30th Anniversary of the Rencontres du Vietnam Aug 6 – 12

ICISE

Windows on the Universe 2023

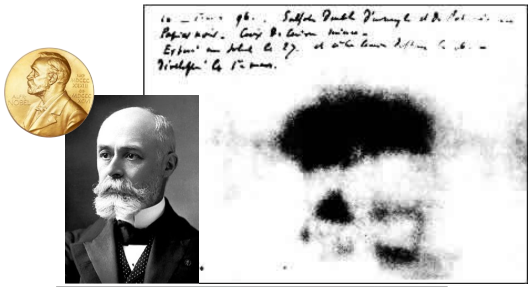
Novel perspectives in radiation detectors for present and future high energy physics experiments

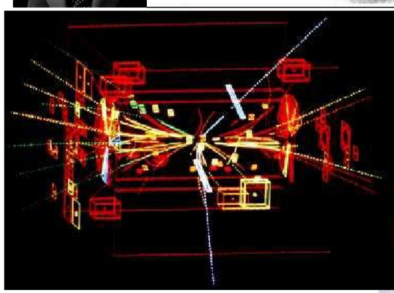
Archana Sharma
(CERN, Geneva)

Grateful to indico.cern.ch and Google.com

August 11th, 2023

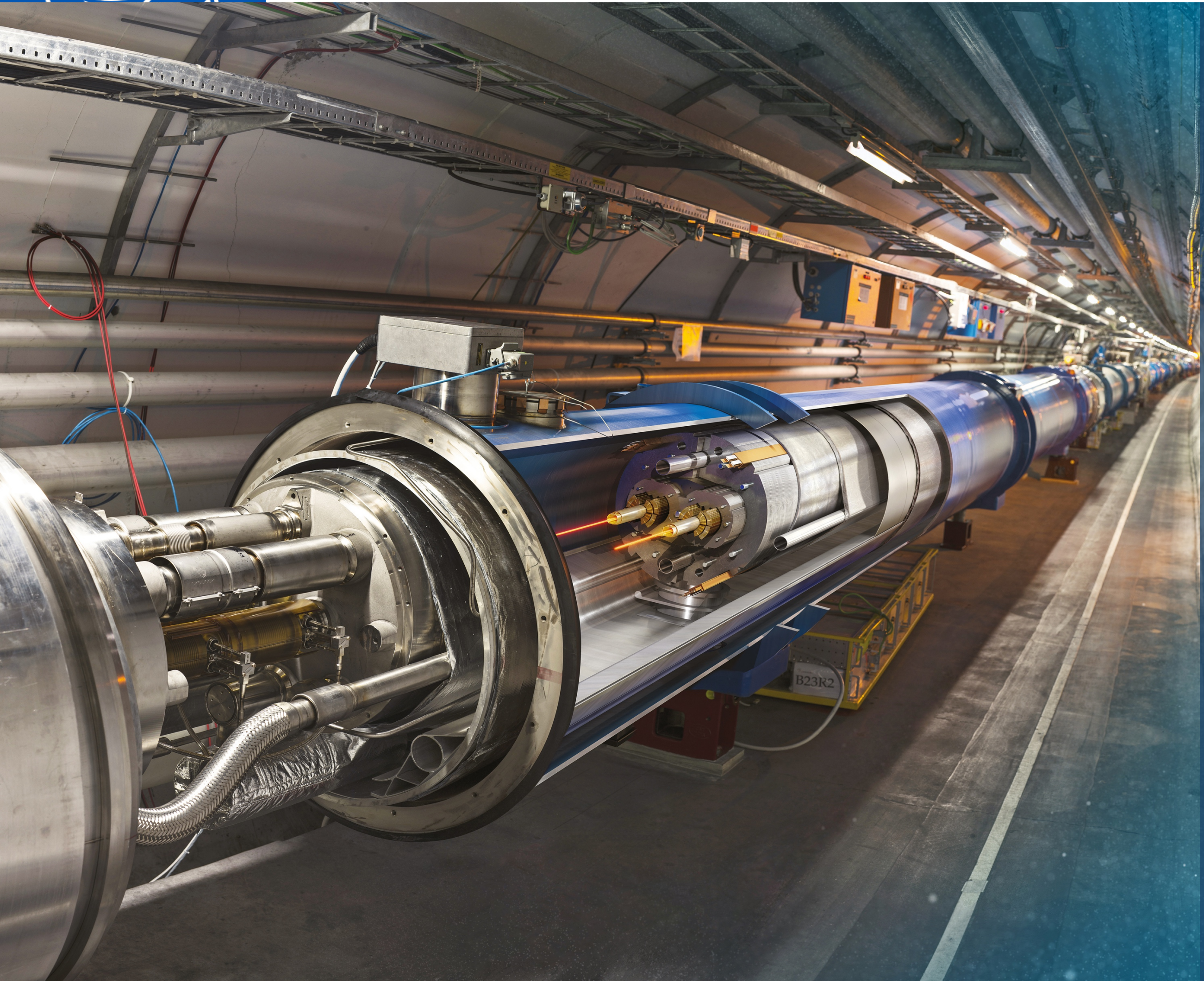
Nobel Prizes: Detection Methods





- 1927: cloud chamber (C.T.R. Wilson)
- 1948: advanced cloud chamber (P.M.S. Blackett)
- 1950: nuclear emulsion (C.F. Powell)
- 1954: coincidence method (W. Bothe)
- 1958: Cherenkov effect (P.A. Cherenkov)
- 1960: bubble chamber (D.A. Glaser)
- 1992: multiwire proportional chamber (G. Charpak)
- 2009: CCD sensor (W.S. Boyle, G.E. Smith)

The Large Hadron Collider (LHC)

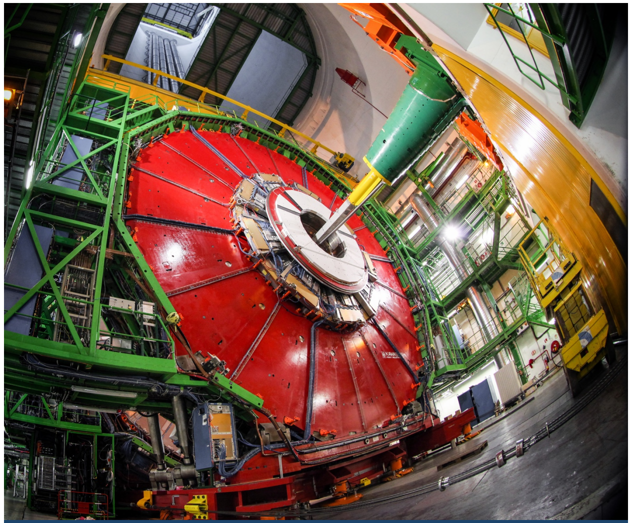


- 27 km in circumference
- About 100 m underground
- Superconducting magnets steer the particles around the ring
- Particles are accelerated to close to the speed of light
- Collision energy (13) 14TeV

Tools of the trade..

- We build the largest machines to study the smallest particles in the universe
- We develop technology to advance the limits of what is possible

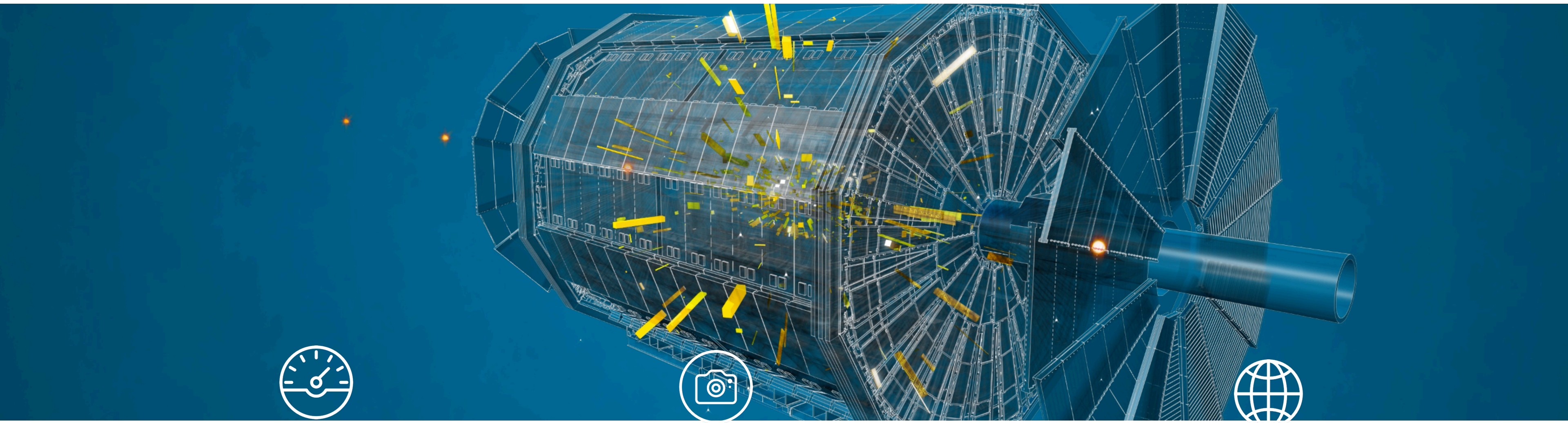
ACCELERATORS



DETECTORS

COMPUTING

The LHC detectors are analogous to 3D cameras

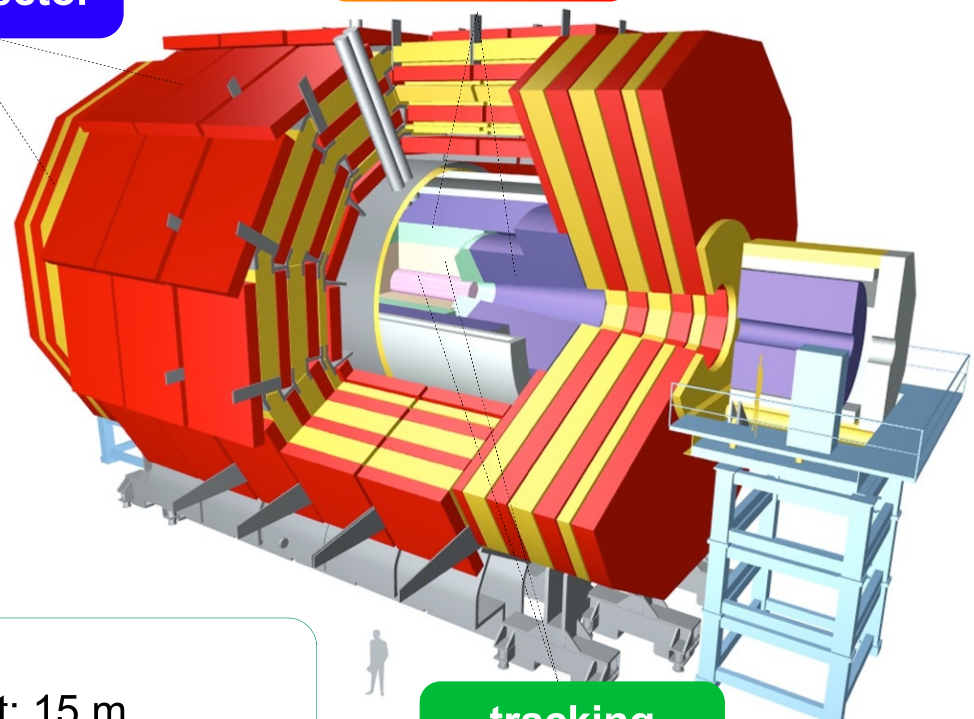


The detectors measure the energy, direction and charge of new particles formed.

They take 40 million pictures a second. Only 1000 are recorded and stored.

The LHC detectors have been built by international collaborations covering all regions of the Globe.

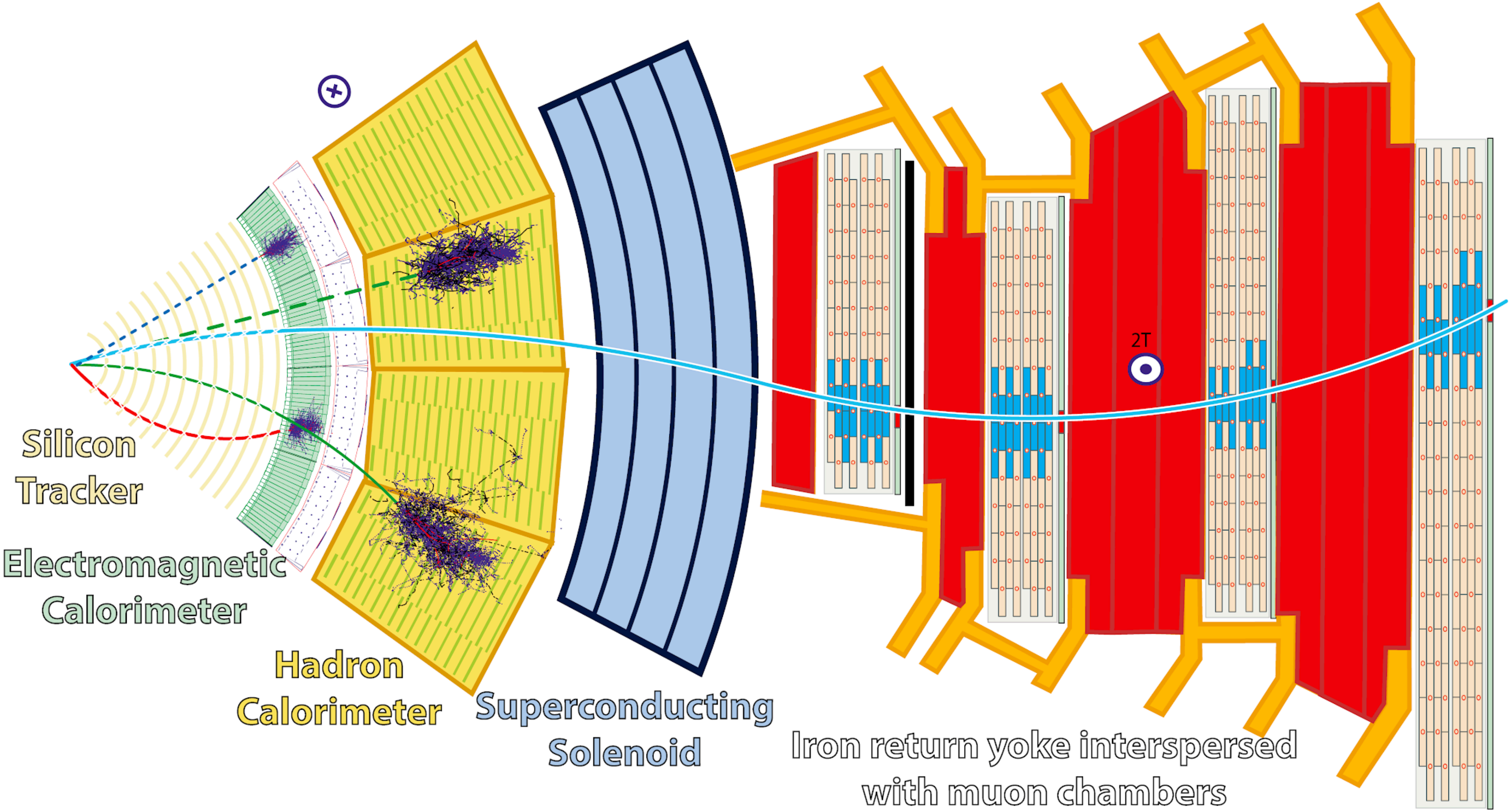
Compact Muon Solenoid



CMS facts:

- Length: 25 m, height: 15 m
- Weight: 14500 metric tons
- 150 million electronics channels

Windows on the Universe



Muon

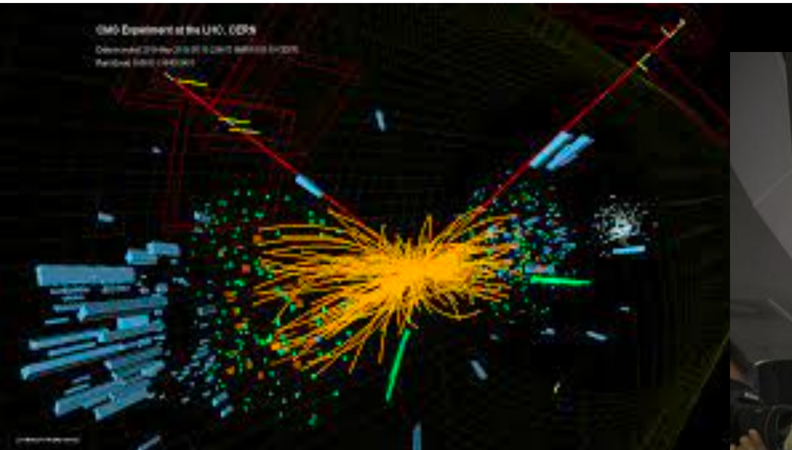
Electron

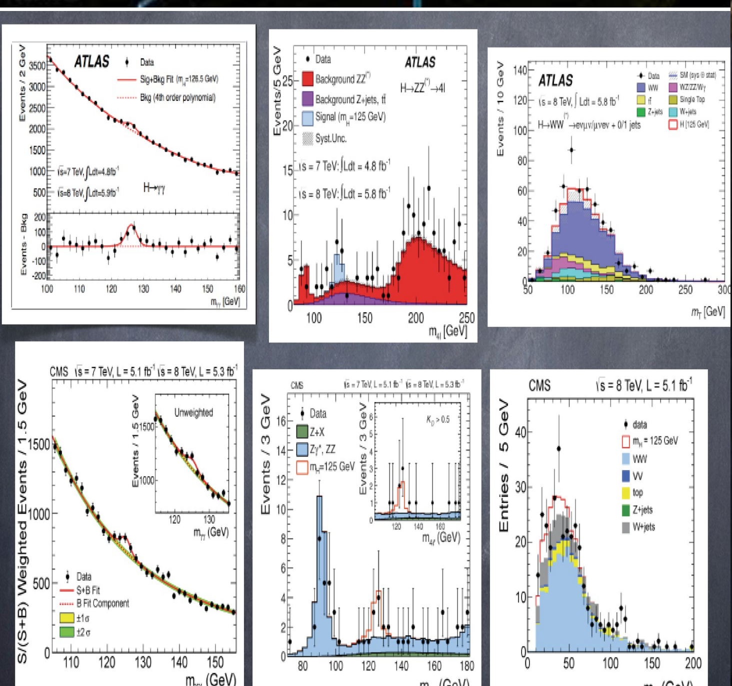
Charged hadron (e.g. pion)

Neutral hadron (e.g. neutron)

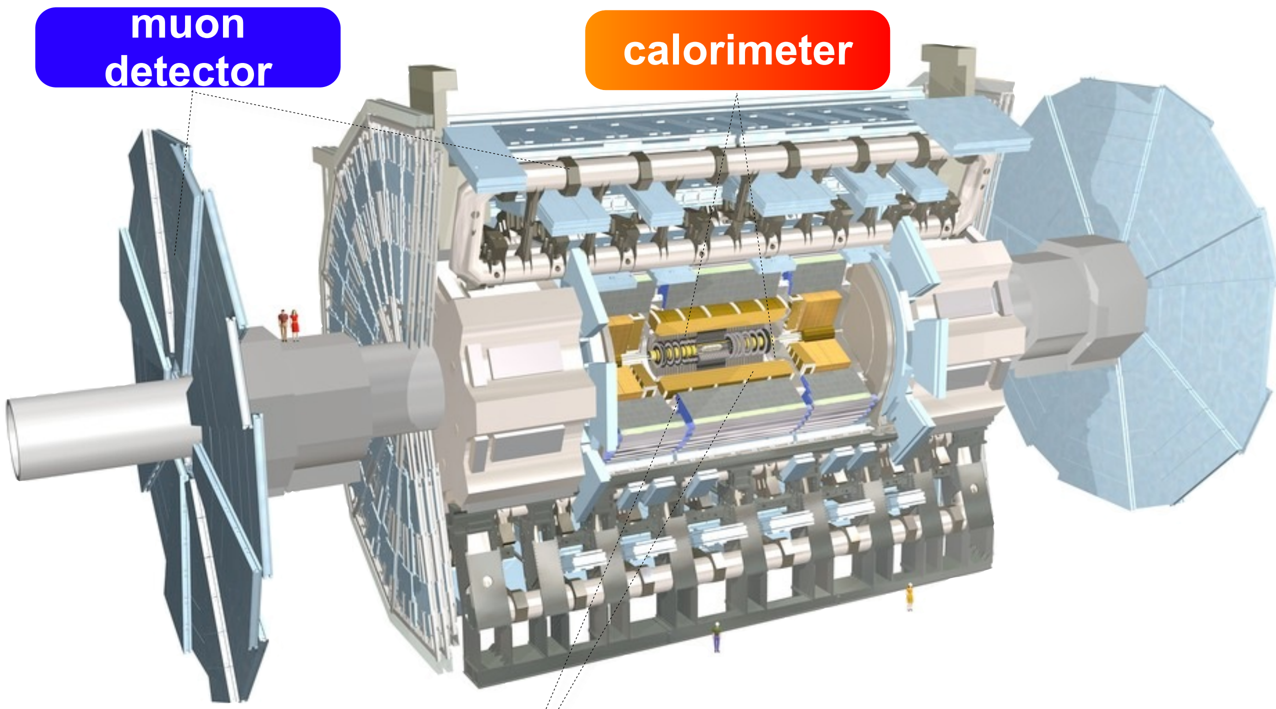
Photon

Nobel Prize 2013





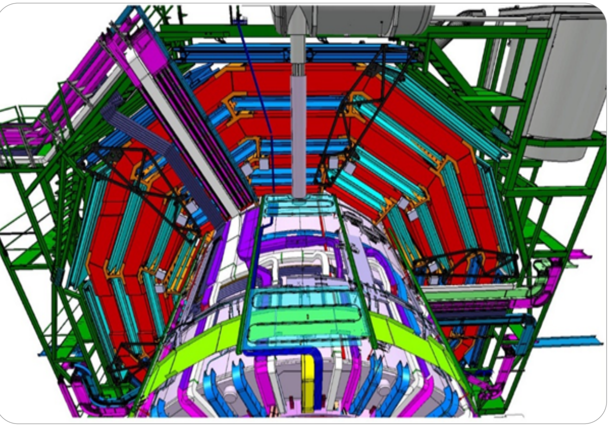
ATLAS Experiment



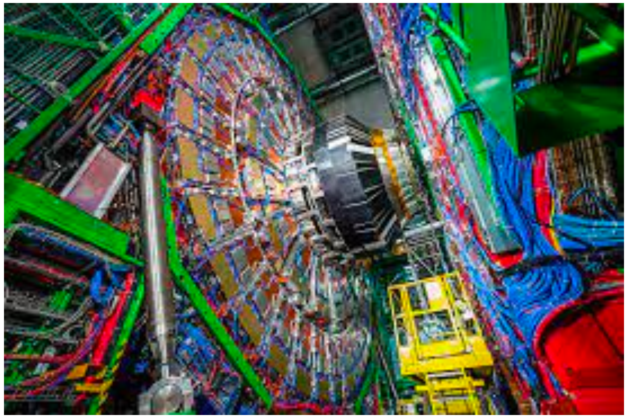
ATLAS facts:

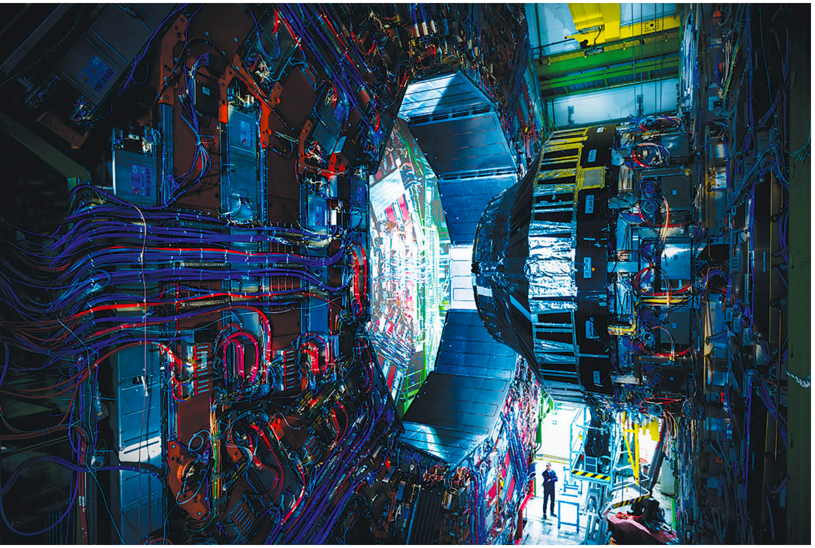
- Length: 45 m, height: 25 m
- Weight: 7000 metric tons
- 150 million electronics channels

Compact integration



Applicable to complex, confined and/or harsh environments, where multiple aspects and diverse technologies need an holistic design approach in order to be integrated into one system.





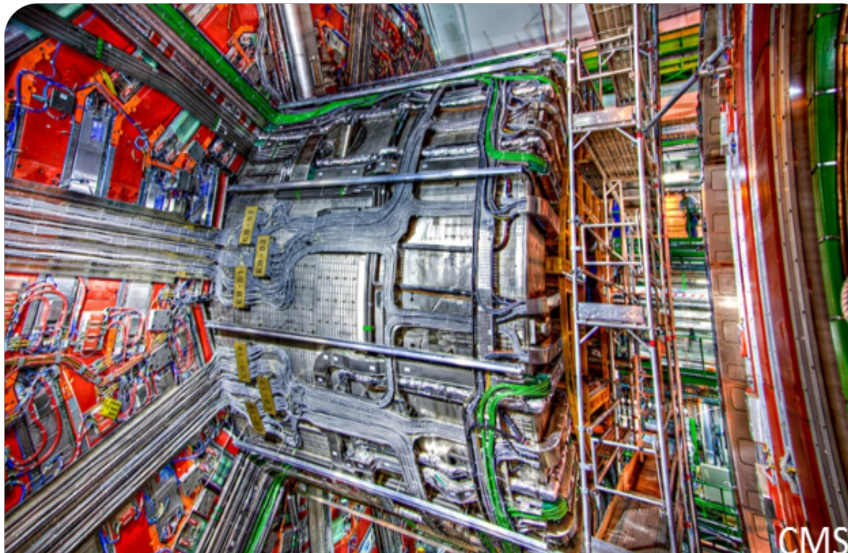
- History of multifunctional design of systems incorporating a broad range of technologies in small volumes:

  → **Ultra-compact integration of complex systems**

- Functional analysis capabilities to facilitate holistic design approach across large systems:

  → **Optimise ratio between core and auxiliaries services**

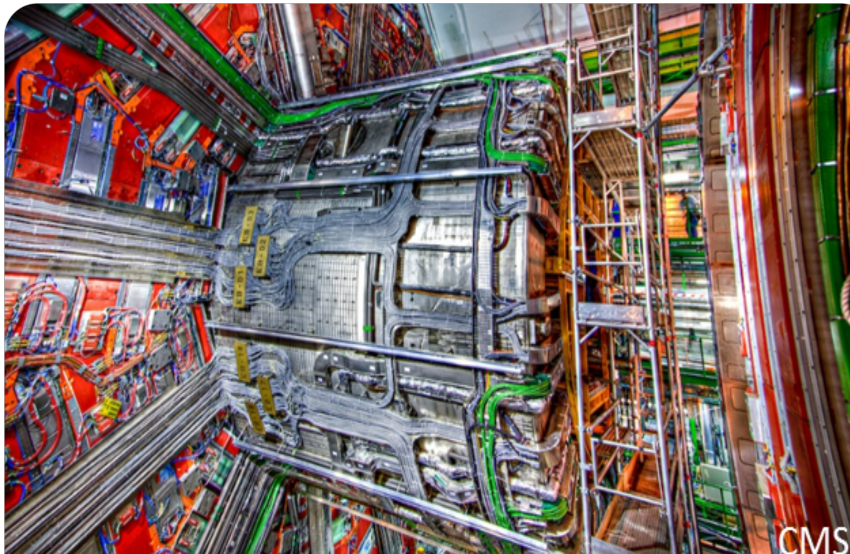
Compact integration



Experiments running around and outside the LHC are extremely complex and large structures
Main challenge is to maximize the volume dedicated to the detector itself minimizing the volume for auxiliaries services integration of technologies is key.

- Integrate several tons of materials for the detectors in confined area with their own specific constraints:
  - Cooling systems (from ambient down to -35°C)
  - Power cables (total FE electronics power in CMS 1MWatt)
  - Front-end and readout electronics (voltage supply, voltage operation, power consumption)
  - Optical fibres (same length for every single fibre for timing)
- Integrate detector control systems and detector safety systems
- Coordination on sub-detectors from institutes all around the world

Compact integration



- Front-end and readout electronics
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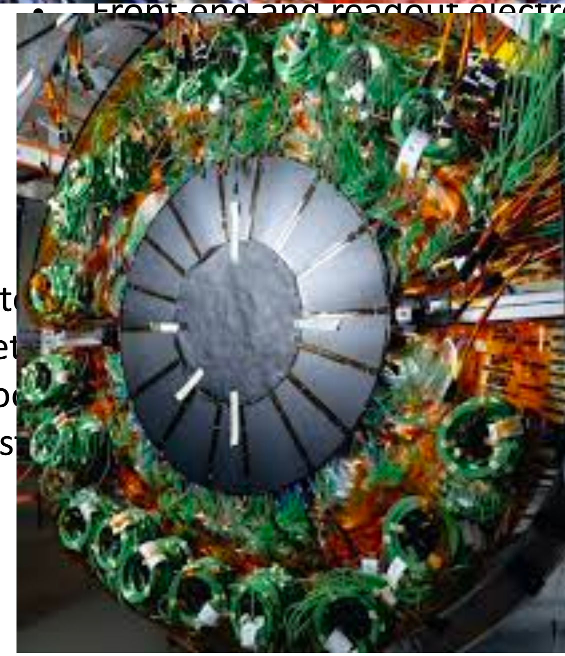

Experiments running around and outside the LHC are extremely complex and large structures
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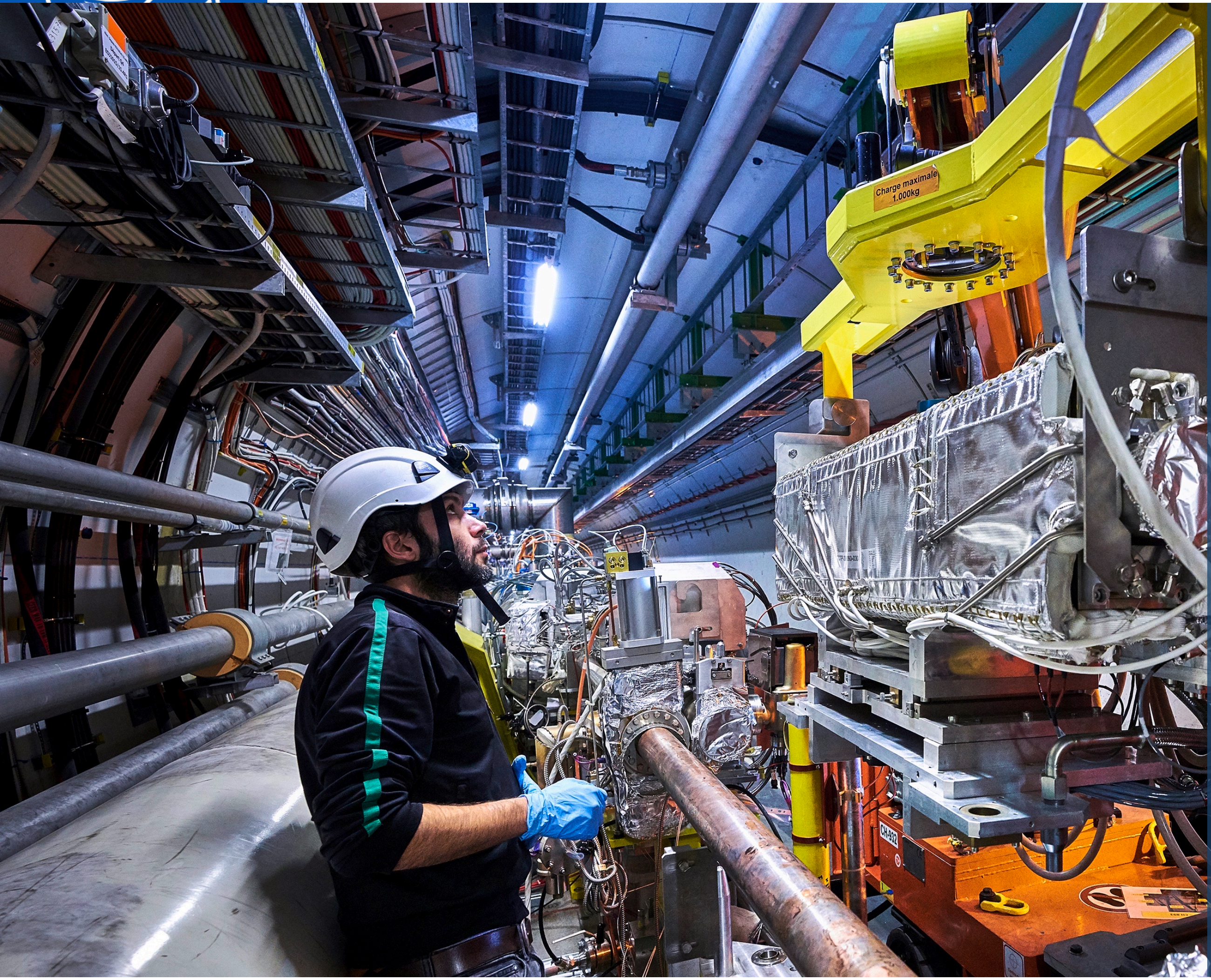


Upgrade to the High-Luminosity LHC is under way

- The HL-LHC will use new technologies to provide
10 times more collisions
than the LHC.
- It will provide greater precision and discovery potential.
- It will start operating in

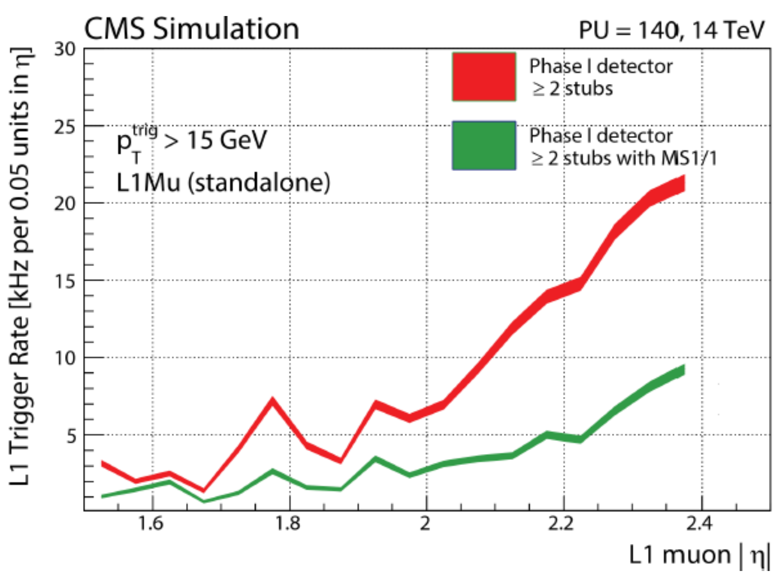
Gaseous Detectors @ CMS, ALICE, LHCb Upgrades

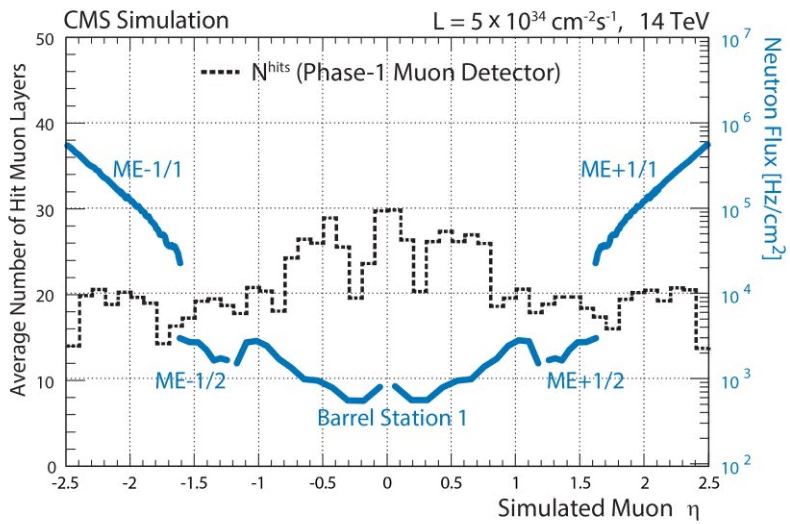
Experiment / Timescale	Application Domain	Gas Detector Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
ALICE TPC UPGRADE CERN LS2	Heavy-Ion Physics (Tracking + dE/dx)	4-GEM / TPC	Total area: ~ 32 m^2 Single unit detect: up to 0.3m^2	**Max.rate**:100 kHz/cm^2 **Spatial res.:** ~300μm **Time res.:** ~ 100 ns **dE/dx:** 11 % **Rad. Hard.:** 50 mC/cm^2	- 50 kHz Pb-Pb rate; - Continues TPC readout - Low IBF and good energy resolution
CMS MUON UPGRADE GE11 CERN LS2	Hadron Collider (Tracking/Triggering)	3-GEM	Total area: ~ 50 m^2 Single unit detect: 0.3-0.4m^2	**Max. rate**: 5 kHz/cm^2 **Spatial res.:** 0.6 – 1.2mm **Time res.:** ~ 7 ns **Rad. Hard.:** ~ 0.18 C/cm^2	Redundant tracking and triggering, improved pt resolution in trigger
CMS MUON UPGRADE GE21 CERN L3	Hadron Collider (Tracking/Triggering)	3-GEM	Total area: ~ 105 m^2 Single unit detect: 0.3-0.4m^2	**Max. rate**: 1.5 kHz/cm^2 **Spatial res.:** 1.4 – 3.0mm **Time res.:** ~ 7 ns **Rad. Hard.:** ~ 0.09 C/cm^2	Redundant tracking and triggering, displaced muon triggering
CMS MUON UPGRADE ME0 CERN L3	Hadron Collider (Tracking/Triggering)	3-GEM	Total area: ~ 65 m^2 Single unit detect: 0.3m^2	**Max. rate**:150 kHz/cm^2 **Spatial res.:** 0.6 – 1.3mm **Time res.:** ~ 7 ns **Rad. Hard.:** ~ 7.9 C/cm^2	Extension of the Muon System in pseudorapidity, installation behind HGCAL
CMS MUON UPGRADE RE3.1, RE 4.1 2023-24 (CERN L3)	Hadron Collider (Tracking/Triggering)	iRPC	Total area: ~ 140 m^2 Single unit detect: 2m^2	**Max.rate**: 2kHz/cm^2 **Spatial res.:** ~1-2cm **Time res.:** ~ 1 ns **Rad. Hard.:** 1 C/cm^2	Redundant tracking and triggering
LHCb MUON UPGRADE CERN LS4	Hadron Collider (triggering)	μ-RWELL	Total area: ~ 90 m^2 Single unit detector: From 0,4x0,3 m^2 To 0,8x0,3 m^2	**Max.rate**:900 kHz/cm^2 **Spatial res.:** ~ cm **Time res.:** ~ 3 ns **Rad. Hard.:** ~ 2 C/cm^2	About 600 detectors

Challenges: HL-LHC

Maintain standalone trigger and reconstruction, mitigation of efficiency loss due to aging of the current detectors can be met if:

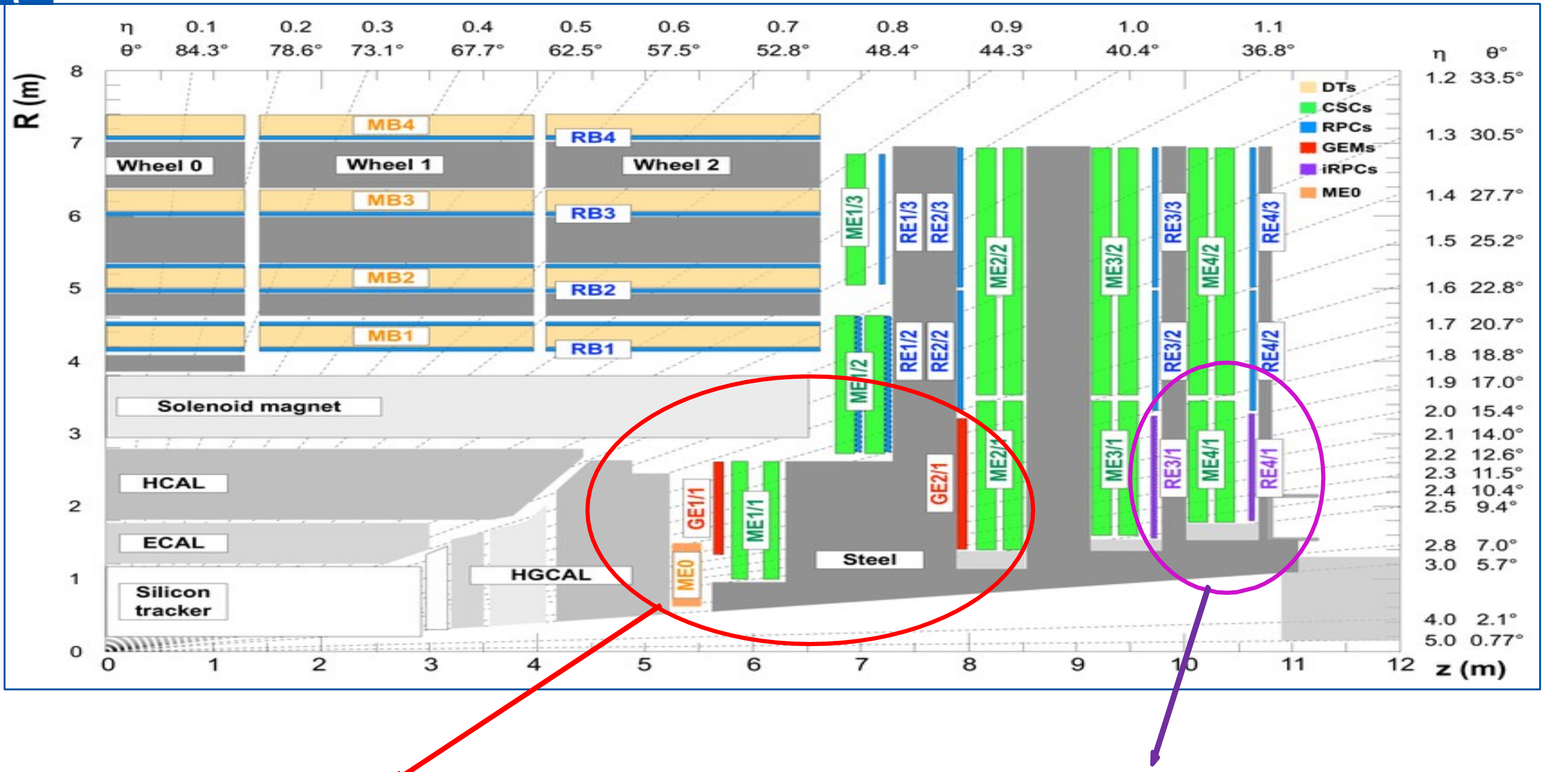
- the number of hits recorded is sufficiently large
- spatial accuracy and the time resolution are very good.
- good momentum measurement for the rejection of unwanted soft muons, mis-measured as high p_t muons → prevent increase in p_t threshold





CMS Muon Spectrometer after LS3

A cross-section of the CMS experiment after the Phase II upgrades



The GEM upgrade: three new stations GE1/1, GE2/1 and ME0 based on the triple-GEM technology

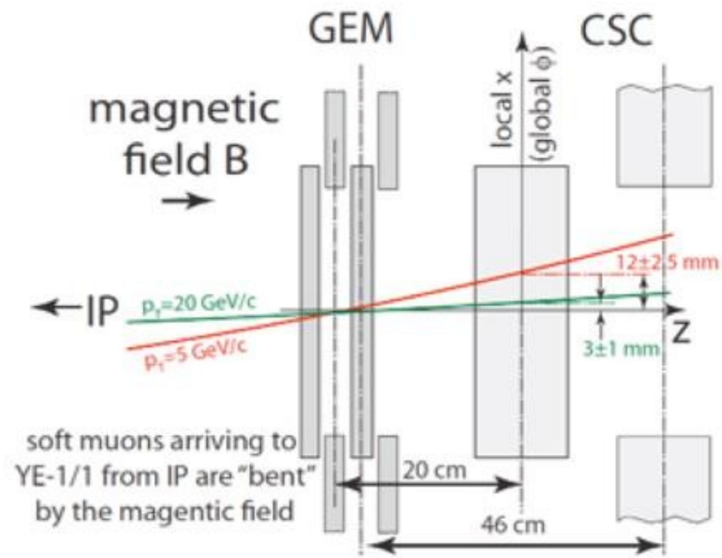
The RPC upgrade: two new stations RE3/1 and RE4/1 based on the improved-RPC technology

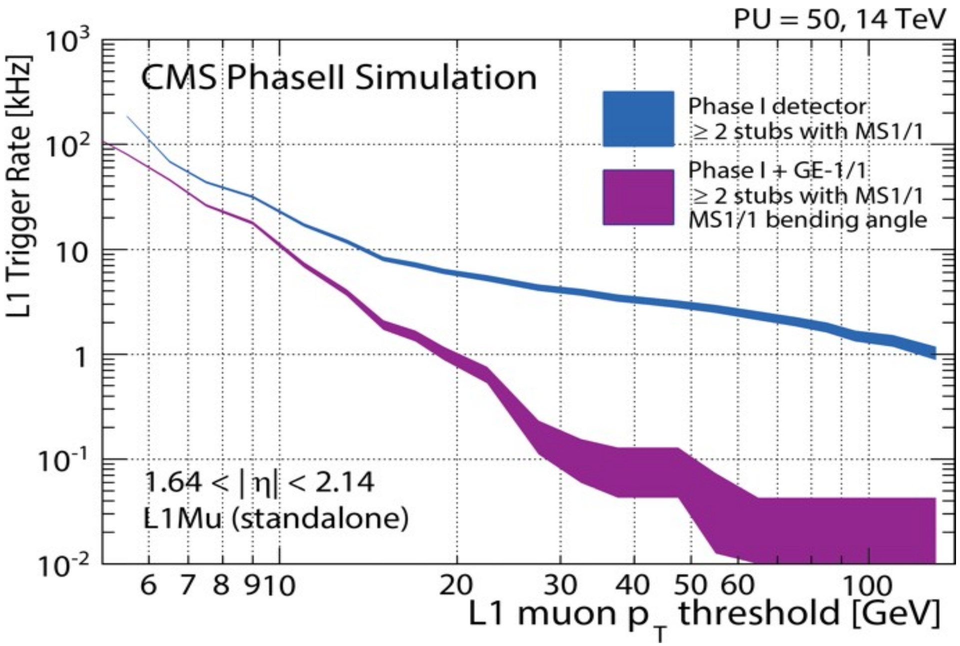
How GEMs will help

GE1/1

Till LS2, forward trigger for $|\eta|>1.6$ relies entirely on the CSC system (ME1/1) strong B field

GEM detector in front of CSC can measure muon bending angle in magnetic field and add redundancy

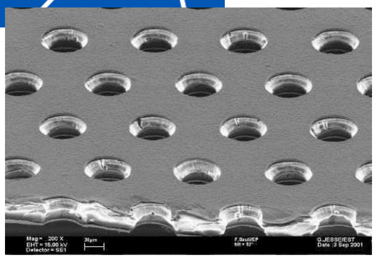


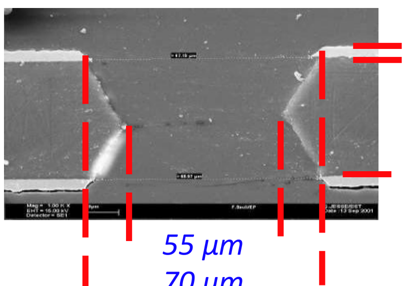


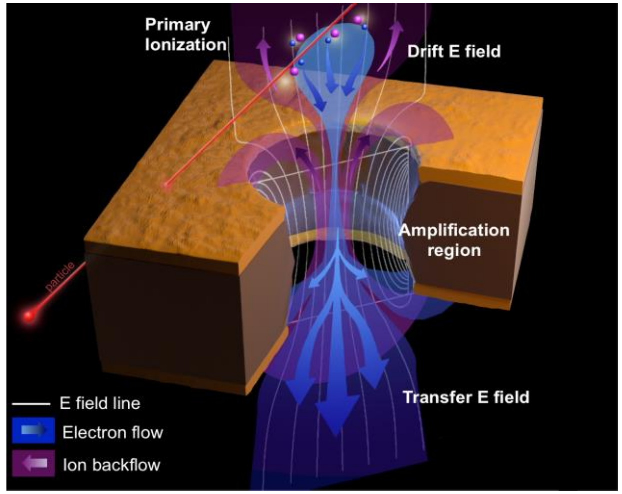
maintain 15 GeV online threshold, keep < 5 kHz rate, high efficiency

What are the GEM

SEM picture of a GEM



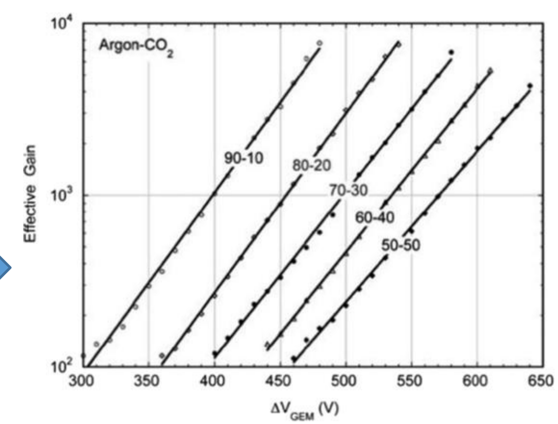




SEM picture of a GEM hole

Electrons entering the GEM holes will accelerate in the intense electric field (~80 kV/cm) and provoke the ionization of gas molecules, giving rise to an electron avalanche

Multiplication: 1 e- input to > 1000e- output (as a function of gas and HV)



Masters of GEM

CERN's Printed Circuit Workshop

The Chamber story

GE1/1-I | GE1/1-II | GE1/1-III | GE1/1-IV | GE1/1-V

2010 | 2011 | 2012 | 2013 | 2014

R&D phase | Toward production phase

GE1/1-I

-> first 1m-class GEM detector ever built
-> single-mask technology
-> 99x(22-45) cm^2
-> 1024 readout channels
-> gap config. 3/2/2/2
-> use of spacer grid and glue

GE1/1-II

-> Optimization of the electric field configuration
-> single-mask technology
-> 99x(22-45) cm^2
-> 3072 readout channels
-> gap config. 3/1/2/1
-> use of spacer grid and glue

GE1/1-III

-> first use of the self-stretching technique
-> single-mask technology
-> No spacers but glue on the external frame
-> Stretching against the external frame

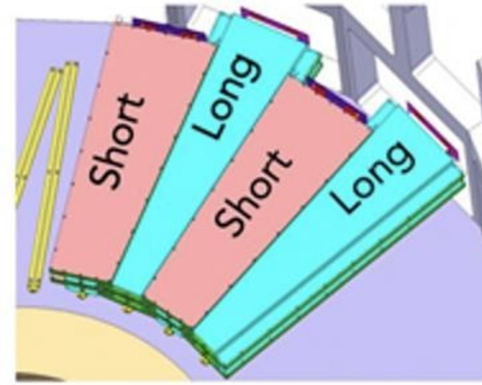
GE1/1-IV

-> Finalization of the stretching technique
-> Introduction of the pull-out
-> No glue/no spacers
-> Assembly time reduced from 1 week to 2h!!!

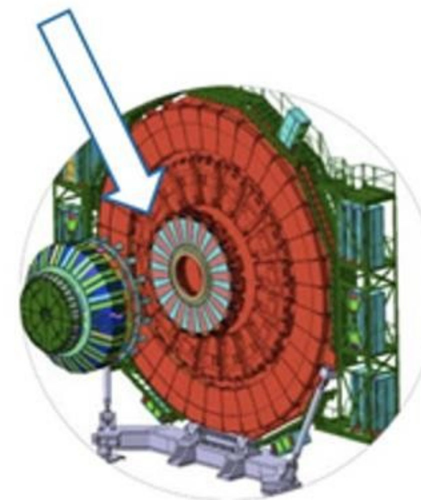
GE1/1-V

-> GE1/1 final layout
-> Modules used to design the QA/QC setup
-> Modules distributed to the production sites for assembly and QA/QC training

Chamber story



GE1/1-VI

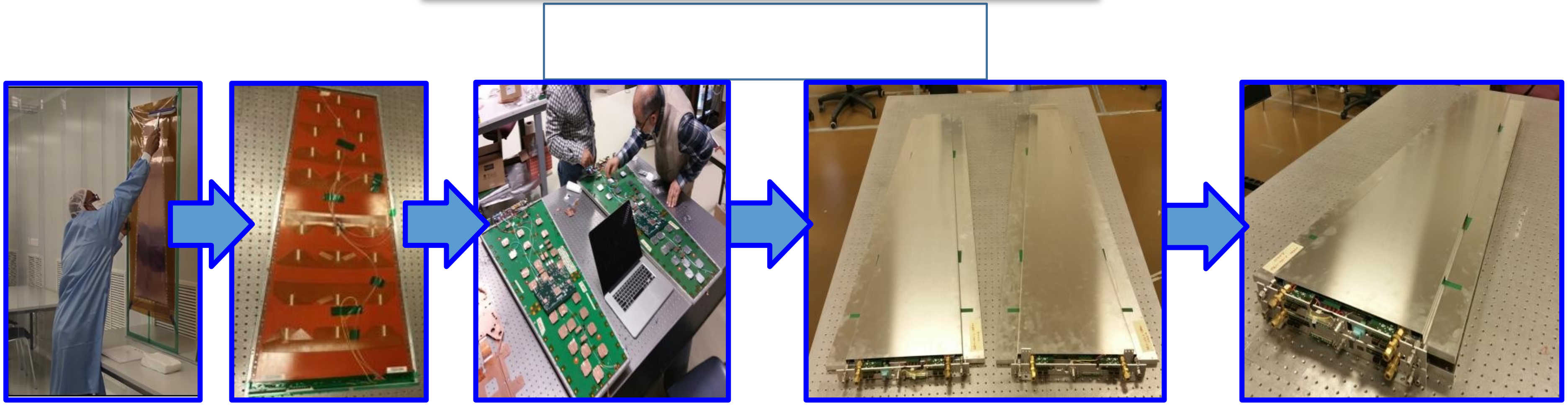


2015	2016	2017-2018-2019
TDR	Slice test installation	Production phas

GE1/1-VI

-> Latest detector design Optimization
-> Final dimensions for maximum acceptance (Long/Short) chamber

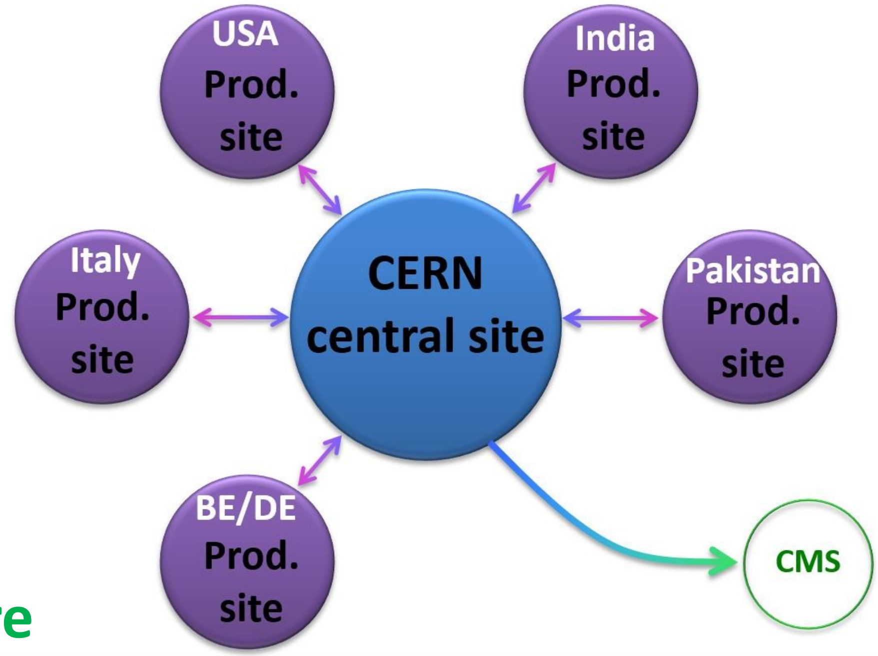
Mass Production & QA/QC



The Plan: General Organization

→ **Distribution of the production in various sites:**

- **Share the effort with CMS - GEM institutes**
- **Generate a large community of GEM experts**
- Equip production sites with infrastructure, tooling and knowledge for GE2/1 and ME0 productions



→ **2-years training program**

- **Using same procedure**
- **Using equivalent infrastructure**
- All Quality Control deliverables validated by the production community

Knowledge transfer

GEM Foils Production

- **Mecaro (KR)** (new producer investigated between 2017 and 2019 – approved in Jan. 2020), GE2/1 GEM Foils (M2, M3, M6 and M7 types)
- Organized an in-depth internal review with KCMS representatives, Mecaro engineers, project management and Rui directly at the Korean factory

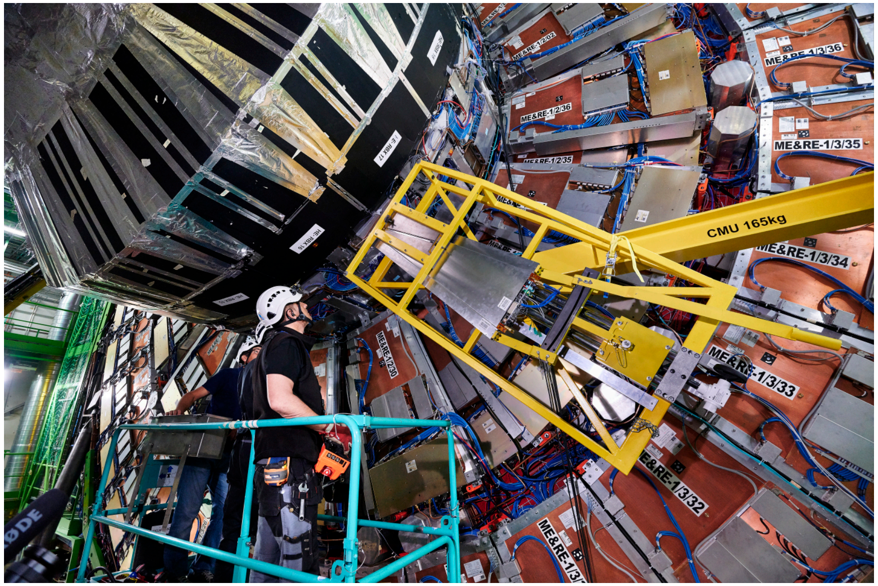
- Excellent experience with the Korean teams from Mecaro and Korea-CMS
  - Large team of experts, almost a constant presence at the factory for the foil validation
  - In-depth inspection and test of all foils in Korea before shipping to CERN for additional cross-check measurements

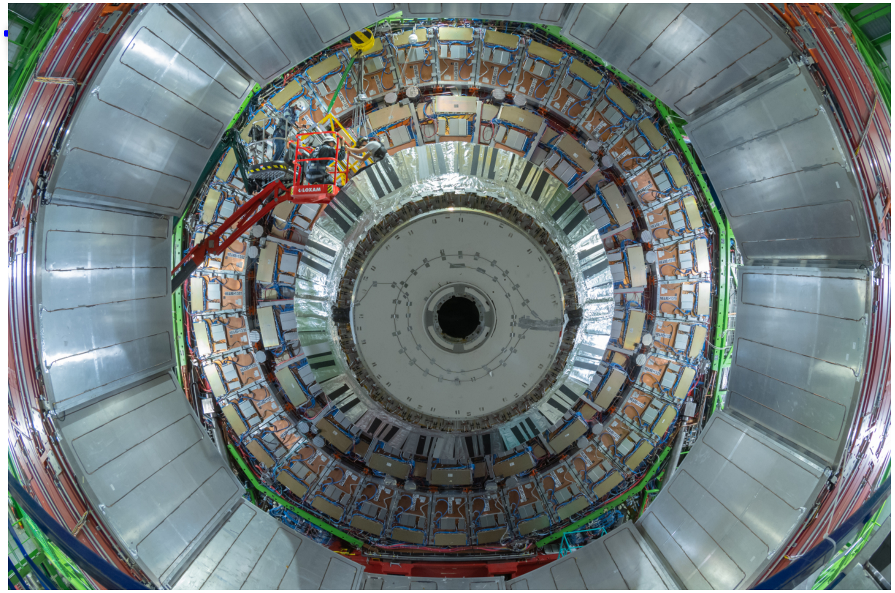
GEM (GE1/1) Production Coordination

Technical Coordination & Detector Integration

GE-1/1 SCs installation in the negative end-cap

- ✓ Installation of all 36 super-chambers for the first end-cap completed in Oct. 2019
- ▪ Multiple installation windows from July 2019 to October 2019



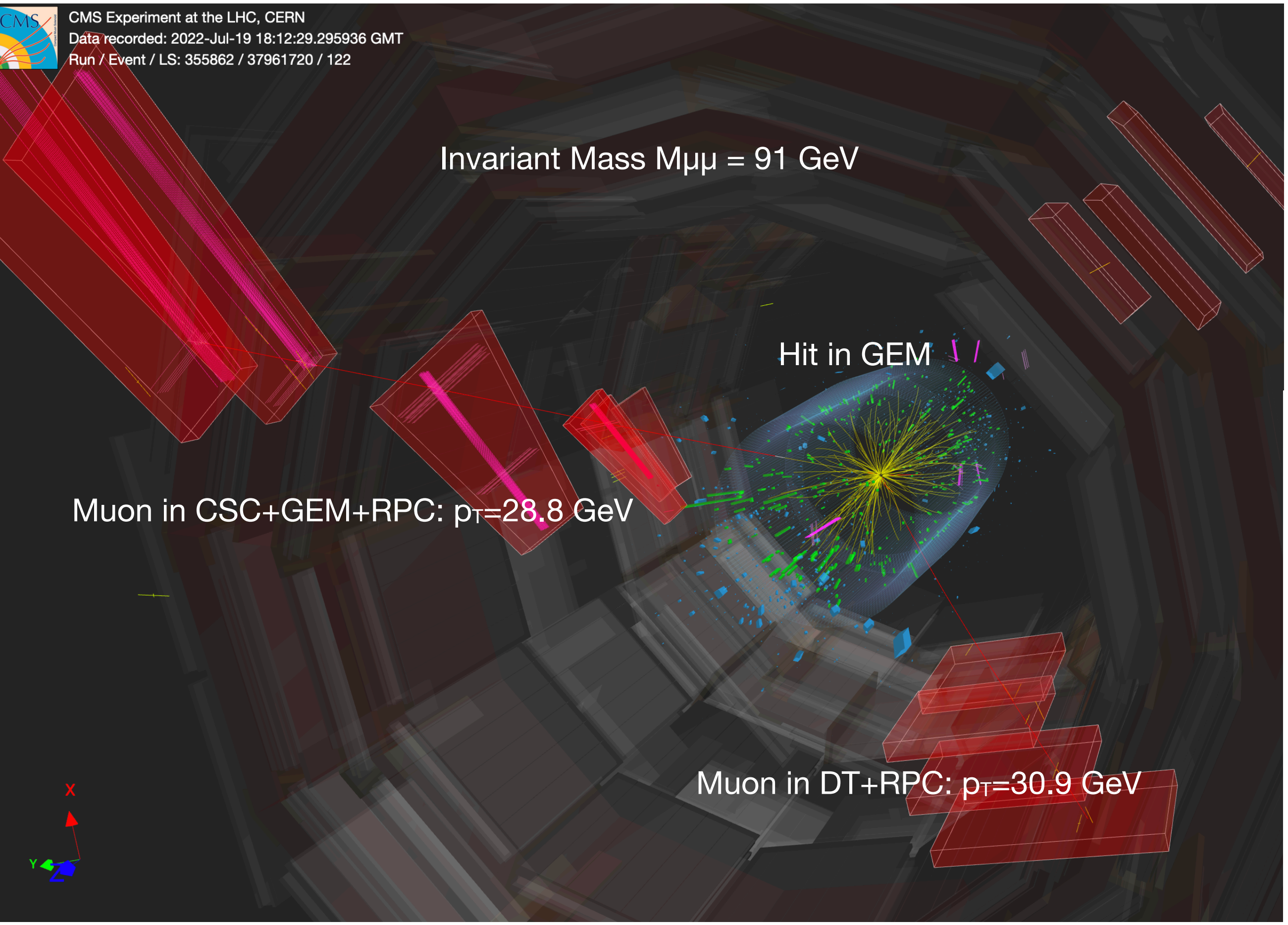


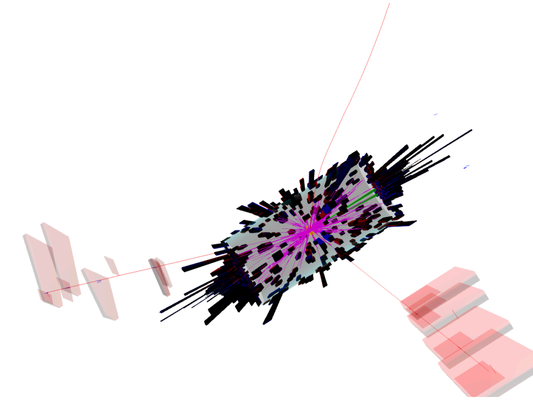
GE-1/1 SCs installation in the positive end-cap

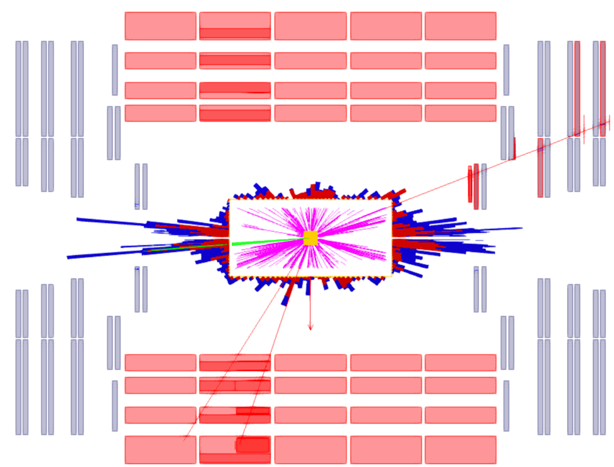
- ✓ Installation of all 36 super-chambers for the second end-cap completed in Sept. 2020
- ▪ Installation and commissioning phase delayed to the COVID-19 lockdown

Nice pictures and movies of this story available at: http://cds.cern.ch/record/2684028 & https://www.youtube.com/watch?v=fU0ujGWbeQ0&feature=youtu.be

CMS Event with muons in all muon subdetectors







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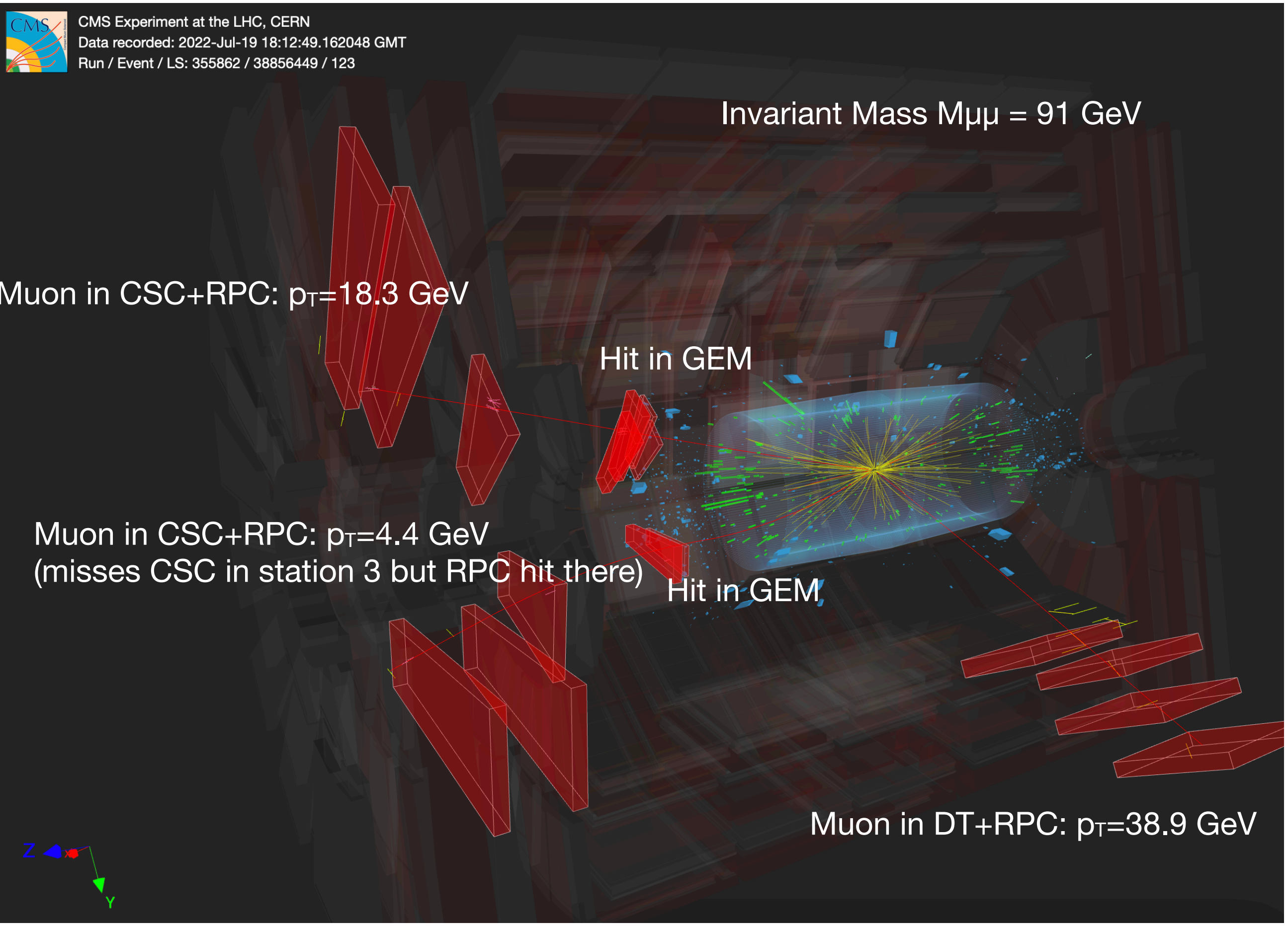

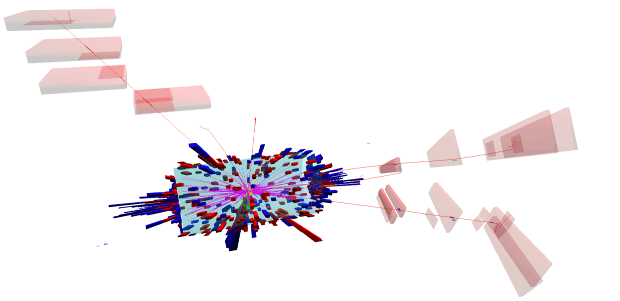

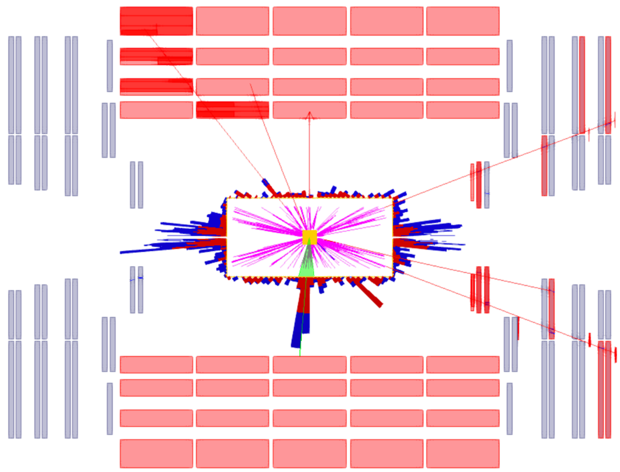

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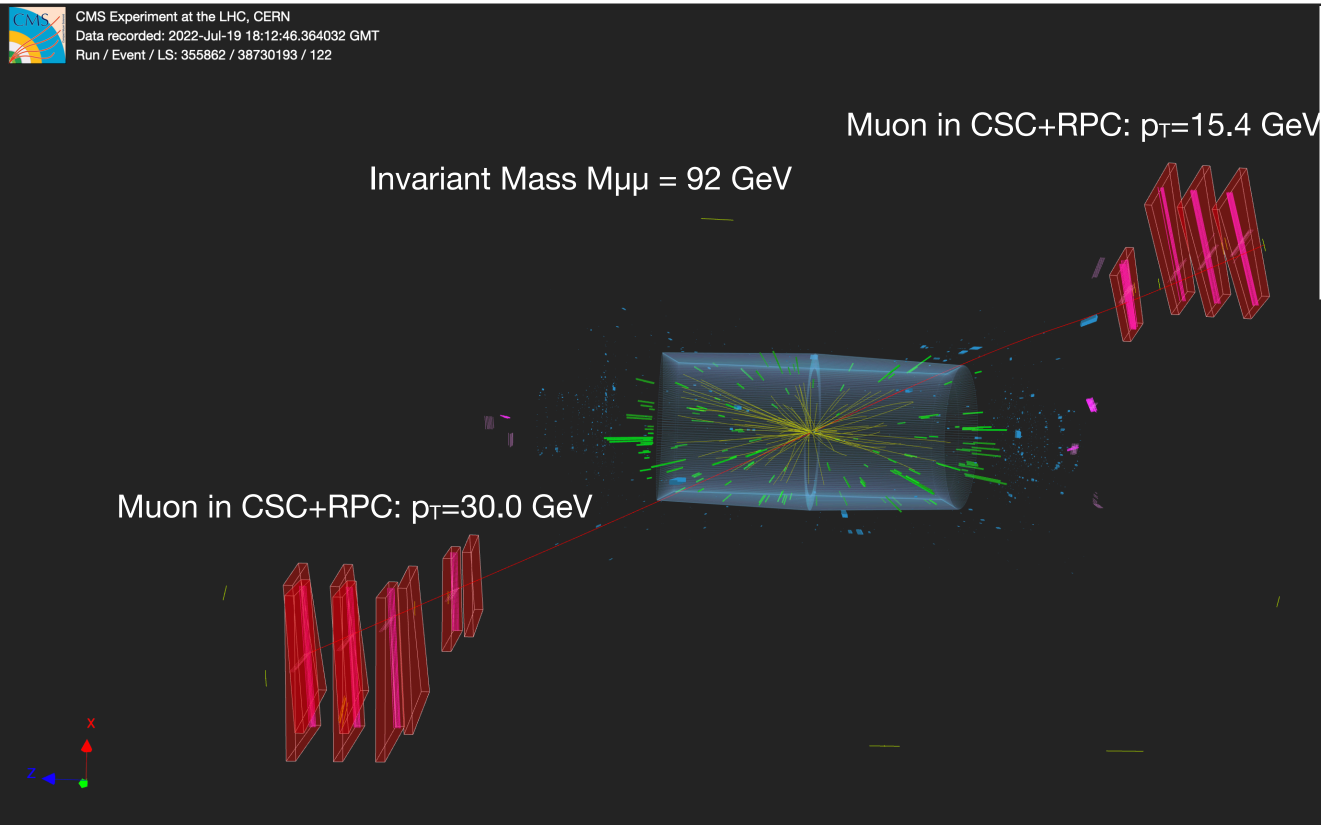
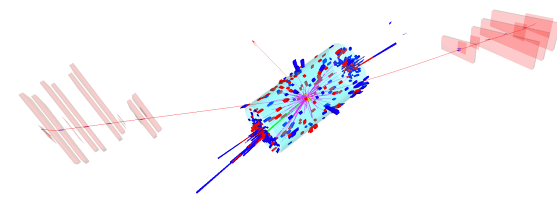
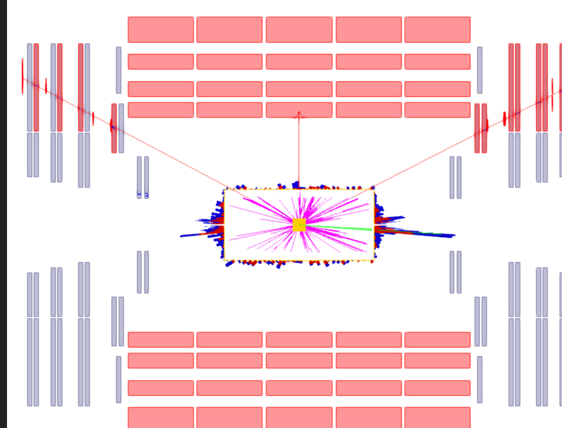
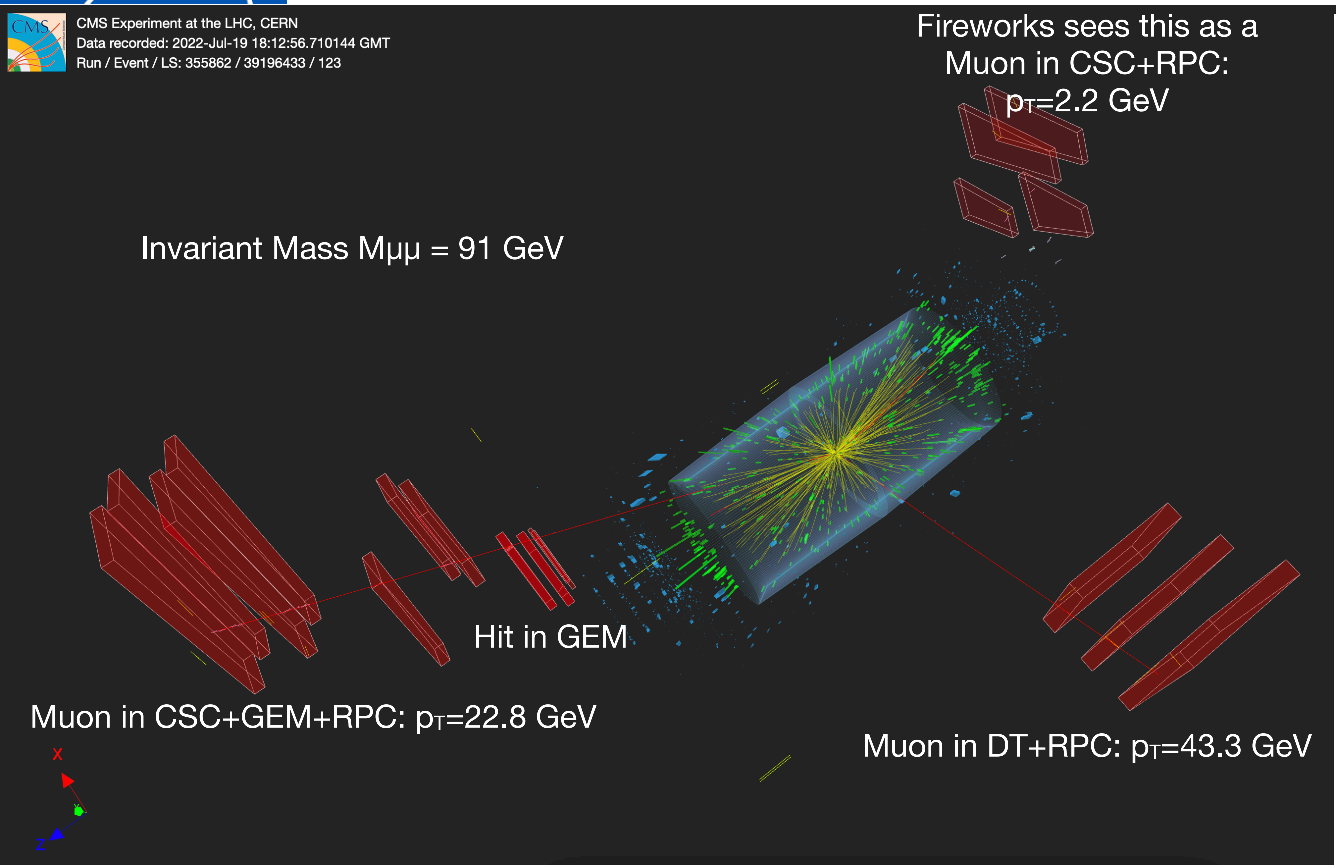
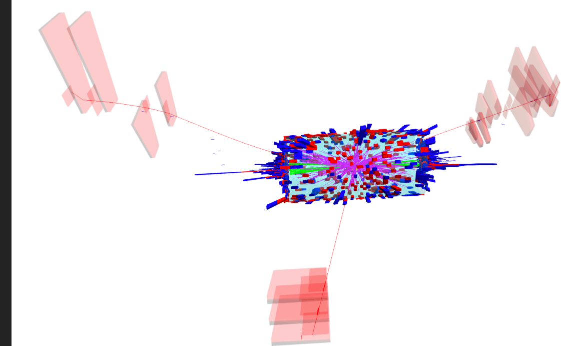


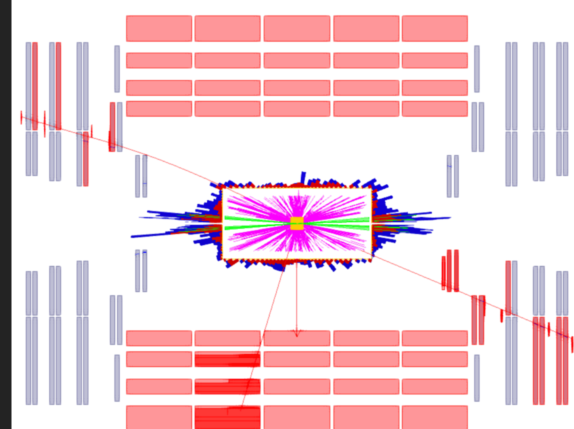




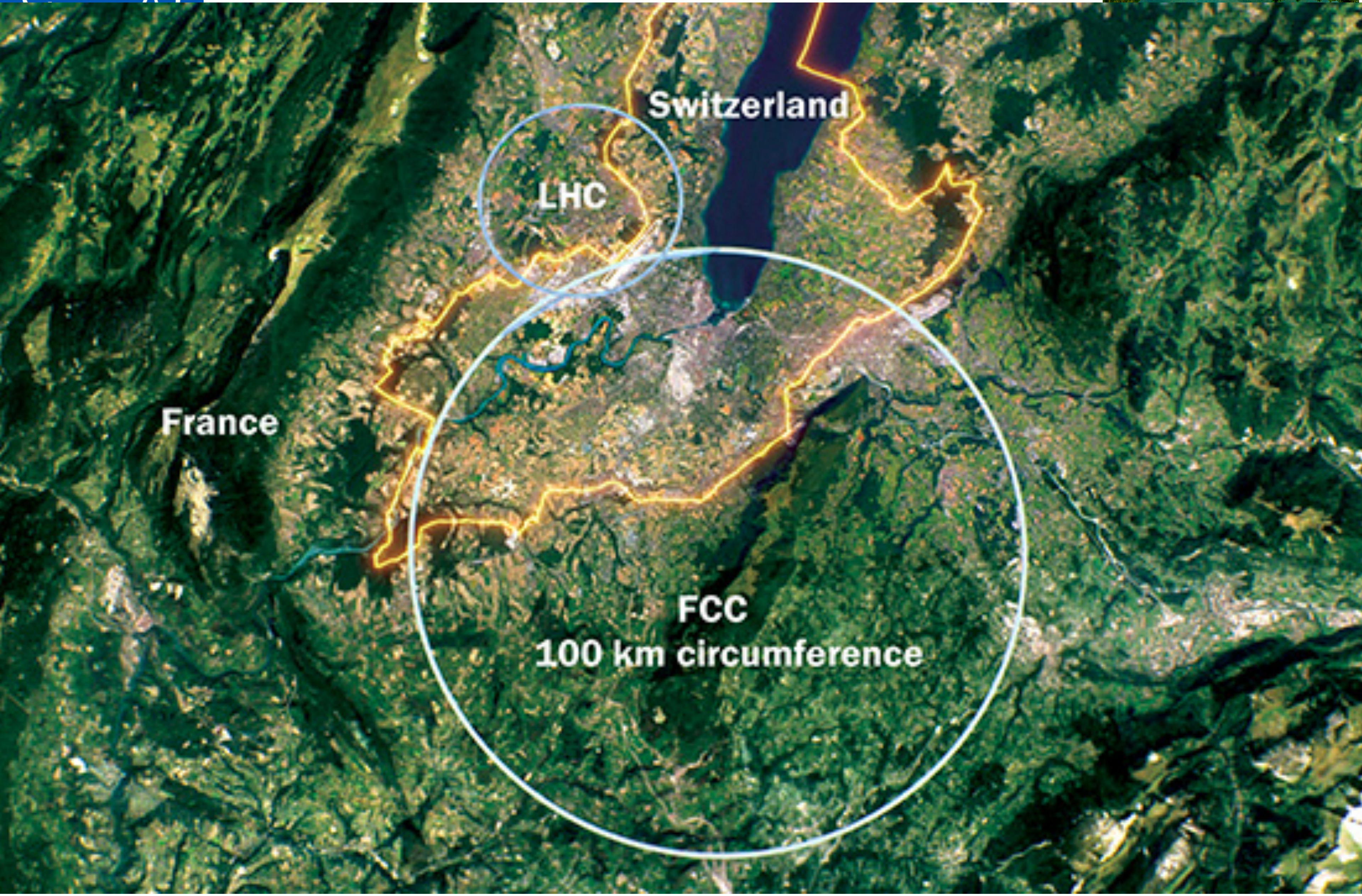
CMS Event with muons in all muon subdetectors







FCC Feasibility Study (FS) 2021-2025



Gaseous Tracking / Muon Detection @ Future Colliders:

Drift Chamber → TPC → RPC → Micro-Pattern Gas Detectors

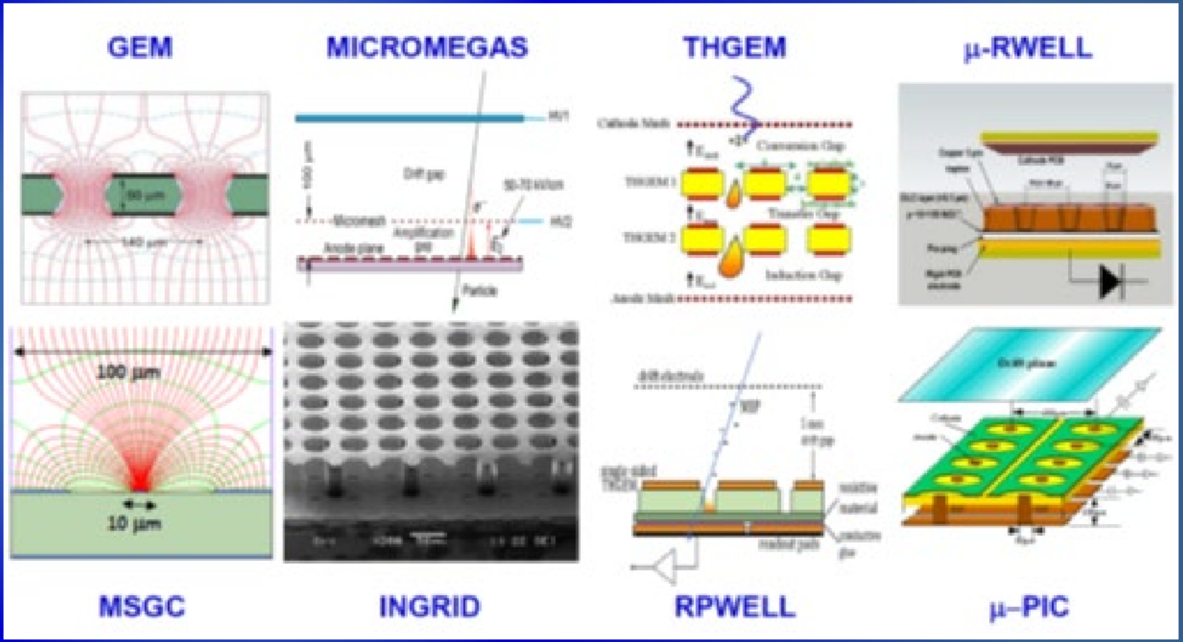
Primary choice for large-area coverage with low material-budget (+ dE/dx measurement)

1990's: Industrial advances in photolithography has favoured the invention of novel micro-structured gas amplification devices (MSGC, GEM, Micromegas, …)

- ✓ Scaling up MPGD detectors, while preserving the typical properties of small prototypes, allowed their use in the LHC upgrades
  → Many emerged from the R&D studies within the CERN-RD51 Collaboration

- ✓ Successful accomplishment of LHC upgrades will help to disseminate MPGD technologies even wider

RD51 extension (2019-2023): arXiv: 1806.09955



HL-LHC Upgrades: Tracking (ALICE TPC/GEM); Muon Systems: RPC, CSC, MDT, TGC, GEM, Micromegas;

Future Hadron Colliders: FCC-hh Muon System (MPGD - OK, particle rates are comparable with HL-LHC)
Future Lepton Colliders: Tracking (FCC-ee / CepC - Drift Chambers; ILC / CePC - TPC with MPGD readout)
Calorimetry (ILC, CepC – RPC or MPGD), Muon Systems (many gas det. are OK)

Future Election-Ion Collider: Tracking (GEM, μWELL; TPC/MPGD), RICH (THGEM), TRD (GEM)

What are the challenges met for LHC?

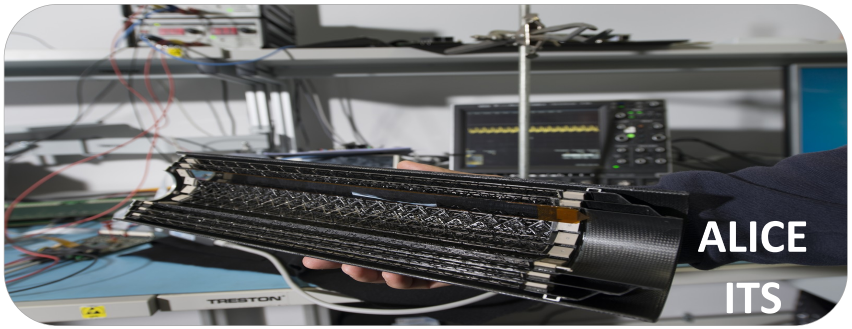
Design of high performance, high resolution and extreme radiation tolerant detectors

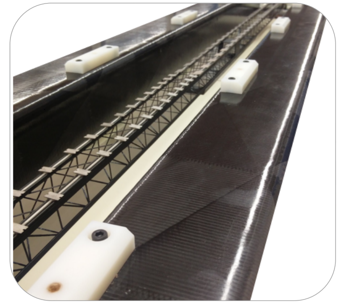
Long term integration complex and large size heterogeneous detector systems in harsh environments

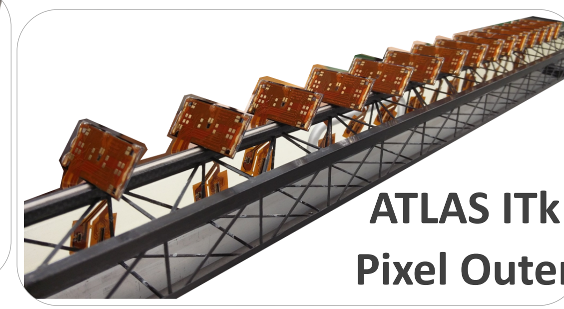
Broad range of assembly, testing and qualifying capabilities, required to develop and commission new detector systems.

Extremely radiation tolerant detector technology	**~10gray / year**
Magnetic field tolerant detector technology	**4T**
Operational frequency resulting from particle collisions every 25nsec	**40MHz**
Number of sensors in the LHC	**150 M**

Designing stable carbon fibre structures







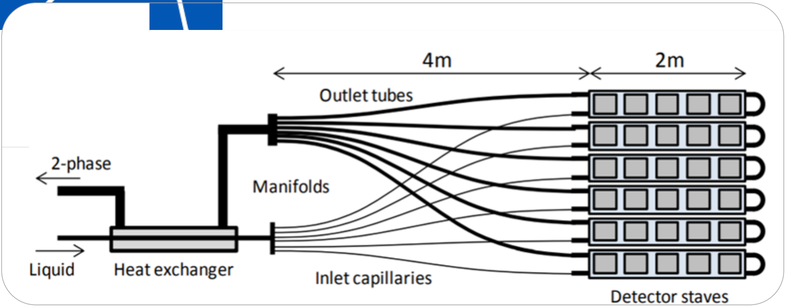
Expertise in the design, manufacture, installation and integration of stable, lightweight support structures based on Carbon Fibre Composite Materials,

Required to provide long lasting structural integrity and stability to the detectors while being exposed to high radiation and magnetic fields.

Expertise and know-how in:

- Filament winding, hand layup and resin transfer moulding.
- Material characterisation.
- Sensor integration for structural health monitoring.
- Integration of electronics components.
- Design and integration of advanced thermal-management solutions (e.g. micro-cooling plates).
- Fittings – Welding, soldering, gluing.

Thermal management using silicon microchannels



The volumetric power density of a LHC Pixel detector is approximately 100 W/dm3 - comparable to the most demanding high power electronics applications. To provide stable and precisely controlled thermal management, CERN experts have developed know-how in the design and manufacture of ultra-thin microchannel cooling plates.

- Proven technology - already adopted in two experiments at CERN
- Cooling up to 100s W/cm2 depending on design
- Down to 150um silicon
- Suitable for single or two-phase refrigerants
- No mismatch in coefficient of thermal expansion (CTE) between integrated circuits
- Significant expertise in the integration of micro-scale components, surface preparation, and bonding techniques
- Ongoing R&D on new microfabrication techniques

Cooling of integrated circuits, particularly where stable thermal management is needed, for example…

- Laboratory coolers
- Manufacturing of specialised components
- Data centres

- Know-how on designs for high power density cooling:

→ **Increase performance and protect electronic equipment from thermal damage**

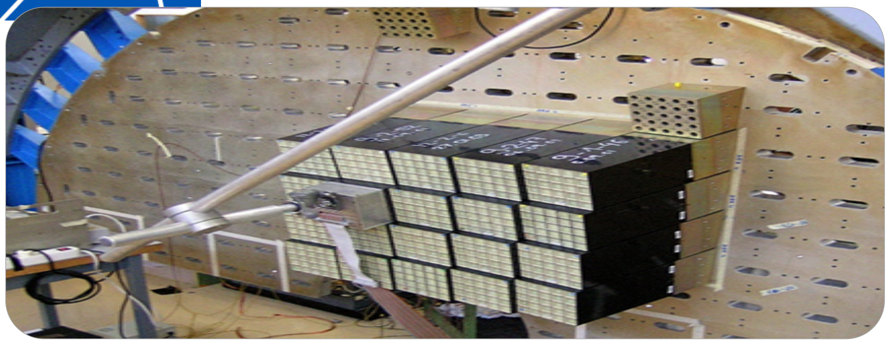
- Ultra-compact, integrated cold plate/heat exchanger:

  → **Reduce space requirements**

- Know-how on interconnection of multiple devices:

  → **Large cooling surfaces possible (>300mm)**

Designing scintillator based detectors



Scintillators are applied in high-energy physics to measure the energy of particles that are produced in particle physics experiments. Therefore, CERN developed highly specialized expertise and infrastructure for research and development of inorganic scintillation technologies for novel ionizing radiation detectors.

- Characterization of scintillation materials and detectors: thermalized benches for characterization of transmission, emission light yield and timing properties, single photon counting and coincidence time measurements, spectrophoto- and fluorimetry, streak camera, pulsed X-rays and irradiation facilities
- Monte Carlo simulation, including ray tracing of light transport and collection
- Nanocrystals, metamaterials and nanophotonics

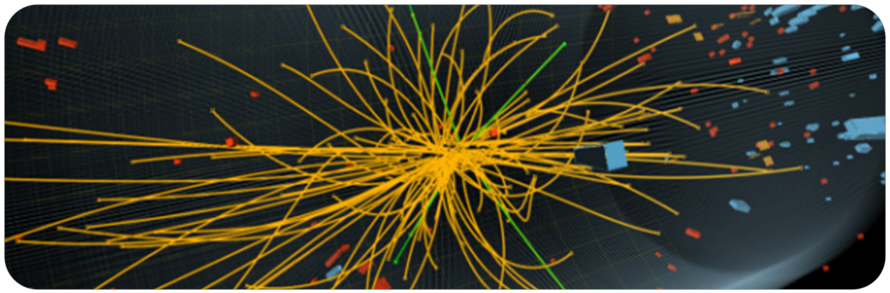
- Particle physics
- Medical imaging – radiology and nuclear imaging
- Radiation protection
- Industrial applications - non-destructive testing

- Complete and versatile scintillator research infrastructure
  → **Characterisation of components and full detector chain**

- Simulation of complex detector systems
  → **Cost-efficient optimization**

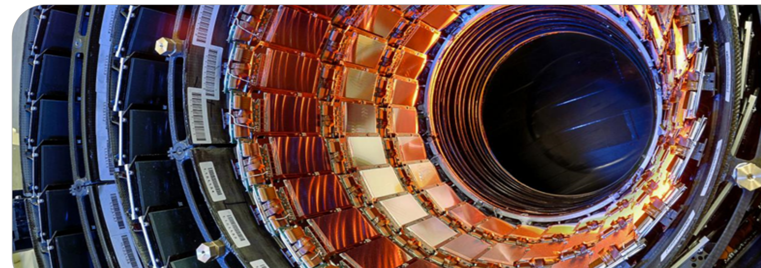
- Broad knowledge in detector materials
  → **Adaptable to many fields of application**

High resolution silicon detectors



The LHC equipment is exposed to high levels of radiation. Therefore, CERN has developed unique expertise in design and integration of high performance and extreme radiation tolerant ASICs. Broad range of testing and qualifying capability for radiation hardness of ASICs. Pushing the limits of mixed-mode circuit design for large detector systems.

- Design of hybrid pixel detectors (Medipix family chips)
- Design of monolithic detectors (ALPIDE, MALTA)
- Design and integration in complex systems including Front-End electronics, mechanical structure and cooling devices



- Medical imaging
- Hadron-therapy beam monitoring
- X rays imaging
- Non-destructive testing
- Particle track reconstruction for Aerospace
- Colour Xray imaging

  → **Detect various components**

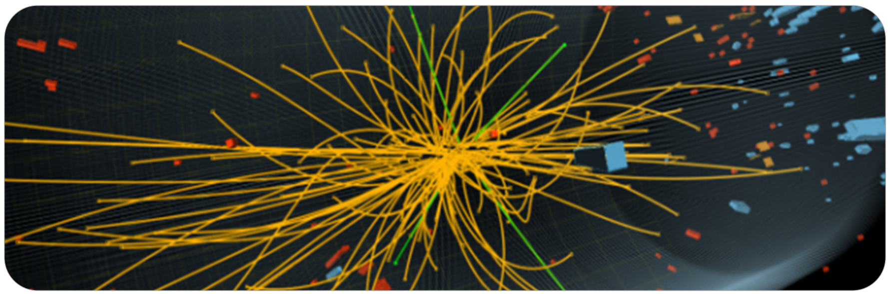
- High resolution, able to count single photons

  → **Designed for particle tracking**

- Can be used on wide range of detection devices

  → **Very broad applicability**

High resolution silicon detectors



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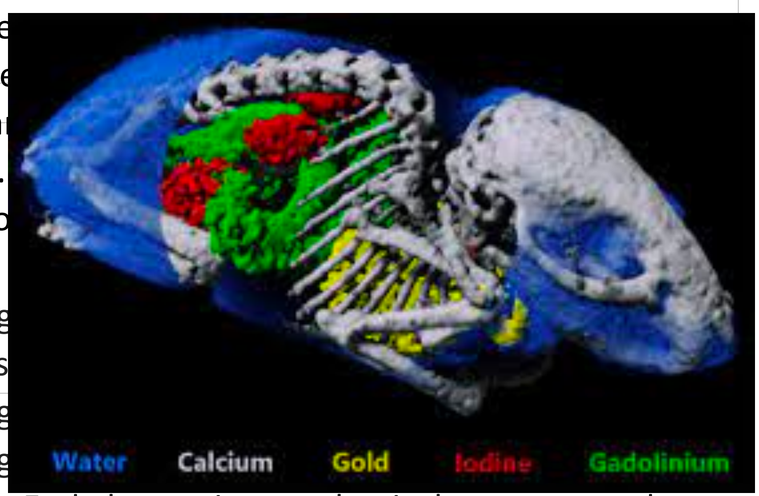
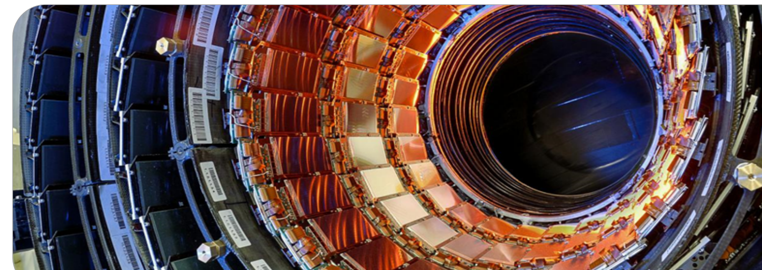




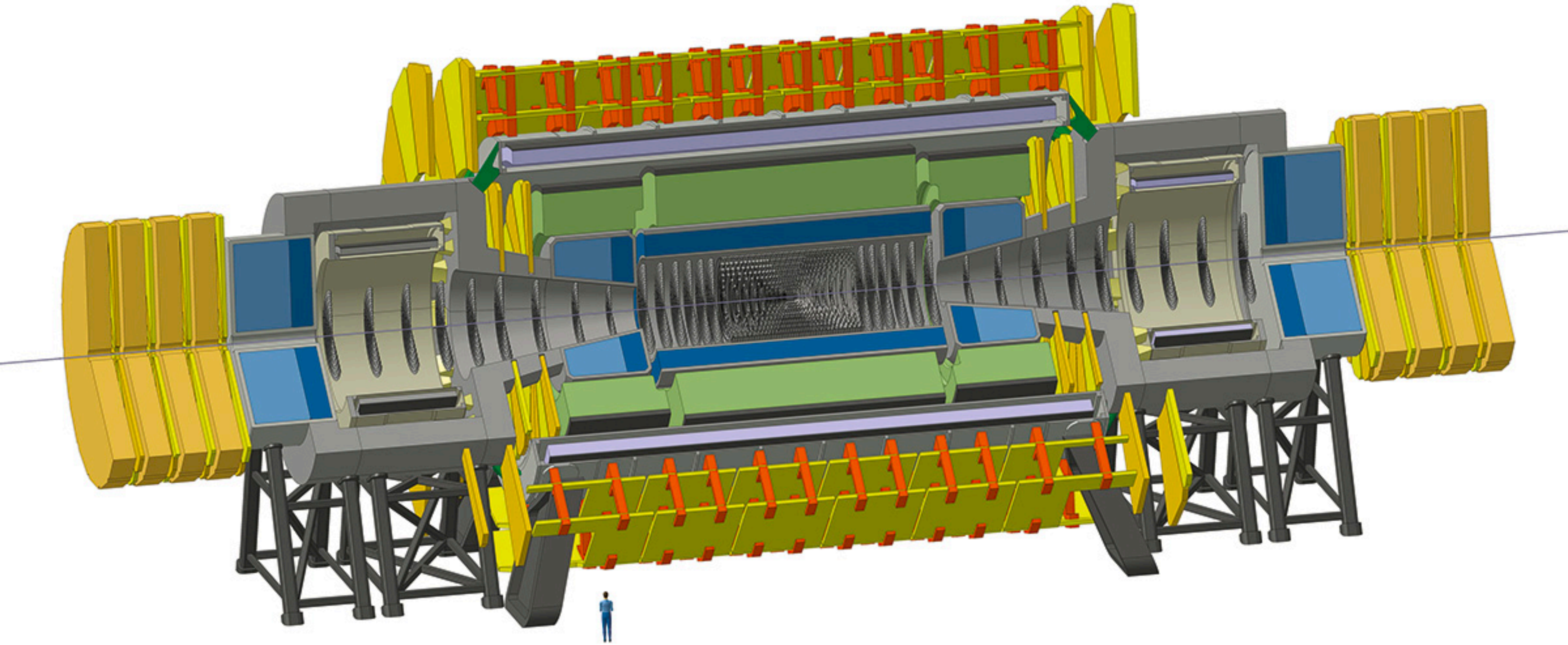
- Medical imaging

→ Designed for particle tracking

- Can be used on wide range of detection devices

→ **Very broad applicability**

A pileup of 1000 proton–proton collisions per bunch-crossing, highly boosted objects and radiation levels up to 10^{18} hadrons per cm^2 are just some of the challenges in extracting physics from a next-generation hadron collider to follow the LHC.



The layout of the FCC-hh reference detector, with a diameter of 20 m and length of 50 m, comparable to the dimensions of the ATLAS detector but much heavier. The central detector houses the tracking, electromagnetic calorimetry and hadron calorimetry inside a 4 T solenoid with a free bore diameter of 10 m (purple). The forward parts are displaced by 10 m from the interaction point, with two forward magnet coils (solenoids shown) providing the required bending power. The muon system is placed outside the magnet coils
Source: CERN Yellow Reports Monographs CERN-2022-002

Towards Large Area in Fast Timing GASEOUS DETECTORS

Multi-Gap Resistive Plate Chambers (MRPC):

- ✓ ALICE TOF detector (160m^2) achieved time res. ~ 60 ps
- ✓ New studies with MRPC with 20 gas gaps using a low-resistivity 400 μm-thick glass → down to 20 ps time resolution

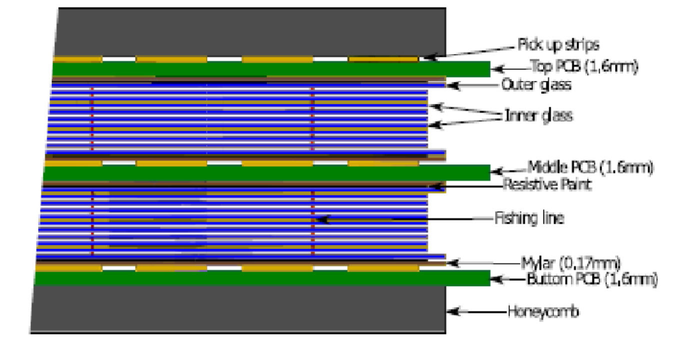
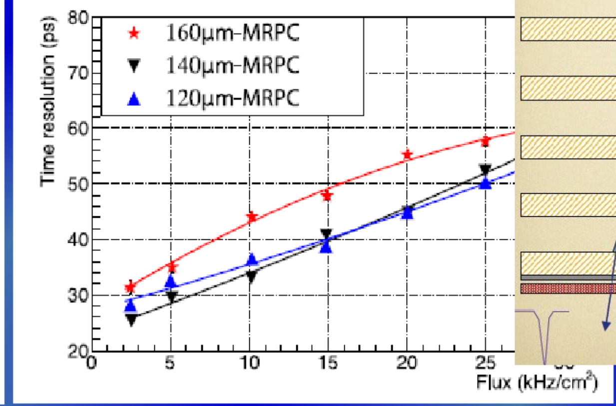
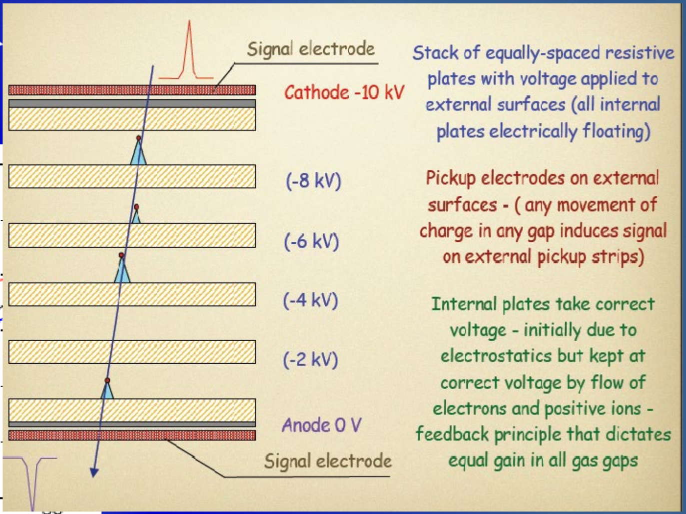


Fig. 1. Cross section of the double stack 20-gap MRPC.



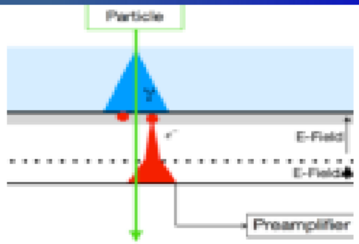


Gaseous Detectors: Micromegas with Timing (RD51 Picosec Collaboration)

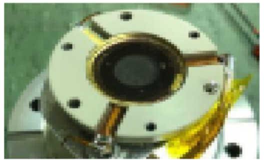
PICOSEC Micromegas

σ ~ 25 ps timing resolution (per track)

Cherenkov radiator + Photocathode + Micromegas

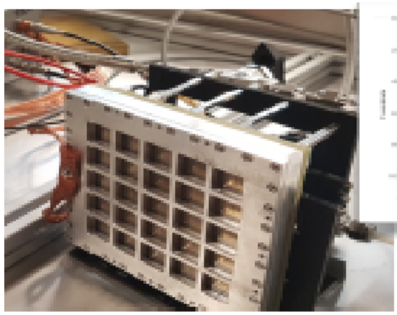


24ps timing resolution

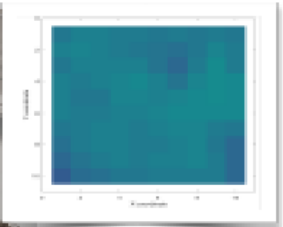


Single pad (2016)
⌀1 cm

Tested in RD51 testbeam July 2021

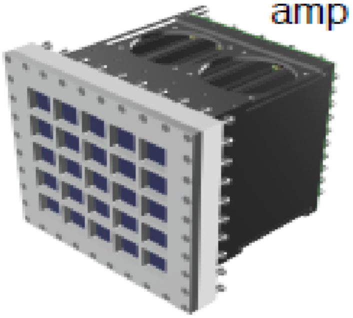


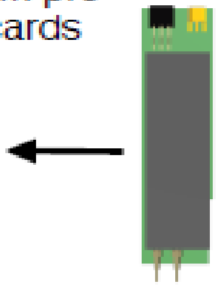
10x10 module
□ 1 cm



Planarity < 10μm

Custom pre-amp cards



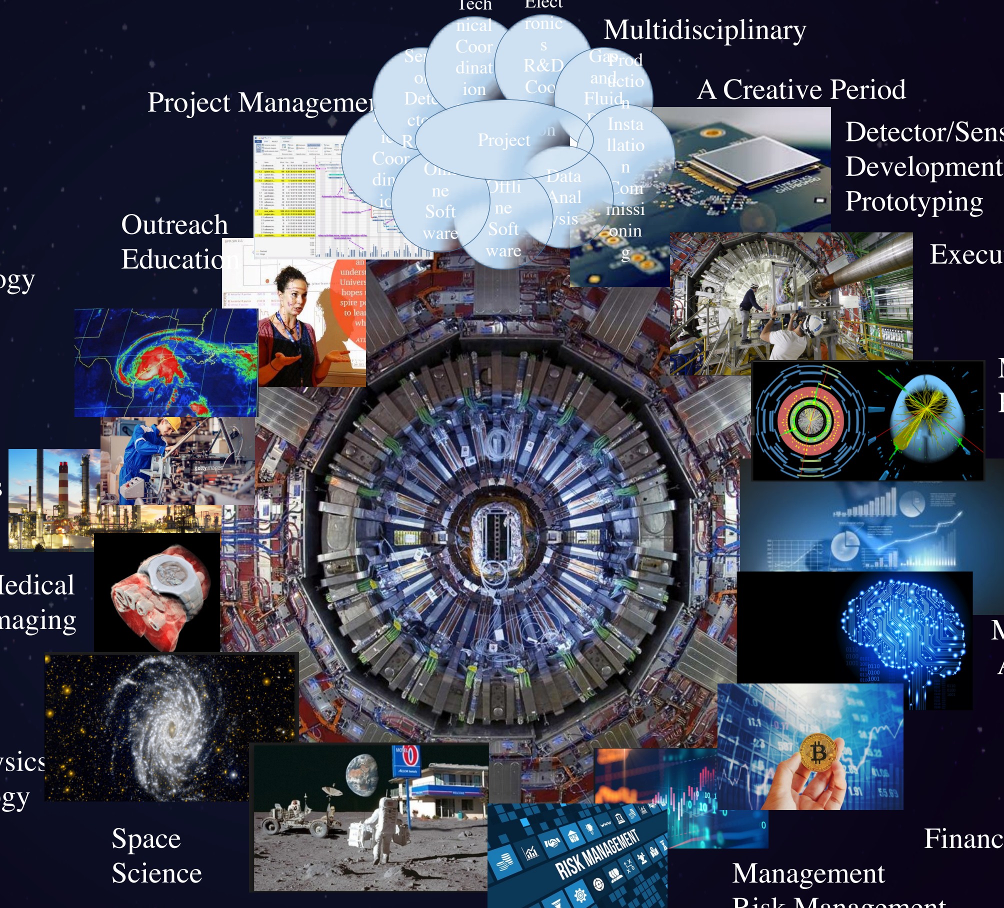


https://indico.cern.ch/event/1040996/contributions/4398412/attachments/2265036/3845651/PICOSEC-update-final.pdf

Gaseous Tracking Systems @ Future Colliders

Experiment / Timescale	Application Domain	Gas Detector Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements/ Remarks
ILC TPC DETECTOR: STARTt: > 2035	e+e- Collider Tracking + dE/dx	MM, GEM (pads) InGrid (pixels)	Total area: ~ 20 m^2 Single unit detect: ~ 400 cm^2 (pads) ~ 130 cm^2 (pixels)	**Max. rate**: < 1 kHz **Spatial res.**: <150μm **Time res.**: ~ 15 ns **dE/dx**: 5 %	Si + TPC Momentum resolution : $dp/p < 9*10^{-5}$ 1/GeV Power-pulsing
CEPC TPC DETECTOR START: > 2030	e+e- Collider Tracking + dE/dx	MM, GEM (pads) InGrid (pixels)	Total area: ~ 2x10 m^2 Single unit detect: up to 0.04 m^2	**Max.rate**:>100 kHz/cm^2 **Spatial res.**: ~100μm **Time res.**: ~ 100 ns **dE/dx**: <5%	- Higgs run - Z pole run - Continues readout - Low IBF and dE/dx
FCC-ee and/or CEPC IDEA CENTRAL TRACKER START: >2030	e+e- Collider Tracking/ Triggering	He based Drift Chamber	Total volume: 50 m^3 Single unit detect: (12 m^2 X 4 m)	**Max. rate**: < 25 kHz/cm^2 **Spatial res.**: <100 μm **Time res.**: 1 ns **Rad. Hard.**: NA	Particle sepration with cluster counting at 2% level
SUPER-CHARM TAU FACTORY START: > 2025	e+e- Collider Main Tracker	Drift Chamber	Total volume: ~ 3.6 m^3	**Max. rate**: 1 kHz/cm^2 **Spatial res.**: ~100 μm **Time res.**: ~ 100 ns **Rad. Hard.**: ~ 1 C/cm	
SUPER-CHARM TAU FACTORY START: > 2025	e+e- Collider Inner Tracker	Inner Tracker / (cylindrical μRWELL, or TPC / MPDG read.	Total area: ~ 2 - 4 m^2 Single unit detect: 0.5 m^2	**Max. rate**: 50-100 kHz/cm^2 **Spatial res.**: ~<100 μm **Time res.**: ~ 5 -10 ns **Rad. Hard.**: ~ 0.1-1 C/cm^2	Challenging mechanics & mat. budget < 1% X0
ELECTRON-ION COLLIDER (EIC) START: > 2025	Electron-Ion Collider Tracking	Barrel: cylindrical MM, μRWELL Endcap: GEM, MM, μRWELL	Total area: ~ 25 m^2	Luminosity (e-p): 10^{33} **Spatial res.**: ~ 50- 100 um **Max. rate**: ~ kHz/cm^2	Barrel technical challenges: low mass, large area Endcap: moderate technical challenges

And the cycle continues….



Multidisciplinary

Project Management

A Creative Period

Detector/Sensor
Development
Prototyping

Outreach
Education

Meteorology

Execution Period

Monitoring
Physics Discovery !

Industrial
Applications

Exploitation Period

Big Data Analytics

Medical
Imaging

Machine Learning
Artificial intelligence

Astrophysics
Cosmology

Space
Science

Financial

Management
Risk Management

Mechanical
Engineering