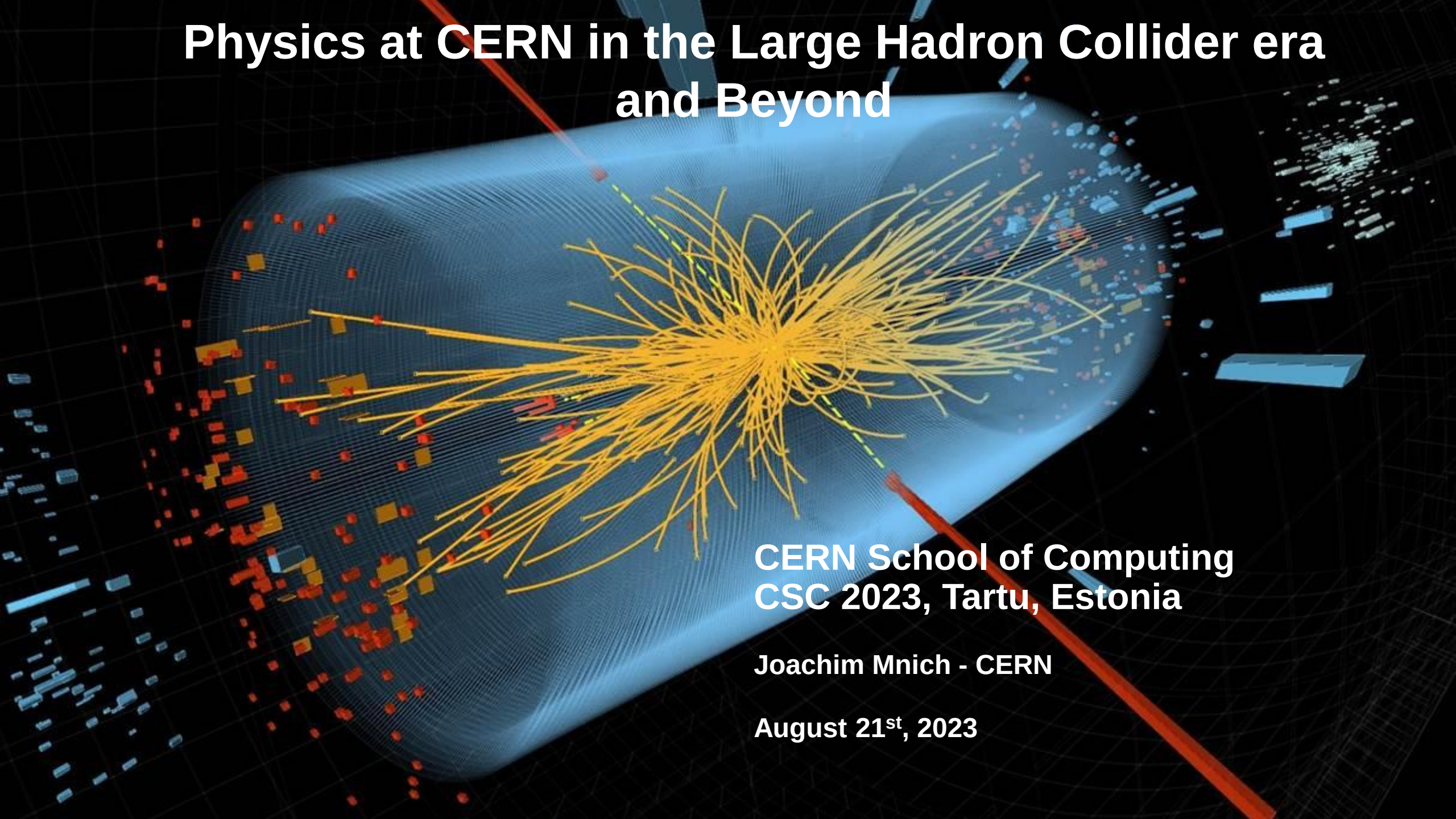
Physics at CERN in the Large Hadron Collider era and Beyond

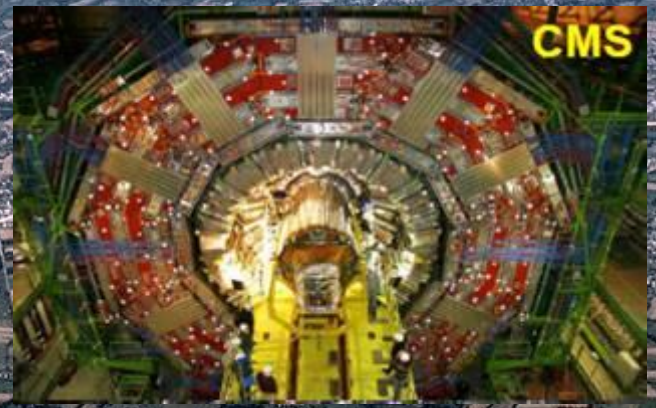


CERN School of Computing
CSC 2023, Tartu, Estonia

Joachim Mnich - CERN

August 21st, 2023

Large Hadron Collider (LHC)



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)

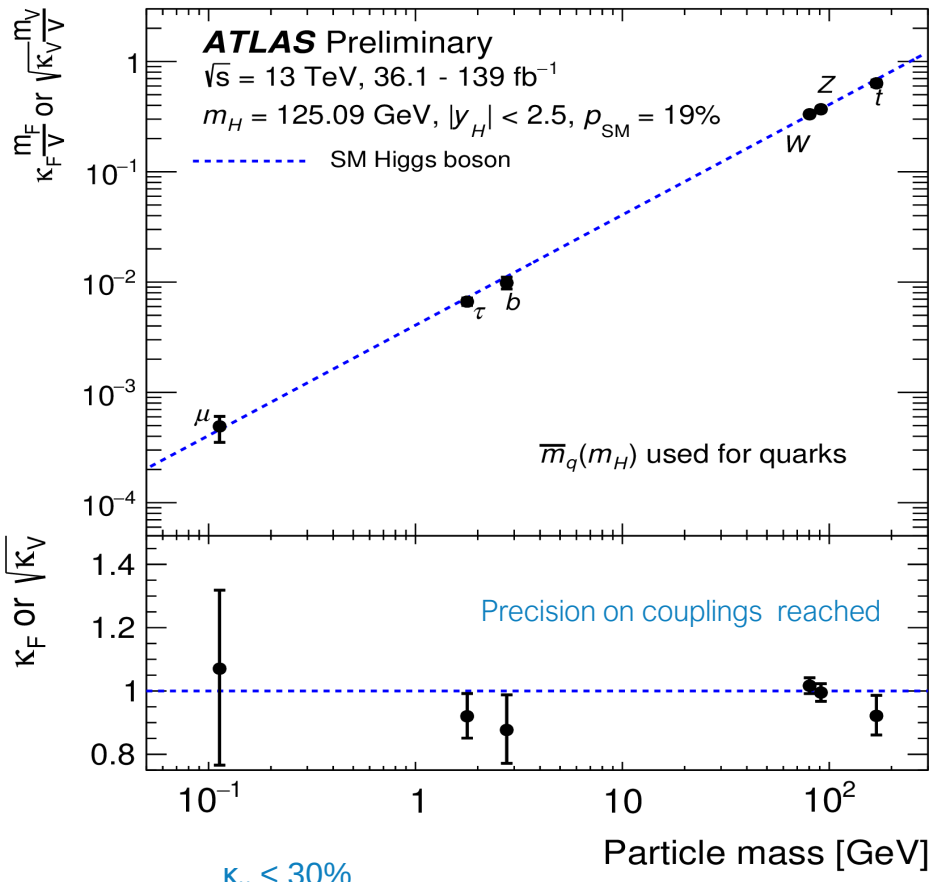
Key prediction of the Standard Model:

- Higgs coupling to particles is proportional to their mass

Impressive verification with an accuracy often better than 10%

Coupling measurements ($B_i = B_u = 0$)

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

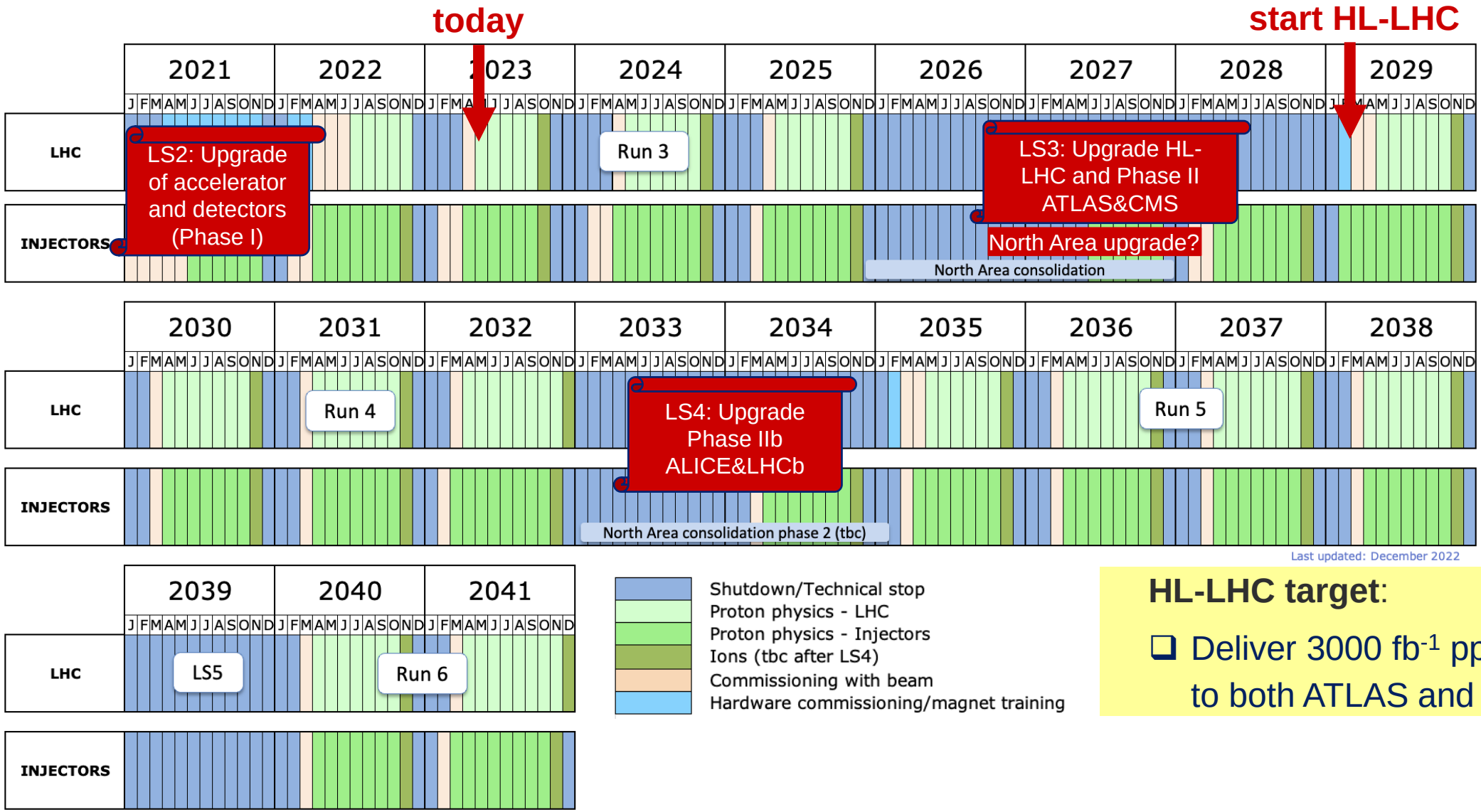


ATLAS-CONF-2021-053

$\kappa_\mu < 30\%$

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

LHC Timeline

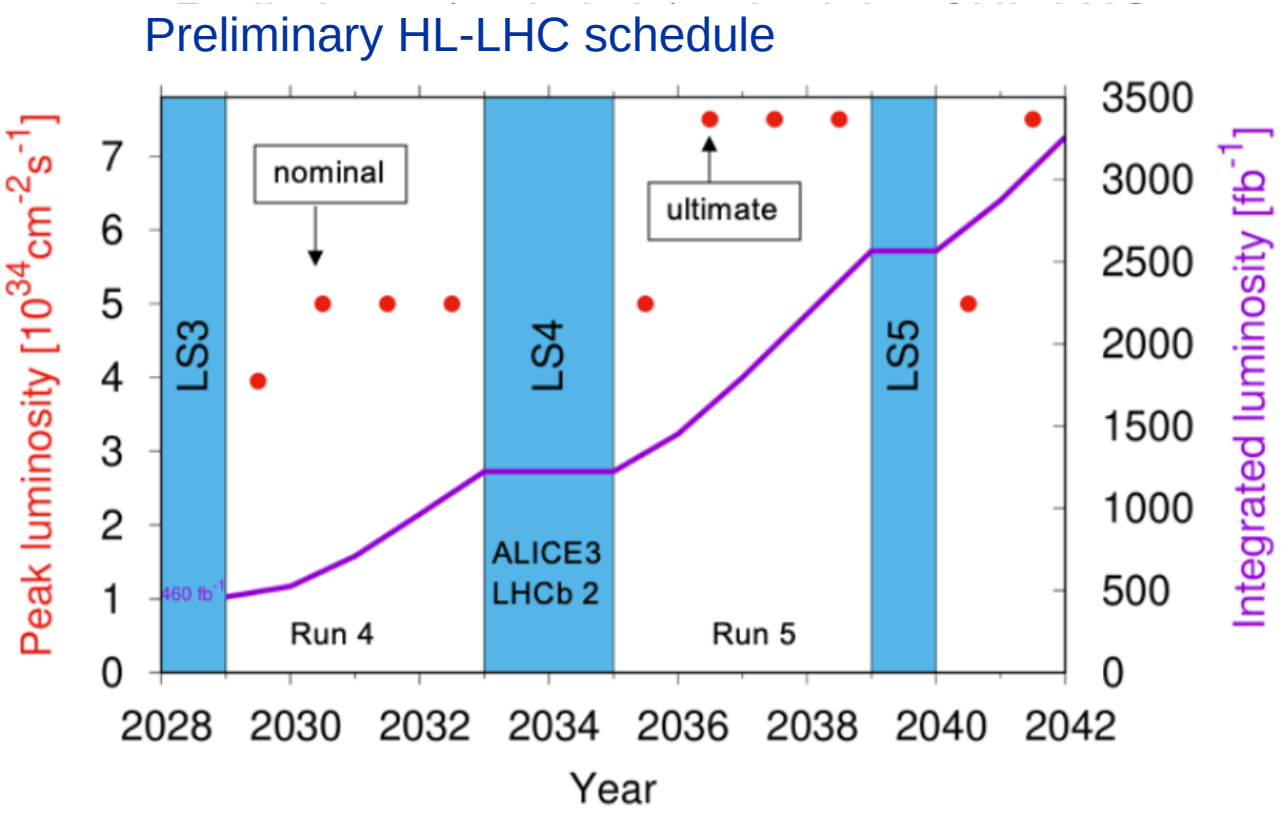


HL-LHC target:

- Deliver 3000 fb^{-1} pp luminosity to both ATLAS and CMS

LHC Programme

- High Luminosity 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

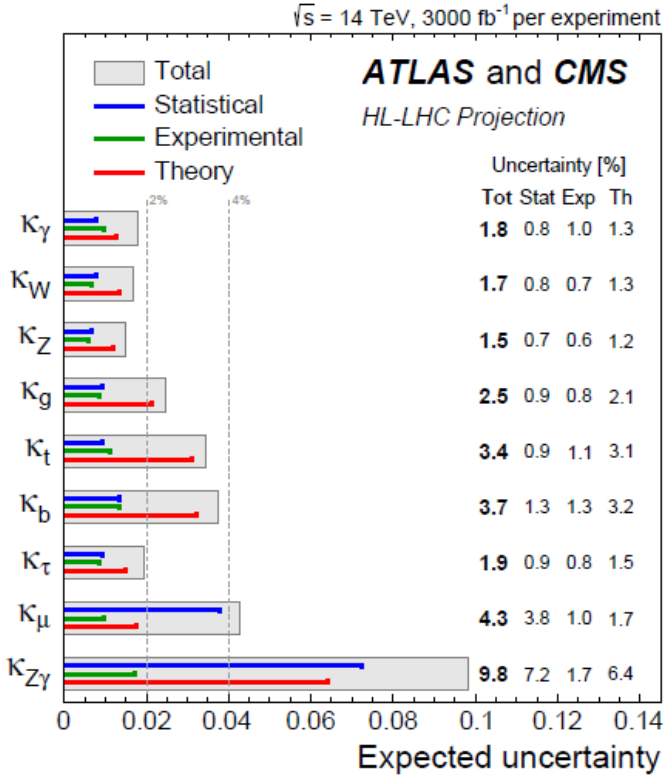


The High-Luminosity LHC

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

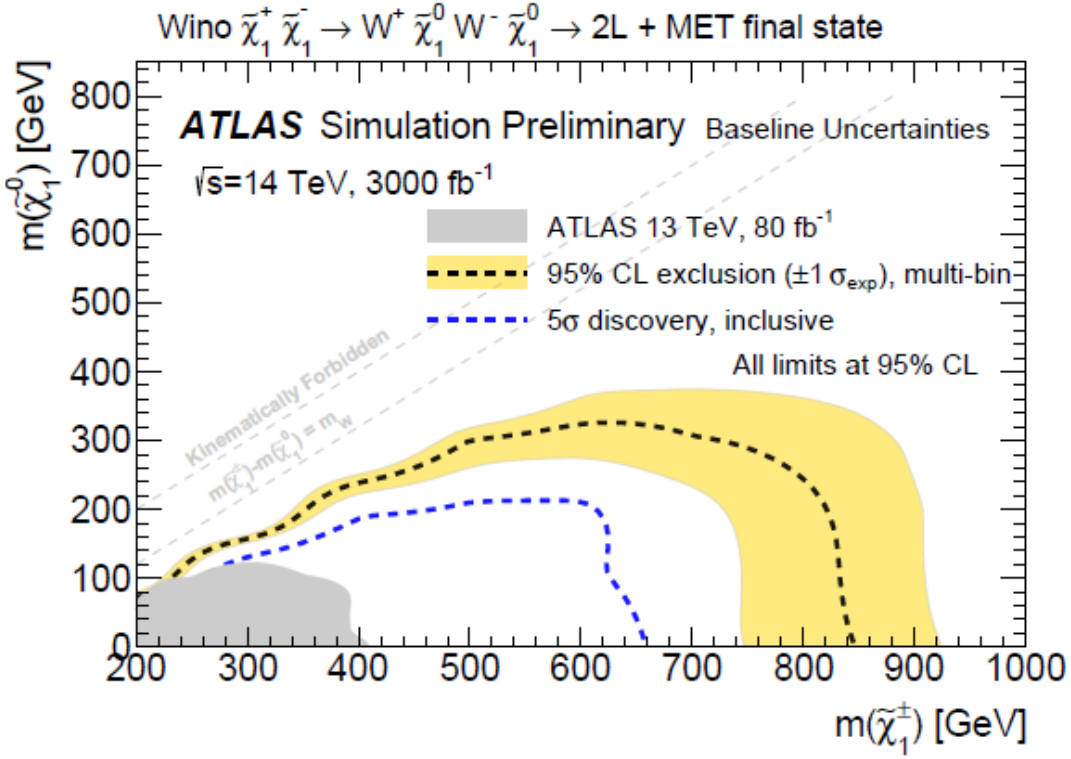
i.e. ≈ 20 times the currently available data

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



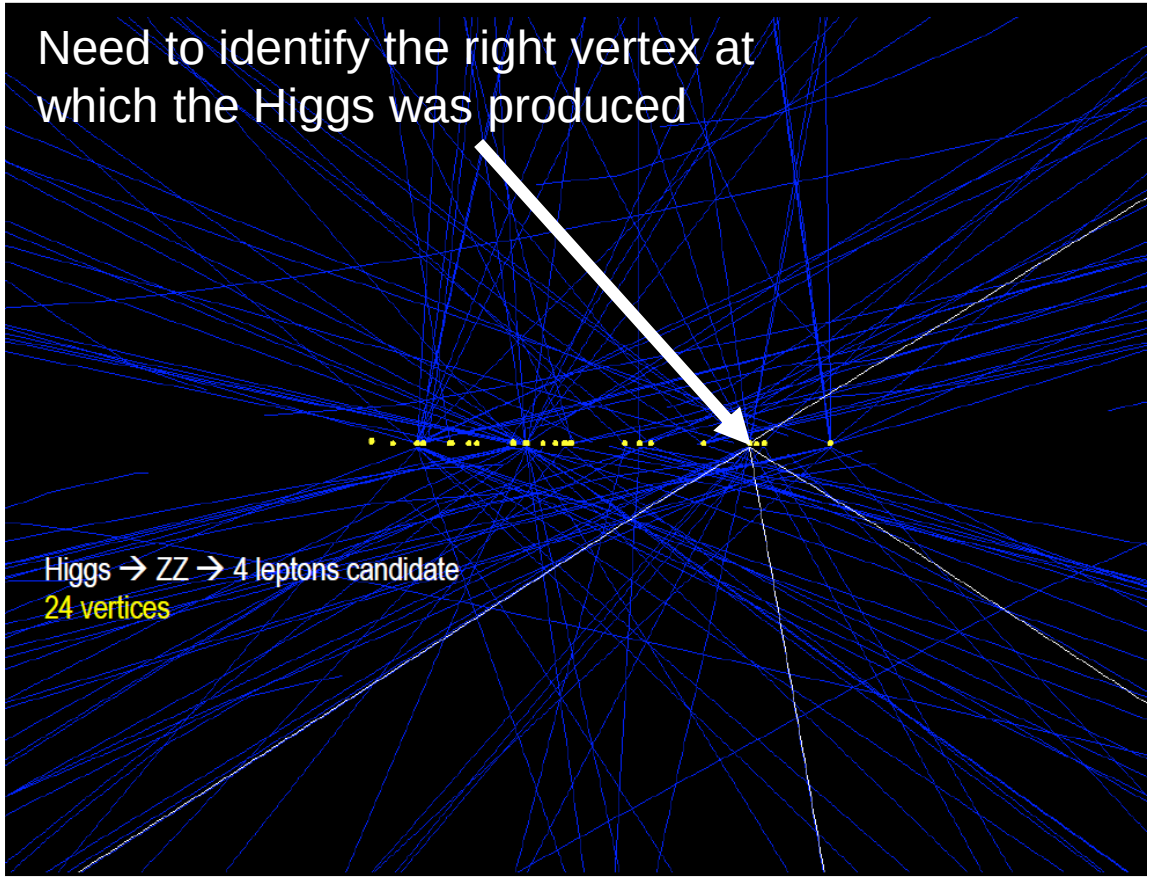
2 examples for illustration

CERN-2019-007

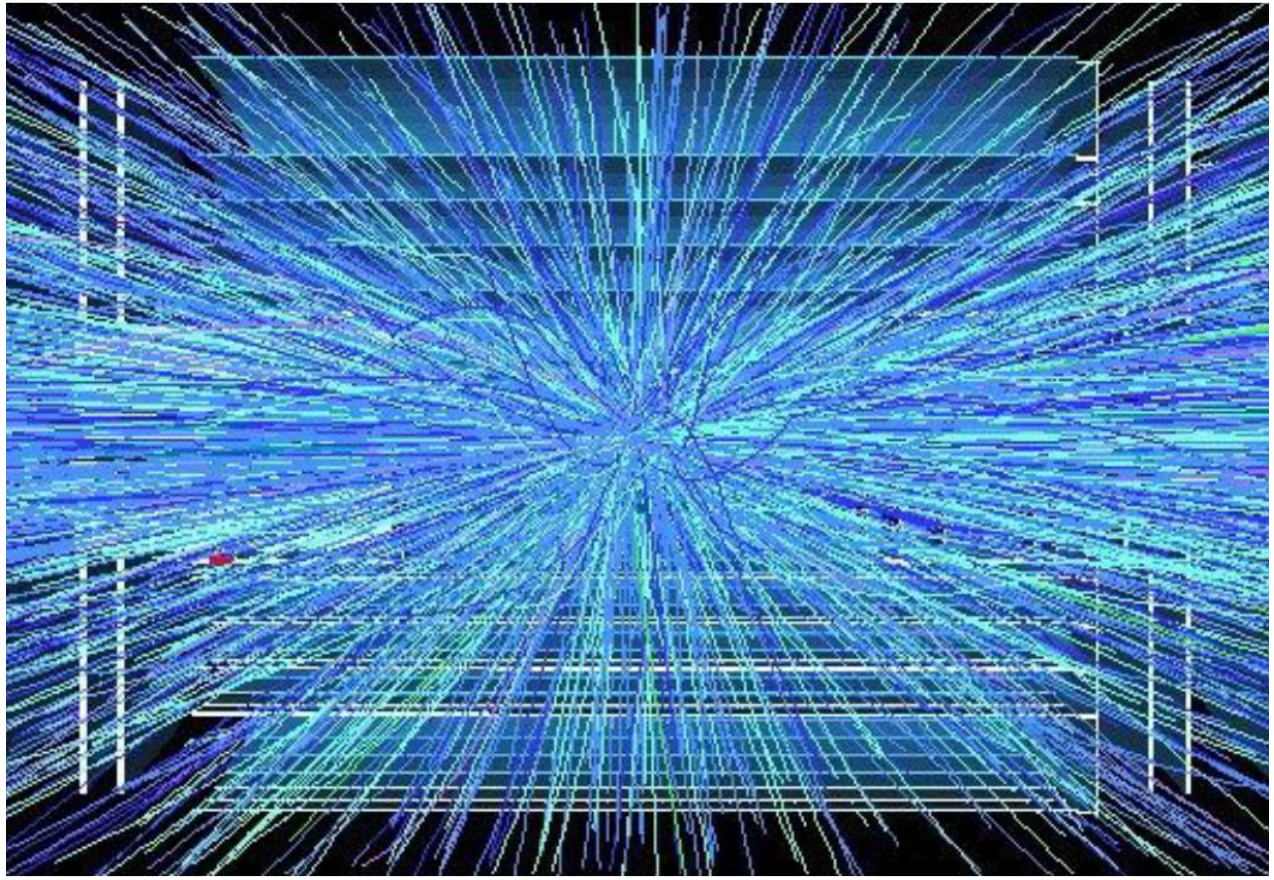


Challenges for the Detectors

- 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

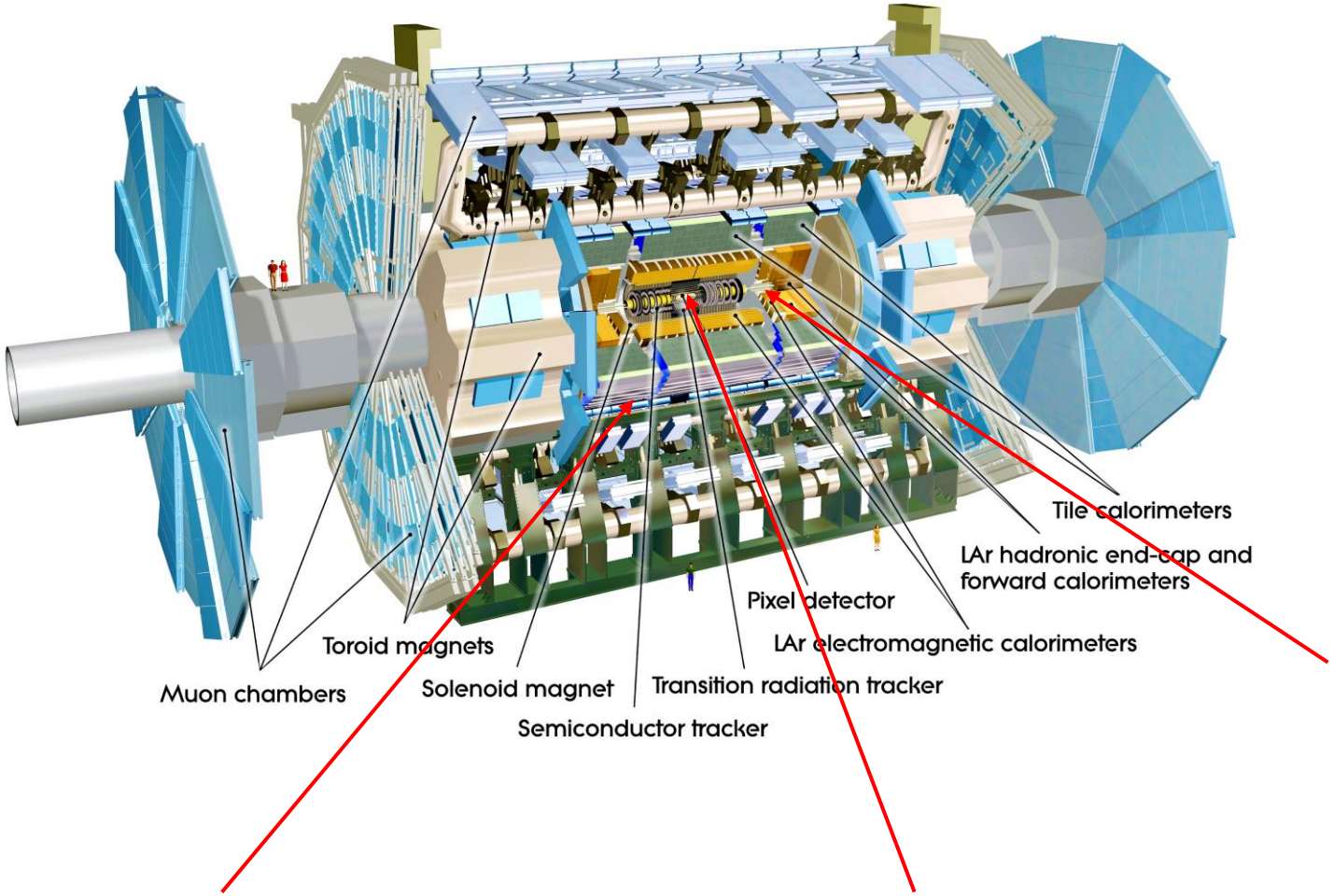


ATLAS Phase II Upgrades

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 $|\eta| = 4$

CMS Phase II Upgrades

L1-Trigger HLT/DAQ

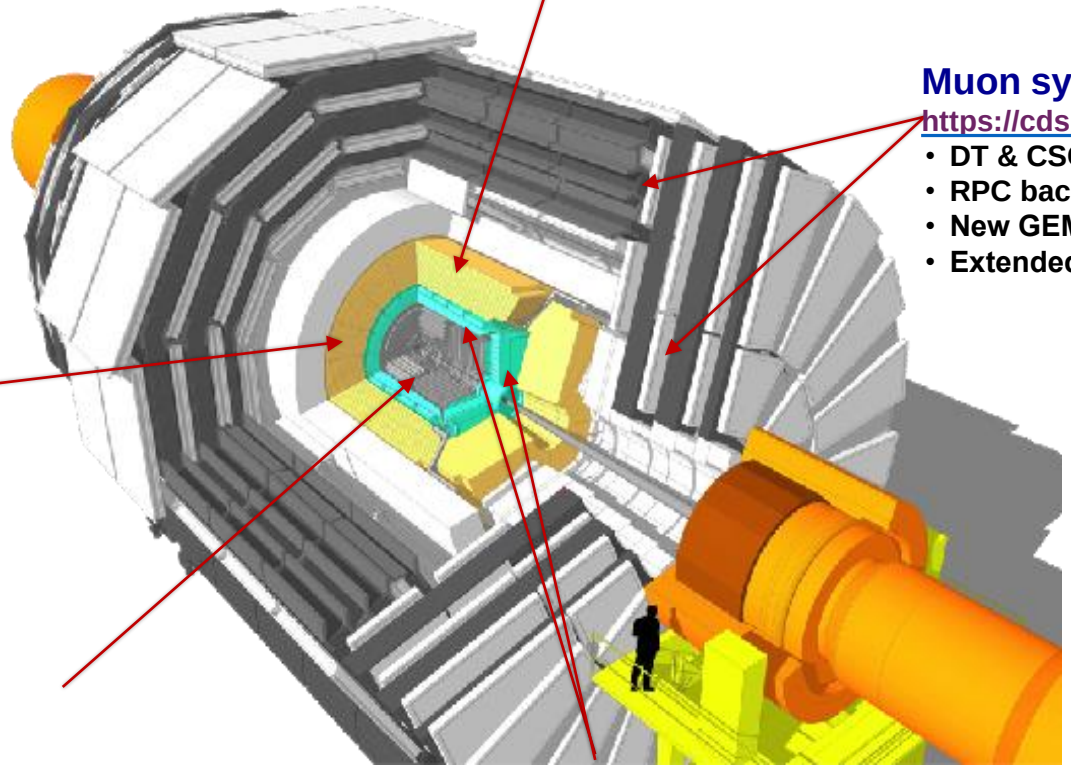
https://cds.cern.ch/record/2714892
https://cds.cern.ch/record/2283193

- 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 $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

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 $\eta \simeq 3.8$

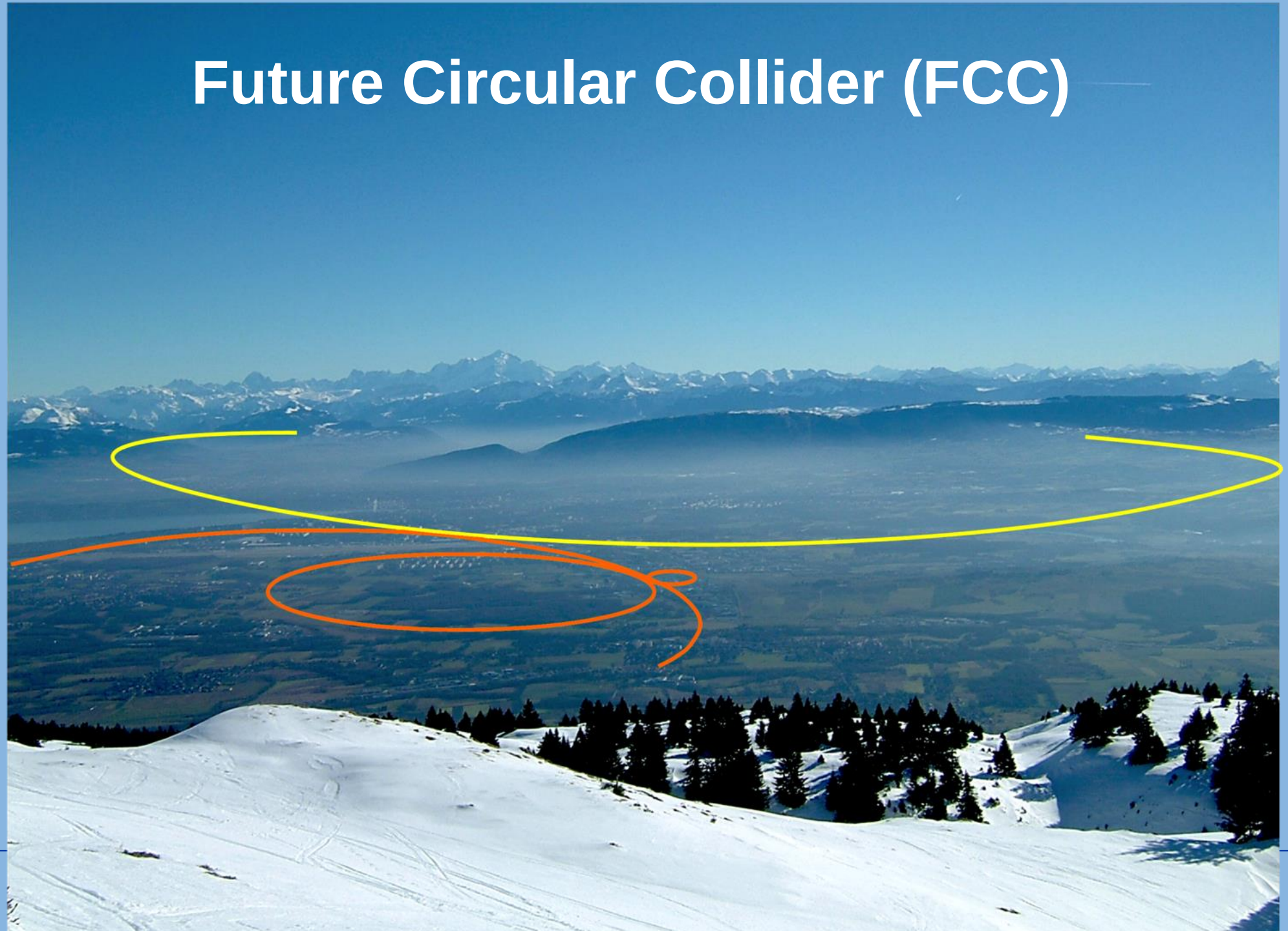
MIP Timing Detector

https://cds.cern.ch/record/2667167

Precision timing with:

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

Future Circular Collider (FCC)

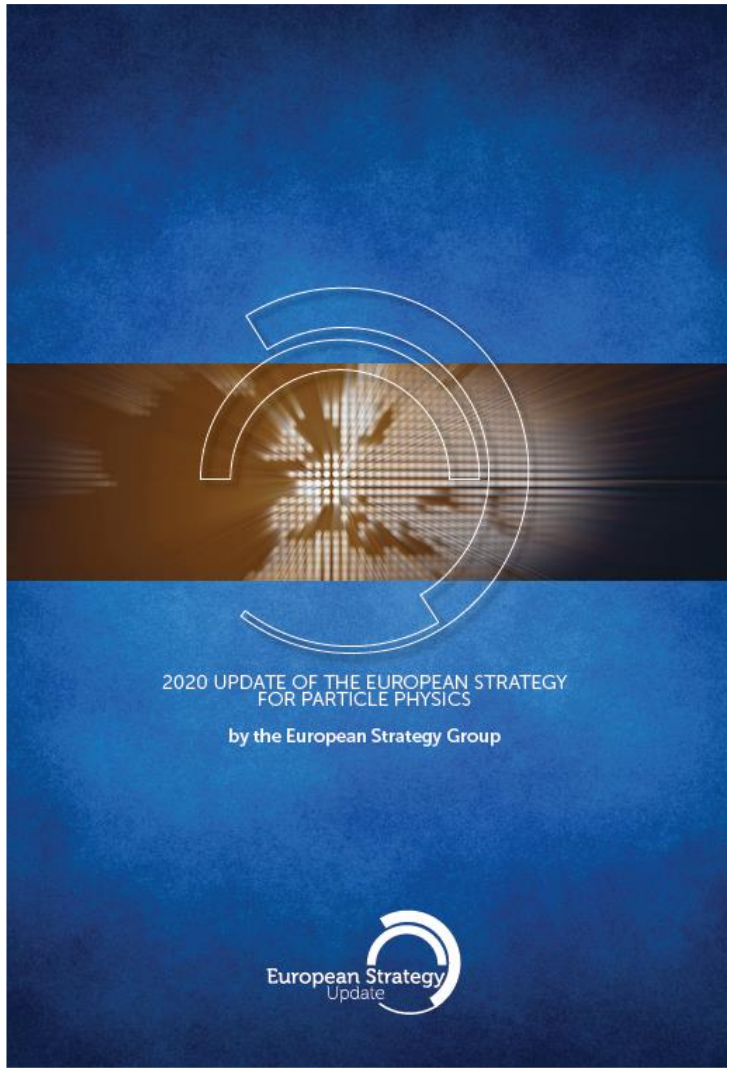


Future Circular Collider (FCC): Feasibility Study

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

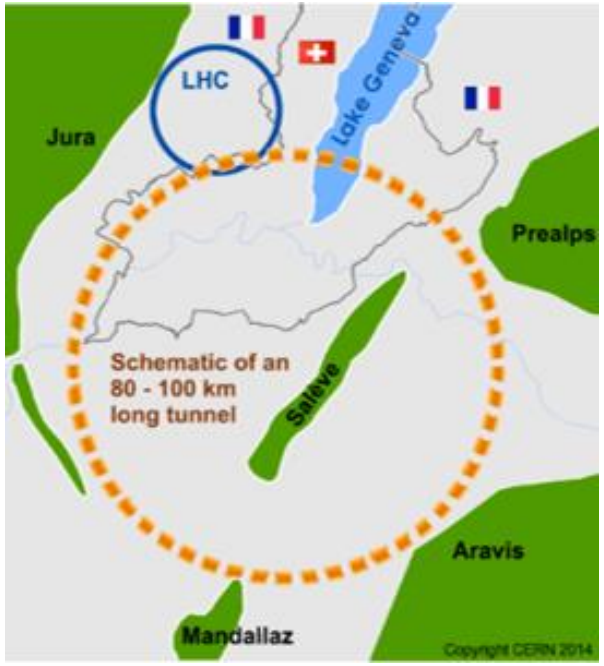


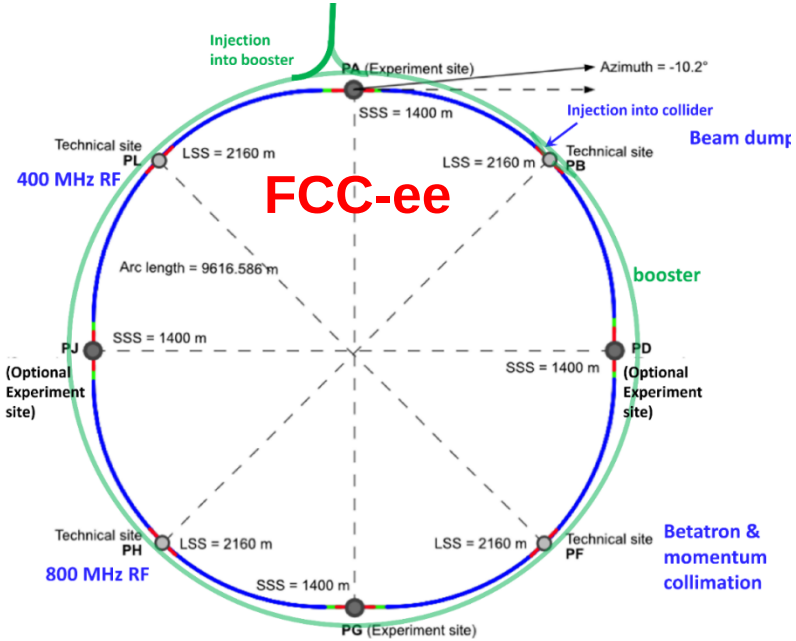
The FCC integrated program inspired by successful LEP – LHC programs at CERN

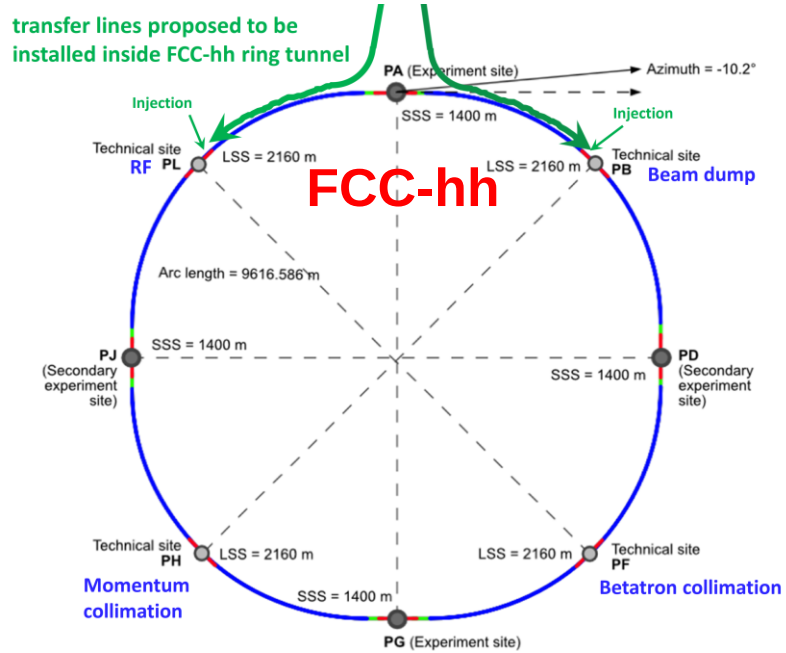
M. Benedikt
April 2022

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

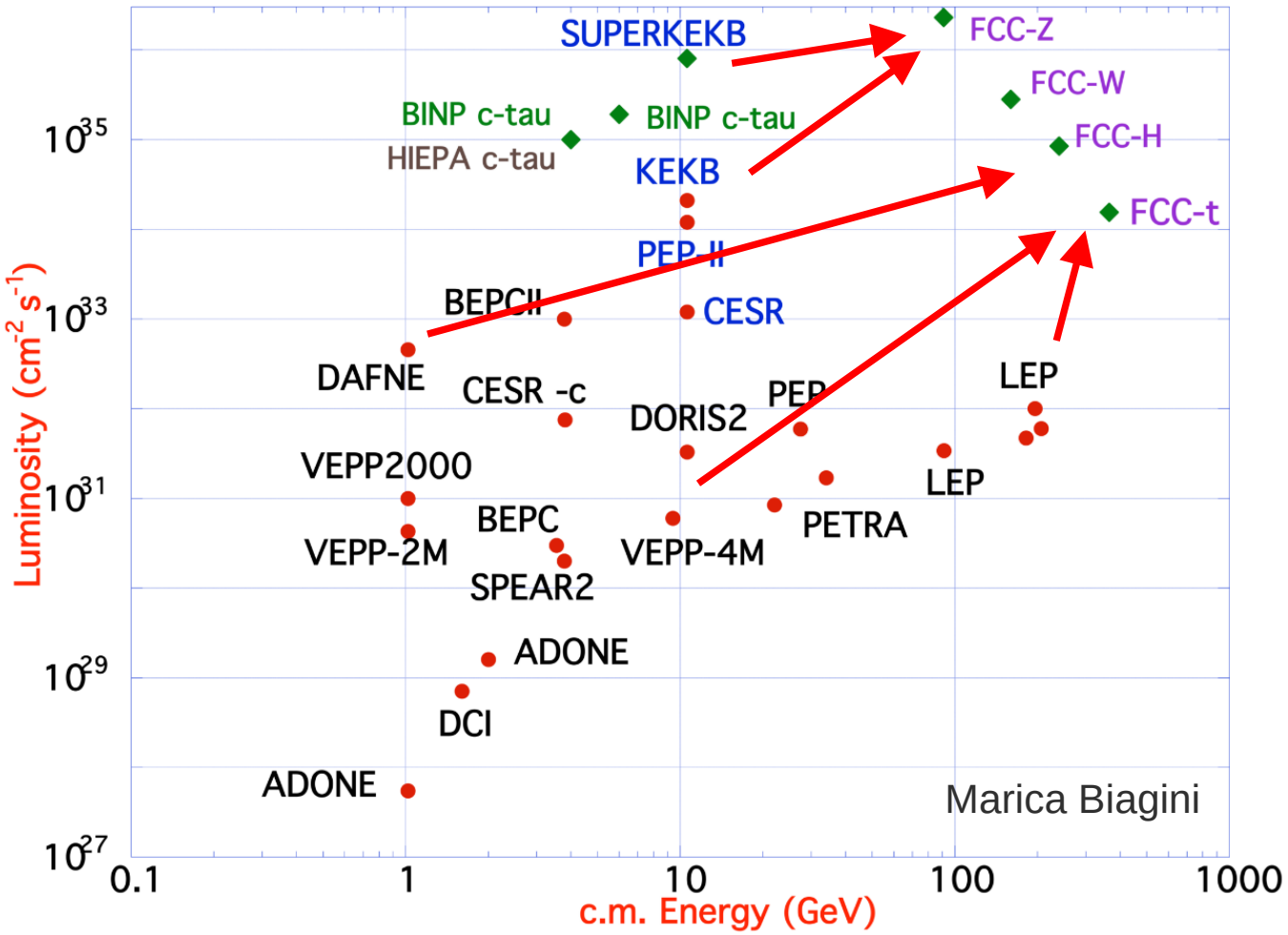






2065 - 2090

FCC-ee Design Concept

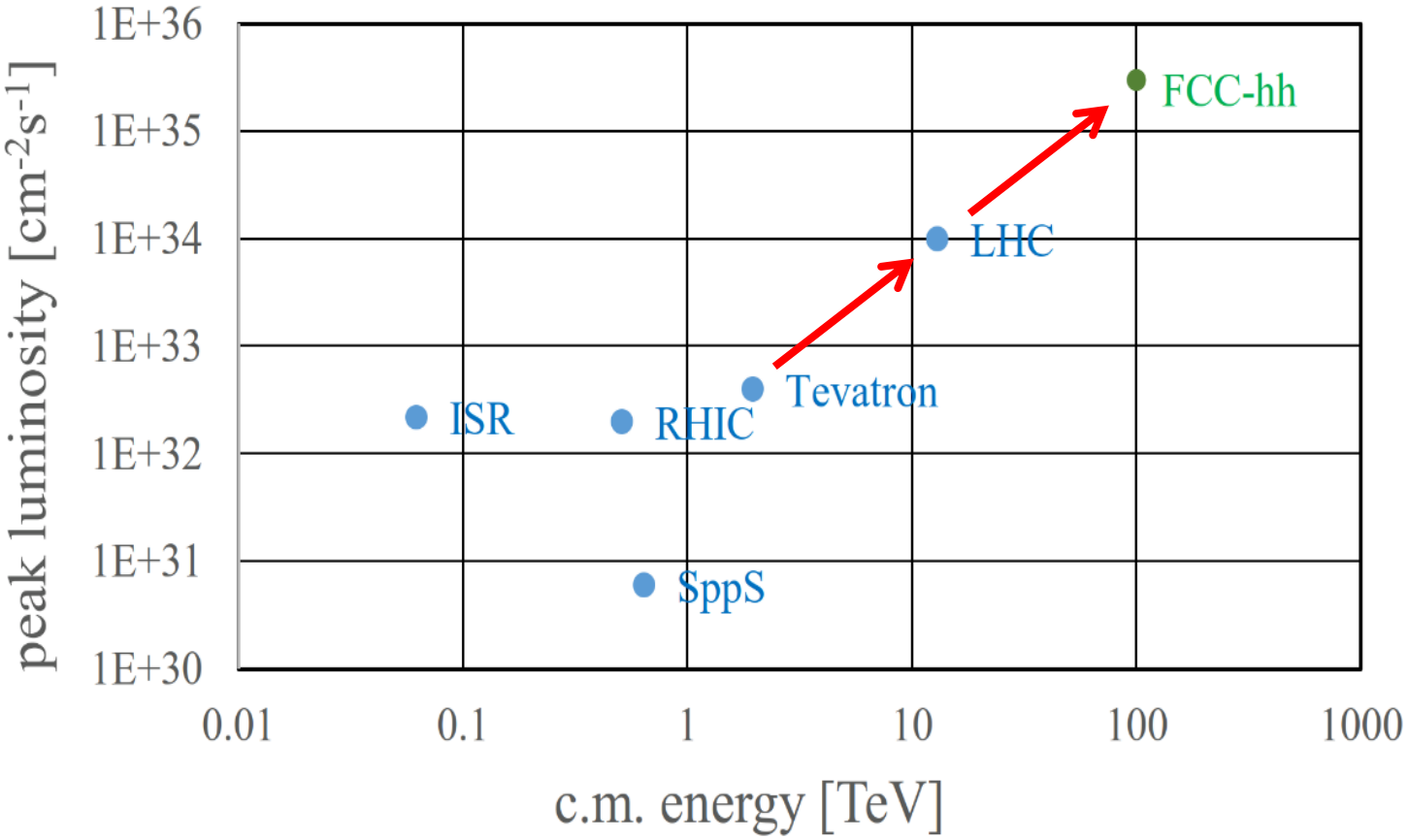


Based on lessons and techniques from past colliders (last 40 years)

- 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

Conclusion

- **The CERN Scientific programme has an agenda for the next 20 to 40 years**
- **The existing LHC machine will continue do deliver unprecedented data for the next 20 years**
- **The future FCC will open new frontiers in the High Energy Physics research and will bring new extreme challenges that will require de 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 delivery education on the solutions needed for scientific computing in large international projects and collaborations**