Karlsruhe Institute of Technology

Institut für Experimentelle Teilchenphysik

Stayin' Alive

Keeping the particle detectors at the LHC up to date

Physikalisches Kolloquium, Universität Siegen, December 16, 2021

Ulrich Husemann, Institute of Experimental Particle Physics, Karlsruhe Institute of Technology

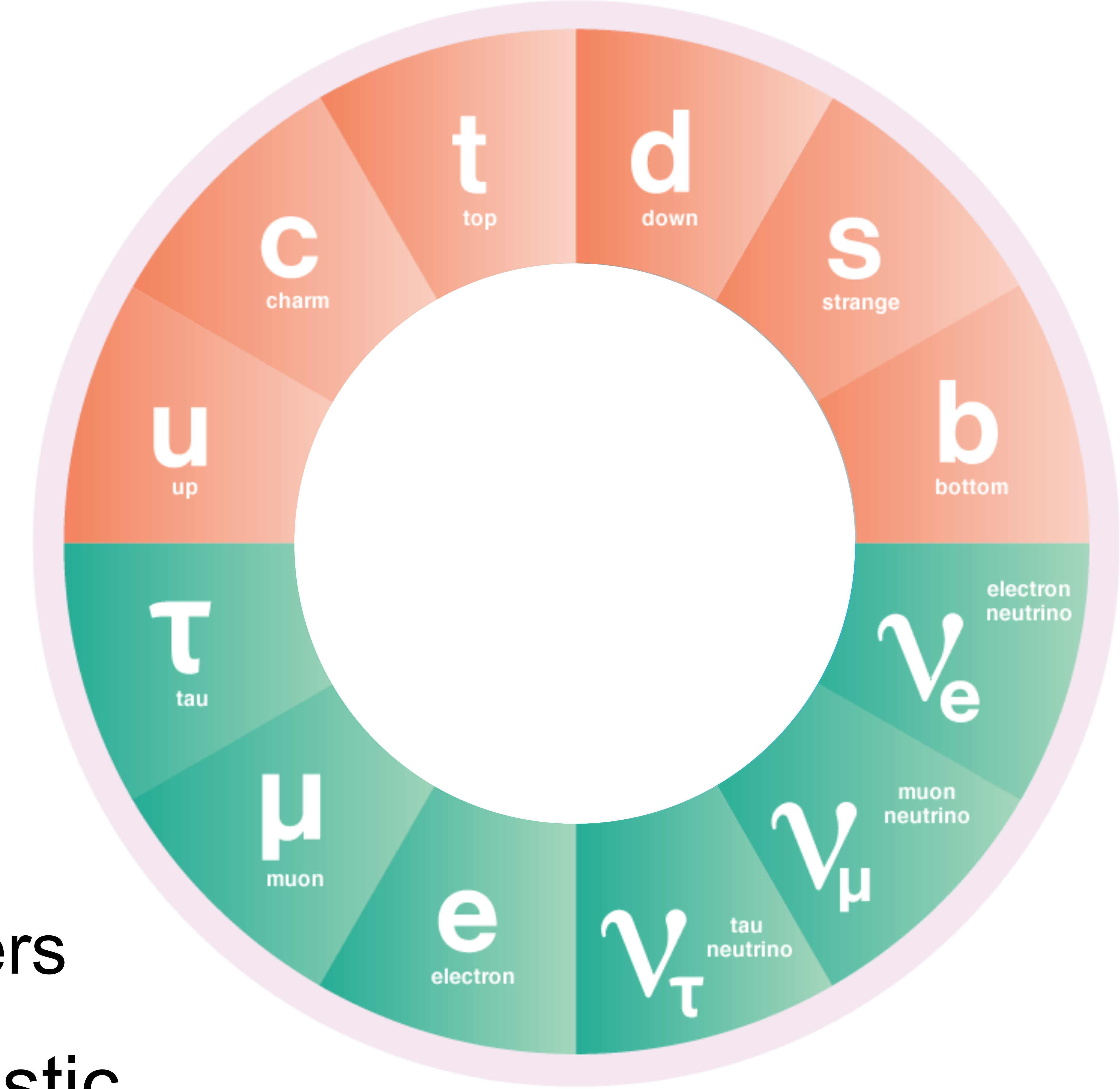
CERN and the Large Hadron Collider

The world’s most powerful particle collider:

- Proton-proton and heavy-ion collisions at the highest energies (so far: 13 TeV center-of-mass energy in pp)
- Four large experiments: ATLAS, CMS, LHCb, ALICE

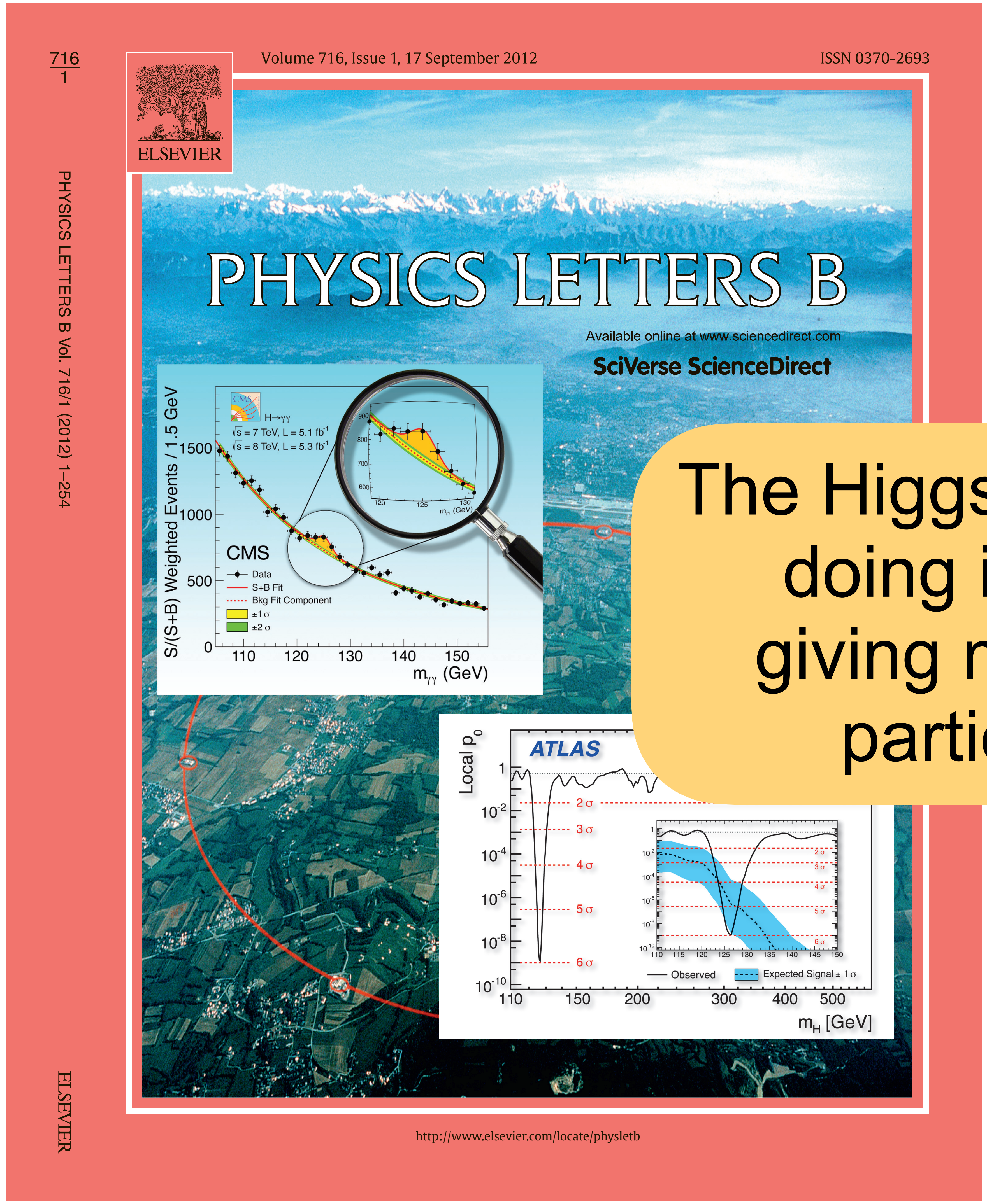
The Standard Model

- Description of fundamental particles and forces in Nature in the **standard model of particle physics**:
  - Matter is made of twelve fundamental building blocks (spin-1/2): six quarks and six leptons (and their antiparticles)
  - Four fundamental forces, mediated by force carriers (spin-1)
  - Higgs boson (spin-0): responsible for masses of quarks, leptons, and force carriers
- **Very successful theory**, based on relativistic quantum field theory and symmetry principles

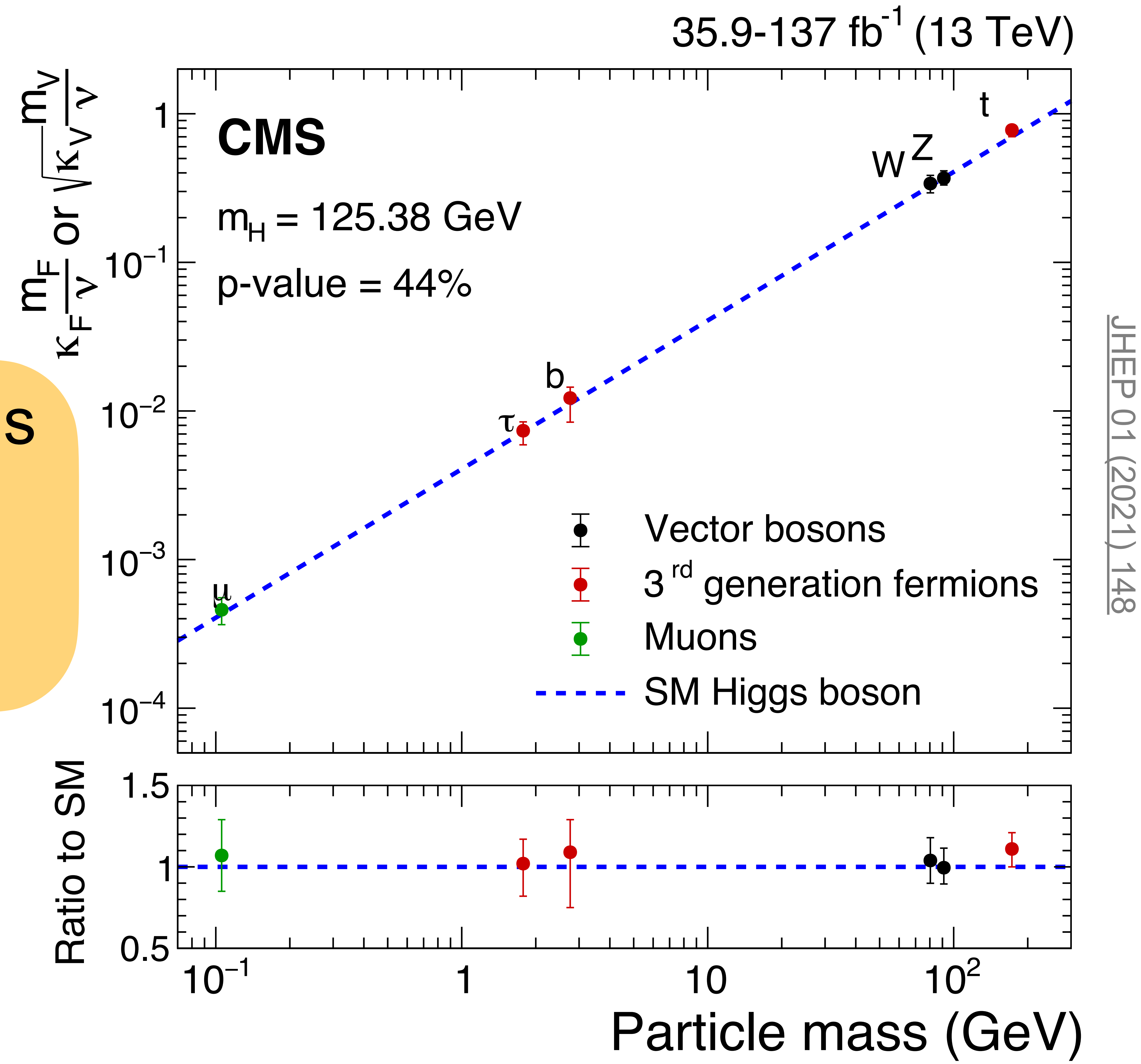


symmetrymagazine.org

Higgs Boson: Discovery & Properties



The Higgs boson is doing its job: giving mass to particles.



A Theorist’s View

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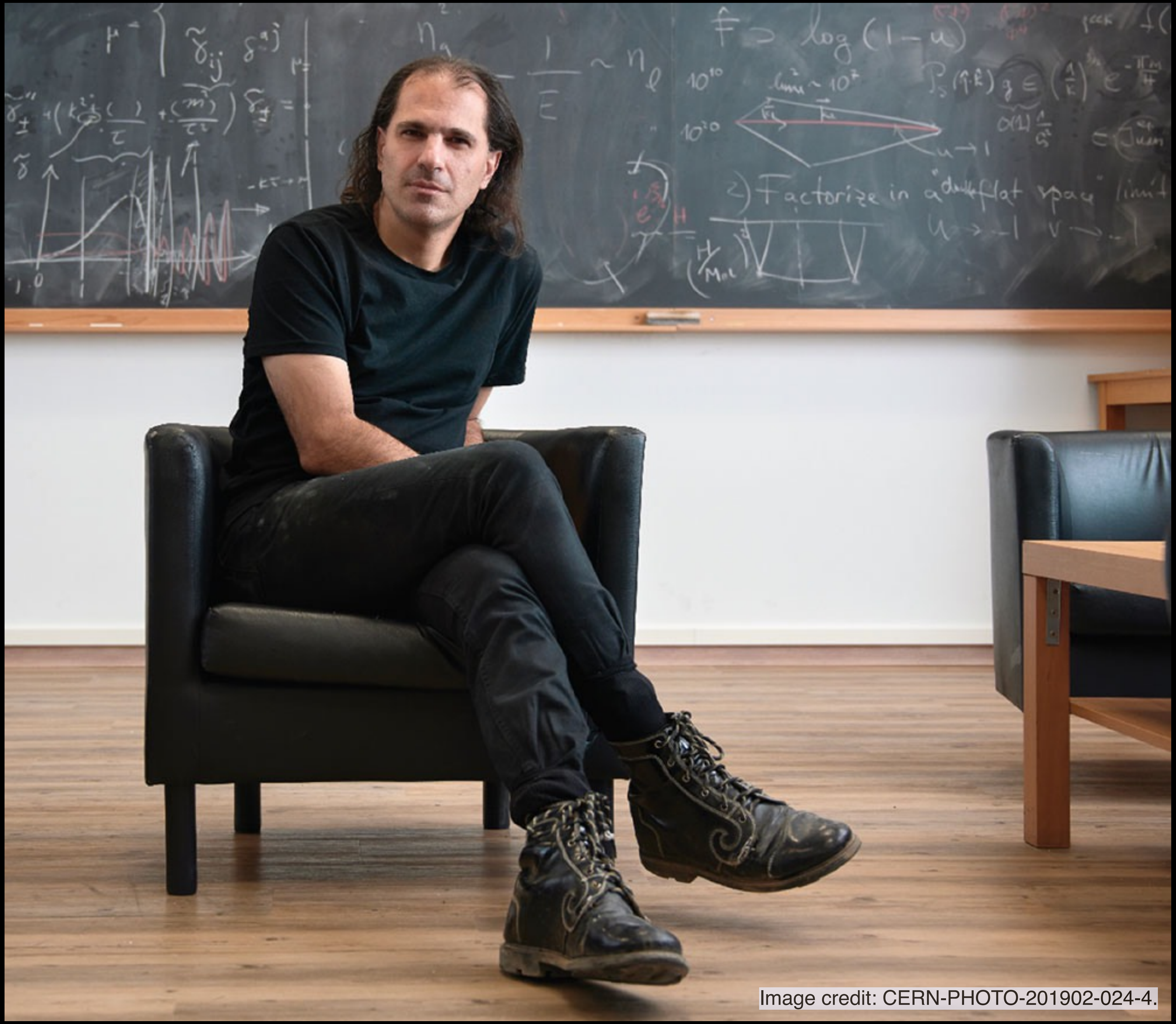
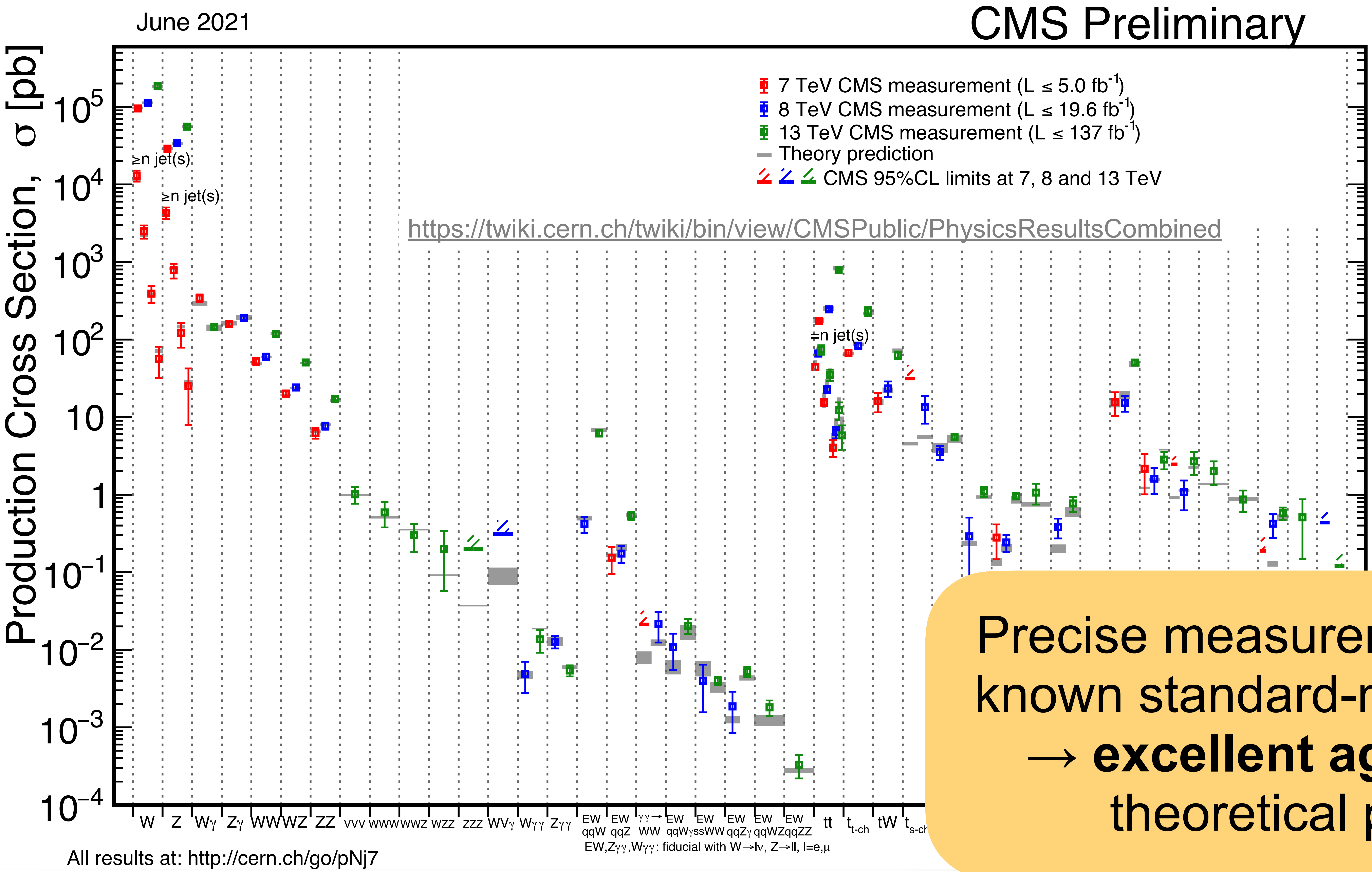


The discovery of the Higgs particle – especially with nothing else accompanying it so far – is unlike anything we have seen in any state of nature, and is profoundly “new physics” in this sense. […] While we continue to scratch our heads as theorists, the most important path forward for experimentalists is completely clear: ***measure the hell out of these crazy phenomena!***

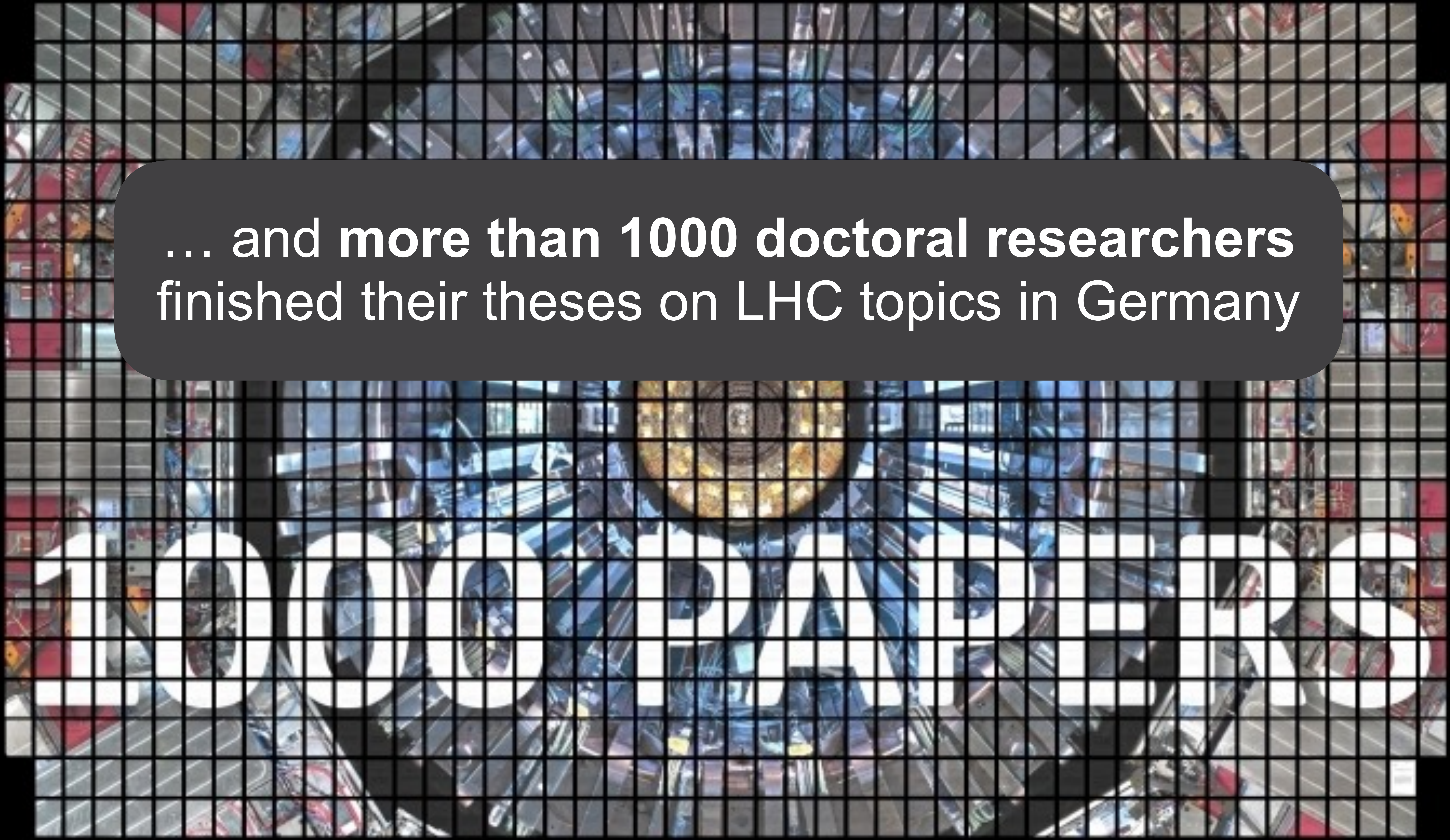
N. Arkani-Hamed,
CERN Courier, March 2019

The CMS Stairway to Heaven



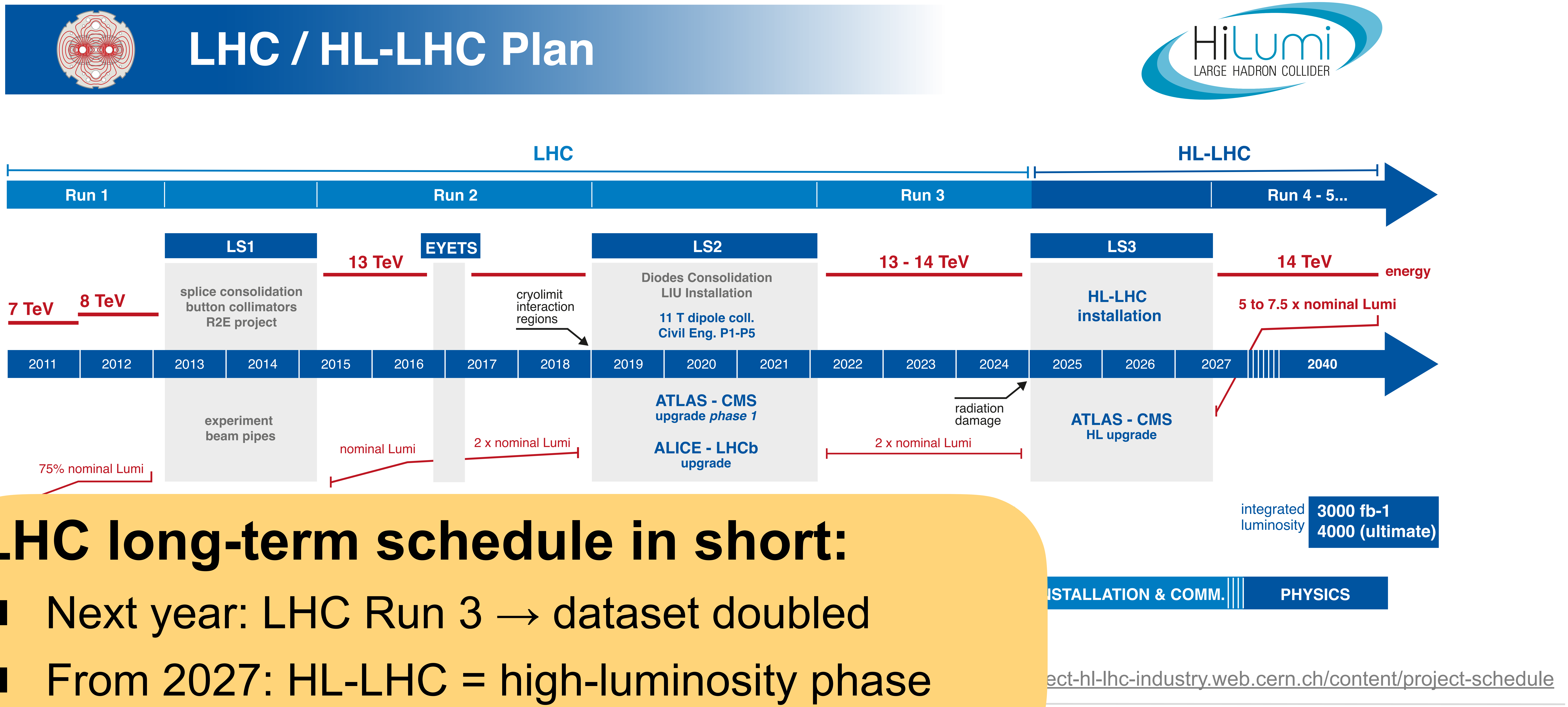
Precise measurements of 100s of known standard-model processes → **excellent agreement** with theoretical predictions

… and **more than 1000 doctoral researchers** finished their theses on LHC topics in Germany



Achieved by CMS on June 18, 2020

What’s Next?



LHC long-term schedule in short:

- Next year: LHC Run 3 → dataset doubled
- From 2027: HL-LHC = high-luminosity phase
  → at least 10× the data of LHC Runs 1–3

What About the Detectors?

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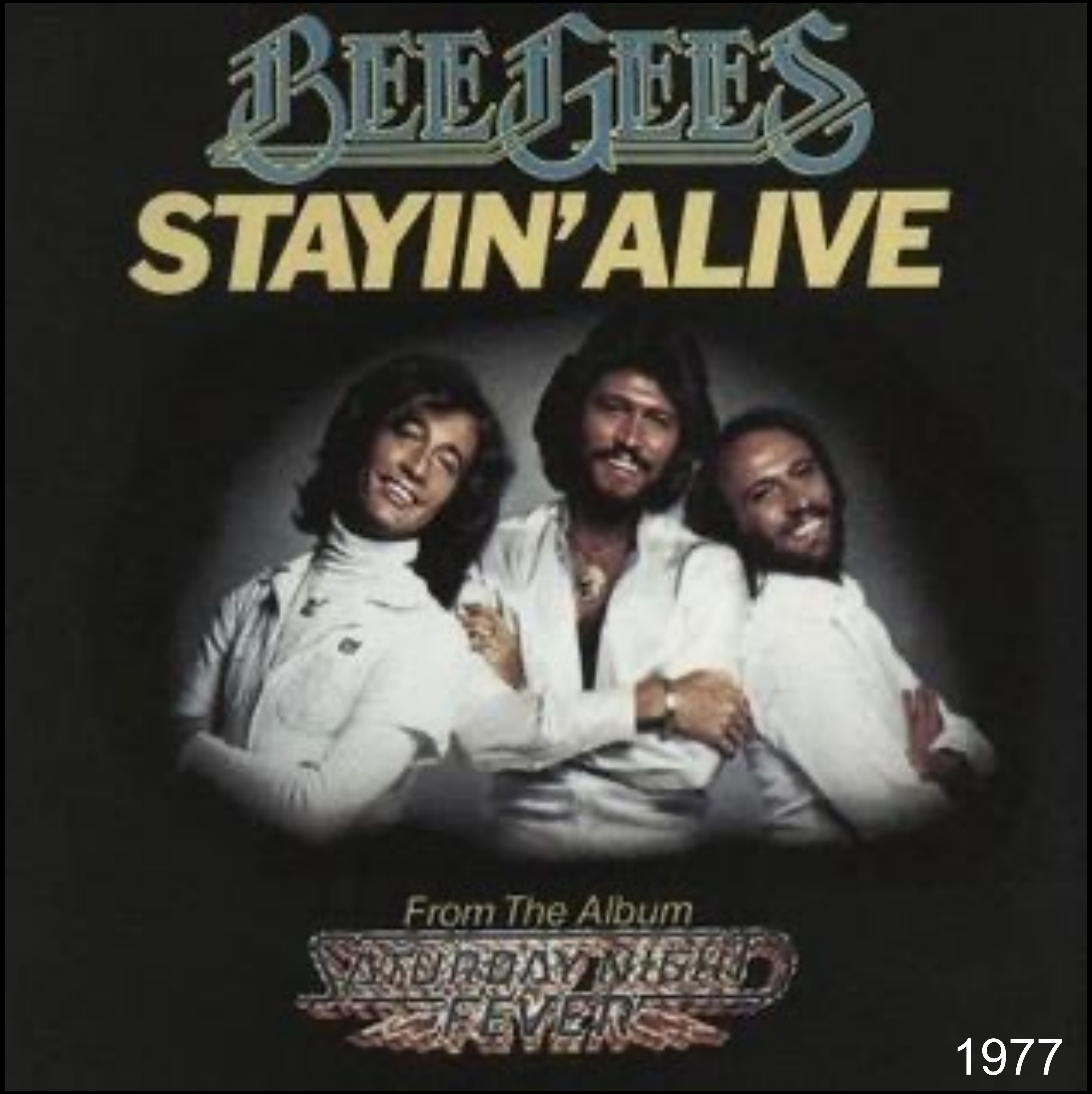
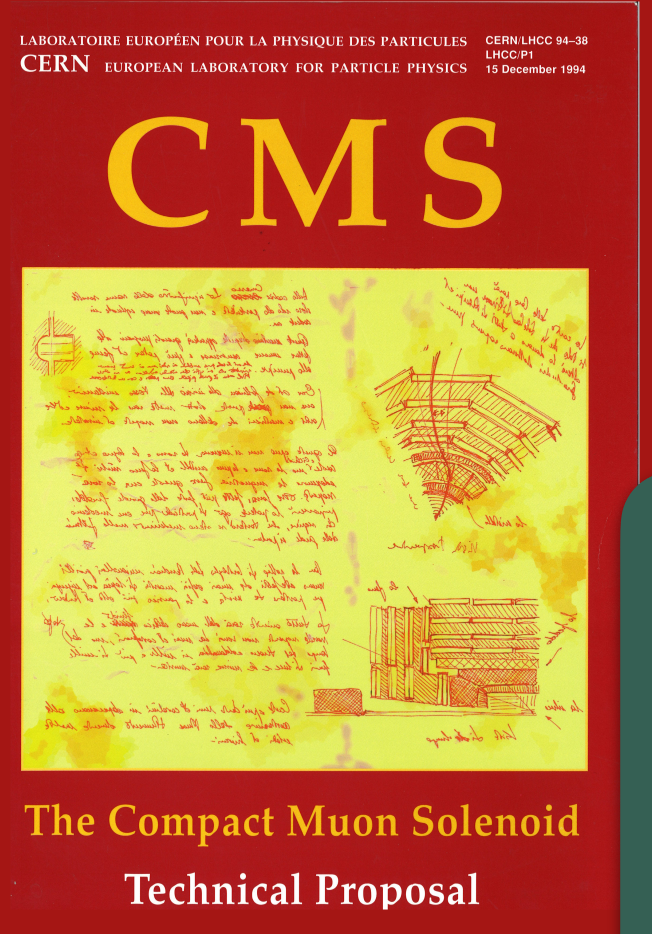
- **Very high readout rates**: 40 MHz collision rate, 1000s of particles per event
- **Harsh radiation environment**: ionizing dose above 1 MGy, non-ionizing fluence above 10^{15} n_{eq}/cm^2
- Prime challenge: keep the LHC detectors **alive and up to date**



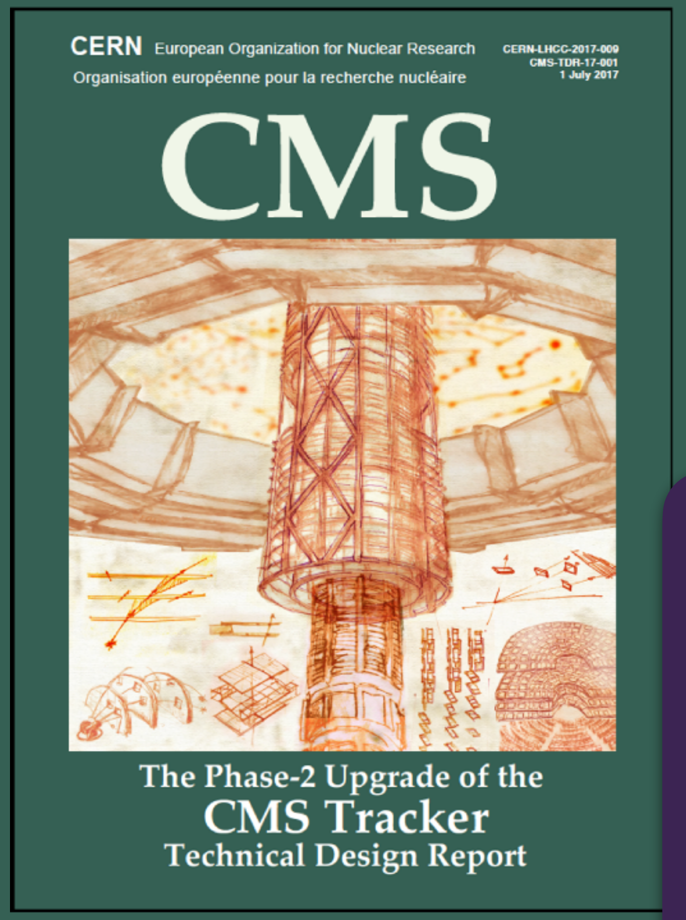
1977

Outline of this Colloquium

How we got here: CMS today



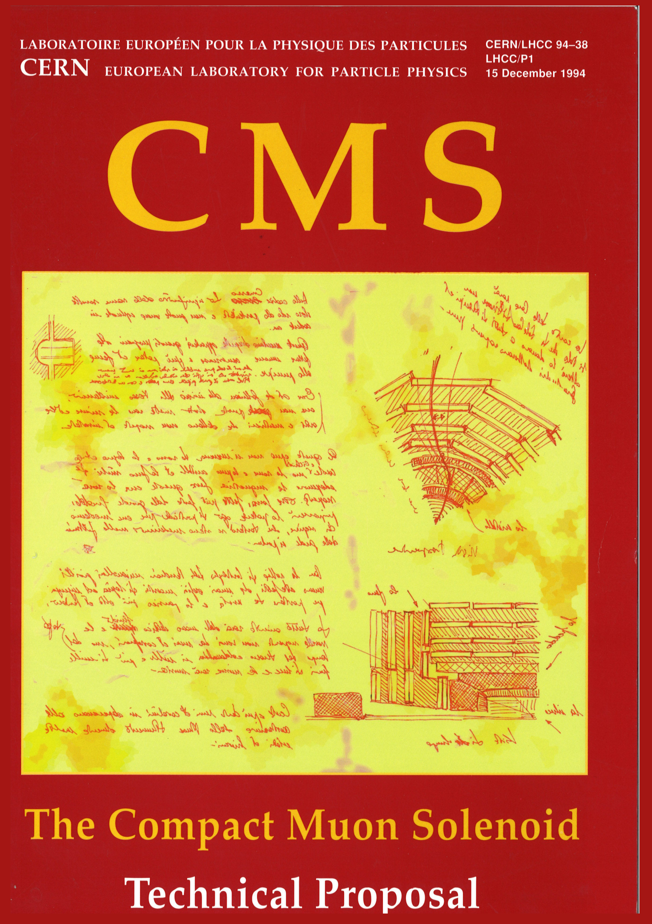
What keeps us busy: Upgrades for HL-LHC



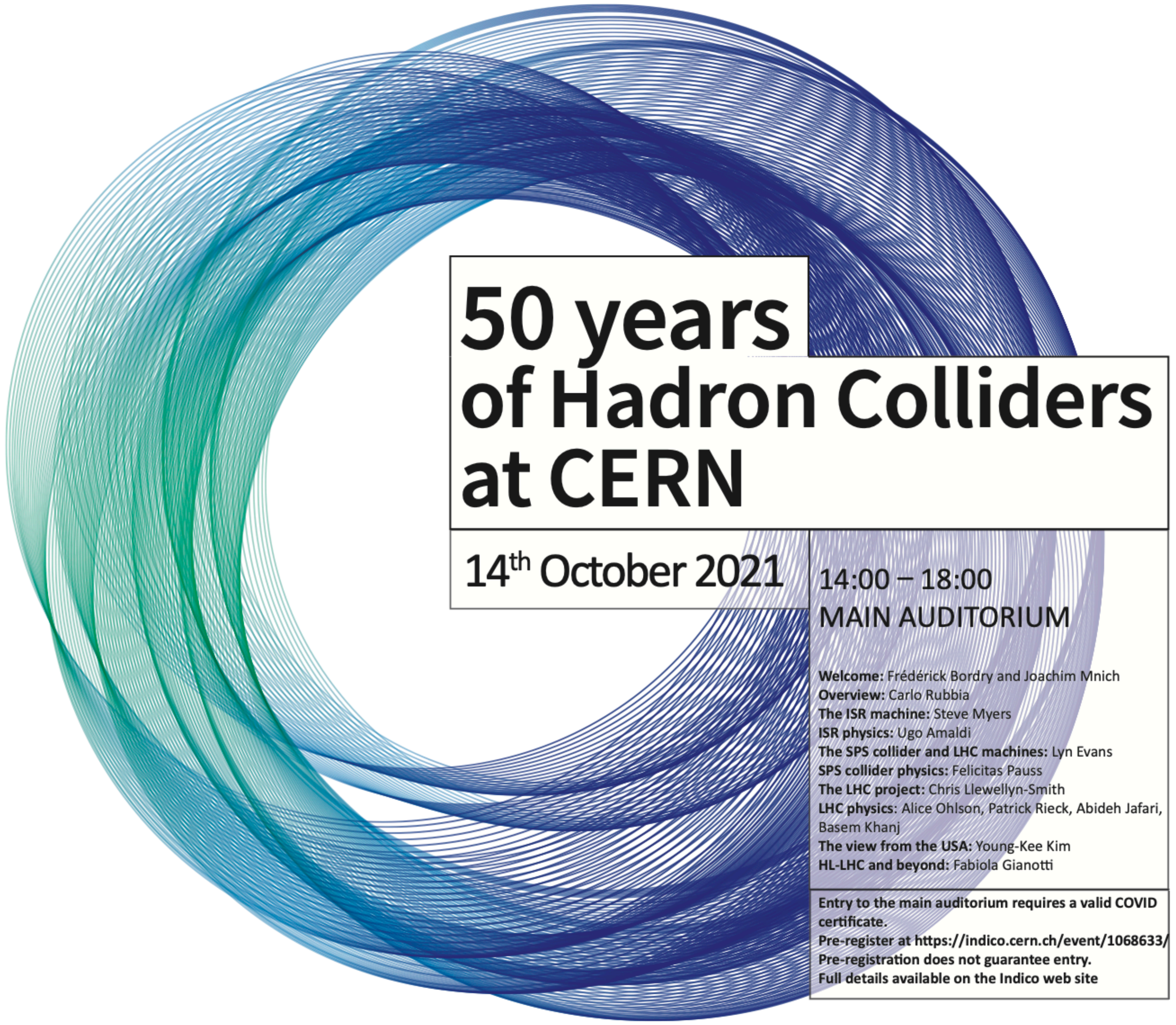
How we prepare for the future

Outline of this Colloquium

How we got here: CMS today



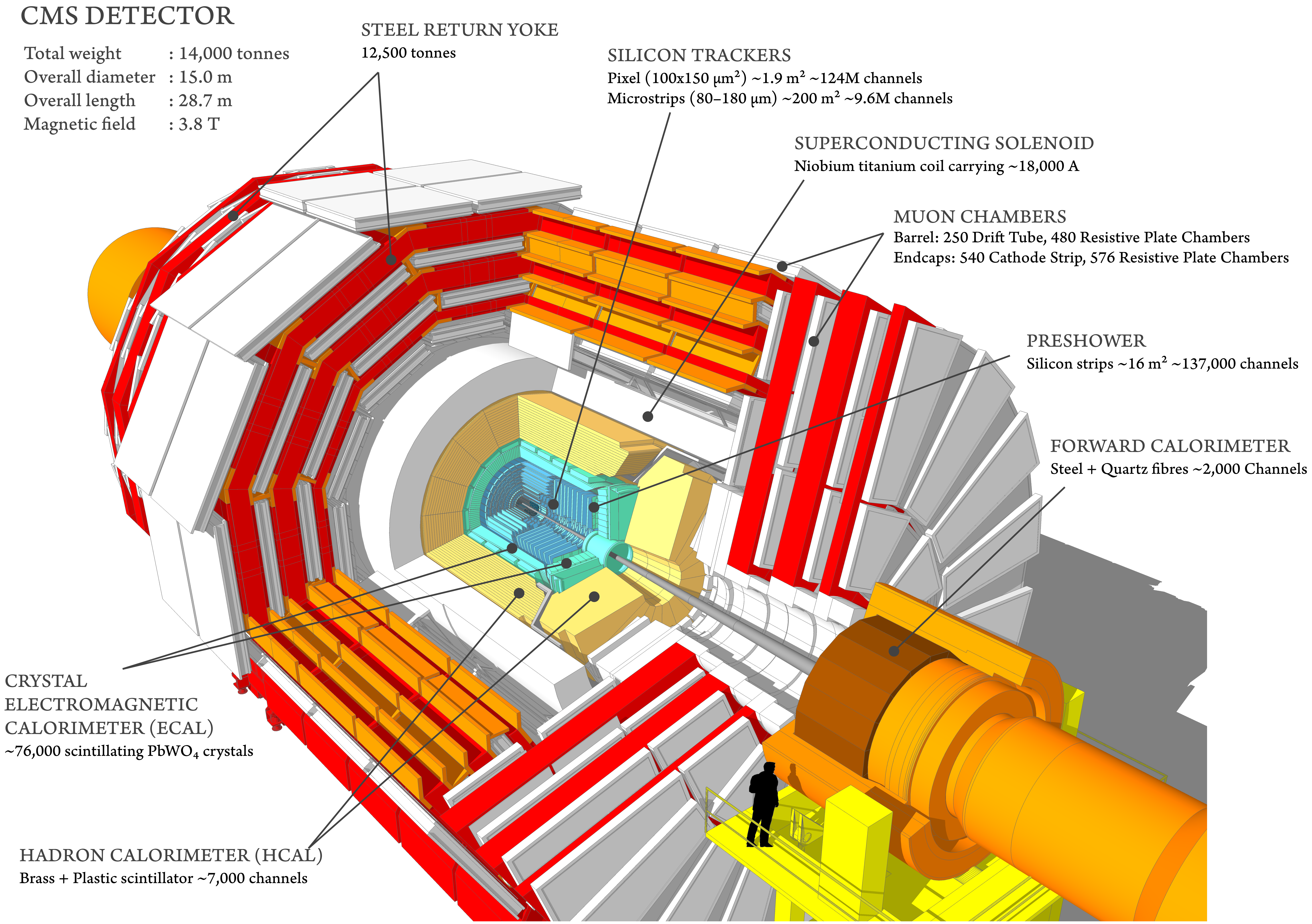
LHC (Pre-)History



https://indico.cern.ch/event/1068633/

- 1976: first ideas for the Large Electron-Positron (LEP) collider at CERN
  → use tunnel for hadron collider later
- 1984: LHC discussed at workshops of European and International Committees for Future Accelerators (ECFA, ICFA)
- 1990–1992: LHC workshops in Aachen and Evian → formation of experimental collaborations
- 1994: LHC approved by CERN Council

CMS History

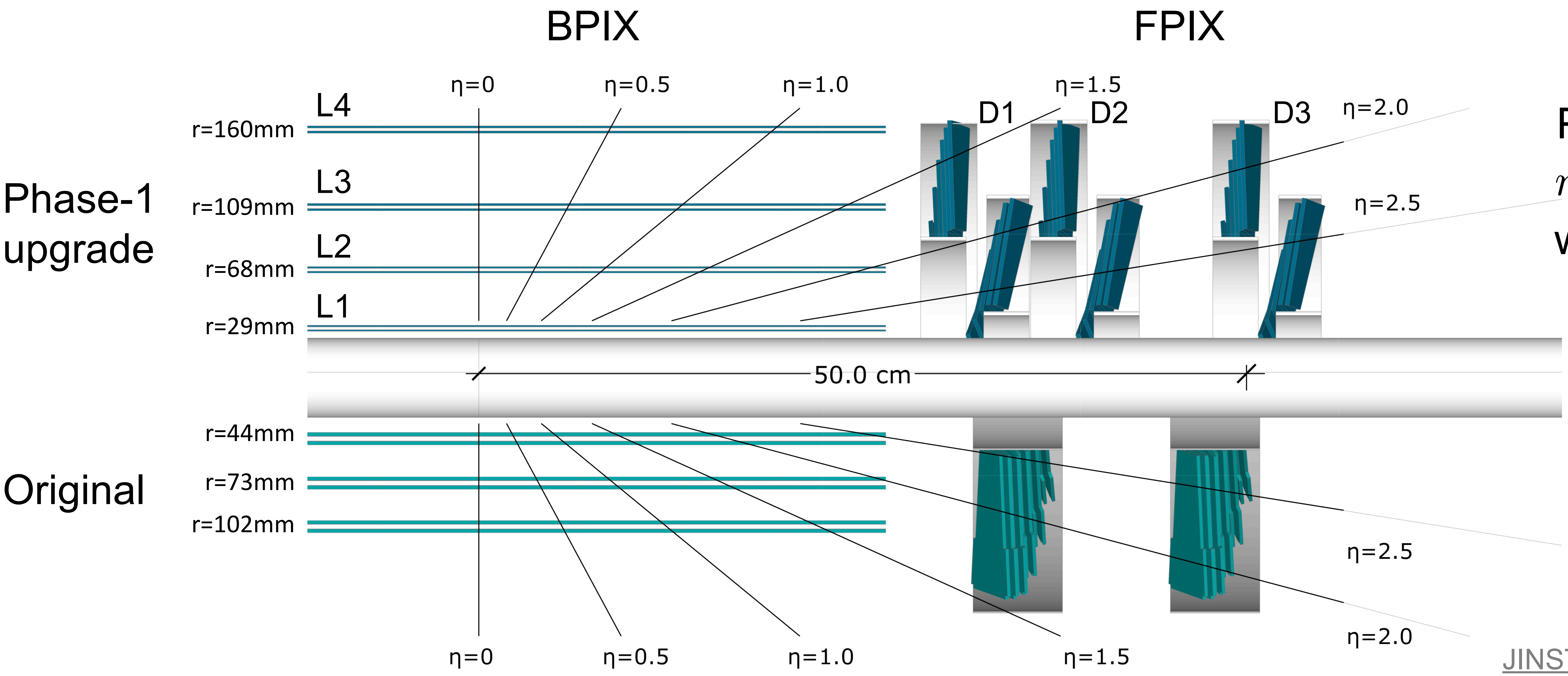


Based on 2014 J. Phys.: Conf. Ser. 513 (2014) 022032

- October 1992: **Letter of Intent**
- December 1994: **Technical Proposal**
- Intense research and development phase → **Technical Design Reports** for all subsystems
- 2008: **first beam** → Run 1: 2010–2012 → Run 2: 2015–2018

2017: Pixel Detector Upgrade

- **New silicon pixel detector** to keep up with LHC performance in Run 2:
  → more layers, smaller inner radius, improved mechanics/cooling/powering
  → new digital readout

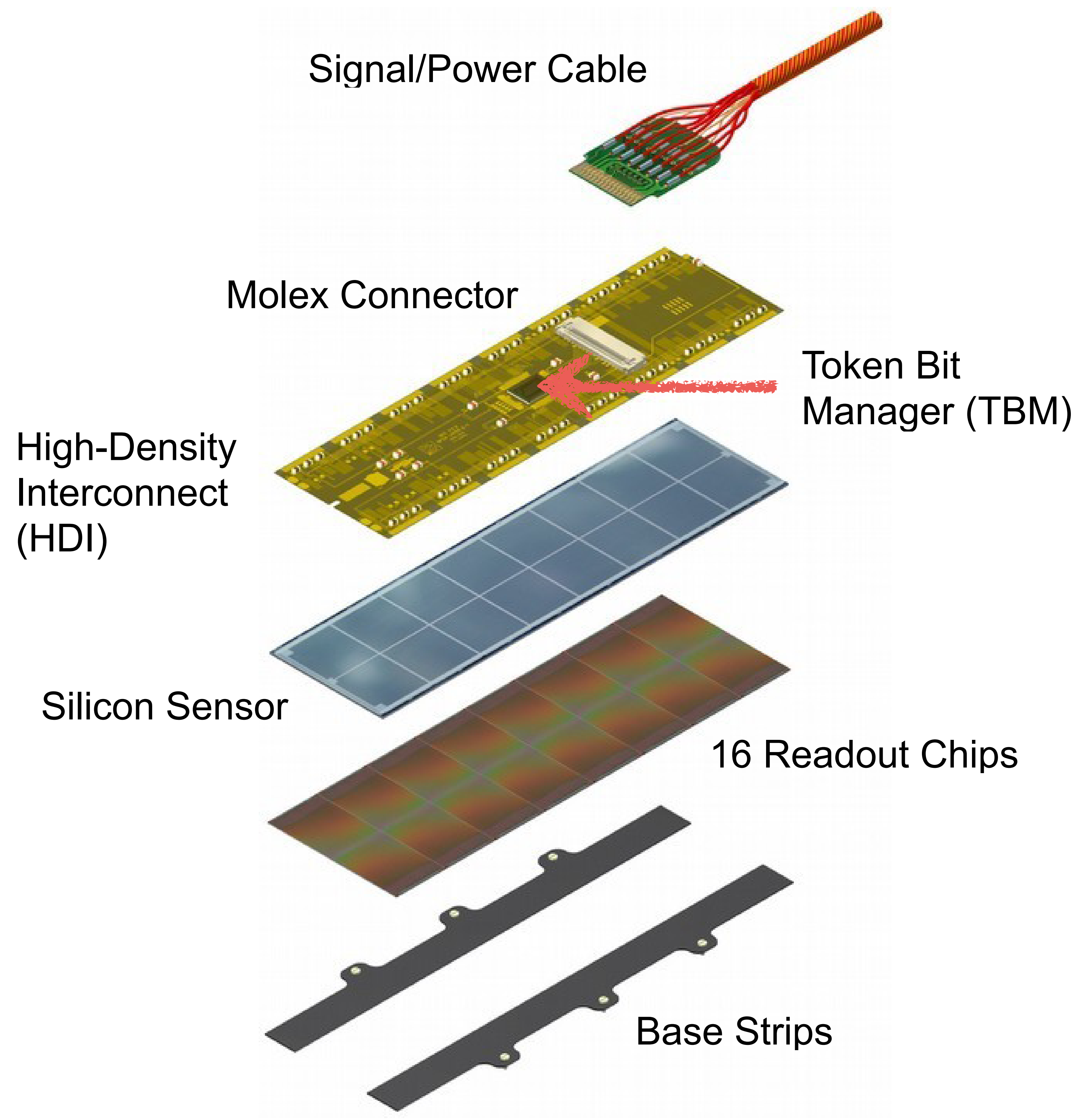


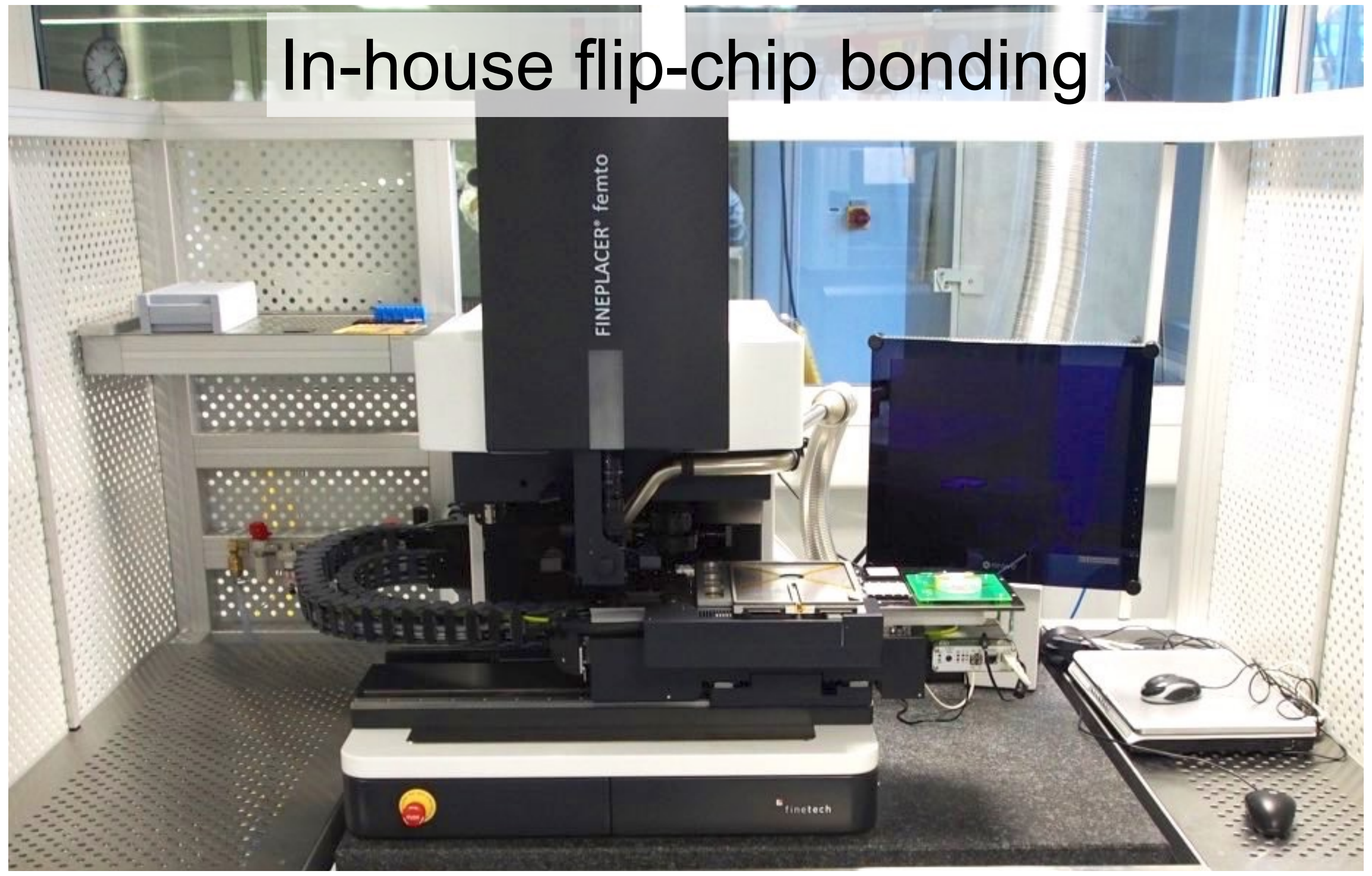
Pseudorapidity:
$\eta = -\ln \tan(\theta/2)$
with θ polar angle

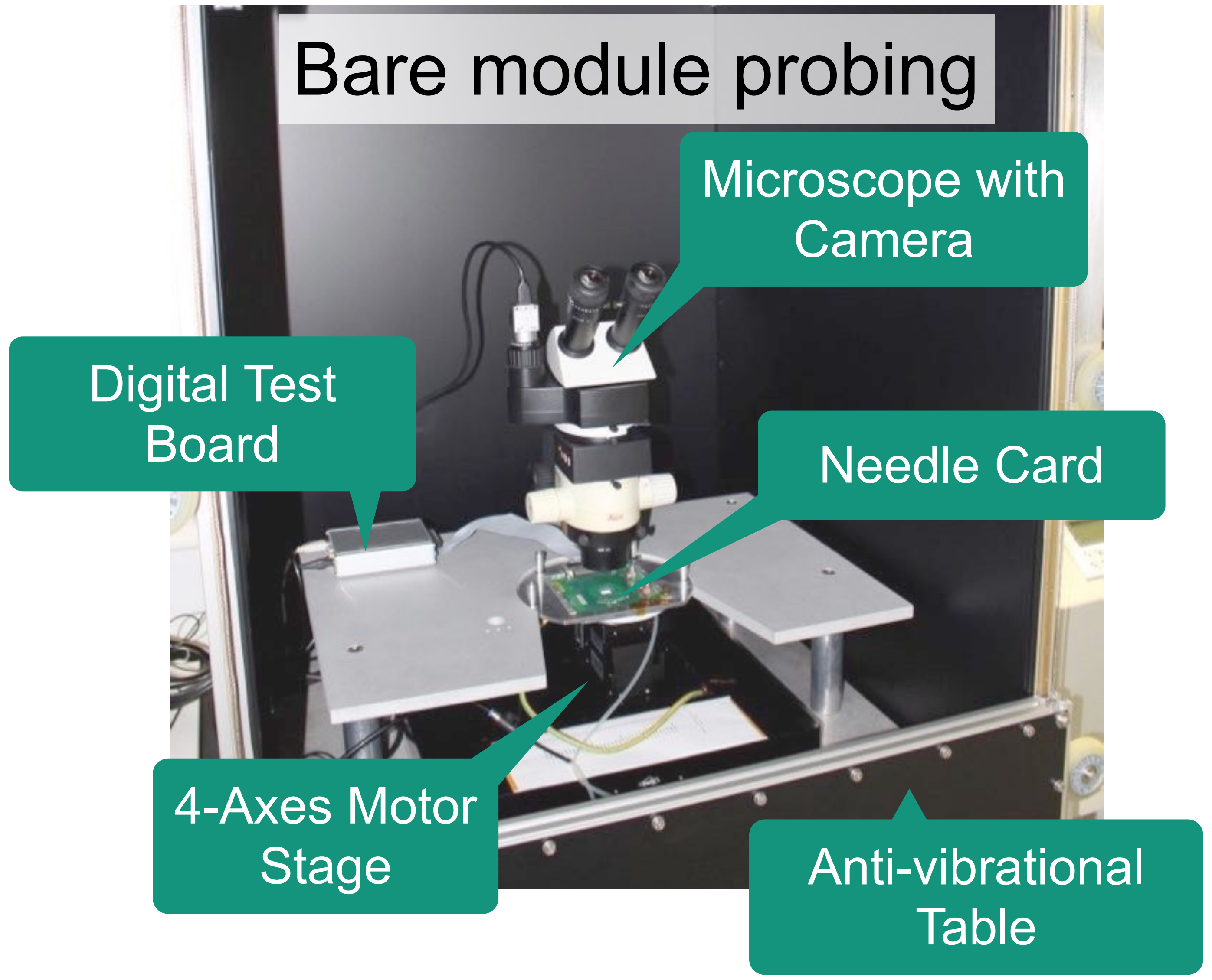
JINST 16 (2021) P02027

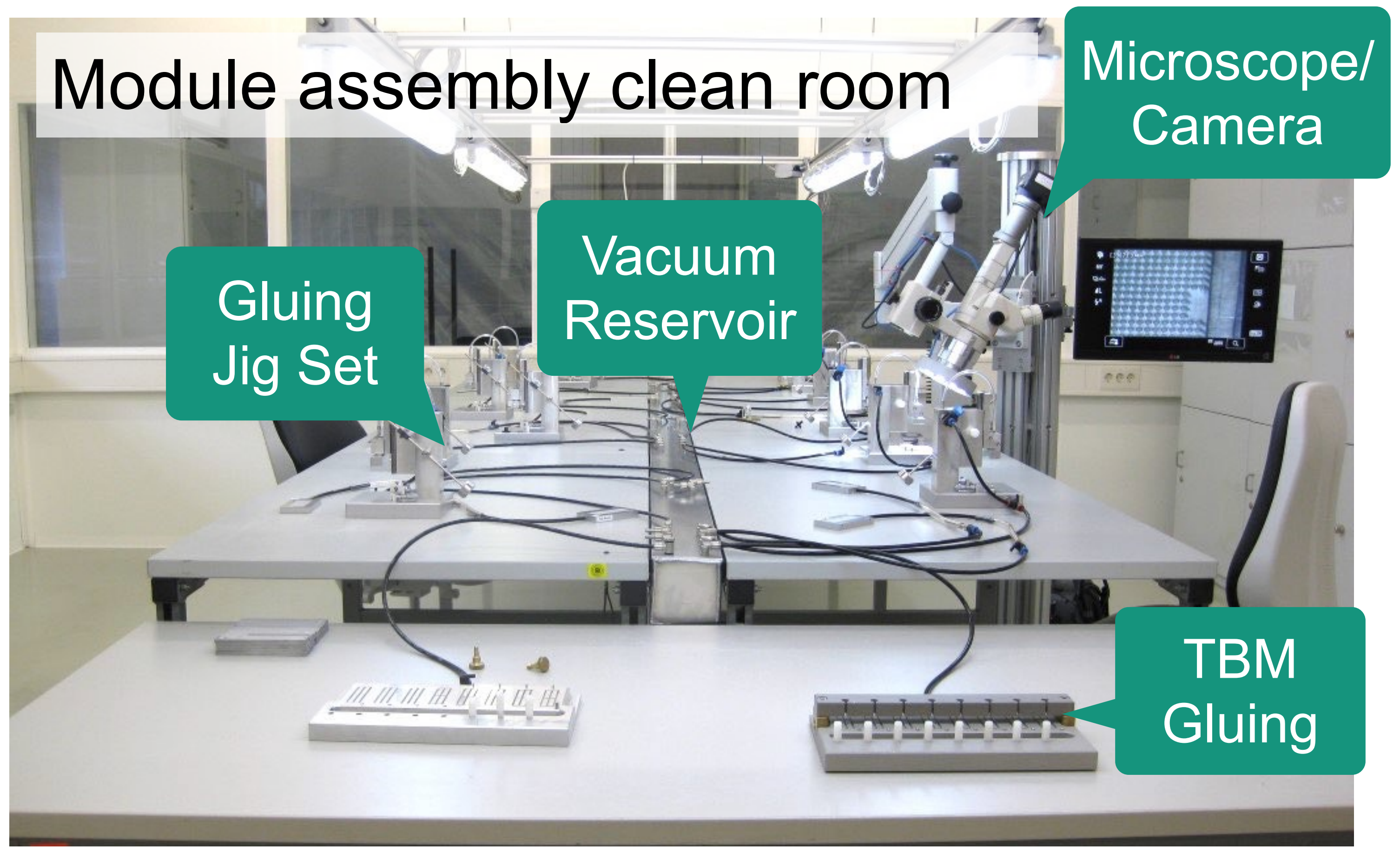
Pixel Module on Handle

Pixel Module Assembly at KIT









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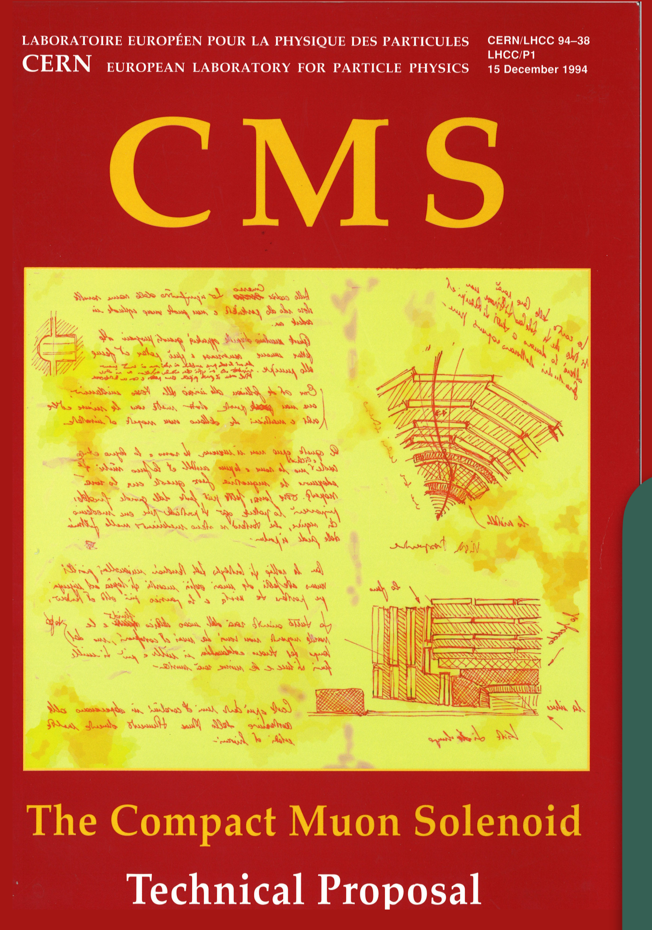
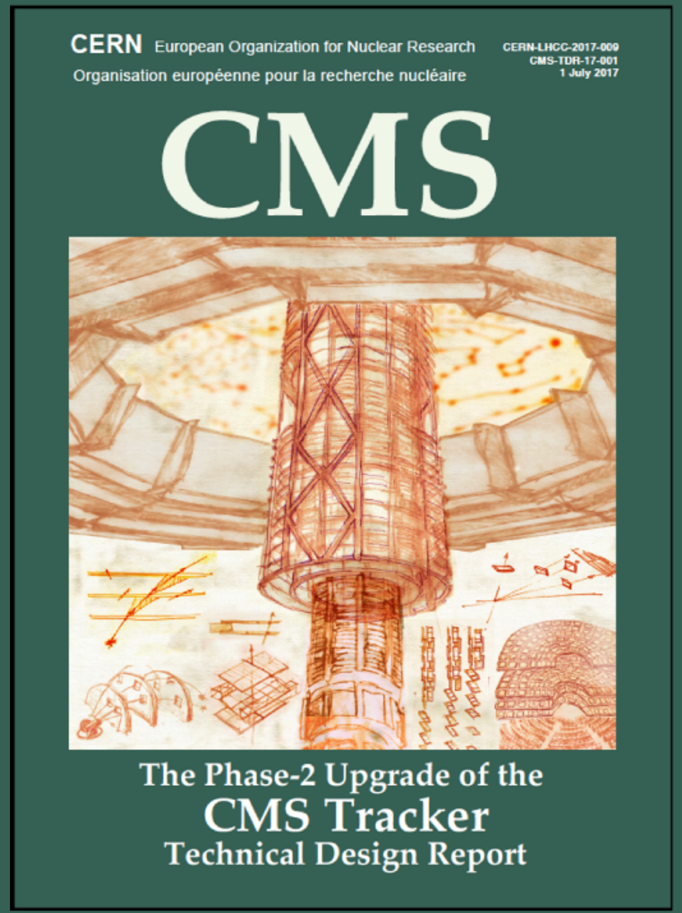
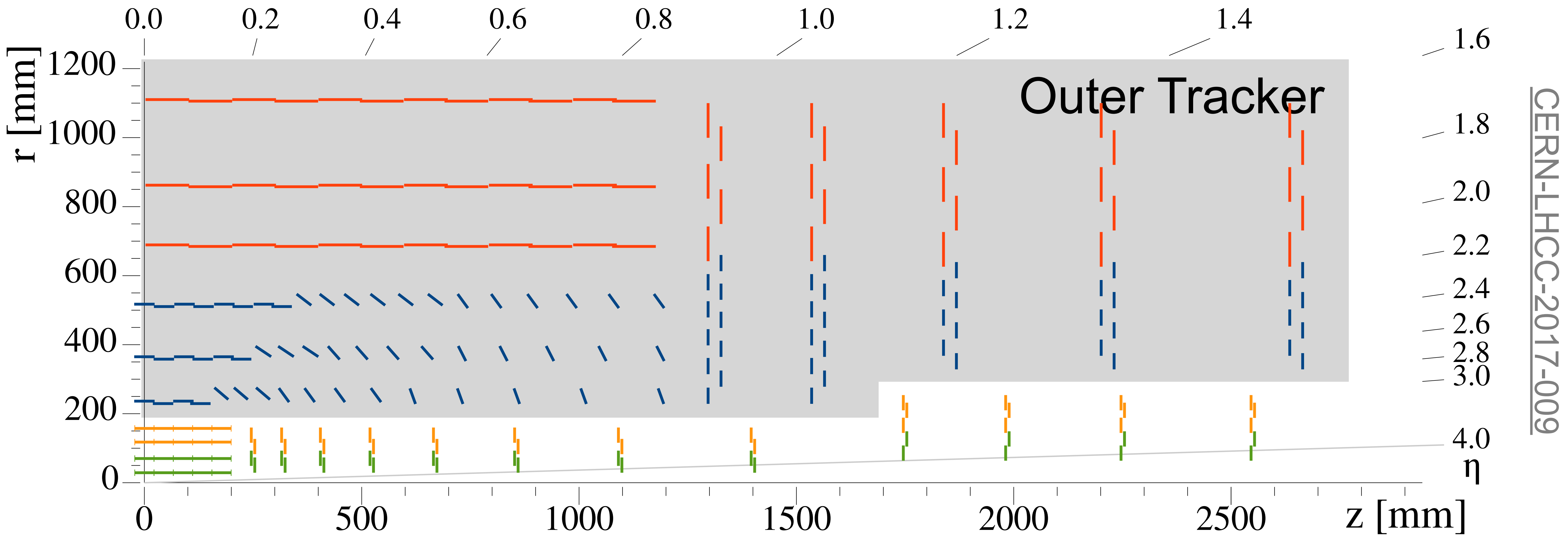


What keeps us busy: Upgrades for HL-LHC



CMS at HL-LHC

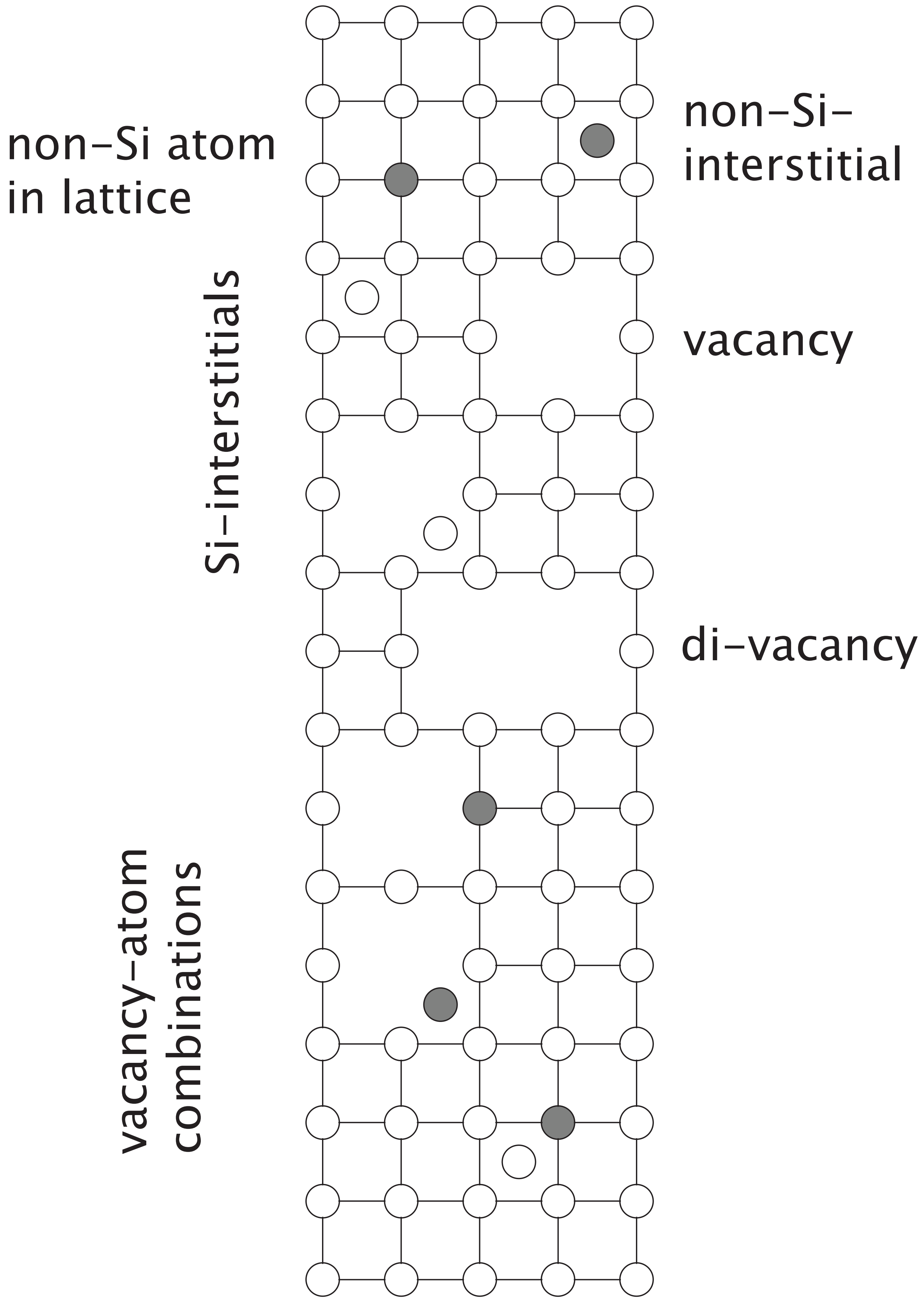
- HL-LHC challenge for tracking detectors: 5× higher rates, 10× more data
- Goal: **comparable performance** in much more difficult environment
  - **Fast** and (even more) **radiation-hard** detectors
  - Tracking up to pseudorapidities of $\boldsymbol{\eta}$ **= ±4** (was η = ±2.5 before)
  - Level-1 (hardware) **triggering** based on **tracking** information



HL-LHC Radiation Environment

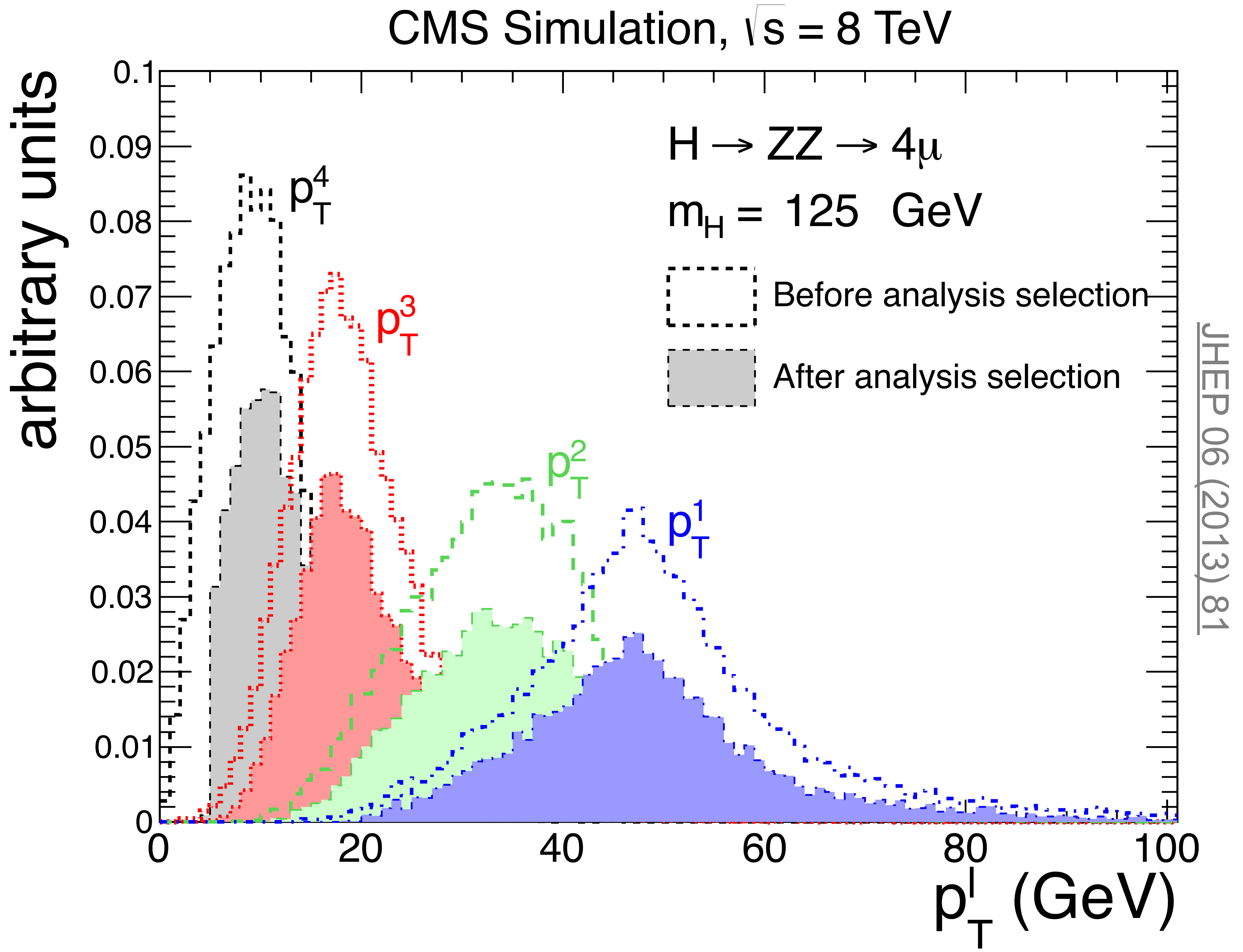
- Proton-proton collisions: **primary** hadrons (mainly pions), **secondary** particles from interactions in detector and **backscattering**
- Effects on silicon sensors and electronics:
  - Ionization: fully **reversible** in sensor **bulk**, but **surface** damage
  - Non-ionizing energy loss (NIEL): **crystal lattice damage** in detector bulk (point and cluster defects) → time and temperature dependent (“annealing”)
  - Consequence: changes in electronic properties → increased **noise** and **heat**, reduced **signal**

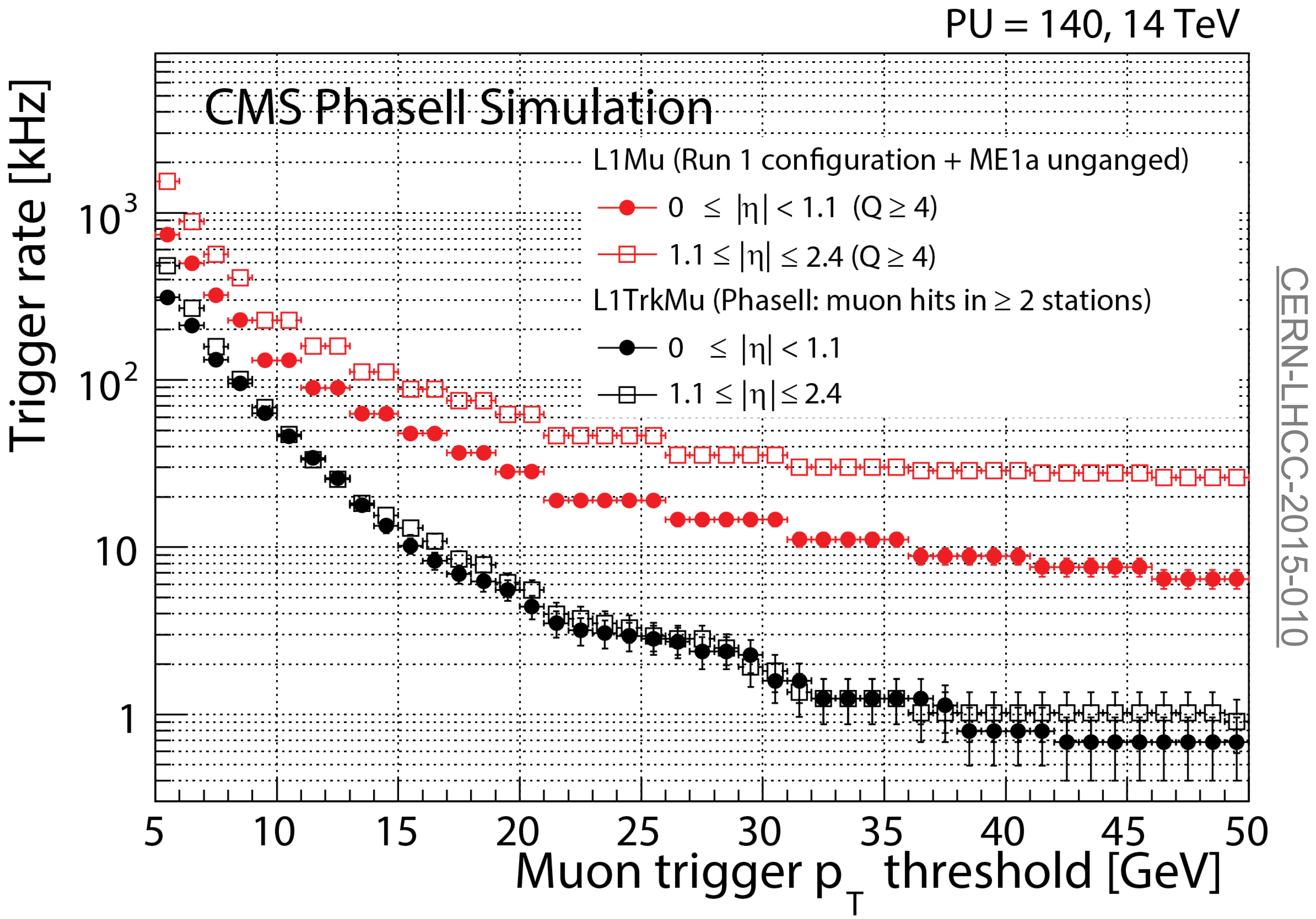
Point Defects in a Silicon Lattice



J. Große-Knetter, Habilitation Thesis, U Bonn (2008), after R. Wunstorf

The Case for L1 Track Triggering

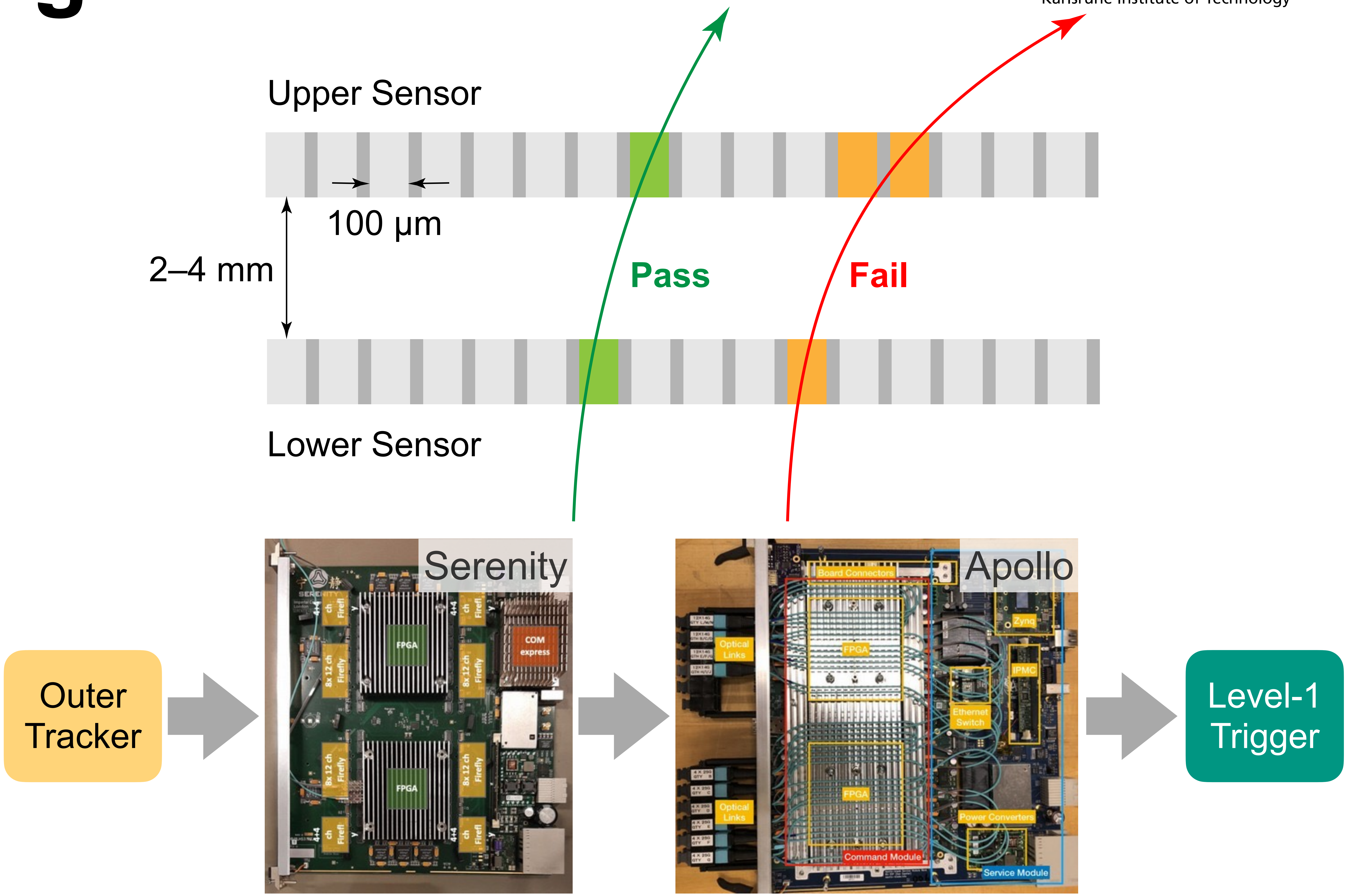




- Relatively **low transverse momenta** remain **relevant** (e.g. Higgs physics)
- **More sensitive level-1 trigger** required to control trigger rate → **track trigger**

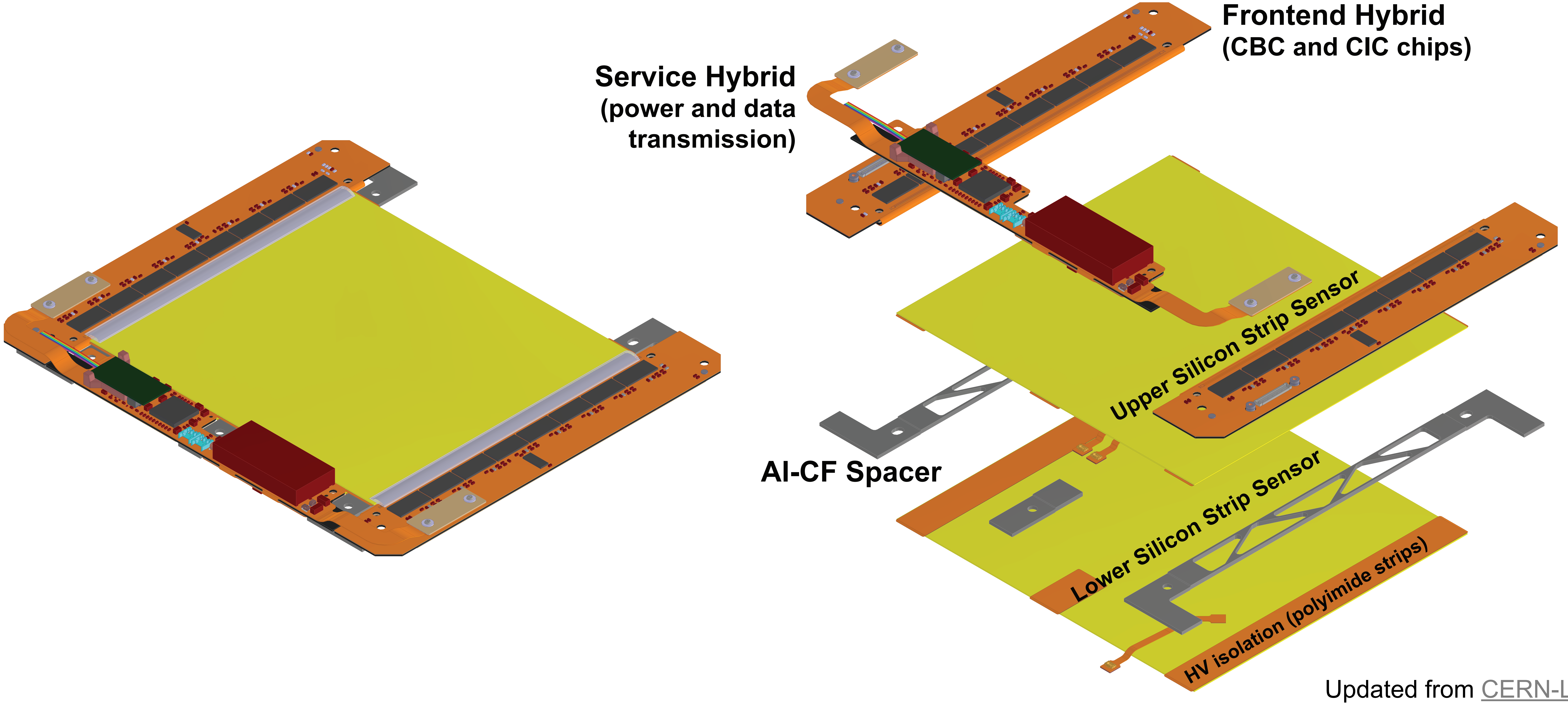
Track Triggering

- Step 1: transverse momentum (p_T) filtering on detector module level
  $\rightarrow$ **p_T modules**
- Step 2: FPGA-based **fast electronics** to provide tracks for Level-1 trigger



p_T Modules

- Outer part of Outer Tracker: **2S modules** → two silicon strip sensors



Updated from CERN-LHCC-2017-009

2S Module Assembly at KIT

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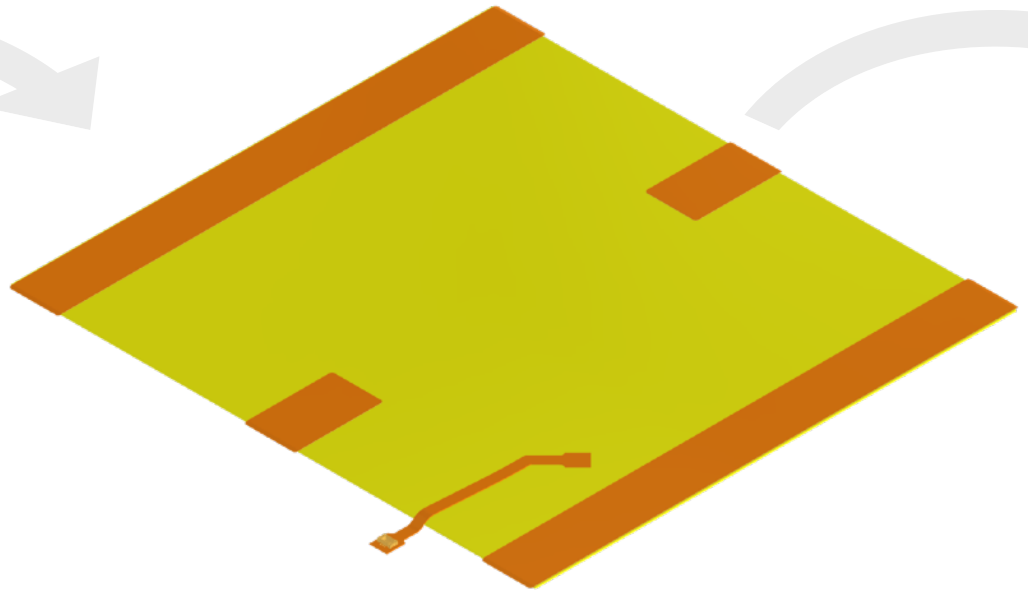
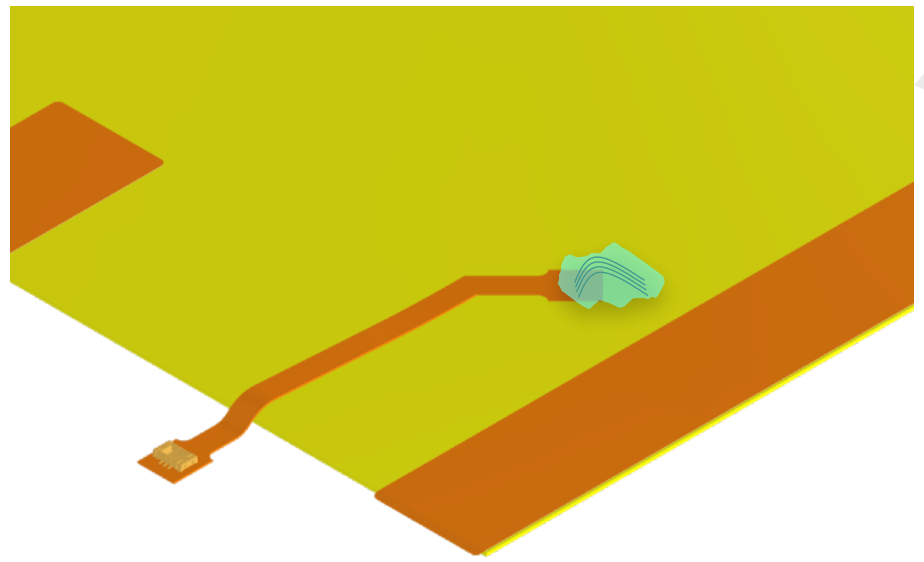
1. Glue polyimide HV isolation and attach HV tails on sensor backside

Check dicing precision (metrology)



Optical inspection

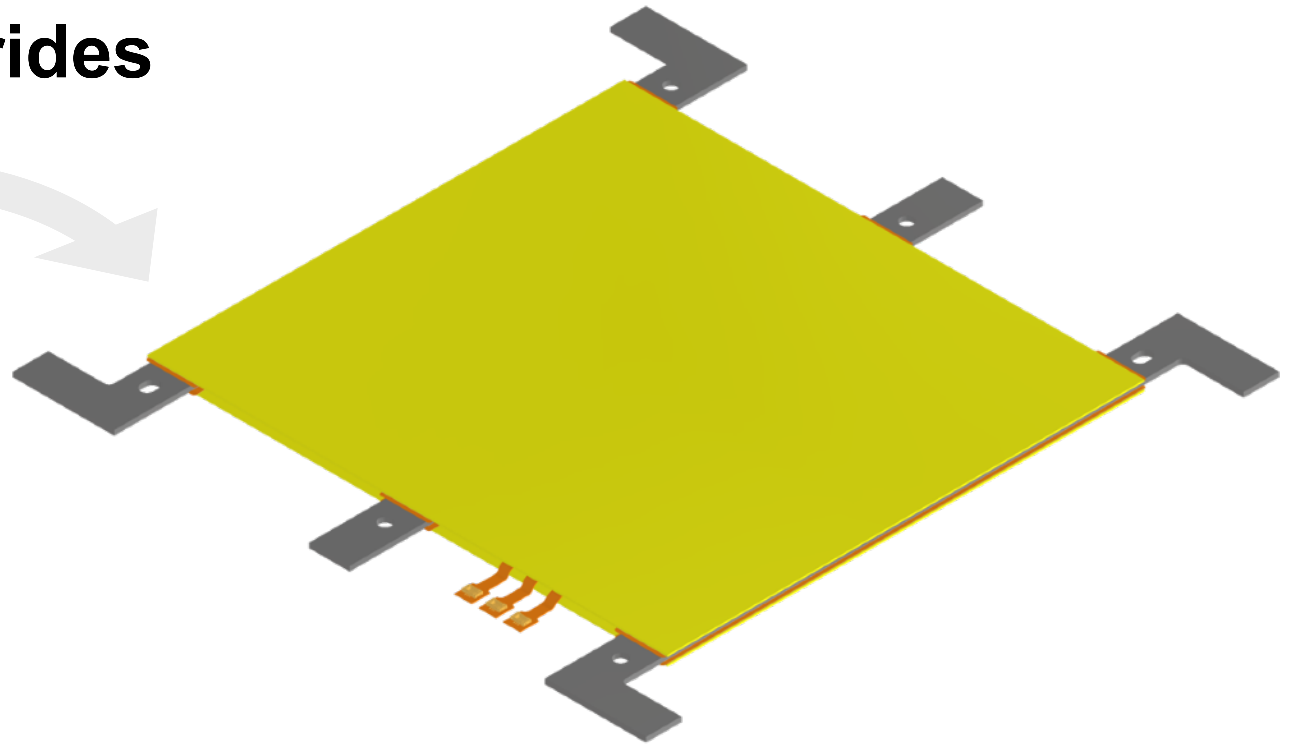
2. Wire-bond and encapsulate HV tails



HV test backside isolation

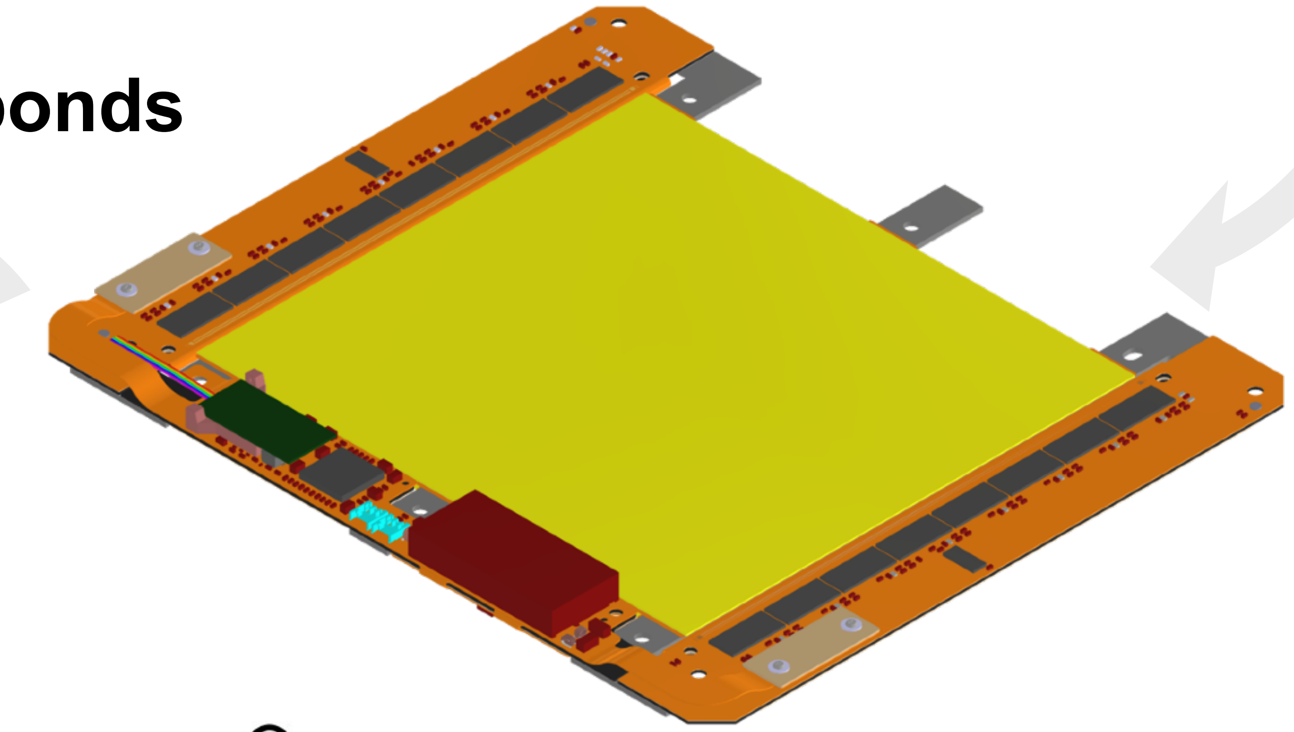
Sensor I(V)

3. Glue sensors on Al-CF brides



Module metrology

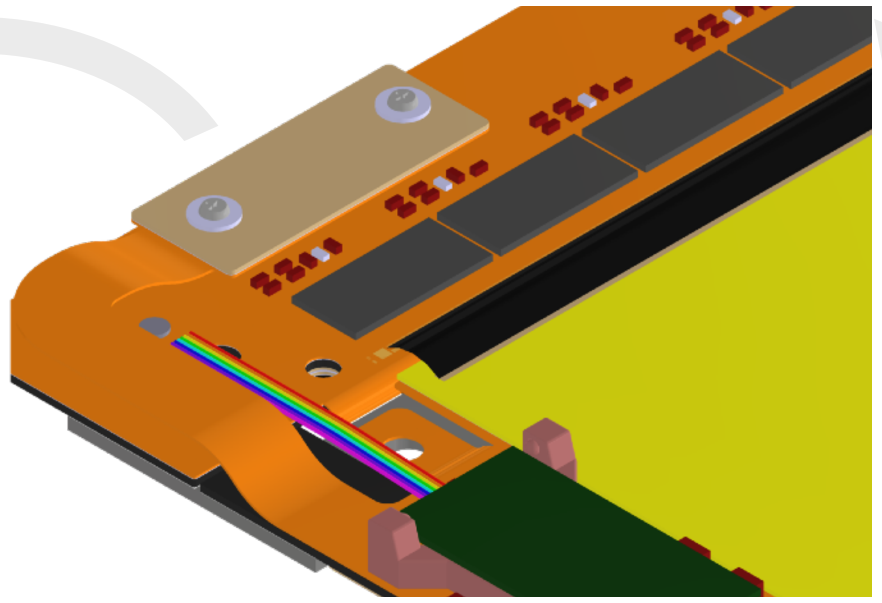
4. Glue readout and service hybrids on bare module



Optical inspection

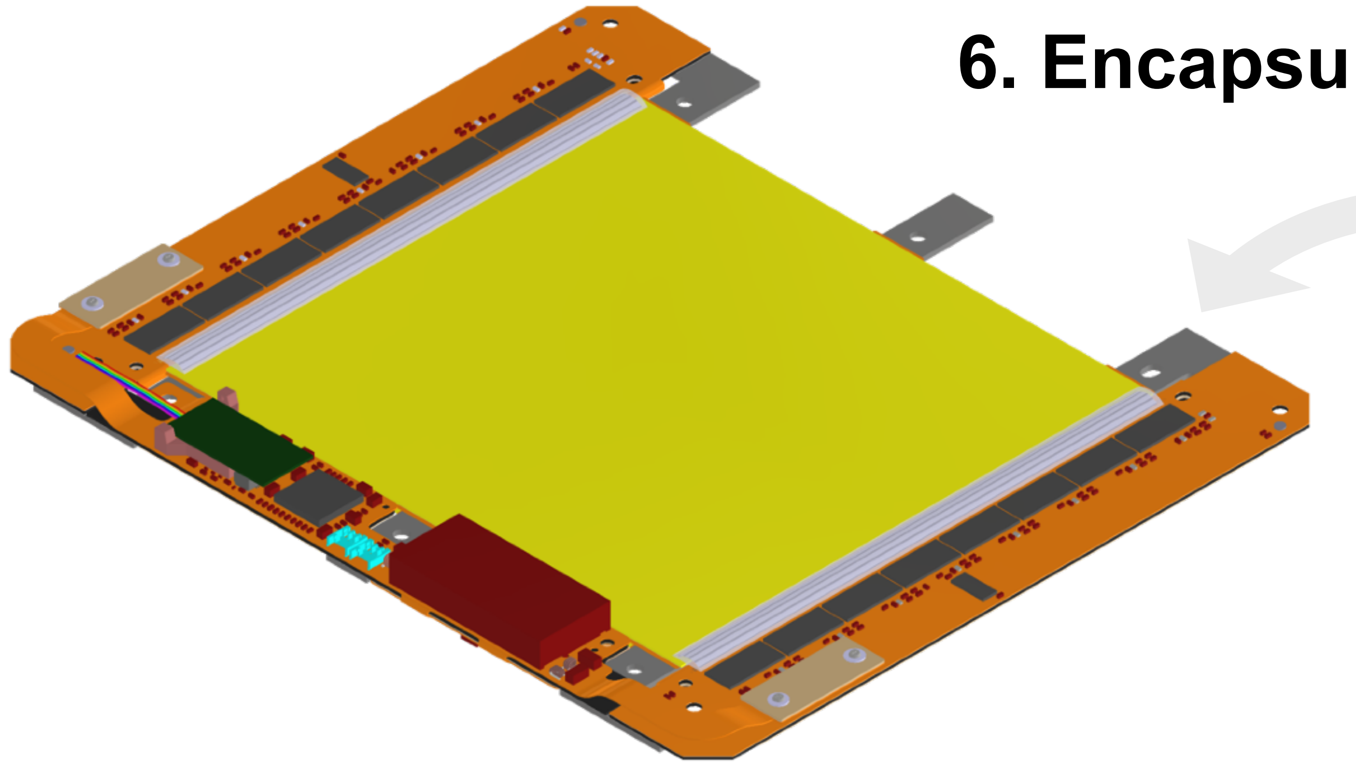
(HV/LV test)

5. Place ~4000 wire-bonds



Module test

6. Encapsulate wire-bonds



Module test

S. Maier

Probe Station & Clean Room

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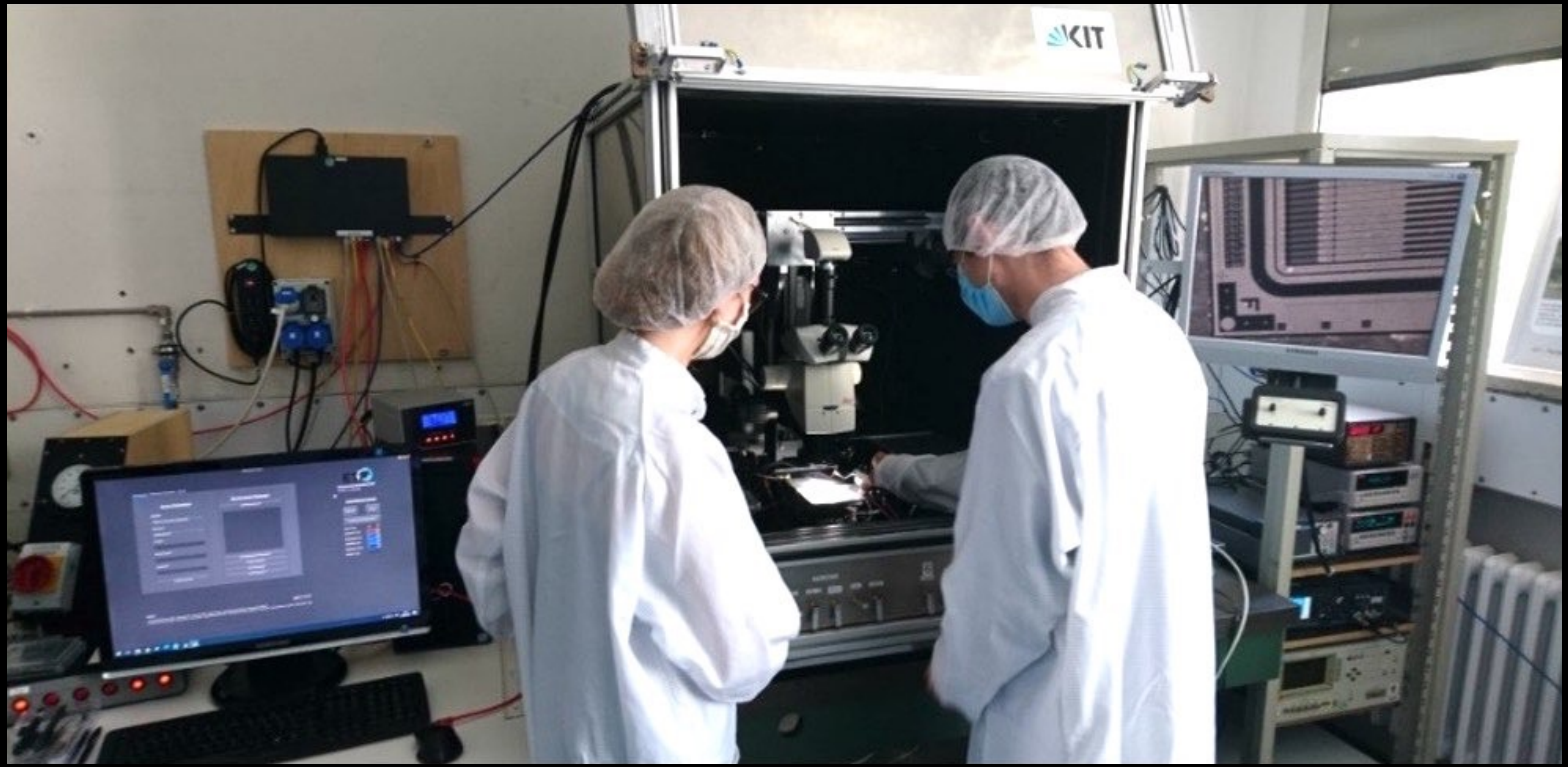

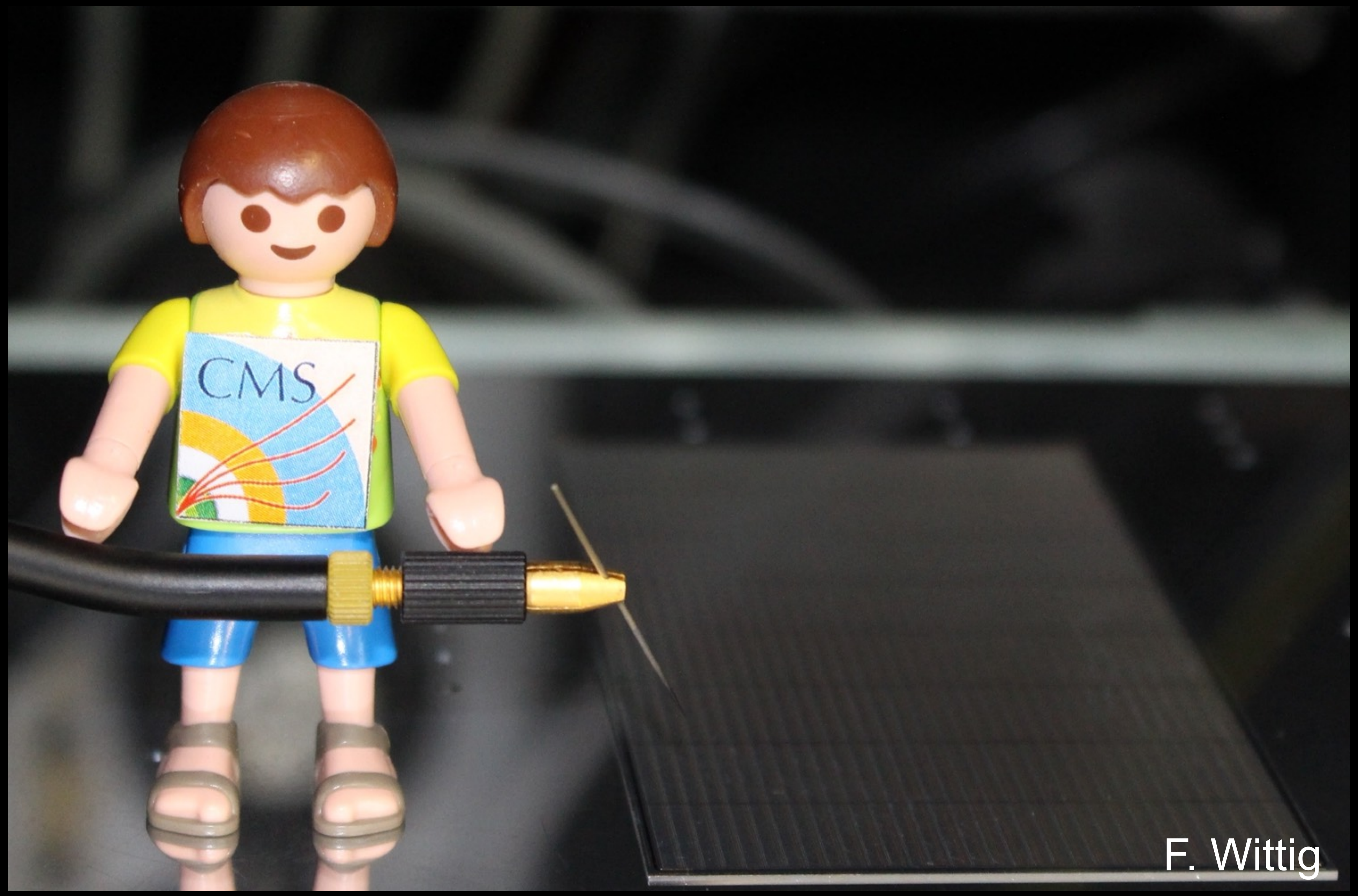

Example: Module Metrology Station

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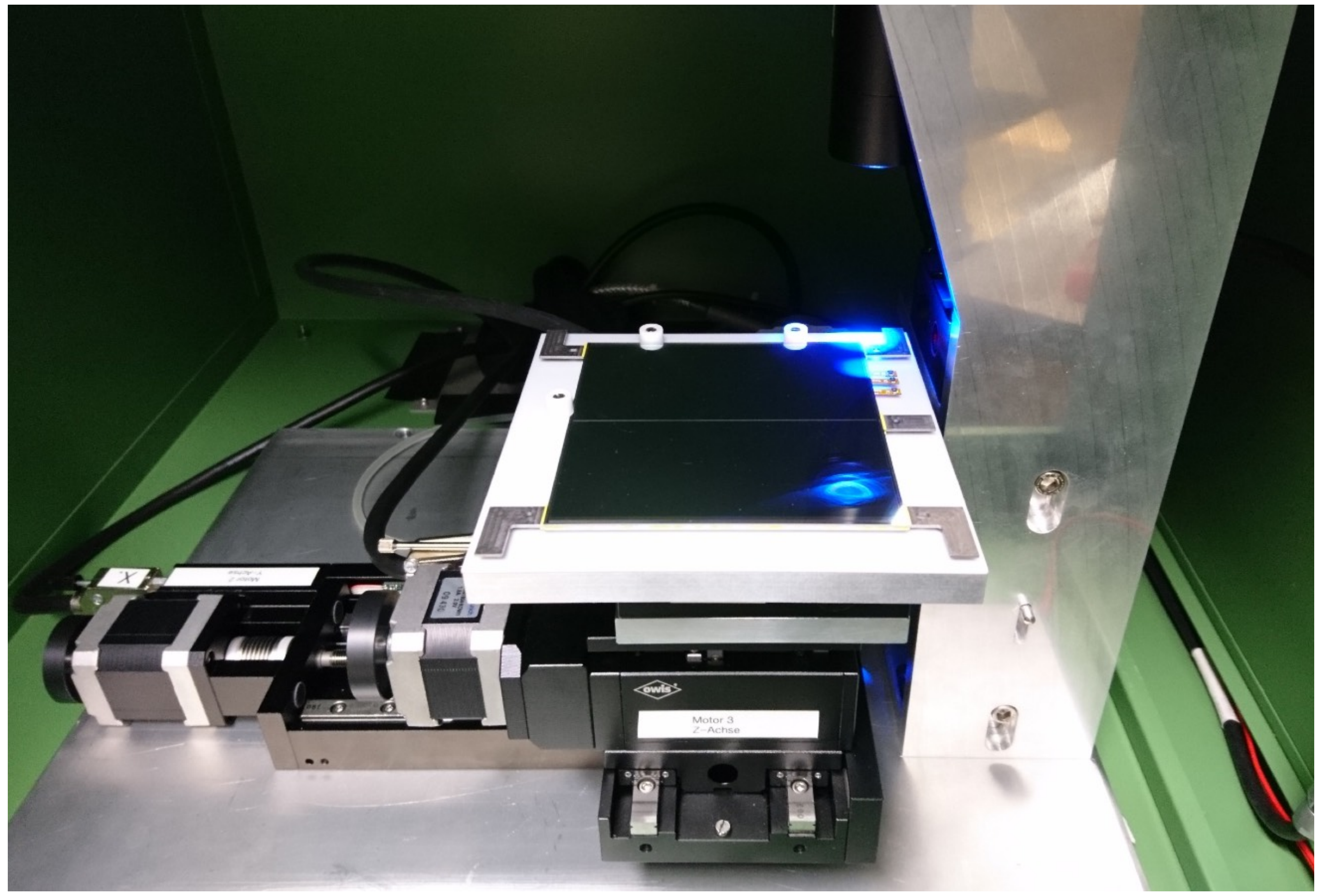
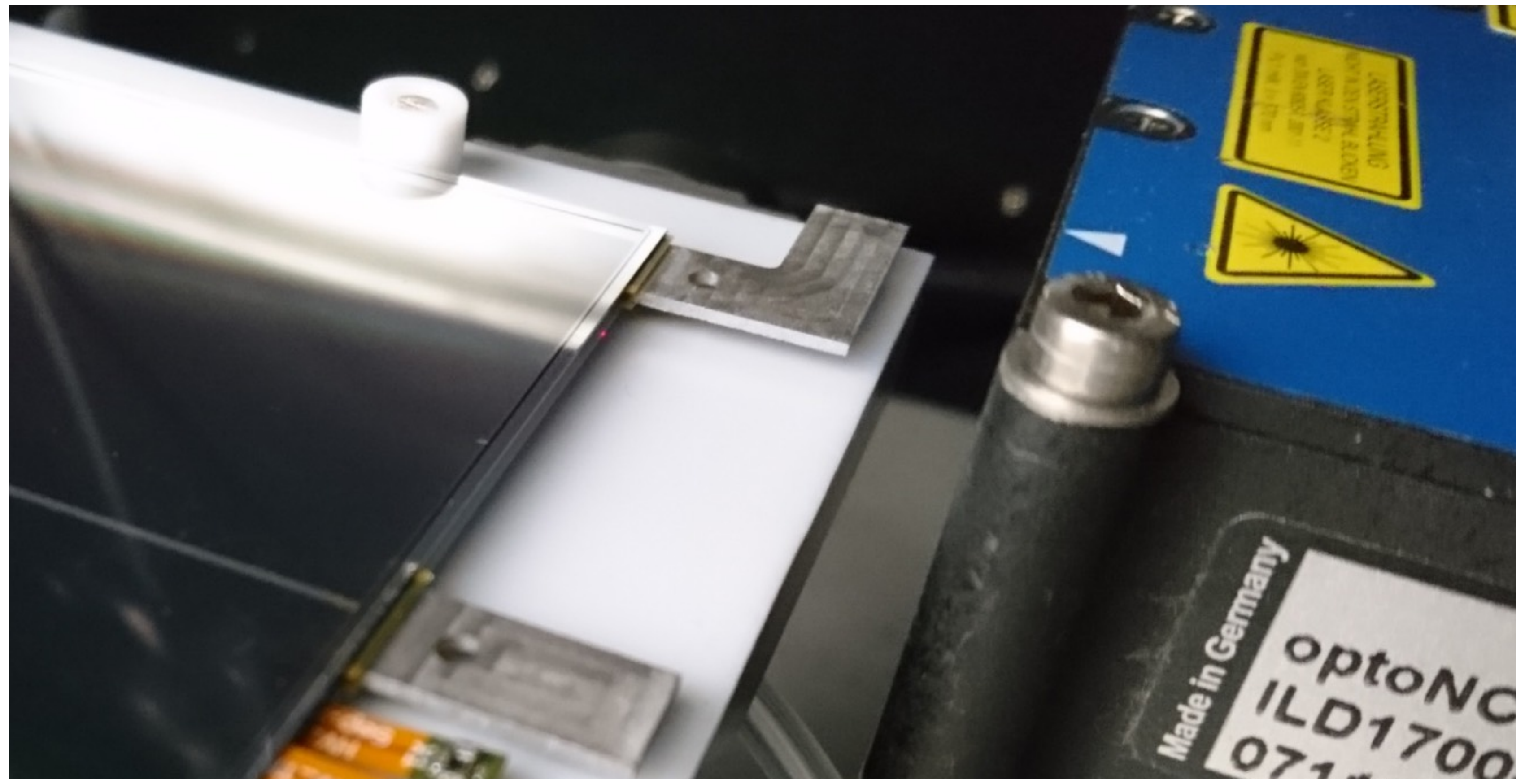
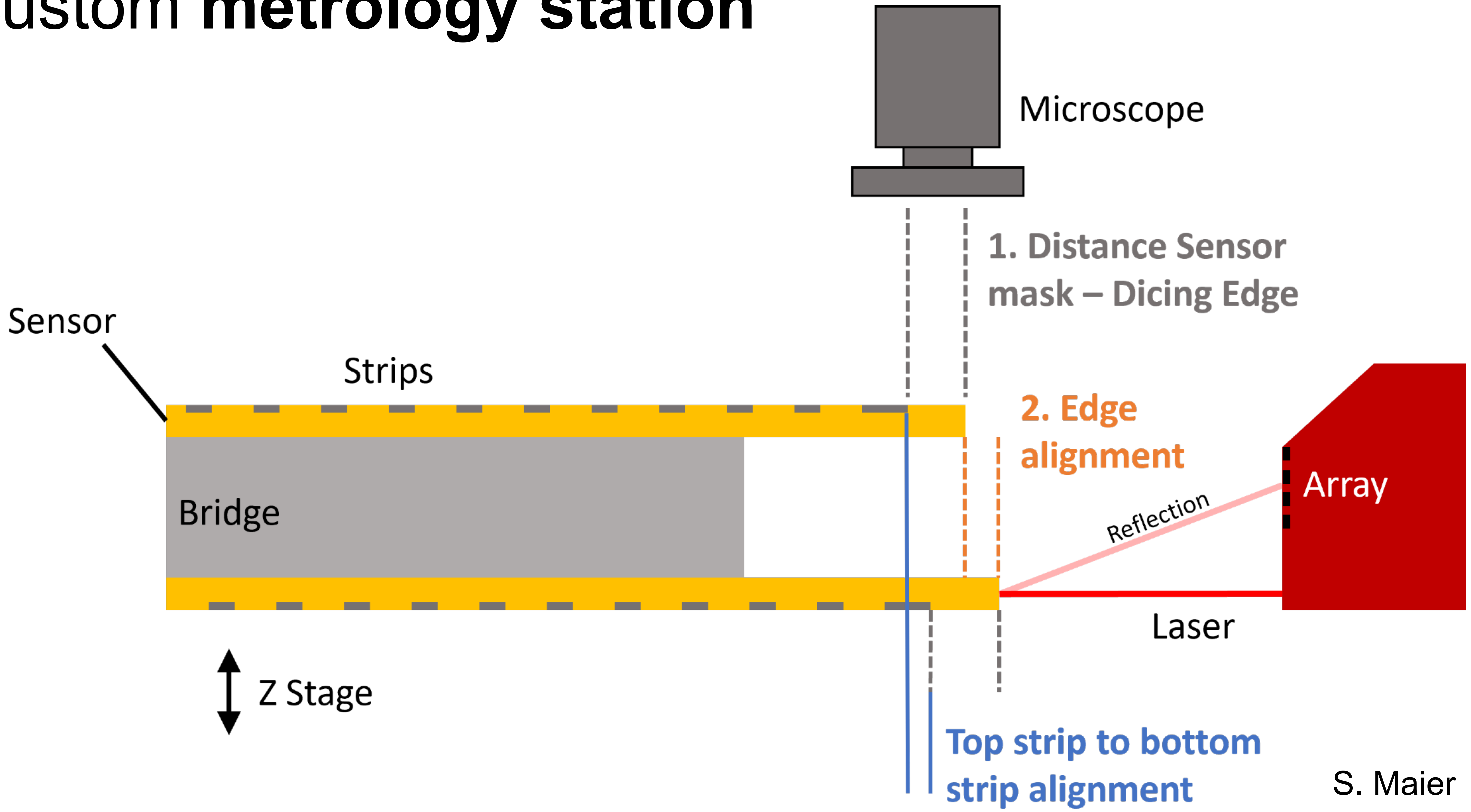


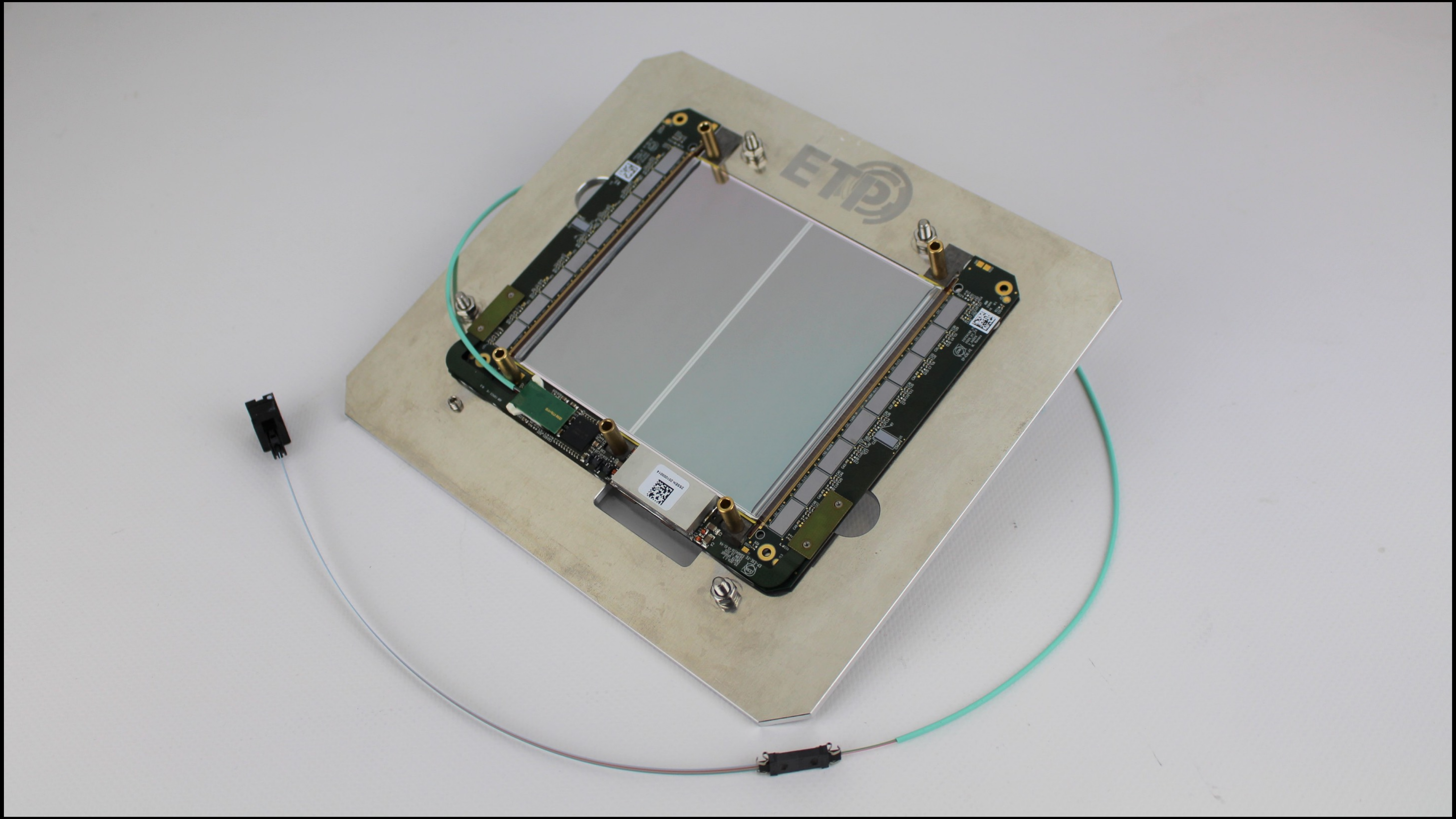


p_T selection functionalities relies on **perfectly parallel sensors** (at most 40 μm tilt on 10 cm strips) → measure **relative coordinates** of sensors in custom **metrology station**



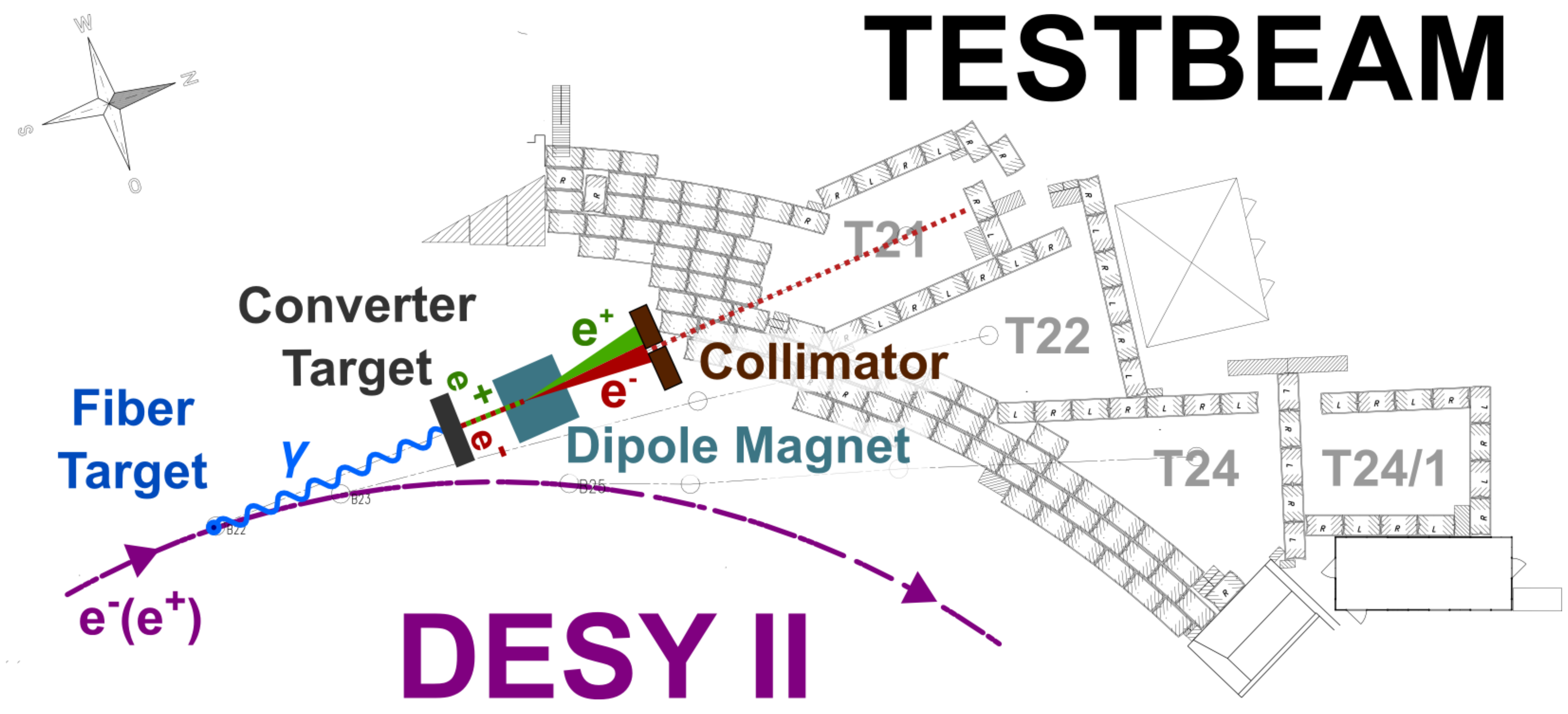
S. Maier

2S Prototype Module on Carrier

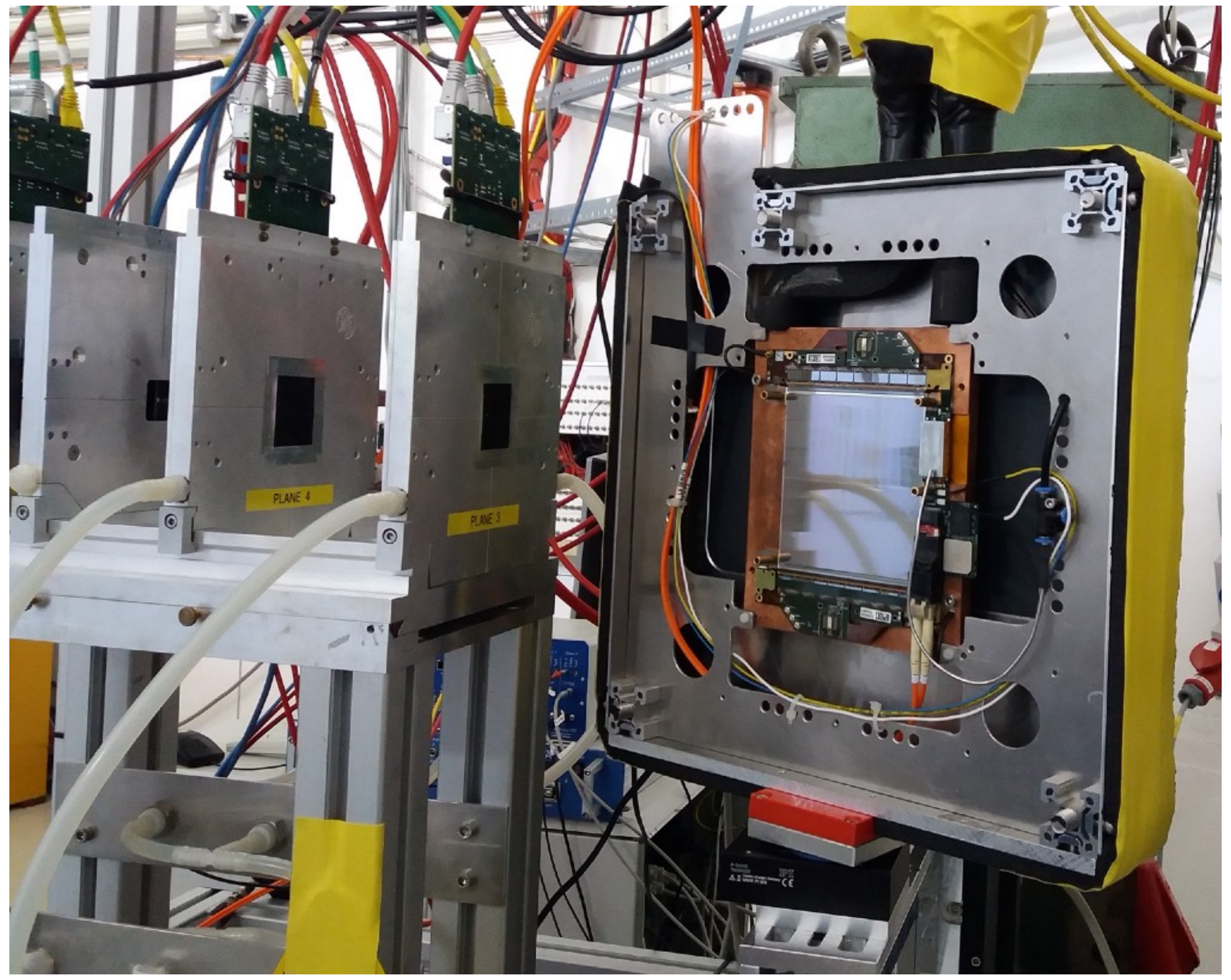


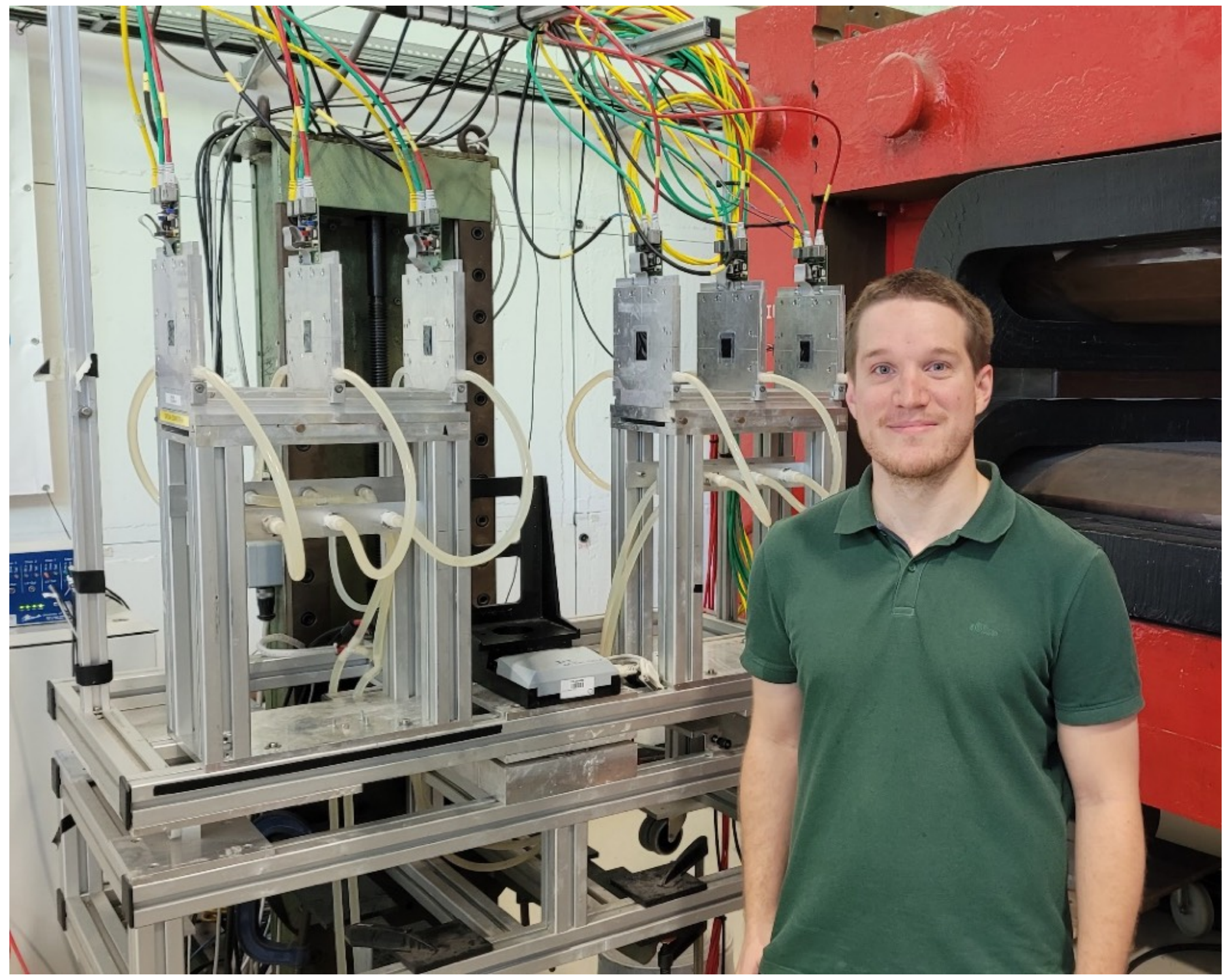
Beam Tests

- Test of prototype detectors in **particle beams**, e.g. at DESY (5–6 GeV e±, beam hodoscope) → spatial resolution, detailed efficiency, …

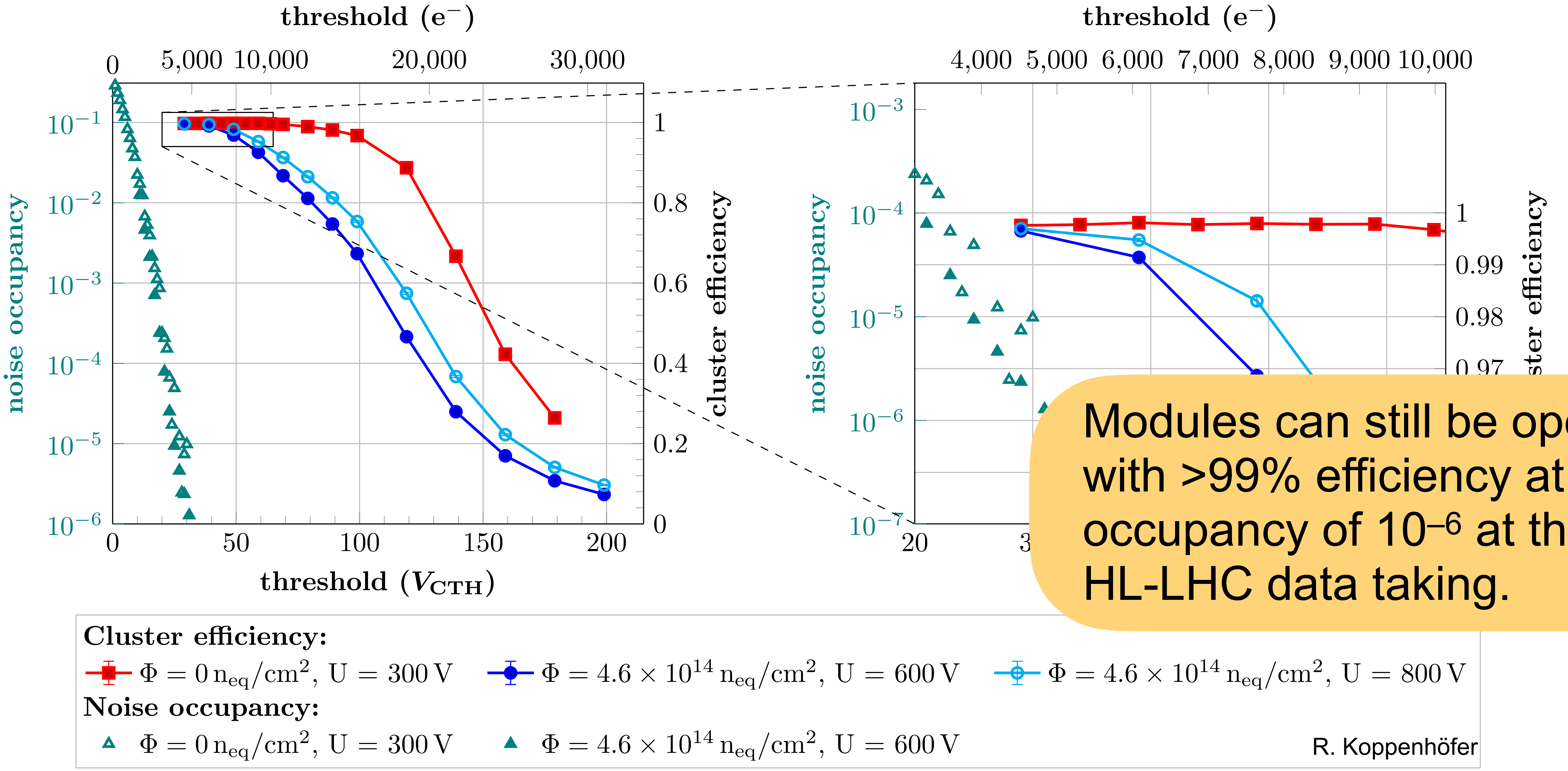


https://particle-physics.desy.de/test_beams_at_desy/beam_generation/index_ger.html





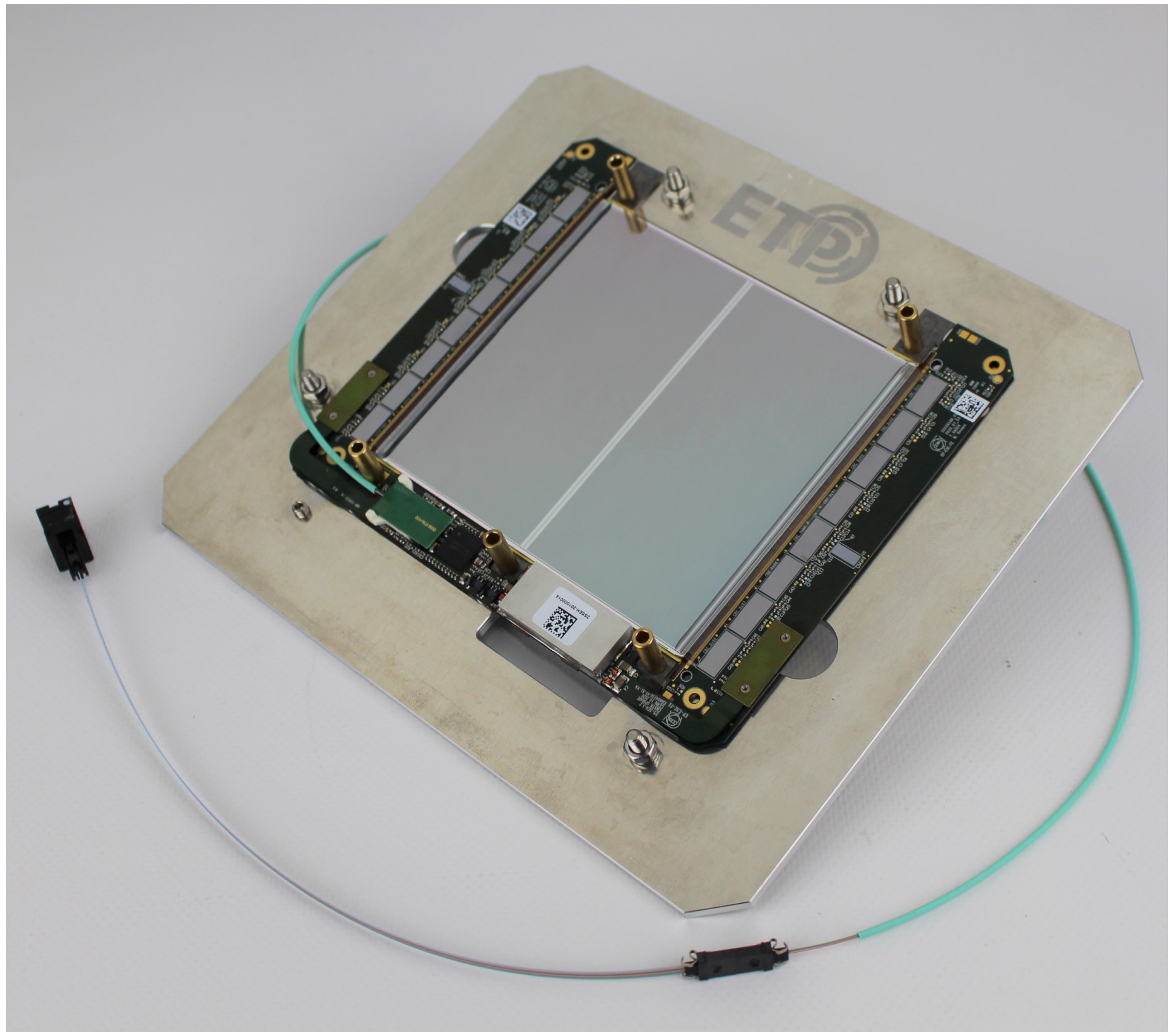
Beam Tests: Results



Modules can still be operated with >99% efficiency at a noise occupancy of 10^{-6} at the end of HL-LHC data taking.

CMS Tracker @ HL-LHC: Outlook

- Where do we stand at the end of 2021?
  - Silicon sensors: **excellent quality** in pre-series production (5% of all sensors)
    → moving to **sensor production**
  - Detector modules: **very advanced prototypes**, all tooling and test stands in place, final optimizations upcoming
    → ready for pre-series in 2022
- **Module production** at KIT:
  about 2000 2S modules in 2023/2024



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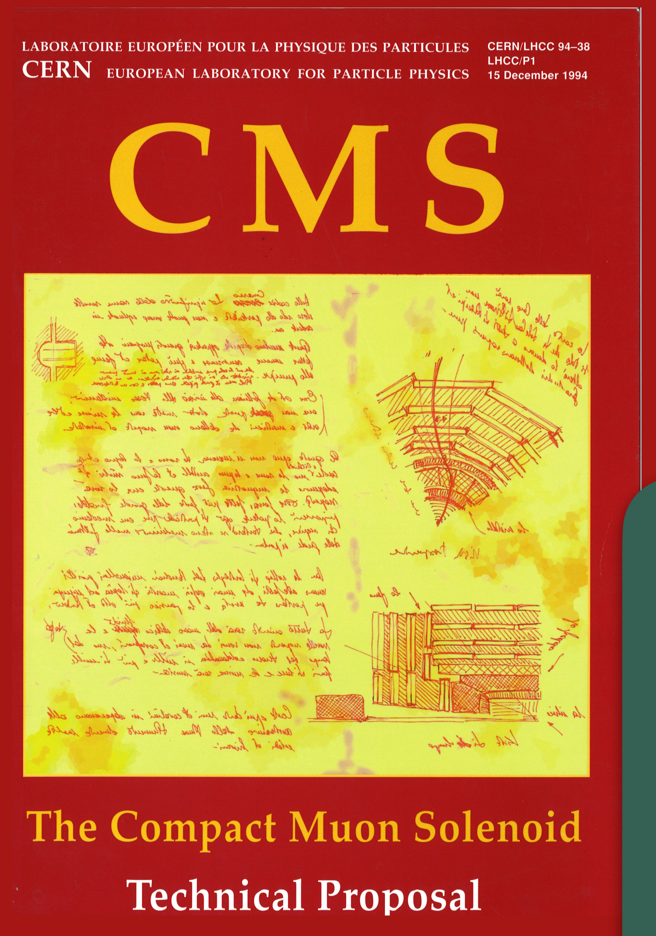
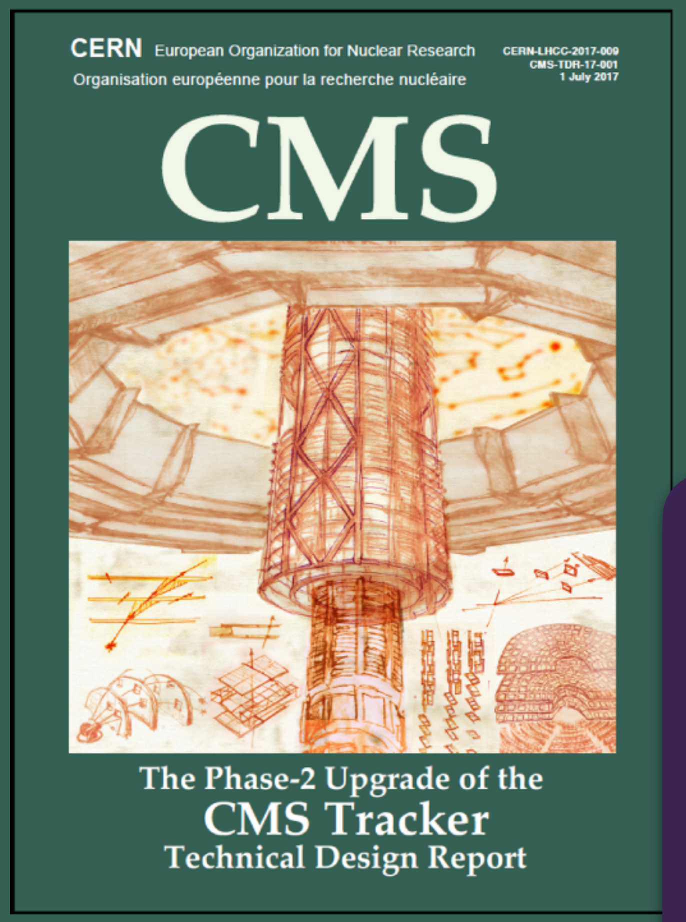
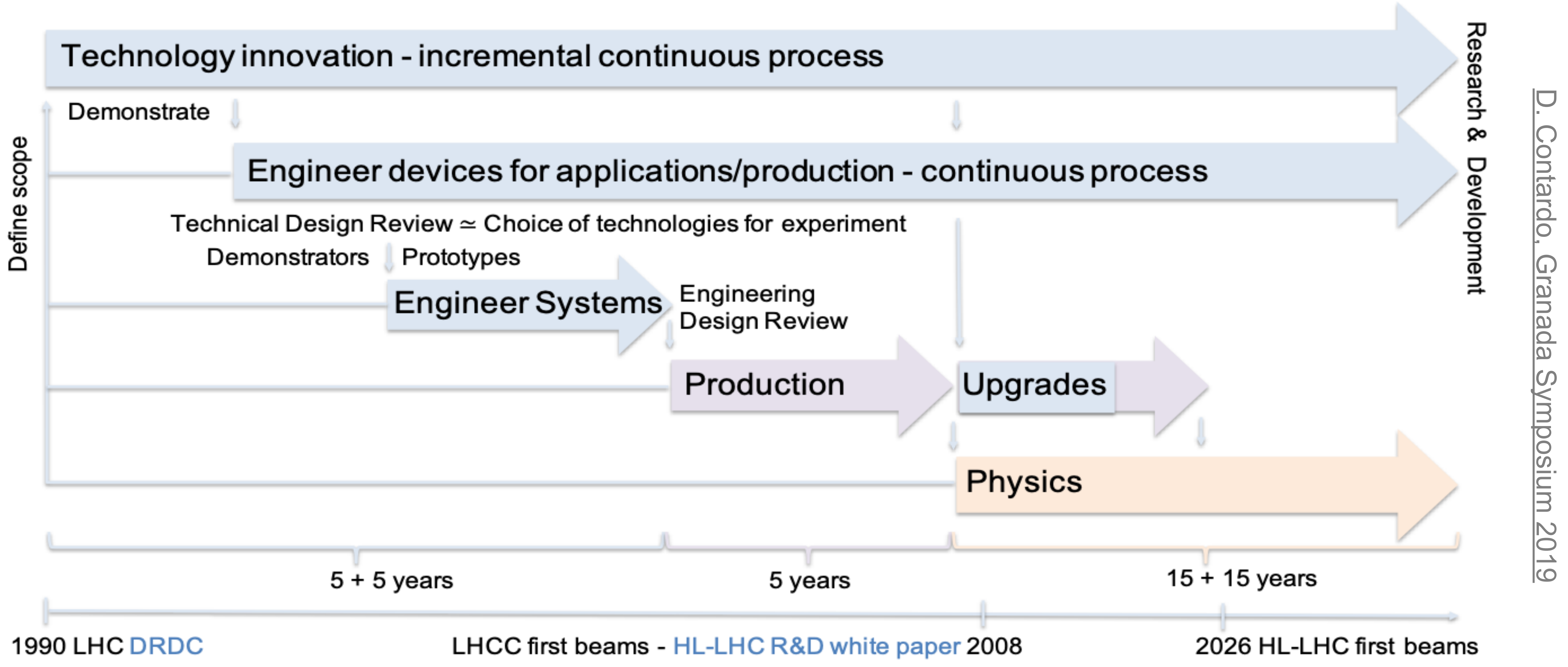


What keeps us busy: Upgrades for HL-LHC



How we prepare for the future

R&D for Future Projects



- LHC and HL-LHC: typical **R&D time scales of 10 years**
- How should the particle physics community organize **targeted R&D programs** in many universities and research centers in the future?

How to Organize Targeted R&D?

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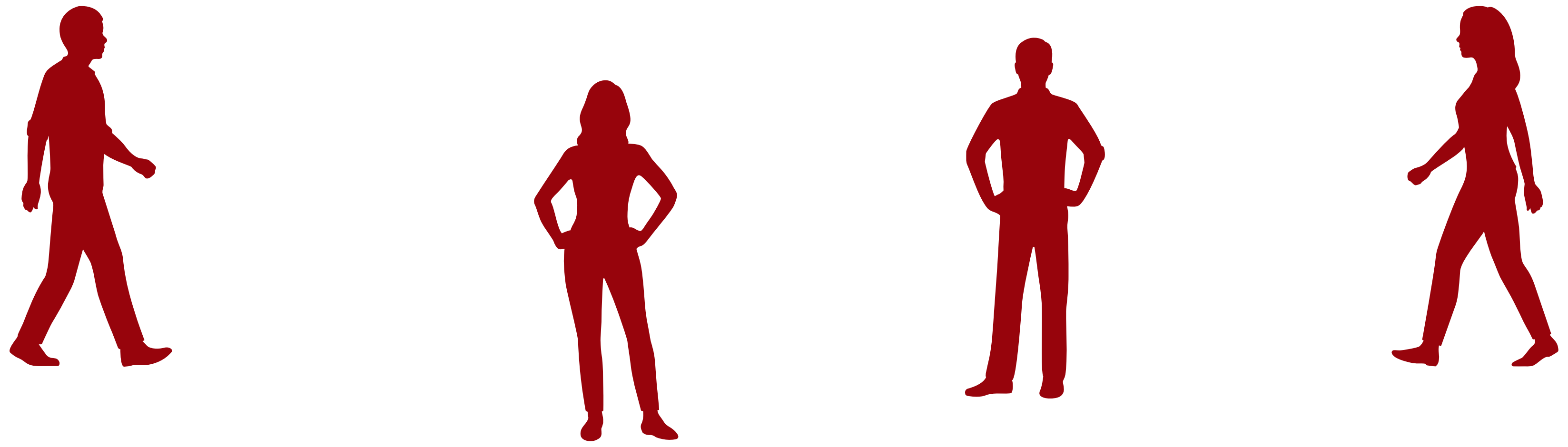
70 – 20 – 10



- Strike **good balance**:
  - **Current** colliders
  - **Future** colliders
  - **Blue-sky** R&D
- **Coordinate** well: pool resources, stay focused, avoid duplication
- Detector builders are **humans**: think of recruitment, training, recognition, careers

How to Organize Targeted R&D?

- Several **successful R&D models** in particle physics community:
  - CERN **RD programs**, e.g. RD50 (radiation hard semiconductor devices)
  - Collaborations to develop **technologies for future colliders**, e.g. CALICE (highly granular calorimetry for energy-frontier electron-positron colliders)
  - **European programs**, e.g. EUDET → AIDA → AIDA2020 → AIDAinnova
  - Partnerships with **industry**

European Strategy for Particle Physics

https://europeanstrategy.cern

- European particle physics community **updated its strategy** in 2020
- Highest priorities:
  - Full exploitation of LHC and HL-LHC
  - Next collider: electron-positron “Higgs factory”
- Document stresses importance of **innovations in accelerators and instrumentation**:

  “*The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels.*”


THE 2021 ECFA DETECTOR
RESEARCH AND DEVELOPMENT ROADMAP
The European Committee for Future Accelerators
Detector R&D Roadmap Process Group
European Strategy
Update
ECFA
European Committee
for Future Accelerators

ECFA Detector Roadmap

https://indico.cern.ch/event/957057/page/23281-the-roadmap-document

Summary

- Collider-based particle physics experiments: truly **long-term projects**
- Experiments require focused **10-year R&D programs**
- **Pushing the boundaries** in instrumentation for future projects remains a strong focus of particle physics

https://pearljam.com/music/album/alive

Acknowledgments

Karlsruhe Institute of Technology

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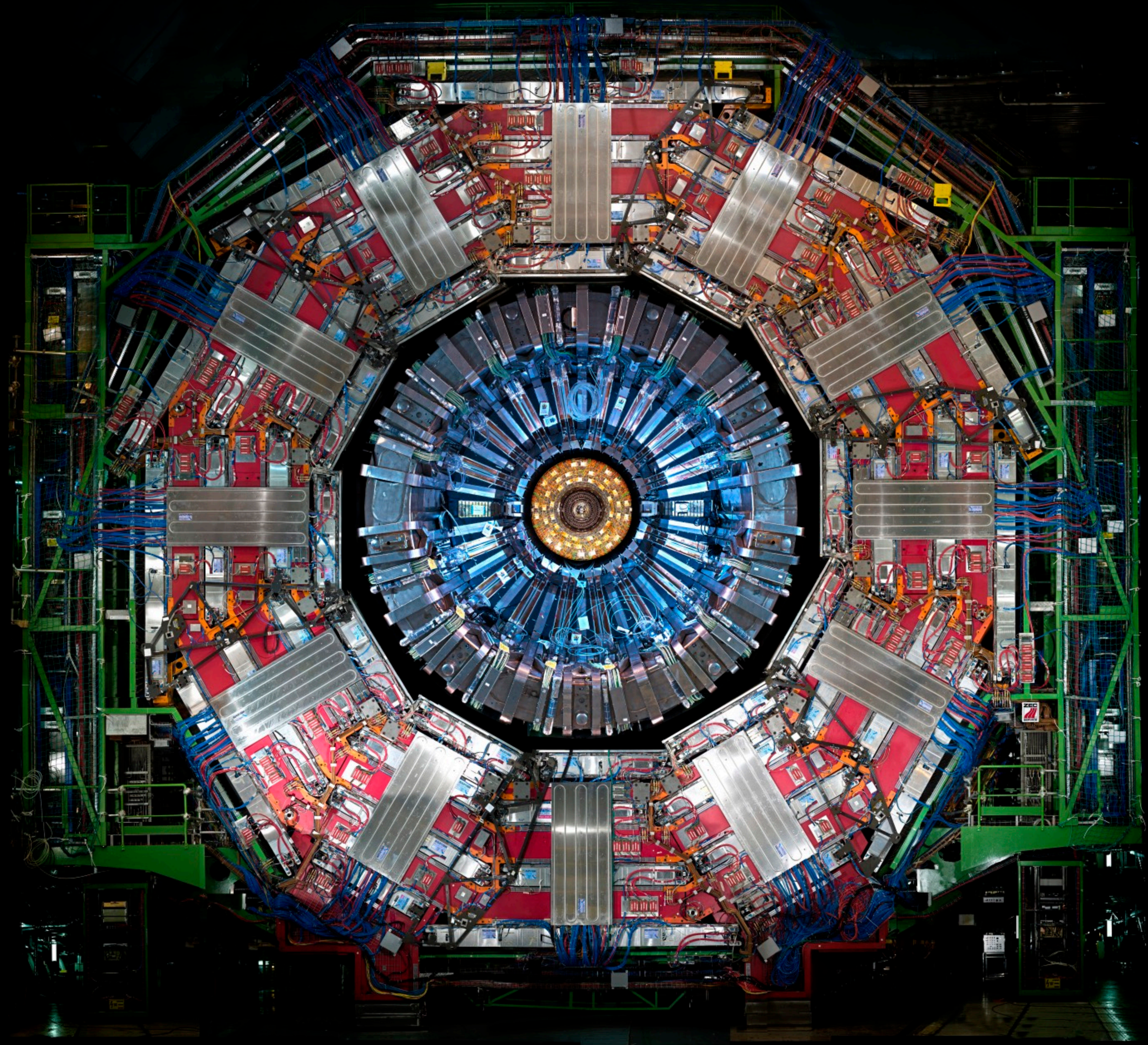

Image credit: CERN