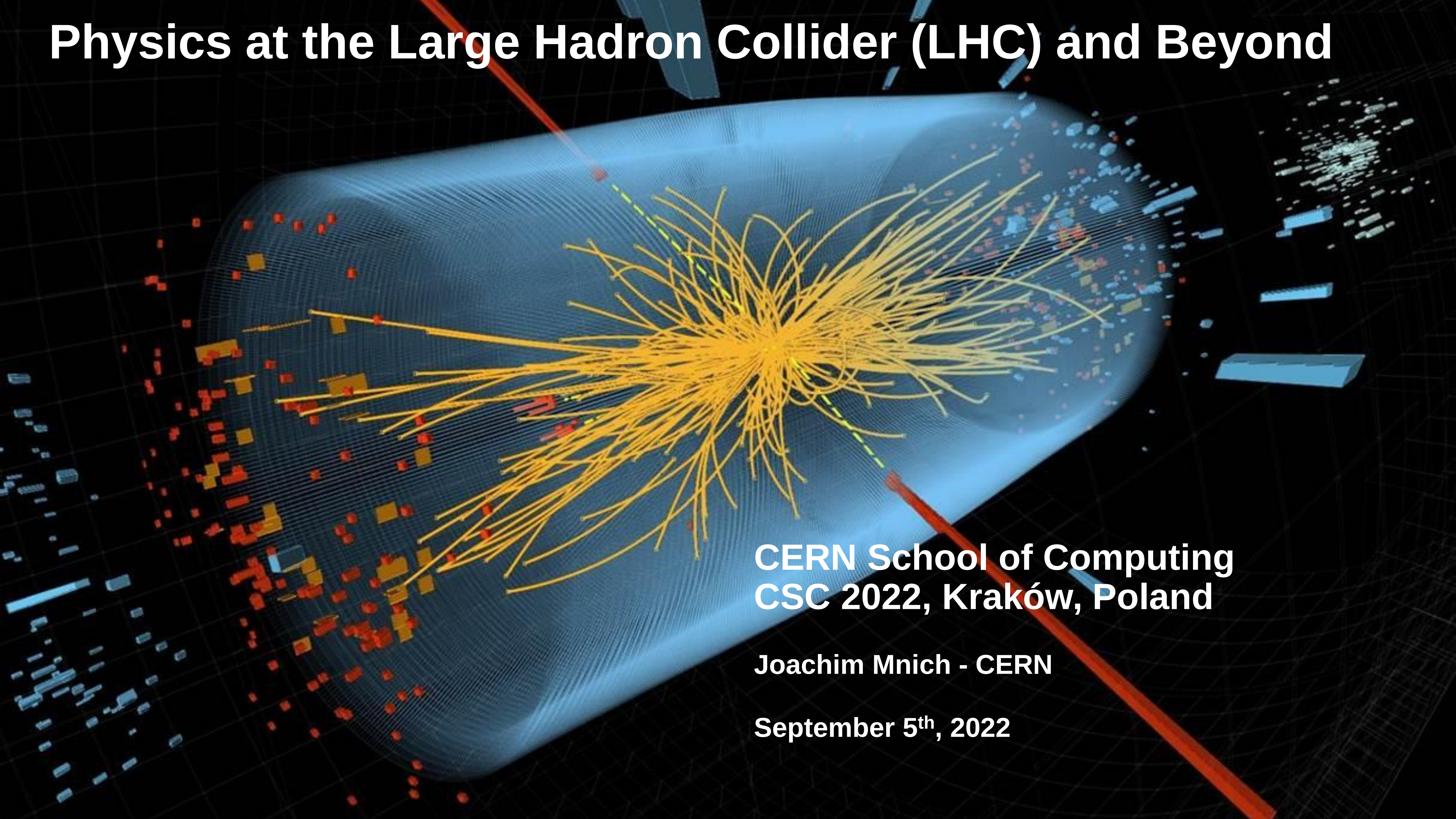
Physics at the Large Hadron Collider (LHC) and Beyond



CERN School of Computing
CSC 2022, Kraków, Poland

Joachim Mnich - CERN

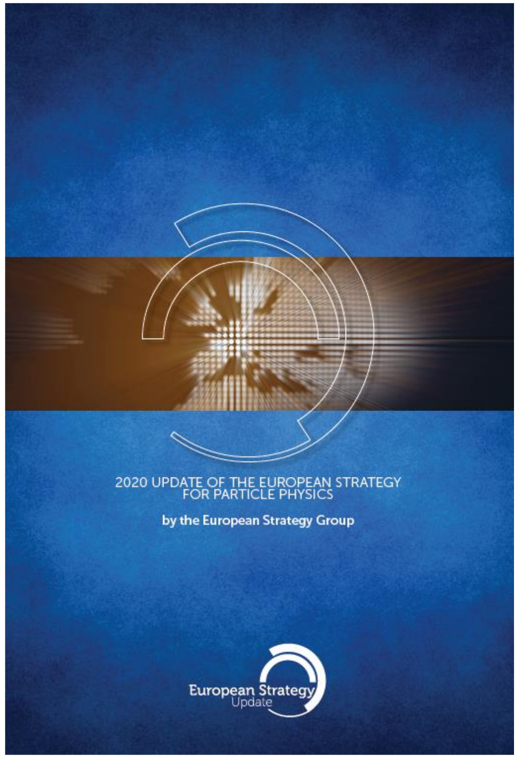
September 5th, 2022

Reminder Update European Strategy for Particle Physics

CERN Council updated the European Strategy for Particle Physics in June 2020

Scientific recommendations

- Full exploitation of the LHC and HL-LHC
- Highest-priority next collider: e+e- Higgs factory
- Increased R&D on accelerator technologies
- Investigation of the technical and financial feasibility of a future ≥ 100 TeV hadron collider
- Long-baseline neutrino projects in US and Japan
- High-impact scientific diversity programme complementary to high-energy colliders
- R&D on detector and computing
- Theory



Other high priority items:

- Exploit synergies with neighboring field, in particular nuclear and astroparticle physics
- Mitigate environmental impact of particle physics
- Invest in next generation of researchers
- Support knowledge and technology transfer
- Public engagement, education and communication

This strategy provides guidelines to CERN and the entire field for the coming years

Large Hadron Collider (LHC)

10th Anniversary of Higgs Boson Discovery

On 4 July 2022, CERN marks 10 years since the ATLAS and CMS experiments announced the discovery of the Higgs boson

Centrepiece was a full-day scientific symposium in CERN's main auditorium celebrating the discovery, give an overview of what's been learned since then, and take a look forward at what's still to come

https://indico.cern.ch/event/1135177/

Achievements since the Higgs Boson Discovery

Example: measurement of the Higgs couplings to fundamental particles

ATLAS result based on the full data set (Run 2)

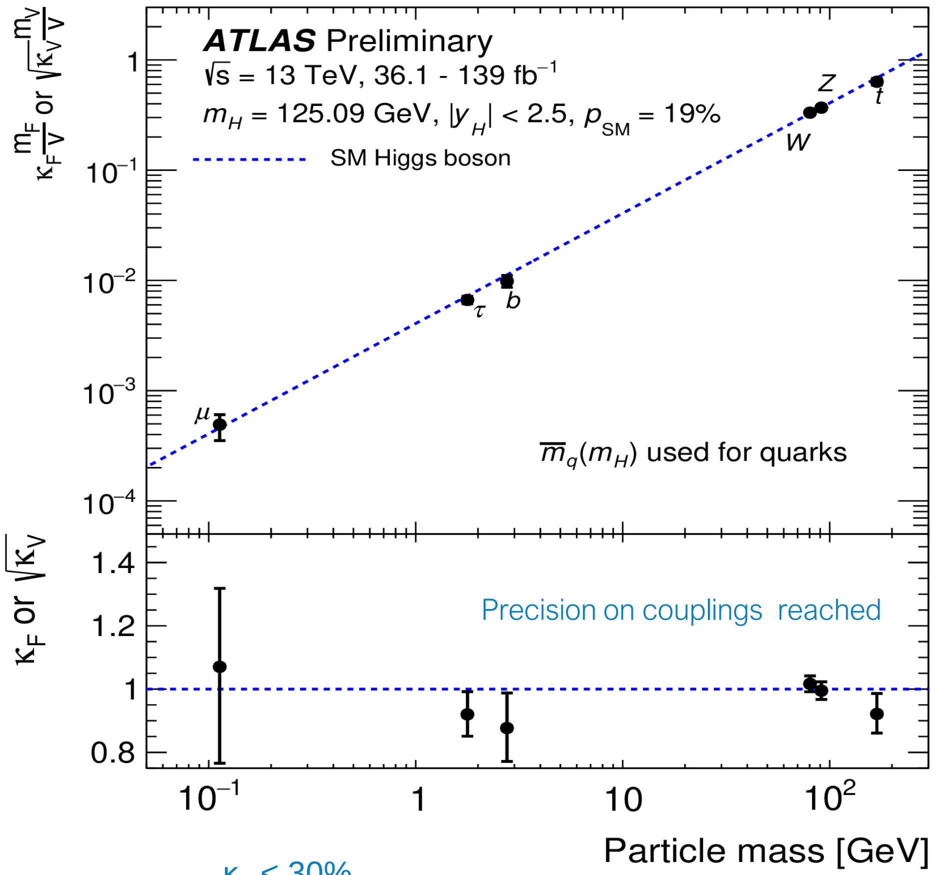
Key prediction of the Standard Model:

- ❑ Higgs coupling to particles is proportional to their mass

Impressive verification with an accuracy often better than 10%

Coupling measurements ($B_i = B_u = 0$)

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

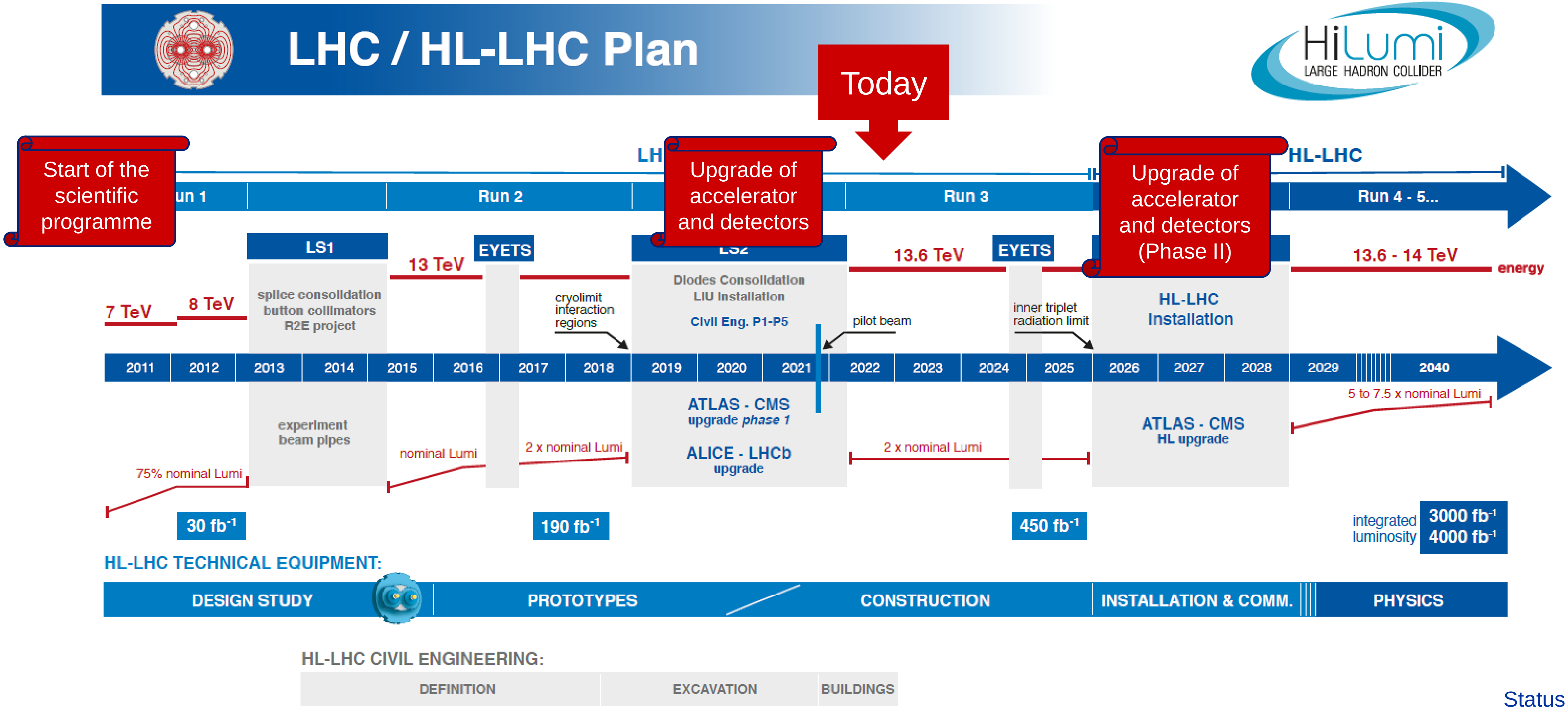


ATLAS-CONF-2021-053

$\kappa_\mu < 30\%$

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

The LHC Scientific Programme

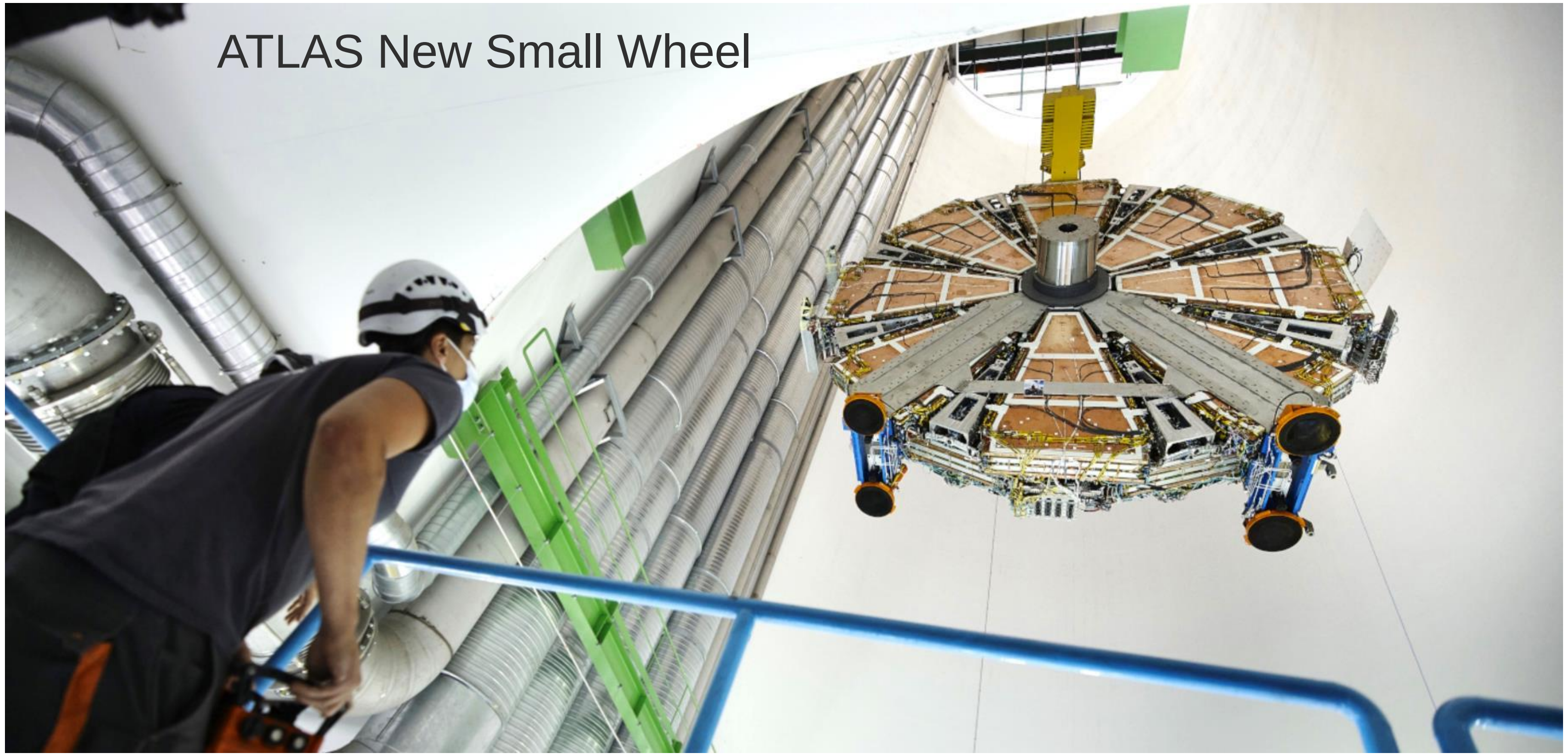


Status Feb 2022

CERN on July 5th

Upgrades of the Detectors

- All 4 LHC experiments improved with new detectors, electronics, DAQ systems
- A few examples:

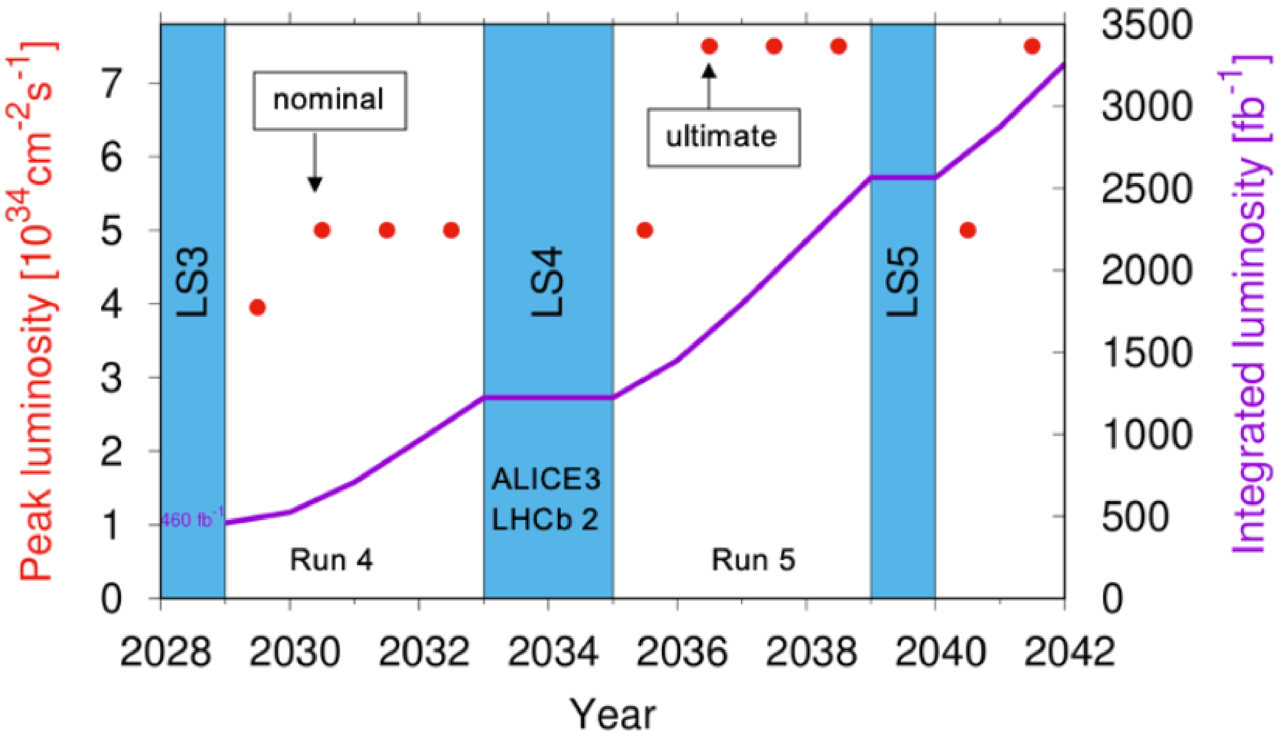

ATLAS New Small Wheel

LHCb Scintillating Fibre Tracker


LHC Programme

- 2022: Re-start LHC again (Run 3)
  - Over the last years significant improvements on accelerator (incl. HL-LHC preparations) and detectors
  - Goal for Run 3 is to approx. double the luminosity for ATLAS and CMS
  - Even more potential for ALICE and LHCb due to increased rate capabilities
- HL-LHC
  - Long shutdown 2026 - 28 to upgrade accelerator and detectors (ATLAS & CMS)
  - Will increase luminosity by factors 5 to 7
- Final goal is > 3000 fb^{-1}
  - About 20 times the luminosity collected until today
- ALICE and LHCb upgrade planned in the 2030ies

Preliminary HL-LHC schedule



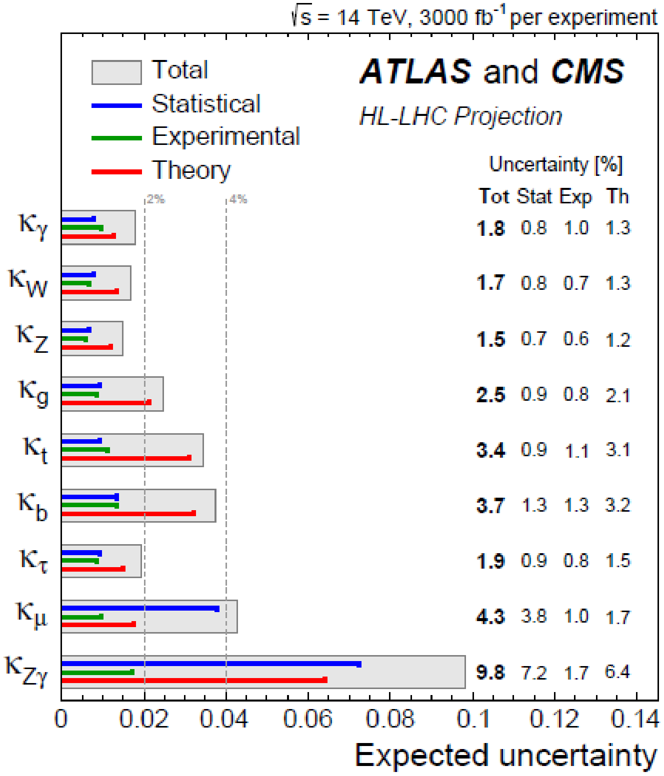
The High-Luminosity LHC

HL-LHC will provide 3000 – 4000 fb^{-1} by ≈ 2040

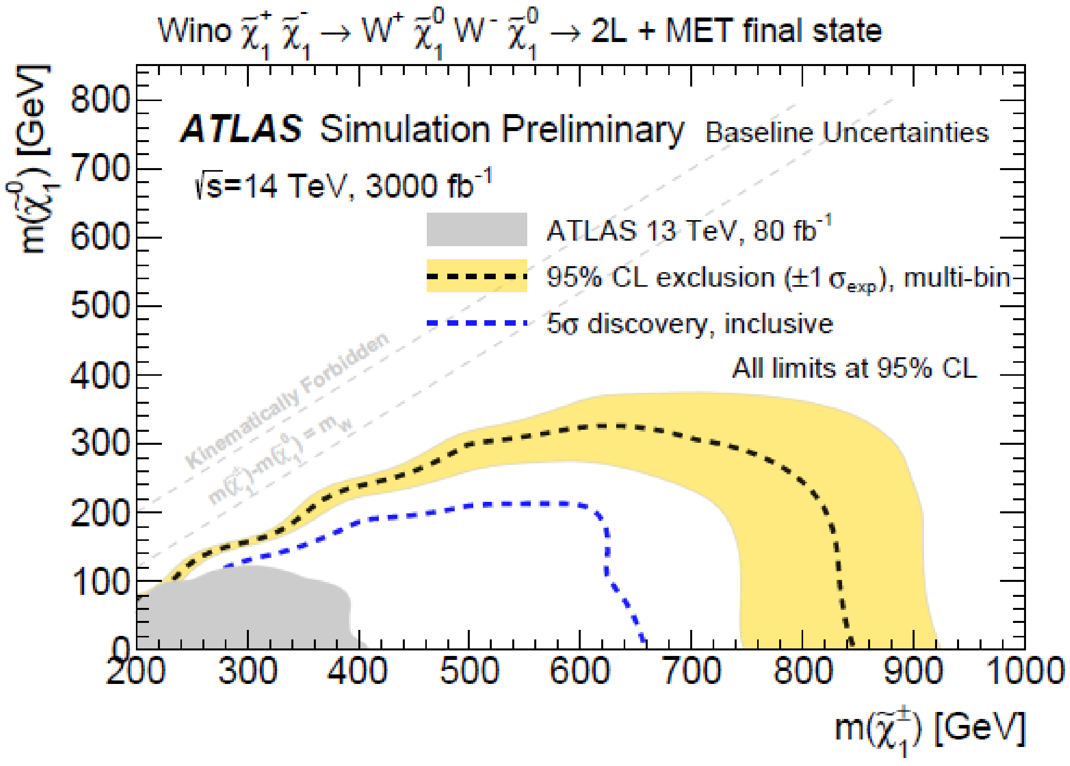
i.e. ≈ 20 times the currently available data

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

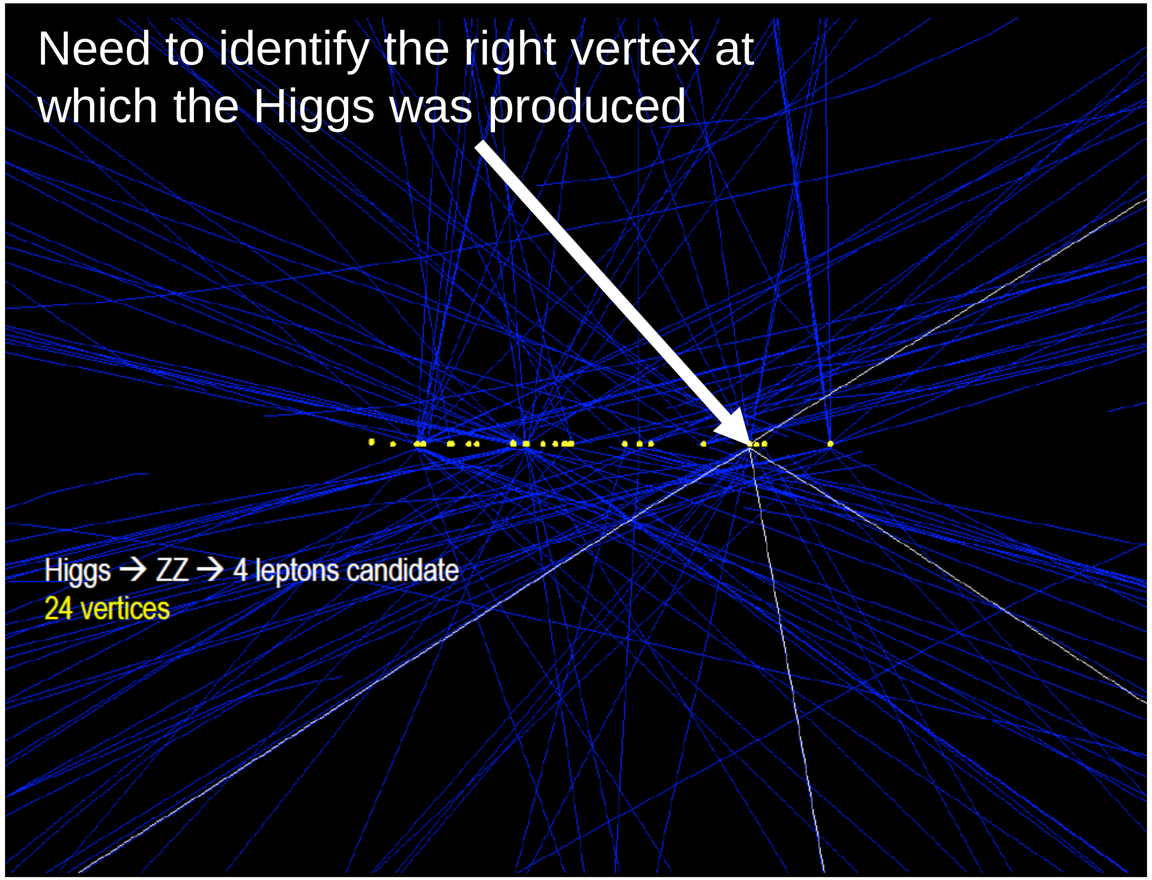


CERN-2019-007

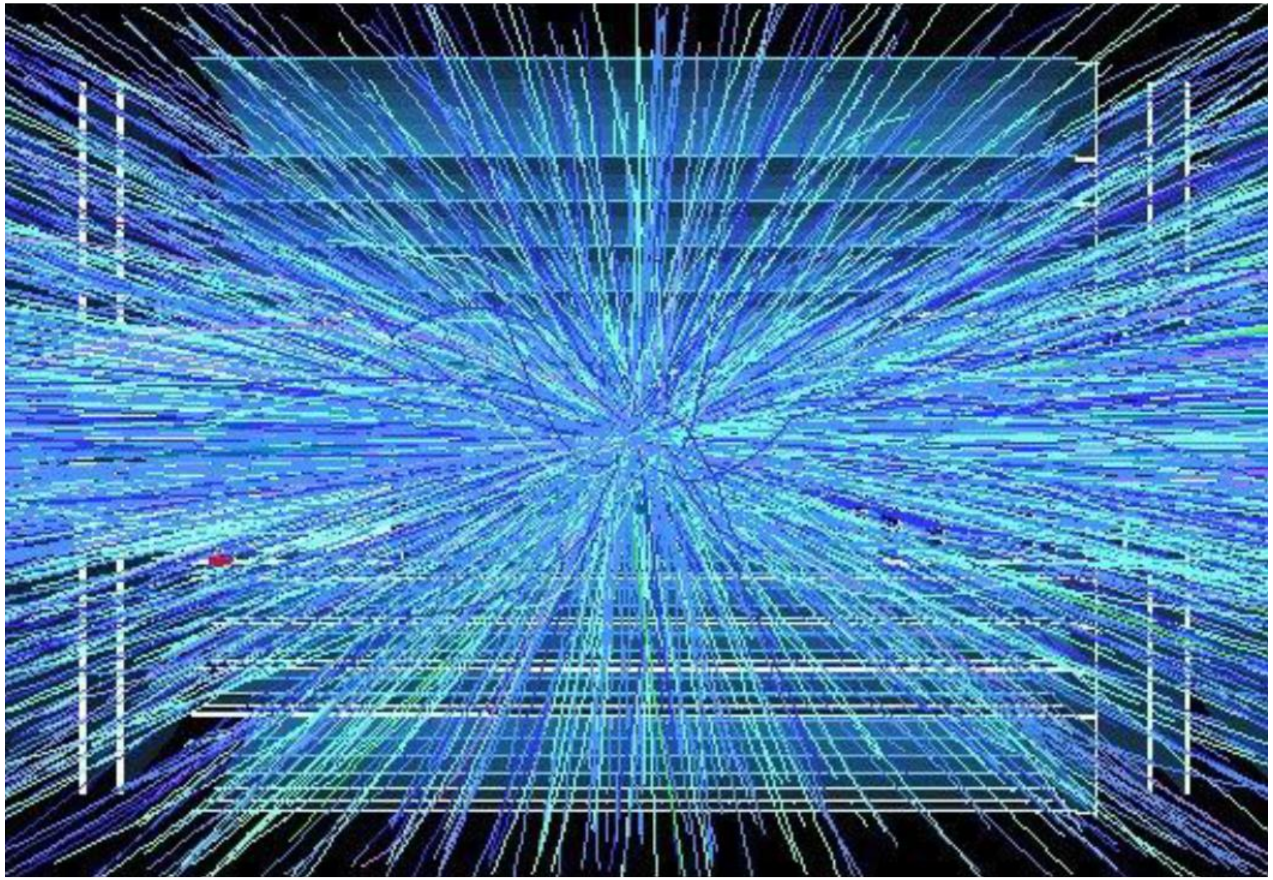


Challenges for the Detectors

- Example: event pile-up in 2018 typically 20 - 40 pp collisions per bunch crossing



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

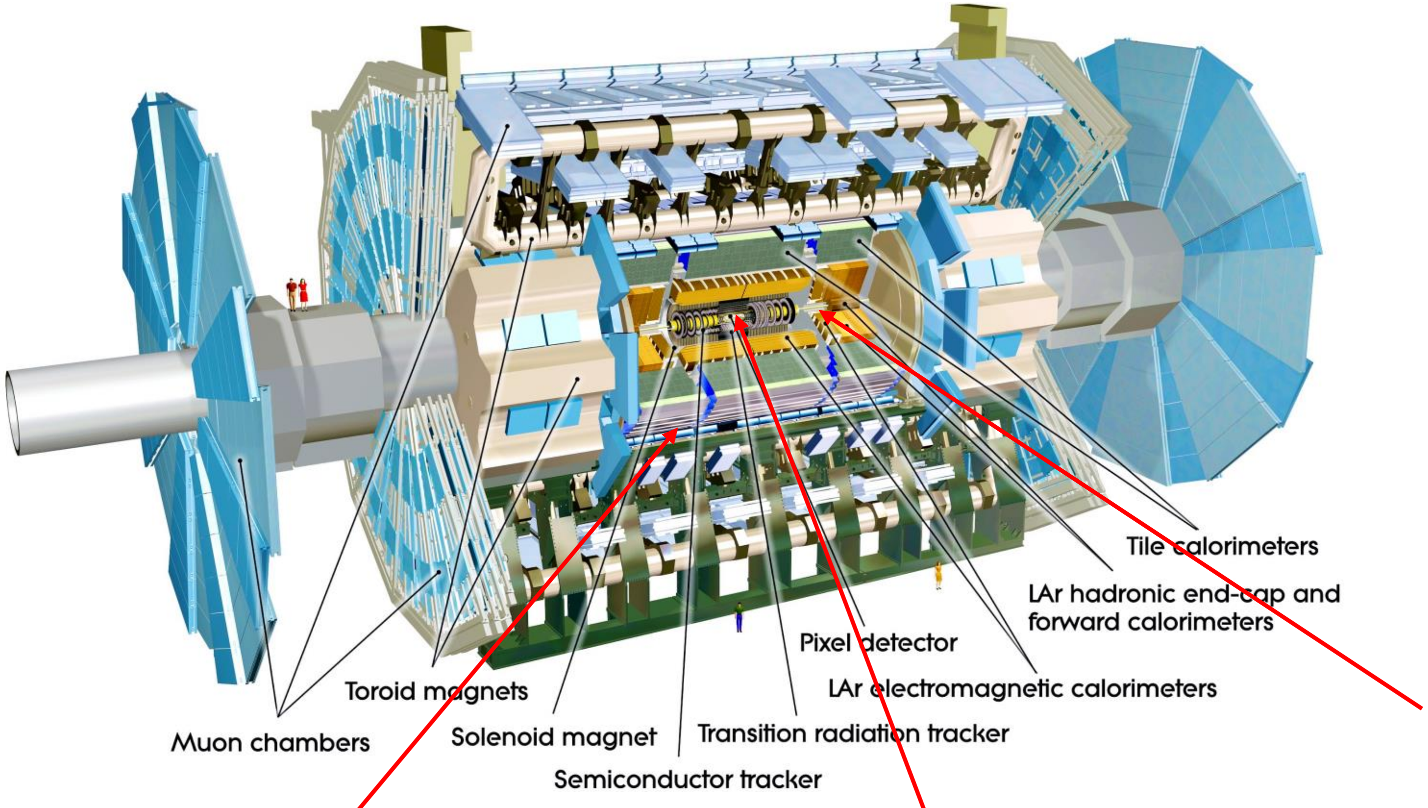


ATLAS Phase II Upgrades

The full scientific exploitation of the HL-LHC requires major upgrades of the detectors, mainly for ATLAS and CMS

- ❑ Higher granularity
- ❑ Better resolution in space and time

→ Phase II upgrades



Upgraded Trigger and Data Acquisition system

L0 at 1 MHz

Improved High-Level Trigger (100 kHz full-scan tracking)

Electronics Upgrades

LAr Calorimeter

Tile Calorimeter

Muon system

High Granularity Timing Detector (HGTD)

Forward region

Low-Gain Avalanche Detectors (LGAD)

New Muon Chambers

Inner barrel region

New Inner Tracking Detector (ITk)

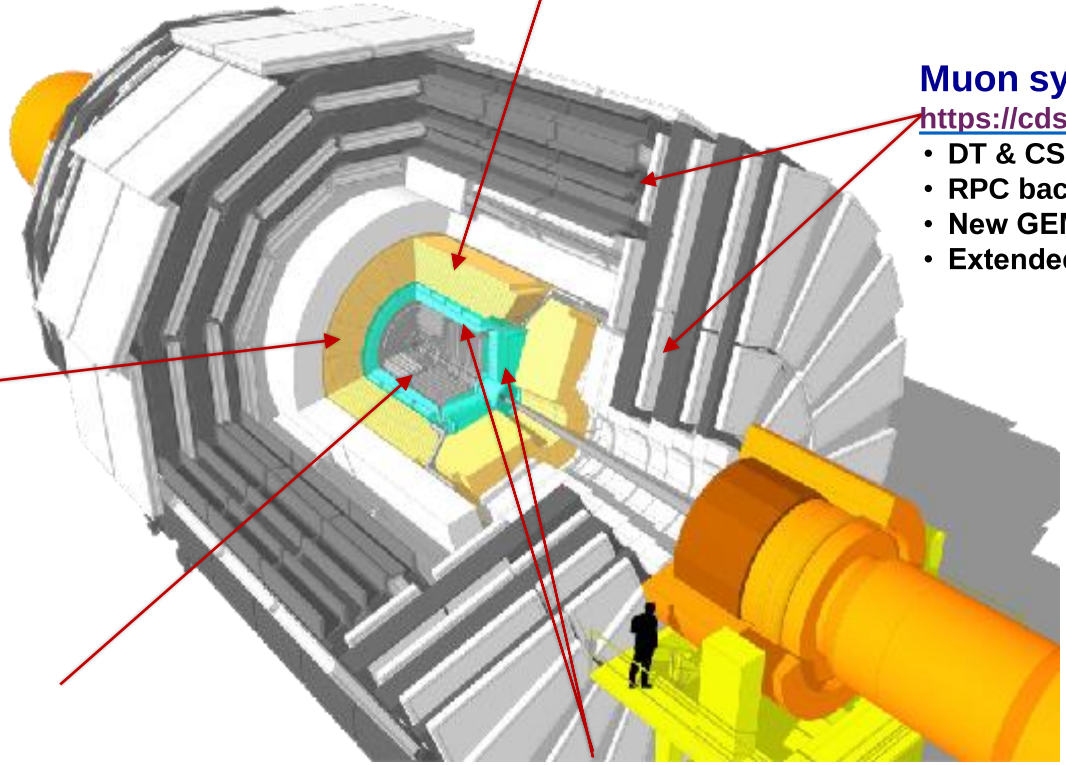
Pixel and Strip detectors

All silicon, up to |η| = 4

CMS Phase II Upgrades

L1-Trigger HLT/DAQ
https://cds.cern.ch/record/2714892
https://cds.cern.ch/record/2283193
- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards



Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≃ 3

Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

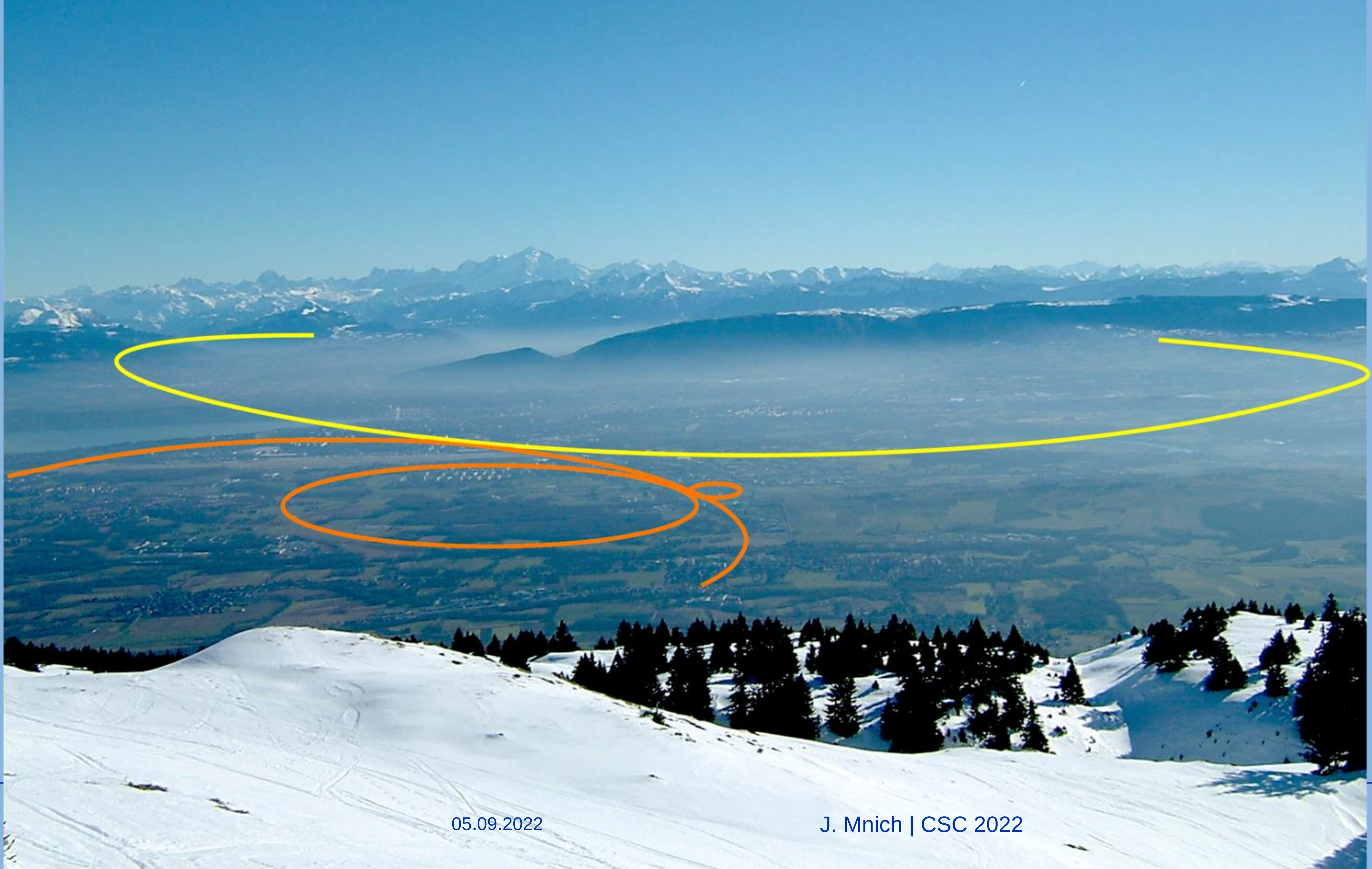
Beam Radiation Instr. and Luminosity
http://cds.cern.ch/record/002706512
- Bunch-by-bunch luminosity measurement: 1% offline, 2% online

Tracker
https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≃ 3.8

MIP Timing Detector
https://cds.cern.ch/record/2667167

Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Future Circular Collider (FCC)

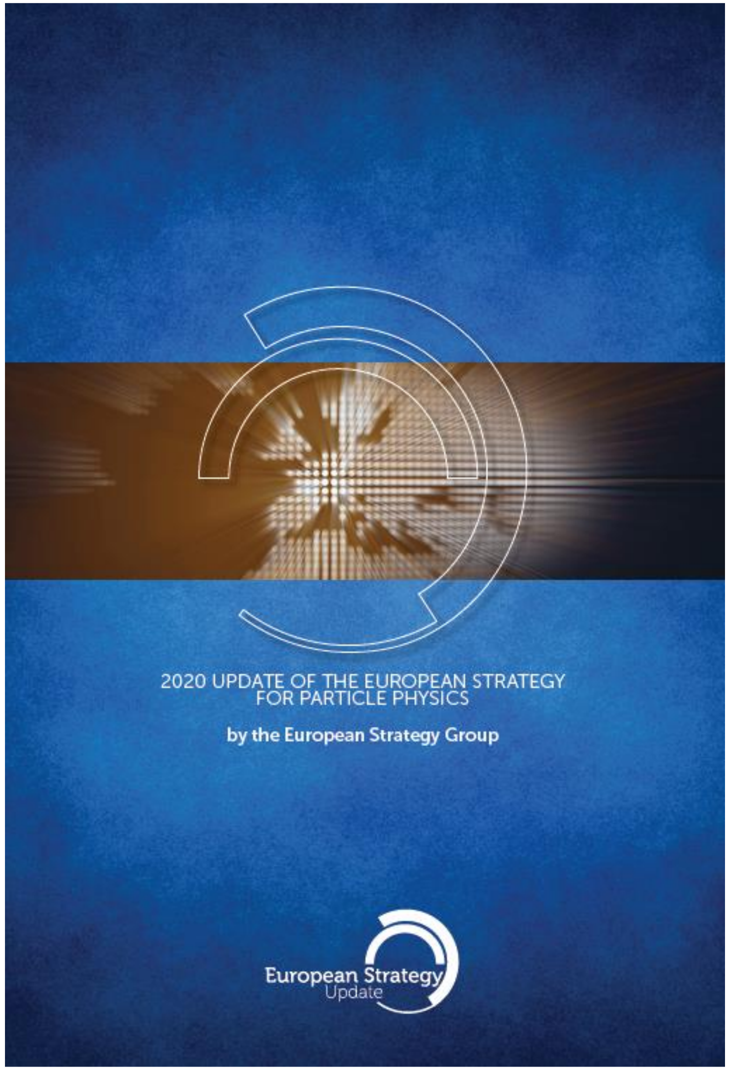


Future Circular Collider (FCC): Feasibility Study

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

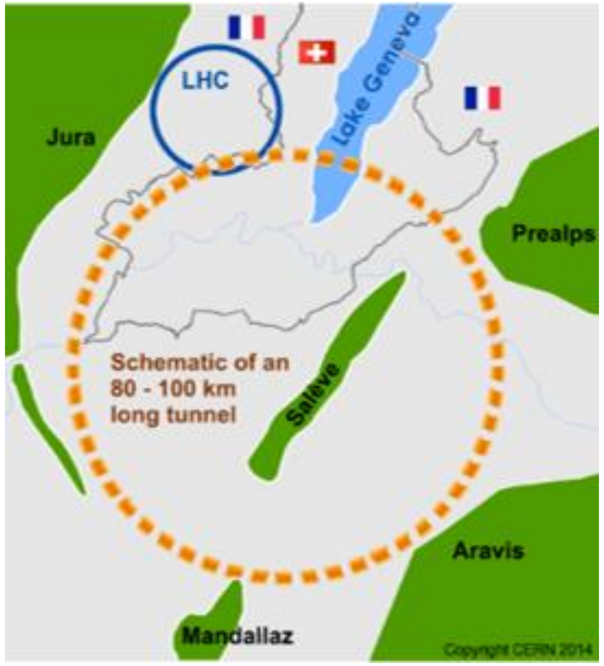


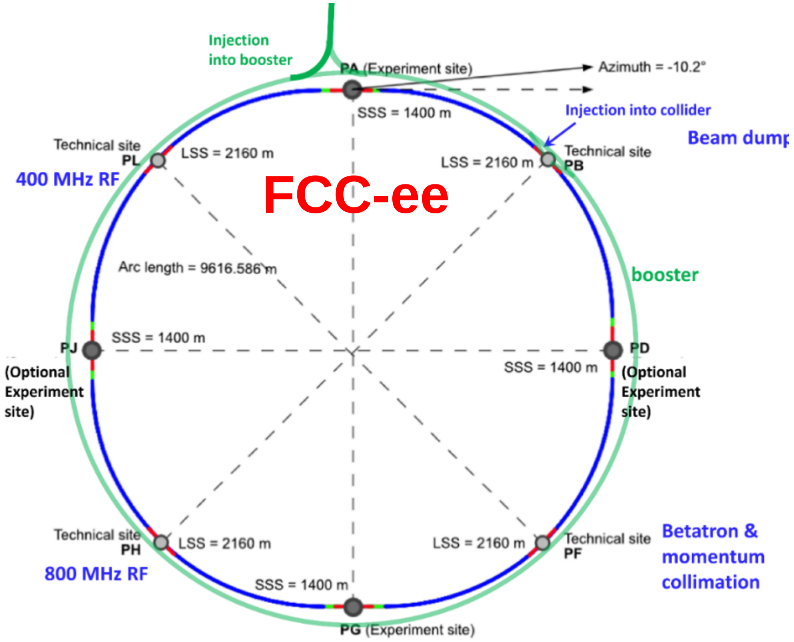
The FCC integrated program inspired by successful LEP – LHC programs at CERN

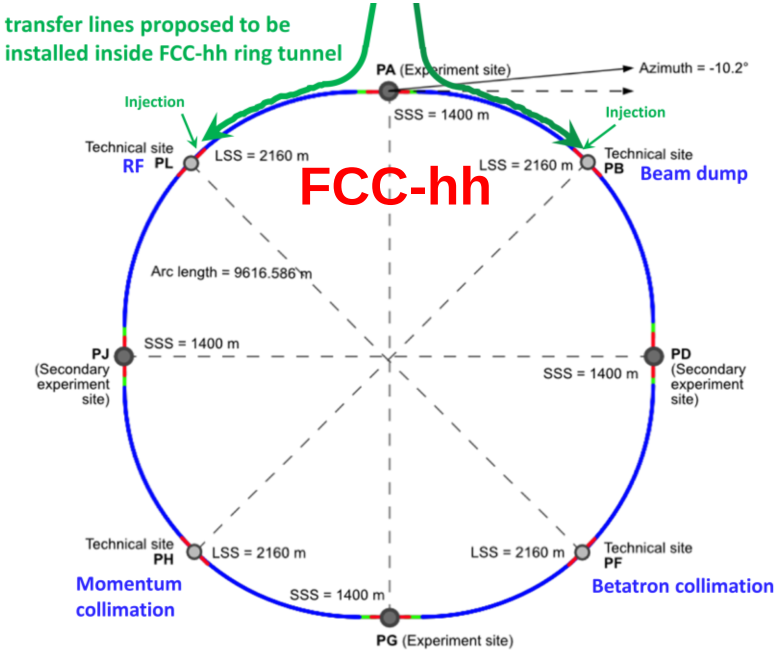
M. Benedikt
April 2022

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

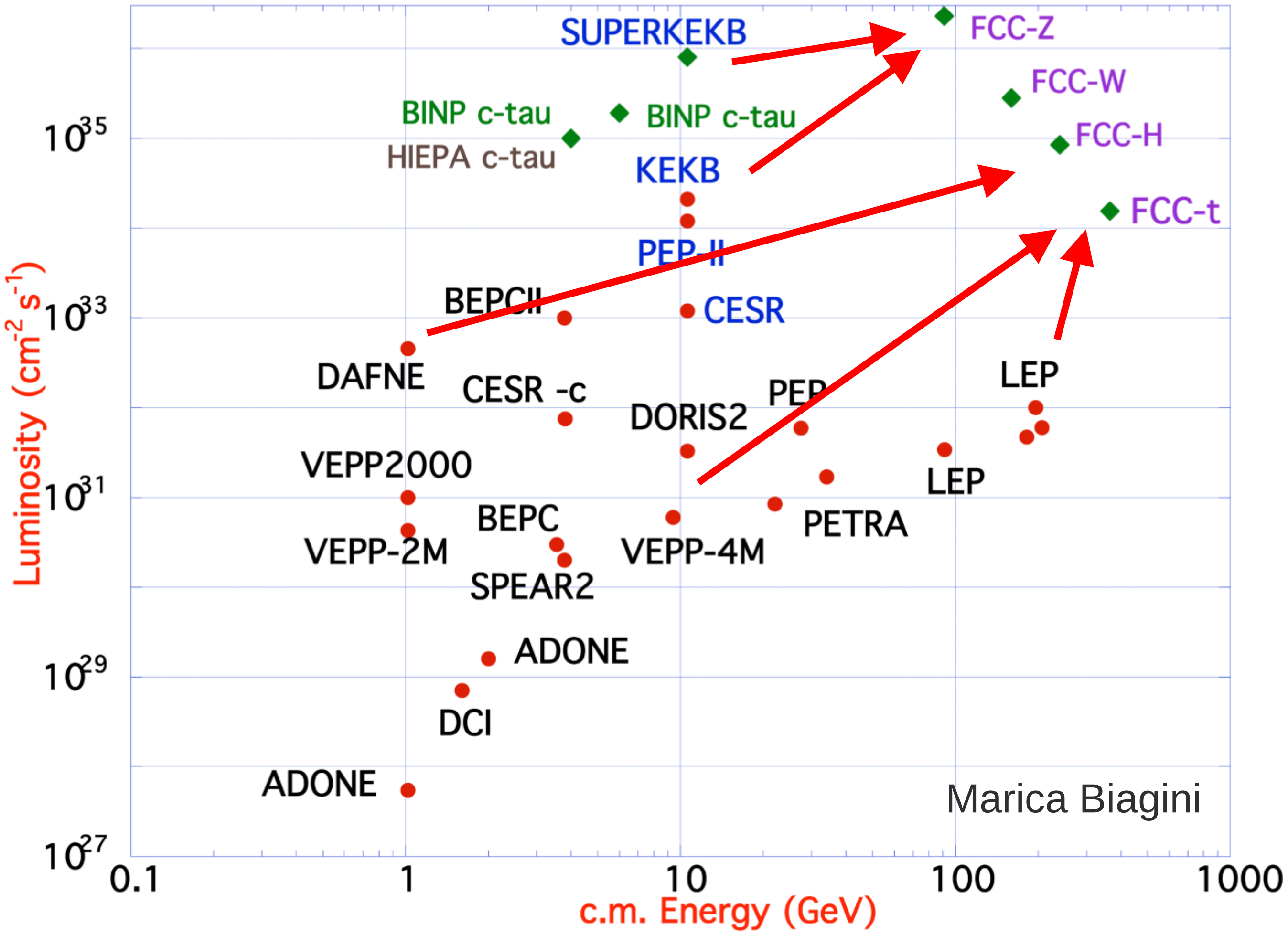






2020 - 2040 | 2045 - 2060 | 2065 - 2090

FCC-ee Design Concept

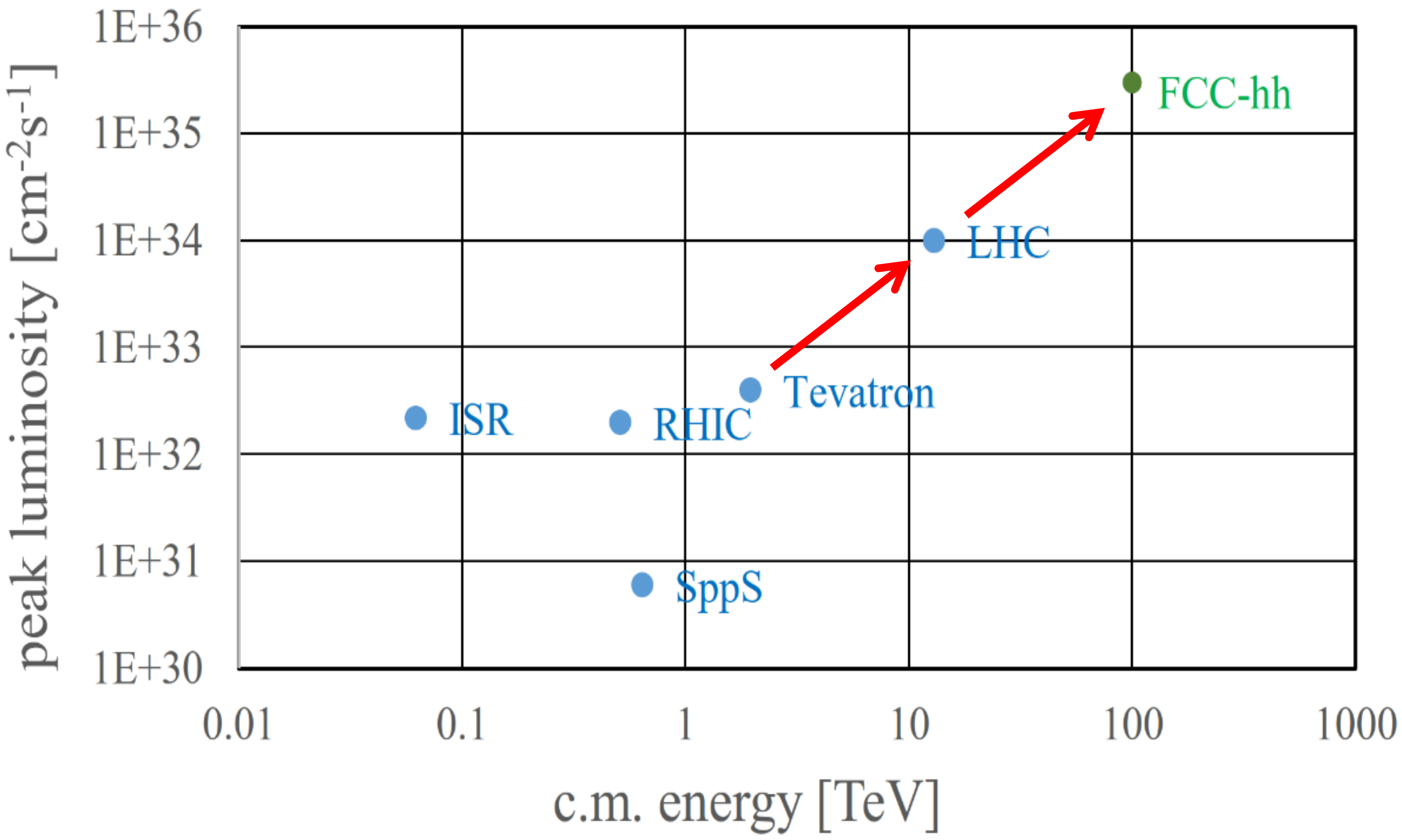


Based on lessons and techniques from past colliders (last 40 years)

- 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

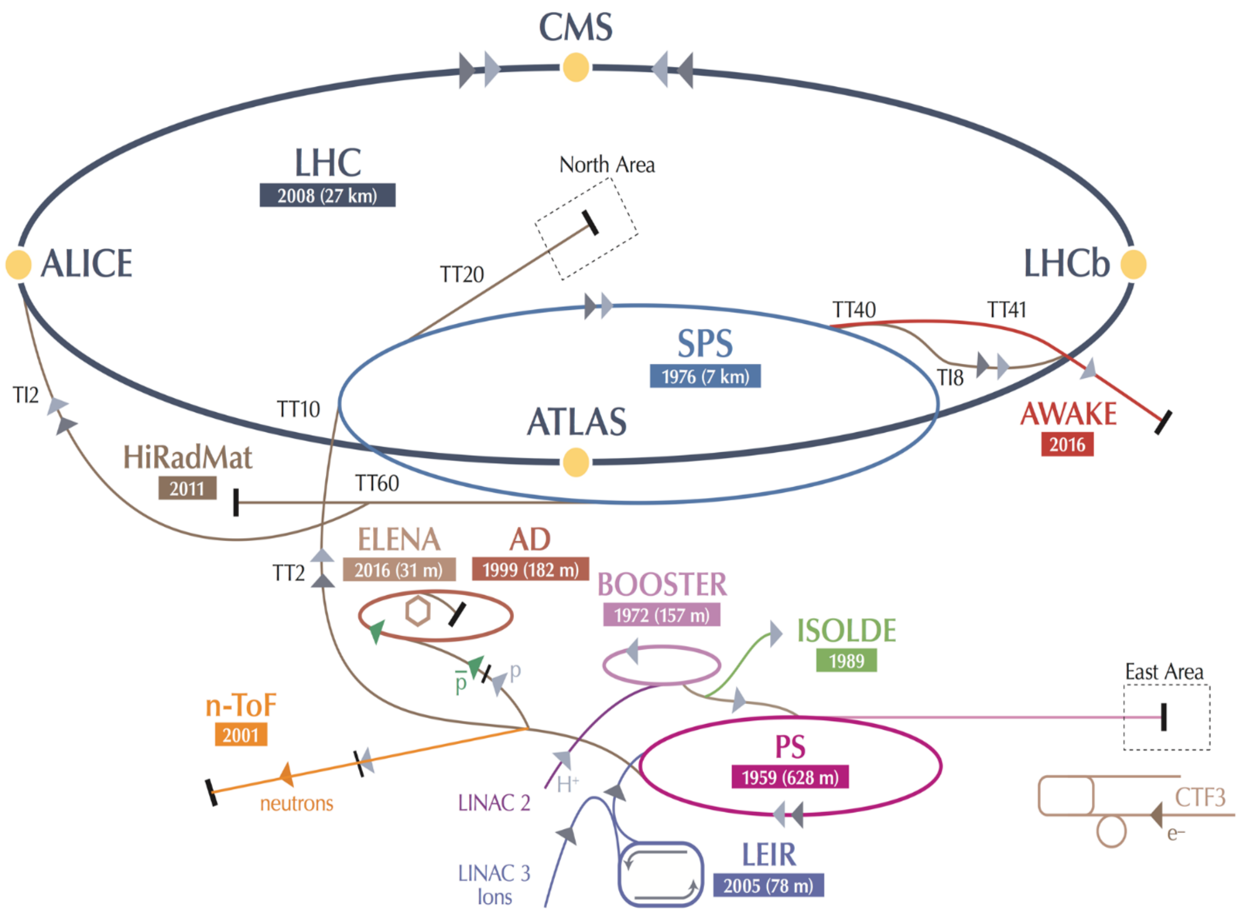
FCC-hh: Highest Collision Energies



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

CERN Diversity Programme



~20 projects other than LHC with > 1200 physicists

AD: Antiproton Decelerator for antimatter studies

AWAKE: proton-induced plasma wakefield acceleration

CAST, OSQAR: axions

CLOUD: impact of cosmic rays on aerorosols 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

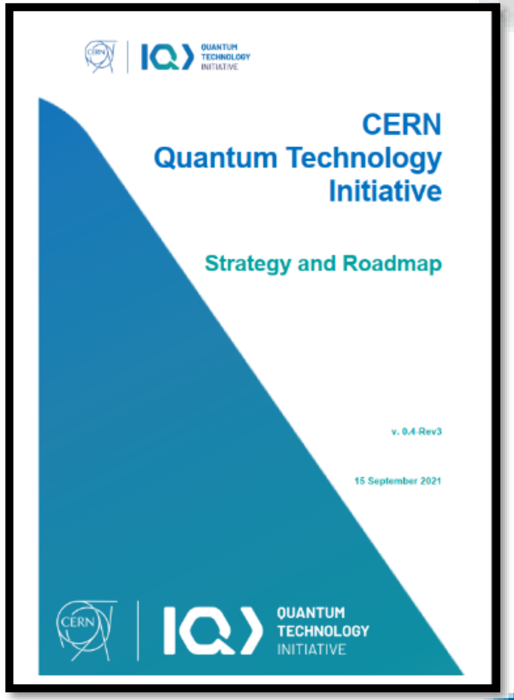
Neutrino Platform: ν detector R&D for experiments in US, Japan

n-TOF: n-induced cross-sections

UA9: crystal collimation

CERN Quantum Technology Initiative

- QTI established in 2020
- Four technical areas:
  - Quantum Computing And Algorithms
  - Quantum Theory and Simulation
  - Quantum Sensing, Metrology and Materials
  - Quantum Communication and Networks


QUANTUM TECHNOLOGY INITIATIVE

CERN
Quantum Technology
Initiative

Strategy and Roadmap

v. 0.4 Rev3

15 September 2021

CERN QUANTUM TECHNOLOGY INITIATIVE

- Collaborations being established in the Member States, US (Fermilab, Oak Ridge) and Japan (Tokyo – ICEPP)
- Signed Quantum Hub Agreement with IBM