A. Shevelev on behalf of the CMS collaboration

CMS BRIL, Muons and HCAL upgrade for Run 2/3 - operations and performance

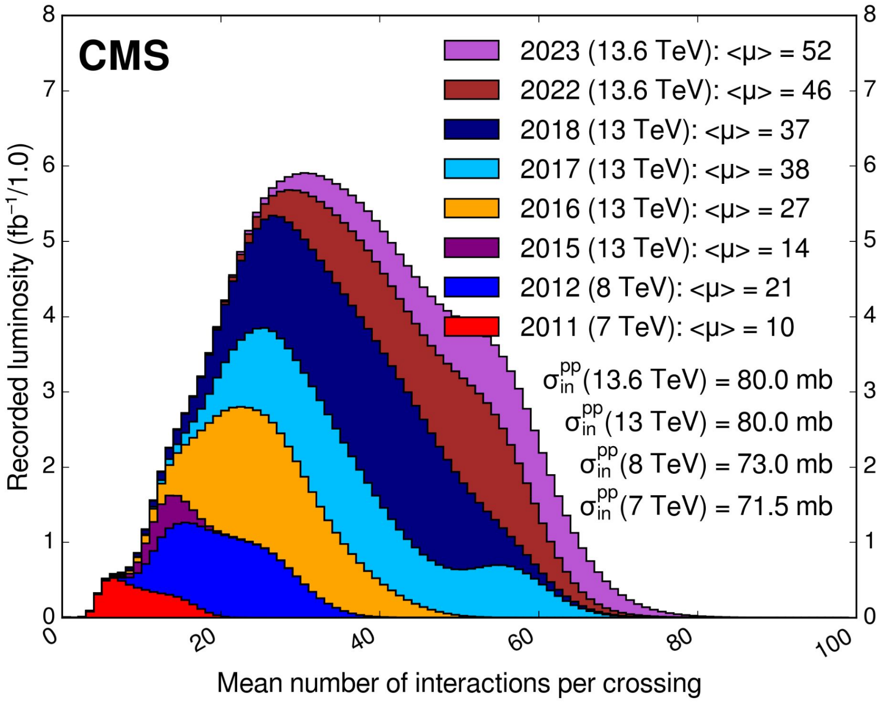
CERN Detector Seminar
3 May 2024, CERN (Switzerland)

BRIL upgrade for Run 2/3 - operations and performance

Beam Radiation, Instrumentation, and Luminosity (BRIL)

Luminosity increase is one of the main challenges

- 2x increase in instantaneous luminosity from original design:
    - And ~10x LHC's design value in Phase-2!
- Stronger requirements for electronics, radiation hardness, reconstruction algorithms



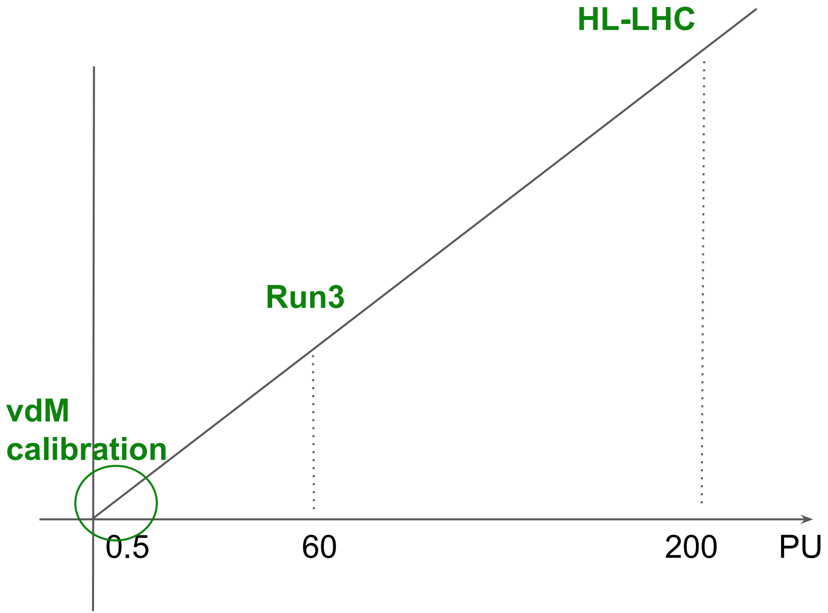
Beam Radiation, Instrumentation, and Luminosity (BRIL)

Luminosity increase is one of the main challenges

- 2x increase in instantaneous luminosity from original design:
  - And ~10x LHC's design value in Phase-2!
- Stronger requirements for electronics, radiation hardness, reconstruction algorithms

Luminosity precision requirements are getting tighter

- One of the largest sources of experimental systematic uncertainty in many physics analyses
- Bigger spread between absolute calibration conditions and data-taking (100x already)



$$R_{det}/\sigma_{vis} = L$$

Beam Radiation, Instrumentation, and Luminosity (BRIL)

Luminosity increase is one of the main challenges

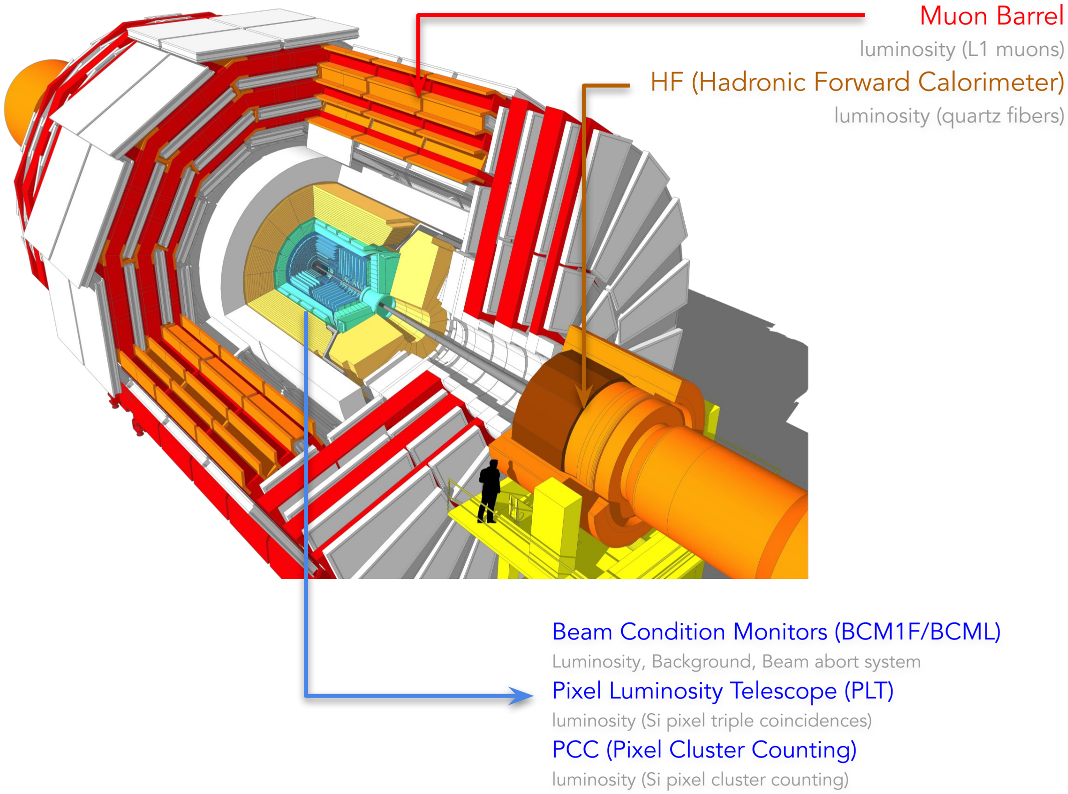
- 2x increase in instantaneous luminosity from original design:
    - And ~10x LHC's design value in Phase-2!
- Stronger requirements for electronics, radiation hardness, reconstruction algorithms

Luminosity precision requirements are getting tighter

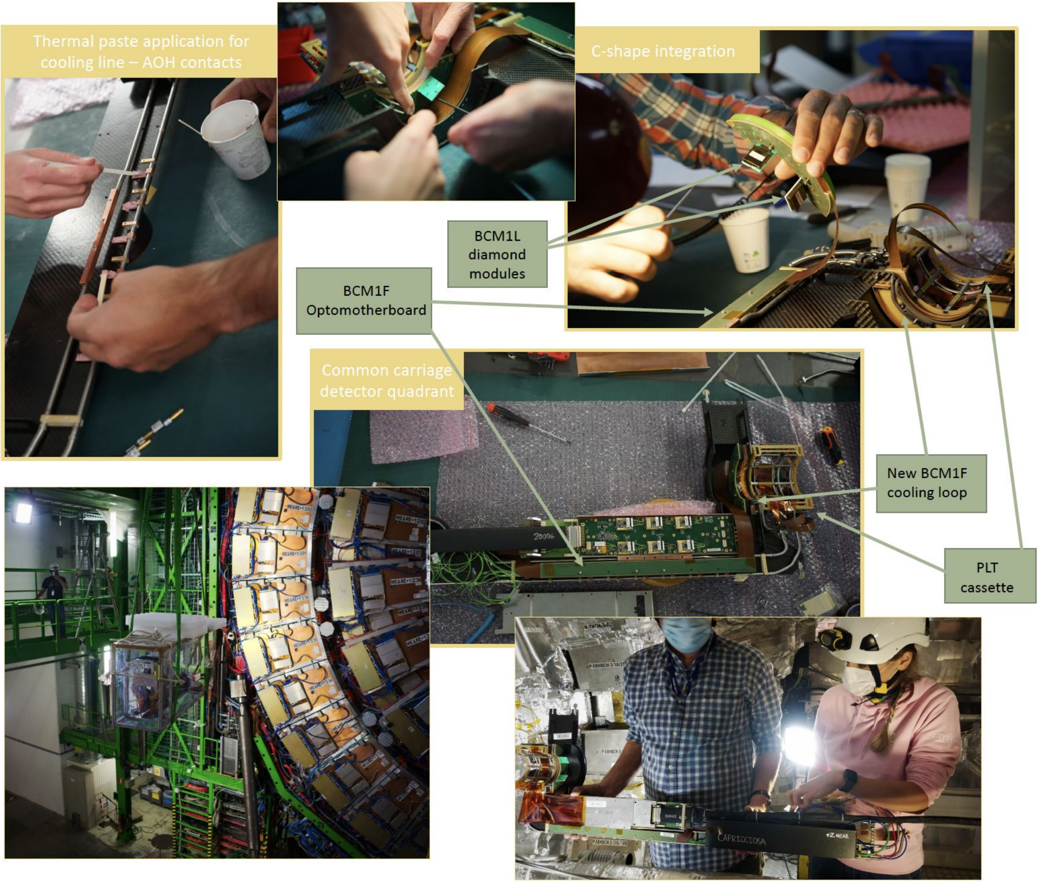
- One of the largest sources of experimental systematic uncertainty in many physics analyses
- Bigger spread between absolute calibration conditions and data-taking (100x already)

BRIL - Beam Radiation, Instrumentation, and Luminosity Project of CMS

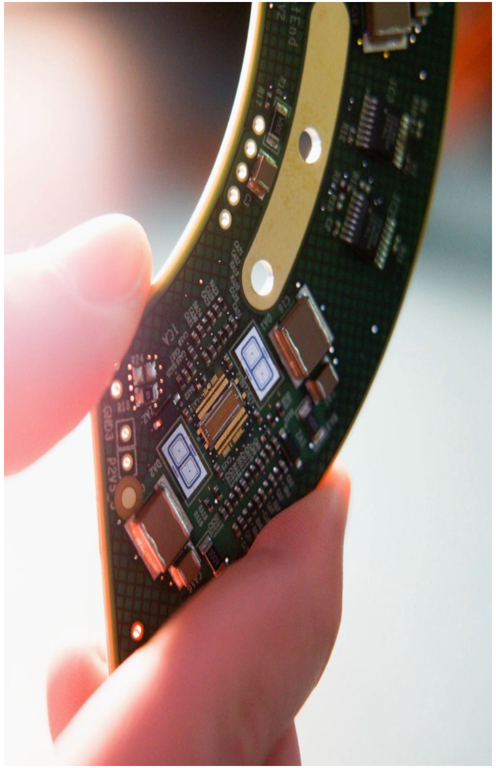
- Beam instrumentation, control of background conditions, monitoring & simulation of radiation environment
    - Beam dump functionality in case of dangerous beam losses events
    - Provides technical triggers for CMS L1 Global Trigger (GT)
- Delivering precise luminosity measurements (together with Luminosity Physics Object Group)

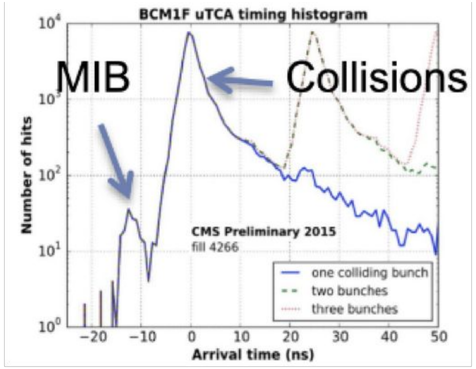


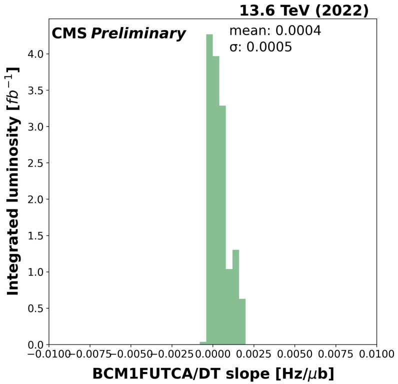
BRIL Upgrade (BCM1F/PLT/BCML1)



BRIL Upgrade (BCM1F/PLT/BCML1)



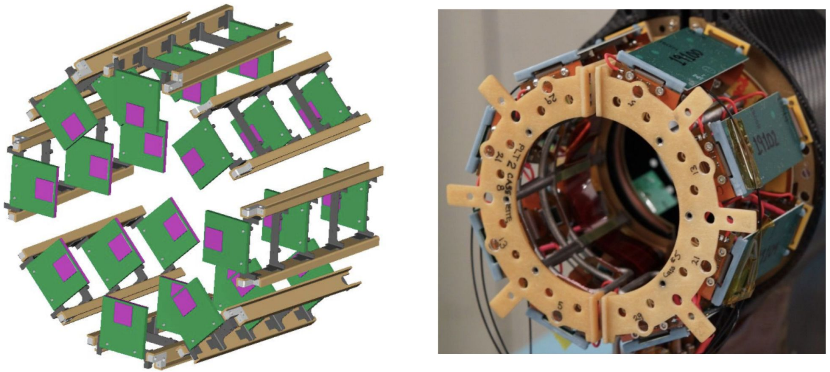




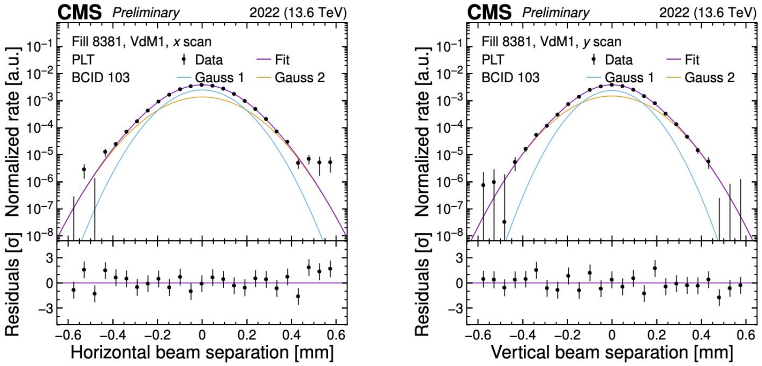
Fast beam conditions monitor (BCM1F)

- Background and luminosity measurement:
  - Up to 6 samples per bunch-crossing for improved background resolution
- For Run 3, diamond sensors were changed to an all-silicon sensor configuration with active cooling:
  - produced on the CMS Phase 2 outer tracker strip wafers
- μTCA backend with peak derivative finder:
  - Excellent stability and linearity

BRIL Upgrade (BCM1F/PLT/BCML1)



Sketch of the general PLT geometry and the actual PLT detector



Double-Gaussian fits to the PLT data recorded during the first vdM scan pair (vdM1), shown for the x (left) and y (right) scan

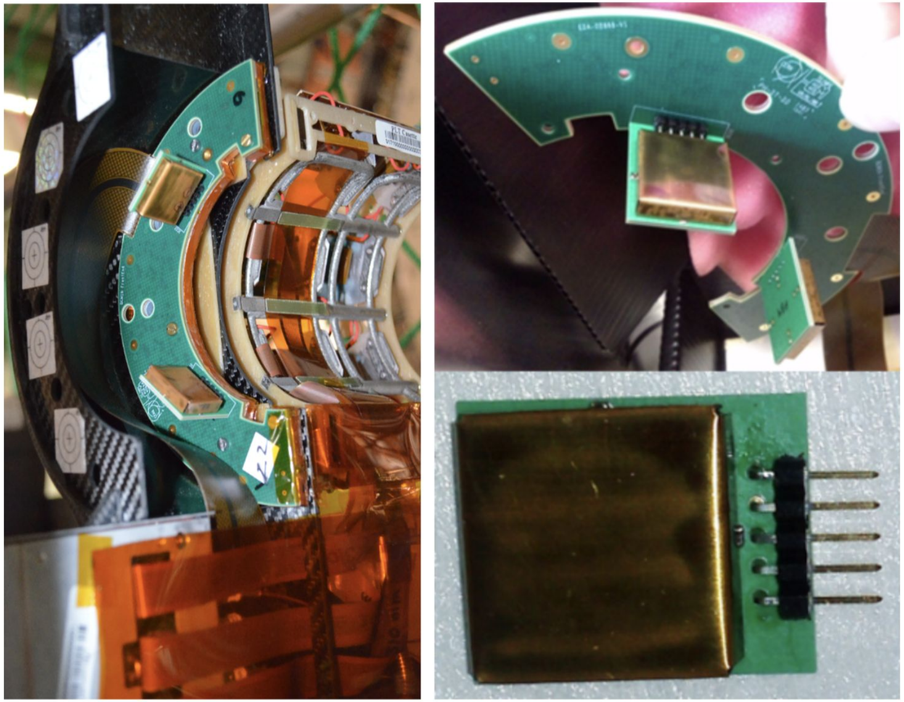
Fast beam conditions monitor (BCM1F)

- Background and luminosity measurement:
  - Up to 6 samples per bunch-crossing for improved background resolution
- For Run 3, diamond sensors were changed to an all-silicon sensor configuration with active cooling:
  - produced on the CMS Phase 2 outer tracker strip wafers
- μTCA backend with peak derivative finder:
  - Excellent stability and linearity

Pixel luminosity telescope (PLT)

- Triple coincidence "fast-or" at the full bunch-crossing frequency of 40 MHz for real-time bunch-by-bunch luminosity measurement
- New triple sensor telescope with Phase 2 silicon

BRIL Upgrade (BCM1F/PLT/BCML1)



New mechanics for the BCML1 detector system

Fast beam conditions monitor (BCM1F)

- Background and luminosity measurement:
  - Up to 6 samples per bunch-crossing for improved background resolution
- For Run 3, diamond sensors were changed to an all-silicon sensor configuration with active cooling:
  - produced on the CMS Phase 2 outer tracker strip wafers
- μTCA backend with peak derivative finder:
  - Excellent stability and linearity

Pixel luminosity telescope (PLT)

- Triple coincidence “fast-or” at the full bunch-crossing frequency of 40 MHz for real-time bunch-by-bunch luminosity measurement
- New triple sensor telescope with Phase 2 silicon

Beam-condition monitor for beam losses (BCML)

- Assert beam dump in case of dangerous background conditions
- Critical Safety System for Tracker and CMS
- New Diamond (BCML1) and Sapphire (BCML2) sensors as Phase 2 demonstrators

Preliminary 2022 Luminosity Results

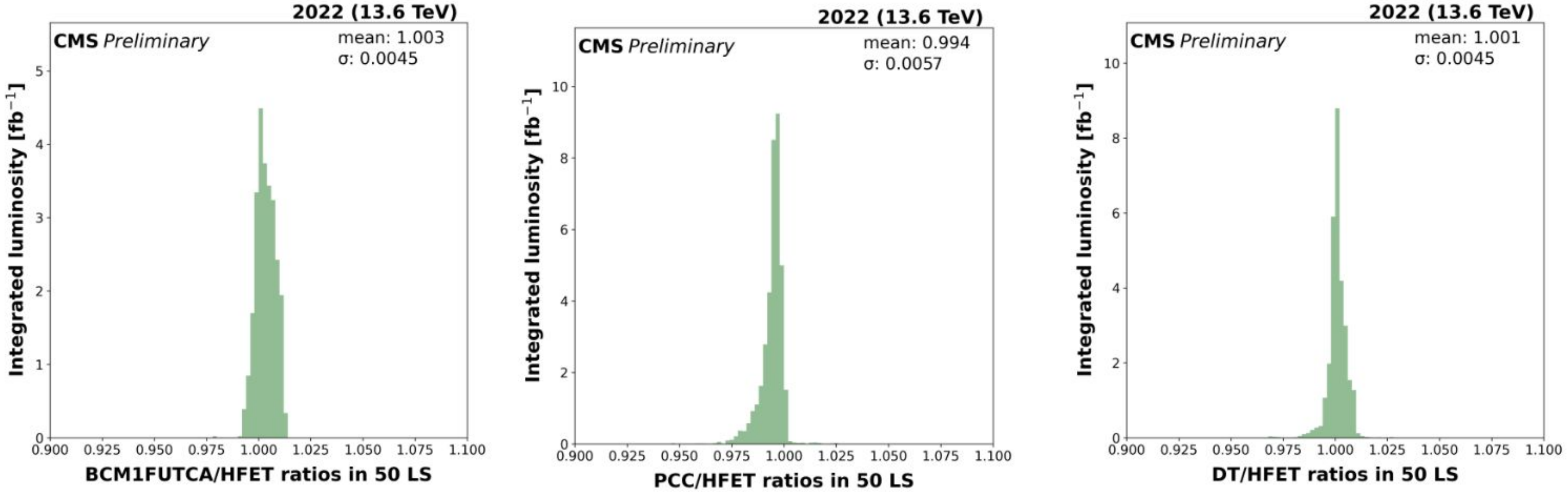
Excellent stability from independent systems!

CMS PAS LUM-22-001

Total uncertainty of 1.4% in 2022

- Both calibration and integration part

Integration	
HFET OOT pileup corrections	0.2
Cross-detector stability	0.5
Cross-detector linearity	0.5
Calibration	1.2
Integration	0.8
Total	1.4

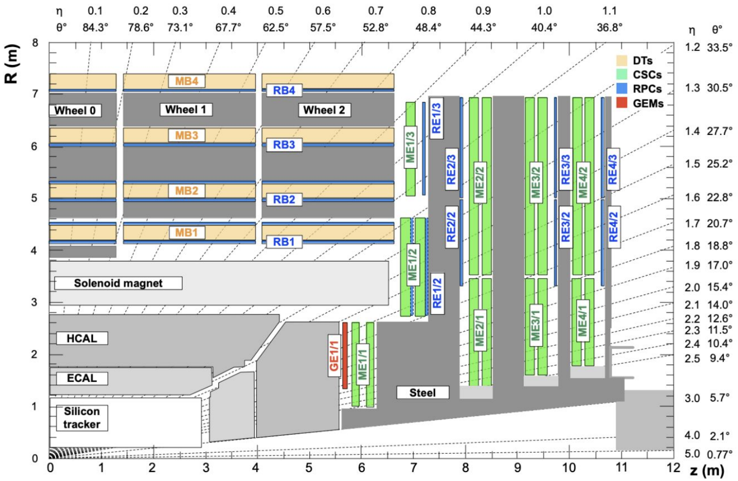


Muons upgrade for Run 2/3 - operations and performance

CMS Muon System

CMS Muon system

- Muon identification, momentum measurement and triggering
- Has been crucial to many of the physics results of CMS, including the discovery of the Higgs boson



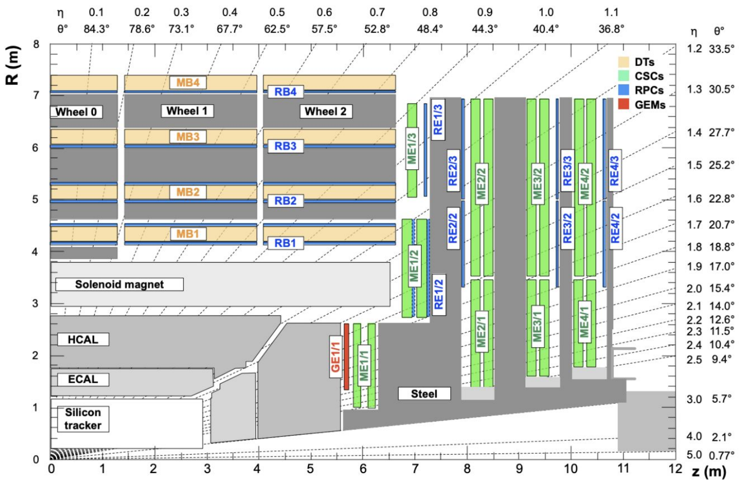
CMS Muon System

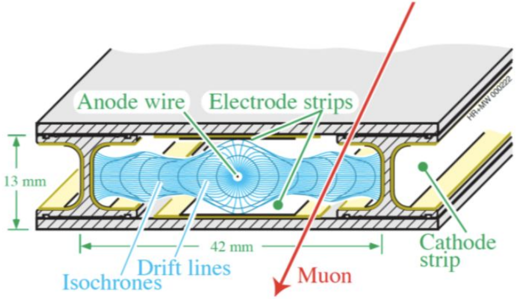
CMS Muon system

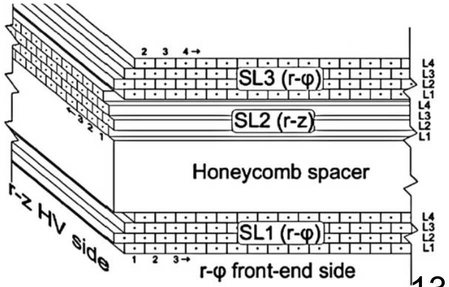
- Muon identification, momentum measurement and triggering
- Has been crucial to many of the physics results of CMS, including the discovery of the Higgs boson

Four detectors based on Gaseous detector technologies

- Drift Tubes (DT):
  - barrel, covers |η| < 1.2 and composed of drift chambers with rectangular cells







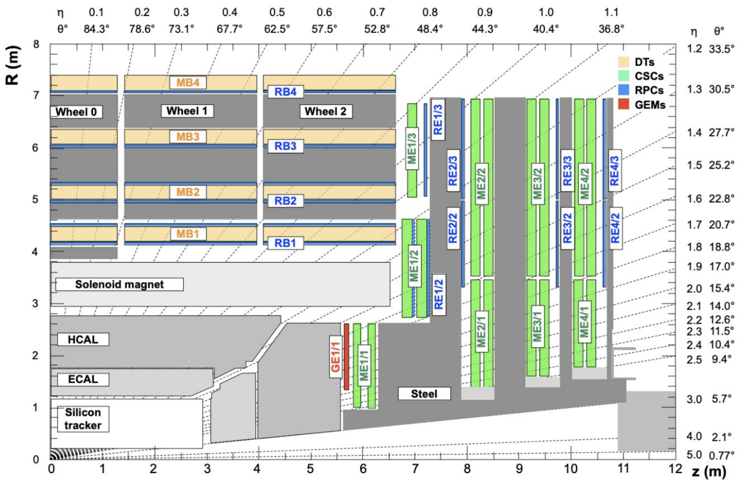
CMS Muon System

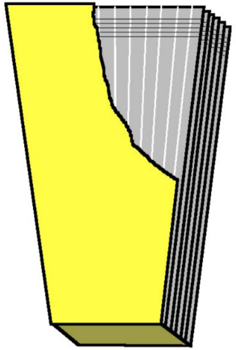
CMS Muon system

- Muon identification, momentum measurement and triggering
- Has been crucial to many of the physics results of CMS, including the discovery of the Higgs boson

Four detectors based on Gaseous detector technologies

- Drift Tubes (DT):
  - barrel, covers |η| < 1.2 and composed of drift chambers with rectangular cells
- Cathode Strip Chambers (CSC):
  - endcap, comprises multiwire proportional chambers having cathode strips, covering the region 0.9 < |η| < 2.4





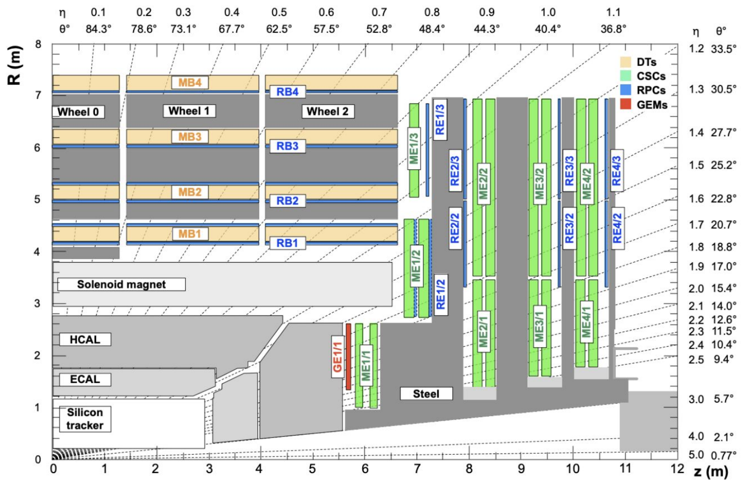
CMS Muon System

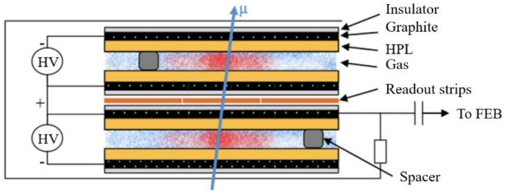
CMS Muon system

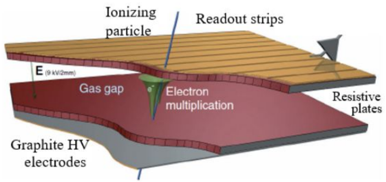
- Muon identification, momentum measurement and triggering
- Has been crucial to many of the physics results of CMS, including the discovery of the Higgs boson

Four detectors based on Gaseous detector technologies

- Drift Tubes (DT):
  - barrel, covers |η| < 1.2 and composed of drift chambers with rectangular cells
- Cathode Strip Chambers (CSC):
  - endcap, comprises multiwire proportional chambers having cathode strips, covering the region 0.9 < |η| < 2.4
- Resistive Plate Chambers (RPC):
  - both the barrel and endcap regions
  - Compliment DTs and CSCs with a fast response time to unambiguously identify the bunch-crossing corresponding to muon trigger candidate







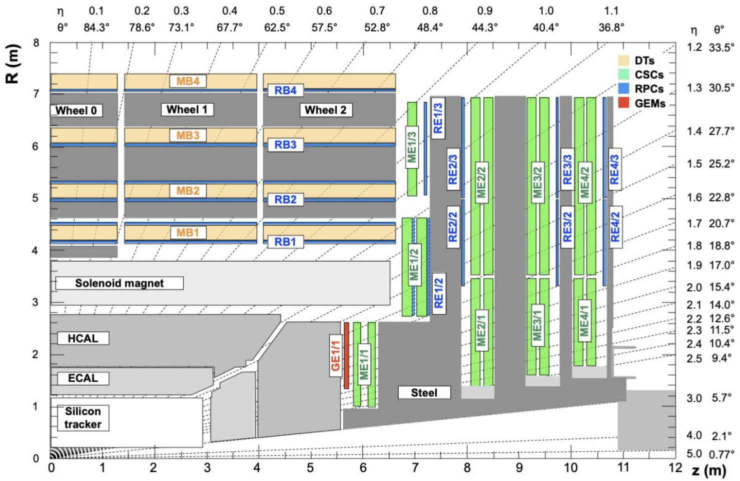
CMS Muon System

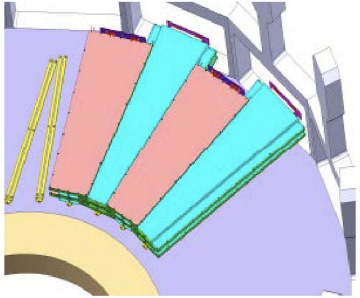
CMS Muon system

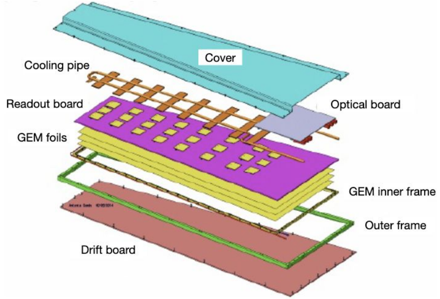
- Muon identification, momentum measurement and triggering
- Has been crucial to many of the physics results of CMS, including the discovery of the Higgs boson

Four detectors based on Gaseous detector technologies

- Drift Tubes (DT):
  - barrel, covers |η| < 1.2 and composed of drift chambers with rectangular cells
- Cathode Strip Chambers (CSC):
  - endcap, comprises multiwire proportional chambers having cathode strips, covering the region 0.9 < |η| < 2.4
- Resistive Plate Chambers (RPC):
  - both the barrel and endcap regions
  - Compliment DTs and CSCs with a fast response time to unambiguously identify the bunch-crossing corresponding to muon trigger candidate
- Gas Electron Multiplier (GEM):
  - located in front of the inner ring of CSC chambers
  - fast response and good spatial resolution







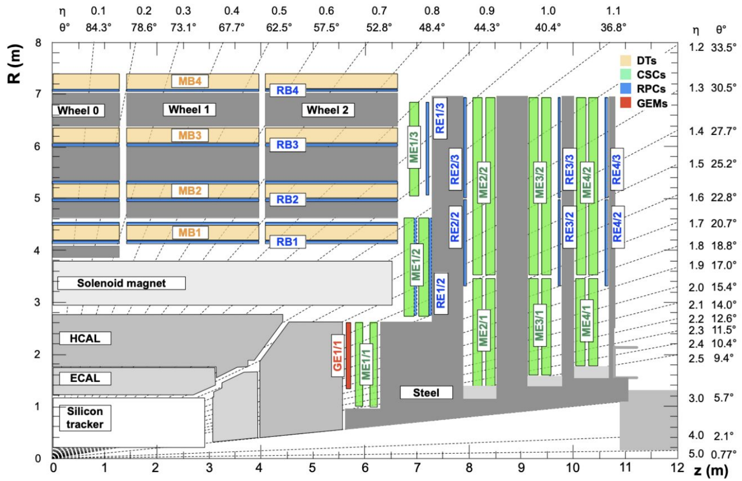
CMS Muon System

CMS Muon system

- Muon identification, momentum measurement and triggering
- Has been crucial to many of the physics results of CMS, including the discovery of the Higgs boson

Four detectors based on Gaseous detector technologies

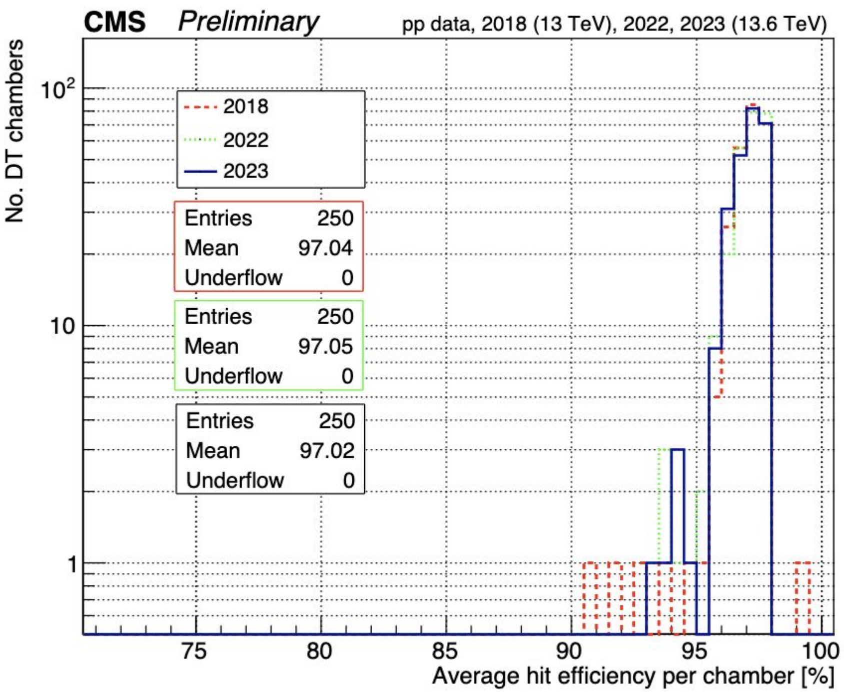
- Drift Tubes (DT):
  - barrel, covers |η| < 1.2 and composed of drift chambers with rectangular cells
- Cathode Strip Chambers (CSC):
  - endcap, comprises multiwire proportional chambers having cathode strips, covering the region 0.9 < |η| < 2.4
- Resistive Plate Chambers (RPC):
  - both the barrel and endcap regions
  - Compliment DTs and CSCs with a fast response time to unambiguously identify the bunch-crossing corresponding to muon trigger candidate
- Gas Electron Multiplier (GEM):
  - located in front of the inner ring of CSC chambers
  - fast response and good spatial resolution



New chambers since Run 1:

- GEMs are introduced for Run 3
- 144 RPCs and CSCs added as fourth layer of endcap (during LS1)

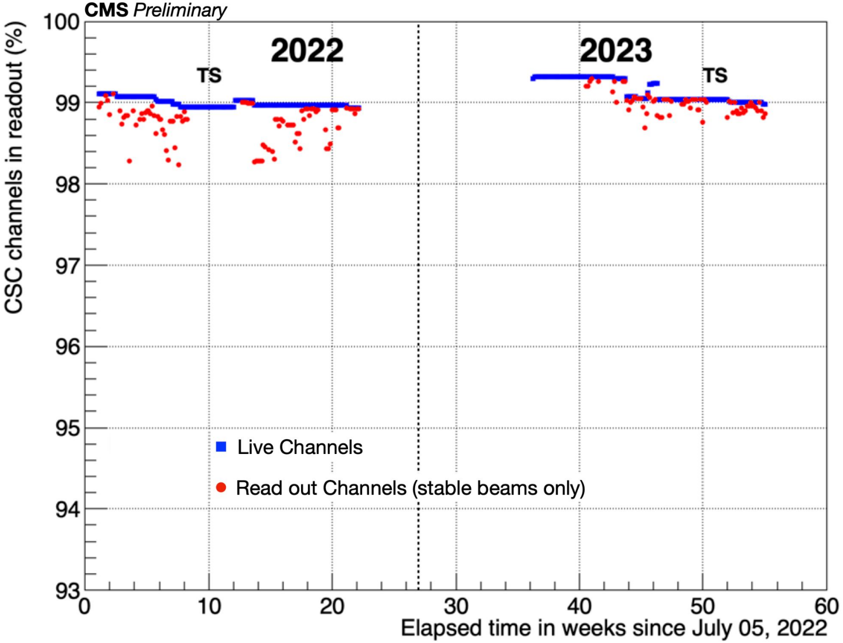
Muons Upgrade and Performance



Drift Tubes (DT)

- DT chambers themselves will operate unchanged throughout the HL-LHC period
- Upgrade of DT backend electronics performed during Run 2
- Stable performance of the system in Run2/3 with hit detection efficiency > 97%

Muons Upgrade and Performance



Live Channels : connected anode or cathode supplies a signal resulting from the passage of a charged particle through a layer of a CSC

Readout Channels: channels which are actually read out to the CMS DAQ

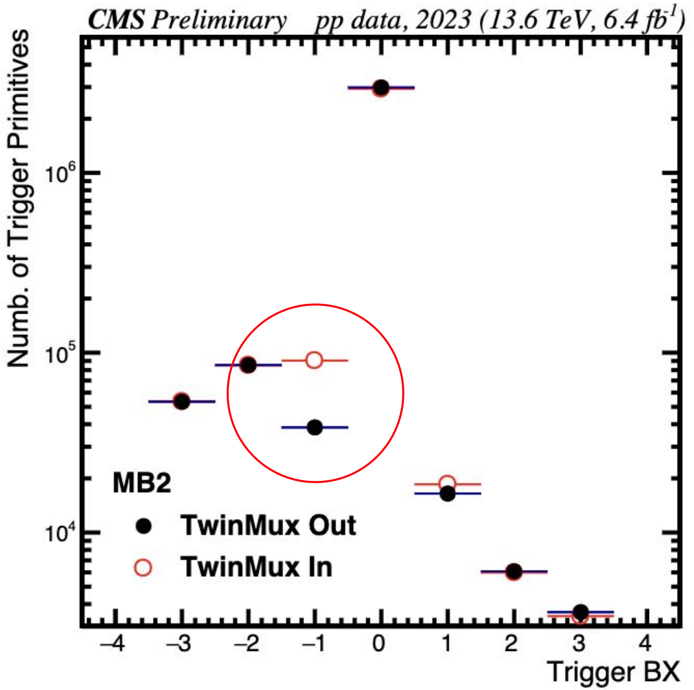
Drift Tubes (DT)

- DT chambers themselves will operate unchanged throughout the HL-LHC period
- Upgrade of DT backend electronics performed during Run 2
- Stable performance of the system in Run2/3 with hit detection efficiency > 97%

Cathode Strip Chambers (CSC)

- Front-end electronics upgraded to handle expected HL-LHC rates:
    - Especially in the high background regions close to the beam pipe (inner rings)
- Run3 Performance: ~ 99% of live and readout electronic channels

Muons Upgrade and Performance



RPC timing information improves the BX assignment in barrel, reducing in particular the “pre-firing” probability to wrongly assign a trigger primitive to BX=-1

Drift Tubes (DT)

- DT chambers themselves will operate unchanged throughout the HL-LHC period
- Upgrade of DT backend electronics performed during Run 2
- Stable performance of the system in Run2/3 with hit detection efficiency > 97%

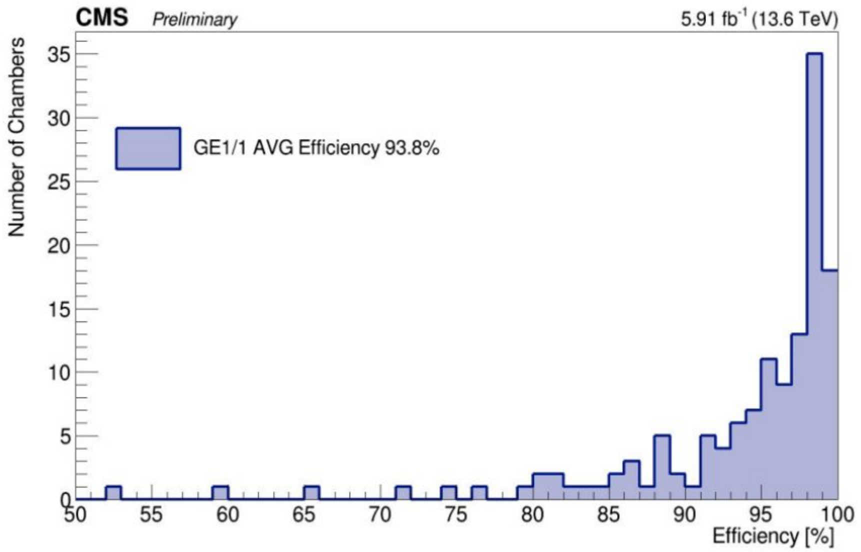
Cathode Strip Chambers (CSC)

- Front-end electronics upgraded to handle expected HL-LHC rates:
  - Especially in the high background regions close to the beam pipe (inner rings)
- Run3 Performance: ~ 99% of live and readout electronic channels

Resistive Plate Chambers (RPC)

- Significant reduction of trigger BX mis-ID by combining DT and RPC information in the new muon barrel backend electronics

Muons Upgrade and Performance



Muon detection efficiency : GEM reconstructed hits matching a propagated hit / total propagated hits

Average efficiency in 2023 around 94% for correctly communicating chambers.

Drift Tubes (DT)

- DT chambers themselves will operate unchanged throughout the HL-LHC period
- Upgrade of DT backend electronics performed during Run 2
- Stable performance of the system in Run2/3 with hit detection efficiency > 97%

Cathode Strip Chambers (CSC)

- Front-end electronics upgraded to handle expected HL-LHC rates:
  - Especially in the high background regions close to the beam pipe (inner rings)
- Run3 Performance: ~ 99% of live and readout electronic channels

Resistive Plate Chambers (RPC)

- Significant reduction of trigger BX mis-ID by combining DT and RPC information in the new muon barrel backend electronics

Gas Electron Multiplier (GEM):

- Installed for the Run 3 to enhance the track reconstruction and trigger capabilities, providing redundancy to CSC and improving pT measurement at trigger level
- Optimization of the front-end parameters and HV settings ongoing for 2024

HCAL upgrade for Run 2/3 - operations and performance

The CMS hadron calorimeter (HCAL)

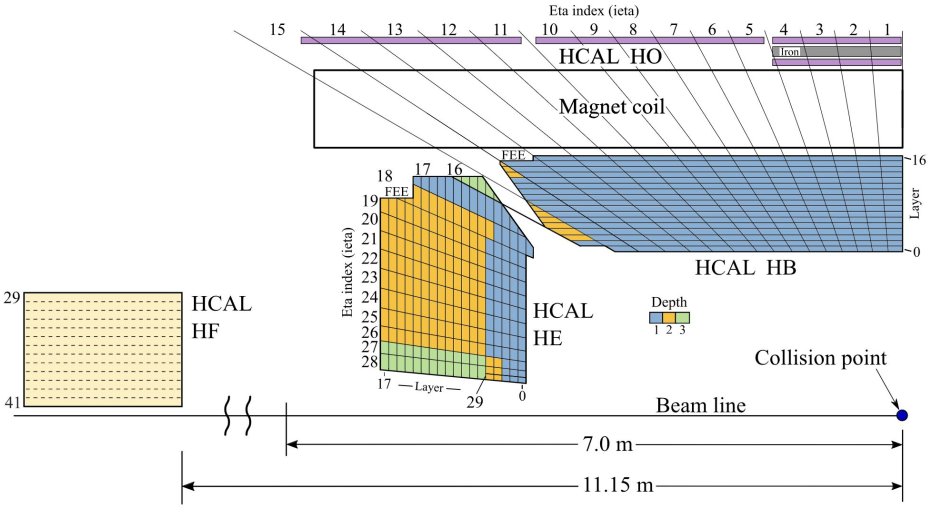
HCAL - The CMS hadron calorimeter

- Designed to measure the energy of charged and neutral hadrons
  - Contributes to the identification of hadrons and the measurement of their properties
  - Aids in the reconstruction of jets and missing transverse momentum, and the identification of electrons and photons

The HCAL is designed to have a good hermeticity

- With the ability to detect hadrons in nearly the full 4π solid angle

Composed of four major subdetectors



The CMS hadron calorimeter (HCAL)

HCAL - The CMS hadron calorimeter

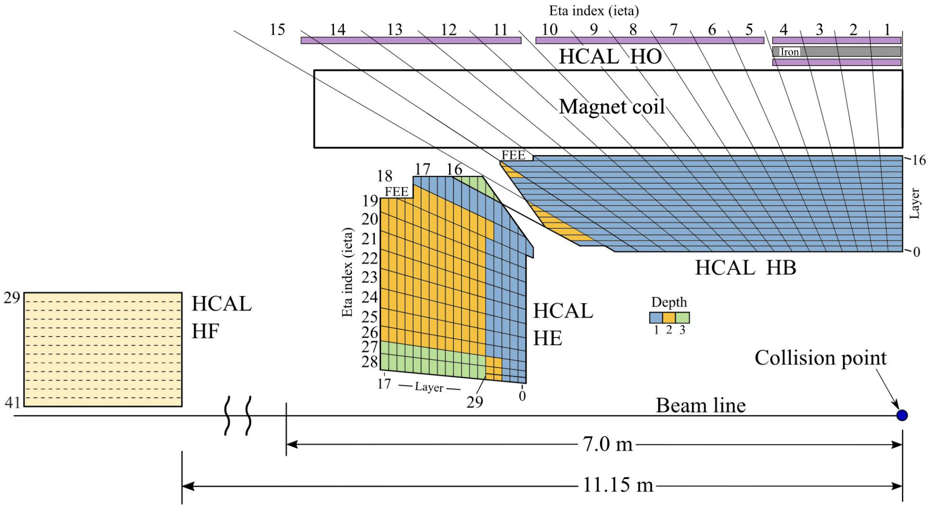
- Designed to measure the energy of charged and neutral hadrons
  - Contributes to the identification of hadrons and the measurement of their properties
  - Aids in the reconstruction of jets and missing transverse momentum, and the identification of electrons and photons

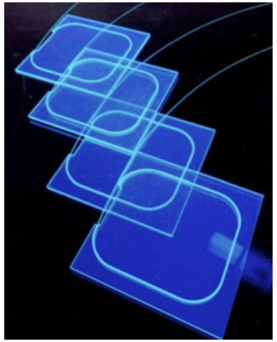
The HCAL is designed to have a good hermeticity

- With the ability to detect hadrons in nearly the full 4π solid angle

Composed of four major subdetectors

- Hadron barrel (HB) and Hadron endcap (HE)
  - brass plates interleaved with layers of scintillating tiles





The CMS hadron calorimeter (HCAL)

HCAL - The CMS hadron calorimeter

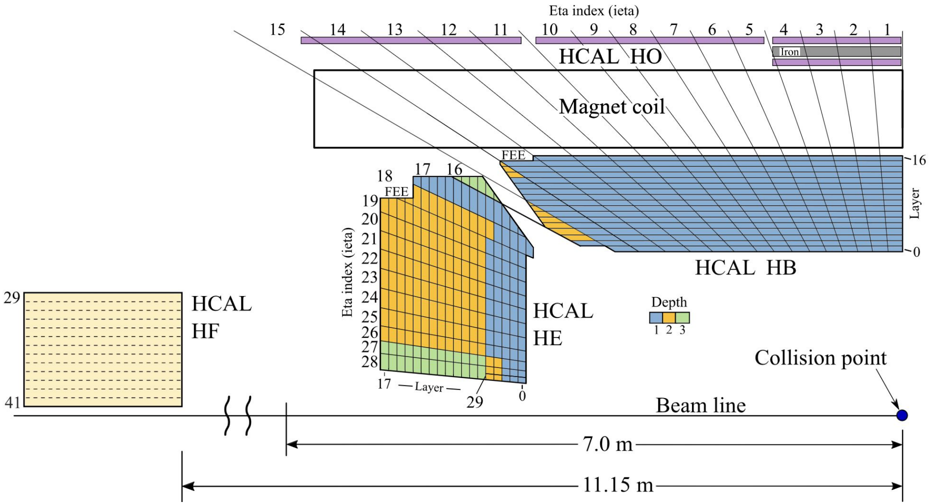
- Designed to measure the energy of charged and neutral hadrons
  - Contributes to the identification of hadrons and the measurement of their properties
  - Aids in the reconstruction of jets and missing transverse momentum, and the identification of electrons and photons

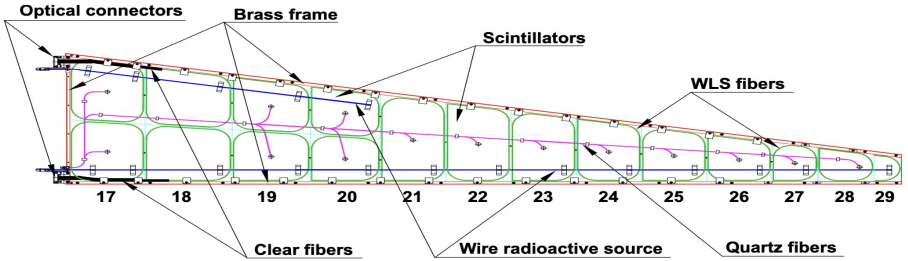
The HCAL is designed to have a good hermeticity

- With the ability to detect hadrons in nearly the full 4π solid angle

Composed of four major subdetectors

- Hadron barrel (HB) and Hadron endcap (HE)
  - brass plates interleaved with layers of scintillating tiles
  - Combined in "megatiles"





Physical arrangement of the scintillator and wavelength-shifting fibers into tiles for an HE megatile

The CMS hadron calorimeter (HCAL)

HCAL - The CMS hadron calorimeter

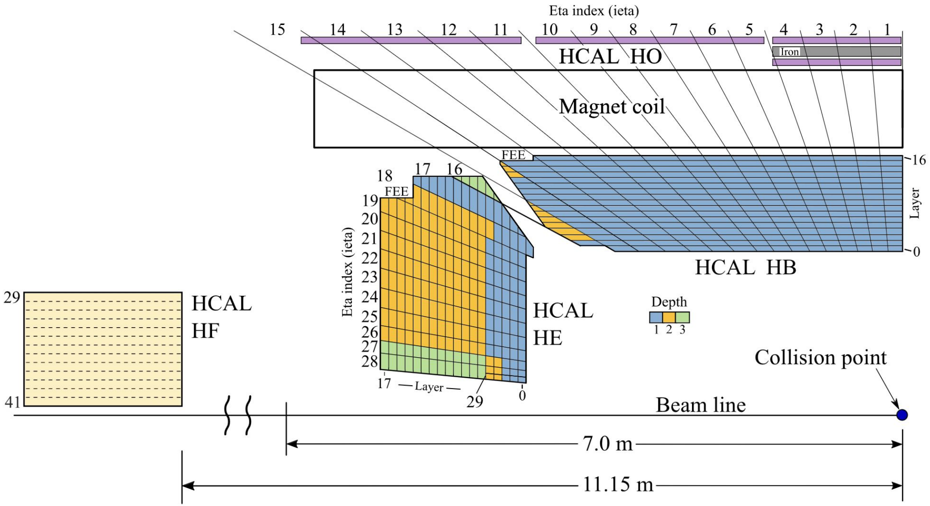
- Designed to measure the energy of charged and neutral hadrons
  - Contributes to the identification of hadrons and the measurement of their properties
  - Aids in the reconstruction of jets and missing transverse momentum, and the identification of electrons and photons

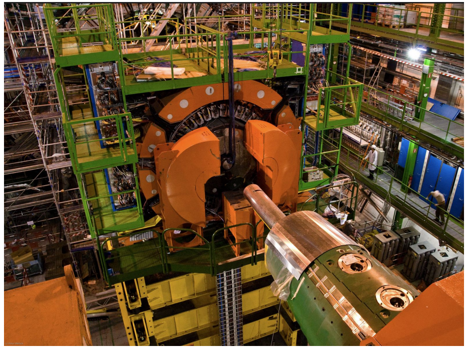
The HCAL is designed to have a good hermeticity

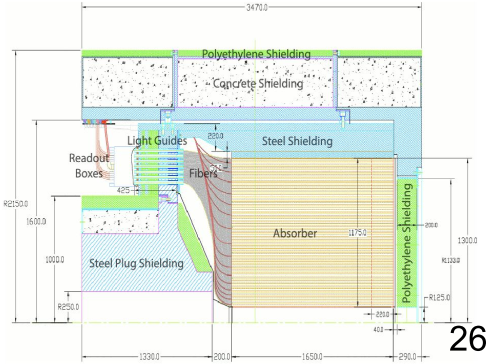
- With the ability to detect hadrons in nearly the full 4π solid angle

Composed of four major subdetectors

- Hadron barrel (HB) and Hadron endcap (HE)
  - brass plates interleaved with layers of scintillating tiles
  - Combined in “megatiles”
- Hadron forward (HF)
  - steel and quartz fibers







The CMS hadron calorimeter (HCAL)

HCAL - The CMS hadron calorimeter

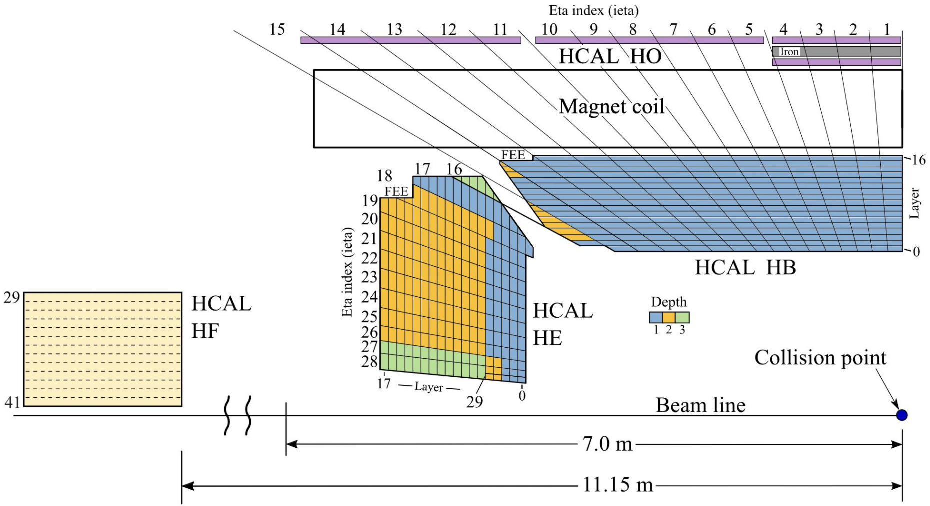
- Designed to measure the energy of charged and neutral hadrons
  - Contributes to the identification of hadrons and the measurement of their properties
  - Aids in the reconstruction of jets and missing transverse momentum, and the identification of electrons and photons

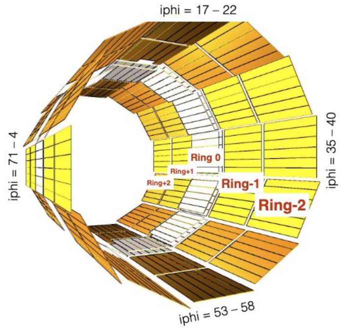
The HCAL is designed to have a good hermeticity

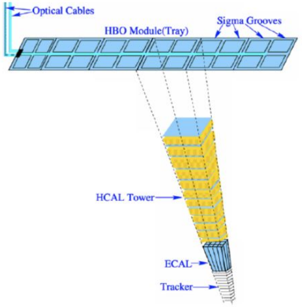
- With the ability to detect hadrons in nearly the full 4π solid angle

Composed of four major subdetectors

- Hadron barrel (HB) and Hadron endcap (HE)
  - brass plates interleaved with layers of scintillating tiles
  - Combined in “megatiles”
- Hadron forward (HF)
  - steel and quartz fibers
- Hadron outer (HO)
  - plastic scintillator and the first layer of the barrel flux return



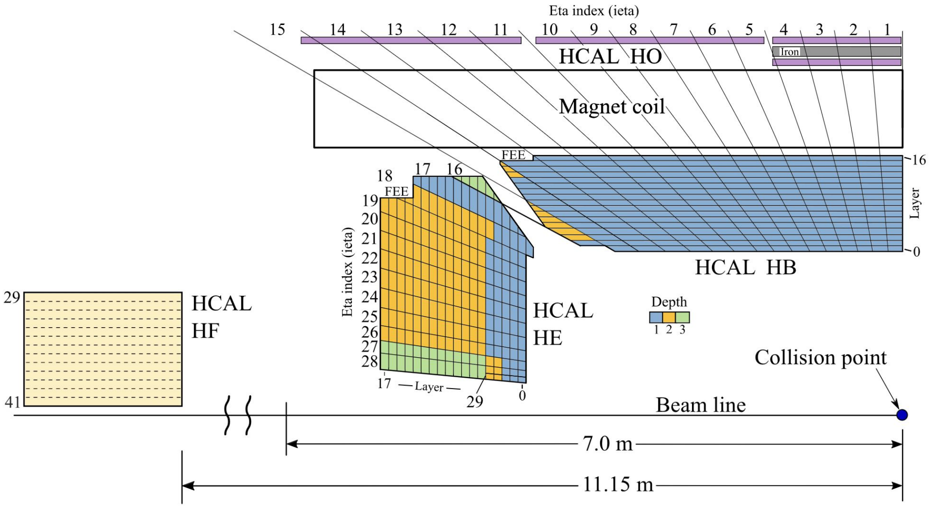


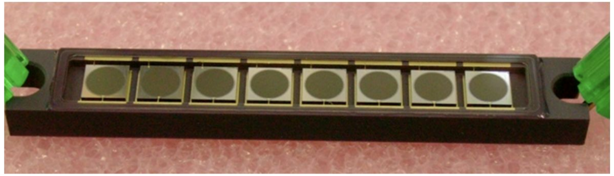


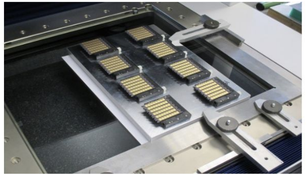
HCAL Phase 1 Upgrade

In HB and HE, the hybrid photodiode detectors (HPDs) were replaced with silicon photomultipliers (SiPMs)

- The SiPM has many advantages over the HPD
  - High photon detection efficiency (PDE), high gain, a large linear dynamic range
  - Rapid recovery time, somewhat better radiation tolerance, and insensitivity to magnetic fields
  - A yield of good SiPMs better than 99%







Left: top and side views of an eight-channel SiPM array in its ceramic package.

Right: ceramic packages at the CERN Metrology Laboratory for characterization measurements

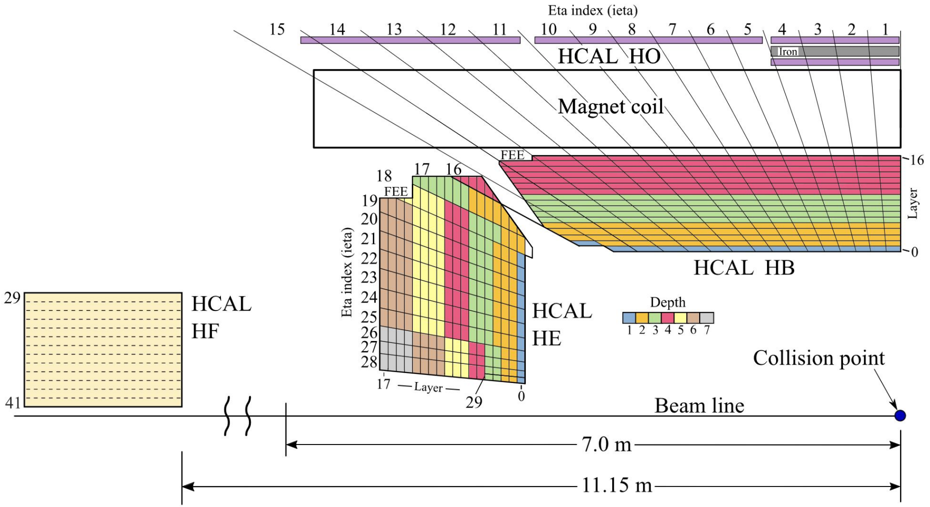
HCAL Phase 1 Upgrade

In HB and HE, the hybrid photodiode detectors (HPDs) were replaced with silicon photomultipliers (SiPMs)

- The SiPM has many advantages over the HPD
  - High photon detection efficiency (PDE), high gain, a large linear dynamic range
  - Rapid recovery time, somewhat better radiation tolerance, and insensitivity to magnetic fields
  - A yield of good SiPMs better than 99%

Increase in the number of readout channels, finer segmentation is achieved

- Up to seven depth in HE and four in HB



HCAL Phase 1 Upgrade

In HB and HE, the hybrid photodiode detectors (HPDs) were replaced with silicon photomultipliers (SiPMs)

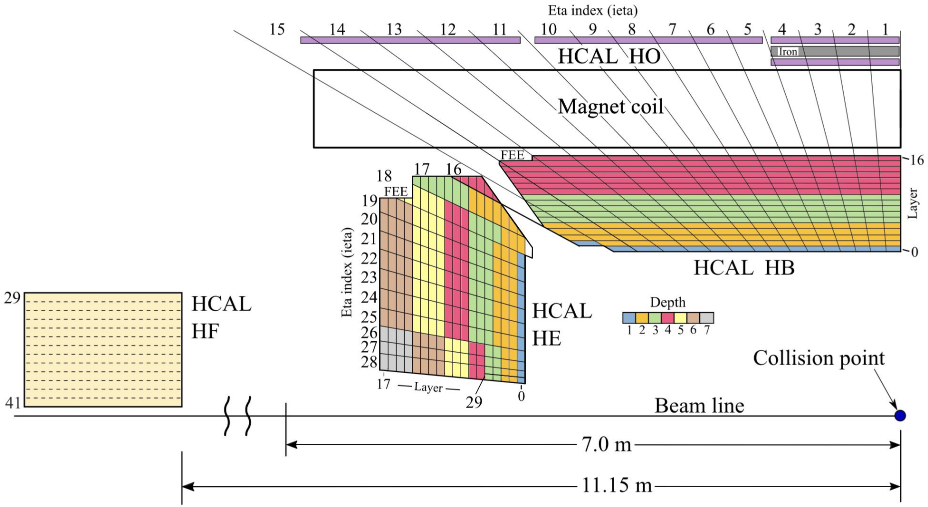
- The SiPM has many advantages over the HPD
  - High photon detection efficiency (PDE), high gain, a large linear dynamic range
  - Rapid recovery time, somewhat better radiation tolerance, and insensitivity to magnetic fields
  - A yield of good SiPMs better than 99%

Increase in the number of readout channels, finer segmentation is achieved

- Up to seven depth in HE and four in HB

The signals from the SiPMs are integrated and digitized by the QIE11 ASICs

- A 6-bit time-to-digital converter (TDC) detects arrival time of the input pulse in 0.5 ns bins
- Integrates negative input charge pulses in 25 ns bucket
- an effective 17-bit dynamic range with approximately 1% resolution



How could we benefit from the improved time and space resolution?

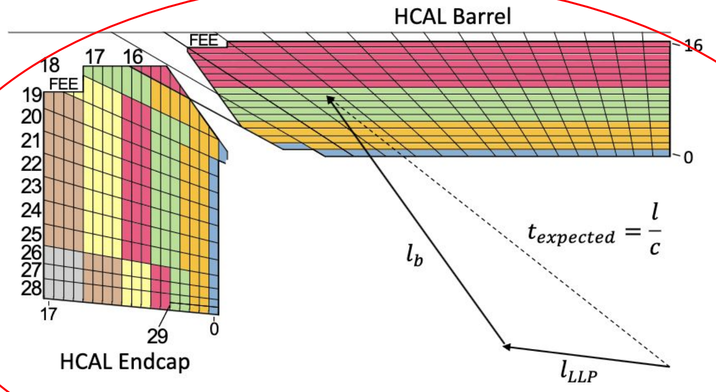
L1 Long-Lived Particles Trigger

A low-level hardware timing trigger is designed and deployed to benefit from greater granularity and additional timing information

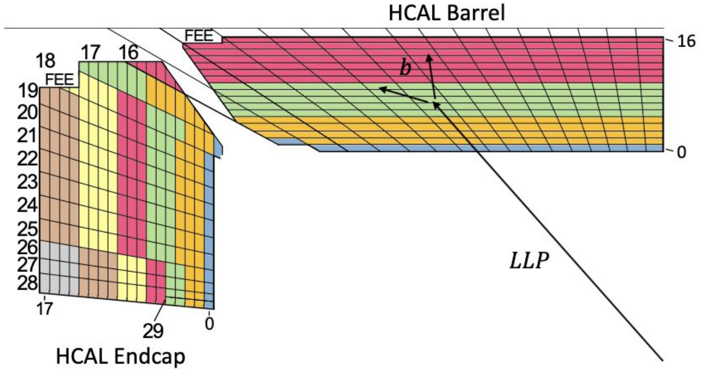
- Timing and segmentation information is used at the hardware level to identify long-lived particle (LLP) candidate events

Introducing a trigger that processes data at 40 MHz

- Jets arriving at delayed times (timing)
- Events with unique depth signatures (segmentation)



$$\Delta t = \frac{l_{LLP}}{v_{LLP}} + \frac{l_b}{c} - t_{expected}$$



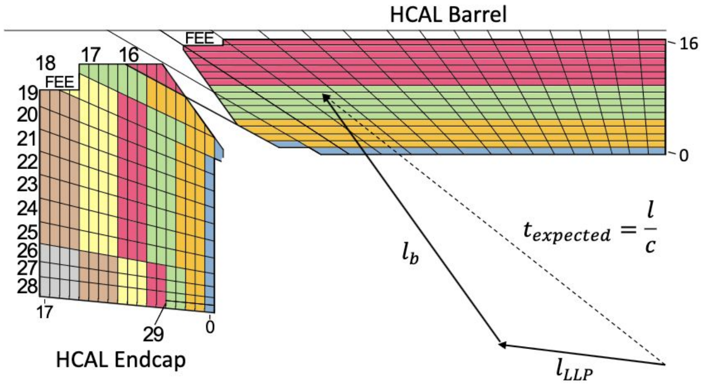
L1 Long-Lived Particles Trigger

A low-level hardware timing trigger is designed and deployed to benefit from greater granularity and additional timing information

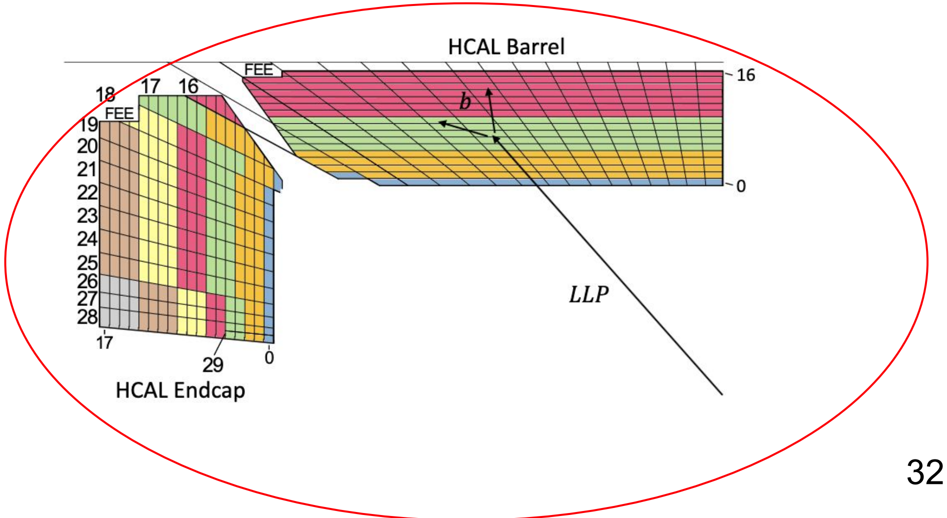
- Timing and segmentation information is used at the hardware level to identify long-lived particle (LLP) candidate events

Introducing a trigger that processes data at 40 MHz

- Jets arriving at delayed times (timing)
- Events with unique depth signatures (segmentation)



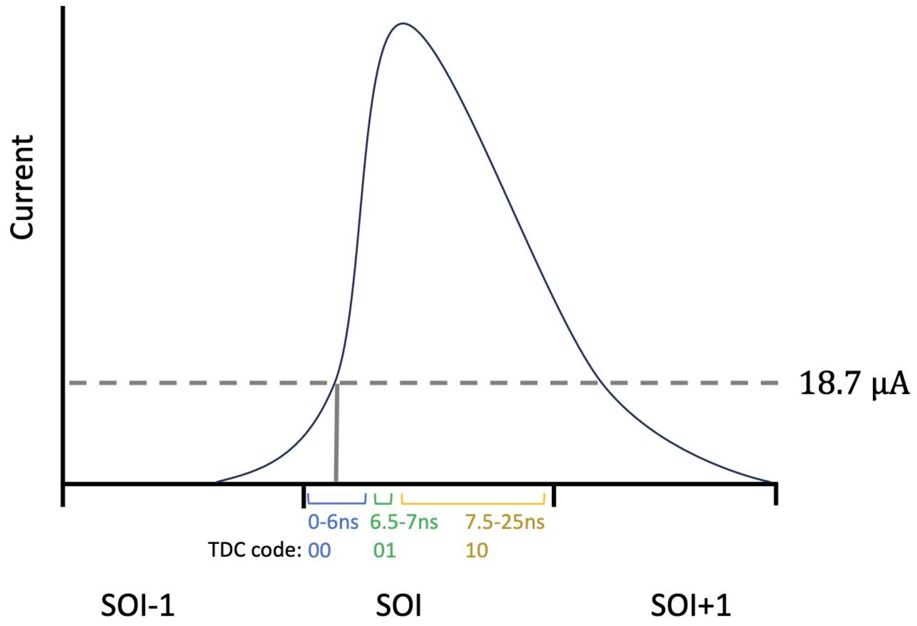
$$\Delta t = \frac{l_{LLP}}{v_{LLP}} + \frac{l_b}{c} - t_{expected}$$



Precise Timing Alignment

For the timing trigger, the TDC information from the sample of interest (SOI) is used

- A rising edge timing measurement:
  - The time at which the current passes the threshold is reported
- The threshold height optimized to exclude triggering from the collisions in a previous bunch-crossings
- Look up table (LUT) used to convert TDC output to 2 bits



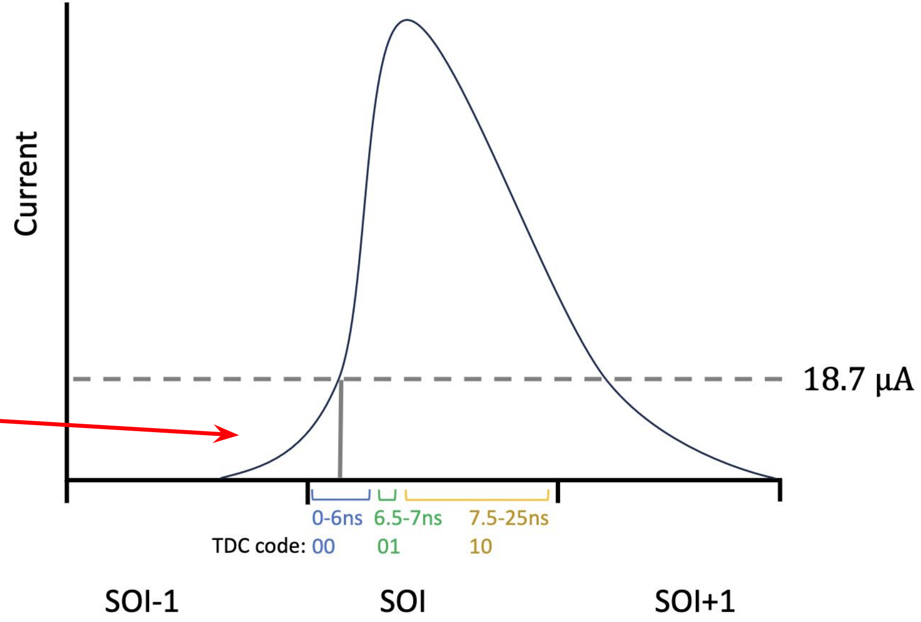
Precise Timing Alignment

For the timing trigger, the TDC information from the sample of interest (SOI) is used

- A rising edge timing measurement:
  - The time at which the current passes the threshold is reported
- The threshold height optimized to exclude triggering from the collisions in a previous bunch-crossings
- Look up table (LUT) used to convert TDC output to 2 bits

2-bit compressed TDC encodes four ranges

- 00 prompt (0-6 ns)
- 01 slightly delayed (6.5-7 ns)
- 10 very delayed (7.5-25 ns)
- 11 invalid or error (>25 ns)



Precise Timing Alignment

For the timing trigger, the TDC information from the sample of interest (SOI) is used

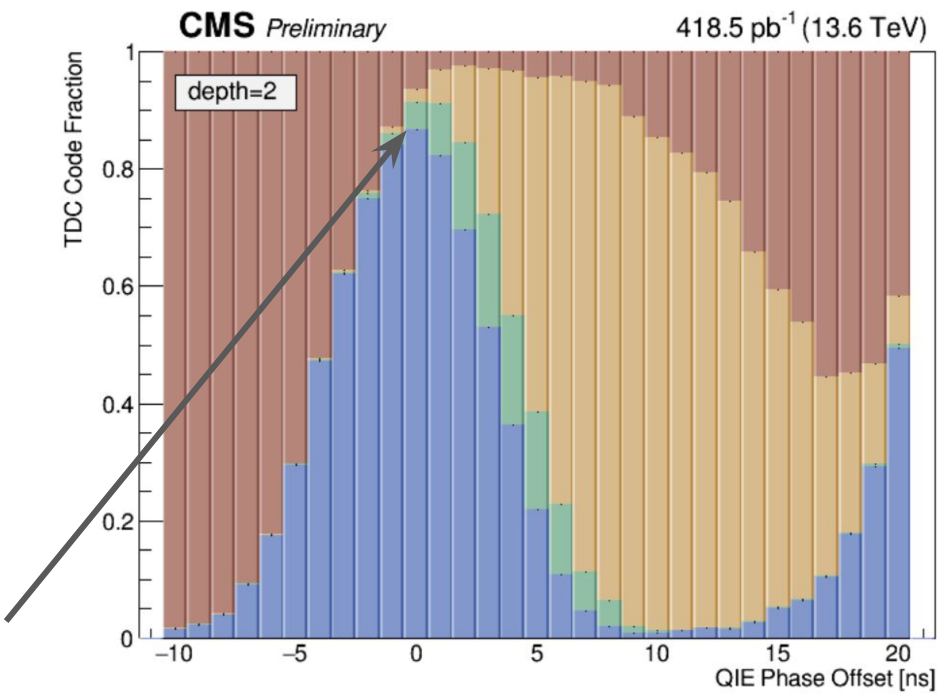
- A rising edge timing measurement:
  - The time at which the current passes the threshold is reported
- The threshold height optimized to exclude triggering from the collisions in a previous bunch-crossings
- Look up table (LUT) used to convert TDC output to 2 bits

2-bit compressed TDC encodes four ranges

- 00 prompt (0-6 ns)
- 01 slightly delayed (6.5-7 ns)
- 10 very delayed (7.5-25 ns)
- 11 invalid or error (>25 ns)

Phase scan, in 1 ns, for timing alignment (LLP trigger) and depth-dependent pulse-shape measurements

- QIE Phase offset = 0, the majority of the pulses are "prompt":
  - Best timing alignment



G. Kopp et al. "A Novel Timing Trigger with the CMS Hadron Calorimeter" [CMS DN-2023/022]

Conclusions

Pileup increase is the significant challenge for the most of the detectors and reconstruction algorithms

- Moreover the determination of the luminosity itself becomes more complicated while having even stronger precision requirements

Prior Run 3 BRIL upgraded luminosity and background instrumentation

- Great performance and linearity of the systems, finer timing for improved beam background resolution
- Combined with the luminosity results from Muons, HCAL and PIXEL total uncertainty below 1.5%

Great performance and longevity from Muons with some important updates

- Newly introduced GEMs to provide better coverage in the endcap region and improve reconstruction efficiency
- Important upgrades of front- and back-end electronics to handle higher rates, even more foreseen for the Phase 2

New SiPMs and improved spatial and timing resolution of HCAL Barrel and Endcap regions

- Better performance, opportunities for “new physics”

Backup Slides

Preliminary 2022 Luminosity Results

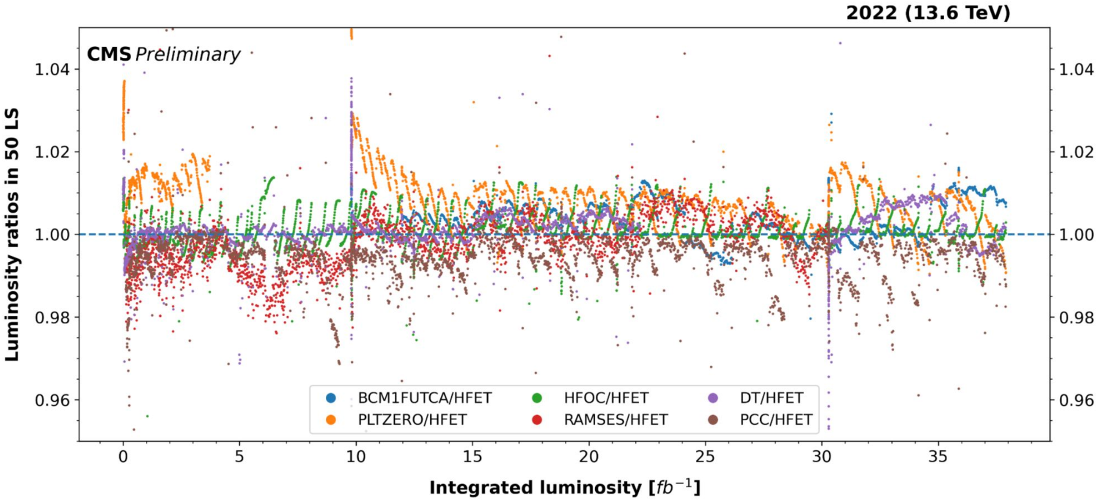
Great stability and linearity of the detectors

- 4 detectors independently calibrated using van-der-Meer scans and 2 detectors (DT/Remus) for consistency checks

Precise calibrations performed

- Total uncertainty of 1.4% in 2022

Source	Correction (%)	Uncertainty (%)
Calibration		
Beam current	3.4	0.2
Ghost and satellite charges	0.4	0.2
Orbit drift	0.1	0.1
Residual beam positions	0.0	0.3
Beam-beam effects	1.0	0.4
Length scale	-1.0	0.1
Factorization bias	1.0	0.8
Scan-to-scan variation	-	0.5
Bunch-to-bunch variation	-	0.1
Cross-detector consistency	-	0.4
Integration		
HFET OOT pileup corrections		0.2
Cross-detector stability		0.5
Cross-detector linearity		0.5
Calibration		1.2
Integration		0.8
Total		1.4



Ratio of the luminosity measured in time windows of 50 LS (about 20 min) between all the luminosity detectors and HFET as a function of the integrated luminosity.

CMS PAS LUM-22-001

DT: Upgrade and Performance

Drift Tubes (DT)

- DT chambers themselves will operate unchanged throughout the HL-LHC period
- Significant upgrade of DT electronics performed during Run 2 to adopt for the doubled instantaneous luminosity:
  - No change to on-board electronics
  - Back-end is moved to UXC:
    - Easy access during LHC running
  - TwinMux component introduced:
    - Combines the data from the DT and RPC chamber to produce L1 “super-primitives”
  - μROS system:
    - 25 boards to aggregate the data and feed to Central DAQ