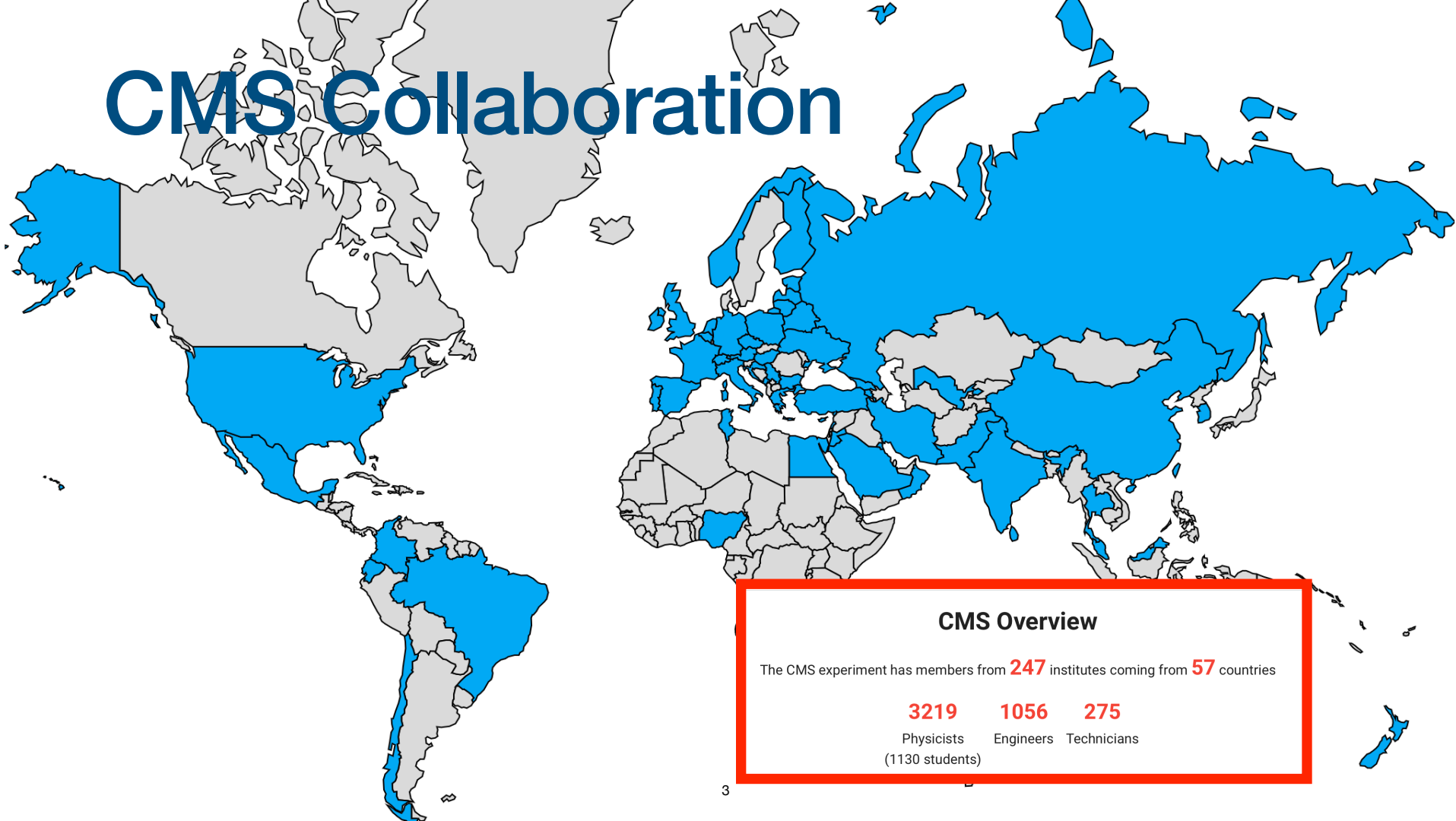
The status of the CMS experiment

Patricia McBride (CMS Spokesperson)
On behalf of the CMS Group at Fermilab
Fermilab Physics Advisory Committee Meeting
18 January 2023

Outline

- Status of the CMS experiment: the international perspective
- Reminder about the role of the laboratory and the group composition
- Status of the HL-LHC CMS Detector Upgrade Project and of the Fermilab's deliverables
- Status of the USCMS Operations Program and of the Fermilab's contributions to S&C operations and to detector operations
- The restart of the Fermilab Remote Operations Center
- Status of the LHC Physics Center
- Recent physics results
- Contributions to Future Colliders and Snowmass
- Postdocs mentoring program
- Efforts in EDI
- Conclusions

CMS Collaboration

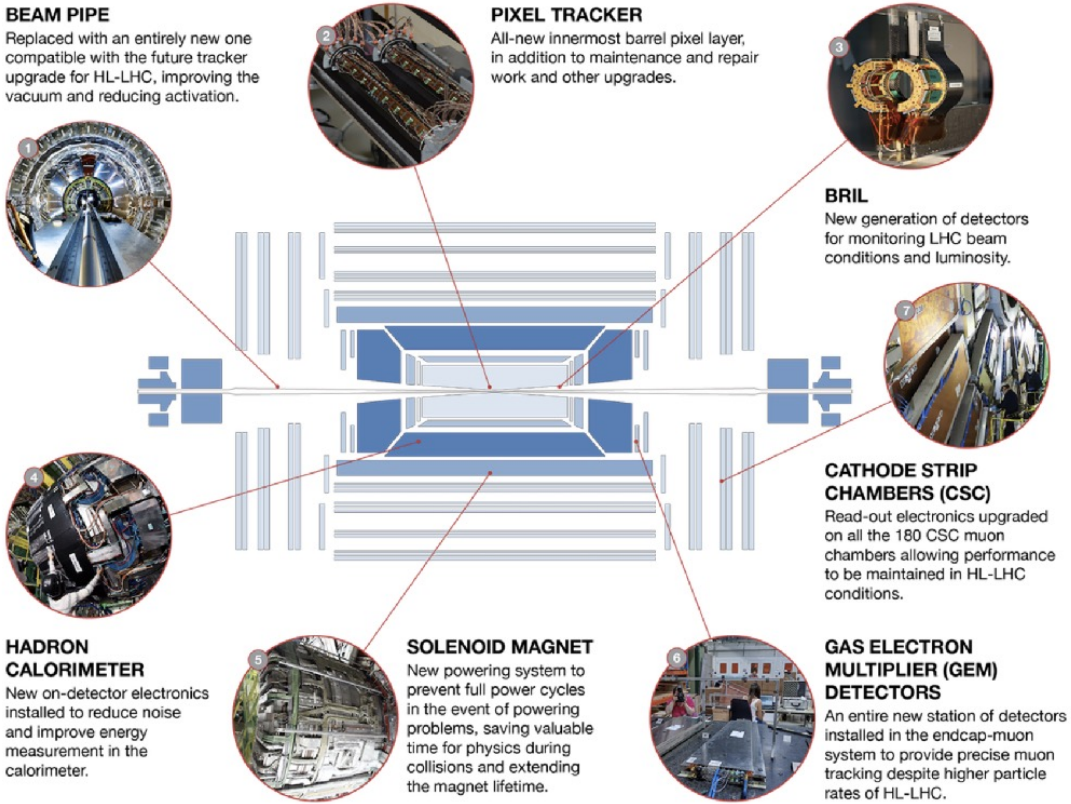


CMS Overview

The CMS experiment has members from **247** institutes coming from **57** countries

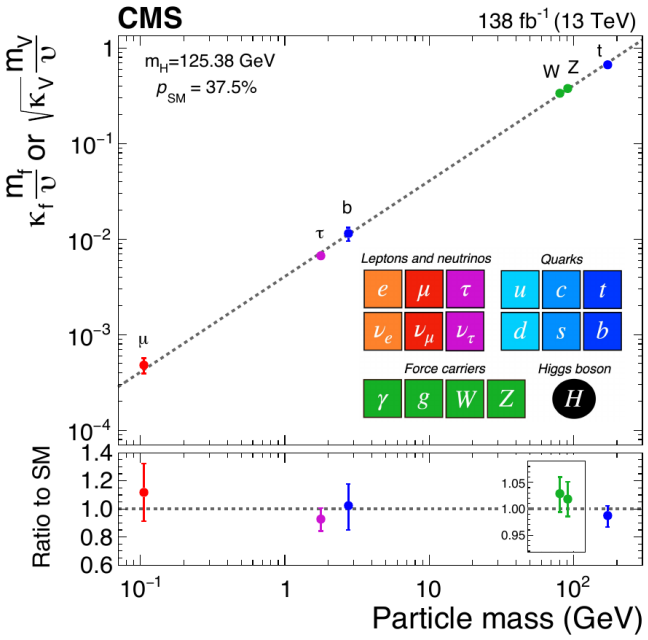
3219	**1056**	**275**
Physicists (1130 students)	Engineers	Technicians

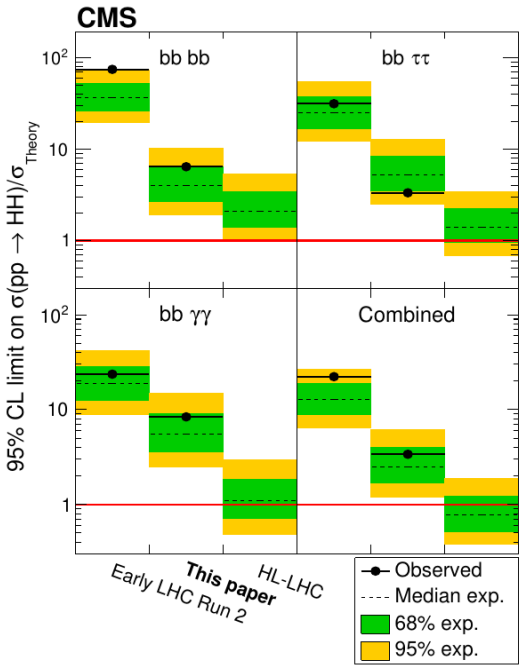
CMS preparations for Run 3



- CMS had a successful LS2 period with the completion of the **Phase 1 upgrades** and the start of the **Phase 2 upgrades**.
  - **Phase 1**: HCAL barrel readout, new barrel inner pixel (layer 1)
  - **Phase 2**: First station of GEM muon chambers installed, upgraded CSC electronics for HL-LHC, new beam pipe
  - Added GPUs to the HLT nodes.
- Demonstrator for Phase-2 muon drift tube electronics and BRIL demonstrators were installed

Ten years since Higgs boson discovery



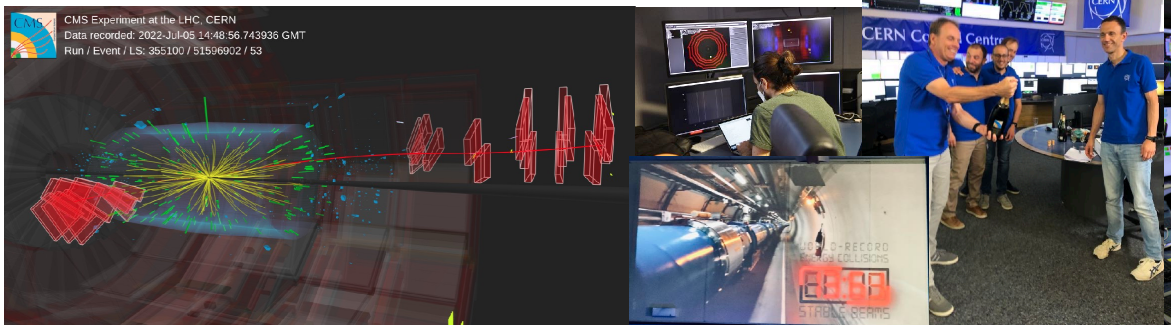


4 July 2022
CERN

Official Launch of Run 3

On the 5th of July 2022, the LHC delivered stable proton-proton collisions at the energy of 13.6 TeV.

- CMS recorded these first collisions with all systems on and working well.
- A big thank you to the LHC team!



Happy Birthday CMS!

Celebrated 30 years since the CMS LOI on Dec 6th with the CMS 30-year Birthday Symposium.

S. Cittolin

CMS 2022 Operations Summary

The 2022 Run ended on November 28

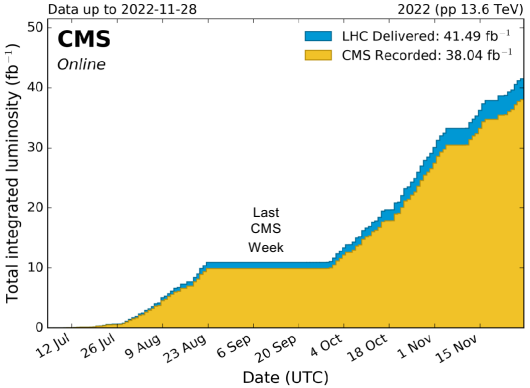
- The run plan was adapted after the unplanned technical stop in August/September.
- Adapted 2022 run plan: No Heavy Ion Run in 2022 and YETS to start two weeks earlier than originally planned (energy crisis).

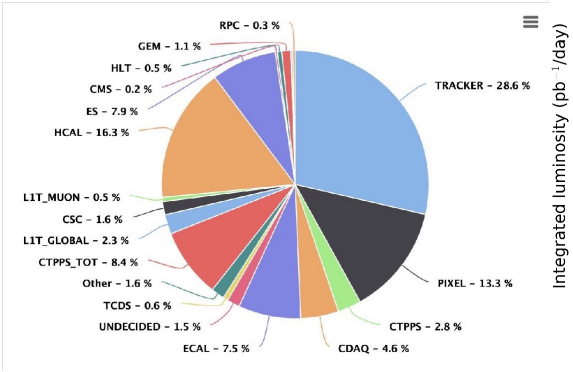
Summary of 2022 running period:

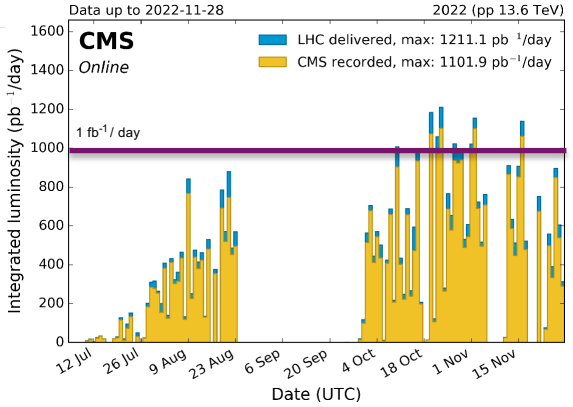
- ~41 fb^{-1} pp delivered; ~38 fb^{-1} recorded by CMS.
  - 91.7% data-taking efficiency overall.

Many records in LHC operations: max Instantaneous luminosity, max Integrated luminosity per day, max pile-up, ...

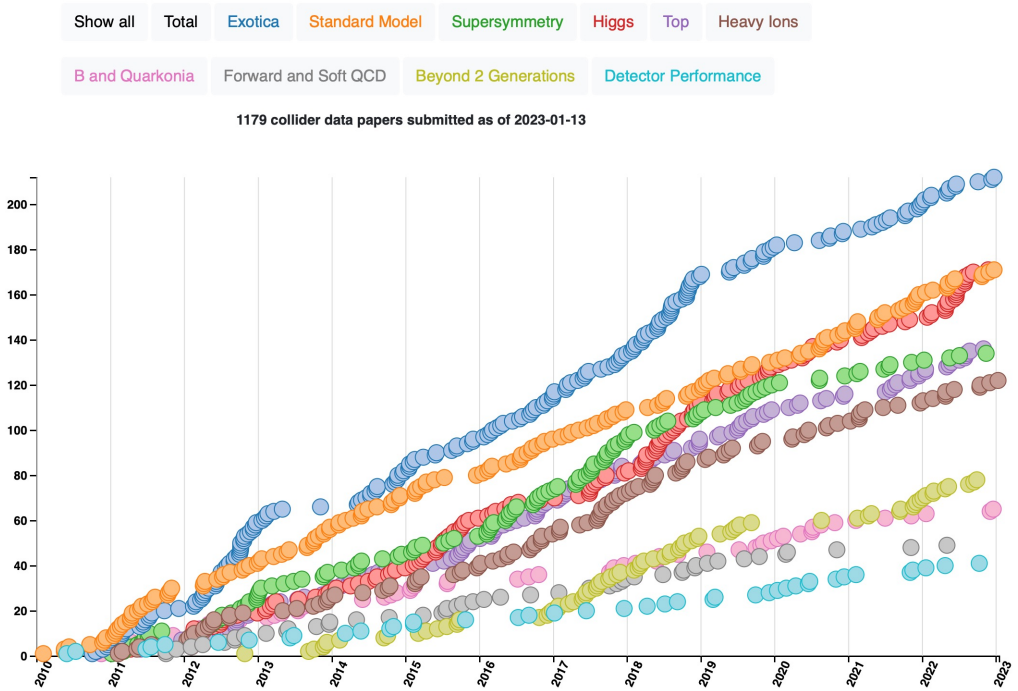
Downtime (from the restart of LHC after the RF incident in September)







CMS Publication statistics



http://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/

1179 papers on collider data published or submitted to a journal

37 papers accepted and on hold awaiting publication (waiting for the resolution of the authorship issue)

Successful physics days in September to discuss the interesting results from Run 2.
Physics Days this week - Jan 18-20.

Many Run 2 results in the pipeline.

First Run 3 result was announced at Top2022 in September.

Impact of the War in Ukraine

The CERN Council announced intention to terminate (or review) the international cooperation agreements (ICAs) with the Russian Federation, Belarus and JINR in June. This action has increased the chances of a shortfall in resources for CMS.

- Our collaborators from Russia, Belarus and JINR continue to contribute to CMS in many areas on a daily basis.
- Despite sanctions, JINR and the Russian Federation have recently been able to transfer funds for M&O payments.

Run 3 Operations: CMS relies on Russian and JINR personnel for essential expertise in operations and technical support at the experiment. The largest impact in operations of a disruption of the ICAs would be seen in HCAL, BRIL and MUON and in the P5 technical crew.

There were also plans for Russian personnel to help with installation and commissioning of HGCAL.

The potential impact of sanctions on Computing Tier 1 resources are significant for CMS. For the moment, these resources are available.

HL-LHC Upgrades

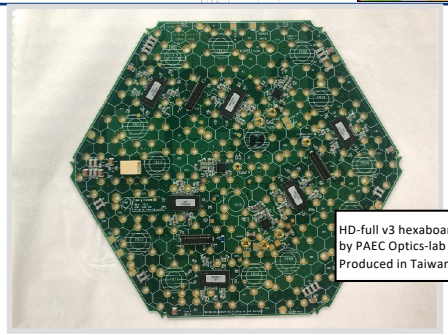
There continues to be good progress on the upgrades, but challenges remain.

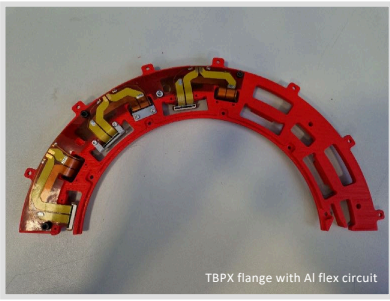
- Many projects transitioning from prototyping to pre-production and production.
- Issues: Inflation, COVID, and the war in Ukraine —> *cost increases.*

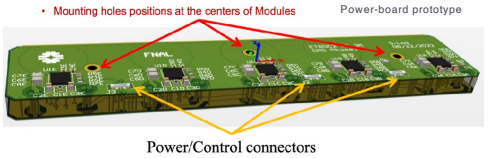
CMS is actively working to mitigate the risk to CMS if the Russian Federation and other countries are not able to contribute as planned.

CERN management and CERN advisory committees (LHCC and P2UG) have encouraged us to pursue risk mitigations for the potential *funding shortfall* caused by the war in Ukraine.

- We have proposed a plan for the Upgrades without Russian contributions that would also be able to incorporate Russian contributions - if they arrive.
- In October, CMS informed the Resource Review Board (RRB) about the plans for a Detector Upgrade Fund to mitigate potential funding shortfalls caused by the Ukraine war.







Fermilab as host laboratory for USCMS

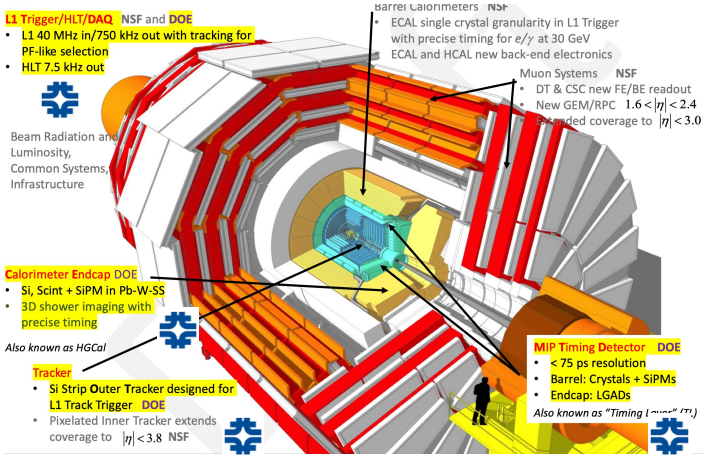
- CMS today has 2189 authors.
  - Fermilab has the largest number of active members, after CERN.
- The U.S. CMS Collaboration (USCMS) is formed of 49 US University plus Fermilab, 425 authors, 1600 active members:
  - USCMS corresponds to of ~30% of CMS.
  - Fermilab is the largest group in USCMS.
- Fermilab is the **host of the USCMS:**
  - We lead the USCMS national programs: Bauerdick, USCMS Operations Program Manager ($37.65M/year); Nahn, HL-LHC CMS Detector Upgrade Project Manager (TPC $200M)
  - We host the USCMS national centers: LHC Physics Center (LPC, co-led by Jayatilaka); Remote Operation Center (ROC); U.S. CMS Computing Facility (Tier-1 & LPC), *the largest computing center outside of CERN*.

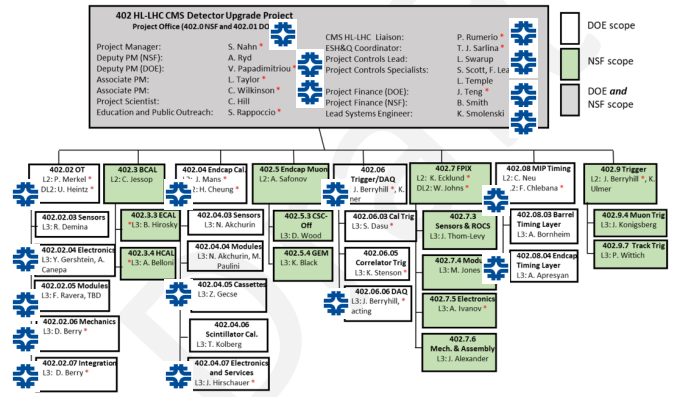
Recent scientific hires, transfers, and awards

- The group currently includes ~30 scientists and ~15 postdocs.
- We are implementing a succession planning through a yearly hiring. Since 2021,
  - (internal) Computing science researcher **E. Sexton-Kennedy**; (internal) Applications Physicist **C. Lee;** Senior Scientist, **N. Bacchetta**, Head of the Sidet facility; Wilson Fellow, **J. Ngadiuba**; Associate Scientist **F. Ravera**; *(Associate Scientist **C. Pena**, with QIS)*
  - Postdocs: A. Grummer, A. Gandrakota, I. Zoi, D. Guerrero, M. Saftari, I. Dutta, O. Amram, G. Cunnings
- Several scientists retired (R. Lipton, L. Spiegel, J. Strait): Mostly expected, risk of losing expertise is mitigated by the current succession planning.
- **Areas of growth in personnel are Detector Operations (including integration and commissioning of the Phase 2 CMS) and Physics.**
- J. Ngadiuba is the PI for DE-FOA-2705 “Designing efficient edge AI with physics phenomena” and selected as a AI2050 Early Career Fellow at Schmidt Futures.

Status of the HL-LHC CMS Detector Upgrade Project

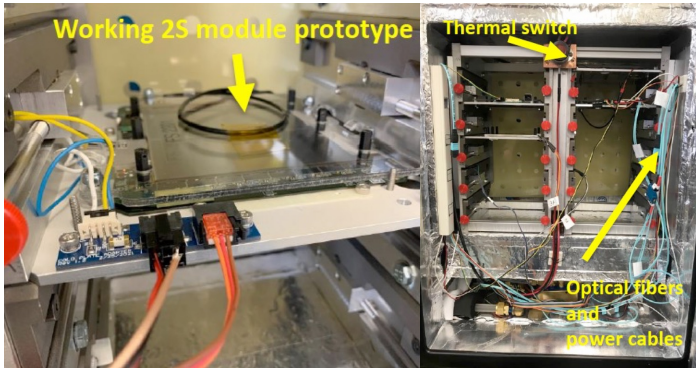
- The HL-LHC CMS Detector Upgrade Project involves the U.S. (DOE and NSF) participation in the upgrade of the CMS detector.
- DOE Scope: Outer Tracker, Calorimeter Endcap, L1 Trigger, Timing Layer.
  - Design Status Characterization: majority of project components design complete or at final stages; assembly procedures maturing in prototyping effort last and this year.
  - Schedule – installed during Long Shutdown 3 (LS-3).
- Critical decisions so far:
  - CD-1 approval December 2019; CD-3a approval on $9M scope June 2020; CD-3b approval on $7M scope June 2022.
- **CD-2/3c next week!**

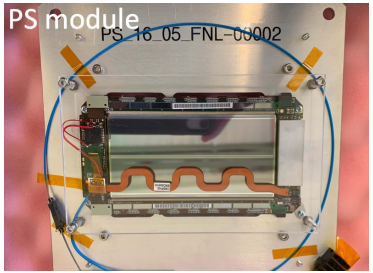


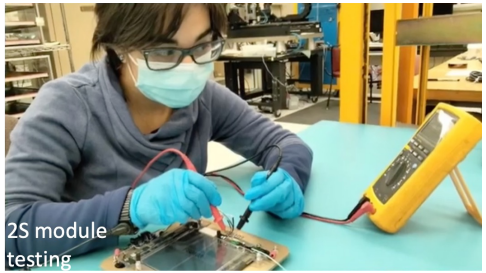


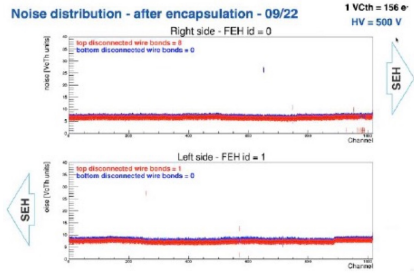
Status of Outer Tracker Project at Fermilab (1)

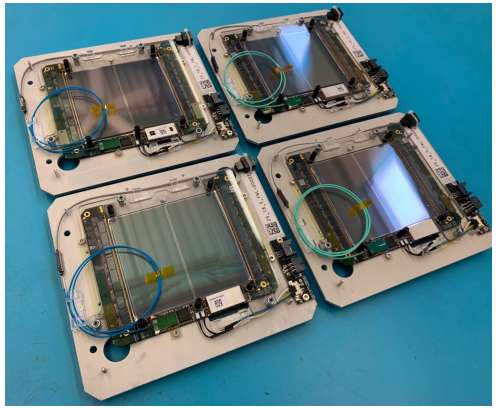
- Fermilab is responsible to assemble **~2500 PS** (pixel-strip) and ~**2000 2S** (strip-strip) modules by 2026.
  - In Dec 22, assembled 4 2S modules in parallel and demonstrated rate capability in accordance with the schedule → invaluable lesson learned to further improve the assembly process in view of the production.
- We developed test stand hardware and software, DAQ and defined testing procedures and grading criteria for production modules.







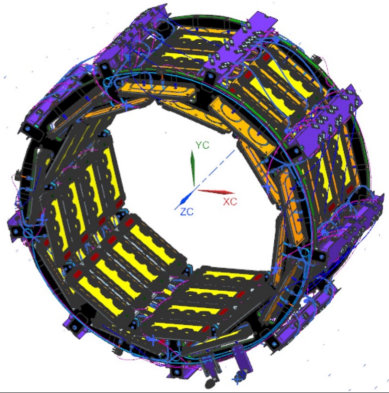




Fermilab

Status of Outer Tracker Project at Fermilab (2)

- Fermilab is responsible for producing **~6000 MaPSAs** (bump-bonded pixel sensor and readout chip):
  - completed design and prototyping; established bump bonding process in collaboration with vendors;
  - developed test system and QC procedures for USCMS and CMS;
  - we are now placing contracts with vendors and overseeing production and QA/QC; USCMS is carrying out testing:
    - received the final prototypes; >90% performing according to the specs.
- We are **designing and producing the 'flat barrel'**, 3 separate hermetic cylindrical barrel layers with PS modules mounted on CF/foam planks with embedded CO2 cooling.
  - Currently assembling the first prototype plank with (a real) PS module and preparing the SiDet infrastructure for cold testing with CO_2; pre-production planks available in Summer 2023.

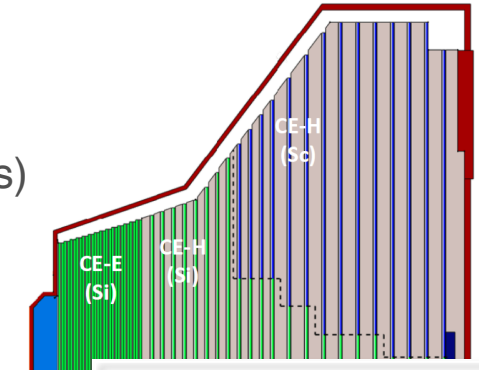


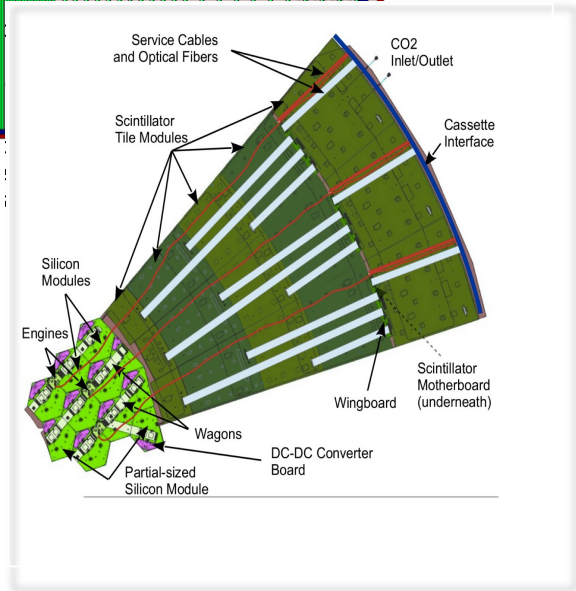
Personnel (esp. micro-assembly tech) and Sidet (esp. CO_2 system) critical to success of the project.

Fermilab

Fermilab's deliverables for the HGCal

- *Fabricate and QC 90K molded scintillator tiles** (~20 types)
- Assemble and QC ~2000 Scintillator Tile Modules (half of total in detector, 20 types)
- Design, *Fabricate, QC* ~525 Copper cooling plates (~54 types)
- Assemble, integrate and cold test 525 30-degree Cassette (100% of the hadronic section)
- Design, Fabricate, QC ~75K Concentrator ASIC (ECON) for on-detector trigger and data handling
  - First AI-on-chip in HEP: Ultrafast ML inference on ASIC to compress and encode data
- Fabricate and QC ~15K associated Concentrator PCB





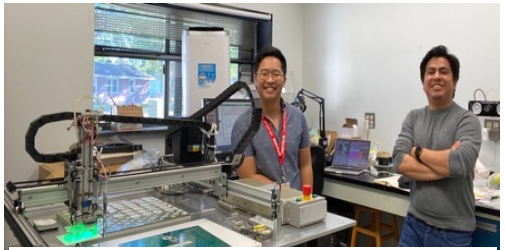
[*] italic denotes adopted scope due to the war in Ukraine.

Fermilab

Status of HGCal Project at Fermilab (1)

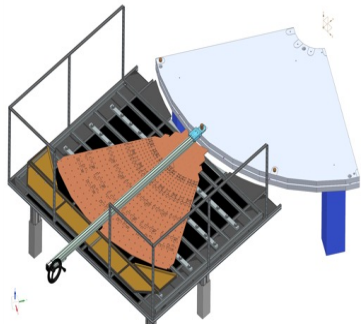
Scintillator Development and Production Facility critical to success of the project.

- We have done three 1-day runs of the injection molding machine
  - Qualified light-yield (LY); optimizing the chemical mix to have ~constant LY. Machine capable of producing ~3000 tiles per day.
- FNAL commissioned the pick&place machine through assembly of dummy modules (2/20 module types have been demonstrated).
- Scintillator tiles and modules have been tested at FTBF.



Scintillator Tile Pick-and-Place Machine

Cassette Assembly, Shipping, Insertion

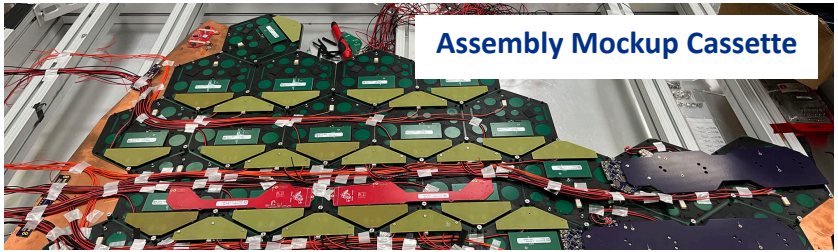


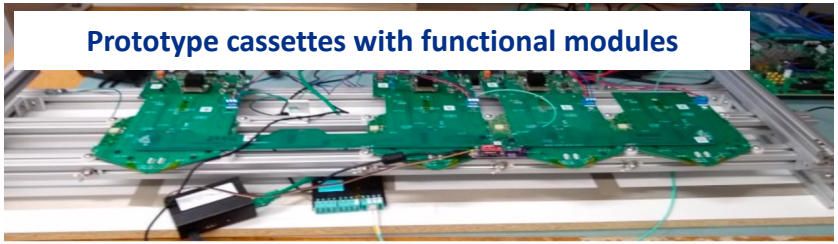
- The design of the cooling plates is advanced; we produced prototype cooling plates and we are validating the design method with 4 plates for fabrication and vendor qualification.
- We completed the design for cooling plate/cassette mounting to absorber and completed design and prototyped the fixtures/tooling to insert cassettes.

Status of HGCal Project at Fermilab (2)

Sidet (esp. CO_2 system)
critical to success of the project.

- The key infrastructure for cassette assembly is complete:
  - Assembly stations, lifting fixtures, testing rack and insulated room, shipping assembly.
- Thermal/mechanical and assembly mockup cassettes made to prototype designs and assembly procedures. Prototype cassette about to be tested with cosmics.

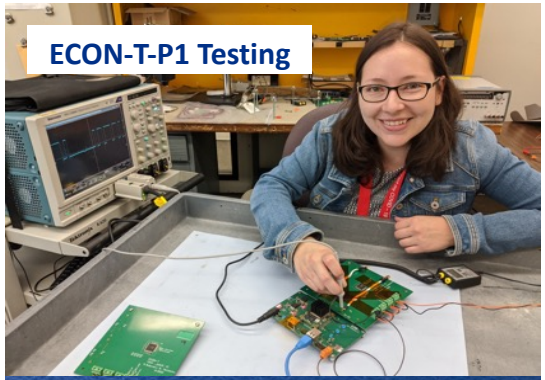




Fermilab

Status of HGCal Project at Fermilab (3)

- The ECON-T-P1 was produced and tested:
  - It works well with only a small list of bugs to fix, further enhance radiation tolerance in final ECON-T.
- The ECON-D is in verification/bug-fix cycle before submission in February 2023.
- The ASIC-testing robot was updated for production testing:
  - Working on production level QC testing and procedures
- We produced the ECON-T-only Concentrator PCB and tested it; the design for PCB with both ECON-T and ECON-D is also done.
- The Fermilab ITA was used for SEE testing.

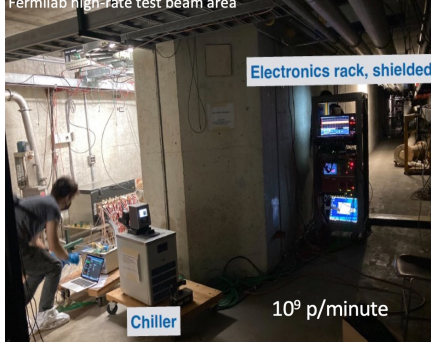


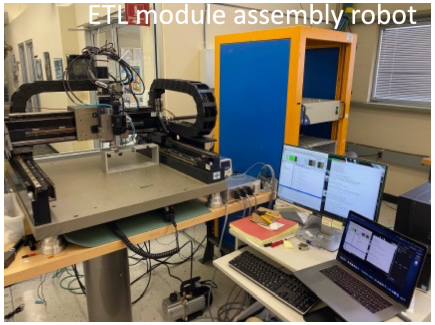
ASIC personnel remains critical.

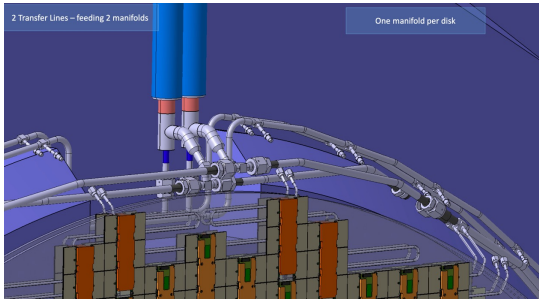
Fermilab

Status of MTD Project at Fermilab (1)

- Fermilab is leading almost **every aspect of R&D, prototyping, production of ETL modules**:
  - ETL modules built from sub-assemblies containing 4 sensors that are bump bonded to 4 ETROC ASICs;
  - ETROC: 16x16-pixel matrix bump-bonded to LGAD sensors;
  - LGAD: silicon sensors with specially doped thin region with high electric field: ~10-30 gain.
- We have completed sensor market survey of the LGAD sensors:
  - FTBF (including its high intensity facility) was critical in establishing LGAD technology and studying unforeseen mortality.
- Fermilab is responsible to **assemble ~2000 modules and plays a major role in the technical integration at CERN**:
  - Successfully assembled full module mock-ups with accuracy of 10 μm.



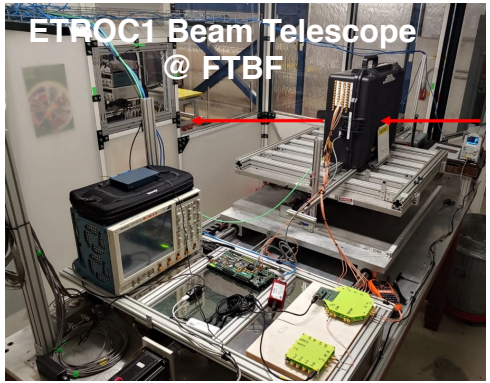




Status of MTD Project at Fermilab (2)

- Fermilab is responsible to **develop, produce, QC the front-end ASIC, ETROC**.
- ETROC is designed to process LGAD signals with time resolution below 50ps per hit, in order to reach ~35 ps per track with two detector-layers.
  - Very challenging design, first generation precision timing chip.
  - 7 successful prototype chips developed, each focusing on different design aspects.
  - ETROC2 first full-size (21mm x 23mm) and full- functionality chip submitted in October 2022.
    - Preparing extensive tests for ETROC2.
  - ETROC3 is being designed as final prototype, possibly final chip.

ASIC personnel remains critical.

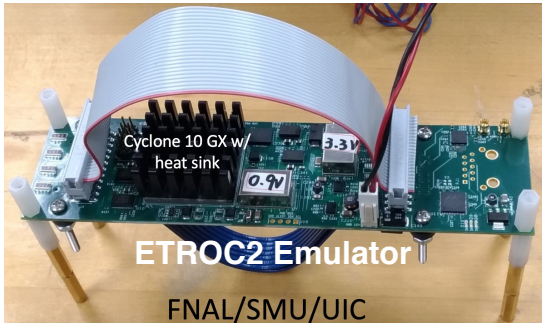


Single-hit timing resolution (ps) with TWC:

$$\sigma_i = \sqrt{0.5 \cdot \left(\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2\right)}$$

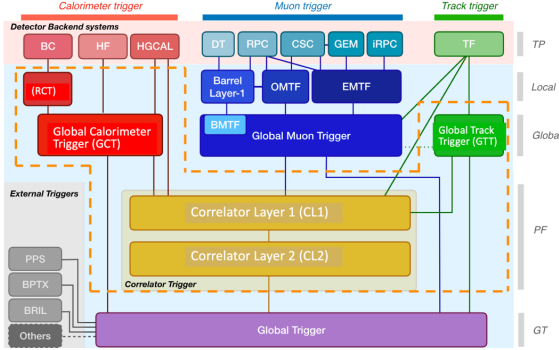
~ 42.0/42.7/41.3 ps (2021 beam test)

~ 41.3/38.0/41.3 ps (2022 beam test)

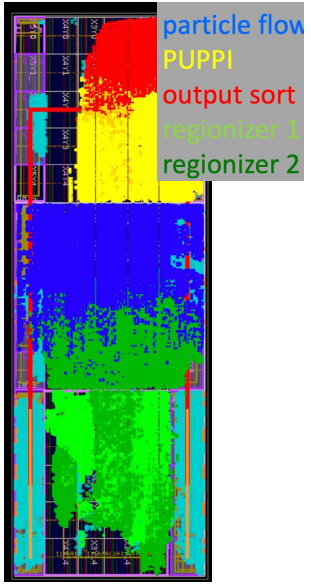


Fermilab

Status of L1 Trigger Project at Fermilab



- Central feature of L1 trigger upgrade is the "**correlator trigger**"
  - Particle-flow (PF) at L1: matching/classification of tracks and clusters, reconstruction of MET, jets, taus; pileup (PU) removal;
  - **Fermilab implements FW for PU removal and PF MET and HT reconstruction**;
  - We have developed pre-production FW: it meets timing with <50% resource use; latency of 1.1 μs is sufficient to meet the requirements; simulation and emulation match in single board tests.
- **ML algorithms** have natural extension to HL-LHC system
  - Endcap muon trigger adopting NN-based, improved muon reco with upgraded inputs and tracks; introduce anomaly detection in HL-LHC global trigger and correlator trigger with PF input; use NN methods for MET regression with PF or other inputs.
- **L1 scouting with PF** output introduces broad 40 MHz physics capability.



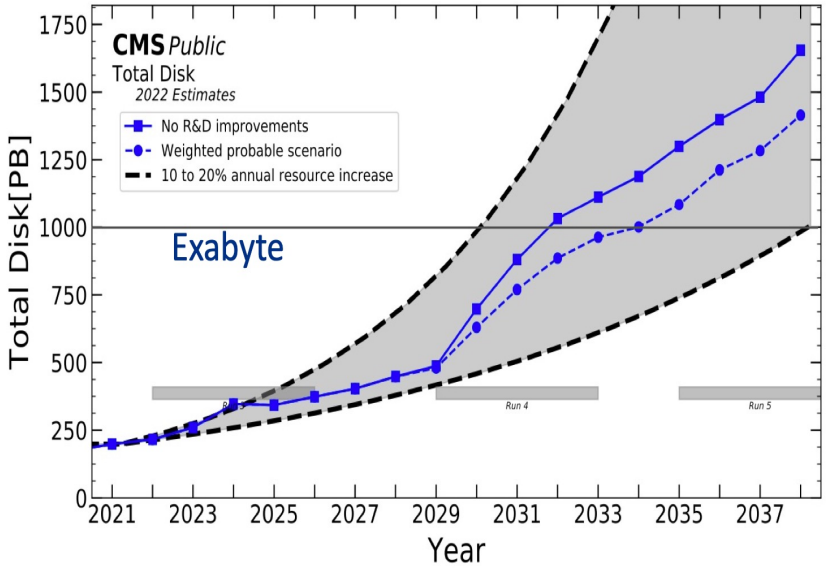
Fermilab

Status of the U.S. CMS Operations Program

- Fermilab scientists lead the U.S. CMS Operations Program
  - manage an extensive program of work, ~100FTE jointly funded by DOE and NSF
  - staff the U.S. CMS Ops program office at Fermilab and at CERN
- Achieved all objectives for LHC Long Shutdown 2 and Run 3 initial run
  - CMS detector and S&C systems were ready for Run3, taking high quality data
  - High-Performance Computing now seamlessly included in US CMS data production chain, providing opportunistic compute cycles to CMS, on average as many as the Tier-1
- Provide technical leadership for the innovative program of R&D
  - developing the HL-LHC software and computing systems
  - working out how to build the exa-scale HL-LHC Tier-1 center and Analysis Facility
  - Elastic Analysis Facility (EAF) multi-experiment facility with full CMS software support

Software and Computing at Fermilab (1)

- The Fermilab group has led **the formulation of 4 "Grand Challenges"** for the USCMS Operations program and aligned its S&C research efforts to address them
  1. Modernize physics software and improve algorithms.
  2. Build infrastructure for exabyte-scale datasets.
  3. Transform the scientific data analysis process.
  4. Transition from R&D to operations.
- The activities target both the ongoing run and the HL-LHC by performing R&D and prototyping.
  - Fermilab is co-coordinating the CMS phase2 O&C Conceptual Design Report process.

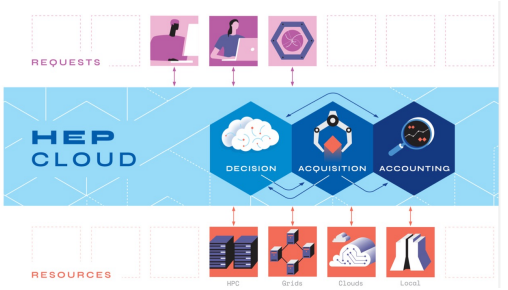


S&C activities leverage the [non-CMS] expertise in the Fermilab Computational Science and AI Directorate.

Fermilab

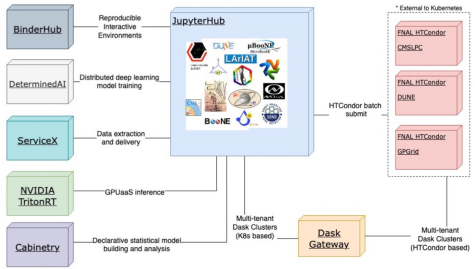
Software and Computing at Fermilab (2)

- **Computing infrastructure thrust**
  - Run-3: deliver new and unique capabilities to CMS.
    - HEPCloud provides seamless portal to HPC and commercial clouds; LPC-CAF provides access to advanced capabilities like GPUs and FPGAs; Elastic Analysis Facility (EAF) is new way to support end-user analysis.
  - HL-LHC: prepare to build Fermilab infrastructure for exabyte-size dataset, with focus on R&D for novel storage and network technologies.
- **Modernize software with novel frameworks**
  - Enabling algorithms to seamlessly use both CPUs and GPUs from different vendors through portability libraries together with DOE's HEP Center for Computational Excellence (HEP-CCE), and supporting them in the framework;
  - Celeritas: a Geant4 adaptation for optimal use of GPUs using the ExternalWork CMSSW framework feature;
  - SONIC: ExternalWork using remote accelerator system.



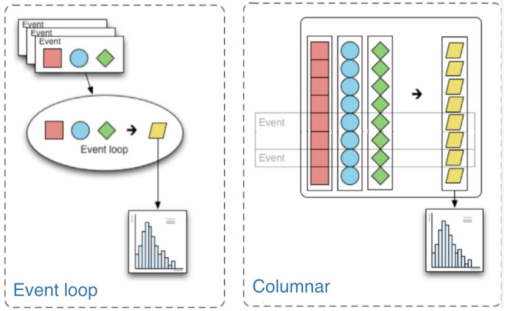
Access to both DOE and NSF supercomputers; the U.S. provided HPC resources as much as the Fermilab Tier-1 (average over 2022, peak over 100k cores)

Fermilab Elastic Analysis Facility



Fermilab

Software and Computing at Fermilab (3)

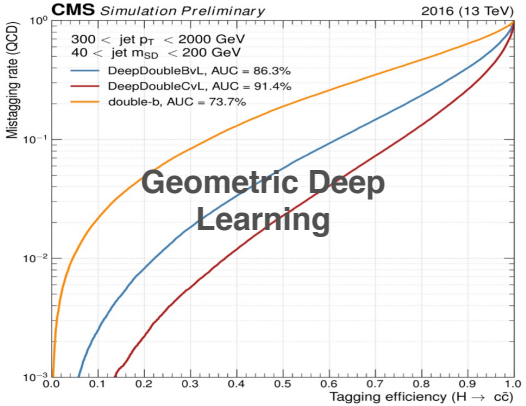


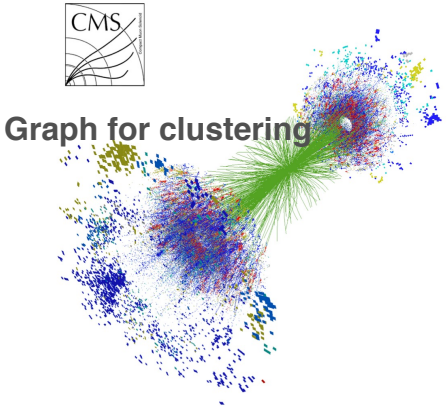
- **Software thrust**
  - Run-3: deliver new capabilities
    - CMS framework can seamlessly use GPUs and FPGAs; Stewarded through the new particle tracking that is optimized for vectorization and is ~10% faster --> deployed for Run-3 (mkFit).
  - HL-LHC**:** physics and analysis software for heterogeneous architectures.
- **Analysis Thrust:** Column Object Framework For Effective Analysis or COFFEA
  - Using industry-standard python-based data science techniques, combined with HEP-optimized data models, significantly speeds up analysis, enables access to novel computational capabilities like advanced computing algorithms, latest ML/AI techniques, etc. Close collaboration with NSF's IRIS-HEP providing foundational libraries to connect HEP with industry tools;
  - > 170 scientists are now using COFFEA
  - Optimizing hardware setups e.g. implement GPU acceleration, data delivery through ObjectStores.
  - The Fermilab Elastic Analysis Facility is spearheading the effort, together with university partners.

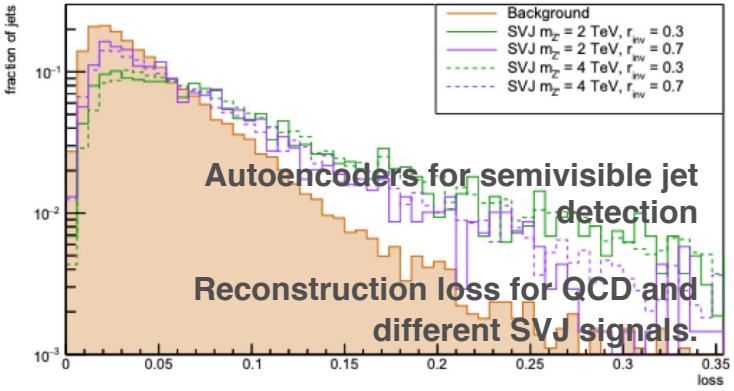
R&D and exploitation of AI/ML

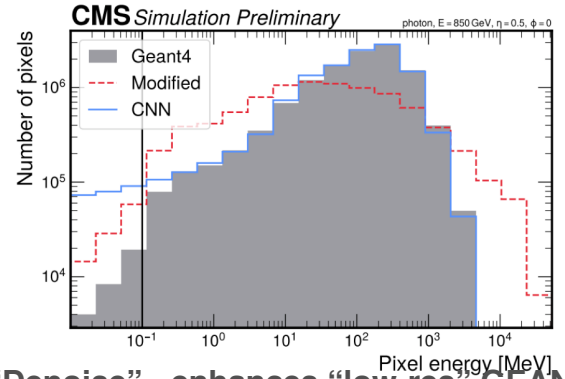
- We are performing cutting edge **R&D in AI/ML embedded in the laboratory's initiative** and enabling breakthroughs in data collection, monitoring, processing and offline data analysis.
- Our **ML research thrusts aligned with physics drivers**: deeper insights & better performance; accelerate time-to-physics; improved operational efficiency
  - Run 2: novel reconstruction algorithms improve sensitivity to exotic searches and Higgs measurements; background estimation robustness in Stealth SUSY.
  - Run 3: new ML reconstruction including graphs, anomaly detection, and semi-supervision; accelerating simulation; broader adoption in the L1 trigger.
  - HL-LHC: exploration of more powerful/robust learning methods for simulation and reconstruction; accelerating workflows with coprocessors; more ML in trigger and moving ML closer to the sensor (ASIC).

Selected examples of AI/ML R&D and deployment

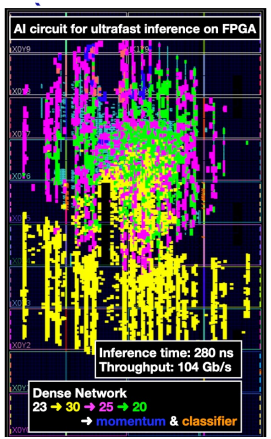








"Denoise" - enhances "low-res" GEANT with generative ML modeling to accelerate simulation



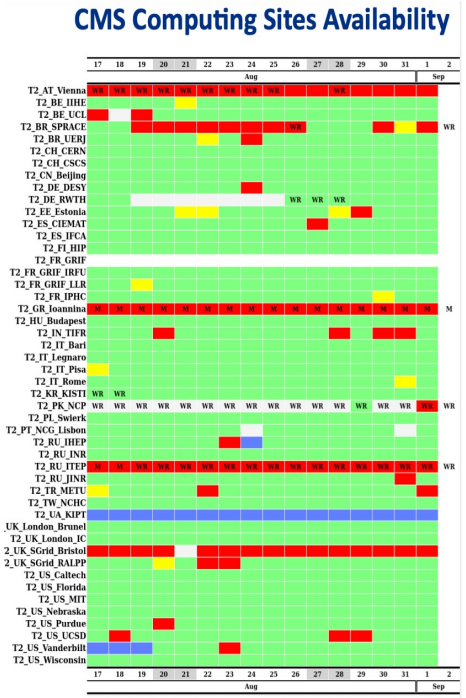
L1 trigger: Run 3 displaced muon ID enables completely new capability; muon momentum regression cuts rate by > 2x for HL-LHC

ECON:
First design and implementation of modern DL for HEP

Fermilab

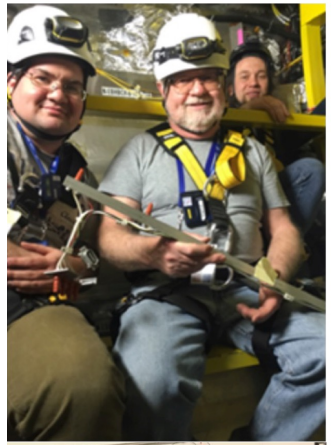
Computing Operations

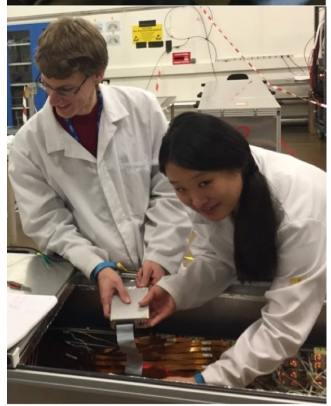
- **Run-2: T**he Fermilab facility provided reliable resources, and CMS operated central services successfully.
  - Fermilab coordinated the operation of data processing,Tier-0, and data transfers, as well as keeping all >70 sites of CMS functional
- **Run-3:** Successful multi-year project to integrate new data management system Rucio.
  - Community solution originally developed by ATLAS, transfers datasets of files between sites and keeps track of location
- **HL-LHC:** on the path to HL-LHC, continually transition R&D prototypes into operation: from R&D to Deployment & Maintenance
  - Data Challenges and prototype facilities provide a test bed.
  - Example is Fermilab's Elastic Analysis Facility for user analysis: scheduled to go into full supported "production" mode in 2023.



Contributions to Detector Operations

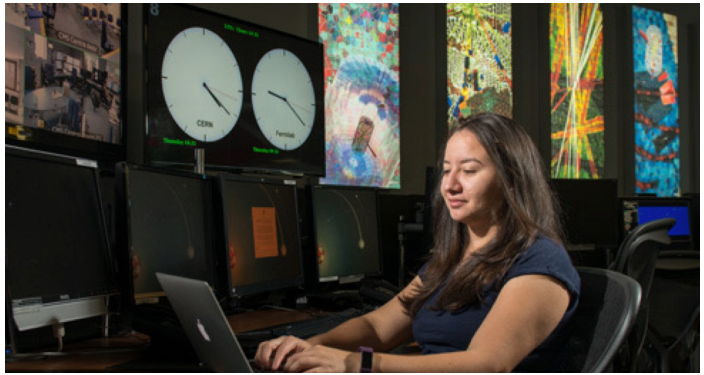
- Fermilab scientists played major roles in Operations during Run2 and LS2:
  - Maintenance, operations, commissioning and integration of Phase1 upgrade detector components, for HCAL, FPIX, Trigger, DAQ.
  - Technical leadership and coordination of CMS DAQ system, Run Coordination, Data Quality Monitoring (DQM), databases, etc.
- Fermilab is leading the CMS Physics Performance & Datasets coordination area:
  - DQM software and calibration workflows (online and offline), certification of offline reconstruction of collision data and Monte Carlo simulations. and validates physics performance of offline and online reconstruction releases.
- **We have stationed an RA and an applications physicist at CERN to help with Run Coordination and shifts, etc.**





Remote Operations Center

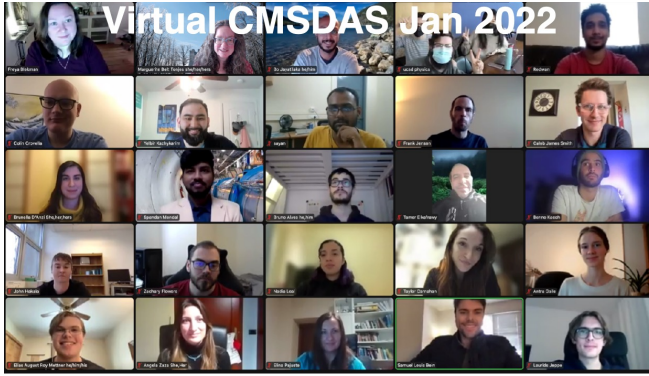
- The ROC is a physical remote-control room, connected with CERN, in Fermilab Wilson Hall.
- ROC was very successful during Run1 and Run2:
  - *E.g.* in 2017, 155 of 304 Tracker Offline shifts done at the ROC 10 institutes involved, 18 shifters.
  - Cost effective way to support online shifts, benefits the community and is synergistic with the LPC.
- **For Run3, the ROC is the 1st ROC in CMS to be qualified for DQM online remote shifts.**
- We are developing new models for taking and training for shifts, and for assisting run coordination from Fermilab, including the possibility of doing some CMS core shifts at the ROC.



An Operations Support Scientist will join the LPC staff in 2023 and will have primary ownership of ROC activities, including central shift management.

The LPC

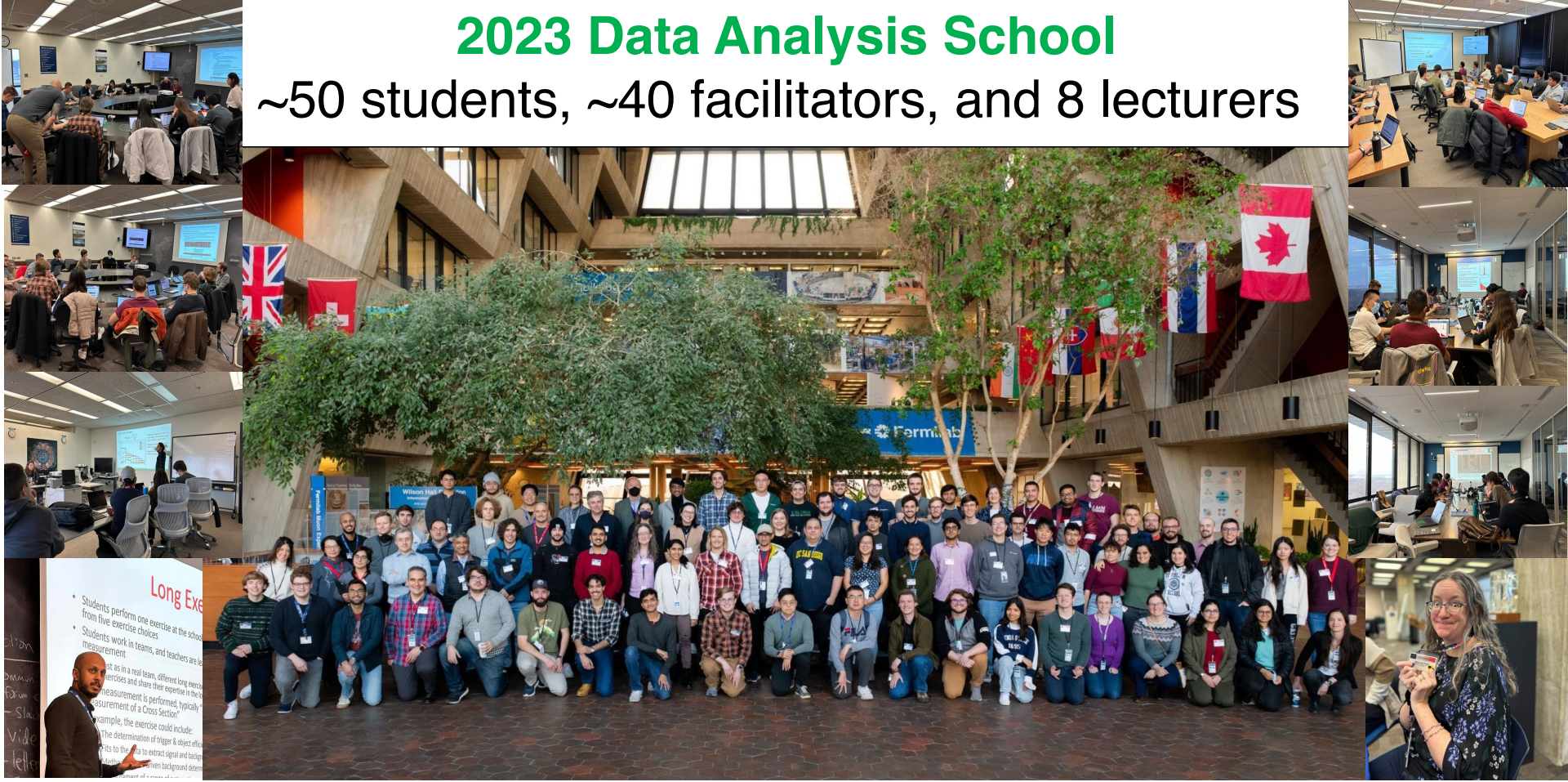
- The pandemic and resulting lockdown of Fermilab moved all LPC activities to be virtual-only
  - LPC community was able to stay “connected” during pandemic lockdown via regular Zoom-based LPC events.
  - LPC proved to be as vital a hub in the work-from-home world as well.
  - LPC G&V program was able to bring users to Fermilab for essential hardware work.
  - Full-scale CMS DAS moved to online-only in 2021 and again in 2022.
- **In 2022 returning to in-person activities:**
  HATS continue to be hybrid (and recorded)
  Most regular seminars/talks now in hybrid form.



Fermilab

2023 Data Analysis School

~50 students, ~40 facilitators, and 8 lecturers



Recent physics results: overview of the group's strategy (1)

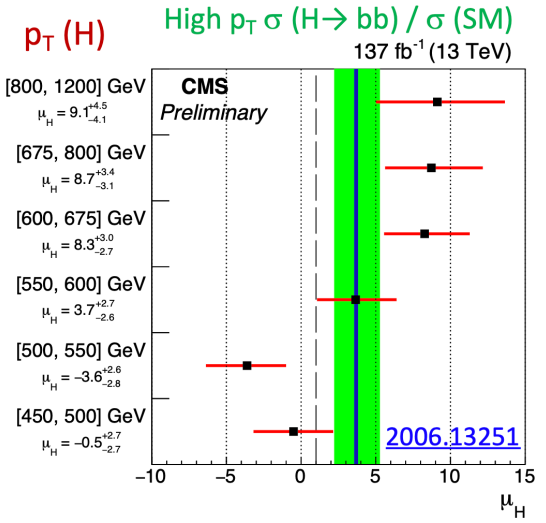
- Our physics program aims at answering three fundamental questions: (1) What is the nature of the Higgs boson? (2) What is the nature of dark matter? (3) What is the fundamental theory of the universe?
- In the recent years, we evolved the program from classic models with classic signatures to incorporate
  - Analyses that benefit from increased luminosity instead of big jumps in energy (which are over).
  - Advanced techniques proposed by Fermilab to increase analysis sensitivity.
  - New signatures to outperform existing published results in classic BSM and precision measurement.
  - New models to explore the latest theoretical ideas.

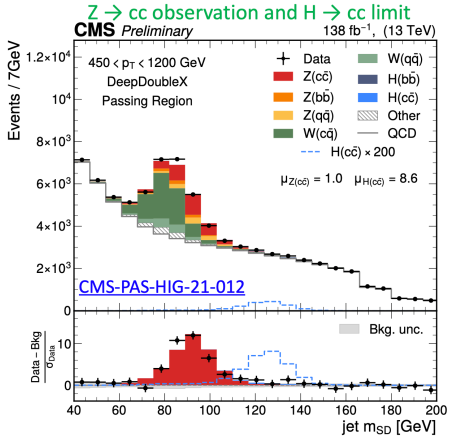
Recent physics results: overview of the group's strategy (2)

- We develop a synergistic Run 2 program with 3 main thrusts aimed at the 3 fundamental questions:
  - Higgs physics
    - Boosted single Higgs (at high pT in ggH, VH and VBF) and Di-Higgs;
    - Higgs via electroweak precision measurement, especially VBS and tribosons.
  - Dark Matter
    - A complete program of dark sector physics and self-interacting and inelastic DM.
  - BSM
    - Long Lived Particle, dijet resonance; SUSY searches, in pursuit of new particles from a fundamental theory.
- *In the following slides, we summarize analyses proposed and brought to publication by Fermilab scientists and postdocs in late 2021 and 2022.*

Boosted Single Higgs Boson Production

- We updated & improved gg→ gH(→ bb) with deepDoubleX tagger: 2006.13251.
- We observed H → bb cross section at high pT is slightly larger than SM prediction.
- We pioneered the search for Higgs couplings to 2nd generation fermions: gg →gH (→ cc)
  - 1st search in high pT regime.
  - Made possible by DeepDoubleX tagger.
  - Observed Z → cc standard candle at well over 5sigma.
  - Limits on H → cc (45x SM).
  - Complementary to VH(→ cc) providing additional sensitivity at high pT.



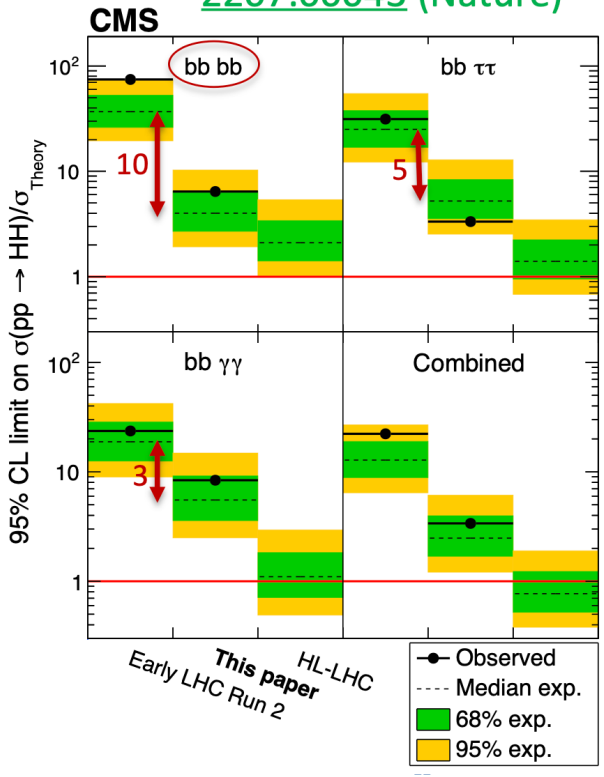


Fermilab

DiHiggs Production

- We enabled a major paradigm shift by adding high pT events from boosted H → bb to the Di-Higgs search.
  - Used a novel algorithm based on a Graph Neural Network to significantly improve ID of H → bb within the DiHiggs process.
- New search improves expected limit by factor of 10 in HH → 4b between the 36/fb and 138/fb analysis.
  - Compared to factor of 3 – 5 advances by other channels.
  - The sensitivity in HH → 4b is now the best for HH searches after the addition of boosted HH → 4b 2205.06667.
- Increased Di-Higgs sensitivity in Run 2 to HL-LHC levels
  - In 2018 expected 1 sigma sensitivity per experiment at HL-LHC
  - Now projecting 5 sigma combined CMS and ATLAS in HL-LHC!

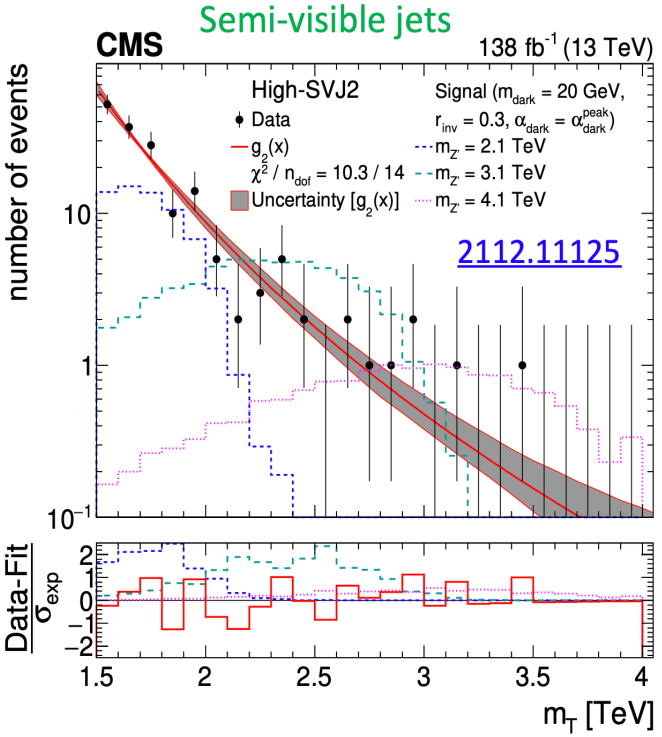
Di-Higgs Xsec Limits
2207.00043 (Nature)



Fermilab

Novel signatures for Dark Matter

- We published the first search for dark matter from a strongly-coupled hidden sector: search for semi-visible jets with MET along jet axis.
  - It sets limits on s-channel Z' $\rightarrow \chi\chi$ which hadronizes in a dark shower of SM particles and dark matter.
  - Advanced analysis technique uses BDT tagger with jet substructure and mass decorrelation were key.
- Other novel searches are well advanced:
  - Searches for long-lived dark matter are inelastic and self-interacting dark matter decaying to collimated lepton pairs;
  - Low mass boosted Z' decaying to semi-visible jets t-channel production of semi-visible jets.
  - Emerging jets: displaced vertices from long-lived dark hadrons.
  - Higgs decaying to dark quarks gg $\rightarrow$ gH($\rightarrow \chi\chi$) with dark shower

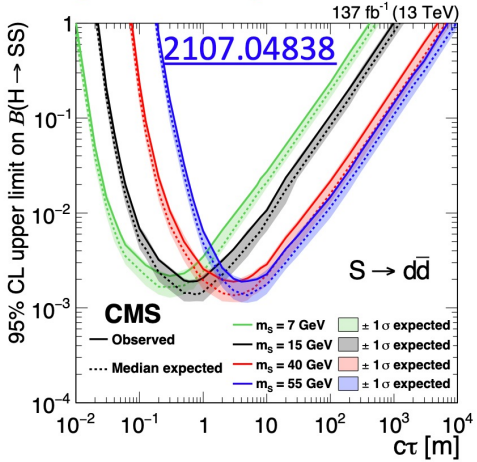


Fermilab

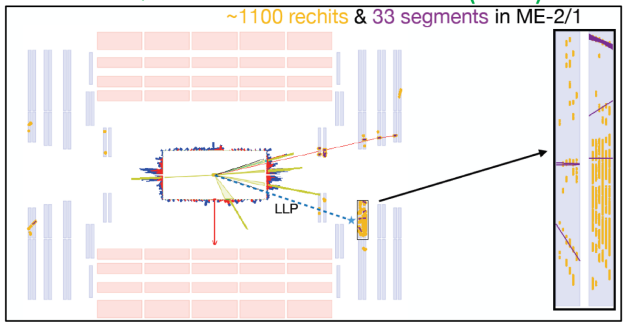
Searches for Long Lived Particles

- Fermilab has a broad and high impact program in LLPs covering a large range of lifetimes
  - Led the search for H → SS with displaced dijets 2110.13218.
  - Pioneered search for H → SS using muon detector shower (MDS) signature 2107.04838.
    - MDS is a completely new signature, sensitive to lower BR, lower mass, and much higher ct than prior searches.
- We developed and led commissioning of High Multiplicity Trigger (HMT) in muon system which uses MDS signature
  - Complete path: counts hits at L1, clusters hits at HLT
  - We installed at P5, took first data in August, supporting now.

MDS Signature: Higher cτ search



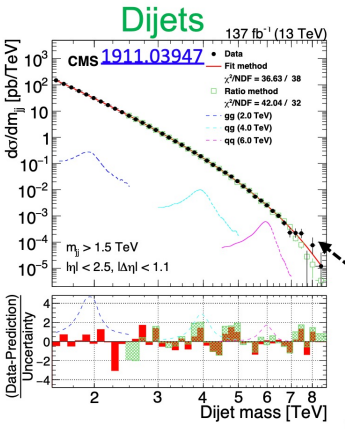
LLP → Muon Detector Showers (MDS)

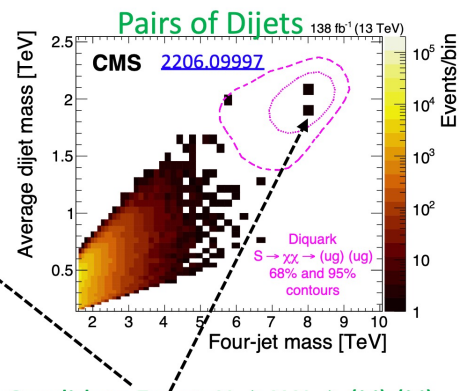


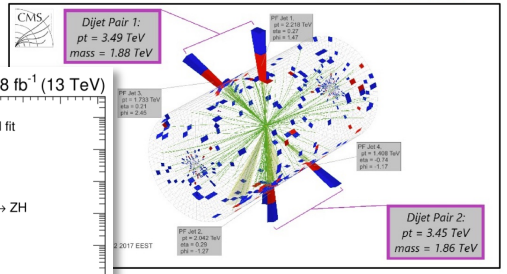
Fermilab

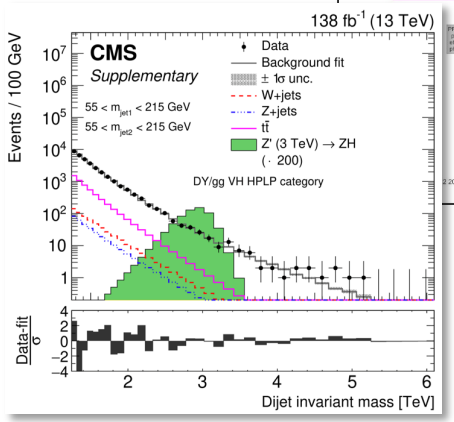
Exotica

- We exploit the energy frontier searching for new physics on the high mass tail
  - Classic exploration at the core of the CMS program
- Search for resonances decaying to pairs of dijet resonances 2206.09997
  - 2 events with 3.9sigma local significance, 1.6sigma global significance for Y → X X → (j j) (j j)
- Recently submitted search for new heavy resonances decaying to WW, WZ, ZZ, WH, or ZH boson pairs in the all-jets final state 2210.00043
  - intriguing excesses at 2.1 and 2.9 TeV, with a maximum local significance of 3.6 sigma (2.3 global).









Fermilab

Contributions to Future Colliders

- A Future Colliders Group (FCG) was formed in 2021 with the following objectives:
  - Develop Fermilab's engagement plans in future collider projects, across aspects of accelerators, technology, particle physics and detectors.
  - Provide a forum to synergize efforts on future colliders across frontiers.
  - Develop a roadmap for further (design) studies and R&D for future colliders.
  - Work with the US university community and international collaborators on pertinent issues and proposals (arXiv: 2203.08088, arXiv:2207.06213; engagement in international efforts like FCC, ILC,…).
- The FCG helped the the Snowmass Accelerator and Energy Frontiers to organize a series of events, intended for all Snowmass participants, to critically discuss physics and technical aspects of different HEP collider concepts.

Contributions to Snowmass

- Overall, CMS scientists and postdocs co-authored 46 Snowmass' White Papers in five broad categories:
  - 14 in Physics; 12 in detectors, technology and experiments; 9 in accelerators; 7 in Software, Computing and Machine Learning; 4 in environment and society.
- The LPC was important in facilitating Snowmass work (many papers have core groups from LPC, seminars, etc).
- Fermilab physicists also played key roles in preparation of the topical group, cross-frontier, frontier, and Snowmass summary reports.

- DPF Leadership:
  - Joel Butler (DPF Chair)
- Frontier Conveners:
  - Petra Merkel (Instrumentation)
  - Oliver Gutsche → Daniel Elvira (Computing)
- Topical Group Conveners:
  - Artur Apresyan (Instrumentation)
  - Jim Hirschauer (Energy)
  - Kevin Pedro (Computing)
  - Don Lincoln (Community Engagement)
- Cross-Frontier Roles:
  - Christian Herwig (Early Career In-Reach)
  - Sergo Jindariani (Muon Collider Forum Coordinator)

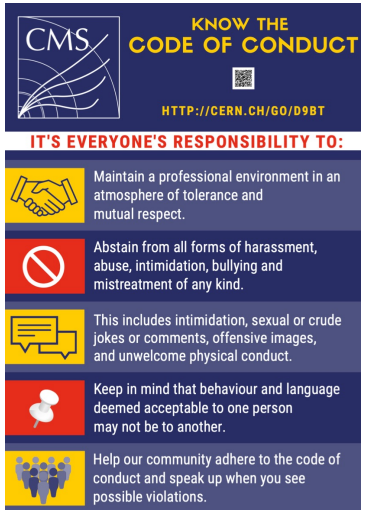
- Berry, Canepa, Ngadiuba, Merkel, Tran were selected as members of the lab's Science Priorities Working Group helping preparing the lab for P5; Bhat providing input to Proton Intensity Upgrade Central Design Group.
- Merkel was appointed as a member of P5.

Postdocs mentoring program

- The CMS group has a formal mentoring program that prepares postdocs to obtain tenure-track positions at universities & national labs or the position of their interest.
- Each research associate is supported by a team of 2-4 scientists. *More information can be provided, including the document presenting the program.*
- The program was developed over a decade within the CMS group. It is being used as a model and propagated to other divisions at Fermilab.
    - 29 (64%) of the 45 research associates who completed the mentoring program found tenure-track positions. APS estimates that roughly 20% of post-doctoral researches in physics move on to tenure-track positions.
    - Individuals who are not interested in tenure-track faculty positions are supported in their career endeavors (Apple, Toshiba Memory, Data Science, …).
- The CMS mentoring program has extensive support from the scientists in the CMS group 33 scientists participate in the CMS group's mentor program since its inception.

Group's plan in DEI (1)

- The CMS group members both lead and participate in DEI efforts, at Fermilab and collaborating organizations (USCMS, CMS), with focus on the the following six key areas:



1. Serve as leaders in DEI programs

- Jayatilaka is the co-founder of the CMS Diversity Office and author of the CMS Code of Conduct; Butler served as a co-chair of the Task Force on Diversity and Inclusion (TFDI), including Jayatilaka; Butler and Canepa serve on the Implementation Task Force on D&I (ITDI). Bauerdick established a formal DEI plan for USCMS; Berry and Elvira serve on the DI task force at the lab; Burkett and Sexton-Kennedy are on the lab's Senior Leadership DEI council.

2. Connect URM candidates with the CMS group, USCMS, and the LPC

- Scientists and postdocs are involved in almost all programs at the lab attracting a diverse undergraduate and graduate community of students at the lab; Elvira is the founder of the Vamos a Fermilab Program.

Fermilab SIST & GEM Interns (2019)

Vamos a Fermilab

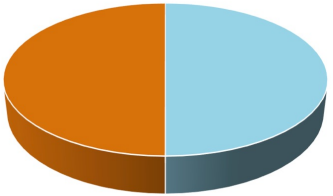
Fermilab

Group's plan in DEI (2)

3. **Provide a fair and equitable hiring process that promotes a diverse candidate base**
   - The CMS group committed to hiring diverse personnel; broad participation in hiring committees at the lab**.** Butler, Jayatilaka, Jindariani serve on the Scientist Hiring Committee, aiming at increasing the number of URM candidates hired to scientist positions.
4. **Provide mentoring, training, and coaching to FNAL group members, LPC Members, and to the HEP community**
5. **Create a welcoming and nurturing environment**
6. **Participate in outreach and community engagement activities**

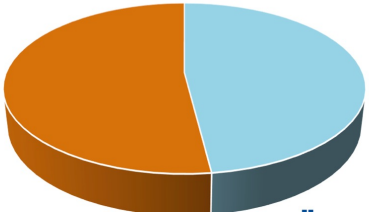
More information can be provided, including a document presenting our efforts and plans.

Tenure and Tenure-Track Hires Sept. 2015 to Sept. 2022



Non-URM URM or Women

Research Associate Hires Sept. 2015 to Sept. 2022



Expanding Your Horizons Program

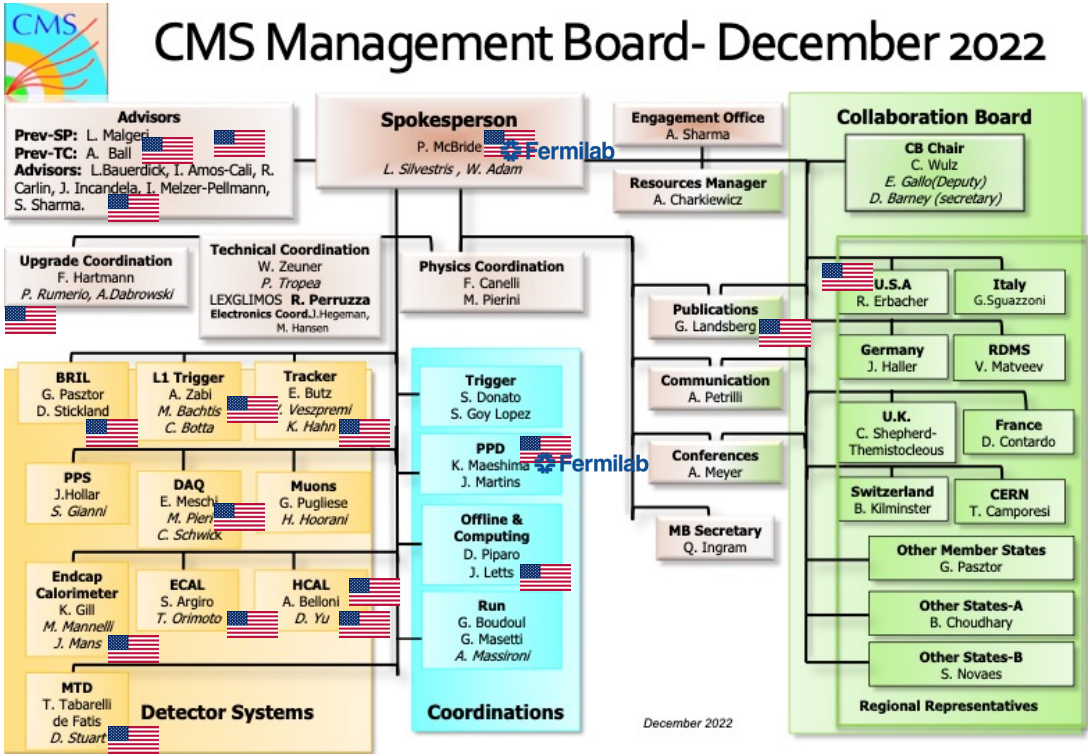
Summary

- The Fermilab CMS group had achieved major milestones in data analysis, detector upgrades (and R&D), detector operations, and S&C R&D.
  - Our strategic plan is aligned to the P5 recommendations and CMS.
- Fermilab scientists and postdocs have continued to be recognized for their critical contributions and selected for high profile awards and leadership positions within CMS, USCMS, and the HEP community.
- Our program and the US HEP community depends on the unique infrastructure provided by Fermilab.
  - Availability and upgrade of facilities (Sidet, FTBF, ITA, scintillator production) and of availability of competencies (ASICs, micro assembly) remain critical.
  - The long-term effectiveness of the LPC depends on re-establishing in-person activities, smooth campus access is key.
- The CMS group at Fermilab has a demonstrated record of accomplishments. It is thus positioned to deliver the CMS program and to play a major role in Future Colliders.
  - The program is however expanding (analysis of Run2 and Run3 data, Run3 detector and computing operations, S&C, detector upgrades). A timely succession planning of scientific and technical staff is crucial.
  - To play a role in the future of collider physics, investments in detector R&D (personnel and M&S) is required.

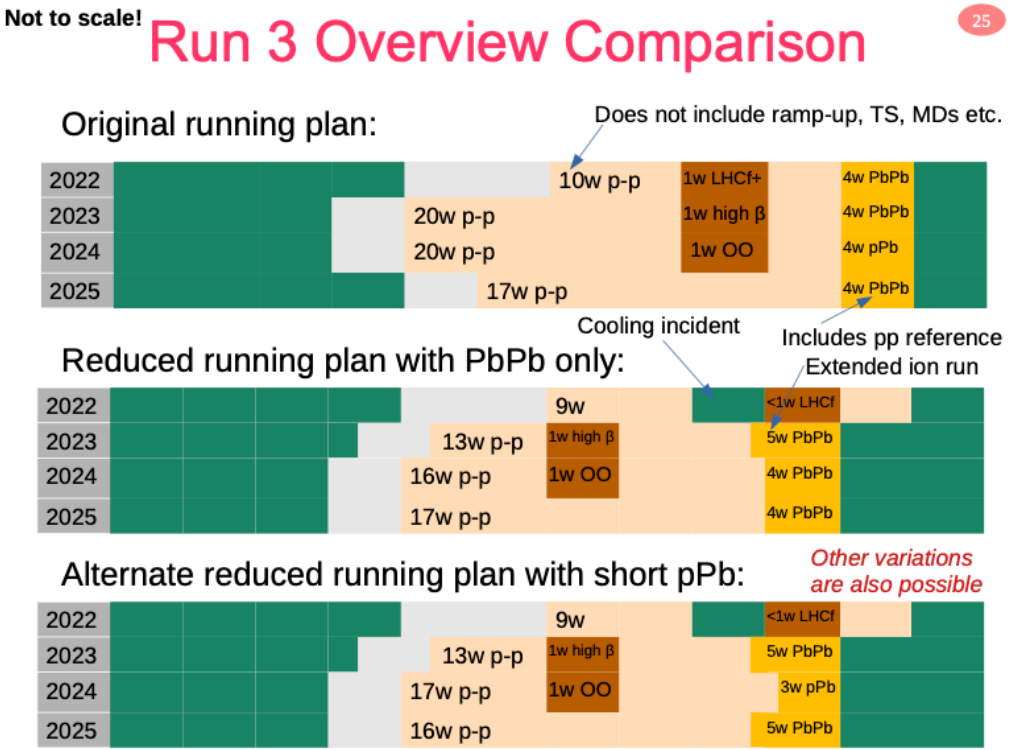
Additional Material

CMS Management Board

- The CMS Spokesperson Team transition on September 1, 2022 - along with several new coordinators.
  - Overall an experienced team
  - Excellent involvement from US CMS.



LHC Run 3 operations



Impact of the energy crisis on LHC operations:

Plan to avoid running during periods when electricity prices are high (Nov-Feb)

==> **~ 20% reduction in running time**

Some relief could come from reduced Machine Development (MD) periods and minimizing setup time - for example, by skipping the HI run in 2022.

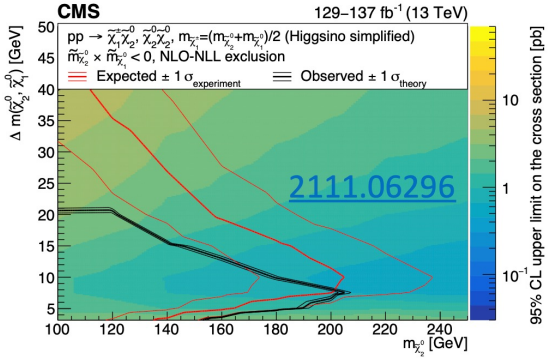
It is still possible that some of these measures could be scaled back in the future.

Author lists for CMS Publications

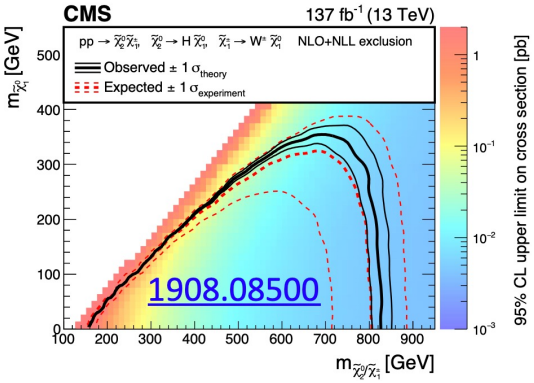
- The reaction to the war in Ukraine within the LHC collaborations and within our funding agencies has made it essentially impossible to continue publishing with the established scheme for author lists. We have been submitting papers to journals and to the archives for nearly a year with only “CMS Collaboration” listed as the author. These papers (37) have not yet been published.
- We are working with our collaboration boards to find an author list representation that is acceptable to the community. Our goal is to continue to recognize the contributions of ALL our colleagues and to maintain the collegial and productive atmosphere of CERN and of the LHC collaborations. Not everyone agrees on how best to do this under the current circumstances.
- The leaders of the LHC collaborations - with support from the CERN management - have worked to keep unity within the collaborations and across the four collaborations during this process.
- In all schemes, the names of all qualified authors will continue to appear on the publications - together with the ORCID.
- The implementation of the selected option will be temporary - only until the end of 2024 at the latest.

And more analyses aligned with our strategic plan …

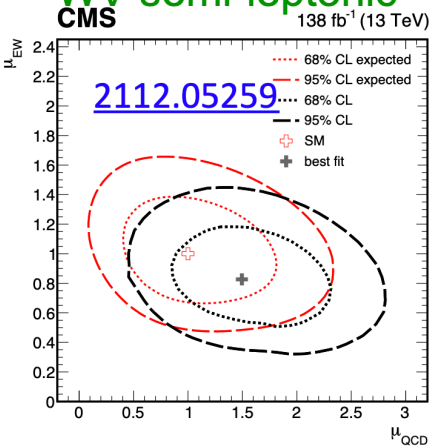
Compressed (Mid-mass $\tilde{\chi}_1^0$)

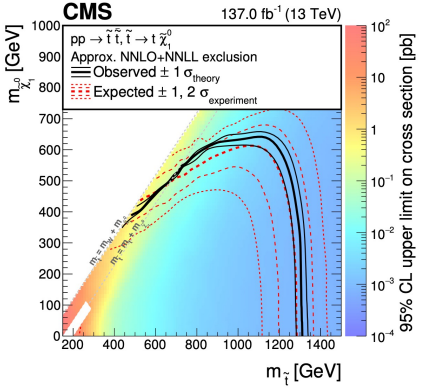


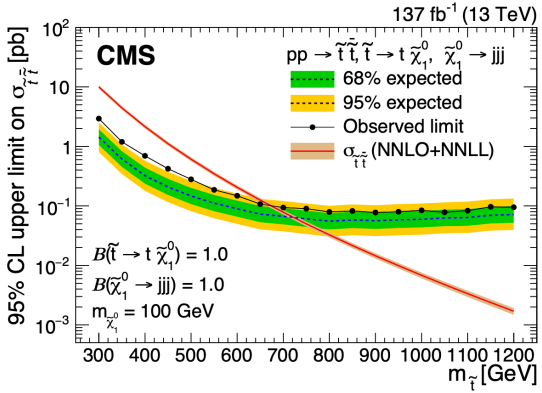
H → bb + MET (High mass $\tilde{\chi}_1^0$)



WV semi-leptonic







Fermilab

The LHC Physics Center: Overview (1)

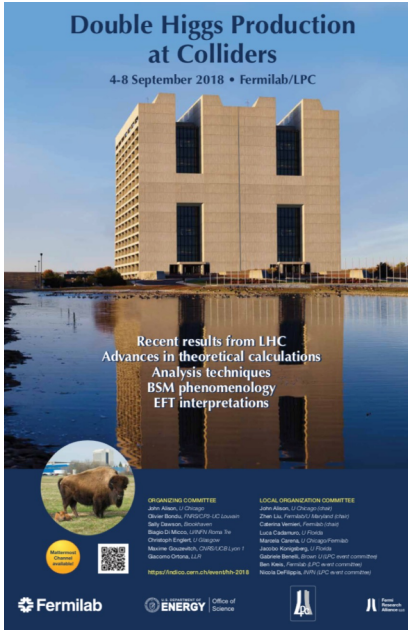
- The LPC is an established center of excellence in CMS founded in 2004
- It serves as an intellectual hub and resource for physics at CMS
  Over 500 LPC users including from over 90% of USCMS institutions
  - Unique resource for CMS physicists. Physically located on the 10th and 11th floors of Wilson Hall. Proximity to broad range of resources and expertise.
  - It provides computing resources, software support, engineering staff, and close connection to the Fermilab theory division.
- The key is the dedicated staff support:
  - Coordinators: K. Black* (UW-Madison), B. Jayatilaka (FNAL); Physics Support: G. Benelli* (Brown), Computing Support: M. Tonjes* (UIC)
- **LPC focus is on three primary thrusts: (1) Community support and engagement (2) Training and education (3) Computing.**
  - To increase the impact of USCMS contributions to physics, detector, and S&C work.

The LHC Physics Center: Overview (2)

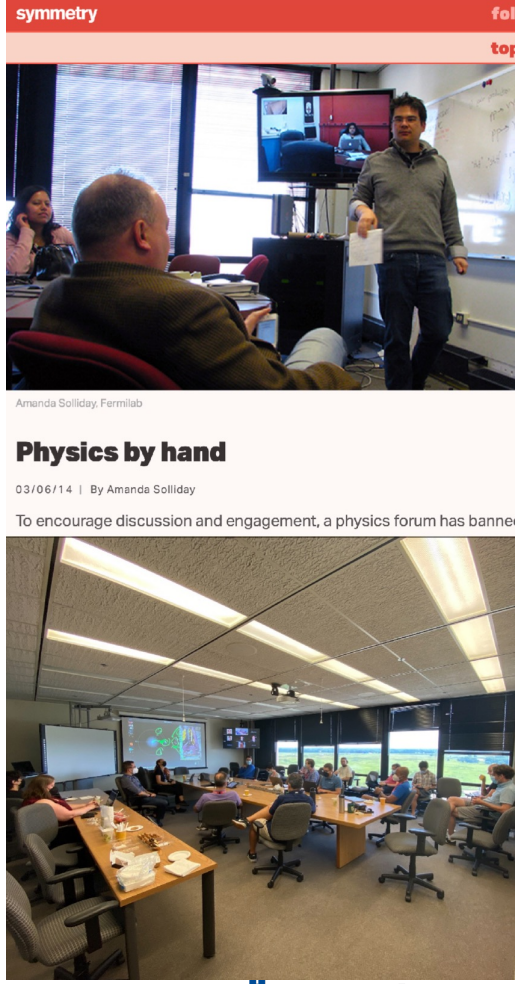
- The LPC Distinguished Researchers (DR) is the flagship program of the LPC.
  - Current and future leaders in CMS; responsible for projects at the LPC.
  - Leading roles in nearly all LPC events.
- The Guest and Visitor (G&V) program facilitates CMS members to spend time at the LPC working on targeted projects:
  - Detector, upgrade, and/or software and often with a physics component.
- The Graduate Scholars (GS) are exceptional PhD students at USCMS institutions spend ~1 year at the LPC pursuing research towards their PhD.
- The AI Fellows spend ~50% time on ML applications for CMS.

The LHC Physics Center: Overview (3)

- Engaging the community at the LPC
- Regular events/seminars:
  - Topic of the week
  - Physics forum
  - Coffee hour
- LPC physics analysis discussion group:
  - DR office hours
  - LPC computing discussion
  - LPC journal club
- Focused workshops/meetings
  - ML@L1 (2022) [**1st in person after pandemic**]
  - Double Higgs workshop (2018)
  - ML for Jets workshop (2018)



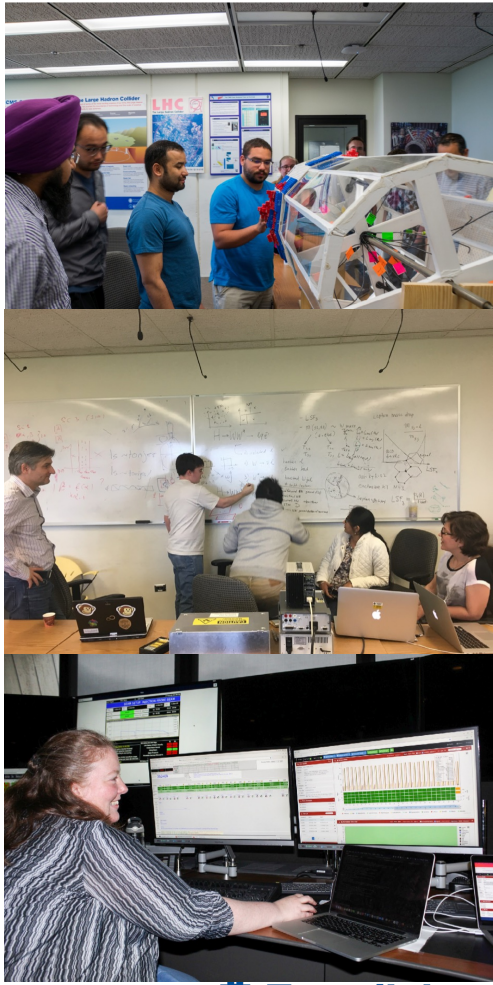
many others ….



Fermilab

The LHC Physics Center: Overview (4)

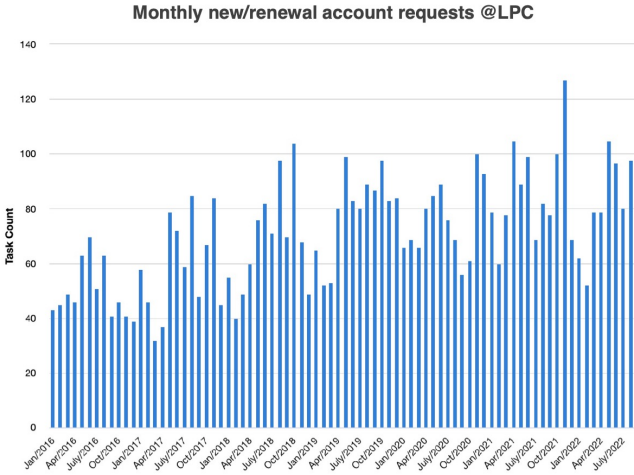
- **Training and education:**
  - CMS Data Analysis School (DAS)
    - 1 week training on CMS analysis for new collaborators. Pioneered at the LPC. Students perform complete CMS data analyses as group exercises. Facilitated by local experts (LPC DRs, Fermilab scientists).
  - Hands-on Advanced Tutorial Sessions (HATS): Hand-on training for specific tools and topics for physics analysis: Jet substructure, particle flow, machine learning, tagging, …
  - Graduate courses and lectures LPC facilitates remote participation in graduate courses taught by USCMS faculty. Recent courses include computational physics, statistics for experimental physics, ML/AI.
- Training and support for shifts at the ROC.

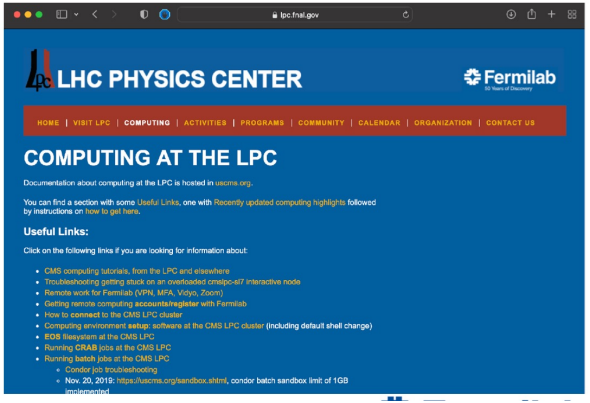


Fermilab

Computing at the LPC

- Dedicated LPC analysis cluster:
  - >5k CPU cores.
  - Open to any CMS collaborator: nearly **900 unique users annually.**
  - Extension of resources at FNAL Tier-1: backed by same expert support.
  - Key resource for CMS DAS.
- Analysis data storage (>5 PB):
  - group quotas granted only for multi-institute collaborations.
- Significant user support resources via LPC.

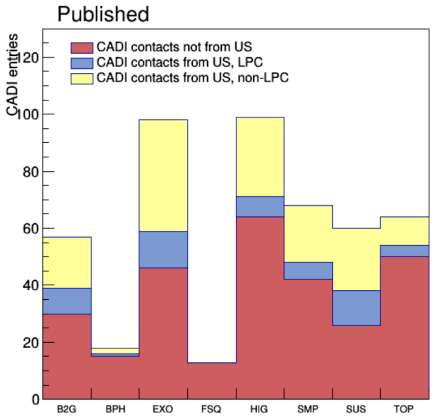




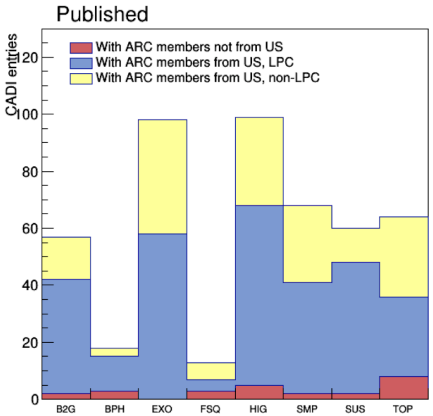
Fermilab

LPC impact on CMS physics

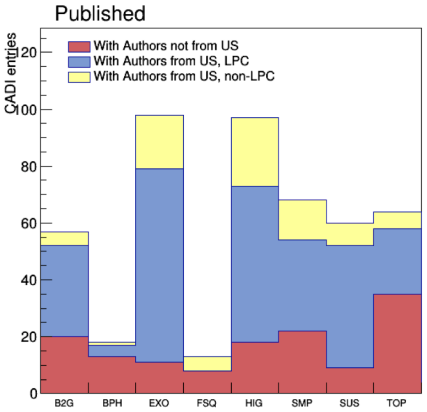
Published CMS papers 2016-2022, by physics group, with LPC users as:



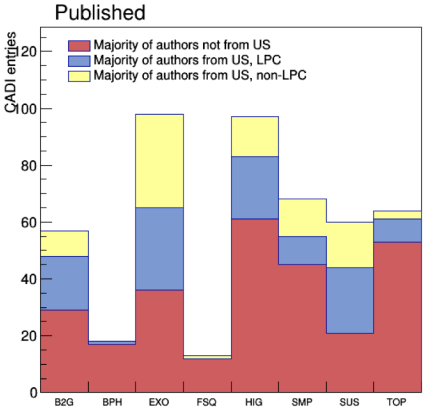
Primary analysis contacts 12%



Analysis Review Committee members 61%



with LPC authors 54%



with *majority* LPC authors 23%

Fermilab