CMS Experiment



C. H. Shepherd-Themistocleous

Large Hadron Collider





Total weight 12500 t, Overall diameter 15 m, Overall length 21.6 m, Magnetic field 4 Tesla

PPD CMS Group

















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Dave





Bob

February 2025

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Run 3 (2022-2026)

- Complete Phase-I data set during PhD
- Sophistication of analyses leading to HUGH improvements
- Perfect time for PhD to get most from Phase I data

Upgrade for Run 4

Major detector component replacements using cutting edge technologies



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What We Work On



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Physics Analysis

Past Physics Analyses & Phenomenology



Higgs in BSM Physics

- Many BSM models predict additional low mass Higgs bosons (e.g. NMSSM, 2HDM)
- Novel channels identified with theorist collaborators
- NMSSM example:
 - DM candidate but no observable missing energy
 - Two light Higgs bosons giving rise to "fat jets"
 - ML plays key role in analysis





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HL-LHC Upgrades

Upgrade of CMS for HL-LHC

L1-Trigger/HLT/DAQ

https://cds.cern.ch/record/2714892 https://cds.cern.ch/record/2283193

- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
 - HLT output 7.5 kHz
 - 40 MHz data scouting

Calorimeter Endcap

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

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

Tracker https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
 - Design for tracking in L1-Trigger
 - Extended coverage to $\eta \simeq 3.8$

Barrel Calorimeters

https://cds.cern.ch/record/2283187 ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV ECAL and HCAL new Back-End boards

Muon systems

- https://ets.cem.ch/record/2283189
 - DT & CSC new FE/BE readout
 - RPC back-end electronics
 - New GEM/RPC 1.6 < η < 2.4
 - Extended coverage to $\eta \simeq 3$

Beam Radiation Instr. and Luminosity

http://cds.cern.ch/record/002706512

• Bunch-by-bunch luminosity measurement: 1% offline, 2% online

MIP Timing Detector https://cds.cern.ch/record/2667167

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

Track Finder

Silicon tracker to be completely replaced for HL-LHC





 $y = \begin{bmatrix} z \\ x \\ z \\ x \end{bmatrix} = \begin{bmatrix} z \\ 1 \\ 0 \\ 0 \\ \mu m \end{bmatrix}$ pass fail $\odot \vec{B}$ $\odot \vec{B}$

Enables track finding at in Level 1 trigger.

Completely new capability

Level 1 Trigger

Level-1 Trigger

- Decides whether any data will be read out from detector
 - Bunch crossing 40MHz L1 output 750kHz
 - L1T critical role in data acquisition!
- Receives coarse granularity data from all major detector systems.
 - Reconstruct events within 12µs
 - Jets, electrons, photons, muons, missing energy
 - ~200 interactions a major challenge



Tracks available in L1T for the first time, enabling **paradigm shift** in algorithms Tracks alone can give interaction point Can reconstruct objects only from tracks (e.g. jets), or combine with calorimeters

Machine Learning and FPGAs

Large Fast FPGAs



Enable ambitious L1 upgrade



Current system will be replaced with latest technologies (FPGAs & optics)

- Hundreds of FPGA-based boards
- Thousands of 25Gbps links
- 3Tbps I/O per board



Machine Learning and FPGAs

Going beyond baseline upgrade

- New Physics we have not thought of will not look like the standard model
- Use ML to look for <u>anomalies</u> that could be New Physics



Autoencoder possibility



- 1) Search for evidence of BSM physics exploiting extended Higgs sectors with light Higgs Bosons.
 - Definitive Phase I analysis using entire dataset.
- 2) Design and implement ML methods for identifying anomalous events in the HL-LHC L1 trigger.

Backup slides

CMS Electromagnetic Calorimeter (ECAL)

The CMS ECAL is a highly-granular crystal calorimeter - excellent energy and position resolution, radiation tolerance and fast response

The ECAL was a **crucial element** in the **discovery** of the Higgs Boson in 2012, in the two golden discovery channels: $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4I$

RAL PPD responsibilities: Design, Delivery, Installation, and Operation of the ECAL





Construction and installation of the ECAL





Two Higgs Doublet Models (2HDM)



Semi-visible jets



Project

Project will encompass:

- BSM physics analysis focusing on more realistic models beyond MSSM.
- Explore potential of NMSSM with enlarged Higgs sector.
- Develop complex jet reconstruction and tagging. Exploit ML techniques
- Develop algorithms for the HL-LHC upgrade of the L1 trigger. Exploit new structure concept and tracks never before available.

Level-1 Trigger Upgrade

- Current system will be replaced with latest technologies (FPGAs & optics)
 - Hundreds of FPGA-based boards
 - Thousands of 25Gbps links
 - 3Tbps I/O per board
- A complex distributed system!
 - Individual boards need to be operated coherently as a single system, e.g. sychronise clocks, align input data
 - Setting up test system at CERN to integrate different board designs and algorithms, and verify operation of the system.





Physics Analyses



- NMSSM Light Higgs 7 Higgs bosons found one so far ③
- This analysis would be the evidence of SUSY in this scenario
- Particular feature no observable missing energy
- "Fat jets" & double b-tagging. Use neural nets.
- Initial analysis good. Will develop scenarios with theorists.

