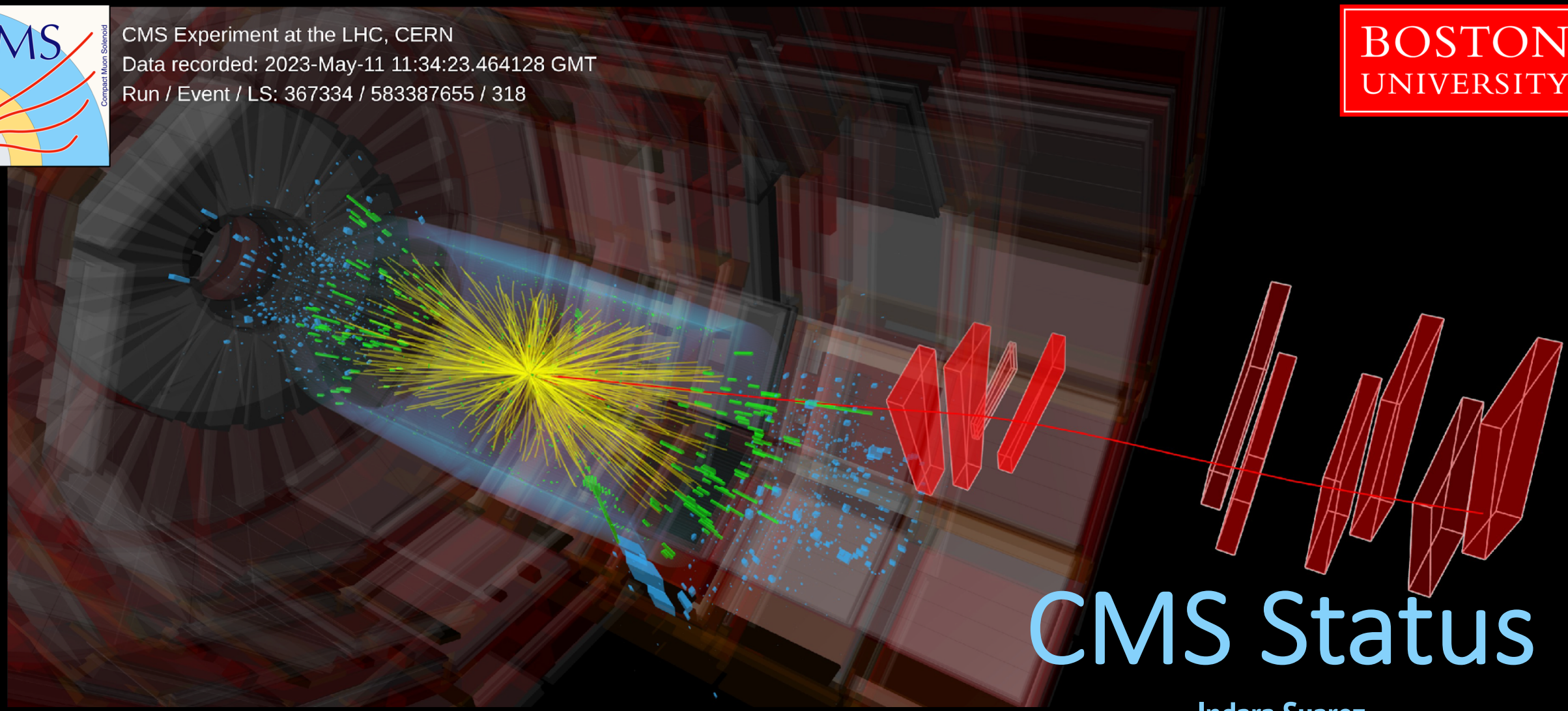


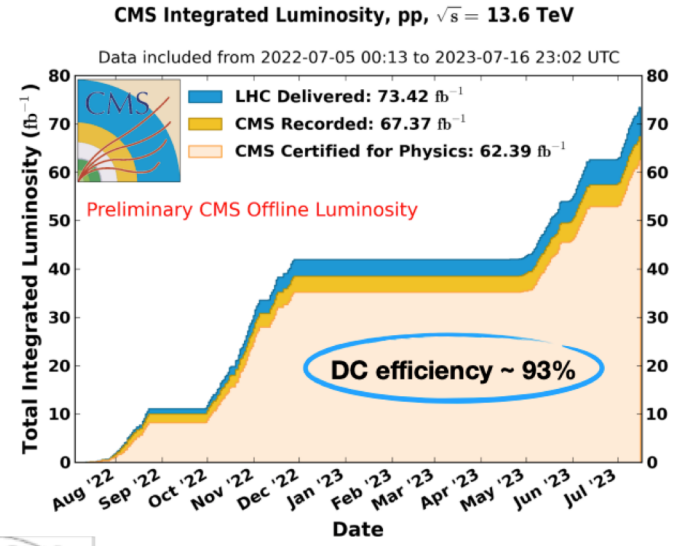
CMS Status

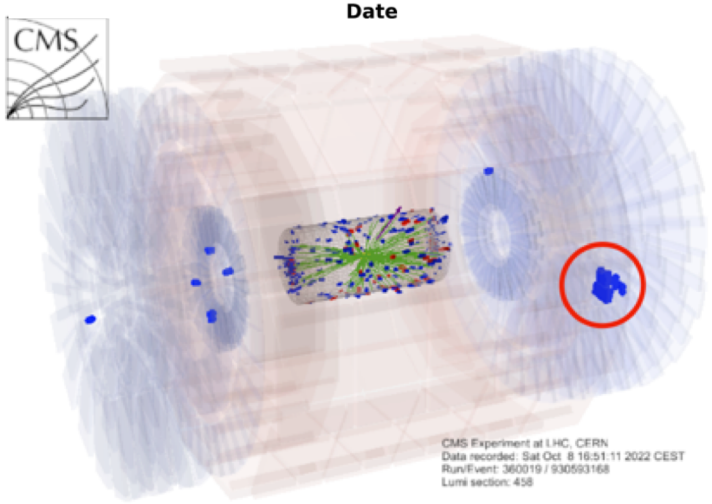
Indara Suarez
On behalf of the CMS Experiment

December 13, 2023, US LUA Meeting

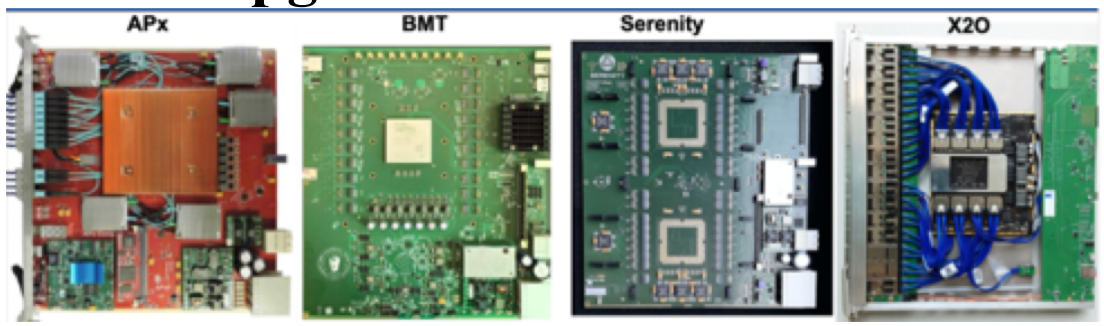
Overview

- **Run 3 data taking and performance**
  - Detectors running smoothly
  - Higher PU
  - Higher trigger rate
  - New trigger capabilities

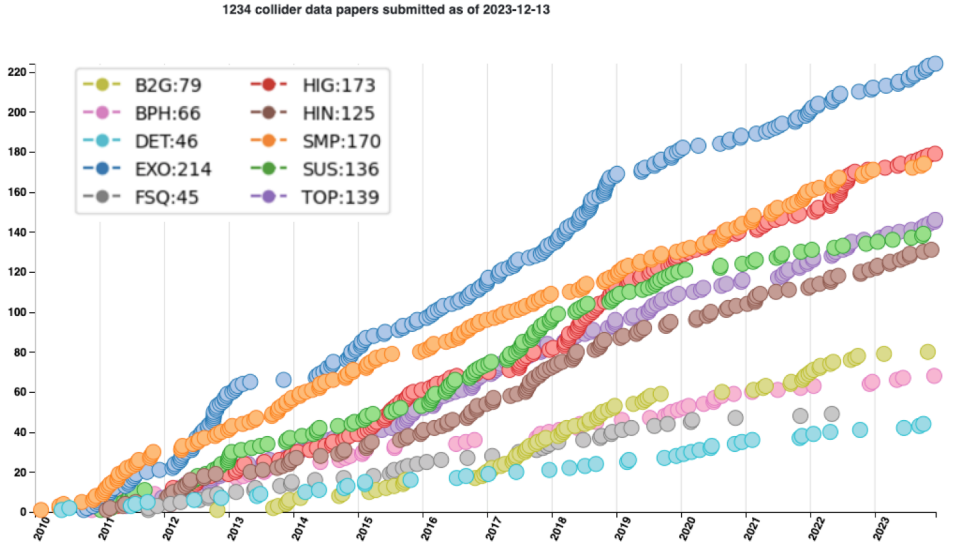




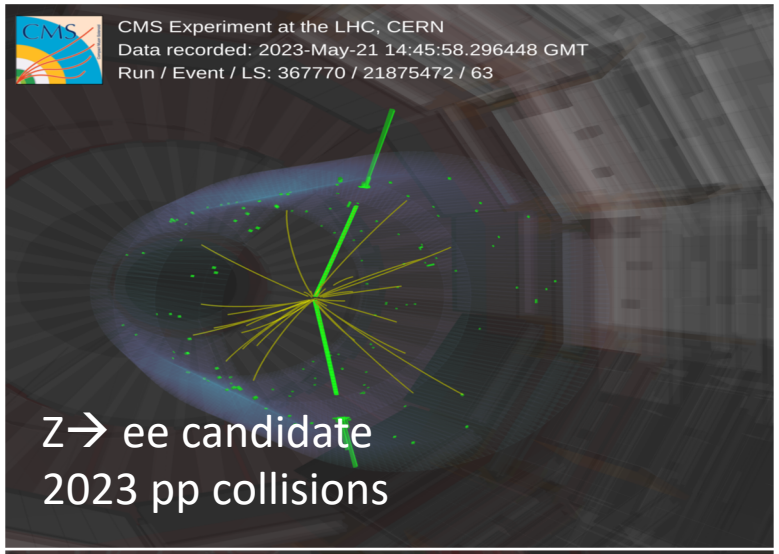
- **Phase 2 upgrade status**

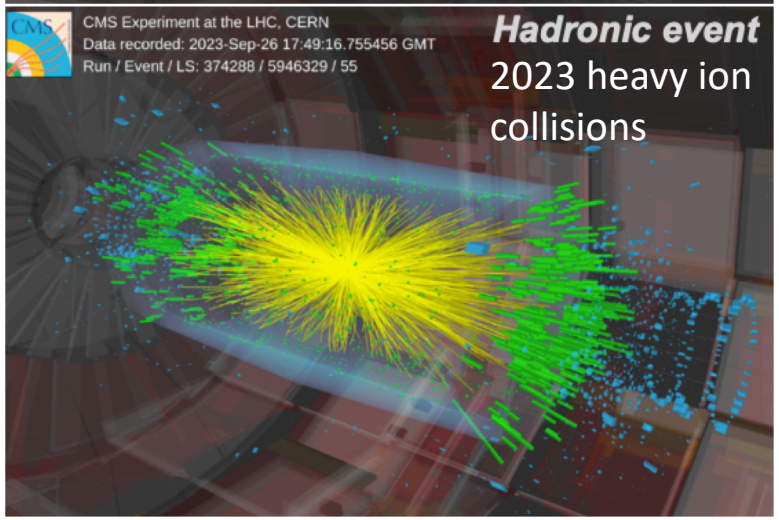


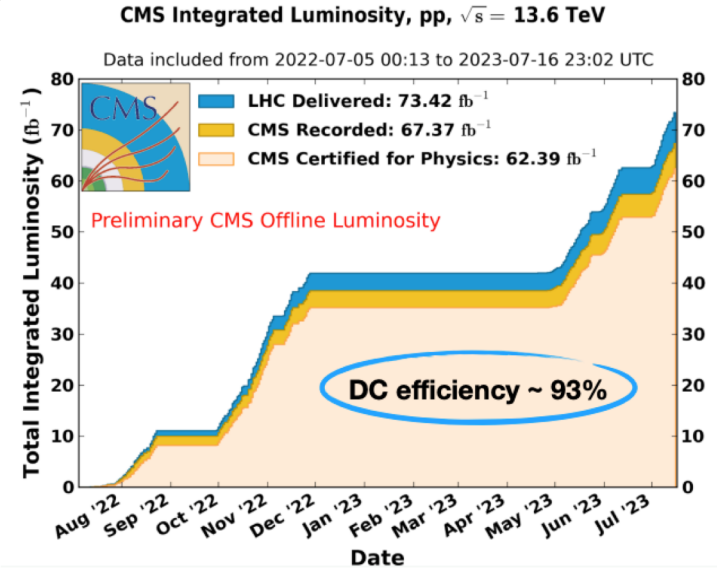
- **Physics analysis highlights**

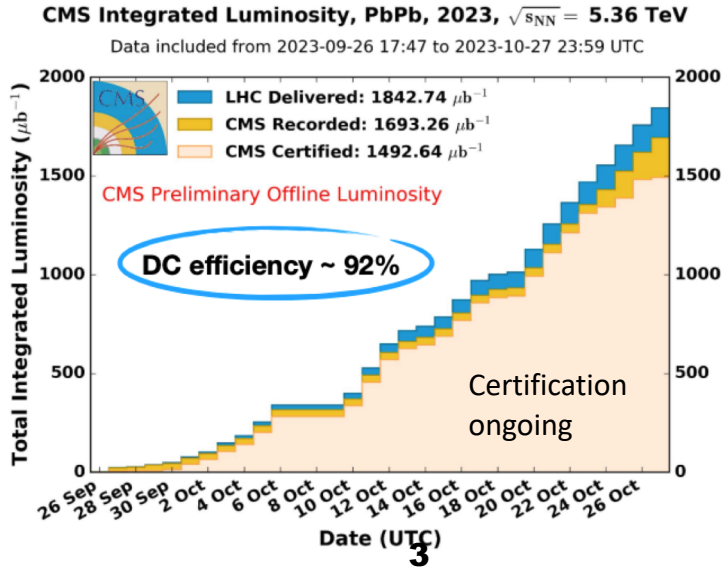


Detectors Running Smoothly During Run 3





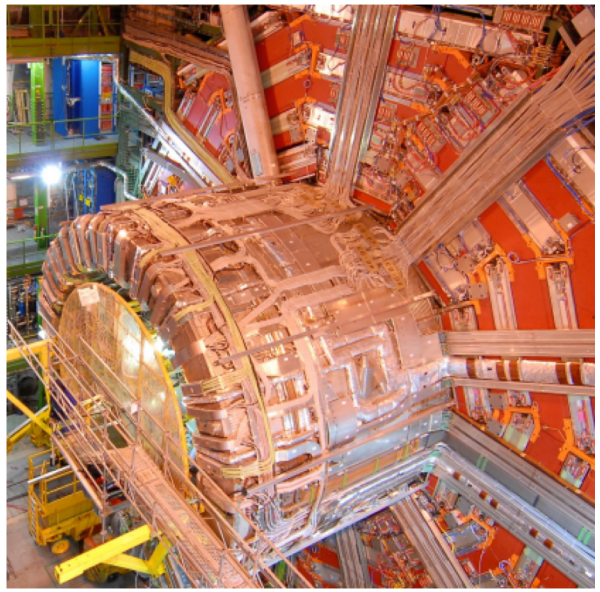




Smooth running of all detectors in both pp and Heavy Ion data-taking

- No major issues in subdetectors
- Dealing successfully with increasing PU: maximizing luminosity without affecting the physics goals
- Acquiring data at high efficiency

CMS Run 3 Detector Paper

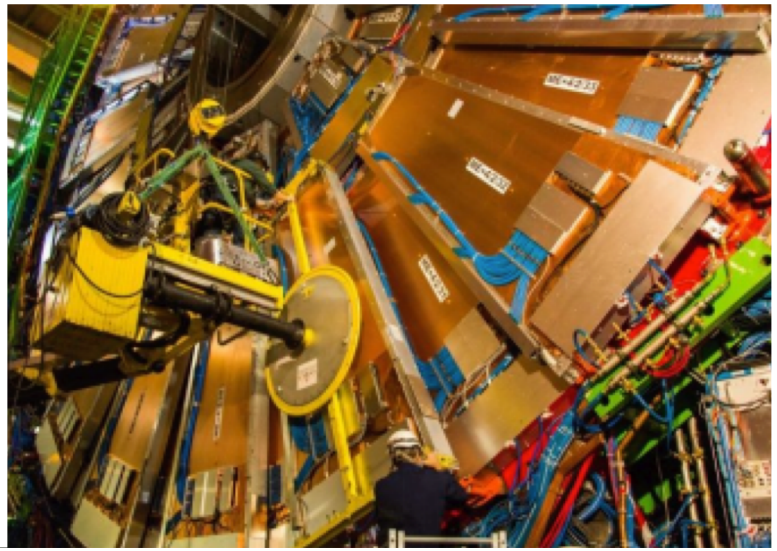


Development of the CMS detector for the CERN LHC Run 3

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.

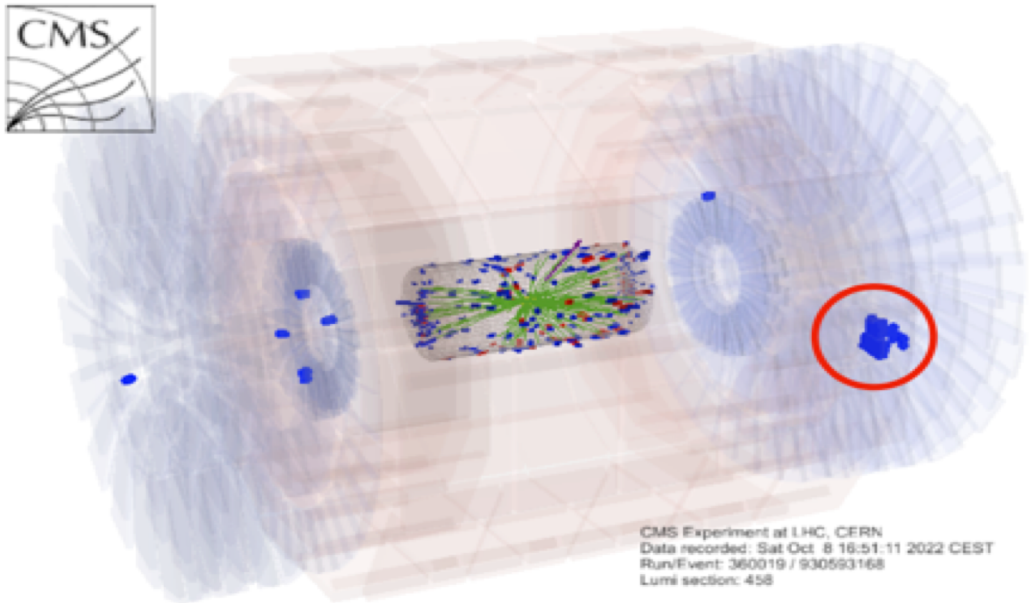


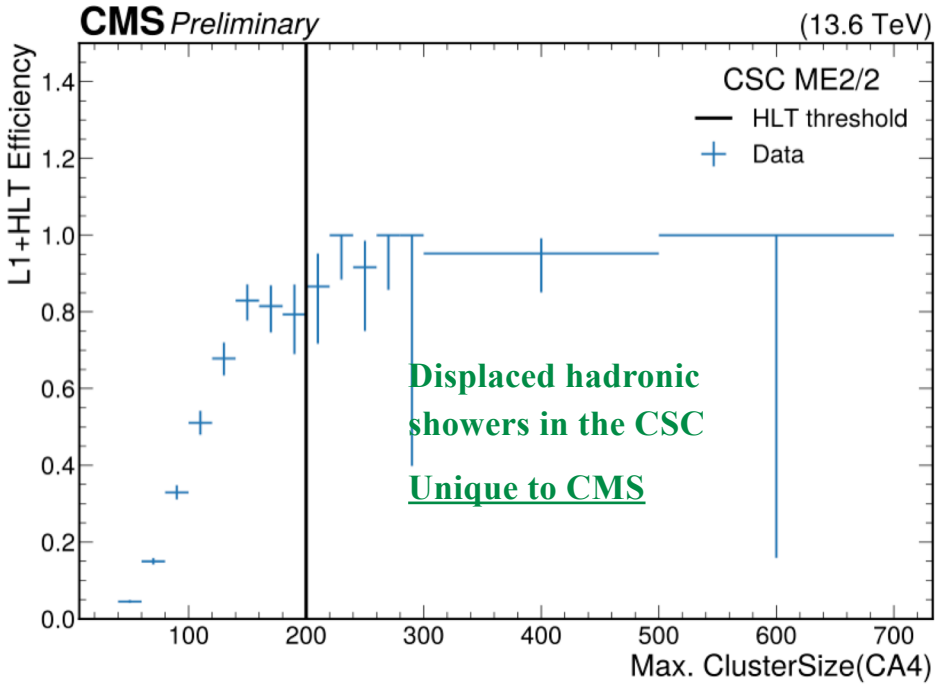
Submitted to the Journal of Instrumentation

https://arxiv.org/abs/2309.05466

New Trigger Capabilities

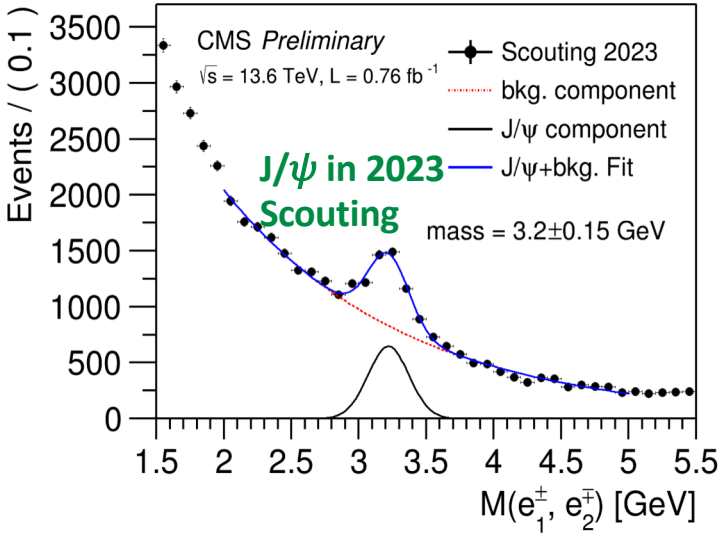
- New trigger algorithms in Run 3 targeting long-lived signatures
  - Displaced muons & displaced/delayed jets in HCAL
  - Displaced hadronic showers in the CSC

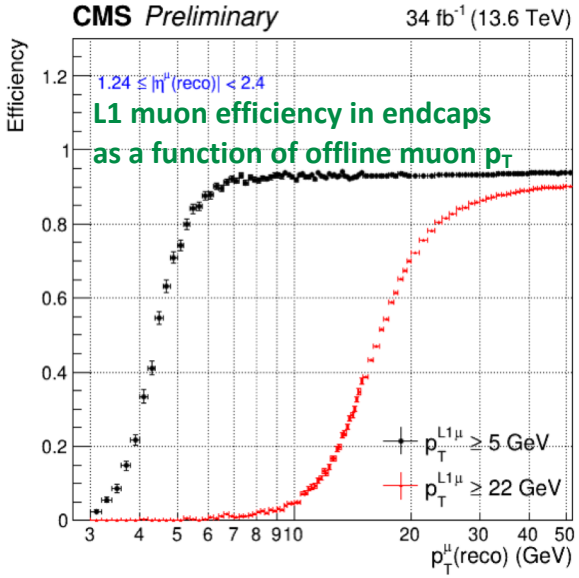


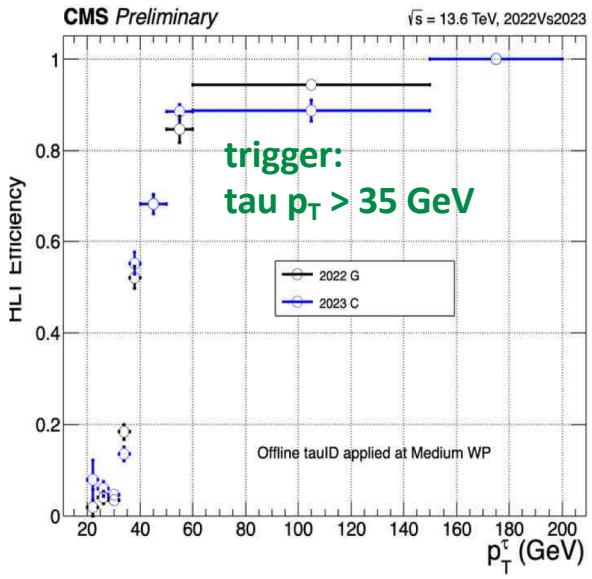


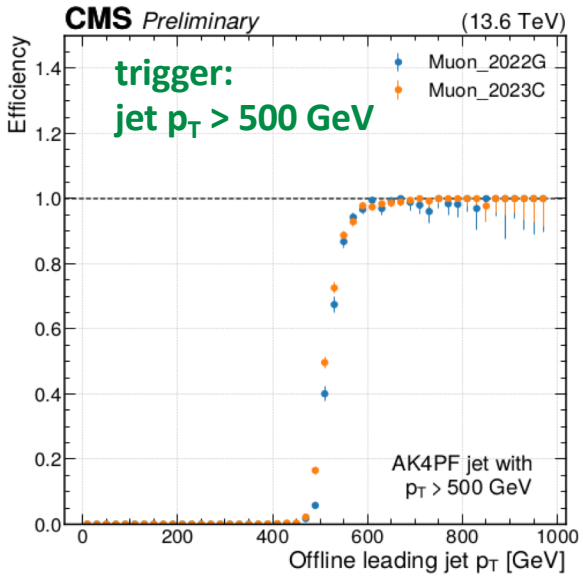
New Trigger Capabilities

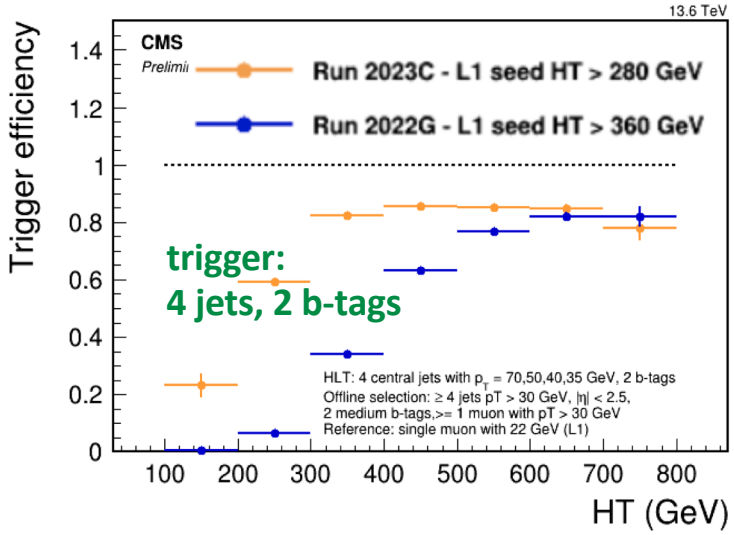
- New Bs→μμ , τ→3μ, and W→3π seeds
- New parking streams dedicated to VBF, LLP, and HH
- HLT output in 2023: ~2.5 kHz prompt, ~3.5 kHz parking, and ~20 kHz scouting





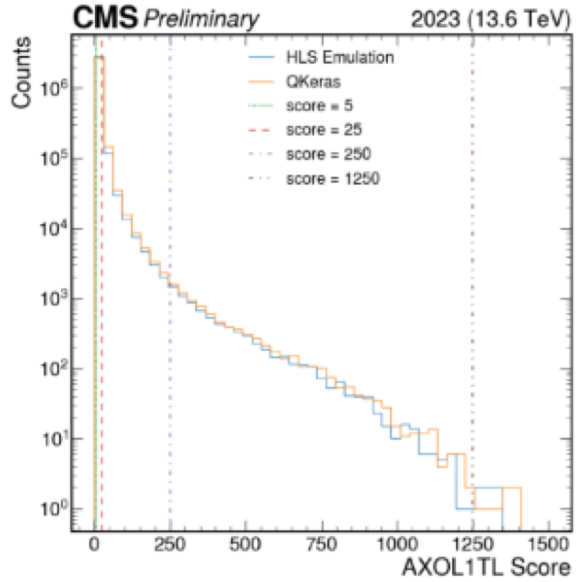




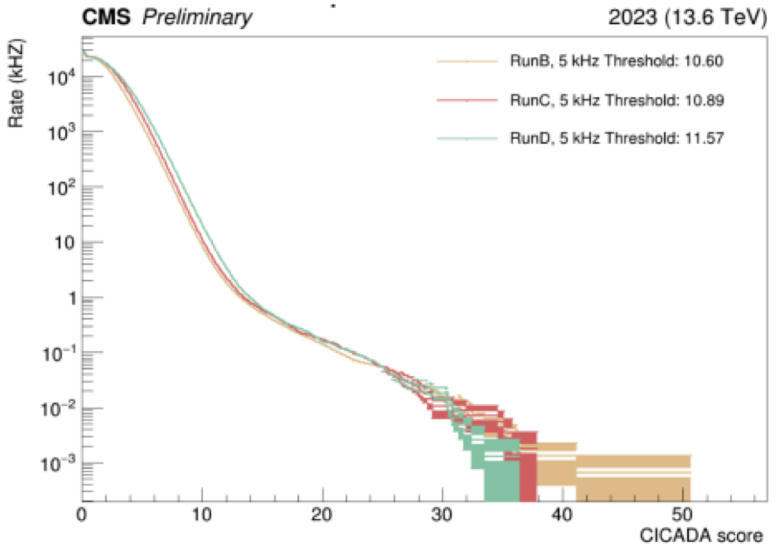


New Trigger Capabilities

- Successful commissioning of neural network-based triggers
  - muon pT regression
  - anomaly detection
    - AXOL1TL: DP-2023-079 : Combines L1 objects (muons, EG, jets, MET) from μGT
    - CICADA: DP-2023-086: CNN auto encoder with calo ET deposits as inputs



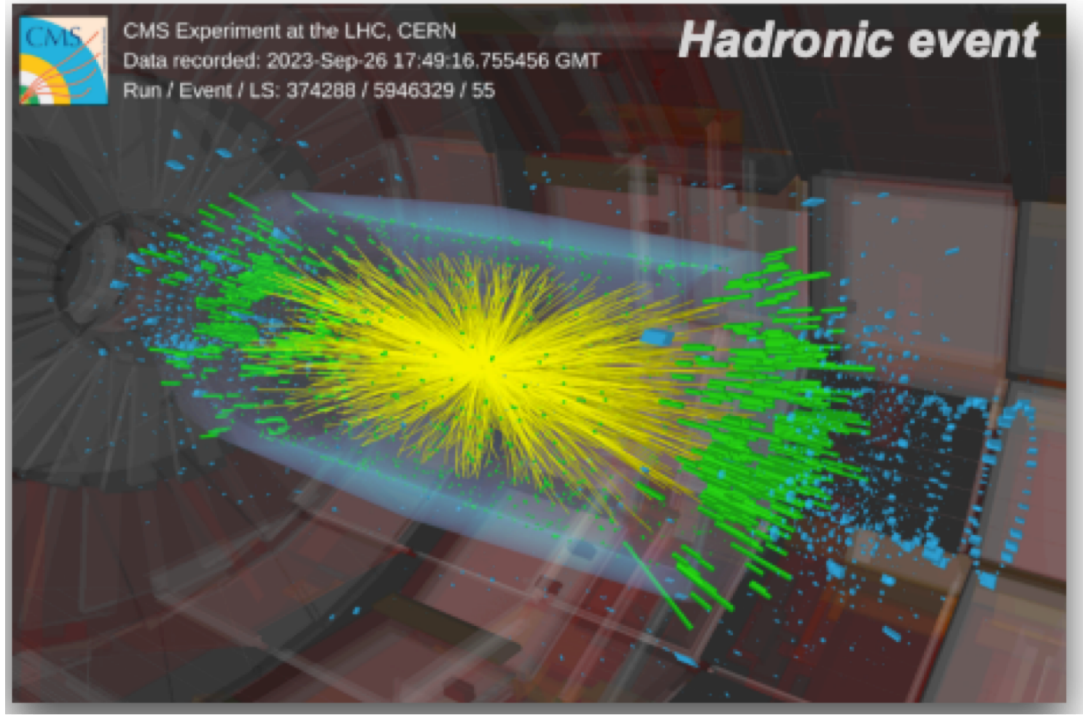
Anomaly score distributions

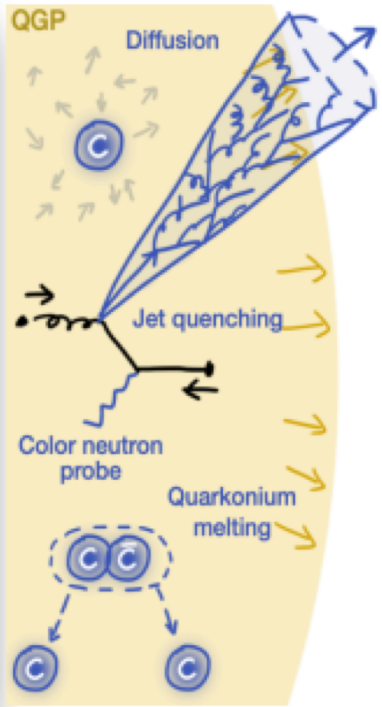


Rate from efficiencies obtained using scores as a threshold

New Trigger Capabilities

- Zero Degree Calorimeter (ZDC) trigger necessary to preserve PbPb Minimum Bias trigger
  - commissioning finalized in time for physics data-taking

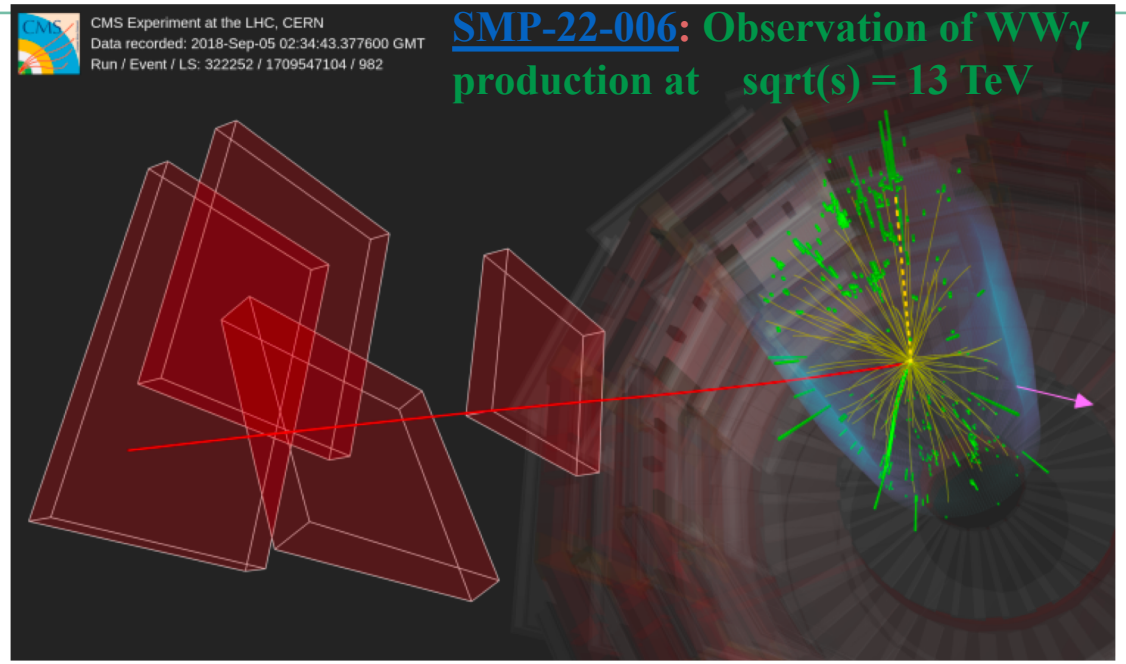




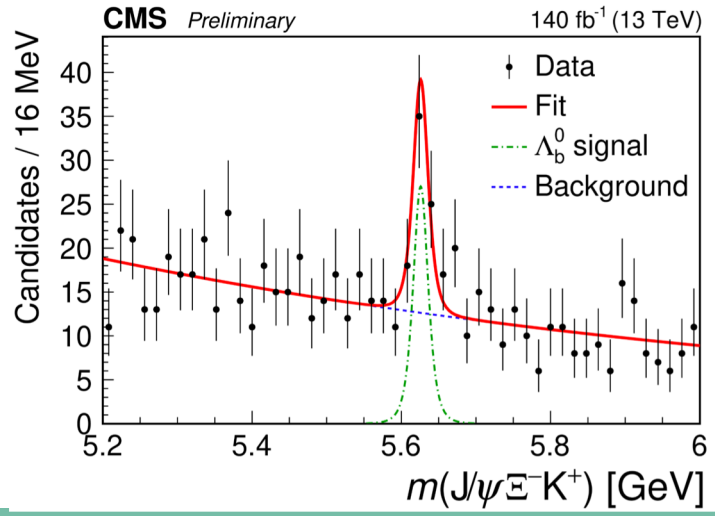
Hadronic collisions: Quark-Gluon Plasma studies

- correlations and flow
- jet quenching
- quarkonia and open-heavy flavor production modifications
- EM probes to control nuclear effects

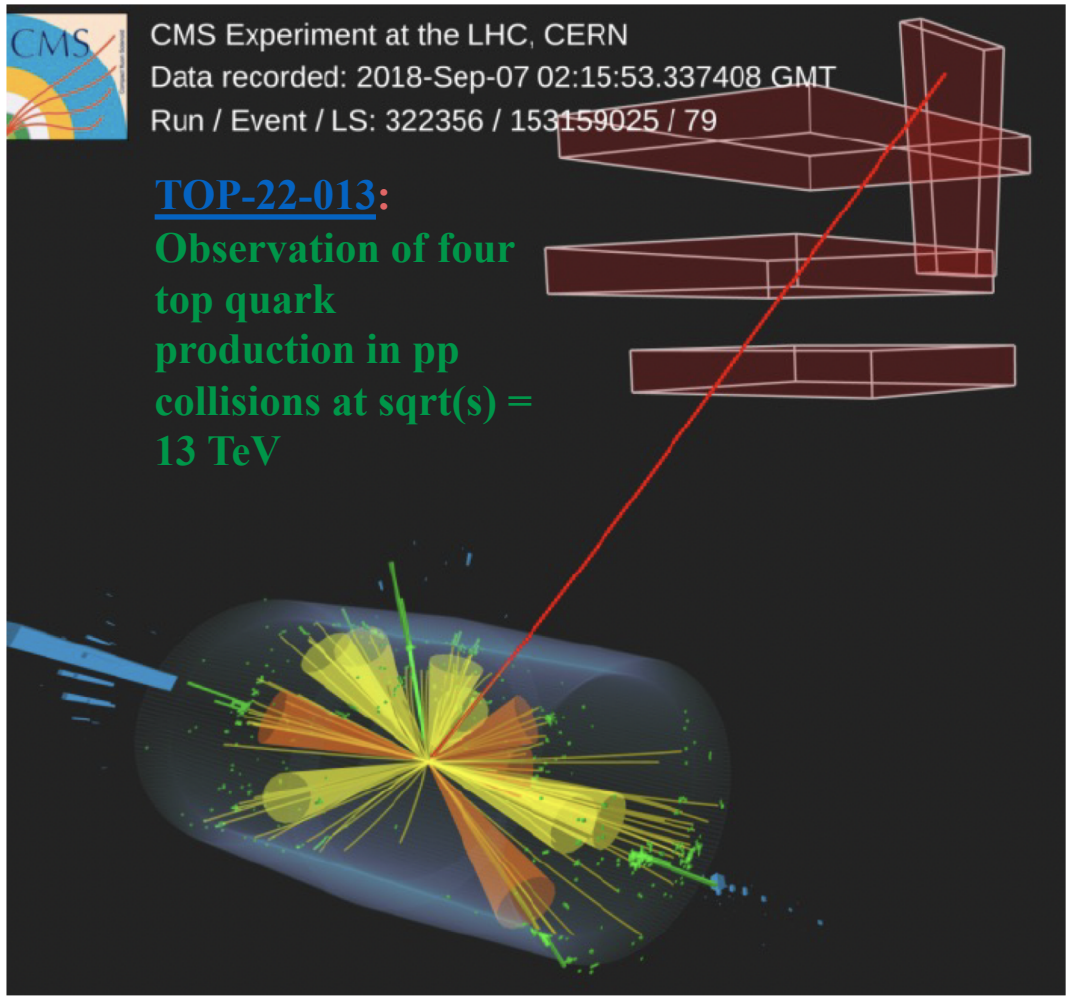
Newly Observed Physics Phenomena



SMP-22-006: Observation of WWγ production at sqrt(s) = 13 TeV



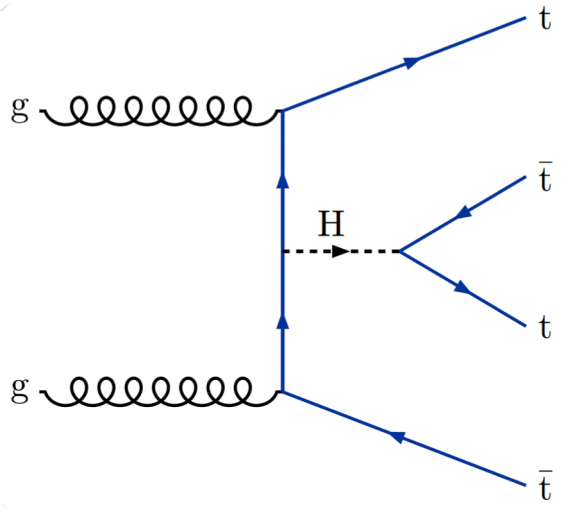
BPH-22-002: Observation and branching ratio measurement of $\Lambda_b \rightarrow J/\psi\ \Xi^-\ K$



TOP-22-013: Observation of four top quark production in pp collisions at sqrt(s) = 13 TeV

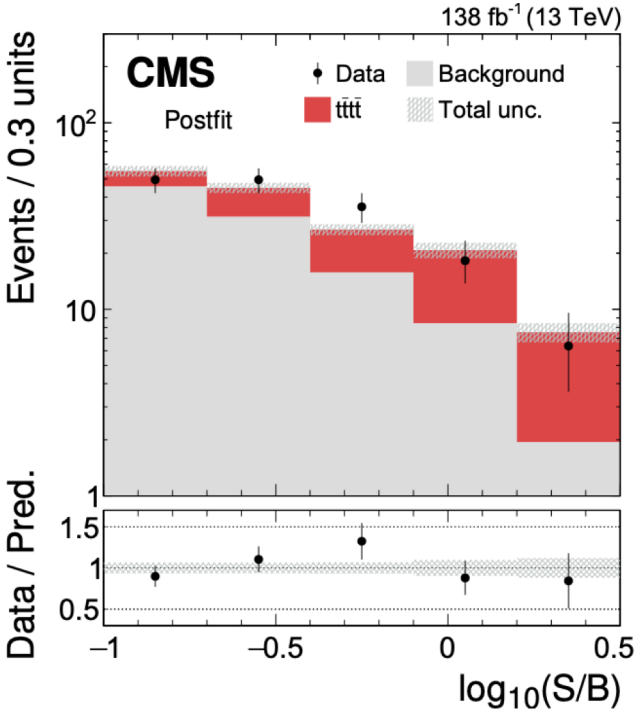
Observation of 4 top quark production

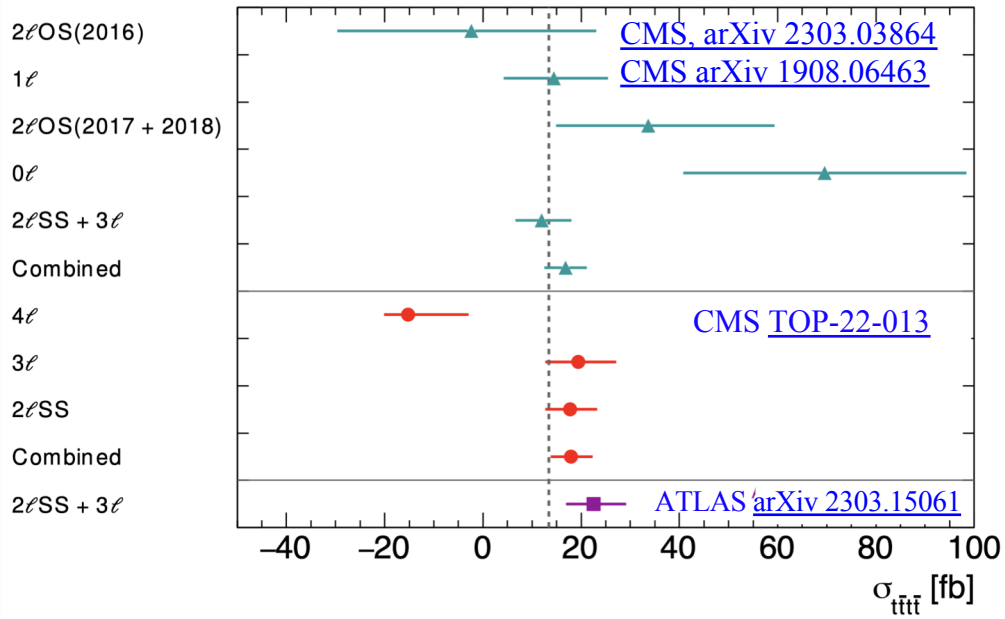
TOP-22-013



- Final states with 2 SS leptons + multilepton. (lepton = e, μ)
- Directly sensitive to top Yukawa
- Background to NP searches
- One of most massive final states that can be observed

- Run 2 data re-analyzed with several improvements:
  - **MVA in the lepton identification**, DeepJet for b-tagging, and UL samples





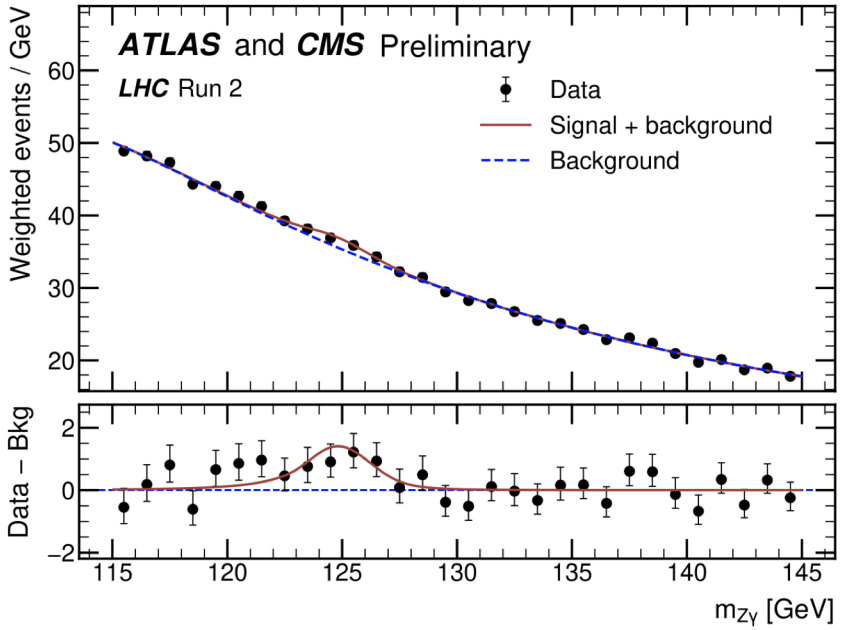
- Observed a signal with 5.6σ significance (4.9 expected)
- Cross section in agreement with SM prediction within errors

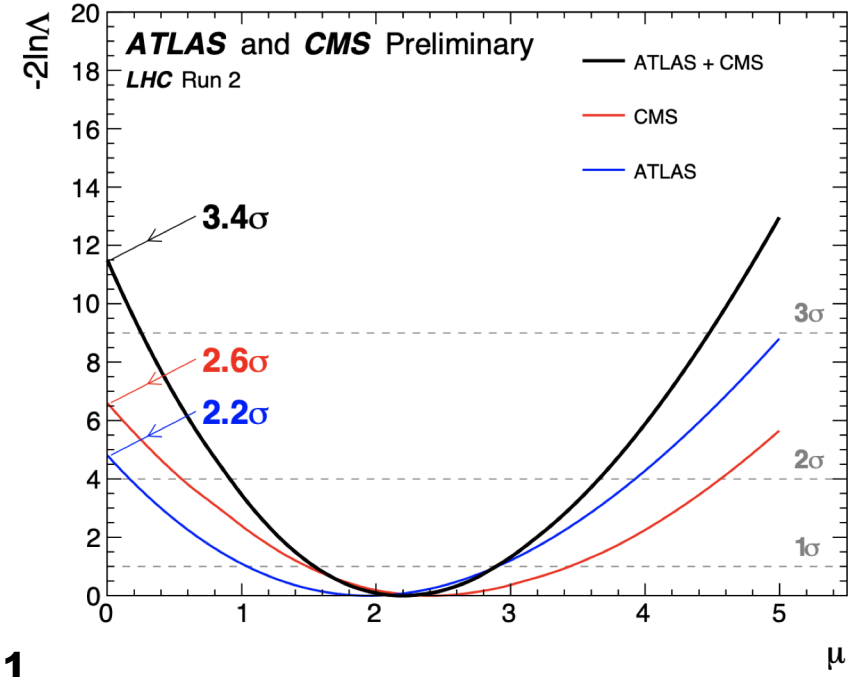
$$17.7^{+3.7}_{-3.5}\ (\text{stat})\ ^{+2.3}_{-1.9}\ (\text{syst})\ \text{fb}$$

Evidence for the Higgs boson decay to a Z boson and a photon at the LHC

HIG-23-002

- Combined evidence of H->Zγ from ATLAS and CMS results
- Similar analysis strategy. Correlated (TH) and uncorrelated (EXP) systematic uncertainties taken into account in the combination
- Observe evidence for a signal with 3.4σ significance (expected 1.6σ)
  - Observed signal cross section corresponds to 2.2 ± 0.7 times the SM cross section
- 1.9σ compatibility with SM prediction

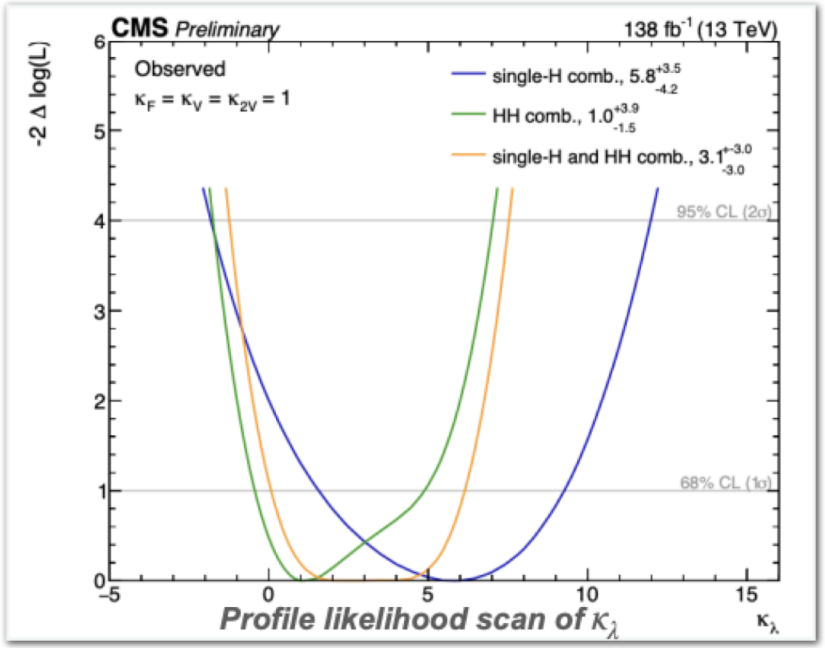


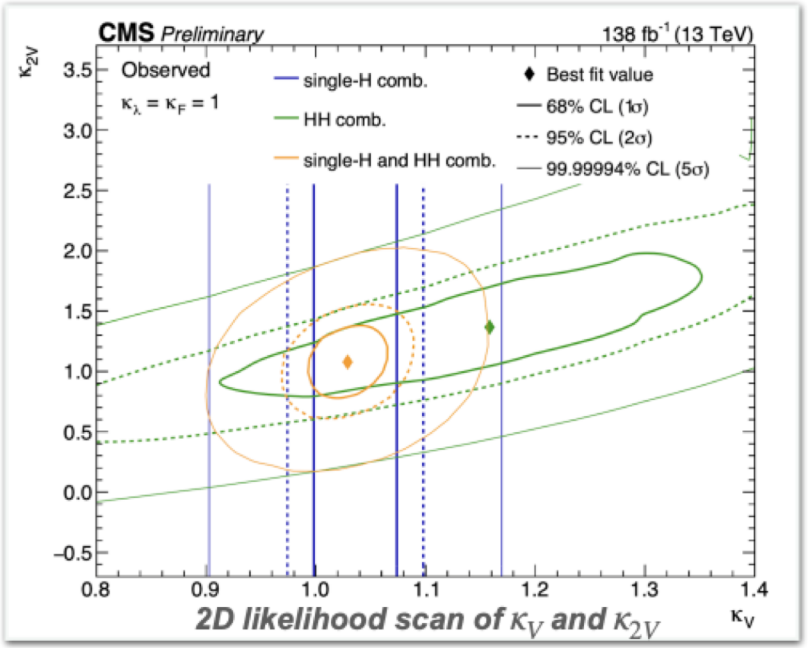


Combination of H measurements and searches for HH to constrain λ_{HHH}

HIG-23-006

- 9 single-H analyses and 6 HH analyses combined, overlap removal studied in details
- **Inclusion of single-H channels improved constraints on Higgs boson trilinear self-coupling λ_{HHH}** under more general assumptions on the Higgs boson couplings to fermions and vector bosons



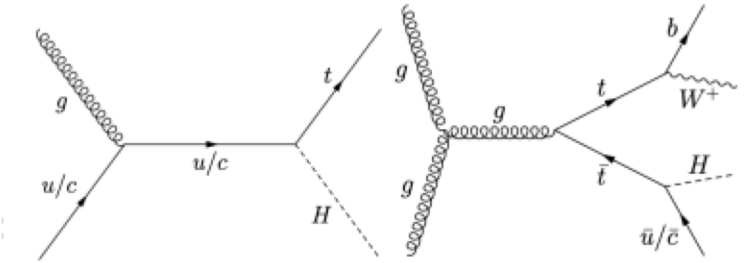


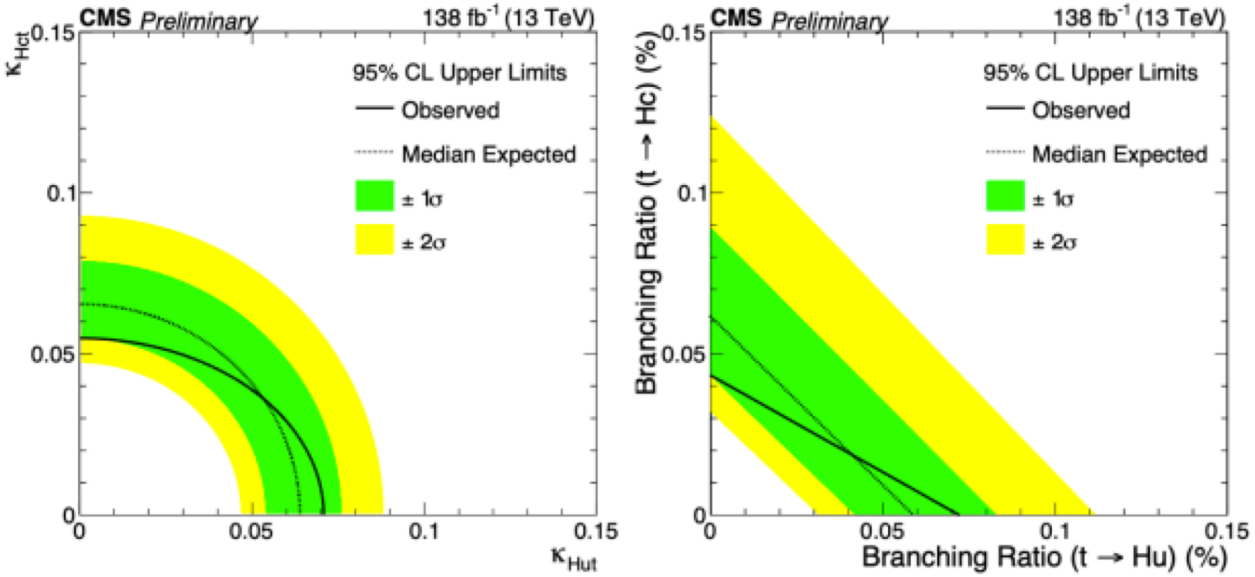
First combination of single-H and HH channels at CMS !

Flavour Changing Neutral Currents in tHq

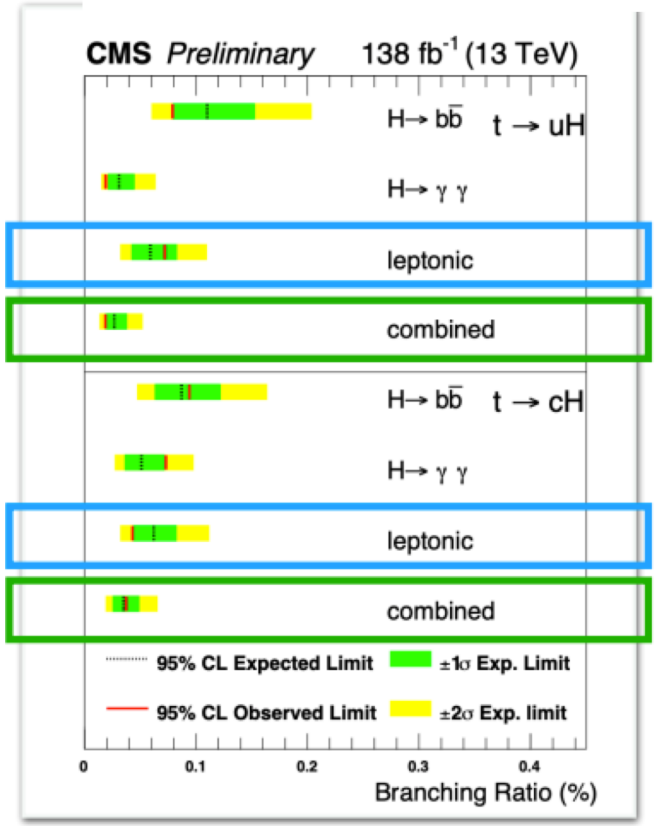
TOP-22-002

- Events containing a pair of leptons with the same-sign electric charge and at least one jet are considered
- Observed (expected) 95% CL upper limits on branching ratio:
  - 0.072% (0.059%) for B (t → Hu)
  - 0.043% (0.062%) for B(t → Hc)
- Constraints on anomalous coupling strengths also derived





Result of combination constitutes the best exclusion limits to date !



Combination of searches for EWK SUSY

SUS-21-008

ENERGY FRONTIERS

CERN COURIER

Reports from the Large Hadron Collider experiments

link

CMS

Searching for electroweak SUSY: a combined effort

The CMS collaboration has been relentlessly searching for physics beyond the Standard Model (SM) since the start of the LHC. One of the most appealing new theories is supersymmetry or SUSY – a novel fermion–boson symmetry that gives rise to new particles, "naturally" leads to a Higgs boson almost as light as the W and Z bosons, and provides candidate particles for dark matter (DM).

By the end of LHC Run 2, in 2018, CMS had accumulated a high-quality data sample of proton–proton (pp) collisions at an energy of 13 TeV, corresponding to an integrated luminosity of 137 fb^{-1}. With such a large data set, it was possible to search for the production of strongly interacting SUSY particles, i.e. the partners of gluons (gluinos) and quarks (squarks), as well as for SUSY partners of the W and Z bosons (electroweakinos: winos and binos), of the Higgs boson (higgsinos), and of the leptons (sleptons). The cross sections for the direct production of SUSY electroweak particles are several orders of magnitude lower than those for gluino and squark pair production. However, if the partners of gluons and quarks are heavier than a few TeV, it could be that the SUSY electroweak sector is the only one accessible at the LHC. In the minimal SUSY extension of the SM, electroweakinos and higgsinos mix to form six mass eigenstates: two charged (charginos) and four neutral (neutralinos). The lightest neutralino is often considered to be the lightest SUSY particle (LSP) and a DM candidate.

CMS has recently reported results, based on the full Run 2 dataset, from searches for the electroweak production of sleptons, charginos and neutralinos. Decays of these particles to the LSP are expected to produce leptons, or Z, W and Higgs bosons. The Z and W bosons subsequently decay to leptons or quarks, while the Higgs boson primarily decays to b quarks. All final states have been explored with complementary channels to enhance the sensitivity to a wide range of electroweak SUSY mass hypotheses. These cover very compressed mass spectra, where the mass difference between the LSP and its parent particles is small (leading to low-momentum particles in the final state) as well as uncompressed scenarios that would instead produce highly boosted Z, W and Higgs bosons. None of the searches showed event counts that significantly deviate from the SM predictions.

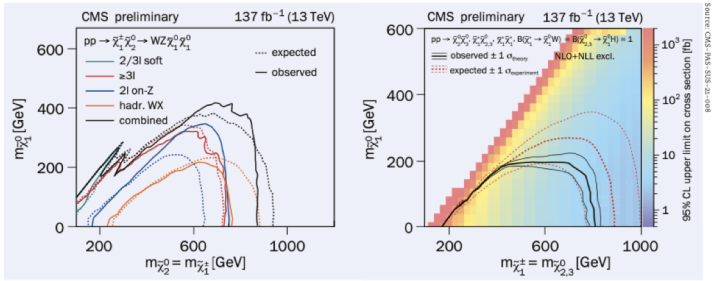


Fig. 1. *Exclusion limits at 95% confidence level for the production of (left) "wino-like" chargino–neutralino pairs decaying via a W and a Z boson, and of (right) "higgsino-like" neutralino–neutralino, chargino–chargino and chargino–neutralino pairs, where the charginos (neutralinos) decay via a W (Higgs) boson, and the lightest chargino and the second- and third-lightest neutralinos are mass-degenerate. On the right, in addition to exclusion limit contours on the mass of the involved SUSY particles, upper limits on the production cross section are also shown.*

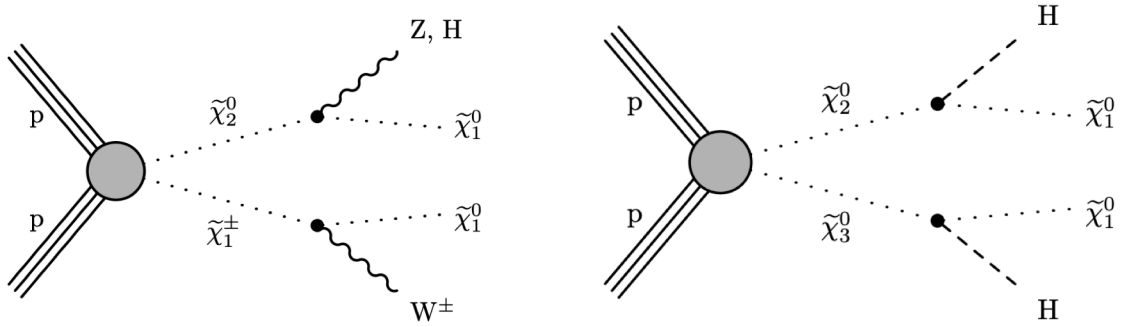
CMS maximised the output of the Run 2 dataset, providing its legacy reference on electroweak SUSY searches

The next step was to statistically combine the results of mutually exclusive search channels to set the strongest possible constraints with the Run 2 dataset and interpret the results of searches in different final states under unique SUSY-model hypotheses. For the first time, fully leptonic, semi-leptonic and fully hadronic final states from six different CMS searches were combined to explore models that differ depending on whether the next-to-lightest supersymmetric partner (NLSP) is "wino-like" or "higgsino-like", as shown in the left and right panels of figure 1, respectively. The former are now excluded up to NLSP masses of 875 GeV, extending the constraints obtained from individual searches by up to 100 GeV, while the latter are excluded up to NLSP masses of 810 GeV.

With this effort, CMS maximised the output of the Run 2 dataset, providing its legacy reference on electroweak SUSY searches. While the same data are still being used to search for new physics in yet uncovered corners of the accessible phase-space, CMS is planning to extend its reach in the upcoming years, profiting from the extension of the data set collected during LHC Run 3 at an unprecedented centre-of-mass energy of 13.6 TeV.

Further reading

CMS Collab. 2023 CMS-PAS-SUS-21-008.

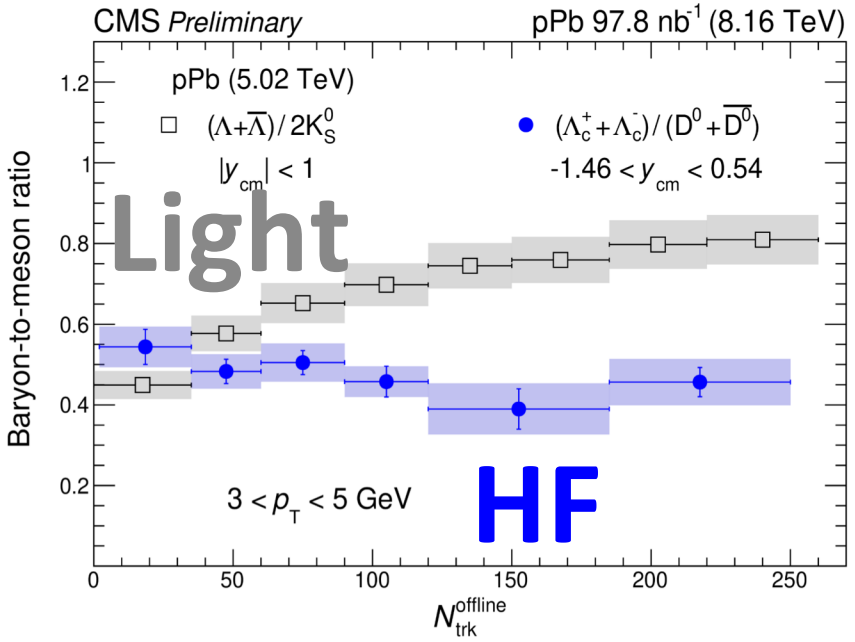


For the first time, six CMS searches were combined

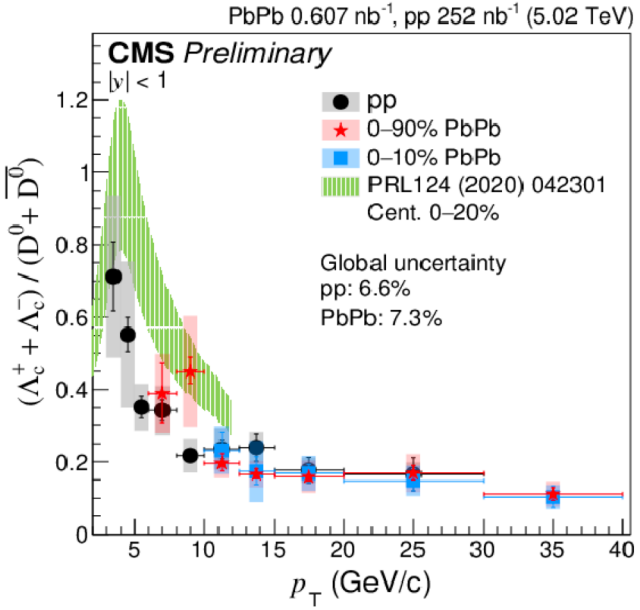
- explores models that differ depending on whether the next-to-lightest supersymmetric partner (NLSP) is "wino-like" or "higgsino-like"
- fully leptonic, semi-leptonic and fully hadronic final states
- Wino-like NLSP: excluded up to masses of 875 GeV
- Higgsino-like NLSPs: excluded up to masses of 810 GeV

Detailed studies of Λ_c^+ production in pPb and PbPb collisions

- First measurement of Λ_c^+/D^0
- No significant multiplicity dependence in pPb [HIN-21-016]

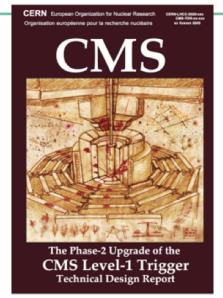


- Extending Λ_c^+ production up to p_T=40 GeV in PbPb [HIN-21-004]
- Λ_c^+/D^0 ratios are consistent between pp and PbPb collisions



- Successful **2023 CMS HIN Workshop** last week: bringing together the heavy ion community

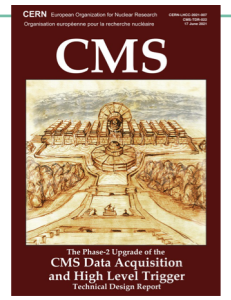
The CMS Phase 2 Upgrade



L1-Trigger

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

- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



DAQ & High-Level Trigger

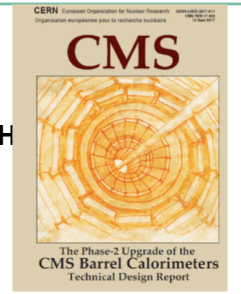
https://cds.cern.ch/record/2759072

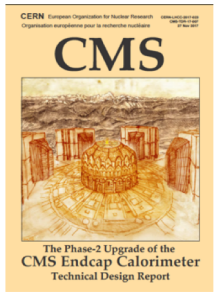
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

Barrel Calorimeters

https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MH with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

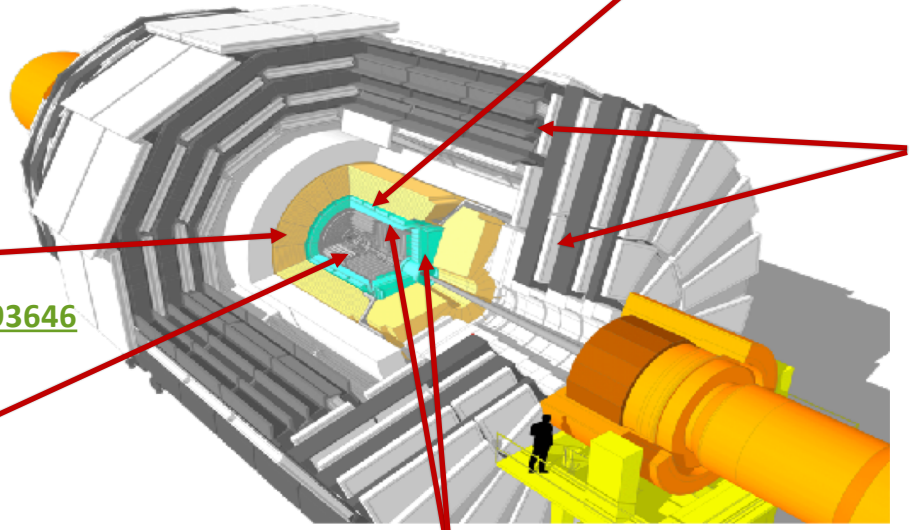




Calorimeter Endcap

https://cds.cern.ch/record/2293646

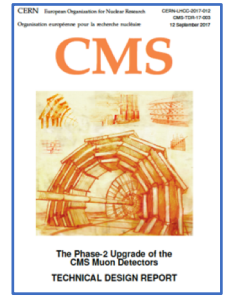
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

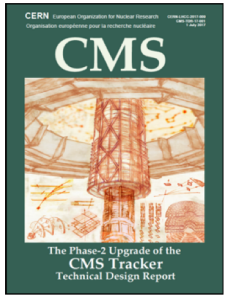


Muon systems

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 $\eta \simeq 3$

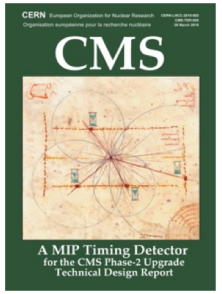




Tracker

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

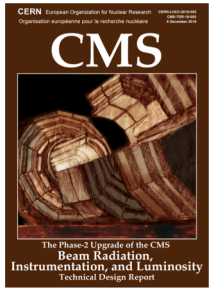
Precision timing with:

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

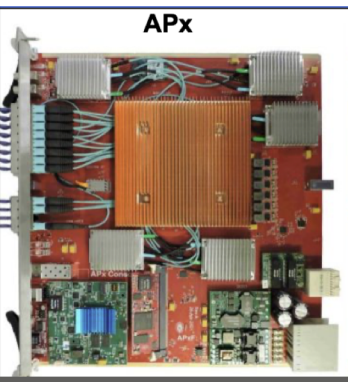
Beam Radiation Instr. and Luminosity

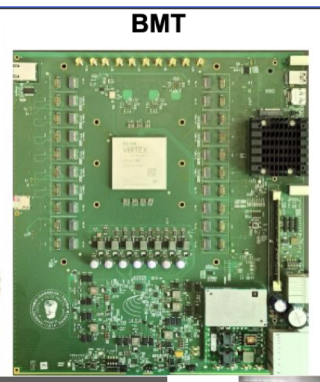
http://cds.cern.ch/record/2759074

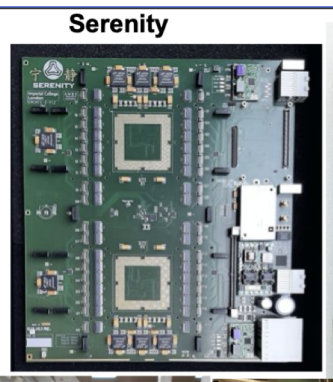
- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity:
  1% offline, 2% online
- Neutron and mixed-field radiation monitors

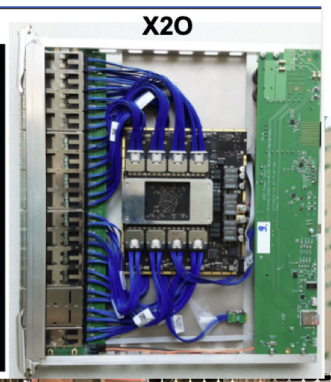


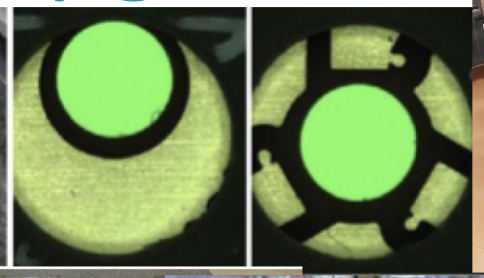
The CMS Upgrade

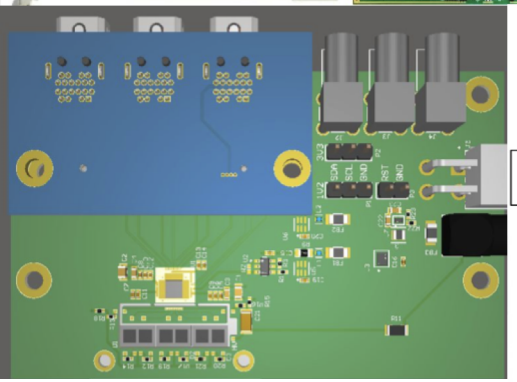




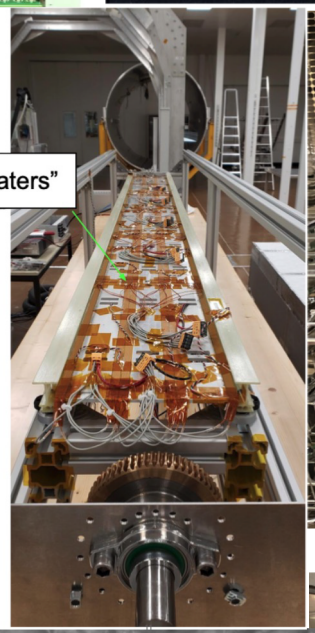


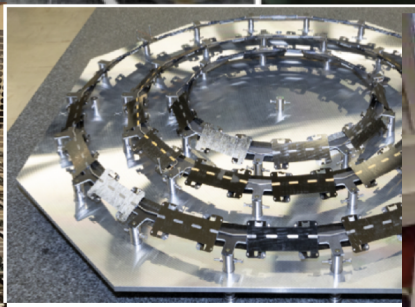


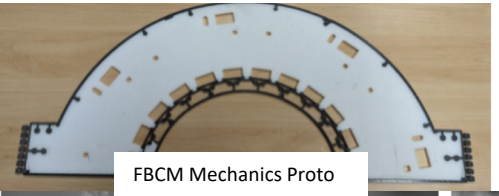




BRIL FBCM ASIC Test board

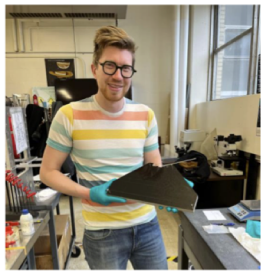


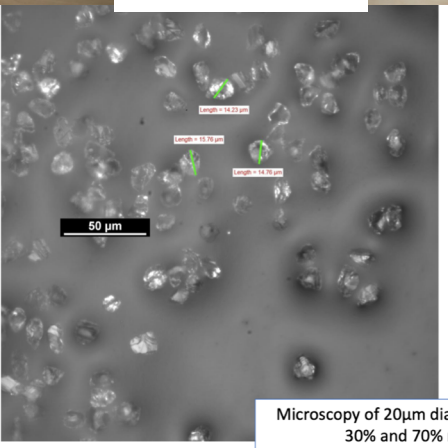


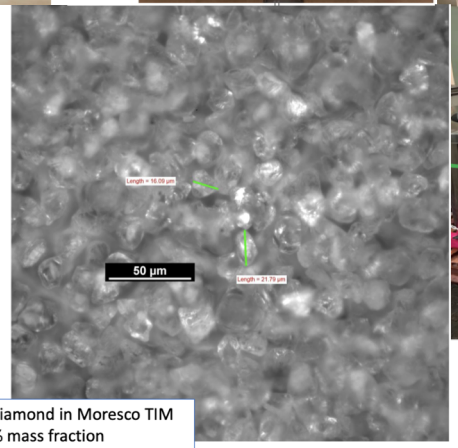


FBCM Mechanics Proto

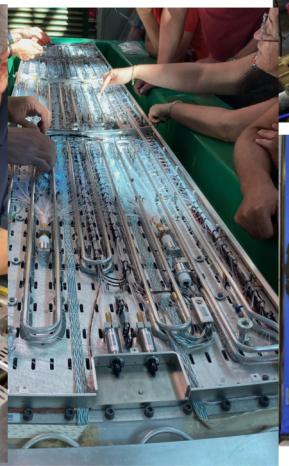
- Ring forged inner cylinders received at CERN.
- Ready to be shipped to Pakistan for final machining.

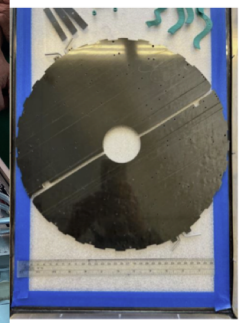


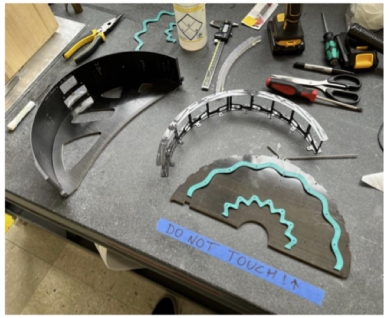




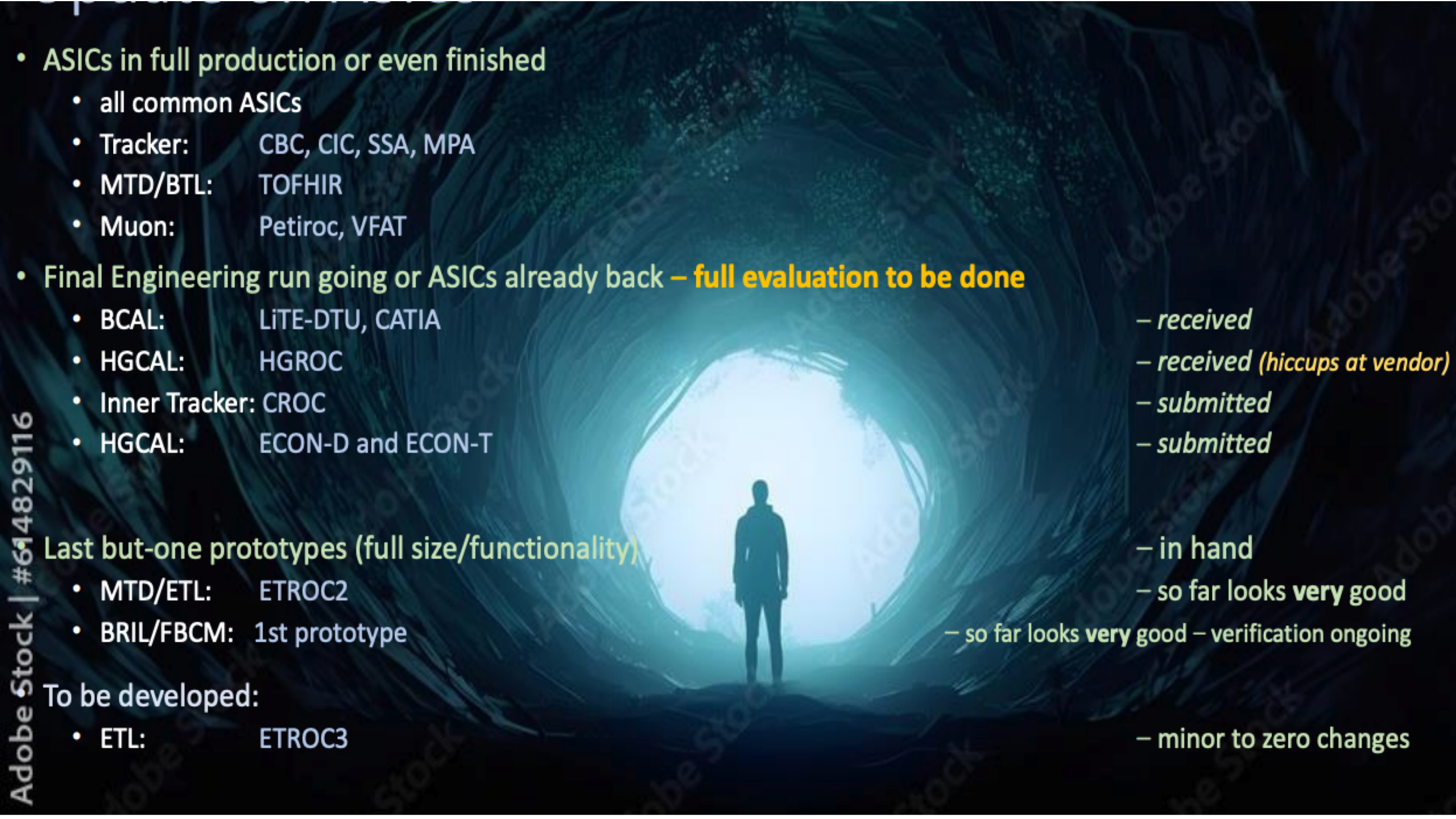
Microscopy of 20µm diamond in Moresco TIM
30% and 70% mass fraction





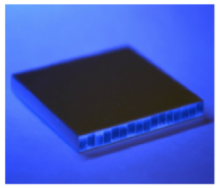


- ASICs in full production or even finished
  - all common ASICs
  - Tracker: CBC, CIC, SSA, MPA
  - MTD/BTL: TOFHIR
  - Muon: Petiroc, VFAT
- Final Engineering run going or ASICs already back – **full evaluation to be done**
  - BCAL: LiTE-DTU, CATIA – *received*
  - HGCAL: HGROC – *received (hiccups at vendor)*
  - Inner Tracker: CROC – *submitted*
  - HGCAL: ECON-D and ECON-T – *submitted*
- Last but-one prototypes (full size/functionality) – in hand
  - MTD/ETL: ETROC2 – so far looks **very** good
  - BRIL/FBCM: 1st prototype – so far looks **very** good – verification ongoing
- To be developed:
  - ETL: ETROC3 – minor to zero changes

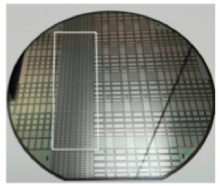


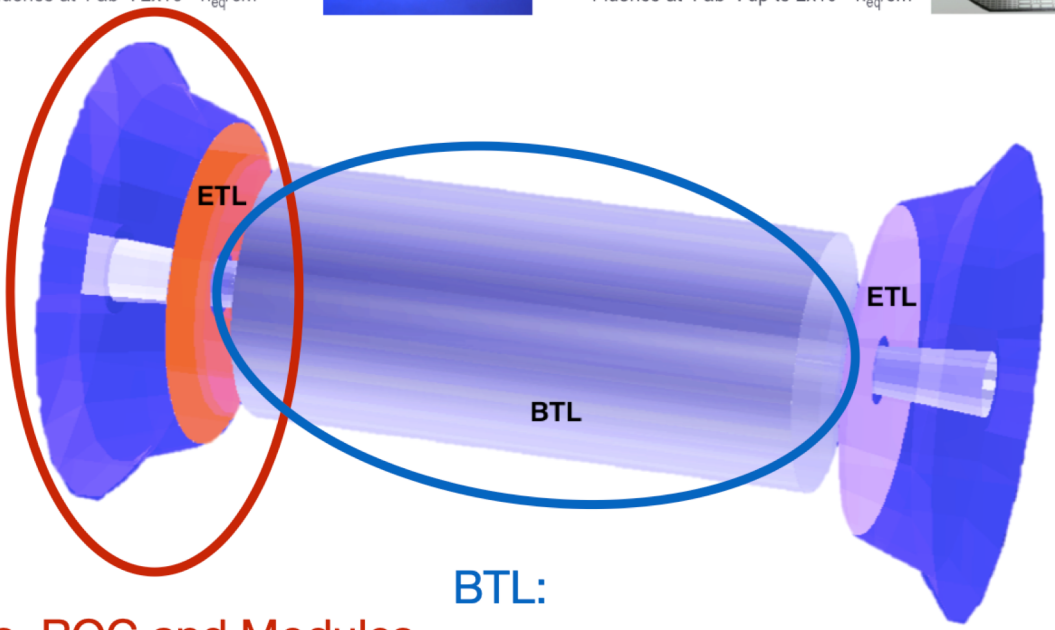
MIP Timing Detector

BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: $2x10^{14}$ n_{eq}/cm^2



ETL: Si with internal gain (LGAD):
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: $315 < R < 1200$ mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to $2x10^{15}$ n_{eq}/cm^2



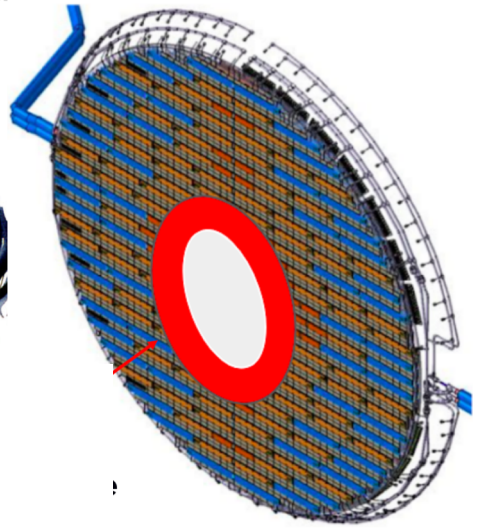


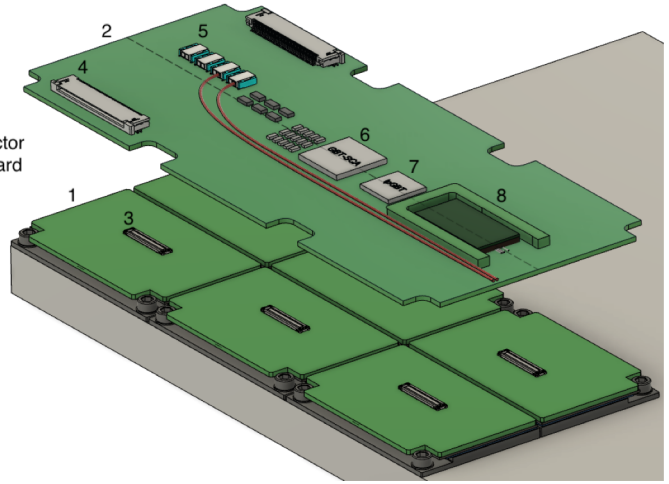
ETL:
- Sensors, ROC and Modules
- System testing
- Mechanics

BTL:
- Conclusion of module optimization and prototyping
- Moving towards mass production

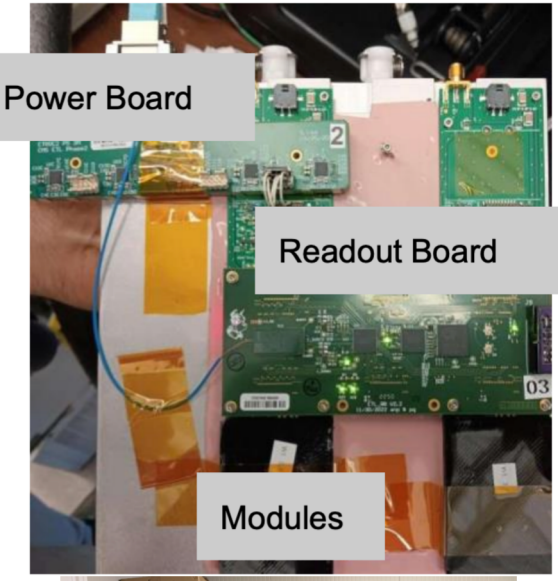
- **Challenging road but large rewards**
  - Significant impact on the HL-LHC physics
    - Recover Phase-I purity of vertices (+25% gain in luminosity)
    - Enhance flavour tagging in pp collisions (B physics)
    - Unique potential for Long-Lived Particles
    - Unique flavor physics with PID in Heavy Ions
  - Bridge to the future
    - Track-timing with (AC)-LGADs at future colliders
    - 5D fine granularity EM calorimetry with crystals + SiPMs

Endcap Timing Layer



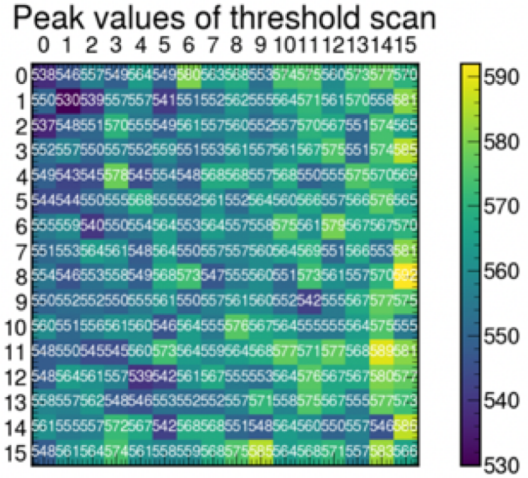


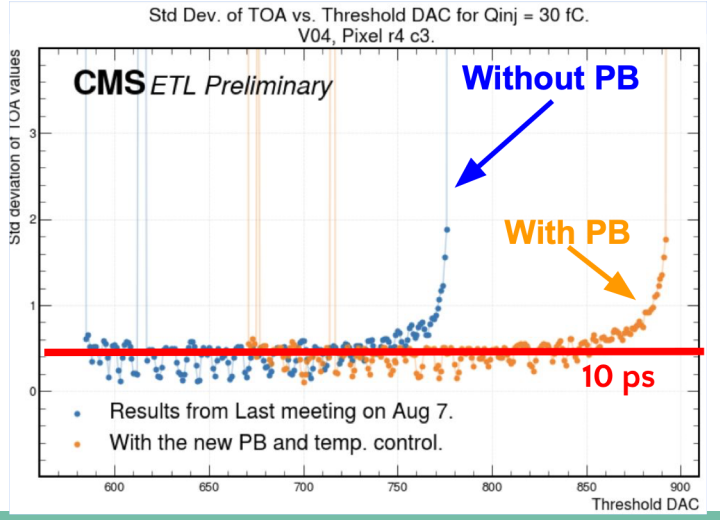
Utilizing 2nd Prototypes for system testing, using feedback to begin working on 3rd prototypes



904 test stand

First results with charge injection & beta/laser, preparing for test beams



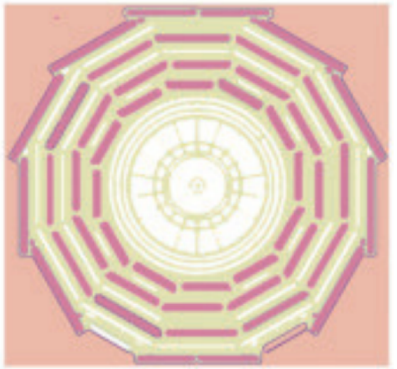


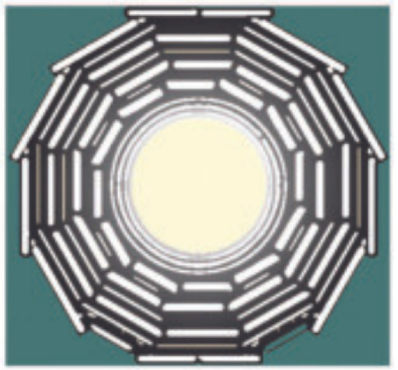
Outlook

- CMS is successfully taking data in 2023
  - New trigger capabilities for Run 3, higher rates, same or better efficiency
  - Dealing successfully with increasing PU
    - maximizing luminosity without affecting the physics goals
  - Acquiring data at high efficiency

- Steady technical progress on Phase 2 Upgrade Activities for HL-LHC
  - Positive feedback from the P2UG, Fermilab Director's Review, and passed CD3!

- CMS continues to produce results with Run 2 data, Run 3 efforts ramping up
  - Ingenuity and creativity for new directions
  - Still exploiting at best our Run 2, with many measurements and results





US LUA Contributions

Thursday

- **Tests of lepton flavour universality violation with Bc meson decays at CMS,** Luigi Marchese (ETH Zürich)
- **A Search for Vector-Like Leptons (VLLs),** Elise Chavez
- **A Search for Vector-Like Leptons: Compact Analysis,** Nadia Talbi (University of Wisconsin-Madison)
- **Tile Module Assembly for the CMS High Granularity Calorimeter at Fermilab,** Ryan Kim (Florida State University)
- **Probing EFT models using associated top production in multiple lepton final states,** Furong Yan (University of Nebraska-Lincoln)
- **CMS ECAL L1 Trigger: Rejection of Anomalous Signals and Effects on e-gamma Candidates,** Cort Thoreson (Northeastern University)
- **Search for charged-lepton flavor violation in the production and decay of top quarks with the CMS detector,** Jack Li (Northeastern University)
- **Search for new physics in CMS Run2 data using MonoJet signature,** Abhishikth Mallampalli (UW Madison)
- **Measurement of ttH Production Rate in the H to bb Decay Channel at CMS,** Abhisek Datta (University of California, Los Angeles)
- **Long Lived Particle Triggering at Level-1 with the CMS Hadron Calorimeter,** Gillian Kopp
- **A Search for Sexaquarks in Parked 2018 Data at CMS,** Wren Vetens (University of Wisconsin - Madison)
- **Development of Front-End Electronic Modules for CMS MIPs Timing Detector, End-cap Timing Layer,** Naomi Gonzalez (Boston University)

Friday

- **A Search for Ultra-heavy Resonances Decaying to Vector-like Quark Pairs at the Run 2 CMS Experiment,** Ethan Cannaert (University of California Davis)
- **Techniques for ML-based Model Agnostic Searches in CMS,** Oz Amram (Fermilab)
- **CMS MTD upgrade and prospects for identified jet substructure measurements for QGP studies,** Enea Prifti
- **Unveiling the Potential for Ultraperipheral Collisions of Heavy Ions: Novel Trigger Strategies and Optimized Physics Performance in the CMS Experiment at 5.36 TeV,** Saray Arteaga Escatel (The University of Kansas)
- **CICADA: Anomaly Detection for New Physics Searches at the CMS Level-1 Trigger,** Ho Fung Tsoi