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"Instrumentation as enabler of Science"

# The Triple-GEM Project for the Phase-2 Upgrade of the CMS Muon System

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CMS
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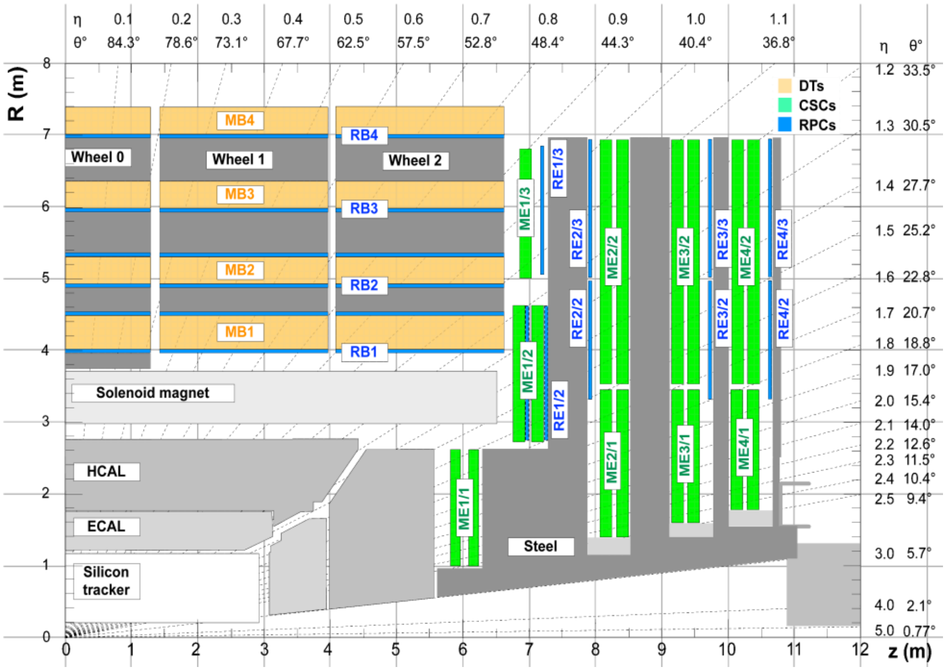
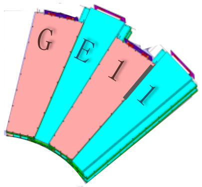
RD51

## Outline

- Introduction
- Trigger Motivation
- Triple-GEM detector prototypes: layout, production and tests
- DAQ and electronics
- Integration into CMS

# The CMS Muon System




**The CMS Muon System combines different technologies:**

- Drift Tubes & Cathode Strip Chambers for tracking and triggering
- Resistive Plate Chambers for triggering

**RE4/2-3 and ME4/2 are added now during LS1**

**After LHC LS1, the |η|<1.6 endcap region will be covered with 4 layers of CSCs and RPCs; the |η|>1.6 region will have CSCs only ...**

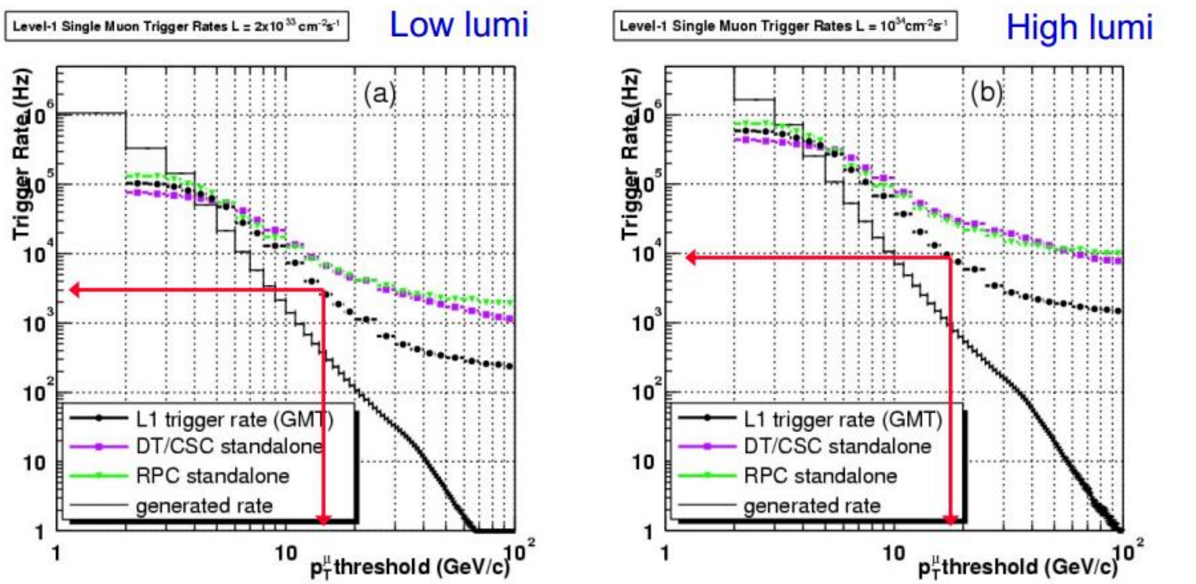
**Standard CMS RPC design not suitable for high rate environment**

| Region | LHC (1034cm -2s -1) | High Luminosity LHC (>LS2) (2-3x1034 cm -2s -1) | LHC Phase II (>LS3) (1035 cm -2s -1) |
|---|---|---|---|
| Max Rate Barrel RPC | 10 Hz/cm2 | ≈ 30 Hz/cm2 | ≈ 100Hz/cm2 |
| Max rate Endcap RPC RE 1,2,3,4 \|η\|<1.6 | 30 Hz/cm2 | ≈ 100 Hz/cm2 | ≈300 Hz/cm2 |
| Expected Charge in 10 years | 0.05 C/cm2 | 0.15 C/cm2 | 0.5 C/cm2 |
| Max Forward Rate Hz/cm2 GE 1,2,3,4 \|η\|>1.6 | 500 -1000 | few kHz/cm2 | few 10s kHz/cm2 |
| Expected Charge in 10 years | 0.05-1 C/cm2 | few C/cm2 | few 10s C/cm2 |

**New technology needed for |η|>1.6 region of muon system**
- Sustain O(MHz/cm$^2$) environment
- Need for good spatial resolution O(100μm): tracking
- Need for good time resolution: triggering

# Muon Trigger Challenges

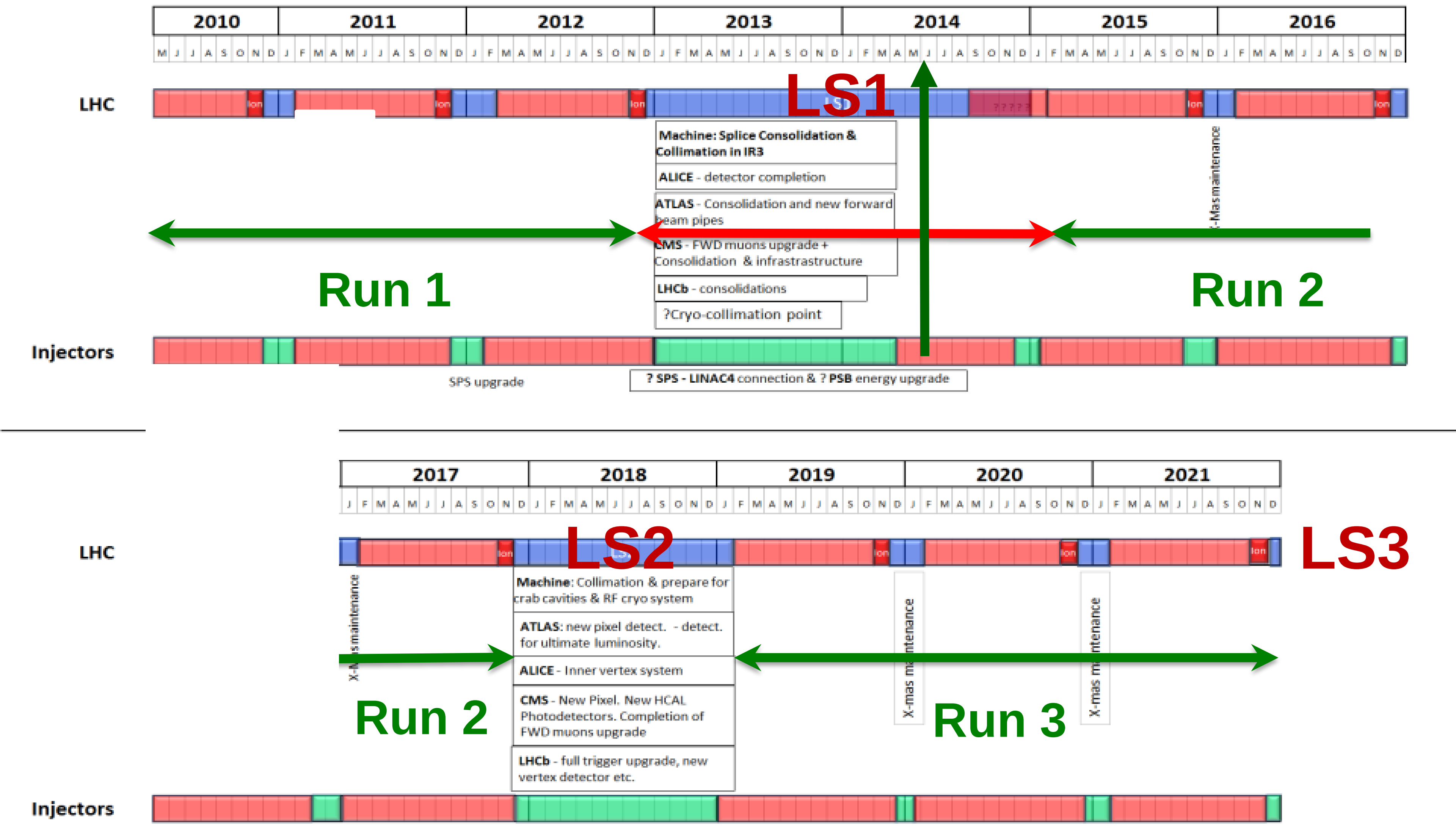
- **Forward region |η|>1.6 trigger relies entirely on CSC system:**
  - General trend is lowering efficiency towards higher eta to compensate for higher background rates
  - Optimal operating point is a function of PU conditions
  - Efficiency losses grow with PU
  - High Level-1 trigger rates in the very forward region
  - Level-1 trigger rates "flattening": multiple-scattering of soft muons in the iron yoke flattens the trigger rate curve; promotion of low-$p_T$ muon to high-$p_T$



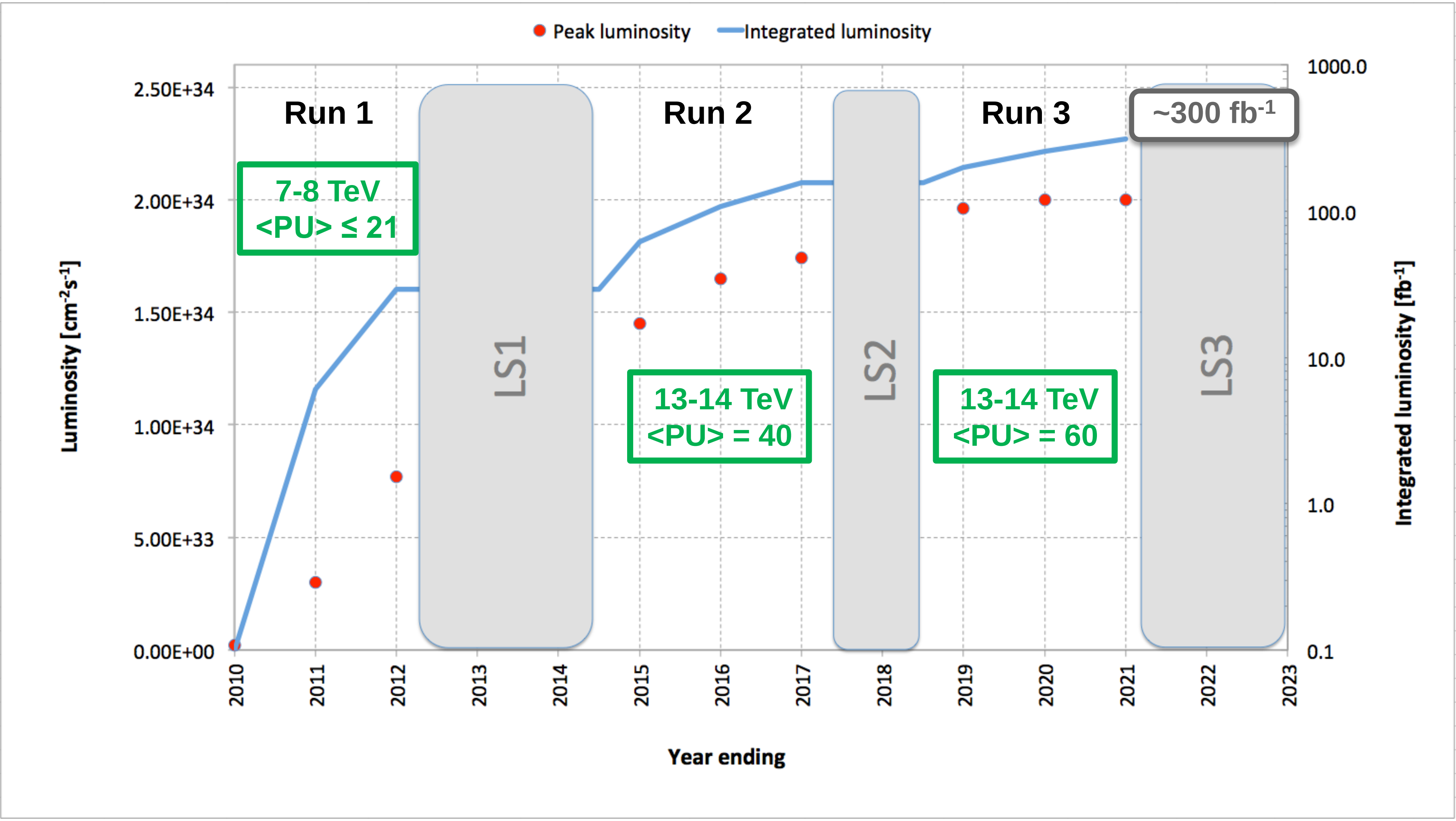

- **Muon momentum from stub positions:**
  - $\Delta\varphi_{XY}=\varphi(\text{ME-X})-\varphi(\text{ME-Y})$
  - Measurement driven by $\Delta\varphi_{12}$: ME-1/1 "drives" precision (least scattering)

- **Period between LS2 and LS3 is the most difficult time:**
  - Current system at the edge and the foreseen Level-1 Tracking Trigger is not yet online

# LHC Phase-1 Schedule



# LHC Beam Evolution

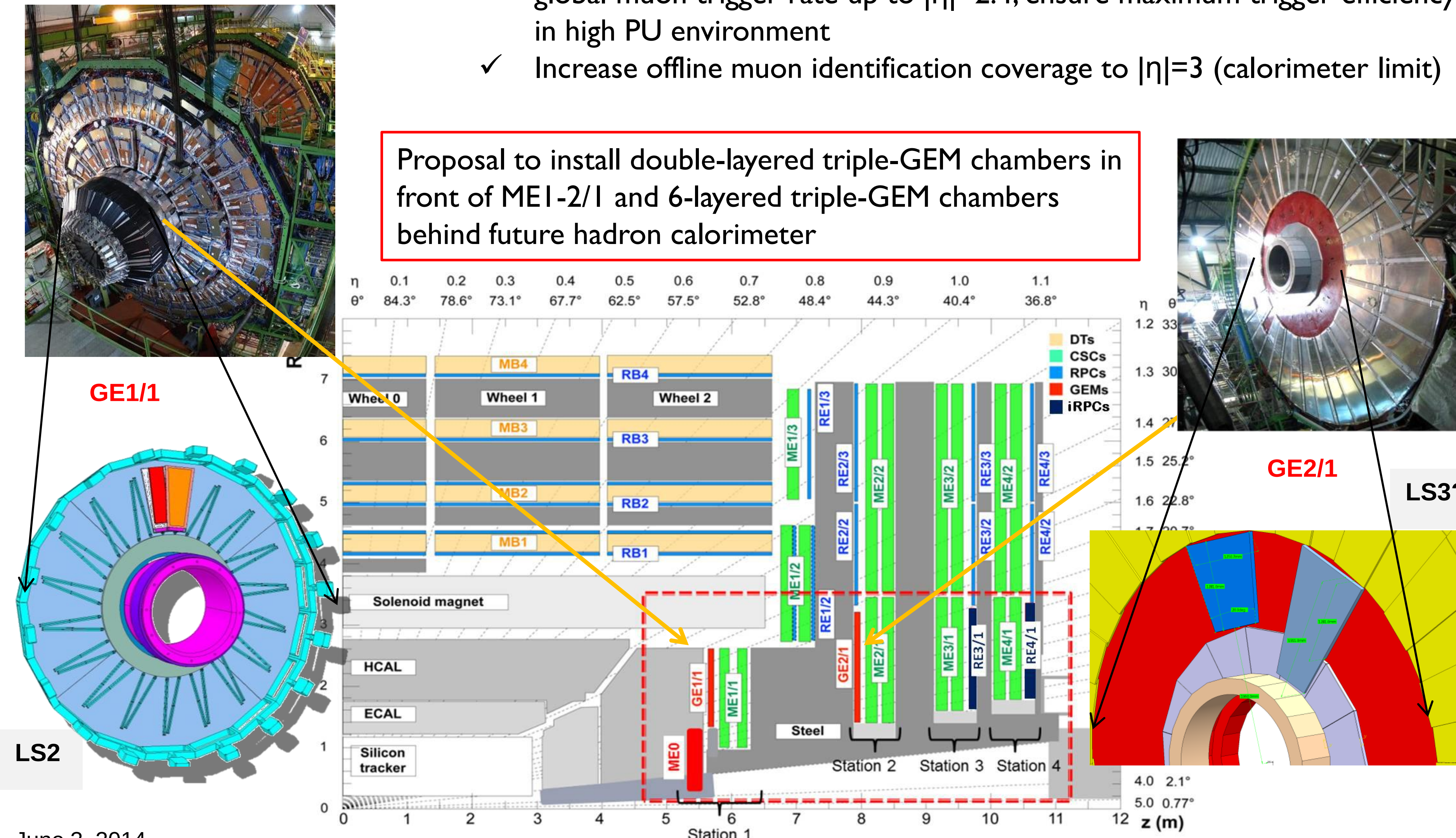


# The CMS GEM Project

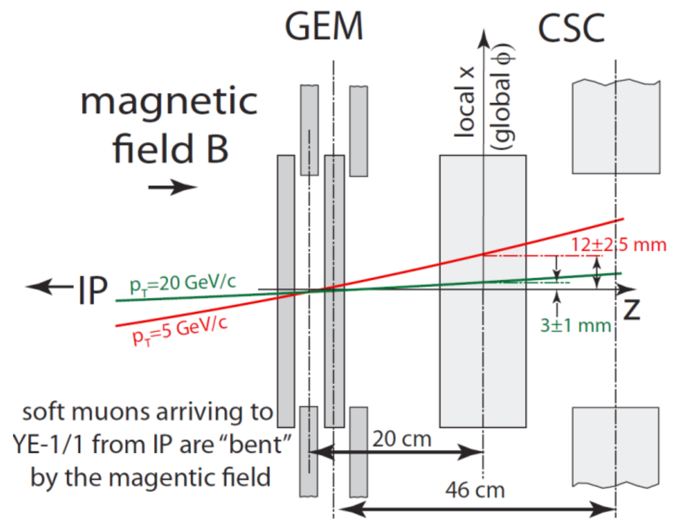
**Goals of CMS Muon Upgrade:**

- ✓ Restore redundancy in muon system for robust tracking and triggering
- ✓ Improve L1 and HLT muon momentum resolution to reduce or maintain global muon trigger rate up to |η|=2.4; ensure maximum trigger efficiency in high PU environment
- ✓ Increase offline muon identification coverage to |η|=3 (calorimeter limit)

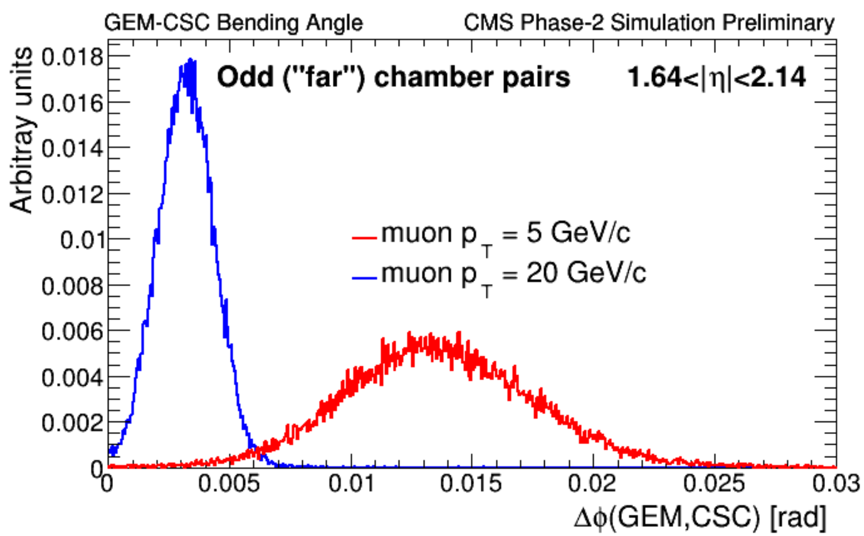
Proposal to install double-layered triple-GEM chambers in front of ME1-2/1 and 6-layered triple-GEM chambers behind future hadron calorimeter

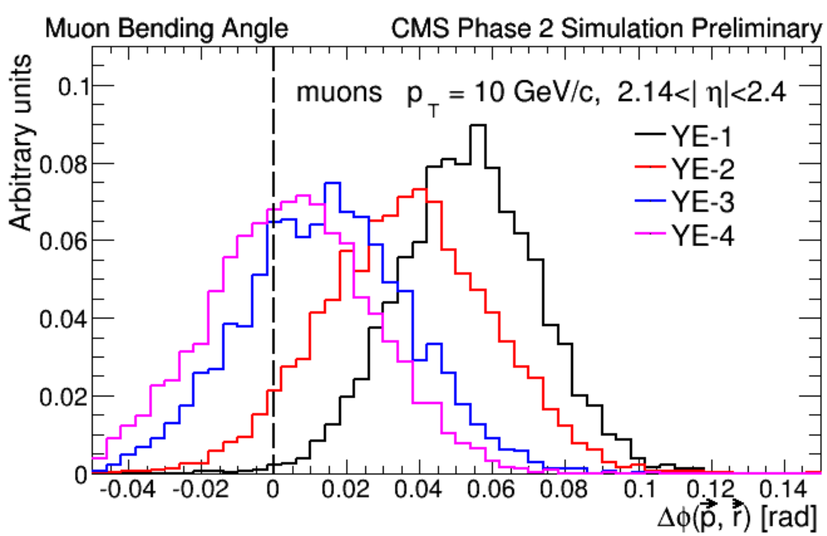


# Trigger Motivation



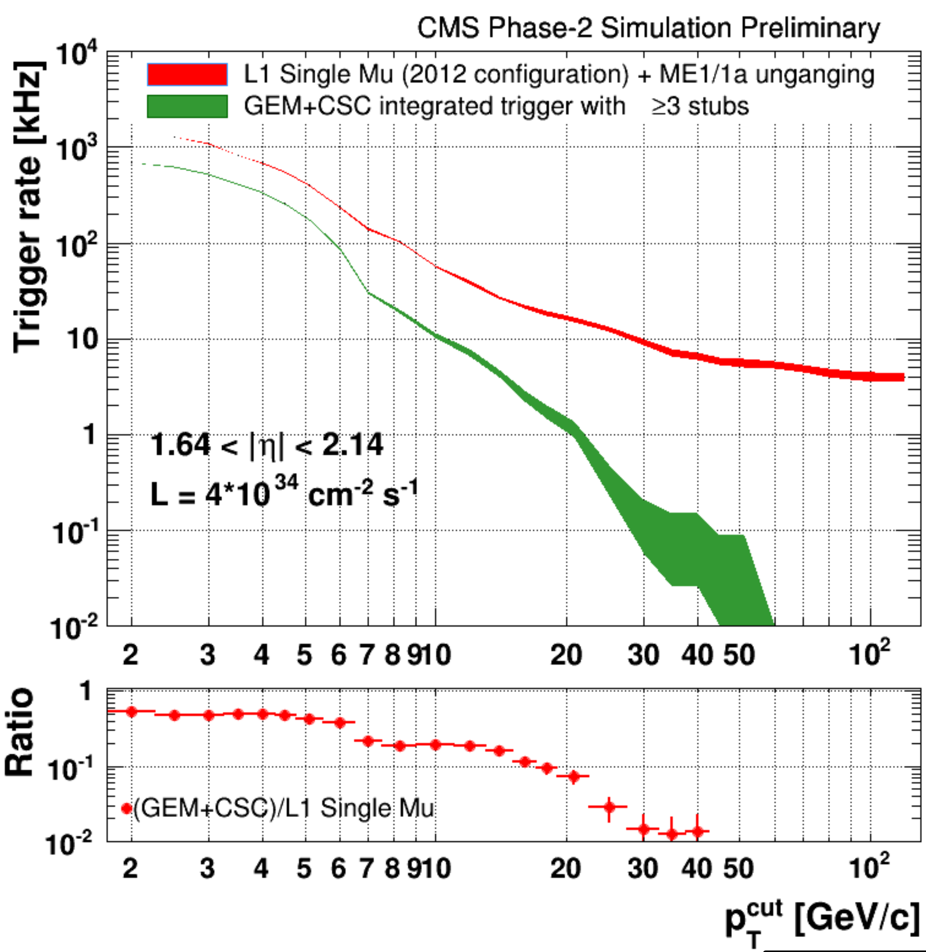

- **Increased trigger efficiency** from added **redundancy**
- Level-1 muon **momentum resolution** can be improved with additional muon systems, allowing to measure the "**bending angle**"
- **Reduced trigger rate from GEM-CSC bending angle**:
  - ME0 & GE1/1 yield the best separation from zero
  - Some gain expected from bending angle in GE2/1

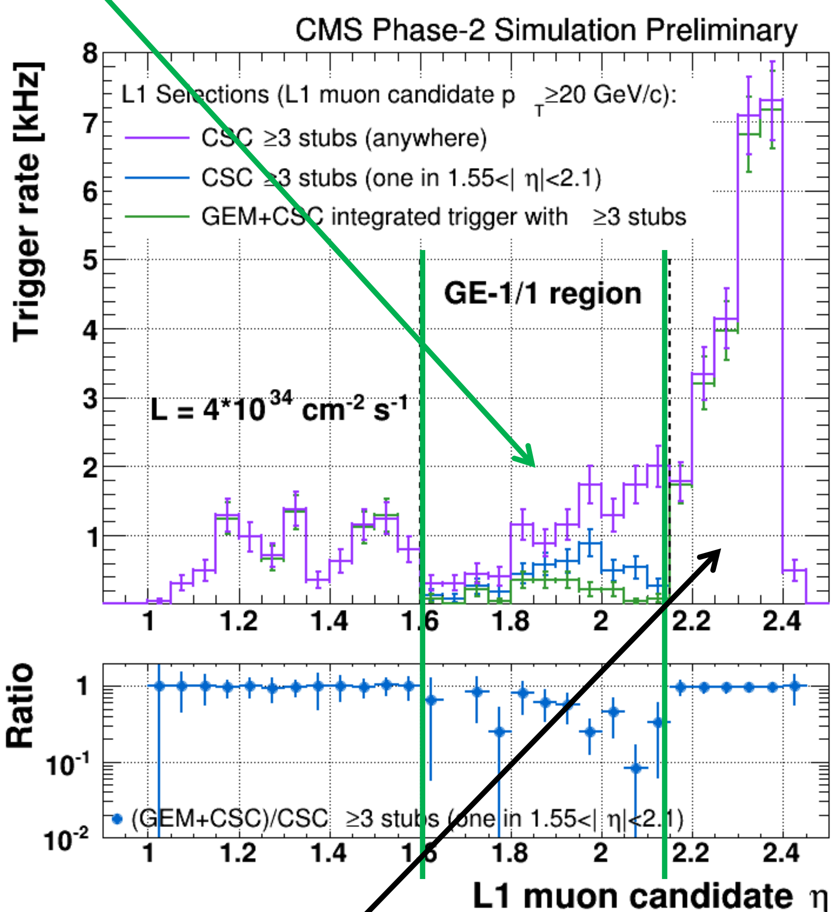


# Trigger Motivation

**Expected L1 trigger rate reduction with GE1/1**



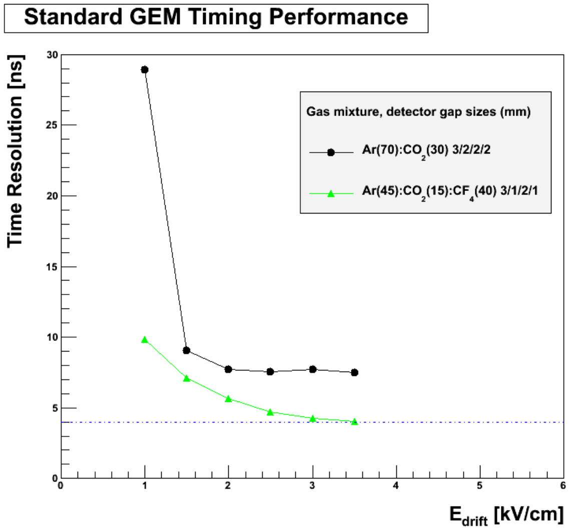




**Combining all proposed stations, expect factor ~4.5 rate reduction in 2.1<|η|<2.4 region**

# Main Achievements (2009-2014)

## Detector Performance

- Detector efficiencies above 98%
- Time resolution of 4ns
- Spatial resolution of about 290µm with VFAT2 (digital) and <110µm APV25 (analog) readout chip
- Operation of GEMs in magnetic field

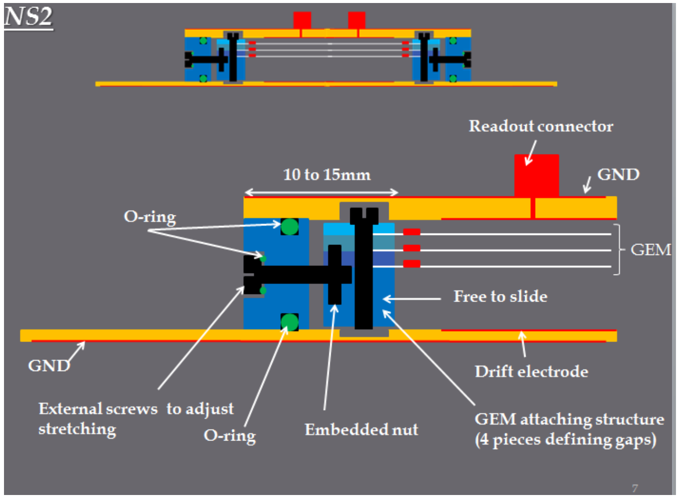


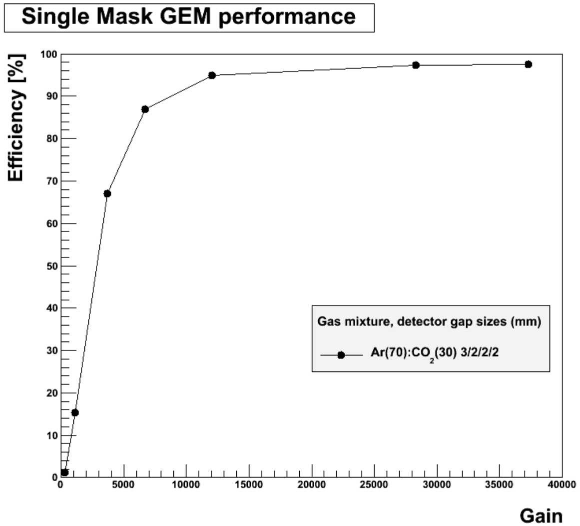

## Detector Technology & Assembly

- Validation of single-mask technology
- Production of large-area GEM foils for GE1/1
- New self-stretching (NS2) technique for triple-GEM assembly

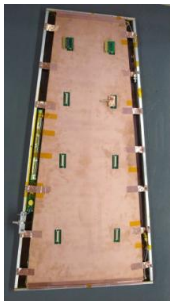
## Detector Integration into CMS

- Successful trial installation of dummy super chambers

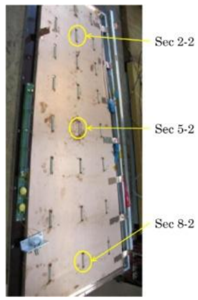



# (GE1/1) Project History

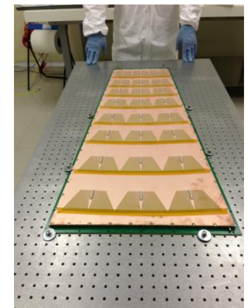


2010




2011

2012



2013

2013/14

**Generation I**
The first 1m-class detector ever built but still with spacer ribs and only 8 sectors total. Ref.: **2010 IEEE (also RD51-Note-2010-005)**

**Generation II**
First large detector with 24 readout sectors (3x8) and 3/1/2/1 gaps but still with spacers and all glued. Ref.: **2011 IEEE** (also **RD51-Note-2011-013)**

**Generation III**
The first sans-spacer detector, but with the outer frame still glued to the drift. Ref.: **2012 IEEE**

**Generation IV**
The current generation that we have built two of at CERN so far, with four more to come from the different sites. No more gluing whatsoever. Ref.: **MPGD 2013, IEEE2013**

**Generation V**
The upcoming detector version that we will install. One long and one short version. Optimized final dimensions for max. acceptance and final eta segmentation. Installation of dummy chambers.

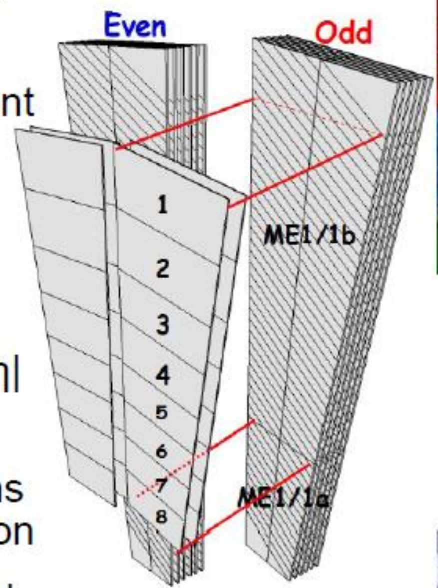
# Towards Final GE1/1 Design

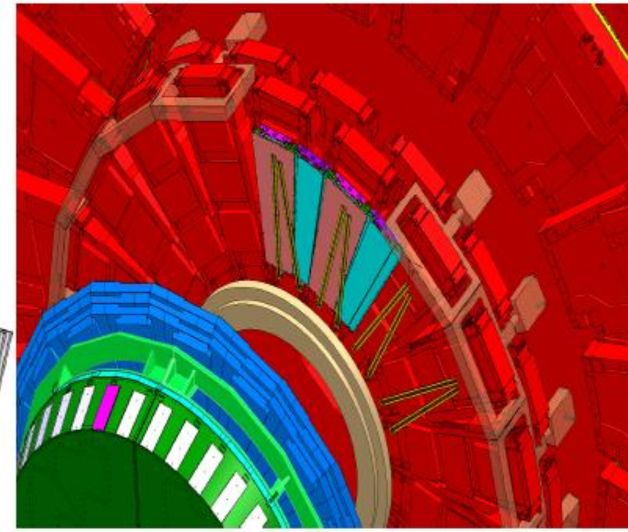
LAYOUT

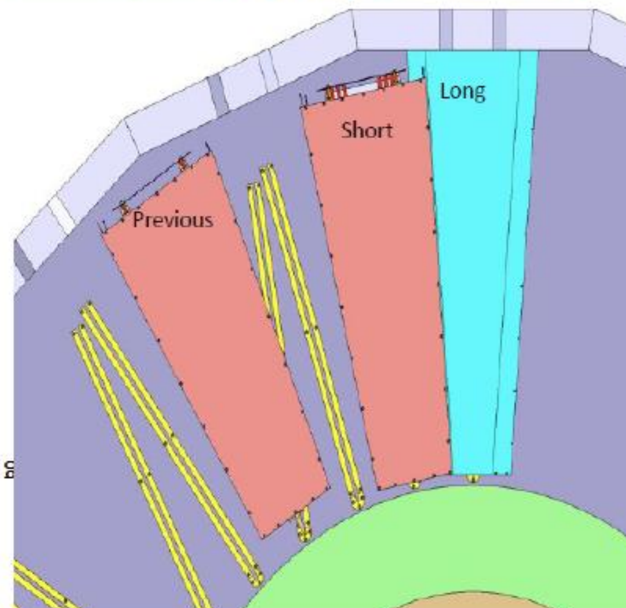
- Two 10° triple-GEM chambers to form a "super chamber"
- 144 total chambers (36 super chambers in one station per endcap)
- Each chamber is segmented into different columns and η region

**Final geometry to be finalized:**

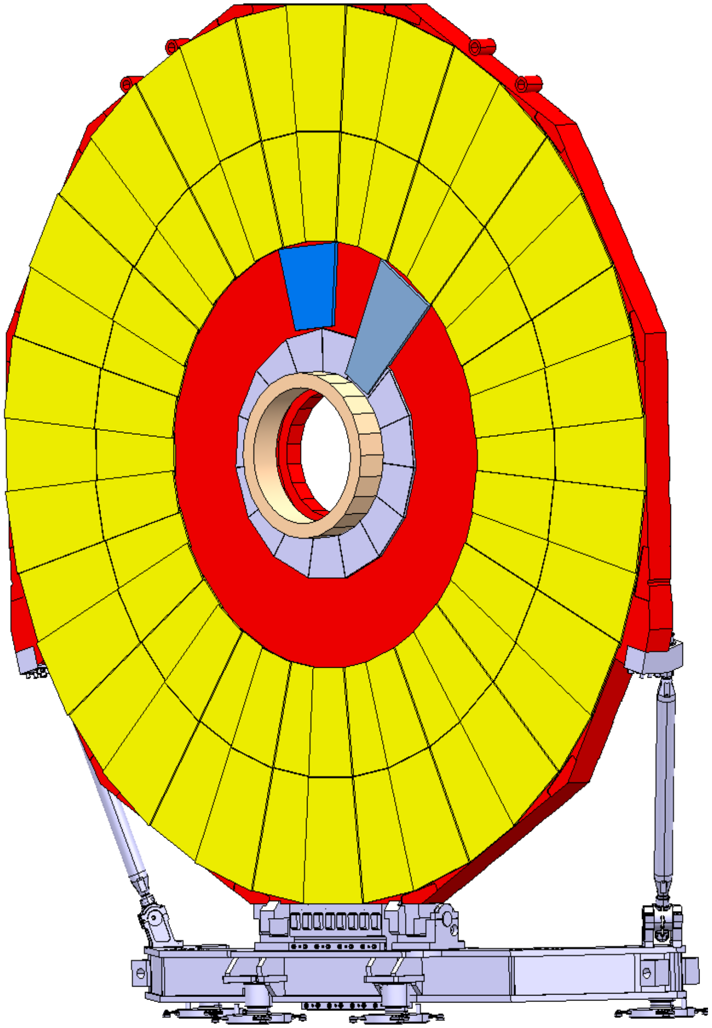
- Short super chambers extend to 1.6 < |η| < 2.2 (due to the steel brackets):
    - 3 columns and 8 η-partitions with 384 strips per η-partition
- Long super chambers extend to 1.5 < |η| < 2.2:
    - 3 columns and 8-10 η-partitions (under studies) with 384 strips per η-partition



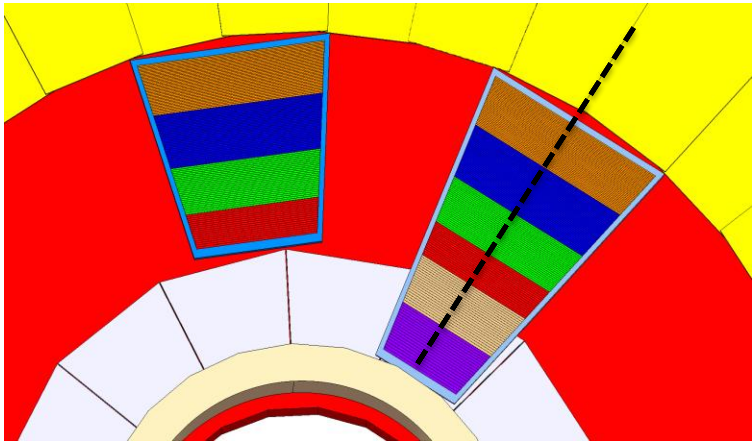





# Towards GE2/1 Design



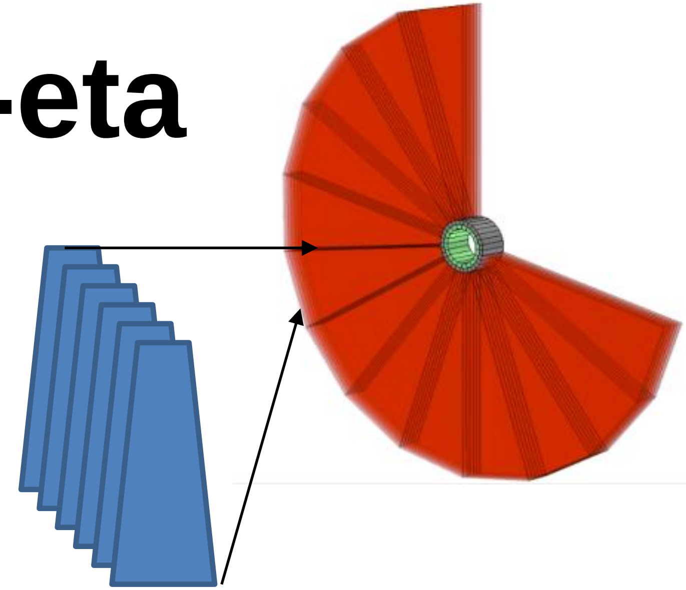
- 20° super chambers
- 2 stations: 8 rolls up to |η|=2.12 & 12 rolls up to |η|=2.4
- Requires R&D on chambers which will be 1.5m long and >1m wide at wide end
- Readout board similar to GE1/1



# ME0 @ High-eta

One ME0 super-module wedge will consist of 6 layers (total width of 30cm only):

- 2 x18 chambers (20° chambers)
- 18432 readout channels – strips one directional in φ

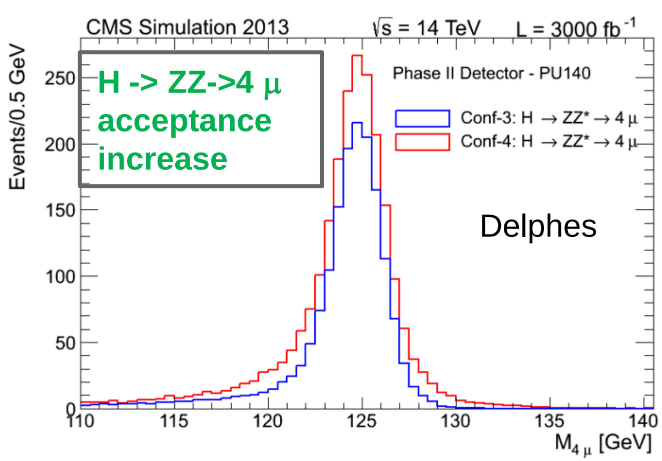


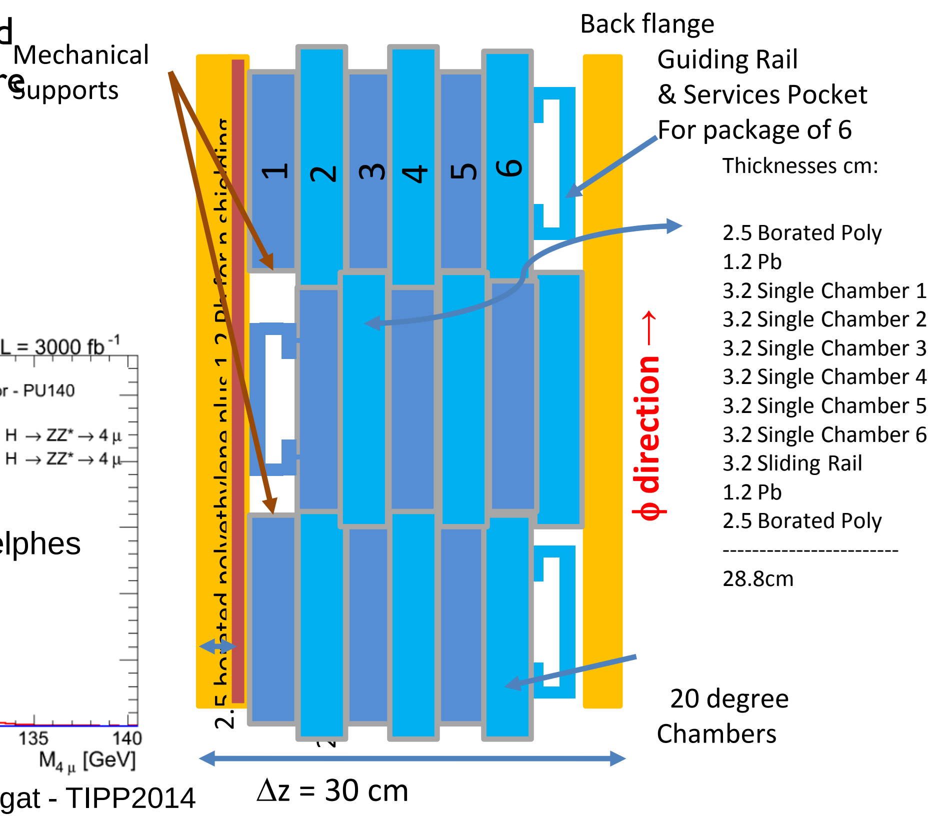
In order to fit in 30 cm exploring the "doublet system":
2 back-to-back triple-GEM chamber with one common drift electrode

New detectors have to operate in very high background environment (expect 10-100kHz/cm$^2$) and high PU: more R&D needed

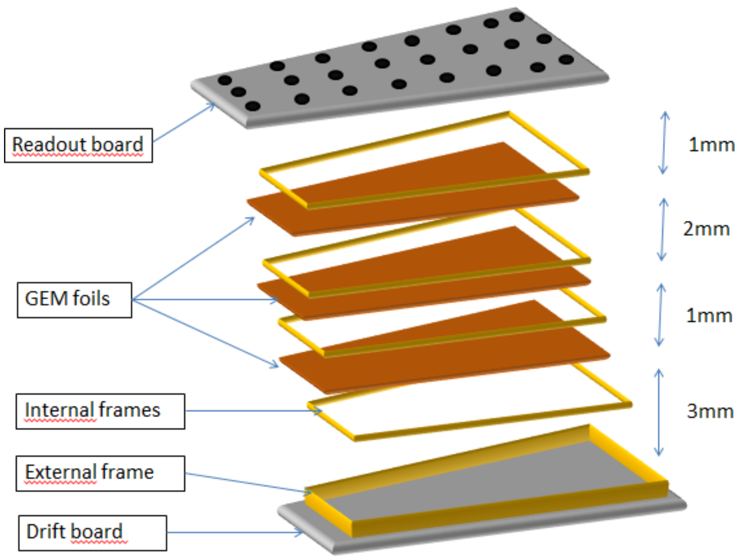
Additional 6 points (neutron background rejection) of measurements extending in high eta

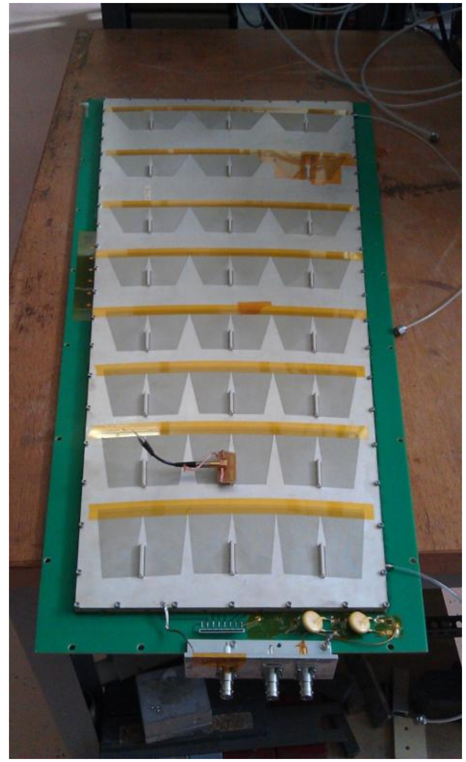
Gain up to 40% in signal selection efficiency with extension up to η=4 for H->ZZ->4μ

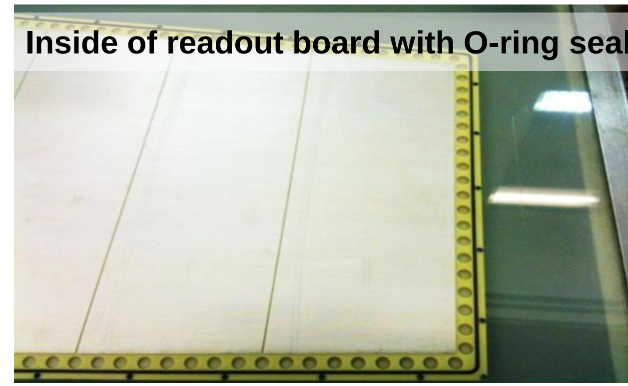


# GE1/1 Detector Layout



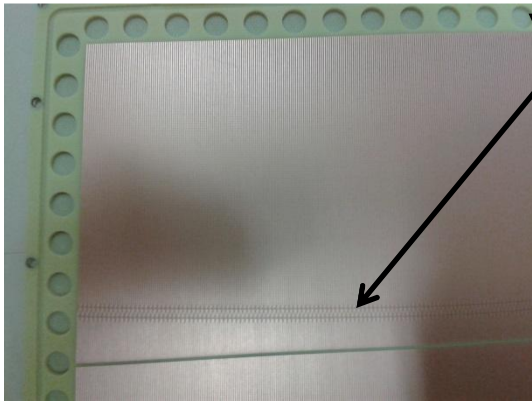




Inside of readout board with O-ring seal

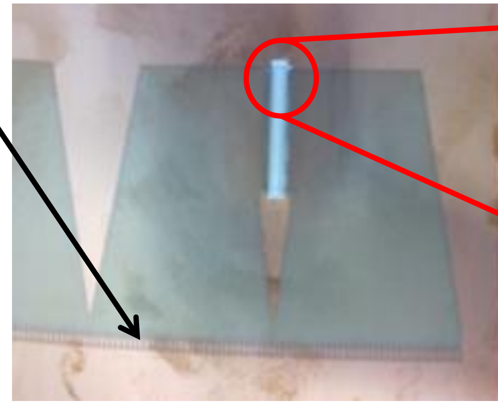
- Single-mask & self-stretching technique @ CERN
- No spacers in active volume
- Active area : 990x(220-455)mm$^2$
- Gap sizes: 3/1/2/1 mm
- Sectors : 3 columns x (8-10) $\eta$ partitions
- Strip pitch: 0.6-1.2mm
- 1D readout of up to 3840 channels
- 35 HV sectors


GEM foil with inner & outer frame

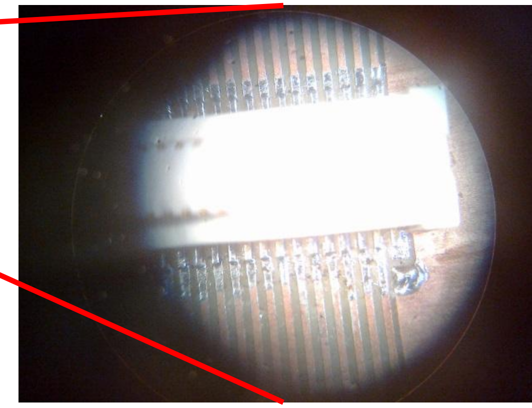
# GE1/1 Readout & Drift Board




Strip side

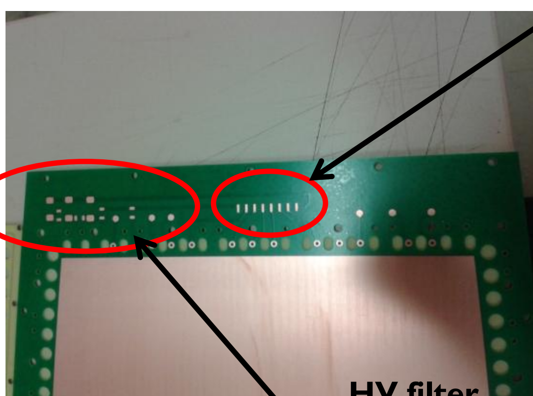


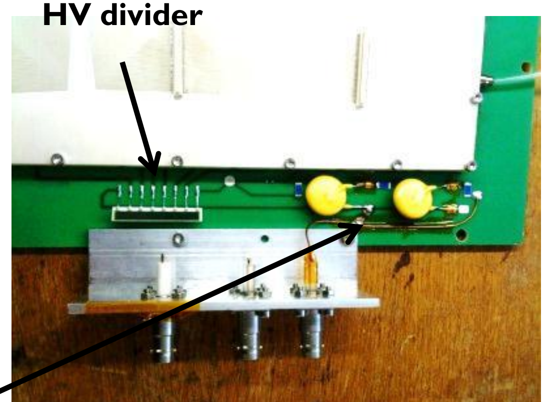
External side

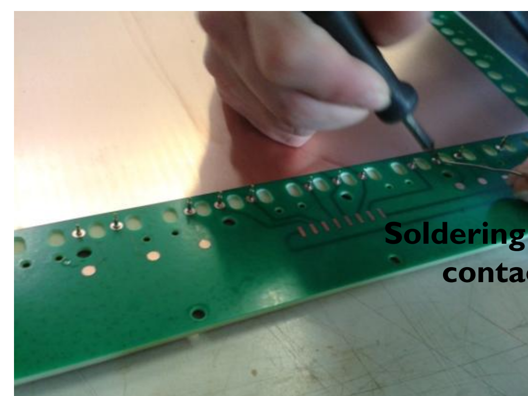


**Readout board:** metalized vias bring the signal to the other side of the board; panasonic connector with 128 entries is soldered on the strips

**Drift board**: HV spring contacts to connect foils to HV; 4 contacts per GEM (Top/Bottom + redundant connection)

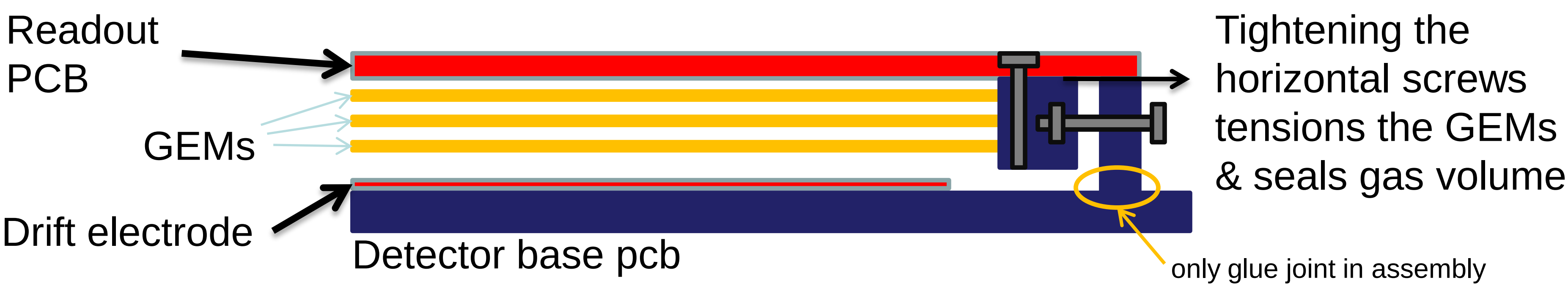


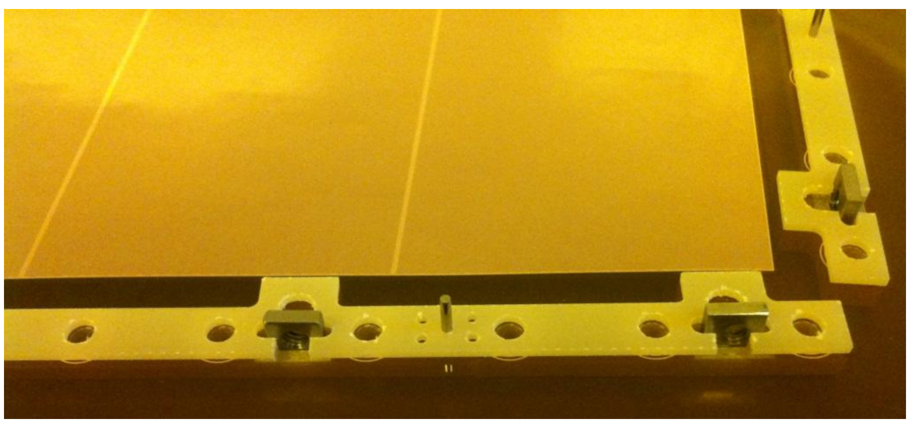



# GEM Self-Stretching Technique

**Current state-of-the-art: Self-stretching assembly without spacers (NS2)**



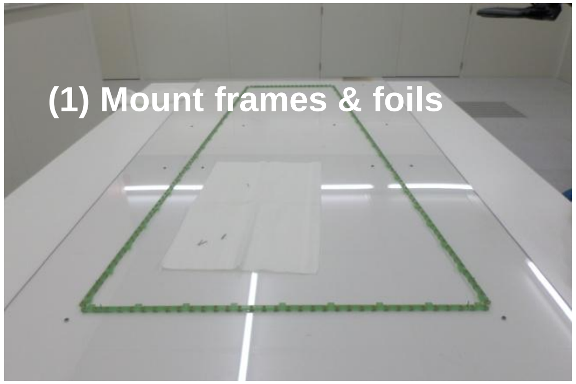
**Allows re-opening of assembled detector for repairs if needed**

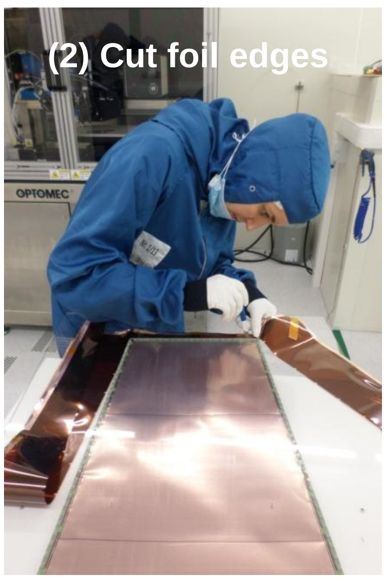
**2012 @ CERN**

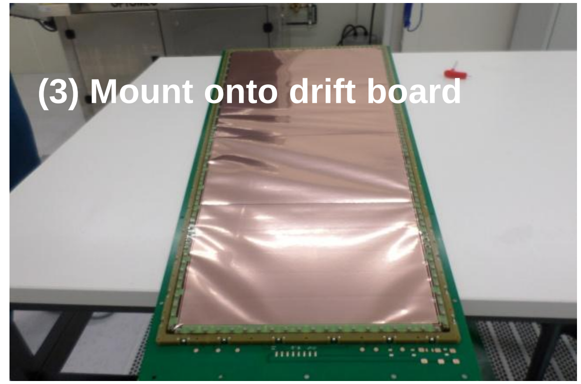
**Allows to assemble a full GE1/1 detector in 2hours time only !**

# GE1/1 Assembly Procedure

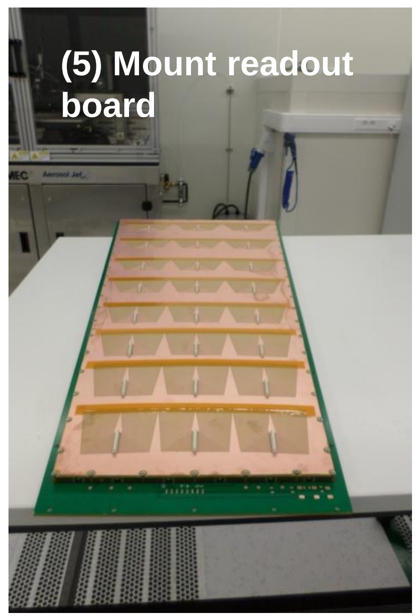
**As an example, GE1/1 assembly @ Ghent University in Dec. 2013**



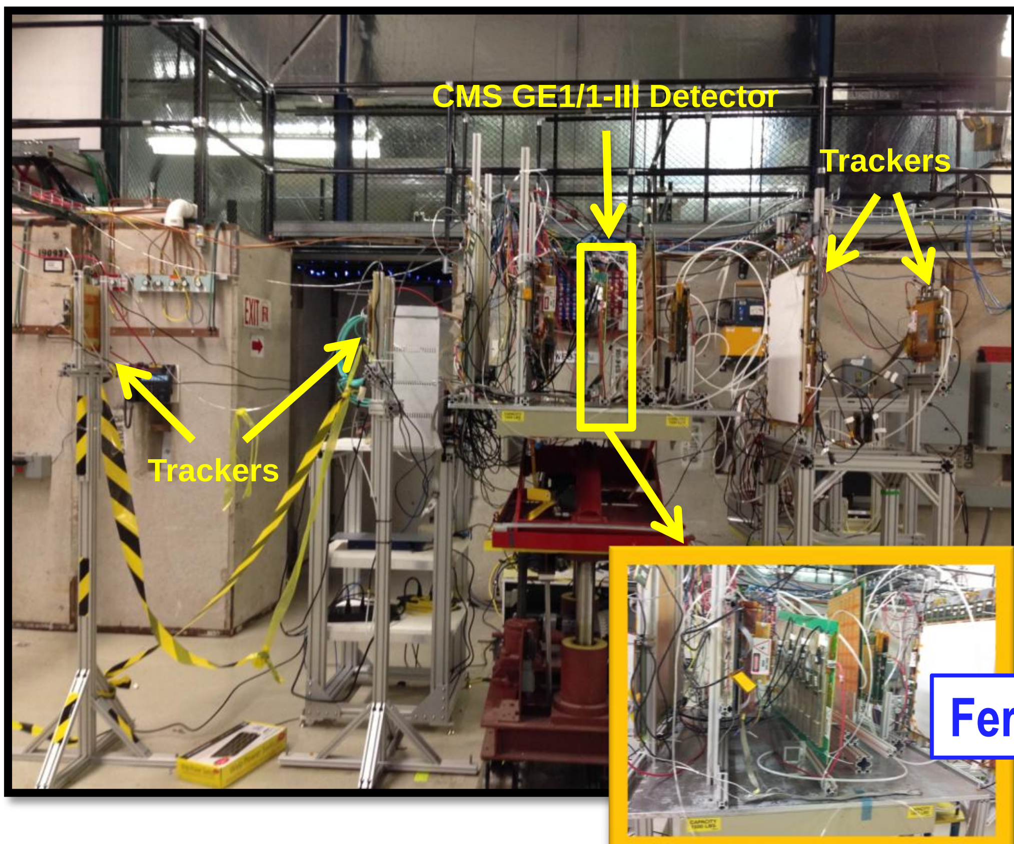


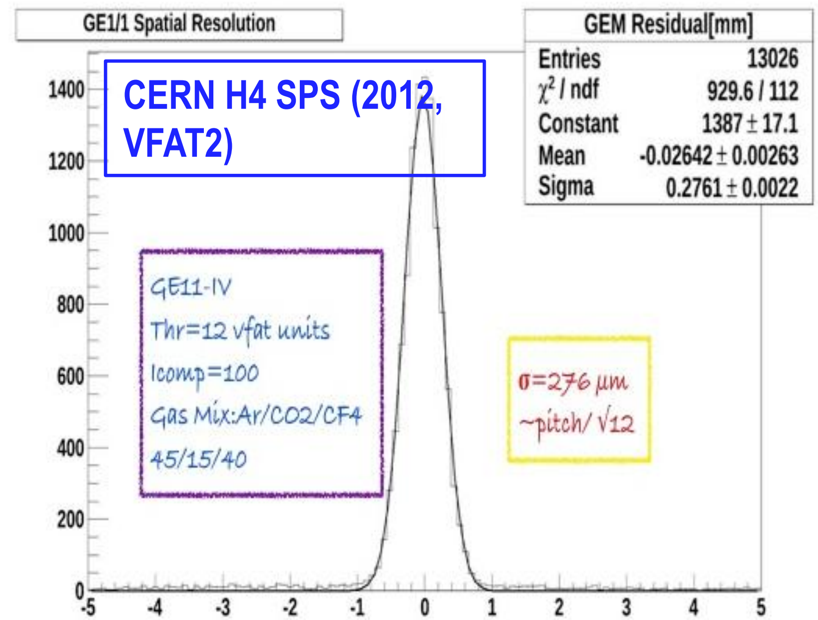


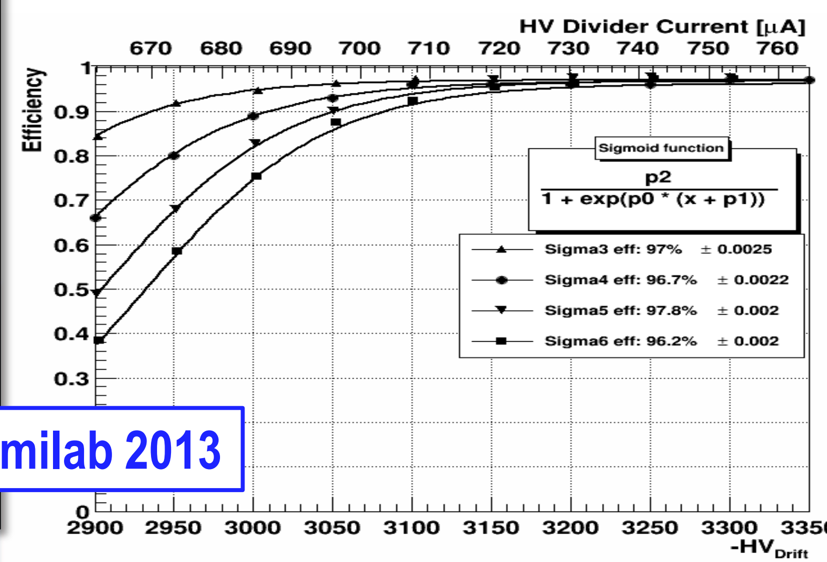

# GEMs in Test Beam

Many test beam campaigns at CERN SPS (2009-2012), Fermilab (2013)

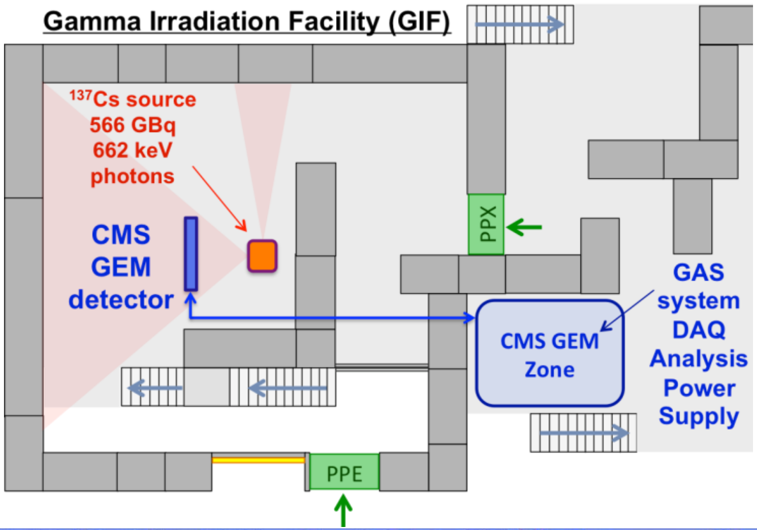
- Spatial resolution: with binary VFAT2 chip: 276μm; with analog APV chip: < 104μm
- Timing resolution: 4 ns achieved
- Efficiencies: ~98% achieved



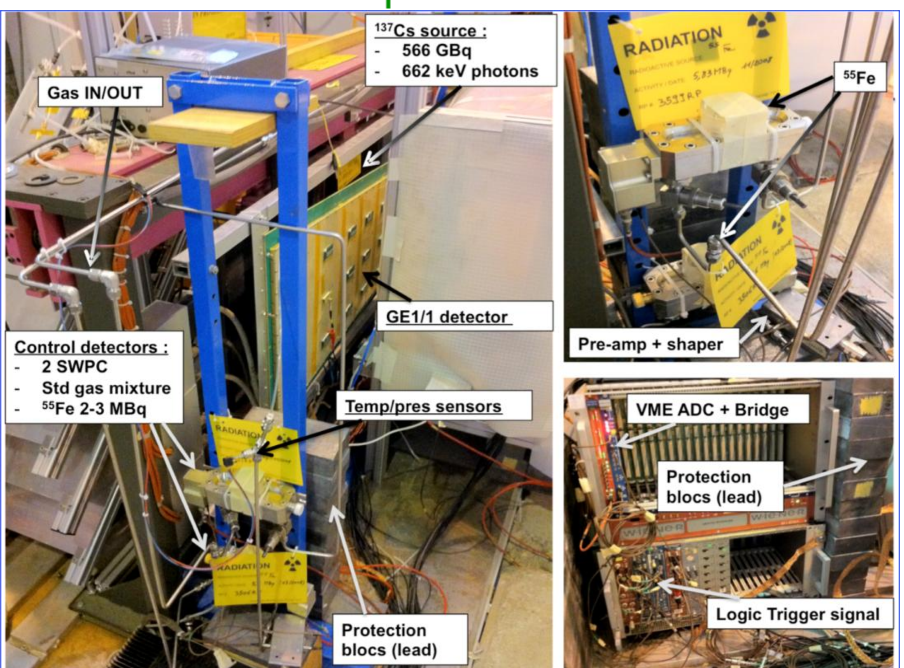



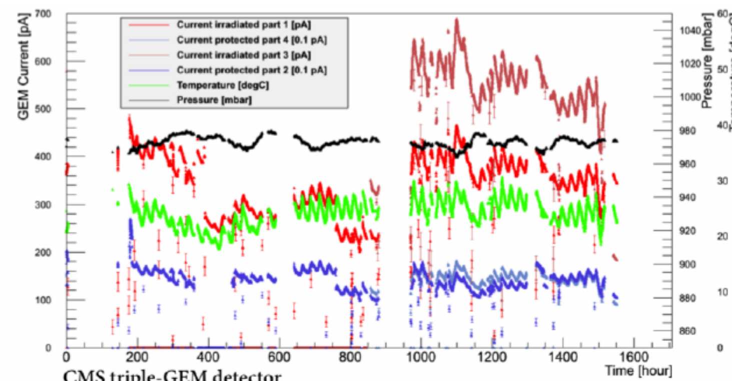
# Aging Test @ CERN GIF

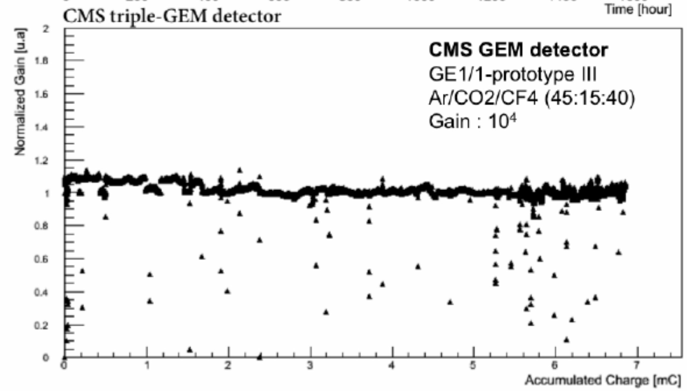



**A CMS GE1/1 detector was installed in the CERN GIF; detector performance and environmental & gas parameters monitored:**

- ❑ Ensure long-term operation inside CMS
- ❑ Understand effects of radiation on the materials
- ❑ Understand ageing origin (if any) and propose solutions



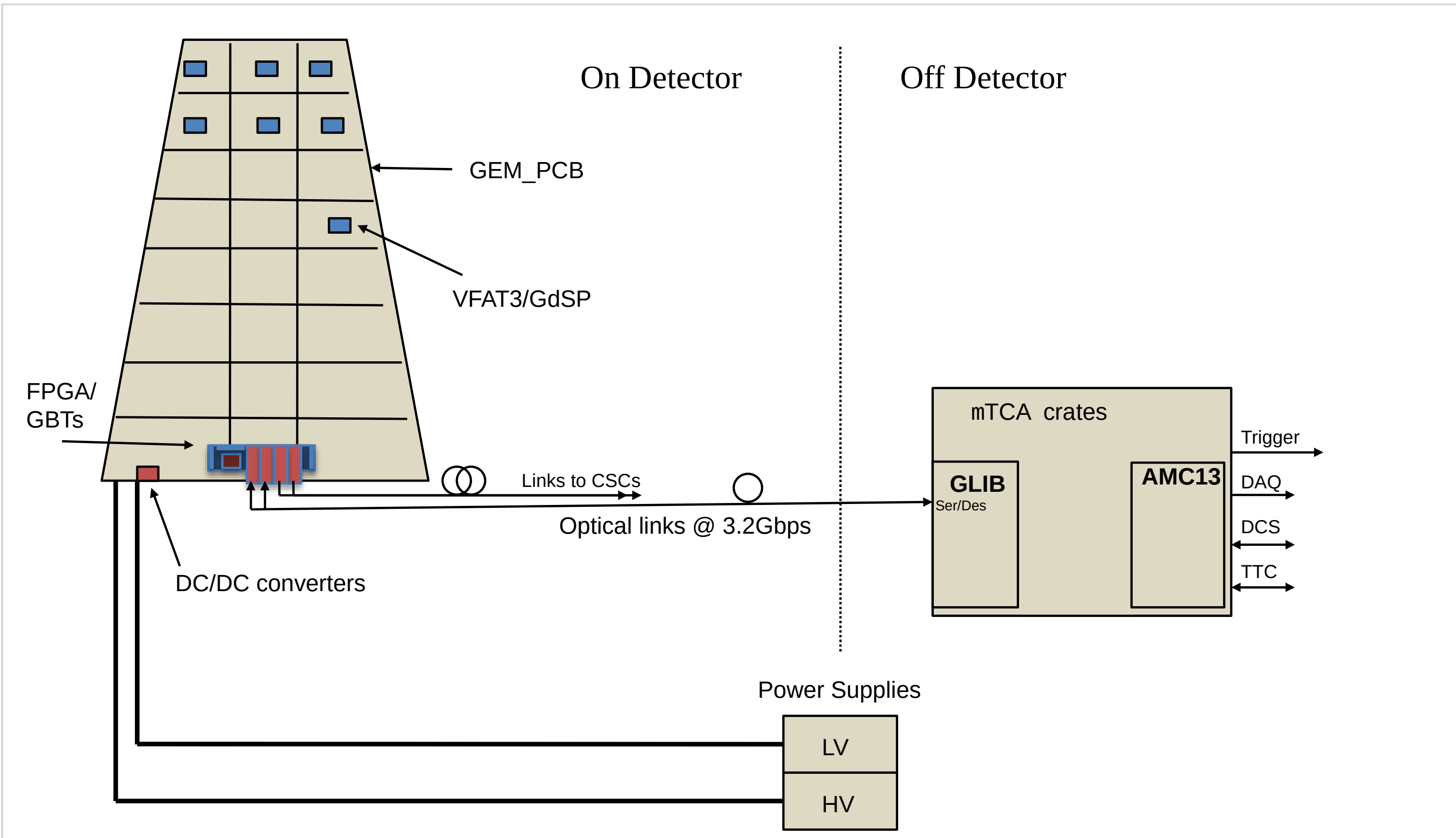




**No effects seen so far (~7mC/cm²; ~kHz/cm²)**
**To be continued at GIF++**

# DAQ and Electronics

**Global requirements: provide necessary input from all GEM detectors for Muon**

- **Triggering:** provide "Fast OR" trigger information with granularity of 2 or more channels to send locally to CSC Trigger Mother Board
- **Tracking:** provide full granularity tracking data on receipt of a LV1A; be compatible with CMS trigger upgrade possibilities (LV1A latency < 20μs, LV1A rate < 1MHz Poisson)



# VFAT3

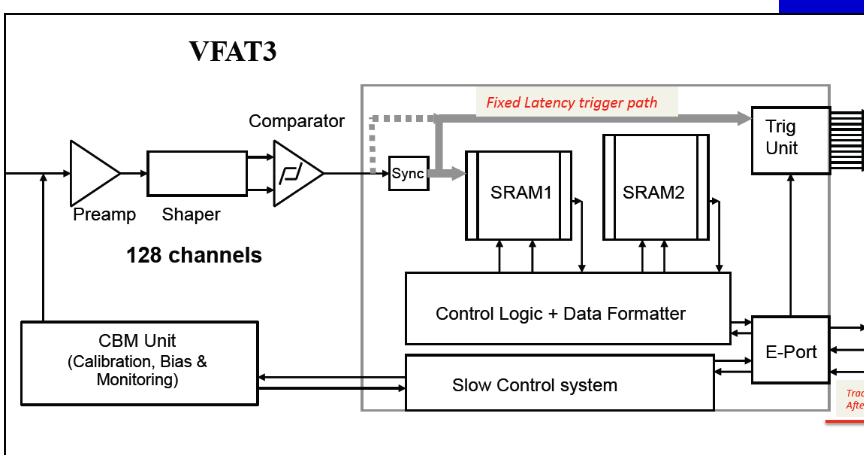
VFAT3: front-end ASIC with programmable shaping time; internal calibration; binary memory; interfaces directly to GBT @ 320Mbps; designed for high rate (10kHz/cm$^2$ depending on segmentation)

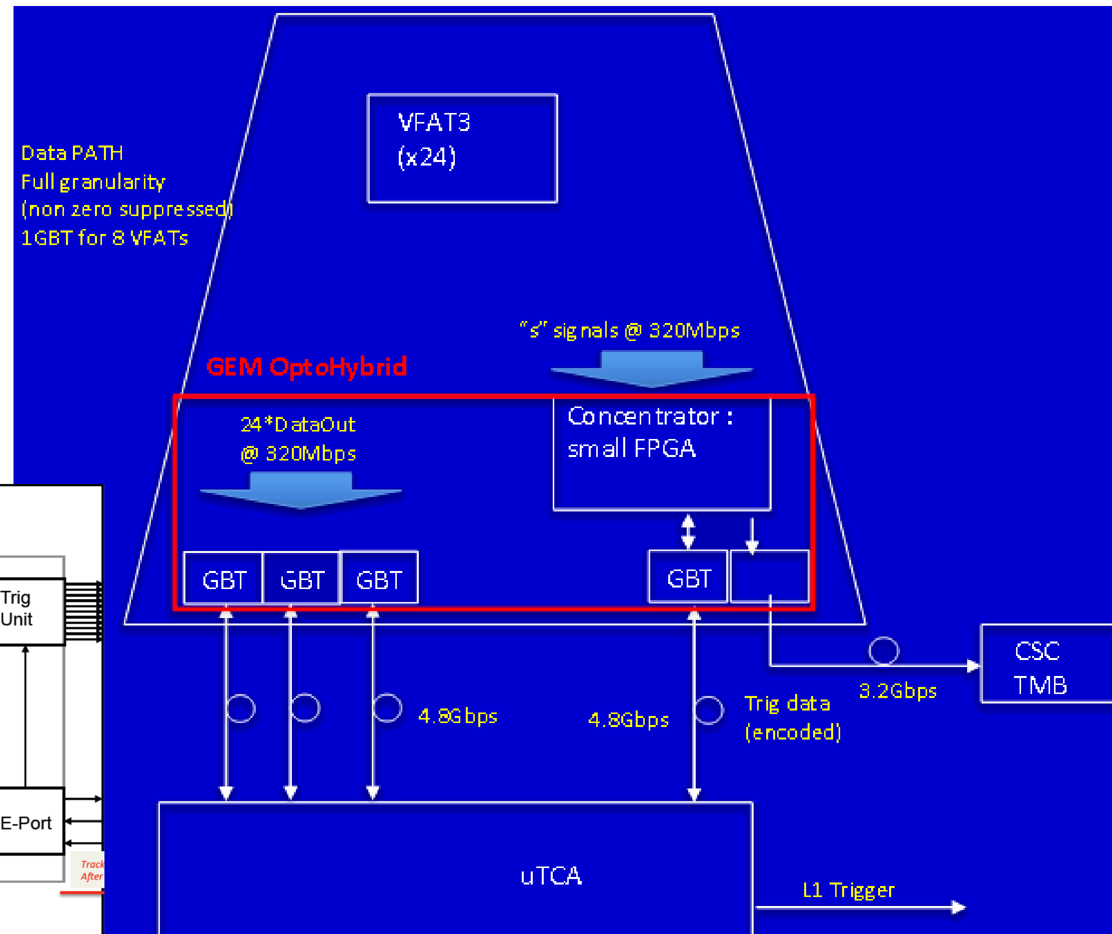
- VFAT3 chosen for GEM Slice Test and GE1/1 full installation during LS2

- VFAT3 analog discriminator will use CFD or TOT to correct time walk

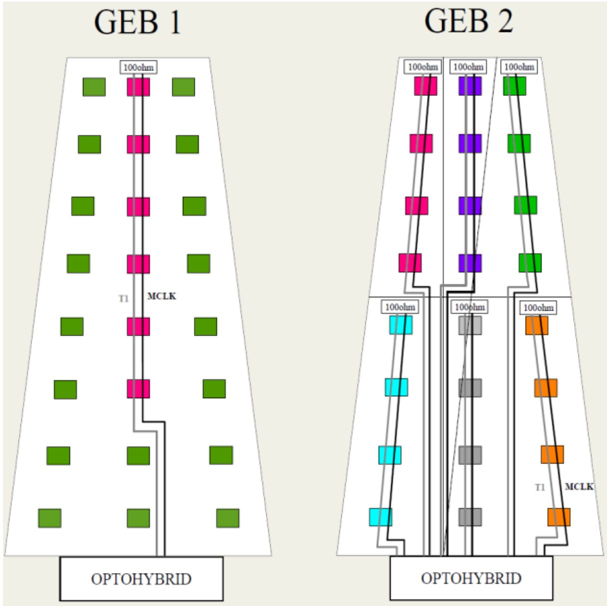
- VFAT3 STT version (Separate Tracking & Triggering)

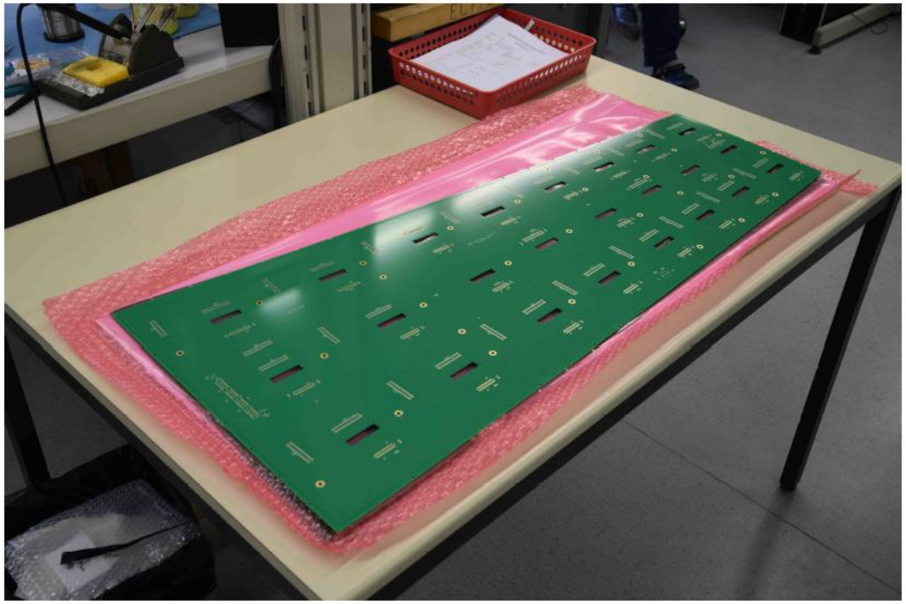
- GEM OptoHybrid contains FPGA performing "concentrator" and driving optical link @ 3.2Gbps; FPGA programming via the GBT



# Frontend Electronics & DAQ

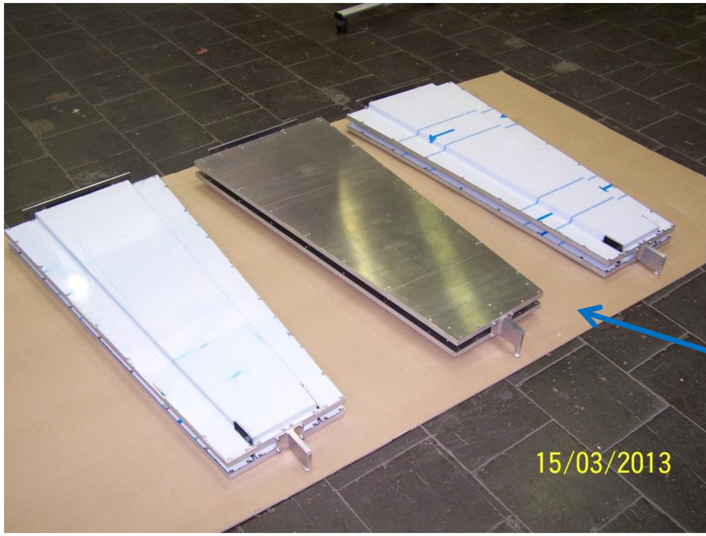


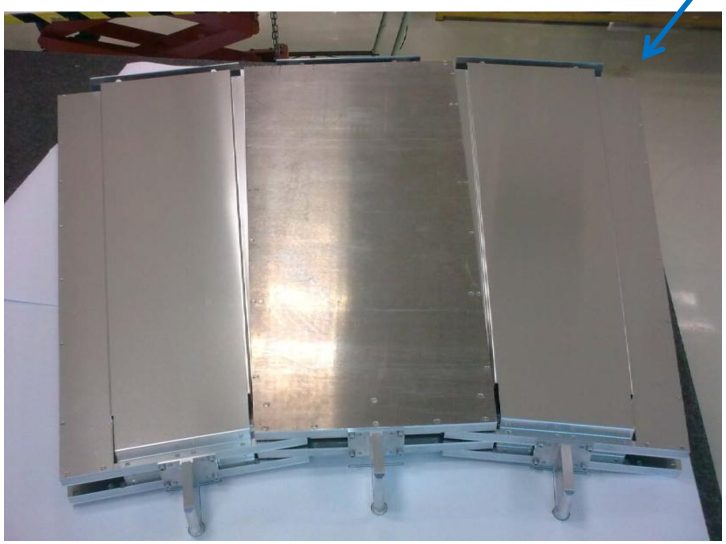



- ❑ First GEB v1 arrived at CERN in Jan. 2014; under test now; GEB v2 design will be submitted as soon as initial GEB tests done

- ❑ Standalone tests of Opto-hybrid v1 ongoing since Oct. 2013; FPGA firmware being developped for VFAT2 control; combined tests with GEB v1 in Feb. 2014

# Super Chamber Dummies



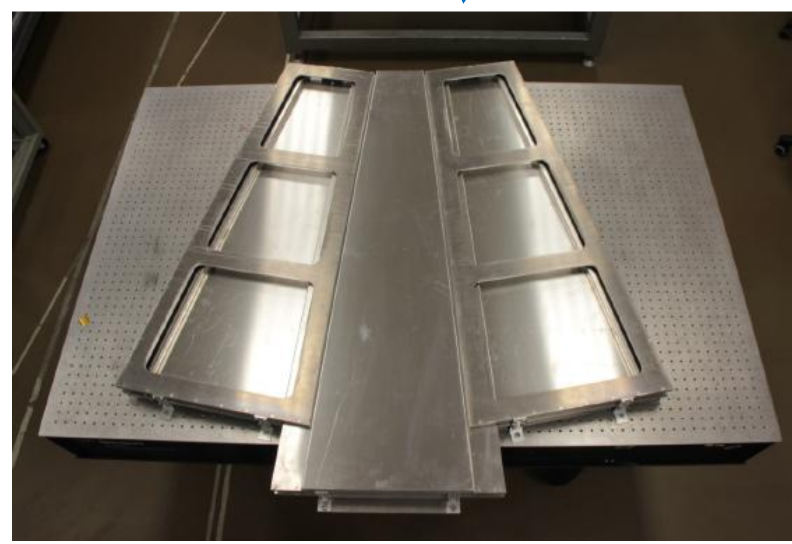



**Super Chamber dummies were produced to optimize design and to perform trial insertion into CMS:**

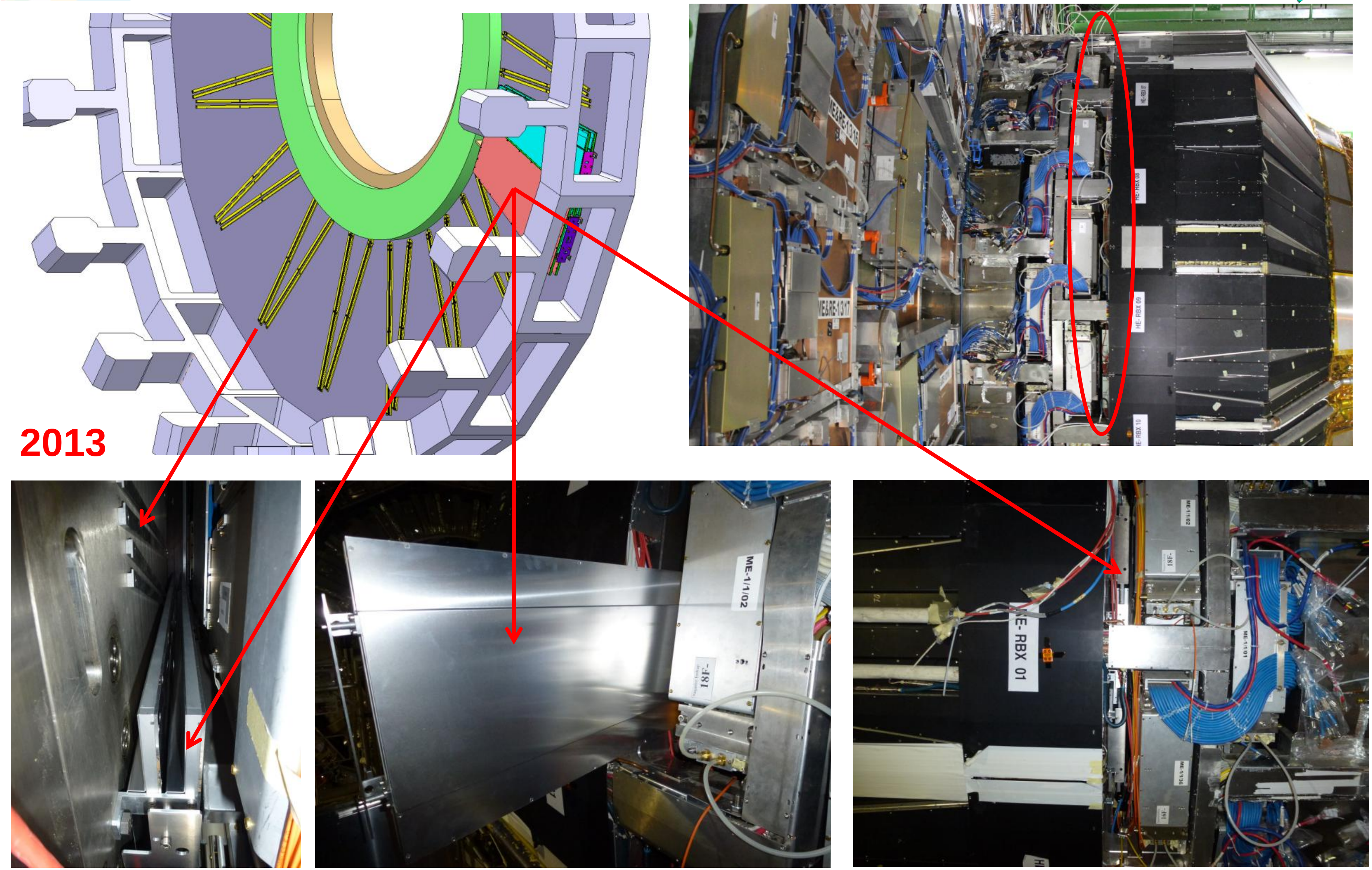
- ❑ no detector and no electronics inside
- ❑ all positions for gas, cooling and electronics connections at the right place
- ❑ weight and dimensions as a real super chamber

**Trial installation of 1st set in Summer 2013**

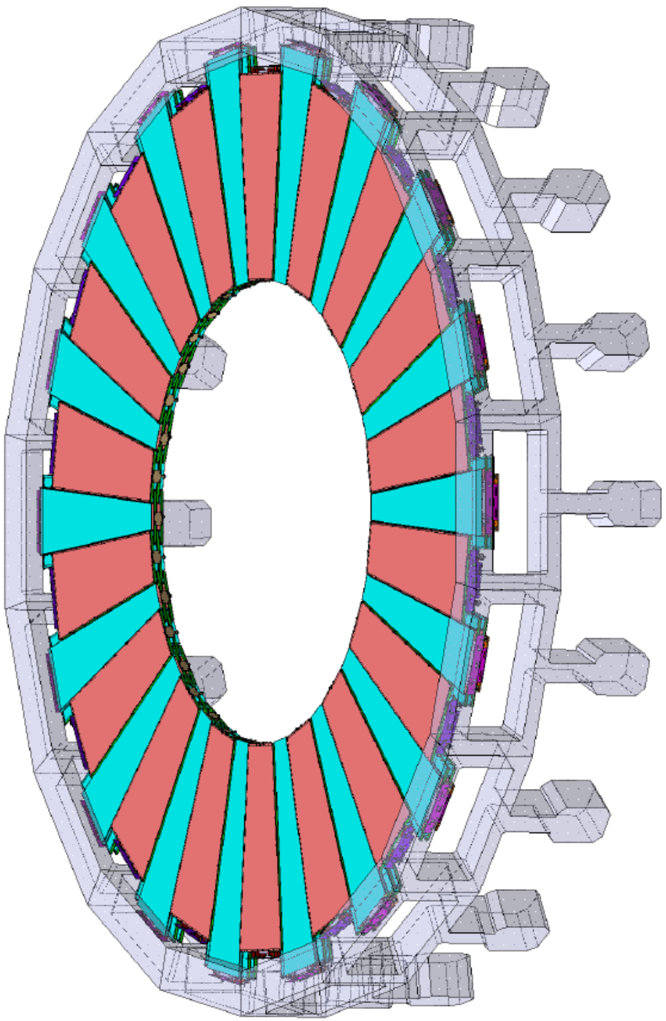
**Trial installation of 2nd set (short and long chambers) in March 2014**



# Trial Installation in CMS



# Summary

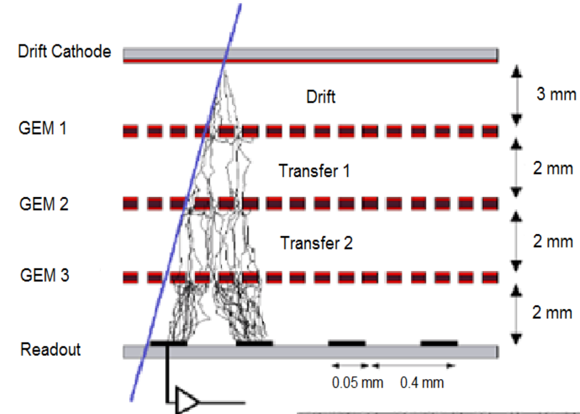


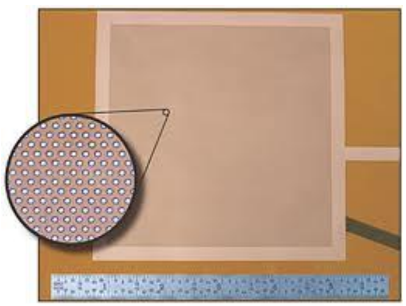
- **C**MS GEM Project started in 2009 in collaboration with RD51; present scope of the project includes new GE1/1, GE2/1 & ME0 stations
- **T**riple-GEMs provide a suitable solution for the CMS muon trigger and tracking needs in the LHC Phase-2 area
- **D**esign of the GE1/1 chambers for installation in CMS close to final
- **I**nstallation of services and cabling for GE1/1 ongoing during LS1
- **D**uring LHC 2016-2017 Year-End Technical Stop two triple-GEM super chambers will be installed inside CMS, in YE1/1
- **A**waiting further green light from CMS for full GE1/1 installation during LHC LS2
- **P**reparing CMS (Muon) Phase-2 Technical Proposal and GE1/1 Technical Design Report to be submitted to LHCC late 2014

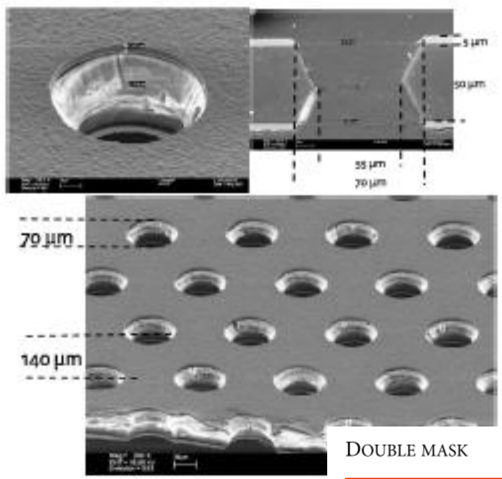
# Backup Slides

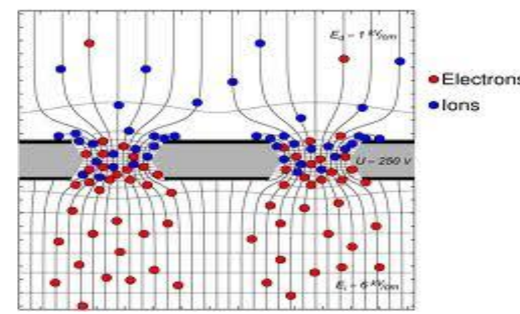
# Gas Electron Multipliers

***Rate capability :*** $10^5$Hz/cm$^2$
***Spatial/Time resolution:*** ~ 100 μm / ~ 4-5 ns
***Efficiency:*** > 98%
***Gas Mixture:*** Ar/$CO_2$/$CF_4$ (45/15/40), non flammable
***Typical Gas gain:*** >$10^4$
***Radiation hard***

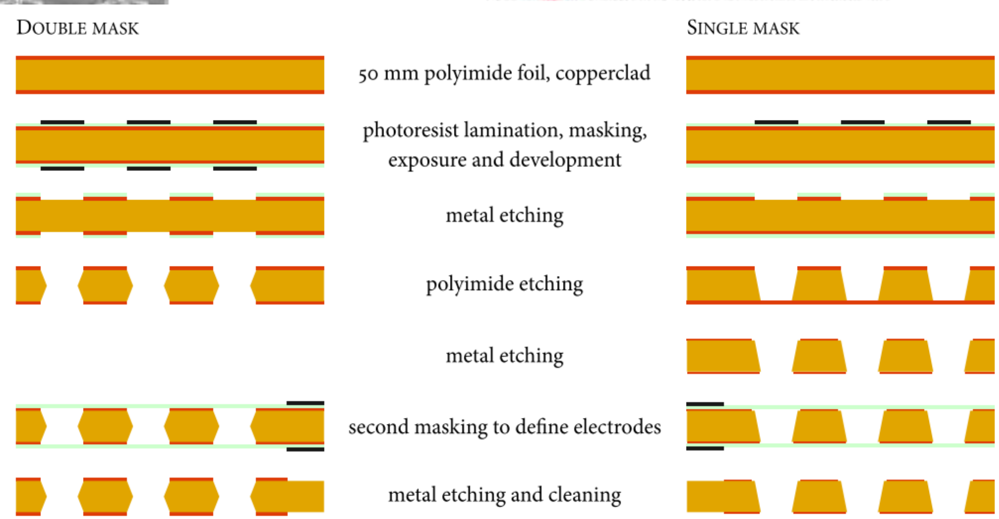





- GEM foils developed using PCB manufacturing techniques
- Large areas ~ 1m x 2m with industrial processes (cost eff.)
- Each foil (perforated with holes) is 50μm kapton sheet with copper coated sides (5μm)
- Typical hole dimensions : Diameter = 70μm, Pitch = 140μm,
- Long term (10 years) operation experience in Compass, and more recently LHCb and TOTEM



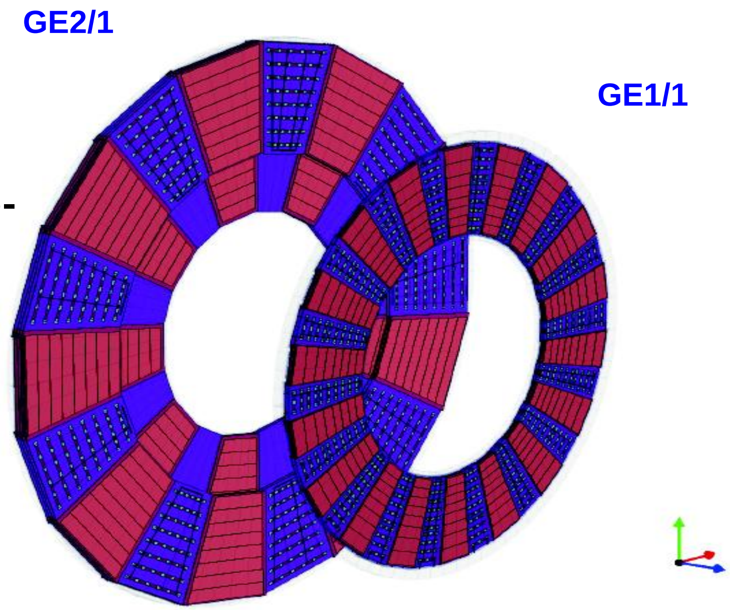
# The CMS GEM Project

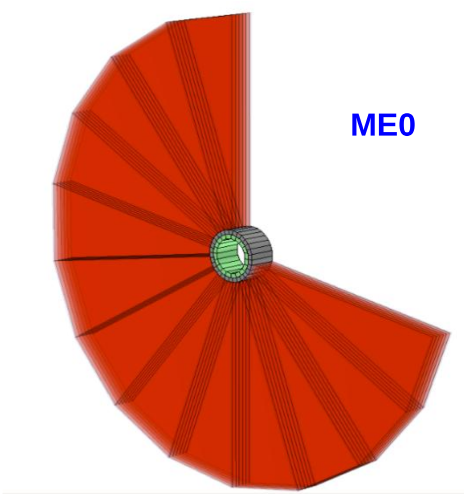
**GE1/1: baseline detector for GEM project**
- 1.55 < |eta| < 2.18
- 36 staggered chambers, each chamber spans 10°
- Several prototype designs with different number of eta partitions
- Short and long super chambers for maximum coverage in pseudo-rapidity

***PROPOSED FOR INSTALLATION DURING LS2***

**GE2/1: station 2 upgrade**
- 1.55 < |eta| < 2.45
- Chambers spanning 20°
- Geometry details to be finalized (Looking into possibility of installing 2 rings of double-layered triple GEMs (1 ring with short, 1 ring with long super chambers)

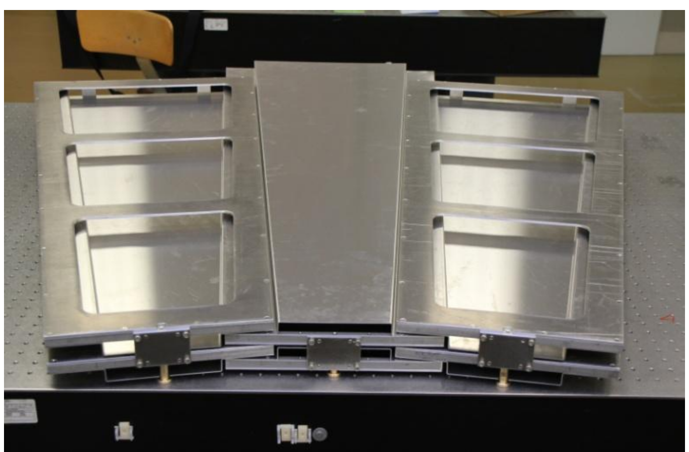
**ME0: near-tagger to be installed behind new Hadron Endcap calorimeter**
- 2.0 < |eta| < ~3.5
- Chambers spanning 20°
- 6-layers of triple-GEM detectors
- Geometry is yet to be finalized

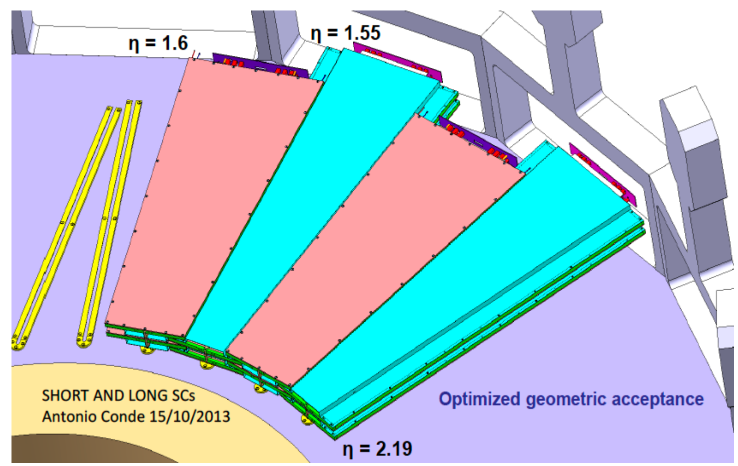


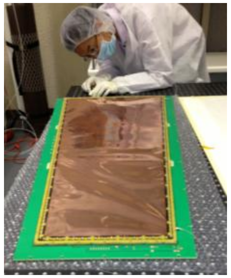
# GE1/1 Schedule

| 2014/15 | YETS 2015/16 | 2016/17 | 2017/18 | 2018/19 |
|---|---|---|---|---|
| Production and QC of detectors<br>First prototype of VFAT3 | Slice installation | Slice and trigger commissioning | QC of Production GE1/1 chambers with final electronics | |
| | | Full-production of chambers and electronics started | | Full installation of GE1/1 with final electronics |





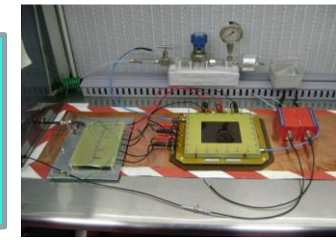
# Production Site Candidates



USA
Florida Tech

CERN: TIF (186)

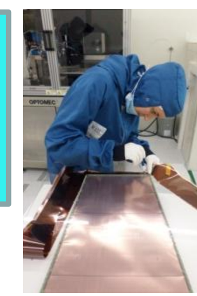
India
BARC



Production,
Final QC,
SC assembly

Italy
Bari
LNF

Belgium
Gent



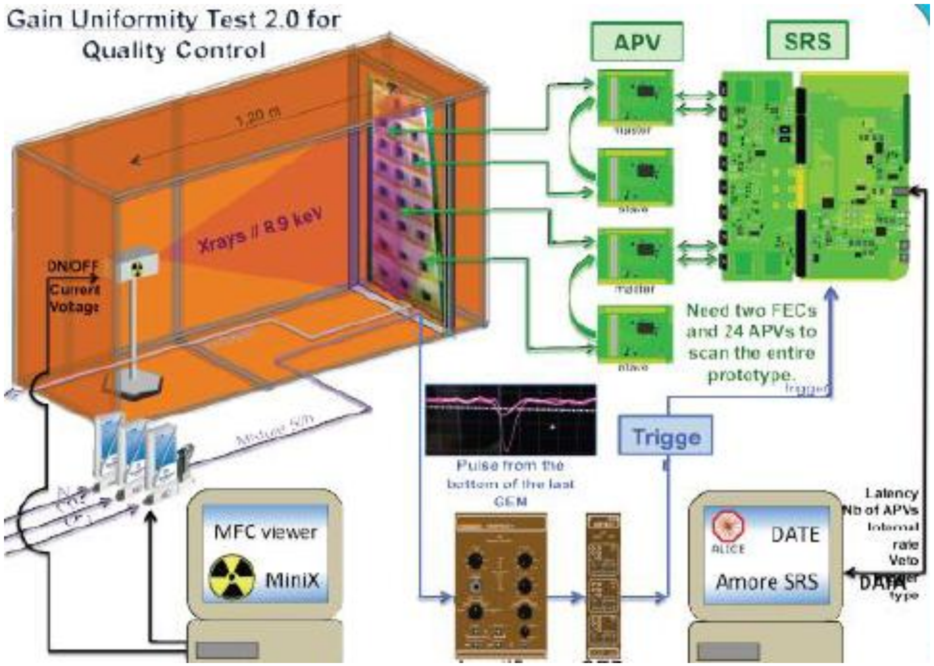
Installation in CMS

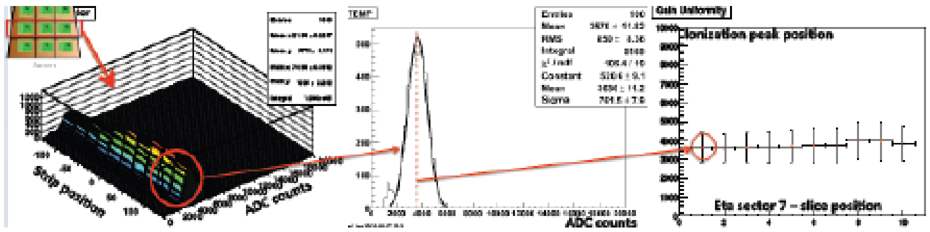
Common chamber production and certification protocols, including production database, for all sites

# Quality Control

Detailed common quality control protocols being prepared for all assembly sites:

- Quality of components before assembly (e.g. visual and electrical inspection of drift and readout boards ...)
- GEM foil connection tests during chamber assembly
- Post-assembly tests (e.g. HV connections, readout strips, gas tightness ...)
- Chamber gain calibration and uniformity scan with x-ray gun
- Chamber performance in cosmic stand



# Integration and Services @ CMS P5

**Ongoing work during LHC LS1 on GE1/1 integration and services at CMS P5:**
GE1/1 powering scheme; fibers; space in UXC YE-1 Near Side Towers for LV Power and Electronics; space in USC Racks for HV and Electronics; cable routing; GE1/1 gas system; cooling