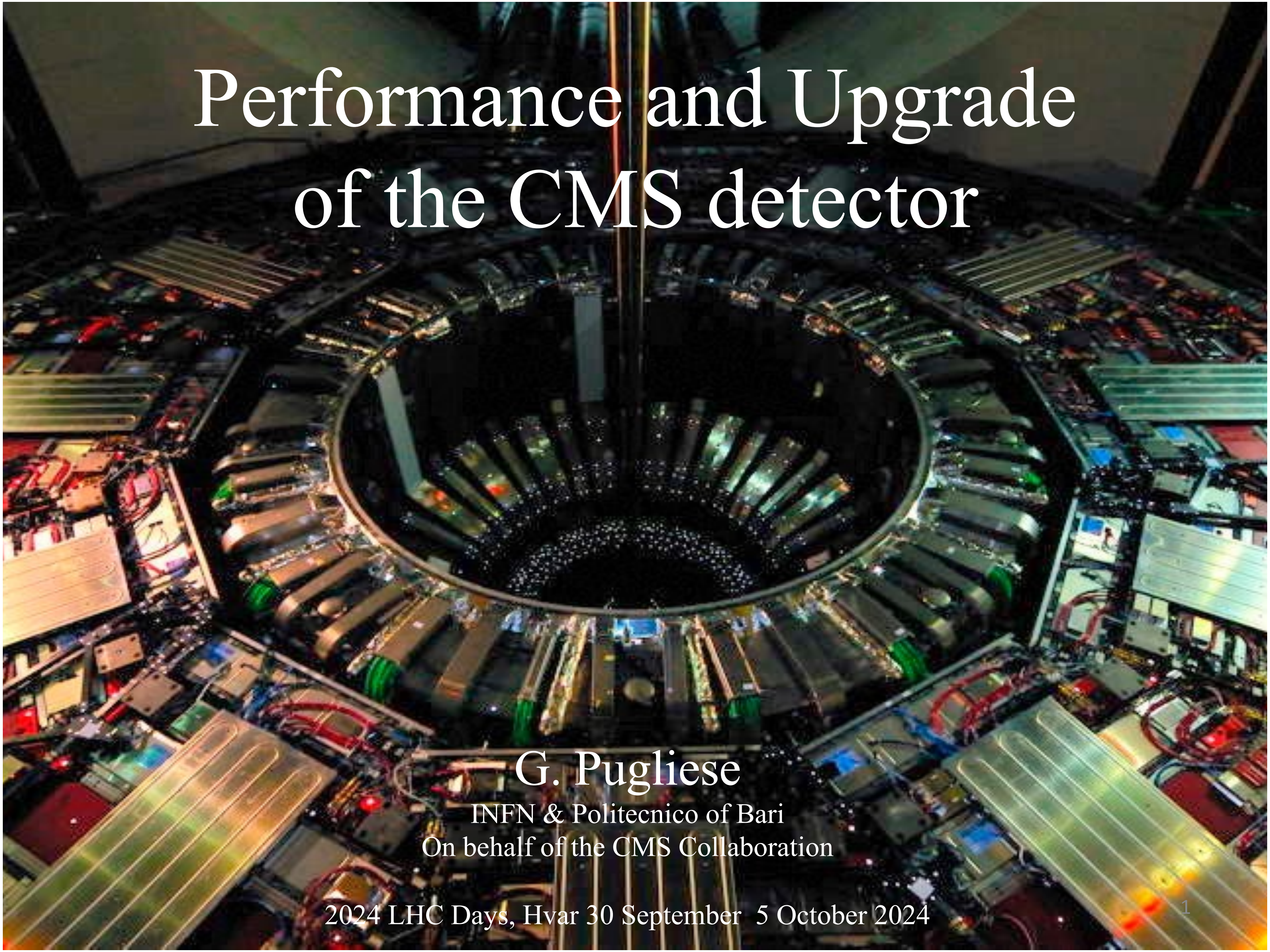


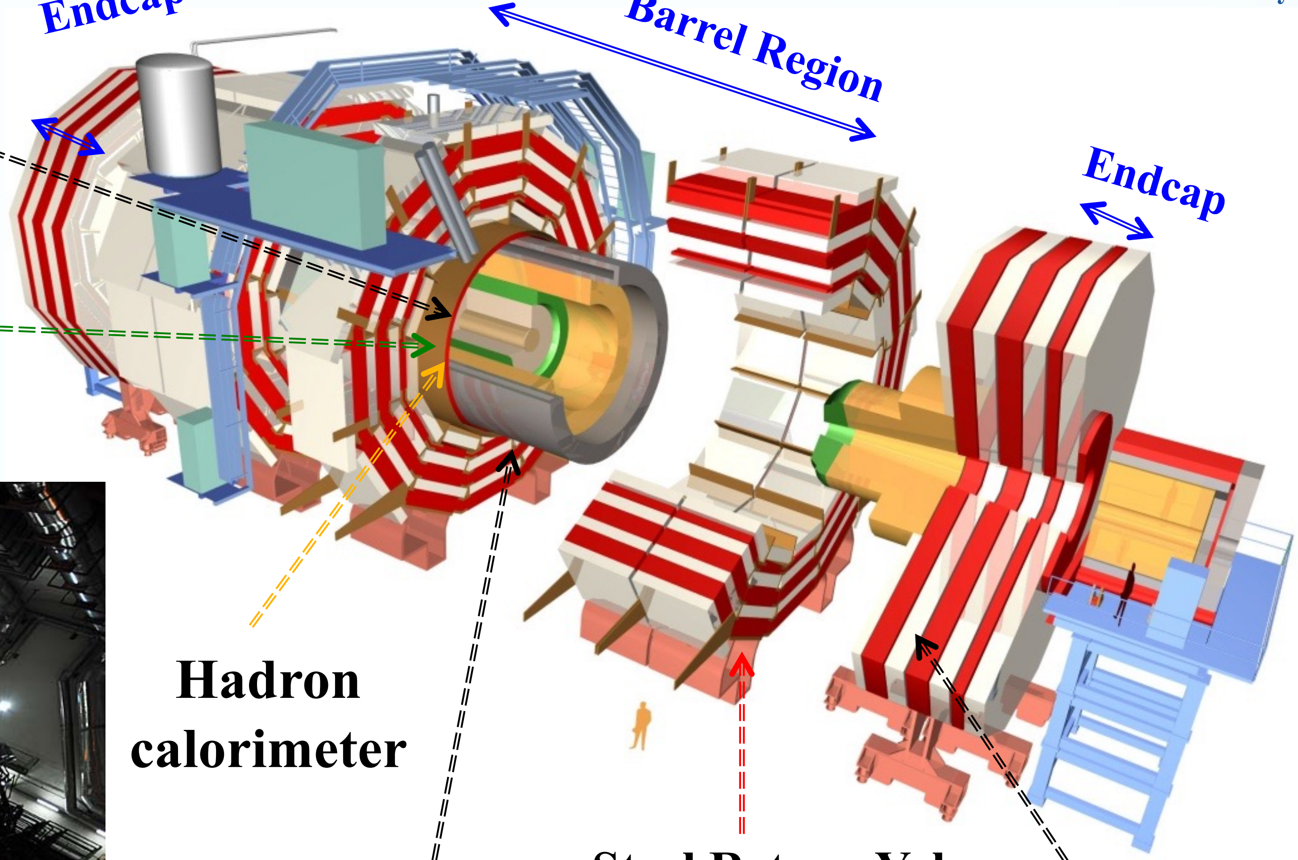
Performance and Upgrade of the CMS detector

G. Pugliese
INFN & Politecnico of Bari
On behalf of the CMS Collaboration

2024 LHC Days, Hvar 30 September 5 October 2024

G. Pugliese

CMS detector



Tracker

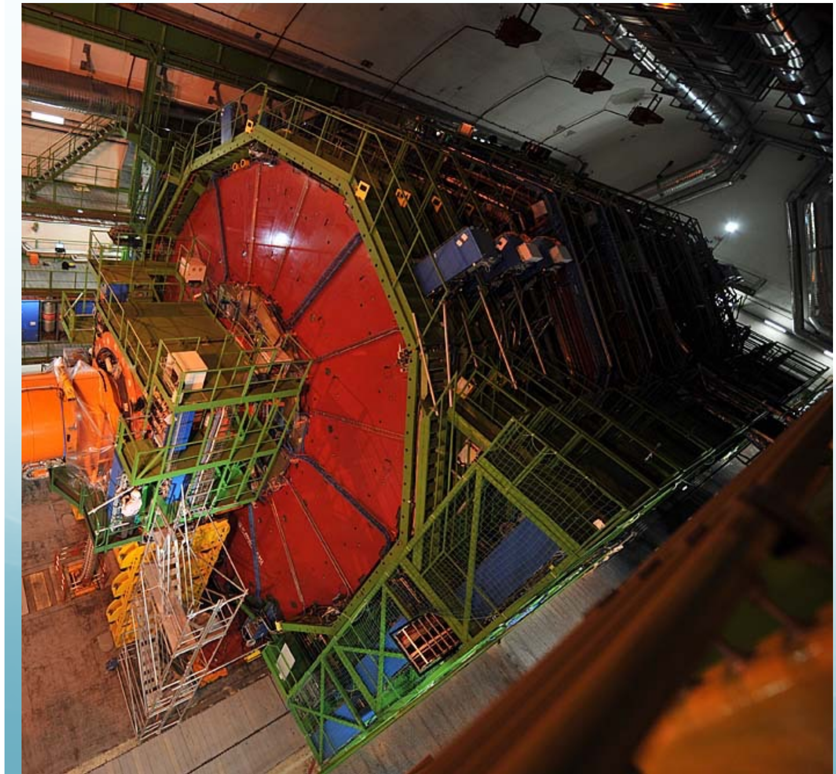
Electromagnetic calorimeter

Hadron calorimeter

Superconducting Solenoid
Niobium titanium coil carrying 18.000 A

Steel Return Yoke

Muon Spectrometer



Weight: 14000 t
Length: 28.7 m
Diameter: 15 m
Magnetic field: 3.8 T

LHC and HL-LHC schedule

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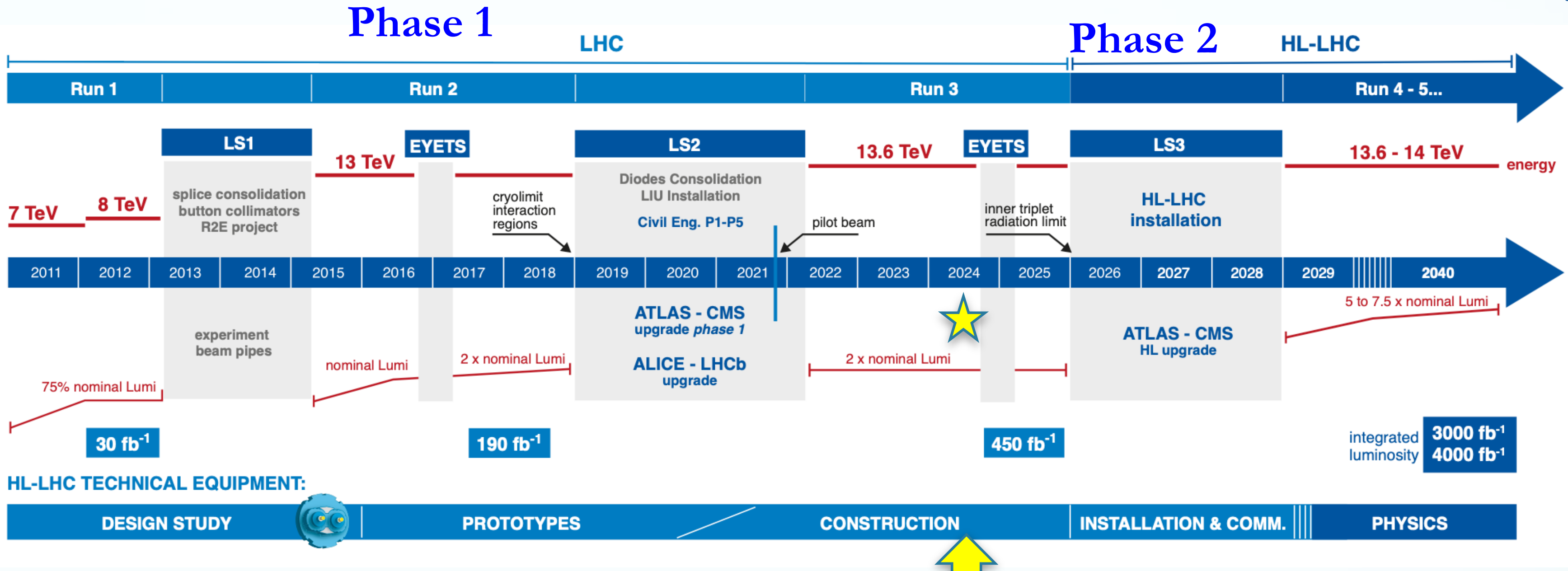
2024 LHC Days



1997 Muon Project TDR

We are here

Outline:

- CMS performance in RUN3
- CMS upgrade project for Phase 2

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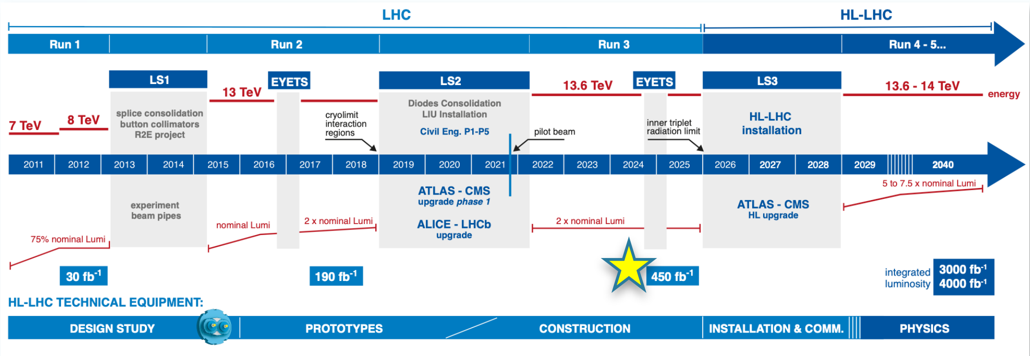
LHC and CMS overview



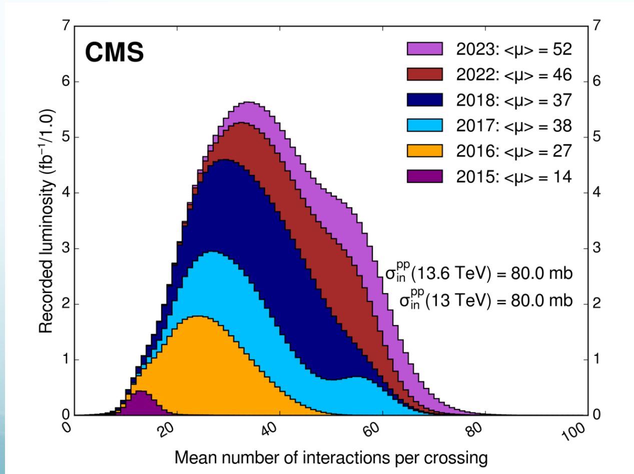
Luminosity delivered to CMS:

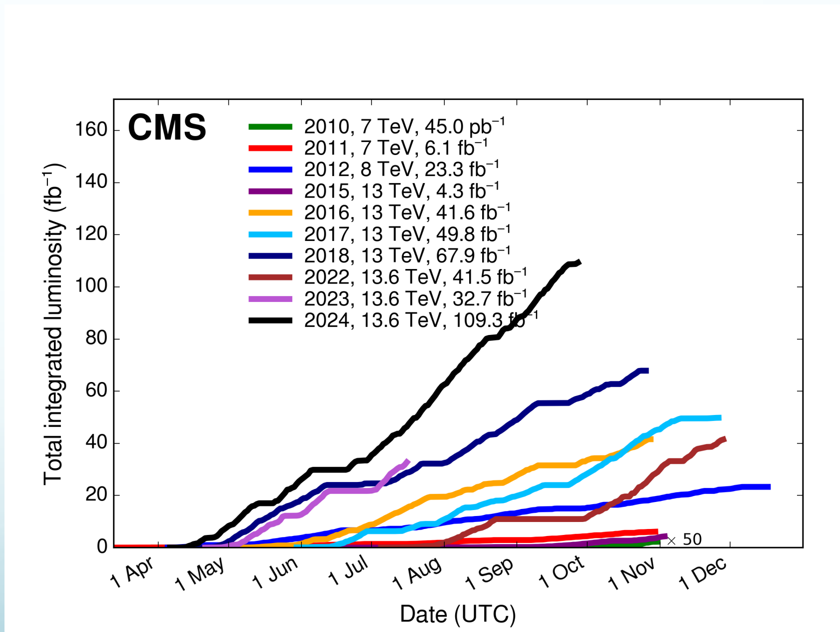
- Run1+Run2+Run3 ~ 377 fb^{-1}
- In Run3 ~ 184 fb^{-1}
- In 2024 ~ 110 fb^{-1}

~93% of the delivered data were recorded by CMS!

CMS instantaneous luminosity ~ 2 10^{34} cm^{-2} s^{-1}

Mean number of interactions per bunch crossing in 2024 ~ 63!





Highly irradiated environment, challenging conditions

CMS Luminosity Public results

CMS performance in RUN3

CMS Tracker

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Silicon Pixel

Sensor technology: n+ implant in n bulk (n-in-n)
100x150 μm^2 pixel

- 79M barrel and 45M forward pixels in 2 m^2
- 4 layers in the barrel and 3 disks in the forward
- Operation: −22°C
- Radiation tolerance: 3×10^{15} $n_{eq}/cm^2/yr$

Silicon Strip

Strip unchanged since Run 1

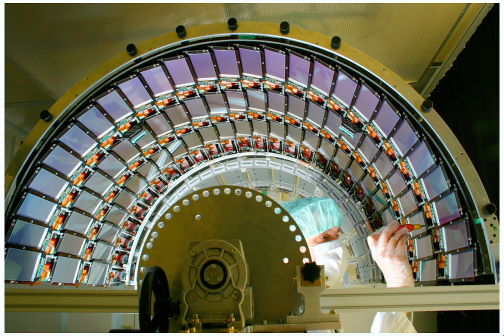
Sensor technology: p-in-n
Outer cell size ~20cm x 100-200μm
Inner cell size ~10cm x 80μm

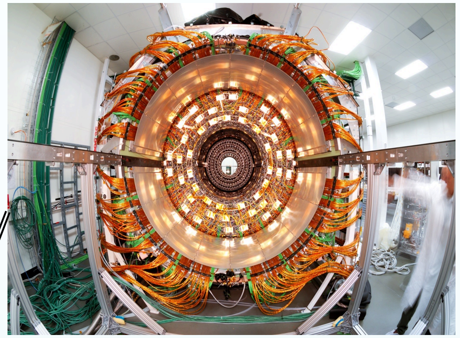
- 10 layers in the barrel and 12 rings in the endcap
- **Operation -25 °C (since June 2024)**
- Radiation tolerance ~1.5×10^{14} n_{eq}/cm^2

$\delta p_T/p_T < 1\%$ for $p_T < 50$ GeV and $< 10\%$ for $p_T = 1$ TeV

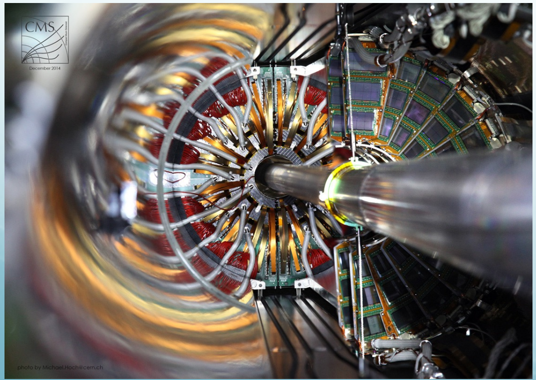
Tracker acceptance: $|\eta| < 2.5$

Inner Barrel

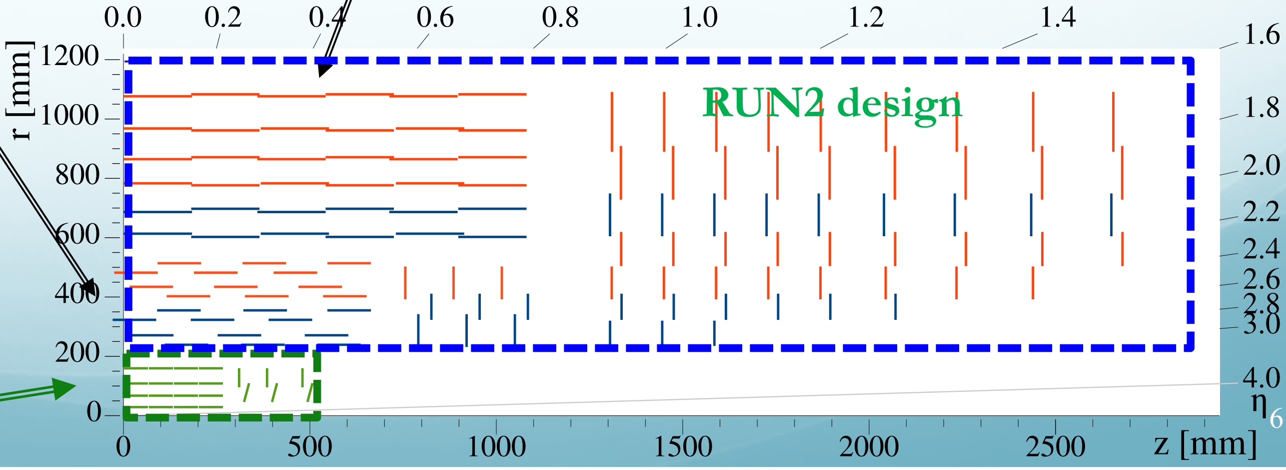




Outer Barrel



Pixel Barrel & Endcap



RUN3 Tracker performance

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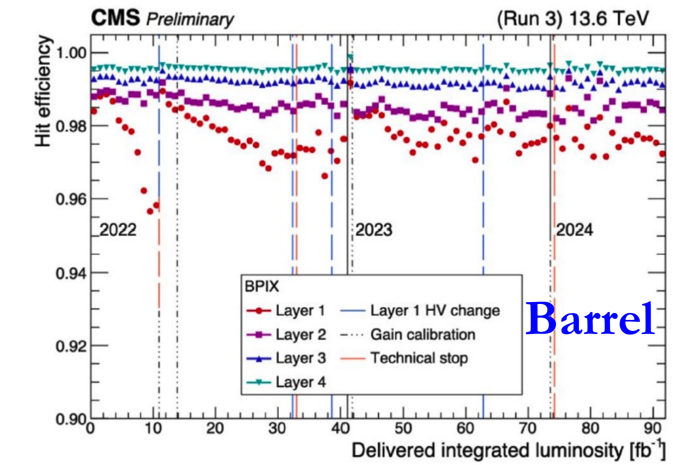
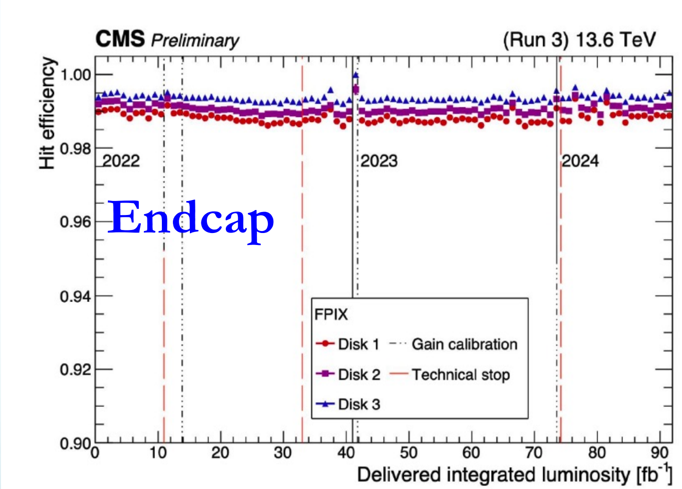
2024 LHC Days

Pixel detector:

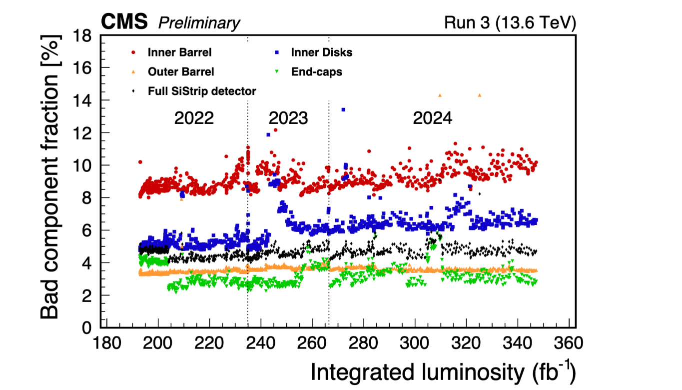
- 96%(Barrel), 98%(Forward) operational channels
- **Excellent performances** (cluster charge, ***hit efficiency,*** hit resolutions, etc.) measured in RUN3. Barrel Layer 1, which was replaced in LS2, is now stabilized





Strip detector:

- ~96% **good detector fraction,** stable

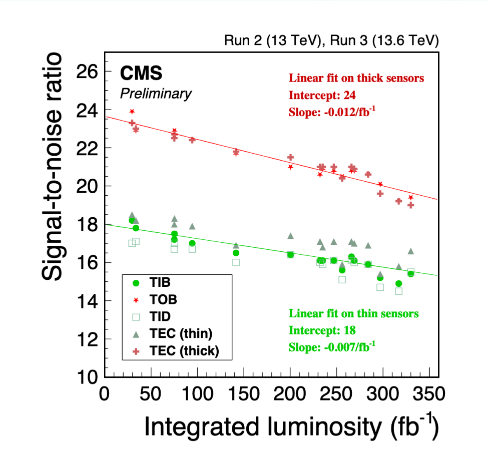


- **Signal/noise**, hit efficiency, continue to be good

Expected S/N at the end of Run 3:

Thin sensor - 14.5

Thick sensor - 18.5



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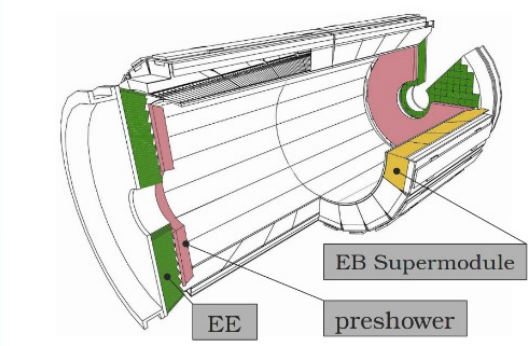
CMS Calorimeters

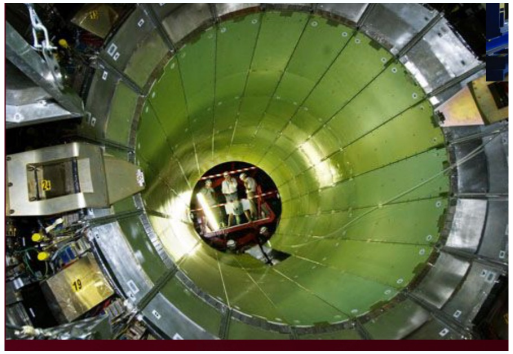
Electromagnetic system

Homogeneous and hermetic with high granularity lead-tungstate ($PbWO_4$) crystals

- **Barrel (EB):** 61200 crystals in 36 super-modules, $|\eta| < 1.48$, ≈ 26 X0, Avalanche Photo-Diode (APD) readout
- **Endcaps (EE):** 14648 crystals in 4-Dees, $1.48 < |\eta| < 3.0$, ≈ 25 X0 Vacuum Photo-Triode (VPT) readout

Pre-shower (endcaps only): 3X0 of Pb/Si strips, $1.65 < |\eta| < 2.6$





Density of 8.3 g/cm3, radiation length 0.89 cm, Molière radius 2.2 cm, ≈ 80% of scintillating light in ≈ 25 ns, refractive index 2.2, light yield spread among crystals ≈ 10%

$$\sigma(E) \sim 1.6 - 5\%/\sqrt{E} \oplus 0.5\%$$

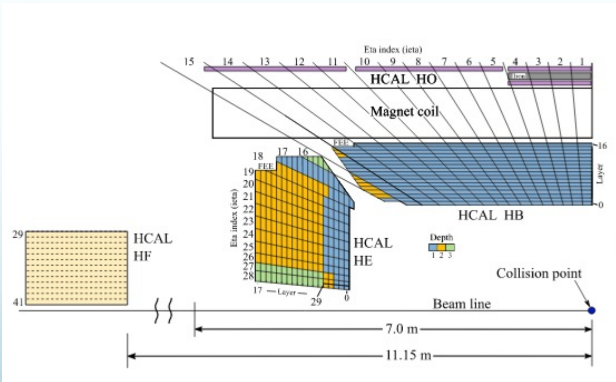
Hadronic system

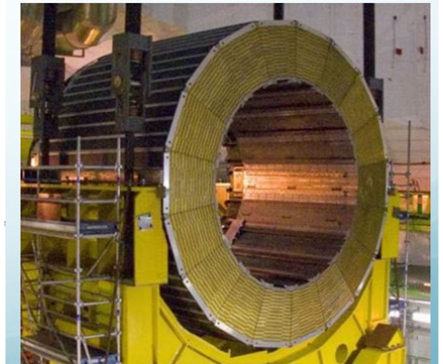
- **Hadronic Barrel (HB) and Endcap (HE) calorimeters:** sampling calorimeter of brass absorber plates and plastic scintillators, $|\eta| < 3.0$
  - **HB:** 36 wedges, brass absorber plates and 17 plastic scintillator tiles; 40000 scintillator tiles
  - **HE:** two brass/scintillator discs with 19 longitudinal layers

Outside the magnet coil:

- **Hadronic Outer (HO) system:** scintillator tiles 1/2 layers, SiPMs readout, $|\eta| < 1.26$
- **Hadronic Forward (HF) system:** 11.5 m from the interaction point. 36 wedges mads of steel absorber with quartz fibers embedded along its length (≈1000km fibers), $3 < |\eta| < 5$

Run2 design





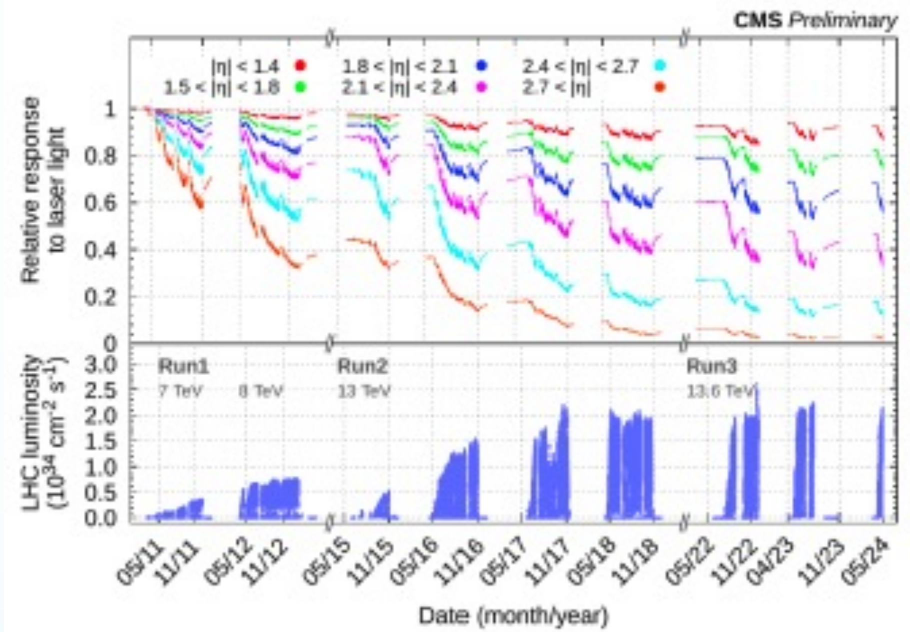
HB Brass absorber

$$\sigma(E) \sim 84.7\%/\sqrt{E} \oplus 7.6\%$$

RUN3 ECAL performance

- **The detector response,** monitored with a laser-based system, is aligned with expectations

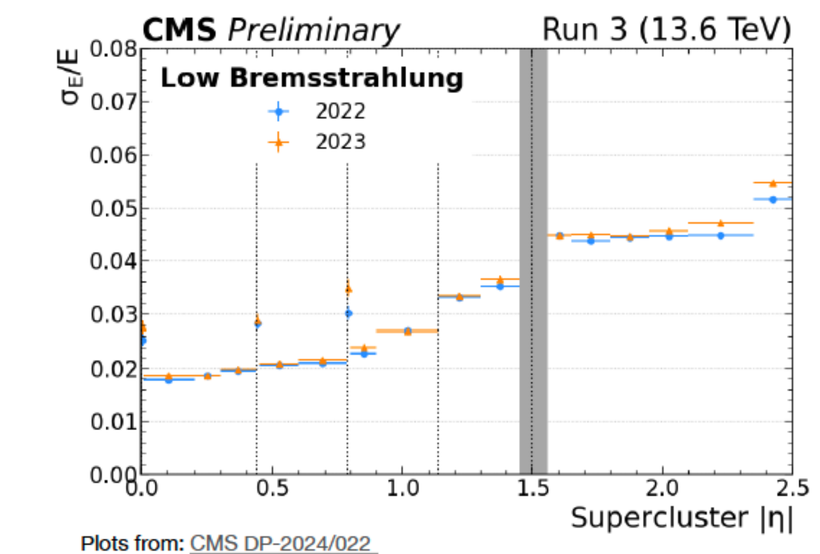
Evolution of the ECAL response to laser light



EB: 90%

EE low eta
40-80%

EE high eta
0-15%



Plots from: CMS DP-2024/022

- **The energy resolution,** as computed with the di-electron invariant mass (Z → e+e−), is stable (2022 and 2023)

- Successfully automated calibration workflow

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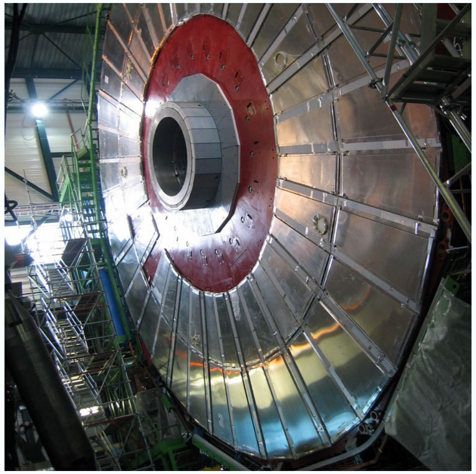
CMS Muon Systems

Muon system: based on ~~three~~ four gaseous technologies for muon identification, timing and momentum measurement



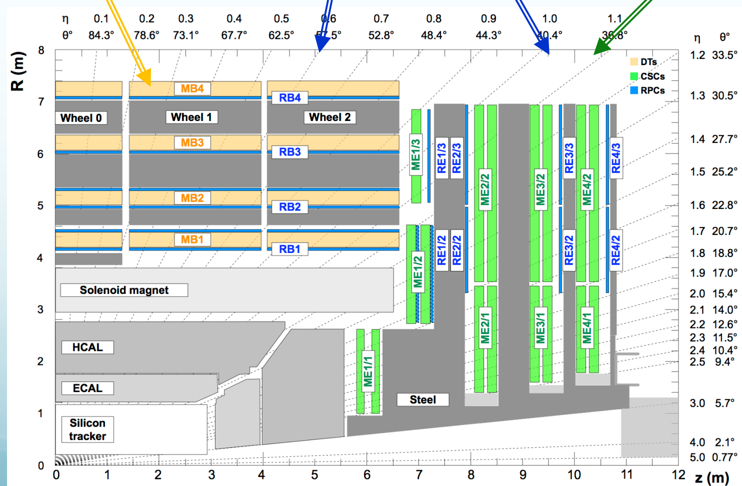
Muon acceptance: |η| < 2.4

Drift Tubes (DT)

- 250 chambers, ≈ 170k channels
- 32 number of hits
- Spatial resolution≈100 μm
- Time resolution ≈ 2 ns

Resistive Plate Chambers (RPC)

- 540 trapezoidal chambers, ≈ 120k channels
- 6 (4) number of hits
- Spatial resolution ≈1 cm
- Time resolution ≈ 1.5 ns



Cathode Strip Chambers (CSC)

- 540 trapezoidal chambers, ≈500k channels
- 24 number of hits
- Spatial resolution≈50 ÷140 μm
- Time resolution ≈ 3 ns

RUN2 design

RUN3 Muon System performance

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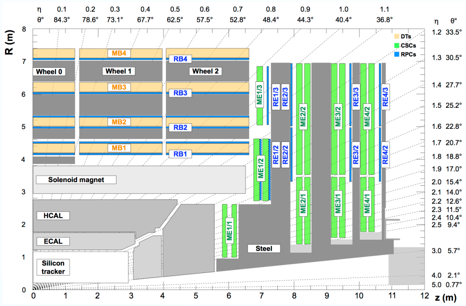
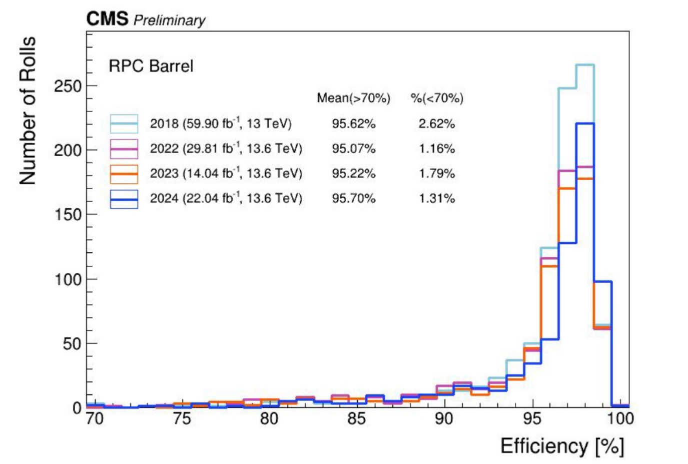
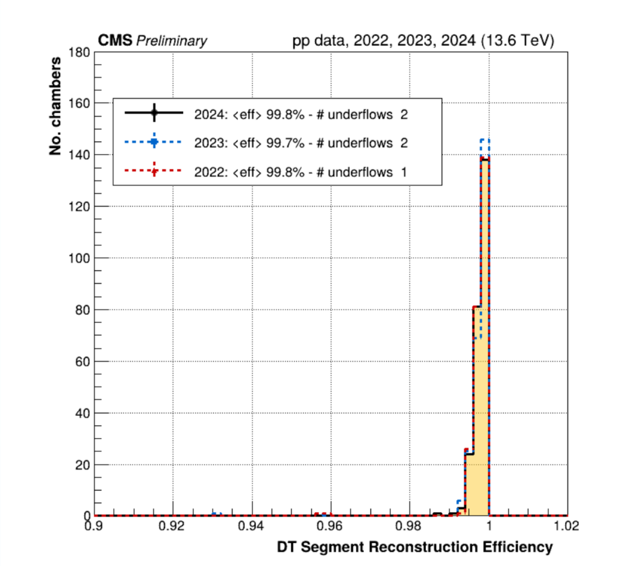
- Stable performance of the Muon legacy system over time and with instantaneous luminosity increases



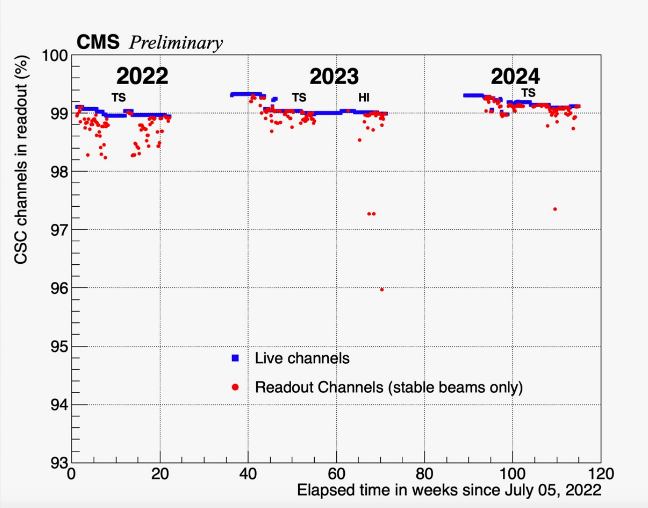


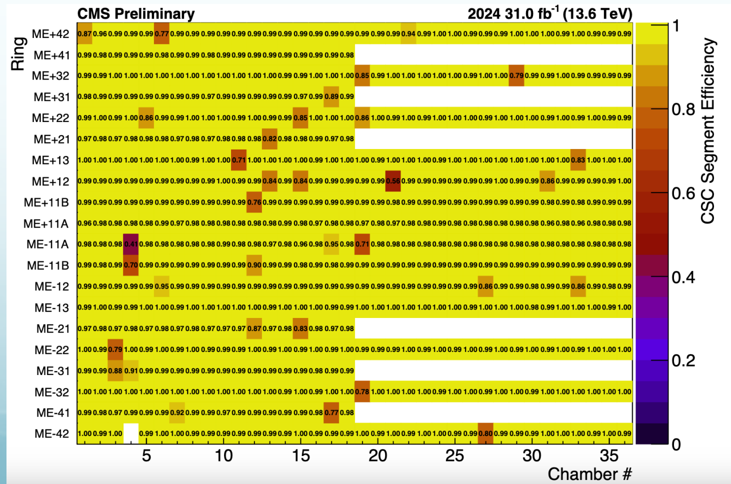
Barrel RPC efficiency in RUN3 (2022, 2023, 2024) and RUN2 (2018)



DT segment efficiencies in RUN3

CSC active channel in RUN3





CSC segment efficiencies in 2024

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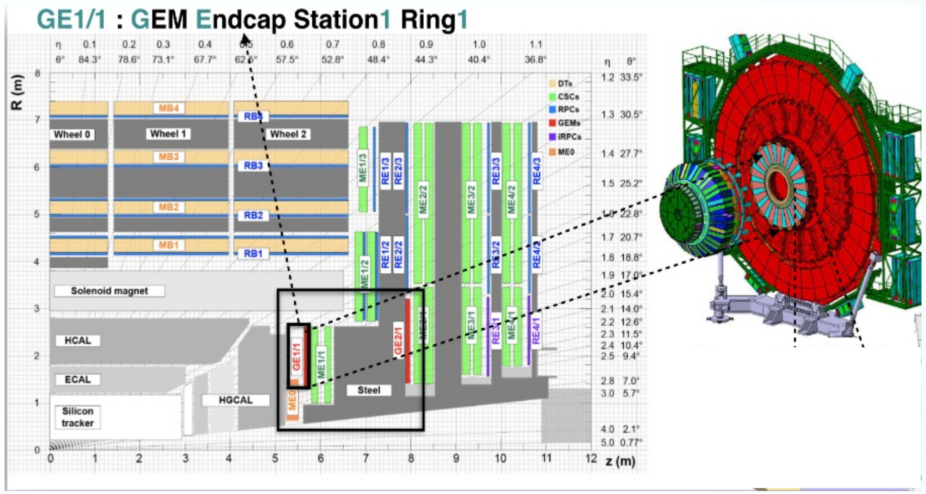
New GEM station

GE1/1 station:

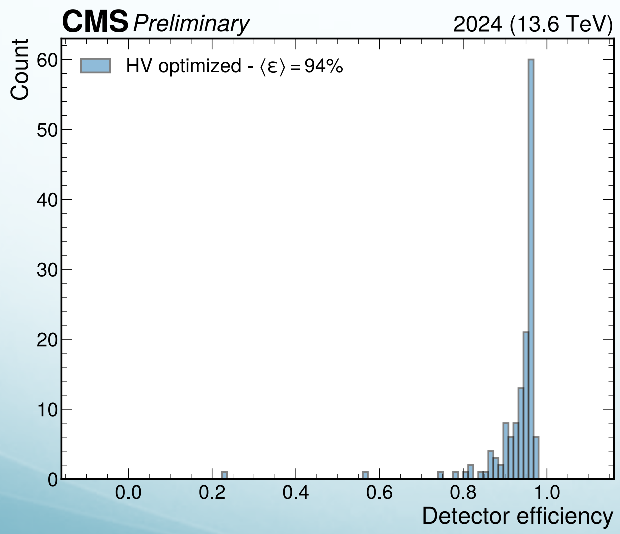
- 72 Super-Chambers (SC), consisting of two triple-GEM detectors
- 3456 VFAT3 chips, 432 GBT and VTRx optical link
- 2 number of hits
- Spatial resolution≈100 mm
- Time resolution ≈ 10 ns

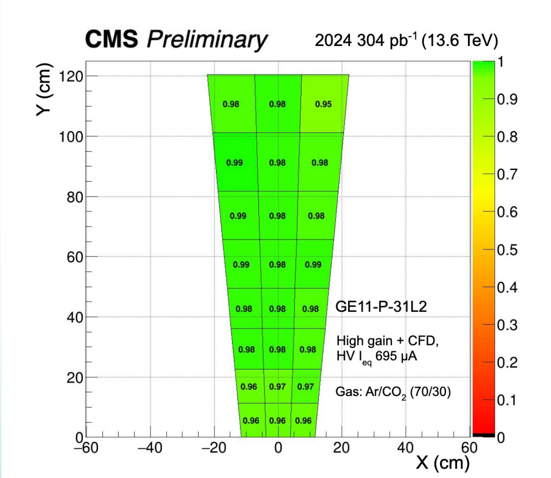
coverage 1.55 < |η| < 2.18

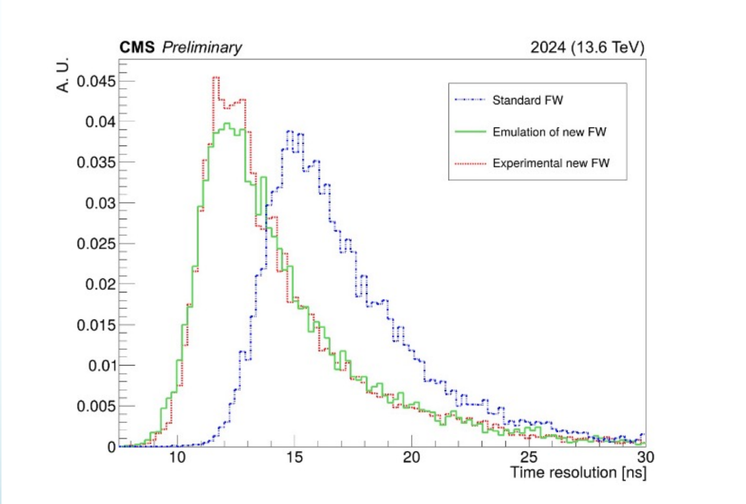
Phase 2 project
Installed in LS2



- **Several calibration** runs successfully taken in 2024 at different HV settings and Frontend chip (VFAT) configurations
- **Chamber efficiencies** optimized reaching **94% efficiency**







- New **on-chamber electronics FPGA firmware** deployed to suppress the strip x-talk significantly improving the time resolution

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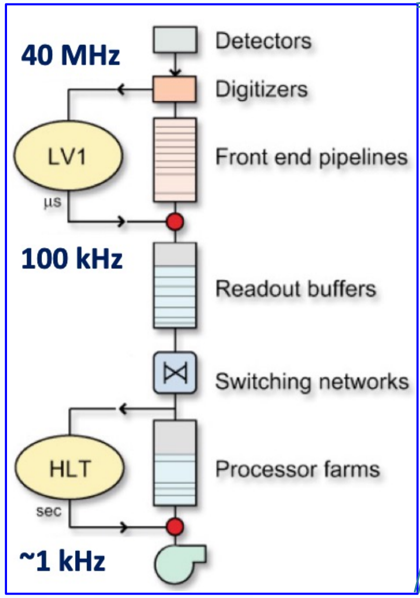
CMS Trigger System

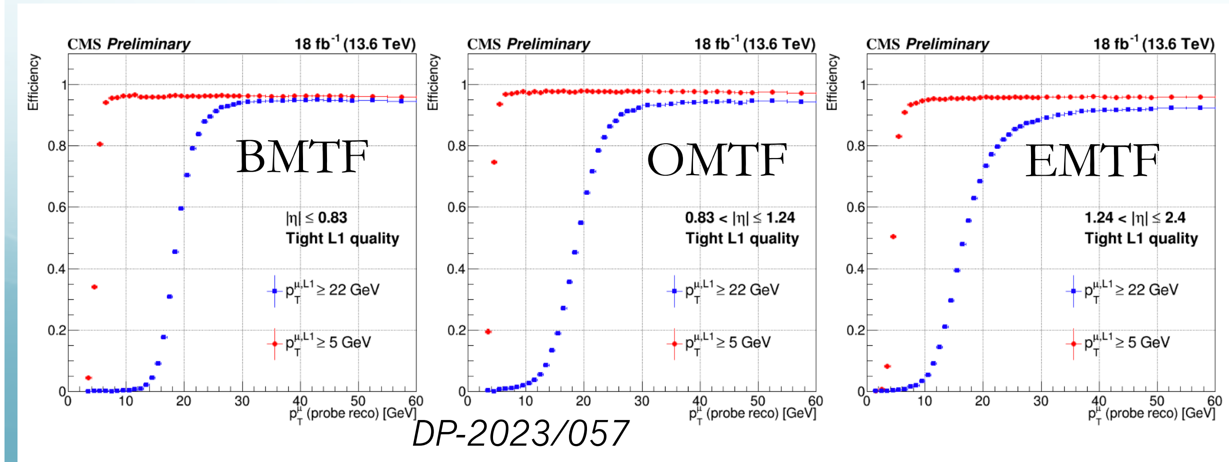


The CMS Trigger System is organized in two levels:

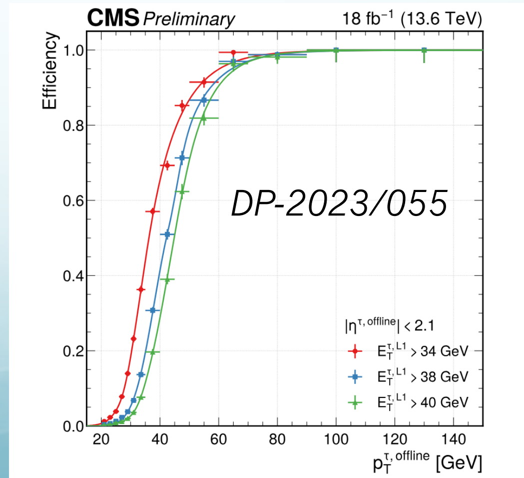
1. **Level-1 Trigger** hardware based reduces the data/event rate from the crossing rate of 40 MHz to no more than **100 kHz**, with **4µs latency**
2. **High Level Trigger (HLT)** filtering events with software running on computing farm, to further reduce the event rate for storage to 1 kHz

- The Level 1 Trigger operations were stable at throughout 2024 collecting data up to 115 kHz recording up to 64 simultaneous collisions/event (2.5x CMS design, 45% of HL-LHC)
- Good performance of all standard Level-1 Trigger Objects

L1 muons efficiency



L1 τ efficiency



Level-1 Trigger & High Level Trigger (HLT) @ RUN3

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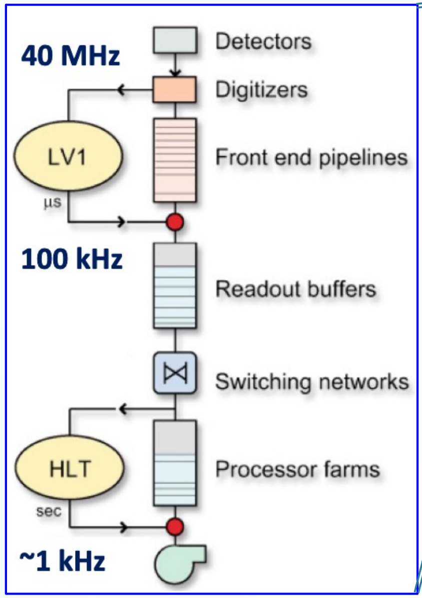

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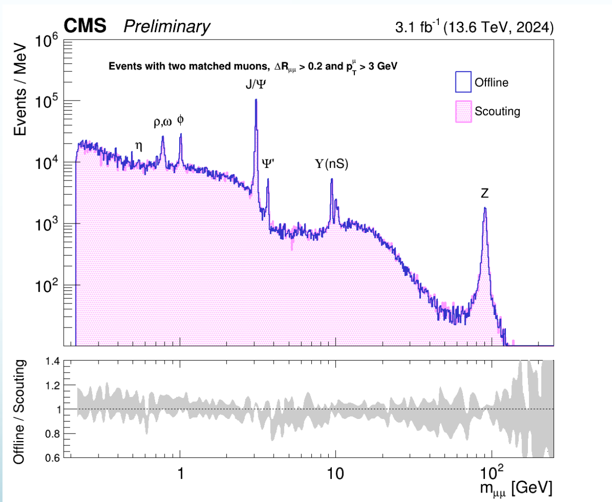
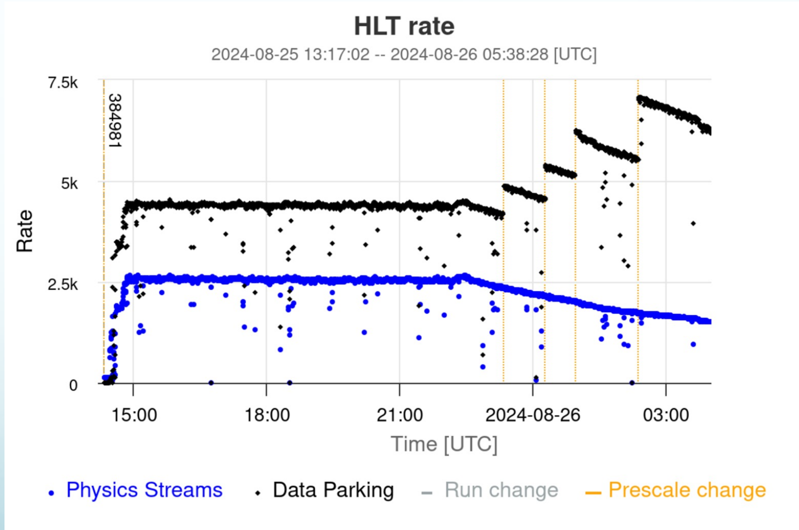
- Smooth data-taking at HLT.
- Average HLT rates: ~2 kHz Promptly reconstructed, ~5 kHz Parked data, ~27 kHz HLT-Scouting





Comparison of the dimuon spectra obtained with scouting and **offline**

CMS upgrade project for Phase 2

LHC and HL-LHC schedule

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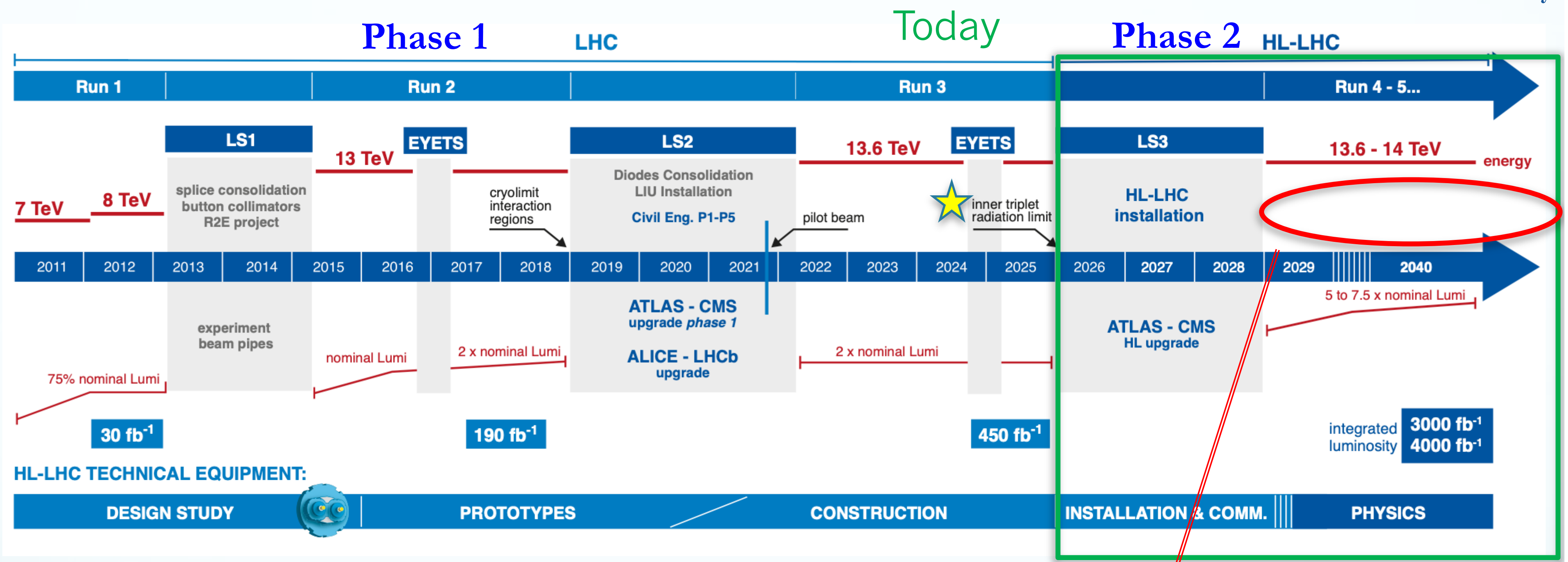

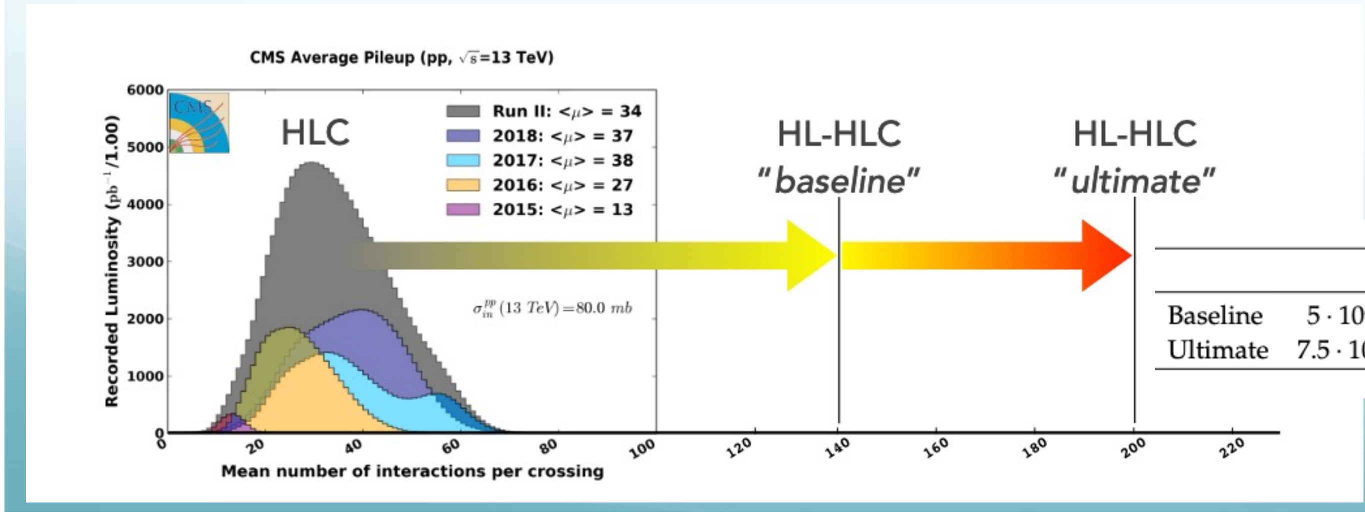

10 years of running at higher rates and radiation doses

	$\mathcal{L}$	$\langle$ PU $\rangle$	Vertex Density	$\int \mathcal{L}$ / year
Baseline	$5 \cdot 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	140	0.8/ mm	$250\,\mathrm{fb}^{-1}$
Ultimate	$7.5 \cdot 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	200	1.2/ mm	$> 300\,\mathrm{fb}^{-1}$

CMS Upgrade Project

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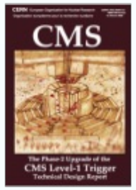
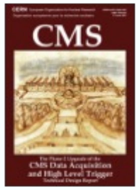
The CMS detector has to be upgraded to cope with expected HL-LHC conditions (highest rate, fluence and pileup ever achieved) for new measurements and new physics searches

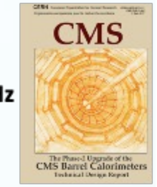


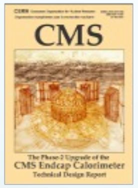
Level-1 Trigger
https://cds.cern.ch/record/2714892
- Tracks in L1 Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



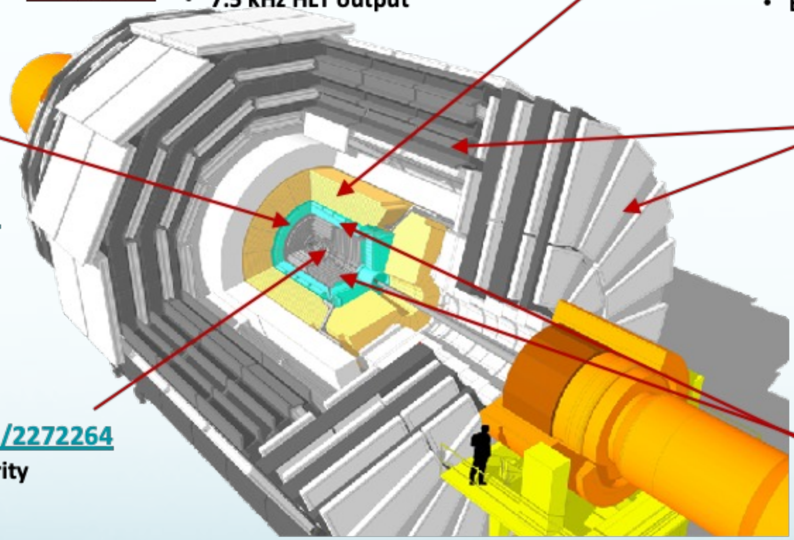
DAQ & High-Level Trigger
https://cds.cern.ch/record/2759072
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

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

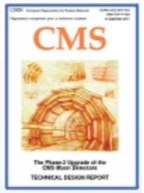


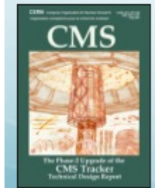


High-Granularity Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scintillator+SiPM in Pb/Cu-W/SS



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

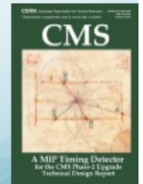




Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Extended coverage to $\eta \simeq 4$
- Design for tracking in L1 Trigger

Beam Radiation Instrumentation 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

MIP Timing Detector
https://cds.cern.ch/record/2667167
Precision timing with:
- Full coverage to $\eta \simeq 3$
- 30-50 ps time resolution for MIPs
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes



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CMS Upgrade Project

2024 LHC Days

Let's focus on the new detectors!

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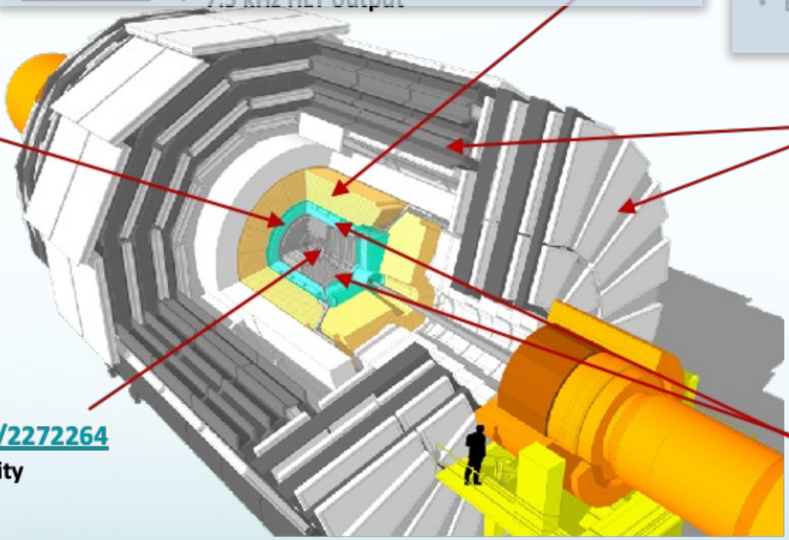
- Spike rejection
- ECAL and HCAL new Back-End boards



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

Jean-Baptiste Sauvan's talk

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

Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Extended coverage to $\eta \simeq 4$
- Design for tracking in L1 Trigger

MIP Timing Detector
https://cds.cern.ch/record/2667167
Precision timing with:
- Full coverage to $\eta \simeq 3$
- 30-50 ps time resolution for MIPs
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Beam Radiation Instrumentation 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

Anne Dabrowski's talk

G. Pugliese

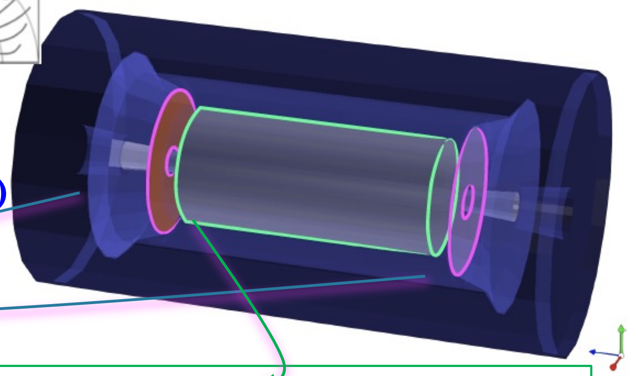
MIP Timing Detector (MTD)

A new detector will be added to measure the Minimum Ionizing Particle Timing Detector (MTD). It consists of:

- Thin layer between tracker and calorimeters
- Hermetic coverage for |η| <3
- **Time resolution** of 30-50 ps to **MIPs**

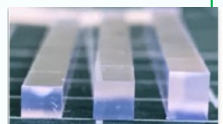
Operating temperature:-30°C

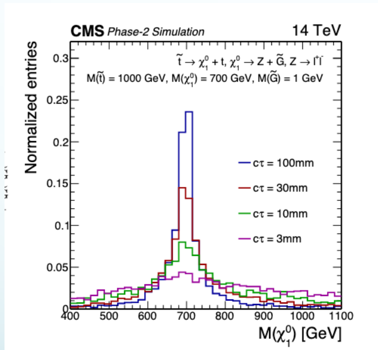
Endcap Timing Layer (ETL)

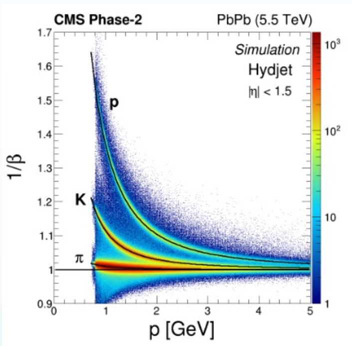


- Significant impact on the HL-LHC physics to:
  - Explore new signatures with Long Lived Particles
  - Boost Heavy Ions and B-Physics capabilities with Particle Identification

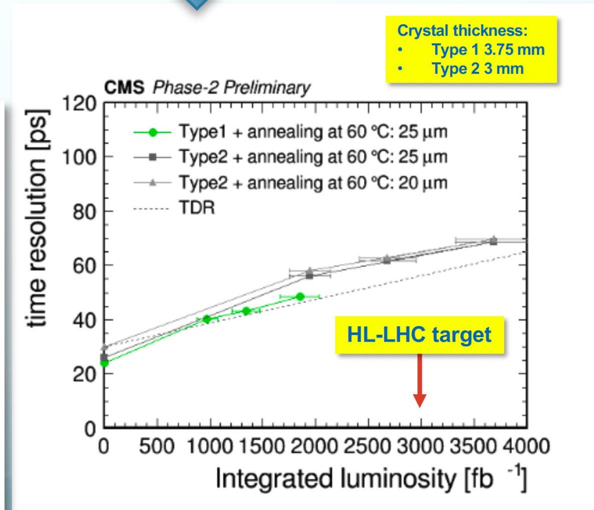
Barrel Timing Layer (BTL)
LYSO crystals with dual end SiPMs read-out
Total surface 38 m^2
Radiation level: 2 10^{14} n_{eq}/cm^2

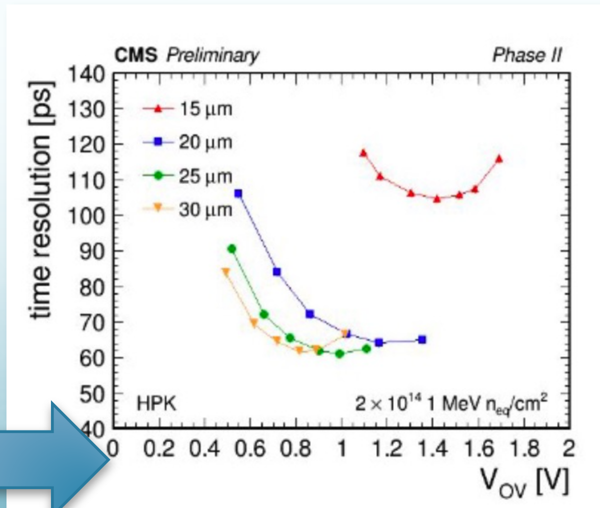






Neutralino mass distributions





Several tests were successfully done optimizing the:
- ✓ SiPM cell size
- ✓ Crystal thickness

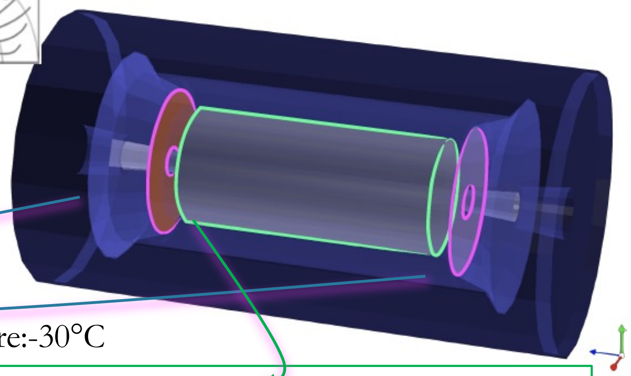
MIP Timing Detector (MTD)

G. Pugliese

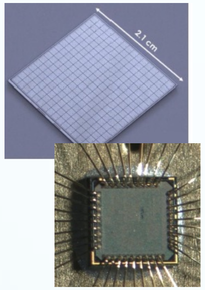
2024 LHC Days

A new detector will be added to measure the Minimum Ionizing Particle Timing Detector (MTD). It consists of:

- Thin layer between tracker and calorimeters
- Hermetic coverage for |η| <3
- **Time resolution** of 30-50 ps to **MIPs**

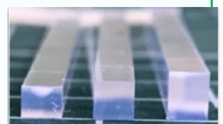


Operating temperature:-30°C

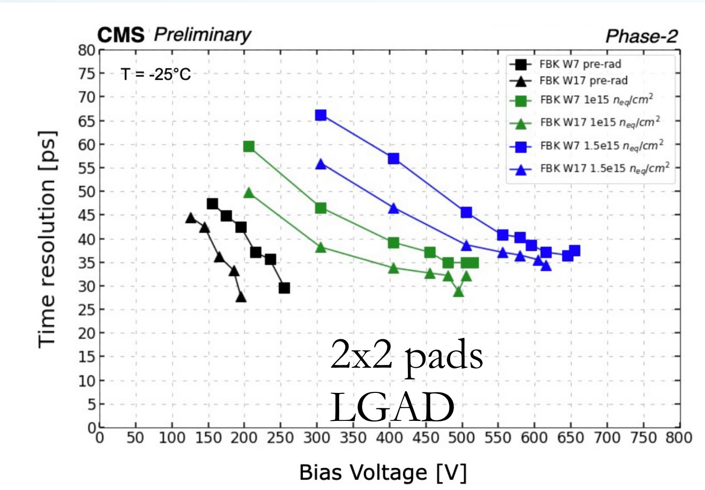


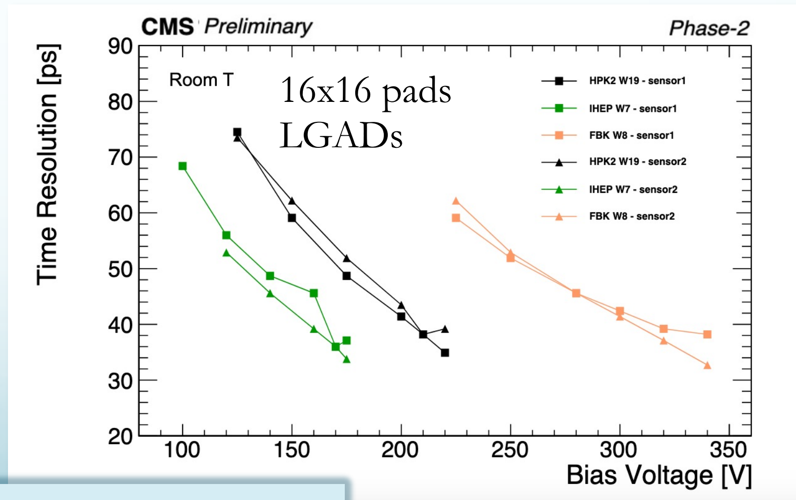
Endcap Timing Layer (ETL)
Two disks for each endcap to ensure 2 hits for each track
Low Gain Avalanche Diodes with ETROC ASIC readout
Total surface 14 m^2
Radiation level: 2 10^{15} n_{eq}/cm^2

Barrel Timing Layer (BTL)
LYSO crystals with dual end SiPMs read-out
Total surface 38 m^2
Radiation level: 2 10^{14} n_{eq}/cm^2



Several vendors tested with 90Sr beta source and electron beam





All devices showed a time resolution lower than 40 ps!

G. Pugliese

Tracker Upgrade

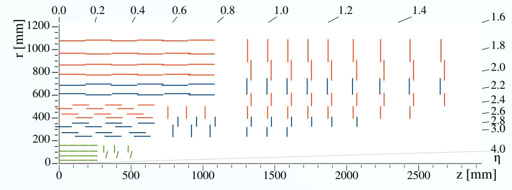
Key features of the new Phase 2 Tracker:

- **Extended tracking** acceptance up to $|\eta| = 4$
- **Increased granularity**

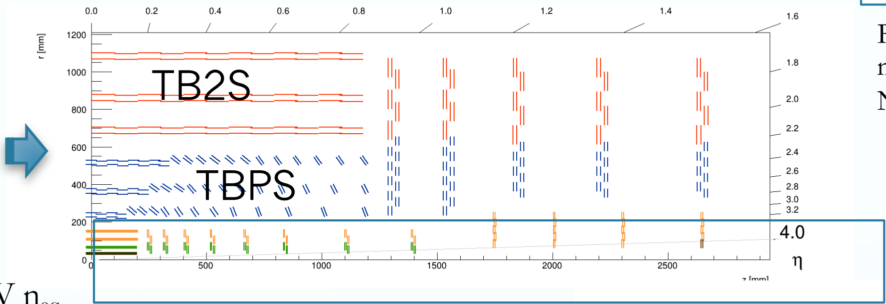
INNER TRACKER
5 m² – 2G channels
TBPX (Tracker Barrel PiXel): 4 layers
TFPX (Tracker Forward PiXel): 8 small disks
TEPX (Tracker Endcap PiXel): 4 large disks

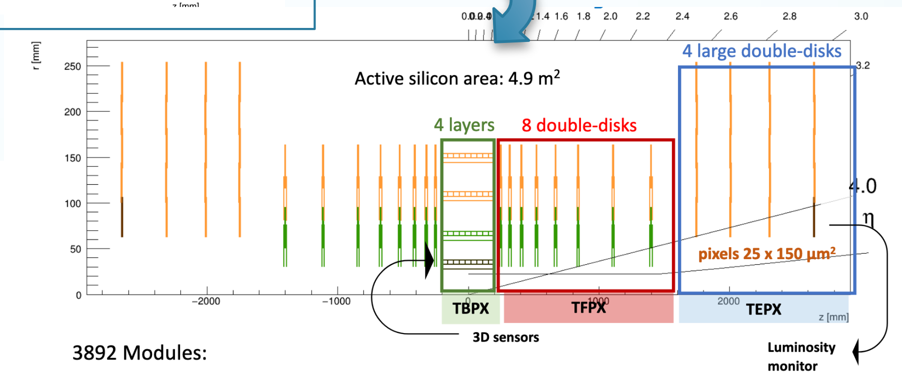
Read Out Chip (ROC) only active element on the module
New technology 65 nm TSMC ASIC

Phase 1

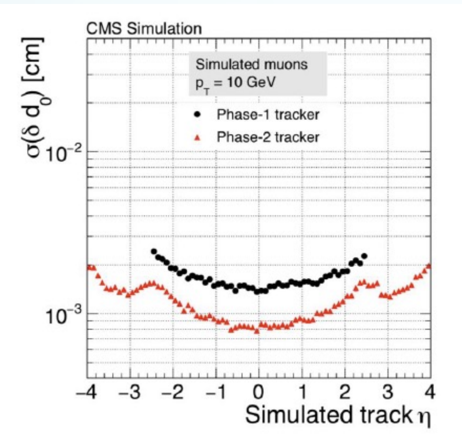


Phase 2

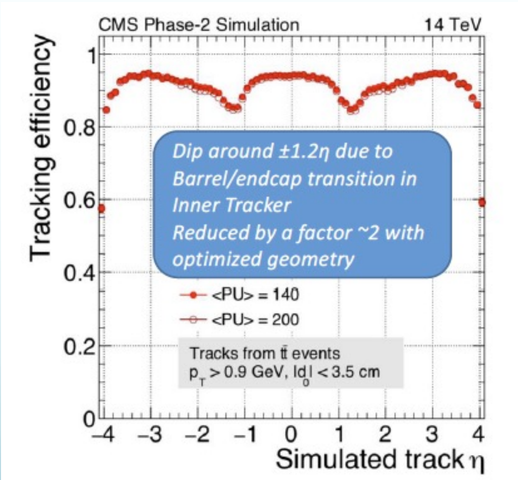




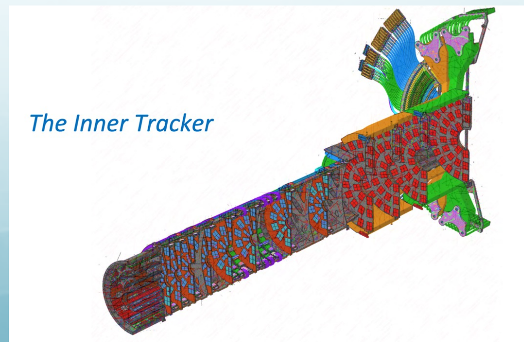
- Radiation tolerance up to 10^{16} 1 MeV n_{eq}
- Expected rate 3 GHz/cm² innermost pixel layer
- Material budget reduced by a factor of 2
- **Improved performance:**



Transvers momentum resolution improved (and extended) wrt. Phase 1



Good **tracking efficiency** (90%) even at PU 200



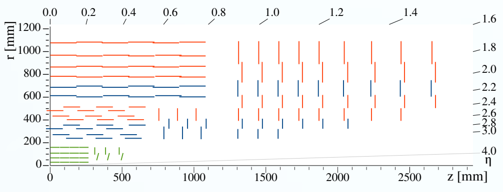
G. Pugliese

Tracker Upgrade

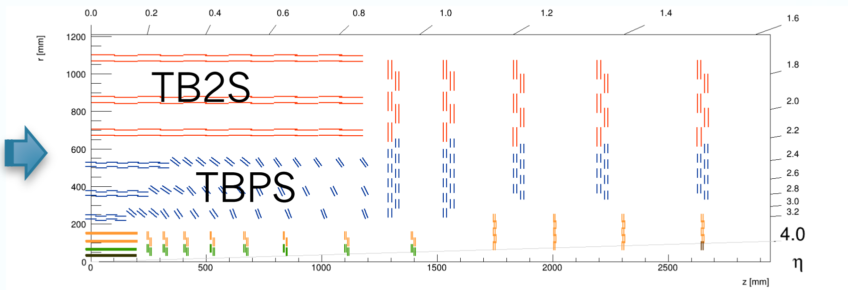
Key features of the new Phase 2 Tracker:

- **Extended tracking** acceptance up to $|\eta| = 4$
- **Increased granularity**

Phase 1



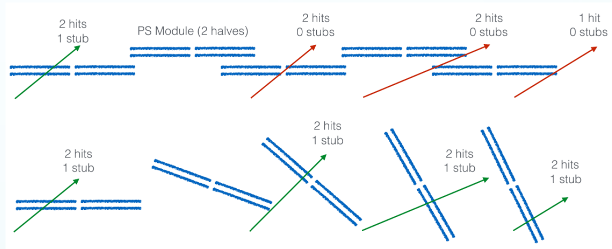
Phase 2



OUTER TRACKER
190 m² – 213M channels
TBPS (Tracker Barrel with PS modules)
TB2S (Tracker Barrel with 2S modules)
TEDD (Tracker Endcap Double Disks)

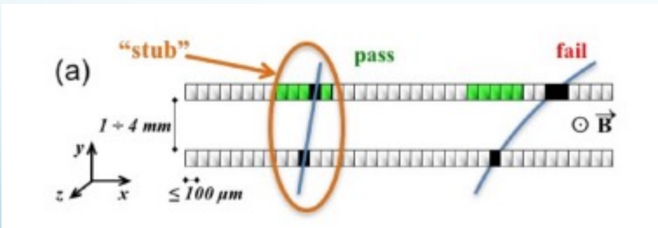
→ Two type of technologies: **micro-strips** and **macro-pixel**

→ **Tilted barrel geometry for** better trigger performance and reduction on number of modules



- New functionally: inclusion of the Outer Tracker data in the Level 1 Trigger

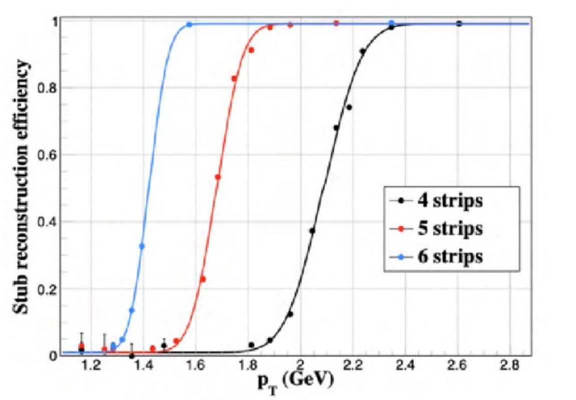
Local transverse momentum (p_T) measurements done using the pair layers on each module (local track-stub finding)



The reconstruction mechanism was verified in test beam campaigns

I. Zoi, https://doi.org/10.22323/1.448.0021

Stub efficiency for 2S prototypes



- The module design is the final
- Almost all components are in pre-production or production
- Good noise performance was found with pre-series PS and 2S modules

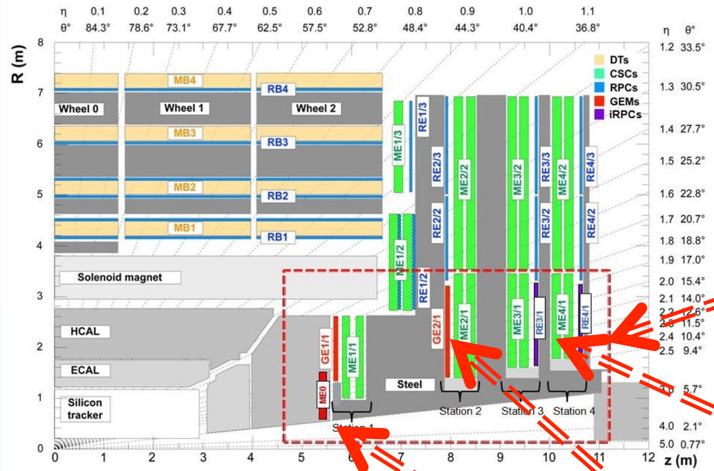
Muon Upgrade Project

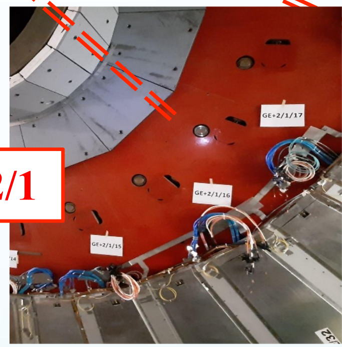
G. Pugliese

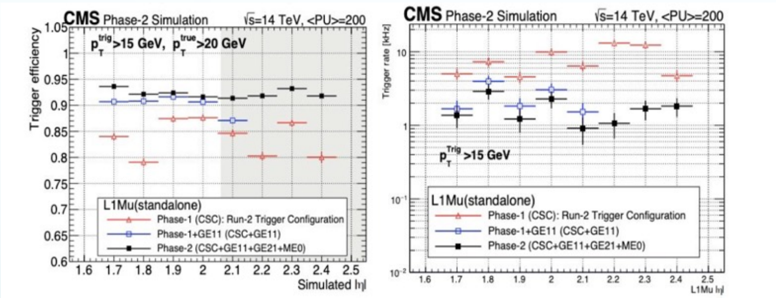
2024 LHC Days

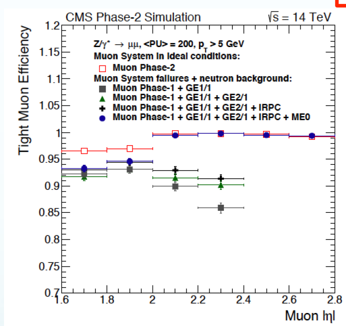
1. **New detectors will be installed in the high-eta region to:**

- Restore redundancy
- Extend the muon coverage up η = 2.8
- Improve Trigger efficiency without increasing the trigger rate
- Improve Muon reconstruction









2. **New electronics for the legacy detectors:**

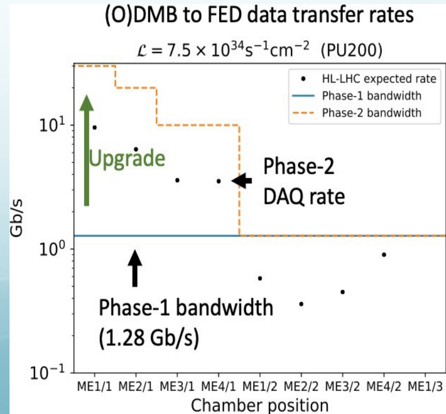
DT: replace all on-board electronics (OBDT), BE

RPC: replace all off-chamber electronics, BE

CSC: replace selected FE boards, replace all BE

3. **Longevity Studies** (including the use of ecological gas mixtures)

Few results in back-up

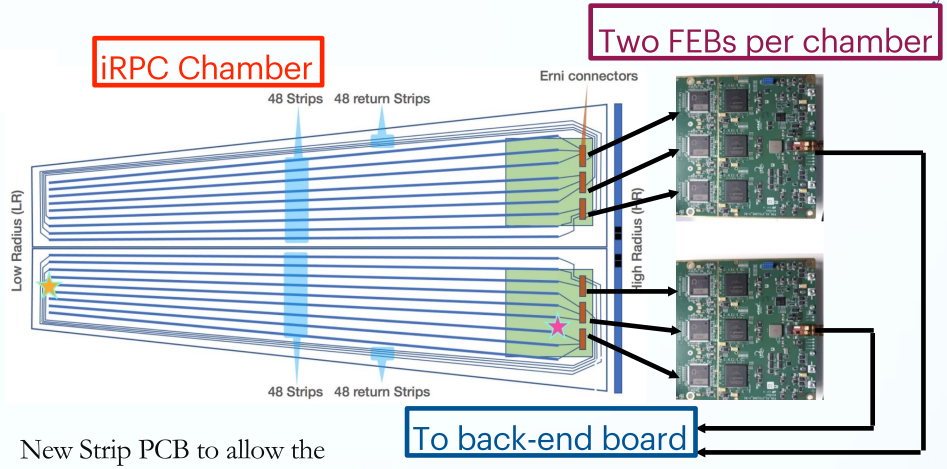


iRPC Design & Performance

G. Pugliese

- New detector geometry, strip layout and Font-End Board electronics (2D readout)

	iRPC	RPC
High Pressure Laminate thickness	1.4 mm	2 mm
Num. of Gas Gap	2	2
Gas Gap width	1.4 mm	2 mm
Resistivity (Ωcm)	0.9 - 3 x 10^{10}	1 - 6 x 10^{10}
Charge threshold	50 fC	150 fC
η segmentation	2D readout	3 η partitions

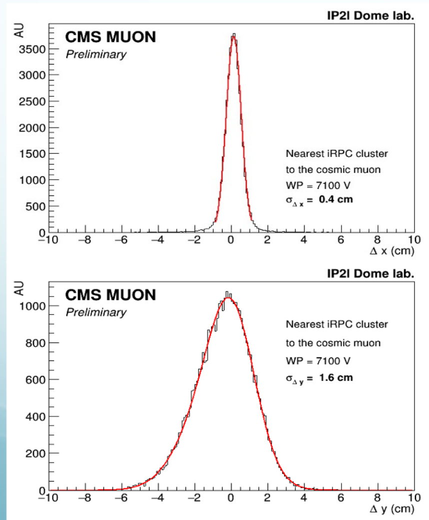


New Strip PCB to allow the return line concept

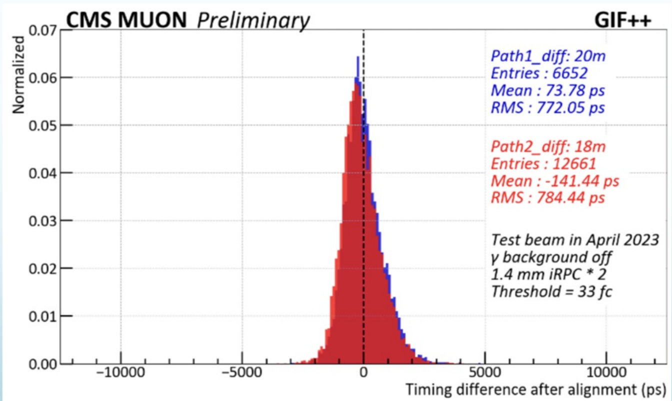
FEB positioned external and @ lowest dose region

- **Requirements:**
  - Space resolution (cm): 1.5 in η and 0.3-0.6 in φ
  - Time resolution (ns): 0.5 ns
  - Rate capability: 2 kHz/cm^2

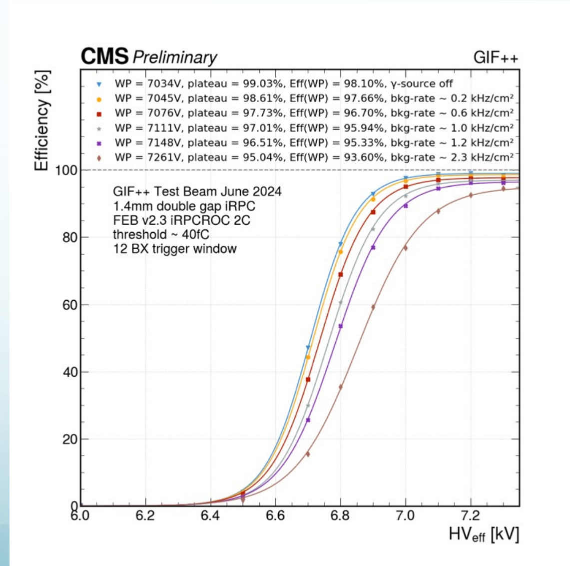
✓ Prototype performance satisfies all requirements



Space resolution: 0.4 cm in φ and 1.6 cm in η



Timing resolution: 780ps/√2= 550 ps

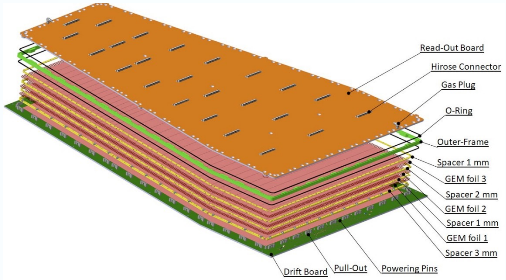


Efficiency @ 2.3 kHz/cm^2 : 95 %
Working Point = 7.2 kV

ME0 design & performance

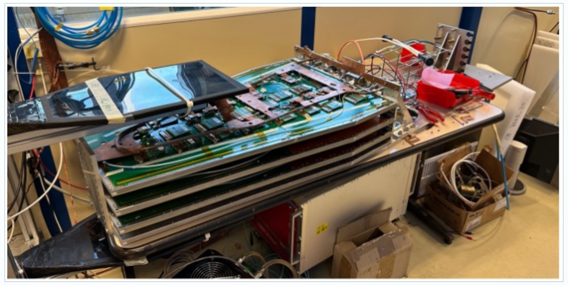
G. Pugliese

2024 LHC Days



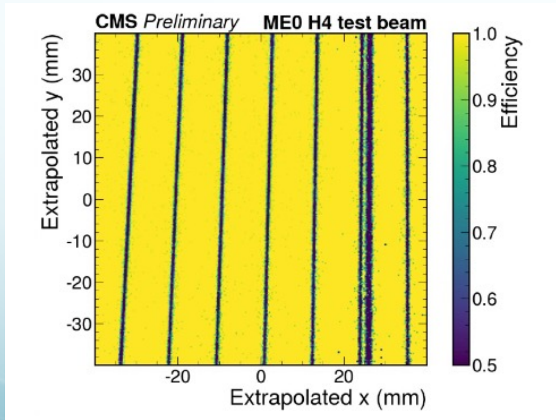
Requirements :

- 97% module efficiency
- < 500 μrad resolution
- 8-10 ns time resolution
- ≤ 15% gain uniformity
- Rate capability: 150 kHz/cm^2
- Radiation hardness: 7.9 C/cm^2

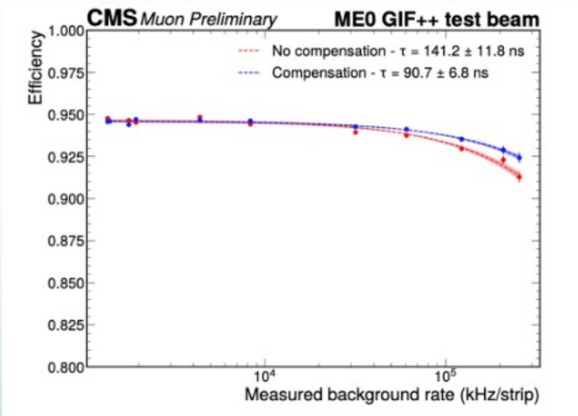


✓ Detector prototype performance satisfies all requirements:

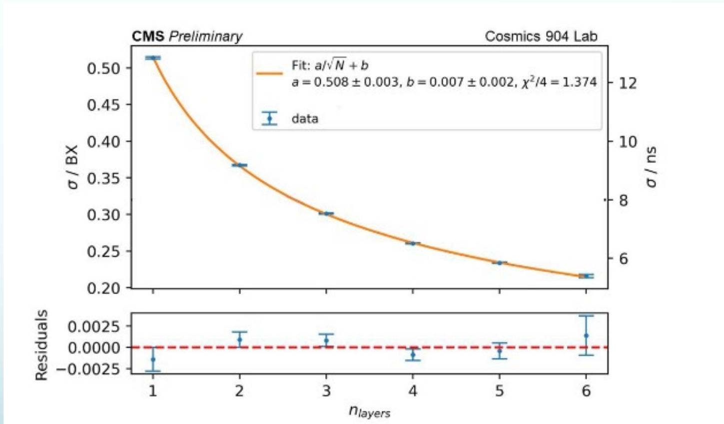
The First ME0 stack prototype was assembled and tested at CERN 904 laboratory and in several test beams



Spatial Resolution: 240 µrad
Efficiency locally > 99%

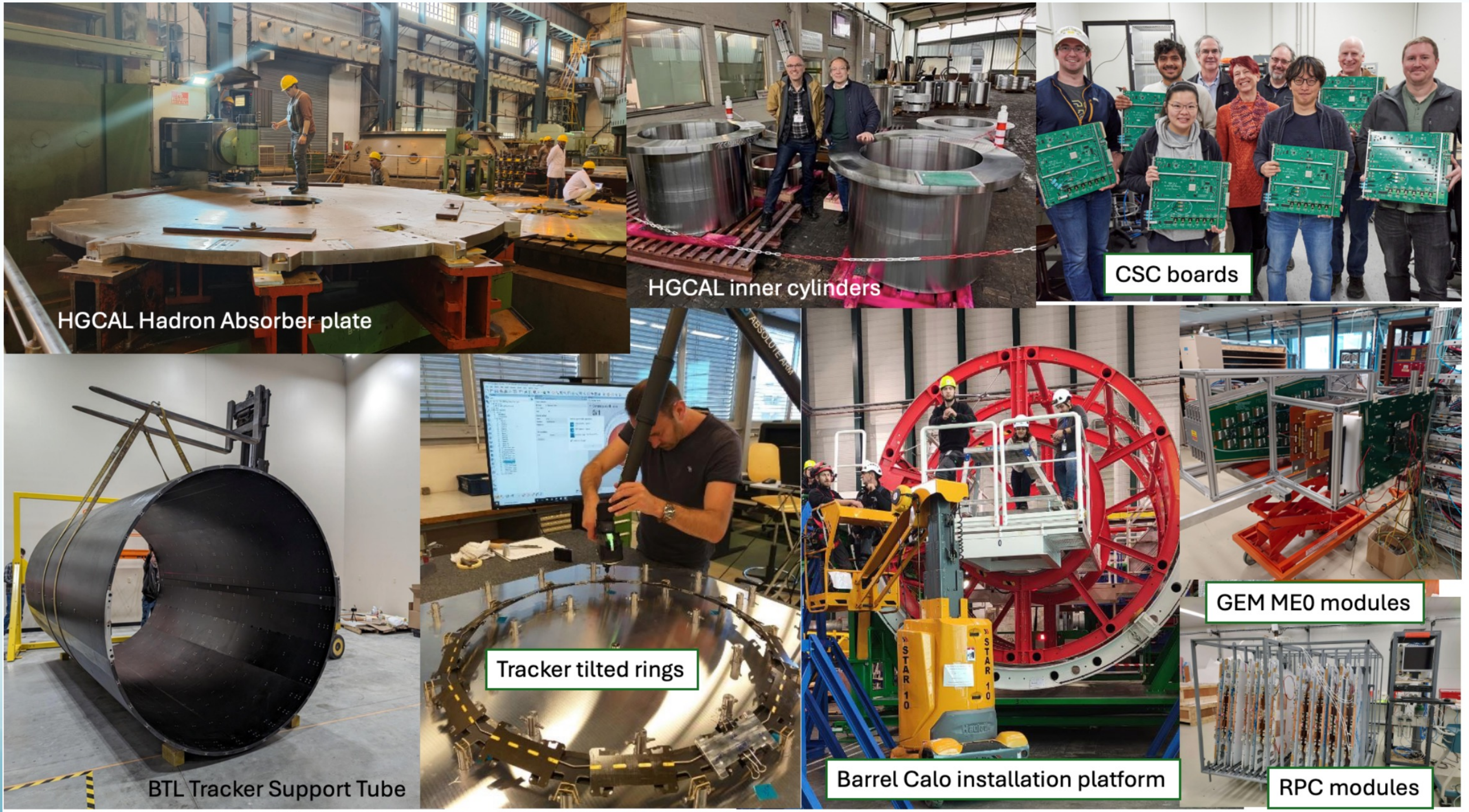


Rate capability: 2.5% efficiency loss with the highest background (loss in highest eta region) mitigated (1%) by the redundancy



Average time resolution of track segments as a function of the number of ME0 chambers (layers) used to reconstruct the segment.
The time resolution 5.4 ns for 6-layer segments

CMS Upgrade in production..



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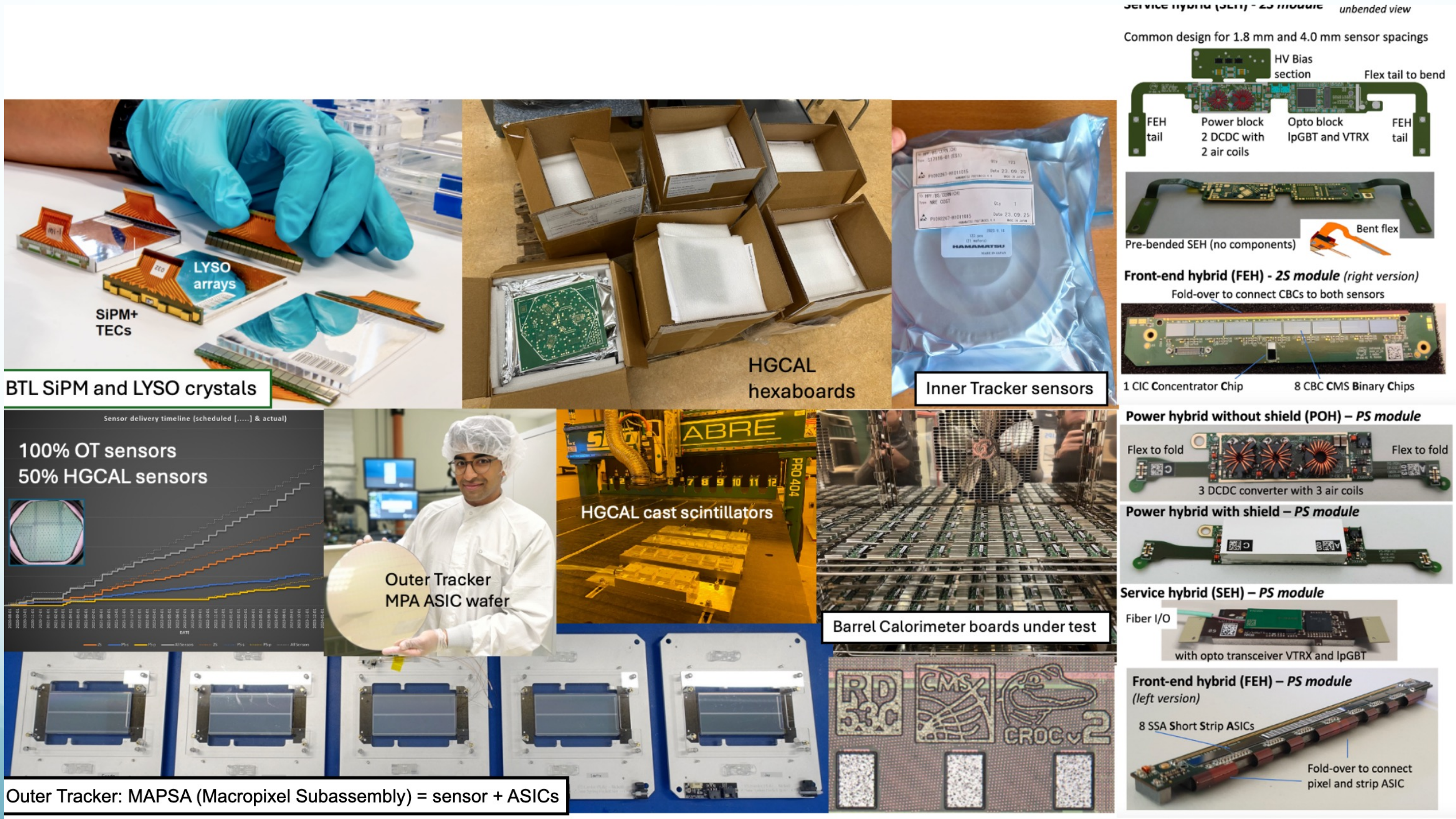
CMS Upgrade in production..



Conclusion

- Smooth RUN3 data-taking and excellent performance of the CMS detector
- We are pushing the detector performance beyond design limits!

- The challenging CMS Phase 2 upgrade project defined to exploit the full potential of the HL-LHC luminosity is progressing well
- Most upgrade projects moved into mass production; a few are finalizing the pre-production validation; GE1/1 chambers have already been installed and integrated into CMS

Thanks!

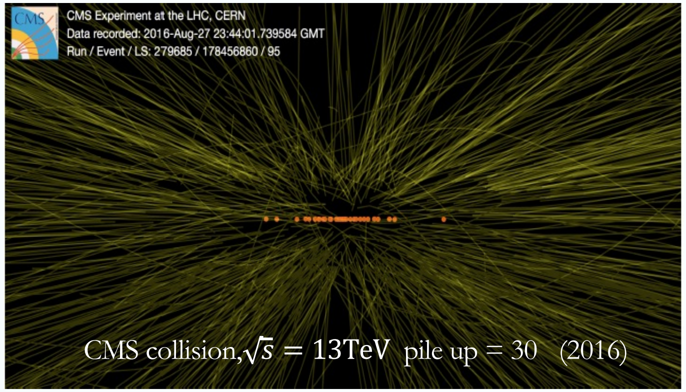
Credits
to the CMS People

Backup slides

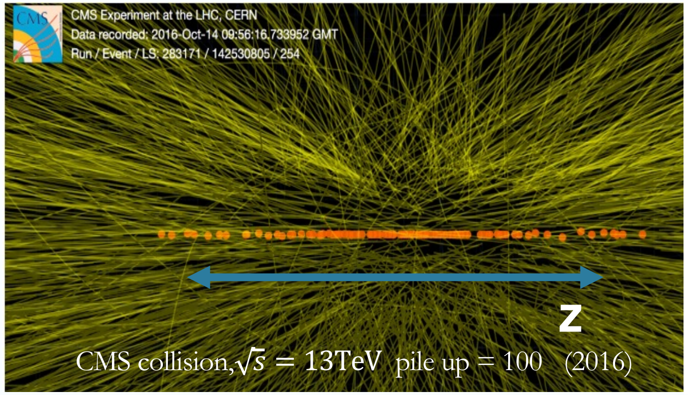
HL-LHC: beyond present detector ability

G. Pugliese

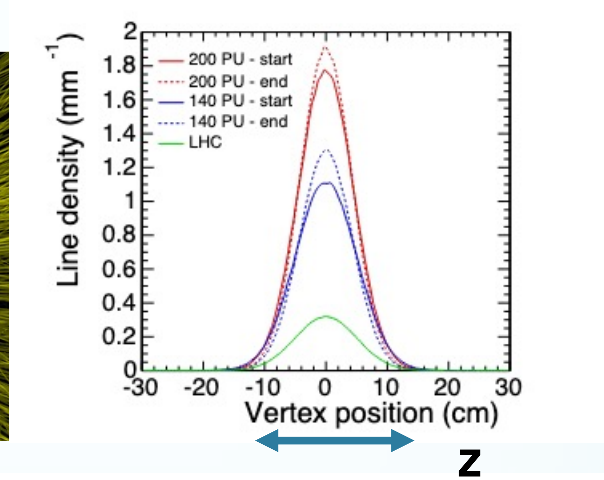
At higher pileup (140-200PU), due to growing spatial overlap of tracks and energy deposits, degradation in resolutions, efficiencies reconstruction, and misidentification rates are expected



CMS collision, $\sqrt{s}$ = 13TeV pile up = 30 (2016)

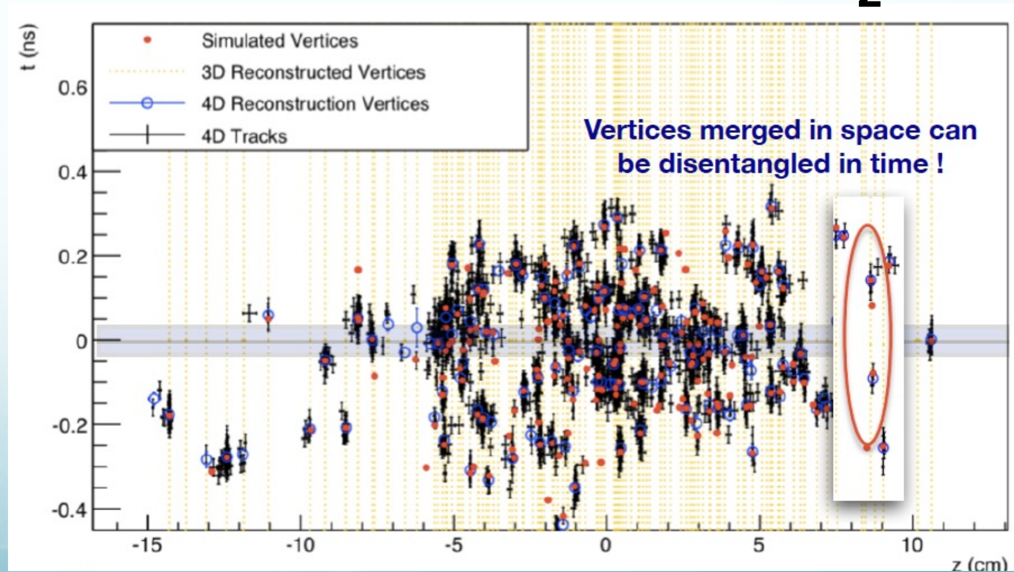


CMS collision, $\sqrt{s}$ = 13TeV pile up = 100 (2016)



In CMS, PU mitigation strategy relies on:

- **4Dimensional** (space and time) vertex reconstruction with unprecedented track-timing precision (~30 ps)
- **Higher detector granularity** to keep almost the same occupancy



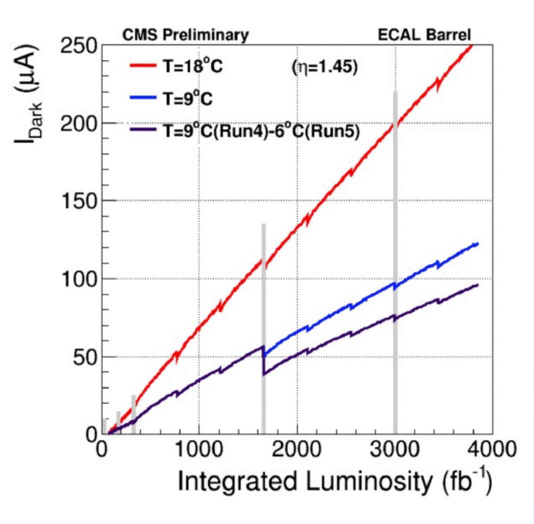
Time and z position of all vertex @ PU = 120

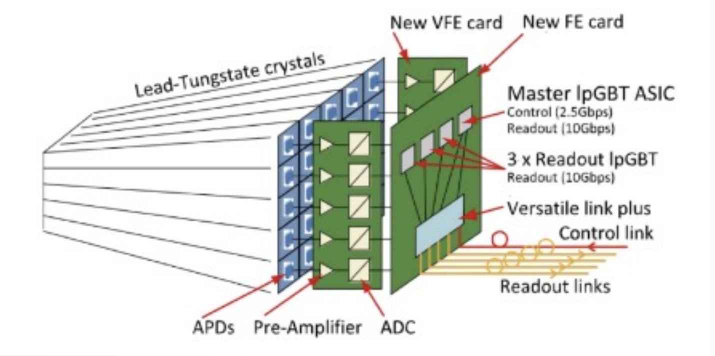
ECAL Barrel Calorimeter Upgrade

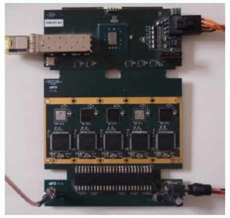
G. Pugliese

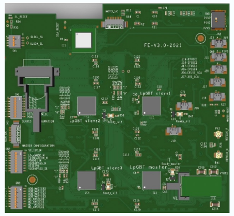
Key features for the Barrel Calorimeter:

- Keep the lead tungstate crystals and APDs
- Decrease operation temperature from 18 to 9°C to mitigate the increase in the APD leakage current
- Replace the on- and off-detector electronics. New front-end boards will allow the exploitation of the information from single crystals in the LV1 trigger

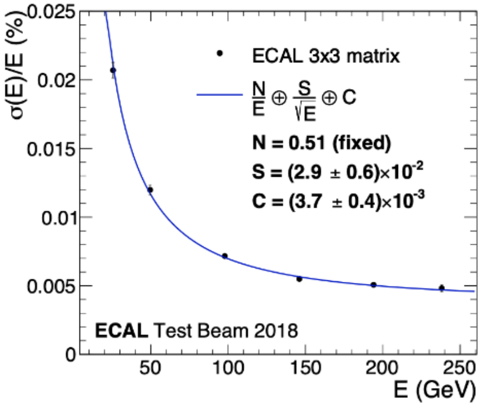


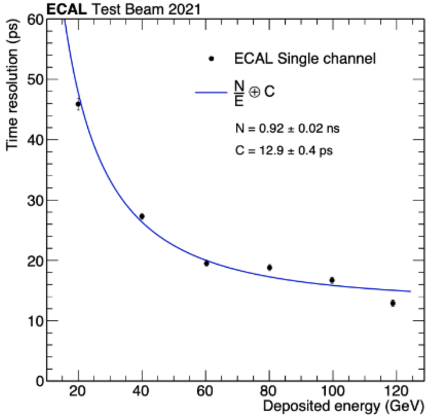






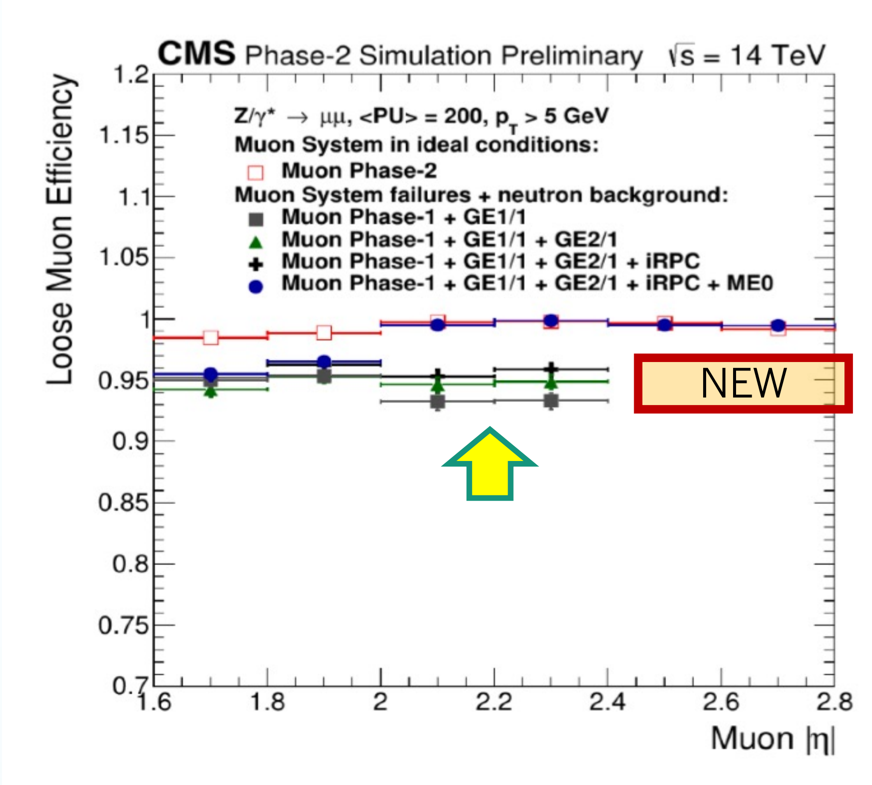
- Test beam campaigns in 2018 and 2021 proved that the new electronics met the requirements for HL-LHC:
  - ✓ Energy resolution in agreement with Phase 1 performance
  - ✓ Time resolution <30 ps with electron energy beam >50 GeV
- Integration test of all electronics chain (VFE-FE card-off detector) expected for fall 2022



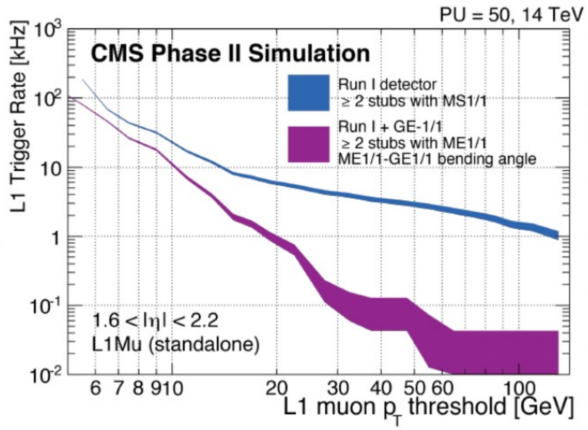


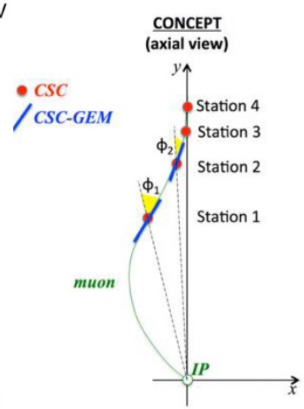
Muon Upgrade

New GEM and RPC detectors needed to improve efficiency reconstruction and trigger performance at HL_LHC



- To maintain the high level performance in HL-LHC environment, the CMS muon system is being upgraded
  - to increase the muon spectrometer redundancy, to sustain the high radiation in the endcap region
  - GEM+CSC allow for muon momentum measurement in a single station, which helps reduce considerably L1 trigger rate



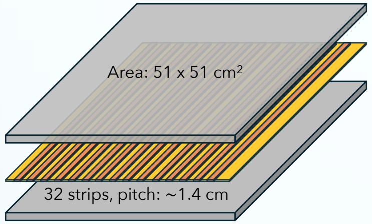


G. Pugliese

R&D on new RPC gas mixtures

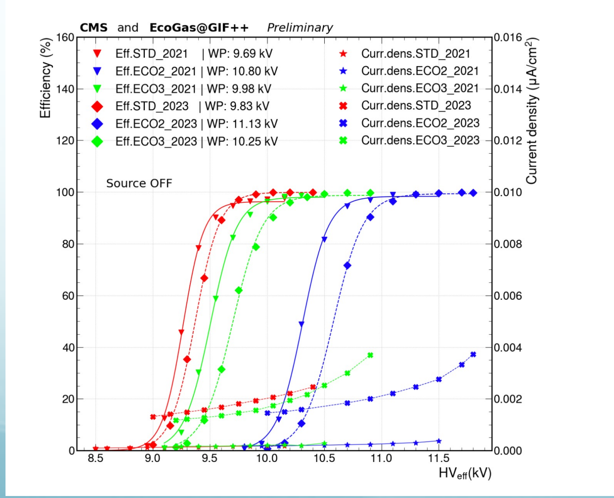
	R134a (%)	HFO-1234ze (%)	CO_2 (%)	i-C_4H_{10} (%)	SF_6 (%)	GWP
STD	95.2			4.5	0.3	1485
ECO2		35	60	4	1	476
ECO3		25	69	5	1	527
Density (g/l)	4.68	5.26	1.98	2.69	6.61	
GWP	1430	7	1	3	22800	

1. Double gap layout of iRPC prototype

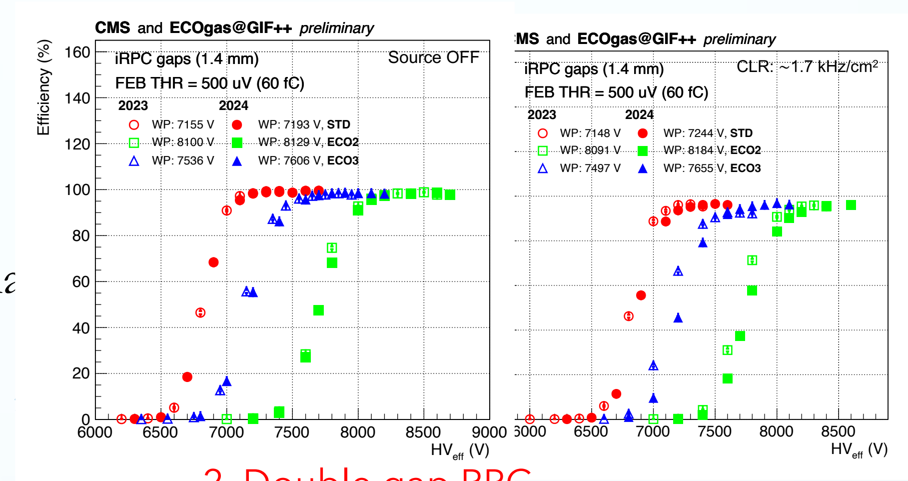


→ ~ 45 mC/cm² of cha
integrated, so far

→ Stable performance with
without gamma background



Aging test with Gas mixture: ECO2 mixture



2. Double gap RPC

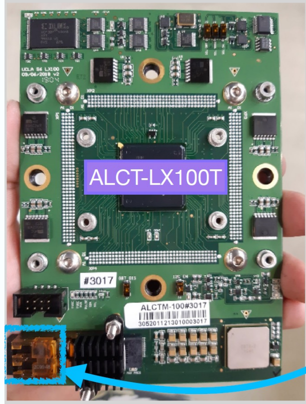
→ ~200 mC/cm² of charge integrated, so far

→ a slight shift of the efficiency curves toward higher voltages in 2023, and an increase in the current density observed

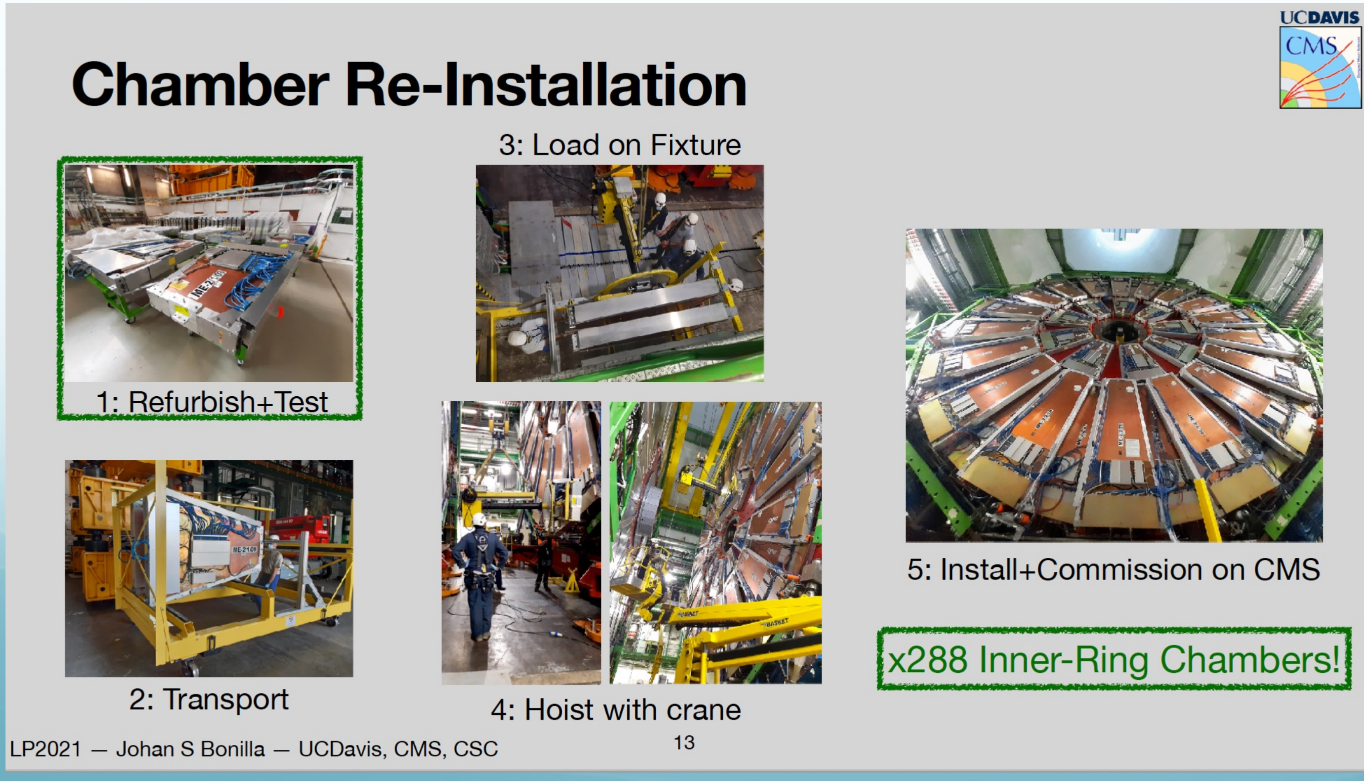
G. Pugliese

LS2 CSC Upgrade activity

The on-detector Refurbishment of Electronics in LS2

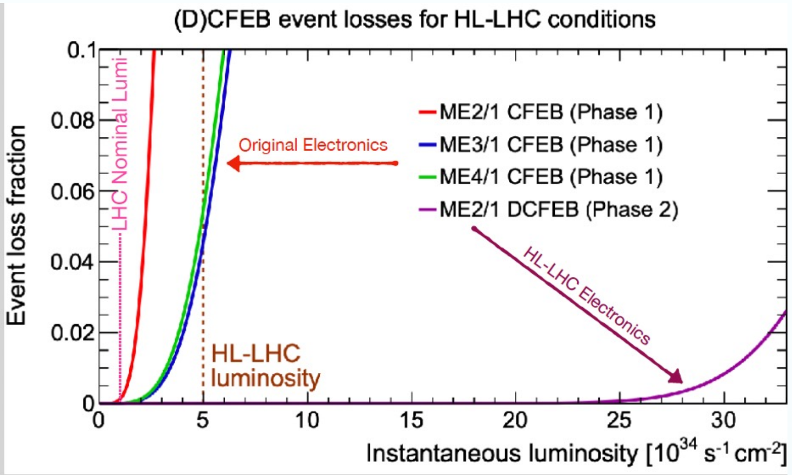


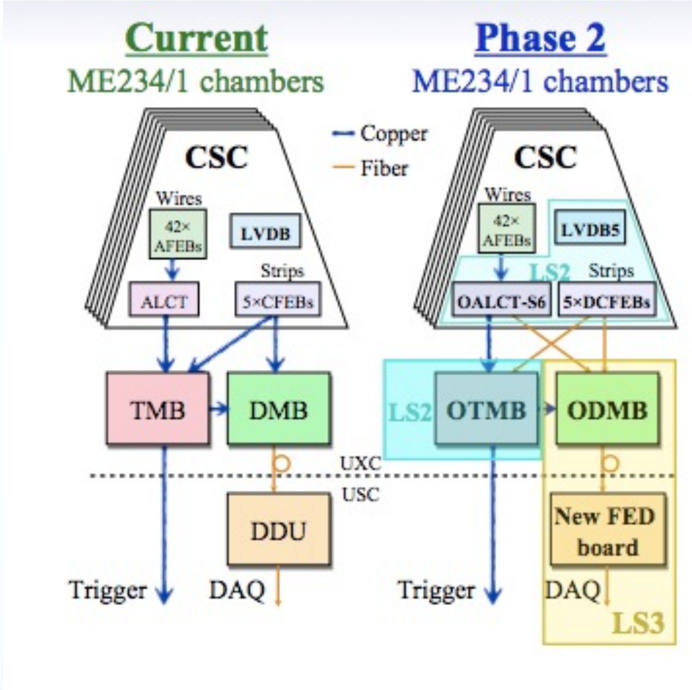
- 108 ALCT-LX150T Mezzanine boards installed in all ME234/1
- 288 ALCT-LX100T Mezzanine boards installed in ME1/1,123/2
- 504 DCFEBv2 installed in ME1/1 and 45 in ME+2/1, older DCFEB from ME1/1 → ME234/1
- New boards capable of optical readout



CSC Electronics Upgrade motivation

On-chamber and off-chamber electronics to be replaced in order to handle the CMS trigger requirements at HL-HC





Board	Num.	Where	Main reasons for upgrade
DCFEB	540	ME12/1	Latency and rate, rad-hardness
ALCT	396	ME1234/12	Latency and rate, rad-hardness
LVDB5	108	ME234/1	Power levels of DCFEBv2s
OTMB	108	ME234/1	Receive optical link from DCFEBv2s
ODMB	180	ME1234/1	Increased DAQ output bandwidth
HV	40/12	ME1234/1	Increased current due to higher occupancy
FED	14	USC	Increased data volume, number of links

LS2

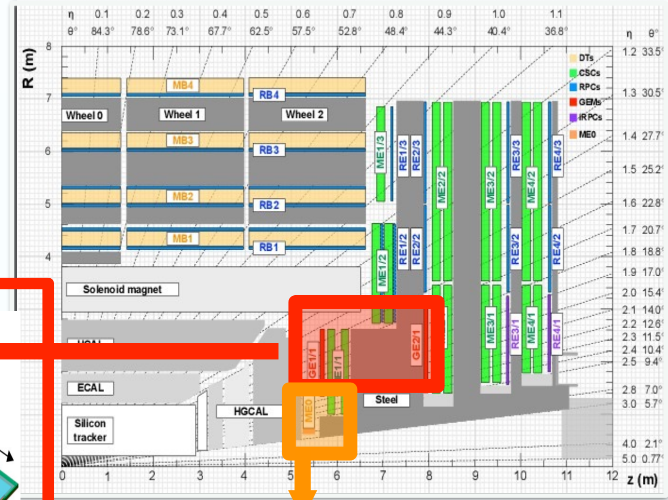
LS3

G. Pugliese

GEM Overview Project

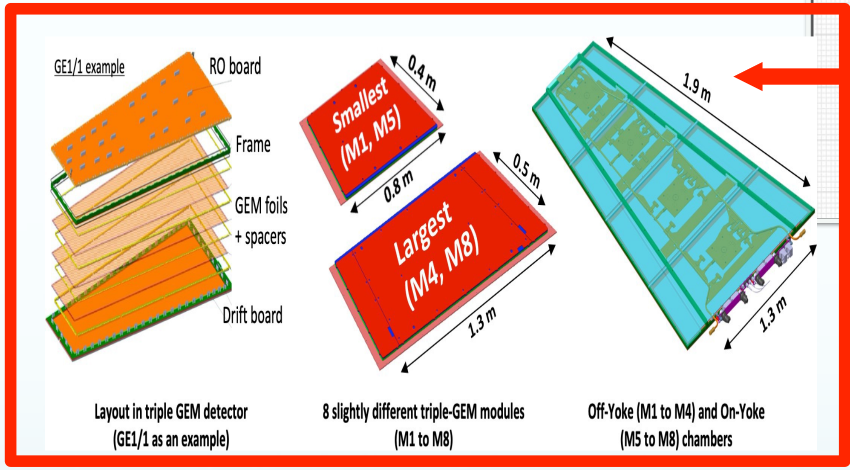
2024 LHC Days

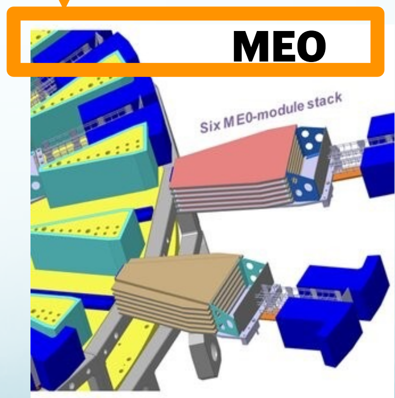
- 3 stations will be equipped with detectors based on **Gas Electron Multiplier (GEM) Technology**
  - **GE1/1, GE2/1 :** complementing CSC in forward region (Station 1 & 2 for Ring 1)



GE1/1 & GE2/1

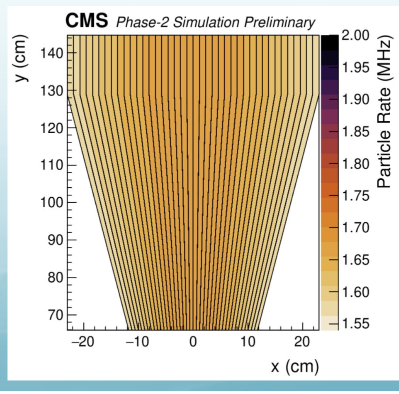
- Both GE1/1 & GE2/1 are based on the same mechanical design principle: 2 triple GEM detectors per Super-Chamber (SC)
- **GE1/1 :** 72 SC (36 per endcap) 10° in φ from 1.6< $|\eta|$ <2.1
- **GE2/1 :** 36 SC (18 per endcap) 20° in φ from 1.6< $|\eta|$ <2.4





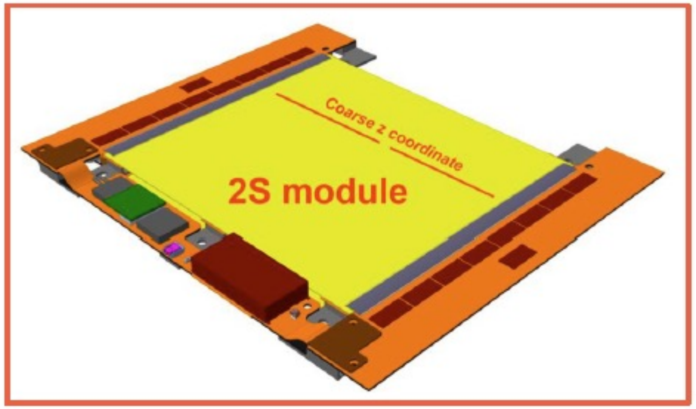
- **ME0:** Extending muon system acceptance in the very forward region up to $|\eta|$ < 2.8

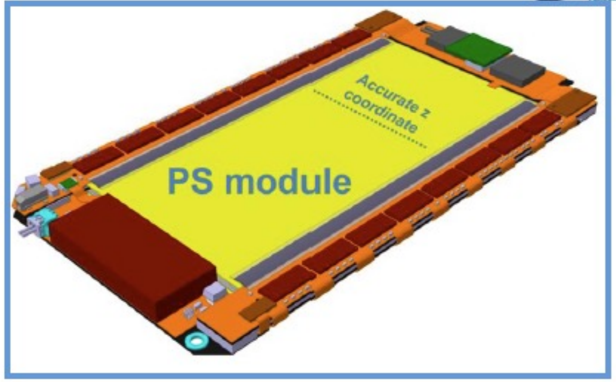
- 18 ME0 stack per endcap, each made of six layers of triple-GEM detector for efficient tagging of muon tracks
- New Radial GEM foil segmentation w.r. to beamline to equalize the background rate (changed wrt original horizontal design)



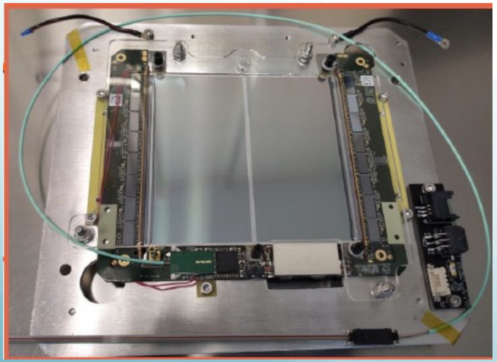
G. Pugliese

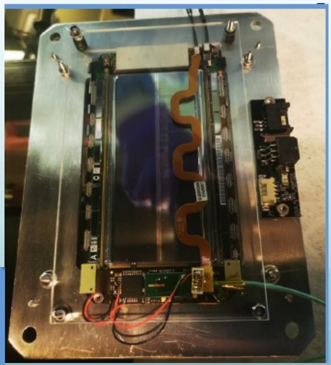
Phase 2 OUTER Tracker modules





- Two type of modules:
  - 2S Modules
    - 2 different spacing : 1.8mm & 4mm
    - 2 micro strip sensors with 5cm x 90µm strips
    - Sensor dimension are 10cm x 10cm
      - two column of 1016 strips
  - PS Modules
    - 3 different spacing : 1.6mm & 2.6mm & 4mm
    - One strip sensor: 2.5cm x 100µm strips
    - One macro Pixel sensor : 1.5mm x 100µm pixels
    - Sensor dimension 5cm x 10 cm
      - two column of 960 strips
      - 32x960 pixels



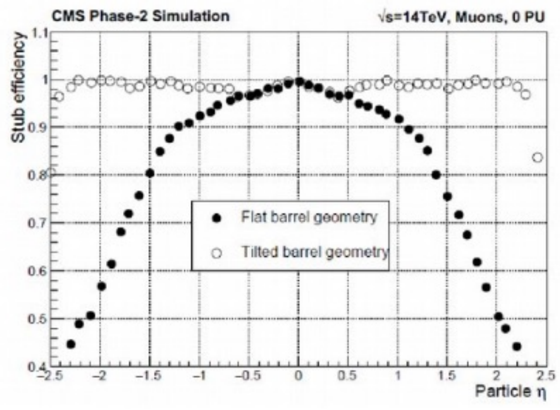


First prototypes (with almost final chips and hybrids) assembled this year → now it's time to test and test and test...

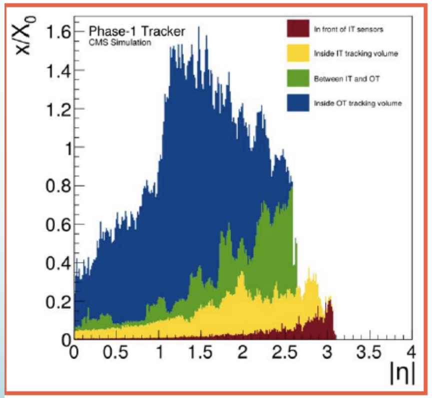
Phase 2 Tracker Upgrade

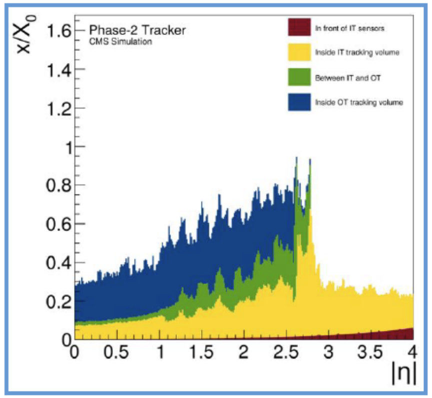
Tilted Barrel Geometry

- Track stubs that cross different modules in lower and upper sensor are lost
- With tilted geometry ineffiencies are recovered

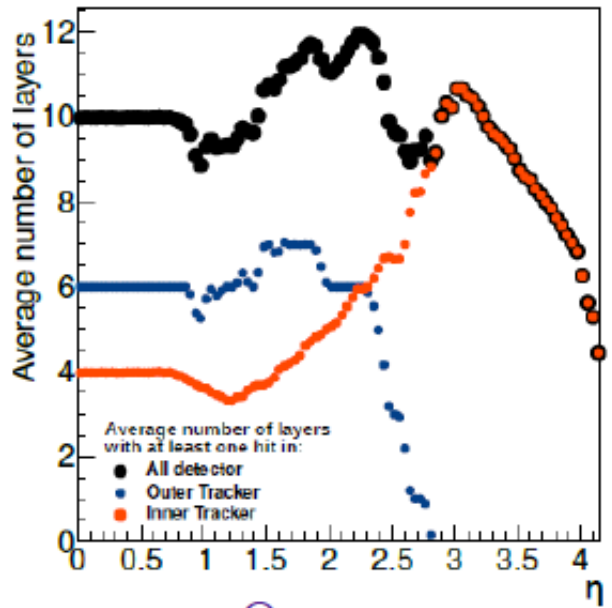


Material Budget





- Material budget much reduced wrt Phase0/1 detector despite an increase in the number of channels
  - *DCDC converters*
  - *Fewer layers*
  - *Lighter materials*
  - *Optimized service routing*
  - *CO2 cooling*
  - *Inclined geometry*



Occupancy no larger than 3%

G. Pugliese

MTD: barrel timing layer Sensors

2024 LHC Days

BTL sensors: LYSO:Ce crystals & SiPMs

LYSO:Ce crystals

- Well established technology (PET)
- Fast scintillation kinetics:
  - rise time ~100 ps
  - decay time ~ 40 ns

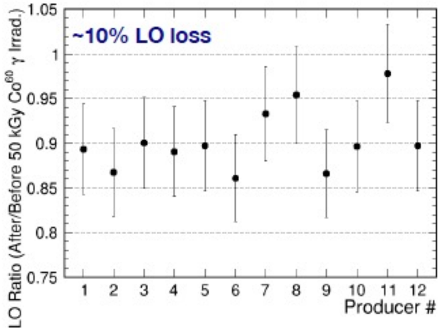
- Radiation hard proven up to:
  - 50kGy with γ from ^{60}Co source
  - 3 x 10^{14} 1MeV neq/cm^2
- High Light Yield: 40000 γ/ MeV

Comprehensive study of LYSO:Ce crystals from 12 producers performed to identify potential BTL suppliers and set the QA/QC requirements for the production stage.

Parameter of the crystal array	Specification before irradiation (mean value)	Specification after irradiation to 50 kGy (mean value)	RMS for crystals within one array
Light output (LO) / end	> 4000 photons/MeV		< 5%
LO (30ns) / LO (450ns)	> 26%		< 3%
Decay time (τ)	< 45 ns		< 3%
(LY/τ @−30°C) / (LY/τ @20°C)	> 1		
Loss of light output after irradiation		< 18%	< 5%
Optical cross talk	< 15% and	< 15%	< 5%

Table 2: Crystal performance within a given crystal array.

https://arxiv.org/abs/2205.14890

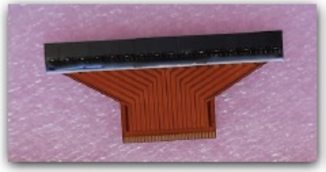


TENDER SUBMISSION BY THE END OF THE YEAR

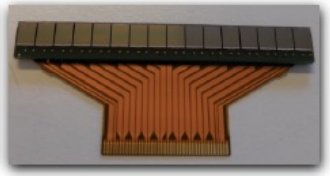
SiPMs

- Well established technology
- Compact and robust
- Insensitive to magnetic fields
- Fast recovery time <10 ns
- High dynamic range (10^5)
- PDE@Lyso emission peak 20-40%
- Radiation hard proven up to:
  - to 2 x 10^{14} 1MeV neq/cm^2

FBK, 20 µm thin glass enc



HPK, 300 µm silicon resin enc.



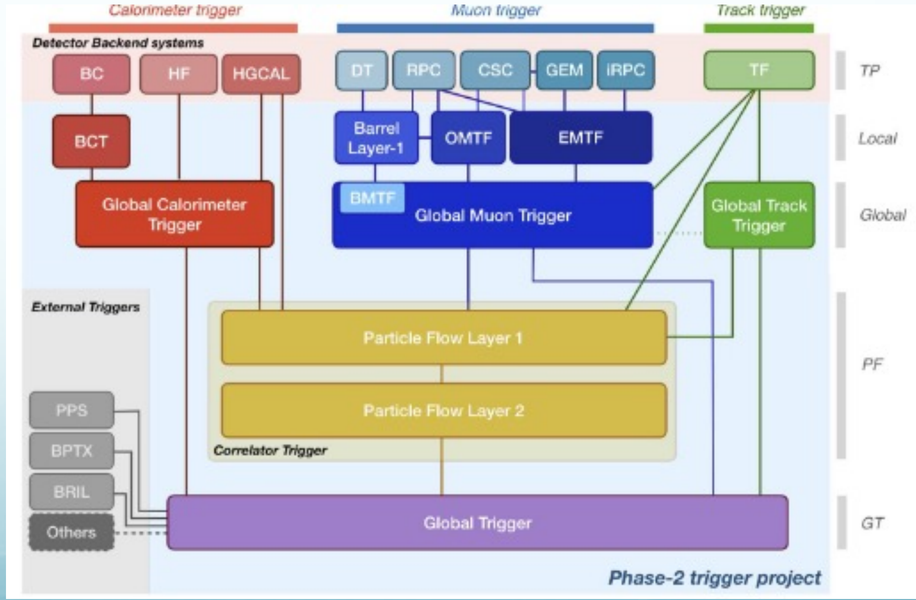
TENDER SUBMISSION: SPRING 2023

(optimized prototype testing on going)

DAQ and Trigger Upgrade

HL-LHC DAQ-HLT Parameters

CMS detector	LHC Phase-1	HL-LHC Phase-2	
Peak ⟨PU⟩	60	140	200
L1 accept rate (maximum)	100 kHz	500 kHz	750 kHz
Event Size at HLT input	2.0 MB [a]	6.1 MB	8.4 MB
Event Network throughput	1.6 Tb/s	24 Tb/s	51 Tb/s
Event Network buffer (60 s)	12 TB	182 TB	379 TB
HLT accept rate	1 kHz	5 kHz	7.5 kHz
HLT computing power [b]	0.7 MHS06	17 MHS06	37 MHS06
Event Size at HLT output [c]	1.4 MB	4.3 MB	5.9 MB
Storage throughput [d]	2 GB/s	24 GB/s	51 GB/s
Storage throughput (Heavy-Ion)	12 GB/s	51 GB/s	51 GB/s
Storage capacity needed (1 day [e])	0.2 PB	1.6 PB	3.3 PB

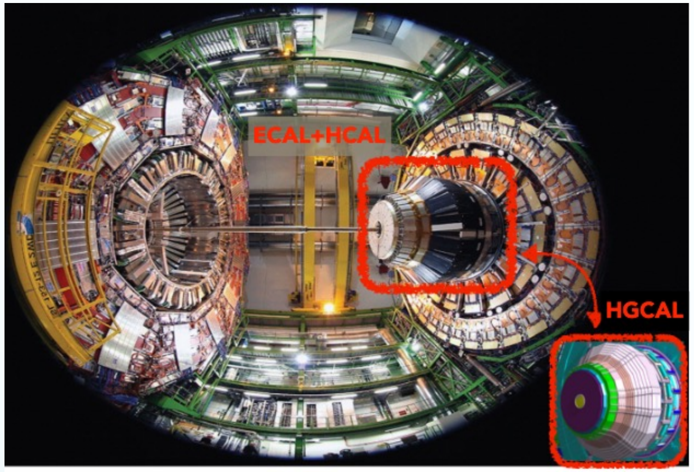


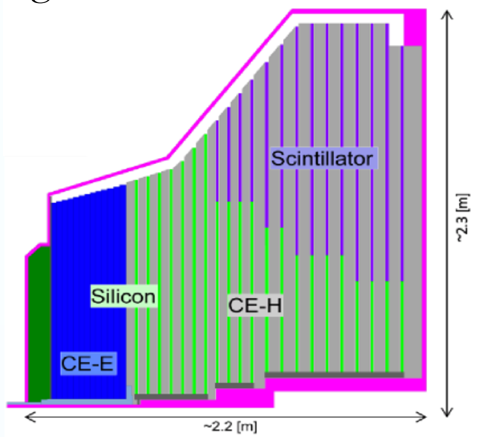
High Granularity Endcap Calorimeter

G. Pugliese

See dedicated talk by Jean-Baptiste Sauvan ((this session)

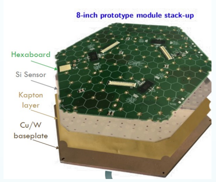
- Brand new calorimeter in the endcap region: the High Granularity Calorimeter (HGCal)
- High **granularity and timing performance** for the electromagnetic and hadronic sampling calorimeters
- Mixed technologies. Challenging integration in CMS

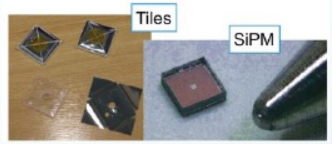




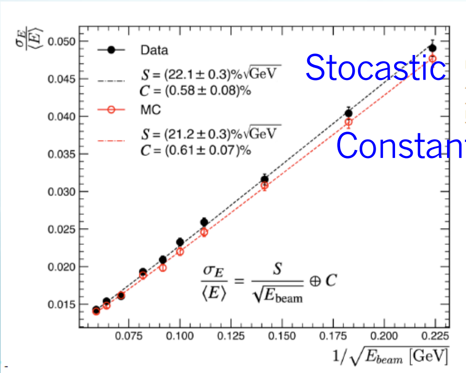
Coverage 1.5 < |<η |< 3
Operational temperature -35°C

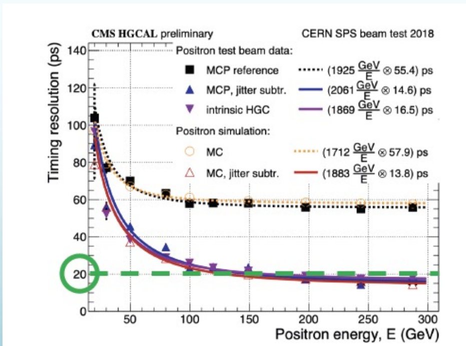
	Electromagnetic CE-E		Hadronic CE-H
Active	**Silicon Sensors** (Hexagonal shape)		**Plastic Scintillator tiles**
Area	620 m²		400 m²
N. of Modules/channels	30k/6M		4k/240k
Channel Size	0.5 -1 cm²		4 -30 cm²
N. of layers	28	22	
Depth	26 X_0/1.7 λ	9 λ	
Absorber	Lead	Stainless Steel	



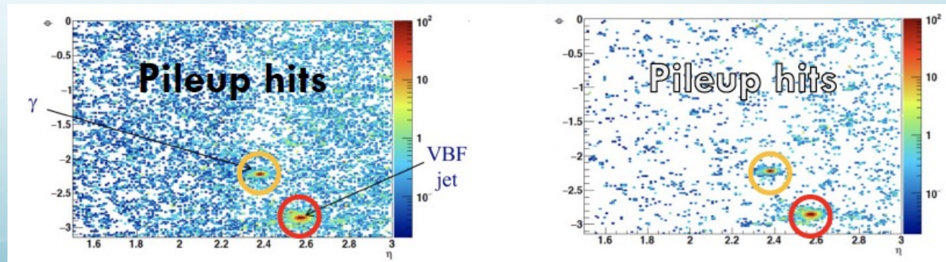


- Prototypes showed excellent results on test beams:





- Space-time precision needed to clearly separate objects and clean pileup hits



Energy rand time resolution (~20 ps for positron energy > 200 GeV)

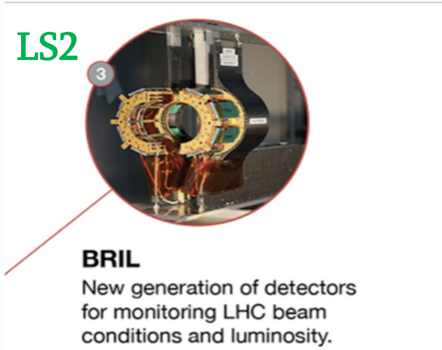
VBF H → γγ

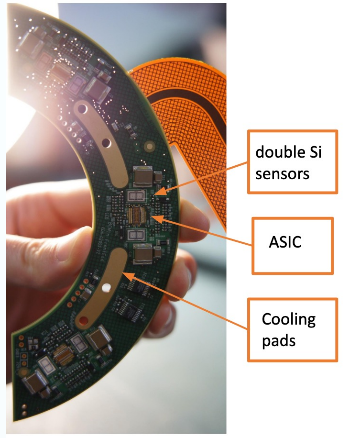
G. Pugliese

Beam Radiation Instrumentation and Luminosity (BRIL)

BRIL system: 14 technical detectors installed in CMS for luminosity measurement, beam induced background, beam loss (abort) and timing monitoring

- The Fast Beam Condition Monitor (BCM1F) and the Pixel Luminosity Telescope (PLT) were upgraded to achieve the required high luminosity precision during the Run 3 and were calibrated in emittance scans at early LHC collisions

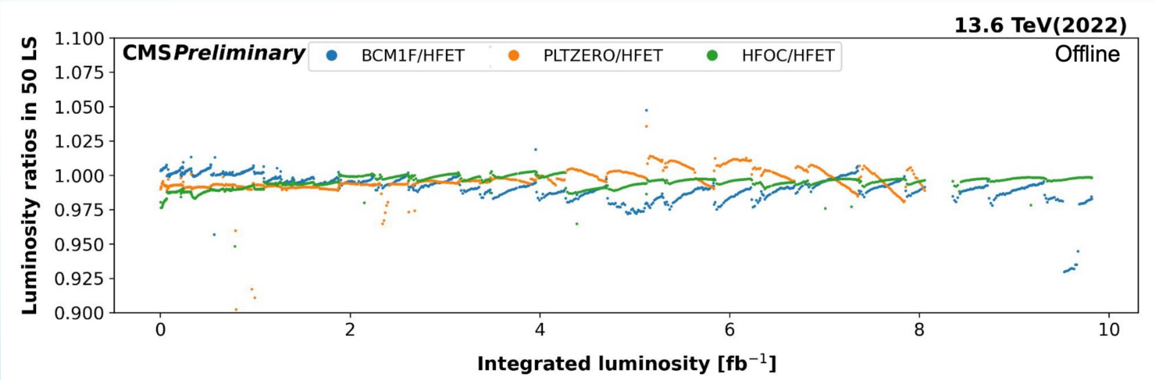




BCM1F C-shape

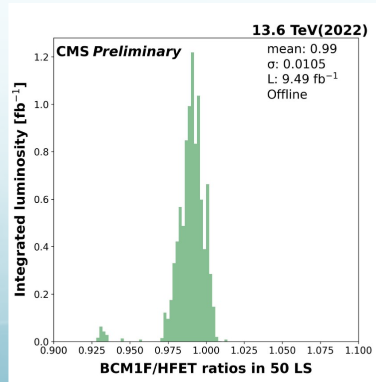
It is located behind the Tracker Pixel detector at
m from the Interaction Point (IP)

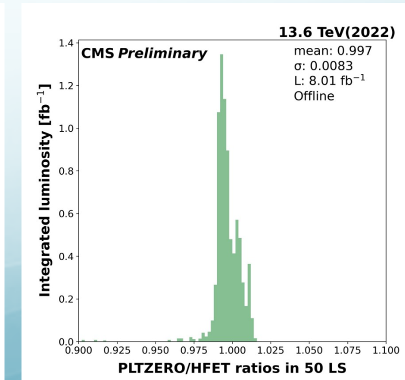
- Luminometers showing excellent performance



HFET/HFOC : Hadron Forward calorimeter with the transverse energy sum method and online occupancy method

- Over full running period all **luminometers within ± 1%**



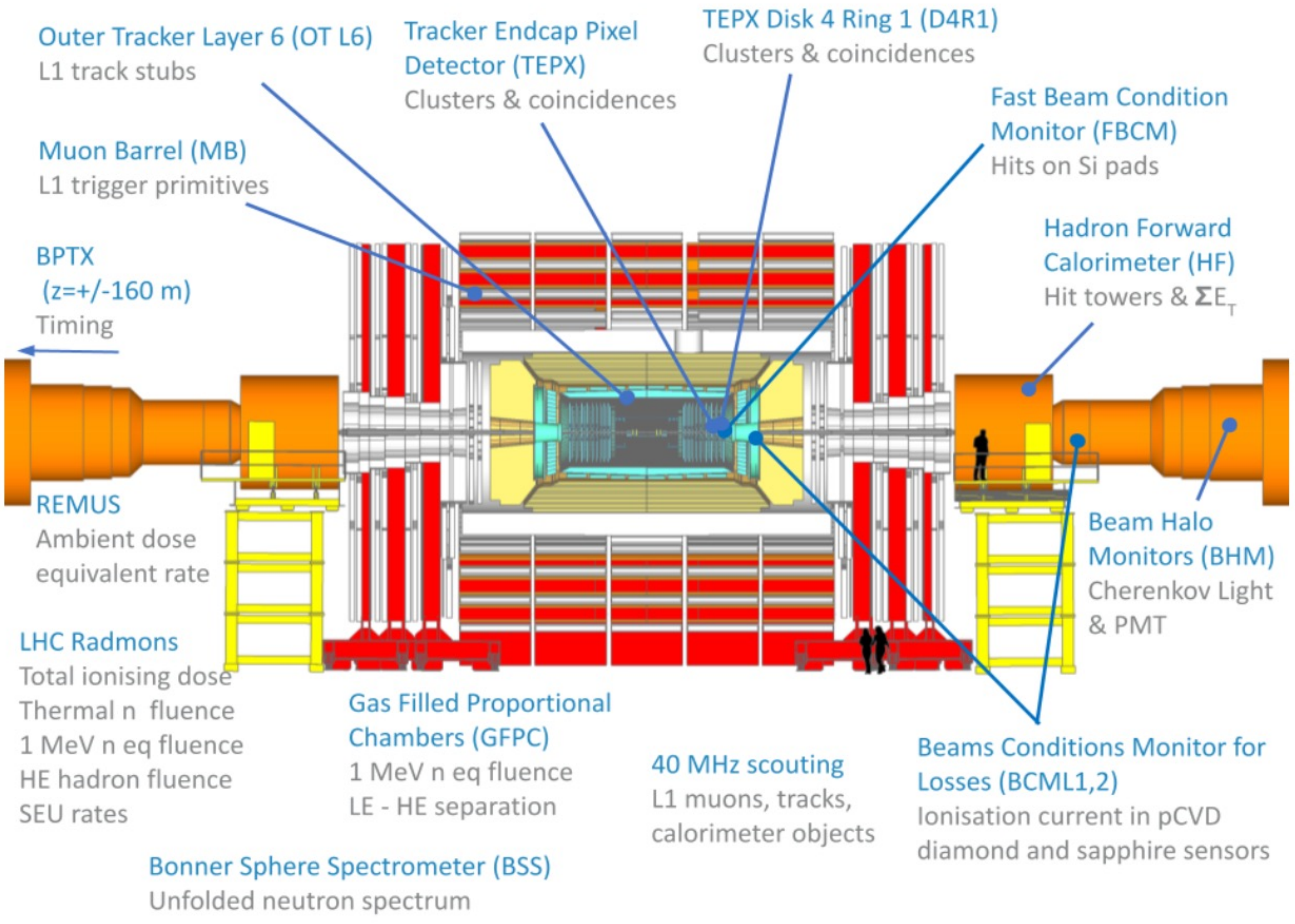


- Background and abort systems all operational
  - Good progress with Beam Halo Monitor

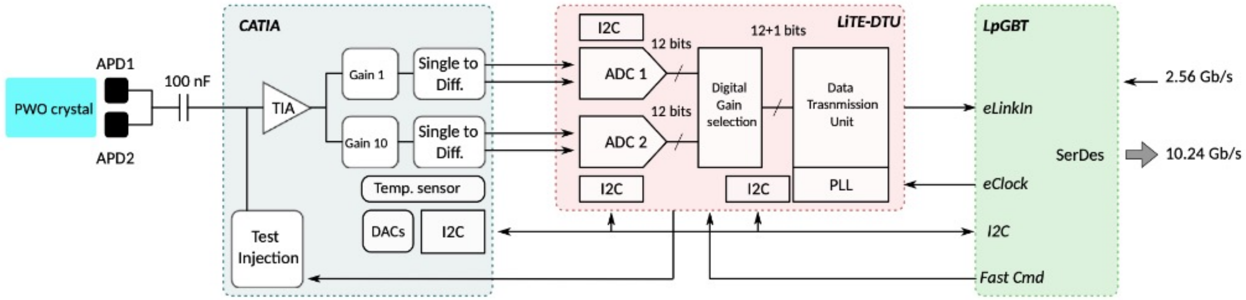
G. Pugliese

BRIL UPGRADE project

2024 LHC Days



Upgraded FE Electronics: Single Channel



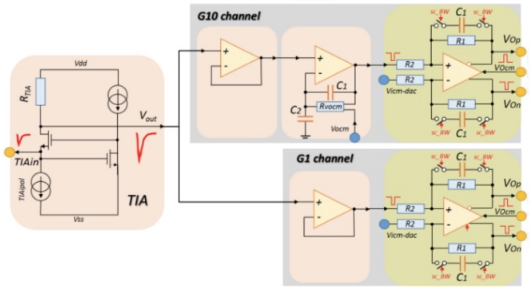
- Crystal and APDs are kept from Phase 1
- Two new ASICs have been designed in the VFE:
  1. The **CATIA** (CAlorimeter Trans-Impedance Amplifier) with two gain channels to cover a dynamic range from 50 MeV to 2 TeV
  2. The **LiTE-DTU** (Lisbon-Turin Electronics Data Transmission Unit) to perform analog-to-digital conversion, gain selection, data compression and transmission
- The data words from the single channel are sent to one of the four **lpGBT** ASICs on the new FE board via **e-links**

C. Borca, SIF2022
https://indico.cern.ch/event/1180856/contributions/4967731/attachments/2499906/4294015/sif-sept22.pdf

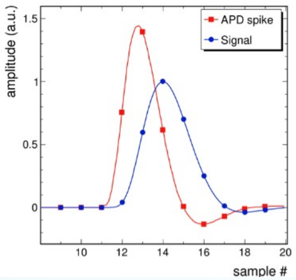
G. Pugliese

ECAL Phase 2 Upgrade

CATIA ASIC Overview

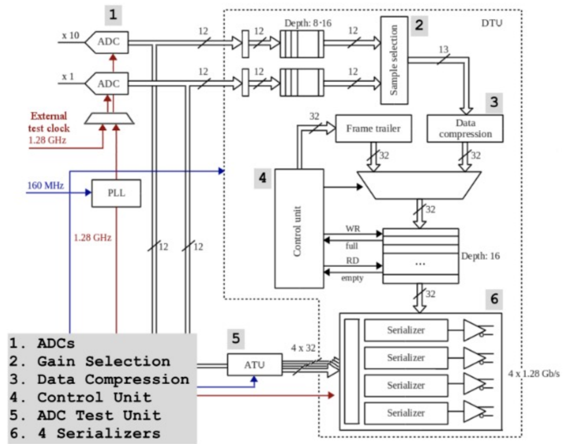


- Two gain stages after the pre-amplifier: G1 and G10
- Implemented in 130 nm (TSMC)
- Range: from 50 MeV to 200 GeV (G10) and 2 TeV (G1)
- Bandwidth: 35 MHz



A faster analog electronics improves
- ➡ Time resolution
- ➡ Spike rejection
- ➡ Noise mitigation

LiTE-DTU ASIC Overview



- Implemented in 65 nm (TSMC)
- Two **12-bit 160MHz ADCs** bought from an external company
- **PLL** from lpGBT design
- Digital logic to perform:
  - Gain selection
  - Baseline subtraction
  - Data compression
  - Serial transmission
- The digital logic and the configuration registers are protected against SEU with TMR

Sampling rate 40 MHz → **160 MHz**
➡ improves time resolution

HCAL Calorimeter performance

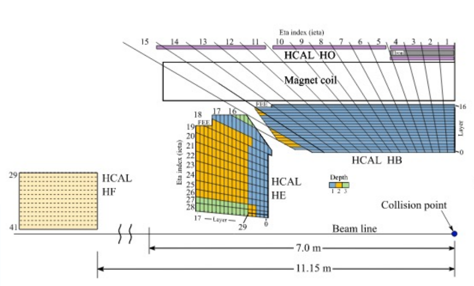
LS2

New silicon photomultiplier devices (SiPMs) installed replacing Hybrid Photo Diodes (HPDs)

Key features:

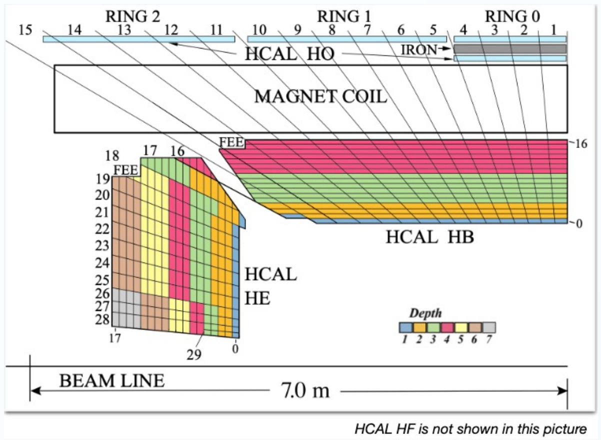
✓Higher photo-detection efficiency

✓Improved depth segmentation

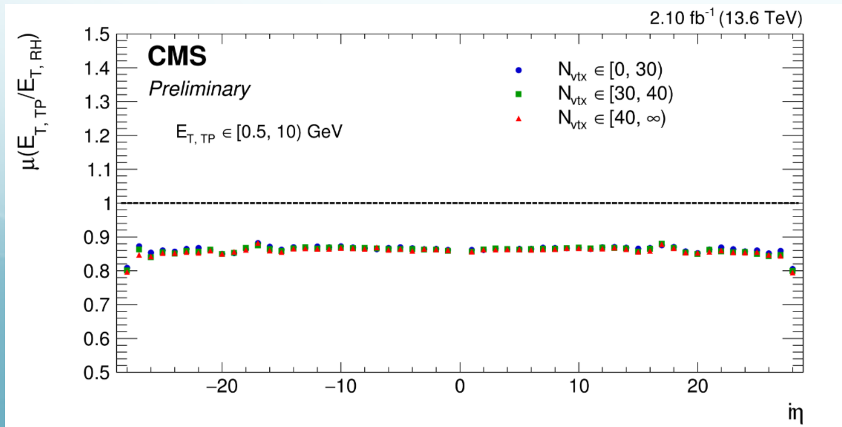


- HB upgrade during LS2
- HE was upgraded before 2018

RUN3



- HCAL is successfully operating in RUN3 collisions with timing and conditions derived using splash events and LHC commissioning runs
- Collision data used for channel-by-channel timing adjustment

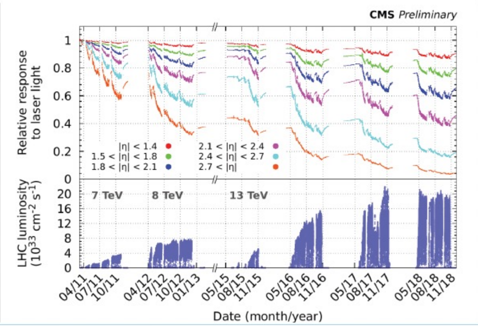


- New online algorithm for Trigger Primitive Transverse Energy ($E_{T,TP}$) deployed and compared with the offline reconstructed hit energy $E_{T,\,RH}$. The response is:
  - consistent across the three different pileup scenarios within uncertainties
  - stable along η in the barrel and endcap regions

ECAL longevity

Lead Tungstate Crystal Longevity

- Main concern for ECAL crystals is ageing due to radiation
- Scintillation mechanism is not affected by radiation
  - Radiation creates crystal defects which reduce the crystal transparency and therefore light output
- Effect is monitored and corrected using a dedicated light injection system
- MC simulations have been used to predict the light output in Phase II
  - Validated using test beam data studying effect of hadron irradiation on crystals

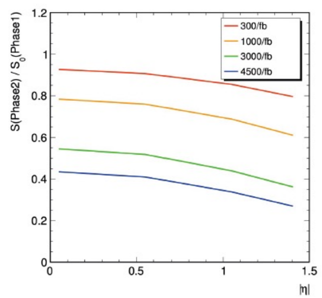


EB: 90%

EE low eta: 40-80%

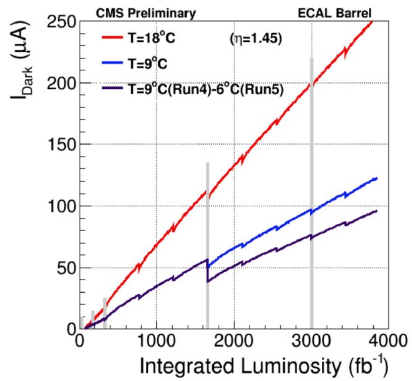
EE high eta: 5-20%

Left: ECAL laser response over Run 1 and Run 2 (2011-2018)
Right: Expected Phase II light output for 50 GeV photon showers with respect to CMS conditions in 2010



Avalanche Photodiode (APD) Longevity

- Two causes of radiation damage to APDs:
  - Gamma rays creating surface defects
    - Increasing surface current
    - Reducing quantum efficiency
  - Hadrons creating bulk damage
    - Causing an increase in the bulk current
- Main concern for HL-LHC is the increase of dark current
  - Electronic noise depends on square root of bulk current
  - Can be mitigated by reducing the operating temperature

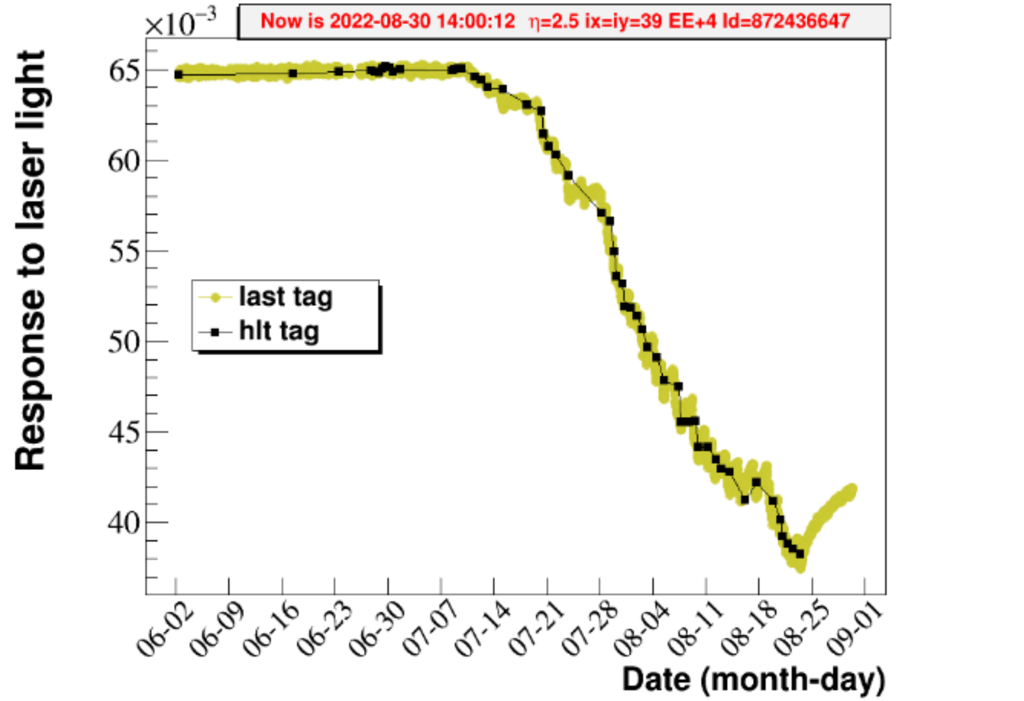


G. Pugliese

Run3 ECAL Calorimeter performance

The new laser workflow, which allows updates to HLT conditions once per fill, has been successfully deployed

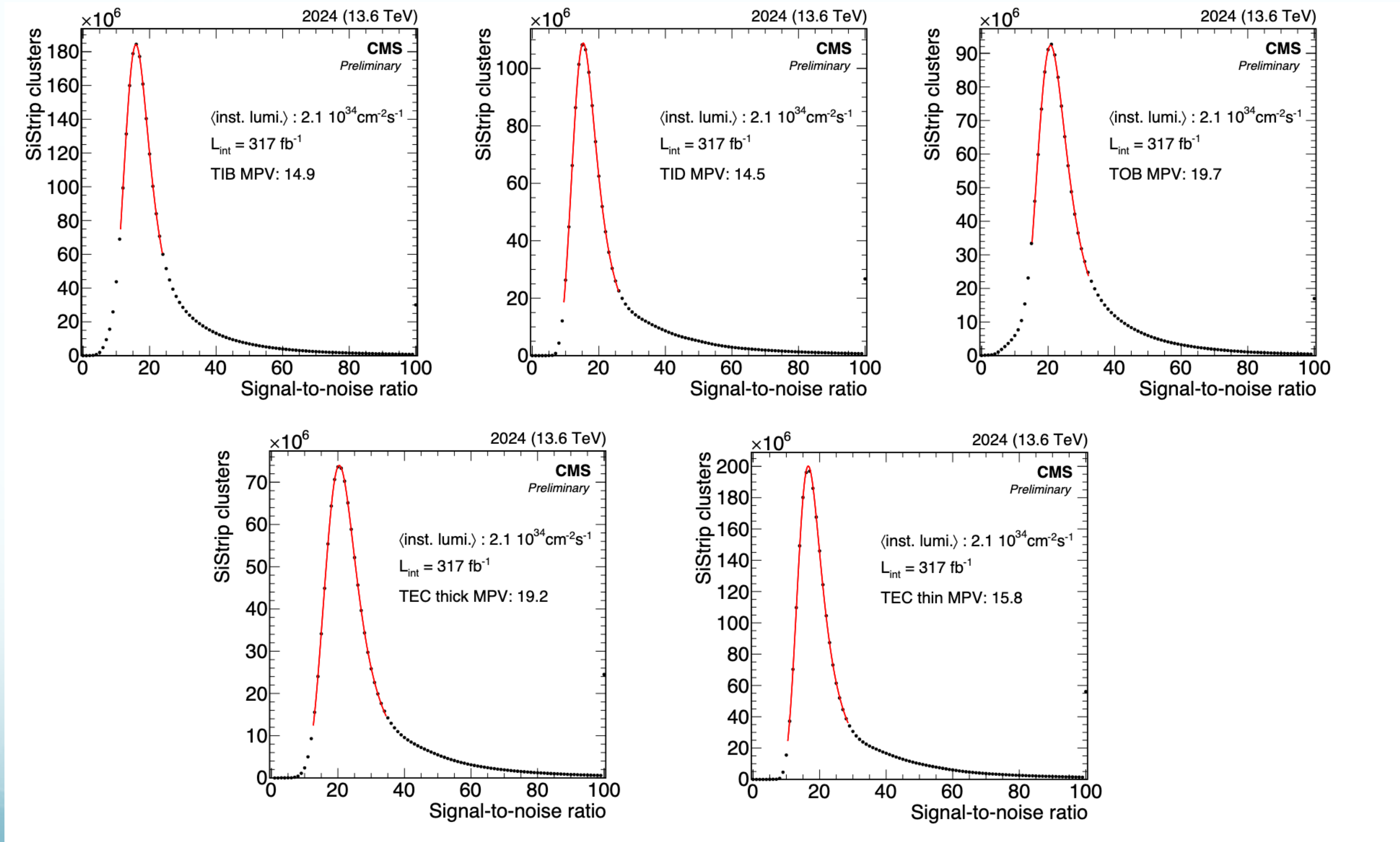
The automation of calibration workflows is also being commissioned



The 2022 history of one channel in EE, showing that the per-fill update of the HLT tag (which is not performed in no-collision periods) follows closely the system response.

RUN3 Tracker Performance

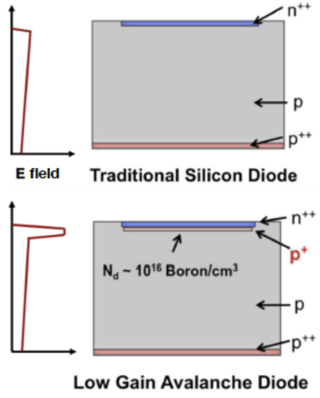
G. Pugliese



MTD: Endcap timing layer

ETL will be instrumented with **Low Gain Avalanche Diodes** (LGADs) optimized for timing measurements

LGADs are provided with a **gain layer**, a highly-doped thin layer near the p-n junction
→ High local electric field producing **charge multiplication**
→ **Moderate gain factor 10-30** to maximize signal/noise ratio



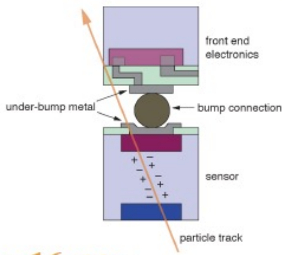
Sensor requirements:
- **Pad size determined by occupancy and read-out electronics** (rather large capacitance, 3-4 pF)
- **Gain uniformity**
- **Low leakage current** to limit power consumption and noise
- Provide **large and uniform signals**, >8 fC when new, >5 fC after highest irradiation point
- Minimized "no-gain" area, **interpad distance < 50 µm**

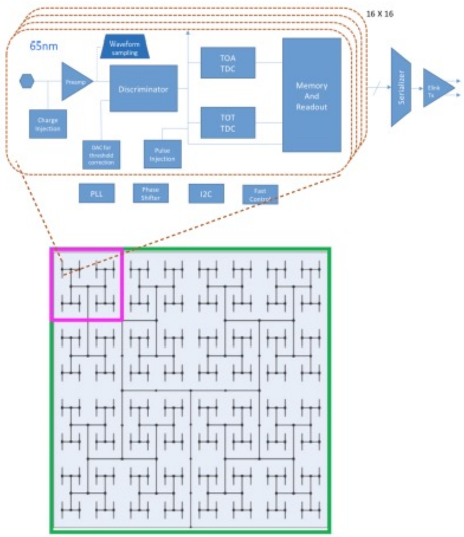
M. Tornago, ICHEP 2022

The final sensor will be a 50 µm-thick 16×16 pad array with 1.3×1.3 mm² pads

The **Endcap Timing Layer Read-Out Chip** (ETROC) is the ETL read-out ASIC

Goal: reach time resolution $\sigma_t < 50$ ps per single hit
- Low noise and fast rise time
- Power budget: 1 W/chip, 3 mW/channel

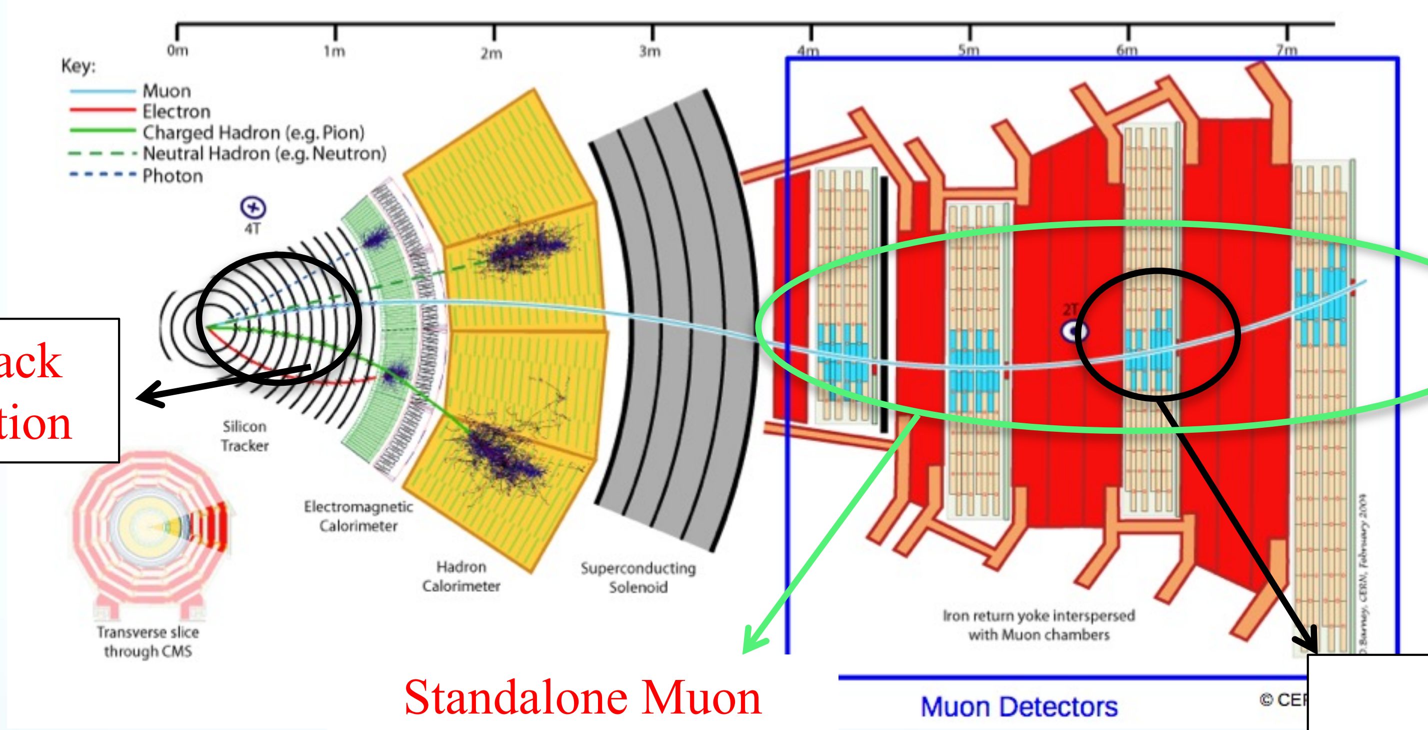




Three prototype versions before the **final full-size 16×16 chip**:
✓ETROC0 and ETROC1 produced and tested
✓ **ETROC0: single analog channel**
✓ **ETROC1: full front-end with TDC and 4×4 clock tree**
➡ **ETROC2 design in progress: full functionality + full size**
➡ **ETROC3:** submission in March 2024, pre-production chip

G. Pugliese

Muon Reconstruction



Tracker track reconstruction

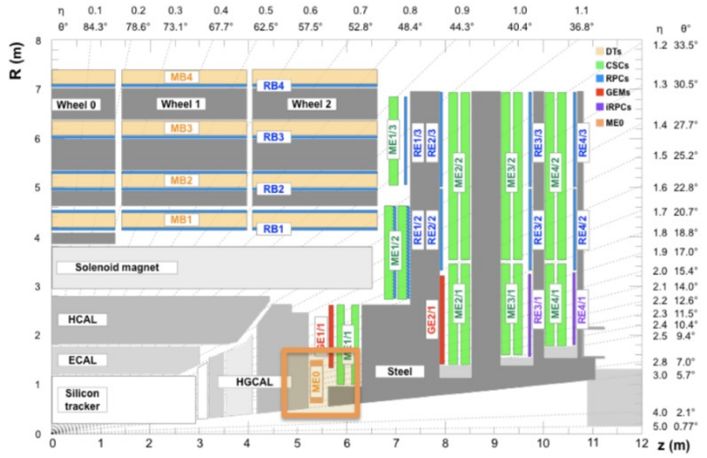
Standalone Muon reconstruction
Performed using DT/CSC segments & RPC hits

Local reconstruction
Performed within single chamber

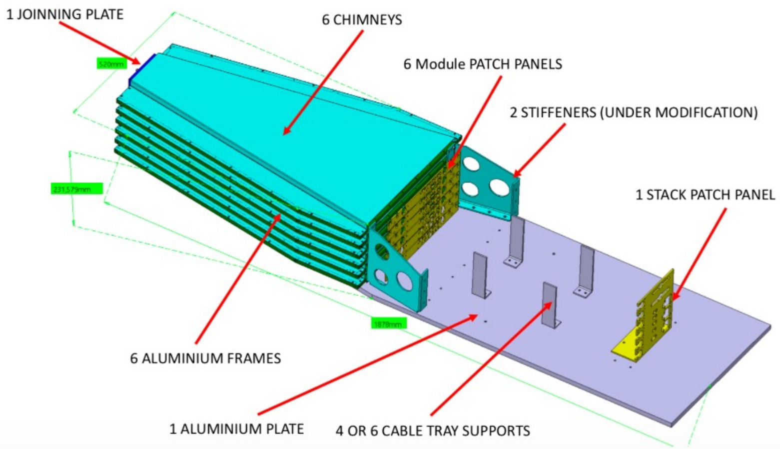
Global muon reconstruction **(out side –in)**: a standalone muon is propagated to match a tracker track. If matching is positive a global fitting is performed.
Tracker Muon **(inside – outside)**: a tracker track is propagated to muon system and qualified as muon if matching with standalone or one segment.

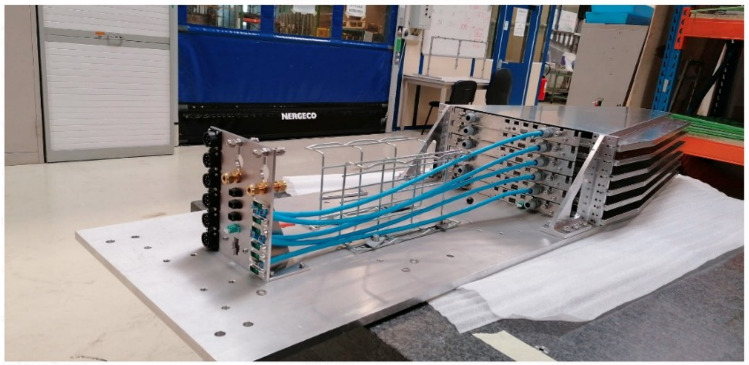
ME0

- ME0 modules based on triple-GEM technology (same as GE1/1 and GE2/1)
- 18 stacks per endcap
- Each stack is made of six triple-GEMs
- Total 216 triple-GEM chambers
- Coverage $2.0 < \eta < 2.8$ and $0.6 < R < 1.5$ m
- 20° trapezoidal shape



Stack design

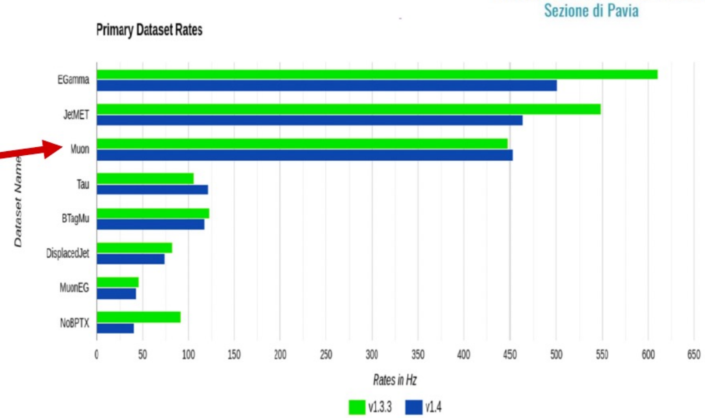




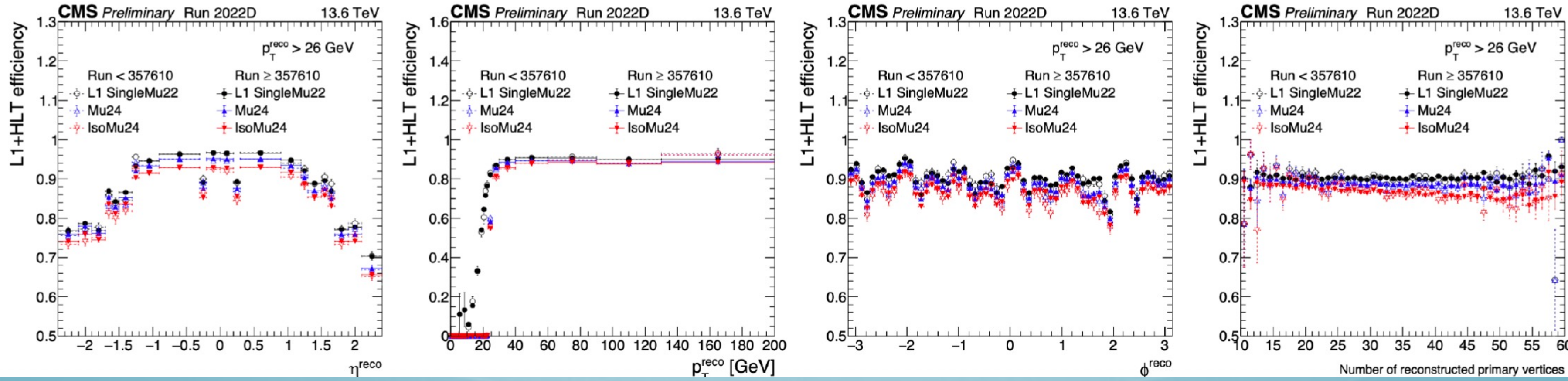
Muons at HLT

Istituto Nazionale di Fisica Nucleare
Sezione di Pavia

- **Total HLT prompt rate** for v1.4 menu = 1771 Hz, excluding rate from parking dataset (calculations done with instantaneous luminosity = $2 \cdot 10^{34}\ cm^{-2}s^{-1}$
  - PhysicsMuon stream rate = ~450 Hz
  - Old SingleMuon and DoubleMuon united in a unique Primary Dataset
- Monitoring the muon reconstruction efficiency at L1 and HLT using Z resonance Tag & Probe



η p_T φ $nvtx$



Muons at HLT

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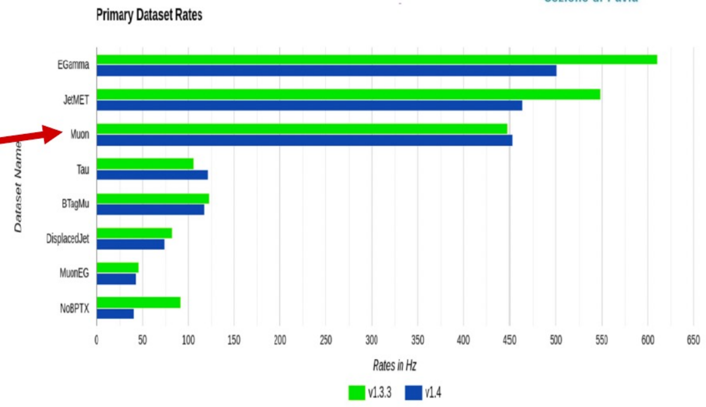
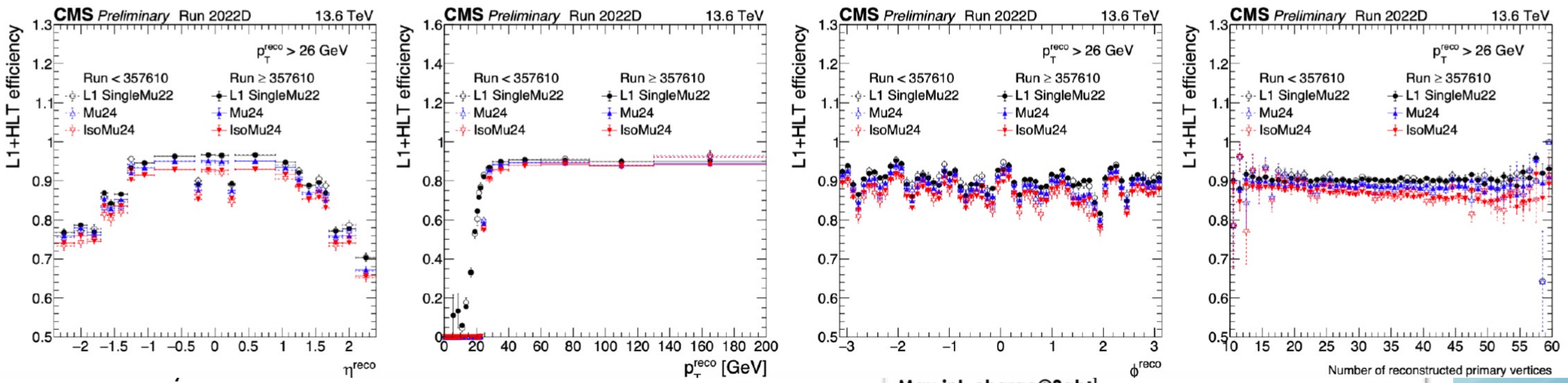


η $\quad$ p_T $\quad$ φ $\quad$ $nvtx$



- Improve Trigger hit time resolution from 25 ns to 1.5ns
- 1376 link boards, 216 control boards

Max int. charge@3ab^{-1} (SF = 3 included)	~ 0.8 C/cm^2	~ 1.0 C / cm^2
Phi granularity	~ 0.3°	~ 0.2°
Eta resolution	~ 20 cm	~ 2 cm
Time resolution	1.5 ns	< 1 ns