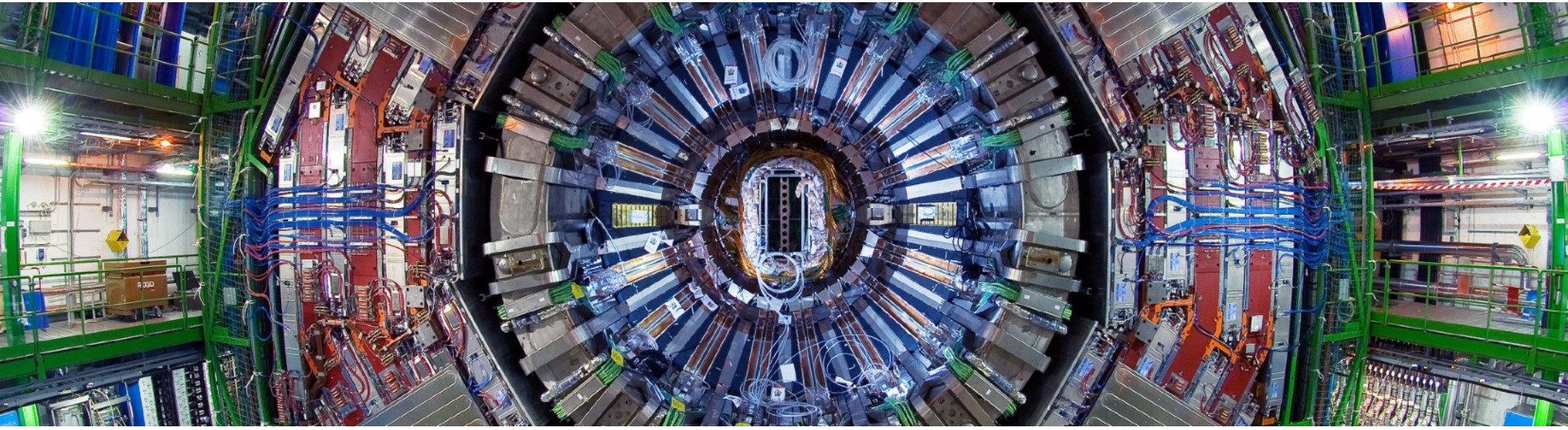
CMS Experiment

Status report 2025–2026
Plans 2026–2027 and beyond



Mikko Voutilainen
University of Helsinki and Helsinki Institute of Physics

CMS experiment project

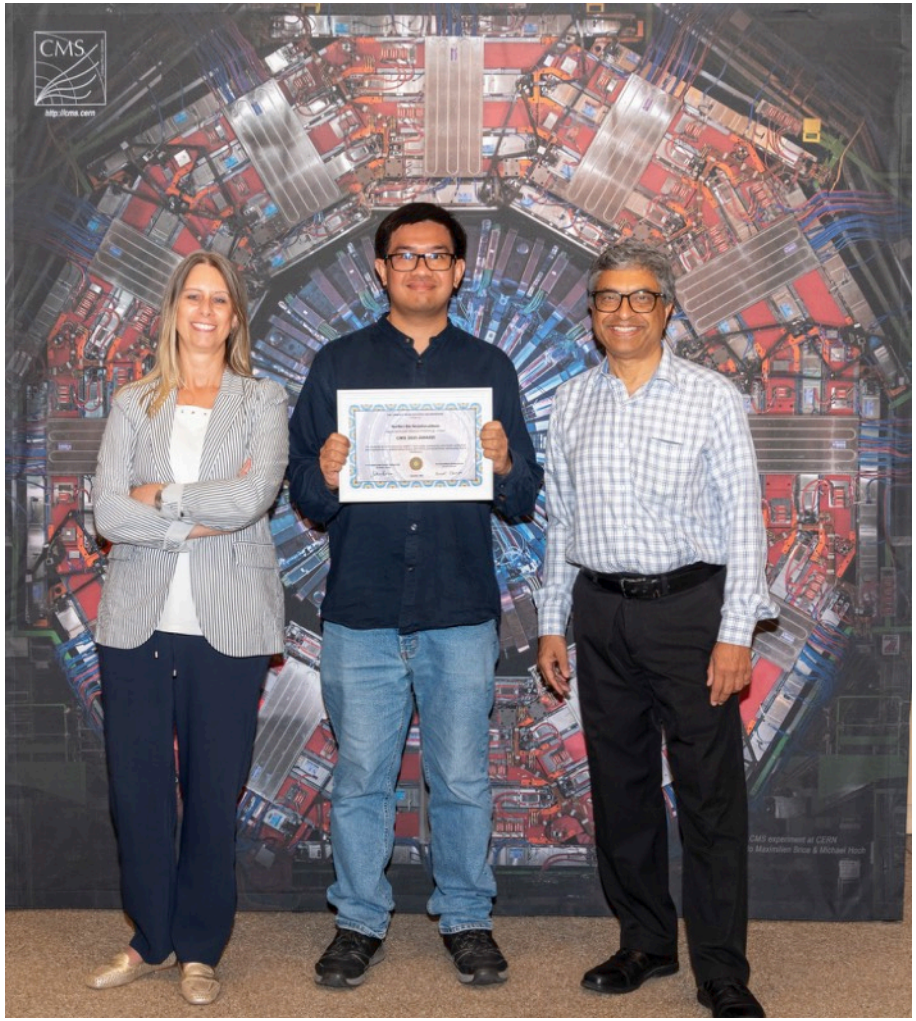
- Personnel **(20+6)**: 5+2 staff, 6 emerita/ adjoint, **4** post-doc, 9 PhD, a few MSc
- **Highlights:**
  - FCC week, JEC4Prompt progress, CMS awards
- **Detector operations:** **Ops**
  - Triggers (L1T+HLT)
  - Prompt Reconstruction (E2E+JEC4Prompt)
  - Jet Energy Corrections (JEC)
- **Physics analyses:** **Phys**
  - **Higgs (Searches)**
    - H^+ ($\rightarrow \tau\nu$), boosted H^0 ($\rightarrow bb$)
  - **Vector bosons (EW symmetry breaking)**
    - Vector boson scattering (all hadronic channel)
  - **Jets (Precision measurements)**
    - Jet measurements, top quark mass
- **Frontier technologies:**
  - Machine learning (ML) **Tech**
  - Trigger-level analysis (scouting)
  - Quantum computing (QC) → agentic AI

Highlight: CMS awards

- Two CMS awards to our scientists this year on our core jets and trigger related topics

Nurfikri Bin Norjoharuddeen

For exceptional commitment to JetMET data quality, advancing calorimeter calibration and reconstruction, collaborating closely with HCAL, and proactively addressing Run-3 challenges.



Patin Inkaew

For outstanding contributions to Run-3 Jet/MET triggers and HLT scouting, and for developing the NanoScouting format enabling advanced physics analyses with scouting data.

Highlight: JetMET+FCC

- **JetMET workshop** in August and **FCC week** in Helsinki in June
  - Started investigation of using LEP (Delphi) NanoAOD open data to study jet properties and α_s in clean events using modern tools (30 years of development!)
  - Easy entry point to FCC-ee physics, extrapolate from LEP to FCC-ee
  - **New spin-off** project for FCC to be presented by Henning Kirschenmann next

Ops Highlight: JEC4Prompt

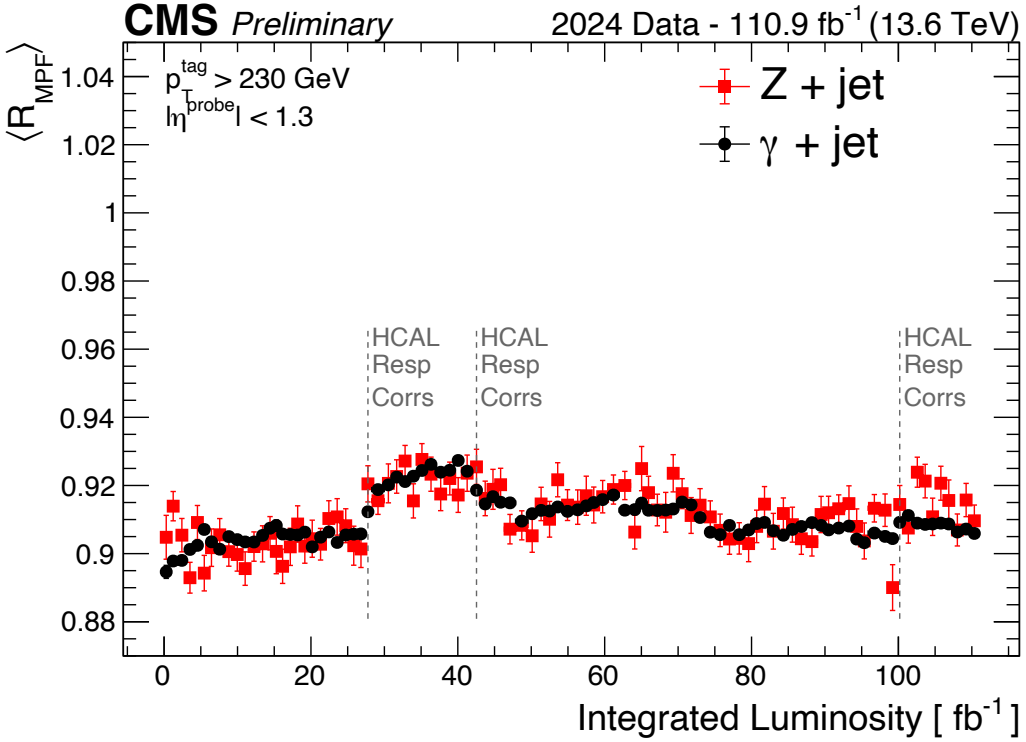
- JEC4Prompt project now in full speed, recruited PD and PhD, core team 6 months at CERN
- First public results presented at summer conferences, achieved 0.1% level monitoring
- Tapio selected as End-to-end Optimisation convener, tightly integrating project in CMS

Research Council of Finland

CMS DP-2026/034

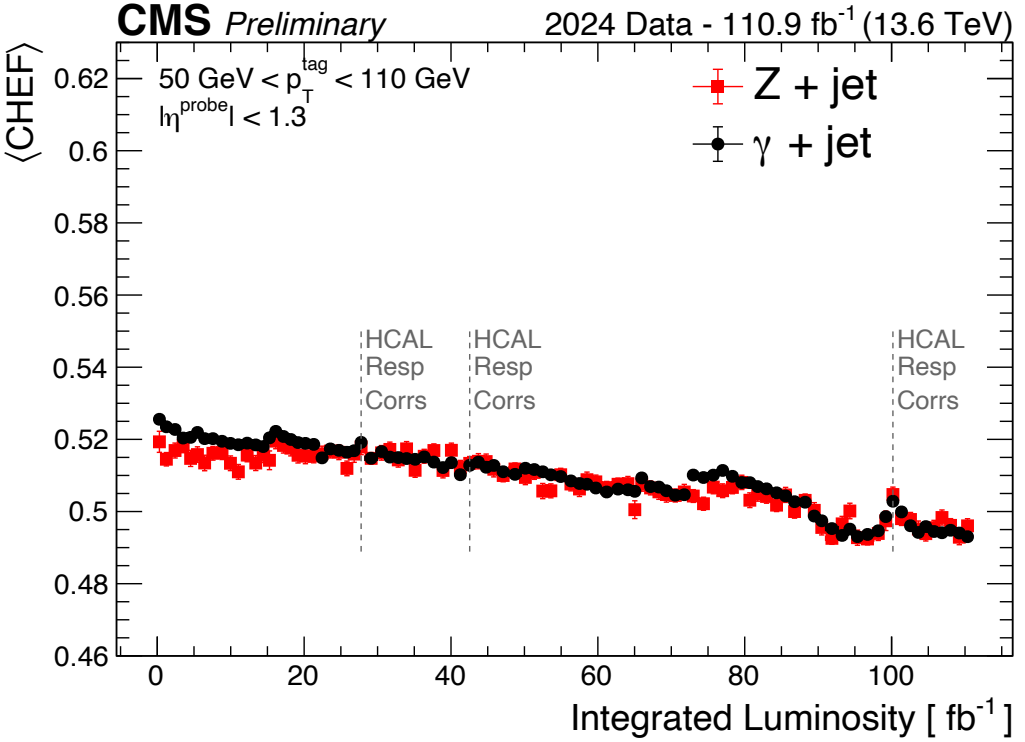
Absolute scale through MPF method

HCAL response corrections updates visible in both Z+jet and γ+jet channel, tracking changes at 0.1% level per day



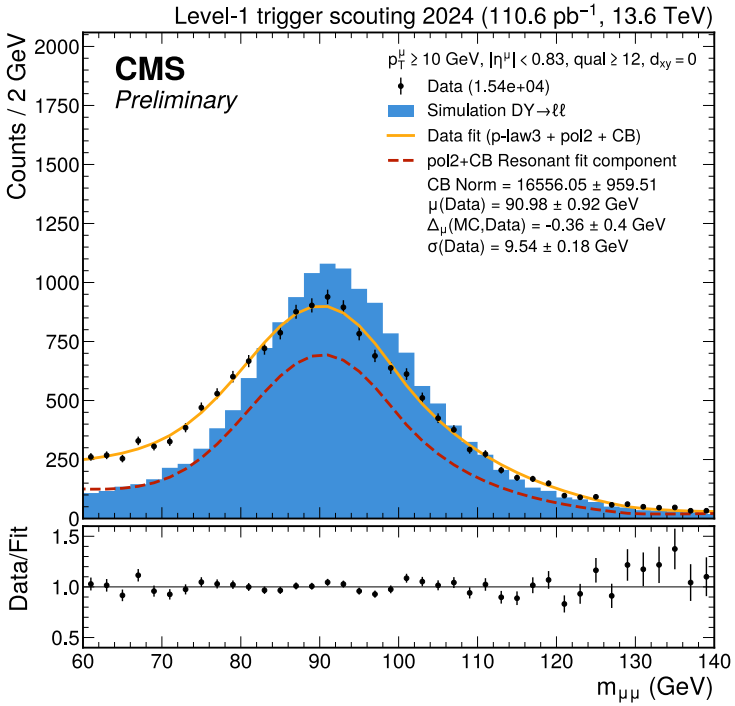
Tracking efficiency through PF charged hadrons

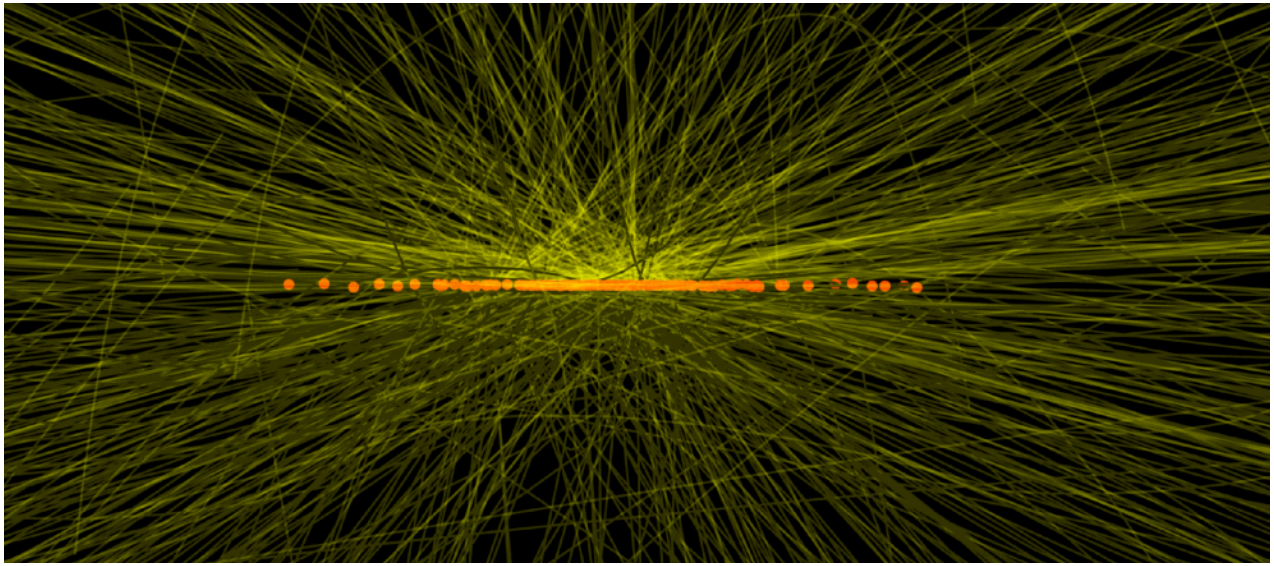
Steady reduction in charged hadron fraction expected due to tracker accumulating radiation damage

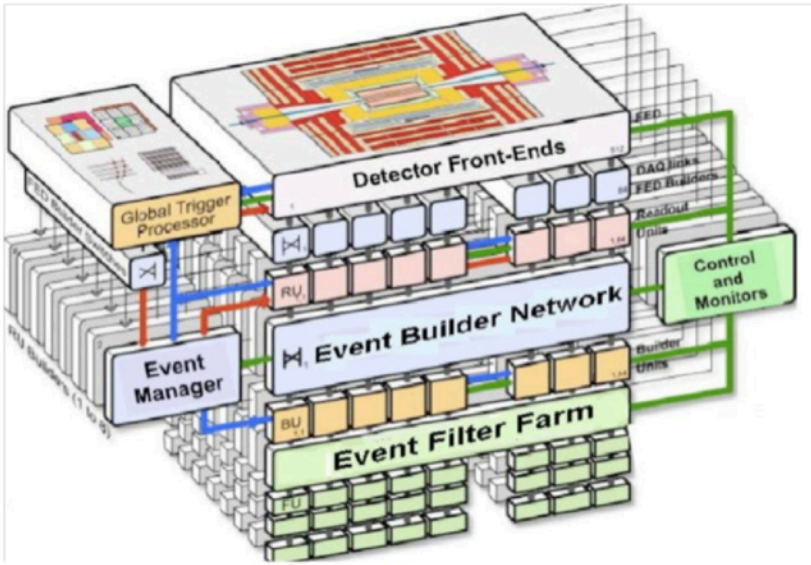


Trigger

- Triggering core operation in CMS:
  - Level-1 (Santeri, Bettina): 40 MHz -> 100 kHz
  - High-Level Trigger (Bettina, Theo): 100 kHz -> 1 kHz
  - Challenges: maintain rates, efficiency, low dead time with PU
- 2025-26 successfully operated at ~110 kHz on narrow Level-1 trigger margin
- Focus now moving towards Phase-2 preparations: new capabilities, PUPPI @ HLT, Next Generation Trigger at L1
- Santeri new CMS **Trigger Officer**, keeping our group tightly integrated into CMS core work, and Patin **Scouting L2** convener, doing physics directly at HLT

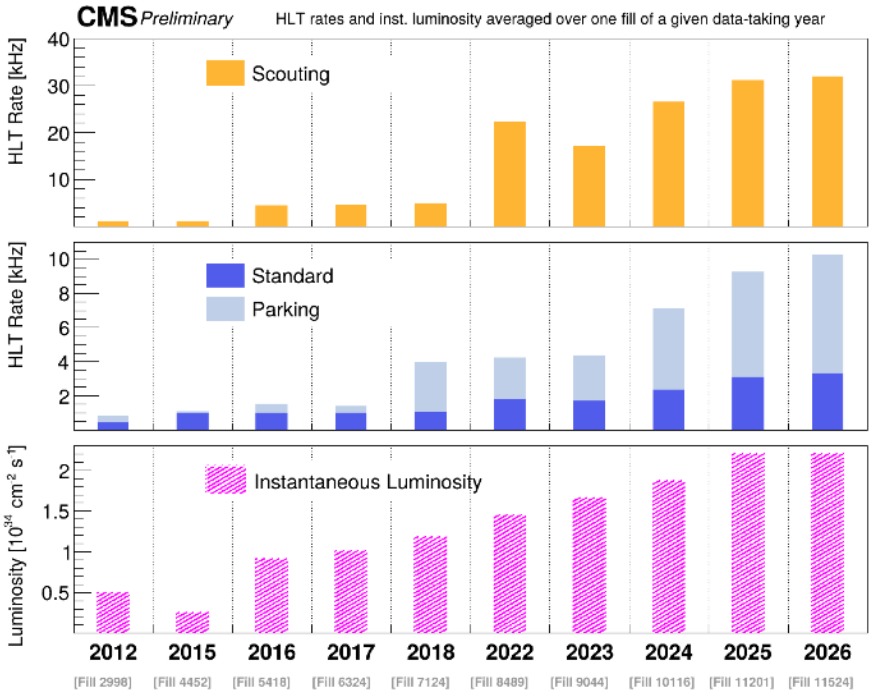






Tech Scouting

- **Scouting** is a modern analysis paradigm: reduced data format, higher rates, fast reconstruction
- Started with High-Level Trigger (HLT), now expanding to Level-1 trigger (L1), rates growing
- Cooperation & PhD theses with LUT (LUT University) Computational Engineering Dept. on FPGA/ML@L1



The real bottleneck is data recording bandwidth (MB/sec), not event rate (event/sec)

Scouting Stream
- reduced data format
- event size reduced
- event rate increased
- based on online reconstruction at HLT (no offline reconstruction)

Standard Stream
- ~ 2.5 kHz
- ~ 1.1 MB/event
- full event
- offline reconstructed at Tier0 after 48 h

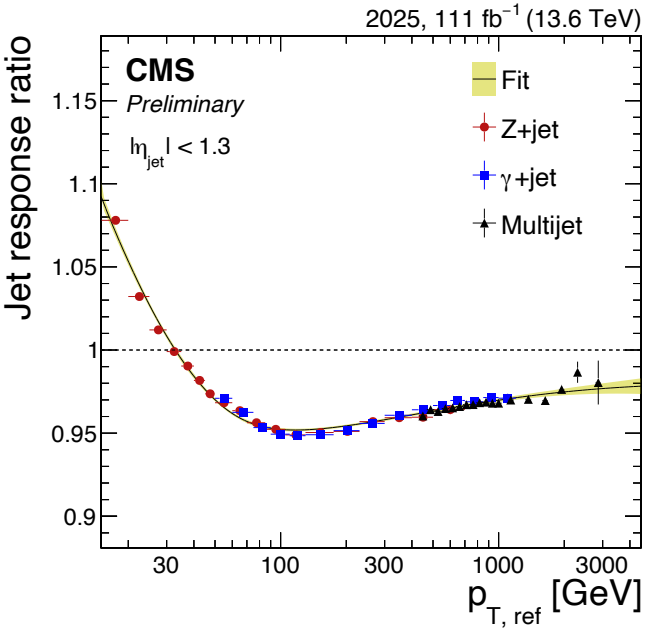
- Patin is CMS **Scouting L2** convener so we are leading the CMS efforts here (CMS Award)
- Core developments in Scouting NanoAOD development and adaptation for more analyses

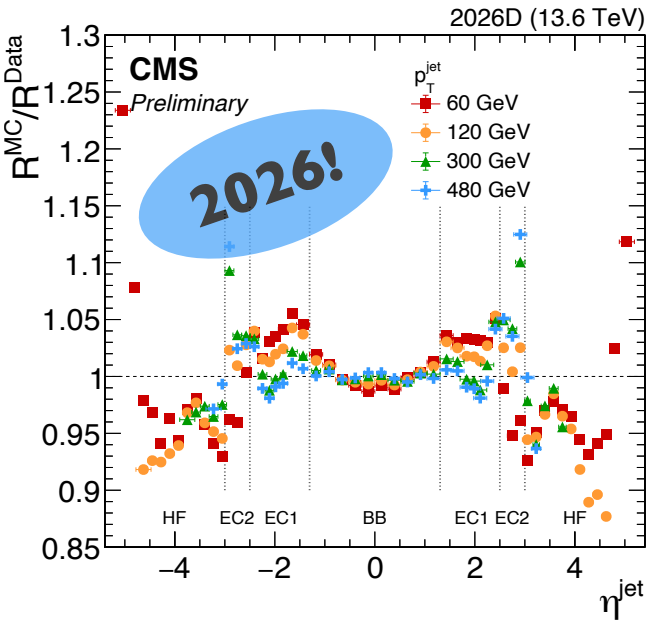
- **Patin (PhD)**

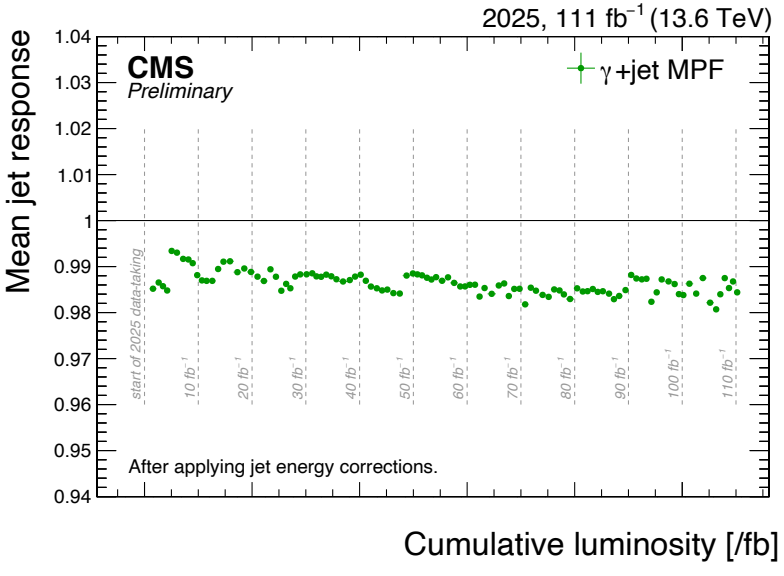
Ops Jet Energy Corrections

- Residual JEC and resolutions provided **entirely by HIP** team in 2025–26
  - Leadership: JetMET L2 (Fikri, CMS award), JME-JERC L3 (Ravindra), JME-JMAR (Nico), JME-Trigger L3 (Bettina, Theo), PPD End-to-end Optimization L2 (Mikko, Tapio) and Trigger Office (Santeri)
  - We produced **2026 HCAL IsoTrack+HF** corrections (Fikri's award) and are taking over PF hadron calibration => control jet analysis chain in-house from HCAL through PF to JME and SMP
- Short-term: document Run 2 and Run 3 results (papers + book)
- Mid-term: automatize JEC on top of Prompt Calibration Loop (JEC4Prompt project)
- Long term: fully automatic and optimised stack from L1 trigger to physics analysis
  - explore opportunities in agentic AI systems for facilitating this

*JEC residuals reduced by **>x6** since early 2024 thanks to HIP efforts, and stability <1%*







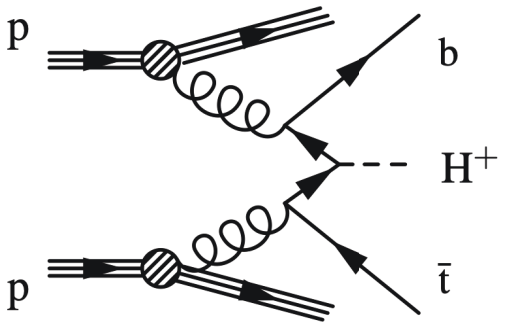
CMS DP-2026/109

Higgs

- Higgs boson(s) core part of LHC physics programme
- Contributing to $H^+(\rightarrow \tau\nu)$ (Sami), $H(\rightarrow bb)$ (Patin) and SM & BSM Higgs (Santeri, Onni / HH)
- Long-term LHC goal is di-Higgs for Higgs vacuum potential shape

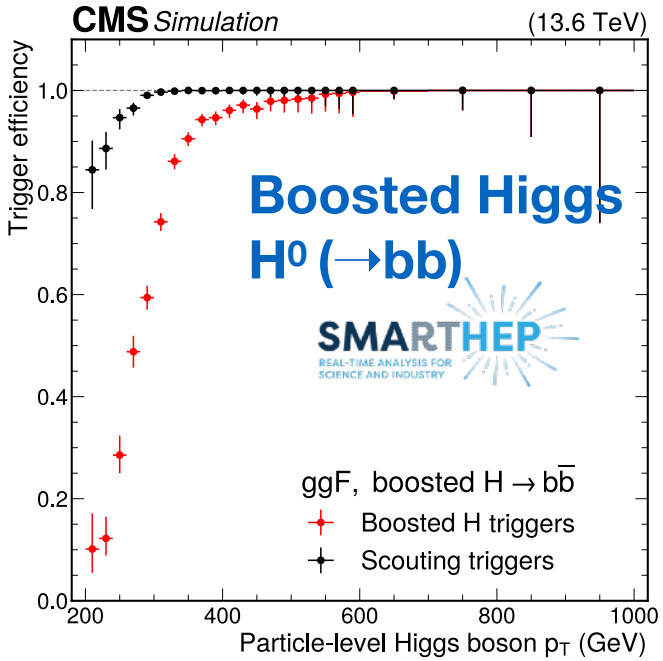
$H^+ (\rightarrow \tau\nu)$

Heavy



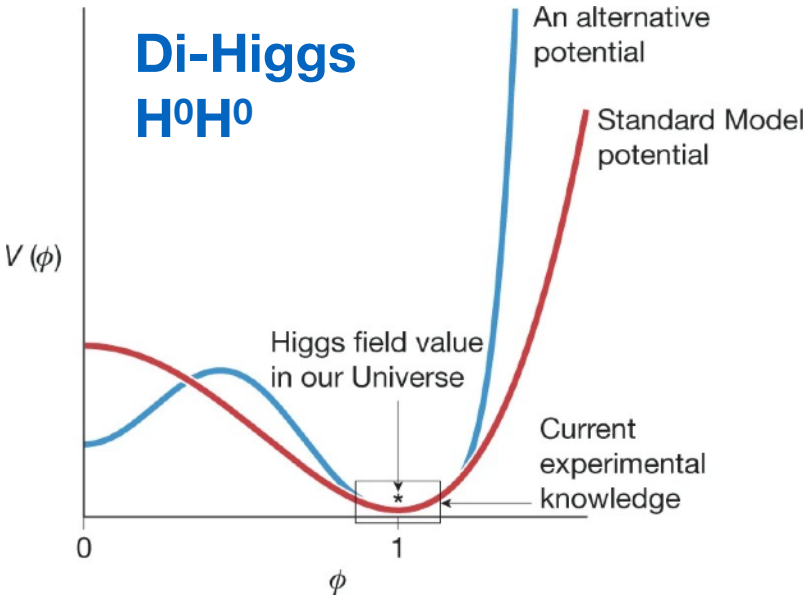
✤ ~~Aapo (PhD)~~

Boosted Higgs $H^0 (\rightarrow bb)$



✤ **Patin (PhD)**

Di-Higgs H^0H^0



✤ **Onni (PhD)**

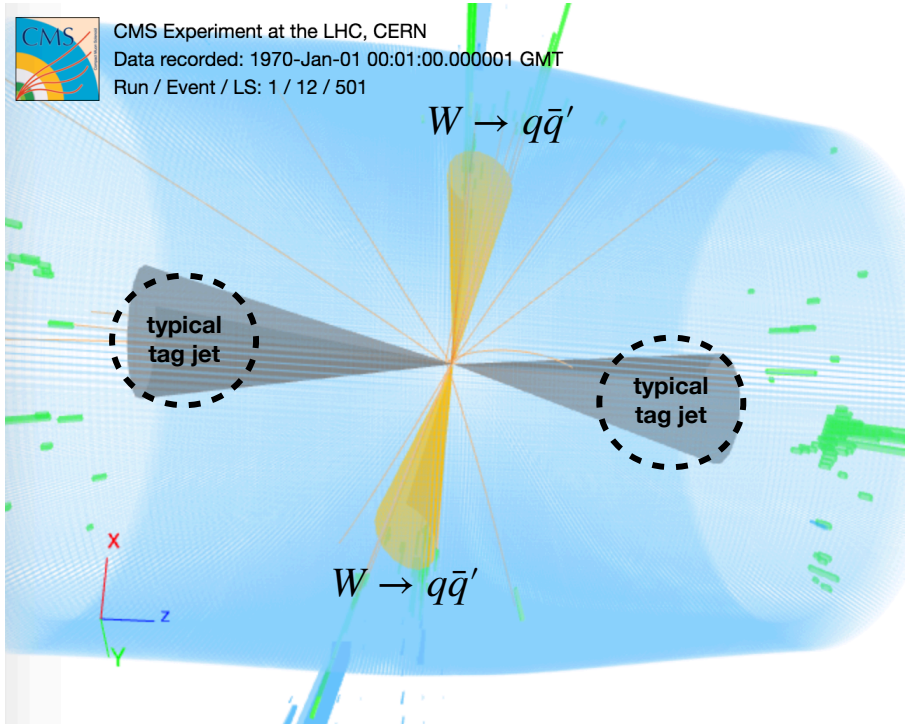
Phys Vector Bosons

- Vector boson scattering in all-hadronic decays:
  - Run 2+3 enough data for Standard Model sensitivity
- Challenges:
  - Large QCD background (all-hadronic final state)
  - Forward quark tag jets (ageing detector and low p_T)
- Enabling ingredients:
  - Forward and low p_T jet calibrations
  - Machine learning for jet classification and regression

- **Recent developments:**
  - Analysis progressing towards CADI line, close cooperation with INFN Padua, FNAL, etc.
  - CMS-internal review coming up soon towards first publication
  - Doing both, strict "all-hadronic" and with MET version
  - COMETA: Workshop with experiment and theory on polarisation tagging

COMETA

Research Council of Finland

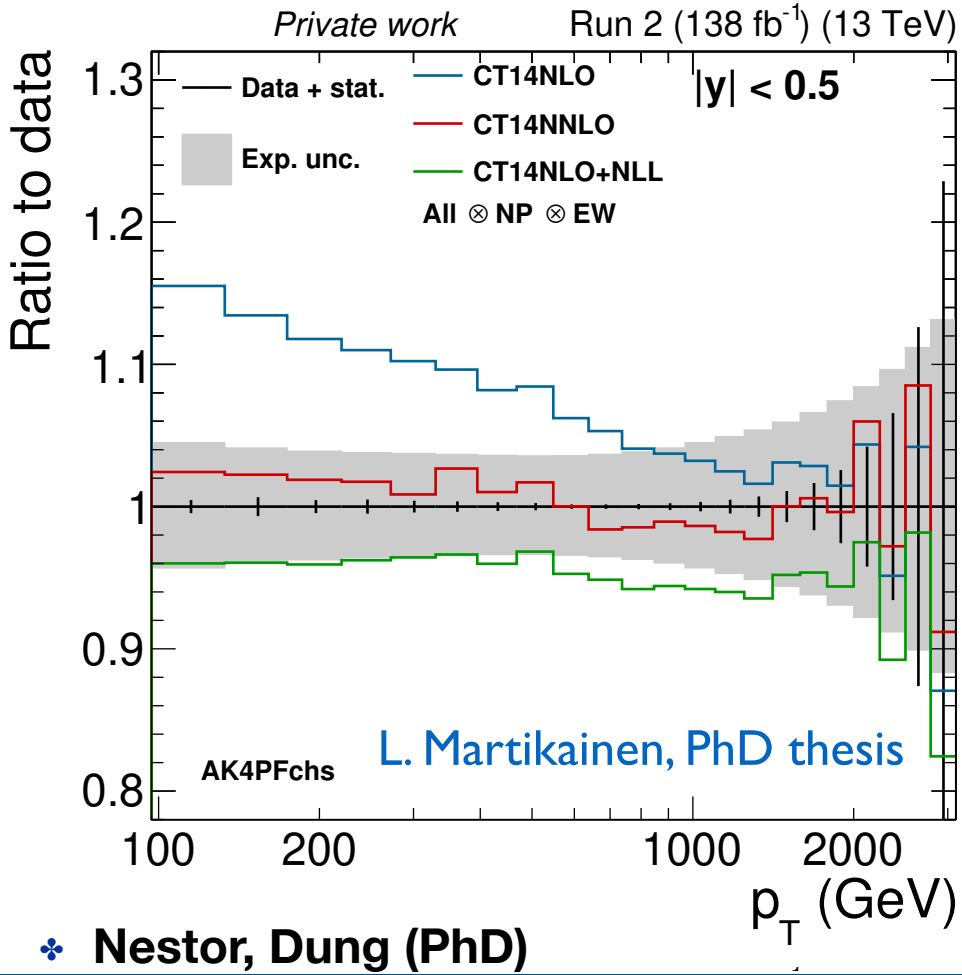


- Perks of all-hadronic VBS:
  - **Highest branching fraction** → strong constraints in high invariant diboson mass region → SMEFT interpretation → BSM handle
  - Access to full kinematics → handle on polarisation → $W_L W_L$

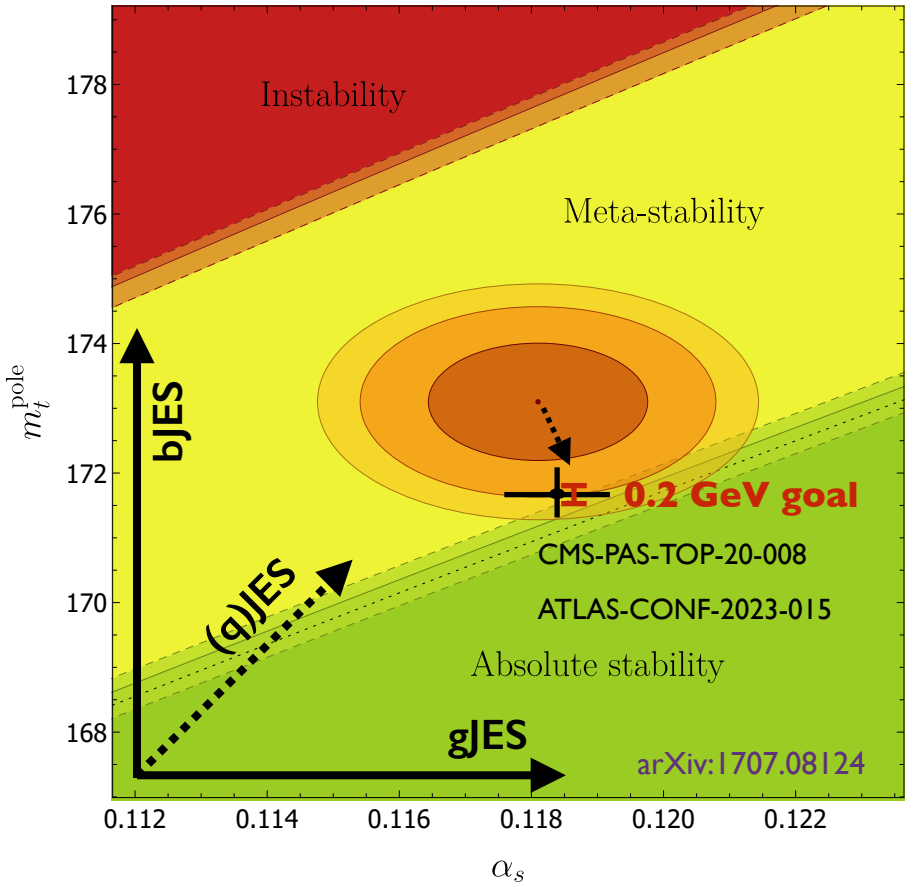
✣ **Nico, Alexi (PhD)**

Phys Jets (α_s) & Top (m_t)

- Jet measurements: precise α_s at NNLO
- Run 3 jet measurements now progressing on **2026 data**, including large **low PU** data set
- Much effort put into calibrating 2026 Prompt data: HCAL depths, HF scale etc.



- Top quark mass fundamental parameter of SM and key to SM vacuum stability
- Full Run 2 analysis in ARC review, staged **unblinding process on-going**
- Future development on W>cs and η_t>$\gamma\gamma$ decay modes



- **Nestor, Dung (PhD)**
- **Mikael (l+jet), Emilia (W>cs), Bettina ($\gamma\gamma$)**

QC -> agentic-AI pilots

- **Quantum computing**: current NISQ systems not yet competitive for our near-term uses
- Our two leading QC students moved to industry (VTT, Väisälä) — positive outcome, but temporarily removes our critical mass. Maintain technology watch, rebuild later
- **Near-term opportunity**: agentic AI can develop and orchestrate complex analysis workflows, closely aligned with our **end-to-end optimisation** of the full jet-analysis chain
- Initial tests with Claude Code and ChatGPT Codex are promising, but still require deep domain expertise, rigorous validation, reproducibility, and human scientific control
  - **2026–27 objective**: pilot agentic workflows in selected analyses and update student training toward AI-assisted software design, verification, and workflow architecture

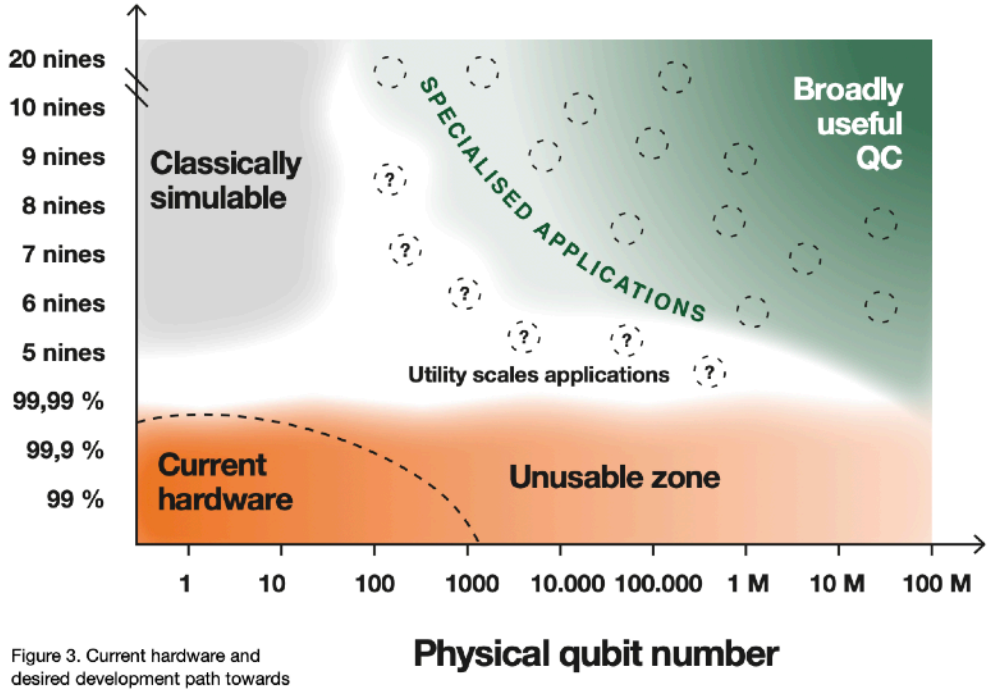
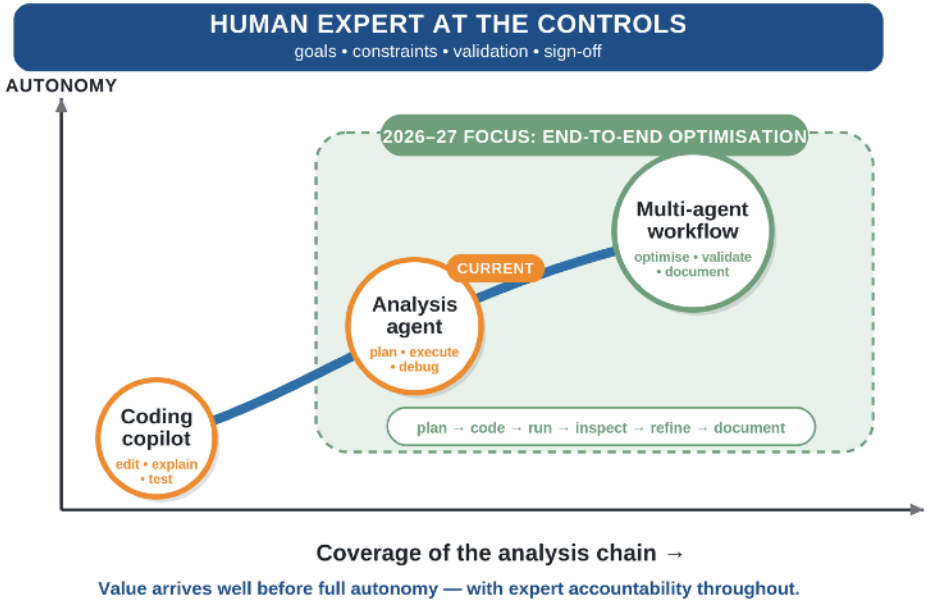


Figure 3. Current hardware and desired development path towards large-scale fault-tolerant quantum computing.[16]



Summary and outlook

- HIP CMS experiment project is running well and reached the critical mass for a local hub
  - HIP team covers full JEC+JER chain and jet triggers, expanded to HCAL, next PF calibration
  - Good Prompt data for jets in 2026 thanks to our efforts, and now continuing to automatize
- Balanced programme with many synergies for 2026—2027
  - Detector operations from trigger through Prompt Calibration to Jet Energy Corrections for physics
  - Physics analyses covering searches (Higgs), electroweak (VBS) and precision measurements (α_s+m_t)
  - Apply frontier technologies in ML, scouting, QC and agentic AI to benefit operations and physics

- Beyond 2027: HL-LHC and FCC-ee
  - Powerful detector upgrade for forward region: HGCAL, timing (MDT), tracker extension
  - Many opportunities for FPGAs and advanced machine learning (e.g. UParT, MLPF)
  - Supports particularly exploration of electroweak symmetry breaking (VBF, VBS, di-Higgs)

Backup slides

Personnel 2026

- Professors (2)
  - Mikko Voutilainen* Jets, PdmV L2 [UH 50%*, ERC]
  - Henning Kirschenmann* VBS, ML [RCF+LUT]
- Senior scientists / Univ. researcher (3+2)
  - Sami Lehti* H^+, Z+jet [20%*]
  - Tapio Lampén PPD-E2E L2, PCL
  - Santeri Laurila* Trigger office, Higgs [75%*]
  - Kati Lassila-Perini Ed. and Open Data [70%*]
  - Tomas Lindén * Tier-2 Operations [100%*]

  *funded (%) from outside CMS Expt. project
- Emerita and adjoint scientists (6)
  - Jorma Tuominiemi — Higgs (emeritus), Matti Kortelainen — Tracking (FNAL), Juska Pekkanen — FCC (CERN), Toni Mäkelä — Jets / bJES (DESY), Jaana Heikkilä — Higgs / A^0 (CERN), Minsuk Kim — Top + jets (GWNU), Laura Martikainen — Heavy ions (Rome)
- Post-docs / visiting scientists (4)
  - Nurfikri Norjoharuddeen* JetMET L2 [RCF]
  - Ravindra Verma* JEC, JME-JEC L3 [ERC]
  - Theodoros Chatzistavrou* PCL, JME-trig. L3 [RCF]
  - Mikael Myllymäki* JEC/top [ERC]
- PhD Students (9)
  - Patin Inkaew* Hbb+ML [Väisälä]
  - Nico Toikka* VBS [PhD pilot]
  - Nestor Mancilla* JEC/jets [ERC]
  - Bettina Lehtelä* JEC/γ+jet [ERC]
  - Emilia Veikkola* JEC/top [ERC]
  - Alexi Stadniski* VBS [PhD pilot]
  - Văn Dũng Lê* Jets α_s [EDUFI]
  - Onni Salmi* di-Higgs [UH grant]
  - Punnawich Chokeprasert* JEC [RCF]
  - ~~Aapo Kössi~~ ~~H^+ + QC~~ ~~[Ehrnrooth]~~
- MSc students (3…)
  - Dan Näsman PCL [Tapio]
  - Matilda Marjamäki VBS [Henning]
- MSc students (…3)
  - Shounak Naik H^+ [Sami]

* on external funding (at least partly)

Some of our alumnae

- From Post-doc:
  - Henning Kirschenmann — full professor at LUT university in Finland
  - Minsuk Kim — assistant professor at GWNU in Korea
  - Matti Kortelainen — permanent staff at Fermilab
- From PhD:
  - Laura Martikainen — post-doc, U. Rome La Sapienza -> ?
  - Kimmo Kallonen — ML engineer at Apple Inc. (SF/London)
  - Hannu Siikonen — software engineer, Planmeca Oy
  - Mikko Lotti — software engineer at SimCorp in Denmark
  - Joona Havukainen — ML engineer at Apple Inc. in California
  - Santeri Laurila — CERN Fellow -> CERN LD -> UH
  - Jaana Heikkilä — post-doc at U. Zurich -> CERN fellow
  - Juska Pekkanen — PD at U. at Buffalo -> CERN LD -> ?
  - Terhi Järvinen — data scientist, OP Financial Group
- From MSc:
  - Aapo Kössi — Väisälä
  - Väinö Mehtola — QC staff at VTT
  - Daniel Holmberg — PhD student at U. Helsinki CS
  - Adelina Lintuluoto — PhD at KIT/CERN
  - Antti Pirttikoski — PhD student at U. Geneva
  - Bettina Lehtelä (nee Schillinger) — PhD student at Aalto CS -> UH
  - Toni Mäkelä — PhD student at DESY -> PD
  - Mikael Kuusela — Asst. Prof. at Carnegie Mellon University

image credit: OP

Funding

- On-going grants, recent grants
  - Laurila, **University of Helsinki Early-Career Boost Grant**, 150 kEUR, 3 years (2026-28)
  - Lampén+Voutilainen, **RCF consortium, JEC4Prompt,** 1.9.2025-30.8.2029
  - Voutilainen, **ERC-CoG, JEC4HL-LHC,** 1.9.2022—30.8.2027
  - Kirschenmann, AoF grant **"ForVVard"**, 1.9.2023—30.8.2027
  - [Voutilainen, Kirschenmann, **SMARTHEP ITN,** 1.10.2022-30.9.2025; finished]
  - Full-year PhD grants:
    - Patin Inkaew, **Väisälä foundation,** 1.1.2026—31.12.2026
    - [Aapo Kössi, Ehrnrooth foundation, 2026–2028; given up]
    - [Mikael Myllymäki, **Jenny and Antti Wihuri foundation**, 1.1.—30.12.2022 , 2023—25 (graduation ~12/2025)]
    - Earlier: Kimmo Kallonen, **PAPU+Väisälä**; Laura Martikainen, **Ehrnrooth**; Hannu Siikonen, **Väisälä**; Joona Havukainen, **Wihuri**; Mikko Lotti, **Väisälä**
  - Part-year PhD grants, mobility grants, travel grants:
    - Van Dung Le, EDUFI, 1-9/2026
    - Waldemar von Frenckell foundation, 3000—5000 EUR travel and mobility grants for most students per year

Convener positions

- Convener positions (bolded on-going or starting/finishing in 2026):
  - Santeri Laurila, **Trigger officer** (2026–28), L1 trigger (DPG L2, 2023—25)
  - Nurfikri Norjoharuddeen, **JetMET (POG L2, 2025–27)**, JME/BTV-SW L3 (24–26)
  - Tapio Lampén, **PPD-End-to-End Optimization (PPD L2, 2026–28), PdmV Validation (DPG L3, 2024–26)**, PCL Manager (DPG L3, 21–23), AlcaDB (DPG L2, 19—21)
  - Patin Inkaew, **TSG Scouting (DPG L2, 2025–27)**
  - Mikko Voutilainen, **End-to-end optimization (POG L2, 2025–26)**, PdmV (POG L2, 23—25), JME (POG L2, 22–23)
  - Sami Lehti, JME-trigger (POG L3, 2023–25)
  - Ravindra Verma, **JME-JERC (POG L3, 2024–26)**, EGamma-TRG (POG L3, 22–24)
  - Bettina Lehtelä, **JME-trigger (POG L3, 2025—27)**
  - Nico Toikka, **JME-JMAR (POG L2, 2026–28)**
  - Henning Kirschenmann, TOP-TMP (PAG L3, 2022—24), JetMET (POG L2, 2020–22)
  - Kati-Lassila Perini, CMS Data Preservation (2016–22, x3)