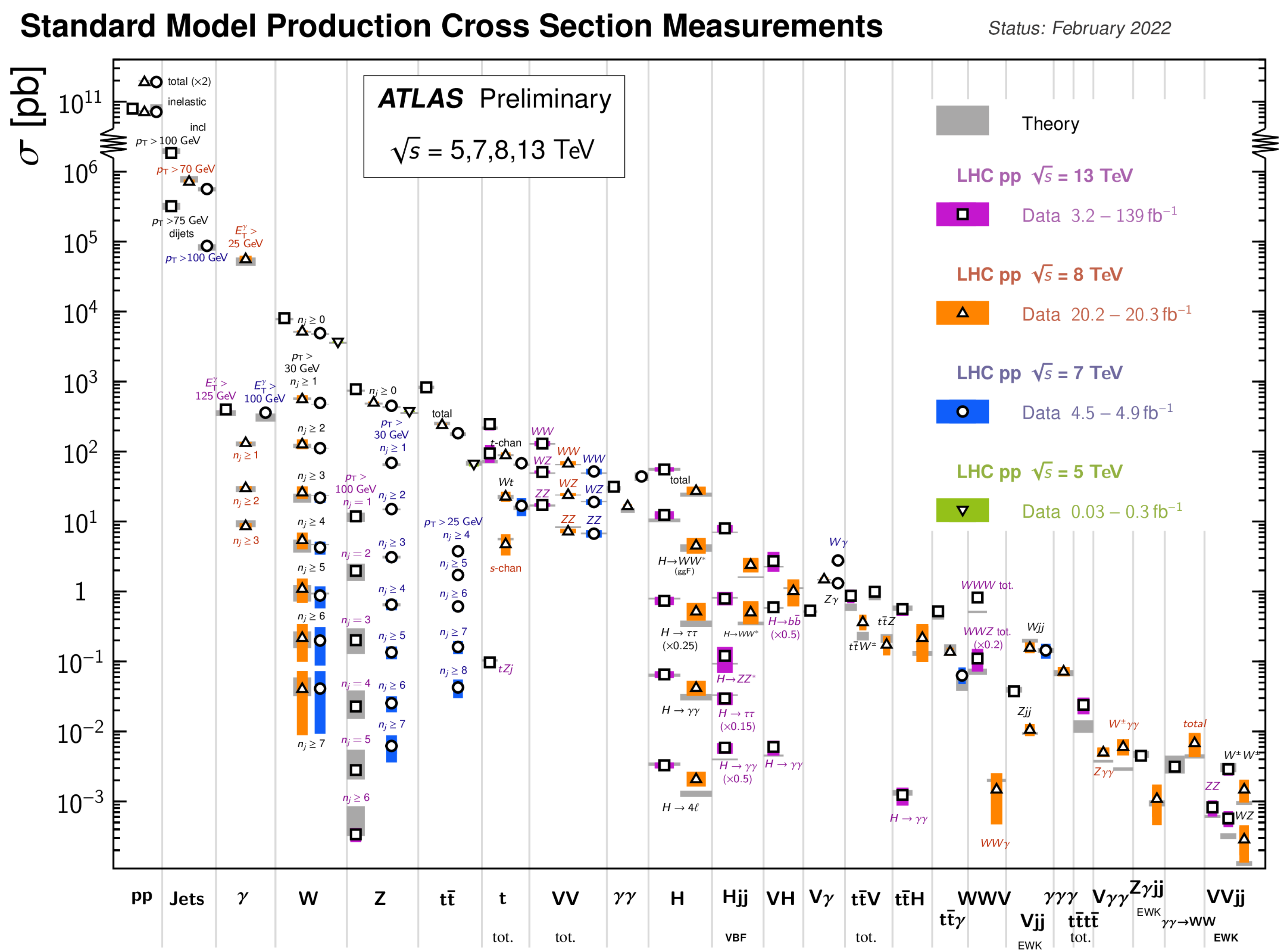
Natural to take the powerful search program at the LHC…..and displace it!



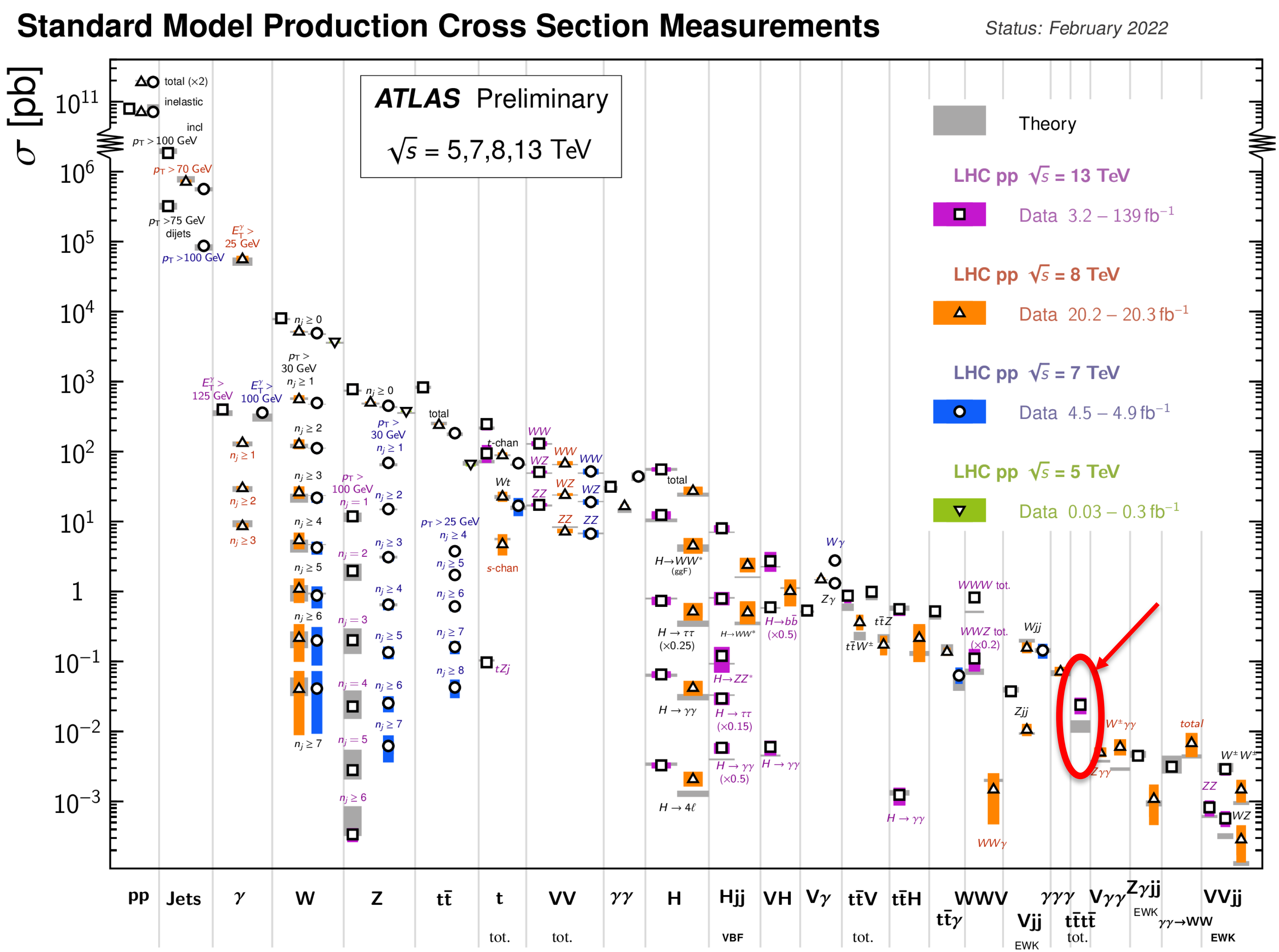
*Much more detail in **Emily Filmer's talk and Hitarthi Pandya's poster for details***

PV = Primary Vertex
DV = Displaced Vertex
LLP = Long-lived Particle
MET = Missing Transverse Momentum

Standard Model Summary



Standard Model Summary

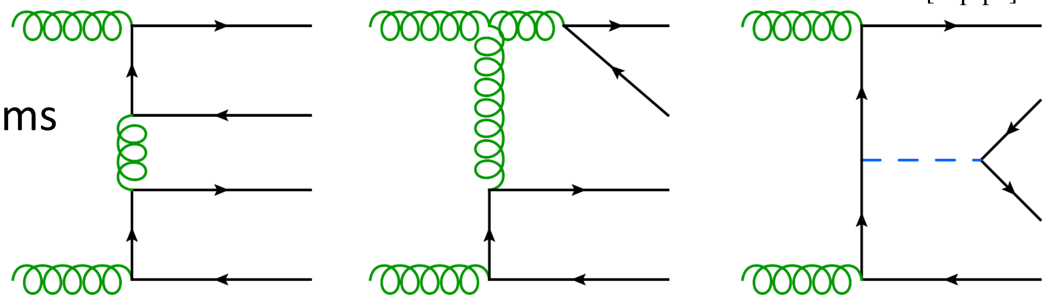


The Four Tops

$t\bar{t}t\bar{t}$ predictions

arXiv:1611.05032 [hep-ph]

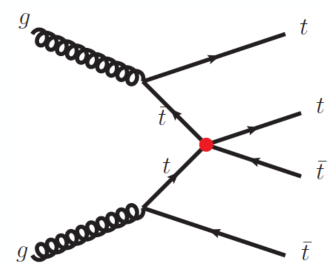
- *Very complicated process*
  - at LO 72 gg+12 qq’ initiated diagrams



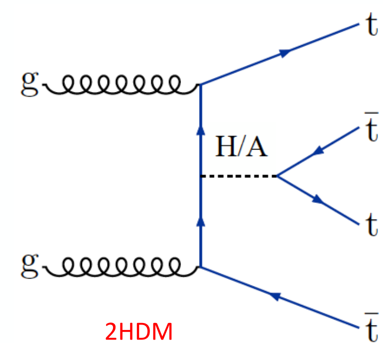
Leading: $O(\alpha_S^4)$

Sub-Leading: $O(\alpha_S^2 y_t^4)$, $O(\alpha_S^2\alpha^2)$

- Sensitive to top-Yukawa coupling (y_t)
  - non-SM value can dramatically change the production via off-shell Higgs



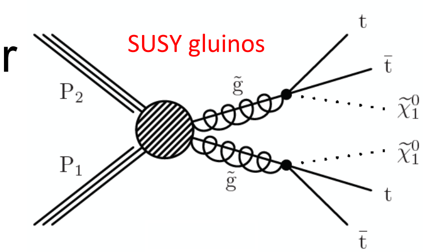
Four-fermion contact interaction



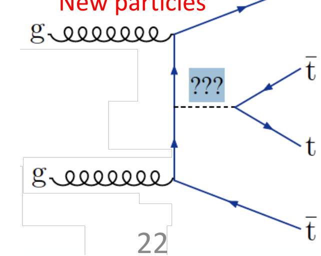
2HDM scalar/pseudoscalar

- Extremely high energy scale production makes it naturally sensitive to many BSM physics models
  - EFTs, incl four-fermion contact interaction
  - Higgs physics: 2HDM scalar/ pseudoscalar
  - SUSY: gluinos, sgluons
  - New particles coupling to top quark

SUSY gluinos



New particles



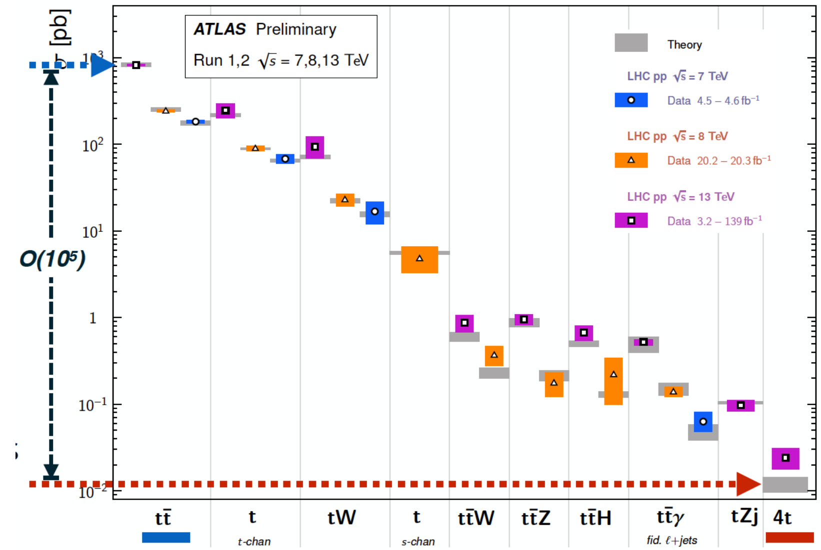
$t\bar{t}t\bar{t}$ production

Tiny cross section in SM.

σ NLO(tttt) = 11.97 fb at NLO QCD + NLO QED at 13 TeV

O(100M) tt events

O(1k) tt tt events

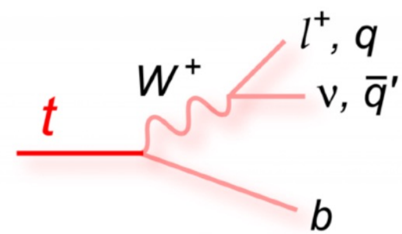


Signatures:

The t→Wb decay means the detector signature is defined by:

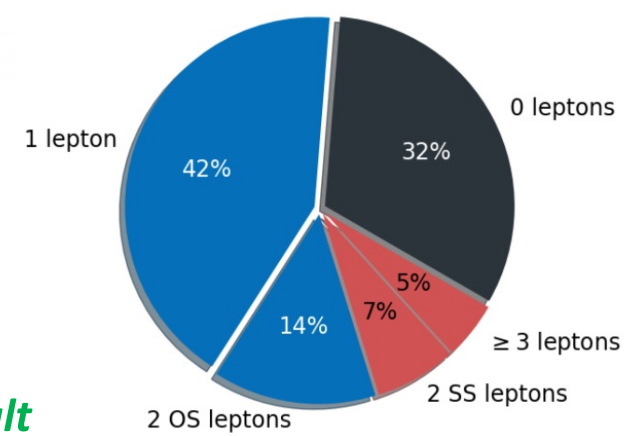
○ The presence of several (up to 4) b-quarks

○ The decays of the W bosons.



1ℓ/2ℓOS: 1ℓ (42%) / **2ℓOS** (14%)

○ Dominant branching fraction, but large irreducible background from tt+jets, tt+heavy flavour jets



2ℓSS/3ℓ: 2ℓSS (7%) / **3ℓ** (5%)

○ Low branching fraction, but small background (ttW, ttZ, non-prompt leptons, charge misidentification)

○ *Most sensitive channel*

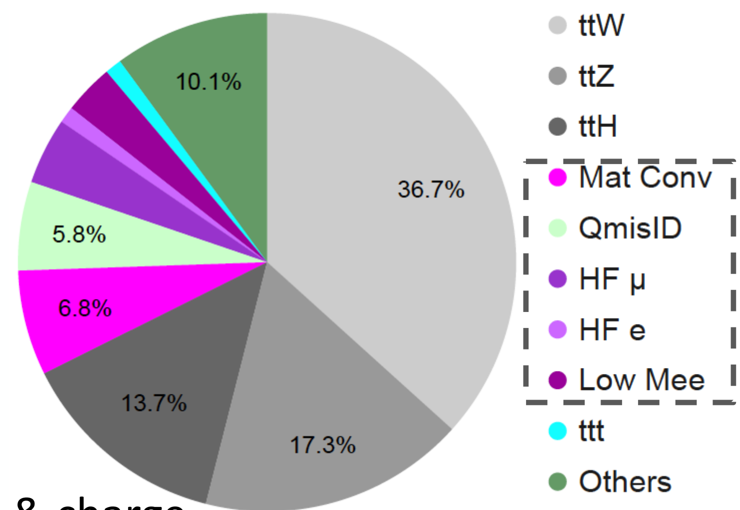
I will briefly discuss this result

$t\bar{t}t\bar{t}$: 2lSS/3l channel strategy

- Targets clean leptonic signatures where at least 2 W bosons decay leptonically
- Selection requirements:
  - ○ 2 same-sign leptons *or* 3 leptons (ℓ=e,μ)
  - ○ **≥ 6 jets** (pT > 25 GeV)
  - ○ **≥ 2 b-tagged jets** (77% efficiency w.p.)
  - ○ H_T > 500 GeV

$$H_T = \sum^{leptons} P_T + \sum^{jets} P_T$$

Backgrounds:



- Reducible backgrounds: fake/non-prompt leptons & charge misidentified leptons
  - electrons(muons) from heavy-flavour decay, HF e/μ
  - Electrons from γ conversions in detector, Mat Conv
  - a virtual photon leading to an e^+e^- pair, Low M_{ee}
- Charge mis-assignment, **Q mis-ID (5.8%)**:
  - Relevant for the 2lSS channel (mostly for electrons)

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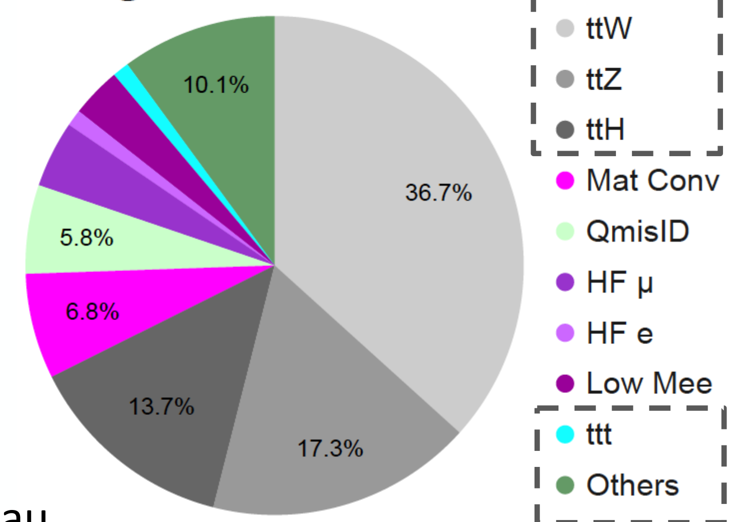
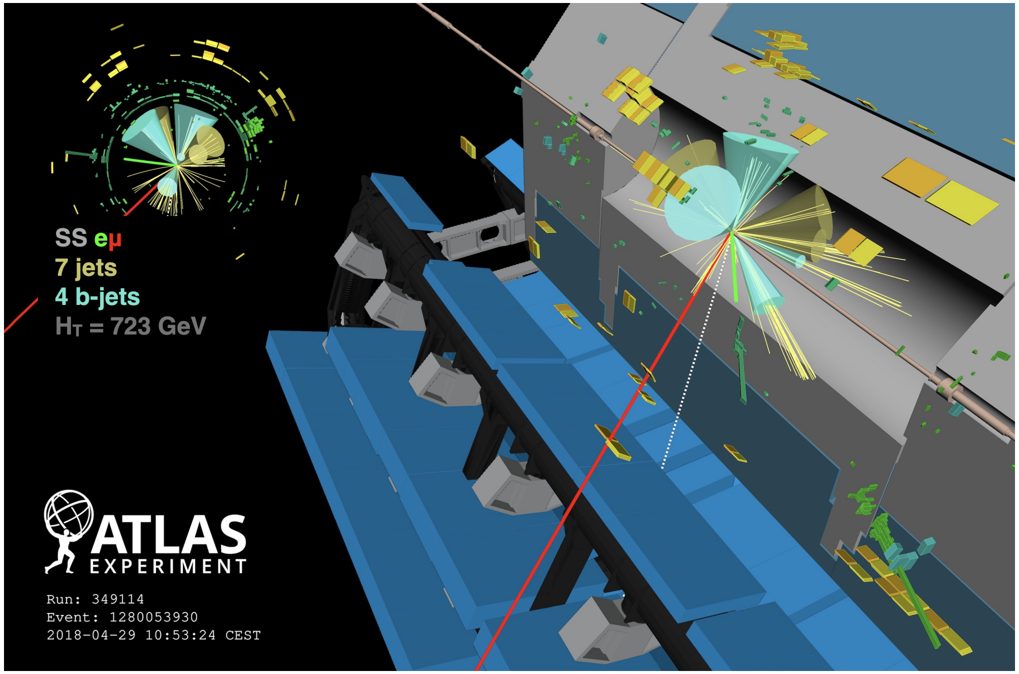


- ○ Irreducible backgrounds: Leptons from W, Z and tau
  - ○ **ttW (36.7%)**, **ttZ (17.3%)**, and **ttH (13.7%)**
    - ○ Processes with SS and multi-lepton+jets (with additional light and b-tagged jets)
  - ○ **Smaller backgrounds: (10% Others) + ttt** Diboson, triboson, VH+jets, ttWW, tWZ, tZq

- ○ Evaluated using MC normalised to SM cross section, except ttW which is floating in the fit

4-top observation



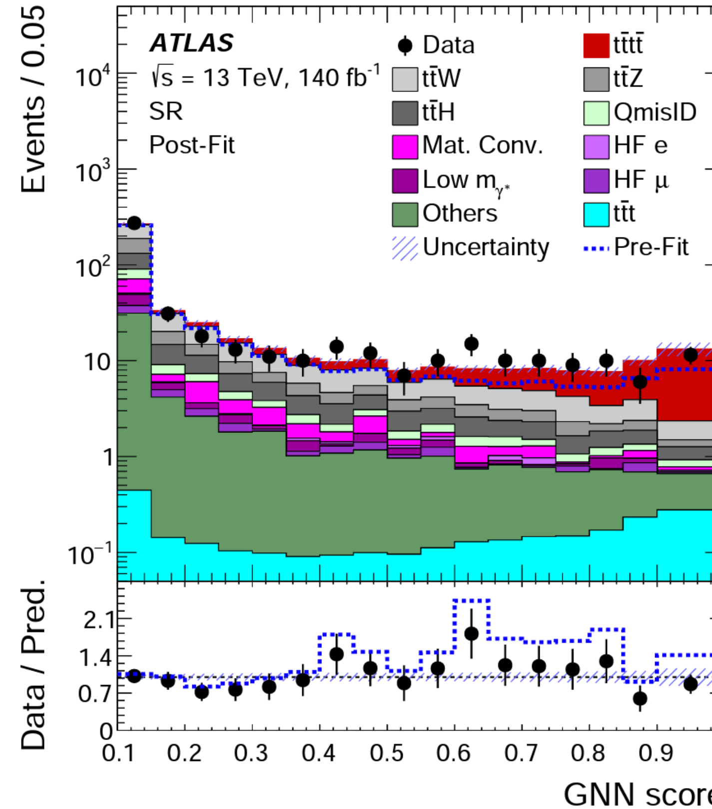
We measured events containing four top quarks for the first time – 2x larger than SM prediction

$$\mu = 1.9 \pm 0.4(\text{stat})\,^{+0.7}_{-0.4}(\text{syst}) = 1.9\,^{+0.8}_{-0.5}.$$

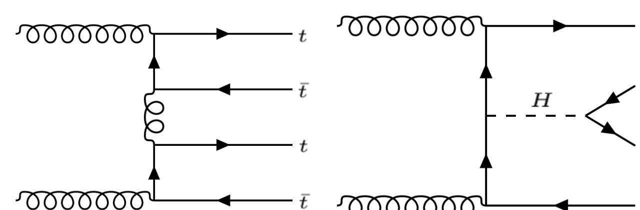
$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})\,^{+4.6}_{-3.4}(\text{syst})\text{ fb} = 22.5\,^{+6.6}_{-5.5}\text{ fb}.$$

Strong 6.1σ (4.3σ expected) discovery

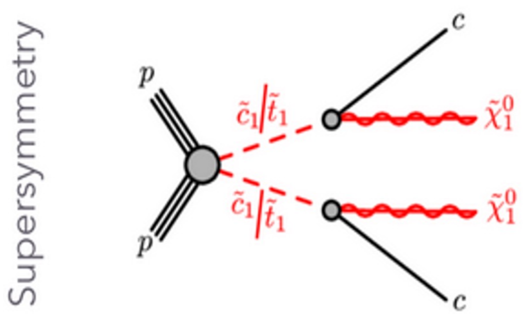
Eur. Phys. J. C 83 (2023) 496



Complex process, potentially sensitive to new physics interactions via new particles and/or forces

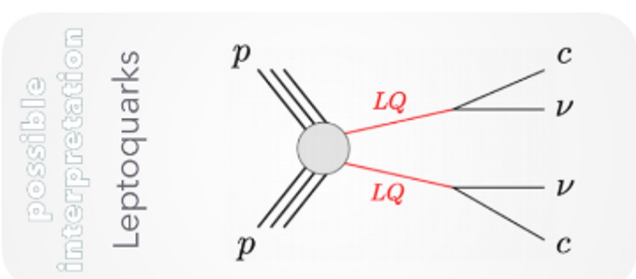


cc+MET and tc+MET

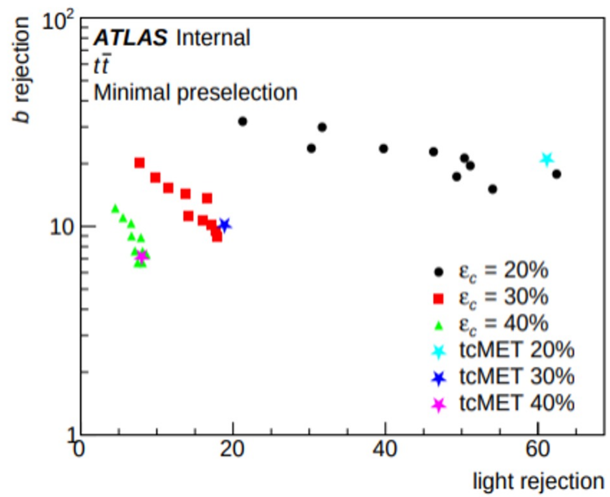


Search for top/charm squarks decaying to charm + neutralinos using full Run 2 dataset

- Also performing a Leptoquark reinterpretation search

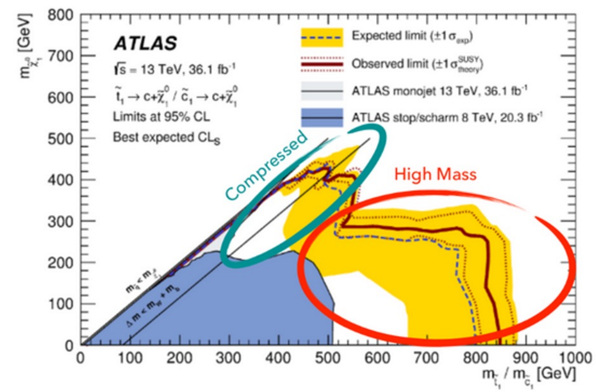


Using novel charm-tagging method



Use 20% tagging efficiency working point

- Most effective and efficient working point - background rejection is very powerful



Two strategies for different **Δ**m(squark, neutralino)

E_T^{miss} significance selection for high m(sq)

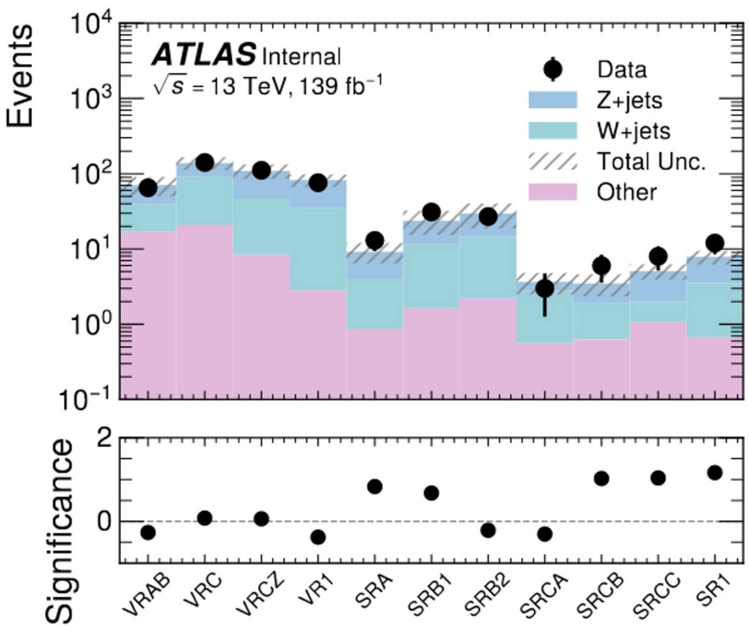
- Parameterizing how important the missing energy is while accounting for detector resolution effects

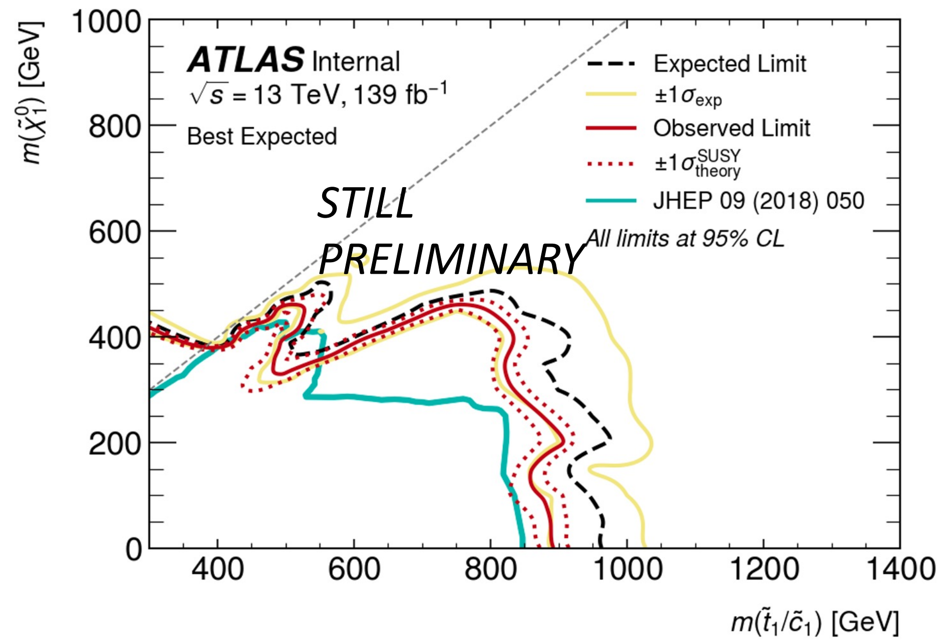
Recursive Jigsaw Reconstruction based selections for low Δm (compressed) signals

- Reconstruction of assumed decay with resolution of ambiguities based on well-founded physical assumptions

cc+MET and tc+MET

Yields in signal regions consistent with SM-only hypothesis





Details on tc+MET in Tristan Ruggeri's talk

Exclusion contours extended significantly from early Run 2 dataset results

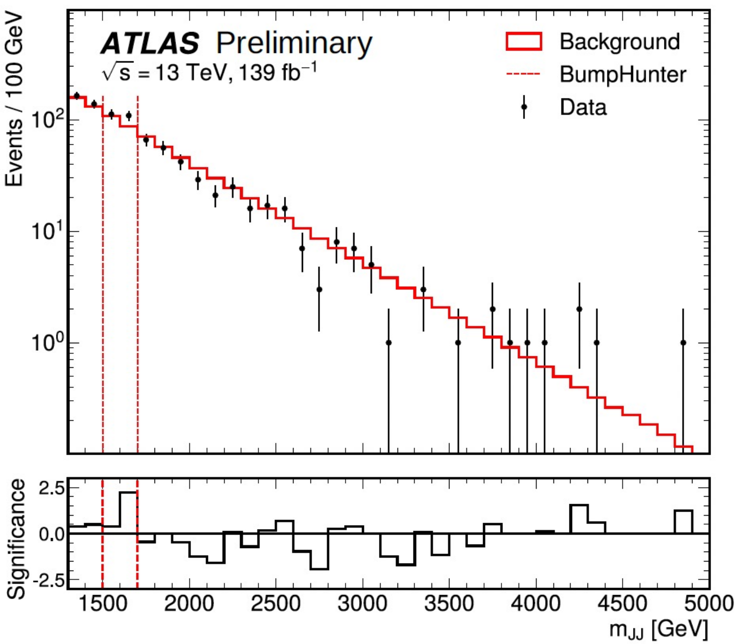
Future work: Pursuing statistical combination with similar tc+MET analysis. Both close to becoming public!

Search for Strongly interacting Dark Sector

Search for dark hadrons produced via Z' and decaying promptly in visible SM particles

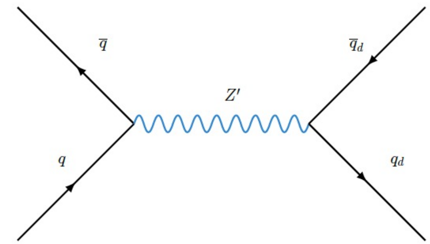
Signature of wider jets with larger track multiplicity than SM jets (hadronization first in dark sector, then in SM)

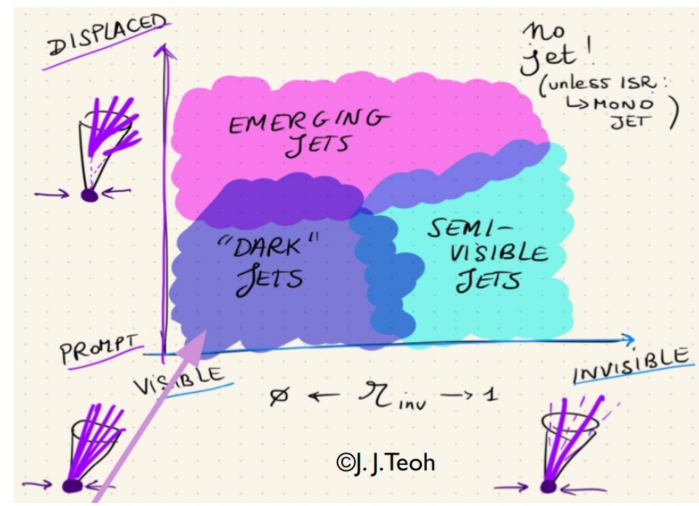
ATLAS-CONF-2023-047



Look for bump in mass spectrum of two large-R & high-multiplicity jets

No excess observed





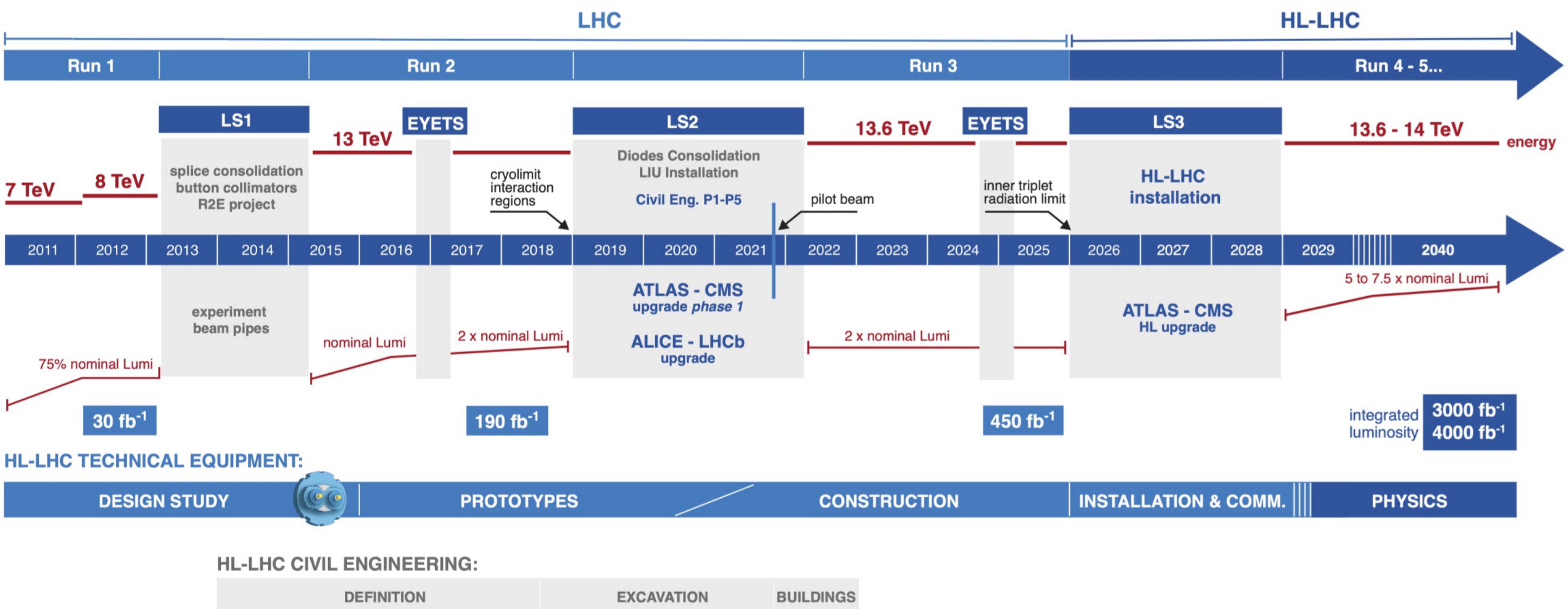
Culture Break

ATLAS EXPERIMENT

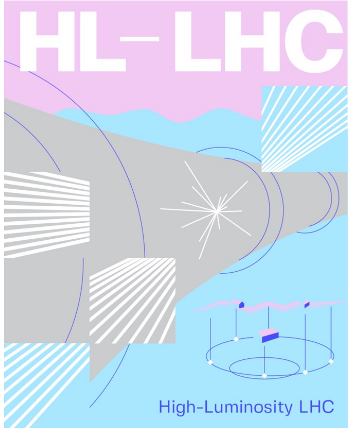
I'm from Bolton in Northern England whose history dates back almost 900 years.

During the English civil war Bolton was known as the "Geneva of the North".
According to a recent survey of the British Association for the Advancement of Science, Boltonians are the friendliest people in Britain.

LHC / HL-LHC Plan



- LHC Run1 and Run 2 have been completed
  - Data analyses in full progress
- LS2 (Long Shutdown 2019-2021) is complete
  - ATLAS phase I upgrade done!
- LS3 (Long Shutdown 2026 -2028) after Run 3
  - LHC major upgrade to HL-LHC (High Luminosity LHC)
  - ATLAS Phase II upgrade
- ***Run 4 and beyond (2029-): The future of particle physics!***



HL-LHC Upgrade

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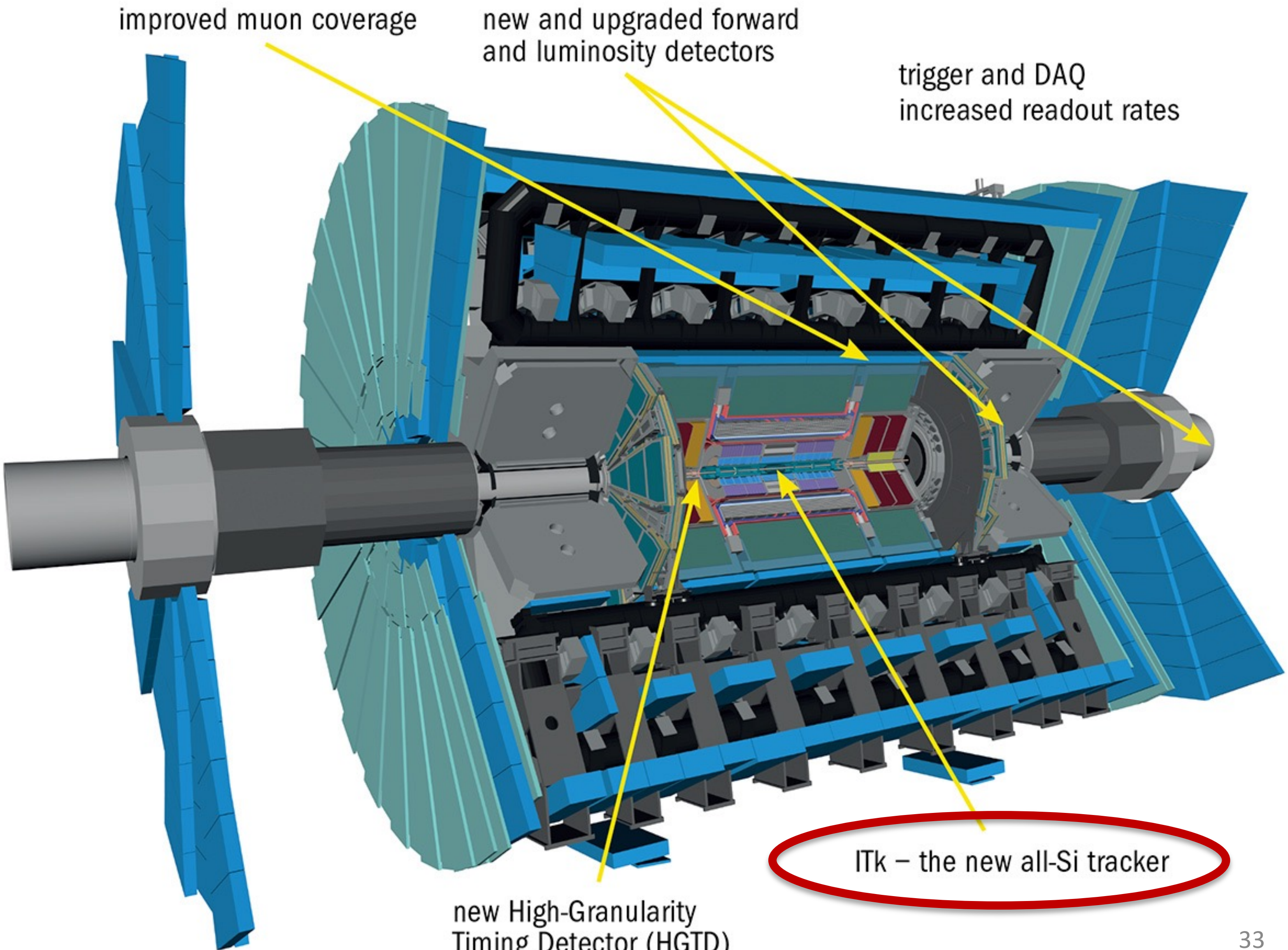
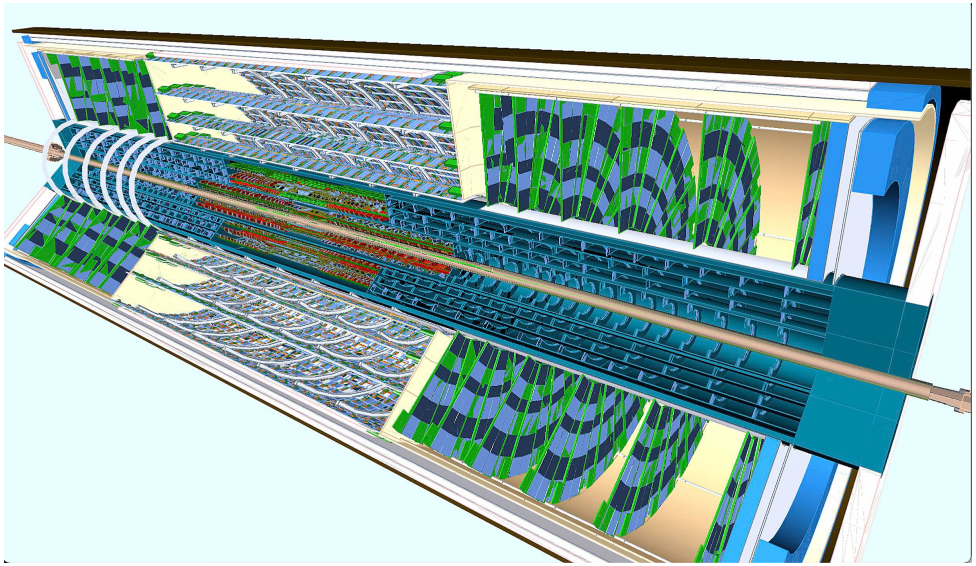
HL-LHC Upgrade

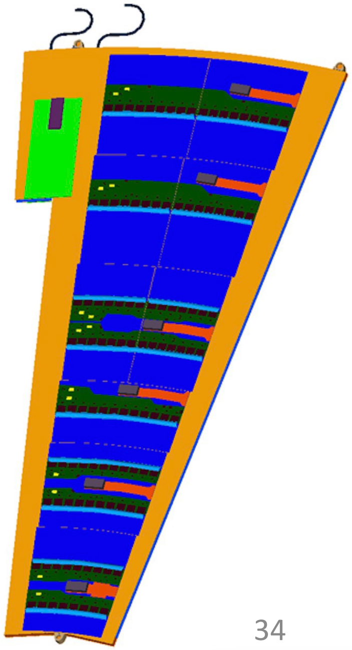


ITK Strips



- Strip detector is comprised of two sections: barrel and the end-cap
- Redesign of inner tracker, extending geometry, sensitivity to larger $\Delta\eta$
- New readout chips (ABCstar) and increased strip granularity

- **End-caps comprised of petals**
- 32 petals comprise a single end-cap disk.
- Each consists of six modules denoted R0 – R5
- Melbourne to build R1 and R4 modules
  - 122 R1 (at expected 85% yields resulting in 108 modules required for installation)
  - 261 R4 (at expected 79% yields resulting in 216 modules required for installation)



ATLAS ITk

Building next generation detectors: ITk

@ TRIUMF

Building and testing an all-new silicon particle detector

@ UBC

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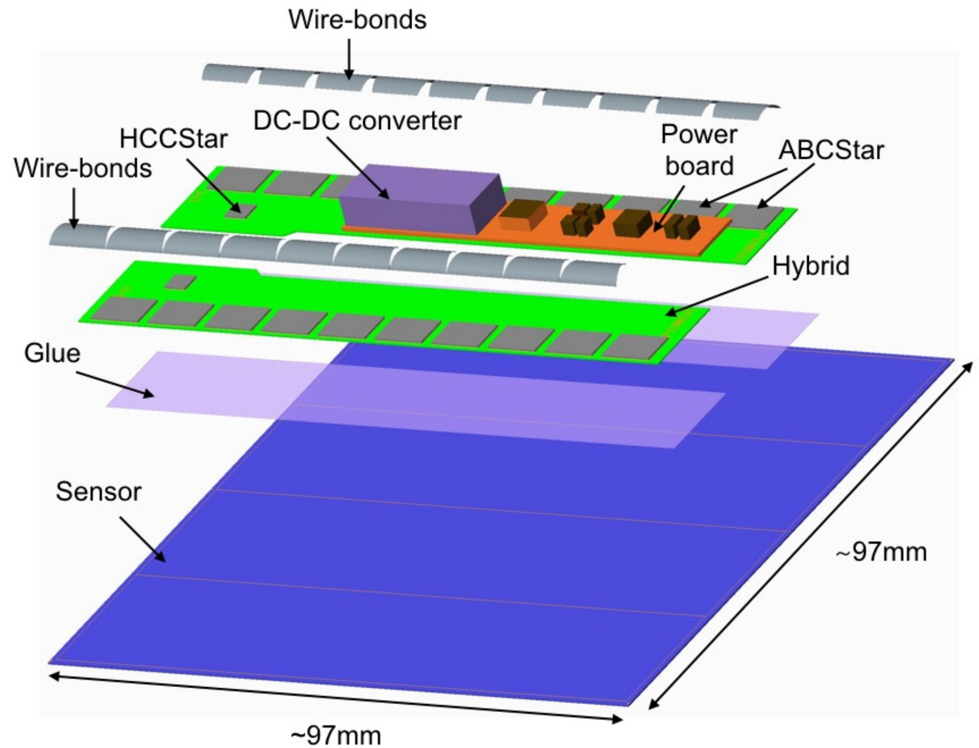
Module Assembly

- Relatively simple design, full assembly requires only a few jigs.
- Gluing performed with stencil - squeegee jig system.
- Hybrids to arrive pre-populated with ASICs (Not for prototyping).

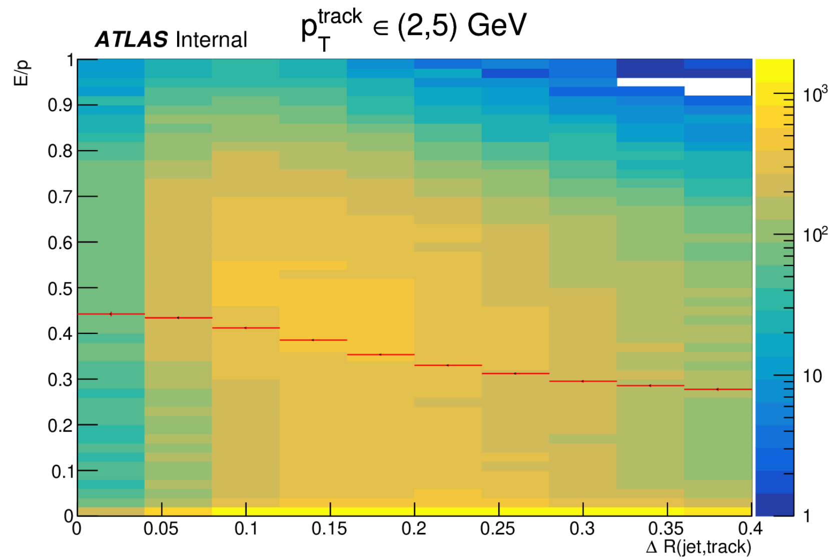


Module Testing

- All electrical testing performed with generic FPGA boards
- Electrical characterisation and thermal cycling to be performed at Adelaide.
- Cold-box for thermal cycling installed in Adelaide and ready.
- Module received from CERN last week!!

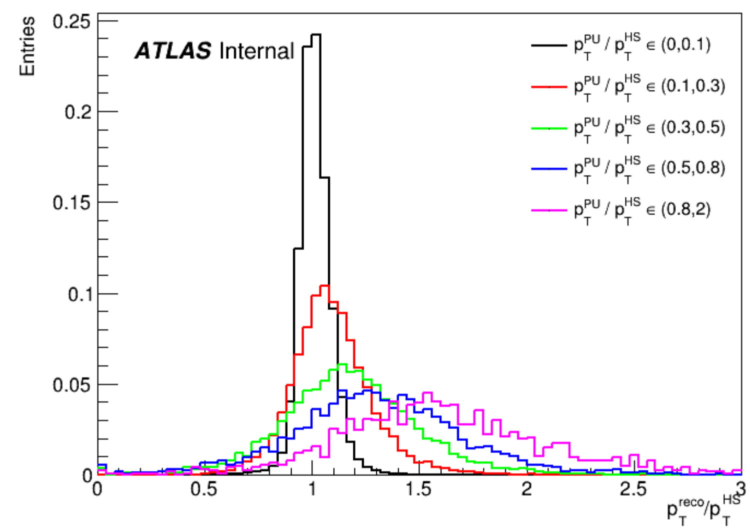
✓ Site qualification near complete.
✓ 2024 we should be making ITk-ready modules

Future jets @ HL-LHC



- In the High Luminosity era of the LHC, the collision environment will experience increased pile-up conditions, including contributions from hard-QCD pile-up.
- 200 interactions per bunch crossing

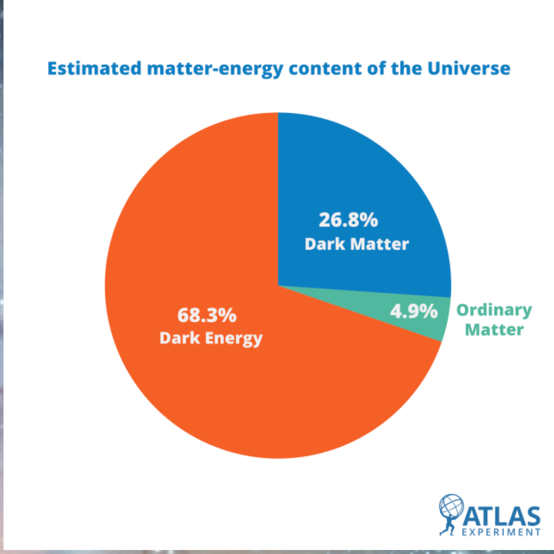
- Two ongoing threads of study relating to hadronic object reconstruction:
  1. characterisation of low-momentum charged particle behaviour in dense environments (important component of Particle Flow)
  2. identifying and correcting for overlaps between hard scatter jets and hard-QCD pile-up jets



work of Edmund Ting

Summary

- The LHC will remain the highest energy particle collider on the planet for the next 20+ years with a broad sensitivity to a wide array of potential DM candidates
- In CDMPP we are:
  - playing our role in the upgrade of the inner tracker in preparation for HL-LHC
  - improving jets and missing transverse momentum performance
  - leading analyses to search for invisibles with heavy flavour-tagged jets and multiple top quarks
  - developing new analysis techniques
  - developing new trigger ideas and contributing to computing

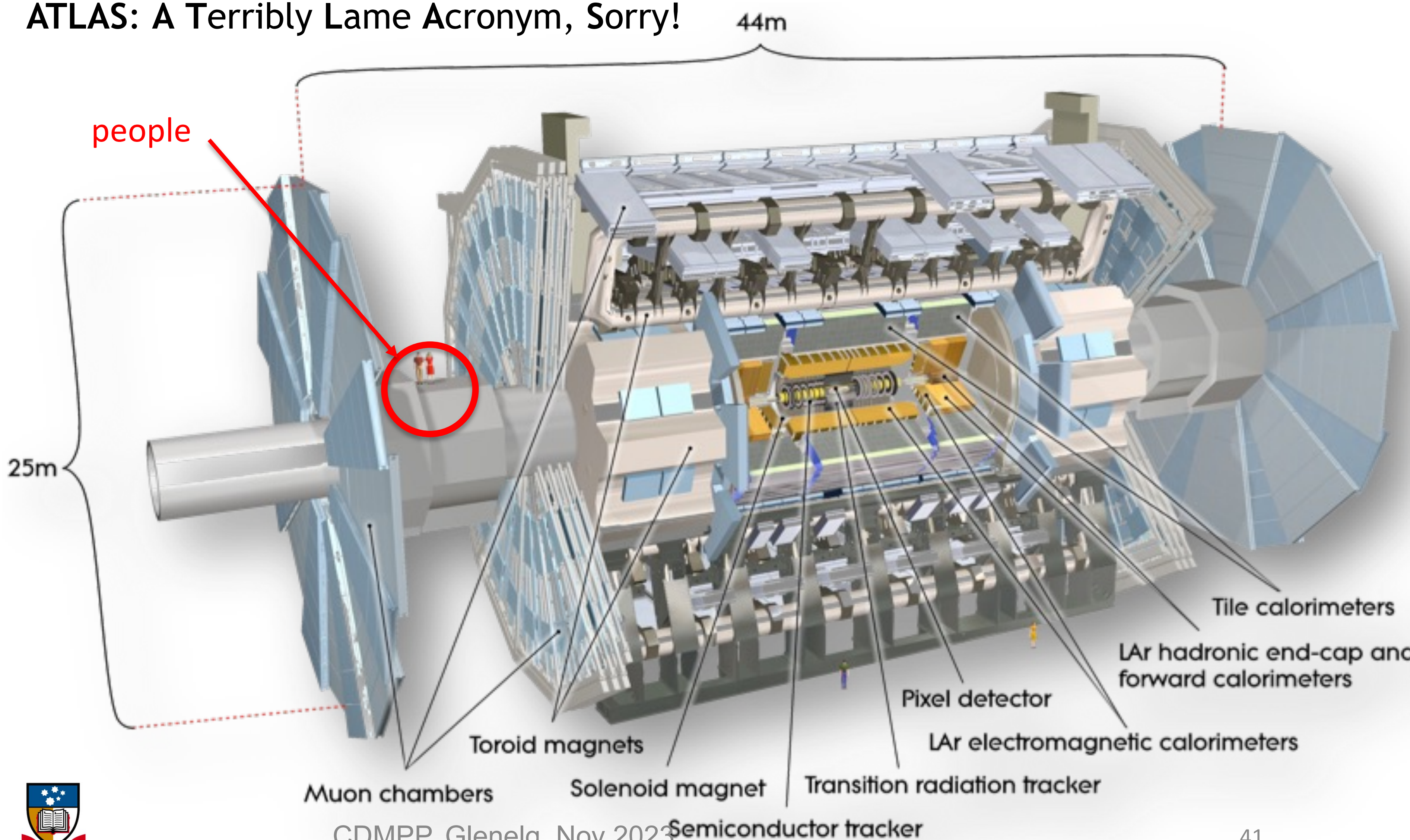


LHC and ATLAS: a uniquely sensitive environment to produce and measure Dark Matter.

More material

ATLAS Experiment

ATLAS: A Terribly Lame Acronym, Sorry!



CDMPP Roles in ATLAS

Albert Kong – Jet ETmiss Working Group Early-data task force Contact Person Run3

Harish Potti – Early-Career Scientist Board member

Harish Potti – Exotics Working Group Derivations Contact

Edmund Ting – Jet ETmiss Working Group Derivations Contact

Tristan Ruggeri – Analysis contact on cc + MET

Paul Jackson – Recently: Executive Board, Publications Committee, Computing Speakers Committee Chair

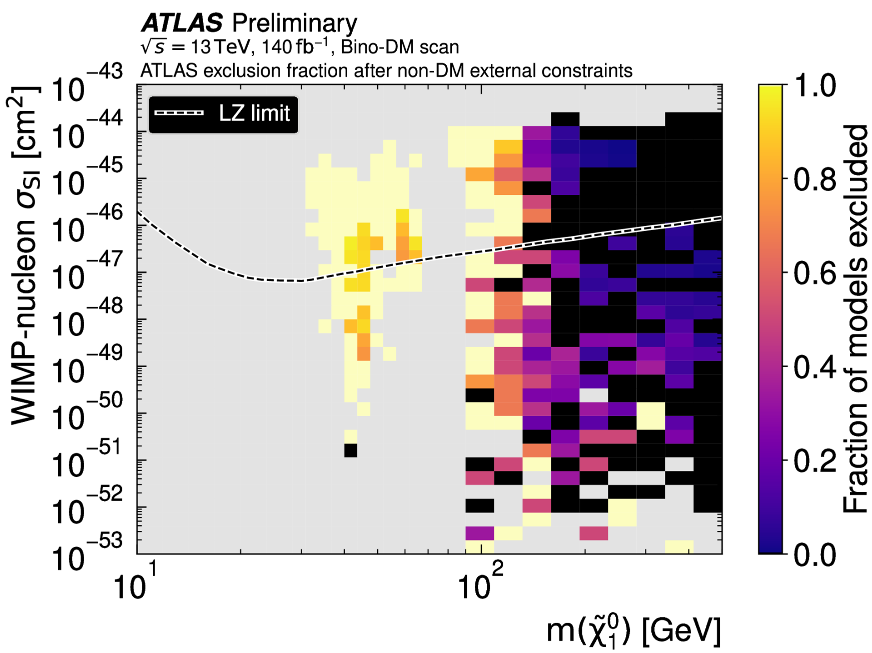
ECRs undergoing/completed qualification tasks in:

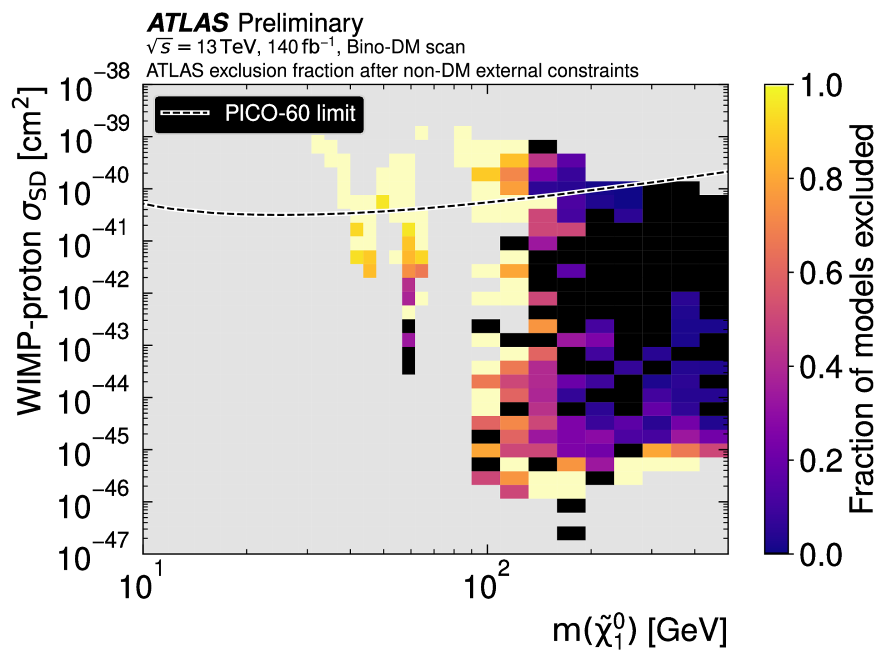
Jet ETmiss, ITK hardware, ITK software, Photon isolation, Luminosity

DM in recent SUSY searches

Paul Jackson

- Continue to produce some of the most stringent limits on Dark Matter candidates
- Colliders are the best place to search for ***laboratory produced Dark Matter***





https://atlas.cern/Updates/Physics-Briefing/SUSY-Dark-Matter
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2023-055/
ATLASHIghlights_EPS