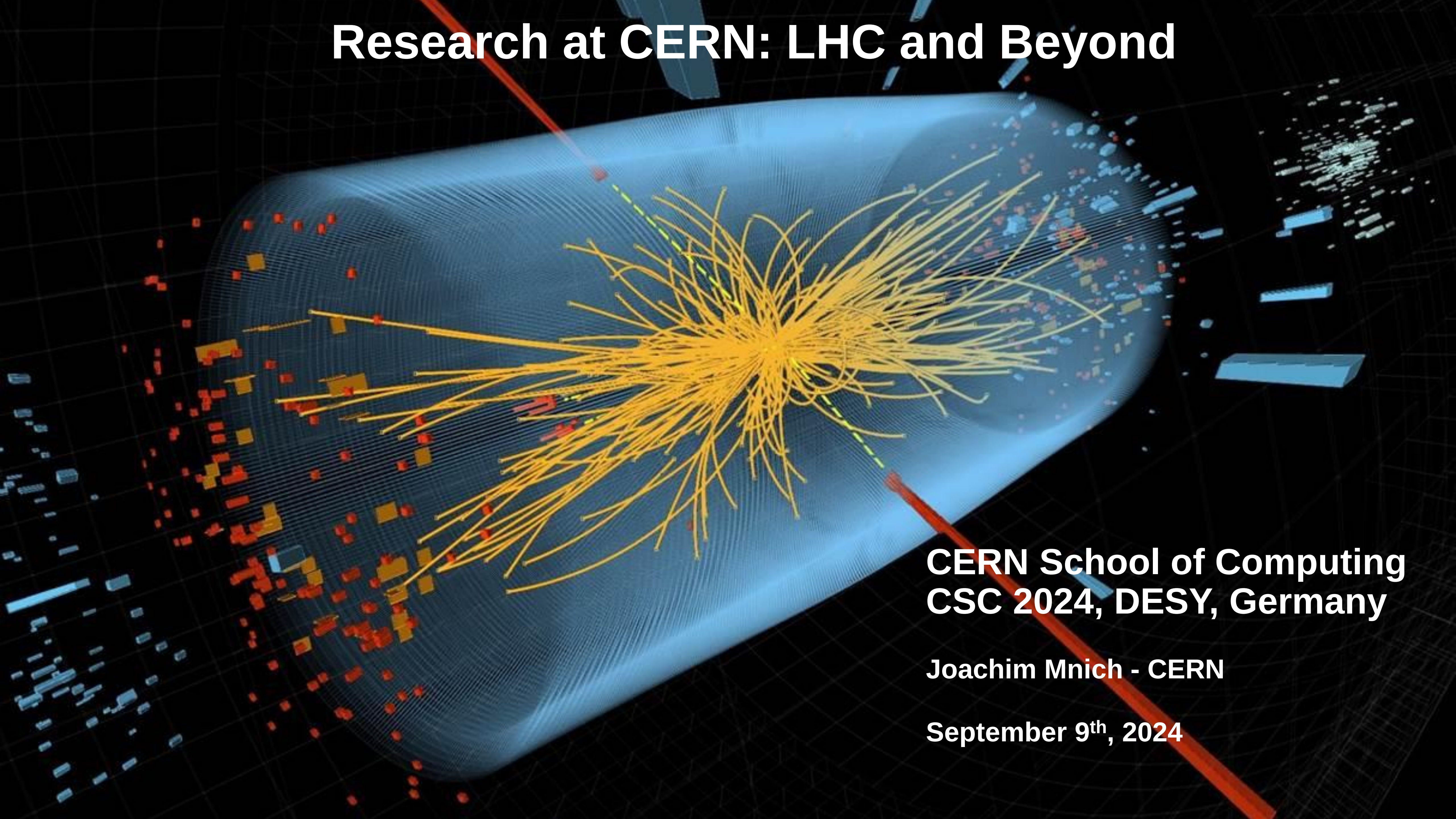
Research at CERN: LHC and Beyond

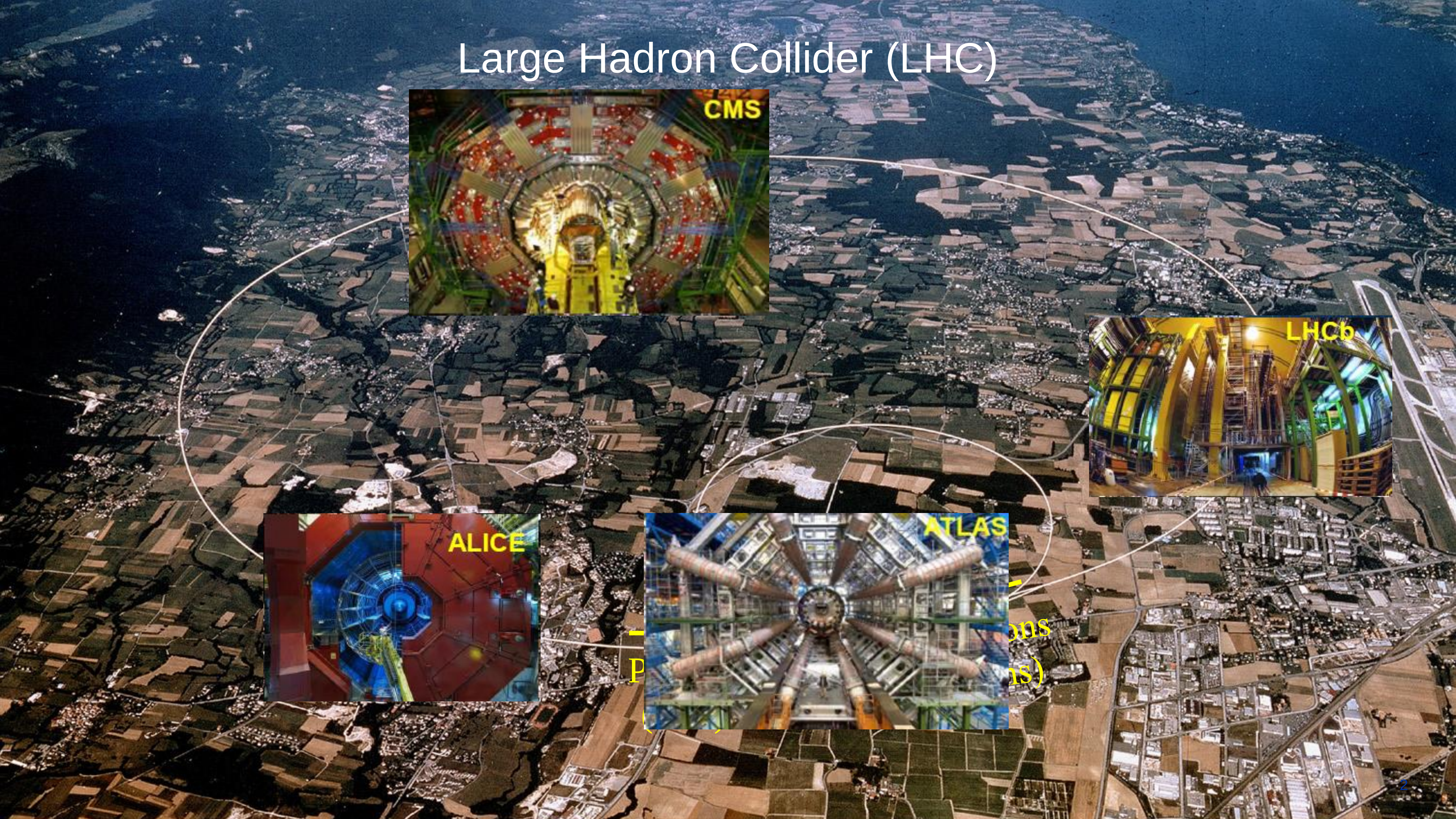


CERN School of Computing
CSC 2024, DESY, Germany

Joachim Mnich - CERN

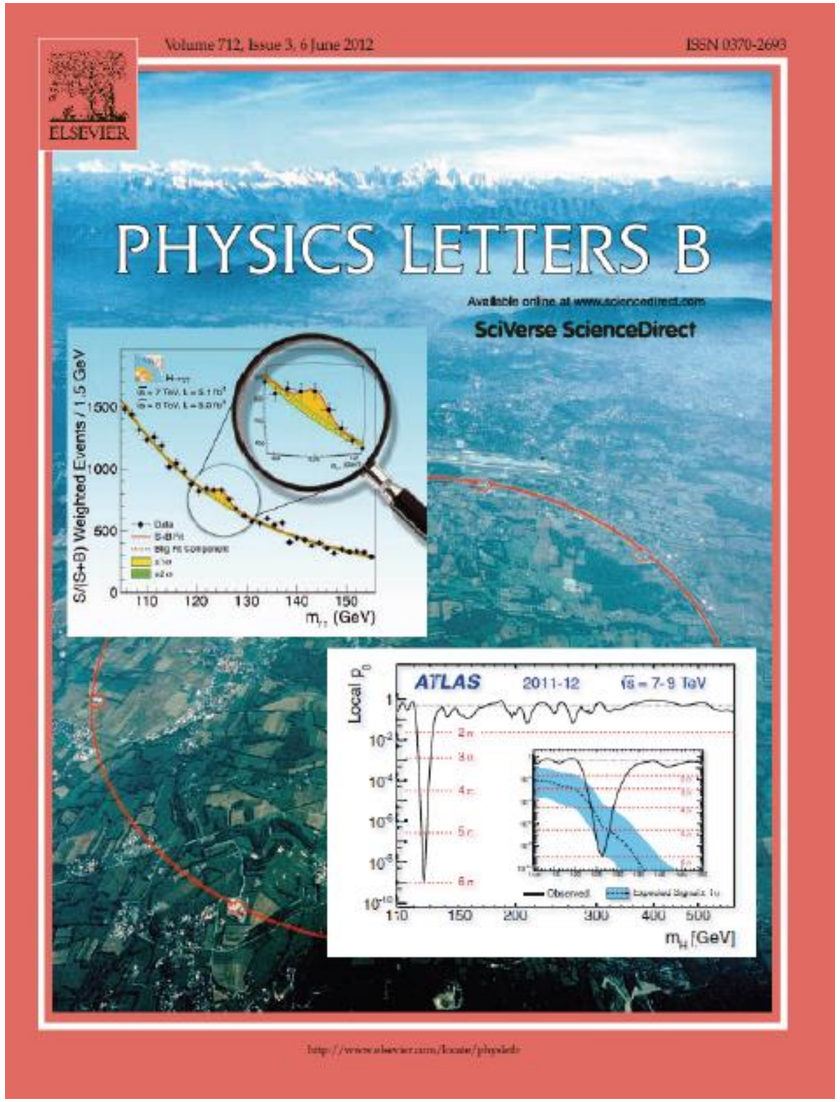
September 9th, 2024

Large Hadron Collider (LHC)



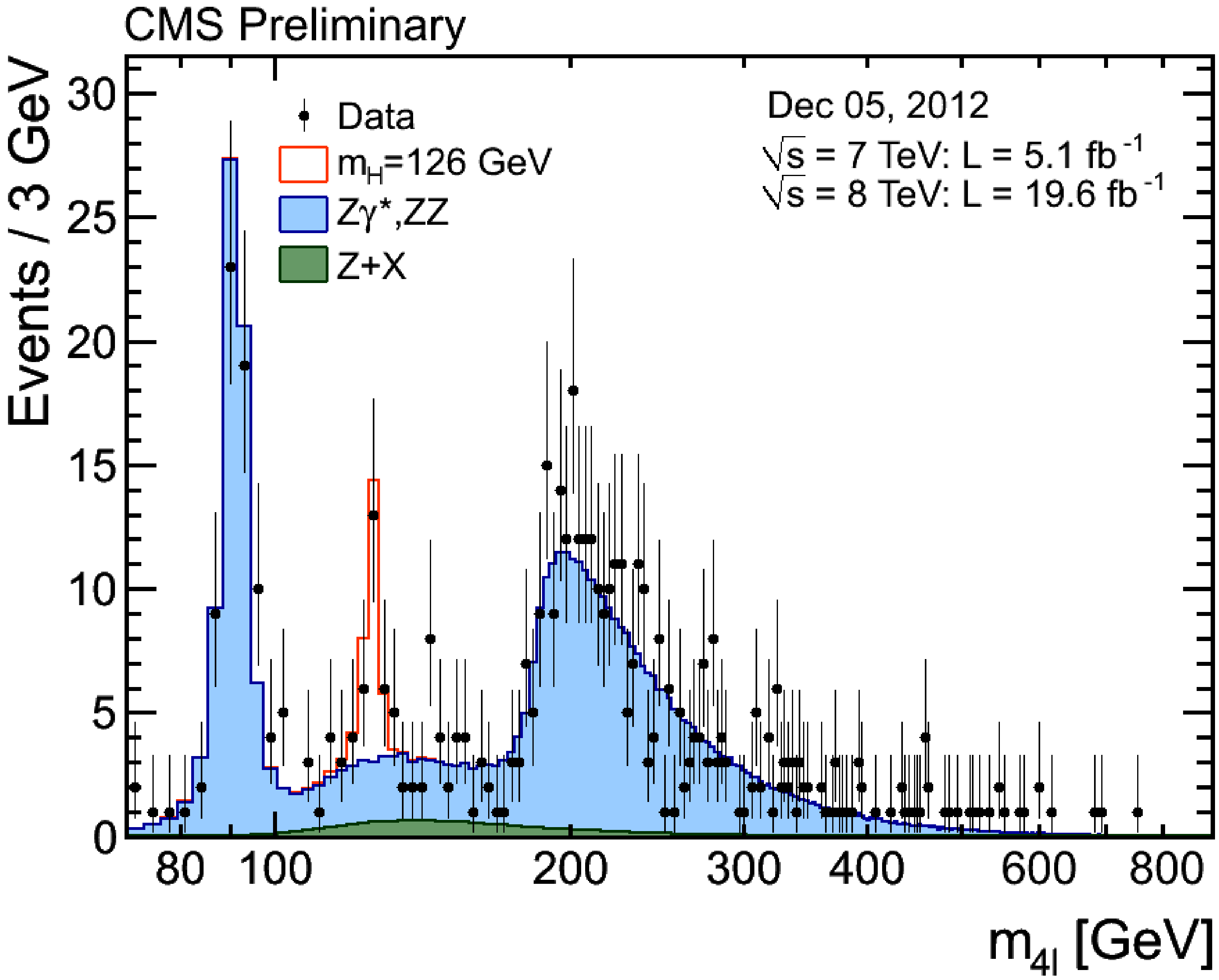
The Discovery of the Higgs Boson

- After first pp collisions in 2009 the LHC and the experiments started operation in 2010
- In 2012 enough data were collected for the first big discovery: the Higgs boson
- Francois Englert and Peter Higgs
  - at the announcement on 4.7.2012
  - Nobel Laureats in physics 2013



How to Discover a New Particle?

Example from CMS:
Higgs-Boson Decay
to 4 Leptons (e,μ)



Achievements since the Higgs Boson Discovery

Example: measurement of the Higgs couplings to fundamental particles

From ATLAS result based on the full data set taken until 2018 (Run 2)

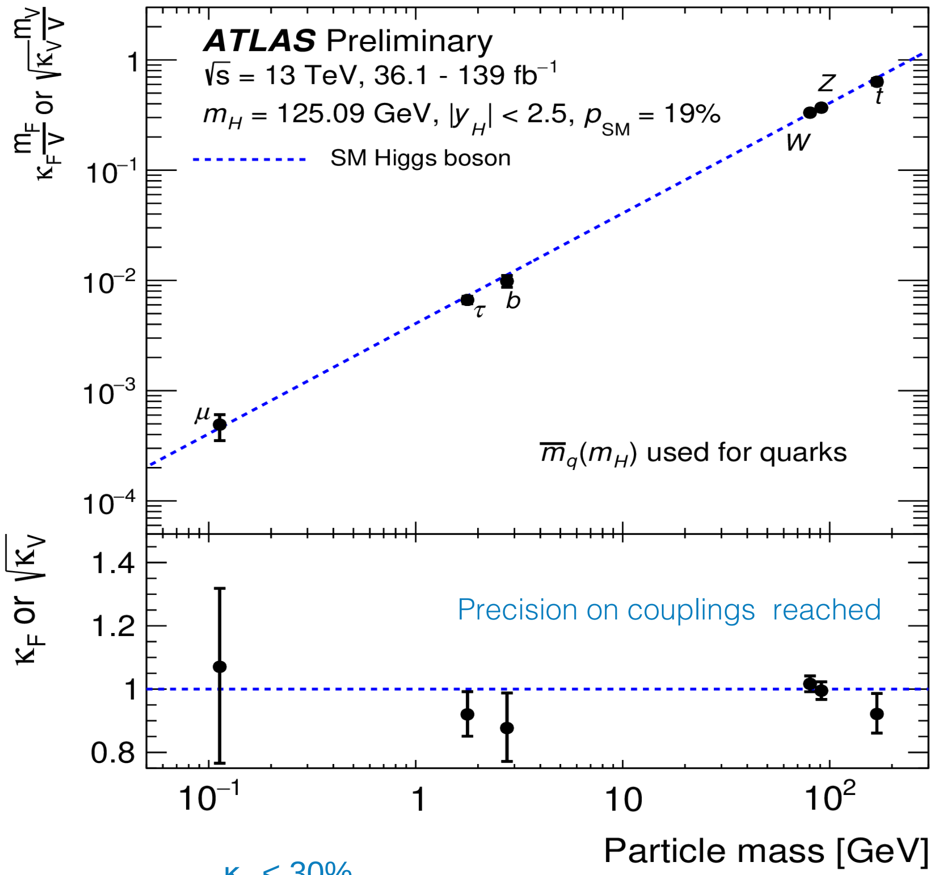
Key prediction of the Standard Model:

- Higgs coupling to particles is proportional to their mass

Impressive verification with an accuracy often better than 10%

Coupling measurements ($B_i = B_u = 0$)

$\kappa_\gamma = 1.04 \pm 0.06$, $\kappa_g = 0.92^{+0.07}_{-0.06}$, $\kappa_{Z\gamma} = 1.37^{+0.31}_{-0.37}$

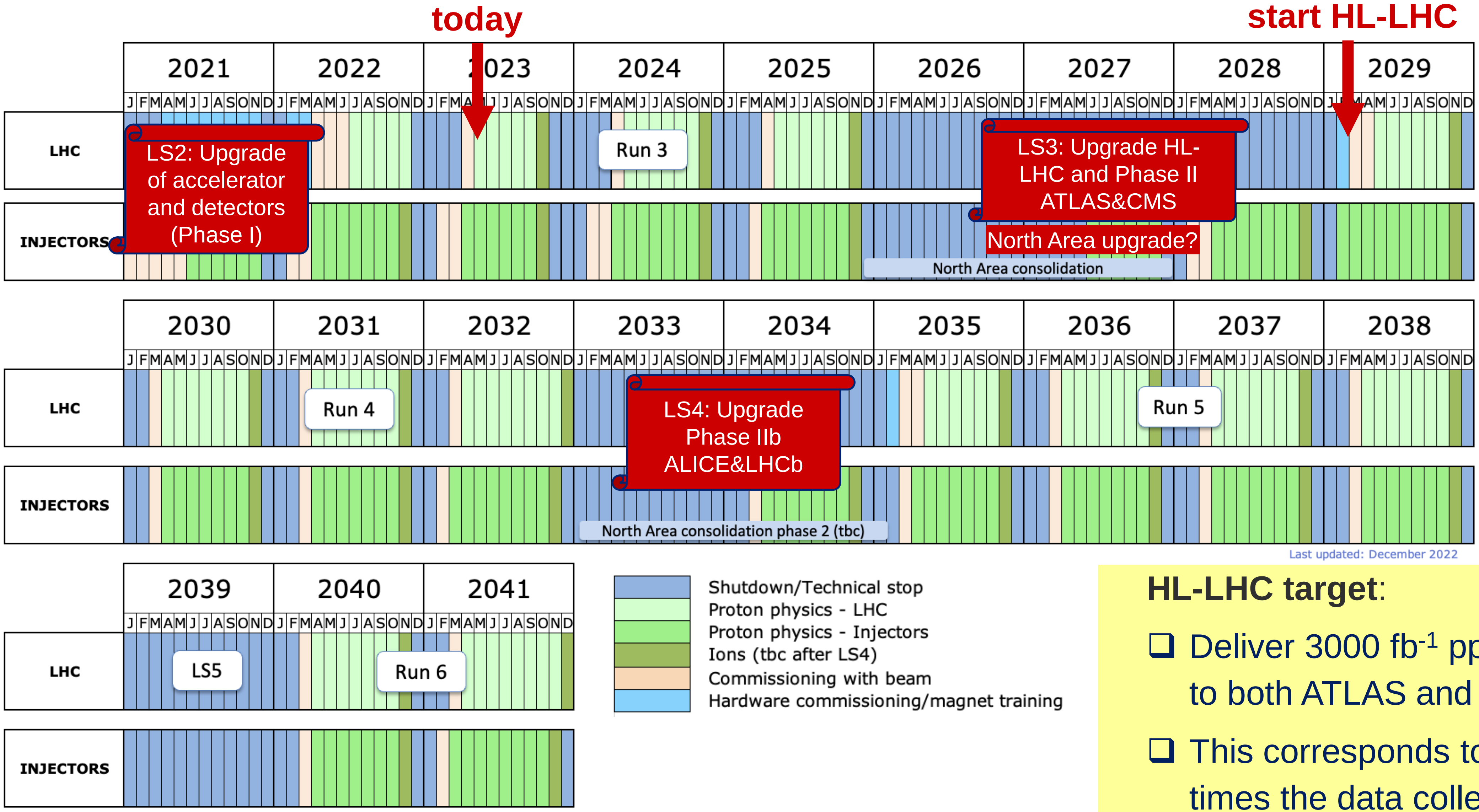


ATLAS-CONF-2021-053

$\kappa_\mu < 30\%$

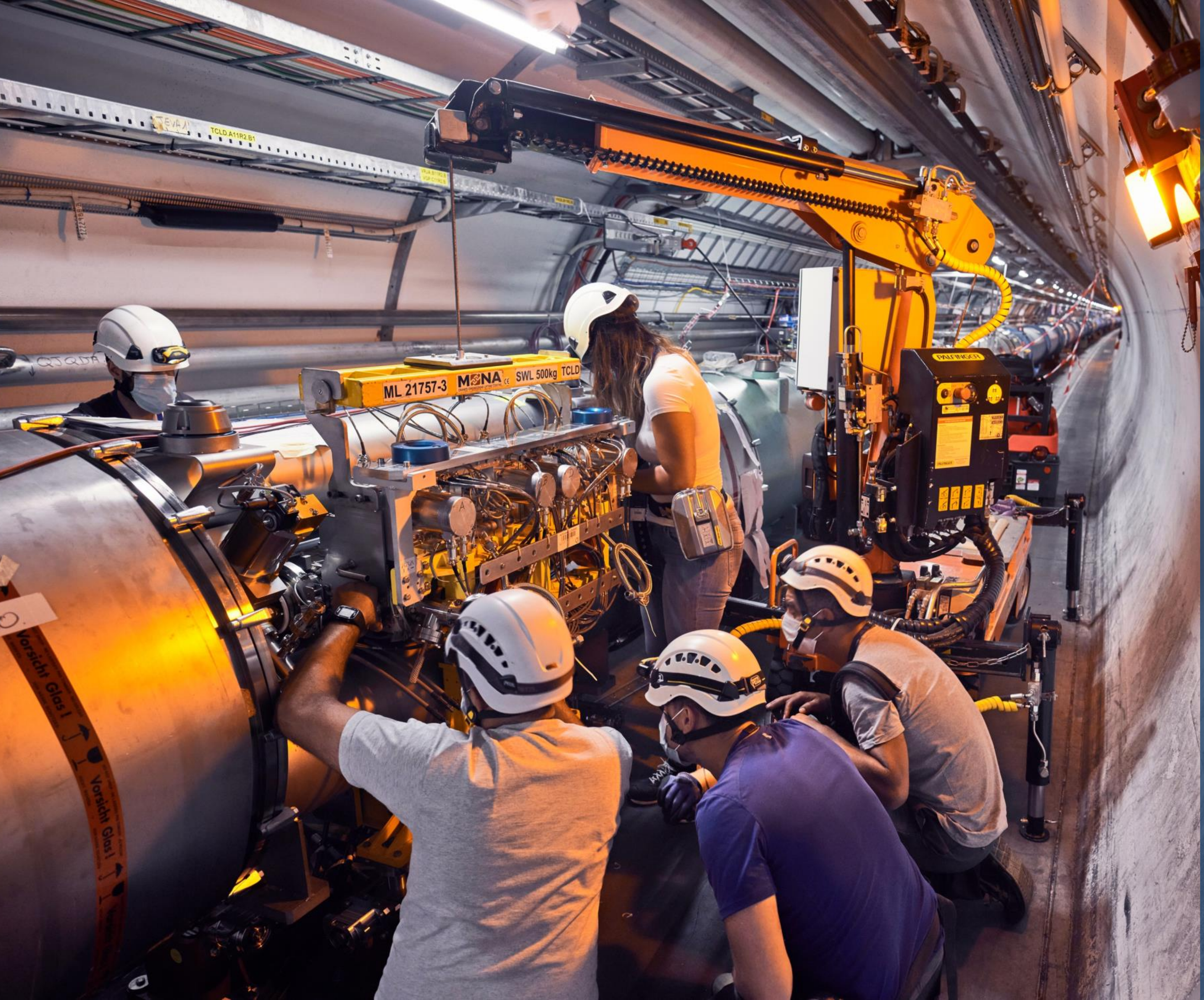
$\kappa_\tau = 7\%$ $\kappa_b = 11\%$ $\kappa_t = 6\%$ $\kappa_{W,Z} = 6\%$

LHC Timeline



HL-LHC target:

- Deliver 3000 fb^{-1} pp luminosity to both ATLAS and CMS
- This corresponds to about 10 times the data collected to date!



Upgrade to the High-Luminosity LHC is under way

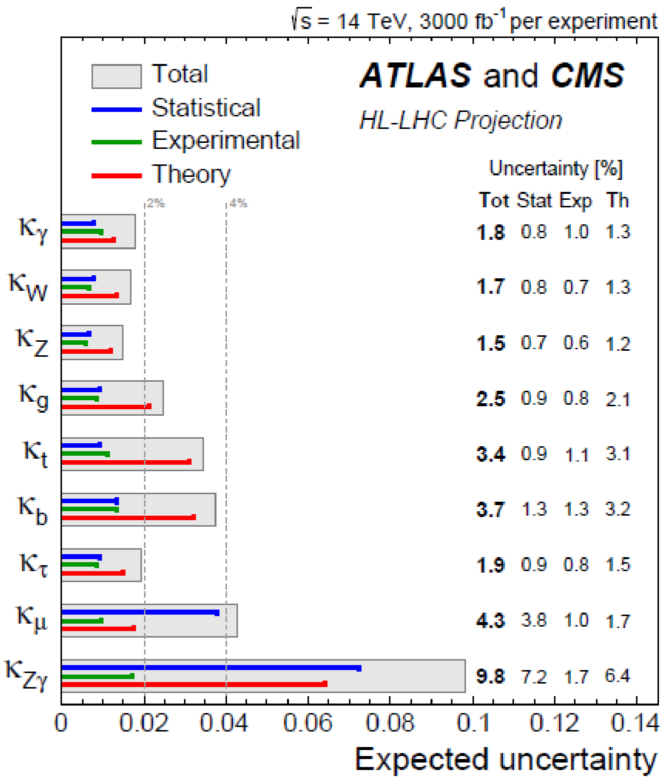
- The HL-LHC will use new technologies to provide 10 times more collisions than the LHC.
- It will give access to rare phenomena, greater precision and discovery potential.
- It will start operating in 2029, and run until 2041.

The High-Luminosity LHC

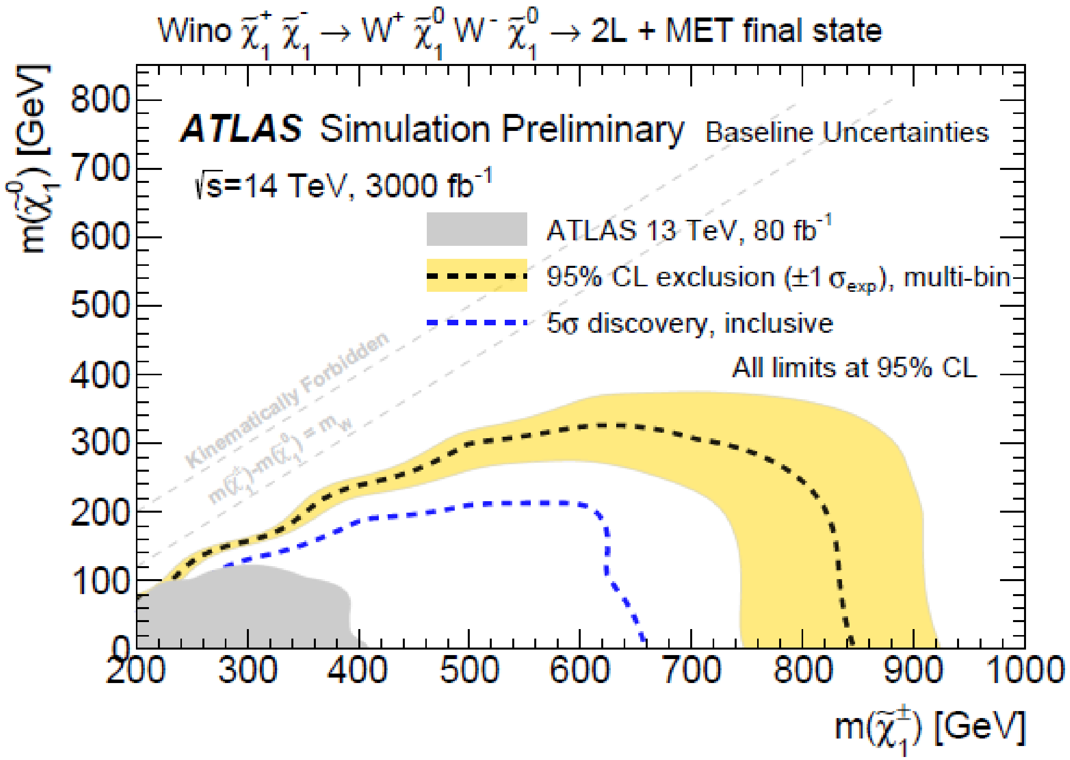
HL-LHC will provide 3000 – 4000 fb^{-1} by ≈ 2040
i.e. ≈ 20 times the currently available data

2 examples for illustration

- ❑ Will allow measurement Higgs couplings to the percent-level incl. establishing Higgs self coupling
- ❑ Significantly extend reach for new physics
- ❑ Start operation in 2029

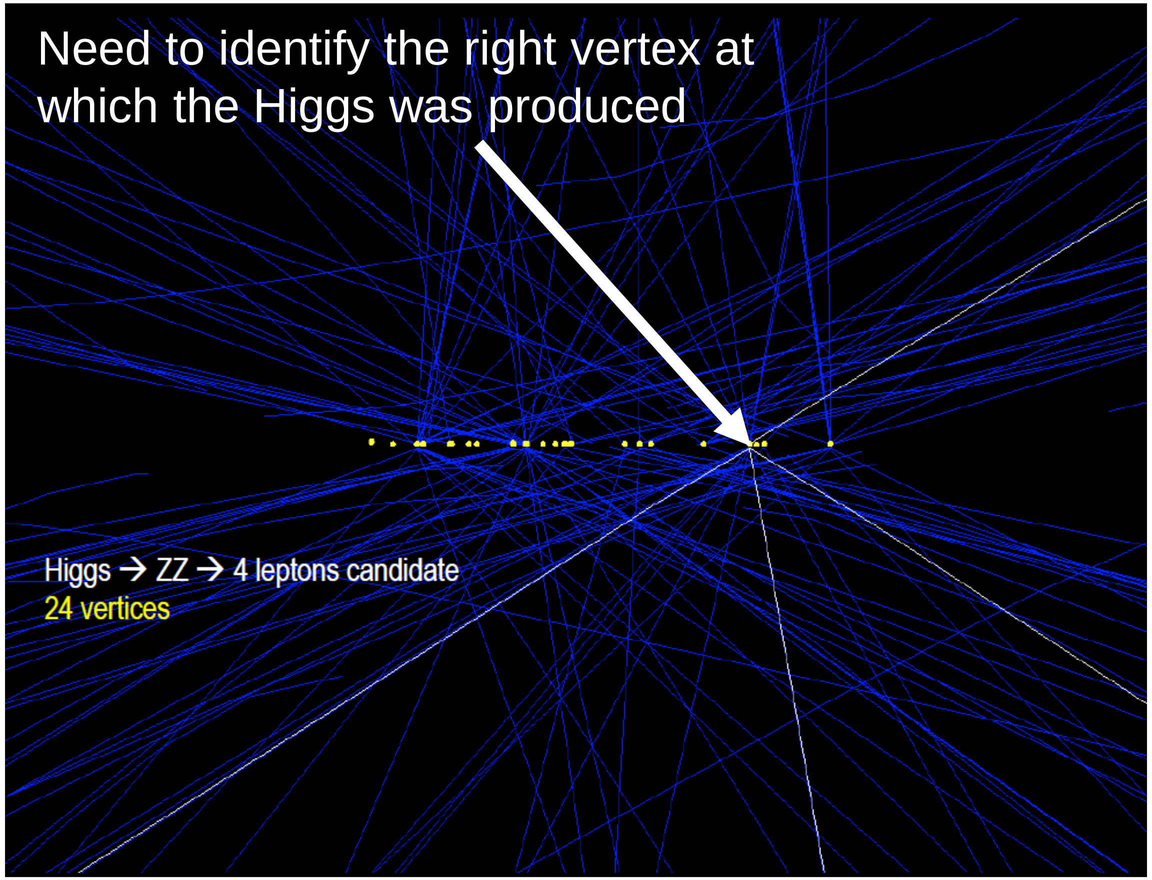


CERN-2019-007

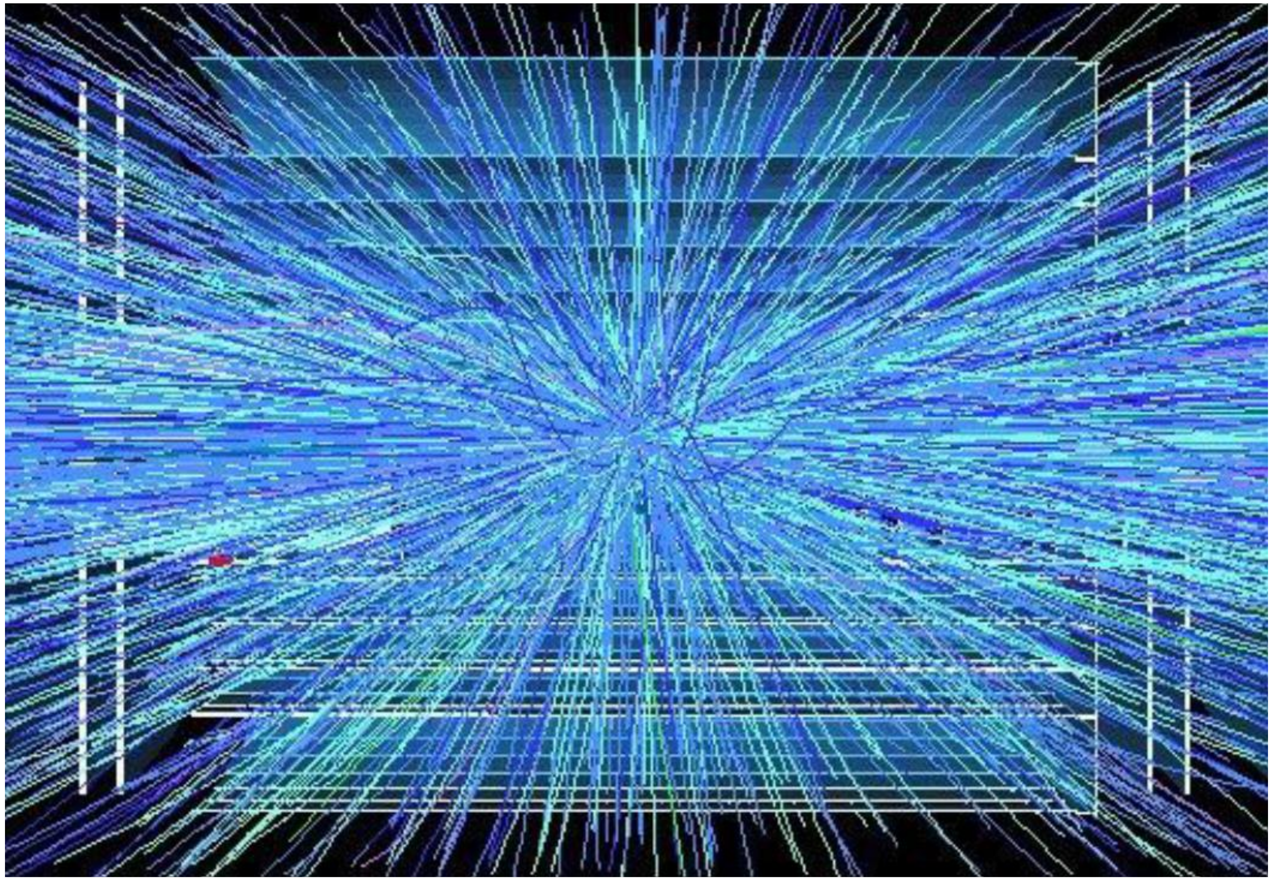


Challenges for the Detectors

- Example: event pile-up
  in 2018 typically 20 - 40 pp collisions per bunch crossing
- 2024: ATLAS & CMS run at pile-up ≈ 64!



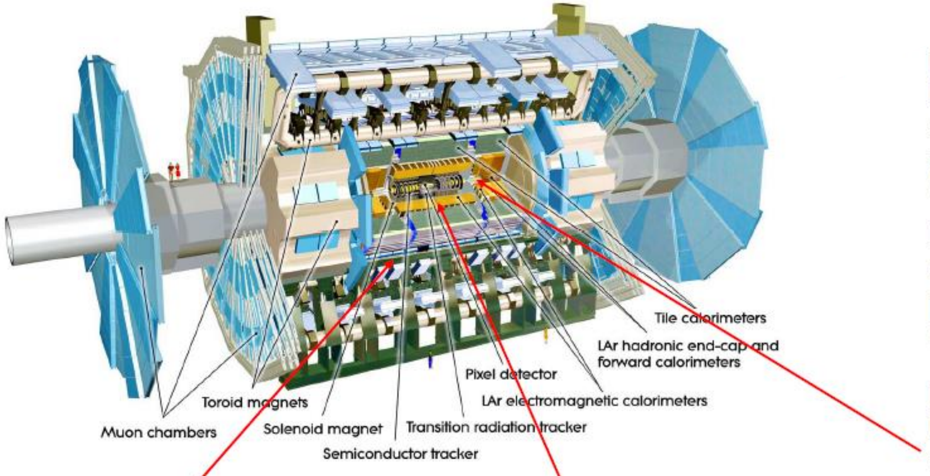
- At the HL-LHC: 150 - 200 pp collisions per bunch crossing expected



Phase II Upgrades

Two major detector upgrade projects

ATLAS



Upgraded Trigger and Data Acquisition system

Level-0 Trigger at 1 MHz

Improved High-Level Trigger (150 kHz full-scan tracking)

Electronics Upgrades

LAr Calorimeter

Tile Calorimeter

Muon system

High Granularity Timing Detector (HGTD)

Forward region ($2.4 < |\eta| < 4.0$)

Low-Gain Avalanche Detectors (LGAD) v
30 ps track resolution

New Muon Chambers

Inner barrel region with new RPC and sMDT detectors

New Inner Tracking Detector (ITk)

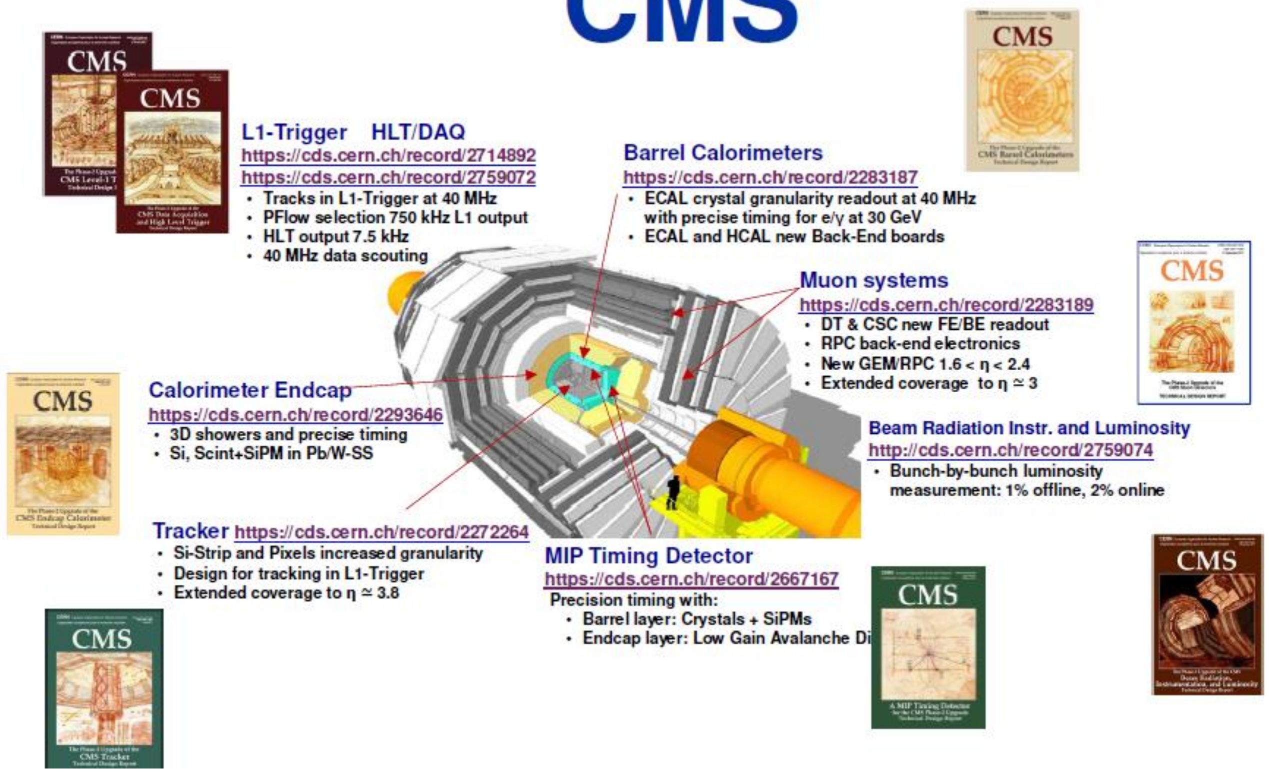
All silicon, up to $|\eta| = 4$

Additional small upgrades

Luminosity detectors (1% precision goal)

HL-ZDC

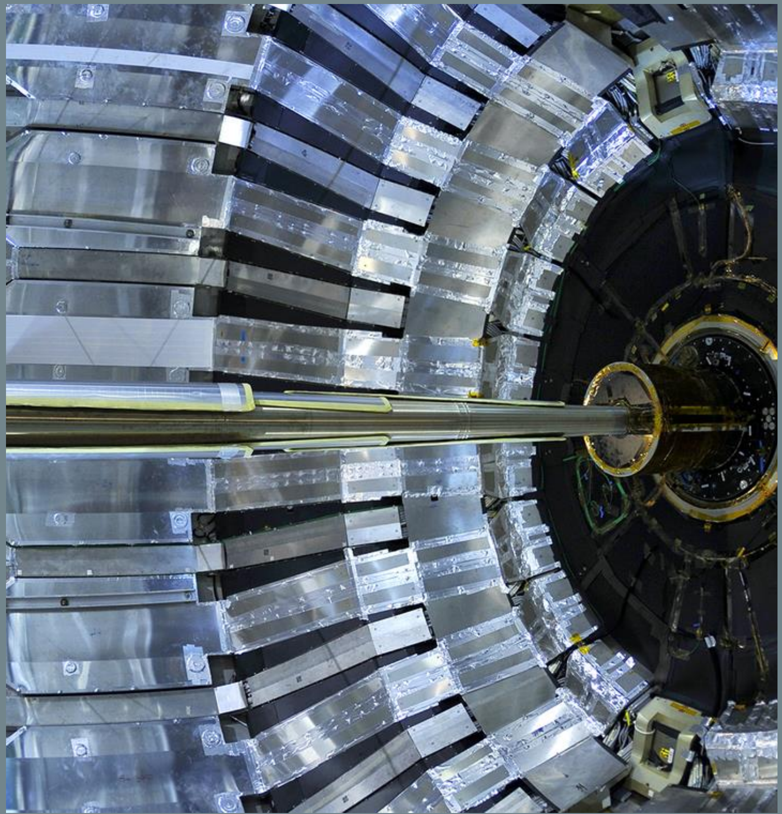
CMS



WHAT IS THE NEXT GENERATION TRIGGERS Project?

The Next Generation Triggers project started in January 2024 as a collaboration between CERN (the Experimental Physics, Theoretical Physics and Information Technology Departments) and the ATLAS and CMS experiments.

The key objective of the five-year NextGen project is to get more physics information out of the HL-LHC data to uncover as-yet-unseen phenomena by more efficiently selecting interesting physics events while rejecting background noise

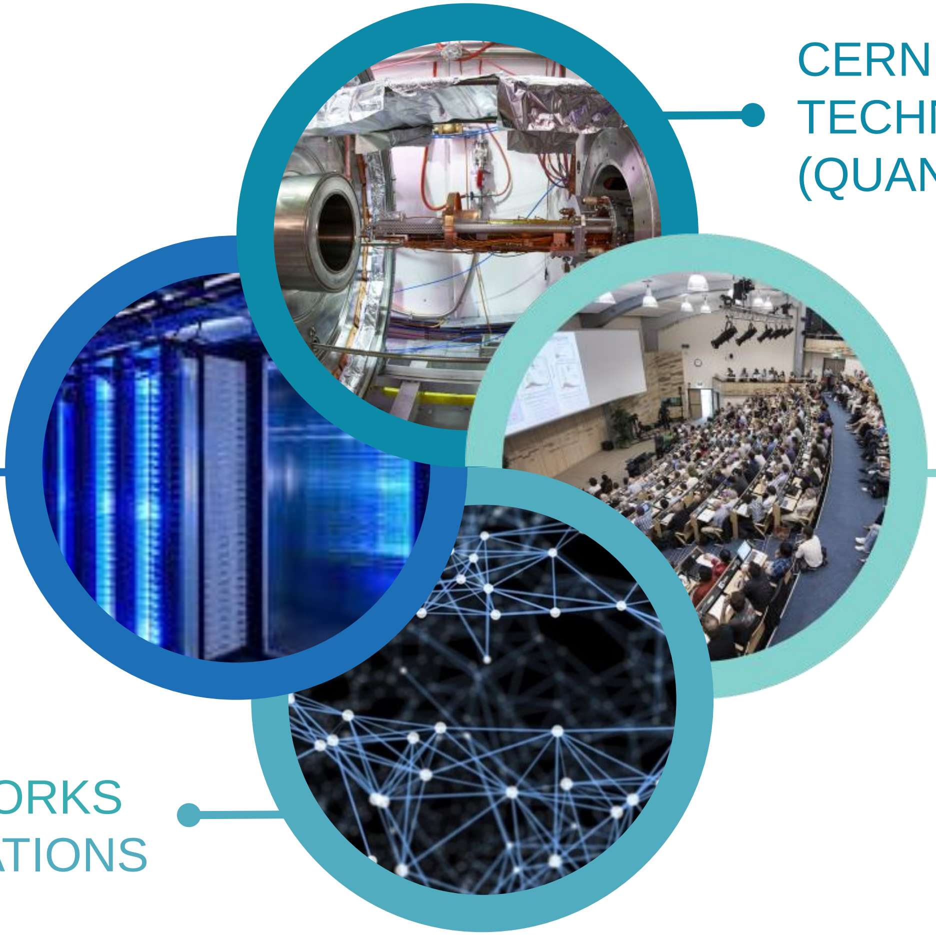


NextGen explores the use of Artificial Intelligence, quantum-inspired algorithms, and high-performance computing to improve theoretical modelling and optimise methods and tools in the search for ultra-rare events.

CERN QTI Phase 2 (2024-2028) – Centres of Competence

CERN QUANTUM TECHNOLOGY PLATFORMS (QUANTUM SENSING)

HYBRID QUANTUM COMPUTING AND ALGORITHMS

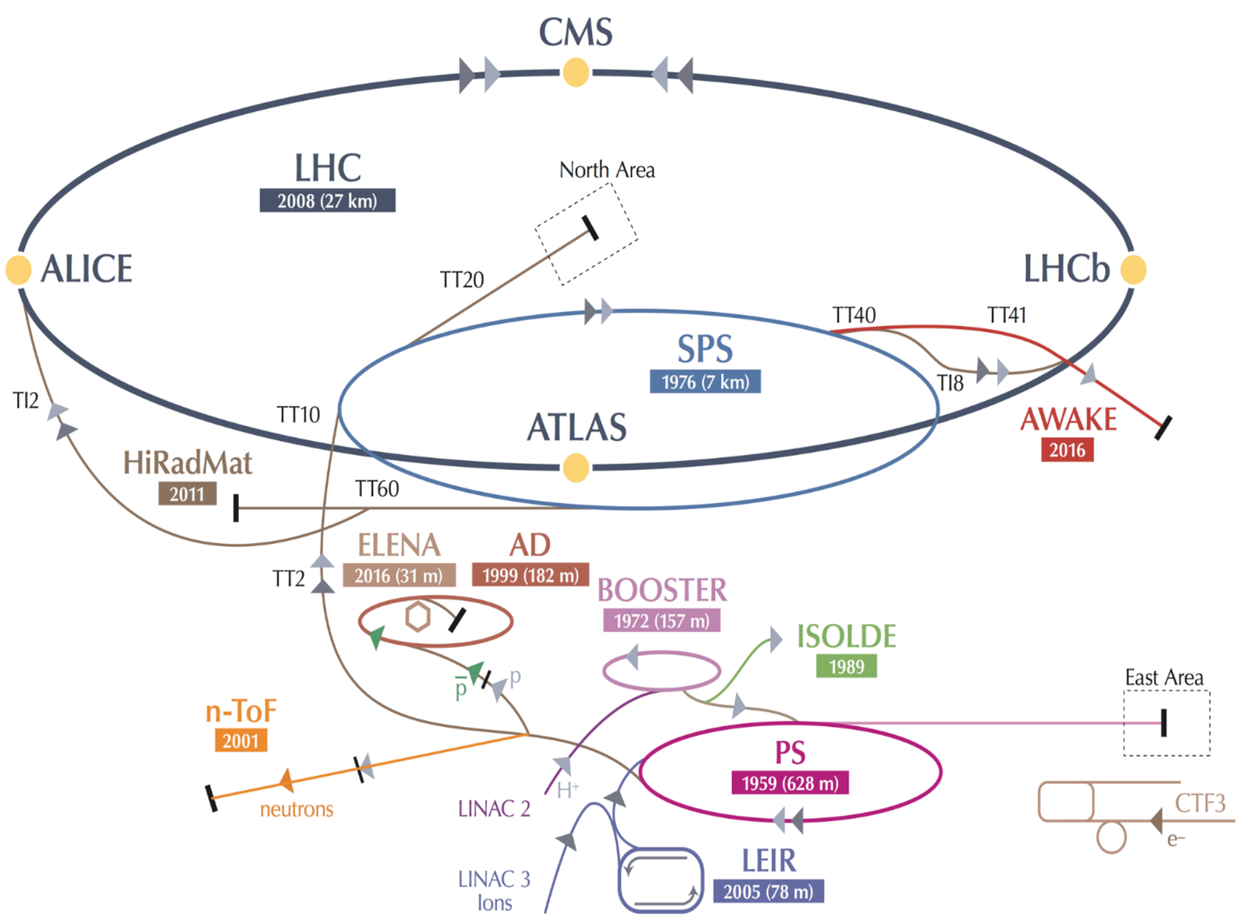


QUANTUM NETWORKS AND COMMUNICATIONS

OQI Open Quantum Institute

QUANTUM TECHNOLOGY INITIATIVE

CERN Diversity Programme



New to come (around 2030):

SHiP experiment at an upgraded beam line in the North Area

AD: Antiproton Decelerator for antimatter studies

AWAKE: proton-induced plasma wakefield acceleration

CAST, OSQAR: axions

CLOUD: impact of cosmic rays on aeorosols and clouds → implications on climate

COMPASS: hadron structure and spectroscopy

ISOLDE: radioactive nuclei facility

LHC

NA61/Shine: ions and neutrino targets

NA62: rare kaon decays

NA63: radiation processes in strong EM fields

NA64: search for dark photons

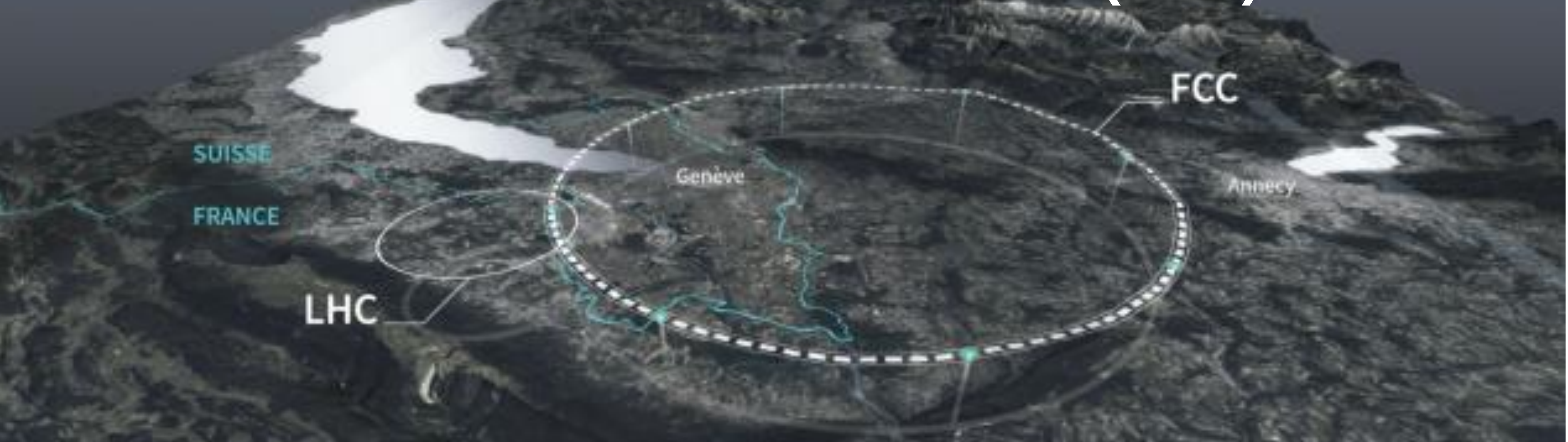
Neutrino Platform: ν detector R&D for experiments in US, Japan

n-TOF: n-induced cross-sections

UA9: crystal collimation

~20 projects other than LHC with > 1200 physicists

Preparing CERN's Future:
The Future Circular Collider (FCC)



Driven by the **2020 Update of the European Strategy for Particle Physics**

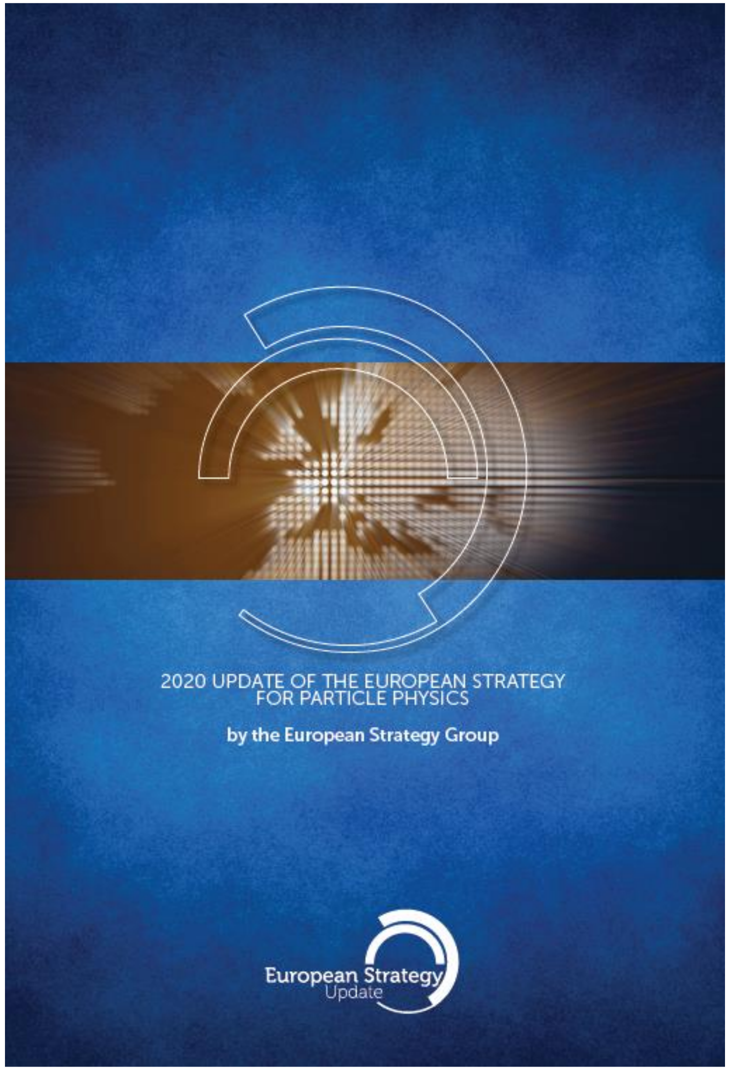
- Technical and financial feasibility study of a Future Circular Collider
- Accelerator R&D to develop technologies for FCC and for alternative options
- Detector and computing R&D
- …

Future Circular Collider (FCC): Feasibility Study

European Strategy for Particle Physics:

- *An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.*
- *“Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage.*
- *Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.”*

CERN has launched the FCC feasibility study to address these recommendations

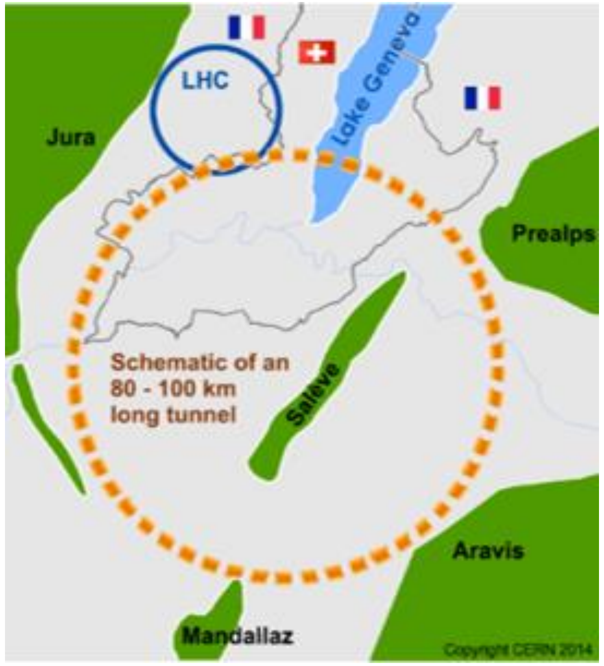


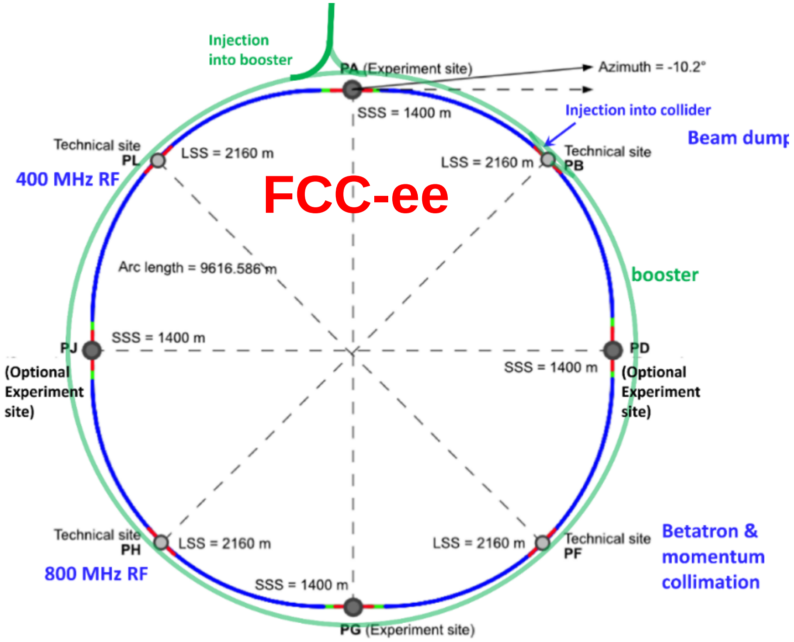
The FCC integrated program inspired by successful LEP – LHC programs at CERN

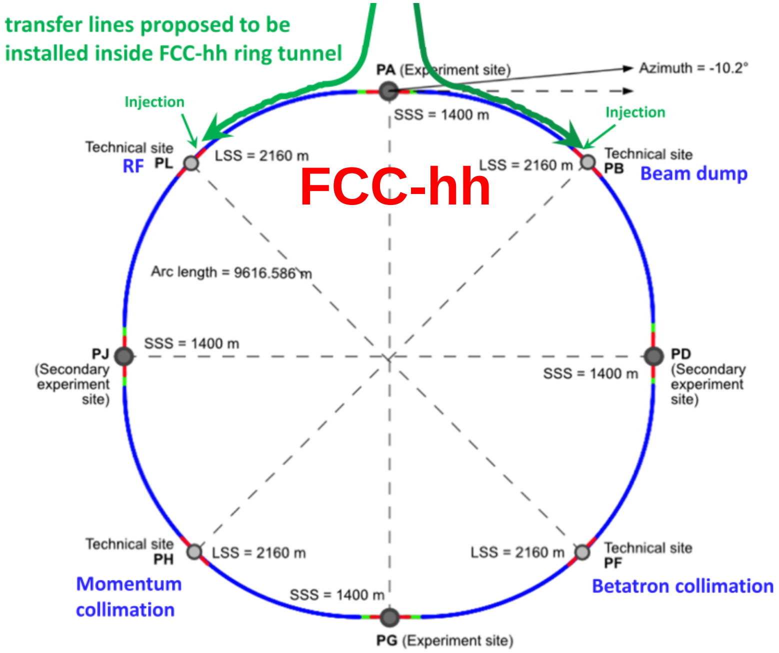
M. Benedikt

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- complementary physics
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after completion of the HL-LHC program

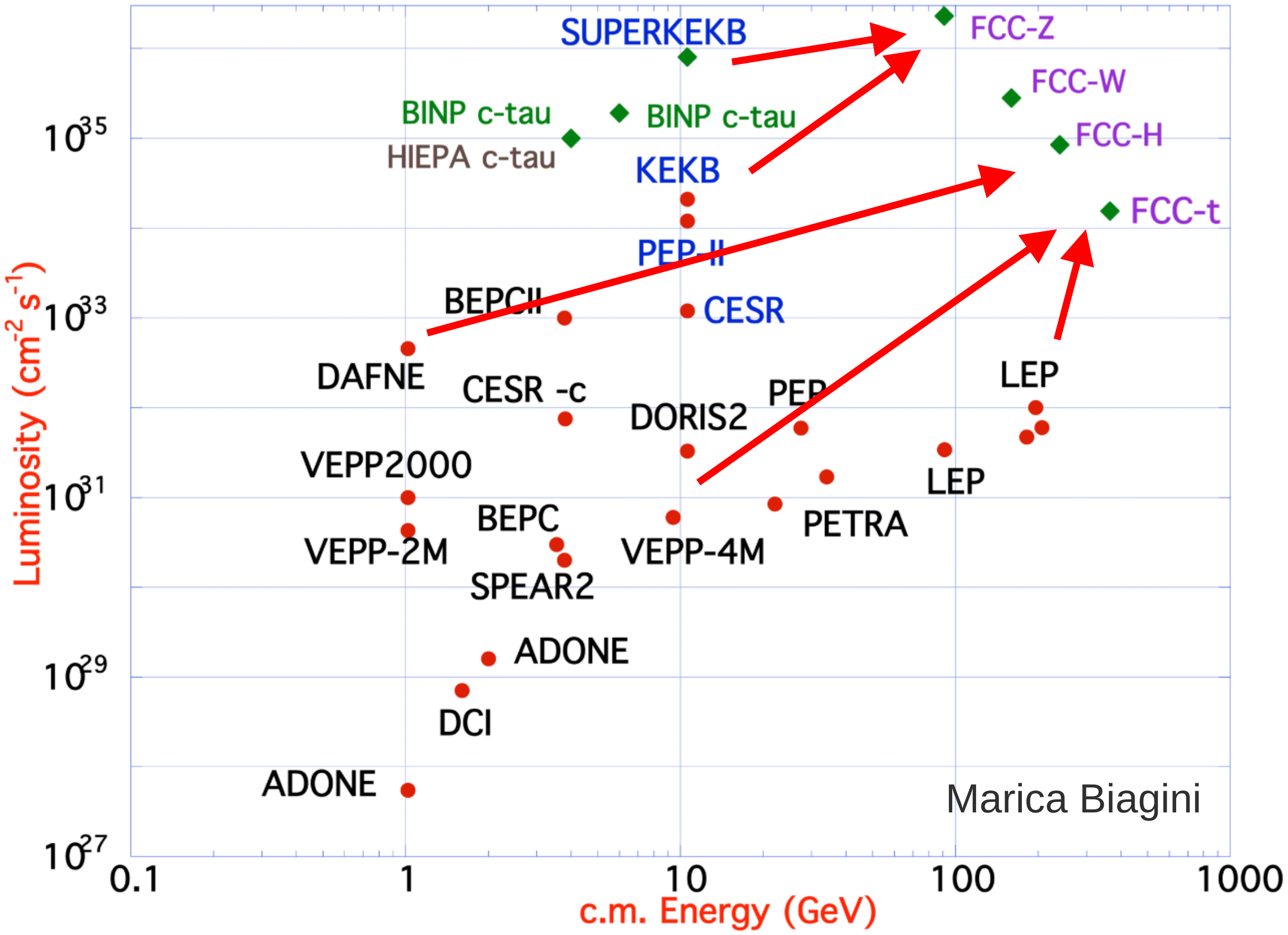






2065 - 2090

FCC-ee Design Concept

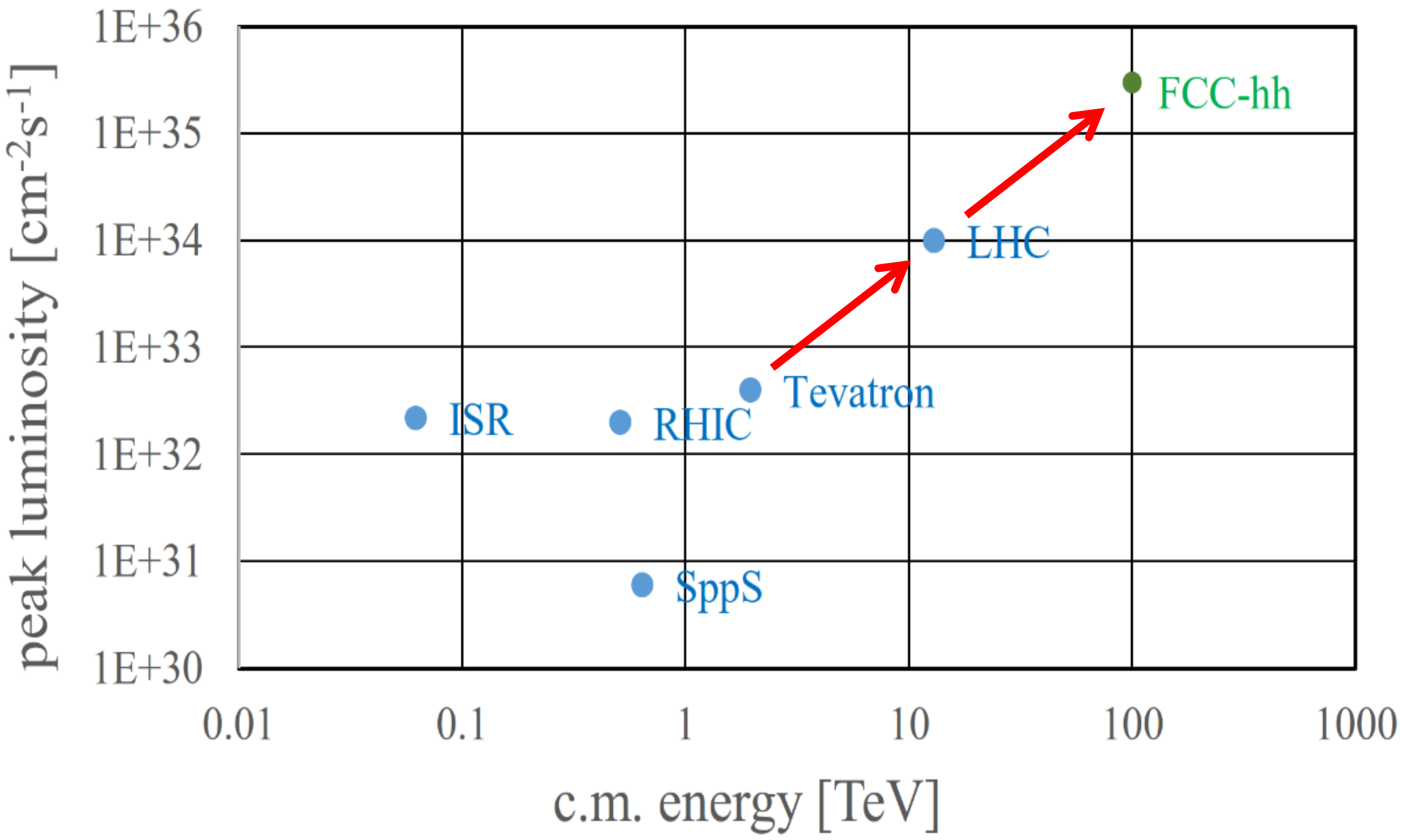


Based on lessons and techniques from past colliders (last 40 years)

- B-factories: KEKB & PEP-II:
  - double-ring lepton colliders,
  - high beam currents,
  - top-up injection
- DAFNE: crab waist, double ring
- S-KEKB: low by*, crab waist
- LEP: high energy, SR effects
- VEPP-4M, LEP: precision E calibration
- KEKB: e^+ source
- HERA, LEP, RHIC: spin gymnastics

Combining successful ingredients of several recent colliders → highest luminosities & energies

FCC-hh: Highest Collision Energies



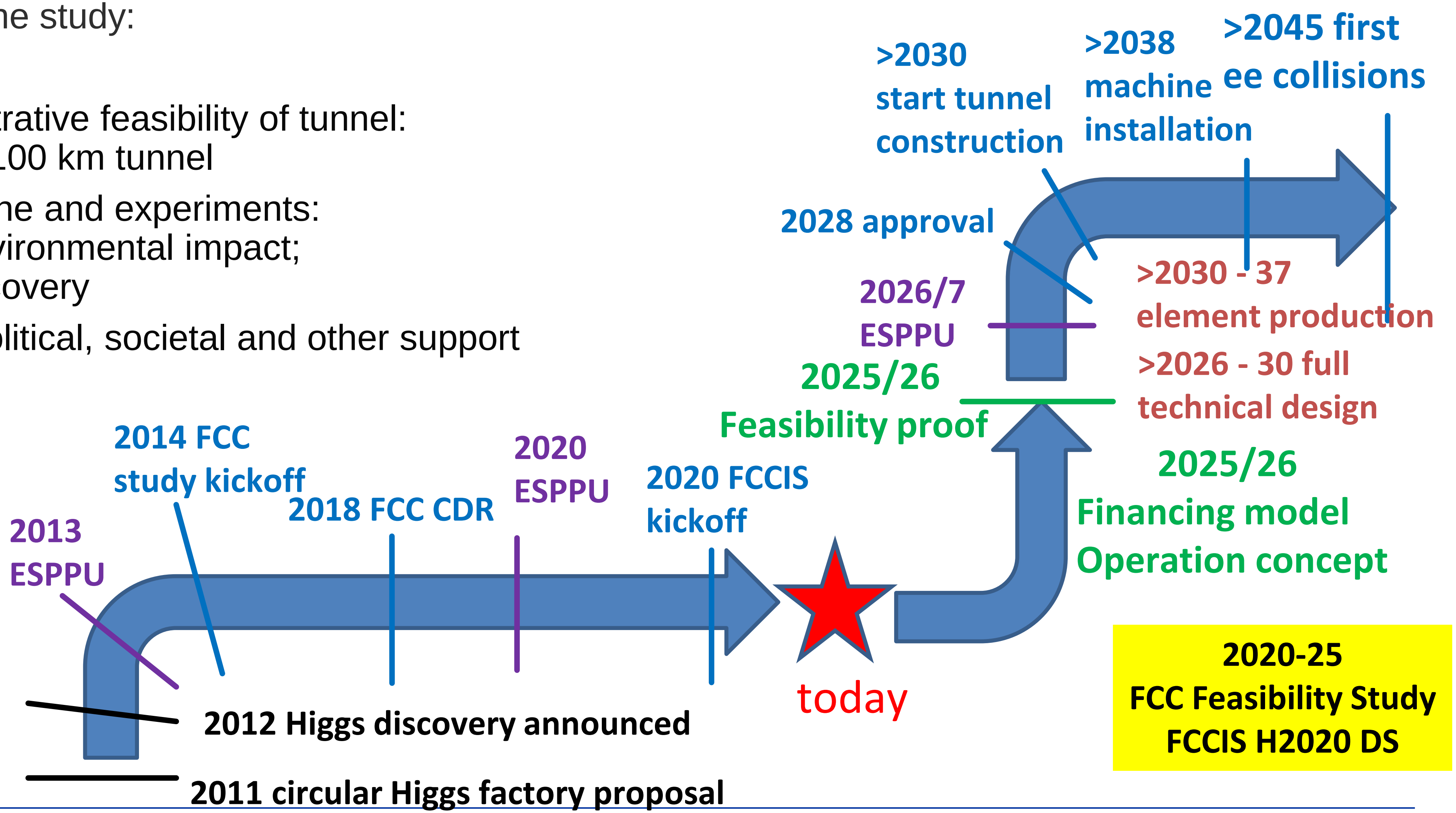
Key challenges:

- Order of magnitude performance increase in both energy & luminosity
- 100 TeV cm collision energy (vs 14 TeV for LHC)
- 20 ab^{-1} per experiment collected over 25 years of operation (vs 3 ab^{-1} for LHC)
- Similar performance increase as from Tevatron to LHC
- Key technology: high-field magnets

FCC Roadmap Towards First e^+e^- Collisions

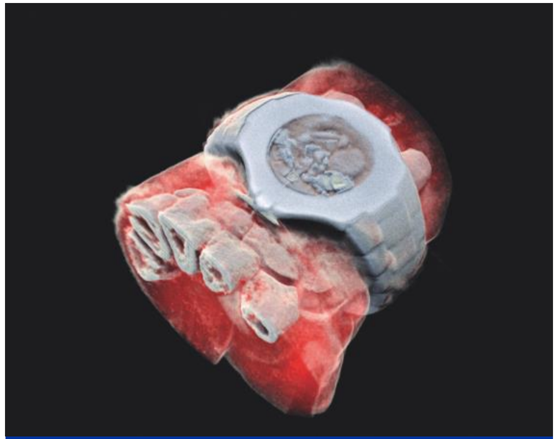
Highest priority goals of the study:

- Financial feasibility
- Technical and administrative feasibility of tunnel: no show-stopper for ~100 km tunnel
- Technologies of machine and experiments: magnets; minimize environmental impact; energy efficiency & recovery
- Gathering scientific, political, societal and other support



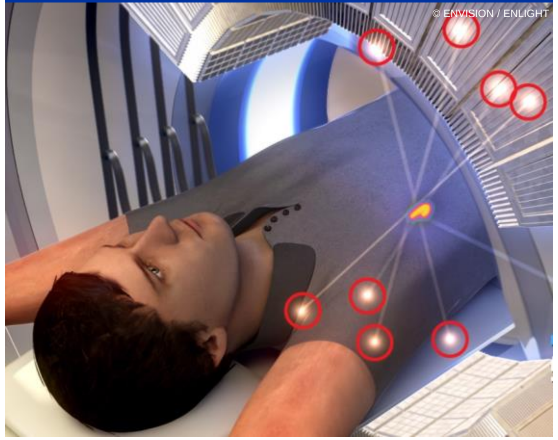
CERN's technological innovations have important applications in medicine and healthcare

Technologies applied at CERN are also used in PET, for medical imaging and diagnostics.

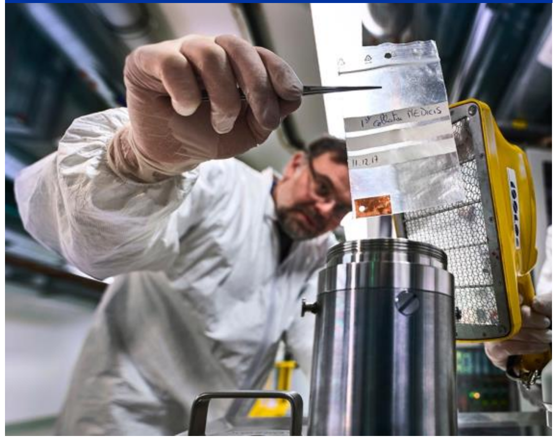


CERN produces innovative radioisotopes for nuclear medicine research.

Accelerator technologies are applied in cancer radiotherapy with protons, ions and electrons.



Pixel detector technologies are used for high resolution 3D colour X-ray imaging.



Conclusion

- CERN has a broad scientific programme with the LHC as the flagship project
- The existing LHC machine will continue to deliver unprecedented data for the next 17 years
- The future FCC will open new frontiers in the High Energy Physics research and will bring new extreme challenges that will require the development of new technologies
- New technologies will be needed for these new research horizons and scientific computing will be one of the main areas of challenges and innovations
- The CERN Schools, and in particular the CERN School of Computing, will be at the forefront of delivering education on the solutions needed for scientific computing in large international projects and collaborations

Thank you for your attention!