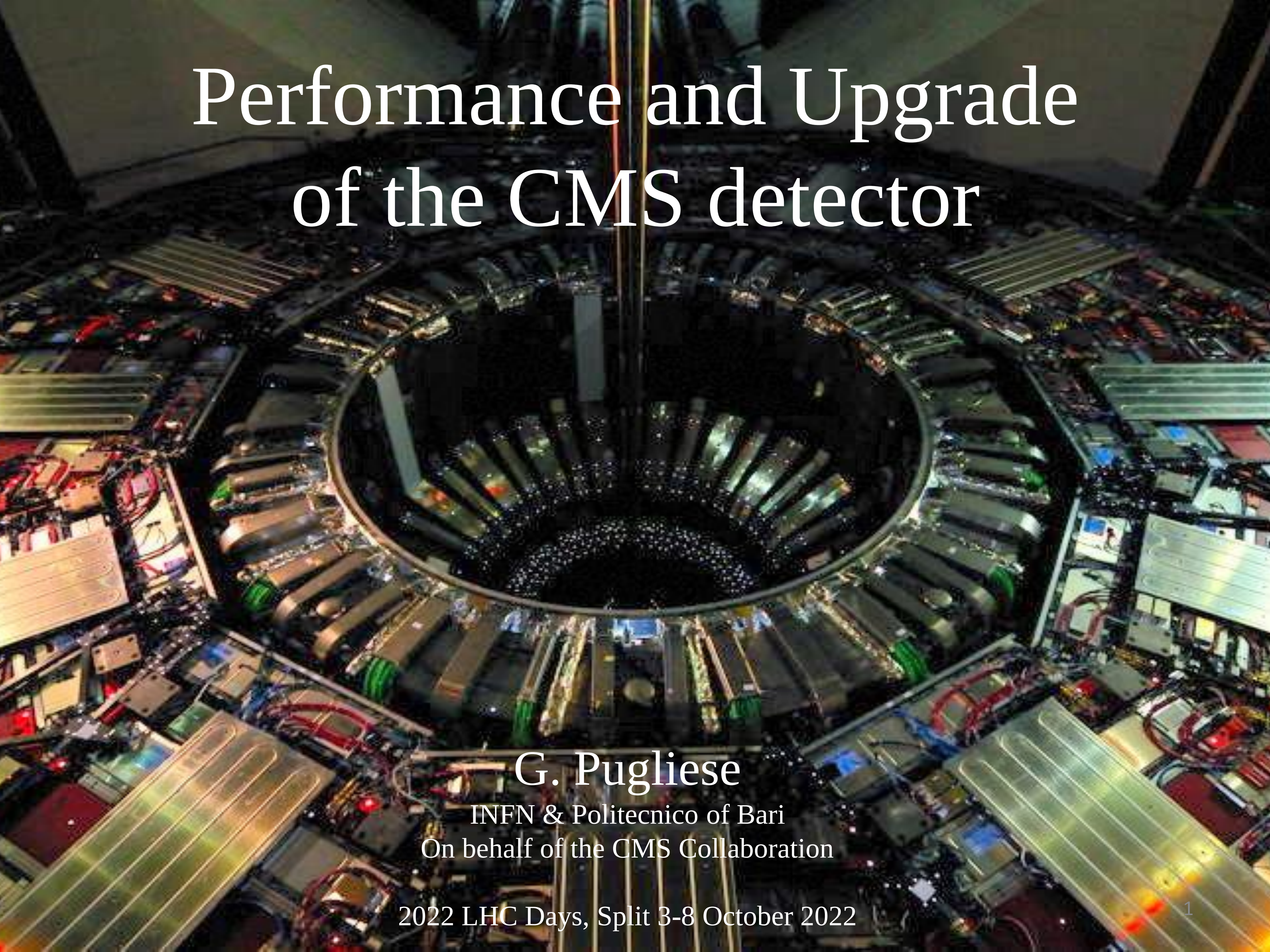
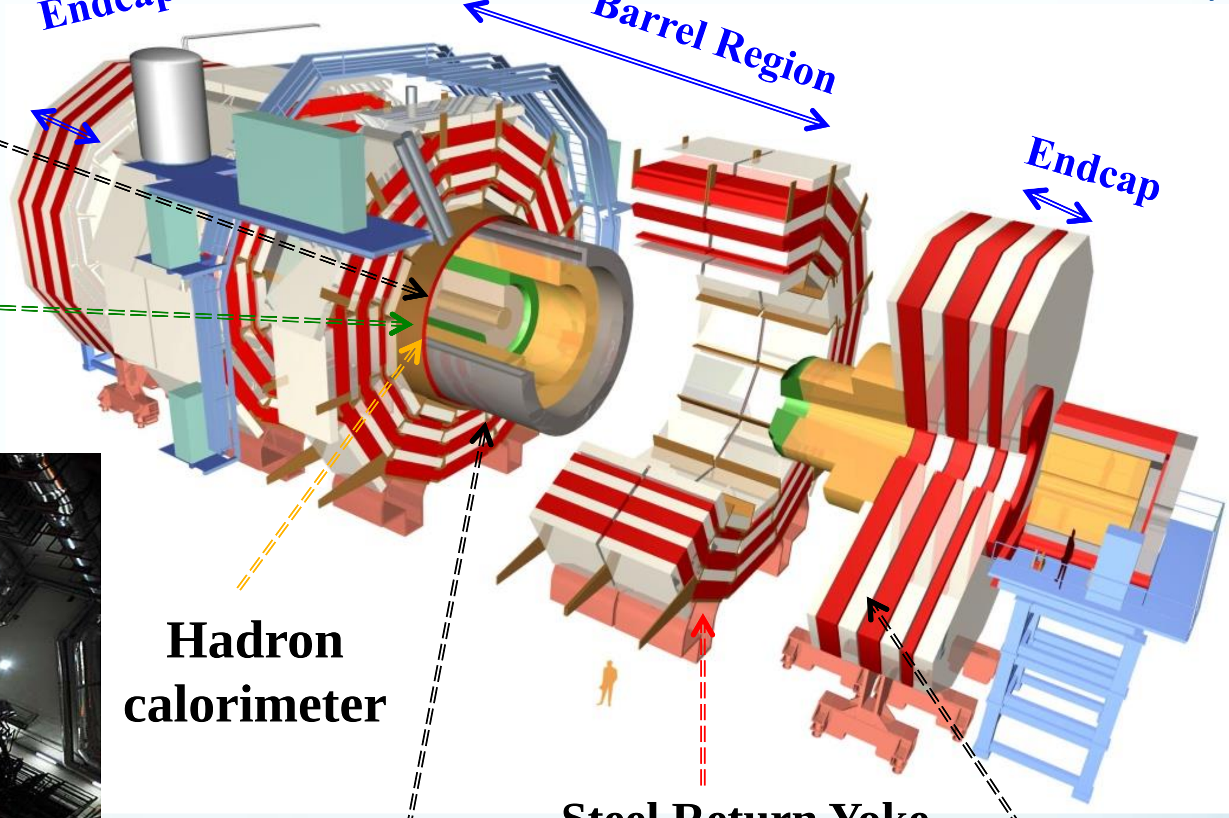


Performance and Upgrade of the CMS detector

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

2022 LHC Days, Split 3-8 October 2022

The CMS detector



Tracker

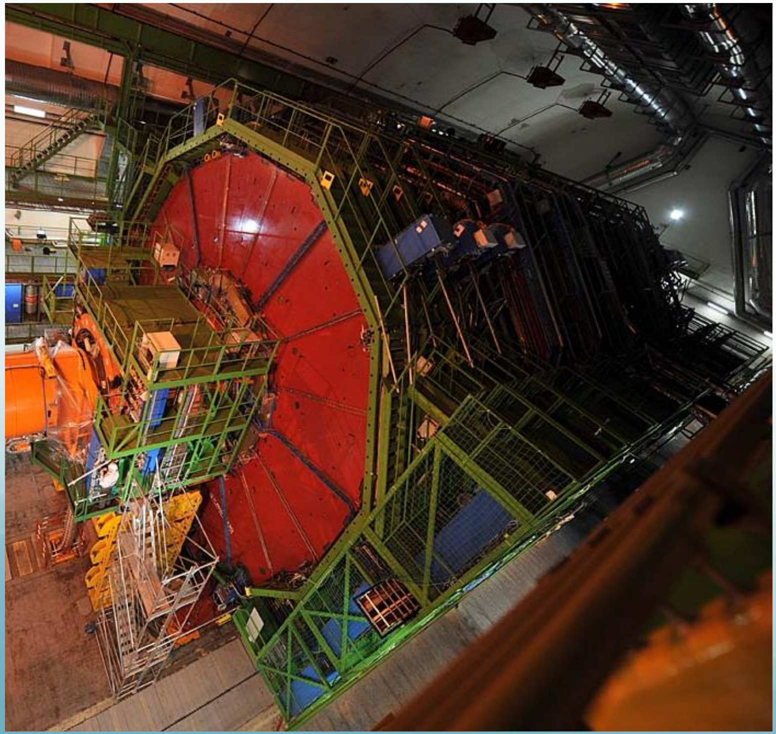
Electromagnetic calorimeter

Hadron calorimeter

Steel Return Yoke

Superconducting Solenoid
Niobium titanium coil carrying 18.000 A

Muon Spectrometer



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

G. Pugliese

The CMS Tracker

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: 3x10^{15} n_{eq}/cm^2/yr

Silicon Strip

Sensor technology: p-in-n

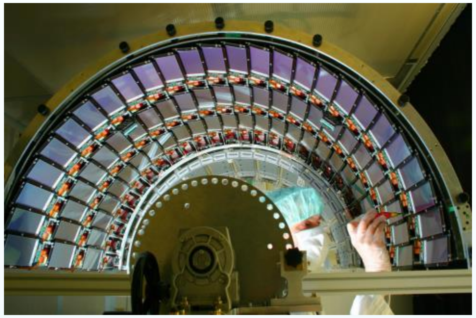
Outer cell size ~20cm x 100-200μm

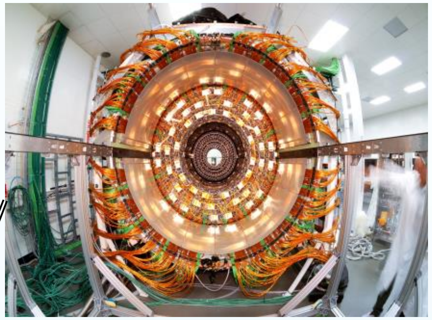
Inner cell size ~10cm x 80μm

- 10 layers in the barrel and 12 rings in the endcap
- Operation -20 °C
- Radiation tolerance ~1.5x10^{14} n_{eq}/cm^2

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

Inner Barrel



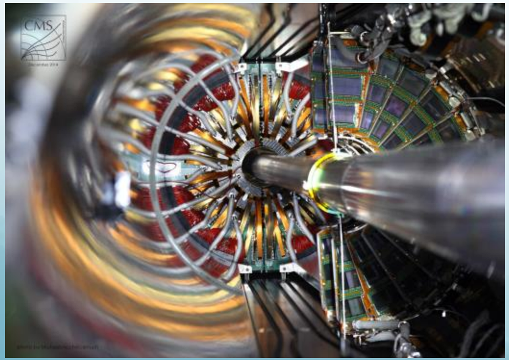


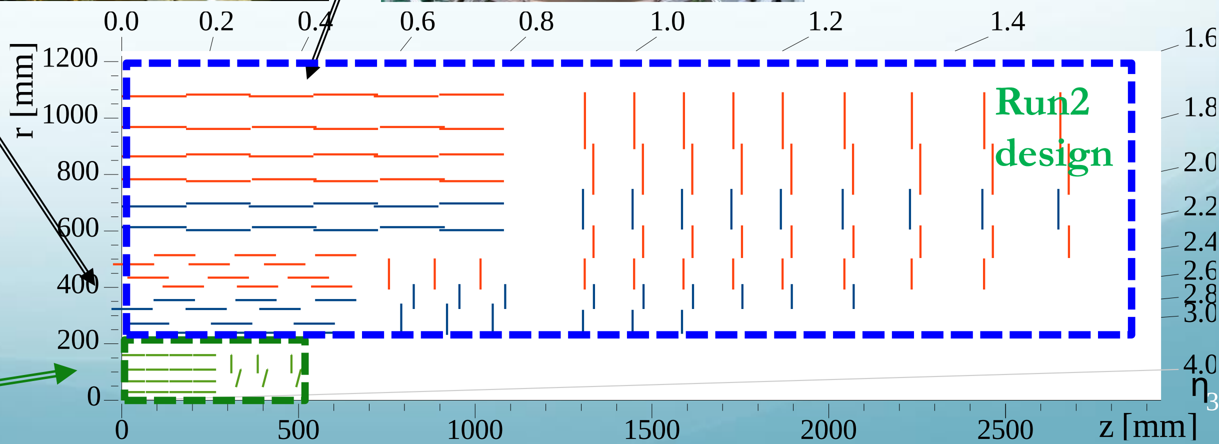
Outer Barrel

Tracker acceptance: |η| < 2.5

Blue: double sided

Red: single sided





Pixel Barrel & Endcap

The CMS Calorimeters

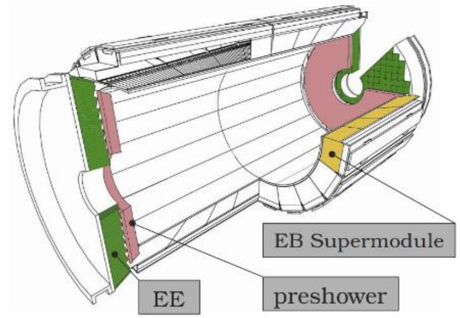
G. Pugliese

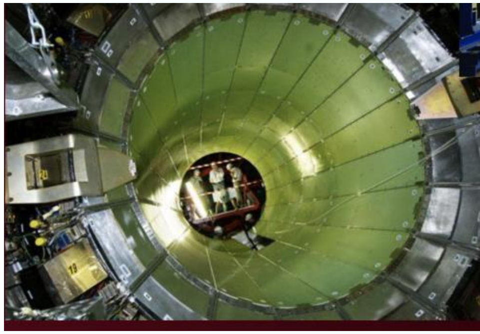
Electromagnetic system

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%

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

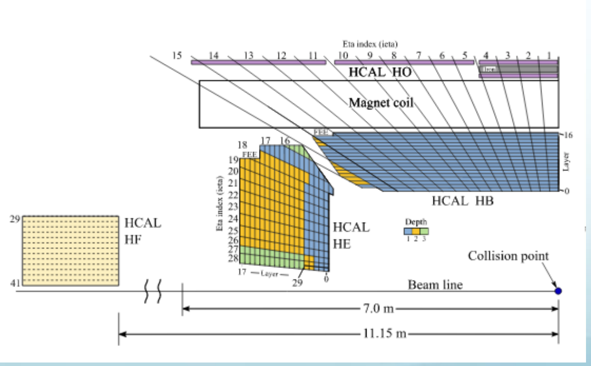
Hadronic system

- **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

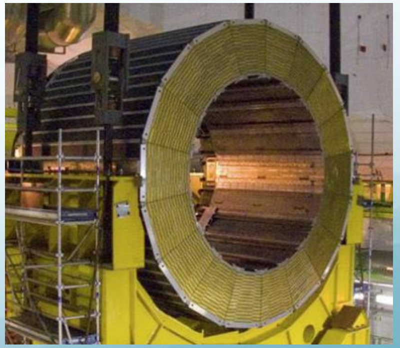
Outside the magnet coil:

- **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



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



HB Brass absorber

The CMS Muon Systems

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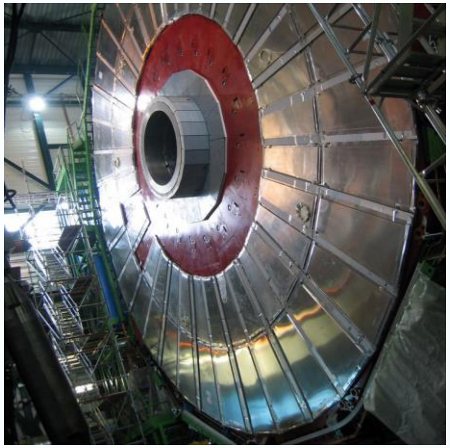
Muon system: based on ~~three~~ four gaseous technologies technologies for muon identification, timing and momentum measurement



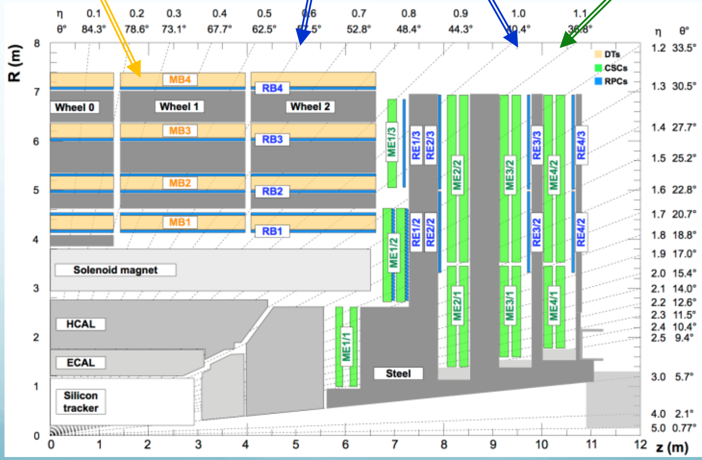
Muon acceptance: |η| < 2.4

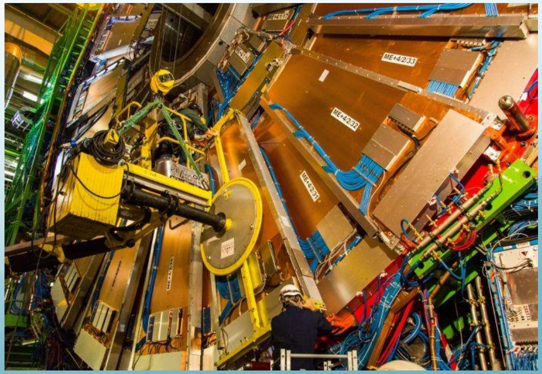
Drift Tubes (DT)
- 250 chambers, ≈ 170k channels
- 32 number of hits
- Spatial resolution≈100 μm
- Time resolution ≈ 2 ns

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





LHC and HL-LHC schedule

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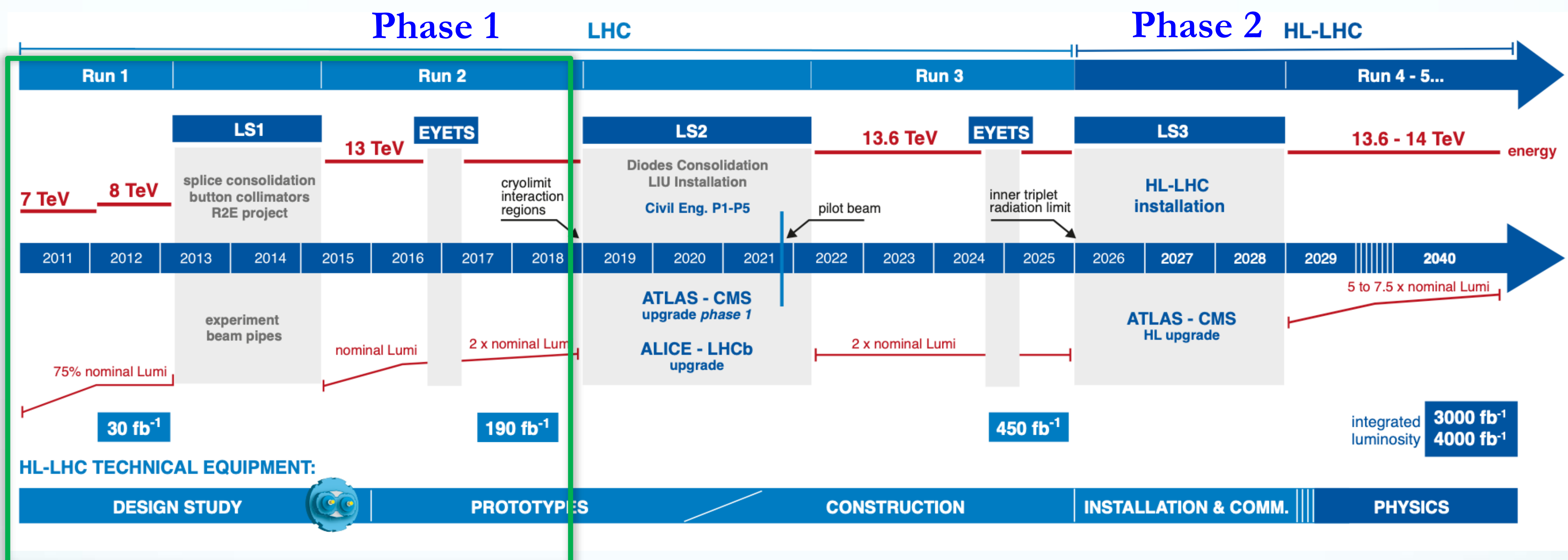
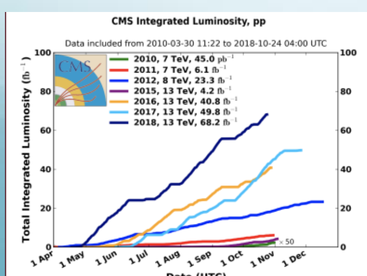
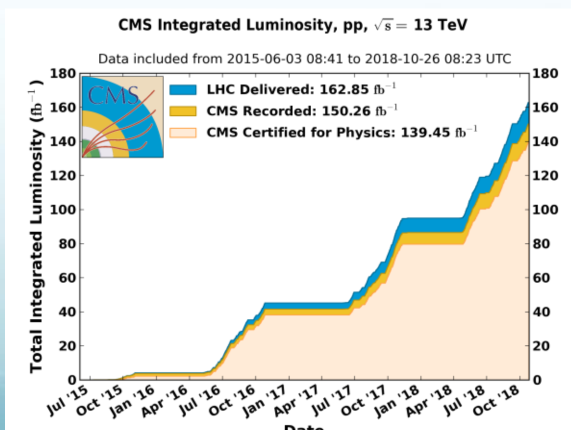
2022 LHC Days



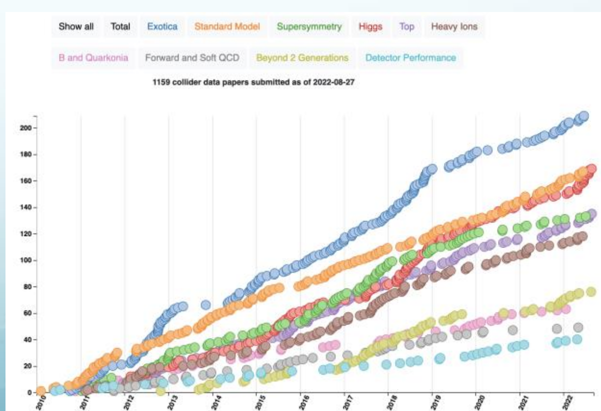
RUN1 & RUN2

→ RUN2 CMS data taking efficiency: 92 %





→ 1159 published paper, so far



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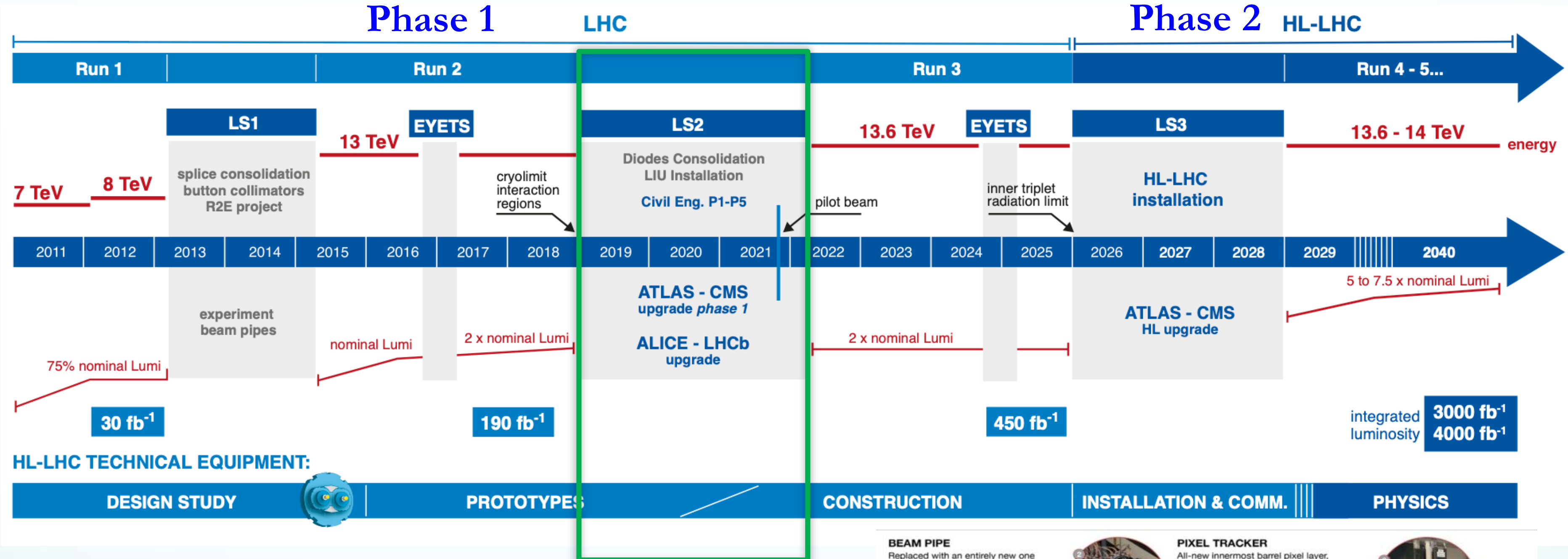
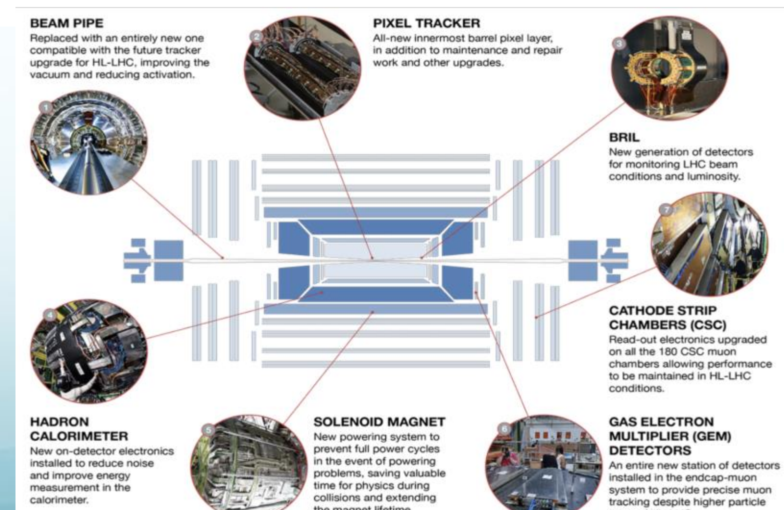
LHC and HL-LHC schedule

2022 LHC Days



Long Shutdown 2 (2019-2021):
extensive work done to upgrade the CMS detector in view of the increase of energy and luminosity in Run3 and beyond



https://home.cern/press/2022/CMS-upgrades-LS2

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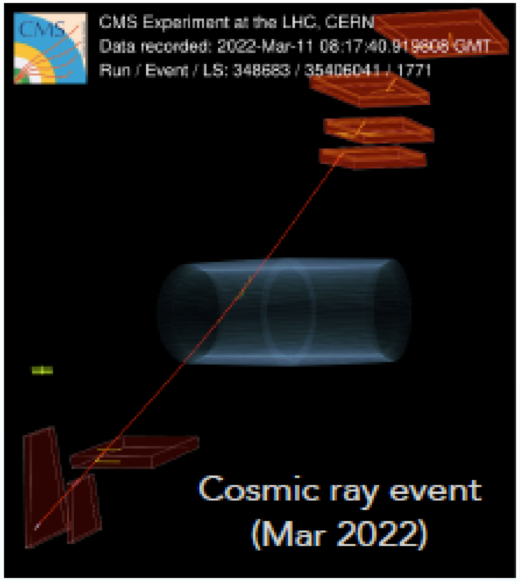
Detector commissioning

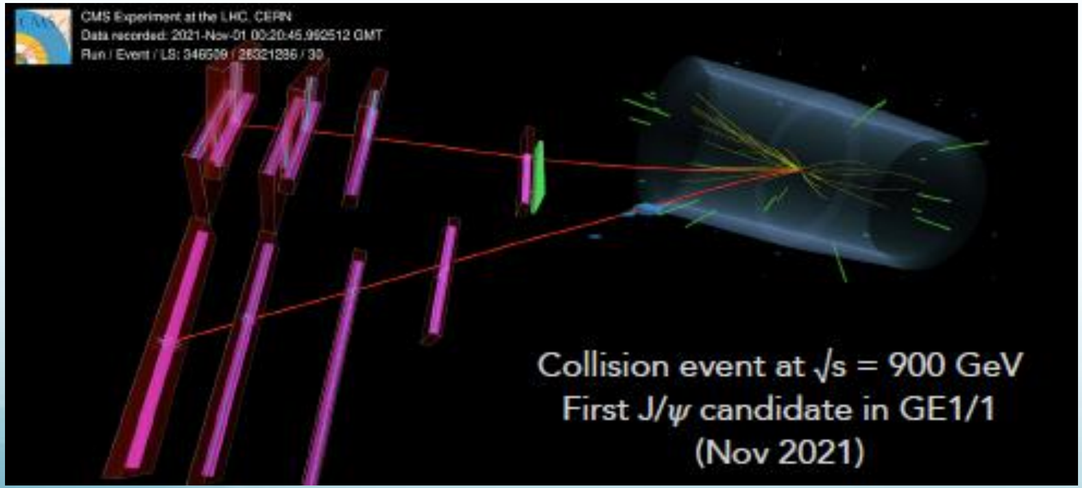
Commissioning with comic muons

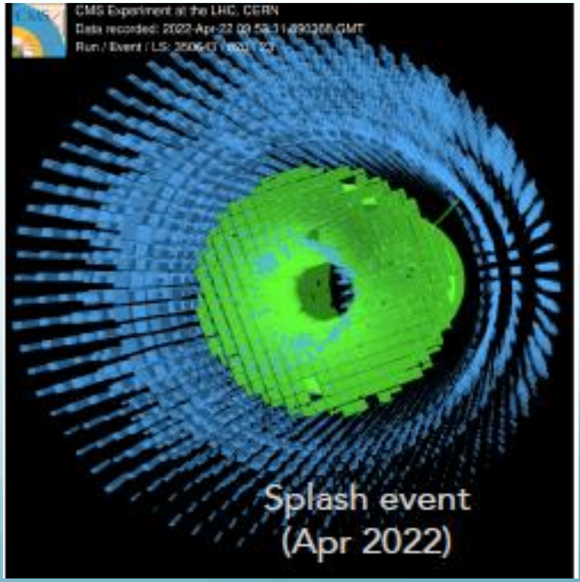
- more than 6.6M cosmic ray events collected for alignment and calibration purposes

Commissioning with p-beams:

- Collisions in stable beams at injection energy (900 GeV)
- Splash events
- Pilot Run @ 13.6 TeV energy







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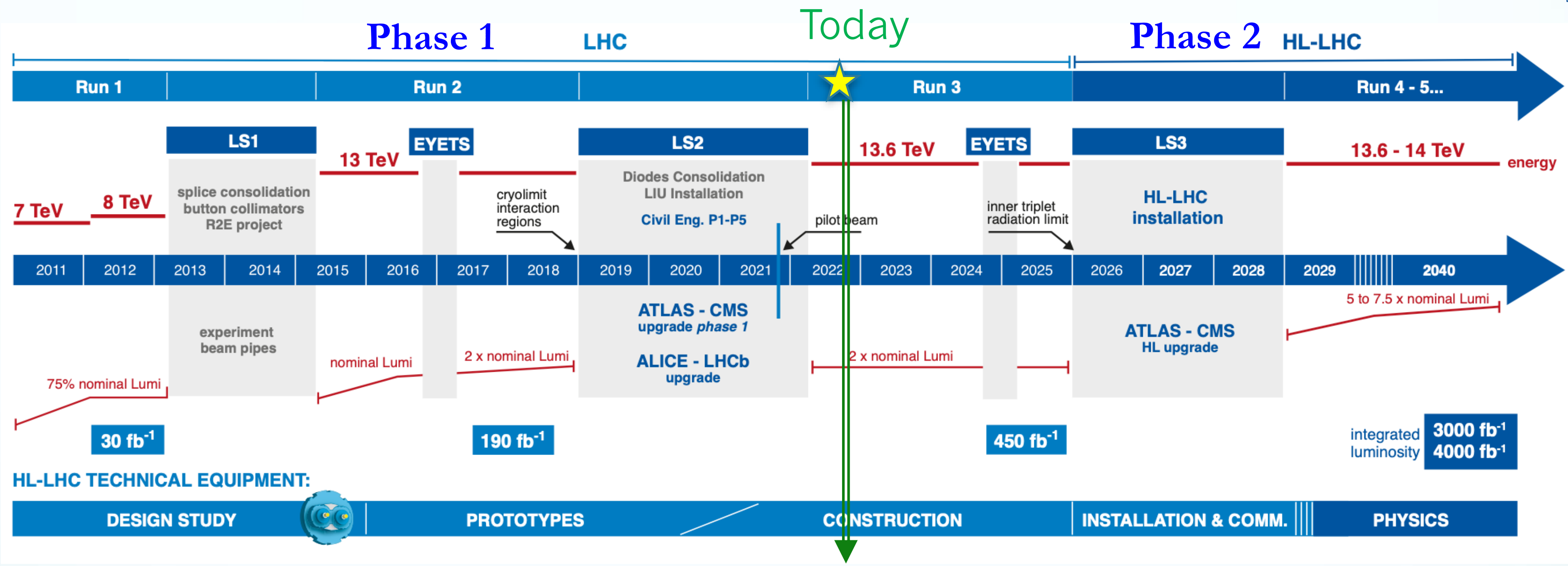
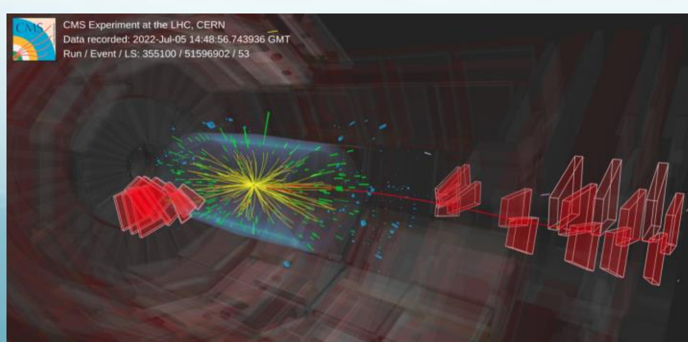
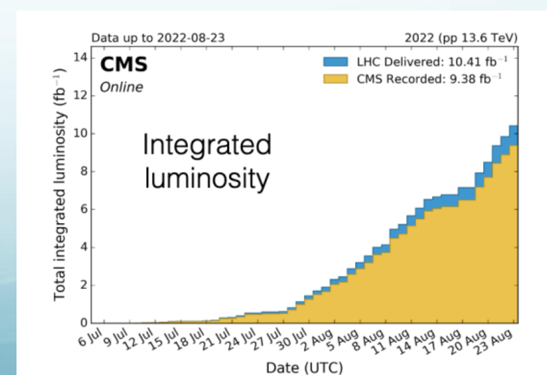
LHC and HL-LHC schedule



First Stable Beams energy record 13.6 TeV on 5th July 2022

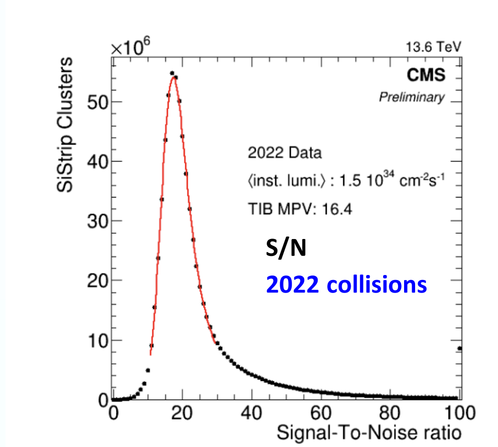
- Over 10 fb^{-1} delivered so far
- 90.2% CMS data taking efficiency

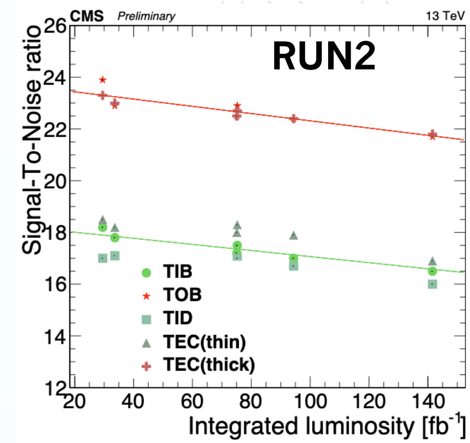




Tracker performance

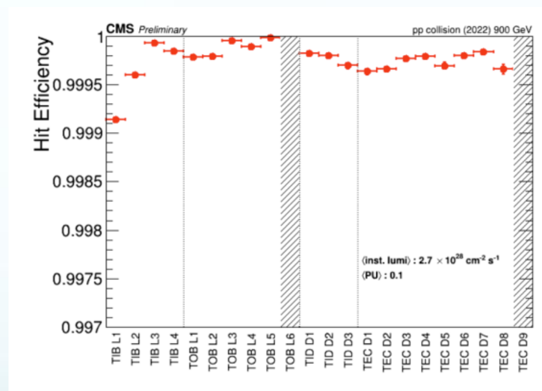
LS2





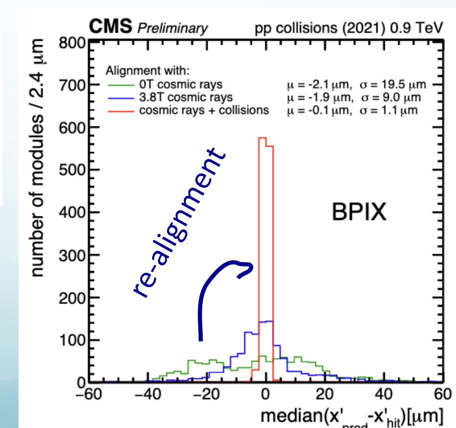
- The **new BPIX layer 1** is taking data successfully in RUN3. New readout chips working well, await more data for full assessment of the system

- Tracker performance being evaluated with RUN3 13.6 TeV energy beam:
  - **Signal to Noise ratio** in agreement with expectations from RUN2
  - **Strip Tracker** layer-by-layer efficiency >99.8%



Strip layer efficiency measured with pp collision @ 900 GeV in 2022

- **Detector alignment** successfully performed using cosmic ray tracks recorded w/o and w/ 3.8 Tesla magnetic field and with collisions

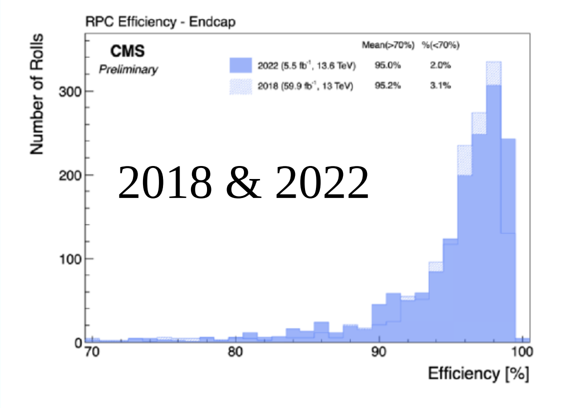


Distributions of medians of unbiased track-hit residuals

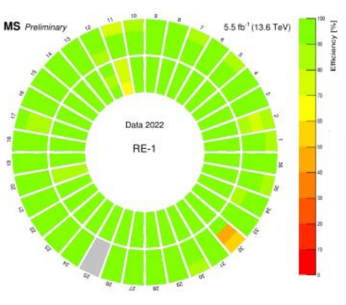
G. Pugliese

Muon System performance

- Muon system successfully commissioned with cosmic muons, LHC Pilot Runs, and calibrations runs (timing, noise, HV, etc.)
- Online and offline analyses on RUN3 data show **detector performance** (efficiency, spatial resolution, etc.) in agreement with RUN2

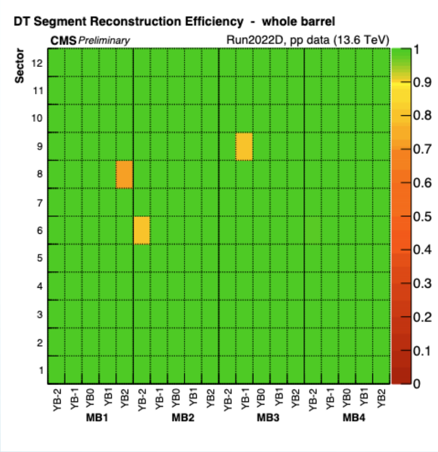


2022 collisions



RPC endcap efficiency

2022 collisions



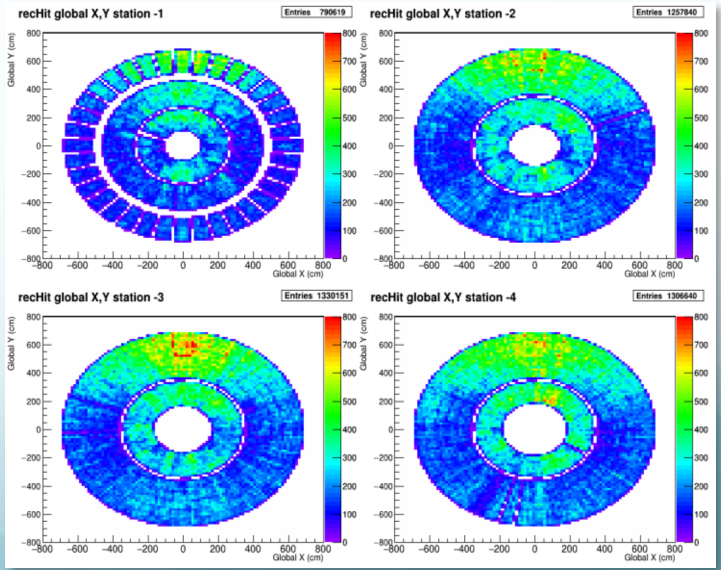
DT Barrel efficiency

Phase 2 project

LS2

CMS preliminary

2022 collisions



CSC occupancy map in 2022

- The **new on-chamber CSC electronics boards** successfully installed and validated. Timing calibration completed by using the first collision data

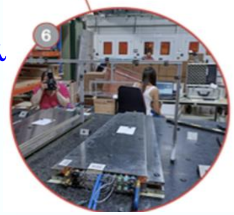
GEM station commissioning

G. Pugliese

2022 LHC Days

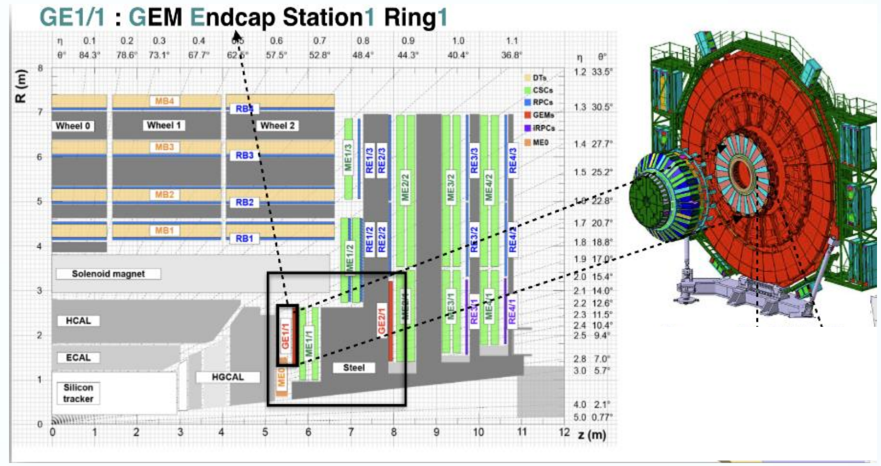
LS2

Phase 2 project



GAS ELECTRON MULTIPLIER (GEM) DETECTORS

An entire new station of detectors installed in the endcap-muon system to provide precise muon tracking despite higher particle rates of HL-LHC.

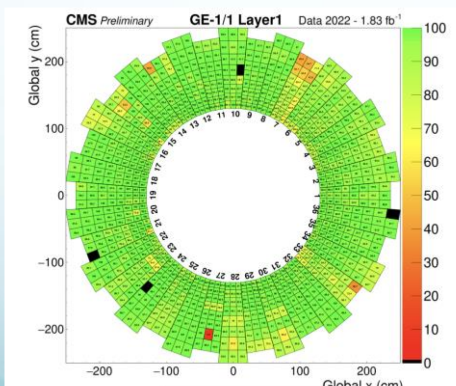


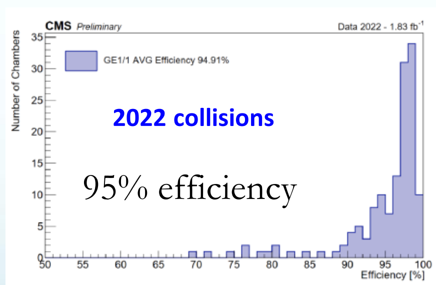
GE1/1 station:

- 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 $1.55 < |\eta| < 2.18$

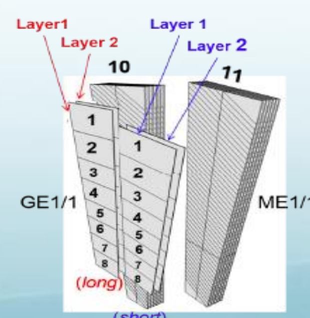
- **HV calibration performed** with promising performance results, further optimization expected

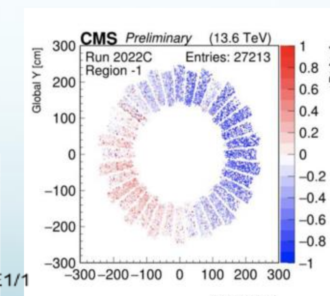




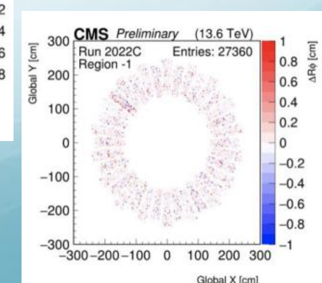
GEM efficiency in 2022

- New back-propagation method for GEM alignment applied: significantly improved accuracy of relative alignment between GEM and CSC chambers





alignment



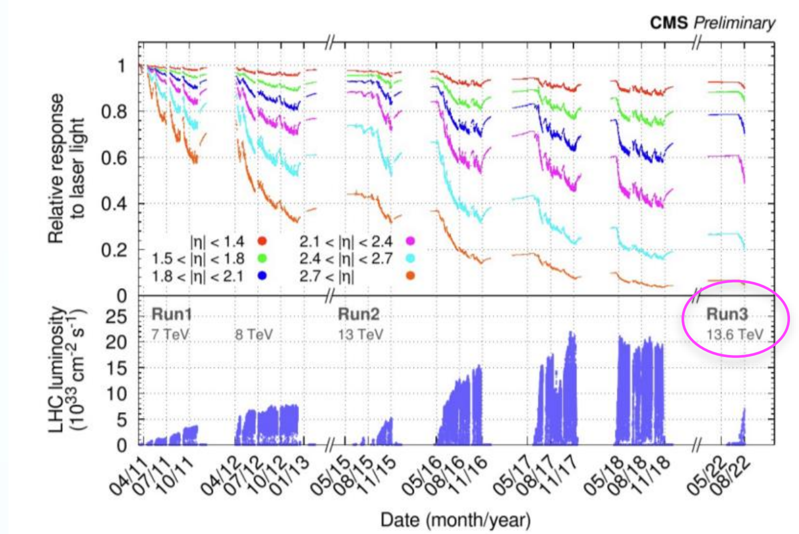
- Novel **GEM-CSC level-1 trigger** extensively verified with cosmic muons. Further tests ongoing to optimize the configuration parameters for LHC collisions. Deployed expected by the end of the year

ECAL Calorimeter performance

G. Pugliese

- ECAL is successfully taking data in RUN3
- **Detector response,** monitored with laser-based system, is in agreement with expectations
- Successfully automated the calibration workflow
- **Alignment and energy calibration** updated and validated with excellent results already

(RUN1, RUN2, RUN3)

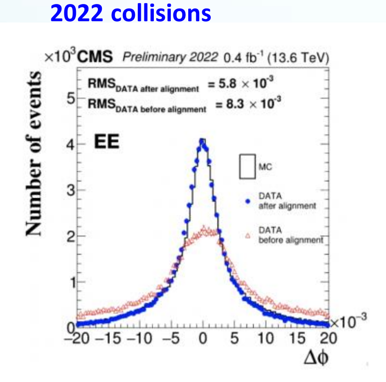


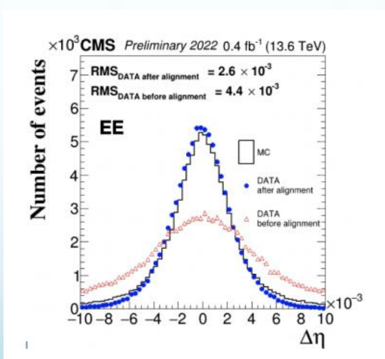
EB: 90%

EE low eta 50-85%

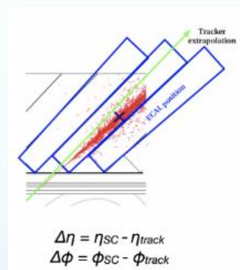
EE high eta 5-20%

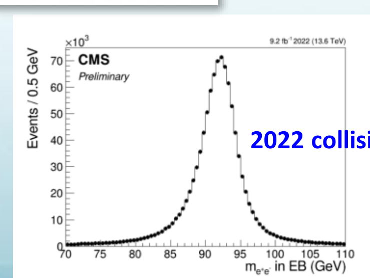
2022 collisions





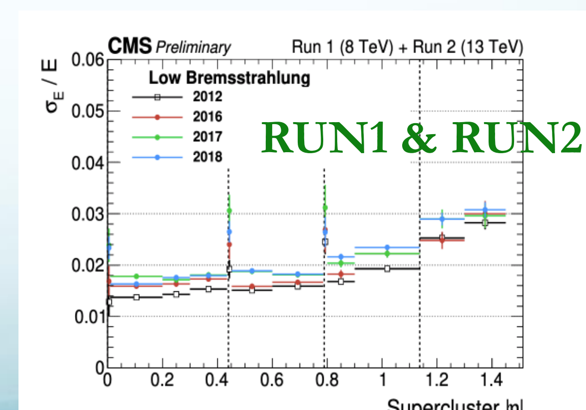
*Residual difference in η and φ between the position of supercluster and extrapolated track position **before** and **after** the alignment*





Z → ee peak reconstruction in EB

- **Energy resolution**



Energy resolution vs. η

HCAL Calorimeter performance

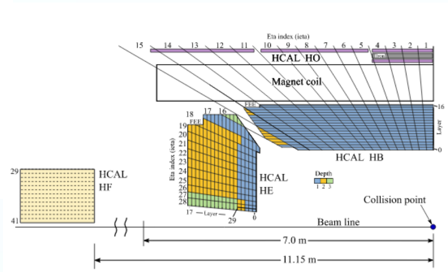
LS2

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

Key features:

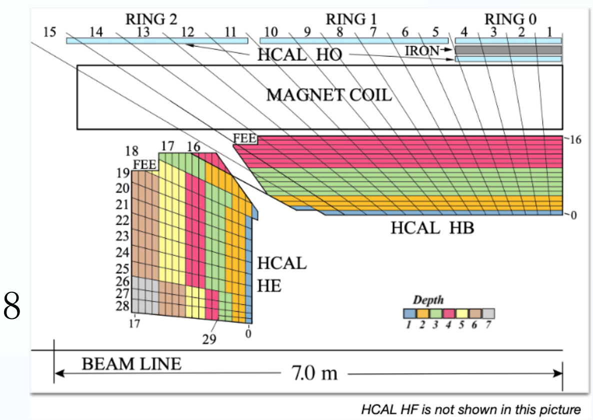
✓Higher photo-detection efficiency

✓Improved depth segmentation

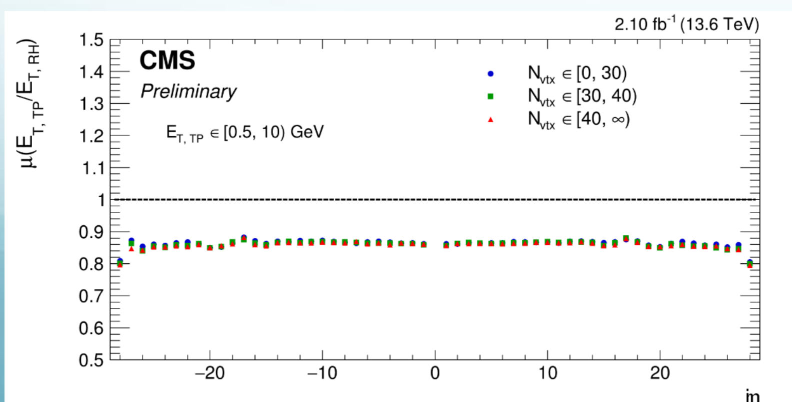


- HB upgrade during LS2
- HE was upgraded before 2018

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

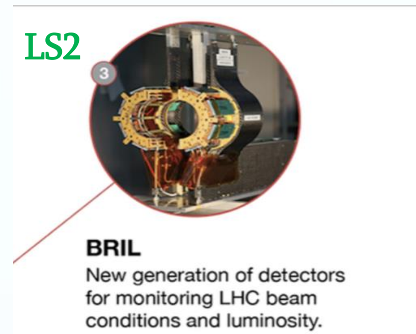
G. Pugliese

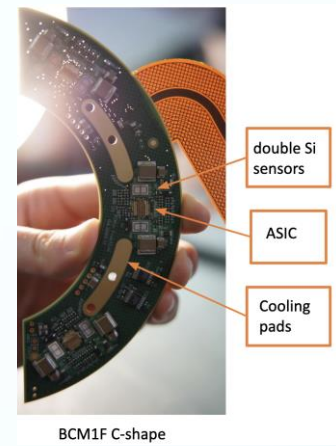
Beam Radiation Instrumentation and Luminosity (BRIL)

2022 LHC Days

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

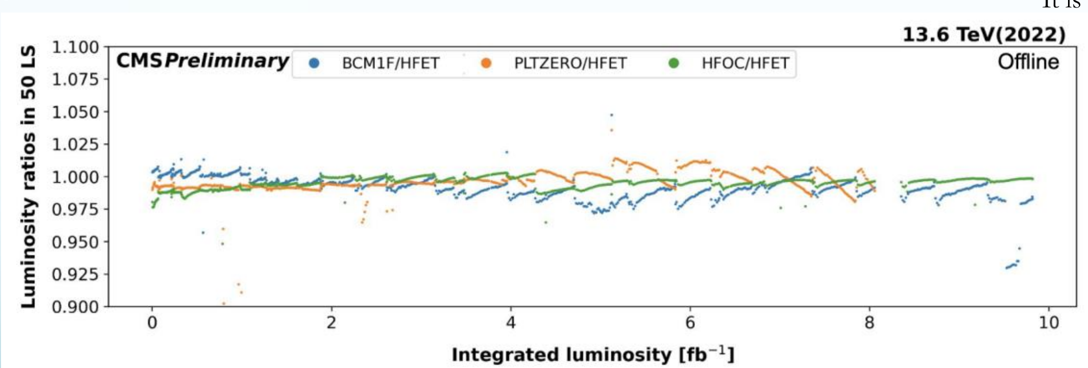




BCM1F C-shape

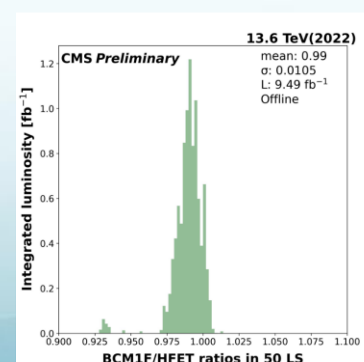
It is located behind the Tracker Pixel detector at m from the Interaction Point (IP)

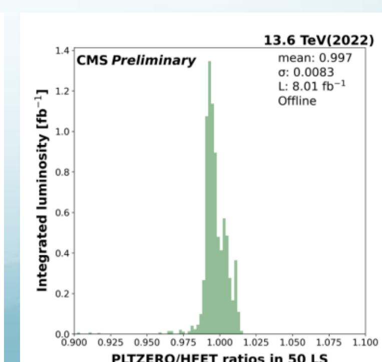
- Luminometers showing excellent performance



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

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

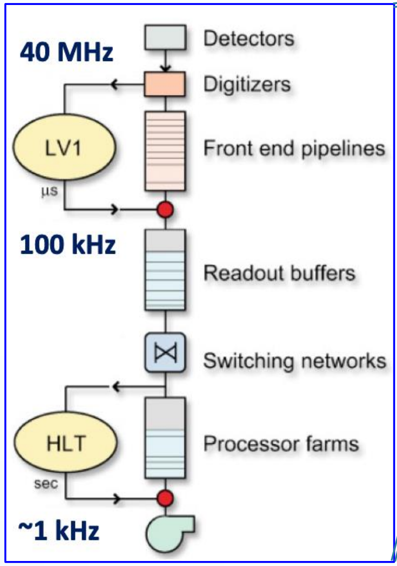




- Background and abort systems all operational
  - Good progress with Beam Halo Monitor

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

G. Pugliese



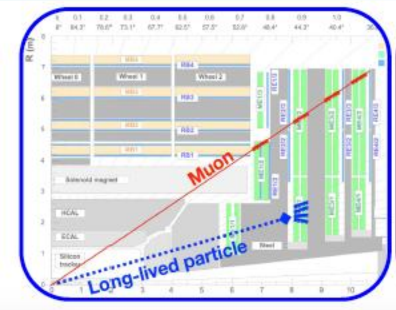
The CMS Trigger System is organized in two levels:

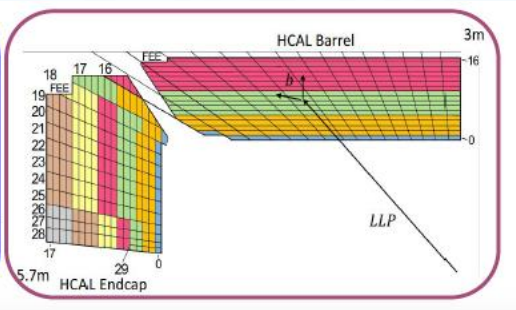
1. **Level-1 Trigger** hardware based reduces the data/event rate from the crossing rate of 40 MHz to no more than **100 kHz**, with **4µs latency**
2. **High Level Trigger (HLT)** filtering events with software running on computing farm, to further reduce the event rate for storage to 1 kHz

➢ For RUN3 new trigger strategies have been investigated both on the LV1 and HLT

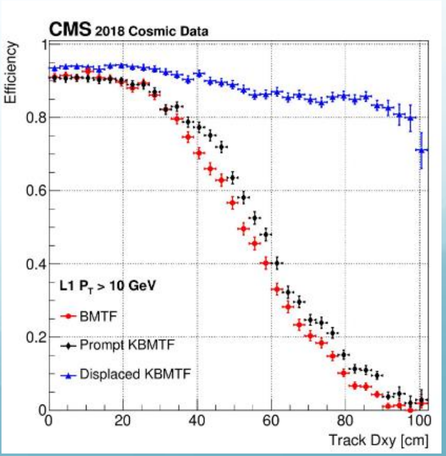
New LV1 triggers developed to detect:

- Hadronic muon showers relying on the CSC Muon stations information (e.g. Long-Lived Particles decaying to jets)
- Delayed/displaced jets using the new HCAL timing capabilities (0.5 ns) and energy deposit information in deep layers
- Displaced muons (using the Kalmar Muon Track Algorithm)





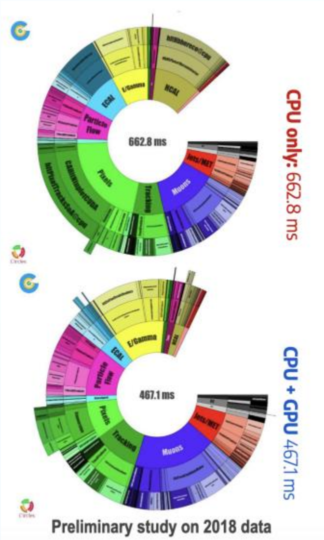
*The Kalman Barrel Muon Track Finder algorithm improves the efficiencies for muon with large **displacements***



G. Pugliese

Level-1 Trigger & High Level Trigger (HLT) @ RUN3 (2)

2022 LHC Days



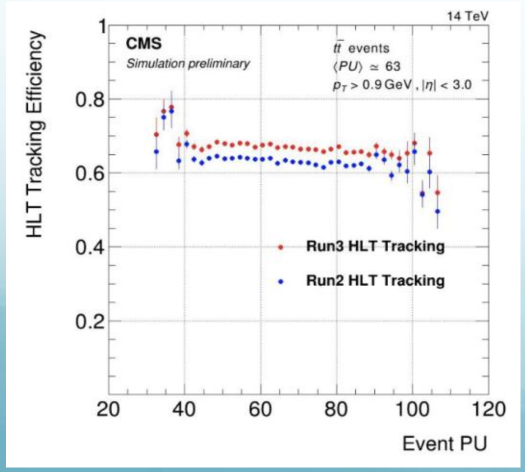
New features in HLT @ RUN3:

Graphics Processing Units: the HLT farm is composed of 200 nodes 25600 CPU cores and **400 GPUs** in total (CPU cores only in 2018)

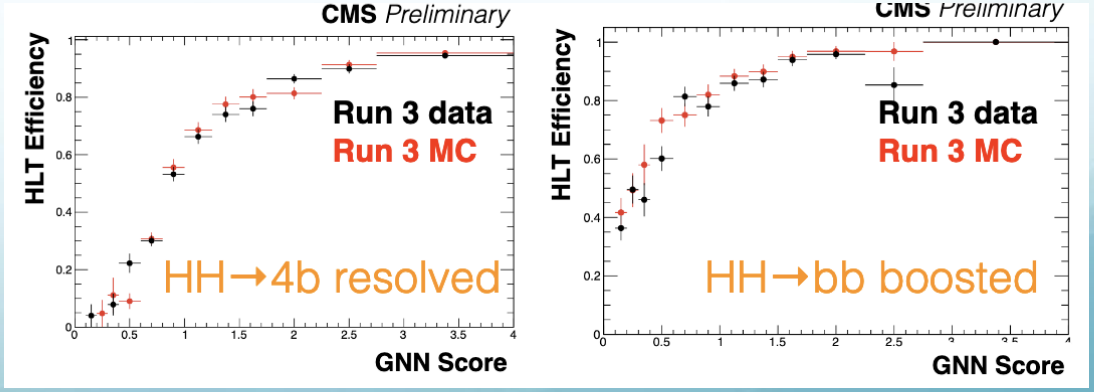
- Gain experience with **heterogeneous architectures** ahead of Phase-2
- Currently, offloaded 40% of the event processing (calorimeters and pixel local reconstruction, pixel tracking and vertex reconstruction)

Several updates on reconstruction and trigger paths to ensure that an interesting physics program can be performed by CMS during Run 3

- **New tracking** based on the optimized pixel track **reconstruction**



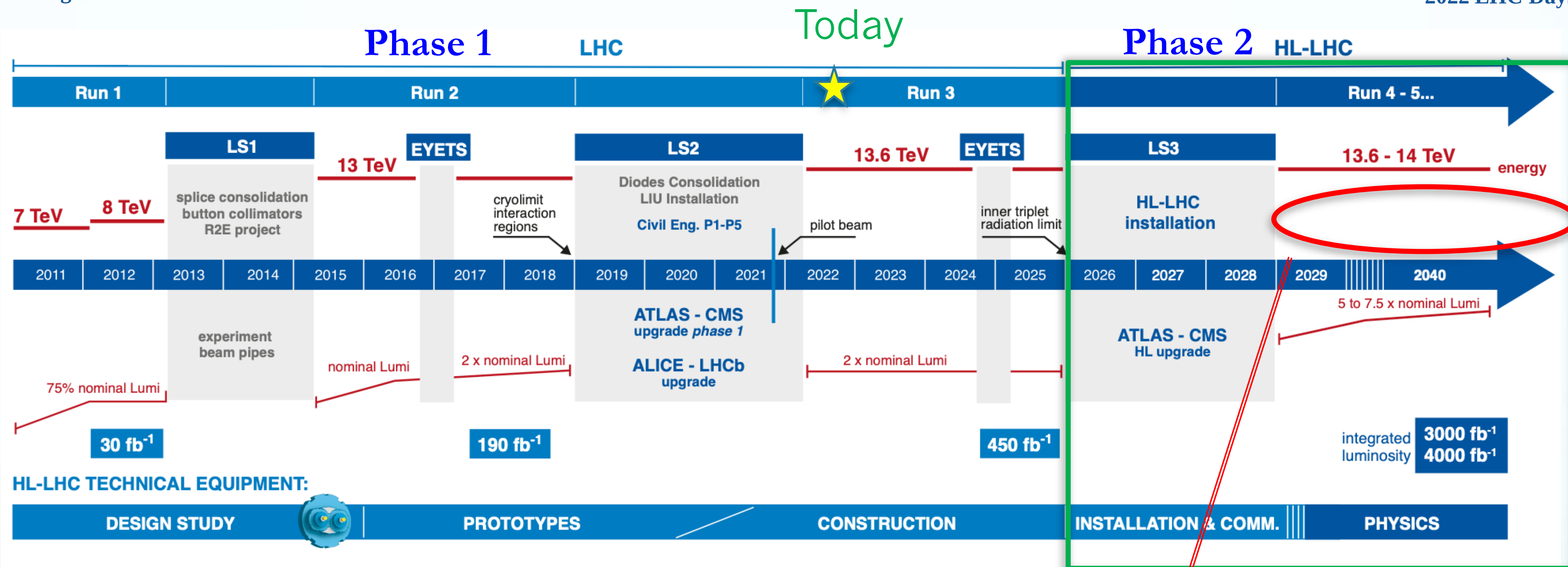
- Graph Neural Networks for **Jet tagging in the searches for HH production**

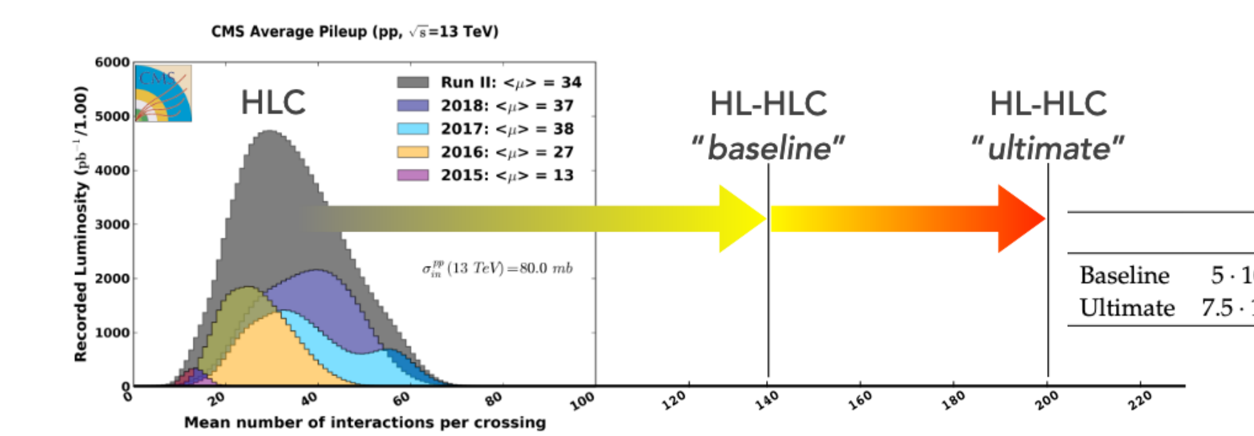


G. Pugliese

LHC and HL-LHC schedule

2022 LHC Days



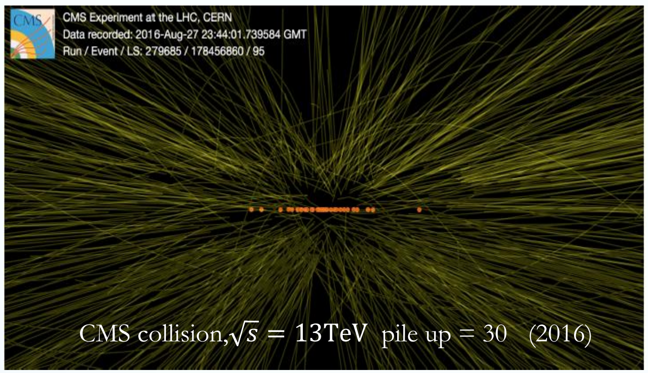


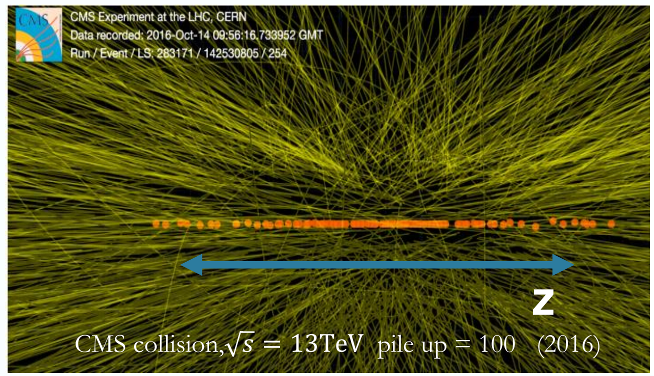
10 years of running at higher rates and radiation doses

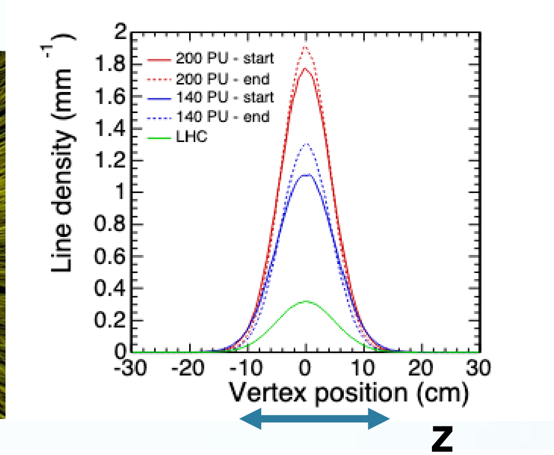
	$\mathcal{L}$	$\langle$ PU $\rangle$	Vertex Density	$\int \mathcal{L}$ / year
Baseline	$5 \cdot 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$	140	0.8/ mm	250 $\mathrm{fb^{-1}}$
Ultimate	$7.5 \cdot 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$	200	1.2/ mm	> 300 $\mathrm{fb^{-1}}$

HL-LHC: beyond present detector ability

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

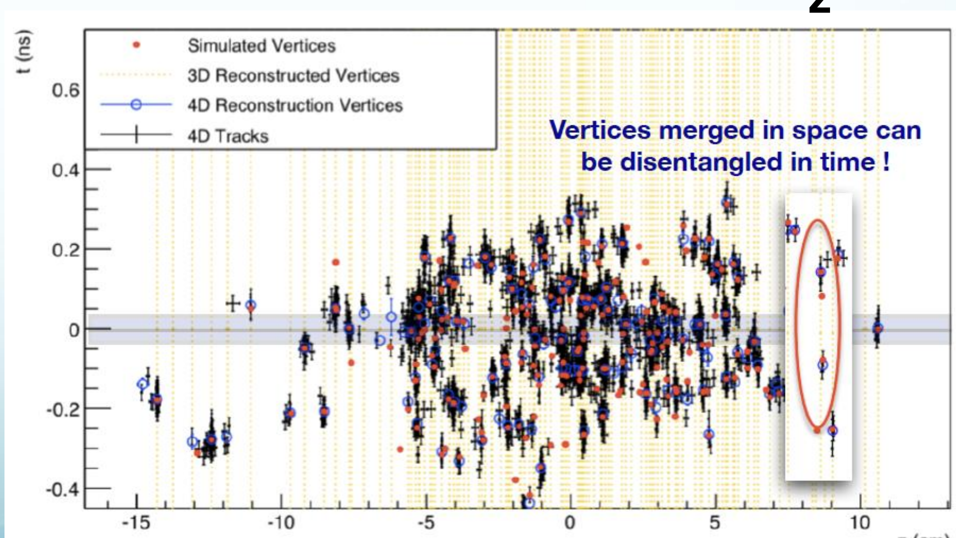






In CMS, PU mitigation strategy relies on:

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



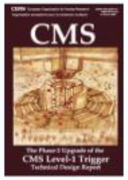
Time and z position of all vertex @ PU = 120

G. Pugliese

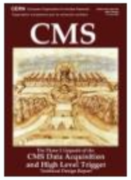
2022 LHC Days

CMS Upgrade Project

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

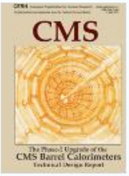


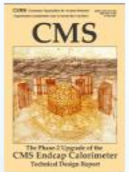
Level-1 Trigger
https://cds.cern.ch/record/2714892
- Tracks in L1 Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



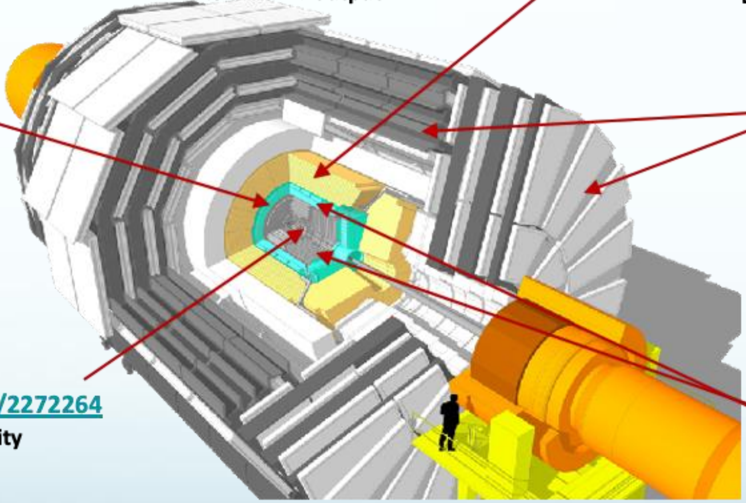
DAQ & High-Level Trigger
https://cds.cern.ch/record/2759072
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

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

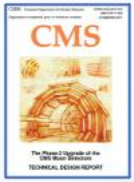


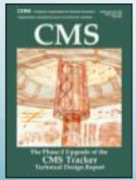


High-Granularity Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scintillator+SiPM in Pb/Cu-W/SS



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 $\eta \simeq 3$

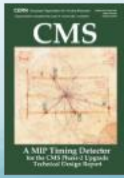


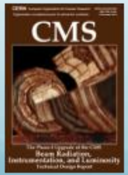


Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Extended coverage to $\eta \simeq 4$
- Design for tracking in L1 Trigger

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





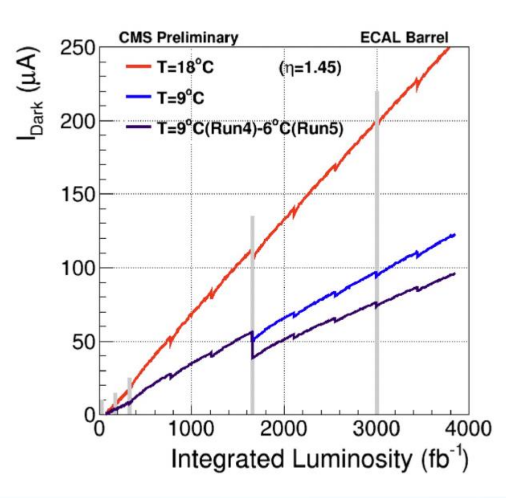
Beam Radiation Instrumentation and Luminosity
http://cds.cern.ch/record/2759074
- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity: 1% offline, 2% online
- Neutron and mixed-field radiation monitors

ECAL Barrel Calorimeter Upgrade

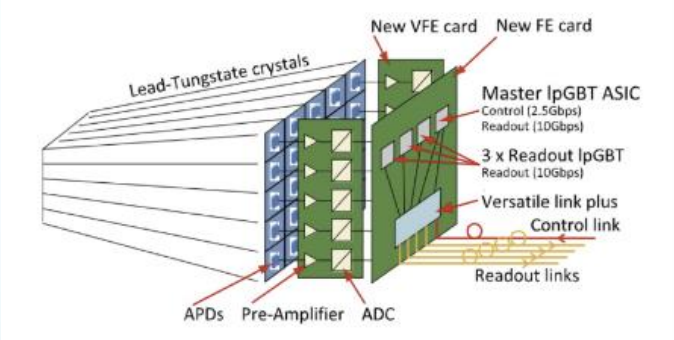
G. Pugliese

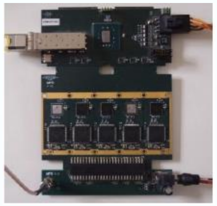
Key features for the Barrel Calorimeter:

- Keep the lead tungstate crystals and APDs
- Decrease operation temperature from 18 to 9°C to mitigate the increase in the APD leakage current

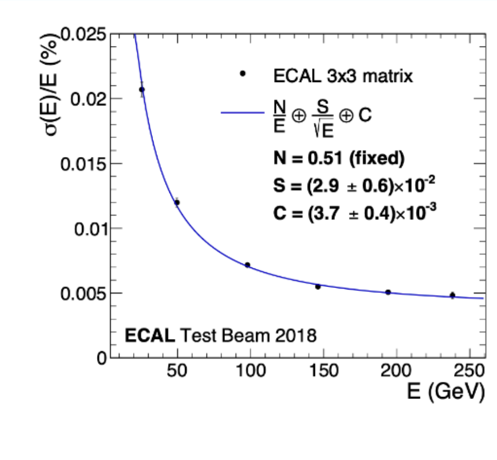


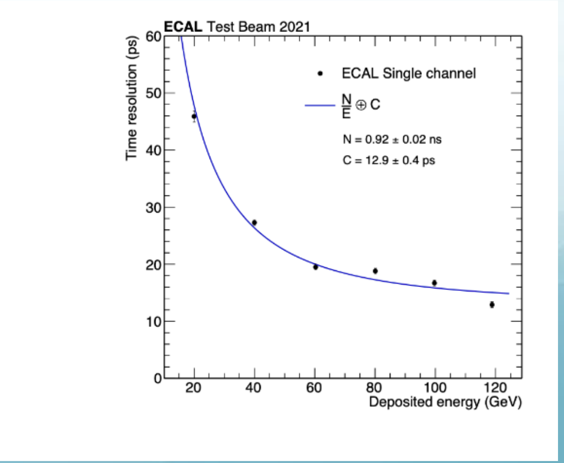
- Replace the on- and off-detector electronics. New front-end boards will allow the exploitation of the information from single crystals in the LV1 trigger





- 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



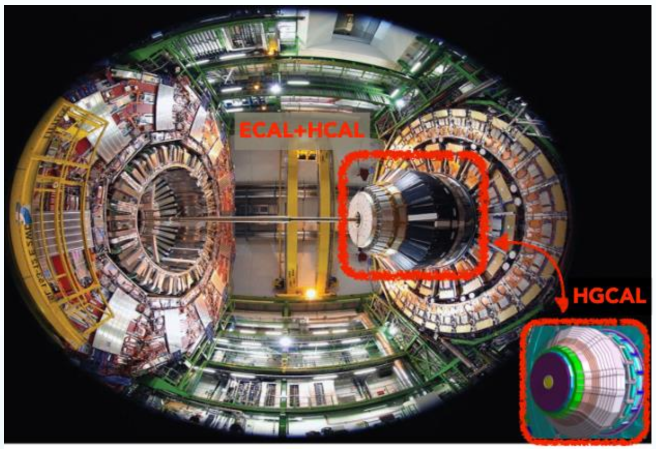


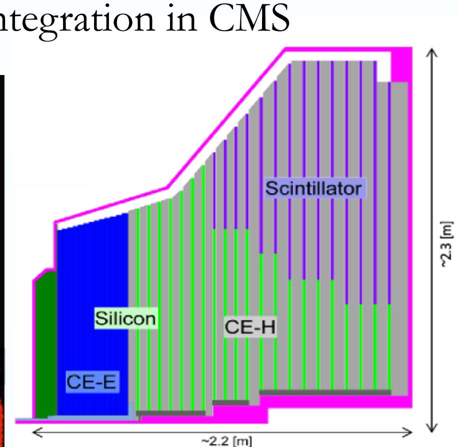
High Granularity Endcap Calorimeter

G. Pugliese

See dedicated talk by M. Mandelli (this session)

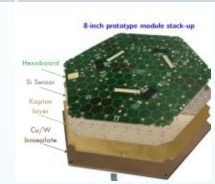
- Brand new calorimeter in the endcap region: the High Granularity Calorimeter (HGCal)
- High **granularity and timing performance** for the electromagnetic and hadronic sampling calorimeters
- Mixed technologies. Challenging integration in CMS

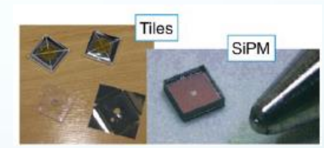




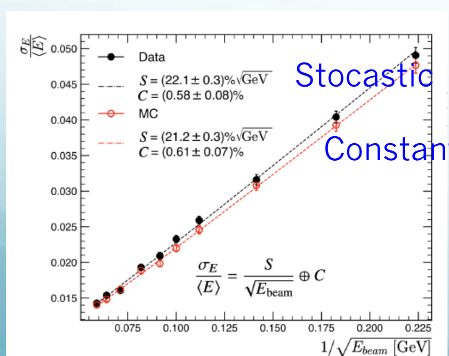
Coverage 1.5 < |<η |< 3
Operational temperature -35°C

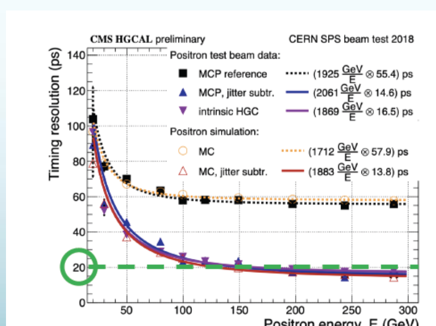
	Electromagnetic CE-E		Hadronic CE-H
Active	**Silicon Sensors** (Hexagonal shape)	**Plastic Scintillator tiles**	
Area	620 m^2	400 m^2	
N. of Modules/channels	30k/6M	4k/240k	
Channel Size	0.5 -1 cm^2	4 -30 cm^2	
N. of layers	28		22
Depth	26 X_0 /1.7 λ		9 λ
Absorber	Lead		Stainless Steel





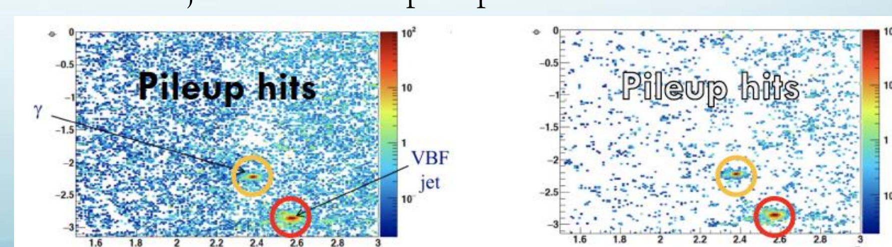
- Prototypes showed excellent results on test beams:





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

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



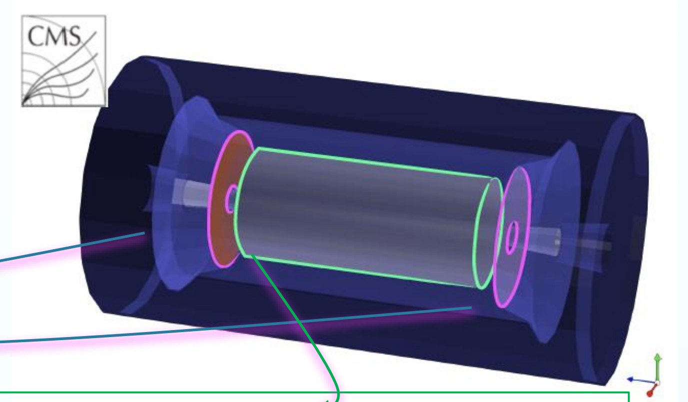
VBF H → γγ

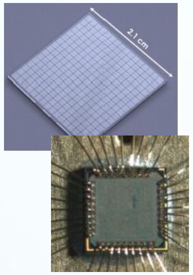
G. Pugliese

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 $|\eta| < 3$
- **Time resolution** of 30-50 ps to **MIPs**

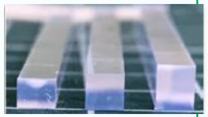




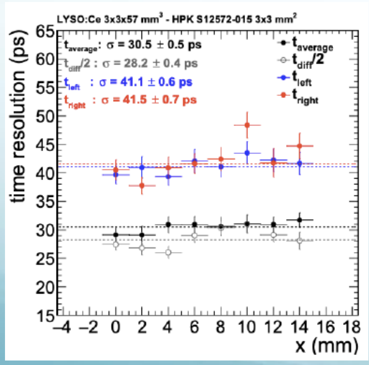
Endcap Timing Layer (ETL)
Two disks for each endcap to ensure 2 hits for each track
Low Gain Avalanche Diodes with ETROC ASIC readout
Total surface 14 m^2
Radiation level: 2 10^{15} n_{eq}/cm^2

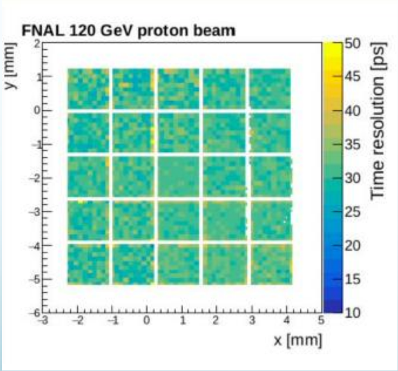
Operating temperature:-30°C

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



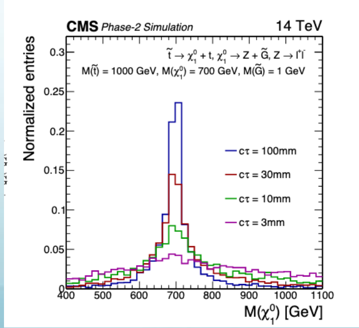
➢ Test beams performed on several prototypes showed:

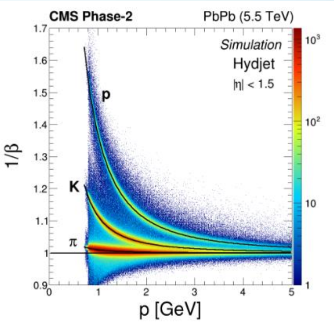




➢ Excellent ~30 ps **time resolution** on BTL and ETL (non irradiated) sensors

➢ 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





Neutralino mass distributions

G. Pugliese

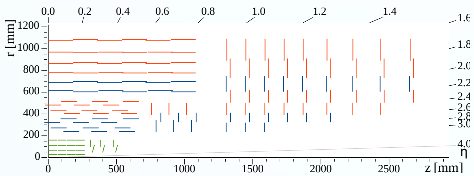
Tracker Upgrade

Key features of the new Phase 2 Tracker:

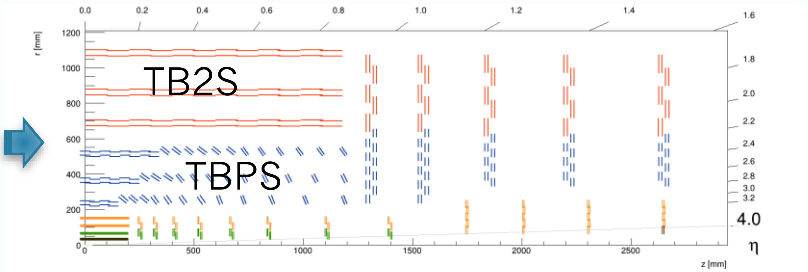
- **Extended tracking** acceptance up to |η| = 4
- **Increased granularity**

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

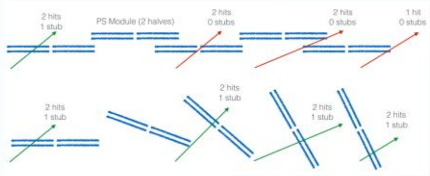
Phase 1



Phase 2

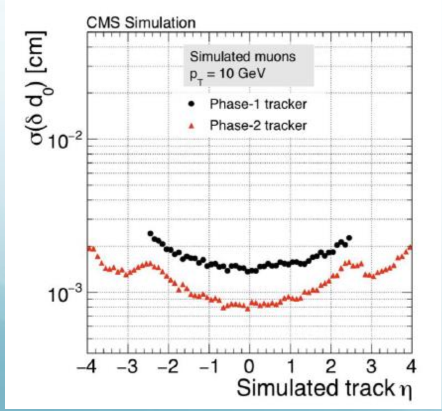


- → Two type of technologies: **micro-strips** and **macro-pixel**
- → **Tilted barrel geometry for** better trigger performance and reduction on number of modules

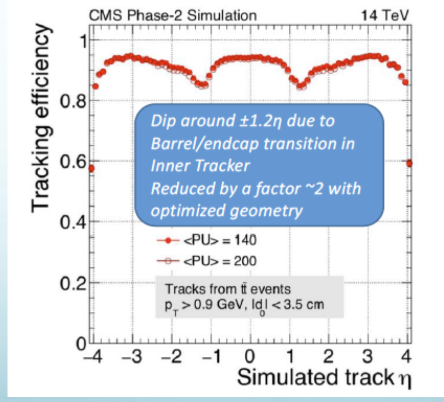


- Radiation tolerance up to 10^{16} 1 MeV neq
- Expected rate 3 GHz/cm² innermost pixel layer
- Material budget reduced by a factor of 2
- **Improved performance:**

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



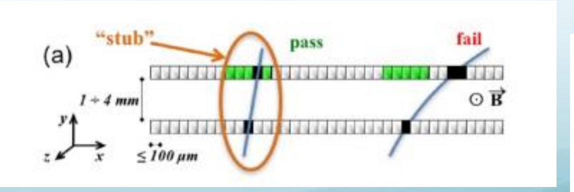
Transvers momentum resolution improved (and extended) wrt. Phase 1

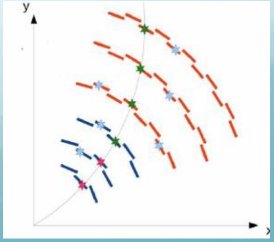


Good **tracking efficiency** (90%) even at PU 200

- **Level 1 Triggering (new functionally):**

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

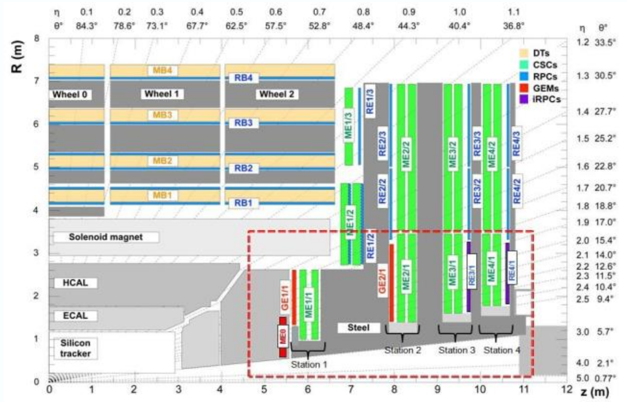




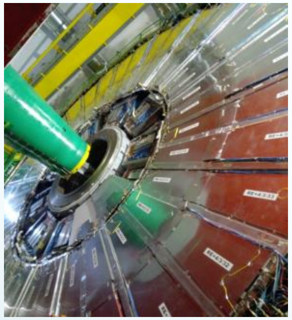
Muon System Upgrade

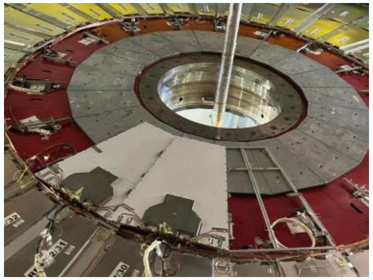
G. Pugliese

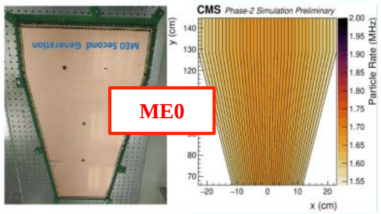
- **New detectors** in the endcap region, to restore redundancy and extend the muon coverage up η = 2.8, based on GEM and improved RPC (ME0, GE2/1, RE3/1 and RE4/1)



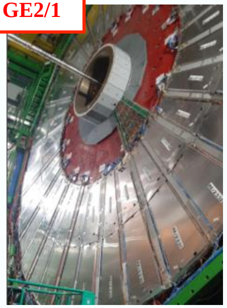
- **RE2/1 mass production** started in 2022
- Four demo-chambers installed in CMS

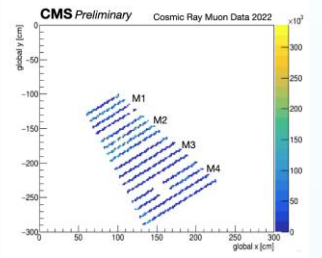






- **GE2/1 mass production** started in 2021
- One demo-chamber installed

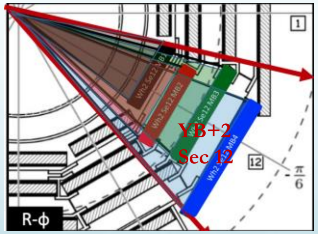




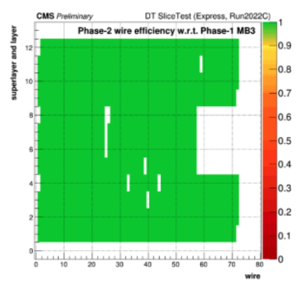
GE2/1 demonstrator occupancy map

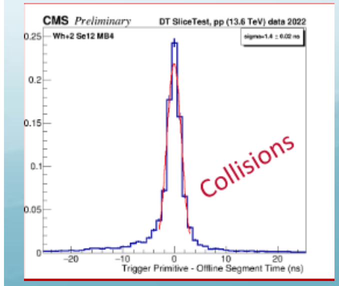
- **New electronics for the legacy detectors:**
  DT: replace all On-Board electronics (OBDT), BE
  RPC: replace all off-chamber electronics, BE
  CSC: replace selected FE boards (**DONE in LS2**), replace all BE

- DT Phase-2 Slice demonstrator equipped with both legacy and new on-board electronics (OBDT_v1).



- Synchronized **inter-channel response** to few ns precision
- Measured Phase-1 and Phase-2 **Hit efficiency:** consistent with 100%
- Measured **Phase 2 trigger primitive's timing** resolution: comparable to the offline reconstruction





Conclusion

- Multiple changes were made to the CMS detector during the last Long Shutdown in view of RUN3 and beyond:
  - New/upgraded detectors and electronics (MUONs, Tracker, HCAL, BRIL)
  - Improved/new trigger algorithms
  - Improved tools and procedures for calibrations and data certification
- CMS detectors was fully commissioned with cosmic muons and first proto-proton collisions
- RUN3 detector performance is being studied and preliminary results are very satisfactory!

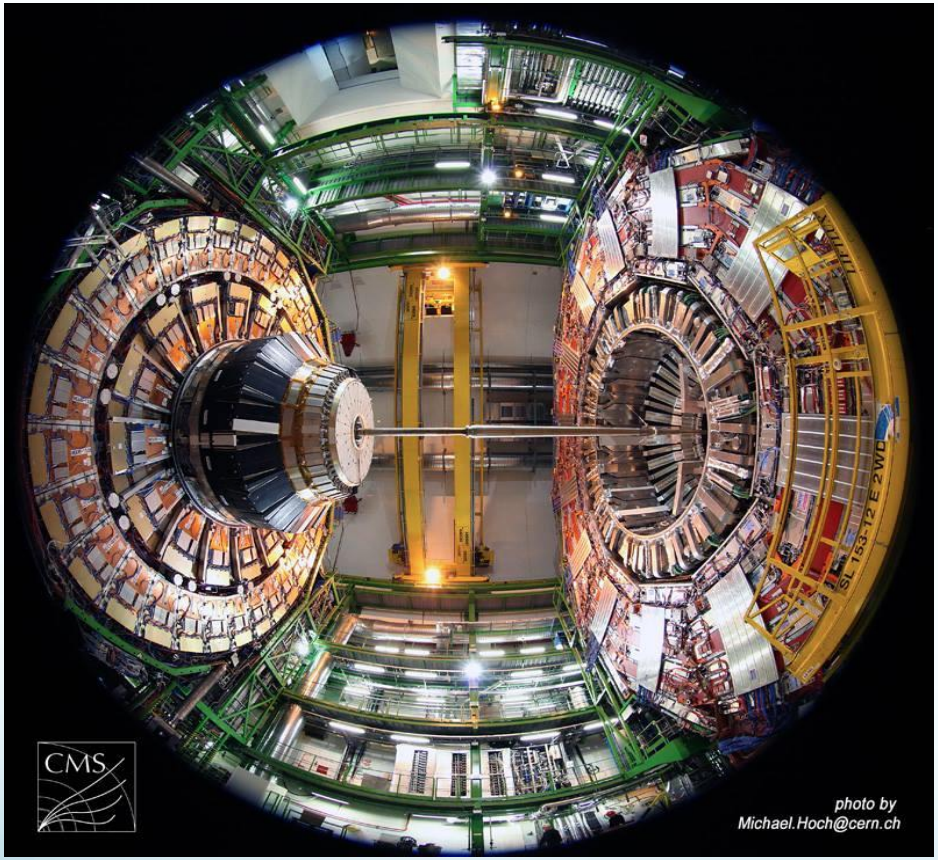
- A challenging CMS Phase2 upgrade project has been defined to exploit the full potential of the HL-LHC luminosity
- All sub-projects continue to make remarkable progress and the transition from final prototyping to pre-production/production is happening now in many areas

- The first phase2 detectors (muon GE1/1) and all planned demonstrators (Muons and BRIL) were installed and fully integrated in CMS

G. Pugliese

Thanks!

Credits
to the CMS People



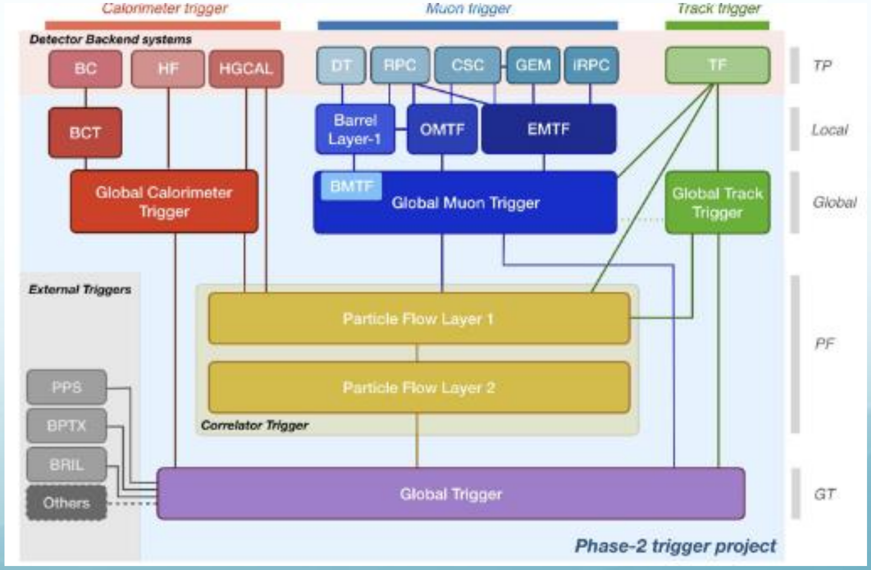
Backup slides

G. Pugliese

DAQ and Trigger Upgrade

HL-LHC DAQ-HLT Parameters

	LHC	HL-LHC	
CMS detector	Phase-1	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

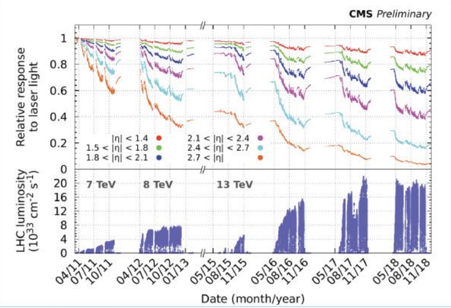


ECAL longevity

G. Pugliese

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

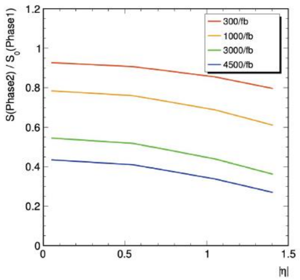


EB: 90%

EE low eta: 40-80%

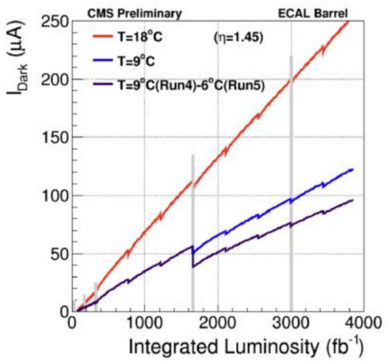
EE high eta: 5-20%

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

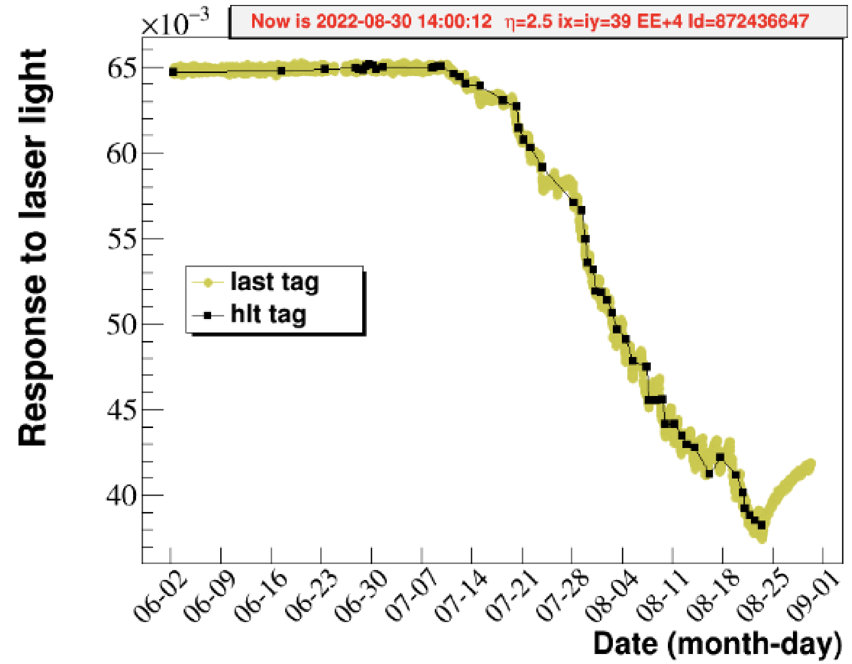
- Two causes of radiation damage to APDs:
  - Gamma rays creating surface defects
    - Increasing surface current
    - Reducing quantum efficiency
  - Hadrons creating bulk damage
    - Causing an increase in the bulk current
- Main concern for HL-LHC is the increase of dark current
  - Electronic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



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.

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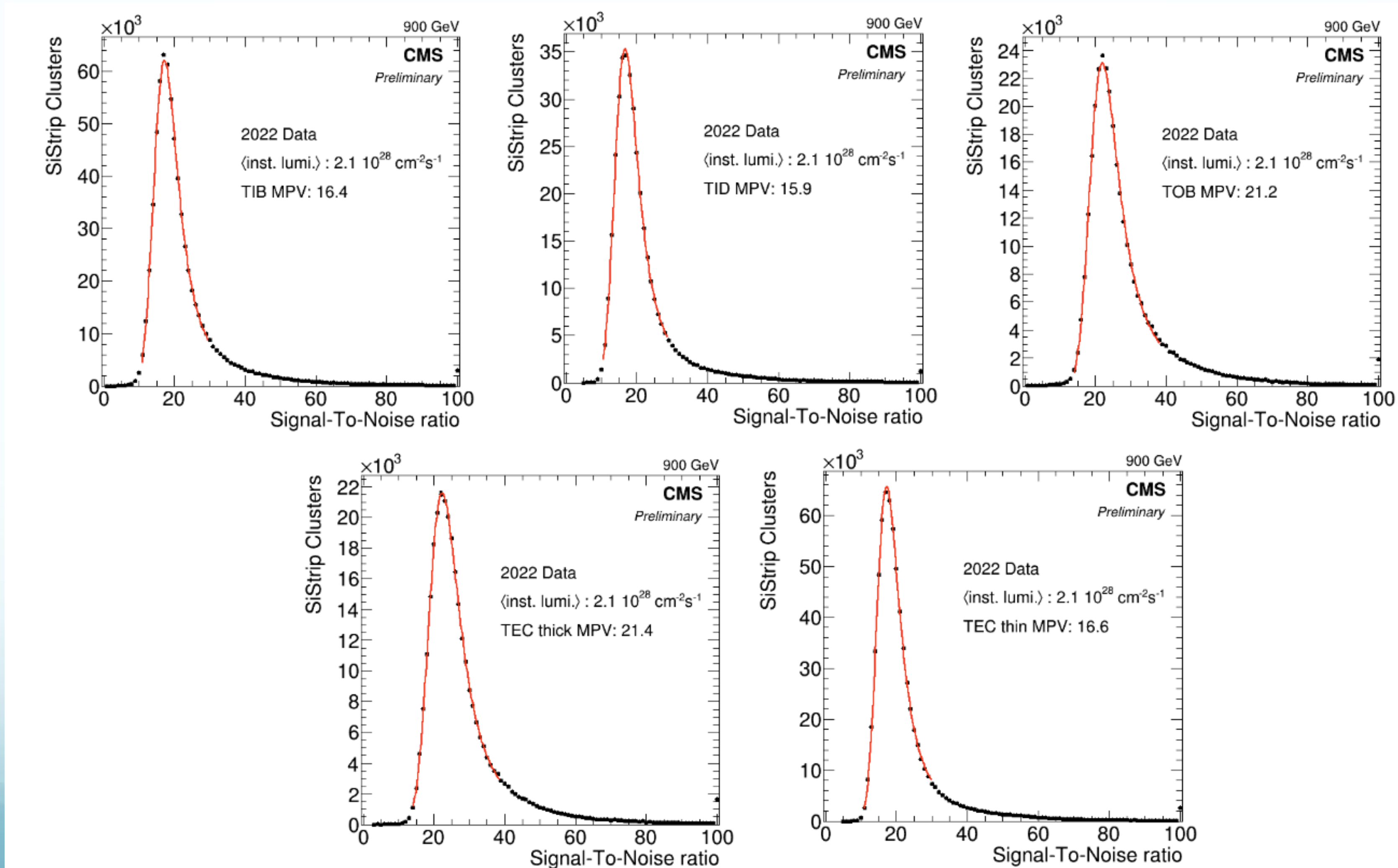
RUN3 Tracker Performance



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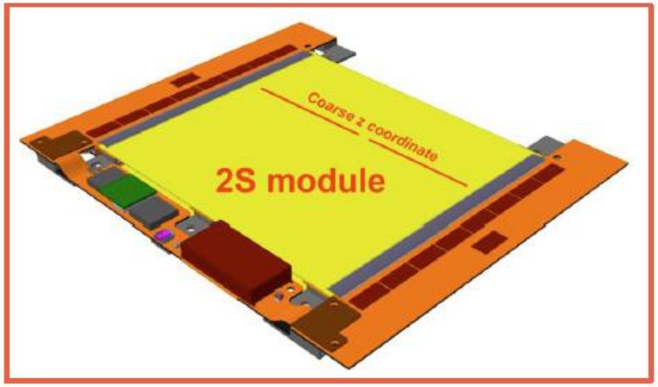
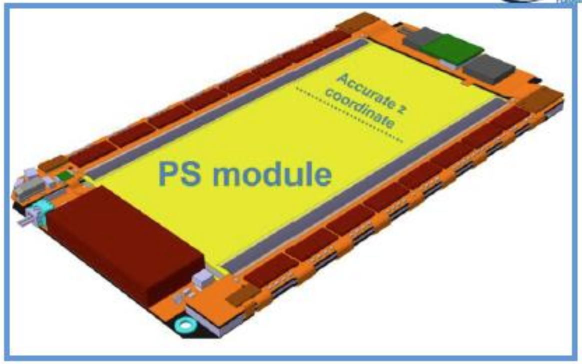
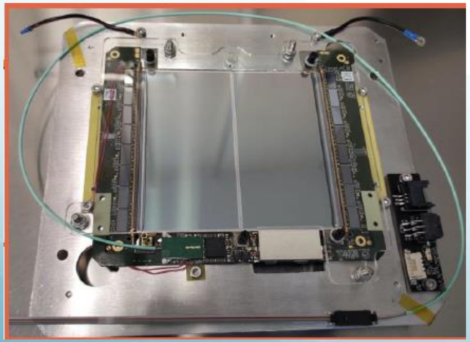
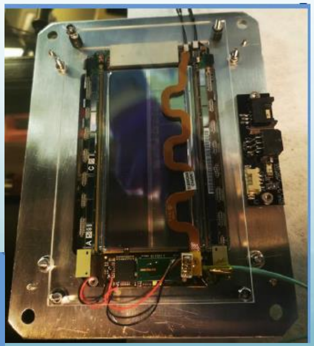
Phase 2 OUTER Tracker modules





- 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…

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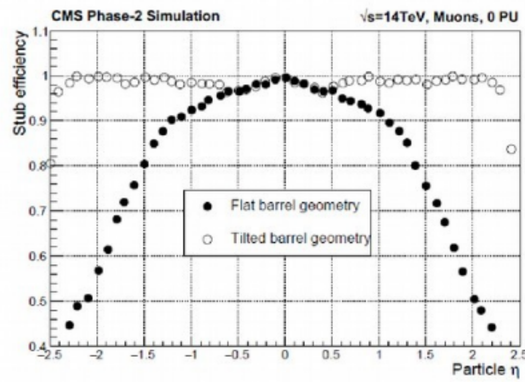
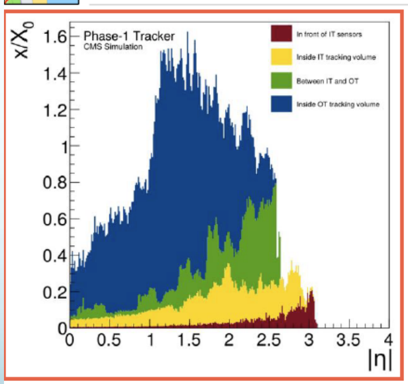
Phase 2 Tracker Upgrade

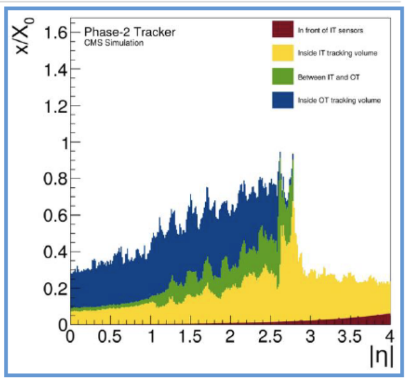
Tilted Barrel Geometry

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

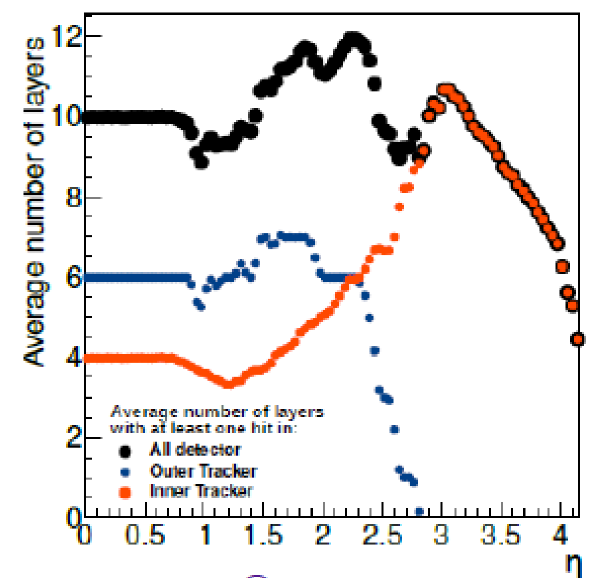


Material Budget





- 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*

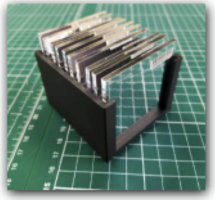


Occupancy no larger than 3%

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

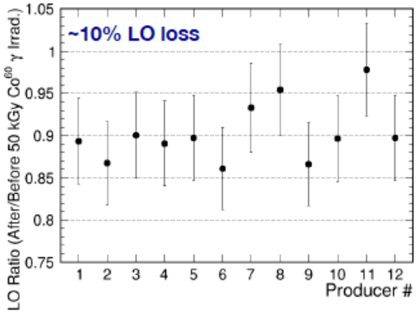


Comprehensive study of LYSO:Ce crystals from 12 producers performed to identify potential BTL suppliers and set the QA/QC requirements for the production stage.

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

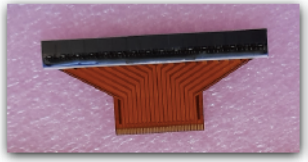


TENDER SUBMISSION BY THE END OF THE YEAR

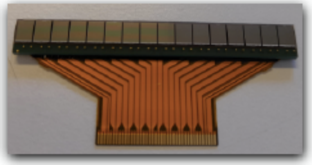
SiPMs

- 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

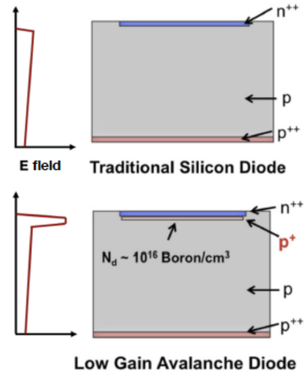
(optimized prototype testing on going)

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**

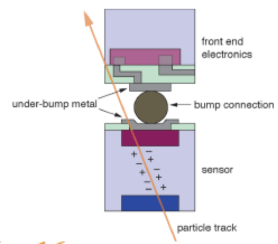
The final sensor will be a 50 μm-thick 16×16 pad array with 1.3×1.3 mm² pads

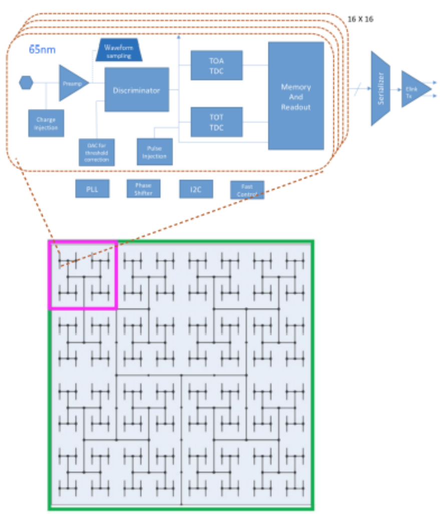
M. Tornago, ICHEP 2022

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

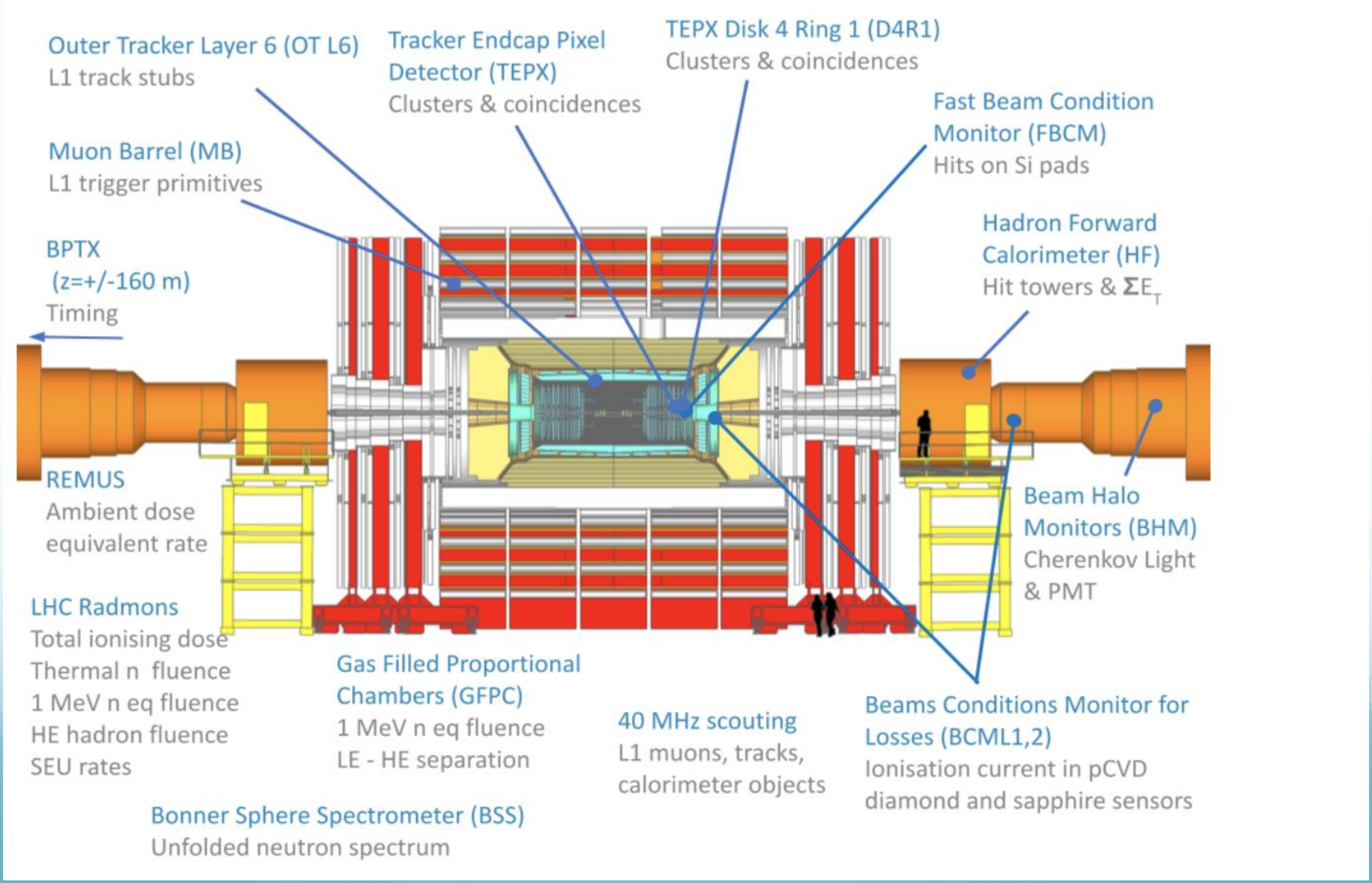
- ✓ **ETROC0: single analog channel**
- ✓ **ETROC1: full front-end with TDC and 4×4 clock tree**

➡ **ETROC2 design in progress: full functionality + full size**

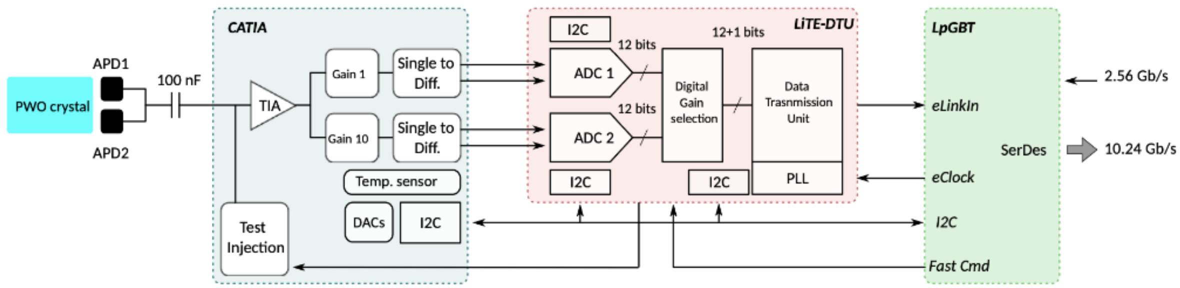
➡ **ETROC3:** submission in March 2024, pre-production chip

G. Pugliese

BRIL UPGRADE project



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

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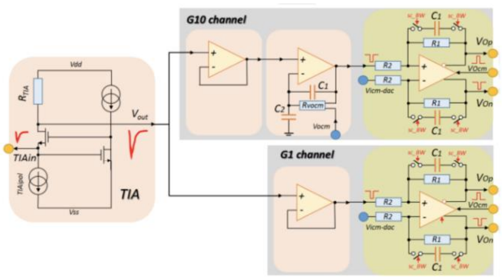
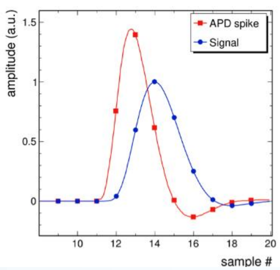
ECAL Phase 2 Upgrade

CATIA ASIC Overview

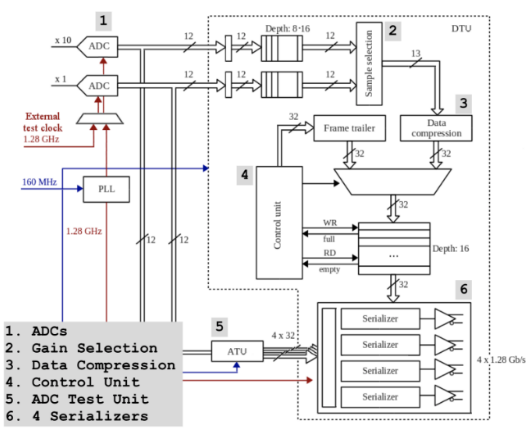


- Two gain stages after the pre-amplifier: G1 and G10
- Implemented in 130 nm (TSMC)
- Range: from 50 MeV to 200 GeV (G10) and 2 TeV (G1)
- Bandwidth: 35 MHz



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

LiTE-DTU ASIC Overview

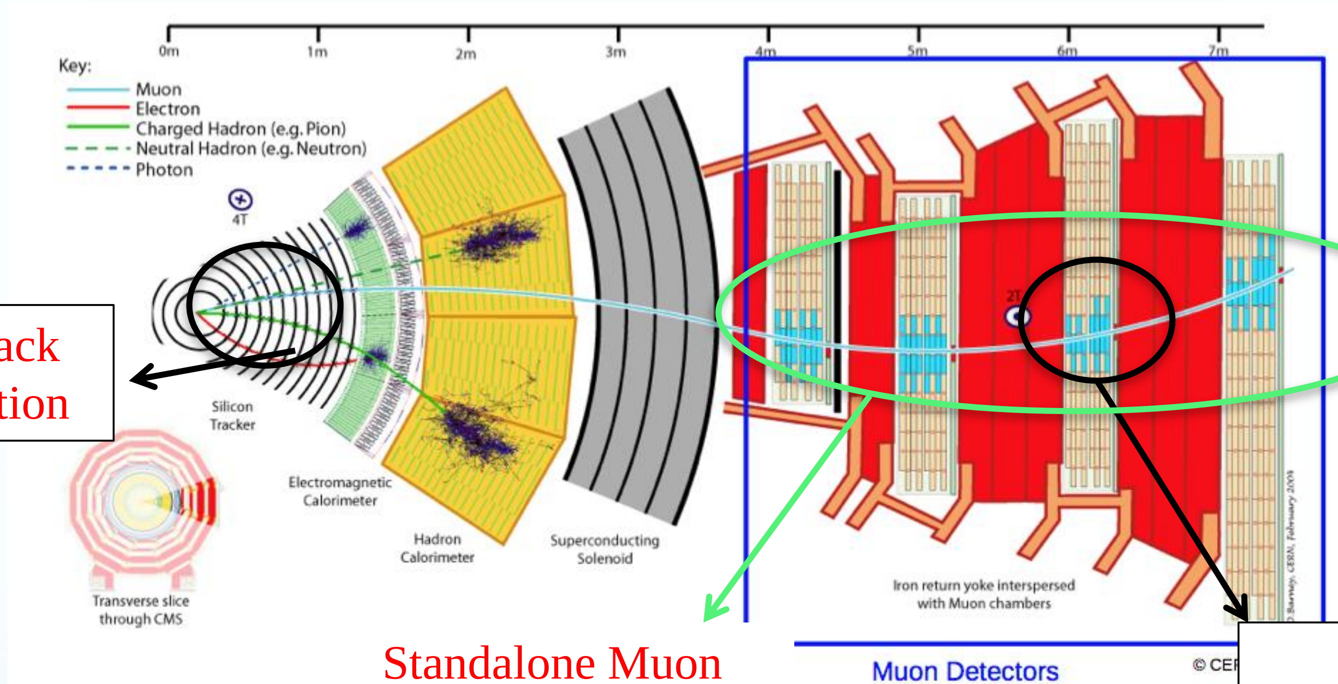


Sampling rate 40 MHz → **160 MHz**
➥ improves time resolution

- 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

G. Pugliese

Muon Reconstruction



Tracker track reconstruction

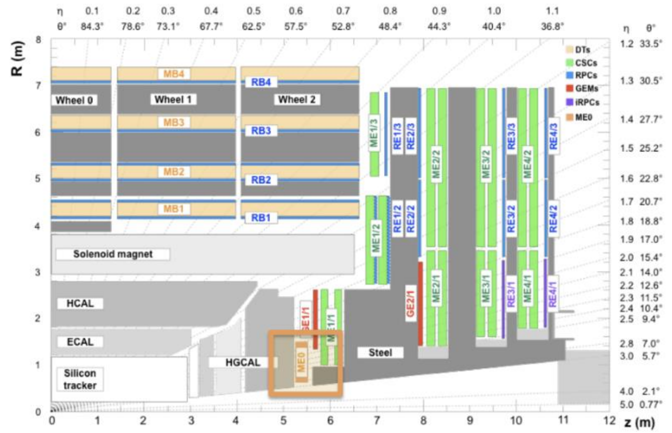
Standalone Muon reconstruction
Performed using DT/CSC segments & RPC hits

Local reconstruction
Performed within single chamber

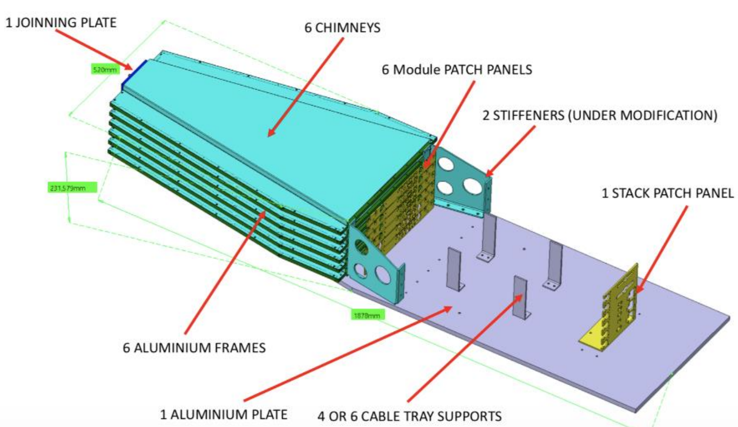
Global muon reconstruction **(out side –in)**: a standalone muon is propagated to match a tracker track. If matching is positive a global fitting is performed.
Tracker Muon **(inside – outside)**: a tracker track is propagated to muon system and qualified as muon if matching with standalone or one segment.

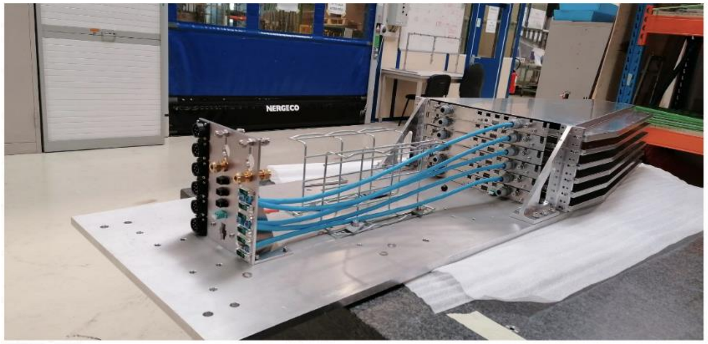
ME0

- 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





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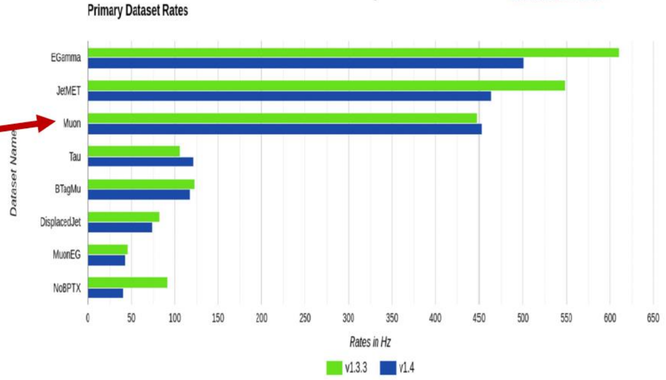
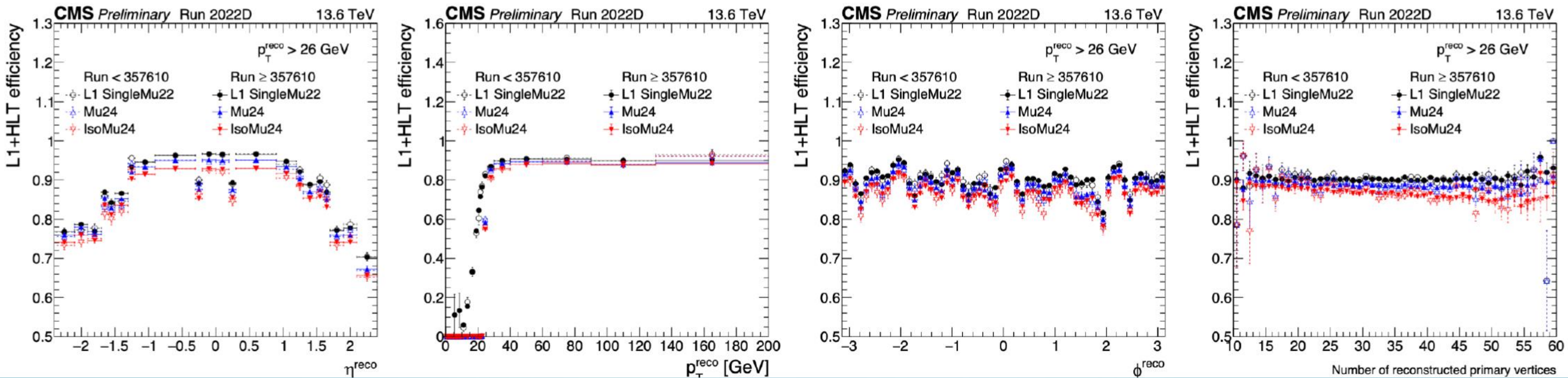
Muons at HLT

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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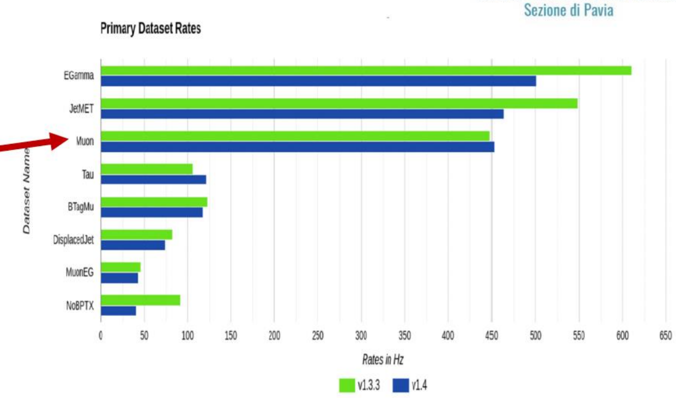

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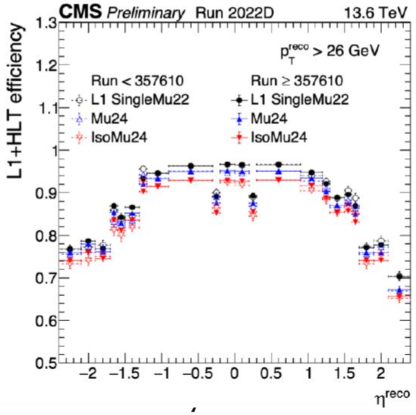
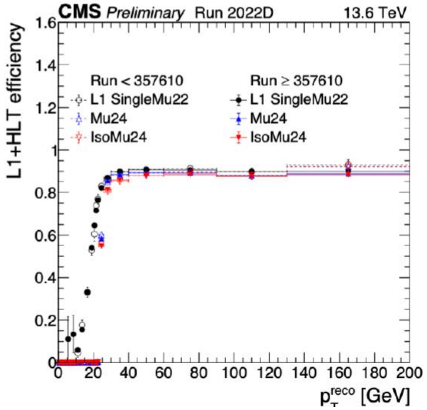


p_T



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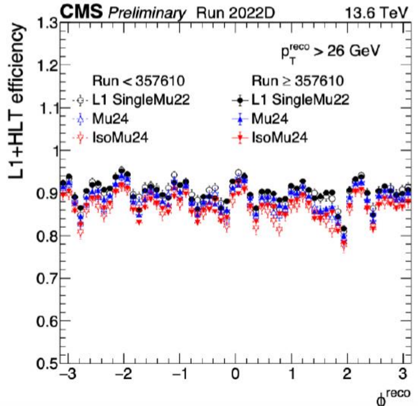
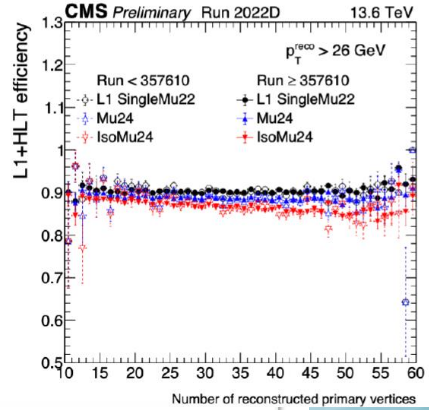


$nvtx$



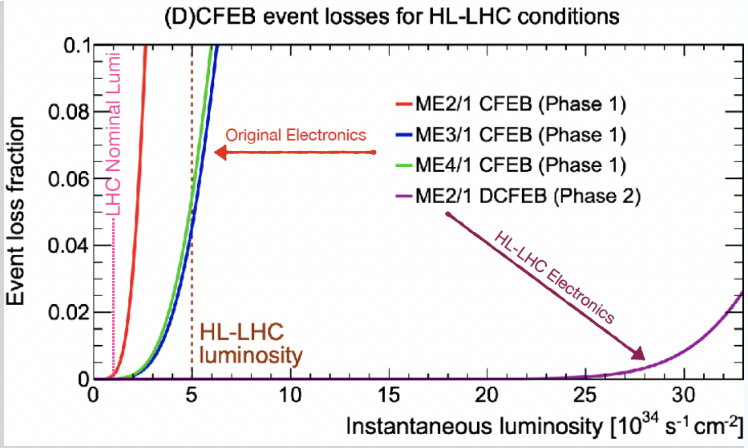
- Improve Trigger hit time resolution from 25 ns to 1.5ns
- 1376 link boards, 216 control boards

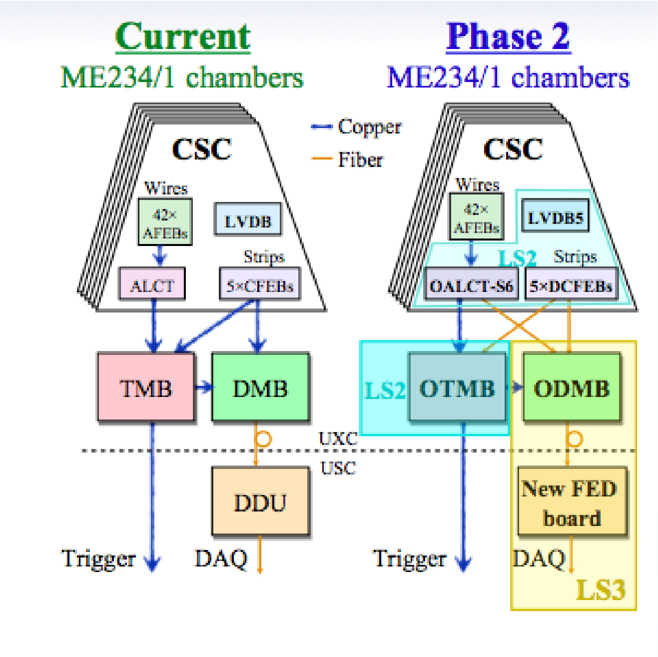
Max int. charge@3ab^{-1} (SF = 3 included)	~ 0.8 C/cm^2	~ 1.0 C / cm^2
Phi granularity	~ 0.3°	~ 0.2°
Eta resolution	~ 20 cm	~ 2 cm
Time resolution	1.5 ns	< 1 ns

G. Pugliese

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

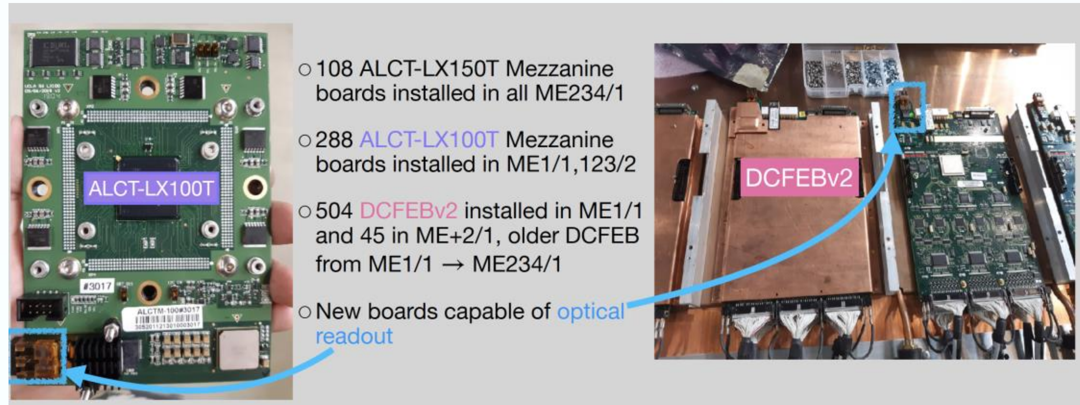
LS2

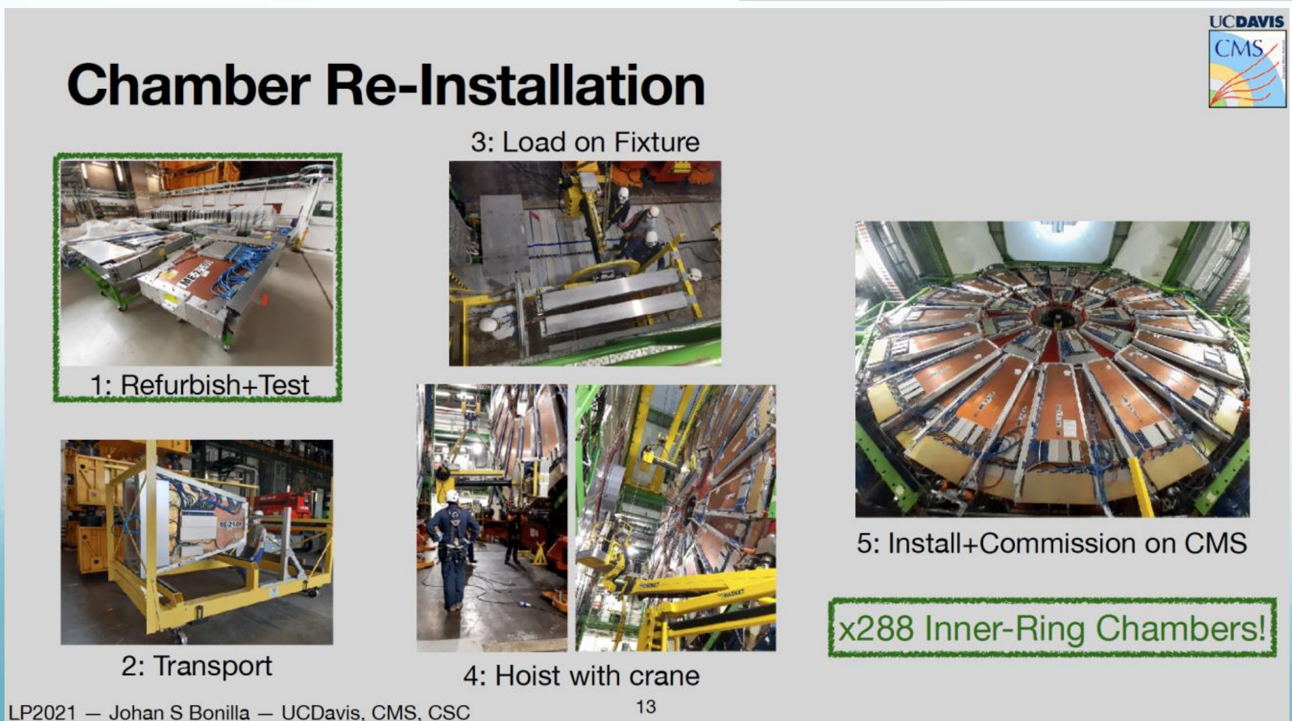
LS3

G. Pugliese

LS2 CSC Upgrade activity

The on-detector Refurbishment of Electronics in LS2

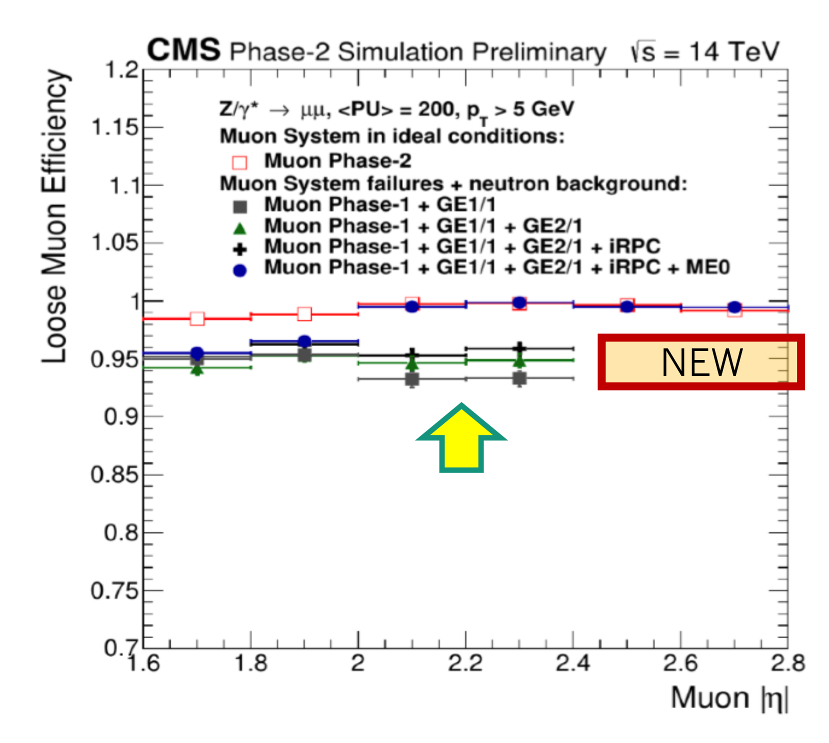




Muon Upgrade

G. Pugliese

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