CMS Cathode Strip Chambers

Upgrades for the High Luminosity LHC

Johan Sebastian Bonilla Castro
Pronouns: They/Them
On behalf of the CMS Collaboration
11 January 2022

30th International Symposium of Lepton Photon Interactions at High Energies
Outline

- CSC@CMS: The What and The How
- HL-LHC: Motivations and Plans
- Upgrades Completed During LS2
- Gearing Up for Run 3
- Outlook on Future Upgrades
CMS at the LHC

- LHC delivers proton-proton collisions at $\sqrt{s} = 13\ TeV$
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HL-LHC Timeline at a Glance
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Run 1
- 7 TeV
- 8 TeV
- splice consolidation
- button collimators
- R2E project
- 75% nominal Lumi
- 30 fb⁻¹

Run 2
- 13 TeV
- EYETS
- cryomagnet interaction regions
- experiment beam pipes
- nominal Lumi
- 190 fb⁻¹

Run 3
- 13 - 14 TeV
- LS2
- Diode Consolodation
- LIU installation
- 11 T dipole coll.
- Civil Eng. P1-P5
- 2 x nominal Lumi
- ALICE + LHCb
- upgrade
- radiation damage
- 2 x nominal Lumi
- integrated luminosity
- 3000 fb⁻¹
- 4000 (ultimate)

Run 4 - 5...
- 14 TeV
- LS3
- HL-LHC installation
- 5 to 7.5 x nominal Lumi

H = Jul 2012
HL-LHC Timeline at a Glance

Run 1
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Run 2
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- 13 - 14 TeV
- LS2
- Diallel Consolidation LIU installation
- 11 T dipole coll. Civil Eng. P1-P5
- 2019-2020
- ATLAS - CMS upgrade phase 1
- ALICE - LHCb upgrade
- 2021-2022

Run 4 - 5...
- HL-LHC
- 14 TeV
- HL-LHC installation
- 2025-2026
- ATLAS - CMS HL upgrade
- 2027-2040

Integrated luminosity
- 3000 fb⁻¹
- 4000 (ultimate)

Notes:
- H = Jul 2012
- ➥ = Jan 2022

LP2021 — Johan S Bonilla — UCDavis, CMS, CSC
HL-LHC Timeline at a Glance

- **Run 1** (2011-2012)
  - **LS1**: splice consolidation button collimators, R2E project
  - **7 TeV**
  - **H**
  - 75% nominal Lumi
  - 30 fb⁻¹

- **Run 2** (2013-2018)
  - **13 TeV**
  - **EYETS**
  - Experiment beam pipes
  - 2 x nominal Lumi
  - 190 fb⁻¹

- **Run 3** (2019-2024)
  - **LS2**: Dipoles Consolidation, LIU Installation
  - 11 T dipole coll., Civil Eng. P1.P5
  - 2 x nominal Lumi
  - ATLAS - CMS
  - ALICE - LHCb upgrade
  - 350 fb⁻¹

- **HL-LHC**
  - **Run 4 - 5**
  - **LS3**: HL-LHC installation
  - **14 TeV**
  - 5 to 7.5 x nominal Lumi
  - ATLAS - CMS
  - HL upgrade
  - Radiation damage
  - Integrated luminosity
  - 3000 fb⁻¹
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**Annotations**
- **H** = Jul 2012
- **★** = Jan 2022

**Legend**
- **LP2021 — Johan S Bonilla — UCDavis, CMS, CSC**
The Compact Muon Solenoid

**CMS DETECTOR**
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m

**Magnetic field**: 3.8 T

**STEEL RETURN YOKE**
- 12,500 tonnes

**SILICON TRACKERS**
- Niobium titanium coil carrying ~18,000 A
- Pixel (100x150 µm²) ~1.9 m³ ~124M channels
- Microstrips (80–180 µm) ~200 m³ ~9.6M channels

**SUPERCONDUCTING SOLENOID**
- Niobium titanium coil carrying ~18,000 A

**MUON CHAMBERS**
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

**FRESHOWER**
- Silicon strips ~16 m³ ~137,000 channels

**FORWARD CALORIMETER**
- Steel + Quartz fibres ~2,000 Channels

**CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)**
- ~76,000 scintillating PbWO₄ crystals

**HADRON CALORIMETER (HCAL)**
- Brass + Plastic scintillator ~7,000 channels

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- Excellent, Robust Muon System
  - Superconducting solenoid creates 3.8T magnetic field in tracker and calorimeters, 2T is steel return yoke
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  - Provides excellent energy resolution for strongly-coupled parton showers
- Excellent, Robust Muon System
  - Superconducting solenoid creates 3.8T magnetic field in tracker and calorimeters, 2T is steel return yoke
- Cost: ~500 MCHF + ~200 MCHF (Upgrades)
What Are Cathode Strip Chambers (CSCs)?
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- Muon system employs different technologies
  - Barrel: Drift Tube + Resistive Plate Chamber (RPC)
  - End-Caps: CSC + RPC + Gas Electron Multipliers (GEM)
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  - Traversing muons ionize gas at HV
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  - Work great in intense, non-uniform magnetic fields
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$\sigma_\phi \sim 50 - 150\mu m$
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\[ \sigma_\eta \sim 50 - 150 \mu \text{m} \quad \sigma_\phi \sim 2.1 \text{ns} \]
Why Upgrade CSCs for HL-LHC (Runs 4+)?
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- LHC Upgrade for Run 3
  - Collision energy increase $\sqrt{s} = 13 \rightarrow 13.6 \text{ TeV}$
  - Luminosity approx. 2x nominal, $2 \times 10^{34} \text{s}^{-1} \text{cm}^{-2}$
  - **Detectors should handle Run 3 easily**
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  - Full design energy $\sqrt{s} = 14 \text{ TeV}$
  - Luminosity to reach 5-7.5x LHC nominal
  - Expected rate: 200 collisions/crossing @ 40 MHz
  - **Higher detector occupancy**
  - **Need faster triggers+DAQ**

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(D)CFEB event losses for HL-LHC conditions

- ME2/1 CFEB (Phase 1)
- ME3/1 CFEB (Phase 1)
- ME4/1 CFEB (Phase 1)
- ME2/1 DCFEB (Phase 2)
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### Table: HL-LHC needs vs CMS 2017 vs CMS upgraded

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![Graph](image-url)
Why Upgrade CSCs for HL-LHC (Runs 4+)?

◦ LHC Upgrade for Run 3
  – Collision energy increase $\sqrt{s} = 13 \rightarrow 13.6 \text{TeV}$
  – Luminosity approx. 2x nominal, $2 \times 10^{34} \text{s}^{-1} \text{cm}^{-2}$
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  – Full design energy $\sqrt{s} = 14 \text{TeV}$
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![Graph of CFEB event losses for HL-LHC conditions](graph.png)
Why Upgrade CSCs for HL-LHC (Runs 4+)?

○ LHC Upgrade for Run 3
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○ CSCs Need Upgrades for HL-LHC
  — Cathode Front End Board (CFEB) needs more memory, analog storage replaced with digital/flash → DCFEB
  — Local track builder need more memory and bandwidth, install new FPGAs with larger buffer
  — New electronics → increased power consumption
  — Optical readout necessary throughout muon systems

### HL-LHC vs CMS nominal vs upgraded

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Electronics of CSCs

ME1/1 is closest to interaction point
Target of most upgrades
Electronics of CSCs

LVDB/LVMB: Low Voltage Distribution (Monitoring) Board

AFEB
Anode
Front End Board

(D)CFEB
(Digital) Cathode
Front End Board

ALCT+Mezzanine
Anode Local Charged Track

ME1/1 chambers

ME1/1 is closest to interaction point
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LVDB/LVMB:
Low Voltage Distribution (Monitoring) Board

CMS-TDR-016
Electronics of CSCs

LVDB/LVMB: Low Voltage Distribution (Monitoring) Board

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AFEBs

CMS-TDR-016

ME1/1 chambers

Peripheral crate (VME)

VCC
CCB
MPC

9×OTMB

FED crate (VME)

12×DDU

9×ODMB

LVDB7

ALCT-S6

ME1/1 is closest to interaction point
Target of most upgrades
Electronics of CSCs

LVDB/LVMB: Low Voltage Distribution (Monitoring) Board

AFEB
Anode Front End Board

(D)CFEB
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ALCT+Mezzanine
Anode Local Charged Track

(O)TMB
(Optical) Trigger Mother Board

(O)DMB
(Optical) Data Mother Board

CMS-TDR-016

ME1/1 is closest to interaction point
Target of most upgrades
Electronics of CSCs

- **LVDB/LVMB**: Low Voltage Distribution (Monitoring) Board
- **AME1**: Closest to interaction point
- **Target of most upgrades**
- **CMS-TDR-016**

**Board Components**
- **AFEBS**: Anode Front End Board
- **(D)CFEB**: Digital Cathode Front End Board
- **ALCT+Mezzanine**: Anode Local Charged Track
- **(O)TMB**: Optical Trigger Mother Board
- **(O)DMB**: Optical Data Mother Board

**Peripheral crate (VME)**
- **VCC**
- **CCB**
- **MPC**
- **9×OTMB**
- **9×ODMB**

**FED crate (VME)**
- **12×DDU**

**Iron yoke**

**Notation**
- **L1A**
- **TTC**

**Diagram**
- ME1/1 is closest to interaction point
- Target of most upgrades
Electronics of CSCs

- ME1/1 is closest to interaction point
- Target of most upgrades

- AFEB: Anode Front End Board
- (D)CFEB: (Digital) Cathode Front End Board
- ALCT+Mezzanine: Anode Local Charged Track
- (O)TMB: (Optical) Trigger Mother Board
- (O)DMB: (Optical) Data Mother Board
- FED/DDU: Front End Driver Detector Dependent Unit

- LVDB/LVMB: Low Voltage Distribution (Monitoring) Board

- CMS-TDR-016

- L1A
- TTC
- Iron yoke

- Peripheral crate (VME): VCC, CCB, MPC, 9×OTMB, 9×ODMB
- FED crate (VME): 12×DDU
Electronics of CSCs

- AFEB: Anode Front End Board
- (D)CFEB: (Digital) Cathode Front End Board
- ALCT+Mezzanine
- LVDB/LVMB: Low Voltage Distribution (Monitoring) Board
- (O)TMB: (Optical) Trigger Mother Board
- (O)DMB: (Optical) Data Mother Board
- CMS DAQ: Front End Driver Detector Dependent Unit

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ME1/1 chambers

- L1A
- Peripheral crate (VME): VCC, CCB, MPC
- 9×OTMB
- 9×ODMB
- L1A
- TTC
- Iron yoke

ME1/1 is closest to interaction point
Target of most upgrades
Preparing for the HL-LHC

Phase-I

DCFEBs for ME1/1
LV for ME1/1
Install ME4/2 Stations
Upgrade Trigger Electronics

Run 1 | LS1 | Run 2 | LS2 | LS2 | Run 3 | LS3 | Run 4
2013   | 2015 | 2018 | March 2020 | 2022 | 2025 | 2027
Preparing for the HL-LHC

Phase-I
DCFEBs for ME1/1
LV for ME1/1
Install ME4/2 Stations
Upgrade Trigger Electronics

Run 1  LS1  Run 2  LS2  LS2  Run 3  LS3  Run 4
2013  2015  2018  March 2020  2022  2025  2027
Preparing for the HL-LHC

Phase-I
- DCFEBs for ME1/1
- LV for ME1/1
- Install ME4/2 Stations
- Upgrade Trigger Electronics

Phase-II
- DCFEBv2+Cooling for ME1/1
- DCFEBs for ME234/1

Run 1
- 2013
- LS1

Run 2
- 2015
- 2018
- LS2

Run 3
- March 2020
- 2022
- LS3

Run 4
- 2025
- 2027

2013
2015
2018
March 2020
2022
2025
2027
Preparing for the HL-LHC

Phase-I
DCFEBs for ME1/1
LV for ME1/1
Install ME4/2 Stations
Upgrade Trigger Electronics

Phase-II
DCFEBv2+Cooling for ME1/1
DCFEBs for ME234/1

Run 1
LS1
2013
2015

Run 2
LS2
2018
March 2020

Run 3
LS3
2022
2025
2027

Run 4
2027
Preparing for the HL-LHC

Phase-I
DCFEBs for ME1/1
LV for ME1/1
Install ME4/2 Stations
Upgrade Trigger Electronics

Phase-II
DCFEBv2 + Cooling for ME1/1
DCFEBs for ME234/1
LV for ME234/1, HV for ME1/1

Run 1
LS1
Run 2
LS2
LS2
Run 3
LS3
Run 4

2013
2015
2018
March 2020
2022
2025
2027
Preparing for the HL-LHC

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- LV for ME1/1
- Install ME4/2 Stations
- Upgrade Trigger Electronics

Phase-II
- DCFEBv2+Cooling for ME1/1
- DCFEBs for ME234/1
- LV for ME234/1, HV for ME1/1
- ALCT Mezzanine for ME1234/1, ME123/2, ME1/3

Diagram showing timeline and locations of various stations and upgrades for different runs:
- Run 1: 2013-2015
- Run 2: 2018, LS2 March 2020
- Run 3: 2022, LS3
- Run 4: 2025-2027

Legend:
- Orange: DCFEBs ME1/1
- Red: LV ME1/1
- Yellow: ME4/2 Stations
- Green: Phase-I LV/HV ME1/1
- Blue: Phase-II LV/HV ME1/1

Diagram shows locations of various stations and upgrades around the CMS detector.
Preparing for the HL-LHC

Phase-I
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- LV for ME1/1
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- LV for ME234/1, HV for ME1/1
- ALCT Mezzanine for ME1234/1, ME123/2, ME1/3
- Upgrade Trigger Electronics

Run 1: 2013 - 2015
Run 2: 2018, LS2: March 2020
Run 3: 2022
Run 4: 2025 - 2027

180 CSC Dismounted, Upgraded, Reinstalled
288 CSC Upgraded In-Situ
Preparing for the HL-LHC

Phase-I
DCFEBs for ME1/1
LV for ME1/1
Install ME4/2 Stations
Upgrade Trigger Electronics

Phase-II
DCFEBv2+Cooling for ME1/1
DCFEBs for ME234/1
LV for ME234/1, HV for ME1/1
ALCT Mezzanine for ME1234/1, ME123/2, ME1/3
Upgrade Trigger Electronics

180 CSC Dismounted, Upgraded, Reinstalled
288 CSC Upgraded In-Situ

We Are Here
On-Detector Refurbishment of Electronics

ALCT Mezzanines and DCFEBs
On-Detector Refurbishment of Electronics
ALCT Mezzanines and DCFEBs

- 108 ALCT-LX150T Mezzanine boards installed in all ME234/1
- 288 ALCT-LX100T Mezzanine boards installed in ME1/1, 123/2
On-Detector Refurbishment of Electronics
ALCT Mezzanines and DCFEBs

- 108 ALCT-LX150T Mezzanine boards installed in all ME234/1
- 288 ALCT-LX100T Mezzanine boards installed in ME1/1,123/2
- 504 DCFEBv2 installed in ME1/1 and 45 in ME+2/1, older DCFEB from ME1/1 → ME234/1
On-Detector Refurbishment of Electronics
ALCT Mezzanines and DCFEBs

- 108 ALCT-LX150T Mezzanine boards installed in all ME234/1
- 288 ALCT-LX100T Mezzanine boards installed in ME1/1,123/2
- 504 DCFEBv2 installed in ME1/1 and 45 in ME+2/1, older DCFEB from ME1/1 → ME234/1
- New boards capable of optical readout
Upgrading the Power for CSCs
Upgrading the Power for CSCs

○ Need to satisfy new power requirement of DCFEBs
  — Current 9.8/5.5 -> 22.8/13.0 Amps, increase of 144 W per chamber

○ Low-Voltage Distribution Boards produced and installed on each of 18 chambers for the inner-rings (1) of ±2/3/4 stations, 108 total
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- Additional 12 Power Supplies, Junction Boxes distributing LV supply installed
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Upgrading the Power for CSCs

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  - Current 9.8/5.5 -> 22.8/13.0 Amps, **increase of 144 W per chamber**

- **Low-Voltage Distribution Boards** produced and installed on each of 18 chambers for the inner-rings (1) of ±2/3/4 stations, 108 total

- Additional 12 **Power Supplies, Junction Boxes** distributing LV supply installed

- ME1/1 LV upgraded during LS1, HV during LS2
ME1/1 Cooling Loop Upgrade

OLD

New
ME1/1 Cooling Loop Upgrade

DCFEBs, ALCT, LVDB
all contact-cooled

OLD

New
ME1/1 Cooling Loop Upgrade

DCFEBs, ALCT, LVDB
all contact-cooled

Old cooling loop had joints, leak risk
ME1/1 Cooling Loop Upgrade

DCFEBs, ALCT, LVDB all contact-cooled

Old cooling loop had joints, leak risk

New cooling loop is single-circuit
ME1/1 Cooling Loop Upgrade

DCFEBs, ALCT, LVDB
all contact-cooled

Old cooling loop had joints, leak risk

New cooling loop is single-circuit

Replaced for all ME1/1
Chamber Re-Installation

1: Refurbish+Test

2: Transport

3: Load on Fixture

4: Hoist with crane

5: Install+Commission on CMS
Chamber Re-Installation

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Chamber Re-Installation

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2: Transport

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4: Hoist with crane

5: Install+Commission on CMS

x180 Chambers!

108 ME234/1
x72 ME1/1
Test $\varphi \varphi$ collisions at 900 GeV - Nov 2021
- A candidate $J/\psi \rightarrow \mu \mu$ event in the CSCs
- Invariant mass of the two global muons = 3.1 GeV
- +RPC rechits on one muon;
- +GEM segment on the other
Summary and Outlook
Summary and Outlook
Summary and Outlook

• CSC upgrades for LS2 is complete
  — On-Chamber electronics updated:
    DCFEB(v2), ALCT Mezzanine, LVDB/LVMB
  — Low Voltage for ME234/1 upgraded
  — High Voltage for ME1/1 upgraded
  — Trigger integration with GEM subsystem underway
Summary and Outlook

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  — On-Chamber electronics updated:
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• All chambers re-installed into CMS
  — Commissioning work since early 2021
  — Successful 900 GeV (test) data taking w/ full magnet in October 2021
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• All chambers re-installed into CMS
  — Commissioning work since early 2021
  — Successful 900 GeV (test) data taking w/ full magnet in October 2021

• Preparations for Run 3 and LS3 underway
  — Run 3 expected to begin Spring 2022
  — ODMB, FED, and possible HV upgrades during LS3
Thanks!
Backup
Detecting Particles in CMS

Tracker:
Measures momentum of charged particles
\((e^\pm, \mu^\pm, \pi^\pm, K^\pm)\)

EM Calorimeter:
Measures energy of EM showers
\((\gamma, e^\pm, \pi^0 \rightarrow \gamma \gamma, K_S^0)\)

Hadronic Calorimeter:
Measures energy of hadronic showers
\((\pi^\pm, K^\pm, K_L^0, p, n)\)

Muon Spectrometer
Measures momentum of surviving minimal ionizing (charged) particles, i.e. muons

\(\pm\)
Electronics of CSCs

**AFEB:**
Anode Front End Board
Relays signals from wires

**(D)CFEB:**
(Digital) Cathode Front End Board
Relays signals from strips

**ALCT+Mezzanine:**
Anode Local Charged Track
Find patterns from AFEB for trigger

**(O)TMB:**
(Optical) Trigger Mother Board
Builds patterns from ALCT/(D)CFEB to build Local Charged Trigger

**(O)DMB:**
(Optical) Data Mother Board
When triggered, exports data to Data Acquisition System (DAQ) system

LVDB/LVMB:
Low Voltage Distribution (Monitoring) Board
Power to on-board electronics

ME1/1 is closest to interaction point
Target of most upgrades
Electronics of CSCs

AFEB: Anode Front End Board
Relays signals from wires

(D)CFEB: (Digital) Cathode Front End Board
Relays signals from strips

ALCT+Mezzanine: Anode Local Charged Track
Find patterns from AFEB for trigger

(O)TMB: (Optical) Trigger Mother Board
Builds patterns from ALCT/(D)CFEB to build Local Charged Trigger

(O)DMB: (Optical) Data Mother Board
When triggered, exports data to Data Acquisition System (DAQ) system

LVDB/LVMB: Low Voltage Distribution (Monitoring) Board
Power to on-board electronics

FED/DDU: Front End Driver Detector Dependent Unit

ME1/1 chambers
ME1/1 is closest to interaction point
Target of most upgrades
Non-Uniform Magnetic Field in Muon End-Caps

— Within barrel ($|z| < 6m$), $\vec{B} \sim B_B \hat{z}$
— In end-cap yoke: $\vec{B} \sim B_{EC} \hat{r}$
— Bending direction changes before muon exits CMS
References

○ The Phase-2 Upgrade of the CMS Muon Detectors:  
  CERN-LHCC-2017-012 ; CMS-TDR-016

○ HL-LHC Public Pages:  
  – voisins.cern  
  – hilumilhc.web.cern.ch

○ CMS Detector Figures:  
  – Particle-flow reconstruction and global event description with the CMS detector:  
    JINST 12 (2017) P10003  
  – Cutaway Diagrams of CMS Detector:  
    J. Phys.: Conf. Ser. 513 022032  
  – Precise Mapping of the Magnetic Field in the CMS Barrel Yoke using Cosmic Rays:  
    JINST 5 (2010) T03021

○ CMS Event Display Generator:  
  http://opendata.cern.ch/visualise/events/cms#