CMS Upgrades

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On behalf of the CMS Collaboration

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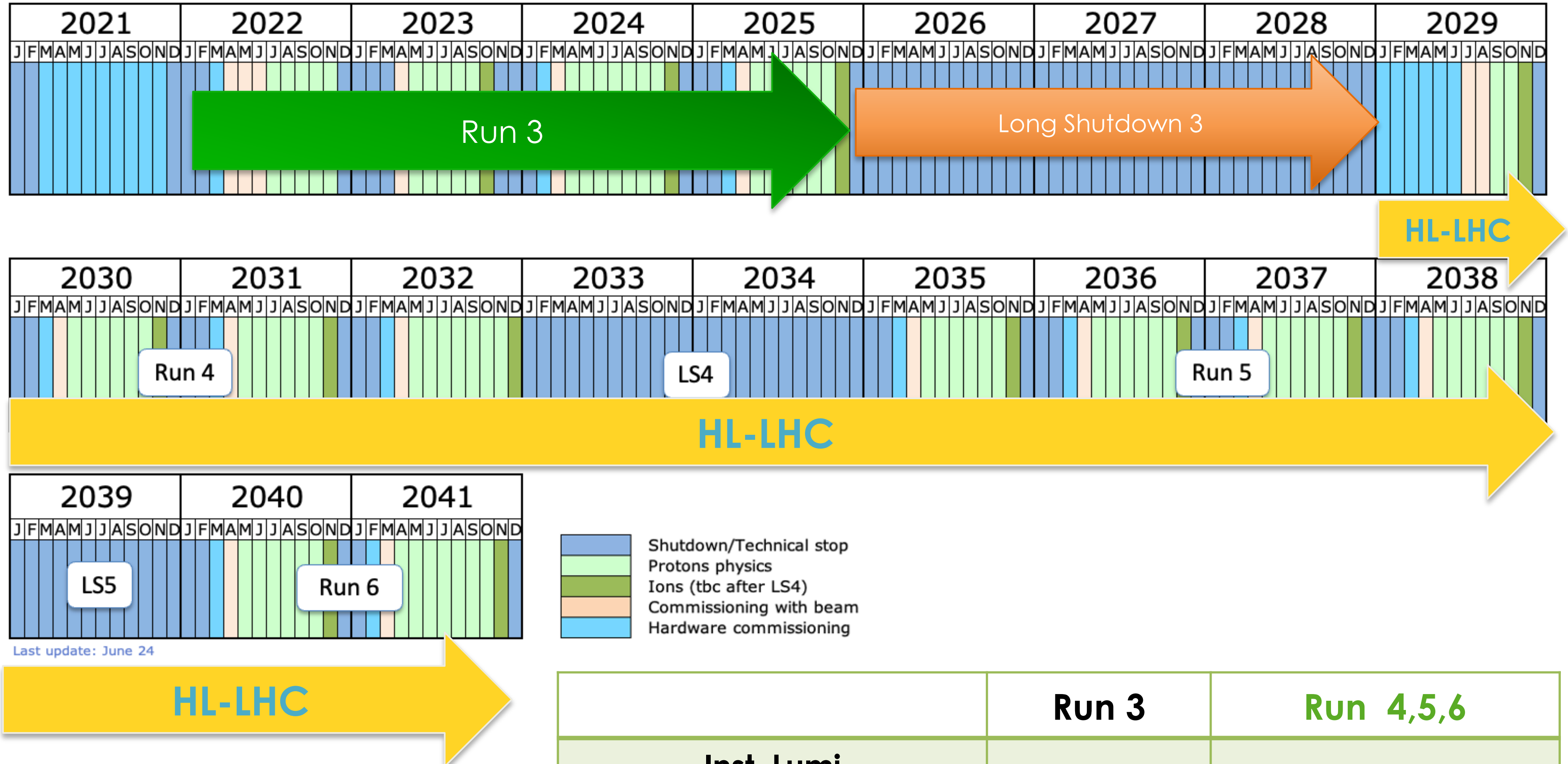
Towards HL-LHC



	Run 3	**Run 4,5,6**
Inst. Lumi ($sec^{-1}\ cm^{-2}$)	$2x10^{34}$	**$5\text{-}7x10^{34}$**
Target int. lumi (fb^{-1})	250	**3000-4000**
Pile up	~50	**~140-200**

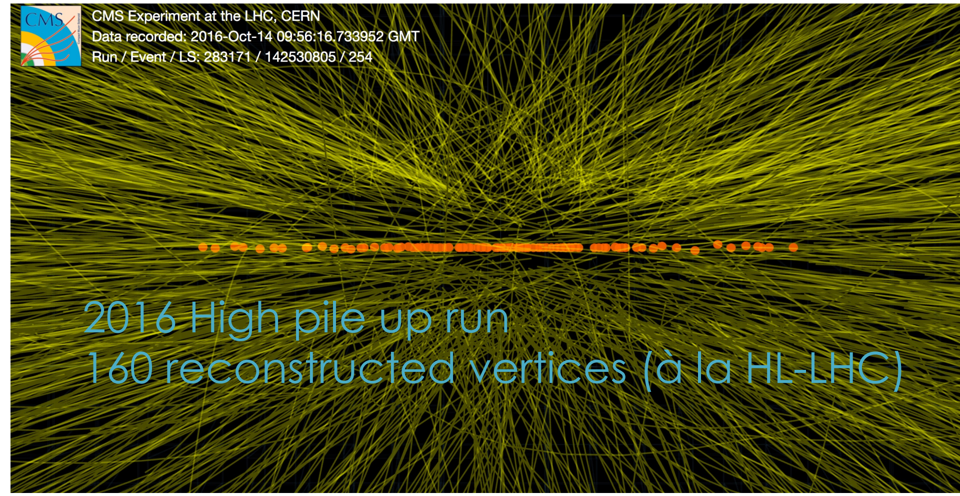
Towards HL-LHC

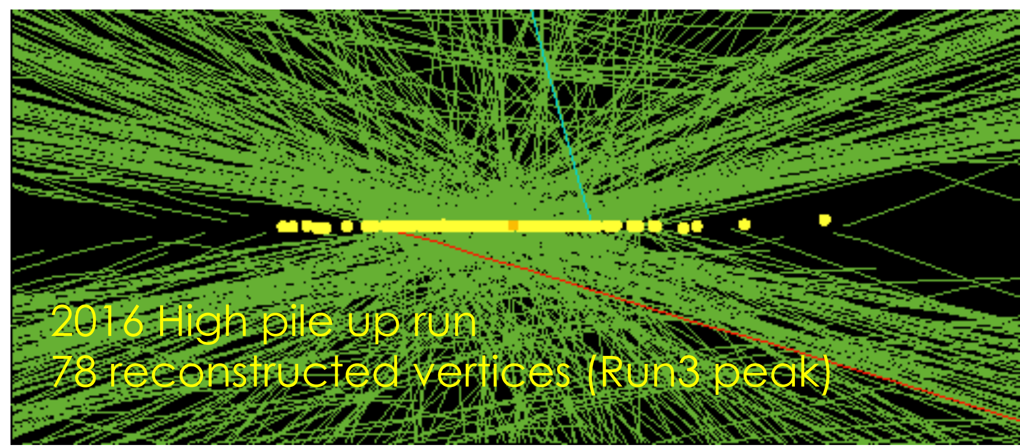
HL-LHC: challanging data taking conditions

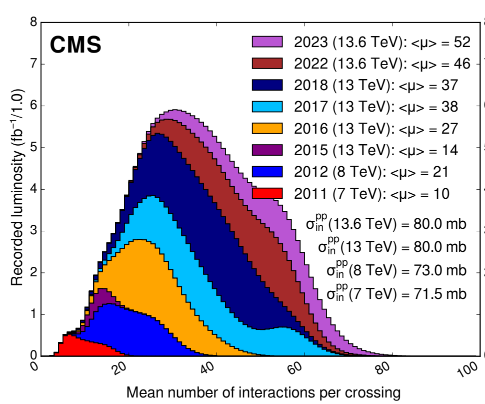
- Detector operations
- event reconstruction
- particle densities x5-10
- →Radiation damage x10

Requirements for experimental apparatus

- Increased detector granularities
- Significant use of (fast) timing
- Radiation hardness

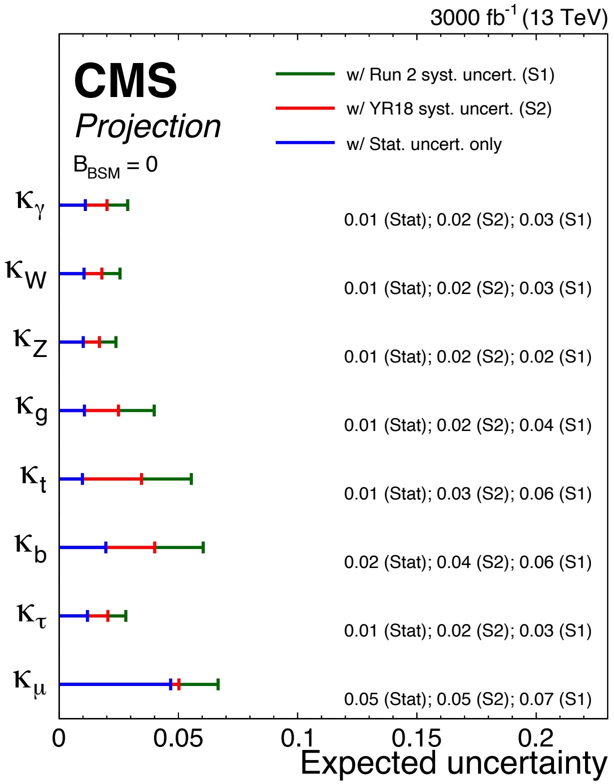


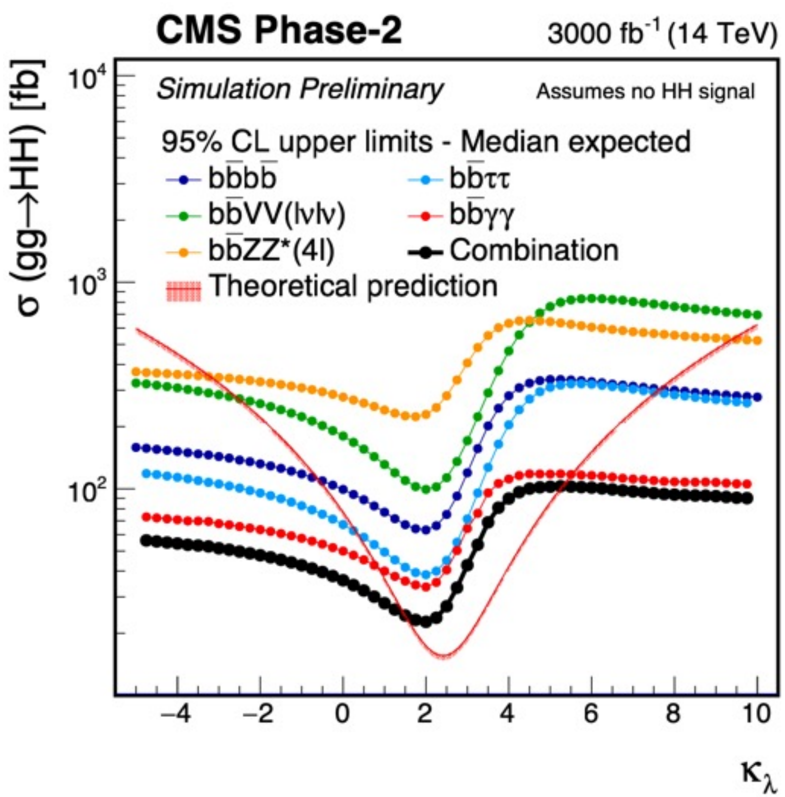




HL-LHC Physics Motivation

- Precisely test the Standard Model, including Higgs boson
- → Searches for rare processes H→cc, HH





https://arxiv.org/pdf/1902.10229

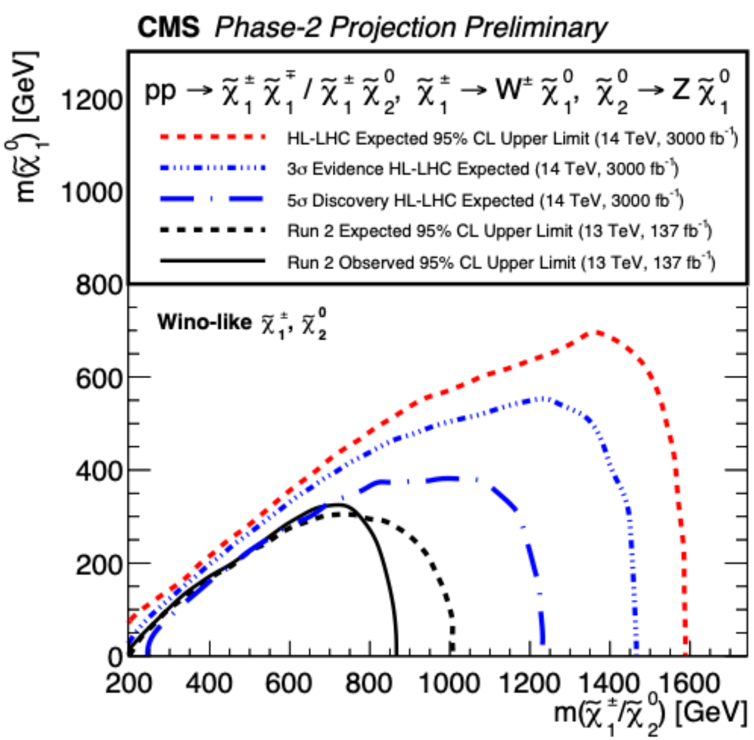
Extrapolation of Run2 analyses (35.9 fb−1)
O(few %) reached on SM couplings

2.6 sigma expected significance on HH
95% CL intervals for k_{λ}: [−0.18,3.6]

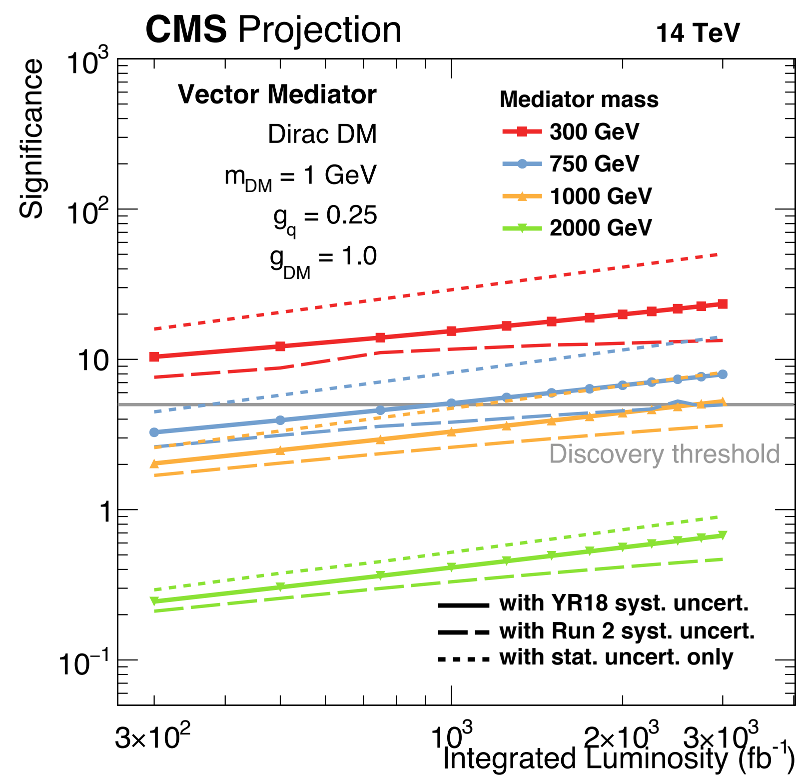
HL-LHC Physics Motivation

Present LHC has excluded large part of the natural SUSY parameter space

- Gaugino masses O(few*100 GeV)→small production cross sections, accessible to HL-LHC
- Hunt for exotic processes, including dark matter
- Full luminosity needed for evidence of new physics



Evidence:
SUSY gauginos with m<1.4 TeV



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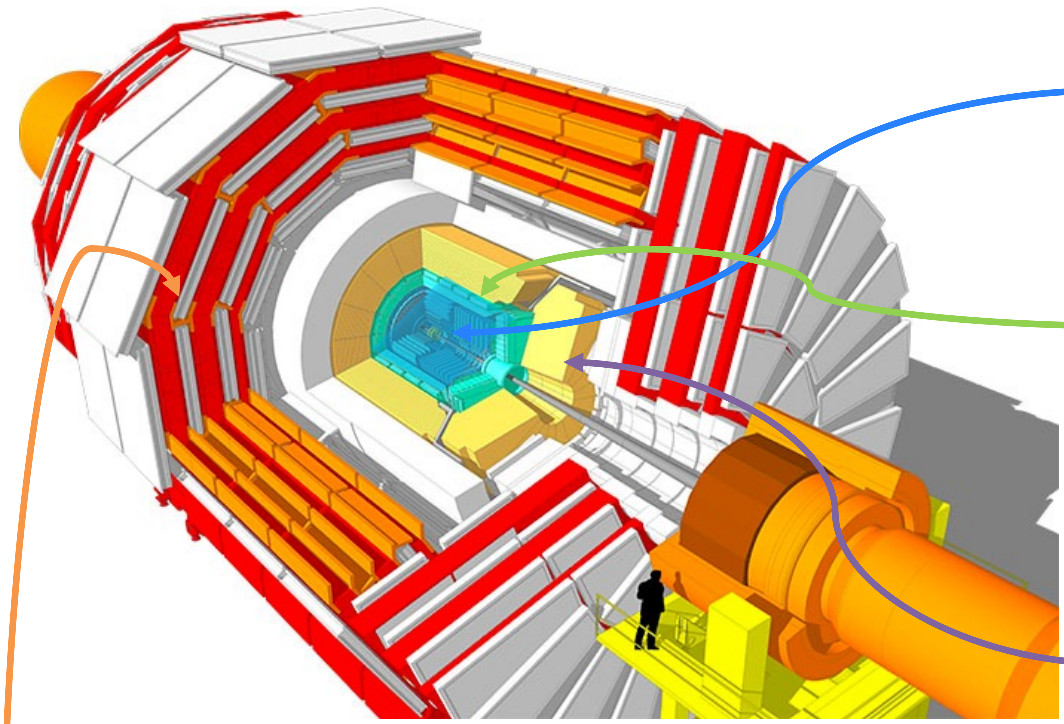
Evidence:
Dark matter with m<750 GeV

CMS Phase II Upgrades



Tracker
- Increased granularity
- Extended coverage to ~|4|
- Designed for tracking in L1T

New MIP timing detector
- 30 ps timing resolution
- Full coverage to $|\eta| \sim 3$

New High-Granularity Endcap Calorimeter (HGCAL)
- Imaging calorimeter
- 3D showers and precise timing

Muon System
- Extended coverage to ~ |3|
- Additional station with improved spatial and time resolution

CMS-PAS-TDR-15-002

Level 1 Trigger
- latency: 12.5 μs
- 750 kHz output
- 40 MHz data scouting

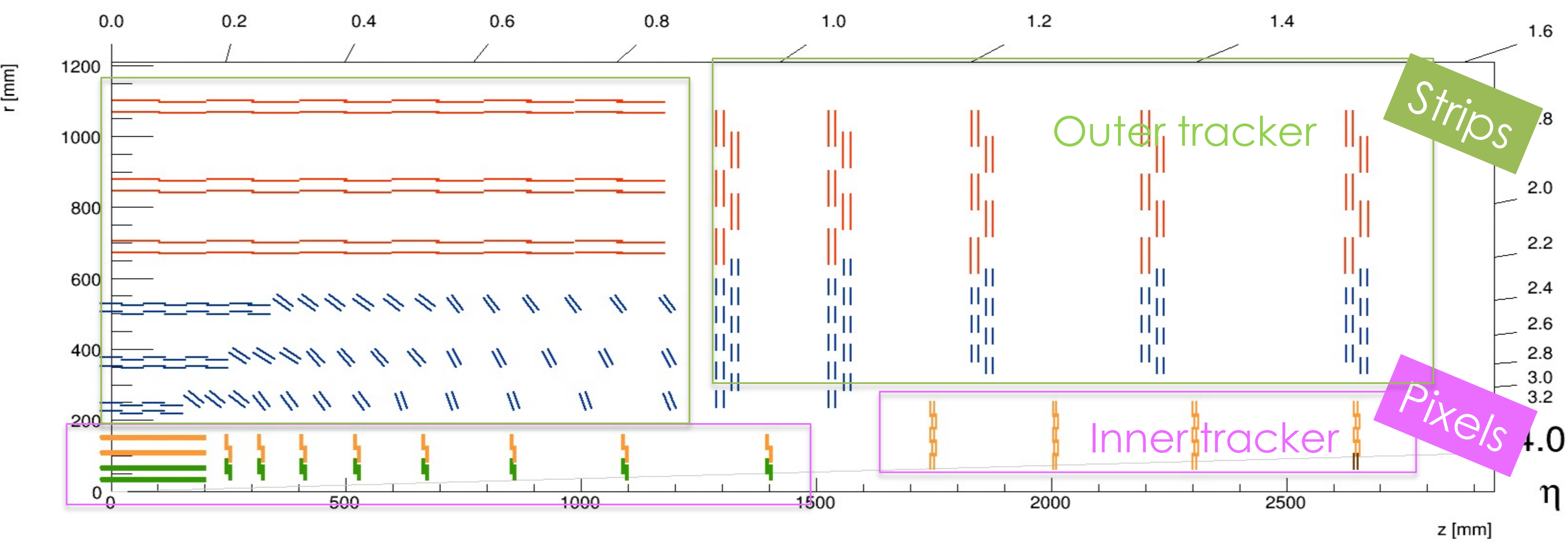
HLT
- Heterogeneous architecture
- 60 TB/s event throughput
- 7.5 kHz HLT output

Electronics Upgrades
- On/off-detector ECAL, HCAL, Muon Detectors
- 40 MHz continuous readout

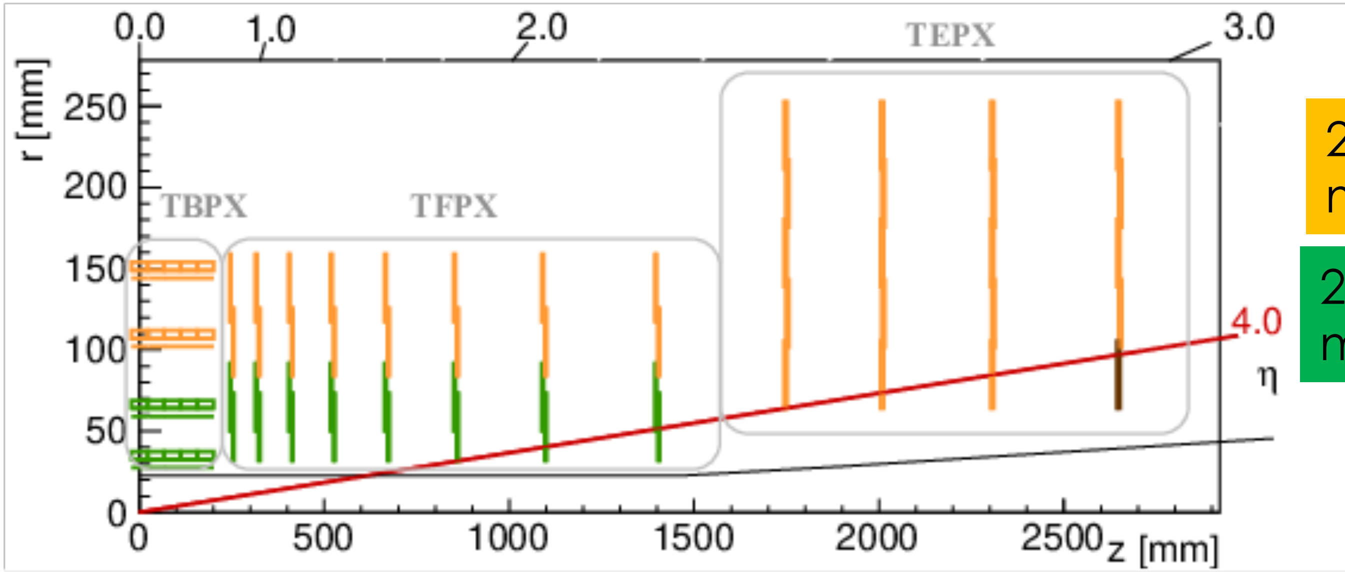
CMS Phase II tracker project

Requirements:

- Radiation hardness: Max fluence up to $O(10^{16})$ n_{eq}/cm^2
- Preserve >= 98% efficiency
- Preserve spatial resolution
- Increased granularity: 1200 tracks / unit of η
- Reduced material: Preserve calorimetric resolution
- Contribution to the L1 trigger



CMS Phase II inner tracker

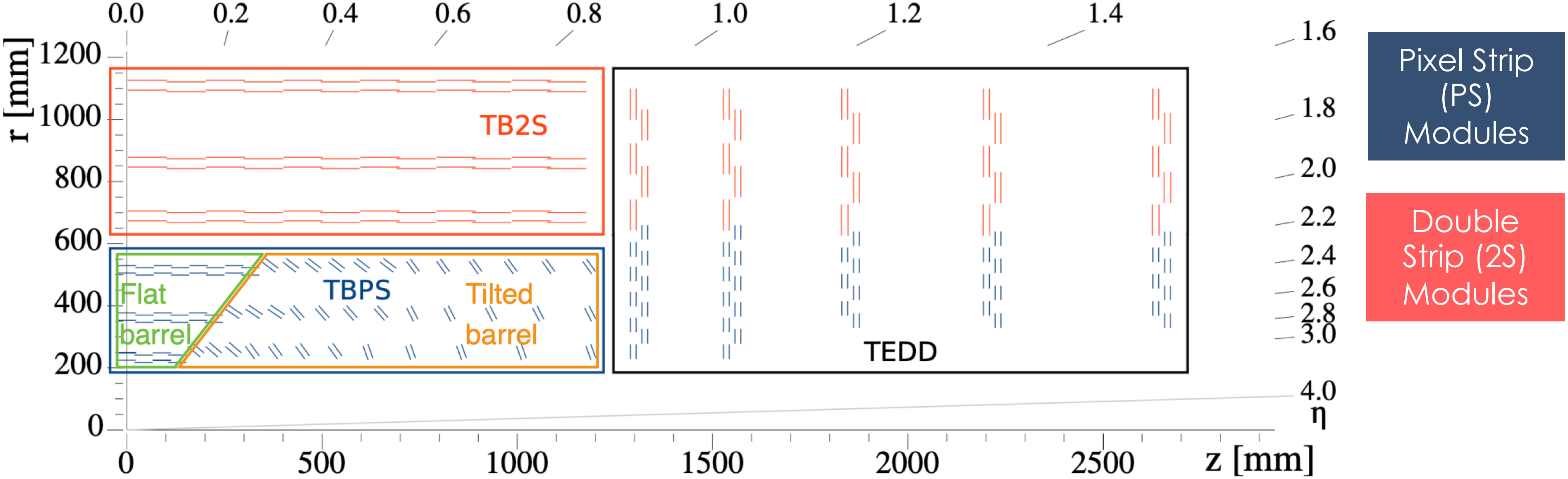


2×2 Pixel Chip modules

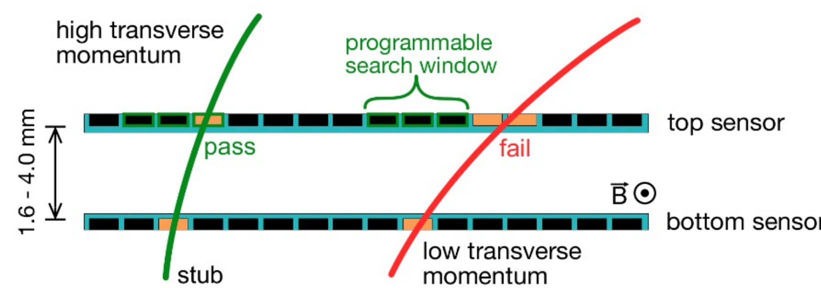
2×1 Pixel Chip modules

- **Cover a total surface of 4.9 m^2 - 2x10^9 channels**
- Barrel: 4 silicon pixel layers
- Endcap: 2x8 small + 2x4 pixel large silicon pixel disks
- n in p silicon, 25x100 μm^2
  - 3D (innermost)
  - Planar (elsewhere)
- New Front-end ASIC in 65 nm CMOS technology (CROC), common R&D with ATLAS

CMS Phase II outer tracker



- **Cover a total surface of 218 m^2 - 174 million macropixels**
- Barrel: 6 layers of pT modules
- Endcap: 2x5 disks of pT modules
- pT modules: 2 layers of n-in-p silicon
  - 2S: 2 super-imposed strip sensors (90 μmx5cm)
  - PS: Macro-pixel sensor (100μmx1.5cm)

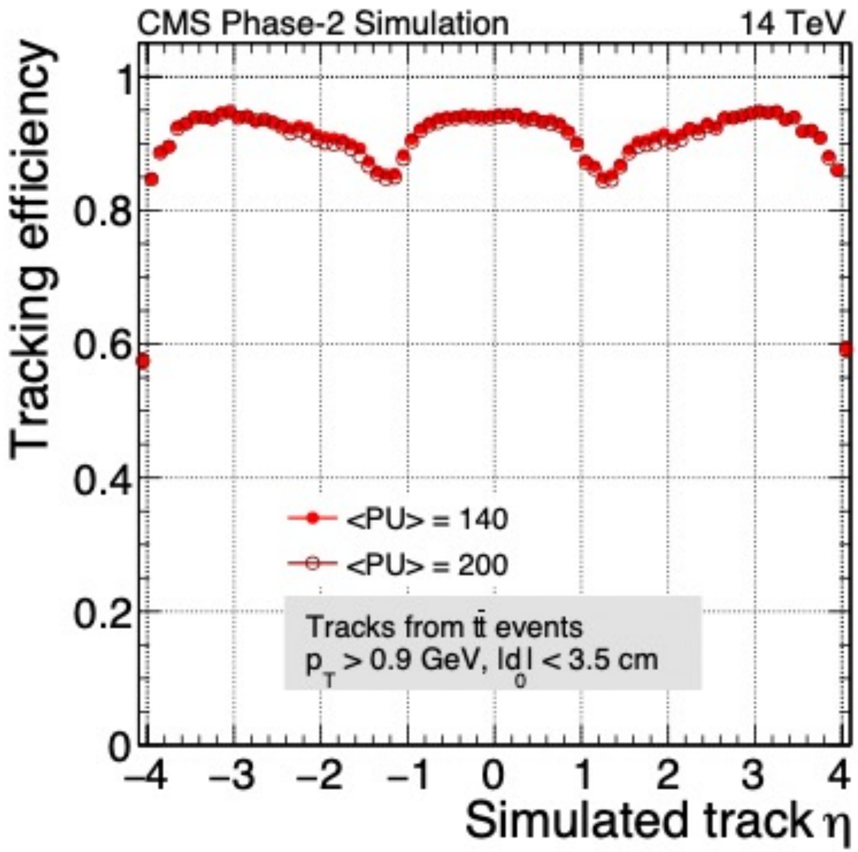


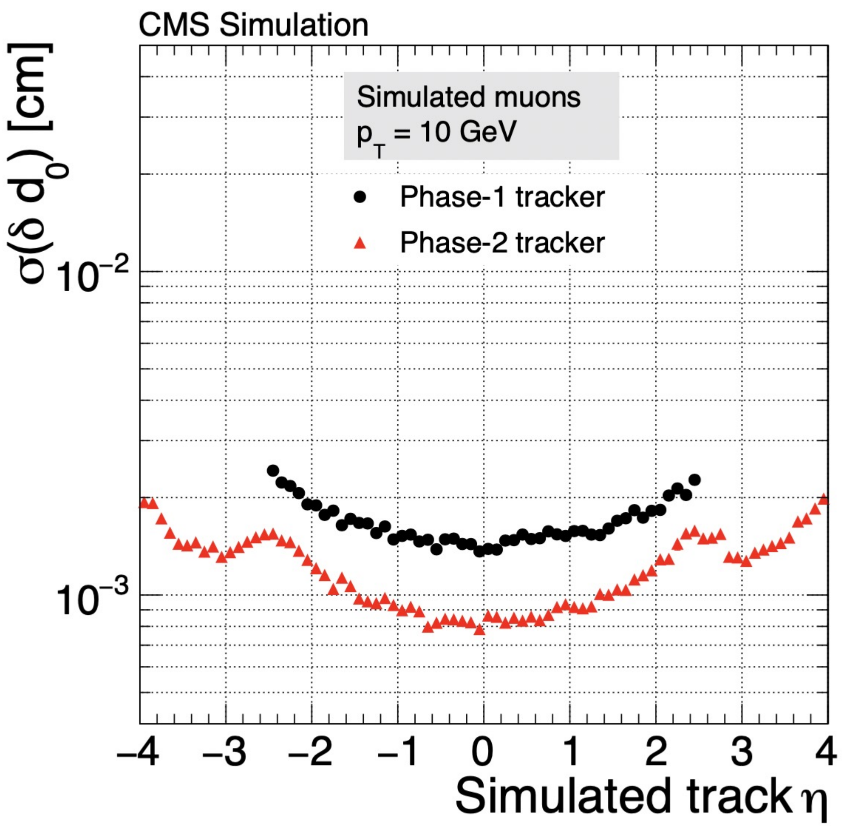
p_T module → provide stubs compatible with tracks p_T >2GeV for L1 trigger rate reduction

CMS Phase II tracker performance

Improvement on tracking efficiency and vertexing, thanks to high granularity even with challenging HL-LHC data taking conditions

CMS-PAS-TDR-17-001



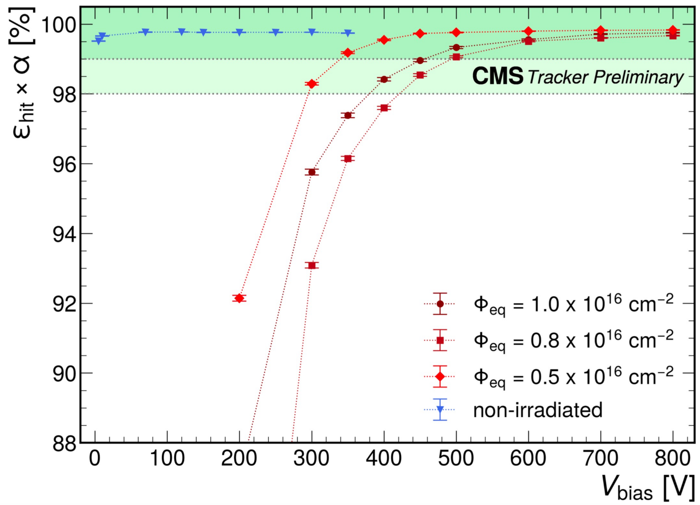


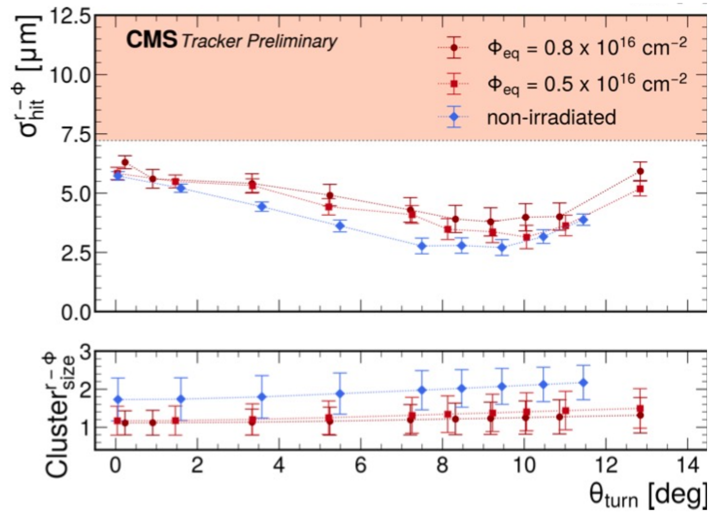
Silicon modules performance

doi/10.22323/1.449.0578

Pixel prototypes

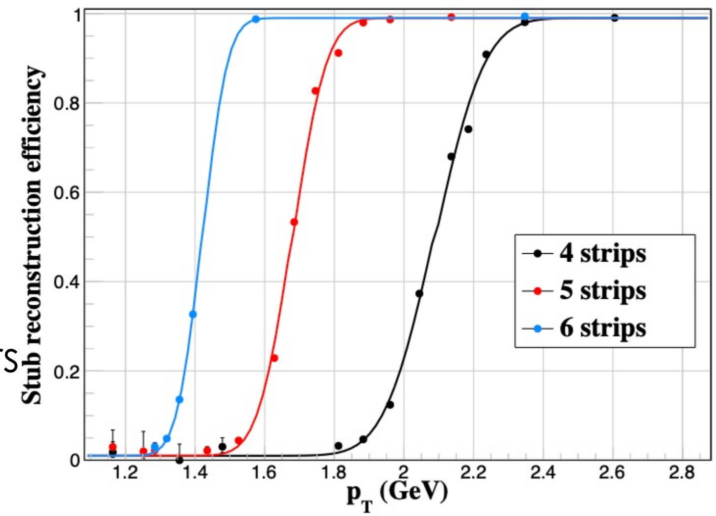
- Single chip assemblies irradiated at CERN
- Performance measured with test beam at DESY
- Hit efficiency > 98% for high irradiation
- Spatial resolution below the single-pixel cluster limit→7.2 μm (*r*-φ)

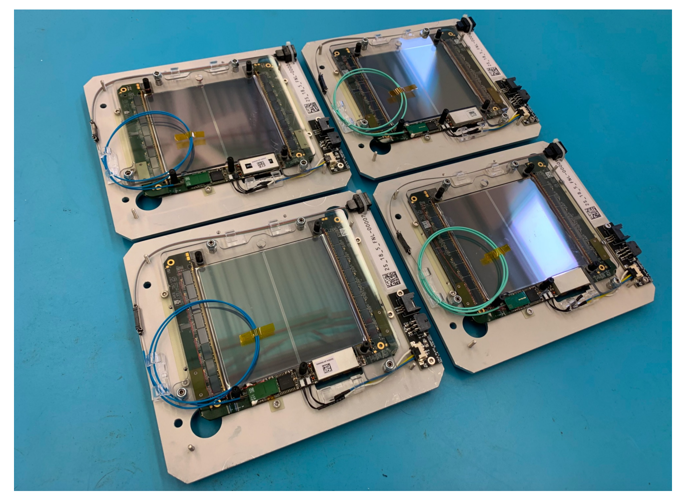




pT modules prototypes

- More than 60 modules built across the various production centers
- Expected performance confirmed

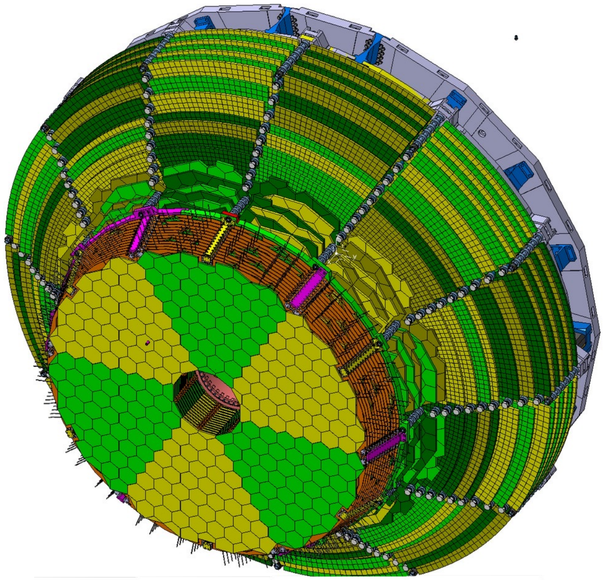




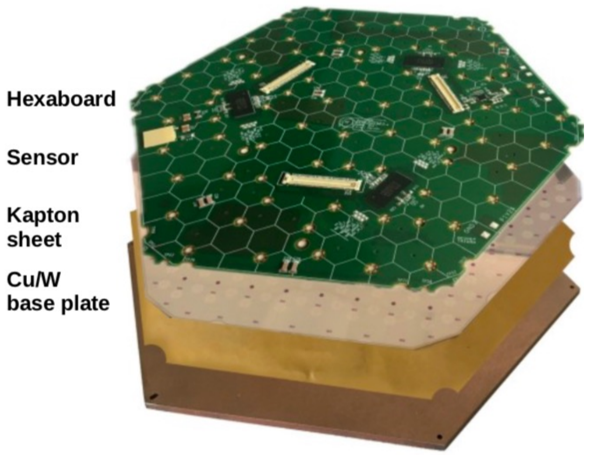
CMS High Granularity Calorimeter

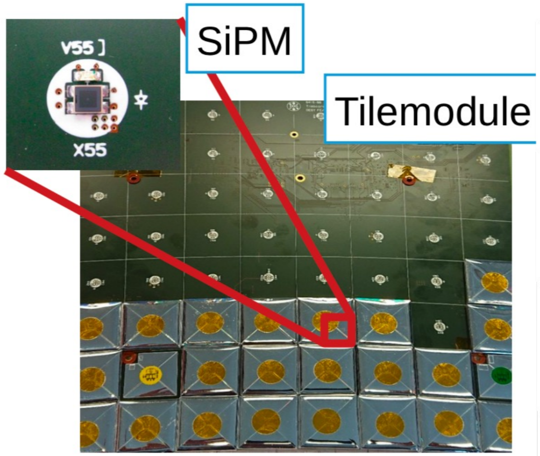
- Highly granular sampling calorimeter in endcaps
- 3D shower reconstruction and precise timing →
- Designed for **Particle Flow reconstruction**
- **ECAL (CE-E):**
  - Silicon sensors
  - Cu, CuW, and Pb absorbers
  - 26 layers, X_0=25 and λ_N=1.3
- **HCAL (CE-H):**
  - Silicon sensors and scintillating tiles with SiPM readout
  - Stainless steel absorbers
  - 21 layers, λ_N=8.5

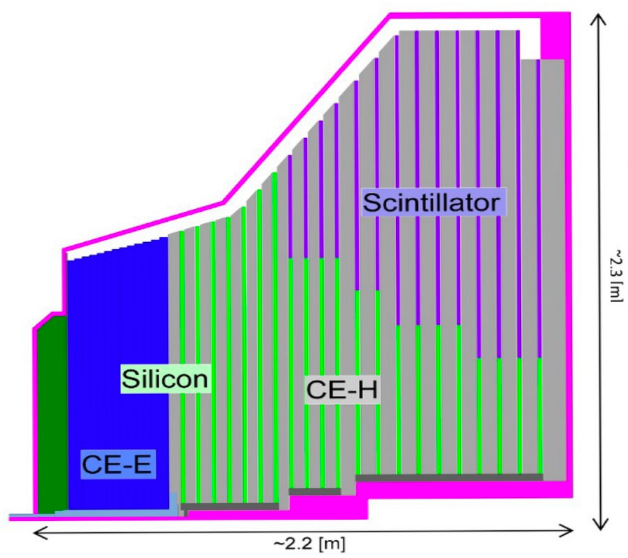
CMS HGCAL overview in B. Akgün talk



CMS-PAS-TDR-17-007





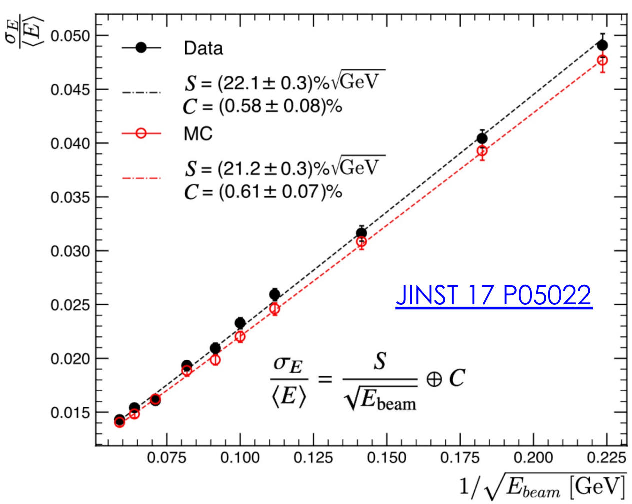


CMS High Granularity Calorimeter

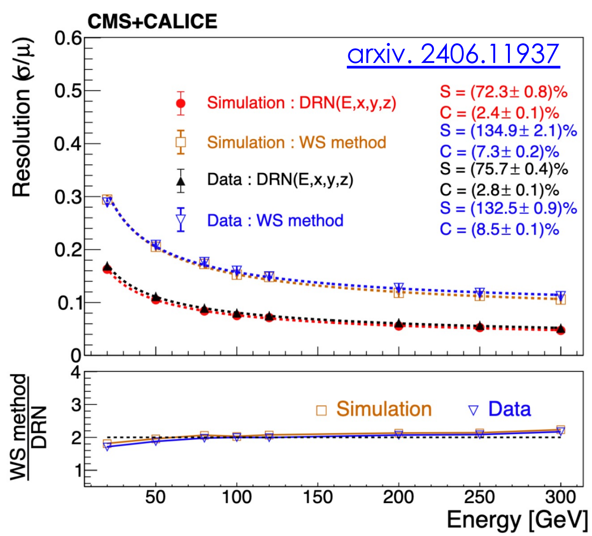
Results from test beam prototypes

- ✓ Energy resolution compatible with the present one for both ECAL and HCAL
  - ✓ Machine learning reconstruction improves the performace
- ✓ 16 ps time resolution → 5D shower reconstruction
- ✓ Unique opportunity to employ modern computing technologies for jet reconstruction and particle ID
  - **Heterogeneous computing**
  - **Machine learning** Use of Convolutional Neural Networks

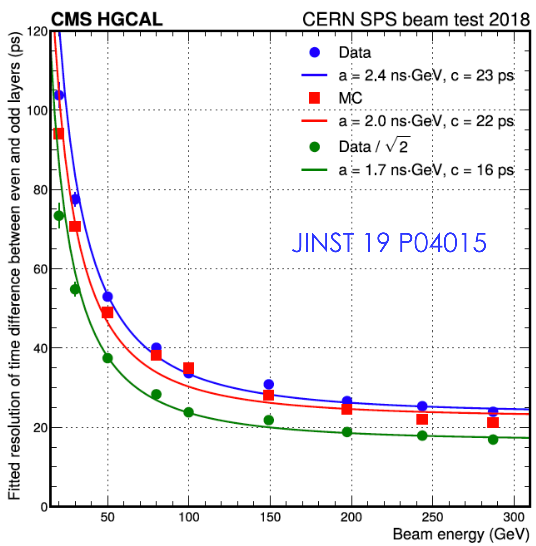
CMS HGCAL overview in B. Akgün talk



Energy resolution
HGCAL CE prototype



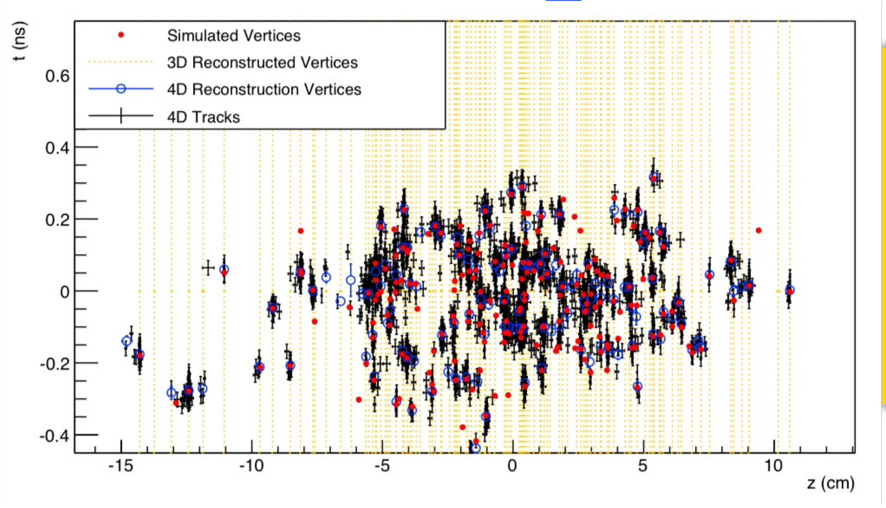
Energy resolution
HGCAL CH prototype



HGCAL prototype
Shower time resolution

MIP Timing Detector (MTD)

CMS-PAS-TDR-19-002



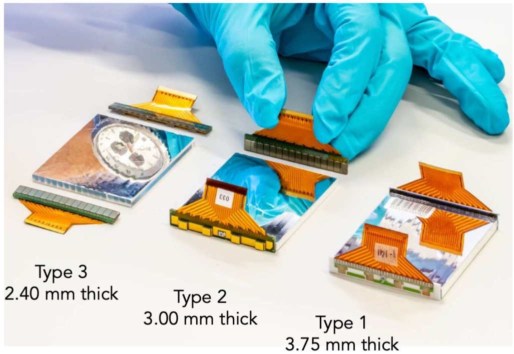
Requirements

- HL-LHC beam spot rms $\mathcal{O}$(5 cm) ⇒ space-overlapping vertices can be separated in time by hundreds of ps
- Measure the production time of minimum ionizing particles is crucial

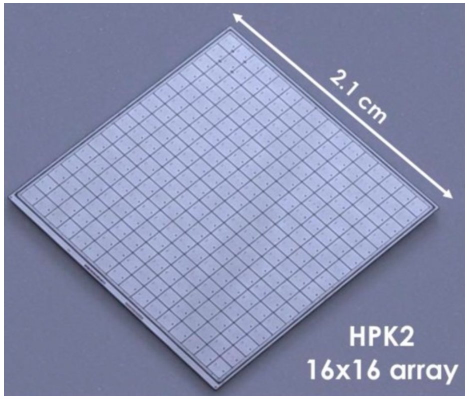
→MTD **with time resolution of O(tenths ps)**

- Disentangle pile-up by using timing information
- Improved tracking and vertexing
  - Particle identification from time of flight
  - Unique potential for Long-Lived Particles

Barrel (BTL)	Endcap (ETL)
$\|\eta\|$ <1.45	1.6 < $\|\eta\|$ < 3
LYSO:Ce + SiPM	Low Gain Avalanche Diode (16x16)
TOFHIR readout ASIC (high gain + noise filter)	ETROC readout ASIC single TDC measuring Time Of Arrival and Time Over Threshold



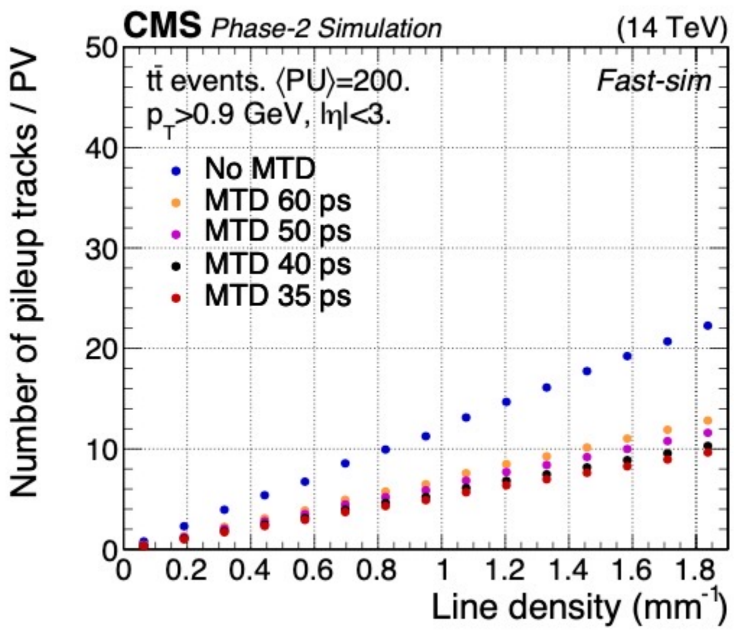
BTL: LYSO+SiPM



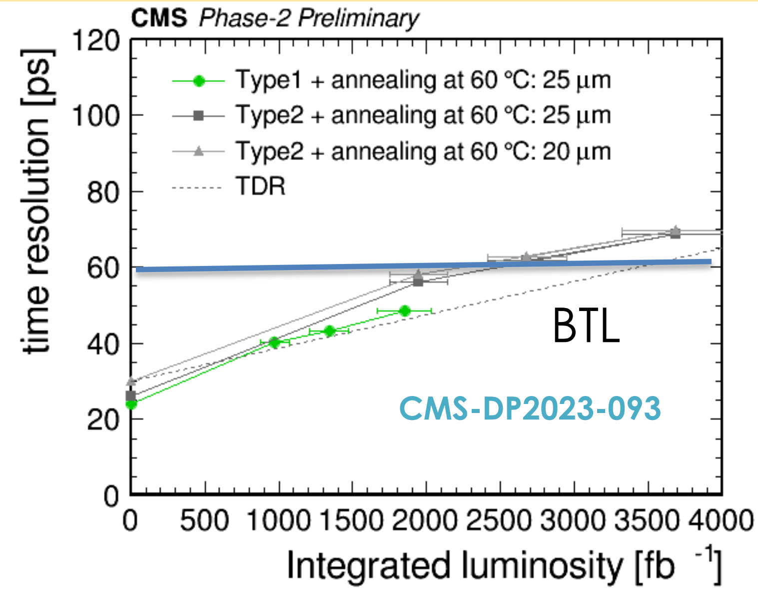
ETL: LGAD

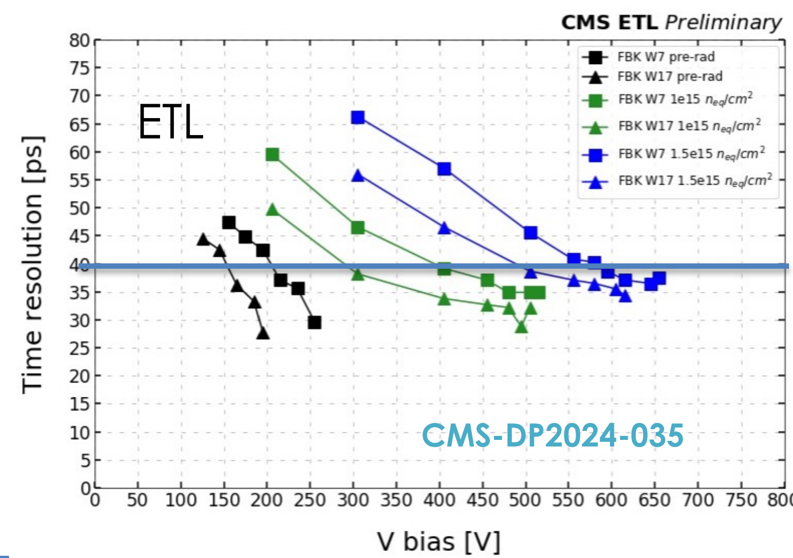
MIP Timing Detector

Target Time resolution	30-60 ps (barrel) 40 ps (endcap)



Detector prototype performance



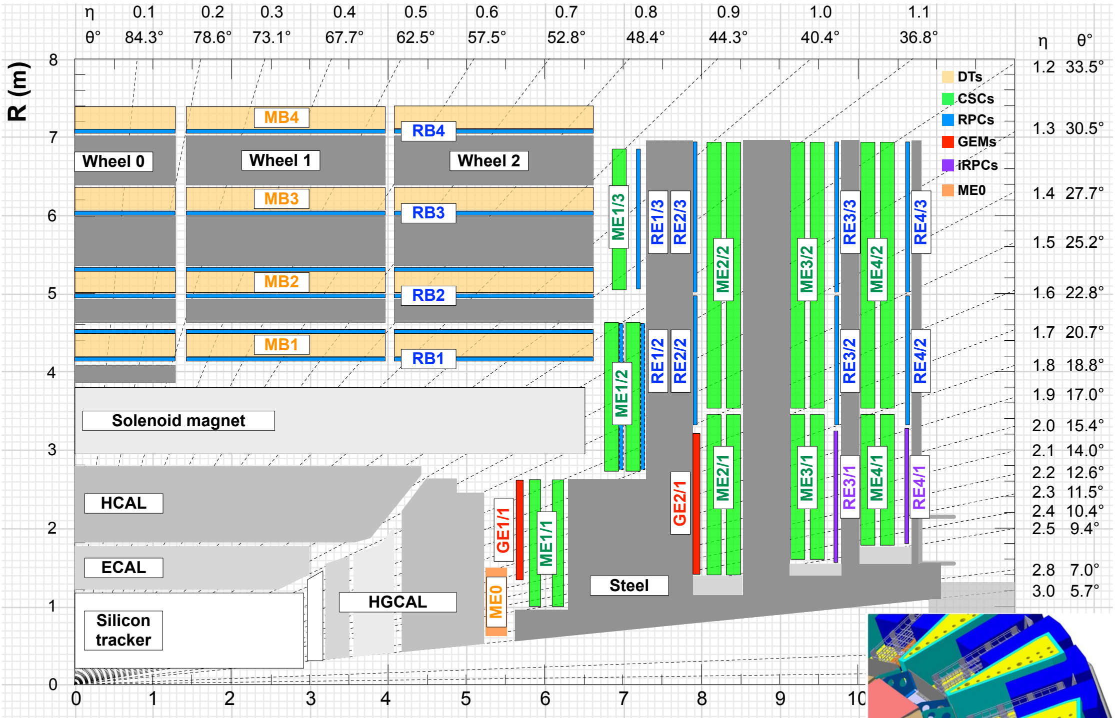


- **BTL:** resolution stay within expectation after irradiation
- **ETL**: LGAD irradiated with β Sr90 source, Target performance achievable by increasing voltage

CMS Phase II Muon System

[CMS-PAS-TDR-17-003]

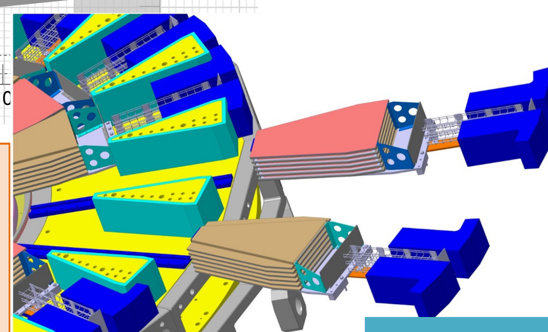
New stations to increase coverage, improve momentum resolution, trigger and track reconstruction

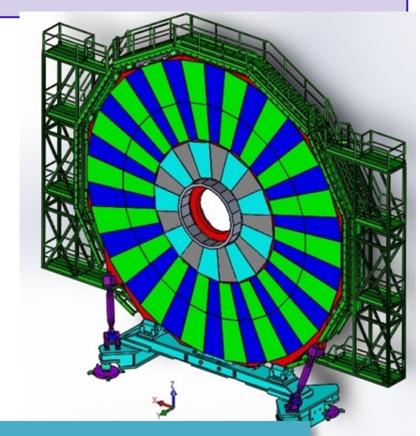


GE2/1
- 1.6 <| η |< 2.49
- 2 rings of two layers of **triple GEMs**
- Additional stub in the muon trigger and offline

RE3/1-RE4/1
- 1.9 <| η |< 2.4
- 2 stations of **improved RPC**
- time and position for trigger and track reconstruction

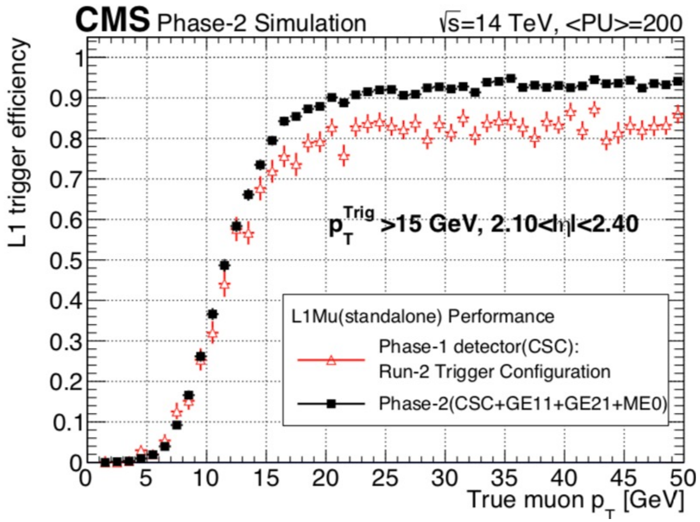
ME0-Muon near-tagger
- 2<|η|<2.8, O(100 kHz/cm2) background
- 6-layers of **triple-GEM**
- additonal information to the tracker



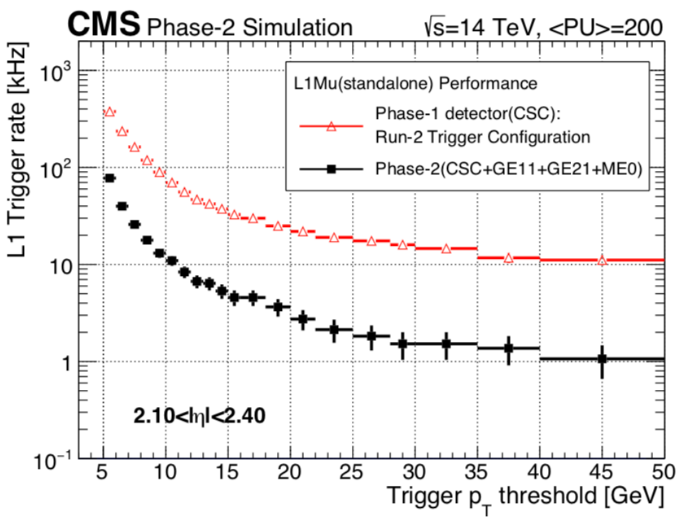


Muon system overview in G. Pugliese talk

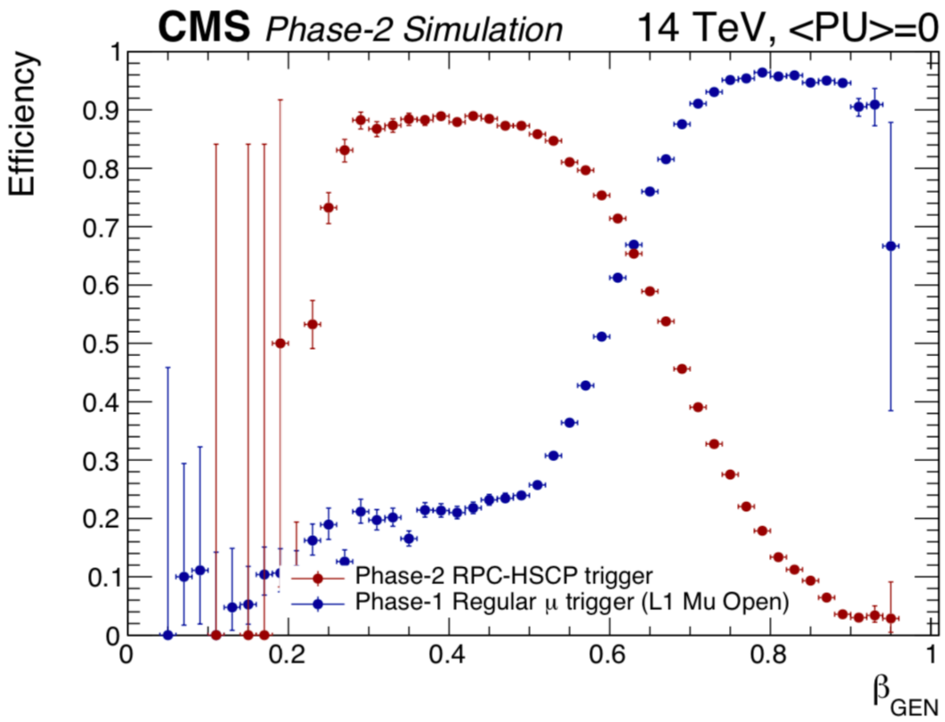
Phase II Muon System motivations



Recover L1 trigger efficiency wrt Phase 1



Reduce L1 endcap trigger rate wrt Phase 1



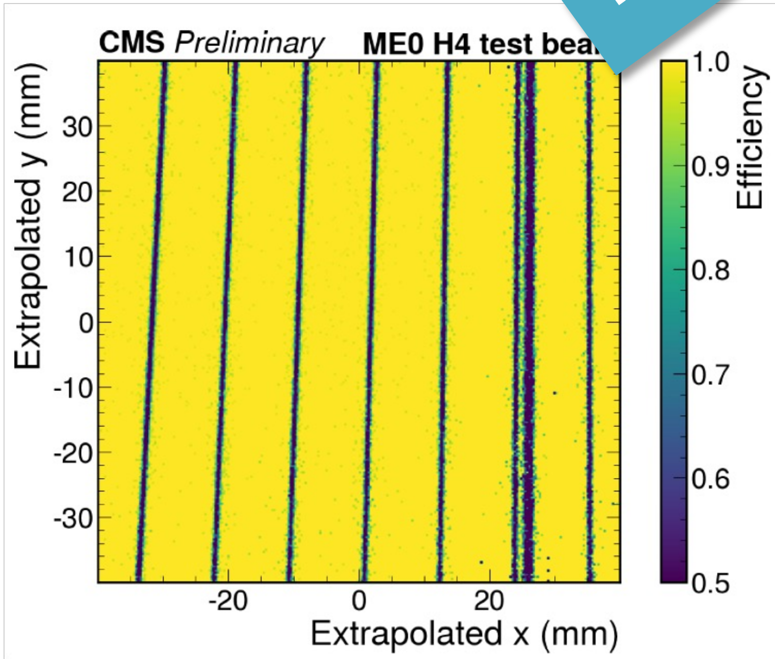
Sensitivity new phyisics, e.g. heavy stable charged particles

Muon system overview in G. Pugliese talk

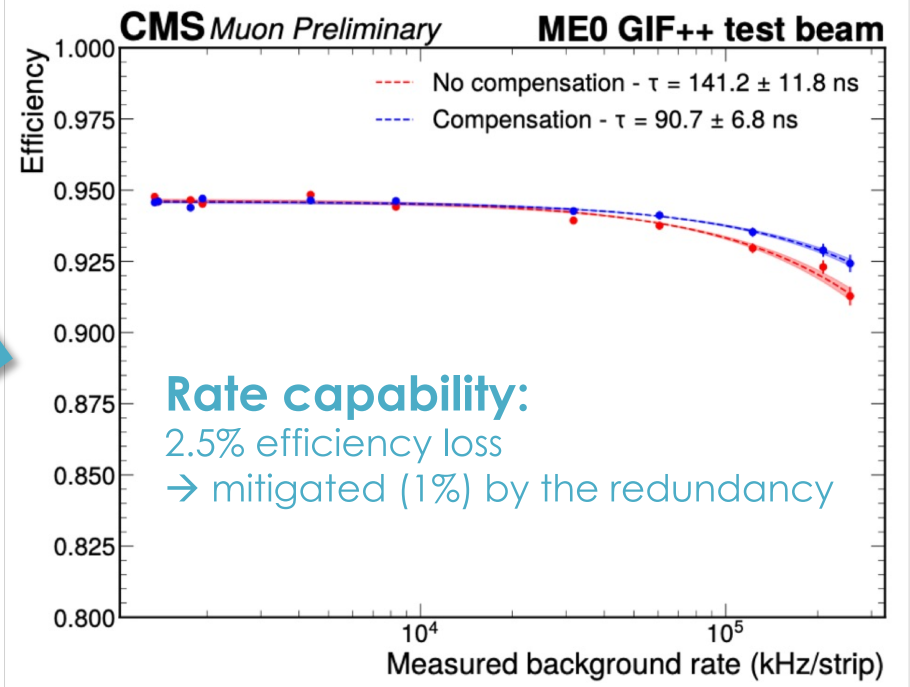
The ME0 station

Requirements :
- Rate capability: 150 kHz/cm^2
- 97% module efficiency
- < 500 μrad resolution
- 10 ns time resolution

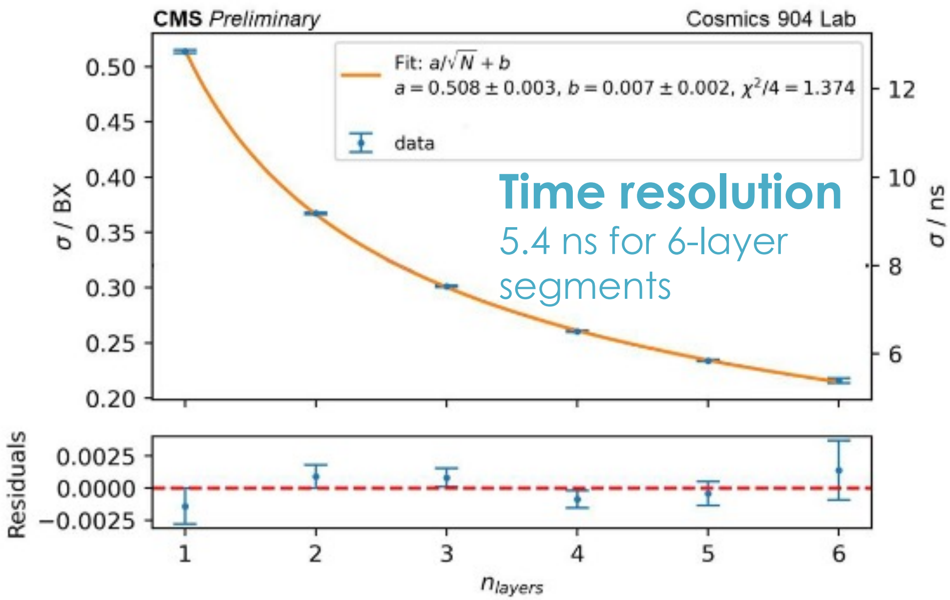
Details in G. Pugliese talk



- **Hit Efficiency: 99%**
- **Spatial Resolution**: 240 µrad



Rate capability:
2.5% efficiency loss
→ mitigated (1%) by the redundancy



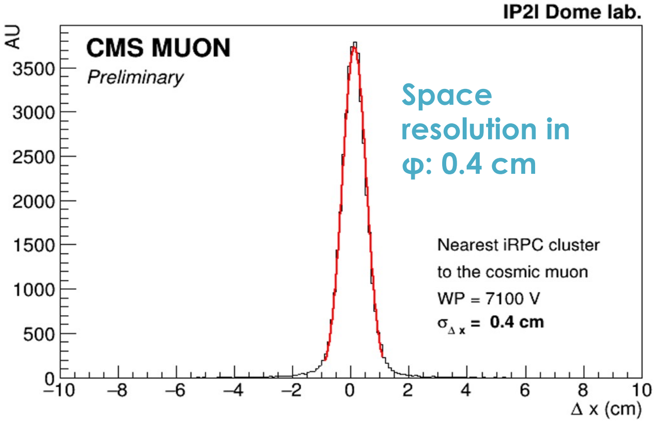
Time resolution
5.4 ns for 6-layer segments

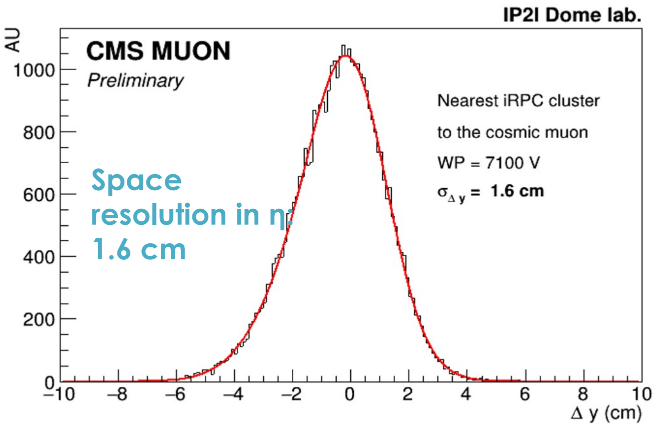
Improved RPC for RE3/1 RE4 / 1

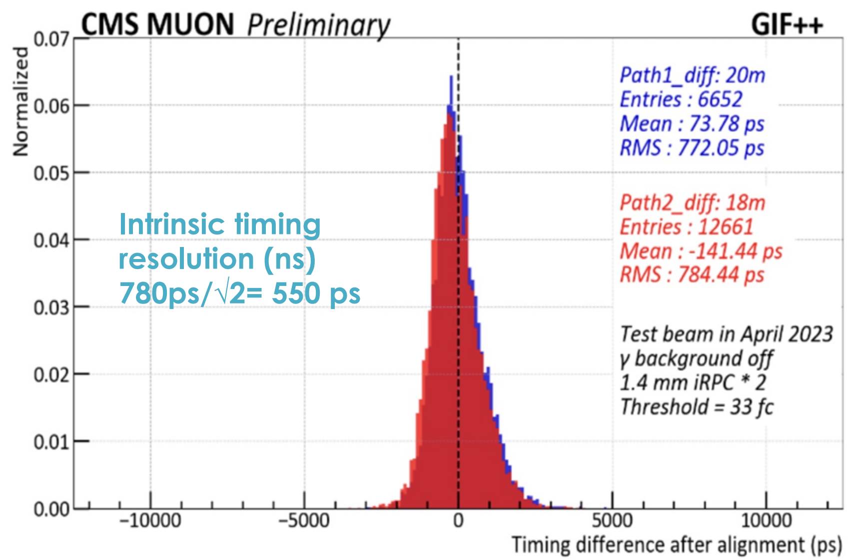
- Reduced gap thickness and resistivity → improvement in spatial and time resolution
- Double readout in the strips high and low radius

	RPC	iRPC
HPL thickness (mm)	2	1.4
Gas gap thickness (mm)	2	1.4
Resistivity (Ωcm)	1 - 6 x 10^{10}	0.9 - 3 x 10^{10}
Charge threshold (fC)	150	30 - 40
Space resolution in η (cm)	20 - 28	1.5
Space resolution in φ (cm)	0.8 - 1.9	0.3 - 0.6
Intrinsic timing resolution (ns)	1.5	0.5

Detector prototype performance







Summary

- Full luminosity needed for the most extensive searches and most precise measurements →Elucidation of the EWSB and of the Higgs boson characteristics
- The HL-LHC conditions will be the harshest to date
- **Phase II CMS upgrades targets *fast timing*, *high granularity*, *radiation hardness***
- **Main CMS experimental apparatus upgrades**
  - New generation of silicon sensors for tracking systems
  - New Timing layer → LYSO and LGAD technologies
  - 5D calorimetry in forward region thanks to fast timing
  - High-rate capability detectors for Muon Systems
- **Status: all sub-systems largely moving to the pre-production phase to the production phase**

Additional benefit: the physics exploitation will be a test bench for usage of modern technololgies in future collider experiments

Thanks for your attention

Backup

Status of the art

Tracker

- Inner Tracker: ASIC final and in production
- Outer Tracker: about to start module production

HGCAL

- SiPM, scintillator production started

MTD

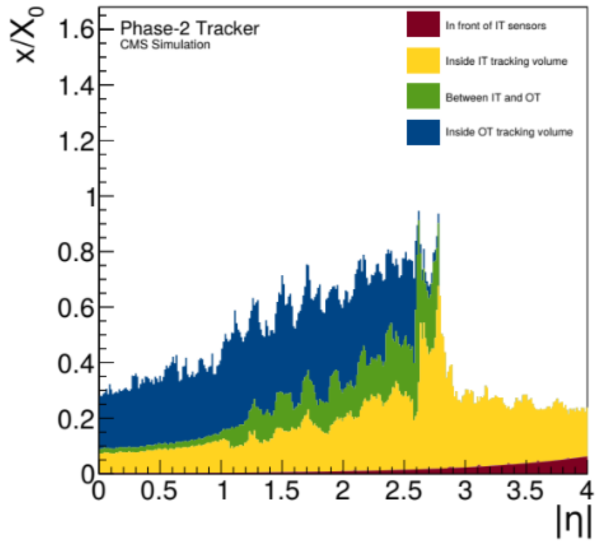
- Barrel: started module production
- Endcap: sensor procurement review in July; ASIC functionality proven

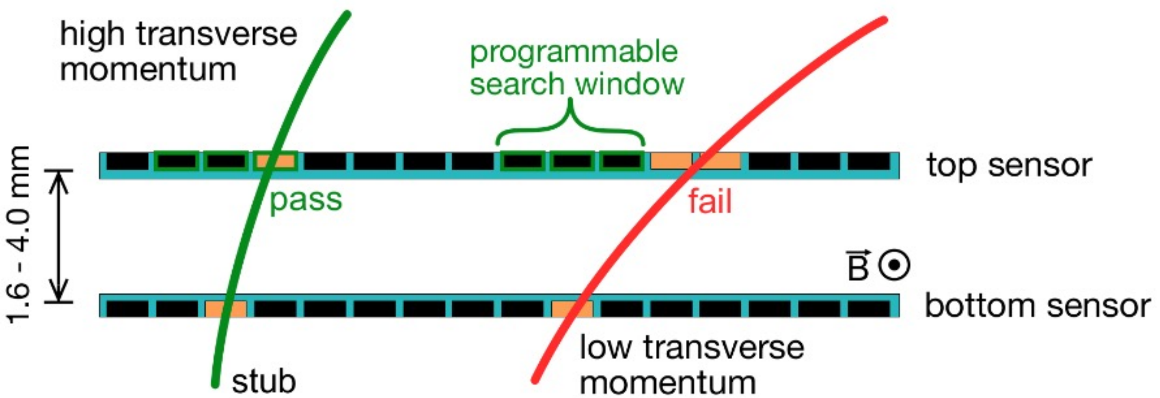
Muon Detector

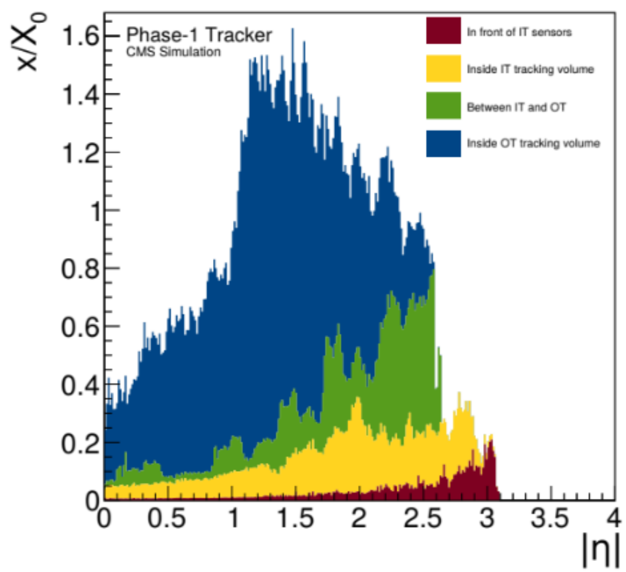
- RPC and GEM chambers production ongoing

CMS Phase II tracker

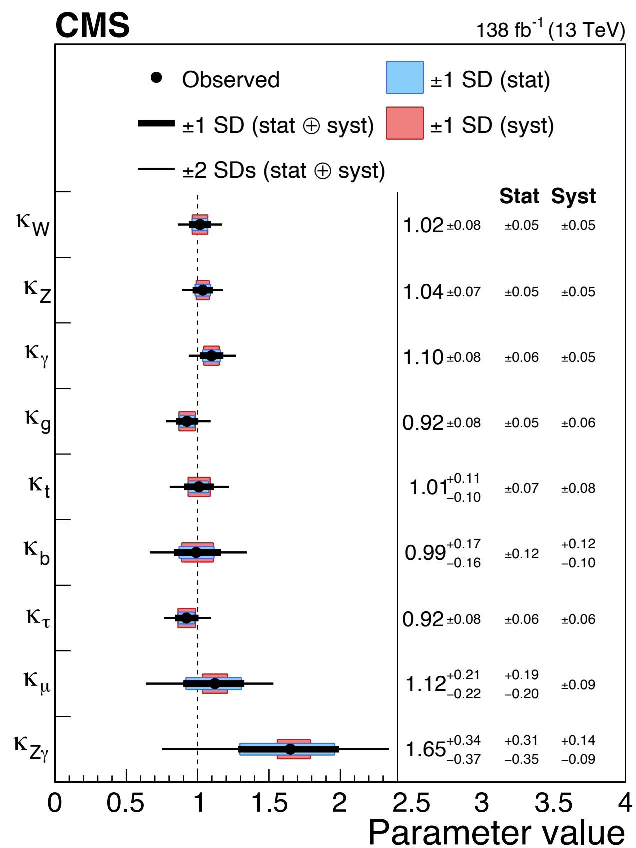
Requirements:
- Radiation hardness: Max fluence up to $O(10^{16})$ n_{eq}/cm^2
- Preserve >= 98% efficiency
- Preserve spatial resolution
- Increased granularity: 1200 tracks / unit of η
- Reduced material: Preserve calorimetric resolution
- Contribution to the L1 trigger:
  - Outer Tracker: pT modules ⟶ stubs compatible with tracks pT > 2GeV

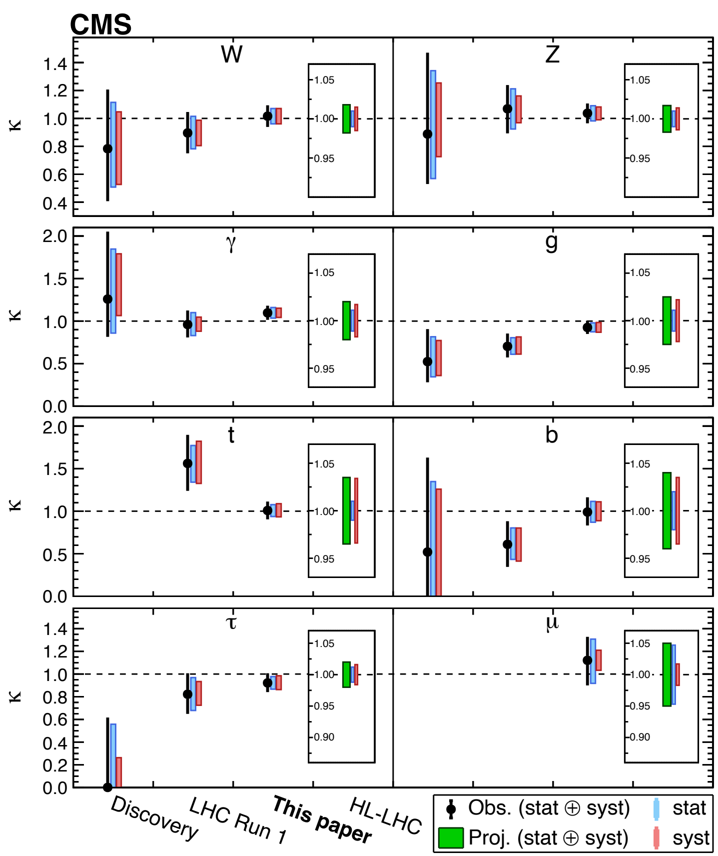




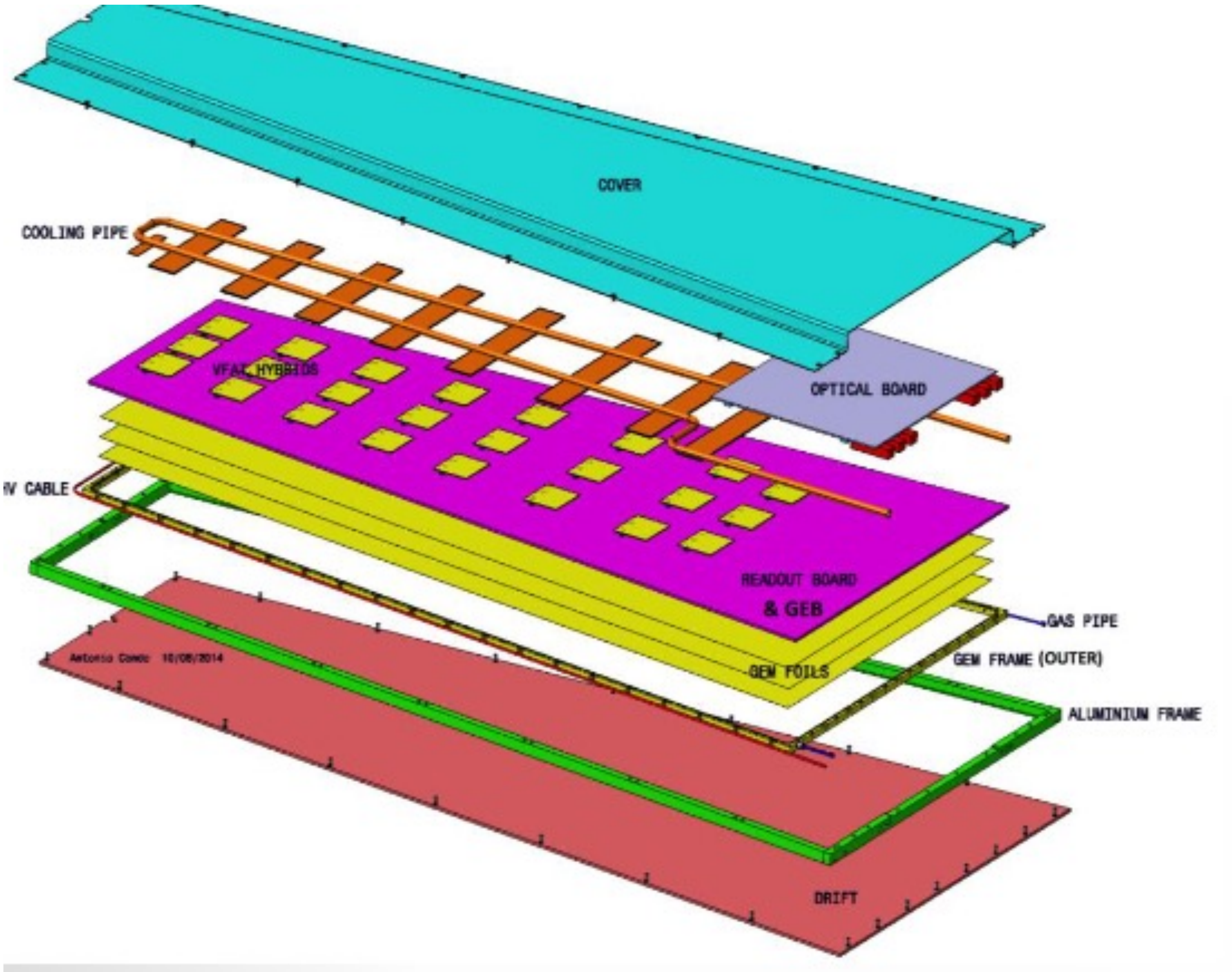


Higgs coupling evolution





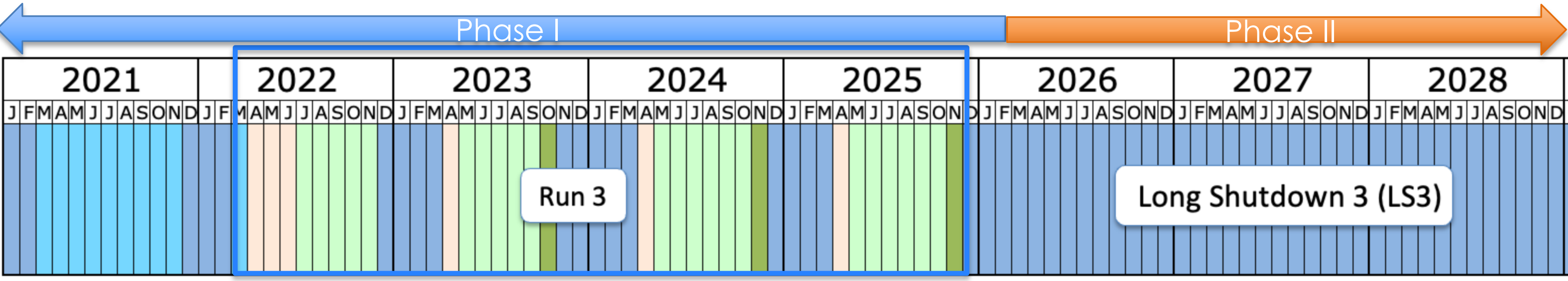
https://www.nature.com/articles/s41586-022-04892-x/figures/4



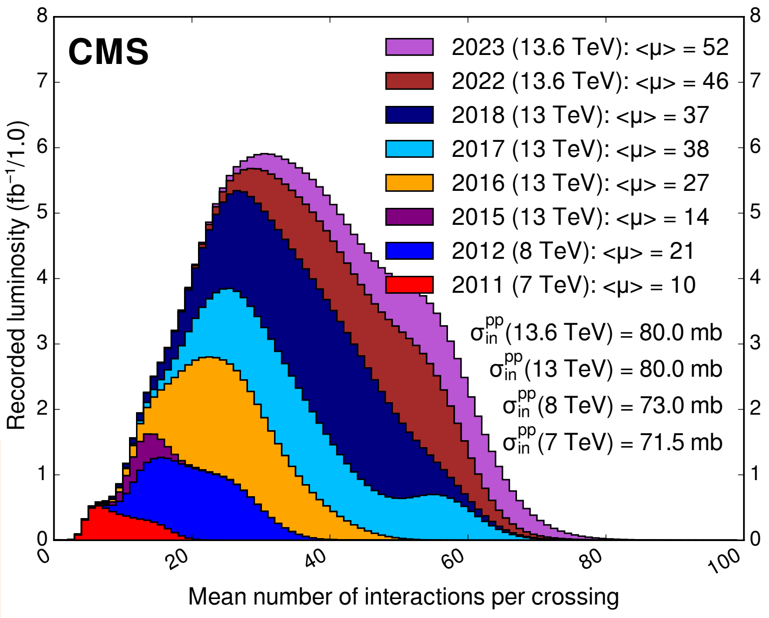
COVER
COOLING PIPE
VFAT HYBRIDS
OPTICAL BOARD
V CABLE
READOUT BOARD
& GEB
GAS PIPE
GEM FRAME (OUTER)
GEM FOILS
ALUMINIUM FRAME
DRIFT

The LHC Run 3

https://lhc-commissioning.web.cern.ch/



	CMS	
	Run 2	**Run 3**
Inst. Lumi (sec^{-1} cm^{-2})	10^{34}	**$2x10^{34}$**
Target int. lumi (fb^{-1})	140	**250**
Pile up	~35	**~50-60**



Increased integrated luminosity

+ acceptance for rare events
+ precision measurements

!! trigger bandwidth

→ Need for detector upgrades

Run3 CMS muon system upgrades

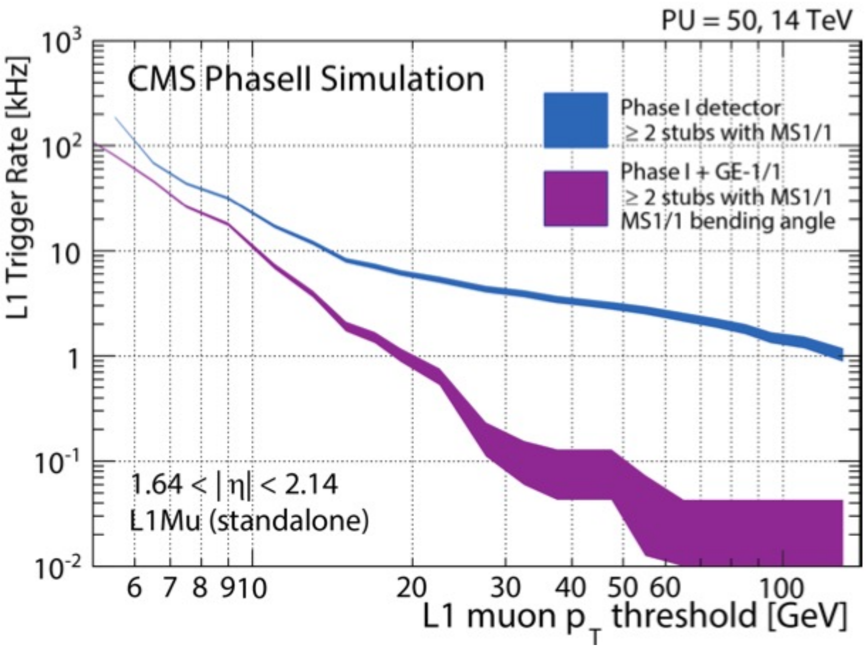
- **Endcap trigger rate dominated by muons reconstructed as high p_T muons**
- p_T mis-measurement due to B-field, multiple scattering
- High neutron background vs low hit multiplicity.

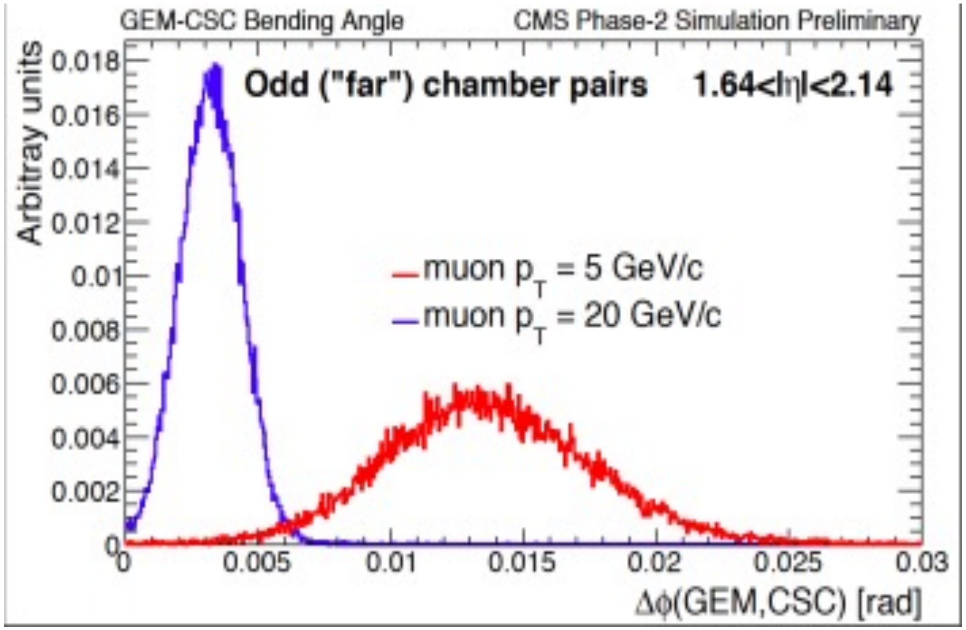
CMS-TDR-013

For the first time large area triple GEMs in HEP experiment: GE1/1 station

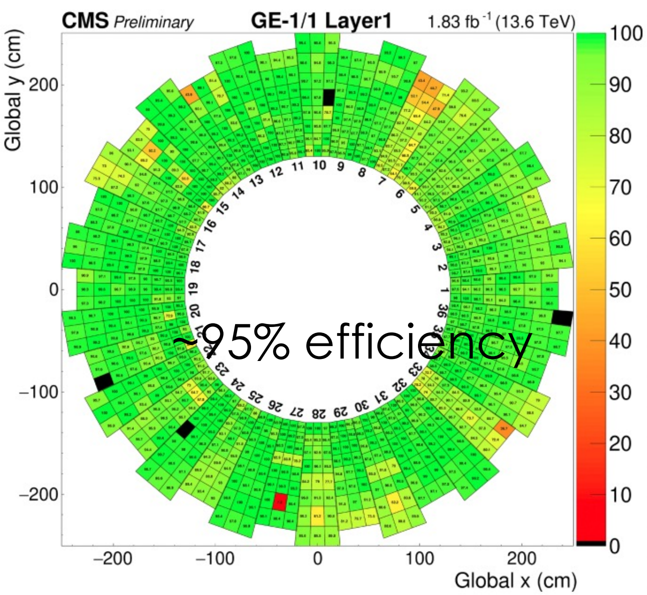
Key role of MPGD

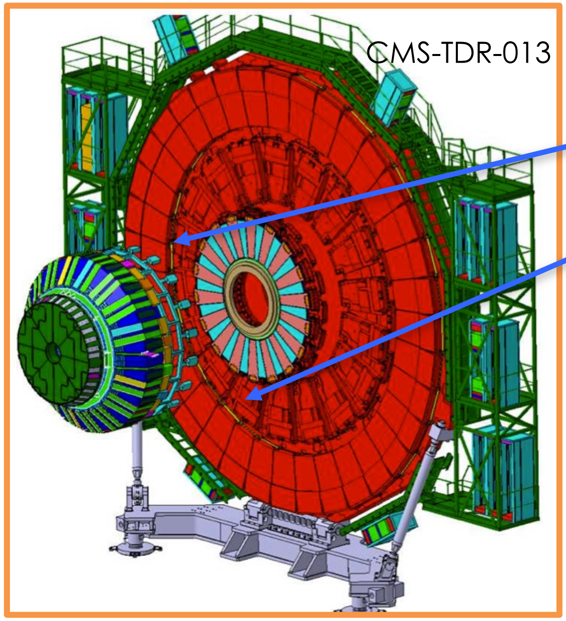
- High rate capability (O(10KHz/cm^2)) and radiation hardness
- Excellent spatial resolution (100-300μm) → few mrad res on bending angle
- Good time resolution (5-10 ns) → stubs included in the trigger

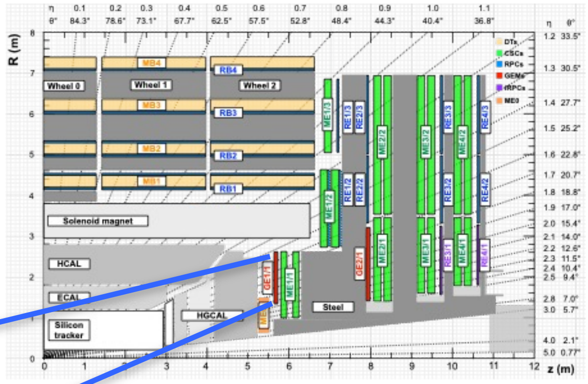




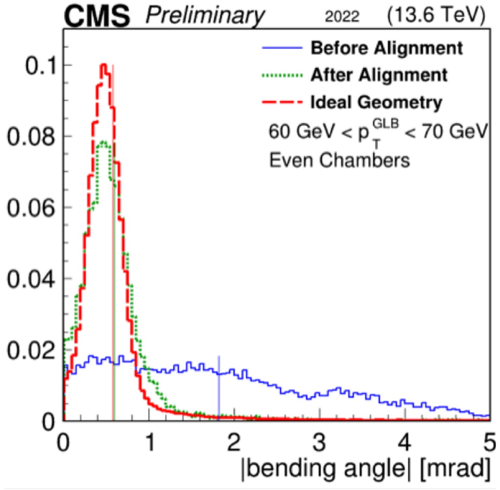
The GE1/1 station at CMS

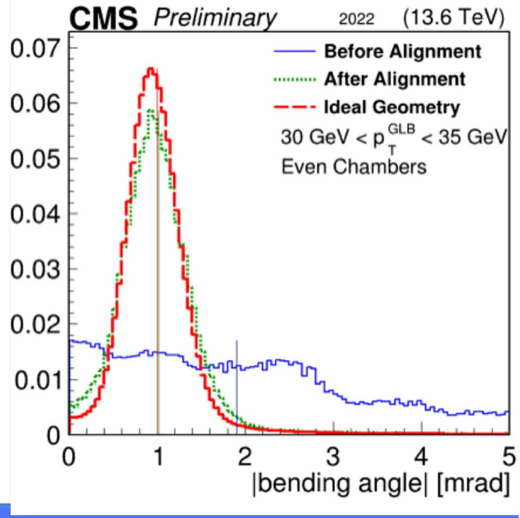






- 144 triple GEM detectors
- One super-chamber = two triple-GEM detectors
- **Eta coverage 1.55 < |η| < 2.18**

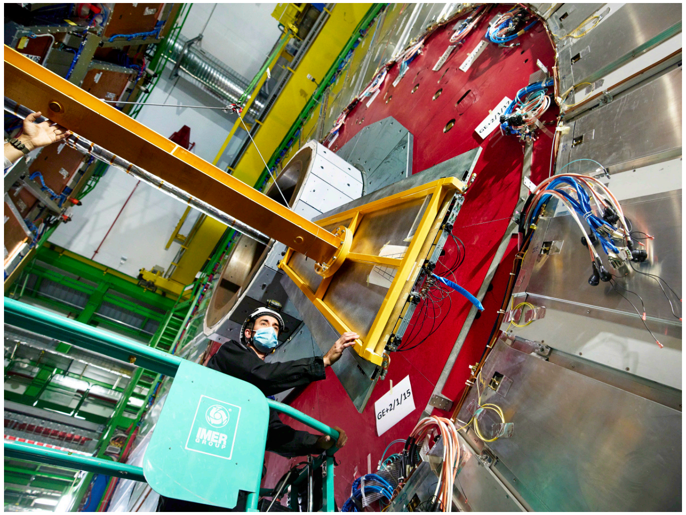




- **Installation completed in 2020**
- **Currently taking data in Run3 with excellent performance**
- Measure of Muon Bending Angles →Clear dependence of the muon p_T

The GE2/1 station

- Additional stub measurement
- Triple GEM is a mature technology based on mechanical foil stretching
- 3 GE2/1 chambers installed and integrated in data taking
  - gain operational experience
  - occupancy, noise, Dead channel, Cross talk
- Efficiency shows the expected performance



Detector prototype performance