CMS Status

Indara Suarez
On behalf of the CMS Experiment
June 7, 2023, 154th LHCC Open Session

June 7, 2023, 154th LHCC Open Session
Overview

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

• **Phase 2 upgrade status**

• **Physics analysis highlights**
Tracker

- **Pixel and Strip detector started data taking successfully**
  - Operational performance of detectors is good up to 65 PU
  - No particular problems running up to L1 rates of 110 kHz
- Timing and bias scans already performed during 900 GeV fills
  - Pixel bias scans 1/week for tight radiation monitoring
  - Alignment automatically runs with fine time granularity on large structures in pixel detector

- **Up to and including 2022**
  - Inner Barrel 2023
Electromagnetic Calorimeter Status

- **Operations**: ECAL has been running smoothly during commissioning period and now during collision runs
  - ECAL participated in all commissioning runs (MWGR, CRUZET, CRAFT)
  - beam splash runs used to make timing adjustments
  - ECAL alignment for EB, EE, ES with respect to Tracker has been performed
  - EB HV settings adjusted to compensate for voltage drop due to increasing APD leakage current
Hadronic Calorimeter Status

- HCAL smooth 2023 operations
- Improving reliability of detector and quality of data
  - Operations: monitoring pedestal and strength of control links; automatic BV upset recovery; per-channel zero-suppression setting
  - Response correction: depth-dependent and including phi-symmetry calibration
- Automatized steps in the detector condition validation and deployment

L1 LLP rate maximized when jets pushed into delayed region

L1 LLP Jet trigger rates [Hz]

10k
1k
100
10
1

0.1
400 500 600 700 800 900 1000 1100 1200

Reference timing (2022)

Default phase delay (0ns)

- Exhaustive phase scan, in 1ns steps, for timing alignment (LLP trigger) and first depth-dependent pulse-shape measurement in HB and HE
Muon Detectors Status

- Muon sub-system is running smoothly during 2023 LHC data taking
- Active channels fraction in readout:
  - DT : 99.2%
  - CSC : 99.0%
  - RPC : 84.7%
    - Barrel : 72.8%
    - Endcap : 99.2%
  - GEM : 91.5%
- Muon chamber performance study with 2023 data ongoing. Preliminary results agree with expectations
- New RPC C$_2$H$_2$F$_4$ recuperation system installed. Commissioning ongoing.
- Operation expected to start in 2-3 weeks.
- 80% efficiency
BRIL Status

All online luminometers independently “calibrated” using emittance scans

- 4 different independent luminometers in this plot (Fill 8822 0.77 fb$^{-1}$)
- Each luminometer tracked with emittance scans. → highly stable.
  - Thank you to LHC!
Precision Proton Spectrometer Status

• Roman Pots (RPs): regularly inserted in standard fills, no operational problems with pileup > 60
• Pixel tracking
  - Major campaign during YETS to address problems seen in 2022
  - Successful start to 2023: all 4 tracking RPs working well
  - First use of new remote vertical movement system to mitigate non-uniform radiation
• Diamond timing
  - All 4 timing RPs working, including 2 newly instrumented for 2023
L1 Trigger

- Smooth operation of the L1 Trigger during collisions
- L1 rate was increased to 110 kHz this year to cope with higher LHC luminosity and pileup
  - Good performances of L1T algorithms in Run 3 ([DP notes for 2022](https://cds.cern.ch/record/2842376?ln=en))
  - New trigger algorithms in Run 3 targeting long-lived signatures
    - Displaced hadronic showers in the CSC
    - Displaced muons & displaced/delayed jets in HCAL
  - Additional physics capabilities in updated 2023 L1T menu
    - April 2023: Bs→µµ, τ→3µ, and W→3π seeds
    - May 2023: new VBF parking seeds and lower mjj threshold for central dijet seeds.
- Updated calorimeter and muon trigger calibrations
  - rates changed are as expected

https://cds.cern.ch/record/2842376?ln=en plots also in this twiki
HLT

2023 data taking vs 2022:
- Luminosity leveling: $1.8 \times 10^{34} \rightarrow 2.1 \times 10^{34}$, Pileup: $54 \rightarrow 63$
- Target L1 rate pre-deadtime: $100 \text{ kHz} \rightarrow 110 \text{ kHz}$

HLT output: ~2.5 kHz prompt, ~3.5 kHz parking, and ~20 kHz scouting
- Introduced new parking streams dedicated to VBF, LLP, and HH
- Excellent trigger performance since the first 2023 data

trigger:
- jet $p_T > 500$ GeV
- 4 jets, 2 b-tags
- Tier-0 input/output rates at the level of fall 2022
- Prompt process of data approaching HL-LHC rates, including parking (~6 kHz)
- Balancing prompt reconstruction load between Run 2 HLT farm, permanently available for offline, and Tier-0

  New operations mode, working very well.

- Prompt reconstruction at Tier-1’s being tested
  - A safety net in case load unexpectedly increases
  - Data at CERN, remote I/O from the sites via xrootd
  - Successfully “replayed” prompt reconstruction from FNAL, other Tier-1’s will follow
Lower efficiency due to the collection of phase-scan data, invaluable in optimizing the performance of HCAL

Improvements in data certification make it possible to certify per lumi section.
Higher efficiency
### 2023 Release and Data/MC processing Plan

**Releases purposes:**

- **13_0:** promptRECO of 2023 + MC for PAGs + Nano v12
- **13_1:** MC for Trigger Phase2
- **13_2:** HI DATA taking + HI MC
- **13_3:** Nano v13 + EOY 2022 full ReRECO + MC for PAGs
- **13_4:** 2024 preparation + MC for TSG, PF and POGs
- **14_0:** promptRECO of 2024 + MC for PAGs

**Partial ReRECO 2022 DATA (12_4_X)**
- SF/Corrections from POGs
- MC for PAGs 2023 DATA
- start with Nano v12 and migrate to Nano v13
- HI Run

**Partial ReRECO of ERAs ABC**
- SF/Corrections from POGs
- MC for HI 2023 DATA

**MC for 2024 preparation**
- EOY 2022 DATA+MC

**MC for 2023 preparation (12_6_X)**
- SF/Corrections from POGs

**Beam commissioning**
- CRUZET
- CRAFT

**HI**
- RunRamp Up
- MWGR #2
- CRUZET
- CRAFT

**P5 operations**
- 12_6_X
- 13_0_X
- 13_2_X
- 13_4_X
- 14_0_X

**Plan is in place for release of data and MC processing**
The CMS Phase 2 Upgrade

L1-Trigger
https://cds.cern.ch/record/2714892
- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting

Tracker
https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \approx 3.8$

Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

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

DAQ & High-Level Trigger
https://cds.cern.ch/record/2759072
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

MIP Timing Detector
https://cds.cern.ch/record/2667167
- Precision timing with:
  - Barrel layer: Crystals + SiPMs
  - Endcap layer:
    - Low Gain Avalanche Diodes

Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \approx 3$

Beam Radiation Instr. and Luminosity
http://cds.cern.ch/record/2759074
- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity:
  - 1% offline, 2% online
- Neutron and mixed-field radiation monitors
The CMS Upgrade

- Ring forged inner cylinders received at CERN.
- Ready to be shipped to Pakistan for final machining.
Story of the month: BTL module optimization

- Last year: a) Unexpected light loss and b) higher Dark Current Rate (DCR) after irrad.
- Significant optimization of configuration recovered nearly TDR $\sigma_t$ performance
  - Smart thermal management with TECs (additional cooling and annealing)
  - SiPM technical choice of 25 $\mu$m cell size to boost signal
  - Thicker LYSO arrays for larger energy deposits
  - TOFHIR2C ASIC optimization for electronic noise reduction
- BTL prototyping phase is concluded and we are ready to start procurement
Progress in all Phase 2 project areas

Some highlights

• **Barrel Timing Layer**: LYSO contract awarded to single vendor that was highly cost-effective. SiPM Production Readiness Review will happen this week.
• **Endcap Timing Layer**: ETROC2 ASIC received and is working
• **Outer Tracker**: Production kick-off batch for hybrid production released
• **Inner Tracker**: Contract placed for planar sensors and 3D sensor vendor chosen
• **HGCAL**:  
  - Successfully passed Engineering Design Review  
  - ECON-D MPW submitted in March; ECON-T-P1 testing completed.  
  - HGCROC ASIC submitted  
  - First pre-production silicon sensors delivered for HGCAL
• **BRIL**: FBCM ASIC submitted
• **Barrel Calo, Drift Tubes, Cathode Strip Chambers**: all items finalized, going to full production

• **The P2UG commended our technical progress but also commented on the tension with respect to the aggressive schedule which has little margin.**
• **They encourage us to close options and transition fully to production.**

ECON: HGCAL concentrator ASIC (data and trigger version)  
ETROC: Endcap Timing Layer front-end ASIC  
FBCM: Fast Beam Condition Monitor
Newly Observed Physics Phenomena

**SMP-22-006**: Observation of WWγ production at \( \sqrt{s} = 13 \text{ TeV} \)

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

**TOP-22-013**: Observation of four top quark production in pp collisions at \( \sqrt{s} = 13 \text{ TeV} \)
Public results since last LHCC: LHCP results

1. **LUM-21-001**: Luminosity measurement with Z boson counting
2. **HIG-20-002**: Low mass di-photon Higgs search with full run 2 data
3. **HIG-21-005**: Search for HH production in the bbWW decay mode
4. **HIG-22-007**: Search for H→aa→2µ2b/2τ2b
5. **HIG-22-006**: Search for Higgs boson pair production with one associated vector boson in proton-proton collisions at sqrt(s) = 13 TeV
6. **HIG-22-003**: Search for H→Za→ll γγ
7. **TOP-22-013**: Observation of four top quark production in proton-proton collisions at sqrt(s) = 13 TeV
8. **TOP-22-009**: Inclusive and differential cross section measurements of ttbb production in the lepton jets channel
9. **SMP-22-016**: Measurement of the Z→ττμμ branching fraction
10. **SMP-22-006**: Observation of WWγ production at sqrt(s) = 13 TeV
11. **SMP-22-007**: Measurement of the primary Lund jet plane density in proton-proton collisions at 13 TeV
12. **B2G-20-012**: Search for heavy mass W’ boson decaying in tb quarks in leptonic final states
13. **SUS-21-008**: Combination of searches for EWK SUSY (full Run 2)
14. **SUS-21-009**: Search for SUSY in events with a photon, jets and MET (full Run 2)
15. **HIN-21-016**: Multiplicity dependence of charm baryon and meson production in pPb collisions at 8.16 TeV
16. **HIN-21-004**: Study of charm hadronization with prompt Λc baryons in proton-proton and lead-lead collisions at sqrt(s_NN)= 5.02 TeV
17. **BPH-21-005**: Search for lepton flavor violating τ→3µ decay
18. **BPH-22-002**: Observation and branching ratio measurement of Λc → J/ψ Ξ- K
19. **TOP-22-007**: Searches for Lorentz invariance violation with tt dilepton final state at 13 TeV
20. **TOP-22-008**: Evidence for SM tWZ process in multi-lepton final states
21. **SMP-22-001**: Measurement of ZZ(4l)+jets analysis with full Run 2
22. **HIG-23-002**: Evidence for the Higgs boson decay to a Z boson and a photon at the LHC
23. **SUS-21-006**: Search for long-lived SUSY with disappearing tracks
24. **EXO-21-013**: Search for long-lived heavy neutral leptons with displaced jet tagger
25. **EXO-22-008**: Search for narrow trijet resonances
26. **EXO-22-016**: Search for a high mass dimuon resonance associated with b quark jets at 13 TeV
27. **EXO-22-018**: Search for leptoquarks produced in lepton-quark collisions and coupling to tau leptons
28. **MUO-22-001**: Machine learning techniques for muon identification and isolation

**Searches**
**Evidence**
**Observations**
**Measurements**
**Detectors and Experimental Techniques**
- Featured in this talk
Observation of 4 top quark production

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

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

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

\[
17.7^{+3.7}_{-3.5} \text{ (stat)} +^{2.3}_{-1.9} \text{ (syst) fb}
\]
Evidence for the Higgs boson decay to a Z boson and a photon at the LHC

- Combined evidence of $H \rightarrow Z \gamma$ from ATLAS and CMS results
- Similar analysis strategy. Correlated (TH) and uncorrelated (EXP) systematic uncertainties taken into account in the combination
- Observe evidence for a signal with $3.4\sigma$ significance (expected $1.6\sigma$)
  - Observed signal cross section corresponds to $2.2 \pm 0.7$ times the SM cross section
- $1.9\sigma$ compatibility with SM prediction
Searches for LLP

- Searches for long-lived particles still a very active front.
  - Search for SUSY with long-lived charginos
    - Predicted in natural SUSY scenarios (weakinos are almost degenerate Higgsinos)
    - Signal characterized as heavy muon stopping suddenly in the tracker
    - A BDT classifiers is deployed to select disappearing tracks while rejecting tracks originating from failures in the reconstruction or from combinatorial effects
  - Complementarity to standard SUSY searches

- Search for Heavy Neutral Leptons (e.g., massive right-handed neutrinos) in LHC events
  - Start with \( W \rightarrow \ell \nu \). HNL would be long-living and decay far from interaction point, to \( \ell W^* \) or \( \nu Z^* \)
  - Signal characterized as cluster of hits in muon stations, unmatched to tracks from inner detector
Search for a high mass dimuon resonance associated with b quark jets at 13 TeV

- Probe Lepton Flavor Universality Violation (LFUV)
  - Present in several NP scenarios with particles coupling preferentially to first or second generation.
- New $Z' + \geq 1b$-jet search uses $m_{lb}^{min}$ to remove $t\bar{t}$ and preserve signal at high mass

$$\mathcal{L}_{BSM} = Z'_\mu \left\{ g_\ell \sum_{f=e,\mu,\tau} \bar{f} \gamma^\nu P_L f + g_\nu \sum_{f=\nu_e,\nu_\mu,\nu_\tau} \bar{f} \gamma^\nu P_L f + g_b \left[ \bar{b} \gamma^\nu P_L b + \delta_{bs} (\bar{\gamma} \gamma^\nu P_L b + h.c.) \right] \right\}. $$
Search for lepton flavor violating $\tau \rightarrow 3\mu$ decay

3$\mu$ provides a clean signature

- Multivariate (BDT) analysis used to target:
  - Taus from Heavy Flavor (HF) decays $\sim 10^{11} \tau/fb$
    - low-pT and high $|\eta|$ → less efficient trigger selection
    - more sensitive to fake signal muons from $\pi$’s, K’s
  - Taus from W decays $\sim 10^7 \tau/fb$
    - harder spectra and more central decay → more efficient trigger selection
    - Additional handles for background suppression (large MET, low hadron activity, larger signal pT)

- Best LHC & BaBar limits

**Observed (Expected) upper limits (with full run2)**

$B(\tau \rightarrow 3\mu) = 2.9 (2.4) \times 10^{-8}$ at 90% CL

- Projected to improve over Belle with Run 3, thanks to new loose triggers in Parking dataset
Detailed studies of $\Lambda_c^+$ production in pPb and PbPb collisions

- First measurement of $\Lambda_c^+/D^0$
- No significant multiplicity dependence in pPb [HIN-21-016]
- Extending $\Lambda_c^+$ production up to $p_T=40$ GeV in PbPb [HIN-21-004]
- $\Lambda_c^+/D^0$ ratios are consistent between pp and PbPb collisions

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

- **CMS is successfully taking data in 2023**
  - New trigger capabilities for Run 3, higher rates, same or better efficiency
  - Dealing successfully with increasing PU
    - maximizing luminosity without affecting the physics goals
  - Already > 50 fb⁻¹ of good data in Run 3, acquiring data at high efficiency

- **Steady technical progress on Phase 2 Upgrade Activities for HL-LHC**
  - Significant optimization of BTL system helped recovered nearly TDR timing resolution performance

- **CMS continues to produce results with Run 2 data, Run 3 efforts ramping up**

- **Successful delivery of new results for LHCP**
  - Ingenuity and creativity for new directions
  - Still exploiting at best our Run 2, with many measurements and results
  - Three new observations, two new evidences for new processes
  - Detailed studies of $\Lambda_c^+$ production in pPb and PbPb collisions
  - $\tau \rightarrow 3\mu$ sets a milestone for our extended physics program beyond core high-pT activity
Backup
Combination of searches for EWK SUSY

For the first time, six CMS searches were combined

- explores models that differ depending on whether the next-to-lightest supersymmetric partner (NLSP) is “wino-like” or “higgsino-like”
- fully leptonic, semi-leptonic and fully hadronic final states
- Wino-like NLSP: excluded up to masses of 875 GeV
- Higgsino-like NLSPs: excluded up to masses of 810 GeV
L1 Trigger

- Smooth operation of the L1 Trigger during collisions
  - Previously operational and available during commissioning and first beam

- L1 rate was increased to 110 kHz this year to cope with higher LHC luminosity and pileup
  - new possibilities for physics
  - L1T/HLT prescales tuned accordingly

- New physics capabilities in updated L1T menu
  - April 2023: Bs→μμ, τ→3μ, and W→3π seeds
  - May 2023: new loose VBF seeds and lower mjj threshold for central dijet seeds.

- Some problems with the Global Trigger firmware after the April update, now fixed
  - Data quality not significantly affected

- Updated calorimeter and muon trigger calibrations
  - rates changed are as expected

![Graph showing L1 trigger rate over time]
Level 1 Trigger performances in Run 3

- Several improvements to data quality monitoring
  - Since 2023: L1 objects added to centrally produced NANOAOD
  - Ongoing development of efficient multi run harvesting
- Good performances of L1T algorithms in Run 3
  - Documented in DP notes for 2022 ([link])
  - Improved or similar performances in 2023

L1 isolated tau efficiency as a function of offline tau $p_T$

L1 muon efficiency in endcaps as a function of offline muon $p_T$

Pseudorapidity resolution of EG objects (offline vs L1)
Level 1 Trigger performances in Run 3

- New trigger algorithms in Run 3 targeting long-lived signatures
  - **Displaced hadronic showers in the CSC → Unique to CMS**
- Displaced muons & displaced/delayed jets in HCAL
- Commissioned during 2022
  - Performances as expected
  - A few adjustments performed for 2023

https://cds.cern.ch/record/2842376?ln=en
plots also in this twiki
Automation Framework (improving PromptReco)

• Developed originally by the ECAL group
• A system designed to automate the data processing necessary to calibrate and monitor
• Primary focus → improve the quality of PromptReco, reduce the time needed to derive and validate conditions
• Hackathon took place in the end of April
  - Goal: extend the system to the other sub-Detectors
  - HCAL, DT, PPS, JME, Pix participated and quickly made significant progress
• PPD is working towards: use of PromptReco for early physics, without End-of-year Rereco.
  - This automation Framework is playing the key role to enable that.
ECAL Laser Lab Relocation

- The installation of the CO2 cooling plant for HL-LHC detectors requires relocation of the ECAL laser lab
- The laser system is essential to precisely monitor radiation damage that affects crystal transparency
- After final inspection from CERN safety, ground-level laser lab is finally available to be occupied by the ECAL team
- Pilot Run is still scheduled to take place during the June Technical Stop
- The new, more powerful green laser, which was acquired to compensate for further radiation-induced transparency loss and increased attenuation from the relocation, was received and commissioned (in the underground lab for the moment)
ECAL Upgrade

• Submission review of the LiTE-DTU suggested that a detailed power analysis of the chip is performed, which is nearly completed. Submission is imminent.

• The necessary preparations for the production of the VFE and FE cards are underway

• Design of the backend BCP v2.0 is being finalized

• Plans for summer test beam plans:
  • Spare super-module (SM36) at H4 beam line (8 readout towers = 200 channels)
  • Full readout tower (25 channels) at CHARM Irradiation Facility
Proposal to re-install existing PPS XRPs for HL-LHC at 196m, 220m, and 234m locations

Continuation and extension of successful Run 2/3 physics program: both larger integrated luminosity, and exploring uncharted range of masses

Detailed scope document and ECR prepared, following Expression of Interest published in 2021

Significant progress in defining exact locations, services, machine interfaces, costs, etc. in the past year

Designs for the relatively small “new” pieces (vacuum vessels, detector packages) prepared