UNIVERSITY OF LIVERPOOL

UNIVERSITY OF BIRMINGHAM

General purpose detectors:

ATLAS and CMS towards HL-LHC

Monica D'Onofrio

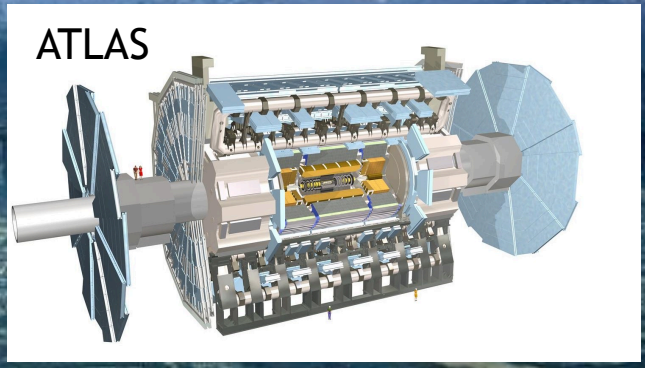
University of Liverpool

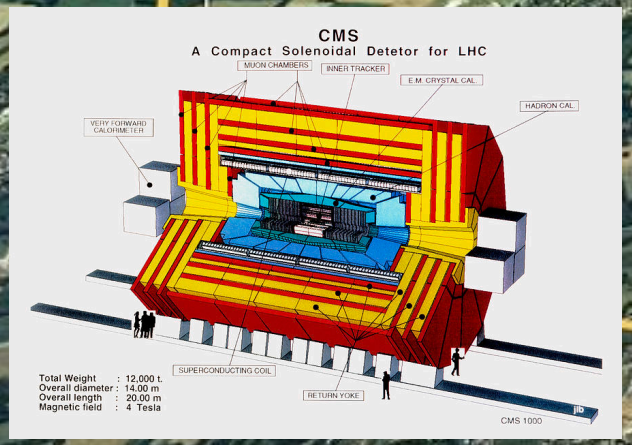
*With many thanks to Alex Tapper, Joel Goldstein, Steve McMahon, Pedro Texeira, Davide Costanzo **and** the fantastic speakers at LHCP presenting ATLAS and CMS talks - take a look if you can!!!*

PPAP Meeting, Birmingham
25/6/2024

The Large Hadron Collider

Hosts of dedicated large (LHCb, ALICE) and small (FASER, SND, MOeDAL, LHCf, TOTEM….) experiments





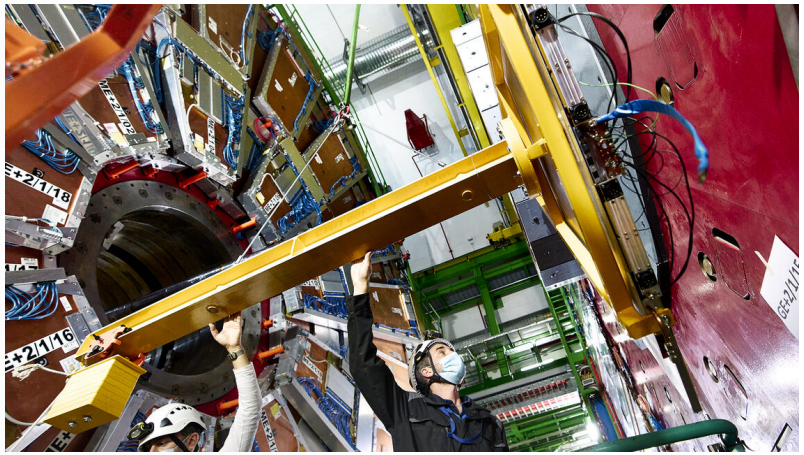
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SUISSE
FRANCE
SPS 7 km
ALICE
CMS
LHC 27 km

On since ~2010, with 7/8/13/13.6 TeV **pp** collisions (+Heavy Ion collisions), the LHC provided huge sets of data and well through its Run 3….

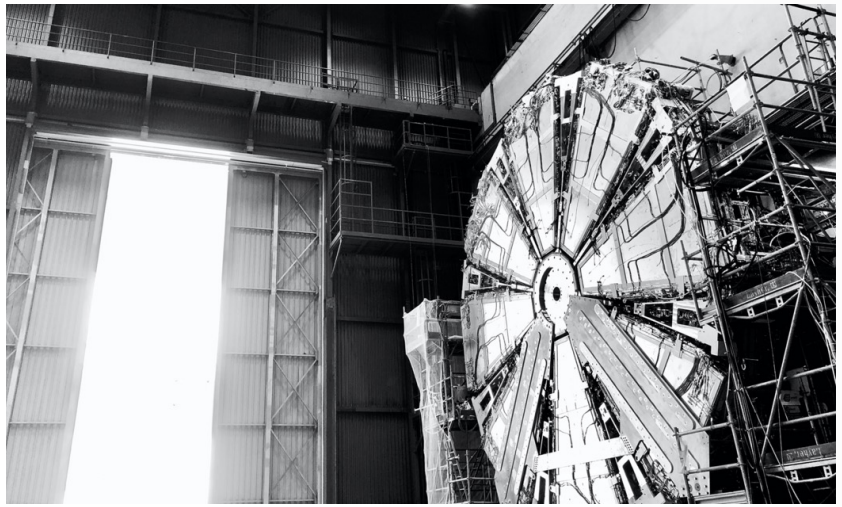
ATLAS and CMS Run 3 data

- **In Run. 3: upgrade of the accelerator**, leading to an increased centre-of-mass energy (13.6 TeV), as well as **renewed detectors** and **novel triggers**
  - Some examples of Phase 1 upgrades

CMS Gas Electron Multiplier



UK contributions:
L1 Trigger

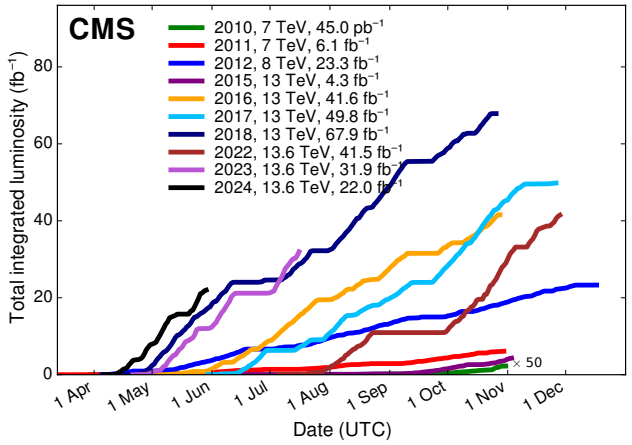


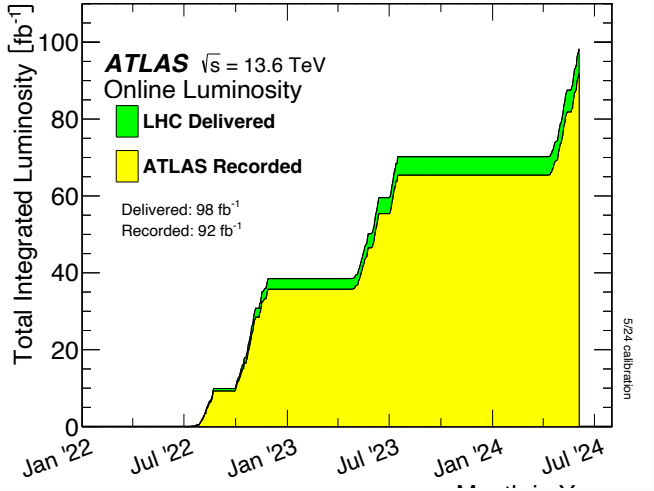
ATLAS New Small Wheel

UK contributions:
hardware, firmware and software upgrades for the L1Calo and HLT&DAQ systems

- **Huge datasets**

~ **20 fb-1** pp collected by each experiment in Run 1
~ **140 fb-1 in Run 2**



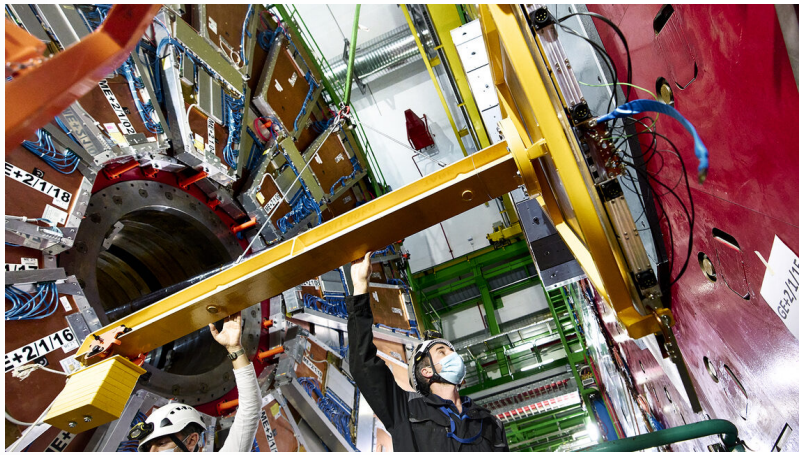


- **98 fb-1** of delivered **pp** luminosity at 13.6 TeV
- **1.91 nb-1** of **PbPb** data during 2023

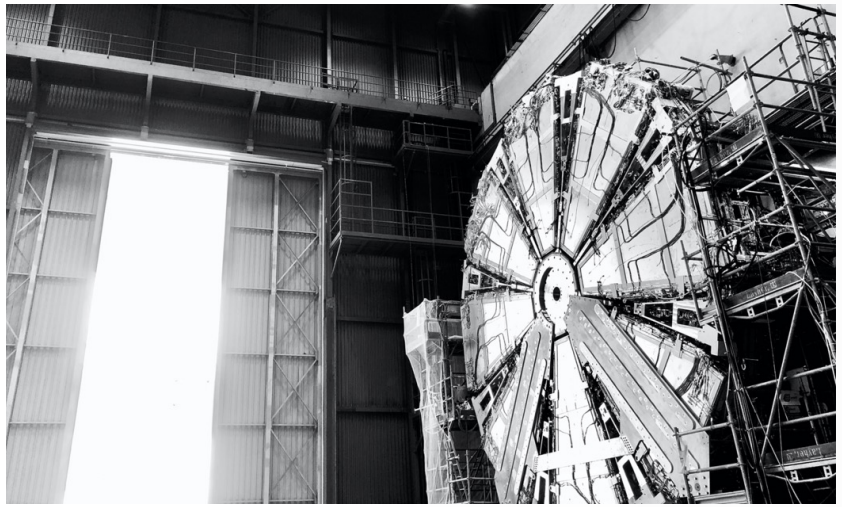
ATLAS and CMS Run 3 data

- **In Run. 3: upgrade of the accelerator**, leading to an increased centre-of-mass energy (13.6 TeV), as well as **renewed detectors** and **novel triggers**
  - Some examples of Phase 1 upgrades

CMS Gas Electron Multiplier



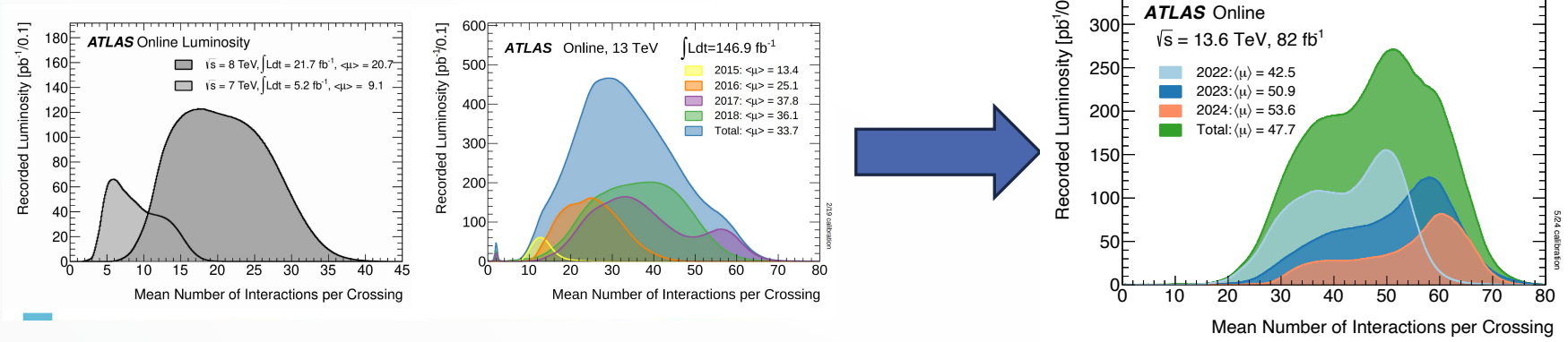
UK contributions:
L1 Trigger



ATLAS New Small Wheel

UK contributions:
hardware, firmware and software upgrades for the L1Calo and HLT&DAQ systems

- **Evolution of pile up**



LHC is currently levelling at $\mu = 63$

- ~ 95% **recording** efficiency

Collaborations

ATLAS Collaboration (status: 1 June 2024)

- 185 Institutions (253 institutes) from 42 countries + 15 Technical Associate Institutes
- 2924 Scientific authors (among which 1979 contribute to M&O share)
- 329 Qualifiers for authorship
- 1178 Physics PhD students
- 1322 Engineers and technicians
- 88 Engineering students
- 6036 Active members

UK: 15 institutes
~300 active authors

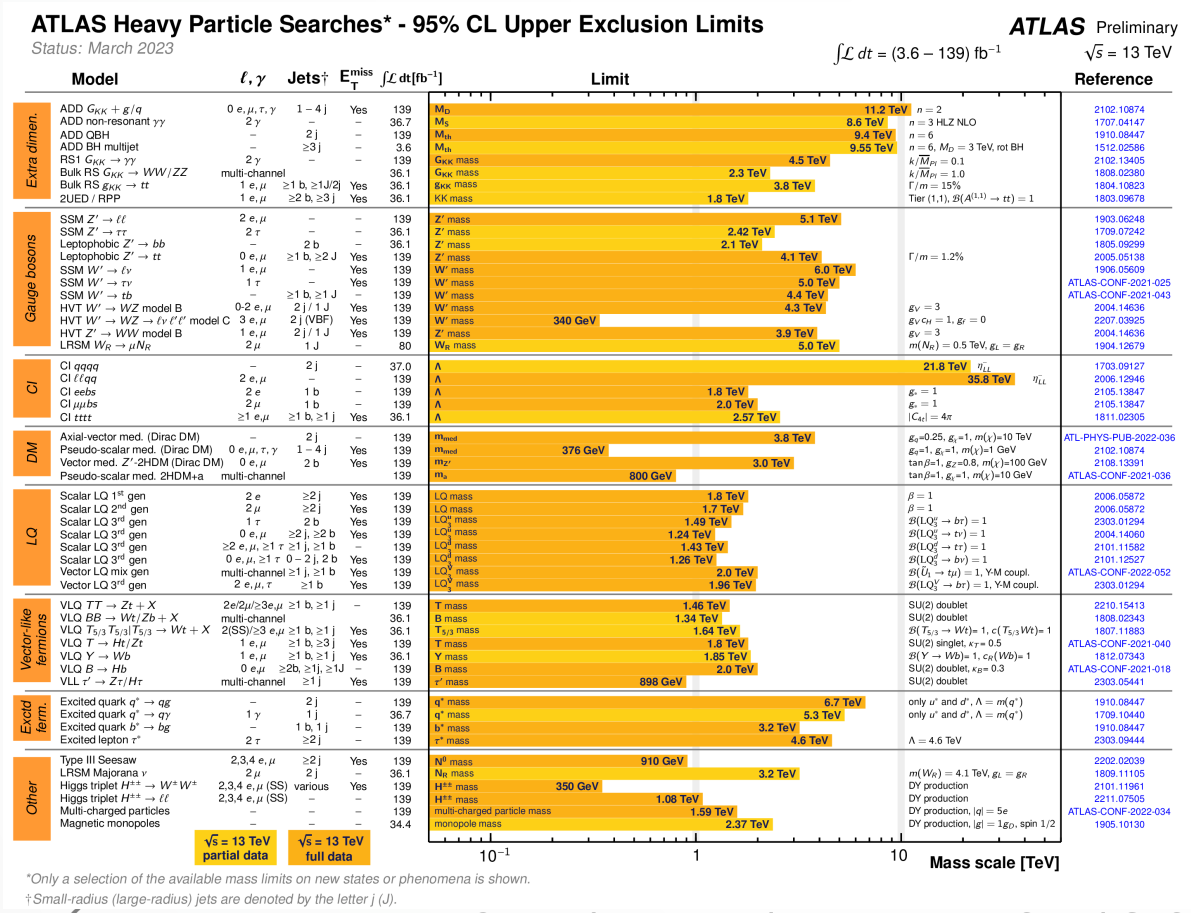
CMS Collaboration

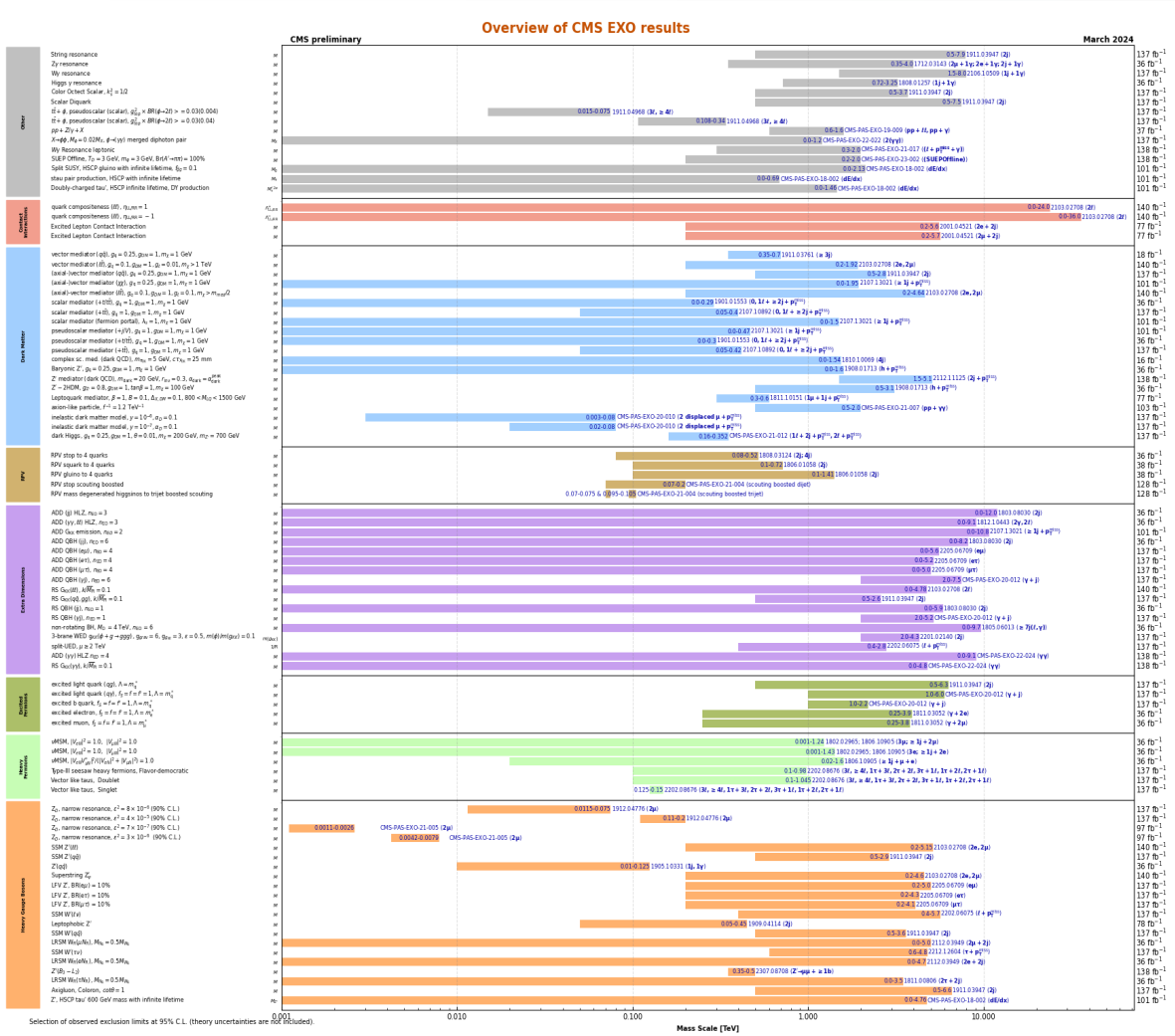
- 6300 persons including 2200 physicists & 2600 students
- 247 institutes from 57 countries and regions, and continuing to welcome new ones!

UK: 4 institutes
~100 active authors

Physics programme: the energy frontier

- A large fraction of the UK HEP community works within ATLAS or CMS
- The physics programme is also huge → usually referred to as *Energy frontier*
  - Searches for (heavy) new particles usually summarized and presented as this …

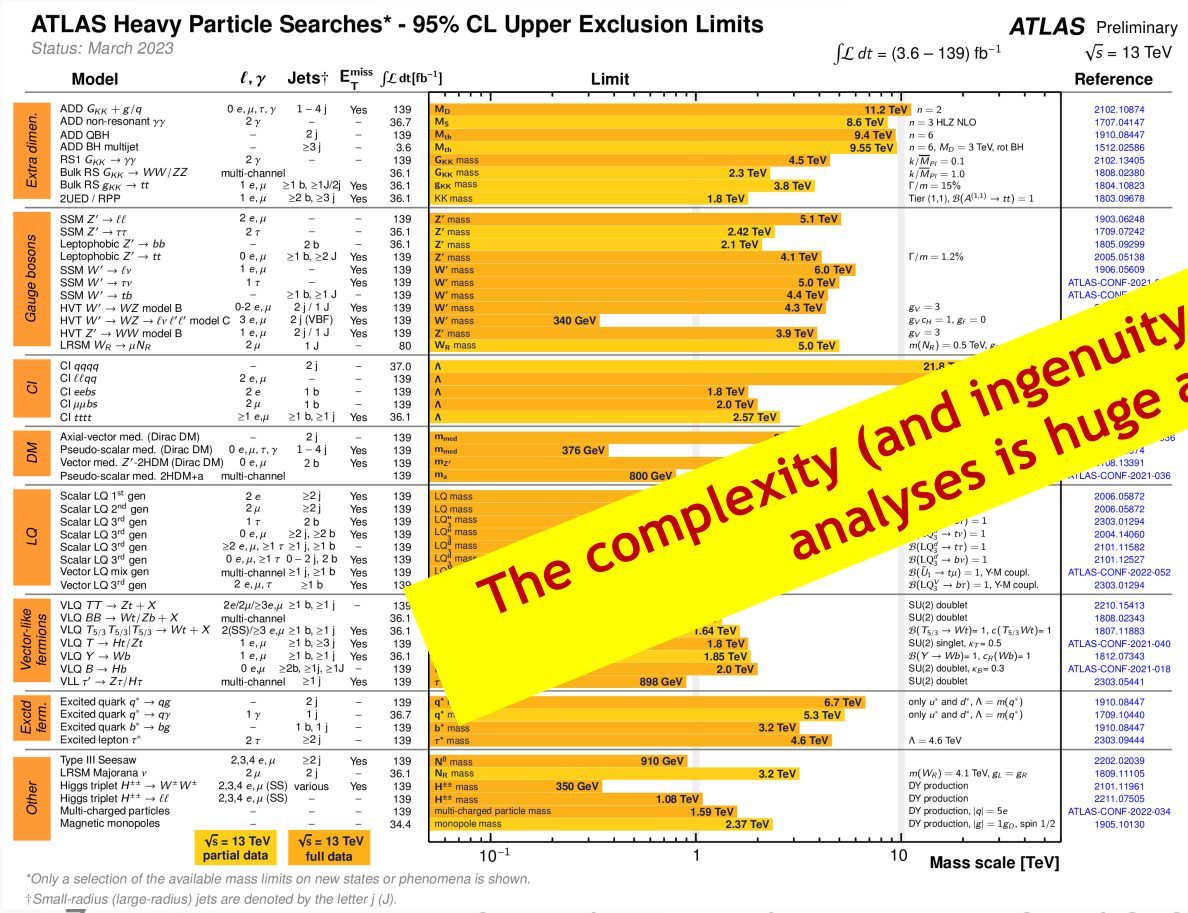




General purpose detectors: ATLAS and CMS towards HL-LHC

Physics programme: the energy frontier

- A large fraction of the UK HEP community works within ATLAS or CMS
- The physics programme is also huge → usually referred to as *Energy frontier*
  - Searches for (heavy) new particles usually summarized and presented as this …



The complexity (and ingenuity needed) behind each of these analyses is huge and often "unseen"

General purpose detectors: ATLAS and CMS towards HL-LHC

Physics programme: the energy frontier (prospects)

- A large fraction of the UK HEP community works within ATLAS or CMS
- The physics programme is also huge → usually referred to as *Energy frontier*
  - Some **HL-LHC prospect studies**, done also to understand the impact of the detectors performance

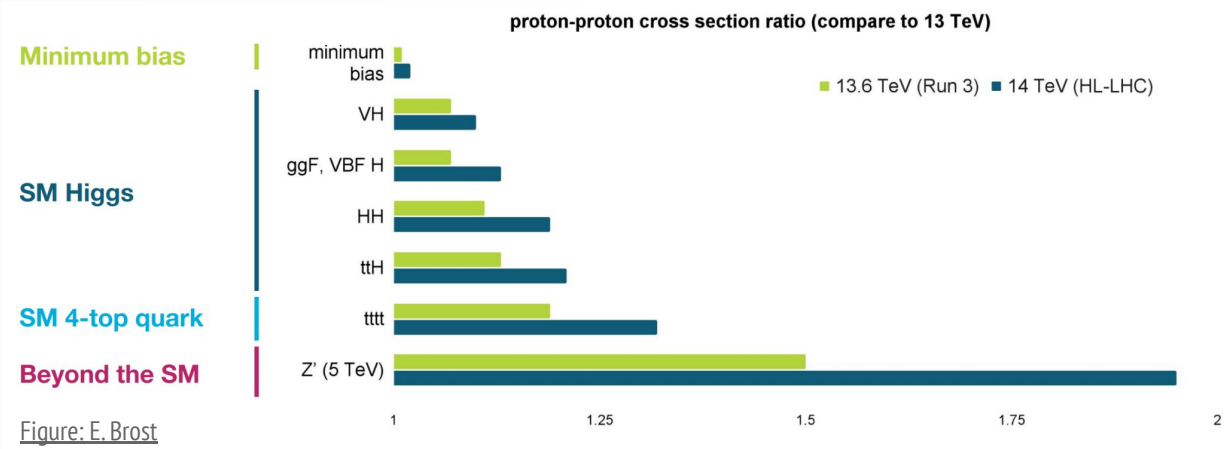
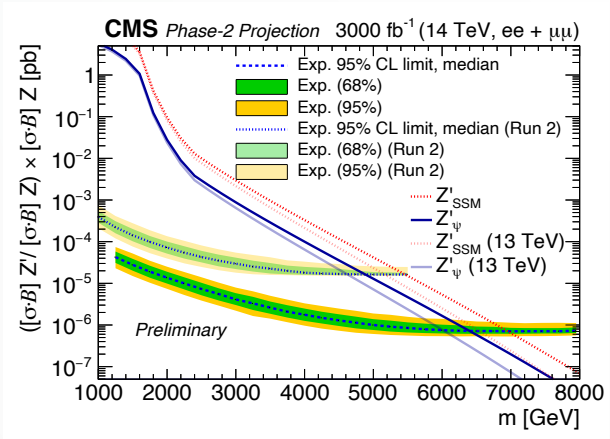
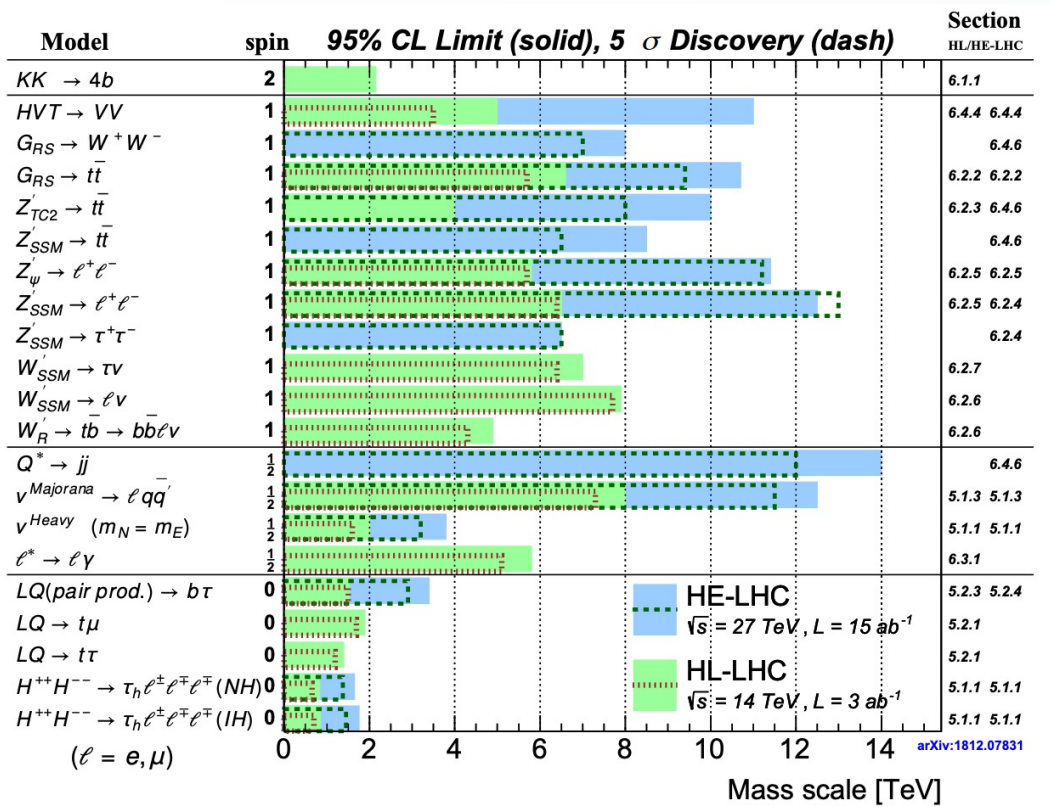


Figure: E. Brost



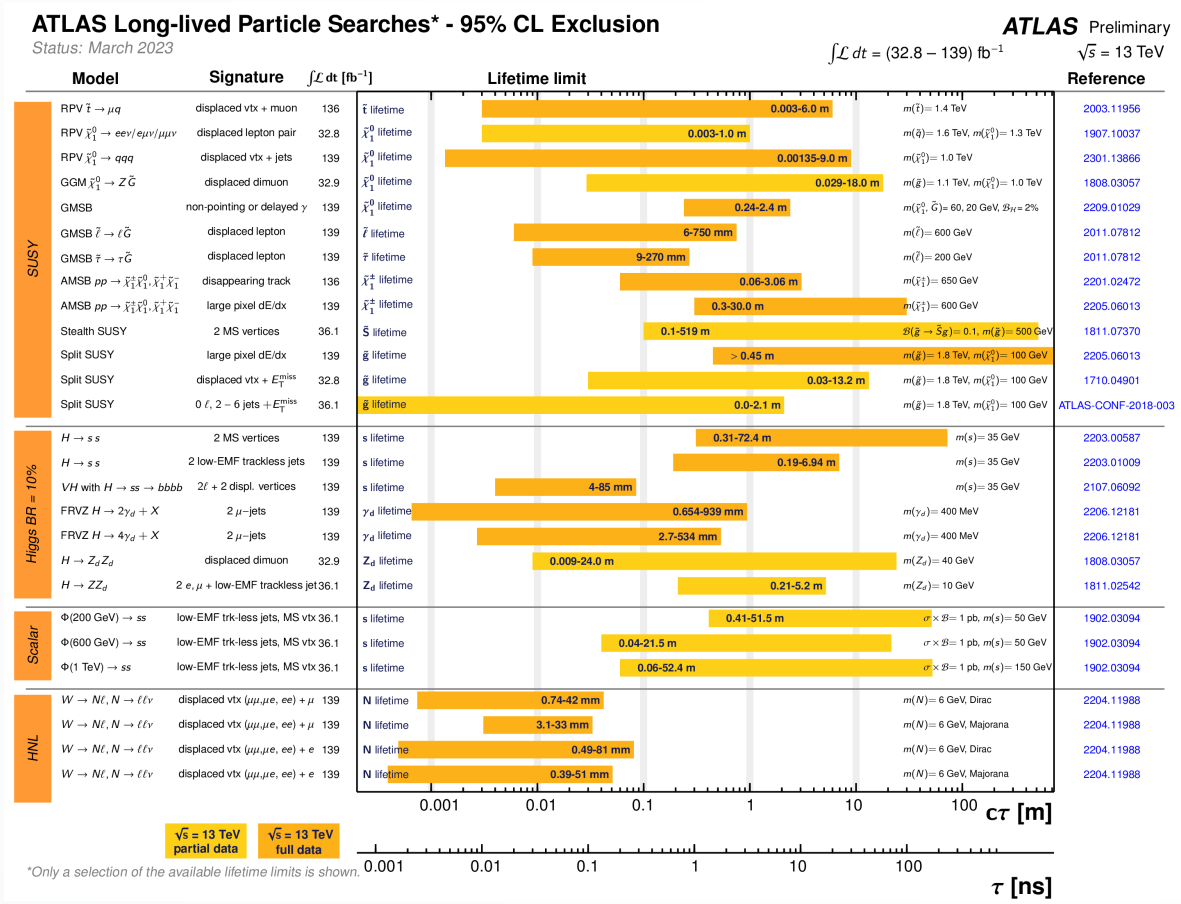
For NP, increase the present reach in mass and coupling by 20-50%

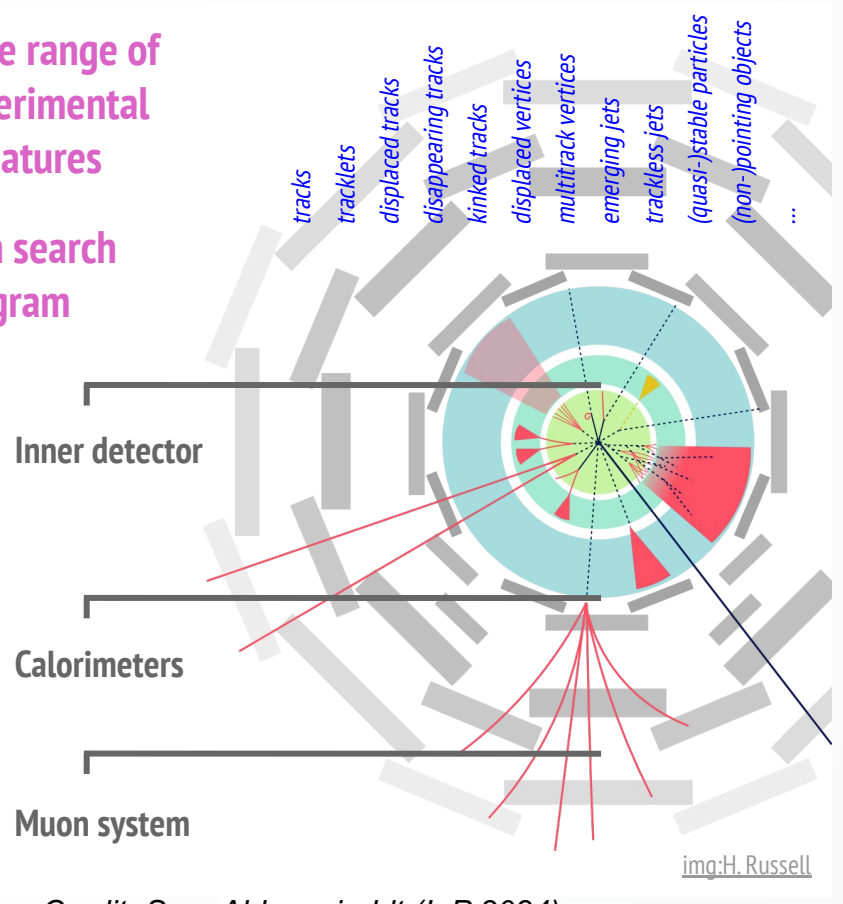


Report on the Physics at the HL-LHC, and Perspectives for the HE-LHC

Physics programme: Long-lived particles

- A large fraction of the UK HEP community works within ATLAS or CMS
- The physics programme is also huge → usually referred to as *Energy frontier*
  - Adding the (life)time dimension: **long-lived** particles (LLP), require specialized and dedicated reconstruction techniques

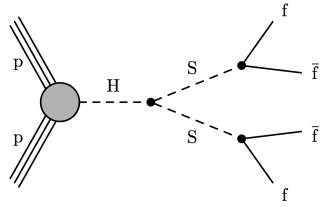


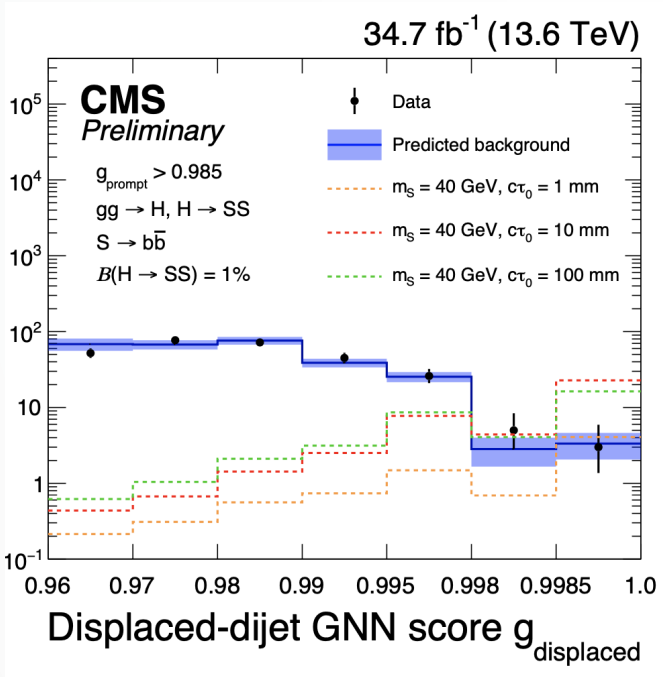


Credit: Sara Alderweireldt (IoP 2024)

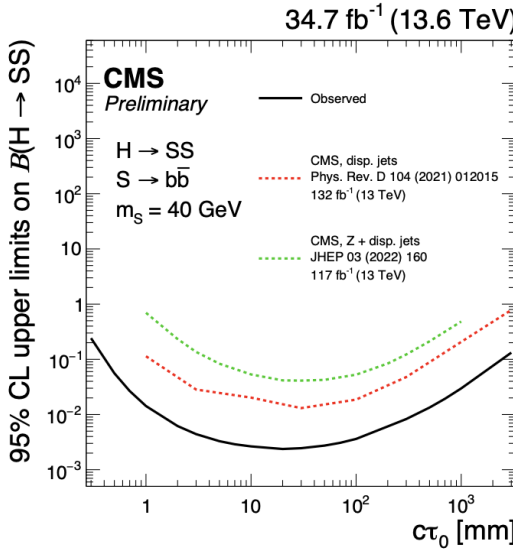
Physics programme: Long-lived particles

- A large fraction of the UK HEP community works within ATLAS or CMS
- The physics programme is also huge → usually referred to as *Energy frontier*
  - Adding the (life)time dimension: **long-lived** particles (LLP), require specialized and dedicated reconstruction techniques
  - E.g.: Higgs decaying in long-lived scalars
    - Reconstruct displaced jets using Graph NN



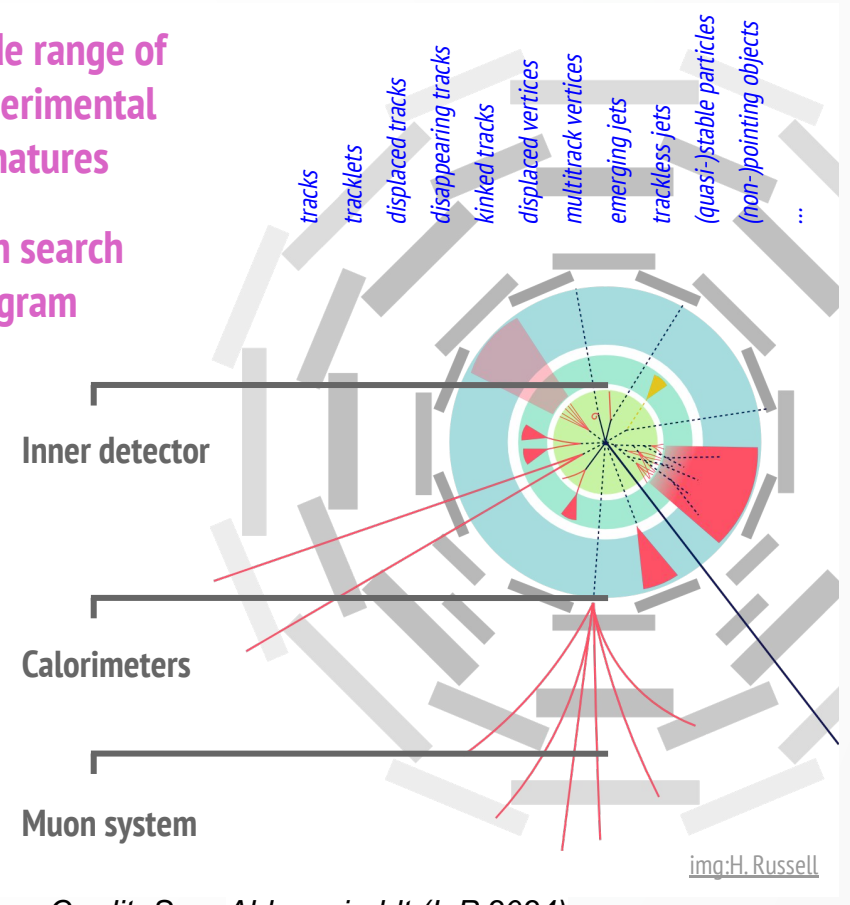


Pushing the boundaries through novel analysis techniques



Wide range of experimental signatures

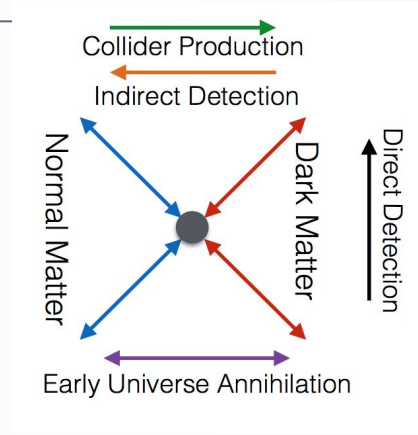
Rich search program



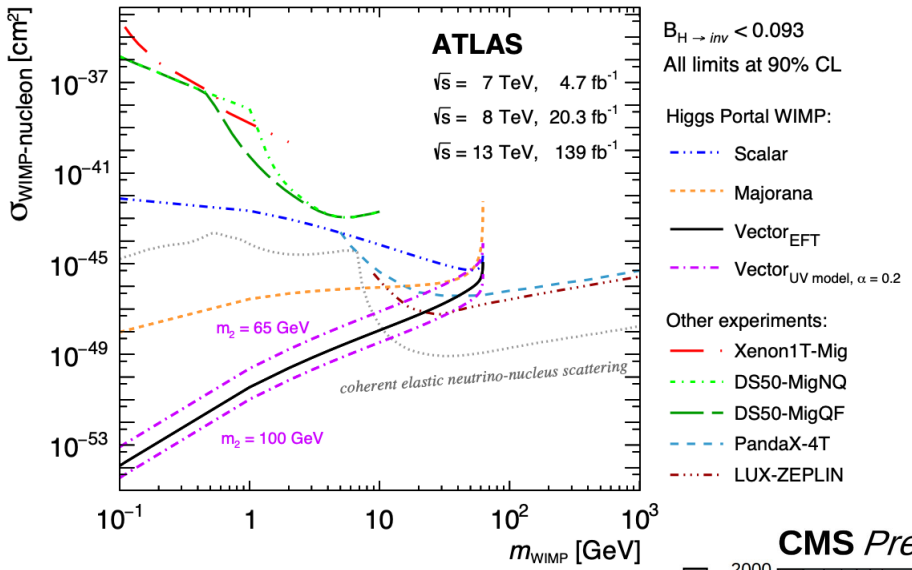
Credit: Sara Alderweireldt (IoP 2024)

Physics programme: beyond our own "definition"…

- **Dark matter** and **hidden (dark) sectors** are a key target for GPDs..



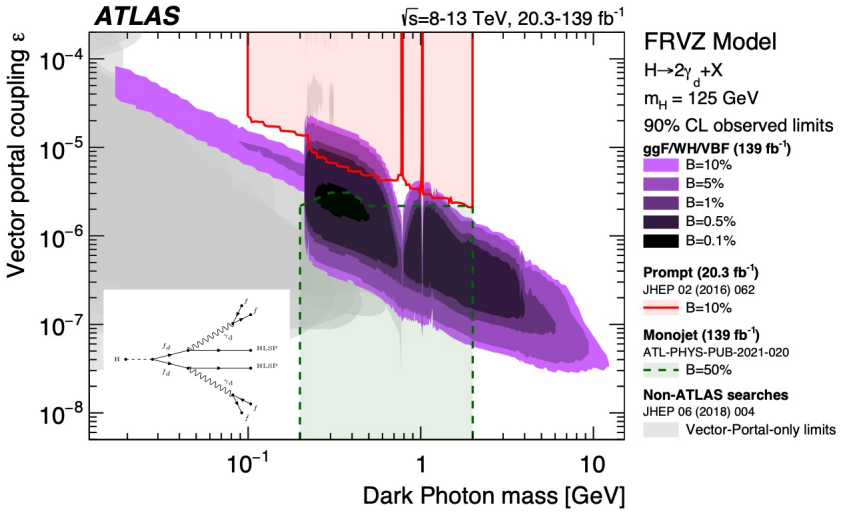
Higgs decaying in WIMP-like DM (**Higgs-portal**)



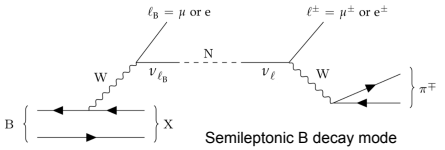
https://arxiv.org/pdf/2403.09292

See also CMS
http://arxiv.org/abs/2405.13778

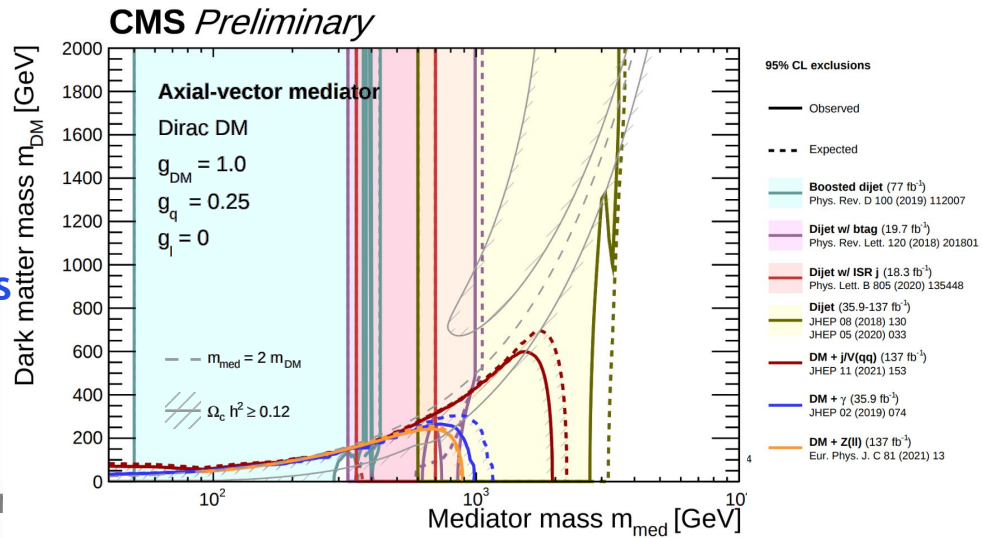
Higgs decaying through **dark photons**

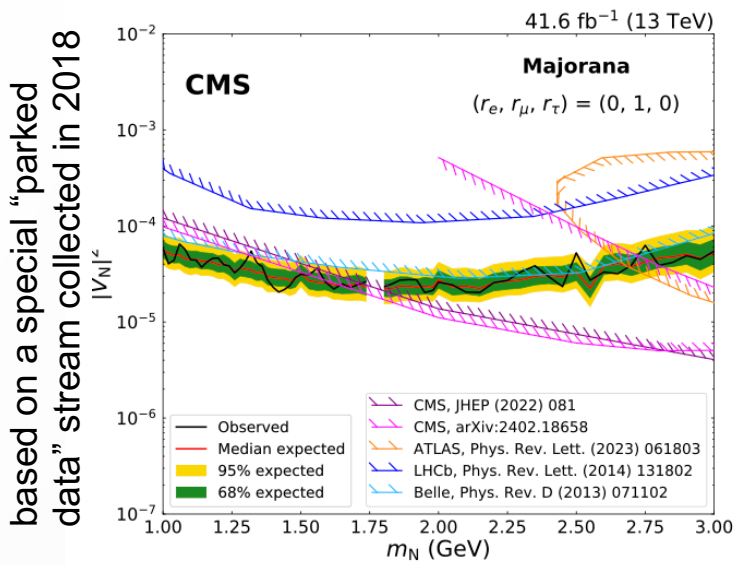


Heavy neutrinos (HNL)



DM through **heavy mediators**



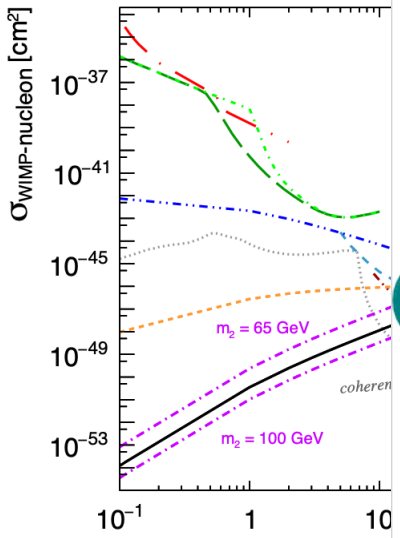


based on a special "parked data" stream collected in 2018

Physics programme: beyond our own "definition"…

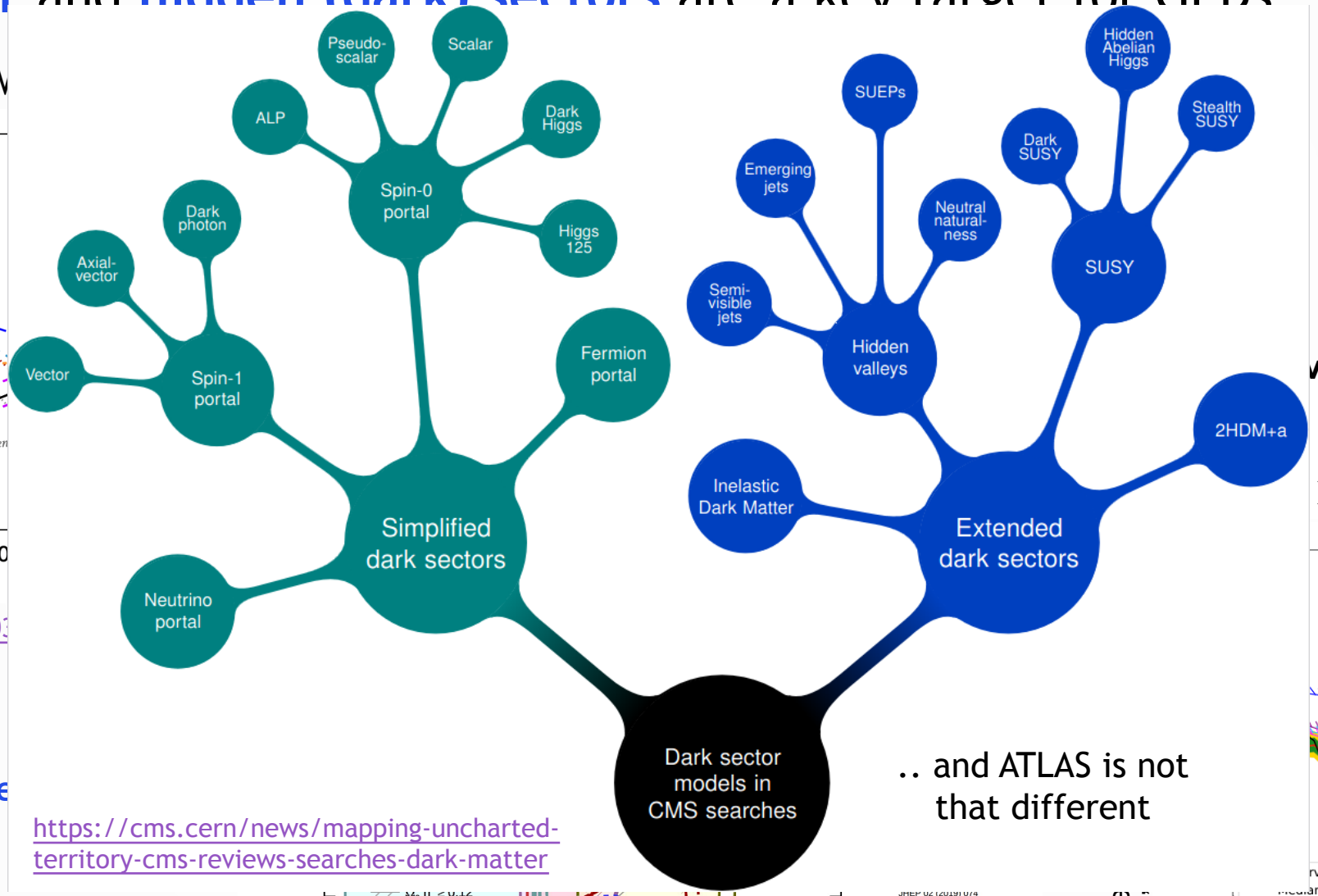
- **Dark matter** and **hidden (dark) sectors** are a key target for GPDs

Higgs decaying in W

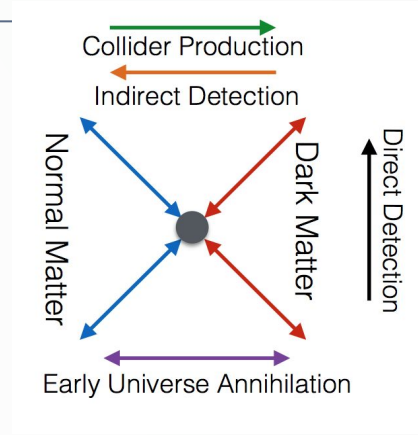


https://arxiv.org/pdf/2403

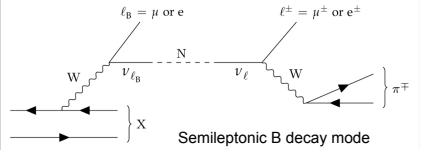
DM through he

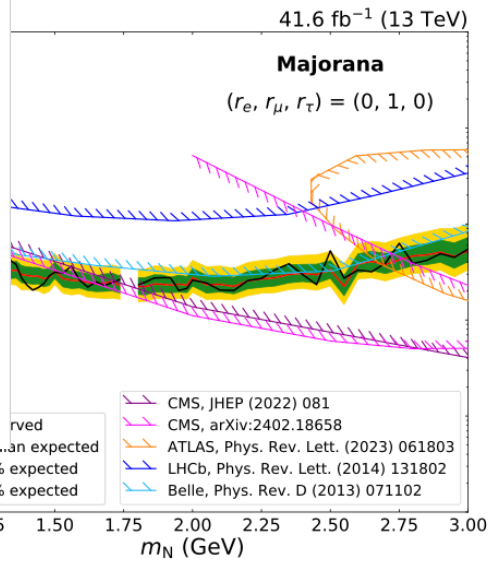


https://cms.cern/news/mapping-uncharted-territory-cms-reviews-searches-dark-matter

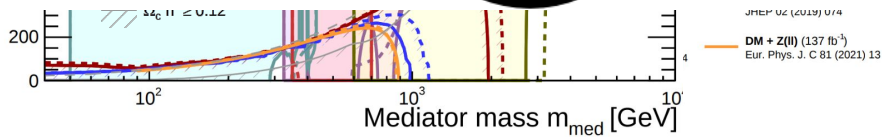


…vy neutrinos (HNL)





.. and ATLAS is not that different



base data

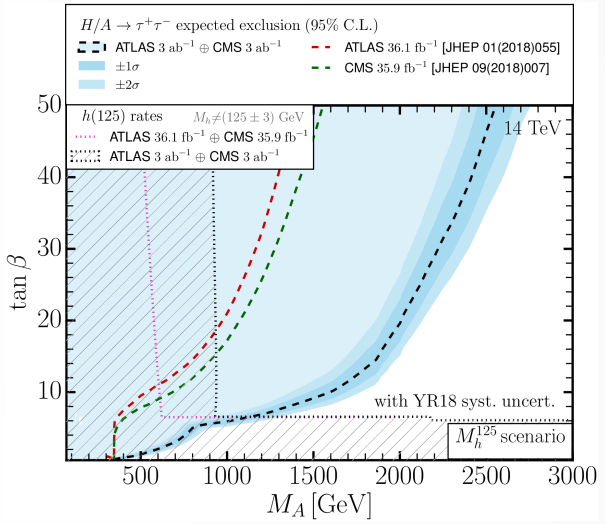
DM and Dark Sectors at HL-LHC

- For HL-LHC not as many models have been scrutinized, but enough feasibility studies made on benchmark models

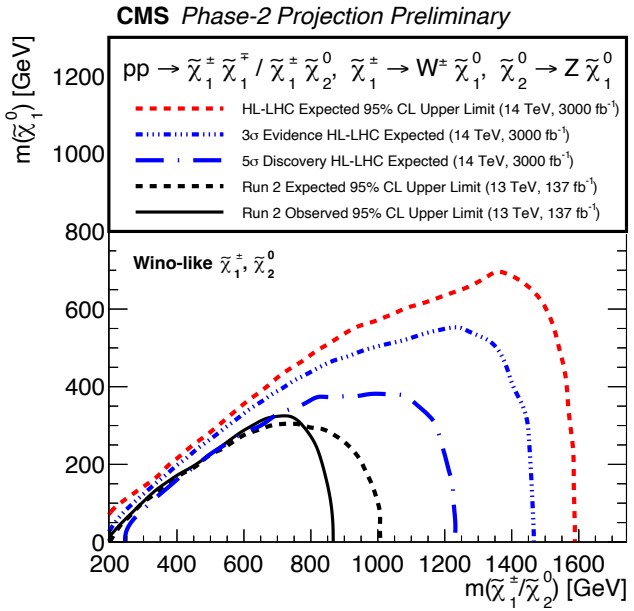
Report on the Physics at the HL-LHC, and Perspectives for the HE-LHC

ATL-PHYS-PUB-2022-018

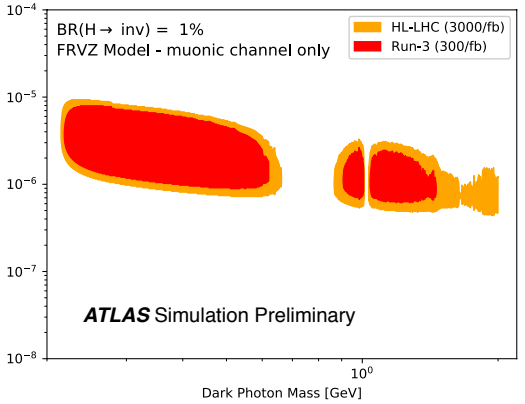
Extended Higgs sectors

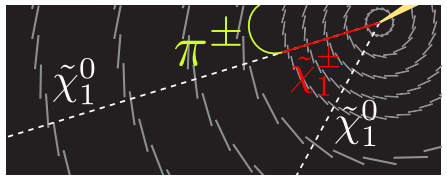


SUSY electroweakinos

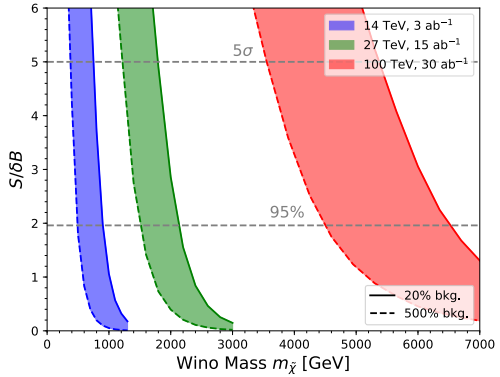


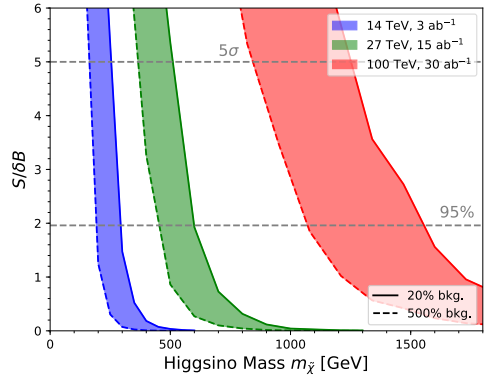
Dark photon (displaced lepton-jets)



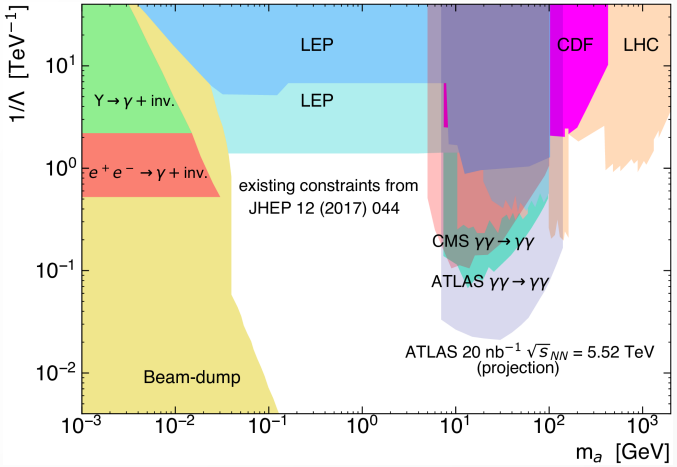


Wino/Higgsino DM with disappearing track



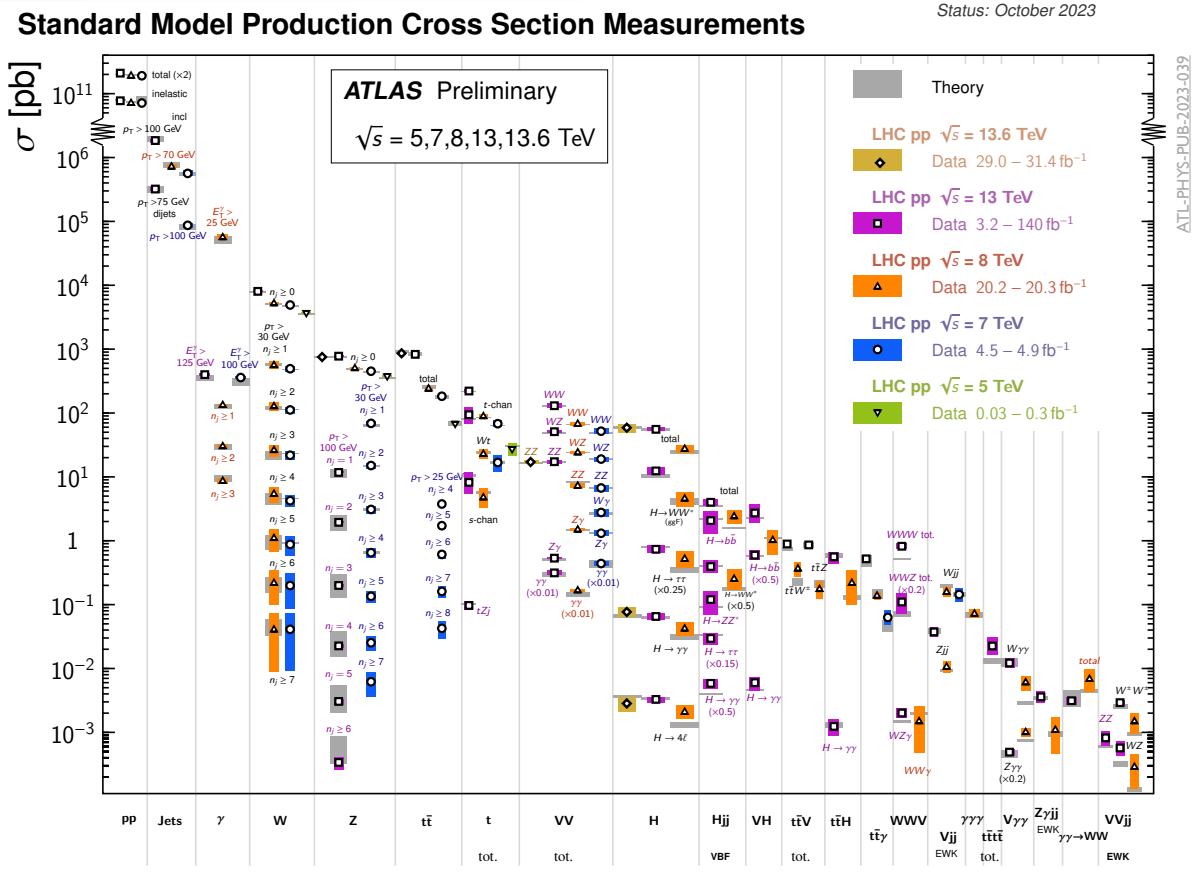


Axion-like particles

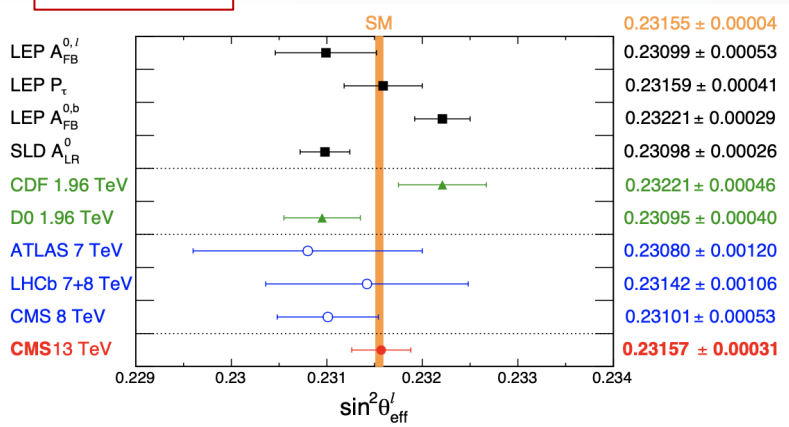


Physics programme: beyond our own "definition"…

- **Precision physics** (sometimes VERY precise…)

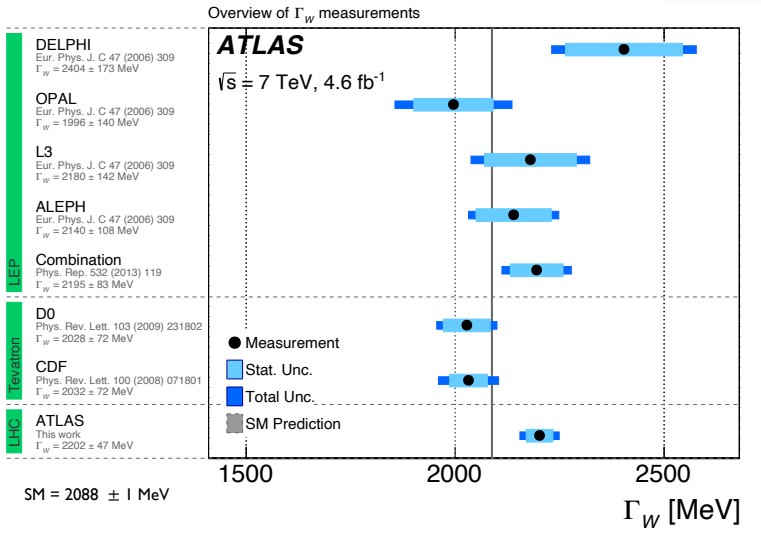


$\sin^2\theta^{\ell}_{\text{eff}}$ extracted from AFB(ee,μμ)

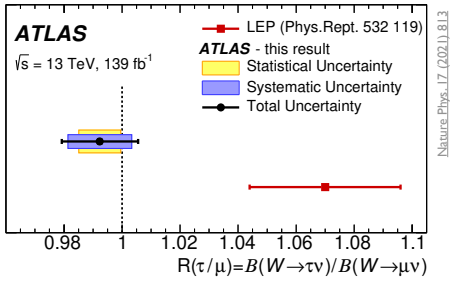


Precision comparable with LEP

First **W boson width** measurement at the LHC



But also, **lepton universality** in W decays

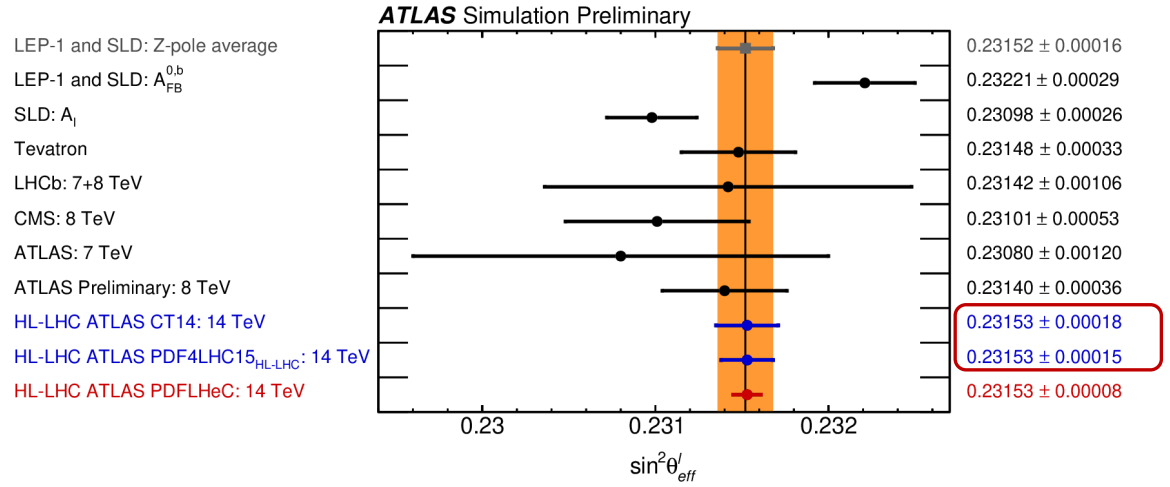


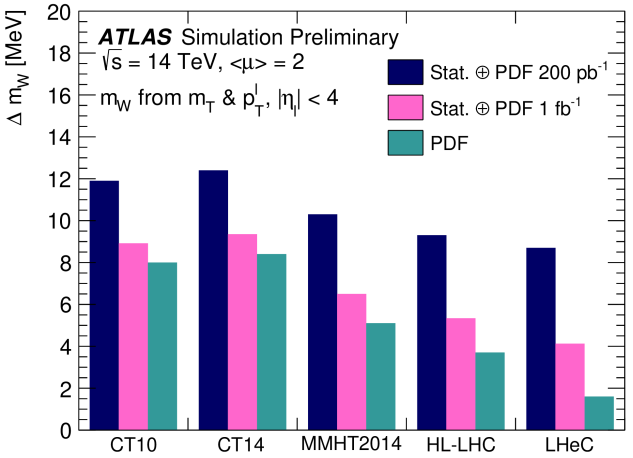
More precise than the world average!

Physics programme: beyond our own "definition"…

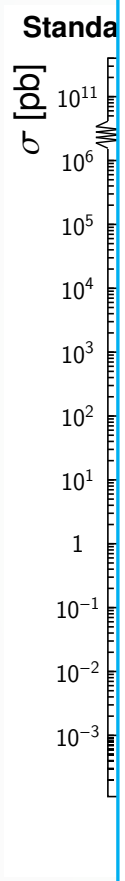
- Precisi

HL-LHC prospects for effective leptonic weak mixing angle and W mass depending on choice of PDF

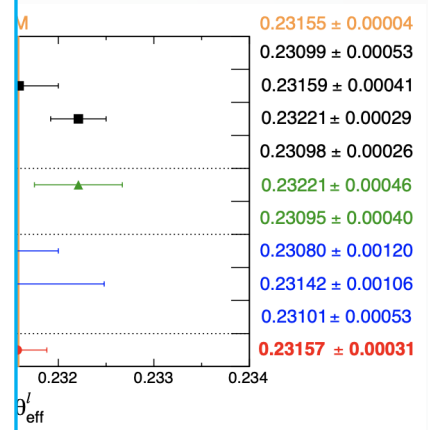


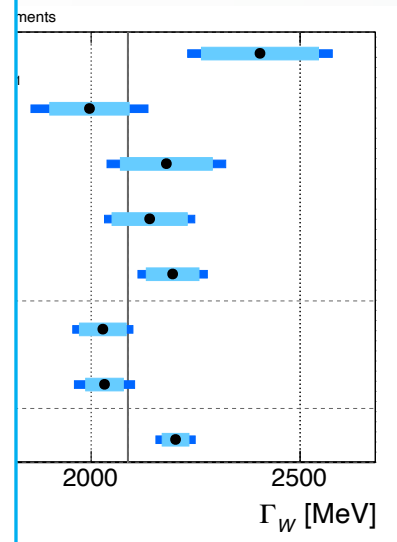


At least a factor of 2 expected in precision



But also, le
universalit

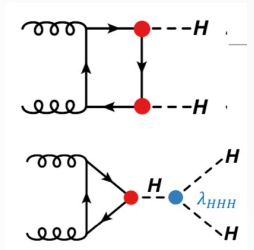




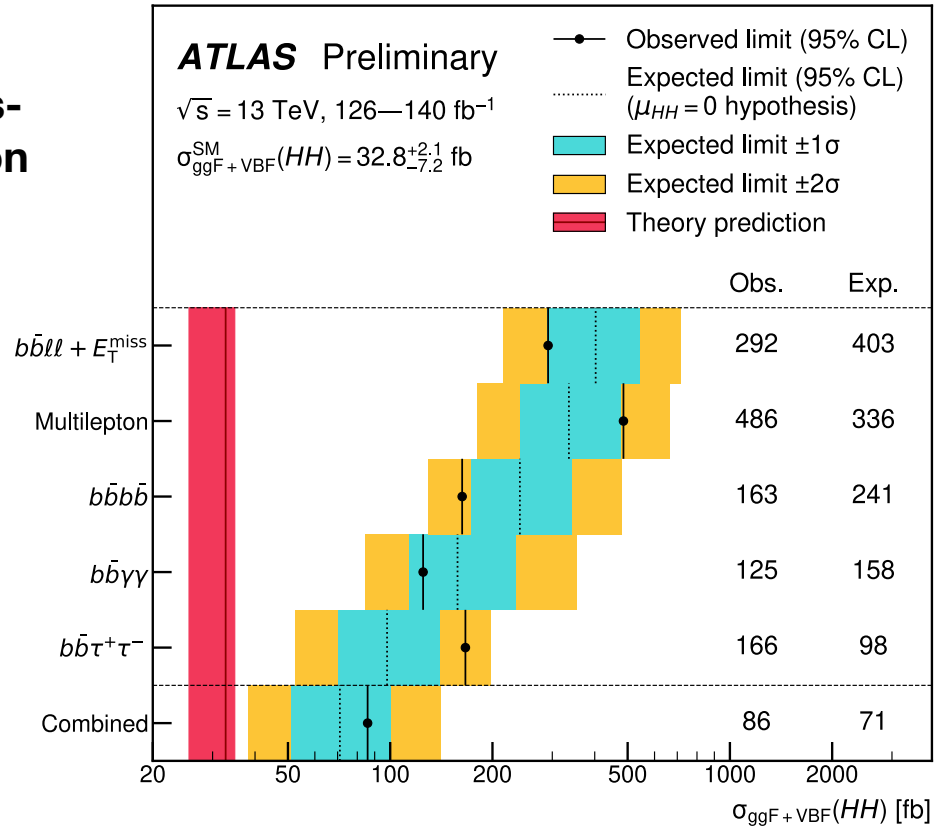
Physics programme: beyond our own "definitions"…

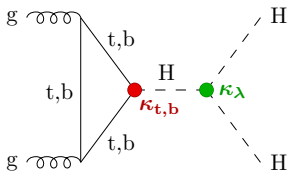
- **EWSB and beyond: Higgs self-coupling**
  - Huge improvements just with the Run 2 dataset reanalysis
  - ~20% improvement over previous result

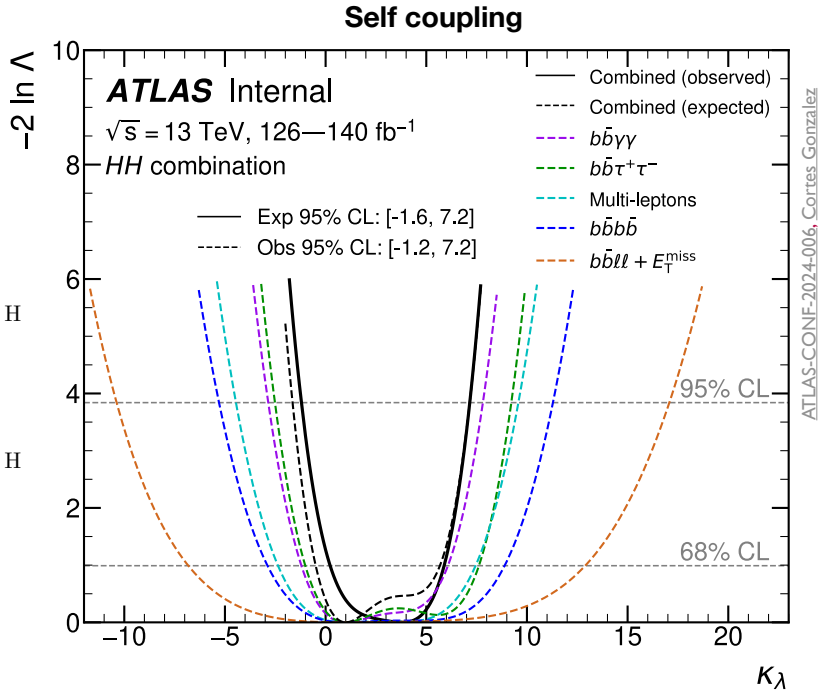
$$\mathcal{L}_h = \frac{1}{2} m_H^2 H^2 + \lambda_3 H^3 + \lambda_4 H^4$$



Cross-section







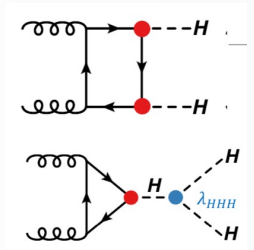
- $\kappa_\lambda \in [-1.2, 7.2] \left(\kappa_\lambda \in [-1.6, 7.2]\right)$
- $\kappa_{2V} \in [0.57, 1.48] \left(\kappa_{2V} \in [0.4, 1.6]\right)$

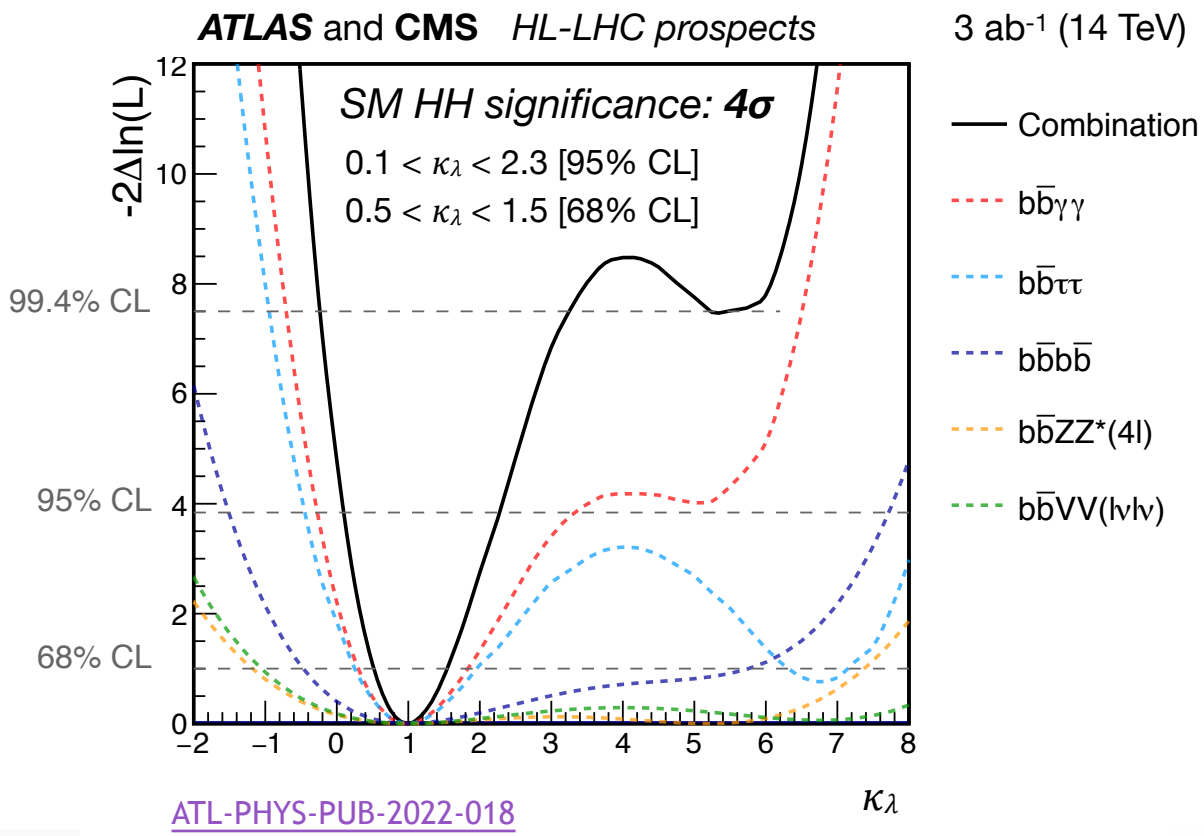
$\kappa_j^2 = \sigma_j / \sigma_j^{SM}$ coupling modifier parameters

Physics programme: beyond our own "definitions"...

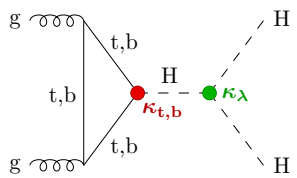
- **EWSB and beyond: Higgs self-coupling**
  - Huge improvements just with the Run 2 dataset reanalysis
  - Reaching our own projections faster than we thought :)

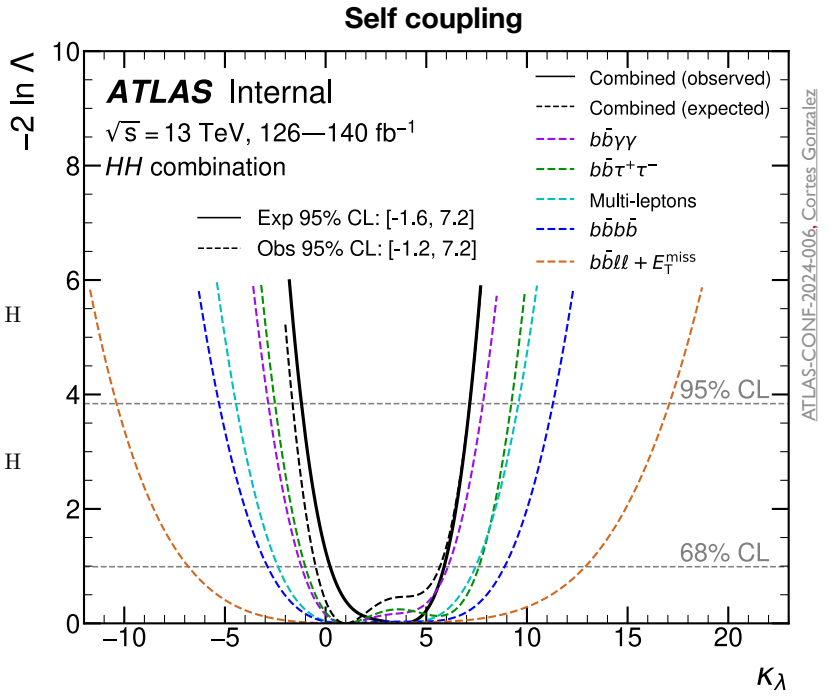
$$\mathcal{L}_h = \frac{1}{2} m_H^2 H^2 + \lambda_3 H^3 + \lambda_4 H^4$$





ATL-PHYS-PUB-2022-018





- $\kappa_\lambda \in [-1.2, 7.2] \left(\kappa_\lambda \in [-1.6, 7.2]\right)$
- $\kappa_{2V} \in [0.57, 1.48] \left(\kappa_{2V} \in [0.4, 1.6]\right)$

$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}}$ coupling modifier parameters

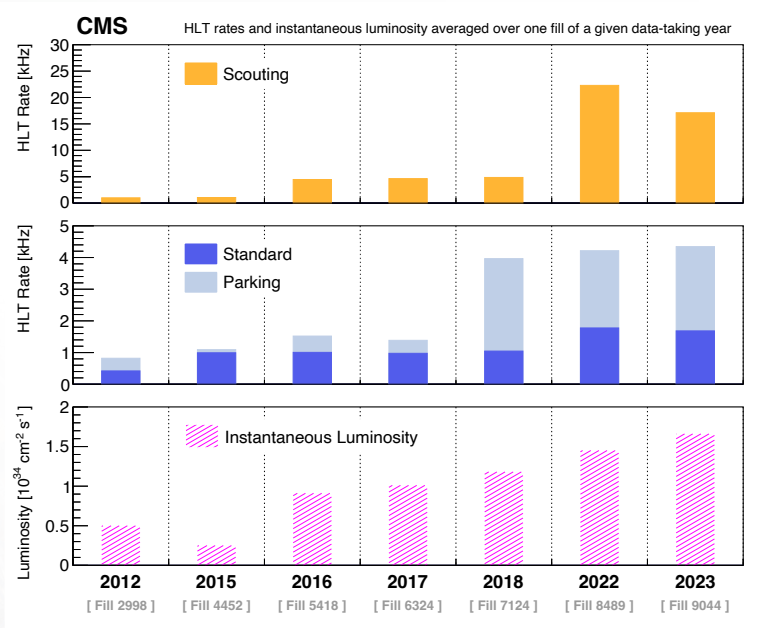
New ideas and cutting-edge technologies

- Amazing results achieved thanks to deployment of new ideas

→ a very dynamic environment – always try to do better! **Examples**

Data Scouting / Trigger Level Analysis

- enhance sensitivity by pushing thresholds
- respect bandwidth limits by only storing reduced event content
- analysis performed with trigger level objects

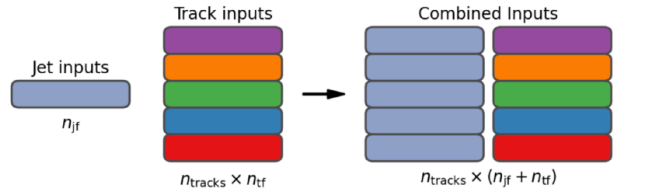


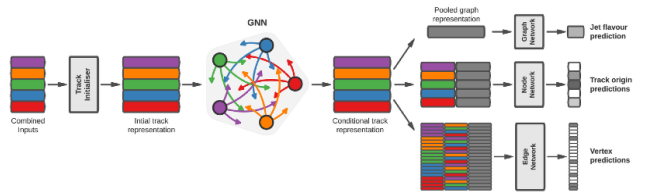
https://cms.cern/news/same-lhc-same-cms-more-physics

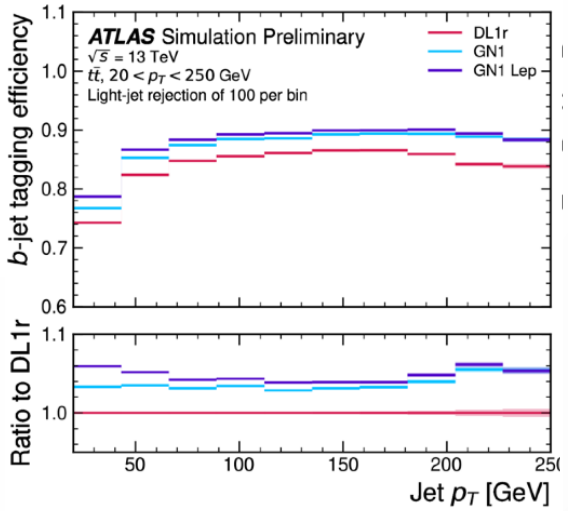
Flavour tagging: b and c jets

ATL-PHYS-PUB-2022-027

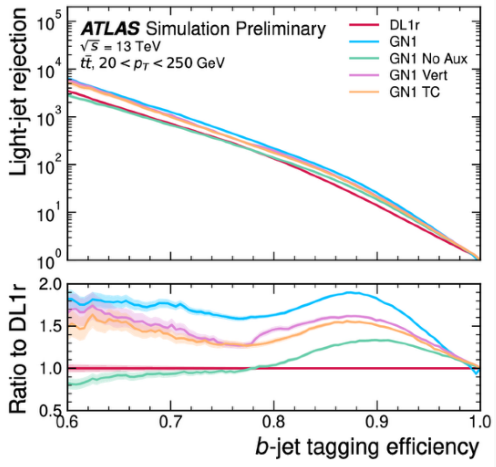
- Novel Graph Neural Network approach → optimised all the discriminating information for b-/c-jets
- Auxiliary tasks: tracks classification and vertex association





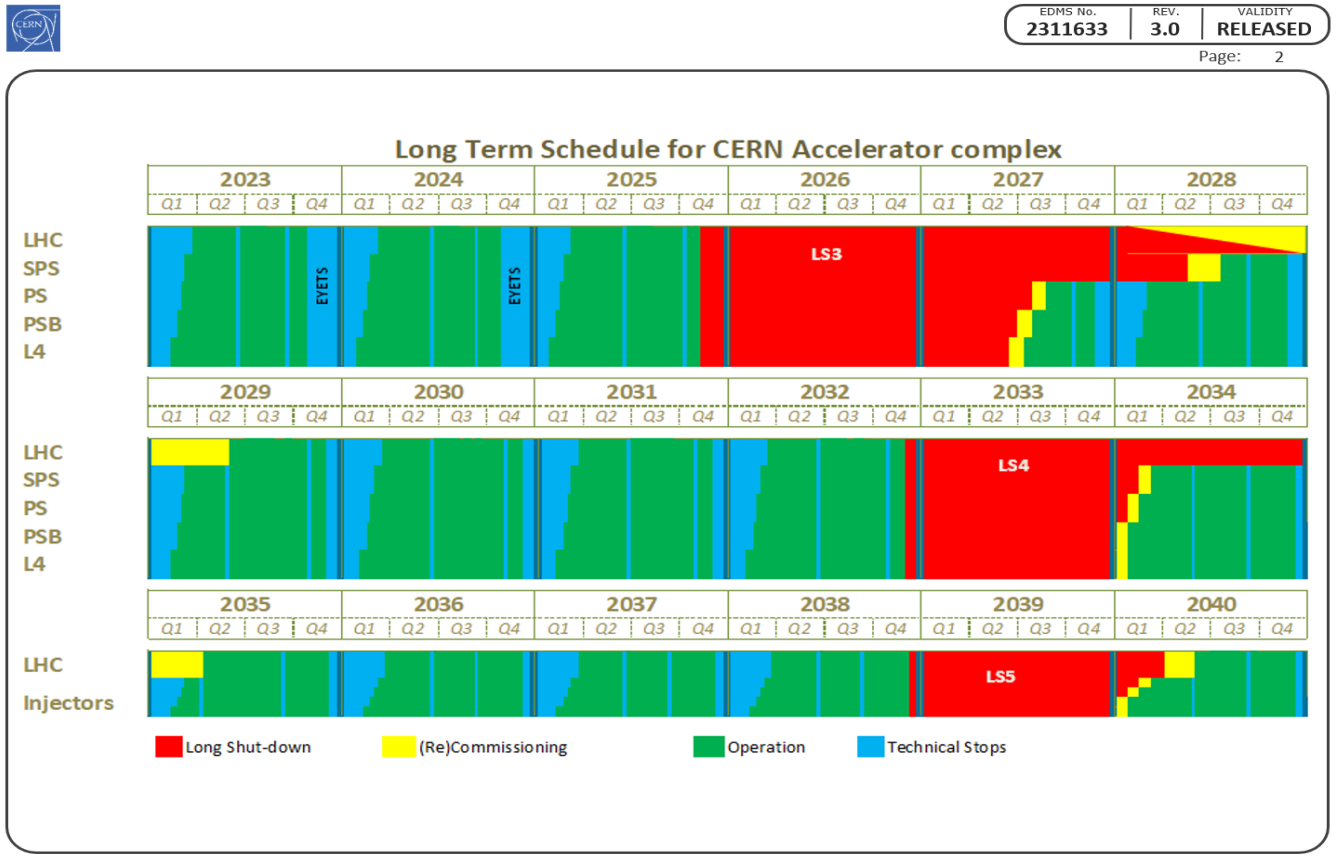


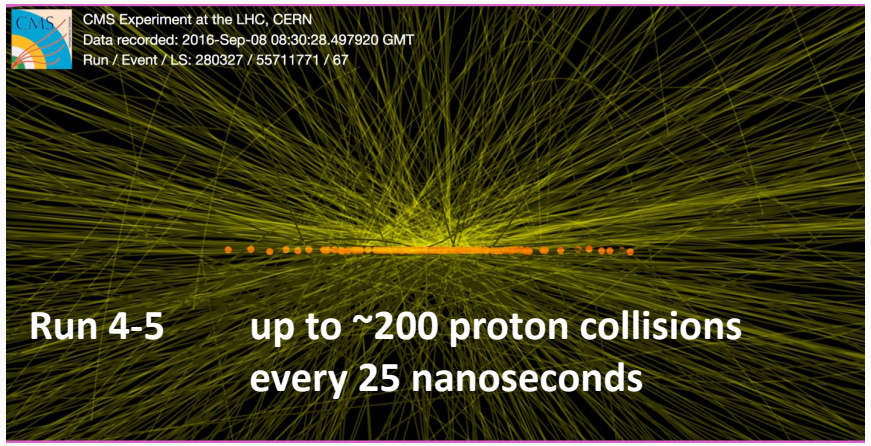
Significantly improved b-tag efficiency and light-jet rejection



Towards HL: the CERN Long-term Schedule

- Where are we going?
  - LS3 (2025-2029) – could shift by 6-9 months
  - Run 4 and beyond (HL-LHC): ~10 years programme a LS4 shutdown in 2033+ → 3 ab-1 / experiment expected
- 14 TeV collisions





- High instantaneous lumi (pileup) → improve granularity and timing info
- **High integrated lumi = high radiation environment** → replacement of tracker and endcap calorimeter
- Huge amount of data (computing, storage) → new trigger & DAQ systems

GPDs upgrade programs at a glance

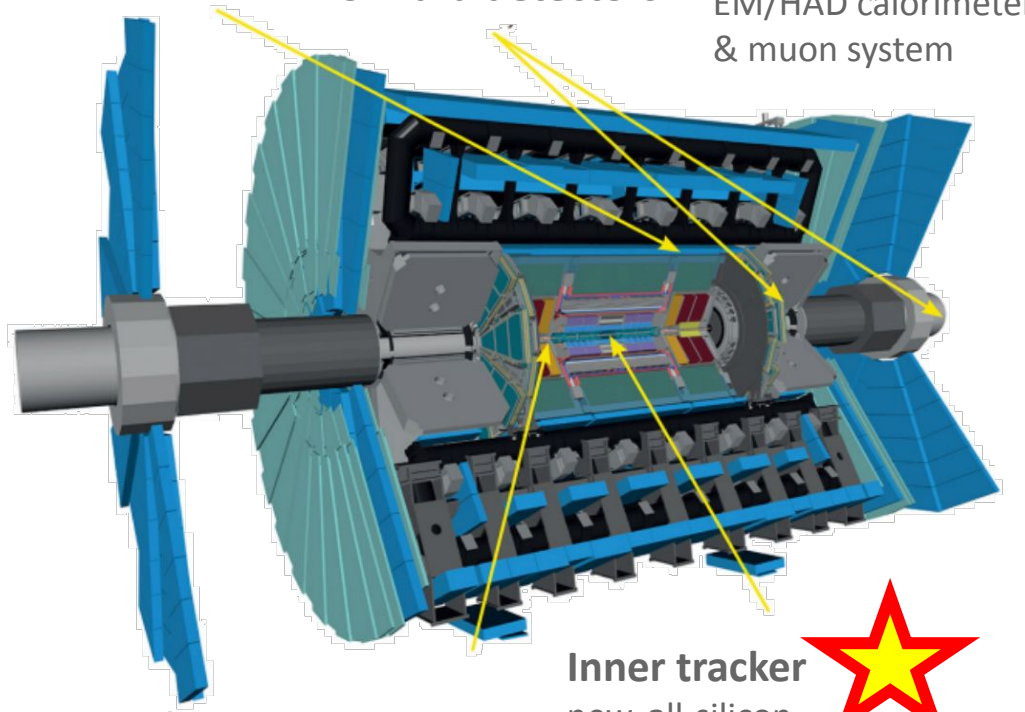
ATLAS detector

Trigger/DAQ
L1/HLT - 1Mhz / 1kHz

Muon detector
improved coverage

Luminosity & forward detectors

Upgraded electronics
EM/HAD calorimeters & muon system



Timing detector
high-granularity timing detector, pile-up mitigation

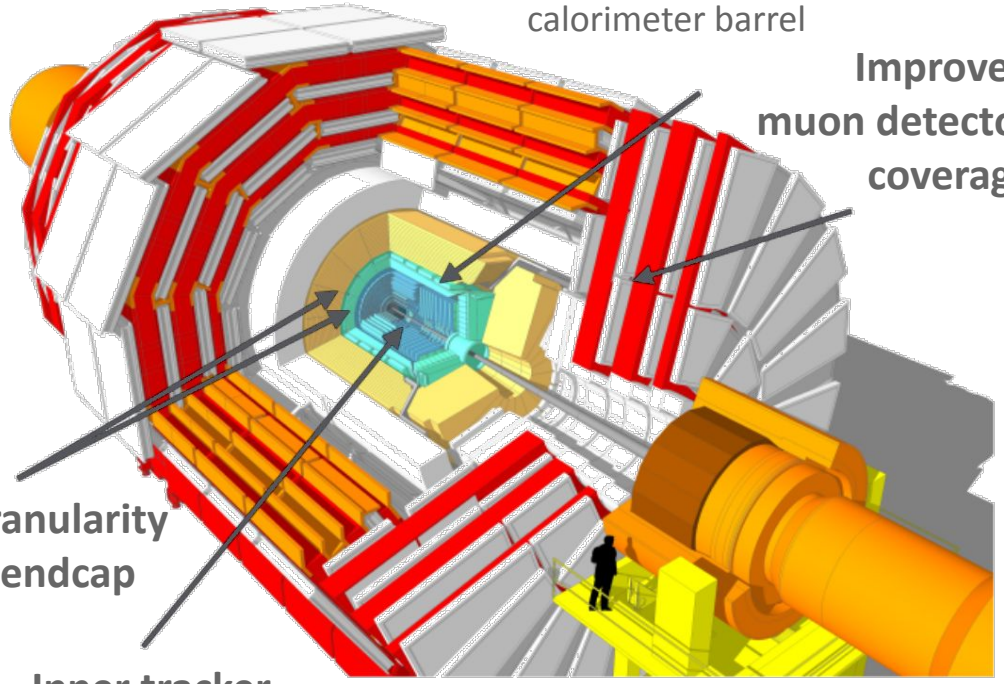
Inner tracker
new, all-silicon, coverage up to $|\eta| < 4$

CMS detector

Trigger/DAQ
L1/HLT - 750kHz / 7.5kHz
Track info at L1

Upgraded electronics
calorimeter barrel

Improved muon detector coverage

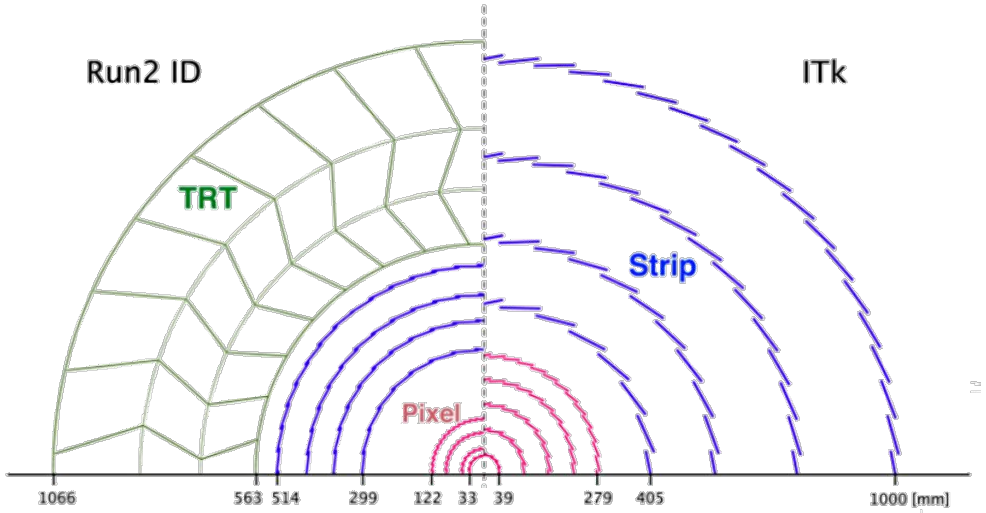


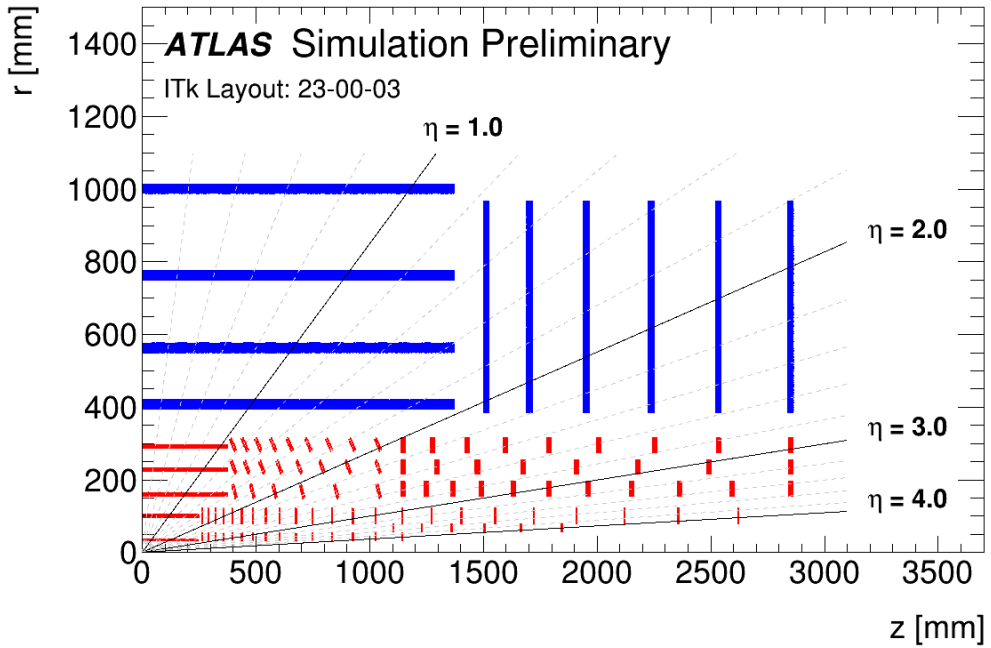
New high-granularity calorimeter endcap

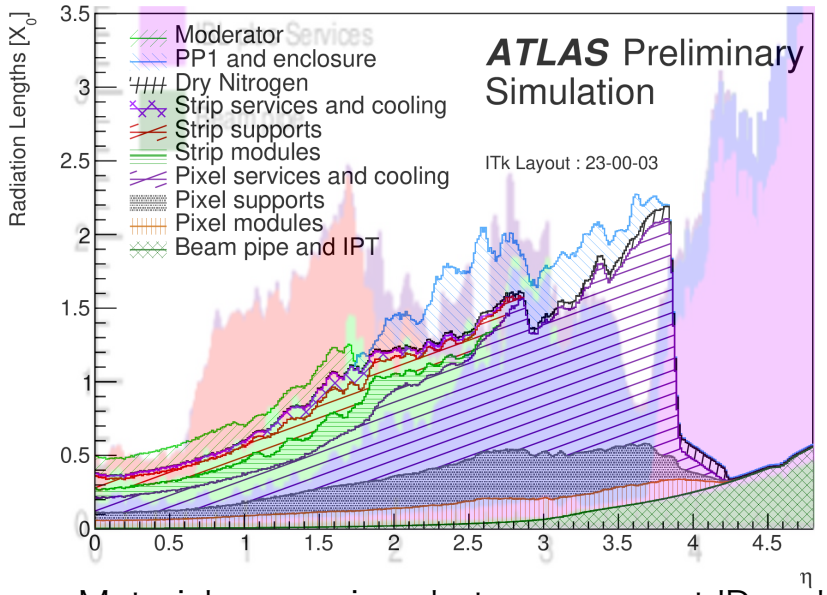
Inner tracker
new, coverage up to $|\eta| < 3.8$

Inner Tracking Detector (ITk)

- One of the **main UK deliverables for ATLAS**
  - Complete replacement of the current inner detector
  - Pixel and Strip sensors for a very large total surface
  - novel powering and cooling and consistency with upgraded DAQ (1MHz)
  - Larger angular coverage (η: 2.5 → 4)
  - High radiation tolerance (up to 1 x 10^{16} neq/cm^2)
  - Reduced material





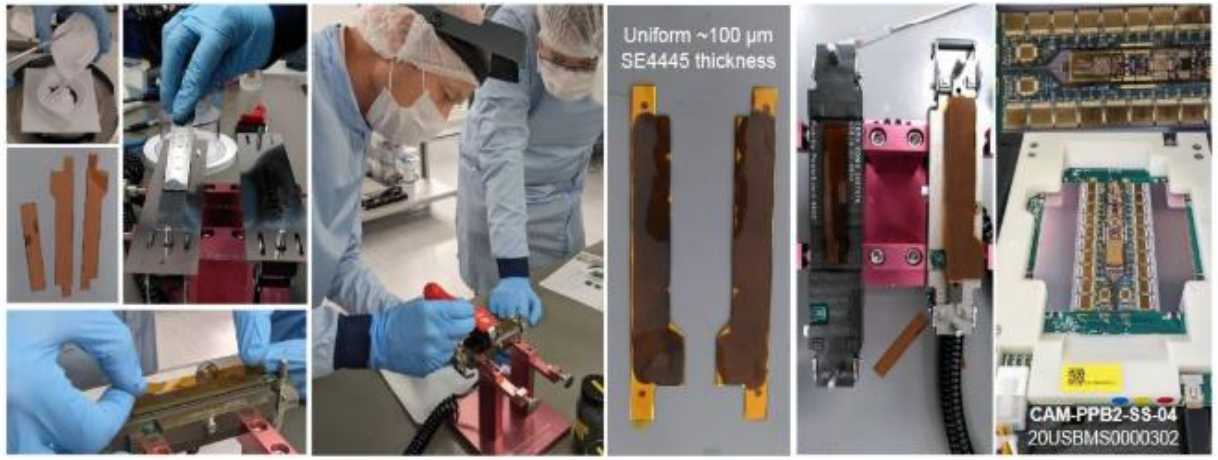


Material comparison between current ID and ITk

Inner Tracking Detector (ITk): status

- A lot of good progress has been made, in UK and elsewhere
- Schedule remains challenging
  - **ITK strips:** issues on sensors → lot of work to understand and solve problems

"Interposer" solution, module design modified



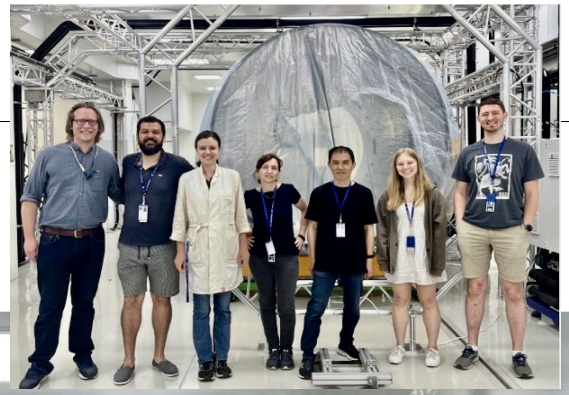
Cold tests (-70 deg) on-going

  - **ITK pixels:** hybridization process and ASICs – to be watched out but only for pre-production
    - Joint task force ATLAS-CMS expert for ASICs

Towards the HL-LHC

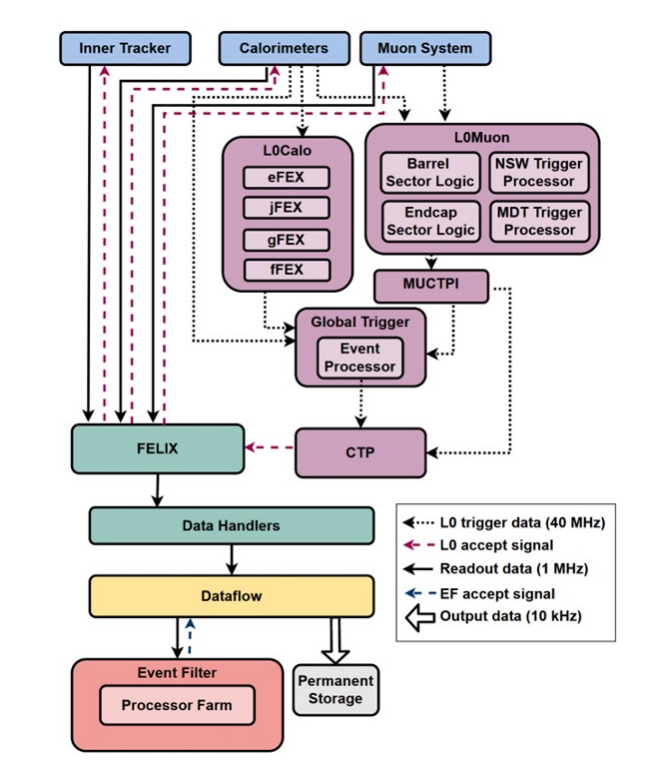
From A.Hoecker
ATLAS week

ITk outer cylinder arriving in SR1 at P1

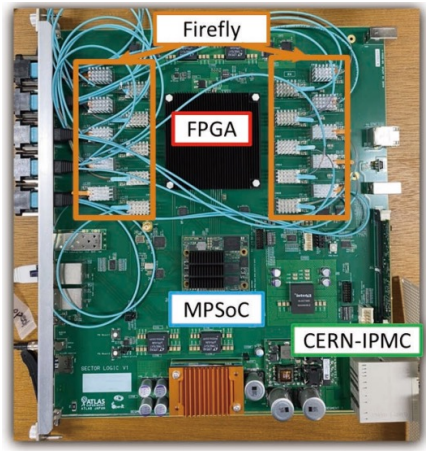


ATLAS upgrade: Trigger and DAQ

- Another important UK deliverable
- Phase II TDAQ specifications are challenging:
  - L0 rate 1 MHz with 10us latency
  - EF output rate 10 KHz
  - Estimate event size of 4.6 MB

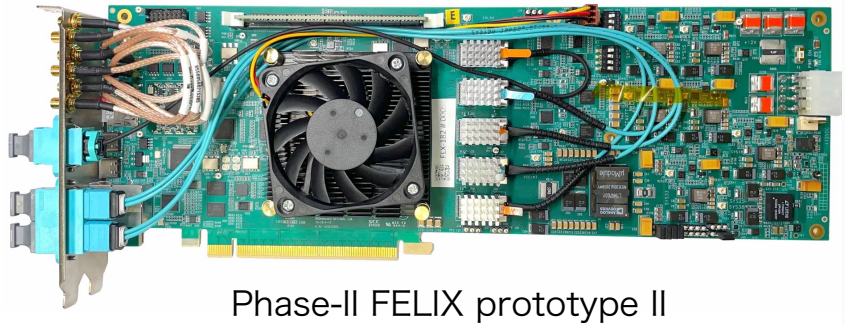


L0 Trigger: prototyping and testing

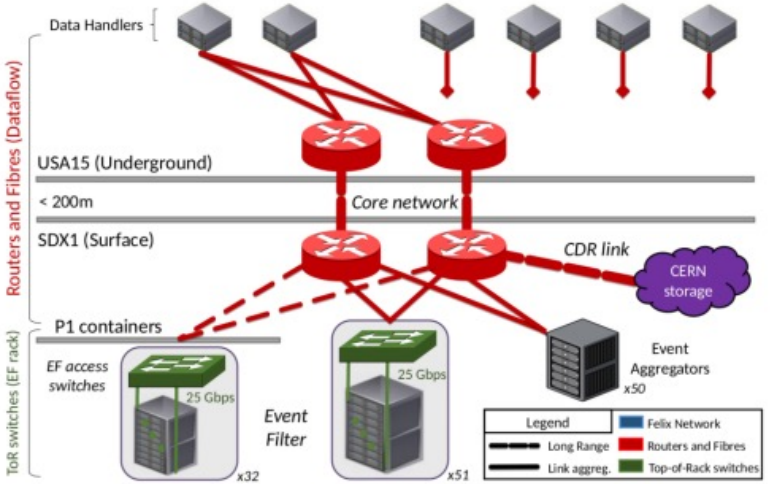


DAQ: FELIX prototype testing on-going

Event filter: demonstrators progressing well and on track, very good progress on GPU and FPGA support in ATLAS software

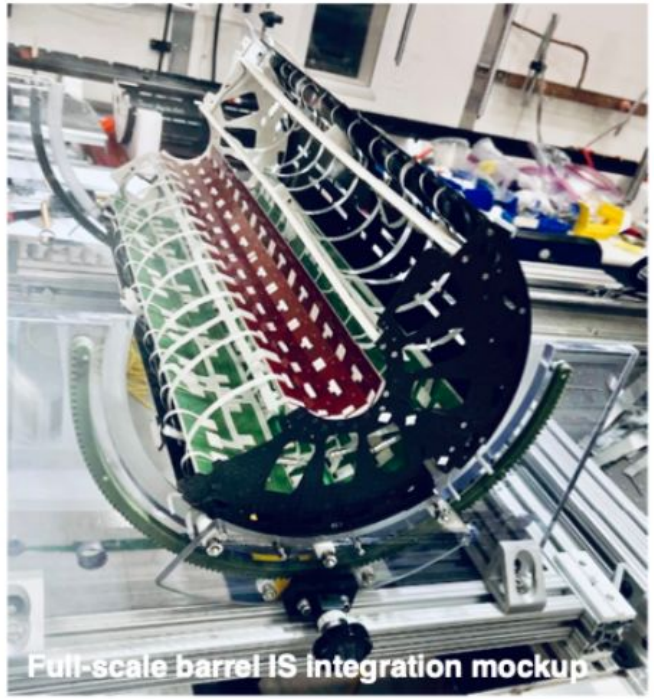


Phase-II FELIX prototype II



GREAT PROGRESS ON ALL SYSTEMS

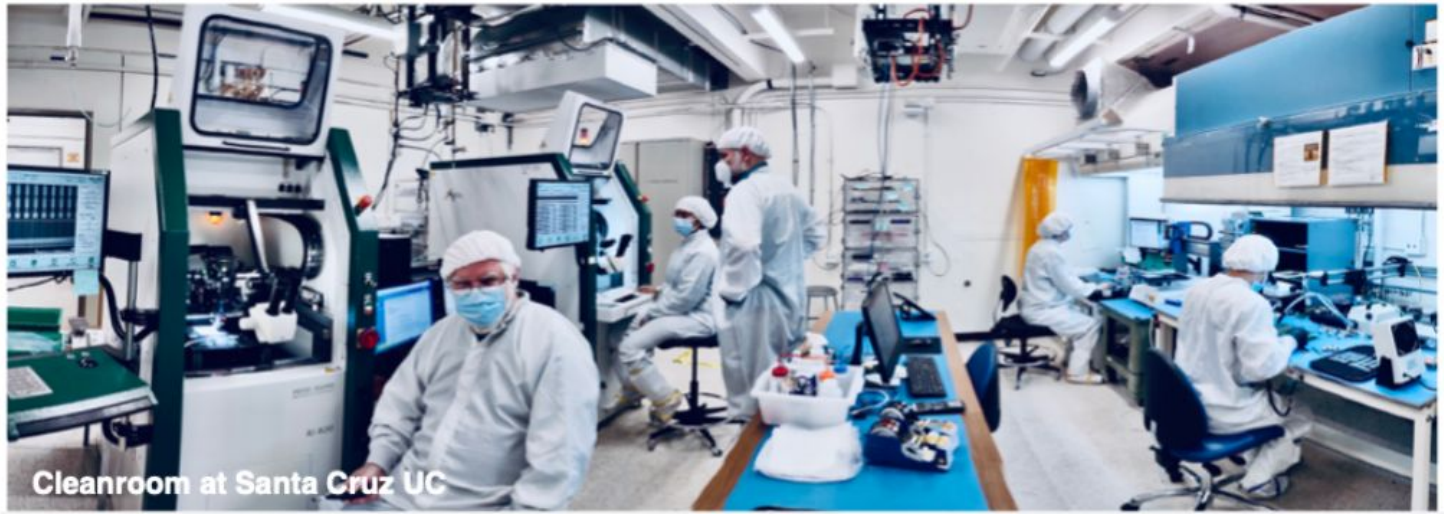

SR1 ITk surface assembly cleanroom at CERN

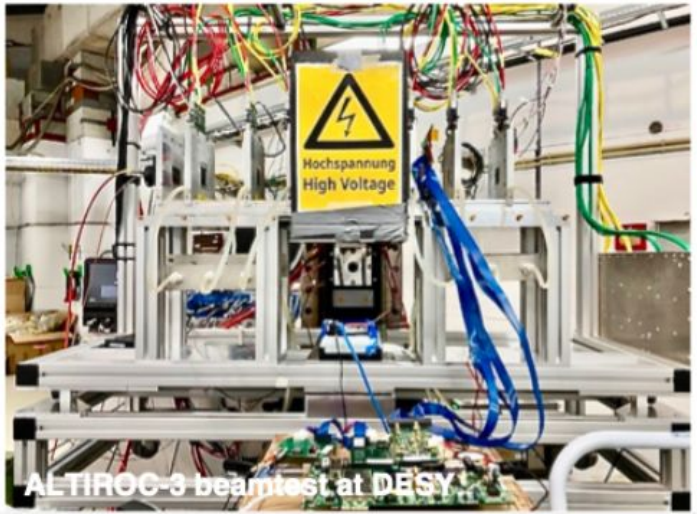

Full-scale barrel IS integration mockup


sMDT chambers at CERN (BB5)

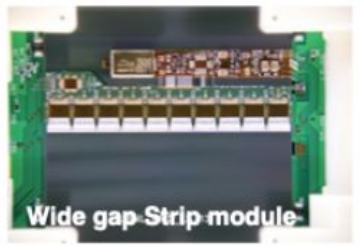

GCM prototype v2b


LAr ALFEv2 ASIC


Cleanroom at Santa Cruz UC



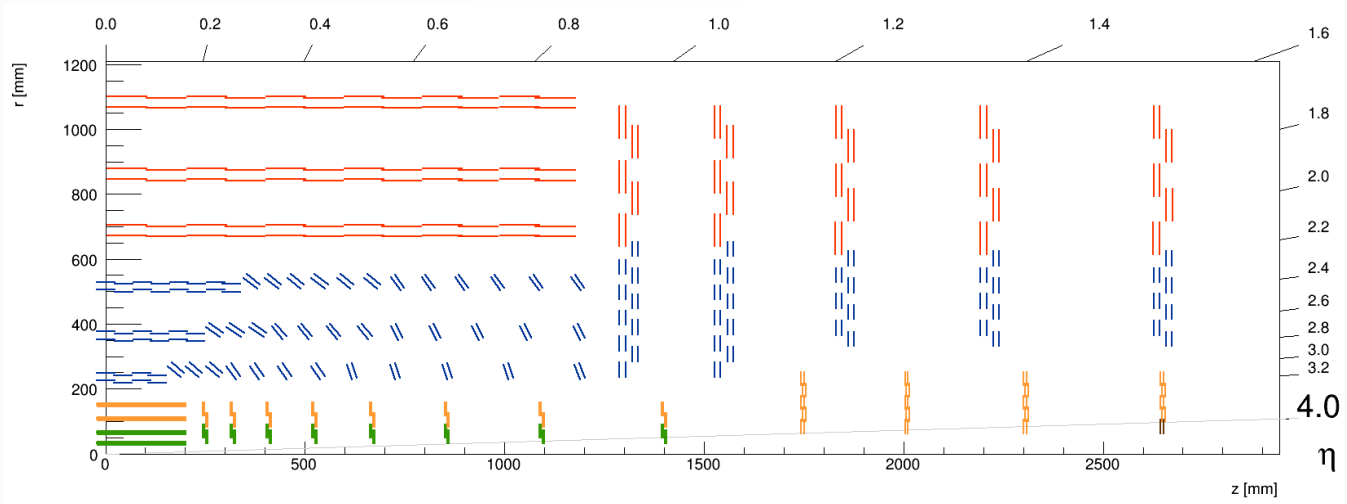
ALTIROC-3 beamtest at DESY

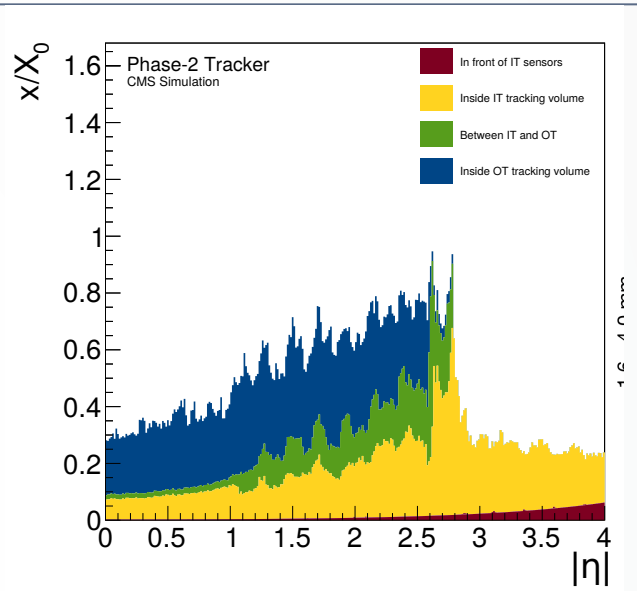

Wide gap Strip module

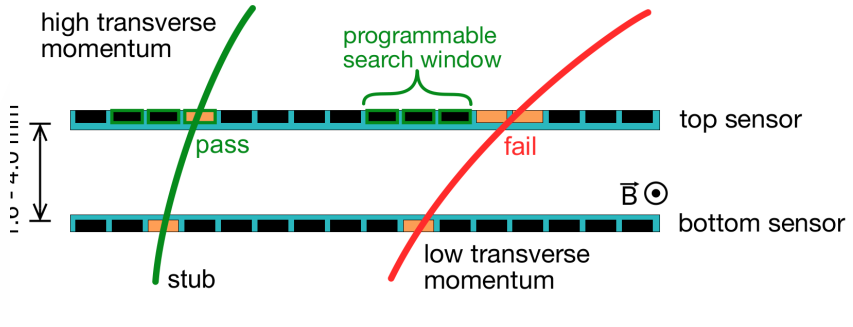

Tile Main Board burn-in test at Chicago

CMS upgrade status: tracker

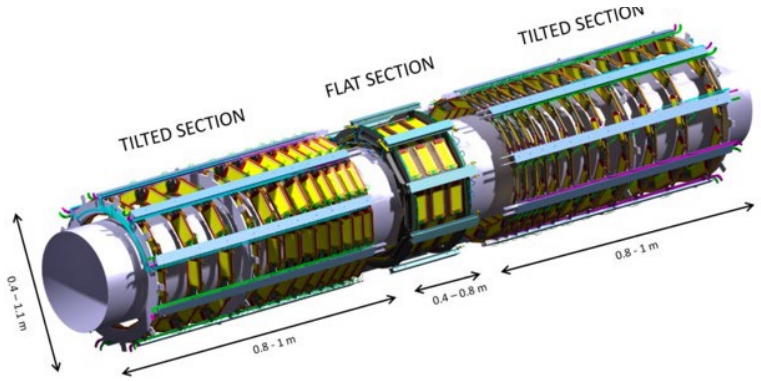
- CMS also going through a total replacement of its tracking system
  - Increased granularity (~1200 tracks / unit of pseudorapidity)
  - Reduced material to preserve calorimetric resolution
  - Contribution to the L1 trigger (outer tracker tracks identification)







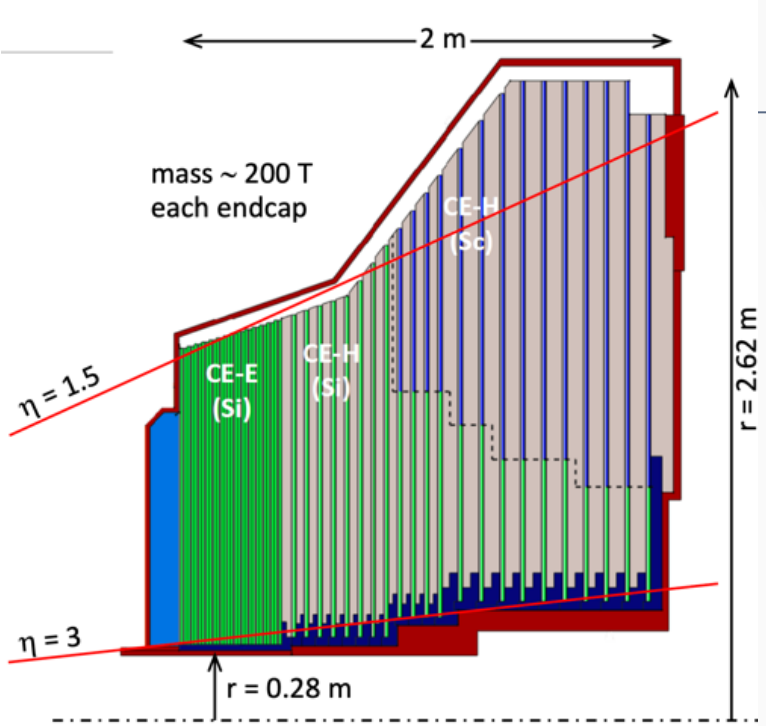
Outer tracker

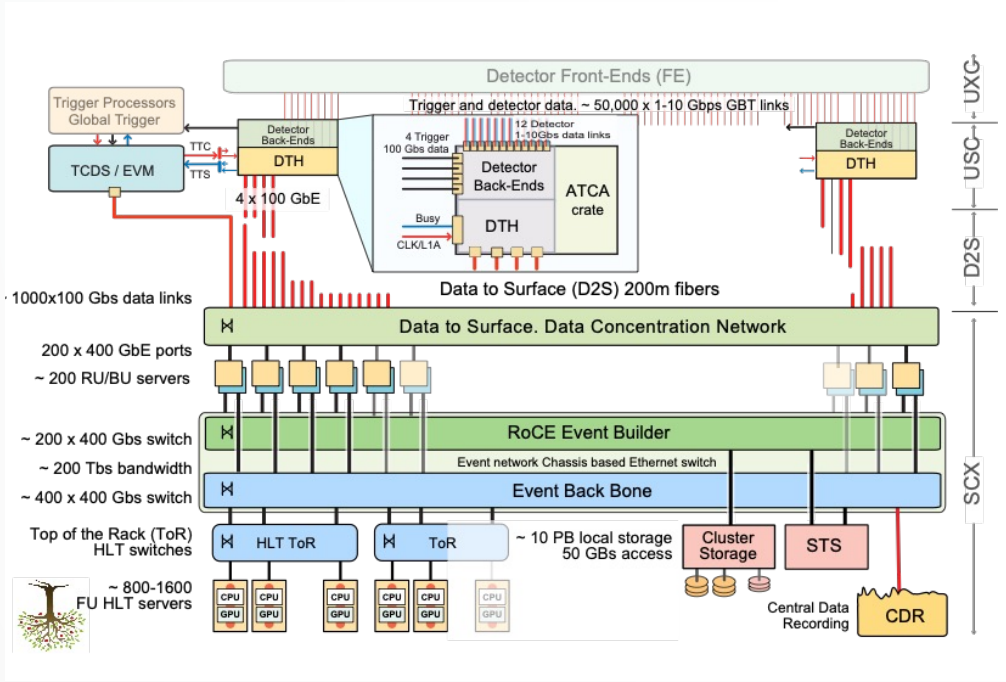


UK deliverables in particular on electronics and algorithms for track trigger, and ASICs → progressing (ASICs completed)!

CMS calorimeter and DAQ

- **CMS calorimeter (ECAL)** system fully upgraded
  - Radiation tolerant, shower lateral compactness, fine granularity
  - Resolution 20 ps /channel and contribution to the L1 trigger
- **DAQ:**
  - 50k high-speed front-end optical links
  - Up to 60 Tb/s data rate, total event size 7-10 MB

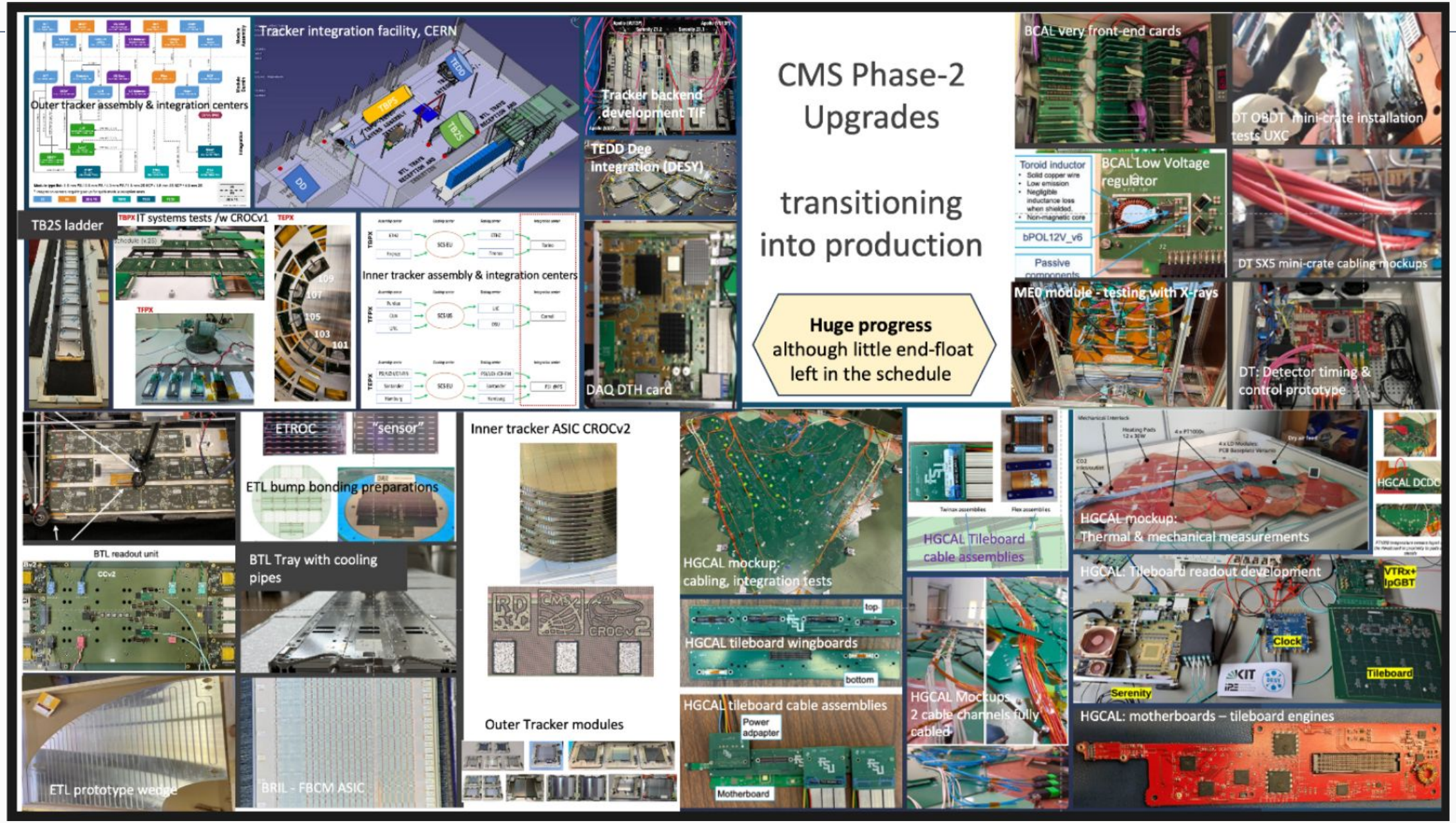




Highlights

- Unified detector readout
  - ATCA form-factor for detector backend
- Dual-function board DTH-400
  - DAQ data aggregation
  - Timing and Trigger Control and Distribution
- Event Network
  - RDMA over Converged Ethernet
- Heterogeneous HLT nodes
  - GPU-equipped servers

UK deliverables in particular on electronics and algorithms for L1 trigger (calorimeter) → progressing!

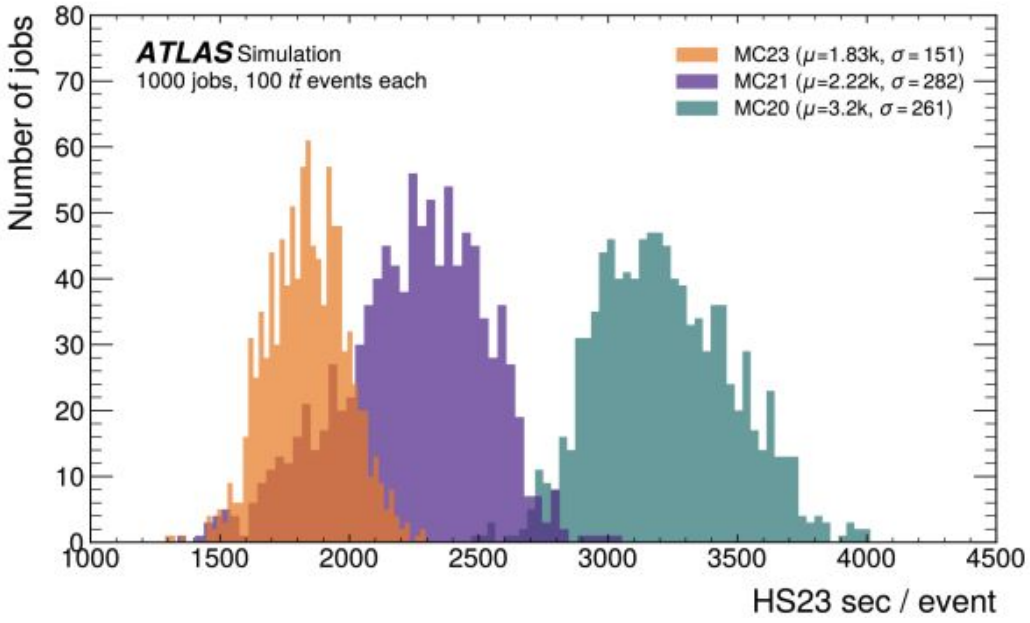

Outer tracker assembly & integration centers
Tracker integration facility, CERN
Tracker backend development TIF
TEDD Dee integration (DESY)
TB2S ladder
IT systems tests /w CROCv1
Inner tracker assembly & integration centers
DAQ DTH card
CMS Phase-2 Upgrades
transitioning into production
Huge progress although little end-float left in the schedule
BCAL very front-end cards
DT OBDT mini-crate installation tests UXC
Toroid inductor
BCAL Low Voltage regulator
DT SX5 mini-crate cabling mockups
ME0 module - testing with X-rays
DT: Detector timing & control prototype
ETROC
"sensor"
ETL bump bonding preparations
Inner tracker ASIC CROCv2
HGCAL mockup: cabling, integration tests
HGCAL Tileboard cable assemblies
HGCAL mockup: Thermal & mechanical measurements
HGCAL DCDC
BTL readout unit
BTL Tray with cooling pipes
HGCAL tileboard wingboards
HGCAL: Tileboard readout development
VTRx+ lpGBT
Clock
Tileboard
Serenity
HGCAL Mockups 2 cable channels fully cabled
HGCAL tileboard cable assemblies
Power adpapter
Motherboard
HGCAL: motherboards – tileboard engines
ETL prototype wedge
BRIL - FBCM ASIC
Outer Tracker modules

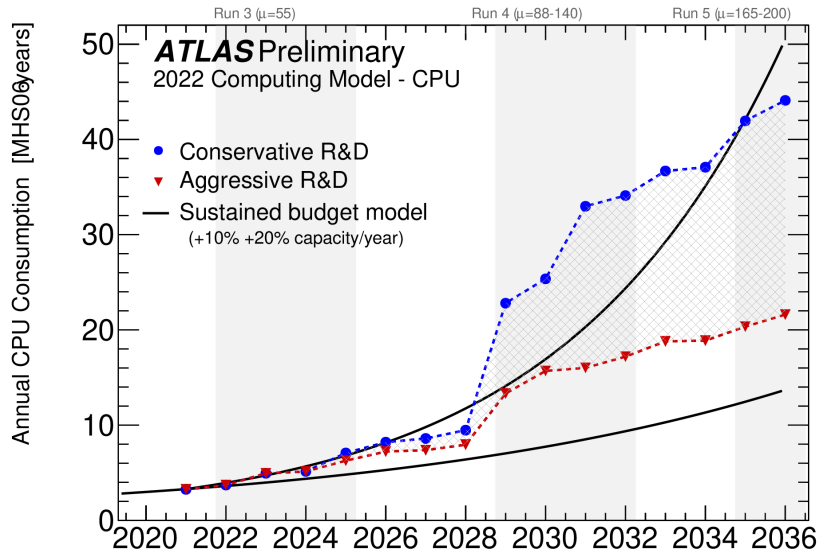
Computing at HL-LHC

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/UPGRADE/CERN-LHCC-2022-005/

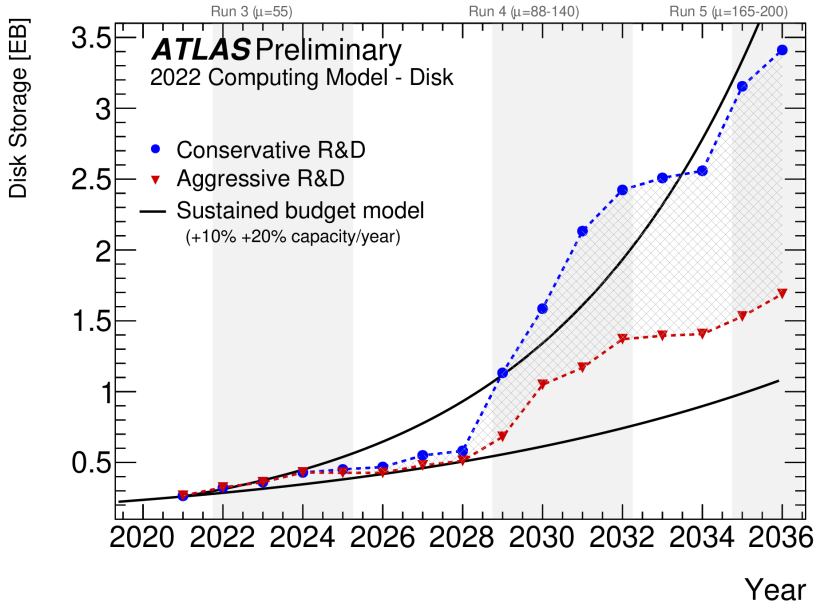
- The HL-LHC presents significant computing challenge
  - A lot of work on-going to cope with that → manageable, exploiting rapidly changing technology landscape and with lot of efforts from people
  - In UK, coordinated efforts (i.e. within the **SWIFT-HEP** project) to address challenges from various perspective → efficient MC production, efficient analysis software etc.
  - Example: **MC simulation improvement (for Run 3)**

CERN courier article





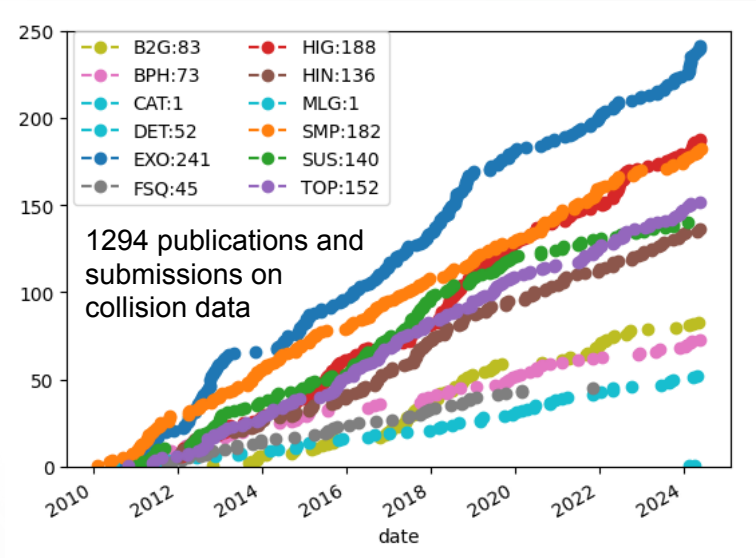
Very similar for CMS!



Summary

- ATLAS and CMS are running efficiently in Run 3 and producing many results key to understand the SM and explore beyond:
  - a **'science powerhouse'**: they are, per-se, facilities rather than experiments, where new ideas are constantly explored → dynamic and innovative
    - **Many UK-lead contributions not mentioned here:** Flavour physics, entanglement in top-pair production, HI physics and more
  - Furthermore: ECR fora and initiatives (physics and upgrade); open collision data that allow diverse collaborations (use of AI, training of next generation of physicists and more..)
  - Scientific outcomes can be 'enriched' with additional small experiments 'using' GPDs (see Josh's talks)
- Physics prospects for HL-LHC offer incredible opportunities:
  - Higgs-self couplings, New physics models, precision physics
  - Probably conservative, given constant improvements!
- The HL-LHC upgrade of both experiments is well on-going:
  - **Challenges are also opportunities**, understanding the complexity of new detectors and technologies is key for future facilities and can become a joined effort!
  - Improvements in computing are relevant well beyond collider experiments → **sustainability** is key

CMS (source: LHCP plenary – Boston 2024)



ATLAS: 1286 papers with collision data
- 111 papers in 2023
- 59 papers in 2024
- 340 Run 2 papers

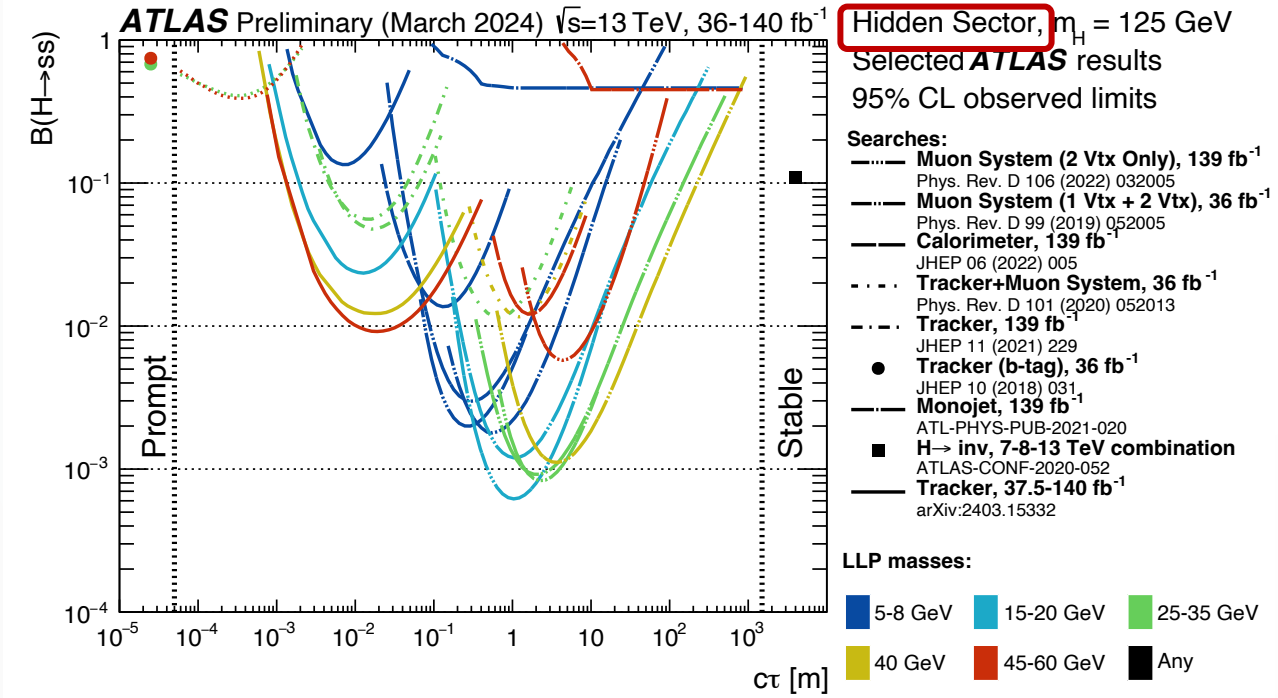
As the last European strategy and the P5 report underline, HL-LHC remains (one of) the highest priority for our community!

Back up

Physics programme: the energy frontier

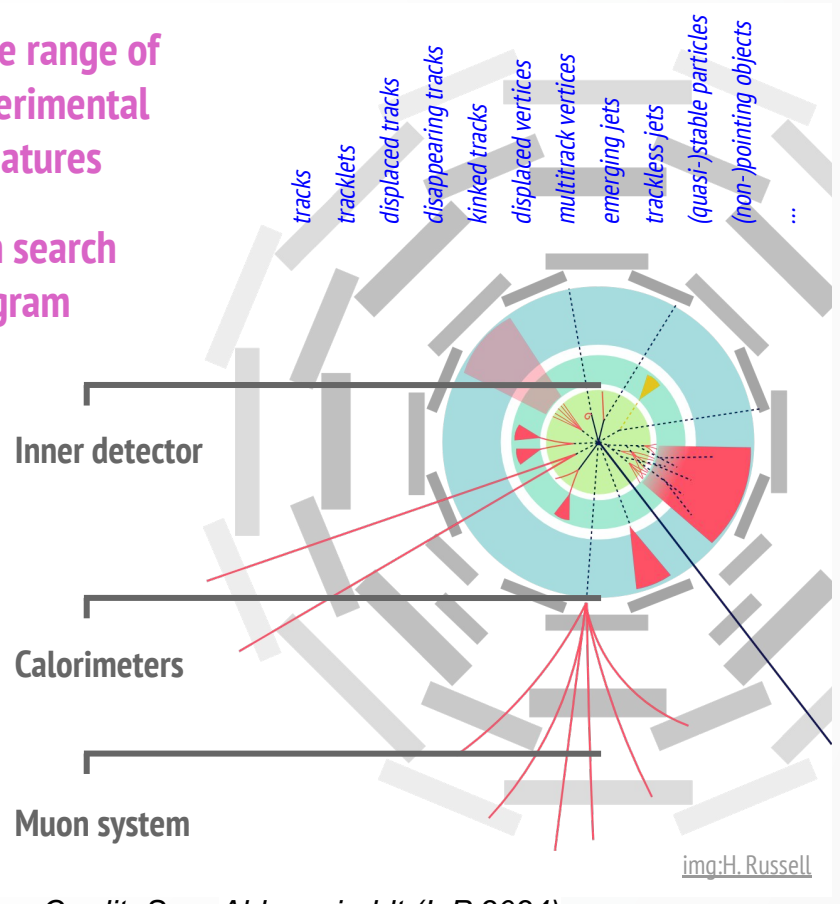
- A large fraction of the UK HEP community works within ATLAS or CMS
- The physics programme is also huge → usually referred to as *Energy frontier*
  - Adding the (life)time dimension: **long-lived** particles, require specialized and dedicated reconstruction techniques
  - E.g.: Higgs decaying in long-lived scalars
    - Leaving no stone unturned…

ATL-PHYS-PUB-2022-007, Frattari



Wide range of experimental signatures

Rich search program



Credit: Sara Alderweireldt (IoP 2024)