Status of the CMS Experiment

Lindsey Gray, *on behalf of the FNAL CMS Group*

November PAC Meeting

16 November 2021

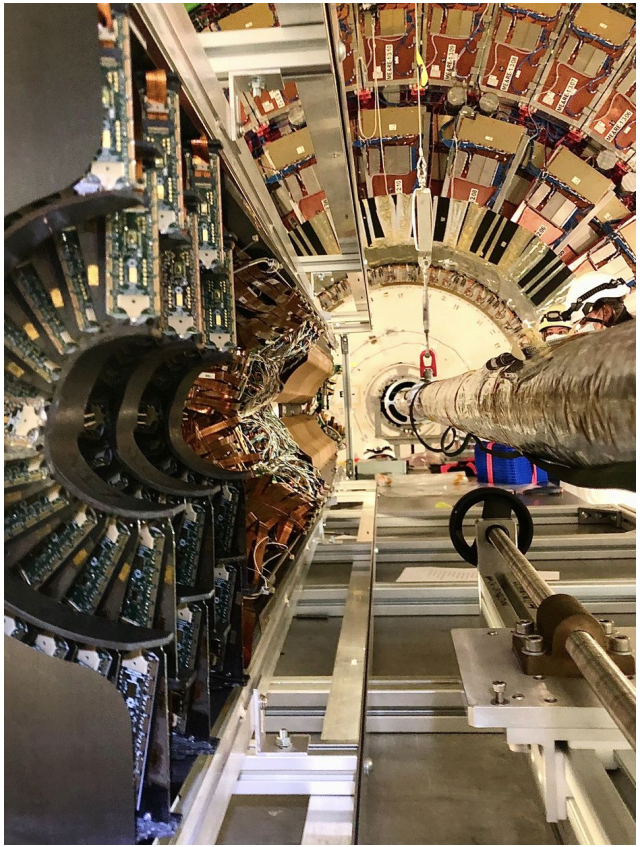
Overview

- The CMS Department & LPC [find in backup]
- Status of CMS
- FNAL contributions to the CMS operations program
  - Computing
  - Detector Commissioning
- FNAL Physics Program [Run 3 & High-Luminosity LHC]
  - Standard Model
  - Higgs
  - Dark Matter
  - Long Lived Particles (LLP)

The Status of CMS

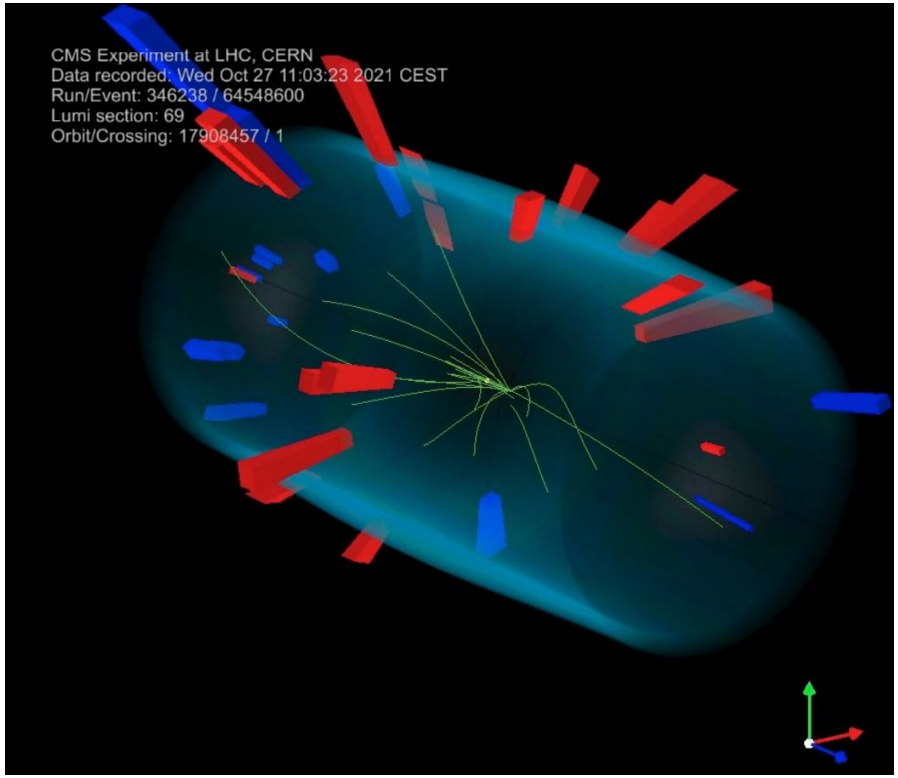
Status of CMS (1)

- CMS is at the conclusion of a successful LS2
  - Achieved all US CMS objectives for work scheduled during LS2
  - Finalized Phase 1 upgrade with I&C of **HCAL Barrel** front end electronics
  - Endcap Muon on-chamber electronics upgrade and refurbishment, laser hut move, etc:
    essential work in prep for HL-LHC that otherwise would have squeezed LS3 schedule
  - Detector repairs (e.g. **Forward Pixel Discs**), replacements (e.g. Pixel Luminosity Telescope), maintenance (e.g. ECAL MARATHON power supplies) – All finished during summer 2021
- Detectors are in stable and fully operational state
  - Detector commissioning is in full swing and headed towards success
  - Cosmic runs, beam splashes, stable beams... first collisions!!



FNAL in **bold**

Status of CMS (2)



- Computing Preparation for Run 3 well on track
  - Many US-led projects during LS2 to prepare CMS for Run 3
  - Significant refresh to data and computing infrastructure with Tier 1 and Tier 2 facility upgrades
  - Modernizing core and physics software
    - **transition tracking to vectorization** with new mkFit algorithm, commissioning in Run 3
    - software framework allows offloading to accelerators, **enables HLT to use GPUs**
    - transition workload management to **Python 3**

FNAL in **bold**

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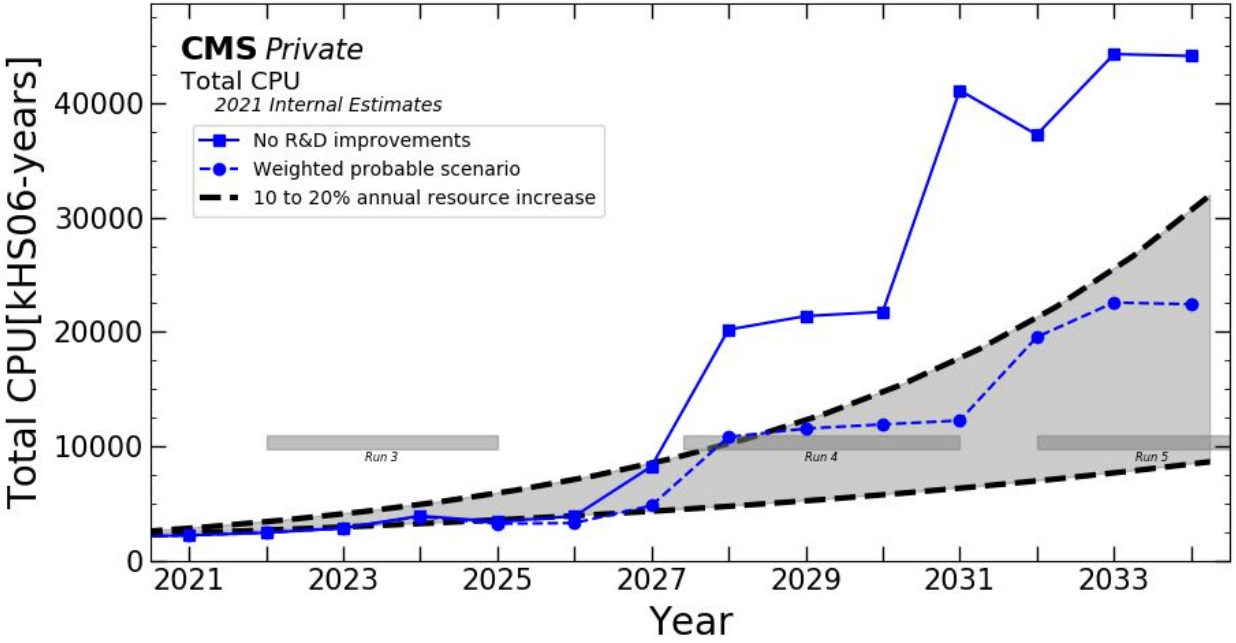
FNAL Contributions to Operations: Software & Computing, Detector

The Computing Challenge of Run 3 & HL-LHC



FNAL provides the underlying systems, and experts to manage them, for all these challenges.

Reproduced from the "US CMS Software and Computing: HL-LHC R&D Strategic Planning Document"

Grand Challenge (1) Modernize Physics Software and improve algorithms	**Grand Challenge (2)** Advancing High-throughput Distributed Data Processing	**Grand Challenge (3)** Building Exabyte-size Active Data Storage	**Grand Challenge (4)** Transforming Scientific Data Analysis Process

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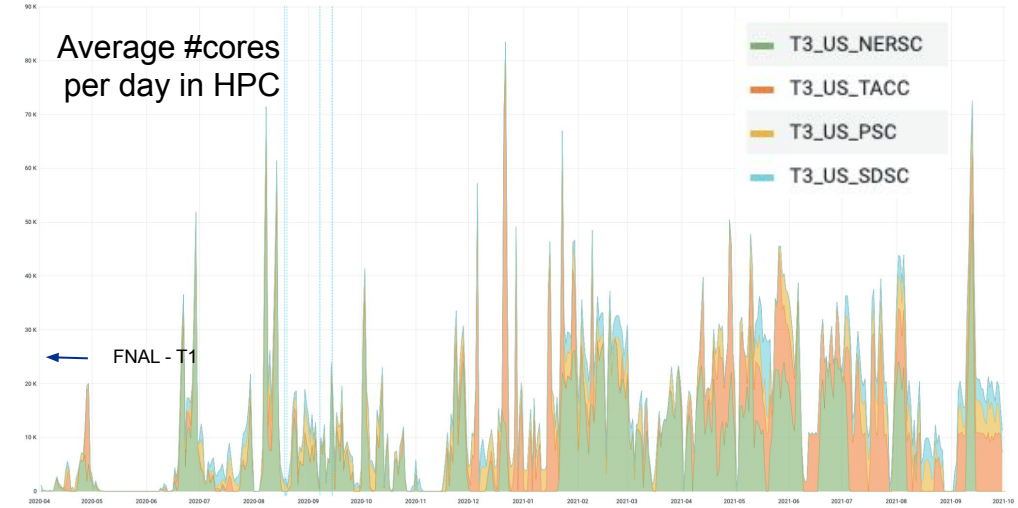
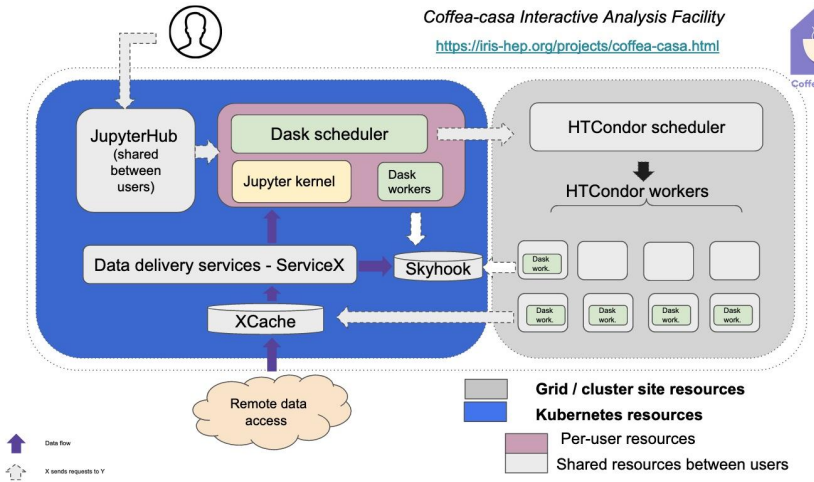
Storage and HPC

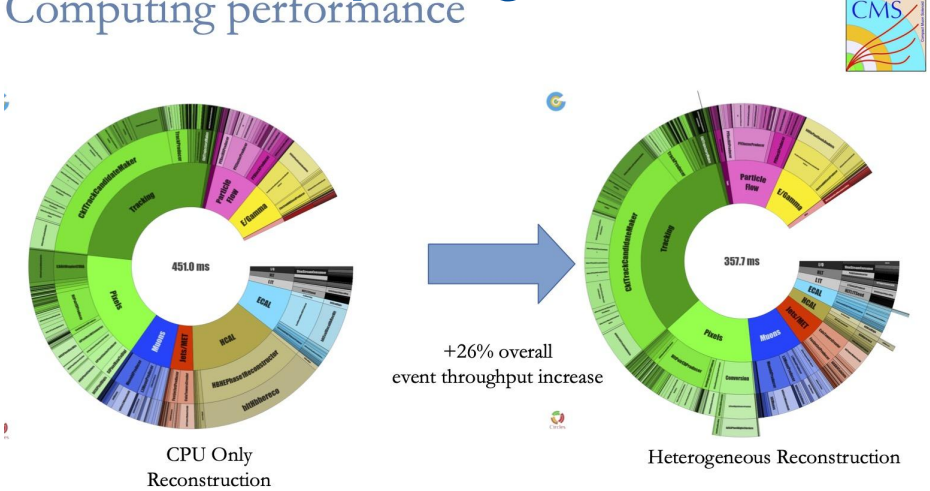
New CMS tape library @ FNAL



- The lab must deliver critical new resources to computing systems for Run 3 & HL-LHC
  - U.S. CMS processes ~ten-billion events per year, hundred billion in the coming decade
  - **Storage still at FNAL**, Run 3 will challenge us to be ready for yearly exabyte demands in HL-LHC
- Run 3 challenge exercises needs for HL-LHC - FNAL leads adoption of HPC resources
  - Thanks to FNAL-led HEPCLOUD efforts can now easily use any allocations received!
  - Average HPC Computing power utilized by CMS in 2021 **close to size of T1** (3x2020, which was 3x2019)

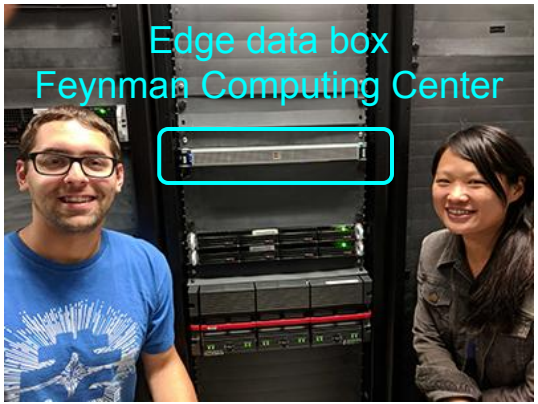
Analysis Facilities and Heterogeneous Computing





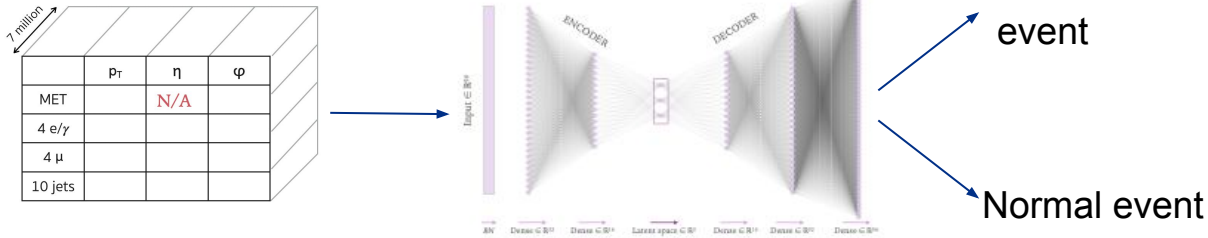
- FNAL delivers next generation "Analysis Facilities" in preparation for Run 3 and HL-LHC
  - Provide easy entry to using **columnar analysis** (e.g. coffea) or **RDataFrames** effectively and at scale
  - Share development with university partners by using kubernetes and "infrastructure-as-software"
  - Significant participation in popularization campaigns like IRIS-HEP Analysis Grand Challenge Workshops
- FNAL-led R&D in portability supports CMS in deploying GPUs in the High Level Trigger
  - **26% improvement** over CPU baseline, lower thresholds, more expansive physics program for CMS
  - **AI/ML *as a service* removes inference overhead** in reconstruction making room for better algorithms (next slide)

Leadership in AI/ML + Heterogeneous Computing



Look for highlight in physics section!

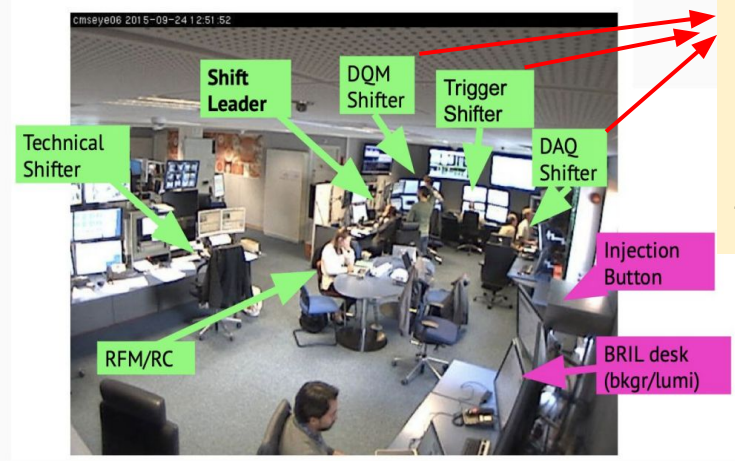
[Deep autoencoders in CMS Run 3 L1 Trigger]



- FNAL CMS group driving force in “inference as a service” for applying AI research to solve Run 3/HL-LHC challenges
  - Graph NNs for reconstruction - **faster reconstruction**, reduced development and maintenance burdens
  - ML for simulation - **reduce time needed to simulate detectors**
- FNAL leads the deployment of real-time AI in embedded/custom electronics
  - AI/ML in FPGAs and ASICs **drives new kinds of searches** in Run 3 and HL-LHC (and even DUNE!)

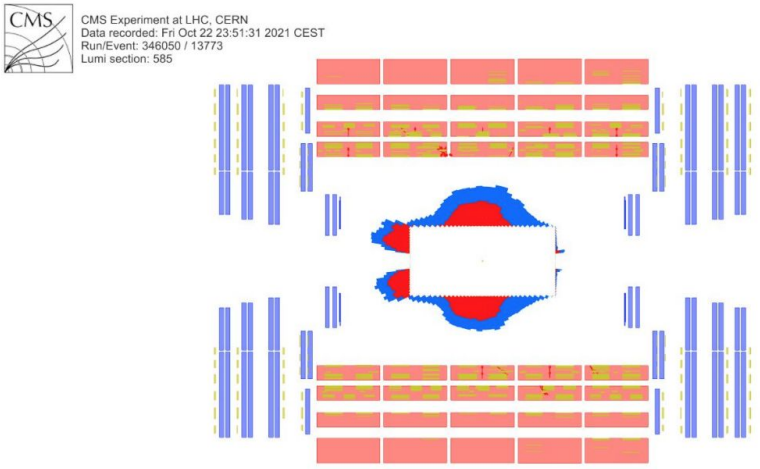
[FNAL CMS develops technology] which is of [broad interest to HEP and beyond]

Detector Operations: Preparing for Run 3



Now offsite

P5 Control room is too small to contain all 5 nominal shift crew due to COVID-19



- FNAL leads the development of Data Quality Monitoring (DQM) - critical to successful re-commissioning of CMS
  - Data quality monitoring is part of the CMS Physics Perf and Datasets group, co-coordinated by FNAL
- We led the effort to migrate DQM, Trigger, and DAQ to remote operations during COVID-19
  - Fully remote shifts since spring 2020, revitalizing Remote Operations Centers necessary
  - Access and travel to FNAL is critical in preparation for Run 3
- All other shifters remain on-site at CMS
  - Travel to CERN remains critical

HL-LHC: FNAL Contributions to CMS Phase 2 Upgrades

Look for highlight in physics section!

TRIGGER **FNAL**

L1 Trigger/HLT/DAQ **NSF** and **DOE**
- L1 40 MHz in/750 kHz out with tracking for PF-like selection
- HLT 7.5 kHz out

Beam Radiation and Luminosity, Common Systems, Infrastructure

FNAL

Tracker
- Si Strip Outer Tracker designed for L1 Track Trigger **DOE**
- Pixelated Inner Tracker extends coverage to $|\eta| < 3.8$ NSF

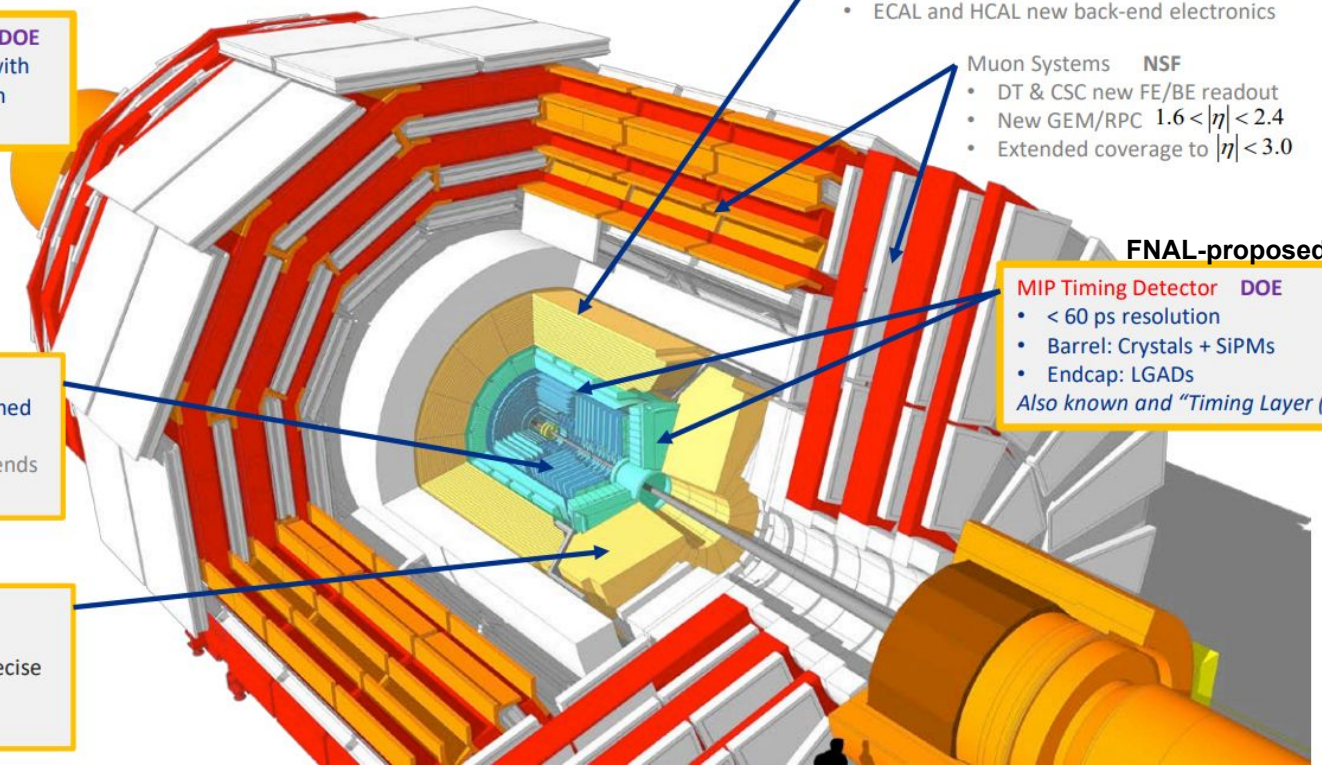
FNAL

Calorimeter Endcap **DOE**
- Si, Scint + SiPM in Pb-W-SS
- 3D shower imaging with precise timing

Also known as HGCal

Barrel Calorimeters **NSF**
- ECAL single crystal granularity in L1 Trigger with precise timing for e/γ at 30 GeV
- ECAL and HCAL new back-end electronics

Muon Systems **NSF**
- DT & CSC new FE/BE readout
- New GEM/RPC $1.6 < |\eta| < 2.4$
- Extended coverage to $|\eta| < 3.0$



FNAL-proposed!

MIP Timing Detector **DOE**
- < 60 ps resolution
- Barrel: Crystals + SiPMs
- Endcap: LGADs

Also known and "Timing Layer (TL)

Physics Analysis

50 Years of Hadron Colliders: We've come a long way...

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Fundamental Questions in HEP FNAL Can Answer in Next Decade

- What is the Higgs Boson?
  - Direct measurement of Higgs properties
  - Comprehensive characterization of EWK sector
- What is Dark Matter?
  - WIMP-like or not?
  - Exploration of rich dark-sectors motivated by theory

- How FNAL-CMS answers them:
  - Innovation in techniques to improve classic analysis strategies
  - Using the detector beyond its original design specifications

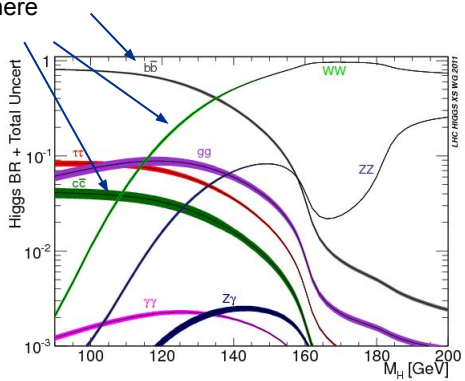
50 Years of Hadron Colliders: … and still exciting times ahead!

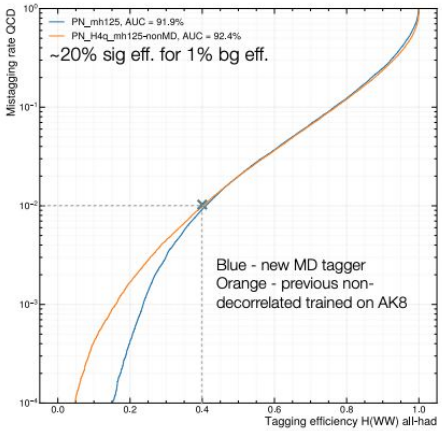
- FNAL's physics pursuits align with our unique capabilities and resources
  - Leadership in developing and deploying AI
  - Advanced knowledge of detector performance through critical contributions to detector R&D and construction - Outer Tracker, Calorimeters, Trigger, MIP Timing detector
  - Fruitful collaboration with the FNAL theory division
  - LHC Physics Center (LPC)

	Higgs	**Electroweak**	**Beyond SM**
FNAL Foci Run 3	Boosted H(bb/cc) (+ VBF) Higgs-Vector couplings Effective Field Theory Di-Higgs	Vector Boson Scattering Double/Triple Gauge Boson Quartic couplings W-mass	SUSY Dark Matter Long-lived Particles Dijet-resonances Anomaly Detection
FNAL Foci HL-LHC	Additional Di-Higgs ch. Differential H(bb) (+ VBF) Eff. Field Theory combos.	Include weak mixing angle	Same areas, qualitatively new capabilities

Boosted H(bb) - Innovation in Taggers, Production & Decay Mode Coverage

Boosted analysis helps here





- Development of breakthrough/novel techniques to reconstruct high momentum objects necessary to achieve sensitivity
  - High pT "boosted" Higgs-jet analysis **require "taggers"** to remove QCD and other backgrounds
  - Expertise in AI lays path for bringing taggers to trigger
- Improved H(bb) makes VBF production mode with boosted Higgs observable in Run 3
  - FNAL a leader in the adoption of **boosted techniques**
  - New taggers provide sensitivity to H(WW), H(cc) (backup)
- VBF differential shape, inclusion of polarization, import for EFT in HL-LHC
  - Upgraded tracker and new HGCAL will improve Particle Flow reconstruction and cover vital forward-jet production regions

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Boosted H(bb) - Innovation in Taggers, Production & Decay Mode Coverage

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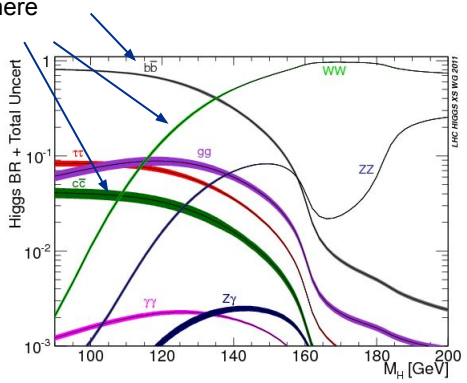

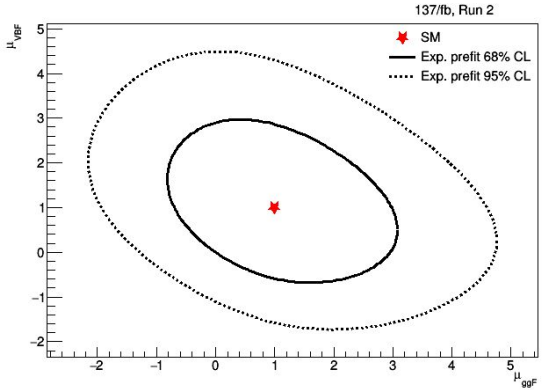

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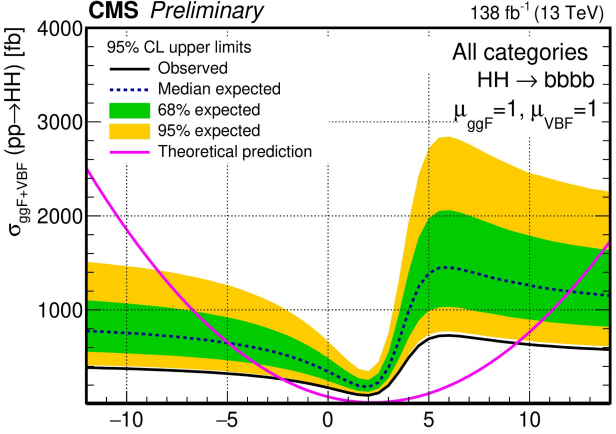
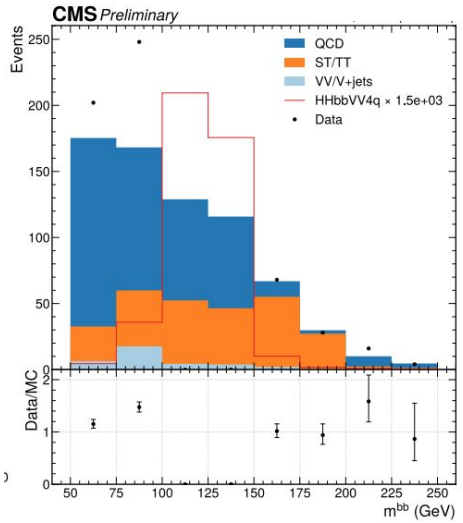
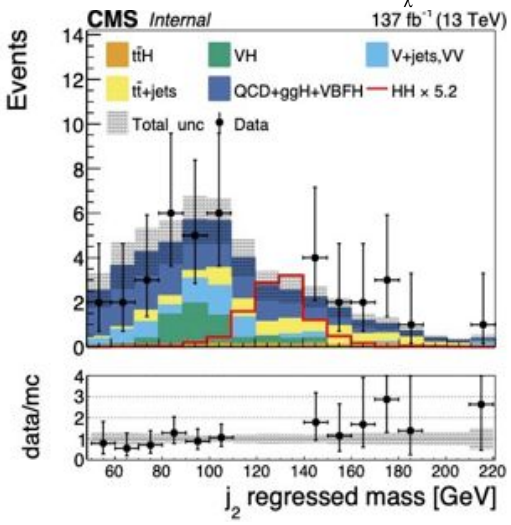
Di-Higgs Searches

- HL-LHC will let us turn Di-Higgs into a stringent test of the SM!
  - Improvements in Run 2 and 3 analysis change nature of HL-LHC measurement!
  - **Pushing analysis techniques and trigger have brought former HL-LHC sensitivities to Run 2**
- New HH→bbWW analysis in progress for Run 3, made possible by new taggers
- HH→4b (CMS-PAS-HIG-20-005)
  - Sensitivity to ~5xσ^{SM} at CMS Run II and world-leading sensitivity for VVHH coupling
  - Observed(expected) σ/σ^{SM} < 3.7(7.3) at 95% CL → best observed sensitivity to date!

TRIGGER







Preparation for Run 3

- Improve **trigger** efficiencies
- **BSM searches** in multi-Higgs final states (HHH, VHH, ttHH)

In HL-LHC 20% more lumi from:

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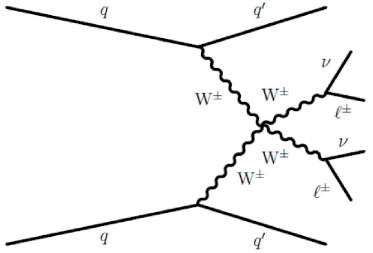
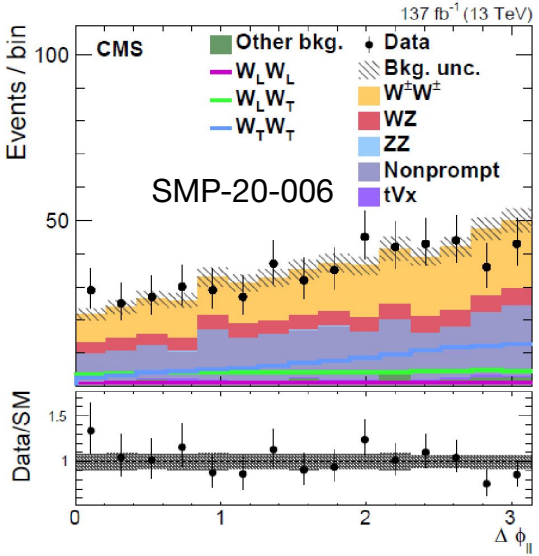
Vector Boson Scattering



- Leading Run 2 measurements of VV scattering:
  - same-sign dilepton and trilepton final states (W+W+/W-W-/WZ, SMP-19-012)
  - semileptonic final state (WV/ZV, SMP-18-006)
  - First analysis of longitudinal polarization (SMP-20-006)
- Key expertise in boosted hadronic V reconstruction, lepton triggering and ID to evolve measurement in Run 3
  - Adding multivariate, multichannel constraints on **polarization** and **anomalous quartic couplings**
  - Will have enough data to use jet substructure reconstruction for **hadronic W,Z fermion angles**
- 10x more data and new detectors in HL-LHC will enable polarized cross sections, stronger EFT/aQGC sensitivity
  - HGCAL reconstruction of forward quark jets
  - Improved triggering and inclusion of **all-hadronic final states**

Final state fermion angles encode the W polarization!



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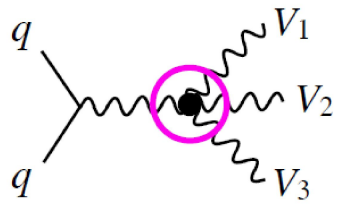
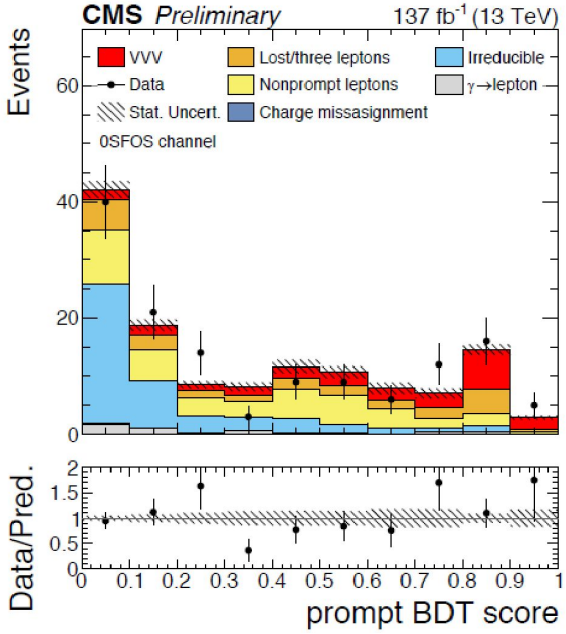
VV and VVV production

TRIGGER



- Led Run 1 measurements of VV production (WW, WV/ZV) and best constraints on anomalous triple gauge couplings (SMP-14-016, SMP-13-008)
  - 10x data in this domain will allow for polarization and aTGC studies of equal value to VBS
- Led the first observation of VVV production in Run 2 (SMP-19-014)
  - Requires precise control of lepton backgrounds, comprehensive multi-channel approach we developed
  - Combined signal just large enough to observe
- Run 3 to HL-LHC VVV data opportunities
  - Measure triple-boson final states (WWW, WWZ) differentially
  - Leading to improvements in EFT/aQGC sensitivity, measurement of SM quartic coupling values.
  - All possible through our consistent innovation at the trigger level



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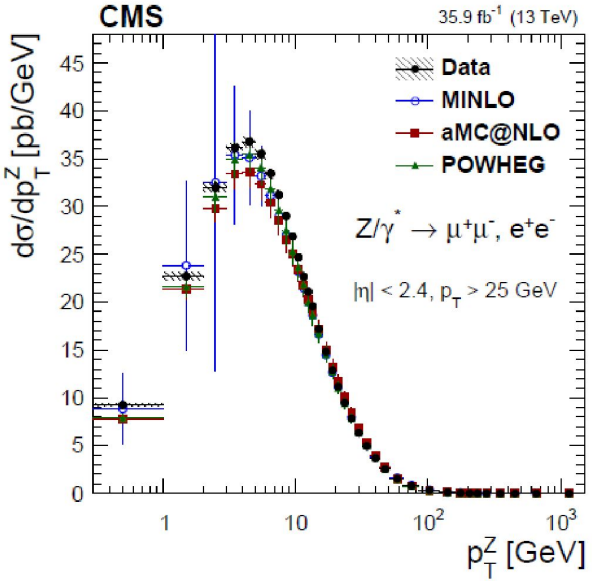
Precision Electroweak Physics

TRIGGER

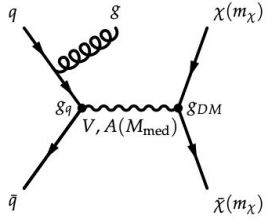
- Proposed & led inclusive and differential W and Z cross section measurements in Run 1 and 2
  - Inclusive W and Z
  - W charge asymmetry, Z AFB
  - Z PT and rapidity
- Focusing on understanding production modeling in W-mass for now / Run 3
  - **Led the collection** of low-pileup data in 2018 to analyze W, Z cross section and p_T with lowest systematics (analysis in progress)
  - **DeepMET reconstruction** to give highest W PT resolution to check & constrain W production modelling
- HL-LHC will provide enough data to measure directly or constrain W and Z production theory nuisance parameters (angular coefficients vs. p_T, e.g.)
  - Giving ultimate precision for W-mass, weak mixing angle, PDFs



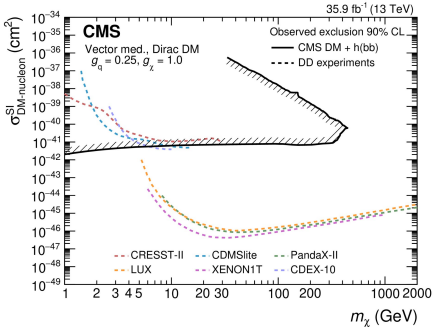
- Techniques developed at FNAL:
  - Endcap muon trigger and reconstruction
  - ML-based PU subtraction + DeepMET
  - Fits with high number of nuisance parameters

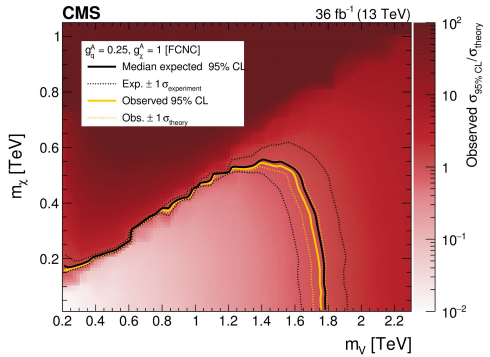
Dark Matter: Simplified Searches

TRIGGER



- Assuming DM particles are not detectable directly, search for production in association with recoiling SM particle(s): **missing ET+X**
  - Dark matter with some coupling to SM could be produced at the LHC, main goal is to understand nature of DM
  - Hadronic **monotop**, **mono-Higgs** (bb decay) published in Run 2
- Currently two searches being completed using full Run 2 dataset
  - **Dark Higgs** (bb)- scalar boson that couples to dark sector
  - **Monotop** including leptonic decays





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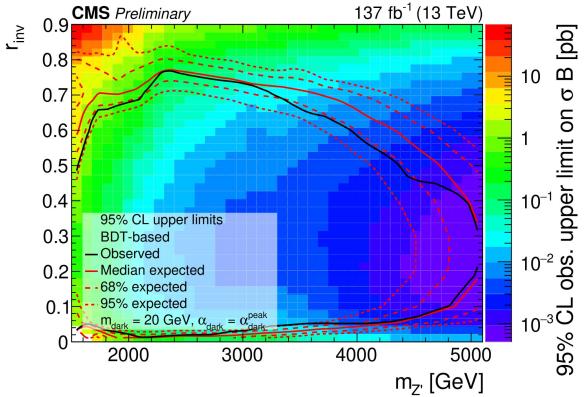
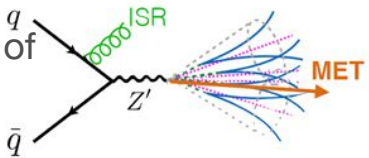
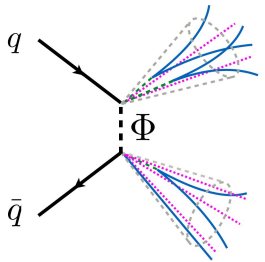
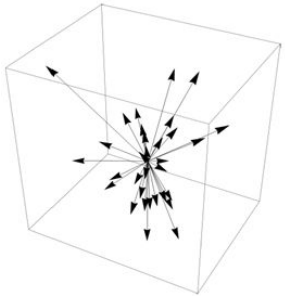
Strongly Coupled Hidden Sectors

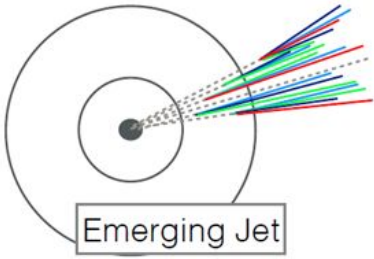


- Complement WIMP searches by looking for unconventional signatures w/ novel phenomenology
- FNAL currently leads search for soft unclustered energy patterns (SUEPs) and contributes to emerging jet search (multiple displaced vertices within jet cone)
  - CMS just released **first collider search** for semi-visible jets (mixture of visible & dark matter), led by FNAL: [CMS PAS EXO-19-020]
  - Program now expanding to **boosted low-mass mediators**, t-channel production
- HL-LHC goals: search for mediators w/ weaker couplings, more sophisticated models, combinations of signatures (emerging semi-visible SUEPs)









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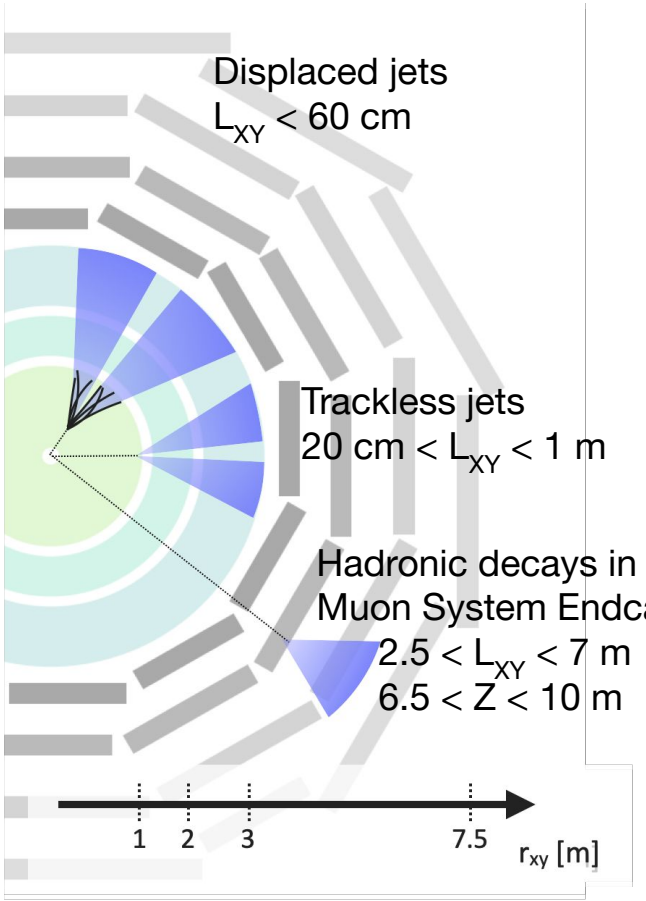
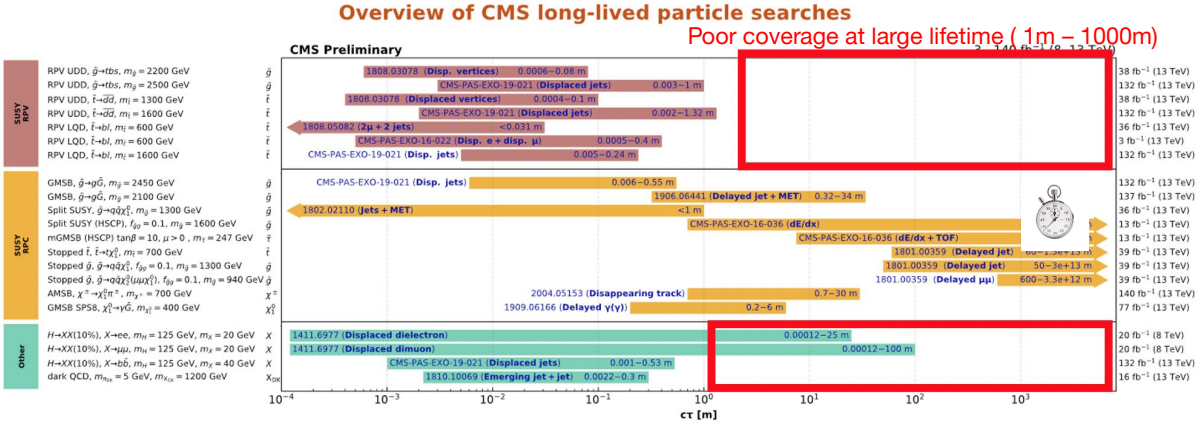
The Case for LLPs



- Long-lived particles (LLPs) are naturally predicted by many new physics models
  - A new angle on answering to the nature of dark matter
  - Apply well-motivated DM models to **growing expertise** in LL searches at CMS
  - Many models generate LLPs: Higgs portal, Axion-like particles, etc…
- Our program comprehensively covers the mm – 10m region
  - Access to light (~ 1GeV) LLPs



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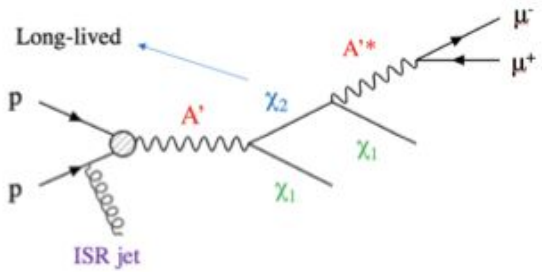
Searches for Dark Matter

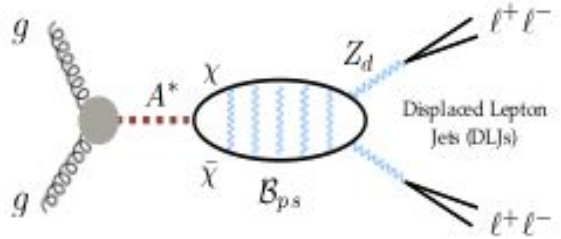
TRIGGER  

- Complex dark sectors can have interactions between DM particles: long-lived states
- Currently leading two searches
  - **Inelastic DM** (iDM)
  - **Self-interacting DM** (SIDM)
  - Both searches involve final states with “lepton jets”
- Work with theory community to develop dark sector models that are motivated by experiment as well as theory
  - e.g., iDM partially motivated by **Xenon1T excess**
- Efficient triggers vital for physics impact
  - Run 3: Searches for LL states heavily trigger limited, applying our expertise to full utilize Run 3
  - HL-LHC: optimize LL searches for upgraded detector (including MIP timing, more capable L1 trigger and HLT)

iDM:



SIDM:



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Topology Driven Searches in Run 3 and HL-LHC

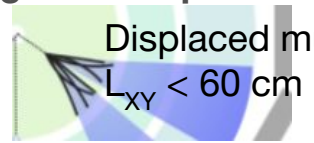
- Major goal for Run 3: improving trigger efficiency for lower mass LLPs (10-100 GeV)
  - Trigger is the best opportunity to go beyond luminosity gains
  - Currently triggers typically have lower efficiency for low LLP masses
  - **Fermilab led development of endcap muon trigger for displaced muons**

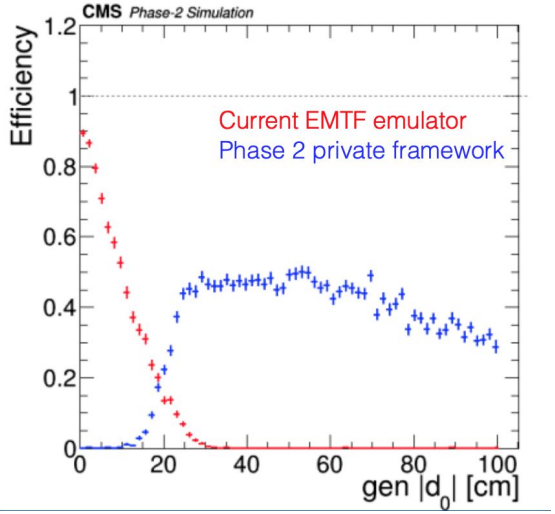
Extend sensitivity to displaced muons in Endcaps - new trigger capabilities!

- Run 2: muon pT assignment requires vertex constraint, efficiency drops with d_0
- Run 3: **Neural network** p_T and d_0 assignment (vertex unconstrained)

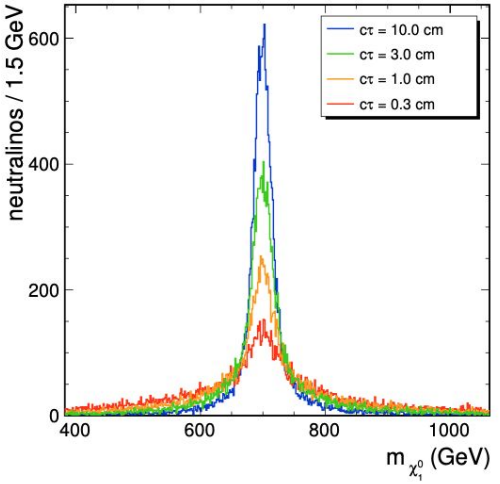
MTD in HL-LHC brings qualitatively new capabilities to searches

- **Reconstruct full momentum** of massive neutral LLPs
- Orders of magnitude improvement in the expected limits (backup)



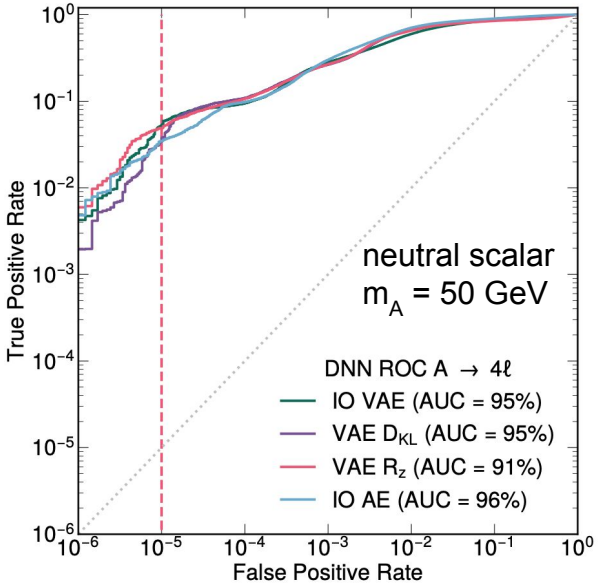


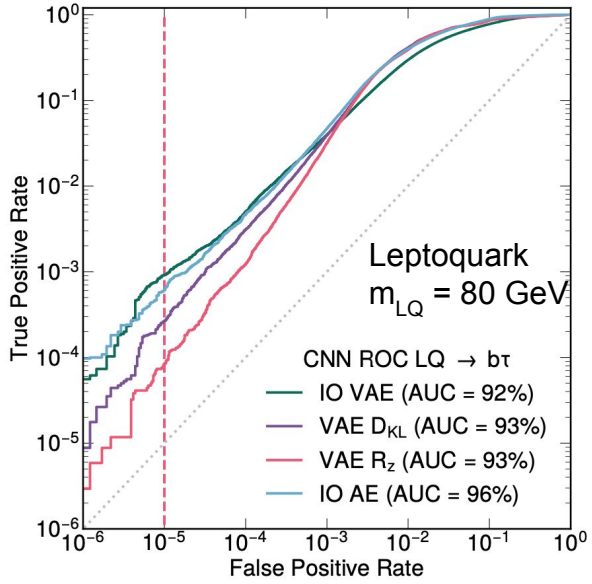
Long lived neutralinos
L_{XY} < 10 cm



Qualitatively New Kinds of Searches with ML-driven Triggers

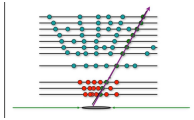
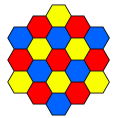
- New anomaly detection, “AD”, based triggers basis for 40 MHz “scouting”
  - FNAL **wide domain of technical expertise crucial** to delivering an effective AD-based trigger
  - First results promising - **sample purity (S/B) enhanced by 2-3 orders of magnitude** with no signal prior
  - Tested models can fit in latency and resource constraints of Run 3 and HL-LHC systems





False Positive Rate ~ 10^{-5} threshold for comparing figures of merit (~1000 events/month)

Concluding Remarks


- FNAL CMS Group is a critical contributor to the experiment
  - Very significant roles across detector construction, operations, and analysis research
  - The depth of our work extends to shaping the CMS Detector itself and expanding its capabilities
  - Collaboration with FNAL Theory Division promotes innovation in nearly all areas

- We are able to address key questions in Particle Physics
  - Large number of Scientists and Postdocs yields significant breadth to program
  - While also maintaining high quality of work and research output

- FNAL remains and will continue being a leader and enabler in the CMS experiment
  - Through Run 3 and the HL-LHC
  - Benefiting and supporting from deep connections to wider community through LPC

Backup for Review

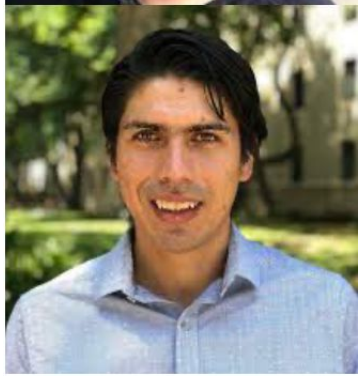
FNAL CMS Department (I)

- The Fermilab CMS Department is composed of **~40 Scientists** and **13 Research Associates**
- In FY21, Fermilab continued to hold leadership roles in the international collaboration B. Klima as the **chair of the Publication Committee** and **18 of the lab's scientists serving as managers or conveners** of CMS projects and working groups.
  - In the recent past, Joel Butler served as Spokesperson of the CMS Collaboration, while Patty McBride was Deputy Spokesperson
- Fermilab led, managed, and supported the national programs including the **U.S. CMS Operations Program,** with **21** scientists serving as **managers of the HL-LHC CMS Upgrade**, and hosts the LHC Physics Center (LPC).
- The group continued to lead in **computing operations**, development of simulation and reconstruction and analysis software, as well as **R&D** for data storage, distribution, frameworks, facilities, and access in preparation for the increased data volume expected in Run 3 and HL-LHC.
  - Kaori Maeshima appointed as L1 coordinator for the Physics Performance and Dataset CMS group in Sept 2021 - 2 year term
  - Lindsey Gray appointed coordinator of the Analysis Tools Task Force in October 2021 - charged until Run 3 start

FNAL CMS Department (II)

- New members of the group
  - **Jennifer Ngadiuba**, expert in AI/ML, triggers, searches for BSM physics (Wilson Fellow, started in March, relocated to FNAL in late September)
  - **Fabio Ravera**, expert in tracking detectors and Higgs physics
  - **Cristián Pena**, expert in timing detectors, quantum internet, searches for BSM physics, accepted a position of AS in the FNAL QIS program but will remain affiliated to CMS
- More than 60% of former CMS postdocs obtained tenure-track faculty positions at either universities or laboratories
  - In 2020, Aram Apyan (Assistant Prof. Brandeis), Allison Hall (Assistant Prof. US Navy Academy), Hannsjoerg Weber (Associate Scientist at Humboldt U. in Berlin), Fabio and Cristián (see above)
  - Prior to 2020, see previous PAC report





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Awards and Recognition 2021

- Exceptional Performance Recognition Awards:
  - N. Smith and E. Vaandering for work on Rucio
  - Bo Jayatilaka for leading the organization of the CPM under snowmass
- CMS 2020 Award
  - Matteo Cremonesi for: “His methodical approach and dedication to solving the problem of speeding up future HEP analyses, co-creating the Coffea analysis framework and exploring innovative infrastructures such as Apache Spark combined with the SWAN service”
  - Cristian Peña for: “For his critical and extensive work in developing and demonstrating the precision timing detector designs for both the barrel and endcap regions of MTD.”
- 2021 Tanaka HEP Experiment Dissertation Award to Cristina Mantilla (at JHU):
  - Probing New Physics Using Initial State Radiation Jets at the Large Hadron Collider.
- 2022 LPC Distinguished Researcher to Karri Folan DiPetrillo

The LHC Physics Center at Fermilab

- Continued operating as a virtual center throughout 2020-21
  - All regular LPC events transitioned to virtual/zoom only
  - Critical for maintaining USCMS during COVID (analysis, seminars, journal club, etc.)
  - Usual (~15) number of Hands on Tutorial Sessions (HATS) held virtually, attendance similar to on-site
  - Organized and held first fully virtual Data Analysis School (CMSDAS)
- LPC support of research continues
  - 2020 and 2021 Distinguished Researchers (DRs) carried out research programs despite COVID limitations and delays
  - Twelve LPC Distinguished Researchers selected for 2022
  - First LPC AI Fellows selected for 2021
  - LPC Guest and Visitor Program continues to support essential work in Operations and Upgrades
- Gearing up for Run-3
  - Plan to revive LPC operations-oriented groups dedicated to discussions and troubleshooting of the early data
  - The ROC will provide an opportunity for the LPC members to take remote shifts
  - Run 3 will be a focus of upcoming LPC workshops

See material provided at Summer 2021 PAC meeting for further information

Extras

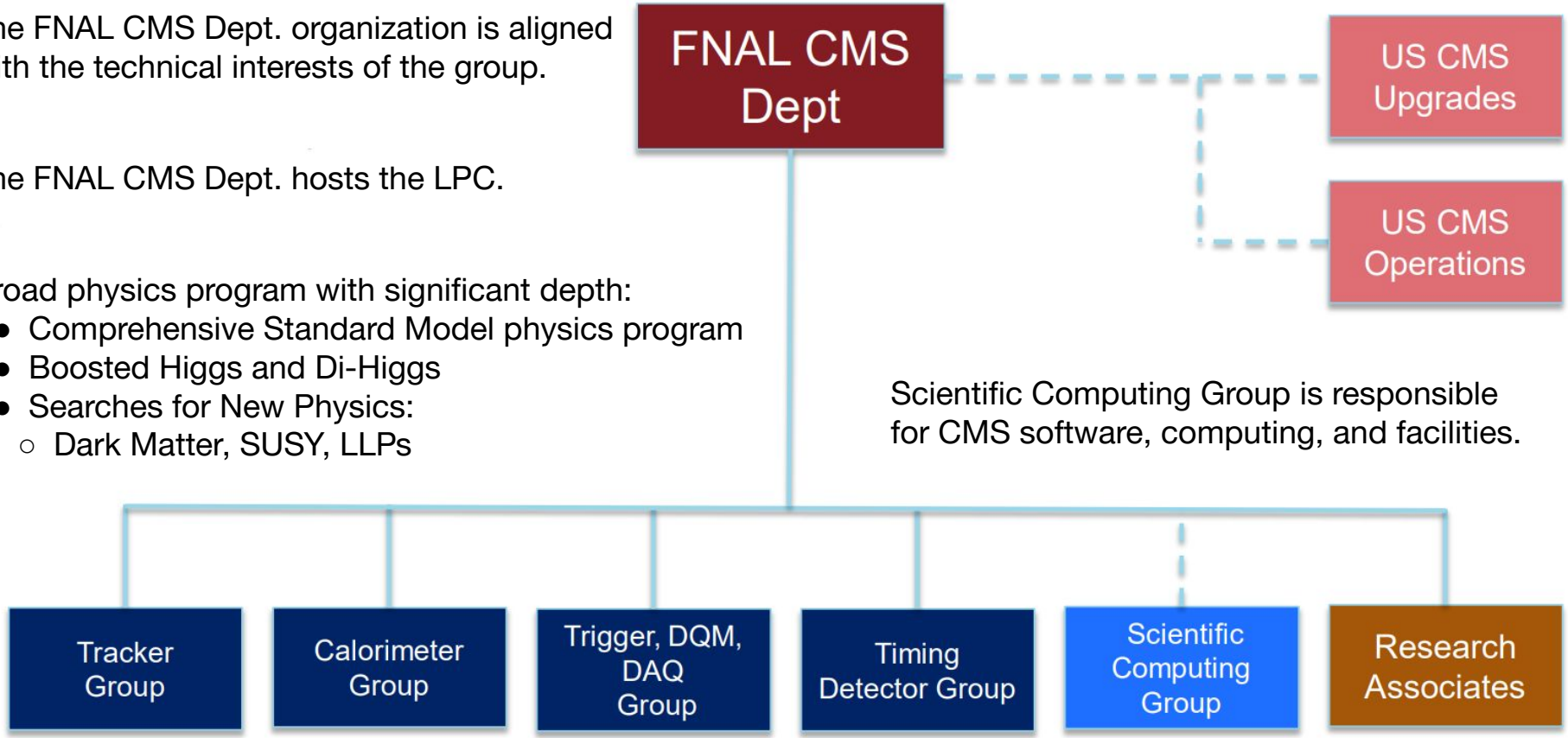
FNAL CMS Department Organization

The FNAL CMS Dept. organization is aligned with the technical interests of the group.

The FNAL CMS Dept. hosts the LPC.

Broad physics program with significant depth:

- Comprehensive Standard Model physics program
- Boosted Higgs and Di-Higgs
- Searches for New Physics:
  - Dark Matter, SUSY, LLPs



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CompOps - T1, FW Software, MkFit

Fermilab's Participation in Community Planning

In FY21, Fermilab scientists were highly recognized within the community for their contributions to cutting edge science and technology.

- Joel Butler vice-chair of DPF
- P. Merkel was served as both **co-chair of CPAD** and **member of the ICFA** Instrumentation Innovation and Development Panel.
- Fermilab scientists are leading the restarted **Snowmass process**:
  - D. Elvira as coconvener of the Computational Frontier
  - P. Merkel of the Instrumentation Frontier
  - A. Apresyan of the Solid State Detectors and Tracking topical group
  - J. Hirschauer of the BSM topical group
  - D. Elvira as topical convener for Theoretical Calculations and Simulations in the Computing Frontier.
- O. Gutsche serves as the technical lead of the Portable Parallelization Solutions project of the **DOE Center for Computational Excellence.**

50 Years of Hadron Colliders: … and still exciting times ahead!

- CMS has a diverse and strong program of physics for Run 3 and HL-LHC
- Standard Model
  - Electoweak (VBF, VBS, VV(V), quartic couplings, W mass and weak mixing)
  - Strong (jets, photons, PDF, multi-parton) & top physics (di-top xsec, 4 top, di-top + V, top mass)
- Higgs
  - Single H decays to: gamma gamma, Z gamma, ZZ*, WW*, taus, muons, bottom
  - Di-Higgs and H self-coupling: VH, EFT, EWK tests, mass, width, rare/invisible decays
- Beyond the Standard Model
  - SUSY (squarks, gluinos, charginos, neutralinos, sleptons), dark matter, long-lived particles
  - LQ, LFV, from B anomalies, resonances (all di-objects & boosted), cascade signatures
  - BSM Higgs: H to aa, aZ, resonant Di-Higgs, YH, Higgs Portal, twin Higgs, 2HDM
- Flavor physics and Heavy Ion
  - Spectroscopy, charm, B physics, LFV and B anomalies in b to sll, c to l+nu, top
  - Flow, correlations, heavy flavor, energy loss, quarkonia, hot and dense QCD

CMS Physics	Electroweak	Strong	Higgs	Beyond SM
FNAL Run 3	VBS, VV(V), quartic couplings, W-Mass	jet physics	Boosted H(bb/cc), VBF, VH, EFTs, Di-Higgs	SUSY, Dark Matter, LLPs
FNAL HL-LHC	Include weak mixing	as above	EFTs, boosted H(bb) diff. xsec, Di-Higgs	As above with new capabilities

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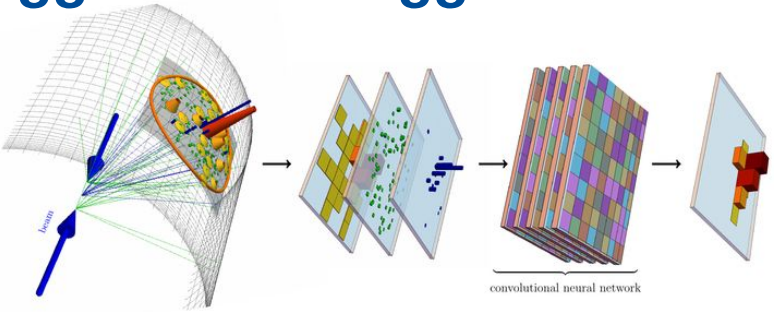
Standard Model Physics

- Historically, we have measured a wide range of cross sections and Standard Model phenomena at the LHC in Run 1/Run 2
  - Inclusive jet and dijet cross sections (and constraints on αS and PDFs)
  - precision top physics (M_t, cross sections, precision production asymmetries and spin correlations)
  - precision electroweak physics (W or Z cross sections, charge asymmetries, angular analysis)
  - Multiboson production (VV and VVV cross sections, vector boson scattering, anomalous gauge boson couplings)
- In Run 4 we intend to pursue a program of multiboson and precision electroweak physics which most strongly extend existing constraints on the electroweak theory by the addition of 10x statistics:
  - Vector boson scattering polarization and VVV differential production which probe electroweak symmetry breaking and anomalous couplings/operators
  - Precision electroweak cross sections and angular analysis which constrain M_w, $\sin^2\theta_W$, and associated theory nuisance parameters

Higgs and Di-Higgs searches

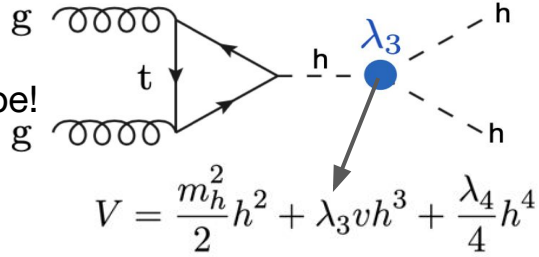


$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a \Phi W^a_{\mu\nu}B^{\mu\nu}$$
$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$

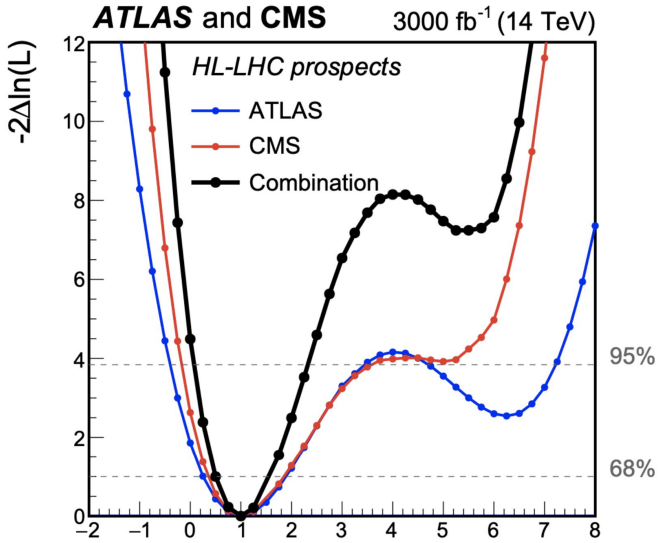
Higgs-focused ML-based heavy-flavor tagging a gateway to rare boosted Higgs production and decay.

Boosted H(bb) final state probes high pT SM Higgs production and Standard Model Effective Field Theory

Di-Higgs give access to the scalar potential shape!



HL-LHC data will allow to exclude kλ = 0 at 95% CL
Able to prove that Higgs self interaction exists!



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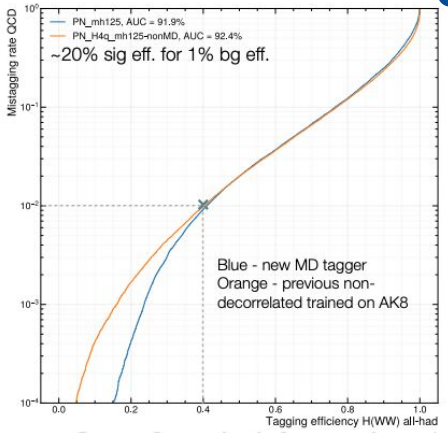
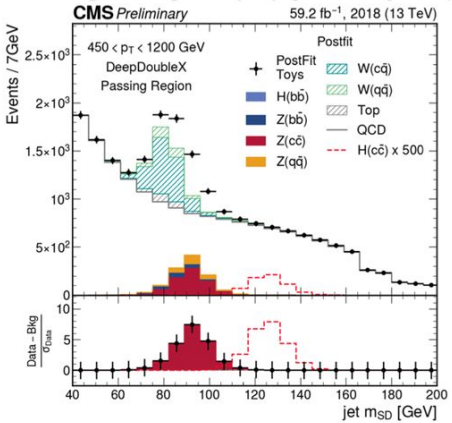
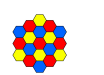
Boosted H(bb) - Innovation in Taggers, Production & Decay Mode Coverage

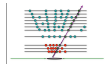


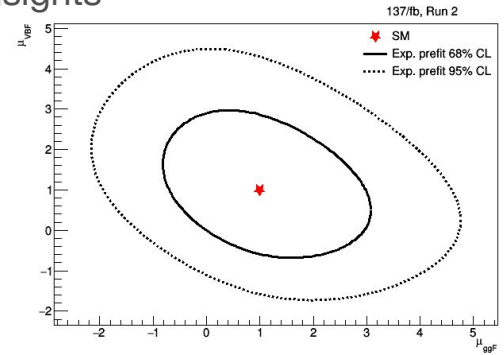


- Mass Decorrelated taggers starting with H(bb) now extended to H(cc), H(WW,4q) - rarer decay modes, constantly pushing to better sensitivity
- These channels were not possible without taggers
  - Expertise in AI to develop these techniques and bring them to the trigger
- Improved H(bb) makes VBF production mode with boosted Higgs viable in Run 3
  - HL-LHC - important for EFT
  - Upgraded tracker and new HGCAL will improve Particle Flow reconstruction
- FNAL-CMS program supports a broad program of boosted Higgs final states each with unique physics insights



TRIGGER





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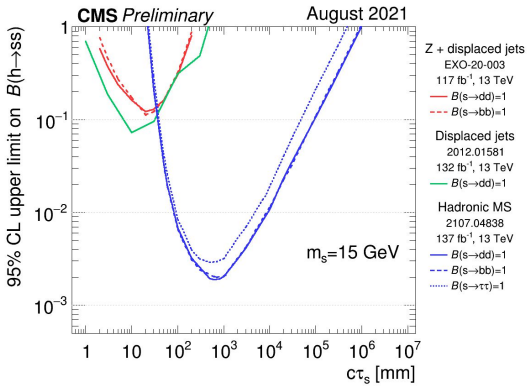
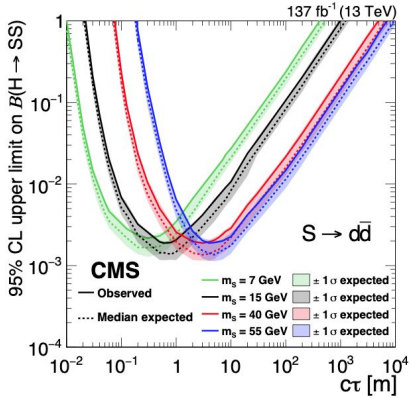
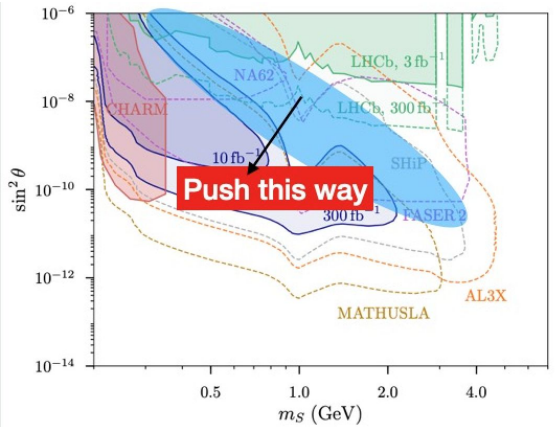
LLP Searches







- Established and led by FNAL scientists and postdocs
  - LPC based effort: Caltech, FSU, KNU, UCSB, UCSD, U of Hamburg
  - Vital collaboration with FNAL theorists: motivation, models
- A new detector signature: showers in Muon System
  - Sensitive to LLP energy rather than mass
  - Sensitive LLP search beyond $c\tau$ ~few meters (submitted to PRL)
- Tracker and calorimeter based LLP searches
  - Displaced jets search based on tracker information (submitted to JHEP)
  - A search for trackless AND delayed jets with DNN tagger
    - Sensitivity to EWK SUSY with long-lived neutralinos
    - More sensitive compared to prompt searches
- Several ongoing analysis to be finalized by Moriond
  - Heavy Neutral Lepton search: prompt lepton AND a MS shower
  - Light LLP search with B-Parking: reach down to 0.1 GeV
  - DNN based delayed photon search: extend GMSB neutralino limits by ~100 GeV

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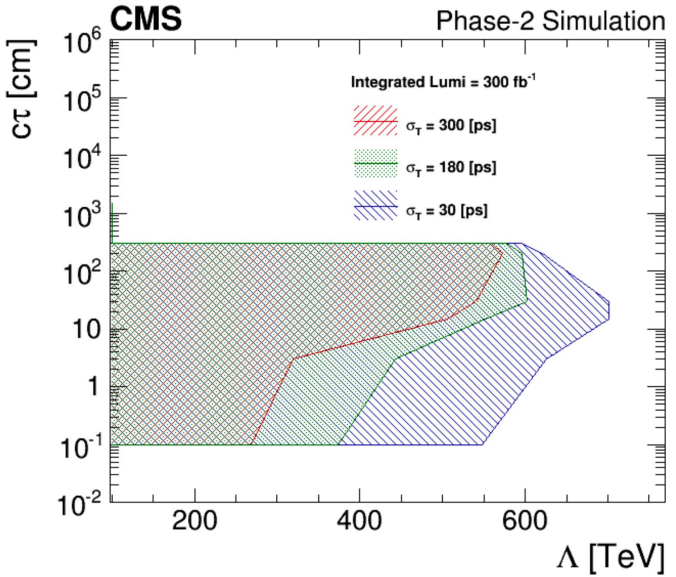
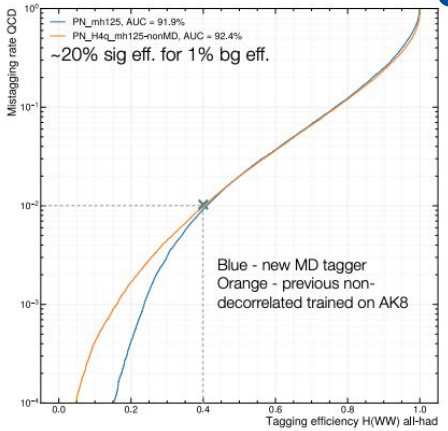
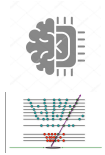
FPix installation

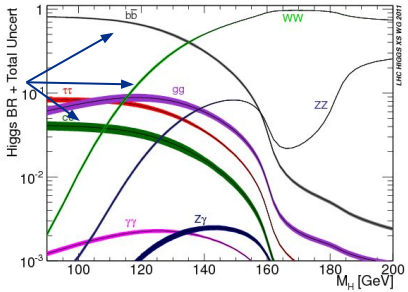

CMS
Phase-2 Simulation
Integrated Lumi = 300 fb-1
σT = 300 [ps]
σT = 180 [ps]
σT = 30 [ps]
cτ [cm]
Λ [TeV]

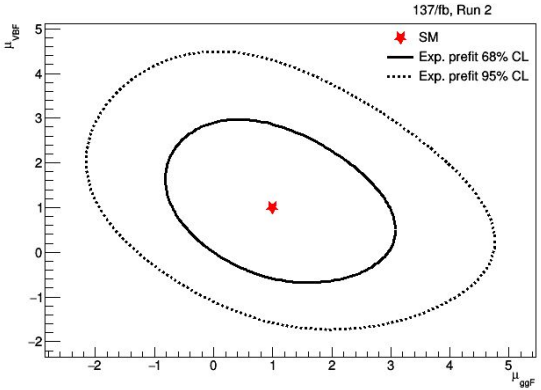
Boosted H(bb) - Innovation in Taggers, Production & Decay Mode Coverage





Boosted analysis helps here





- FNAL-CMS program supports a broad program of Higgs final states each using high pT “boosted” Higgs-jets with unique physics insights
  - Boosted signatures reduce background in high branching-fraction hadronic Higgs final states at cost of reduced acceptance
- Development of breakthrough/novel techniques to reconstruct high momentum objects necessary to achieve sensitivity
  - Expertise in AI to bring it to the trigger
- Improved H(bb) makes VBF production mode with boosted Higgs observable in Run 3, new taggers provide sensitivity to H(cc) (backup)
- HL-LHC - VBF important for EFT, inclusion of polarization
  - Upgraded tracker and new HGCAL will improve Particle Flow reconstruction and cover vital forward-jet production regions

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Di-Higgs Searches

HL-LHC will let us turn Di-Higgs into a stringent test of the SM!

In HL-LHC 20% more lumi from:

TRIGGER

Improvements in Run 2 and 3 analysis change nature of HL-LHC measurement!

Pushing analysis techniques and trigger have brought former HL-LHC sensitivities to Run 2

HH→4b low/high p_T (CMS-PAS-HIG-20-005)

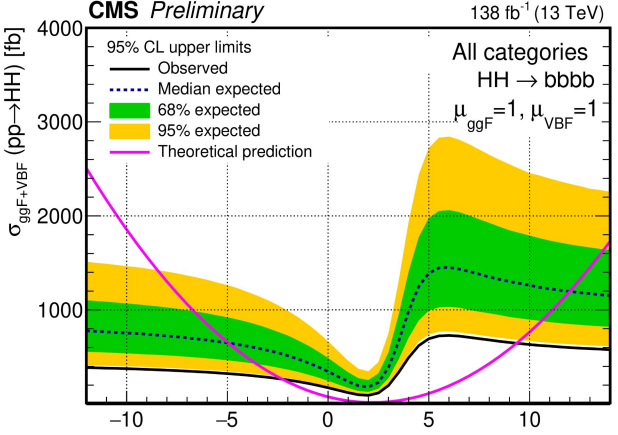
- Observed(expected) $\sigma/\sigma^{SM} < 3.7(7.3)$ at 95% CL → best observed sensitivity to date!
- Sensitivity to ~5xσ^{SM} at CMS Run II and world-leading sensitivity for VVHH coupling

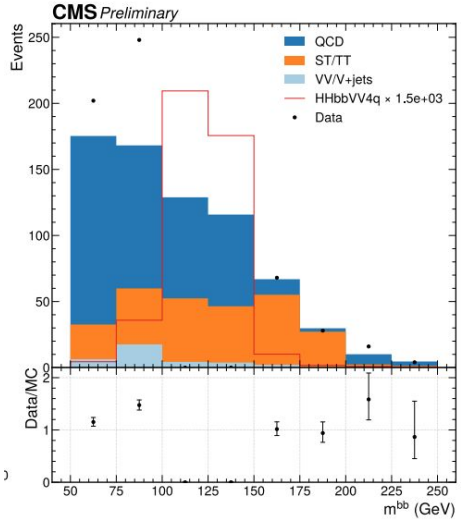
HH→bbWW (analysis in progress for Run 3)

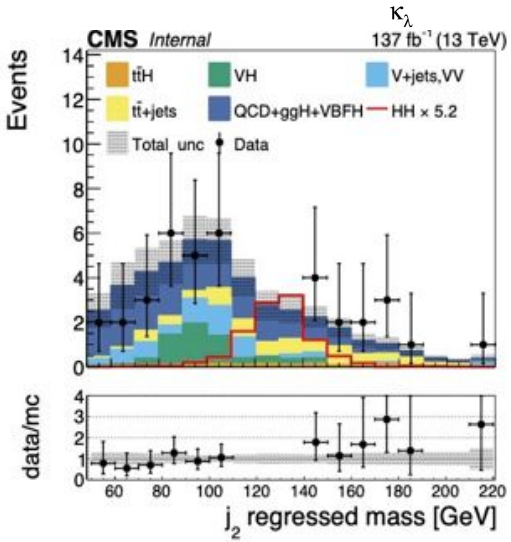
- Better sensitivity with new h→WW tagger

Preparation for Run 3

- Improve **trigger** efficiencies
- **ML techniques** for high quality taggers
- **BSM searches** in multi-Higgs final states (HHH, VHH, ttHH)







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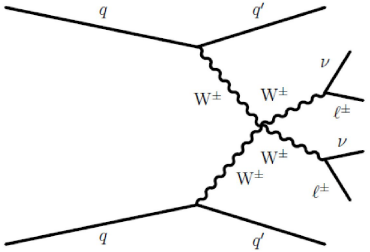
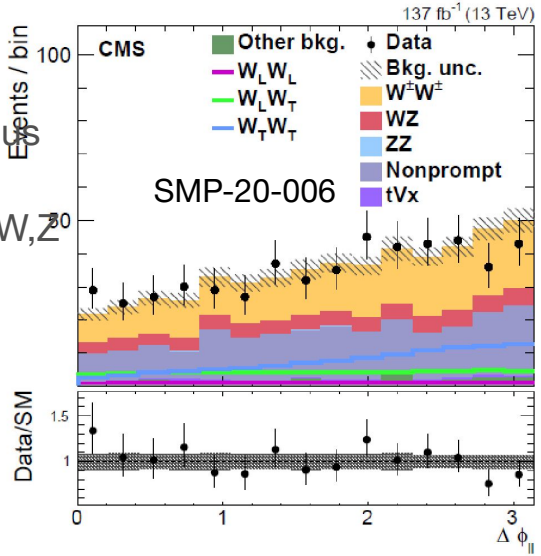
Vector Boson Scattering

TRIGGER



- Leading Run 2 measurements of VV scattering:
  - same-sign dilepton and trilepton final states (W+W+/W-W-/WZ, SMP-19-012)
  - semileptonic final state (WV/ZV, SMP-18-006)
  - First analysis of longitudinal polarization (SMP-20-006)
- Key expertise in boosted hadronic V reconstruction, lepton triggering and ID to evolve measurement in Run 3
  - Adding multivariate, multichannel constraints on polarization and anomalous quartic couplings
  - Will have enough data to use jet substructure reconstruction for hadronic W,Z fermion angles
- 10x more data and new detectors in HL-LHC will enable polarized cross sections, stronger EFT/aQGC sensitivity
  - HGCAL reconstruction of forward quark jets
  - Improved triggering and inclusion of all-hadronic final states

Final state fermion angles encode the W polarization!



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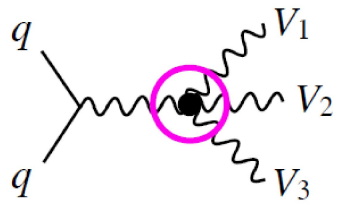
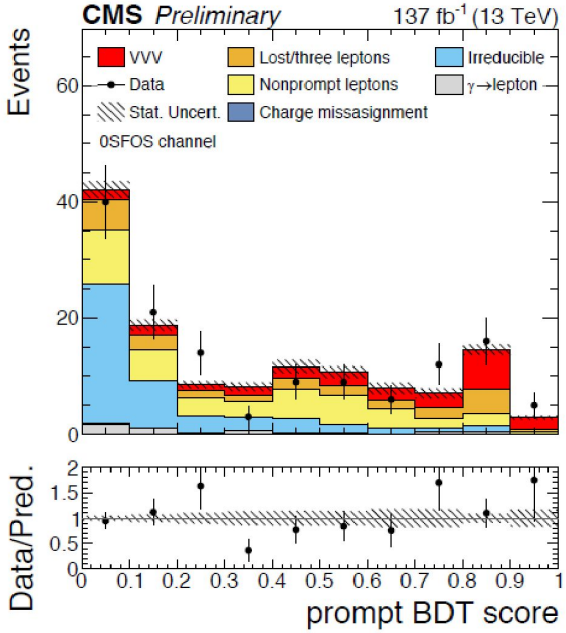
VV and VVV production

TRIGGER



- Led Run 1 measurements of VV production (WW, WV/ZV) and best constraints on anomalous triple gauge couplings (SMP-14-016, SMP-13-008)
  - 10x data in this domain will allow for polarization and aTGC studies of equal value to VBS
- Led the first observation of VVV production in Run 2 (SMP-19-014)
  - Requires precise control of lepton backgrounds, comprehensive multi-channel approach we developed
  - Combined signal just large enough to observe
- Run 3 to HL-LHC VVV data opportunities
  - Measure triple-boson final states (WWW, WWZ) differentially
  - Leading to improvements in EFT/aQGC sensitivity, measurement of SM quartic coupling values.
  - All possible through our consistent innovation at the trigger level



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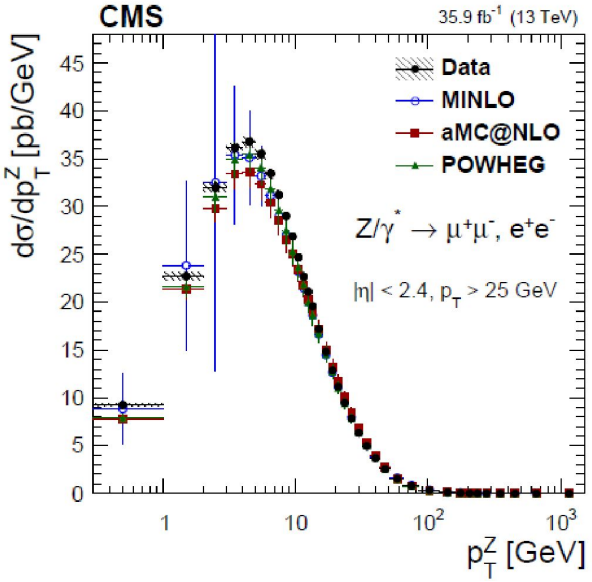
Precision Electroweak Physics

- Proposed & led inclusive and differential W and Z cross section measurements in Run 1 and 2
  - Inclusive W and Z
  - W charge asymmetry, Z AFB
  - Z PT and rapidity
- Led the collection of low-pileup data in 2018 to analyze W, Z cross section and PT with lowest systematics (analysis in progress)
  - DeepMET reconstruction to give highest W PT resolution to check & constrain W production modelling
- HL-LHC will provide enough data to measure directly or constrain W and Z production theory nuisance parameters (angular coefficients vs. PT, e.g.) giving ultimate precision for MW, weak mixing angle, PDFs

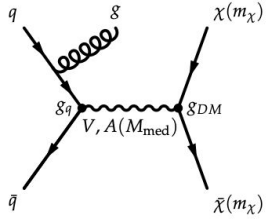


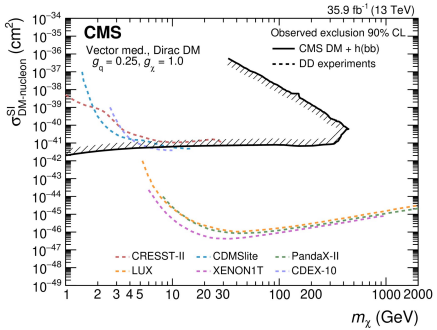
- Techniques developed at FNAL:
  - Endcap muon trigger and reconstruction
  - ML-based PU subtraction + DeepMET
  - Fits with high number of nuisance parameters

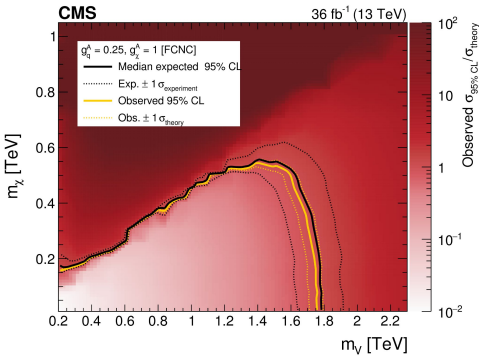
Dark Matter: Simplified Searches

TRIGGER

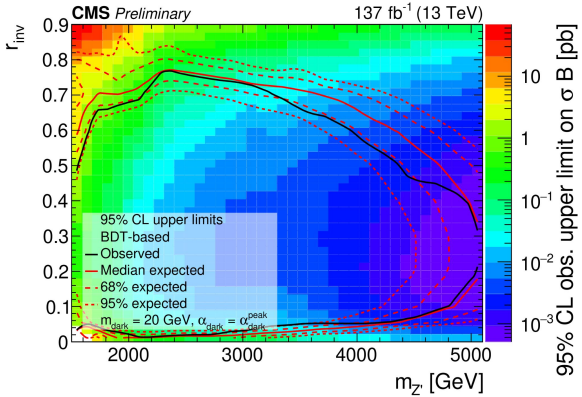
- Dark matter with some coupling to SM could be produced at the LHC, main goal is to understand *nature of DM*
- Assuming DM particles are not detectable directly, search for production in association with recoiling SM particle(s): **missing ET+X**
- Run 2 searches focused interpretation using simplified models
- FNAL group led several published Run 2 searches
  - Hadronic **monotop**
  - **Mono-Higgs** (bb decay)
- Currently two searches being completed using full Run 2 dataset
  - **Dark Higgs** (bb)- scalar boson that couples to dark sector
  - **Monotop** including leptonic decays



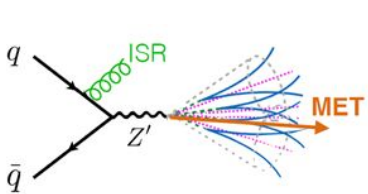


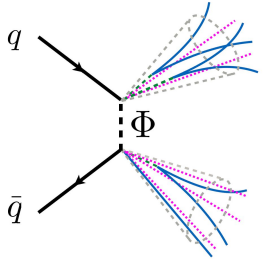


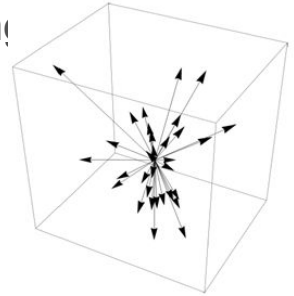
Strongly Coupled Hidden Sectors

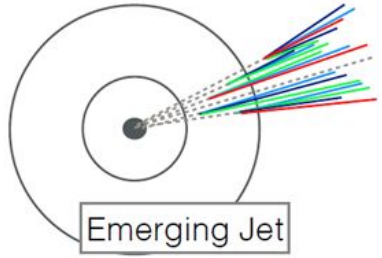


- Complement WIMP searches by looking for unconventional signatures w/ novel phenomenology
- CMS just released *first collider search* for semi-visible jets (mixture of visible & dark matter), led by FNAL: [CMS PAS EXO-19-020]
  - Program now expanding to boosted low-mass mediators, t-channel production
- FNAL currently leads search for soft unclustered energy patterns (SUEPs) and contributes to emerging jet search (multiple displaced vertices within jet cone)
- HL-LHC goals: search for mediators w/ weaker couplings, more sophisticated models, combinations of signatures (emergin semi-visible SUEPs)
- Enabled by FNAL expertise in event generation & AI/ML
- Strong connections to university groups through LPC









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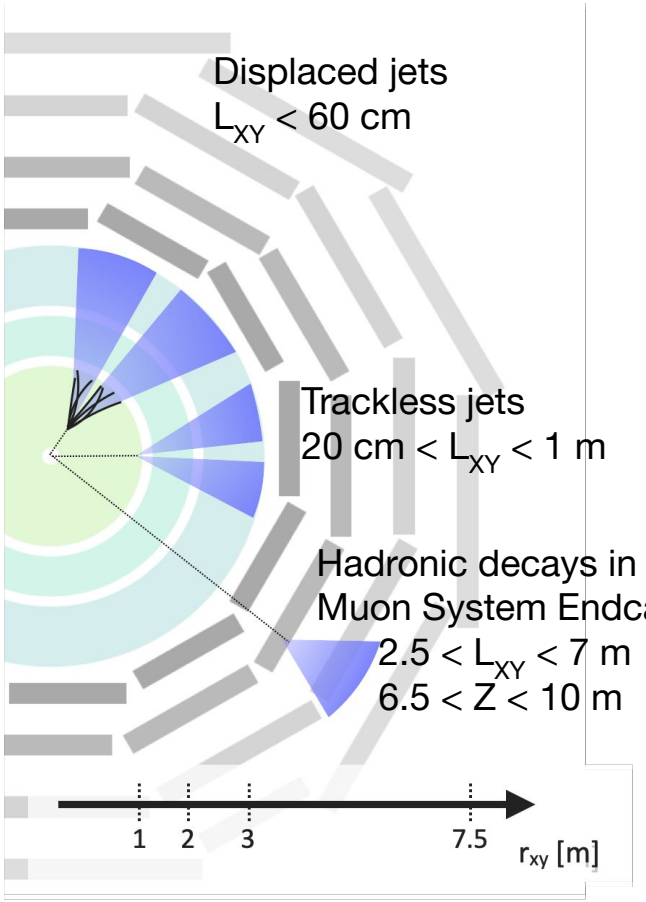
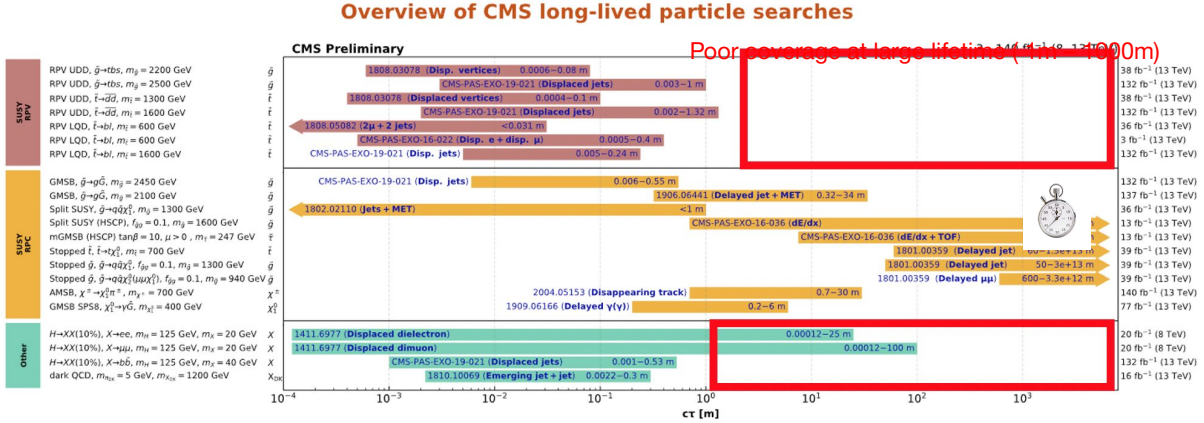
The Case for LLPs



- Apply well-motivated DM models to growing expertise in LL searches at CMS
- Long-lived particles (LLPs) are naturally predicted by many new physics models
  - Answers to fundamental questions: Dark Matter, neutrino mass, CP violation, hierarchy problem …
  - Higgs portal, Axion-like particles, heavy neutrinos, dark photons, and flavor changing decays, etc…
- Our program comprehensively covers the mm – 10m region
  - Access to light (~ 1GeV) LLPs



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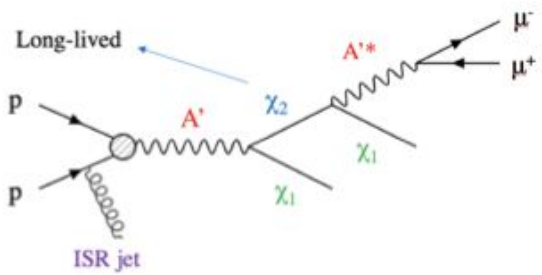
Dark matter with long-lived signatures

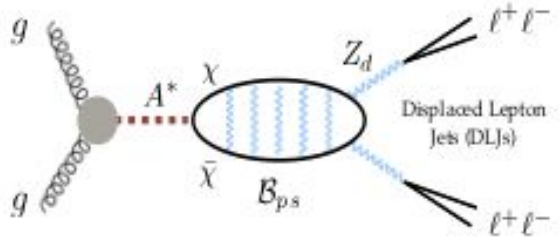
TRIGGER

- Complex dark sectors can have interactions between DM particles: **long-lived states**
- Currently leading two searches
  - Inelastic DM (iDM)
  - Self-interacting DM (SIDM)
- Both searches involve final states with “lepton jets”
  - Collimated lepton pairs; spin-offs for other searches
- For Run 3 and HL-LHC
  - Searches for LL states heavily trigger limited; development of optimized triggers vital
  - HL-LHC: optimize LL searches for upgraded detector (including MIP timing, more capable L1 trigger and HLT)
  - Work with theory community to develop dark sector models that are motivated by experiment as well as theory (e.g., iDM partially motivated by Xenon1T excess)

iDM:



SIDM:



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Long Lived Particles in Run 3

TRIGGER

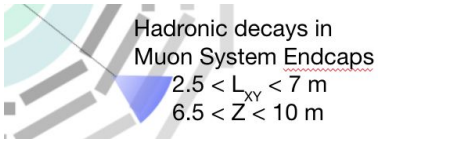
- Major goal for Run 3: improving trigger efficiency for lower mass LLPs (10-100 GeV)
  - Trigger = best opportunity to go beyond luminosity gains
  - Currently triggers typically have lower efficiency for low LLP masses
  - Fermilab LPC LLP group is involved in several major Run 3 trigger efforts

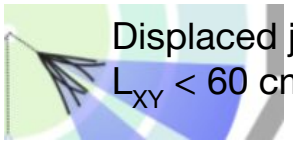
Extend sensitivity to displaced muons in Endcaps - new trigger capabilities!

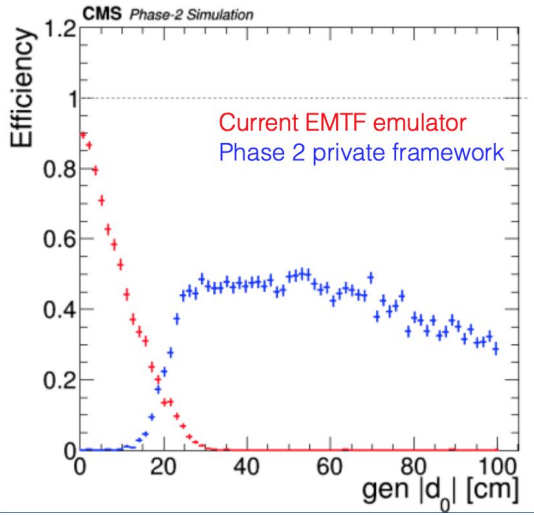
- Run 2: muon pT assignment requires vertex constraint, efficiency drops with d0
- Run 3: Neural network (NN) pT and d0 assignment (vertex unconstrained)
- Last presentation in LL

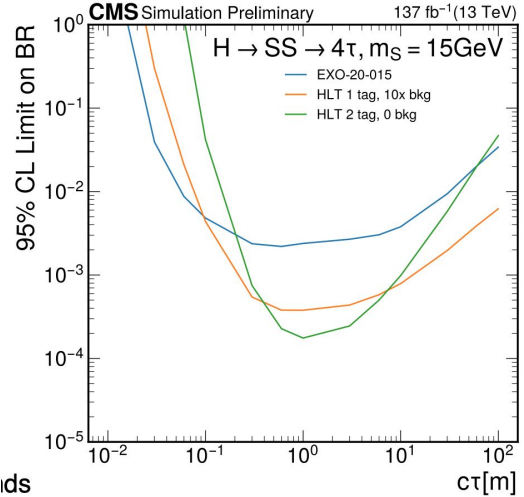
New trigger for Hadronic LLP Decays in muon System

- Run 2: MET trigger (~1% acceptance)
- Run 3: New L1 + HLT up to 8x gain
- EXO Trigger workshop









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LLP Searches at HL-LHC

TRIGGER

- An LLP-aware detector in HL-LHC:
  - Muon Showers at Level-1 trigger: > x10 improvement in sensitivity
  - Improved timing in ECAL: x10 increase in signal acceptance
  - New timing detector, MTD: entirely new methods and searches become possible
    - Extended mass reach for all new physics portals
    - Qualitatively new capabilities for SUSY, Exotica searches: reconstruct mass of neutralinos
- Unique data processing challenges for LLP analysis:
  - Standard CMS data tiers do not contain low-level detector info needed for sensitivity to novel signatures
  - Modernize data access architecture to enable future creative solutions: unique expertise in FNAL group
- Vertically integrated effort: theory, triggers, analysis, algorithms, leading to impactful publications