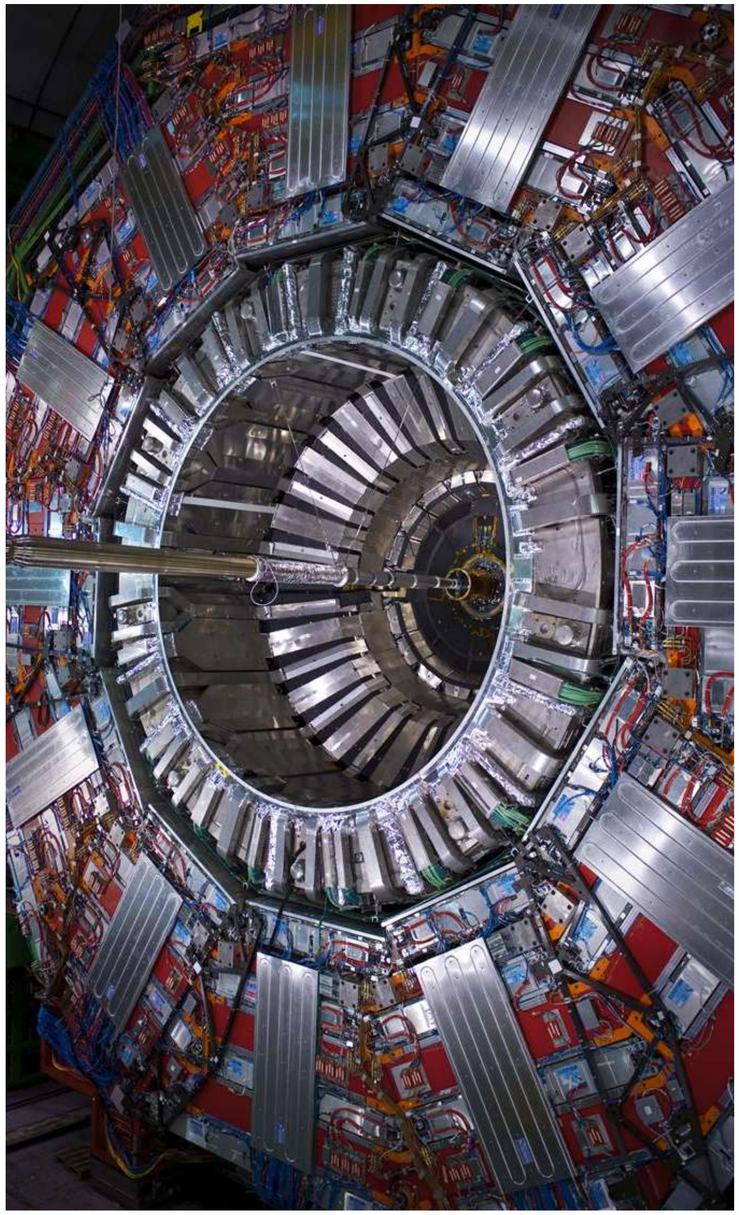
CMS & PPS/TOTEM Experimental Overview

Santeri Laurila

Particle Physics Days, Lammi, Finland
28 November 2024

CMS Is Many Experiments at Once

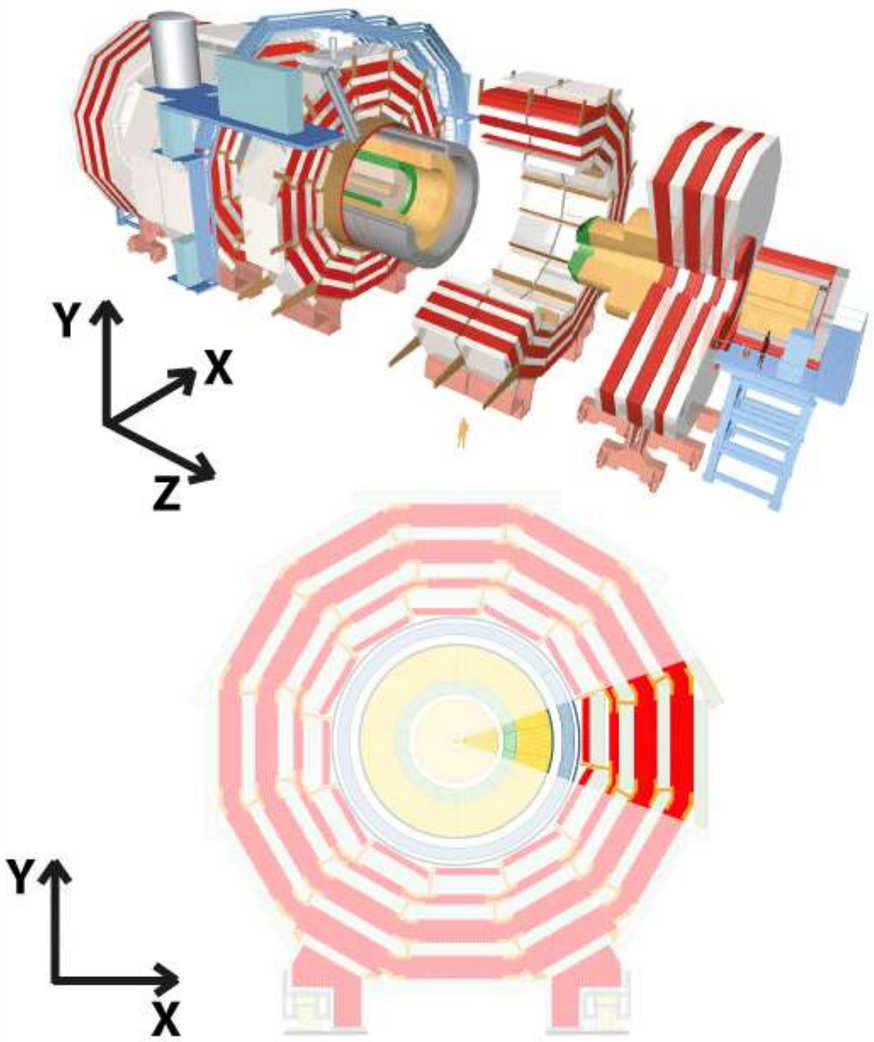


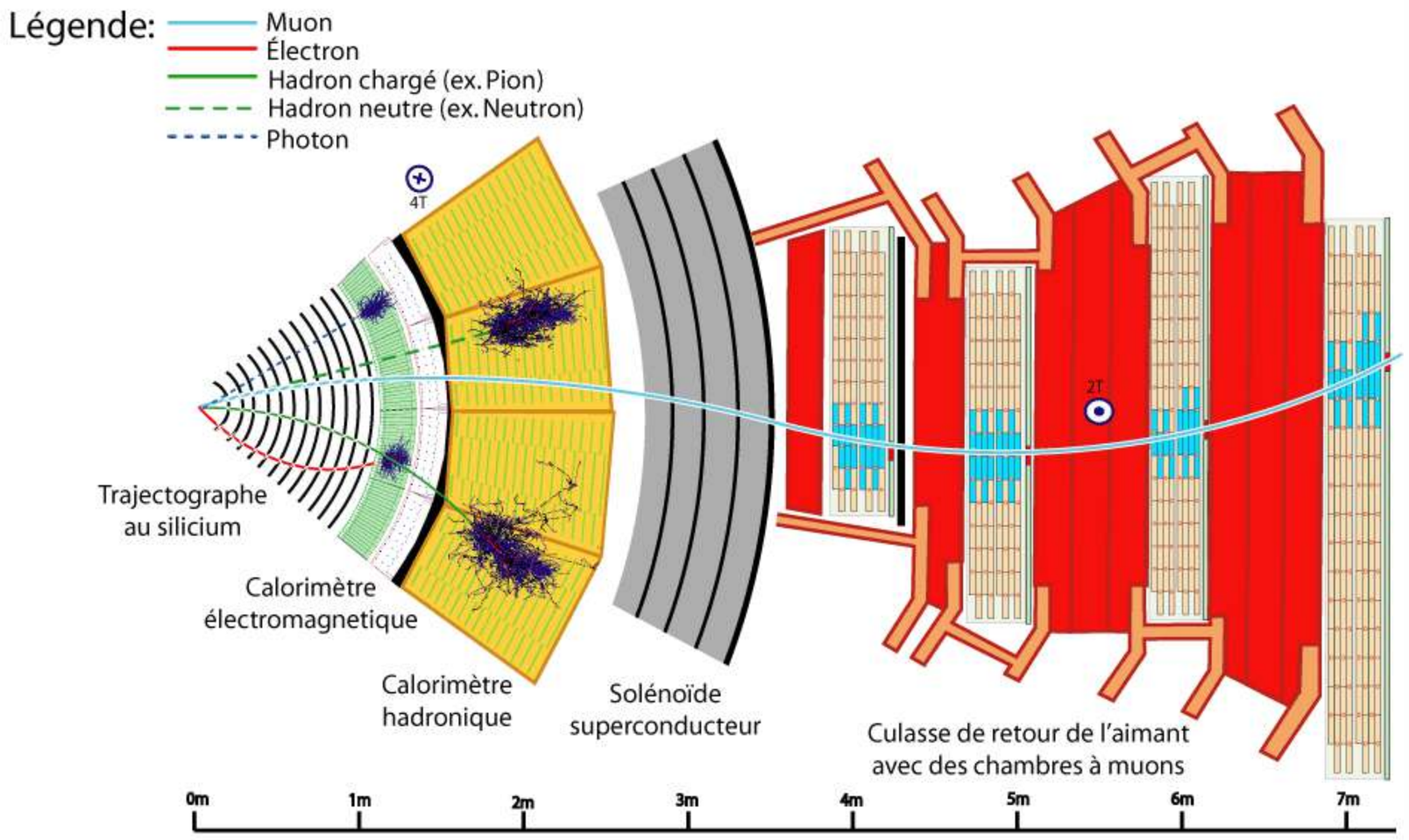
- CMS is a "general-purpose detector", i.e. **many experiments at once**:
  - At the energy frontier: wide BSM **search** program in the TeV range
  - At the intensity frontier: Higgs and EW **precision** program
  - **Flavor** experiment: top physics + dedicated data streams for b, c, and τ
  - **Heavy ion** experiment: PbPb and pPb LHC runs
  - **Forward physics** experiment with proton tagging capabilities (**PPS**)
  - **Photon collider** experiment (ultra-peripheral heavy ion processes)

- In addition, CMS is a **driver for new technologies and methods**, e.g.:
  - Advanced **realtime analysis** with **FPGAs**, including unbiased **anomaly detection**
  - Fast and accurate reconstruction on **GPUs**
  - **Automation** towards self-calibrating detector
  - Early adopter of **machine learning** techniques throughout the analysis chain

Finnish contributions highlighted with orange HIP logo

CMS Detector



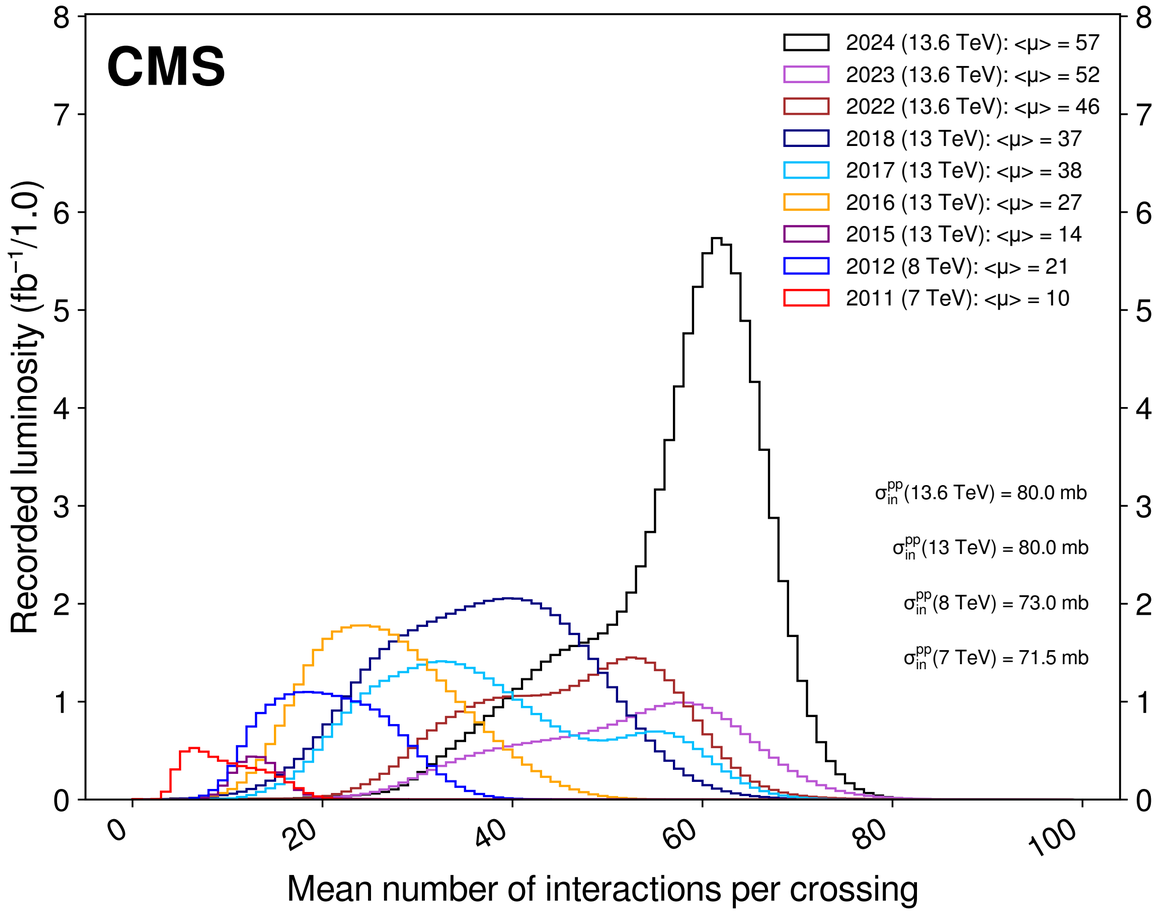


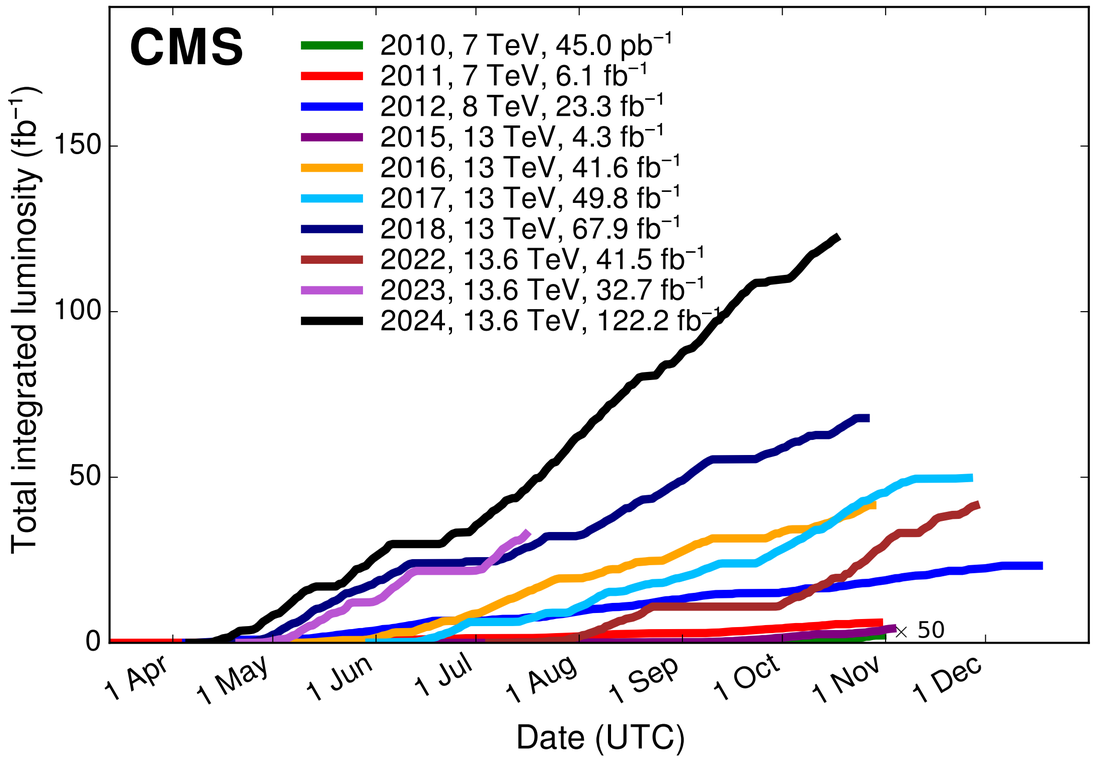
- Interplay of all **well-calibrated subdetectors** is critical to reconstruct particles with **Particle Flow** algorithm

HIP CMS Experiment Project

- Project for Finnish CMS work (not related to detector upgrades)
- Thanks to the recent ERC and RCF grants, the HIP CMS Project is now bigger than ever
- LUT extending its contribution to the CMS Experiment project
  → Even more people joining soon!

CMS Run-3 Data-taking





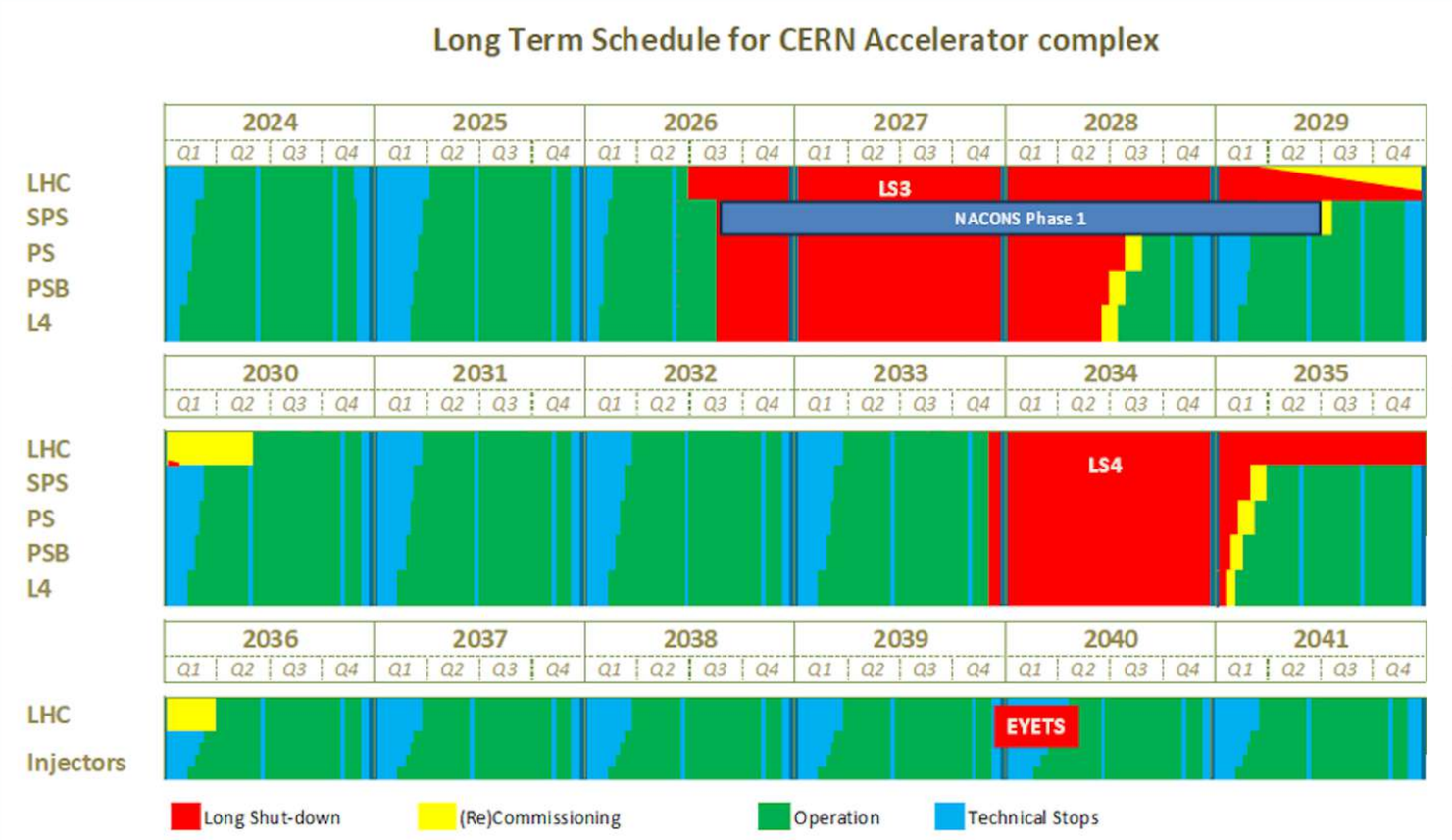
- Record-high amount of **pp** collision data collected in 2024, at record-high **pileup**
  - Run-3 dataset now exceeds Run-2
- Also this year's **HI** run was productive: 1.9 nb^{-1} collected

Revised LHC Schedule

- In total, CMS has now recorded **360 fb-1** of data since 2010 – this is only **~10%** of the total planned LHC data yield
  - While we are halfway through the LHC journey in time, we are **still in the beginning** in terms of data!

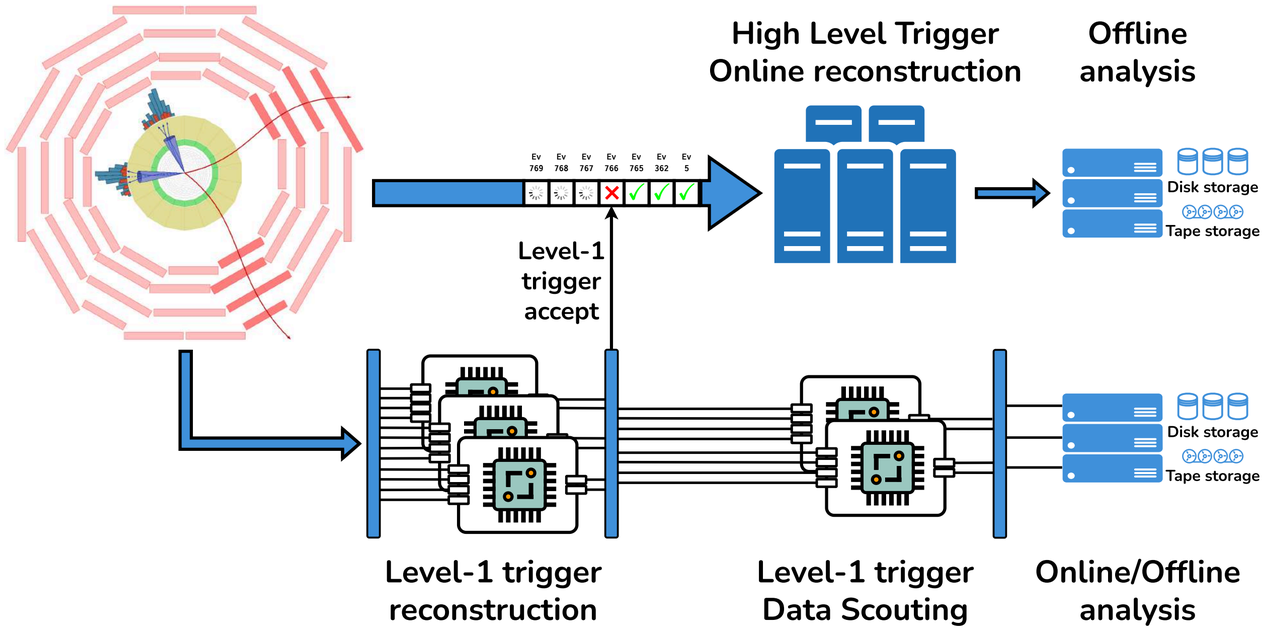
- This September, the **CERN Council decided to revise the LHC schedule**:
  - Long Shutdown 3 now scheduled to start in **July 2026** (+7.5 months)
  - In addition, it is extended by +4 months
  - Total effect: HL-LHC operation expected to start in **June 2030** i.e. **one year later** than previously planned
  - Main reason: delays in ATLAS and CMS upgrades, partially due to COVID and the invasion of Ukraine

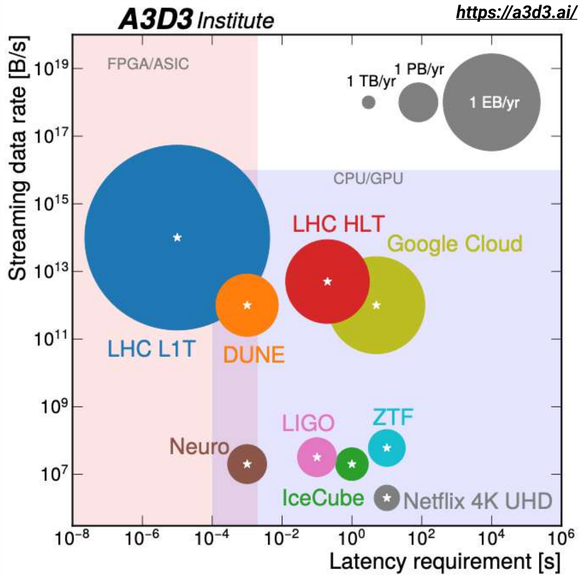
- In **2025**, the LHC operation will start in April, pp physics production in **mid-May**
  - Another O(100fb^{-1}) of pp data expected
  - First **O-O** & **p-O** runs scheduled in July, and a **neon** run is under discussion
  - Heavy ion run planned in November

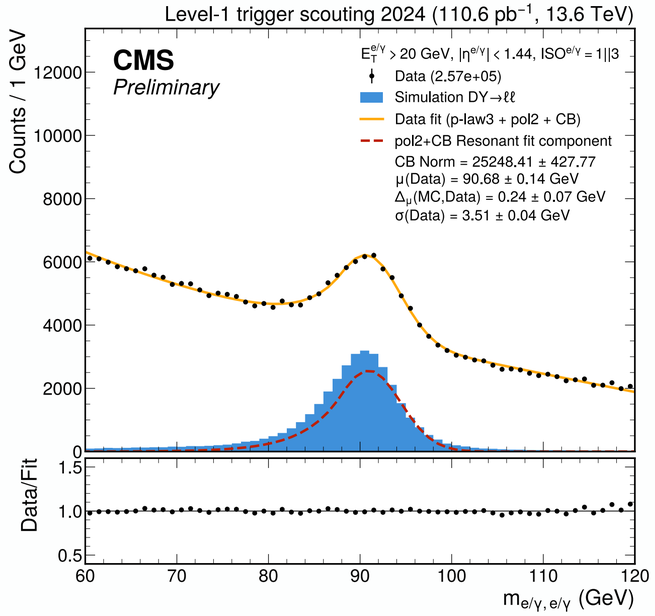


CMS in 2024

CMS Hardware Trigger



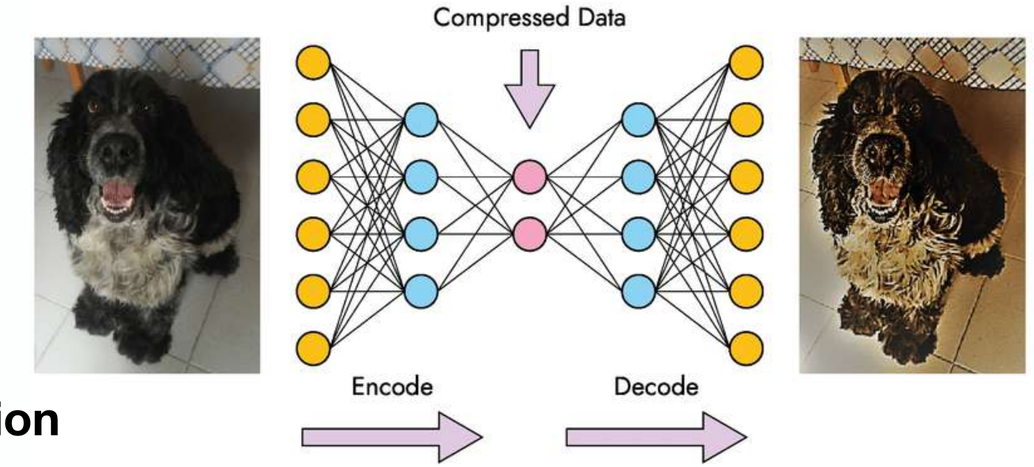


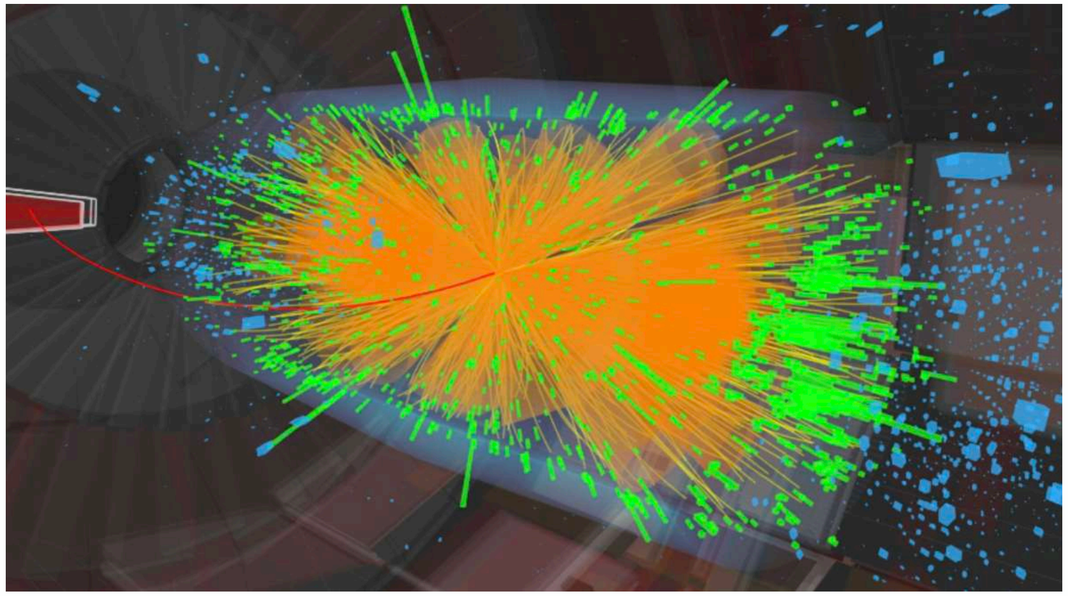


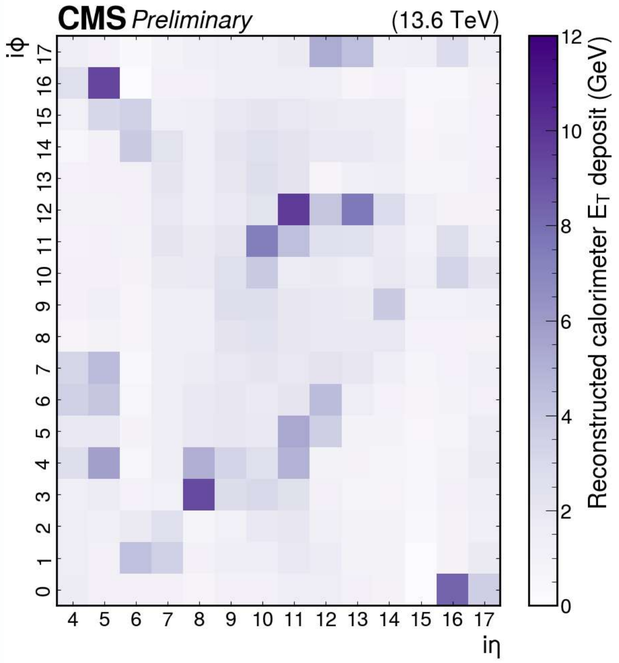
- CMS Level-1 Trigger (L1T) processes collision events at full **40 MHz rate**
  - Each event analyzed in **<4 us** in using custom electronics
  - Smooth operation in 2024, with output trigger rate of **100-115 kHz** (design value 100 kHz)
  - **Zero Degree Calorimeter** was integrated in L1T in late 2023 for more efficient triggering of ultraperipheral HI colision events
  - New algorithms for **low-p_T muons** (B physics) and **displaced muons** (long-lived particles) introduced in 2024
- New analysis paradigm: **L1T scouting**
  - Store the trigger-level objects at 40 MHz and use them directly for physics analysis
  - Allows to **perform analysis without any preselection** of collision events

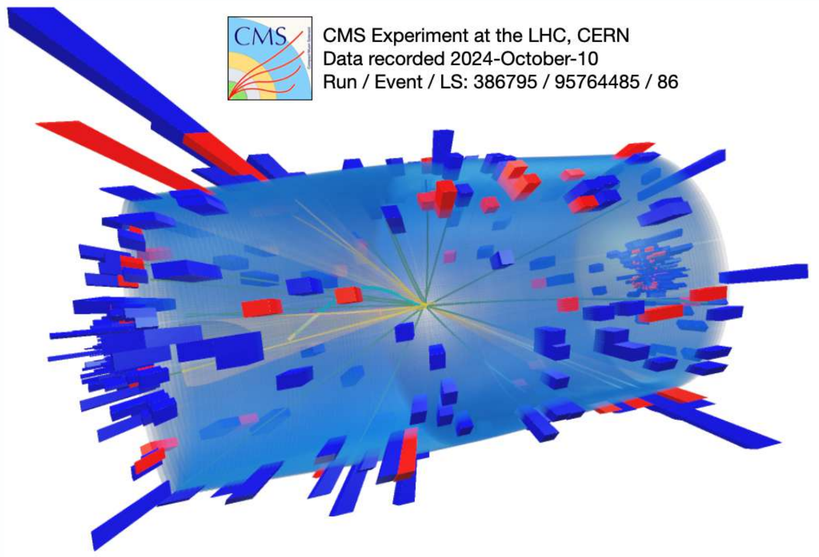
CMS Trigger-level Anomaly Detection

- What if we are not observing new physics because we don't know how it looks, and therefore how to trigger it?
  → Solution: train **anomaly detection** algorithm using common SM physics and **trigger any events that look unusual**
- In 2024, CMS **deployed two new ultrafast autoencoder-based anomaly detection algorithms** in the Level-1 Trigger
  - **AXOL1TL** (Event-level anomaly detection with variational autoencoder in the L1 Global Trigger): based on **properties and correlations of reconstructed trigger-level objects**
  - **CICADA** (Calorimeter Image Convolutional Anomaly Detection Algorithm): based on **patterns in low-level calorimeter information**

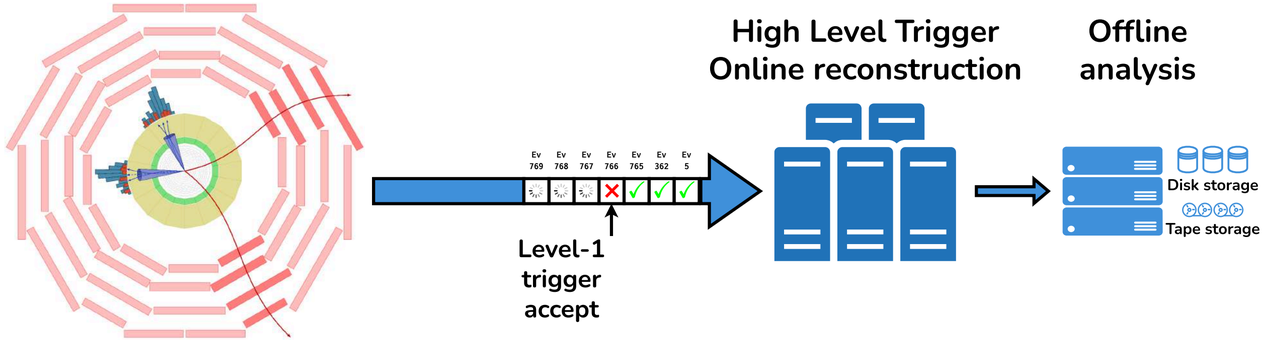


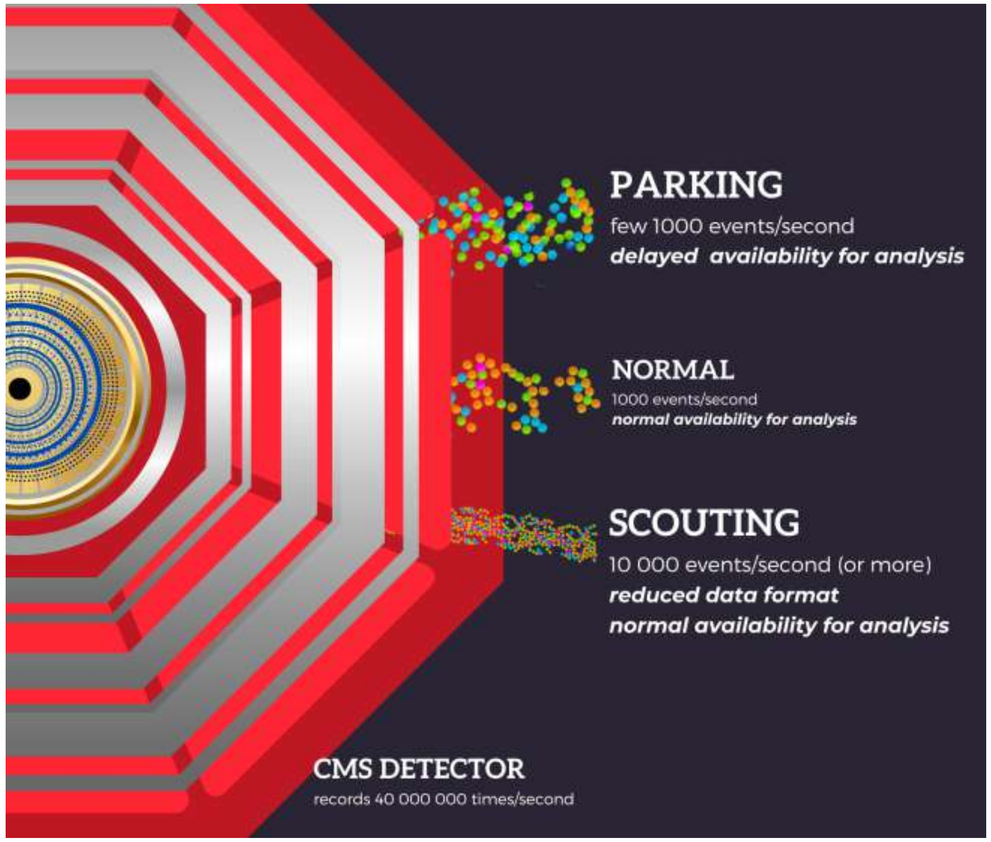




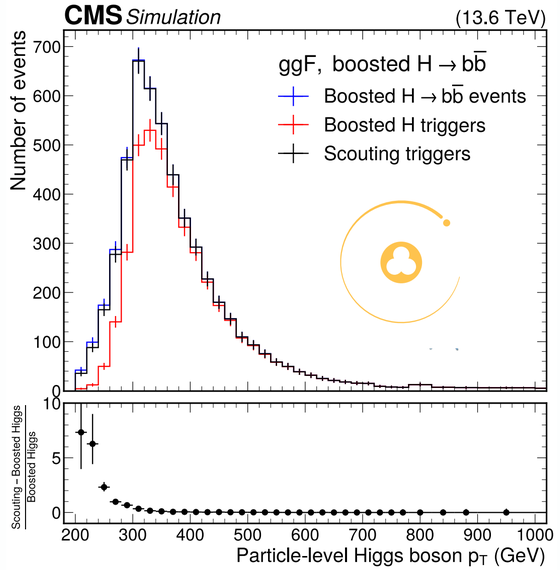


CMS Data Streams



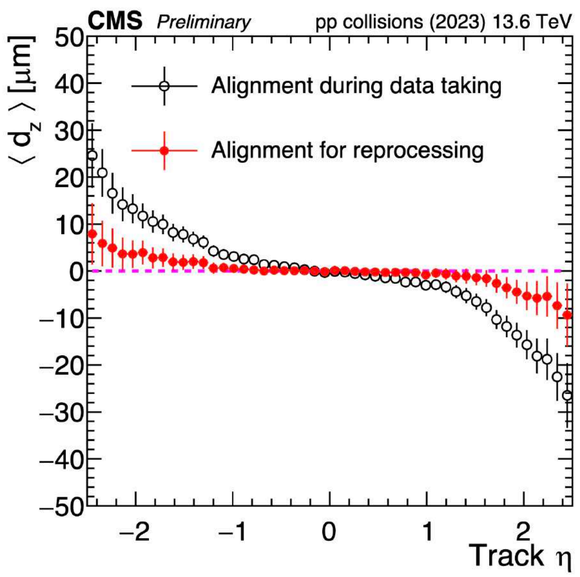


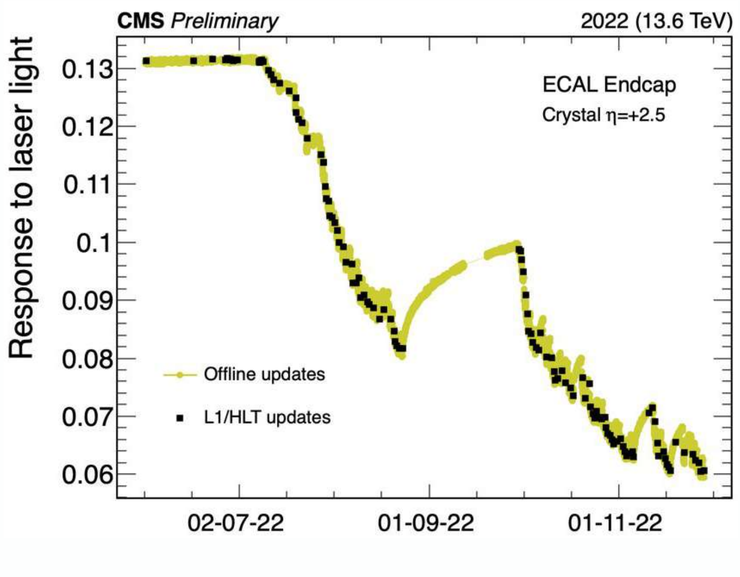
- In the second step, CMS software trigger, **High Level Trigger** (HLT), reconstructs the events selected by L1T
  - Capacity increased by 20% in 2024
  - GPU-accelerated reconstruction in O(100 ms) per event
  - Increasingly ML-based object identification
- **Record-high rates of events stored in 2024:**
  - **~2 kHz** for prompt reconstruction (twice the design value)
  - **~5 kHz** for opportunistic reconstruction ("**parking**")
  - **~27 kHz** for **HLT Scouting** i.e. analysis with HLT-reconstructed events and objects

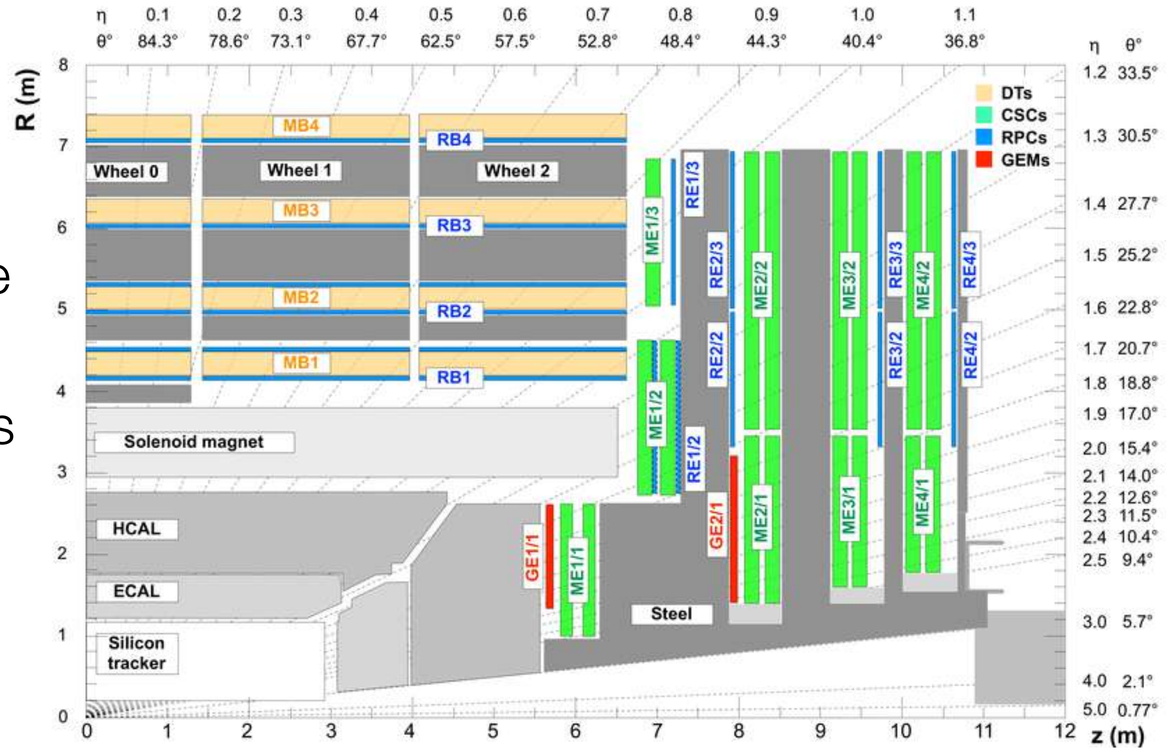


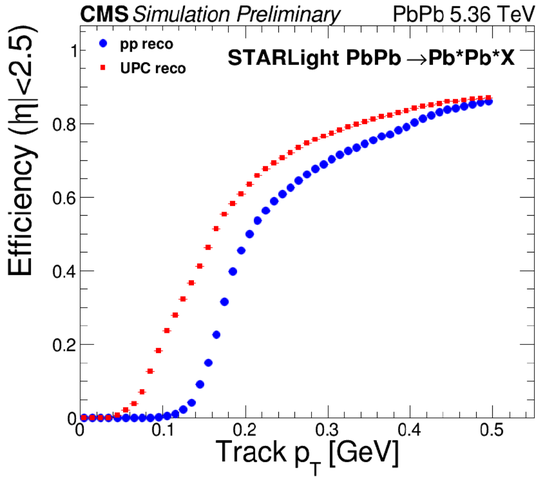
CMS Calibrations

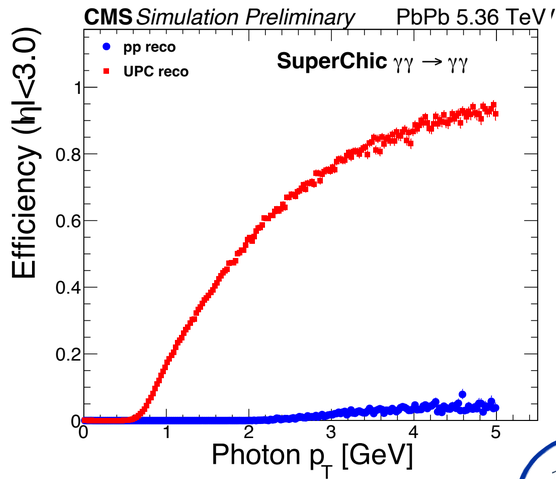
- Several **calibration improvements** introduced:
  - **Tracker**: improvement of alignment with a new technique using Z→μμ events
  - **HCAL**: frequent automatic calibrations to compensate for radiation-induced evolution (similar to ECAL)
  - GEM **muon** time resolution improved from 15 to 12 ns







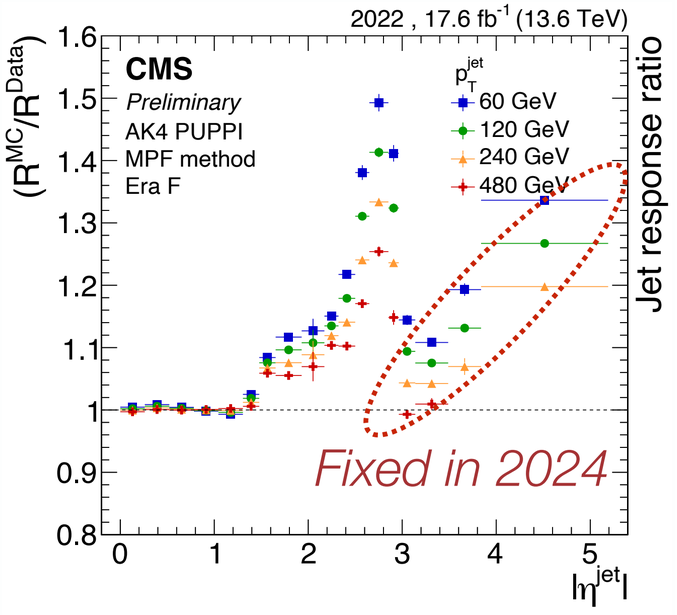


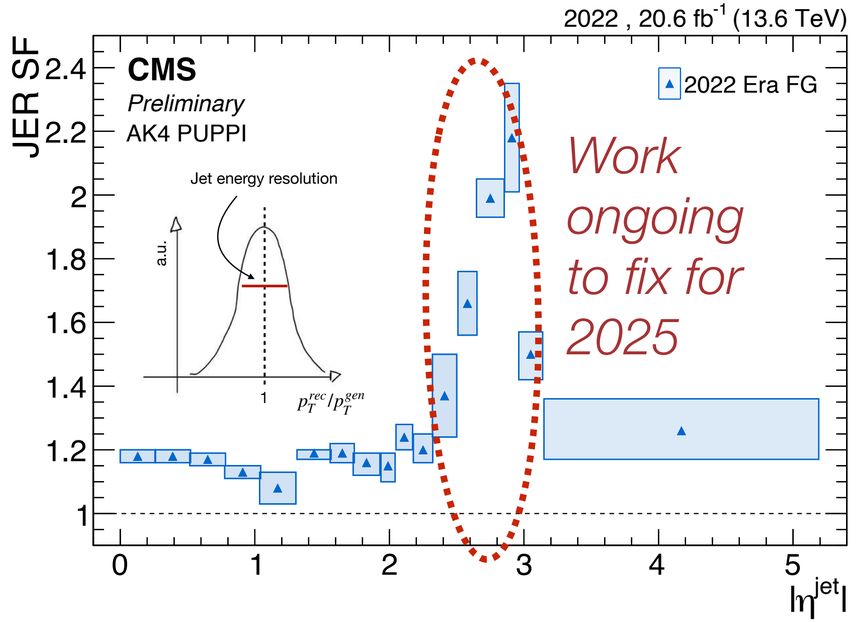


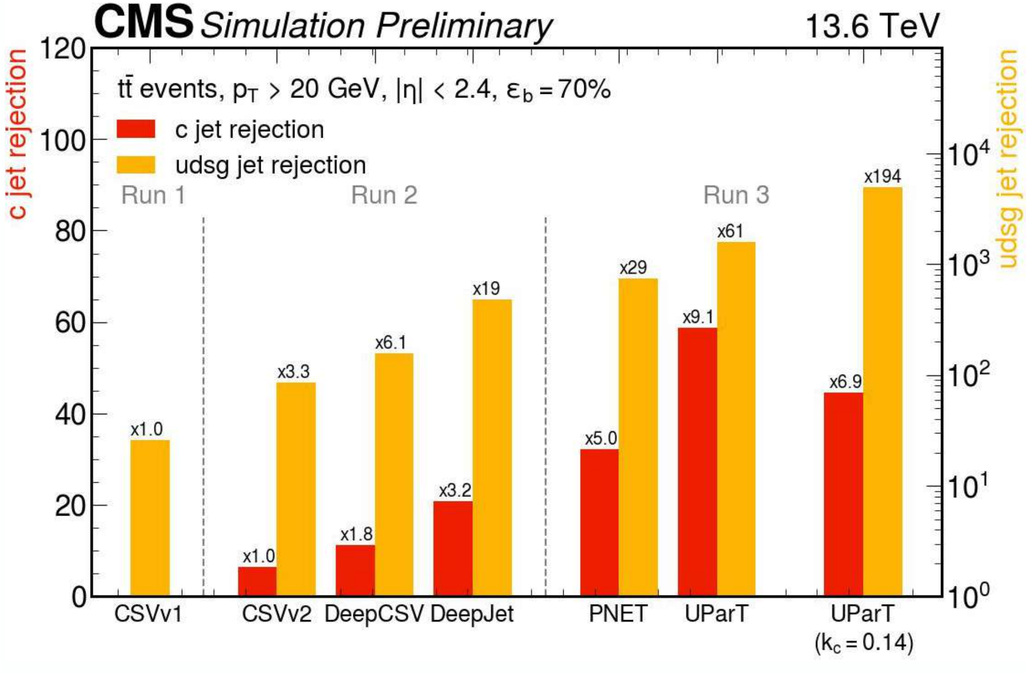
- Dedicated reconstruction settings for **Heavy Ion run**, improving efficiency for low-p_T hadrons and electrons

Highlight: CMS Jets

- The Finnish CMS team has a long expertise in **jet calibrations**, and has now taken ownership of the full jet calibration workflow of CMS
  - ERC project "J**EC4HL-LHC**" to bring jet energy uncertainties from 1% to **0.1% level**, in time for HL-LHC
  - Significant progress this year in **addressing the root causes** limiting precision, i.e. calorimeter calibrations
- At the same time, new ML techniques improve **jet flavor classification** performance significantly
  - Quick adoption of state-of-the-art architectures such as **graph neural networks** and **transformers**





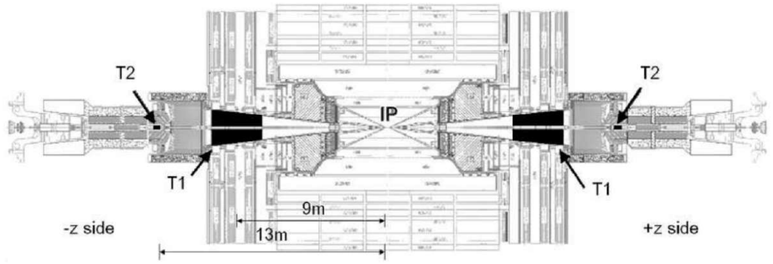


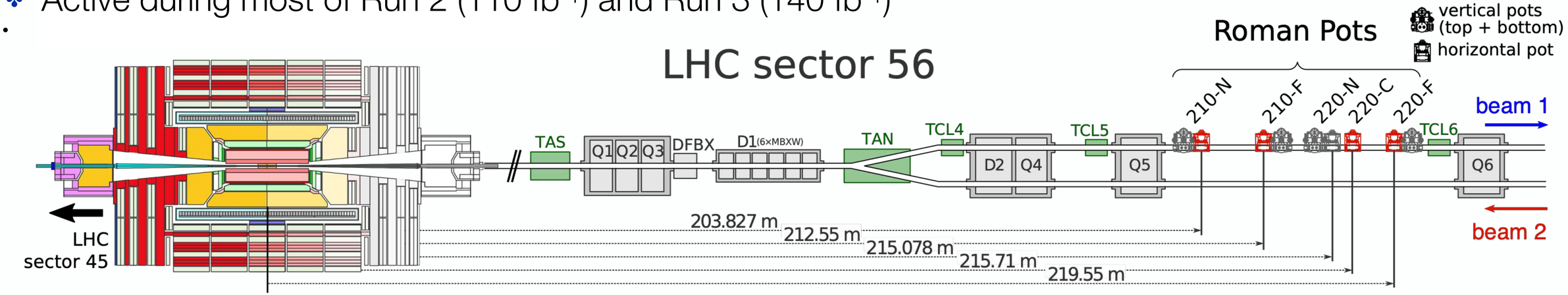
More on jets in Fikri's talk later today!

Forward Physics with TOTEM & CMS PPS

Forward Physics with TOTEM & PPS

- CMS **Precision Proton Spectrometer** (PPS) and **TOTEM** are forward physics detectors at the LHC
  - Tracking and timing detectors located along the LHC beam line, at 210-220 m from the CMS interaction point to **measure protons scattered at very small angles**
  - Detectors hosted in horizontal **Roman pots**, allowing sensor approach to the beam (in the LHC plane) down to few mm – TOTEM is complemented by **inelastic forward trackers** placed inside CMS
- **TOTEM experiment** focuses on elastic and diffractive scattering to measure the total proton cross section and proton structure
  - CMS+TOTEM special runs in 2023 concluded the TOTEM data-taking
- **PPS** is a **CMS subdetector**, i.e. integrated in CMS data acquisition and reconstruction to study central exclusive production and rare processes
  - Active during most of Run 2 (110 fb^{-1}) and Run 3 (140 fb^{-1})



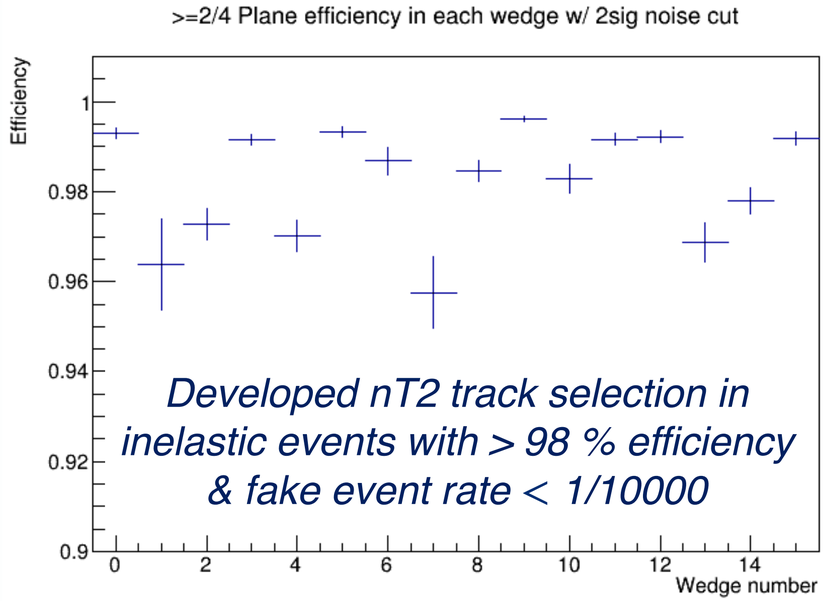


Forward Physics: Contributions from HIP

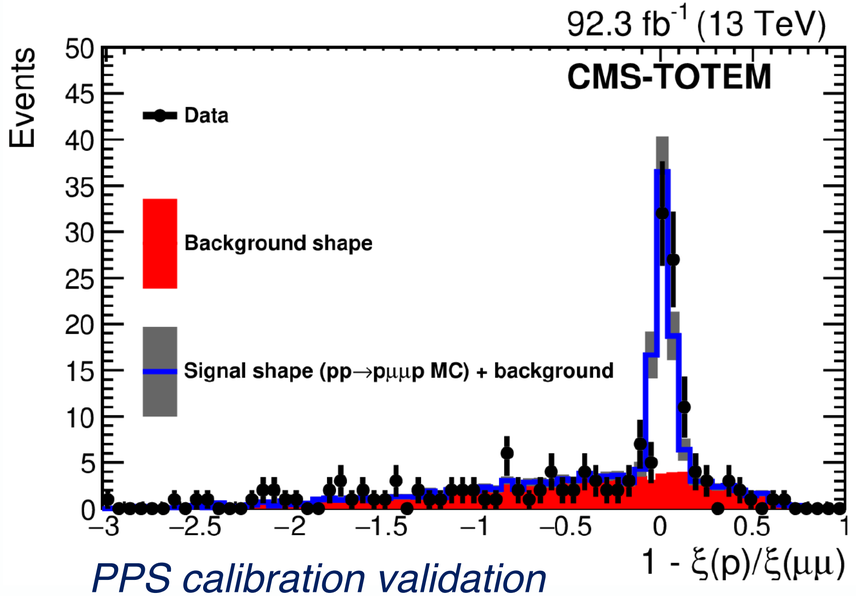
- **TOTEM physics coordination**

- **Soft diffraction** with TOTEM:
  - Elastic analysis & inelastic rate for luminosity-independent σ_{tot}, σ_{inel} σ_{el} at 13.6 TeV
  - Comparison of elastic & differential cross sections at 1.96 TeV (”odderon”)

- **Exclusive processes** with CMS(-TOTEM):
  - Validation of PPS calibrations with exclusive dimuon events
  - Search for exclusive produced doubly-charged Higgses (H++) with PPS
  - Tensor & pseudoscalar glueball studies (f2’s & η’s) with CMS-TOTEM special run data



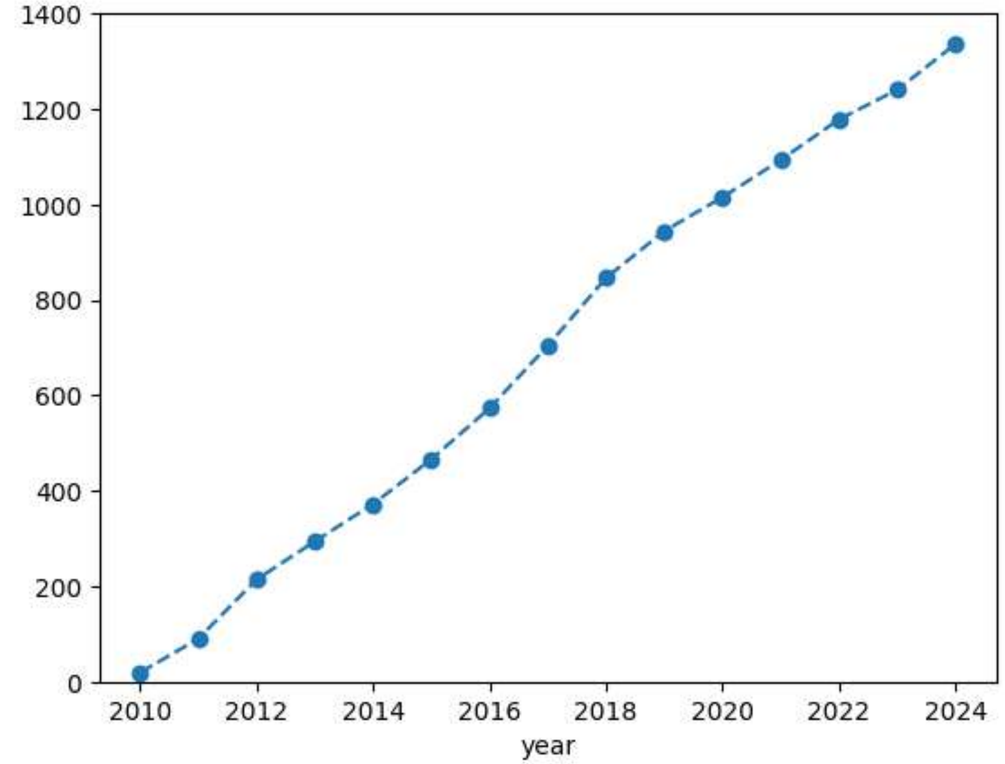
Developed nT2 track selection in inelastic events with > 98 % efficiency & fake event rate < 1/10000

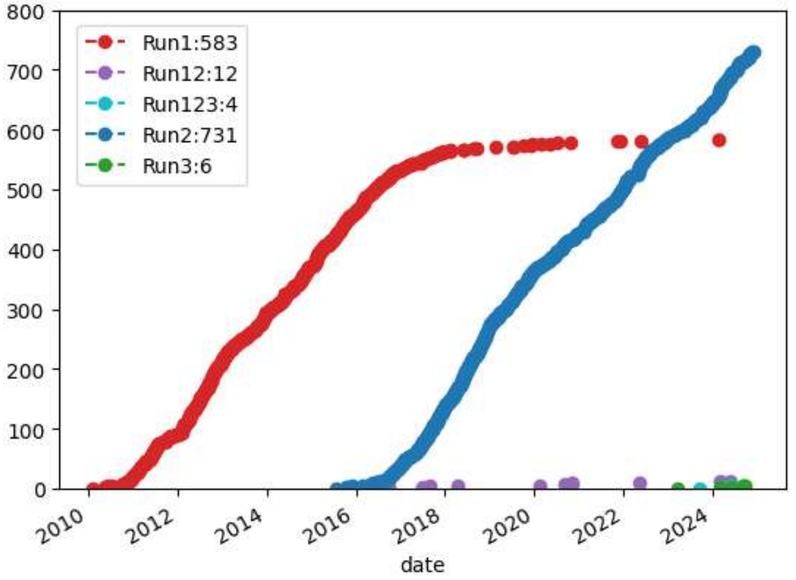


PPS calibration validation
JINST 18 (2023) P09009

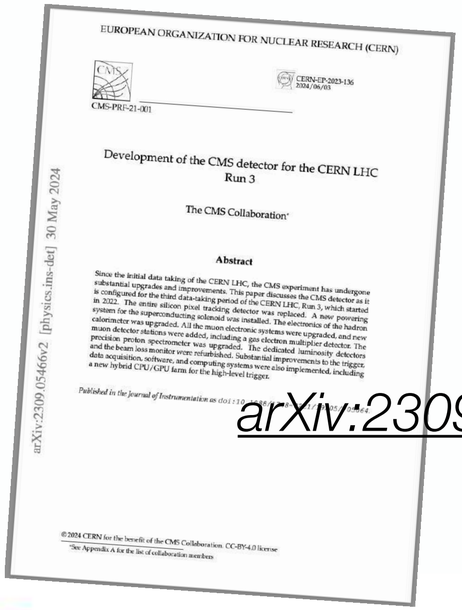
CMS in 2024: Highlights of Physics Results

CMS Publications





- *New CMS detector paper published in JINST*


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2023-136
2024/06/03

CMS-PRF-21-001

Development of the CMS detector for the CERN LHC Run 3

The CMS Collaboration*

Abstract

Since the initial data taking of the CERN LHC, the CMS experiment has undergone substantial upgrades and improvements. This paper discusses the CMS detector as it is configured for the third data-taking period of the CERN LHC, Run 3, which started in 2022. The entire silicon pixel tracking detector was replaced. A new powering system for the superconducting solenoid was installed. The electronics of the hadron calorimeter was upgraded. All the muon electronic systems were upgraded, and new muon detector stations were added, including a gas electron multiplier detector. The precision proton spectrometer was upgraded. The dedicated luminosity detectors and the beam loss monitor were refurbished. Substantial improvements to the trigger, data acquisition, software, and computing systems were also implemented, including a new hybrid CPU/GPU farm for the high-level trigger.

Published in the Journal of Instrumentation as doi:10.1088/1748-0221/19/05/P05064

arXiv:2309.05466v2 [physics.ins-det] 30 May 2024

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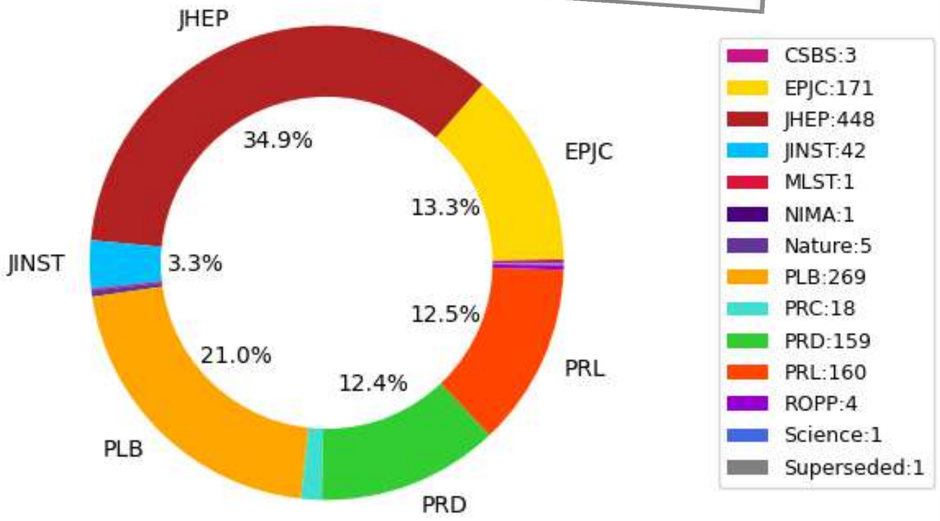
*See Appendix A for the list of collaboration members

arXiv:2309.05466

- Balance expected to switch to **Run-3** publications soon

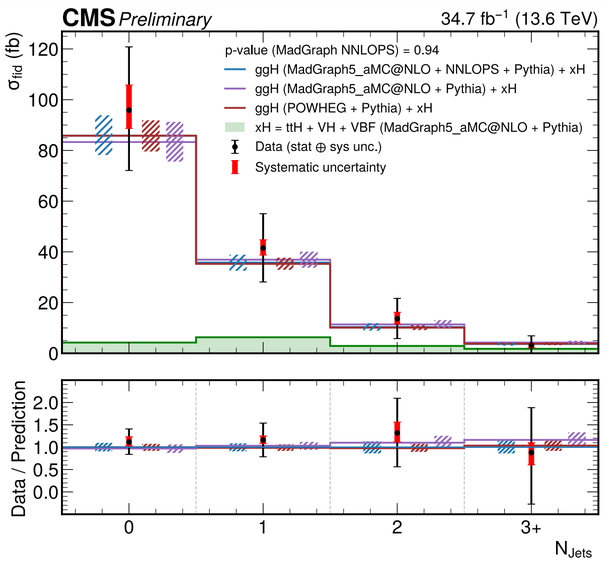
- Steady output flow of publications
  - **96** published in 2024 and counting
  - **1337** publications in total (as of today)

- *In the following, just a few highlights from this year's results*

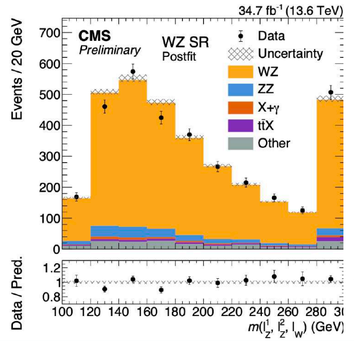


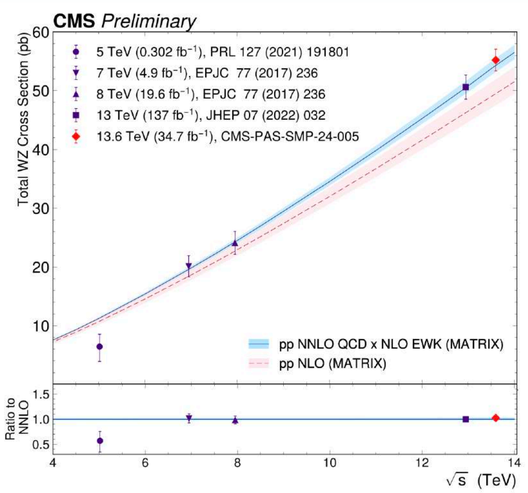
Run-3 Result Highlights

- **H→γγ** cross section at 13.6 TeV [HIG-23-014]
  - Inclusive and differential cross sections measured
  - New ML method, normalizing flow, used to correct data/MC difference photon energy resolution

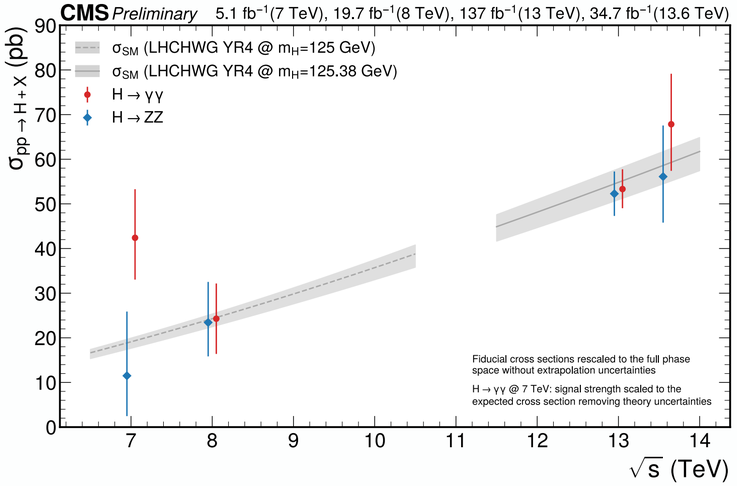


- **WZ production** in multilepton final states [SMP-24-005]
  - New ML-based lepton ID
  - Relative uncertainty comparable to Run-2 legacy result

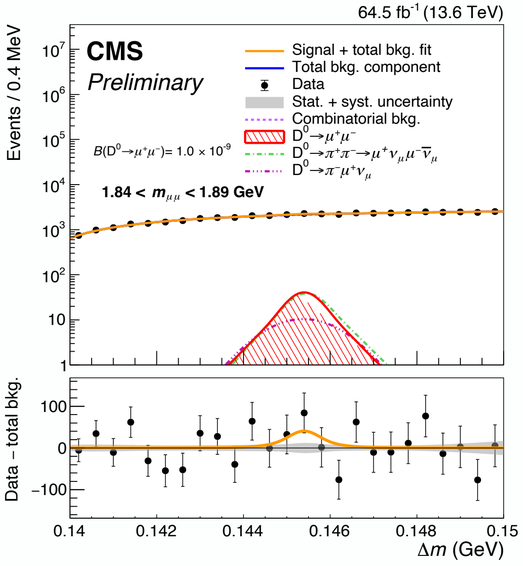




- **H→ZZ→4l** cross section at 13.6 TeV [HIG-24-013]
  - Exploiting the clean four-lepton signature
  - Both results consistent with the theory prediction

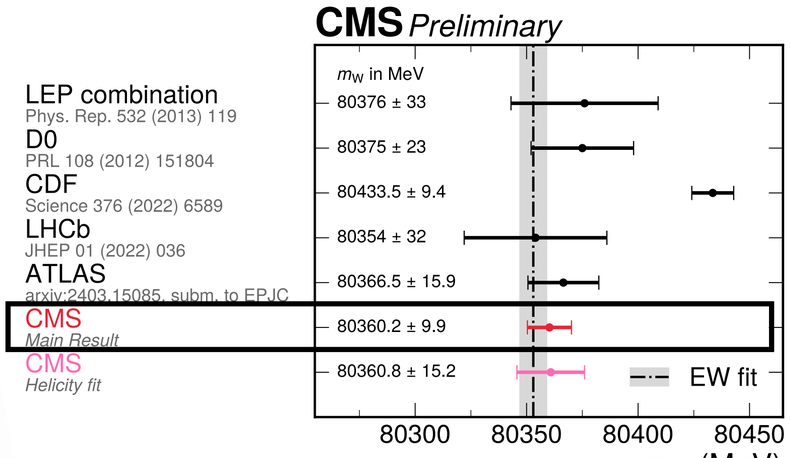


- Search for **rare charm decays** using **parking** [BPH-23-008]
  - First CMS result on BR($D^0 \to \mu^+\mu^-$), using $D^{*+} \to D^0\pi^+$
  - Achieving **world-best limit** BR < 2.6 x 10^{-9} at 95% CL



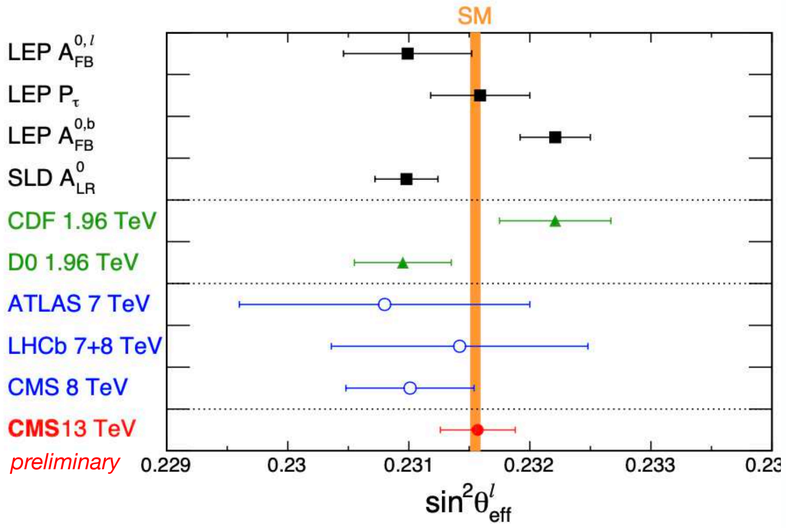
Pushing the Precision with Run-2 Data

- The long-awaited CMS measurement of **W boson mass** was made public this September **(SMP-23-002)**
  - Very precise muon momentum calibration required
  - Long and challenging analysis effort: **100 million** reconstructed W decays, **4.5 billion** simulated events, **3000** fit parameters for systematic uncertainties



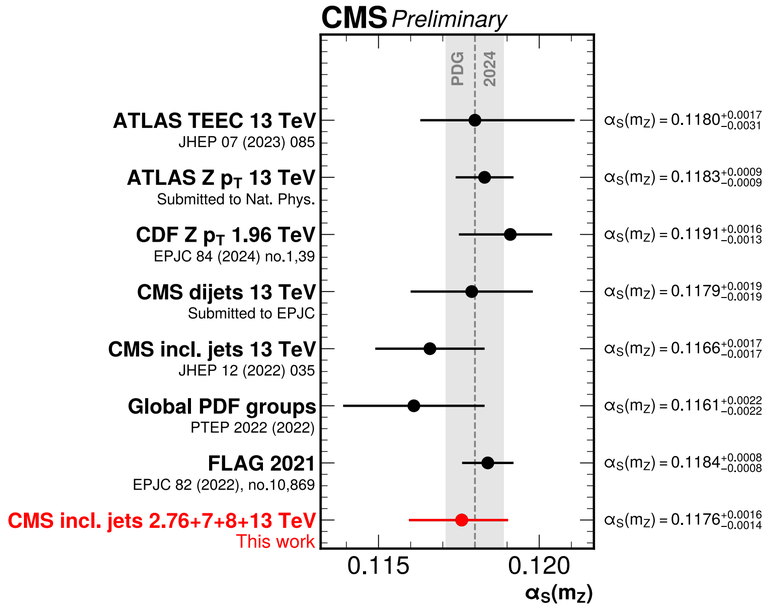
m_W = 80360.2 ± 9.9 MeV

- The **effective weak mixing angle** measured using Z/γ→μμ/ee (SMP-22-010)
  - Extracted from kinematic properties of muons and electrons, so accurate calibration is critical
  - The **most precise** measurement at a hadron collider, comparable to those at LEP and SLD



$\sin^2\theta^l_{eff}$ = 0.23157 ± 0.00031

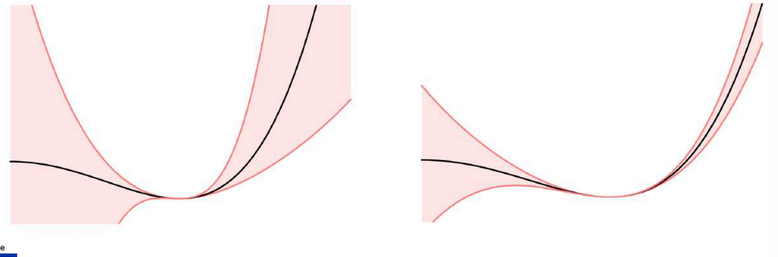
- **Strong coupling** α_s and its running extracted from inclusive jet measurements (SMP-24-007)
  - PDFs extracted simultaneously
  - The **most precise** measurement of α_s from jet cross sections



$\alpha_s(m_Z)$= 0.1176 $^{+0.0016}_{-0.0014}$

Chasing the Higgs Self-Interaction

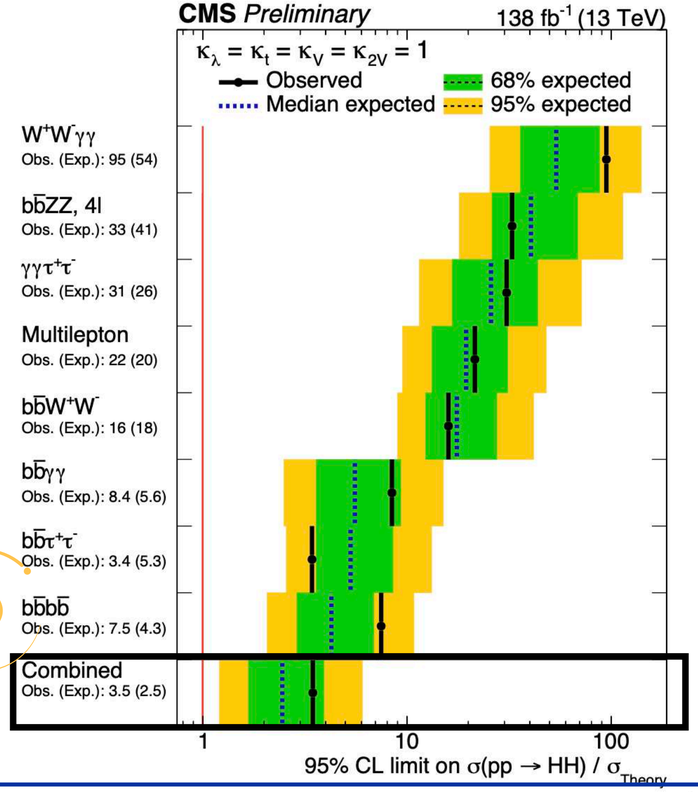
- One of the key physics goals of the LHC physics program is measuring the **Higgs trilinear self-coupling**, which directly affects the **stability** of the electroweak vacuum

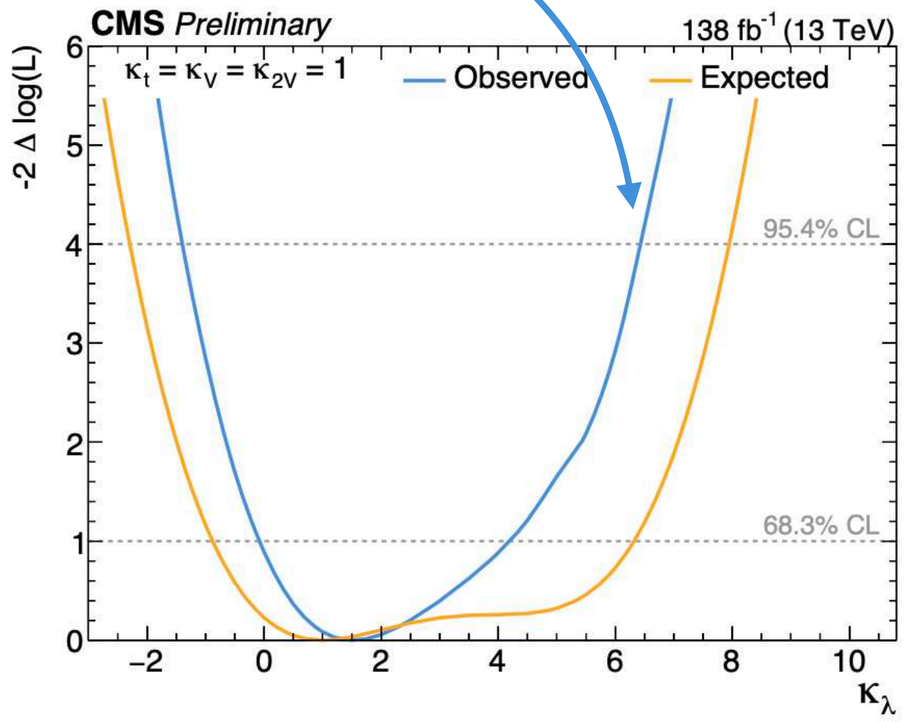


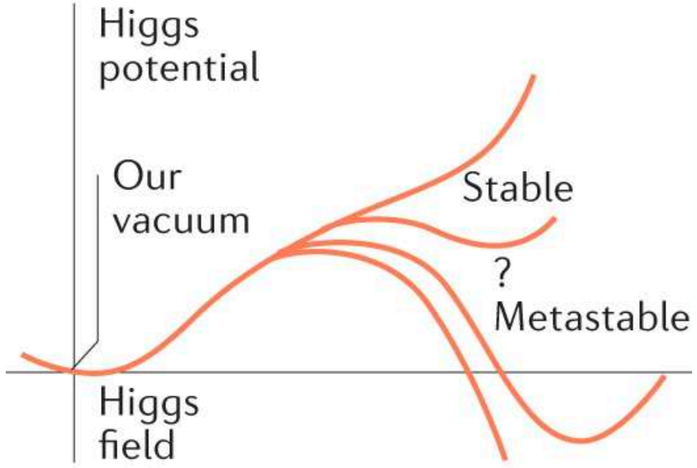
Current LHC → HL-LHC

Combined di-Higgs measurement using Run 2 inputs in 8 HH decay channels

- Observed (expected) 95% CL upper limit on HH production: **3.5 x SM σ (2.5x SM σ)**
- Constraint on Higgs self-coupling: $-1.4 < \kappa_\lambda < 6.4$ (95% CL)



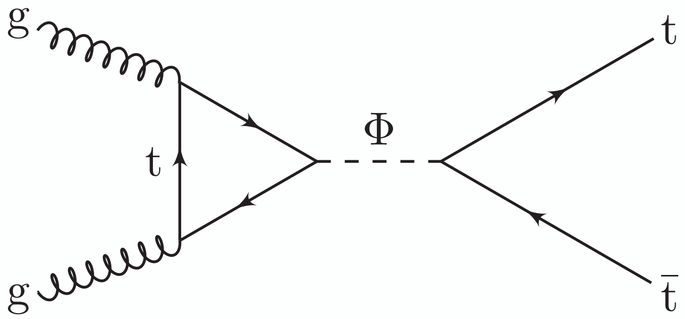


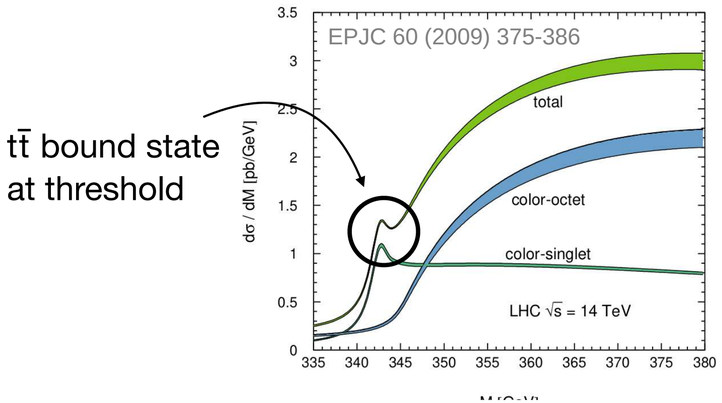


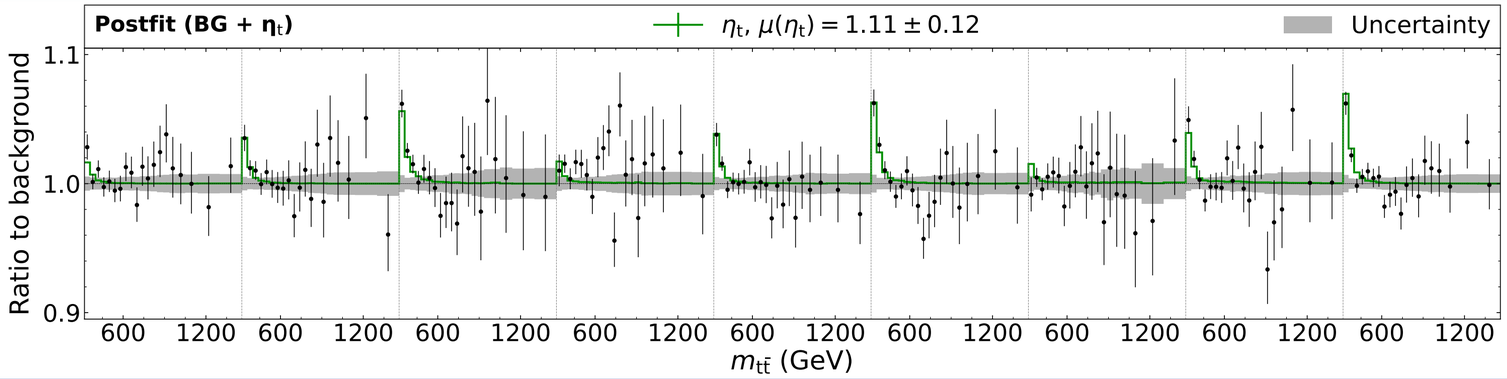
- Results from the latest CMS combination comparable to those from ATLAS – the race continues

Exploiting LHC as Top Factory

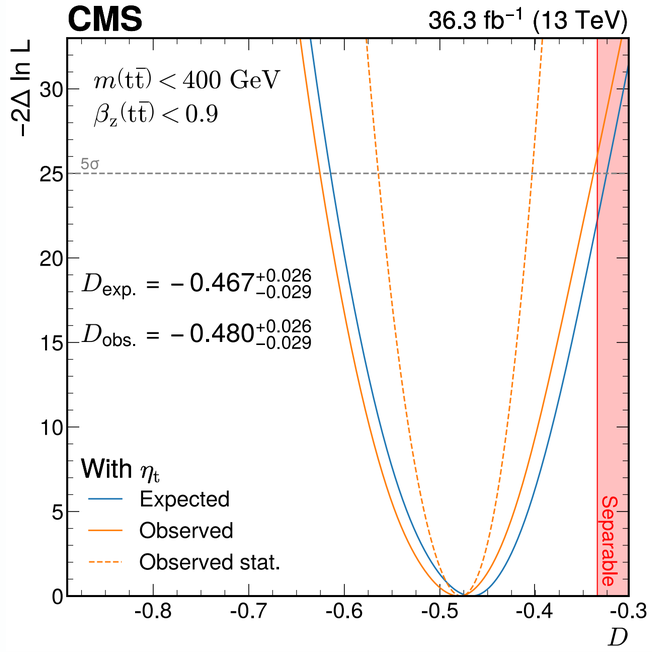
- Search for (pseudo)scalar top-antitop resonances [HIG-22-013]
  - **>5σ excess** close to ttbar production threshold observed
    - Compatible with a top-antitop bound state, **toponium**, as predicted by a simplified model of nonrelativistic QCD







- Top pairs used also to measure quantum **entanglement** [TOP-23-001]
  - Based on the spin correlation of top quark decay products
- Entanglement confirmed at **5.7σ**
  - *Fundamentals of quantum physics can be probed at colliders!*

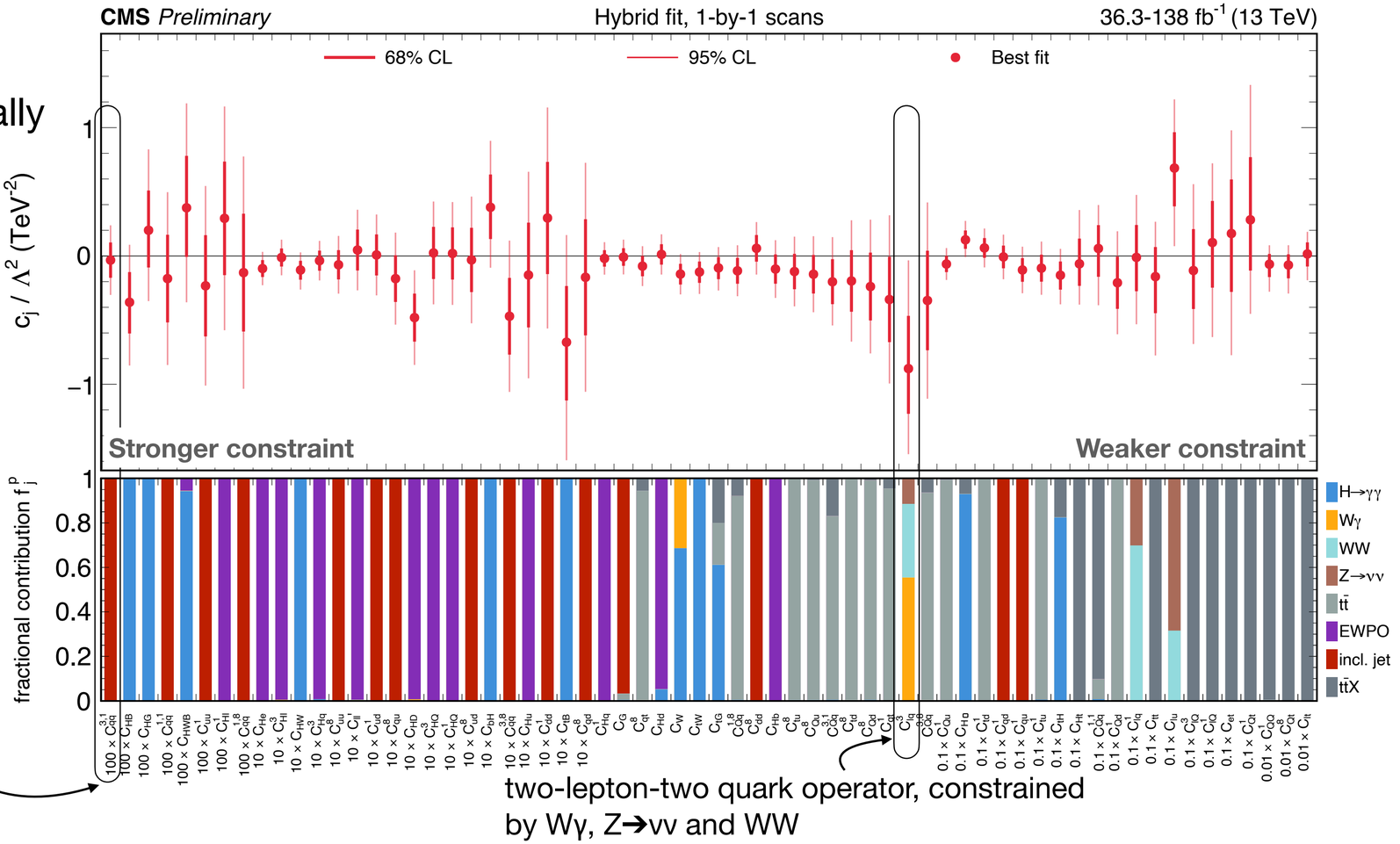


Stress-testing the SM with Effective Field Theory

- Effective Field Theory (EFT) approach allows to correlate various different measurements without assuming a specific model
  → Obtain constraints for Wilson Coefficients (WCs) i.e. weights for various BSM operators
- Statistical combination of Higgs (**H→γγ**), top (**tt**, **ttX**), electroweak (**WW**, **Wγ**, **Z→νν**), and QCD (**inclusive jets**) measurements performed, using these together with **electroweak precision observables** from LEP and SLC (SMP-24-003)

Constraints on **64 WCs** individually (**42 linear combinations of WCs** constrained simultaneously)

Combined interpretation - gain from complementarity of different measurements

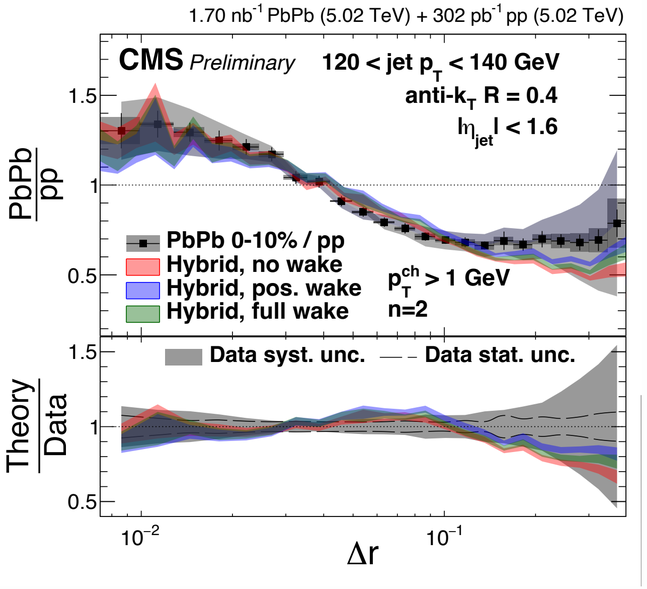


Four-quark operator, constraint multiplied by 100. Constrained by jet measurements

two-lepton-two quark operator, constrained by Wγ, Z➔νν and WW

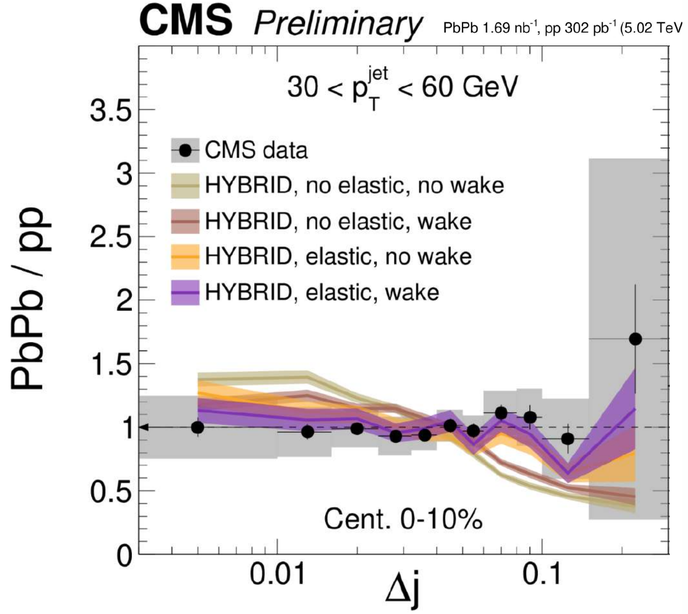
Heavy Ion Highlights

- Probing **quark gluon plasma** (QGP) with **jets** (HIN-23-004)
  - Complementary observable to unserstand **energy loss** mechanisms in QGP
  - Energy-energy correlators measured in PbPb collisions for the first time



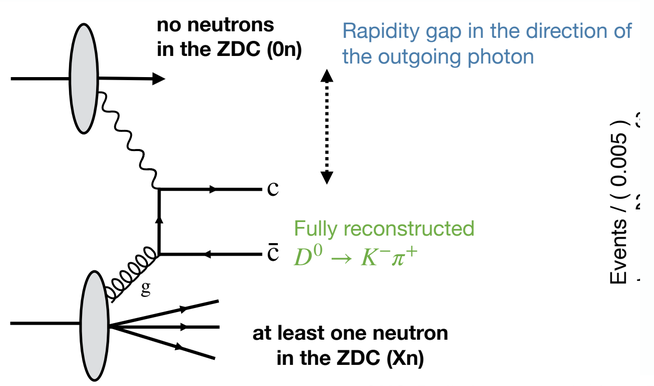
Energy-energy correlator PbPb/pp ratio compared to predictions with different loss mechanisms

- Using **γ+jet** events to probe **large-angle scattering effects** in QGP (HIN-21-019)
  - Photon "transparent" to QGP, while jet interacts with it
  - Measure decorrelation of jet axis from photon momentum

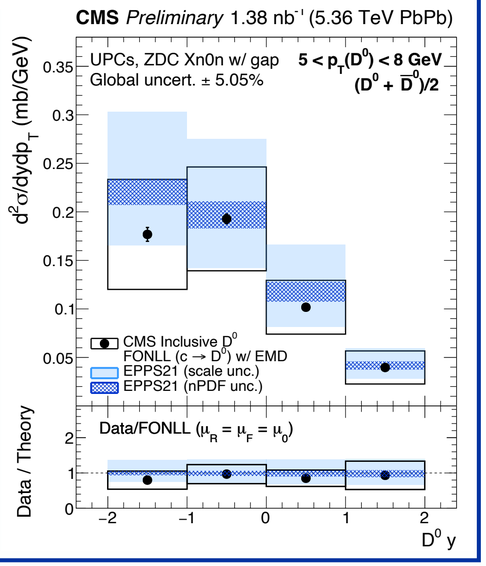


Jet axis decorrelation PbPb/pp ratio compared to different theory predictions

- Measuring **D⁰ photoproduction** in ultraperipheral collision (UPC) events (HIN-24-003)
  - Use 0nXn events with a rapidity gap

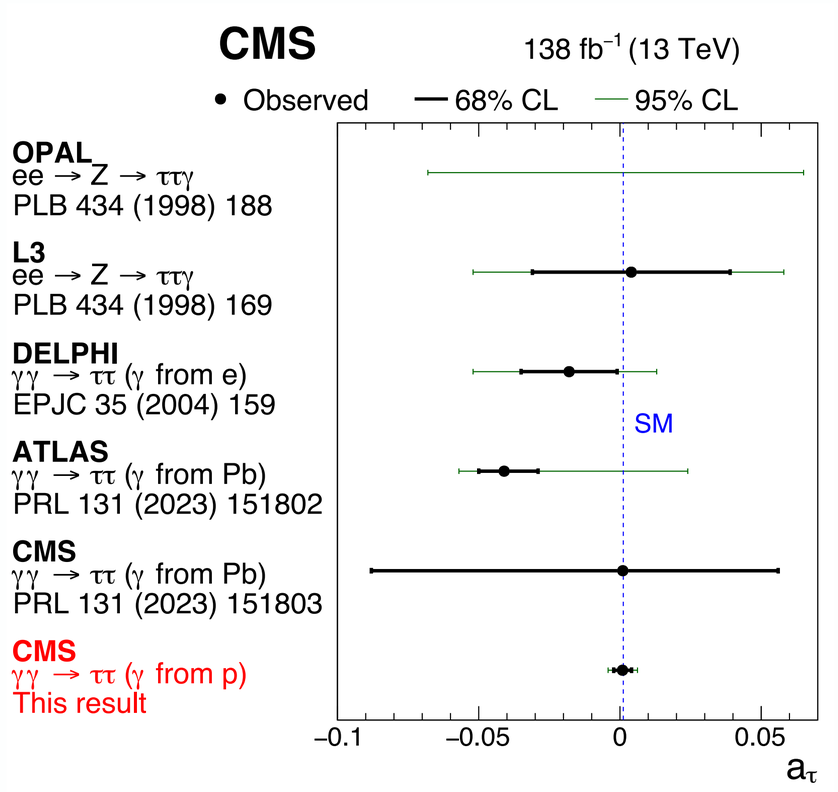


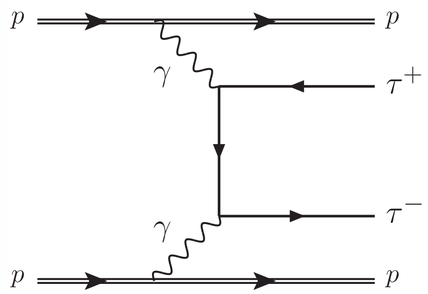
First *measurement of this process!*



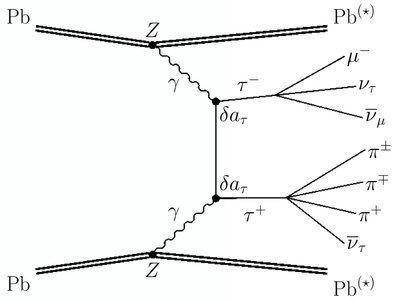
CMS as Photon Collider Experiment: Case τ g-2

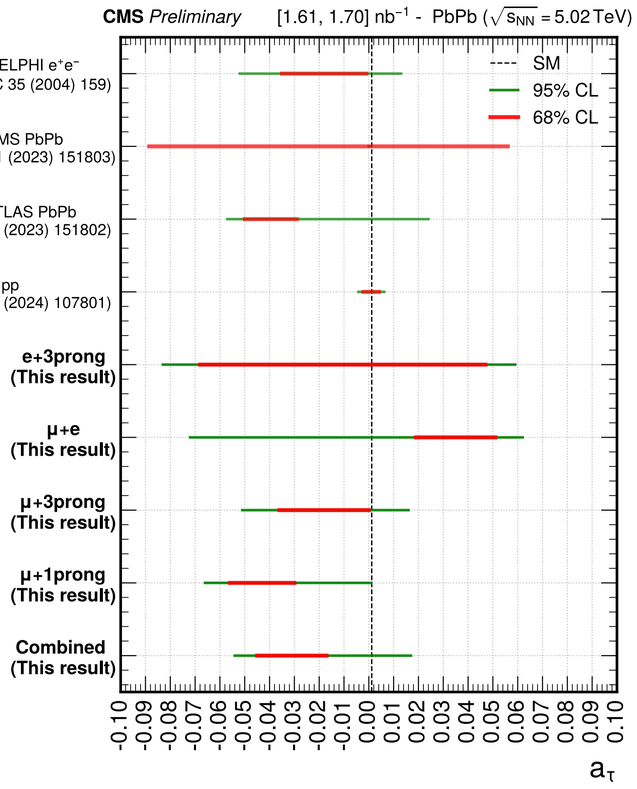
- Setting **world-best limits on τ g-2** [SMP-23-005]
  - Challenging in pp collisions due to high pileup
    → Isolate a sample of photon-photon fusion events by requiring no tracks close to the tt vertex
  - **First observation** of γγ→ττ process in pp collisions





- Measurement performed also with Heavy Ion data using **UPC events** [HIN-24-011]
  - Combine cross section information and kinematic distributions from several τ decay channels

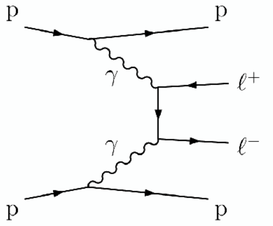


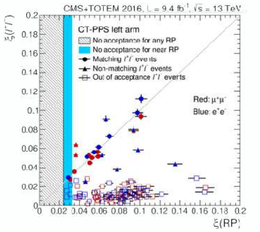


Forward Physics: Highlights of Run-2 Results

- Observation of proton-tagged, central (semi)exclusive production of high-mass lepton pairs

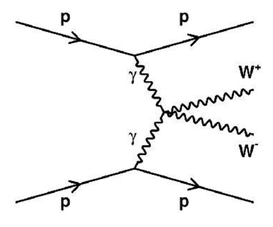
JHEP 07 (2018) 153

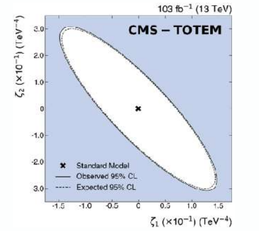




- Search for high-mass exclusive $\gamma\gamma \rightarrow WW$ and $\gamma\gamma \rightarrow ZZ$ production

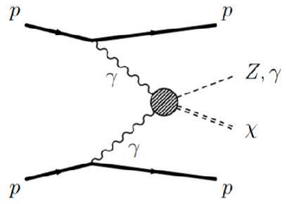
JHEP 07 (2023) 229

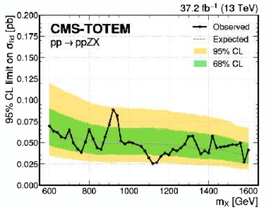




- Search for new physics in central exclusive production using the missing mass technique in $pp \rightarrow p\,(Z,\gamma)\,X\,p$

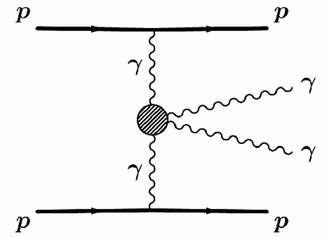
Eur. Phys. J. C 83 (2023) 827

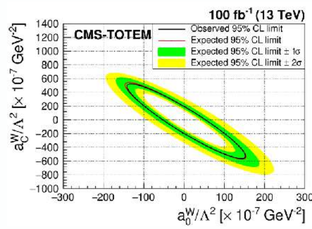




- Search for high-mass exclusive diphoton production with tagged protons

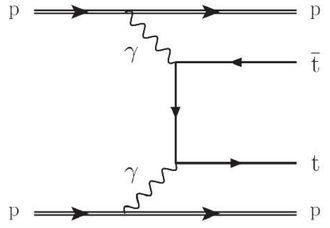
Phys. Rev. Lett. 129 (2022) 011801



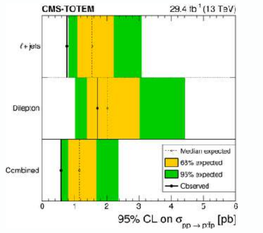


- Search for central exclusive production of top quark pairs with tagged protons

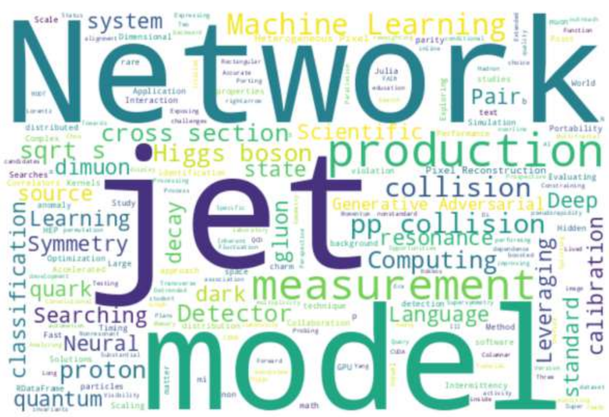
Phys. Rev. D 110 (2024) 012010



JHEP 06 (2024) 187

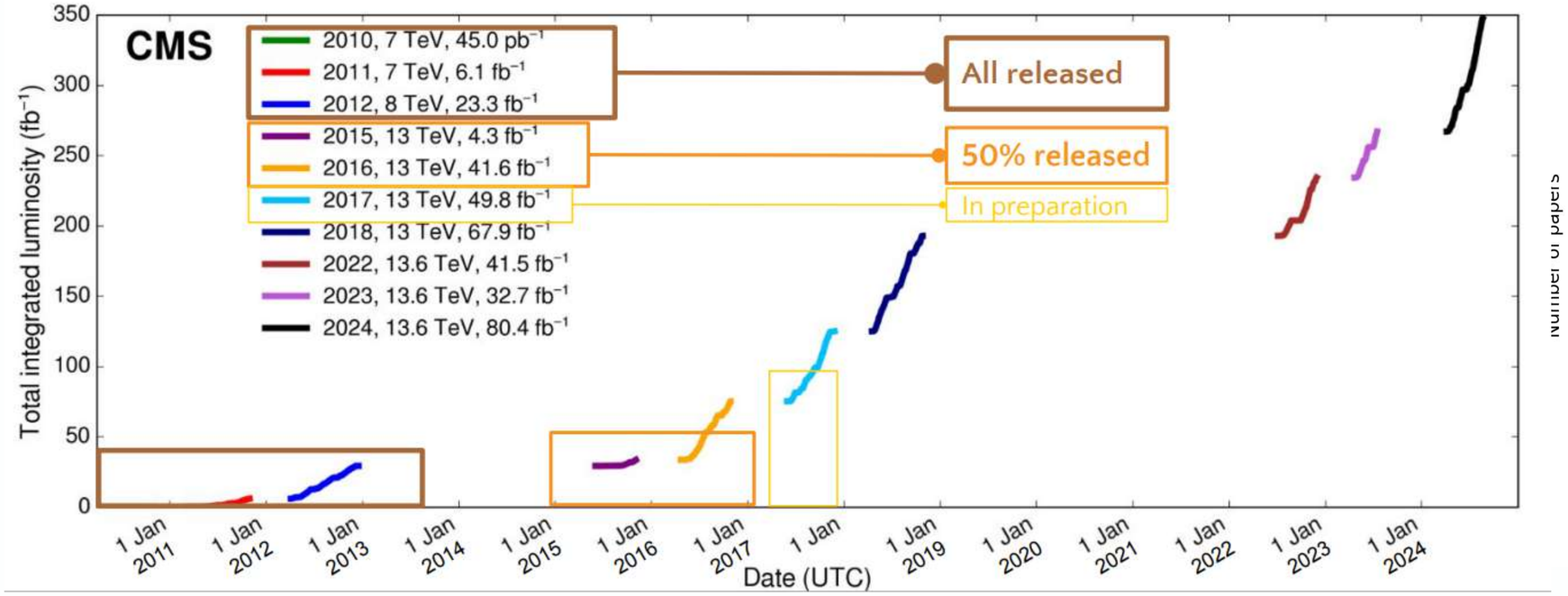


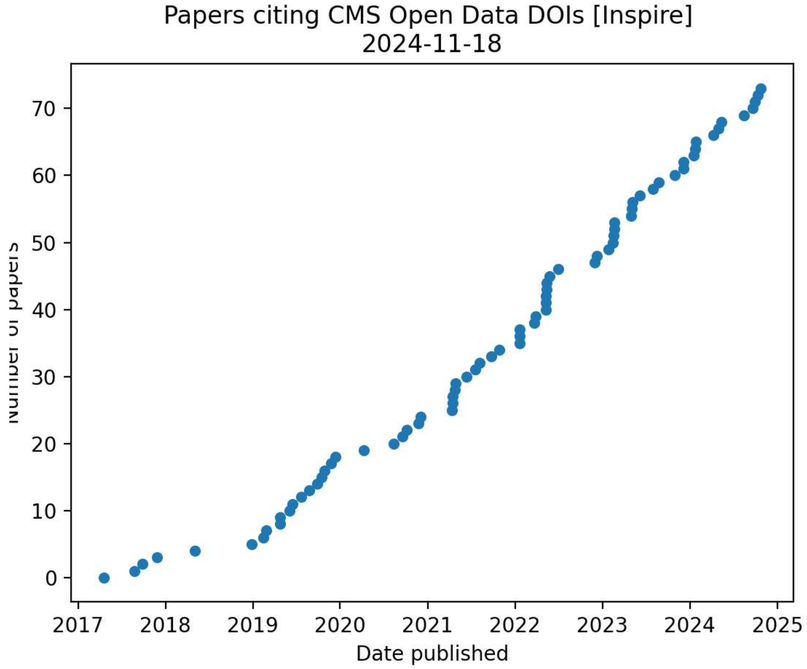
CMS Celebrates a Decade of Open Data



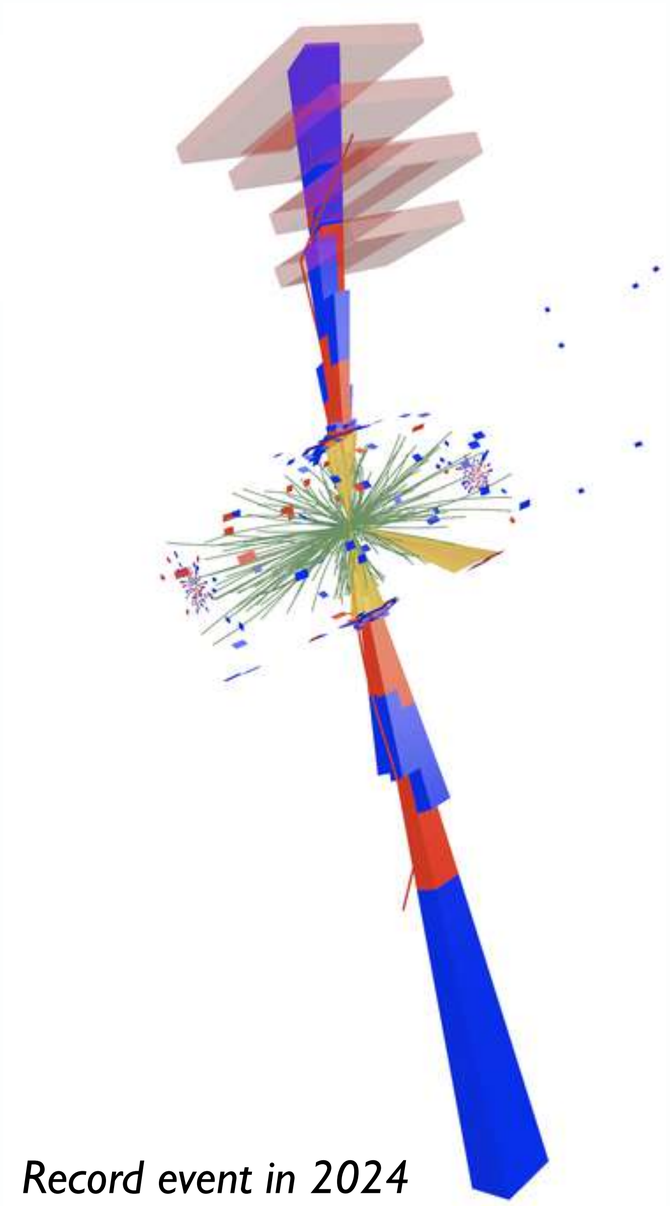
Word cloud from papers using CMS open data

- First data from 2010 released for public use on 20 November 2014
  - Now **all Run-1** pp and heavy ion data, and **partial Run-2** pp data released
  - More to come in the future – *CMS stands out as a leader in this domain*
- Publicly available data, metadata and analysis examples **preserves CMS analysis knowledge** for future
  - **External usage** for physics, machine learning, data science, education, etc.





Summary & Outlook



Record event in 2024

- In terms of physics reach, CMS is actually **many experiments in one**, and a **technology driver** in the field
- 2024 was a **good year for the LHC**
  - The **first Run-3 results** at 13.6 CM energy are out already, but most of them follow in a few years
  - In terms of data-taking, **the LHC journey has only begun** – 90% of the data (and work) still awaits!
- Finnish CMS & TOTEM teams are playing key roles in several areas, pushing **strategic developments** that will enable full exploitation of the tenfold data set from HL-LHC
  - **Acceleration** with FPGAs and GPUs, **automation** of calibration and analysis workflows
  - Entering **precision era in jet physics**, with precise control of the full calibration chain – *see Fikri's talk*
  - Starting to explore **quantum computing** applications for CMS data analysis – *see Väinö's talk*

Thank you!