ATLAS physics prospects for HL-LHC and ATLAS upgrade

– some highlights

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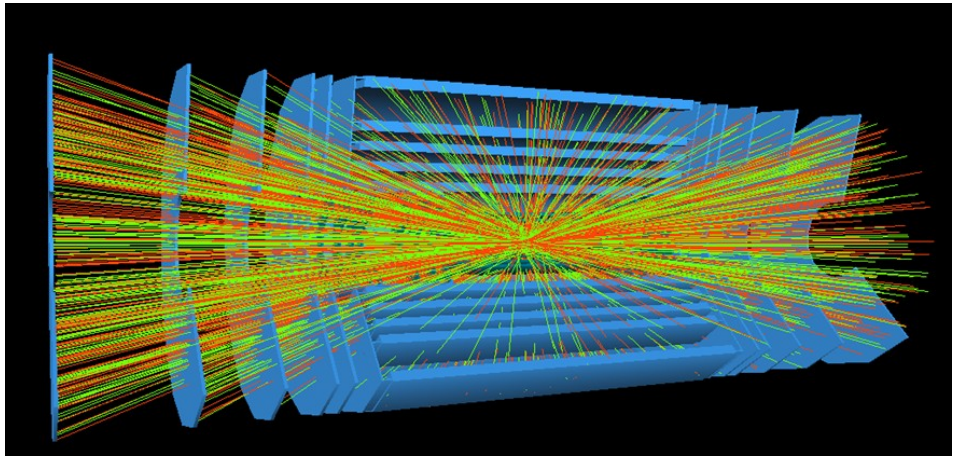
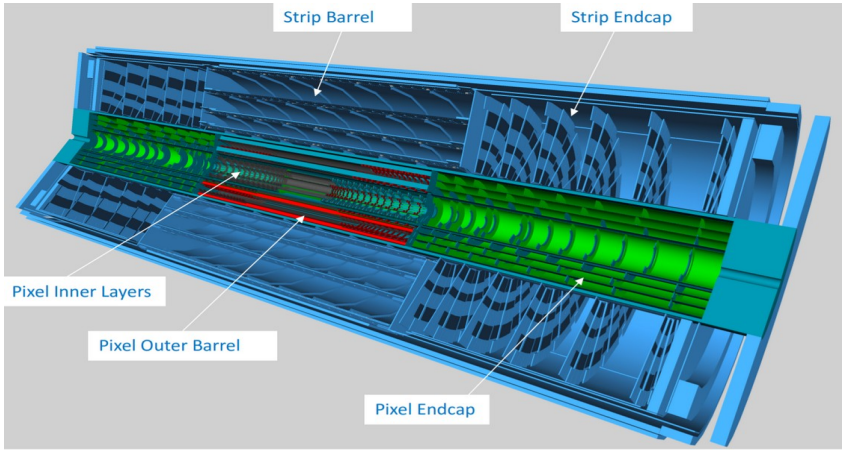


Outline:

- High luminosity – a particle physicists' view
- Upgrade of ATLAS
- Physics prospects



HL-LHC in numbers

- Expected integrated luminosity between 3000 fb^{-1} and 4000 fb^{-1}. 10 times more than all LHC data so far.
- Collision energy between 13.6 and 14 TeV

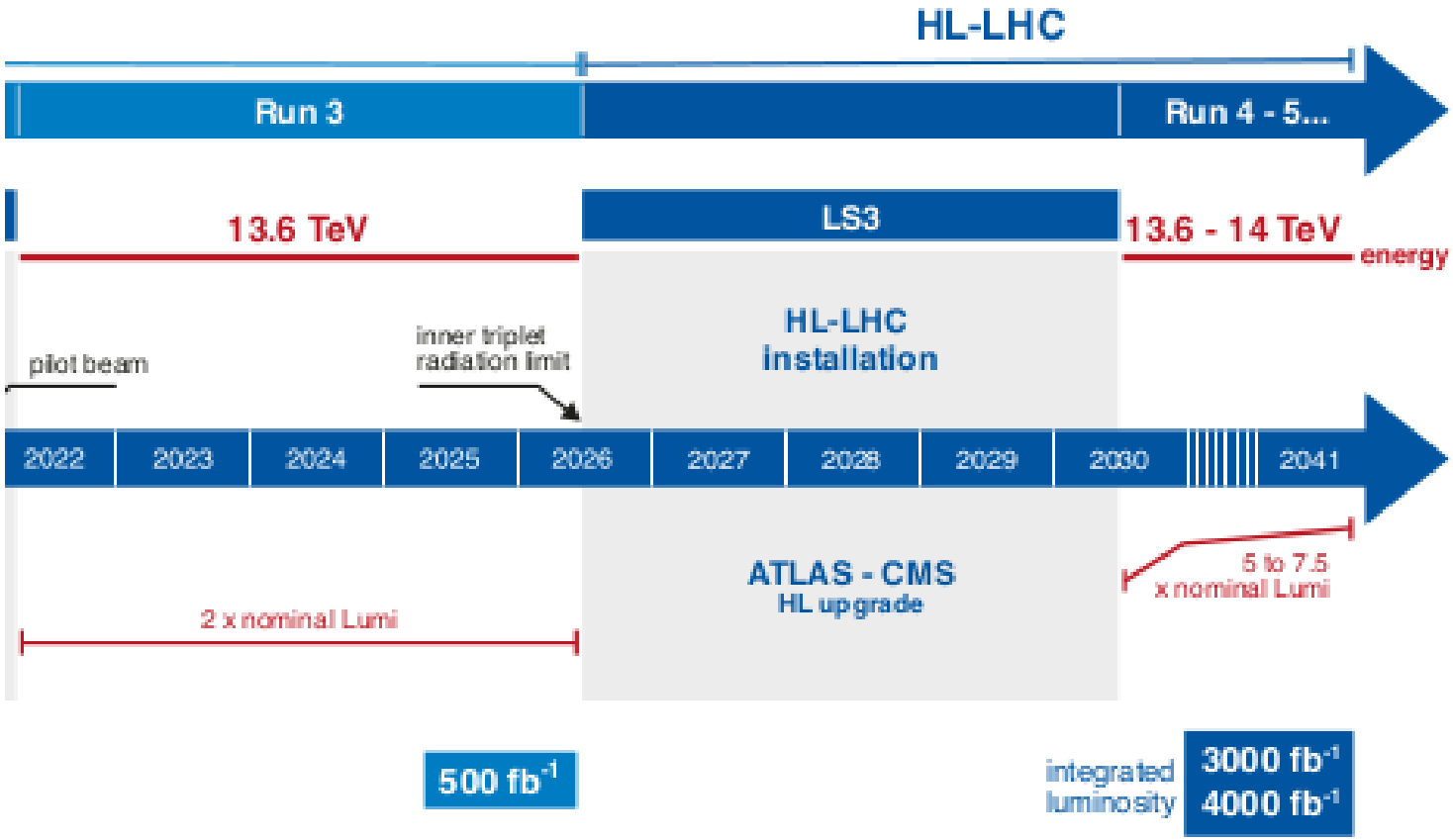
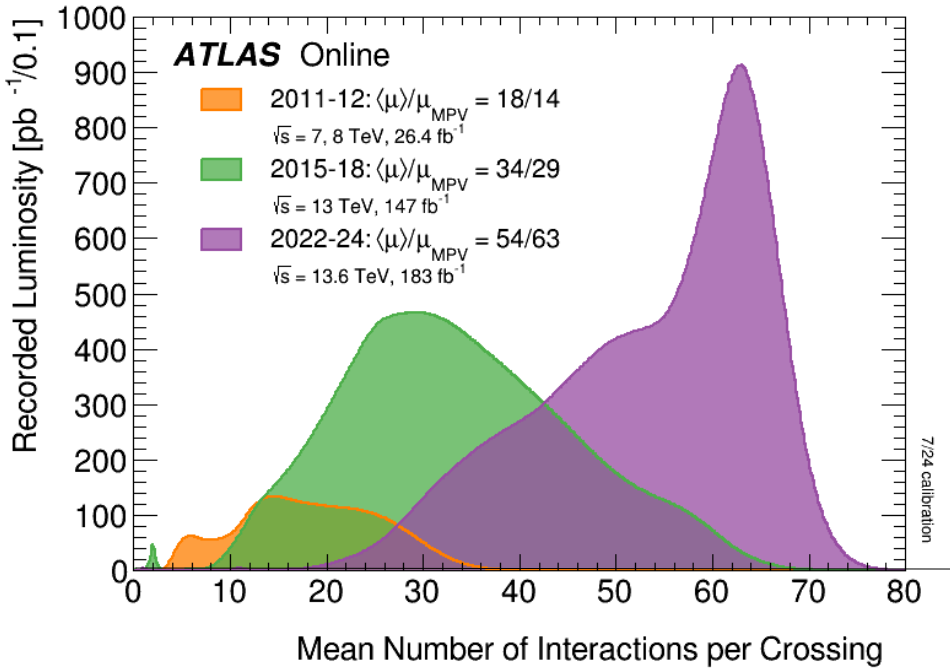
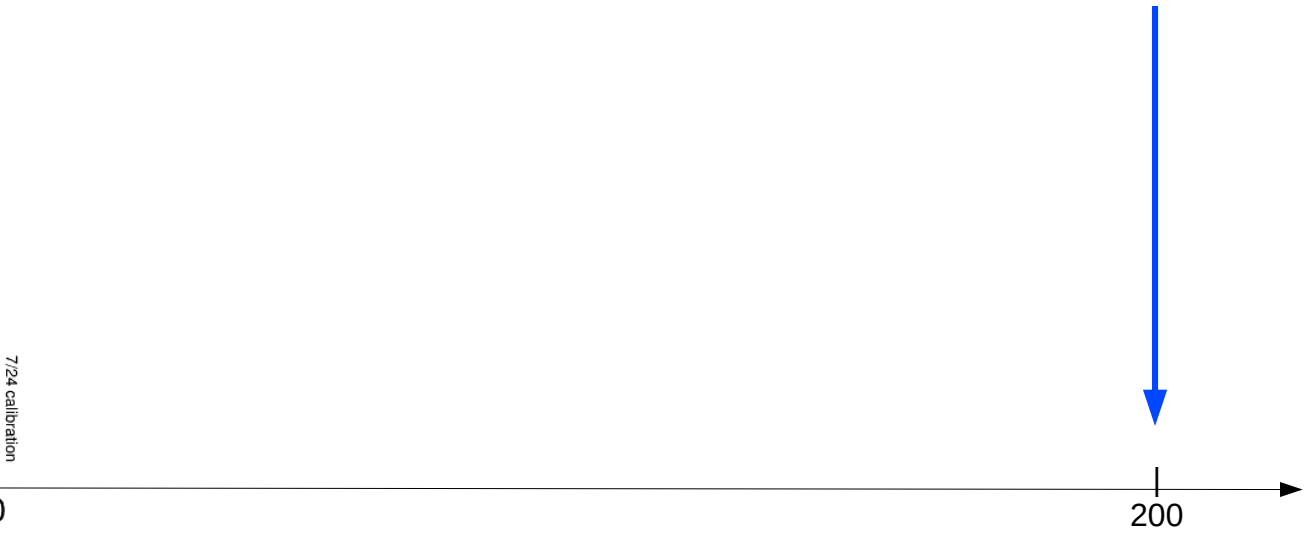


Image (cropped) from
https://hilumilhc.web.cern.ch/content/hl-lhc-project

High luminosity means many events per unit time

This has some consequences: many events per bunch crossing (pile-up)

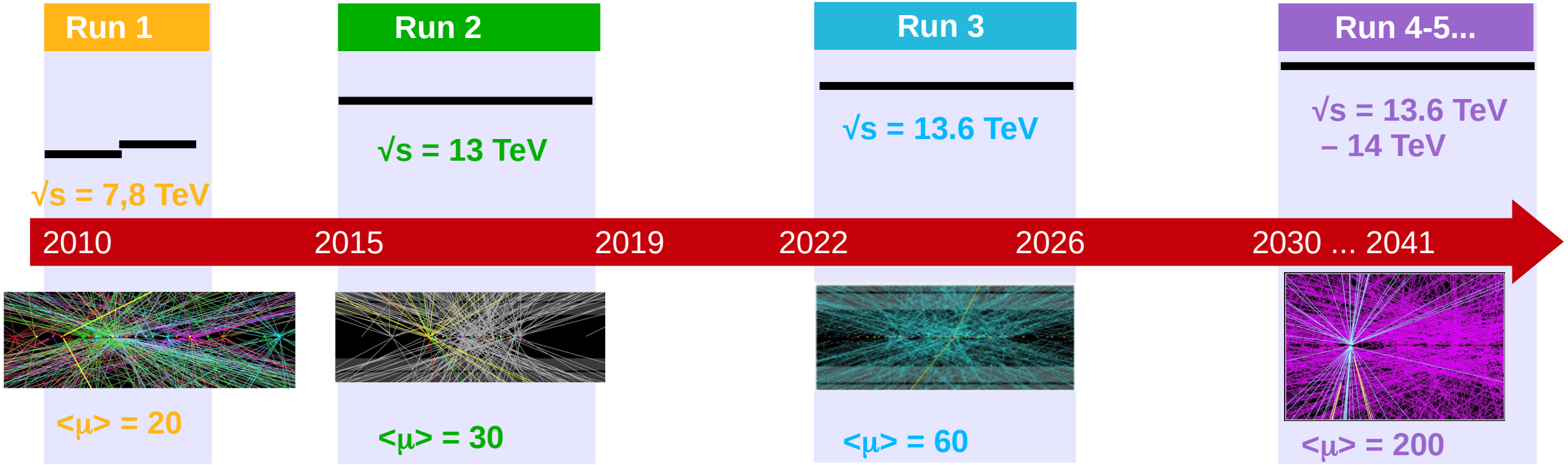




Plot from https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun3
HL-LHC logo https://hilumilhc.web.cern.ch
Layout Livia Soffi

More events per time means higher demands on detectors, read-out systems, triggers, analysis techniques...

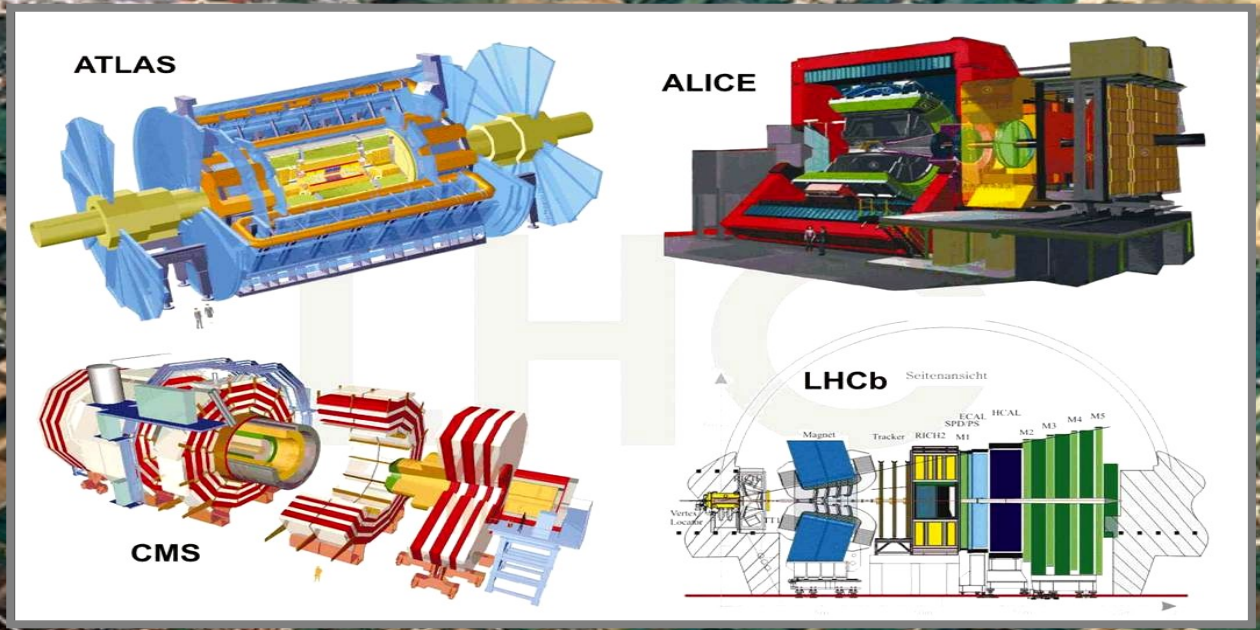
As well as increased radiation



Images: ATLAS Collaboration
Layout idea from Elizabeth Brost's talk in the Higgs10 symposium, 2022
https://indico.cern.ch/event/1135177/

Also the detector needs to be upgraded

LHC



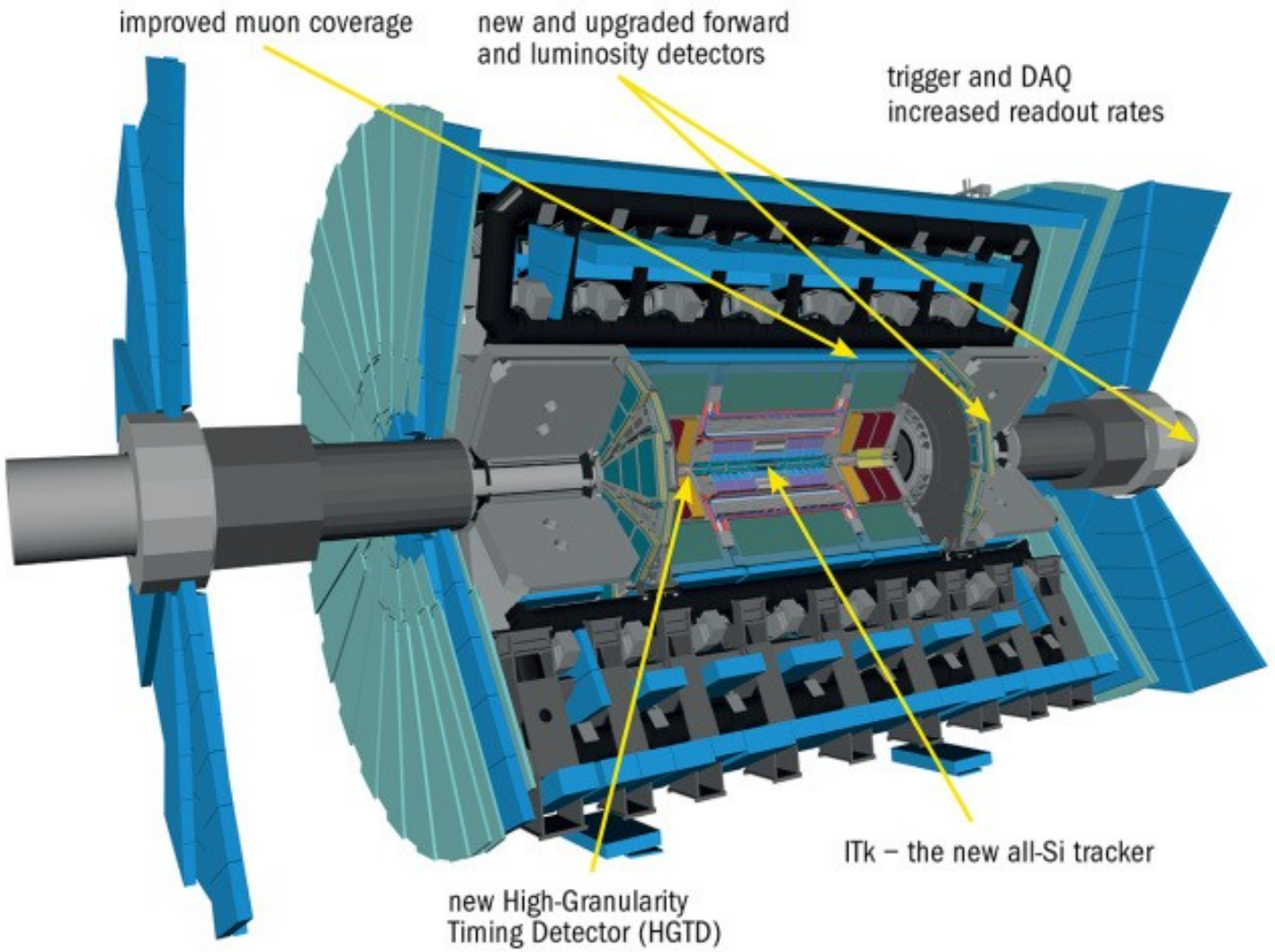
experiments

ATLAS upgrades for HL-LHC

New Detectors:

New Inner Tracking Detector **ITk** (all silicon tracker)

High Granularity Timing Detector **HGTD**



ATLAS-PHOTO-2023-002-4

Upgraded **Trigger and Data Acquisition System**

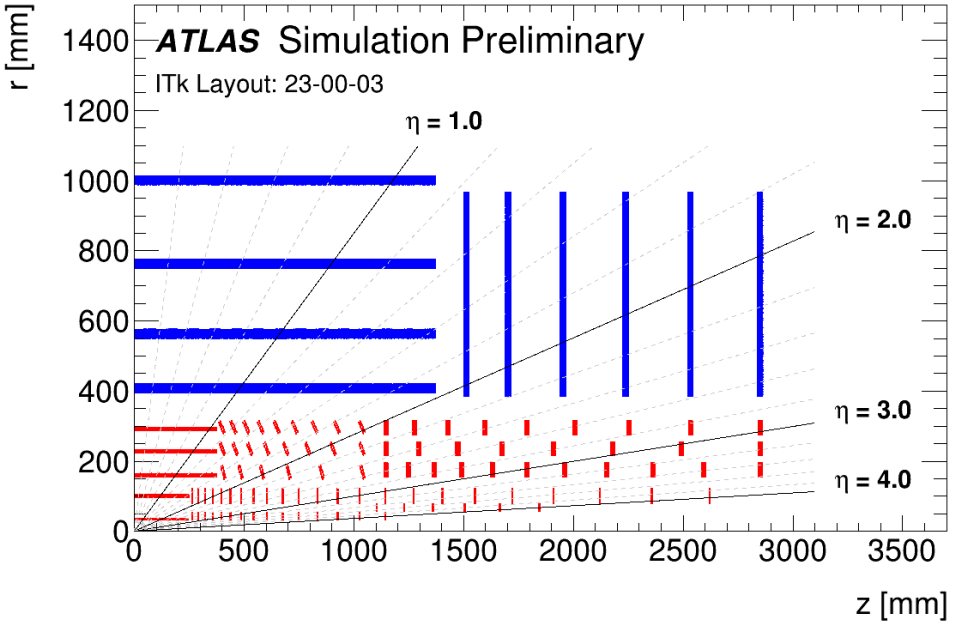
- First-level triggering also on ITk data
- Read-out to permanent storage increased from ~4kHz to ~10kHz

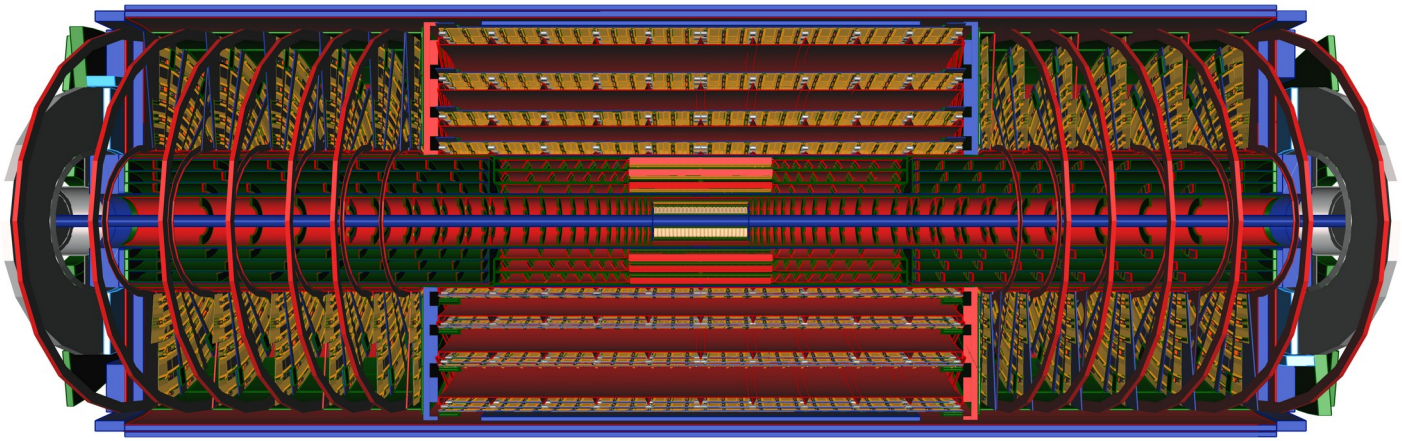
Electronics Upgrade:

- LAr and Tile Calorimeters
- Muon system

The ATLAS Inner Tracker – ITk

- Increased radiation at HL-LHC: replace the existing Inner Detector (ID) with a new *full-silicon* Inner Tracker (ITk).
- ITk composition: Pixel and Strip sub-detectors
- Extend the pseudo-rapidity coverage up to |η| = 4



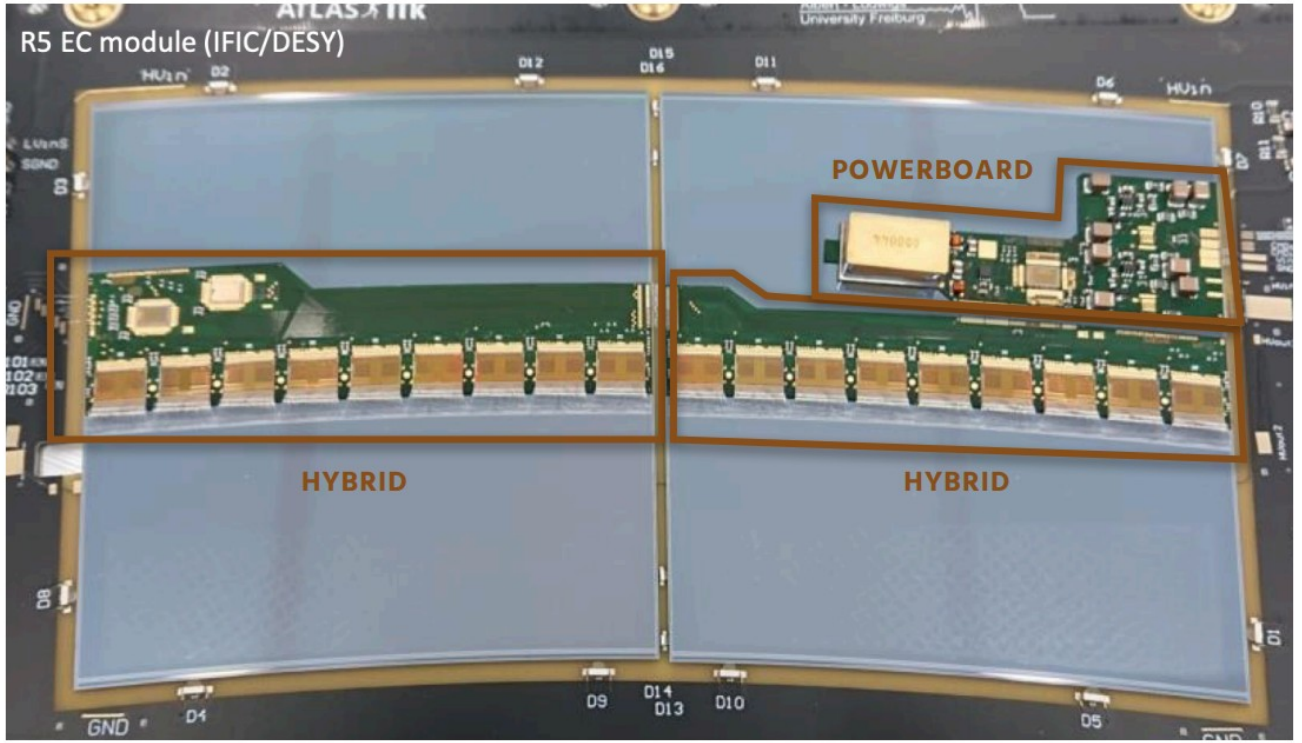


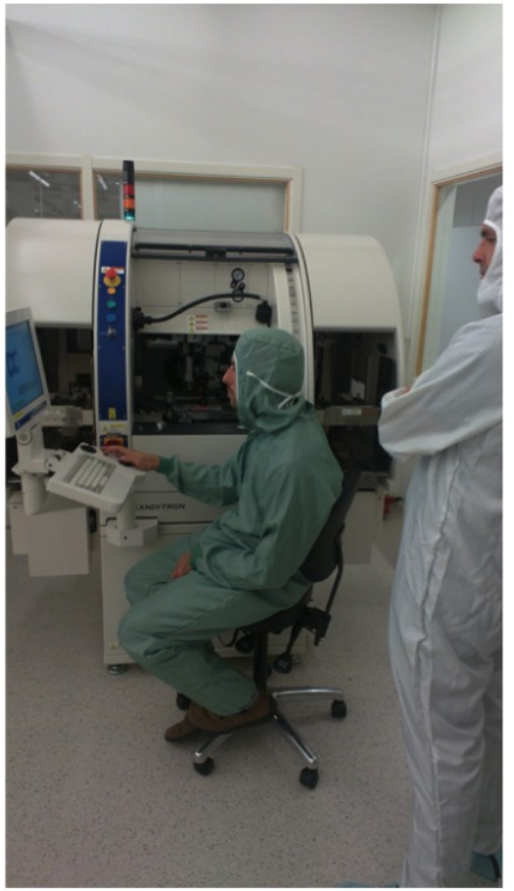
Images: ATL-PHYS-PUB-2021-024

ITk strip module production

Two Swedish institutes are involved in ITk strip module production: Uppsala and Lund.

Production in collaboration with industry (NOTE in Norrtälje)





Images: H Herde, G Mullier

Simulated $t\bar{t}$ event in ITk, pileup 200

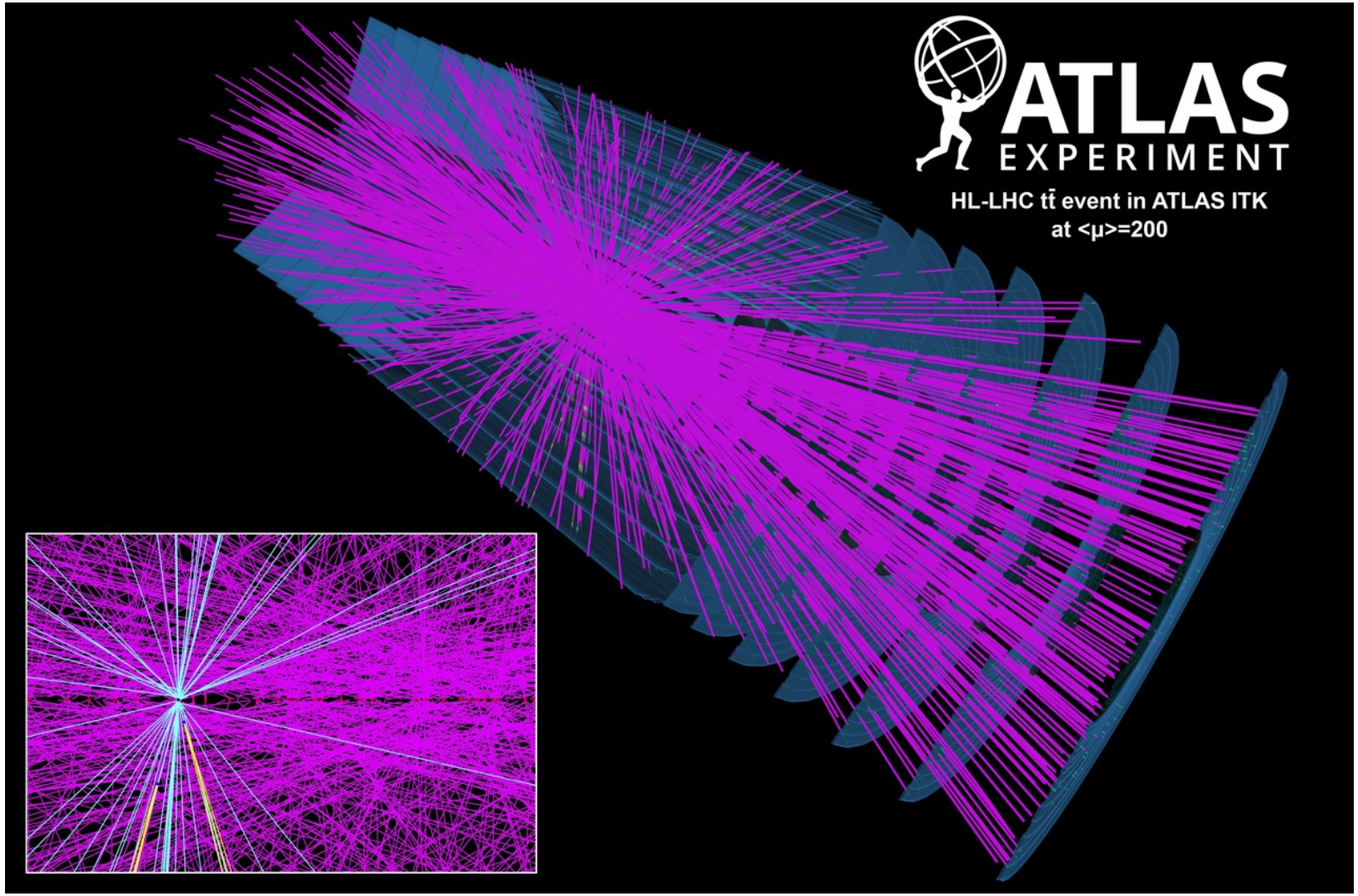
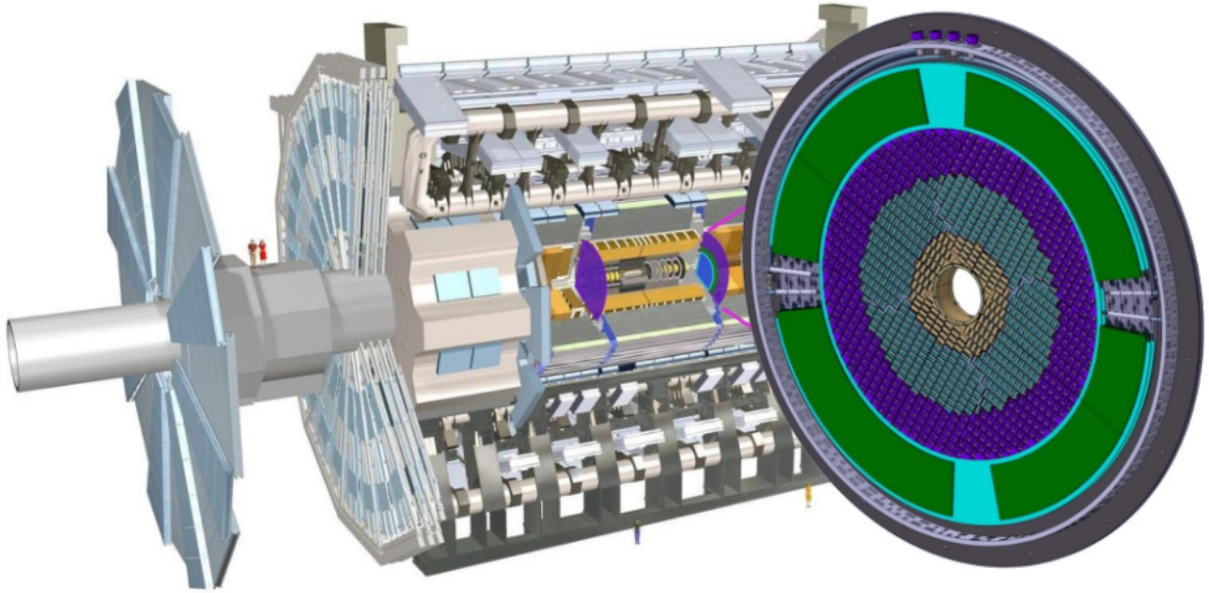
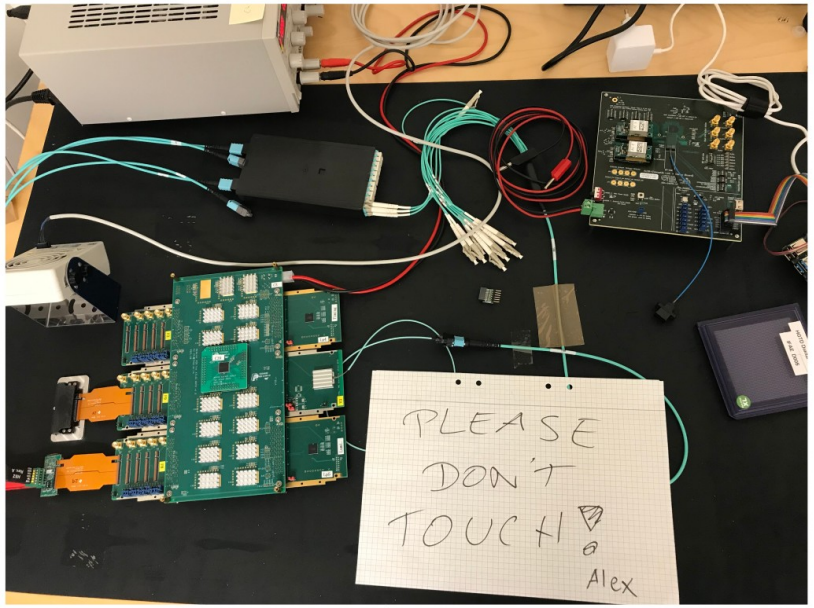


Image: https://atlas.cern/updates/news/scientific-potential-high-luminosity-lhc

High-Granularity Timing Detector, HGTD

- Mitigate the pile-up: find a way to distinguish between collisions which occur close in space but separated in time.
- Four layers of silicon modules, covering $2.4 < |\eta| < 4.0$
- KTH in Stockholm develop software and firmware for HGTD for luminosity measurements





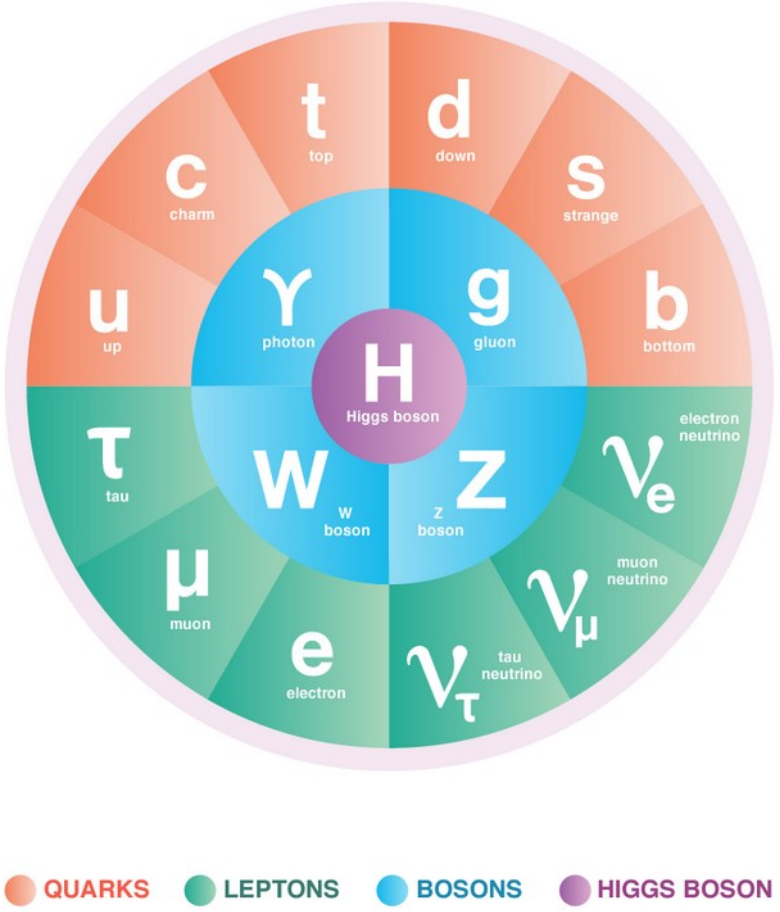
Images: ATLAS-TDR-031, KTH (via H Herde Fysikdagarna 2023)

Physics prospects

The Standard Model (SM) is an extremely successful theory of particles and interactions, but it is incomplete

Open questions in particle physics:

- What is the nature of the Higgs boson? Elementary or composite? Part of an extended sector of Higgs bosons?
- What is the shape of the Higgs potential?
- What is the nature of dark matter?
- Why is there so much more matter than anti-matter in the universe?
- What about the quark-gluon plasma?



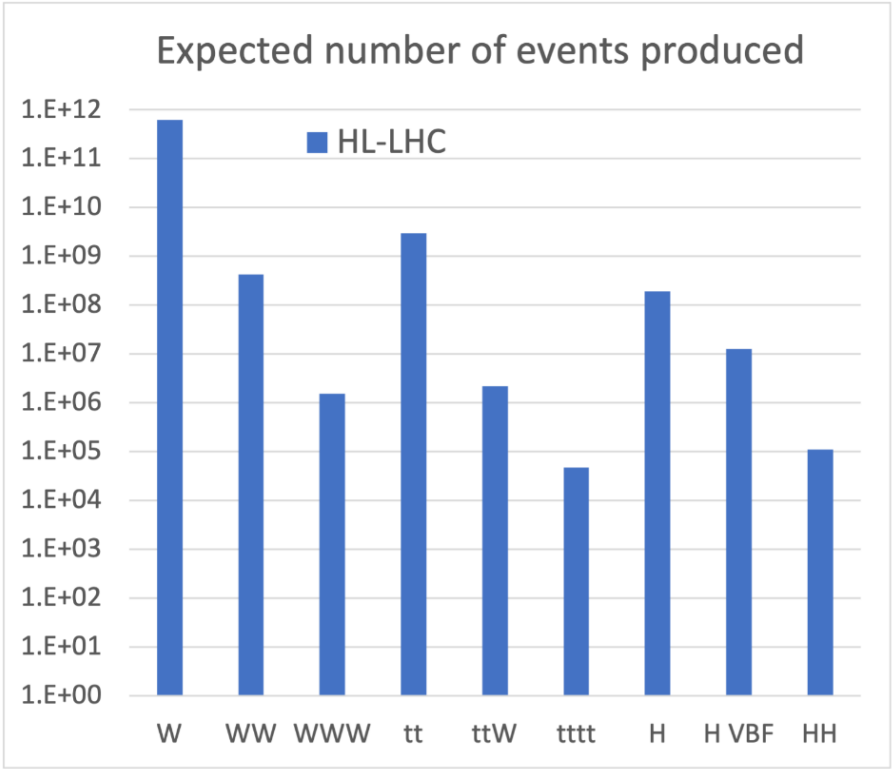
Symmetry magazine

Physics prospects

Possible E_{CM} increase from $\sqrt{s}$ = 13.6 TeV to $\sqrt{s}$ = 14 TeV will give substantial cross section increase for heavy particles only.

Number of particles produced (expected) for ATLAS with 3,000 fb^{-1} at $\sqrt{s}$ = 14 TeV

- ~600,000,000,000 W bosons
- ~3,000,000,000 $t\bar{t}$ pairs
- ~190,000,000 Higgs bosons
- ~120,000 HH pairs
- ~50,000 $t\bar{t}t\bar{t}$ events



Stephane Willocq, LHCP2024

Properties of the Higgs boson

- HL-LHC will be a Higgs boson factory
- The Higgs mechanism is what gives elementary particles their mass.
  The Higgs boson is the manifestation of this mechanism.
- Important to investigate the properties of this newest addition to the SM
- Measure coupings and branching ratios with high precision
- Deviations from SM? Possible new physics!

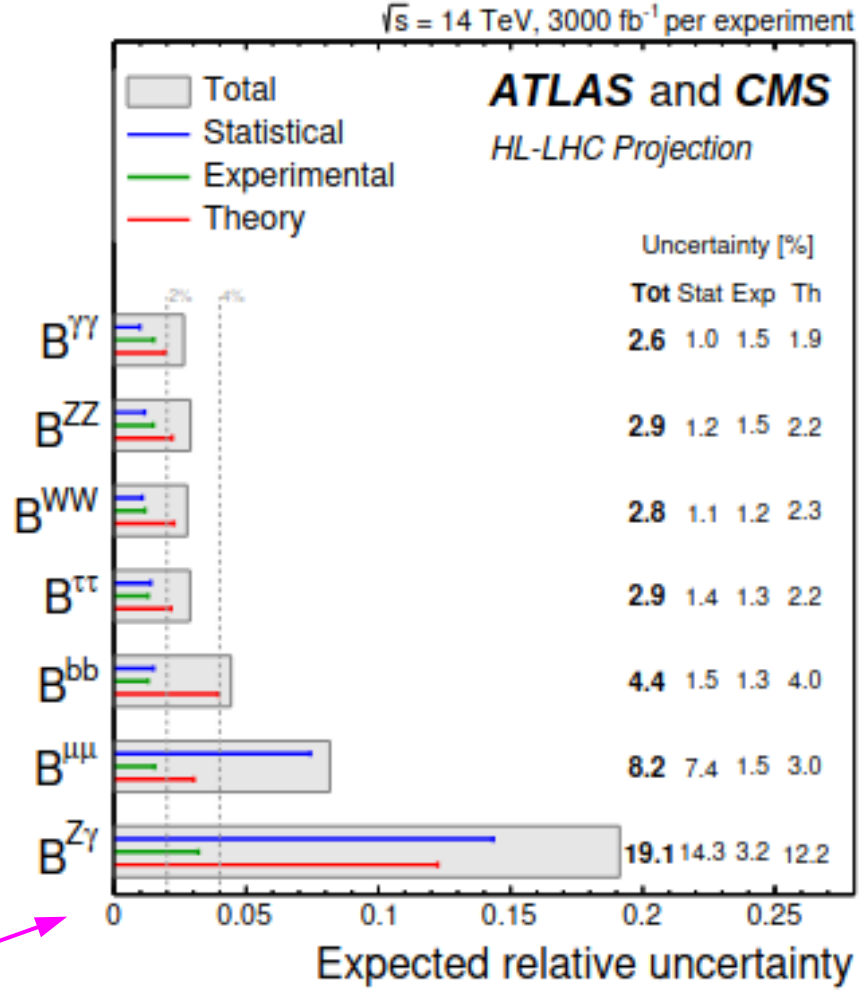


Figure:
Expected relative uncertainty of the branching fraction of the Higgs boson when decaying into γγ, ZZ, WW, tt, bb, μμ, Zγ

CERN-2019-007 (Yellow Report) p 285

Measurement of the Higgs potential

- The Higgs boson has mass – so it interacts with itself!
- How? What is the nature of the Higgs potential?
- The SM Higgs potential is close to a metastable state – the fate of the universe depends on this!

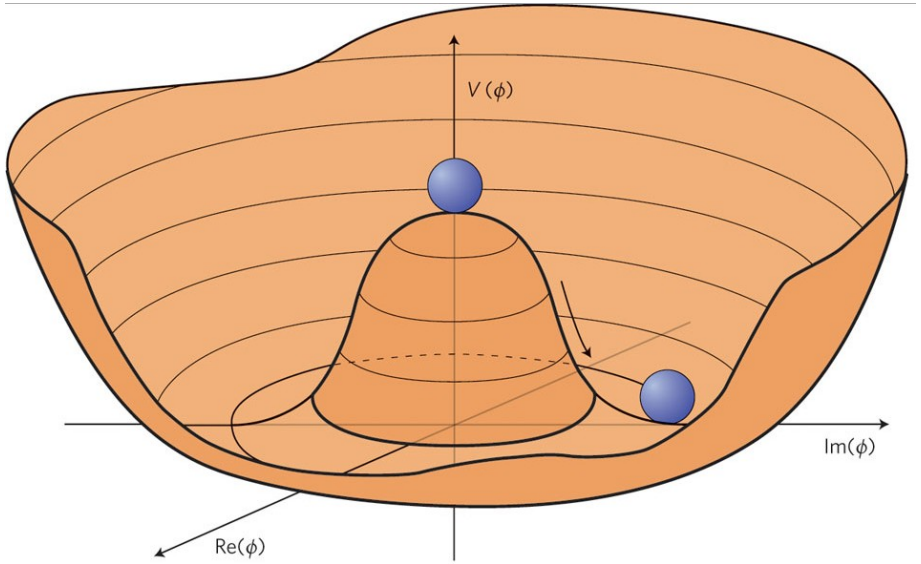


Image: arXiv:1309.0721

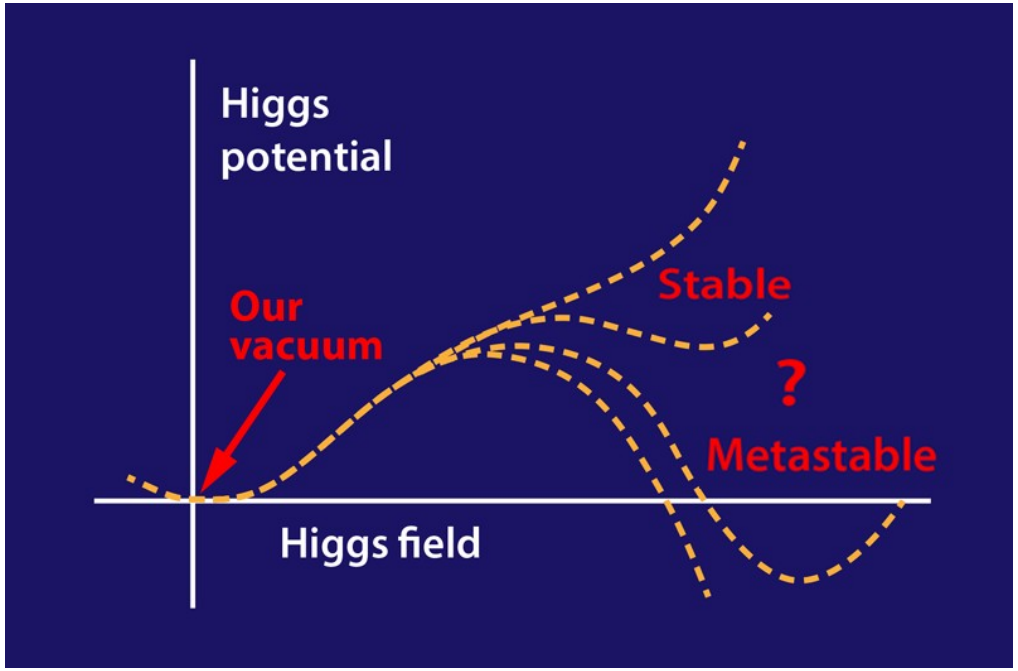
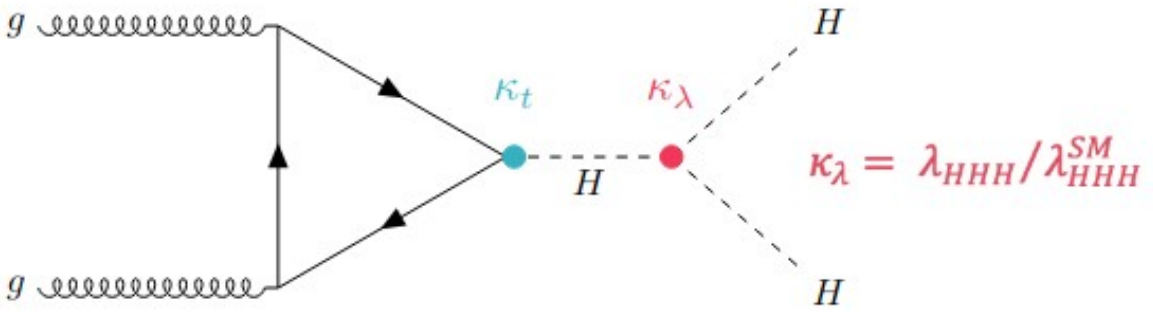
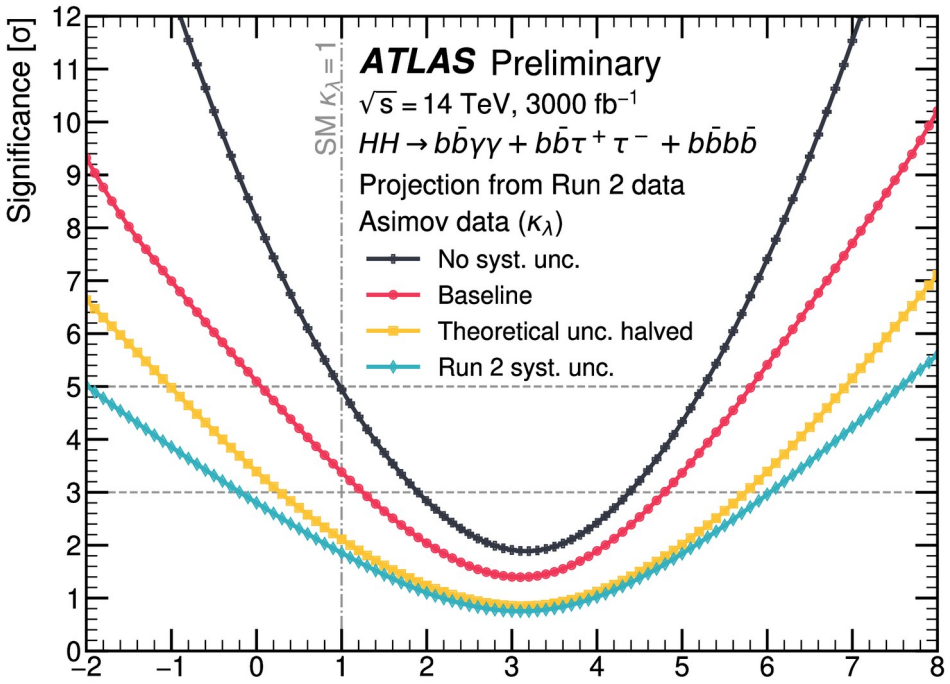


Image: APS / Alan Stonebraker

Measurement of the Higgs potential: HH production

- The production of pairs of Higgs bosons offers a way to probe the Higgs self-coupling.
- ATLAS expected to reach 3.4 σ in HL-LHC (SM couplings)
  Discovery together with CMS might be possible!





C Dimitriadi, Phenomenology 2023 Symposium

ATL-PHYS-PUB-2022-053

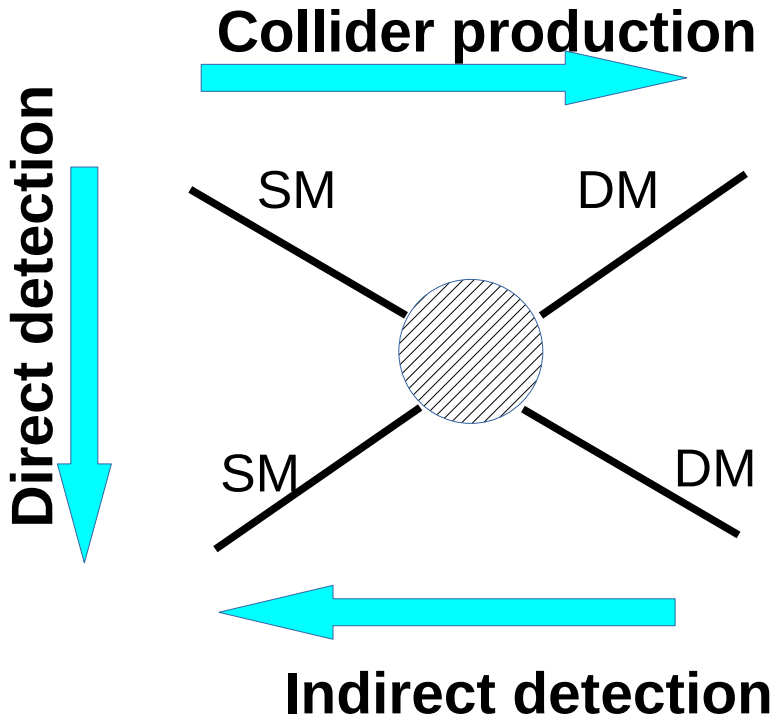
What is the origin of Dark Matter?

- Dark matter exists, it constitutes about ~25% of the universe, ...and we don't know what it is...

Bullet Cluster
http://apod.nasa.gov/apod/ap060824.html

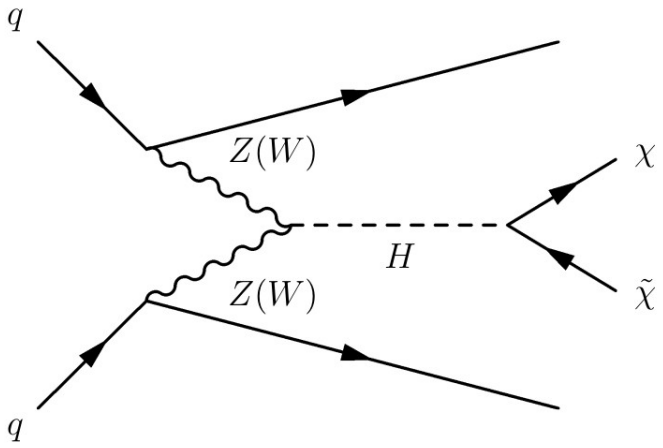
Detection principles

- **Direct detection** – DM scatters off SM (nuclear recoil, annual modulation)
- **Indirect detection** – observation of products of decays, annihilations
- **Collider** production of DM. New invisible particles created, transverse momentum seemingly not conserved.



Dark matter through a Higgs portal?

- Possibly the Higgs boson interacts with a dark sector
- Search for H → invisible (H → ZZ* →νννν has a low BR in the SM)



- Increased luminosity will help setting limits on (or finding...) Higgs to invisible, feebly inteacting particles, long-lived particles..

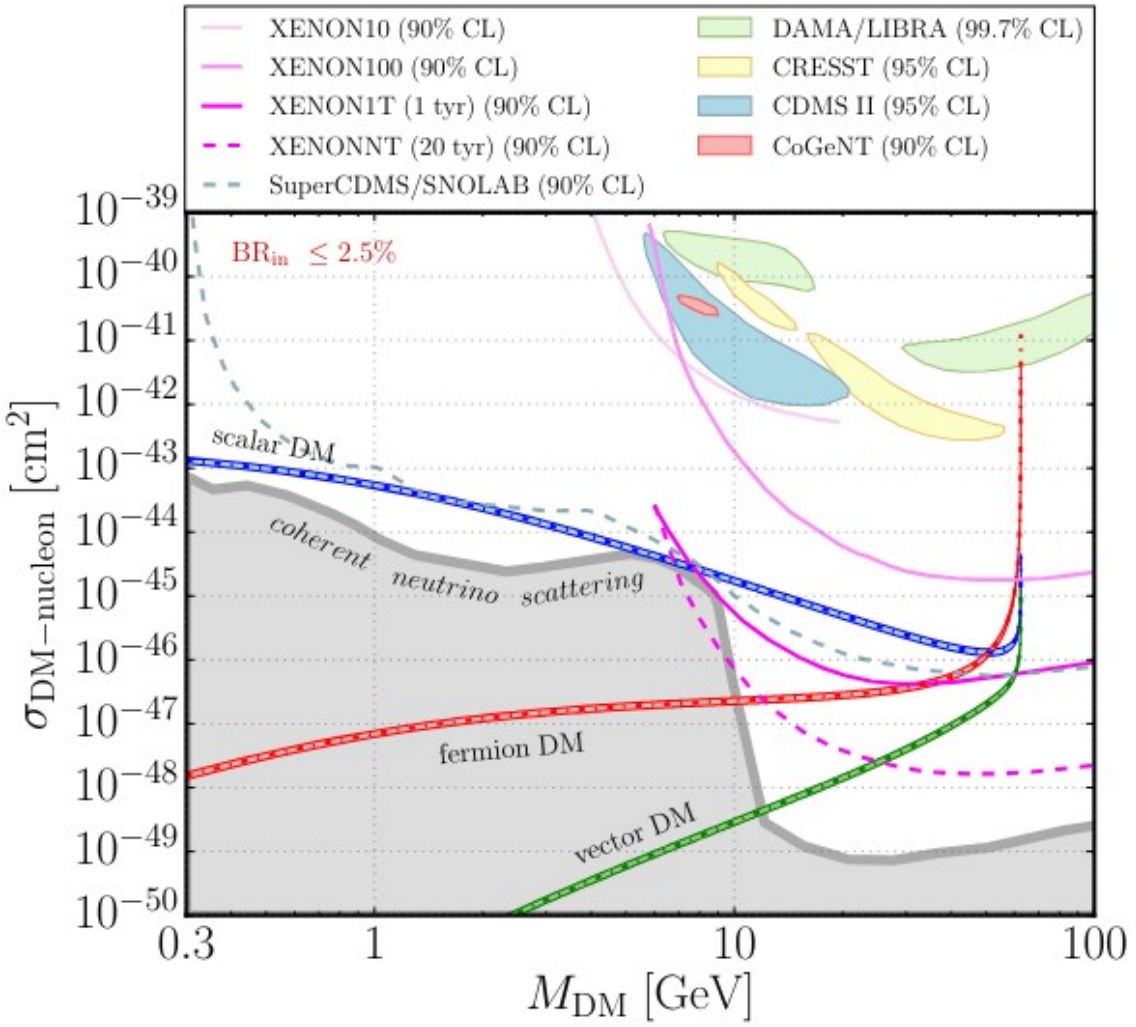


Figure: DM-nucleon cross section expectations at HL-LHC, compared with direct detection experiments. Grey area is inaccessible to direction detection.

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Summary

- HL-LHC will bring significant challenges (pile-up, increased radiation)
- ... but also en enormous increase in the amount of data
- Swedish institutes are involved both in the upgrade of ATLAS and in studies which will greatly benefit from the incrase in data (HH searches, Higgs precision measurements, long-lived particles...)
- We have so far analysed only about 10% of what we expect LHC and HL-LHC to deliver!

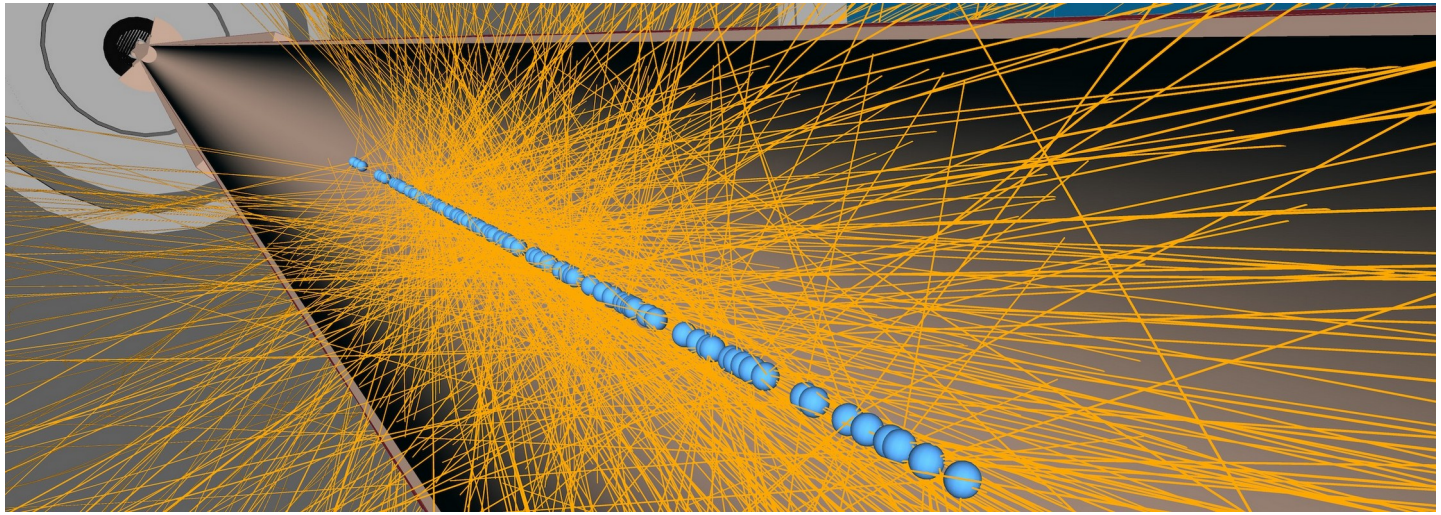

Image: https://atlas.cern/Updates/Feature/High-Luminosity-ATLAS