Upgrade of the CMS Muon System with Triple-GEM detectors

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On behalf of the CMS GEM Collaboration
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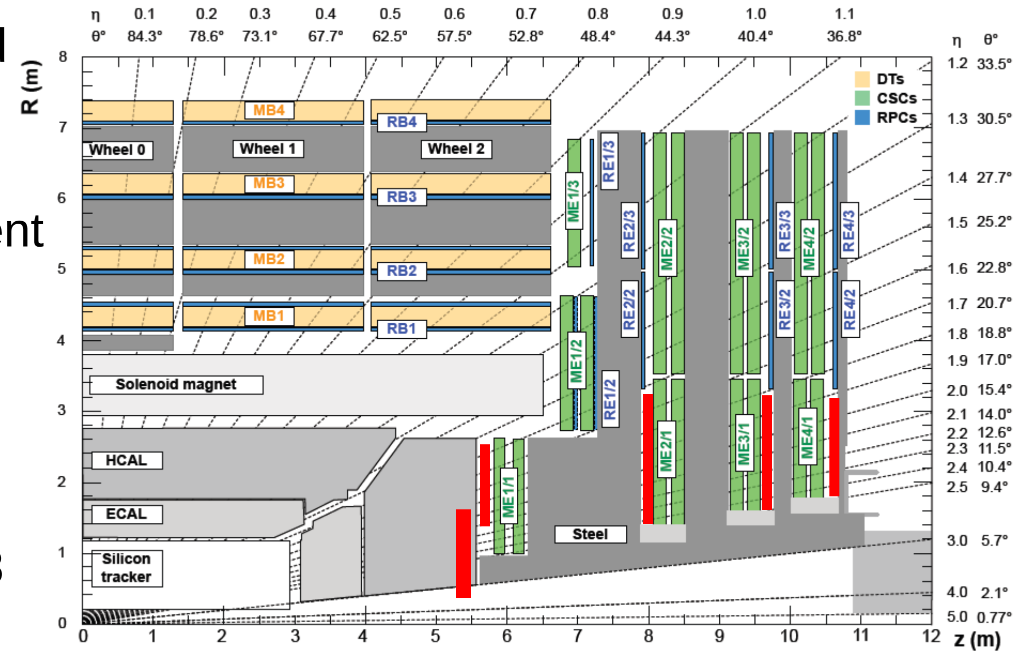
Outline

- CMS Muon System
- The GEM project
- Impact on trigger and physics
- Detector prototype development and tests
- DAQ and electronics
- Integration into CMS
- Summary and outlook

The CMS Muon System after LS1

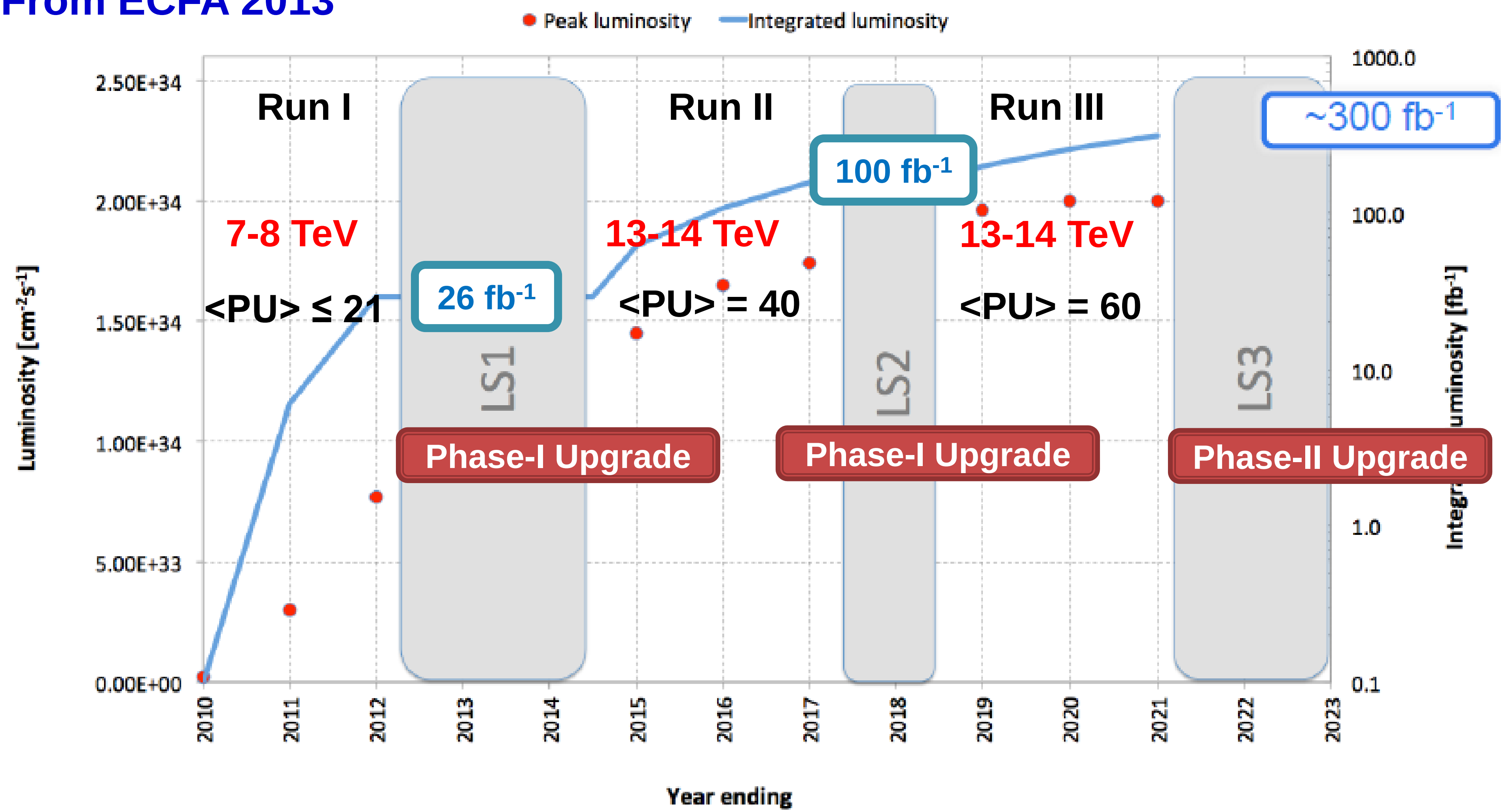
- CMS detector: designed to detect and reconstruct muons with superb precision
- The CMS Muon system uses 3 different types of detectors
  - Resistive Plate Chambers : triggering
  - Cathode Strip Chambers and Drift Tubes: tracking and triggering
- After LS1 CMS will be instrumented with RPCs and CSCs up to |eta| < 1.8
- Phase-II CMS needs handles to cope with high rate between LS2 and LS3
  - Tracking trigger won't be installed until ~2022
- **High eta region** has vacancies after LS1: good opportunity to install new detectors
  - Current CMS RPC design is not able to sustain with the high rates



- High eta region requires a **new technology** that satisfies requirements:
  - High rate capability O(MHz/cm^2)
  - Good time resolution: triggering
  - Good spatial resolution O(100µm): tracking

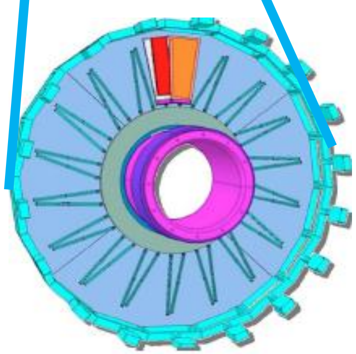
Evolution of LHC and CMS

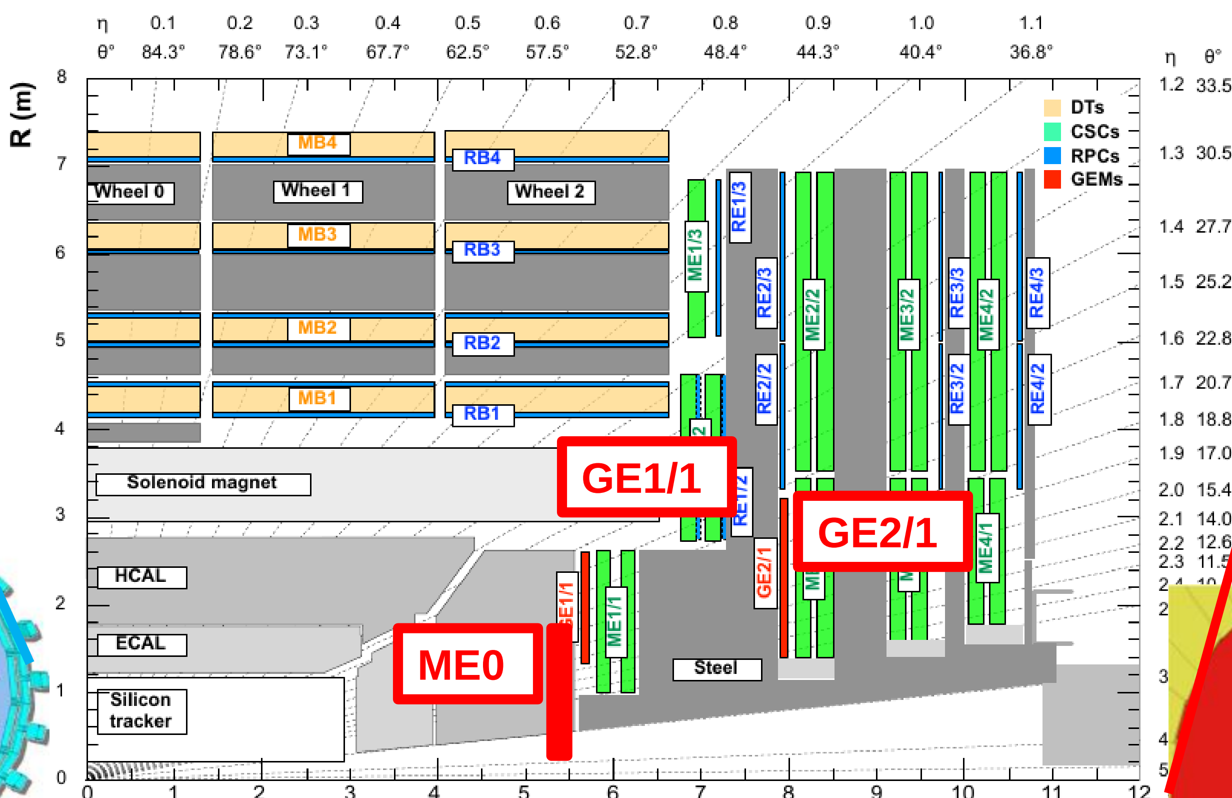
From ECFA 2013

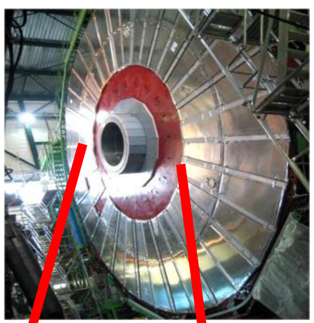


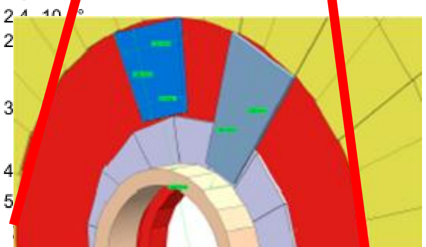
The CMS GEM project

- Install double-layered triple-GEM chambers in the presently vacant positions in front ME1/1 (after LS2) and ME2/1 (after LS3), and a 6-layered triple-GEM near-tagger behind the future shortened hadron callorimeter (after LS3)









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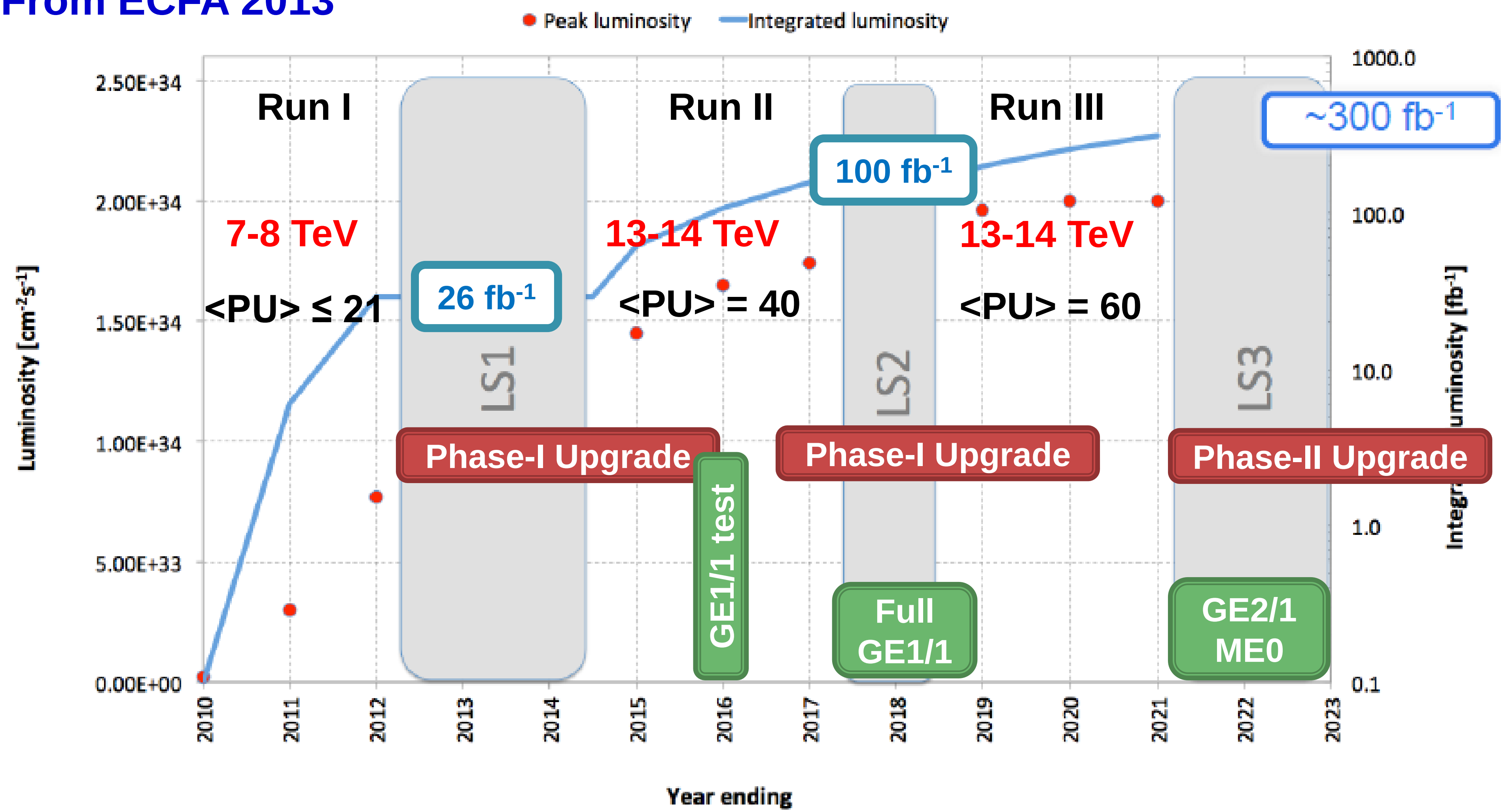
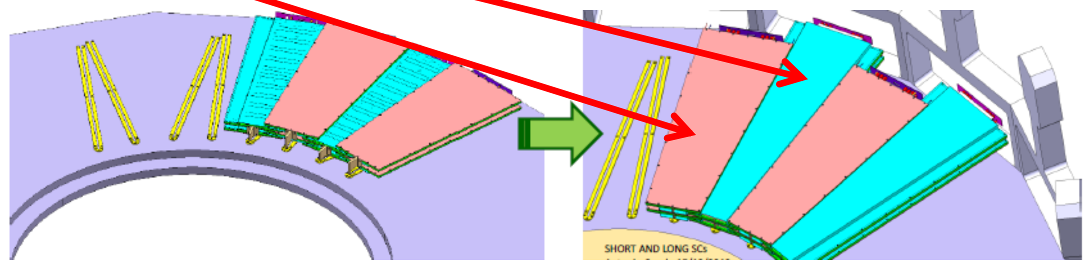


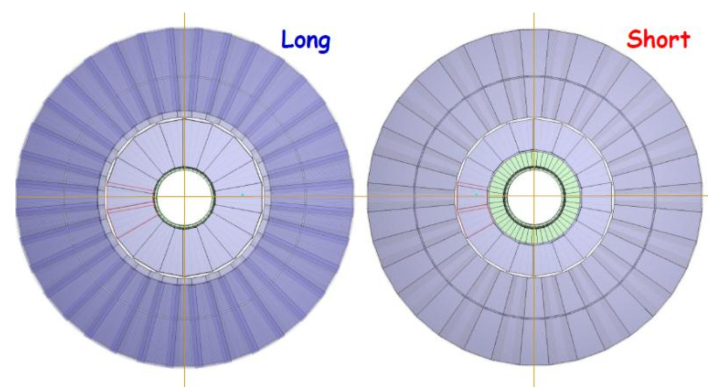
The CMS GEM project

- **GE1/1**: baseline detector for GEM project
  - 1.55 < |eta| < 2.18
  - 36 staggered super chambers, super chamber = 2 chambers, each chamber spans 10°
  - Several prototype designs with different number of eta partitions
  - Major conclusion from ECFA 2013: **short** and **long** super chambers for maximum coverage in pseudo-rapidity



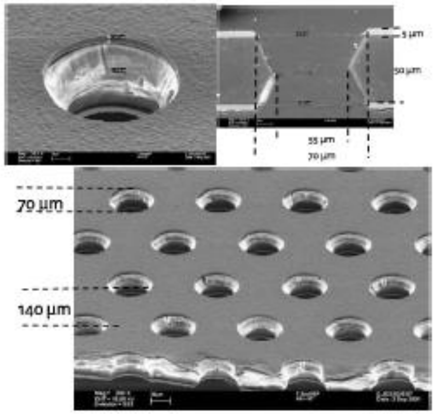
- **GE2/1**: station 2 upgrade
  - 1.6 < |eta| < 2.45
  - Chambers spanning 20°
  - Geometry details to be finalized
    - Looking into possibility of installing 2 rings of double-layered triple GEMs (1 ring with short, 1 ring with long super chambers)

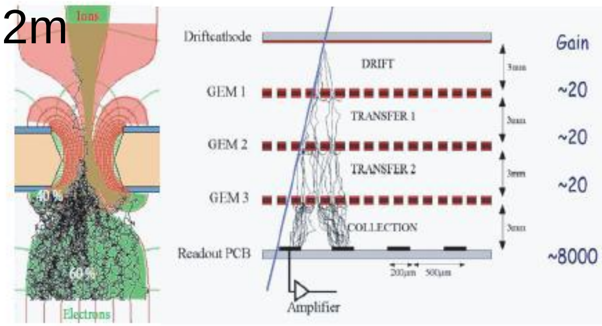
- **ME0**: near-tagger to be installed behind new HCal
  - 6-layers of triple-GEM detectors
  - 20° super chambers
  - 2.0 < |eta| < 3.5
  - Geometry is yet to be finalized

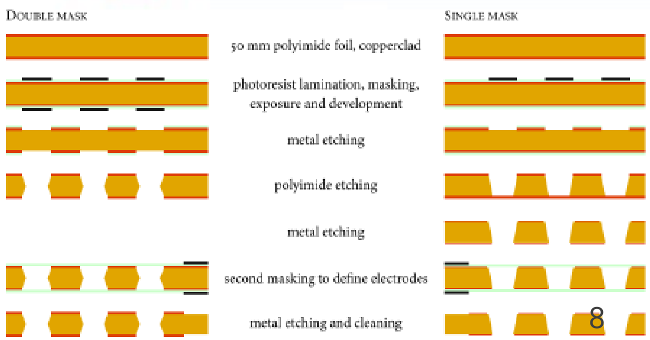


Gas Electron Multipliers

- Micro-pattern gaseous detector
  - Polyimide foil (50µm thick) in between 2 conductive layers, usually copper (5µm thick).
  - Foil is perforated with (bi)conical holes in a hexagonal pattern (hole diameter 70µm, pitch 140µm)
- Foils are developed using PCB manufacturing technique
- Cost-effective industrial production of large areas ~1m x 2m
- Excellent spatial and time resolution (O(100)µm, ~5ns)
- Efficiency ~98%
- High rate capability ~1MHz/cm^2
- Radiation hardened
- Non-flammable gas mixture: Ar/CO_2/CF_4 (45/15/40)



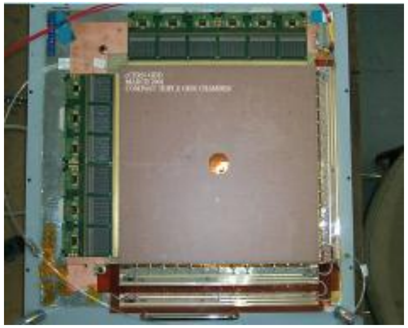


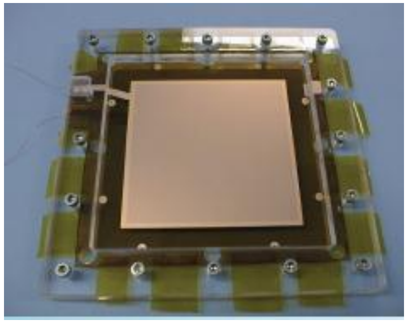


Excellent material to build triggering and tracking detector

GEMs at other CERN experiments

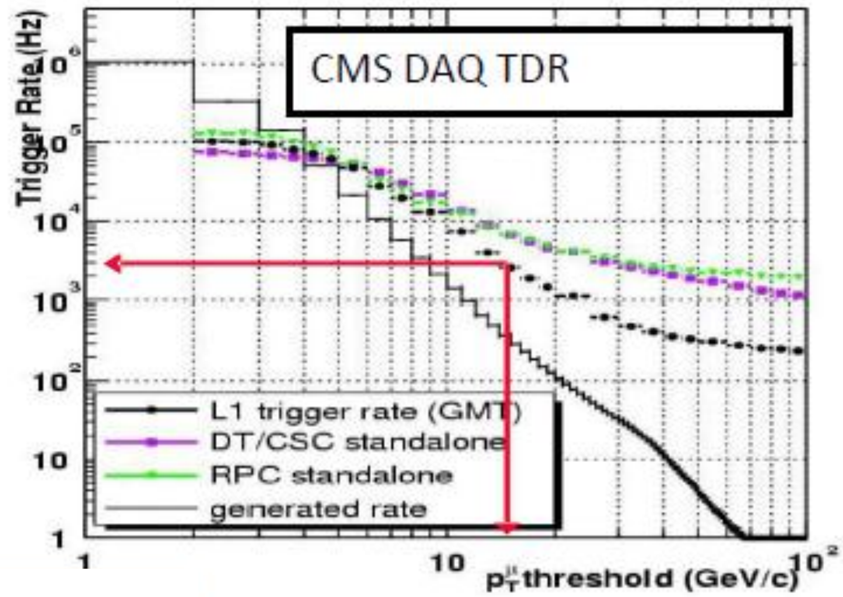
- TOTEM
  - Triple-GEM with Ar/CO_2 mixture (70/30) located at $5.3 \leq |\eta| \leq 6.5$
  - Rate ~ 12MHz/cm^2 (1000 x GE1/1 in CMS Phase-II)
  - **No aging effects due to polymerization**
  - **No change in material properties**
- COMPASS
  - Triple-GEM with Ar/CO_2 mixture (70/30)
  - Rate ~2.5MHz/cm^2 (500 x GE1/1 in CMS Phase-II)
  - **No decrease in gain, efficiency, or deterioration of energy resolution or time resolution up till now**
- LHCb
  - Triple-GEM with Ar/CO_2 mixture (45/15/40)
  - Rate ~500 kHz/cm^2 (50 x GE1/1 in CMS Phase-II)
  - **No decrease in performance after 10 LHCb years**

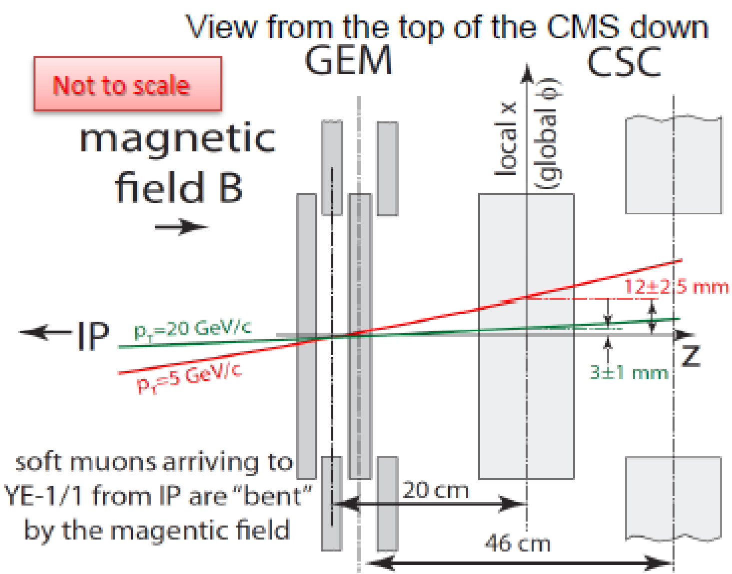




Global Muon Trigger rate at HL-LHC

- Scattering of soft muons in the iron yoke flattens the trigger rate curve
  - Promotion of low-p_T muon to high-p_T
- Additional muons stations can help to reduce the trigger rate
- Efficiency of single muon trigger at 20 GeV is about 85% in high eta region

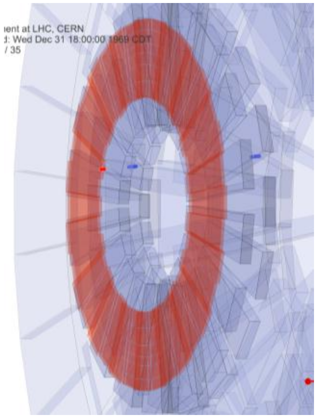




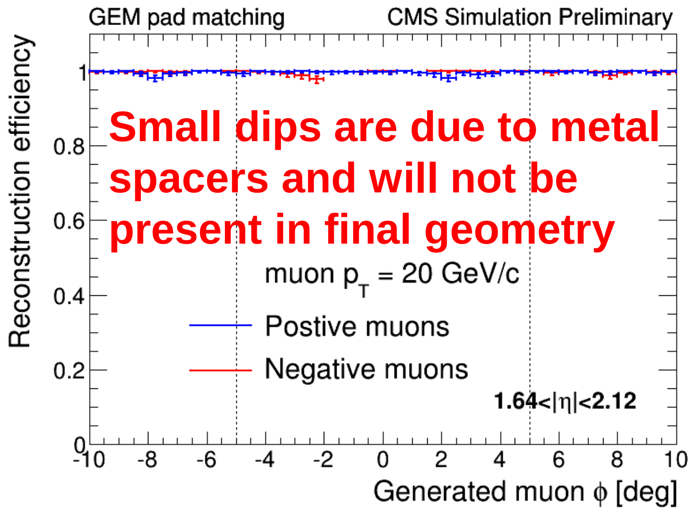
- Additional GEM detector in front of ME1/1 can measure muon bending angle in magnetic field.
- By letting the GEM and CSC **talk to each other** we get a powerful new tool
  - **Rate reduction with GEM-CSC bending angle**
  - **Stub efficiency recovery in ME1/1 CSC TMB**

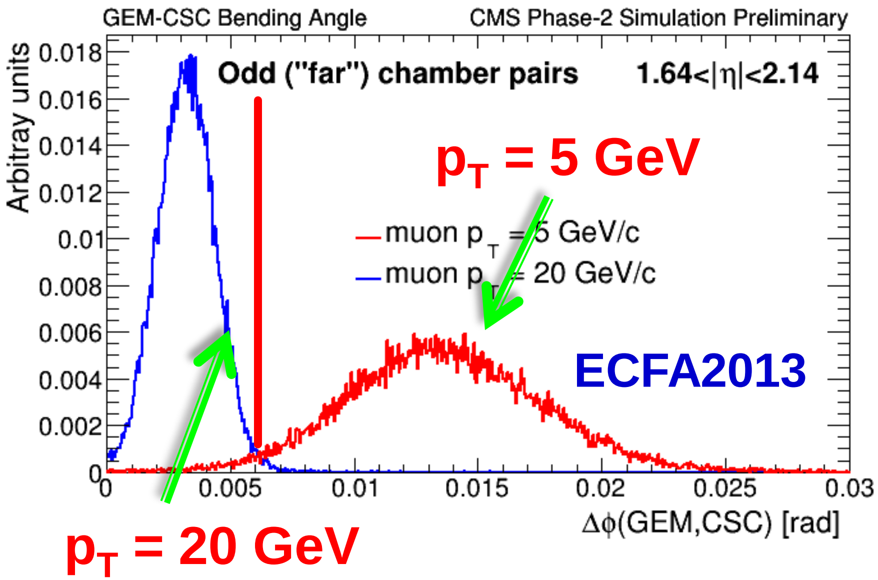
GEM-CSC bending angle

- 36 GEM chambers in GE1/1. Each chamber spans 10 degrees and is covered with 384 strips (strip ~1 mrad)
- For trigger purposes: group 4 strips in OR'ed collection: **GEM-CSC trigger pad**
- Nearly 100% efficiency to reconstruct trigger pad
- GE1/1-ME1/1 bending angle provides **clear separation of hard and soft muons** (~4 mrad, dX ~8mm)
  - GEM-CSC bending angle power in ME0 is of the same order
  - GE2/1 has much less bending angle power

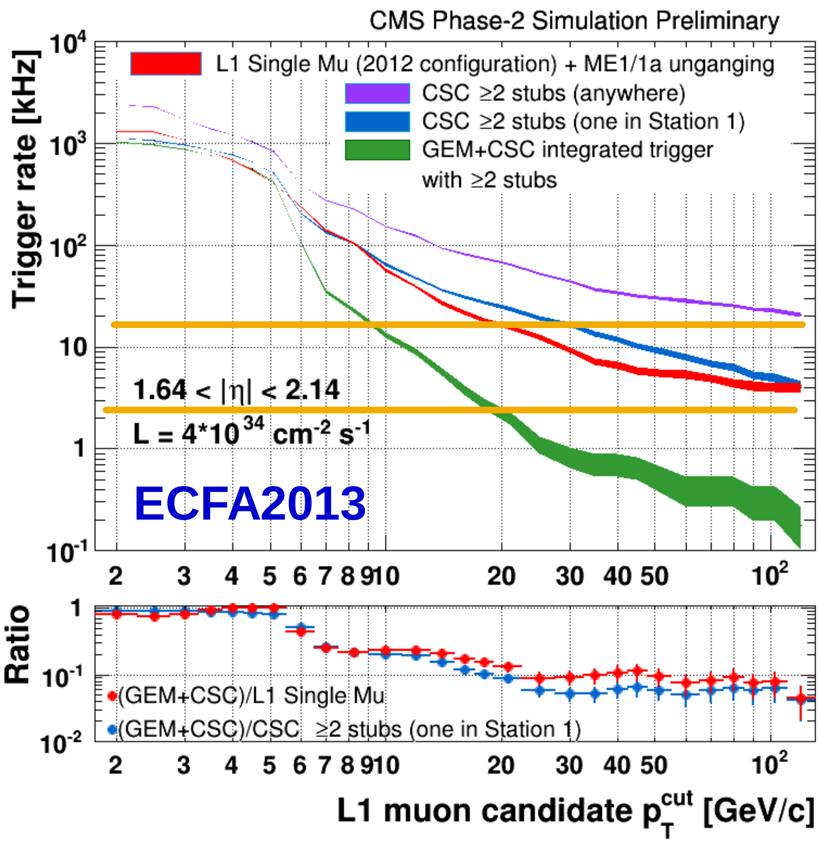


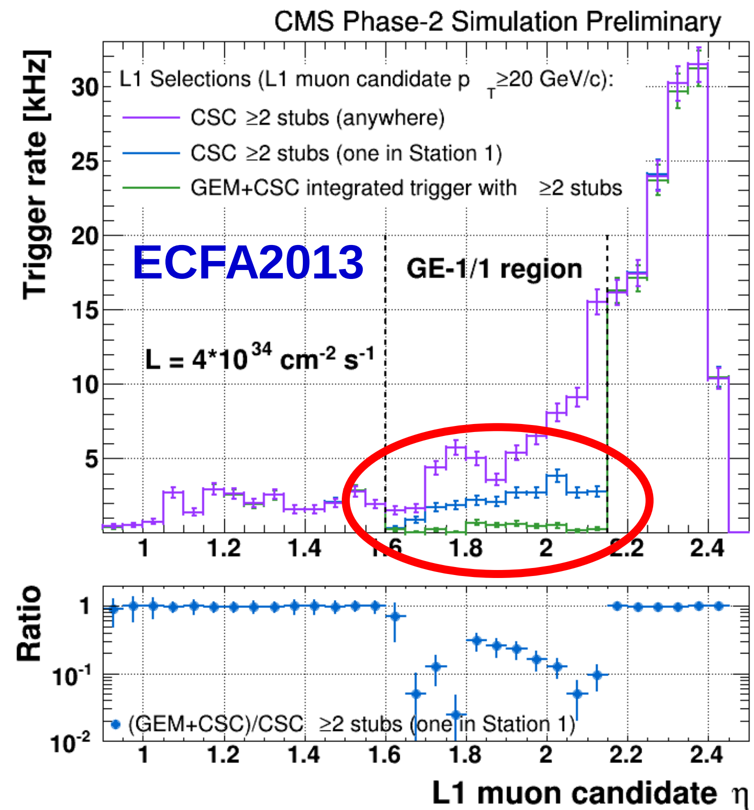
GEM chambers in simulation





Impact on trigger rate: results for prototype ILT

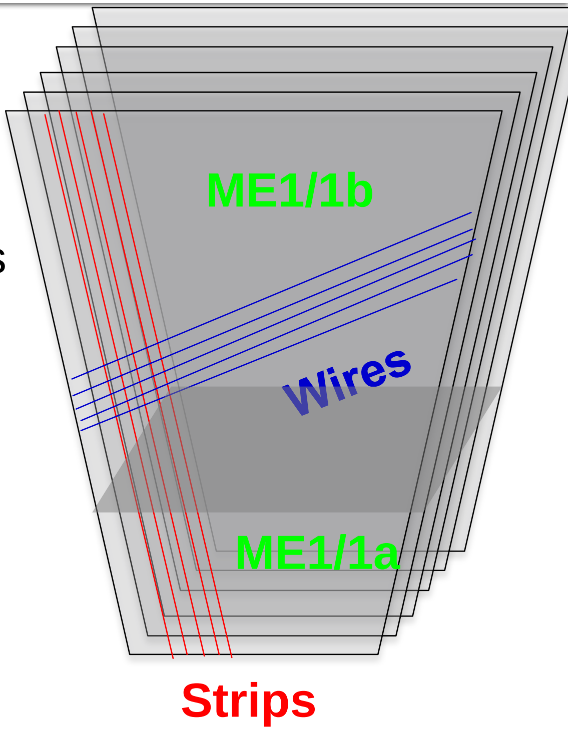




- Typical trigger rate reduction for 20GeV muon: **20kHz/cm2 to 2kHz/cm2**
- Preliminary results with not fully yet optimized trigger algorithm

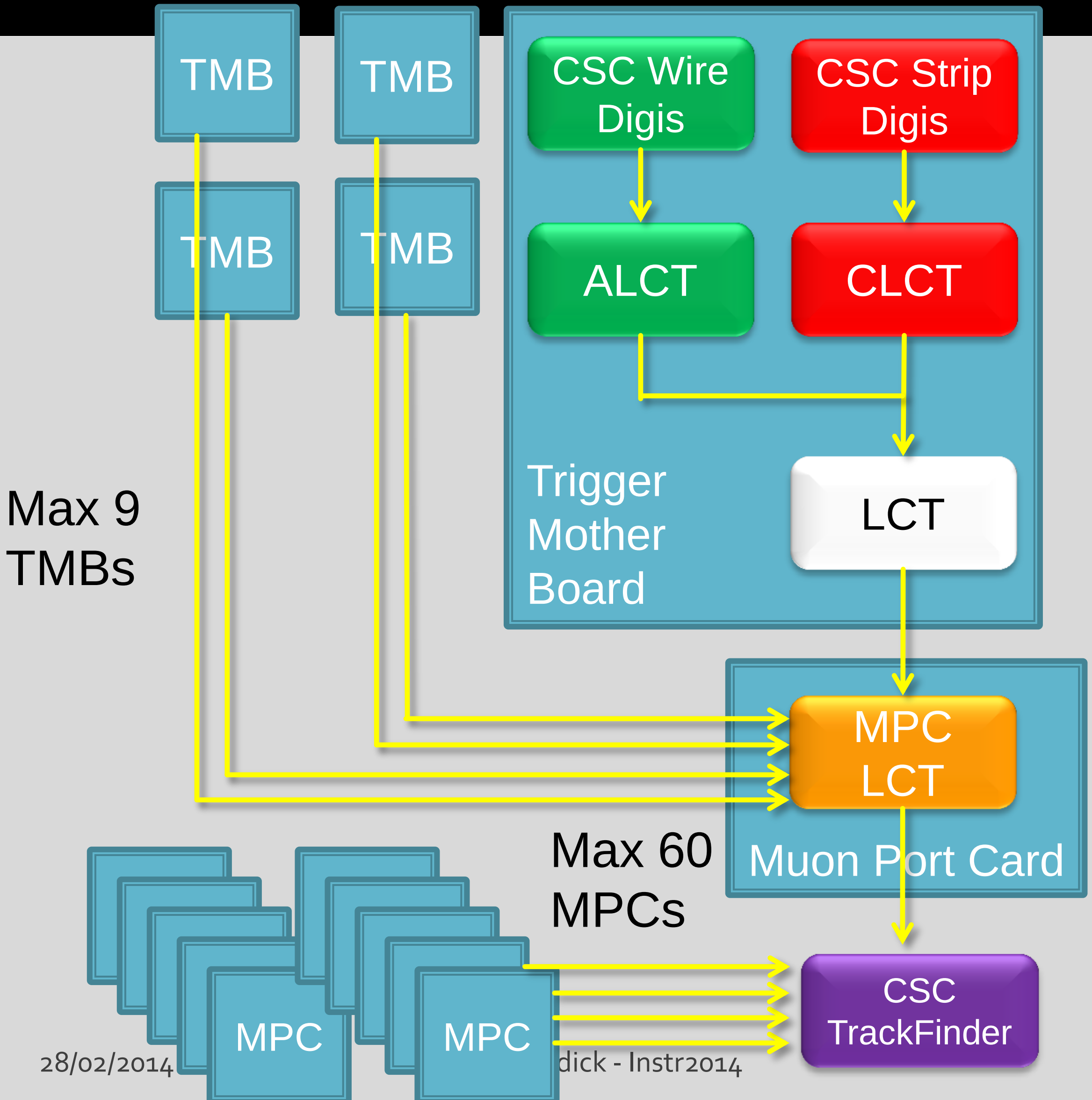
CSC trigger logic and shortcomings

- CSC chamber in ME1/1
  - 6 layers of anode wires in wire groups (slanted due to magnetic field) and cathode strips
  - ME1/b (top), ME1a (bottom) with different readout for strips
- CSC stub = combination of anode wire group stub (**ALCT**) with cathode strips stub (**CLCT**) in the CSC trigger mother board
- CSC stubs are sent upstream to be used in the CSC track-finder as track segments

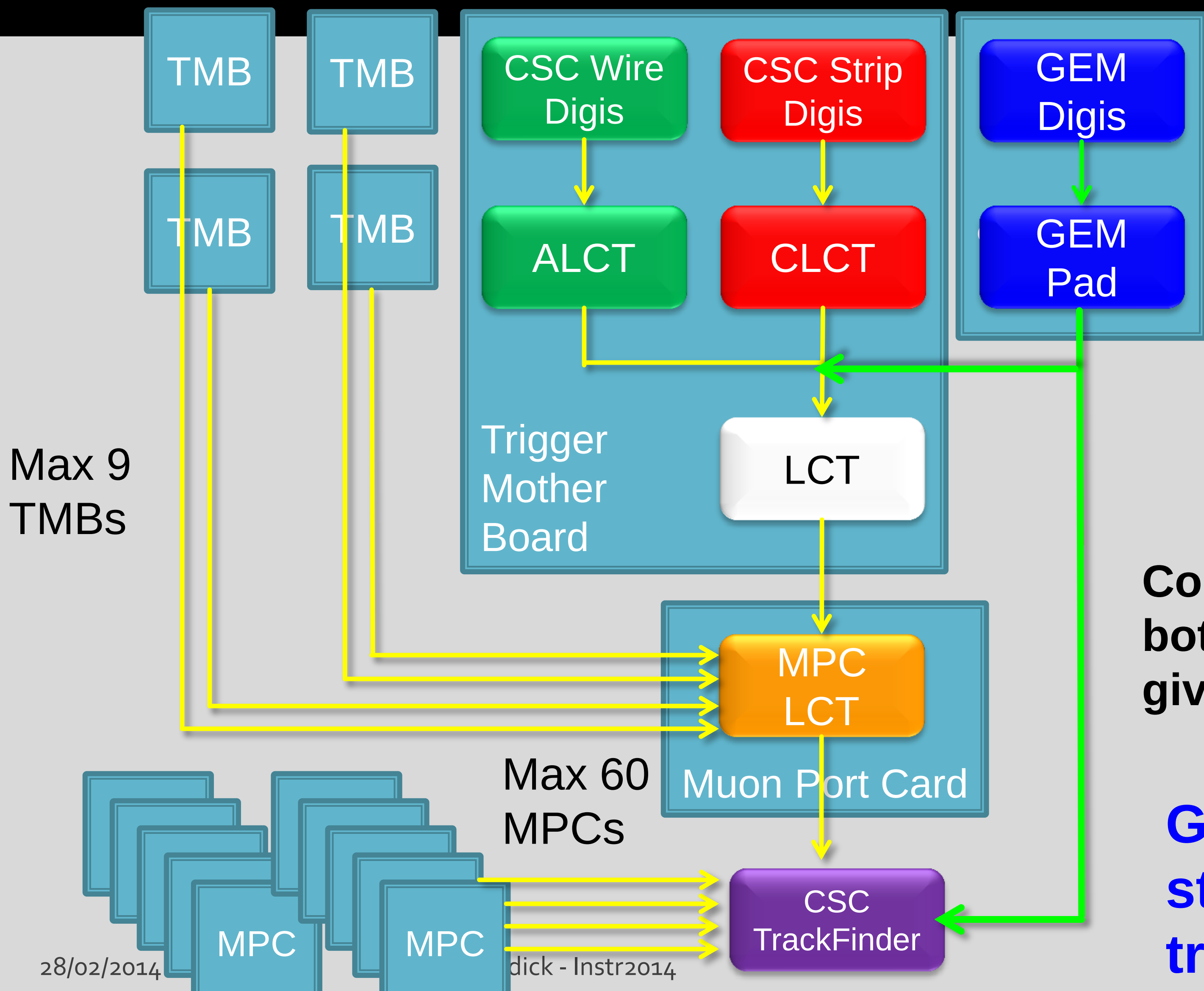


- Known issues with current CSC trigger logic
  - Unable to reconstruct a CLCT (insufficient hits to pass trigger requirement)
    - Important effect in **chamber edges** and the **ME1/1a-ME1/1b** overlap region
  - Multiple CLCTs are reconstructed for a given ALCT
    - Fake stubs are sent upstream
  - CLCT timing is off

GEM triggering options



GEM triggering options



GEM-CSC integrated local trigger

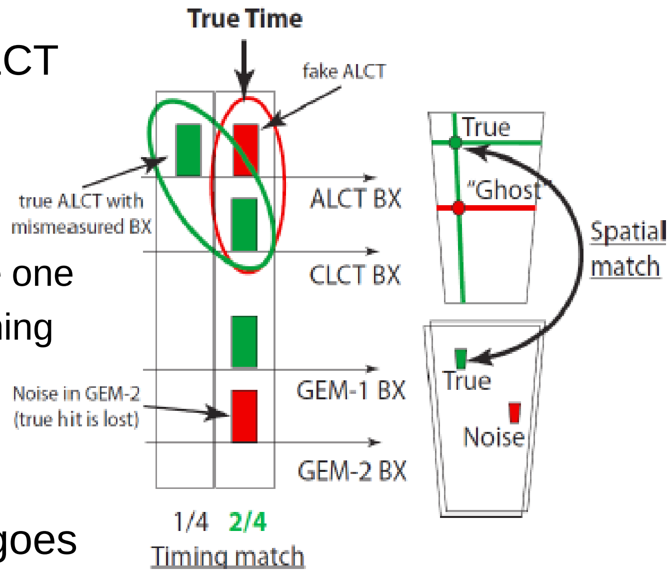
Combination of both paths will give best results

GEM standalone trigger

Efficiency recovery in ME1/1 CSC and TrackFinder

GEM-CSC integrated local trigger

- Generalize the notion of an ME1/1 stub: any 2/3 of ALCT, CLCT and GEM pad
- Many options to improve stub reconstruction efficiency
  - Unable to reconstruct ALCT or CLCT → replace by GEM pad
  - Fake stubs → Use GEM information to figure out which is the true one
  - Incorrect stub timing → If there is GEM coincidence, use GEM timing
- Requires change in the CSC stub dataformat to TrackFinder
  - New dataformat has been finalized and blessed by electronics experts
- Preliminary studies show that LCT reconstruction efficiency goes up from ~90% to ~96% in high pile-up scenario (PU140)



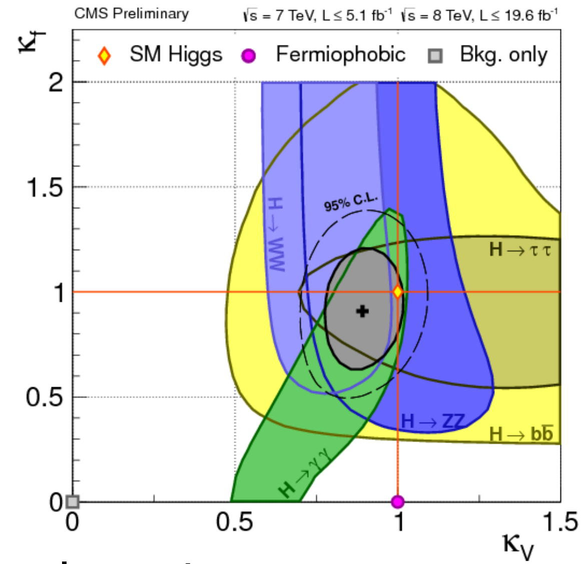
Standalone GEM trigger

- Combine information from CSC integrated stubs, GEM coincidence pads and RPC stubs in single algorithm to reconstruct muon tracks in high eta region
- Studies ongoing how to use GEM pads in current CSC TrackFinder and future Muon TrackFinder

GEM Physics benefit

- Discovery of Standard Model like scalar boson in 2012.
- Carry out precision measurements of Higgs couplings.

- **CMS Muon system is critical:**
  - H→ WW/ZZ are key to precision on HVV boson couplings
  - WH→μνττ is key for measuring fermion couplings H_f.
    - Muon + hadronic tau is most sensitive.

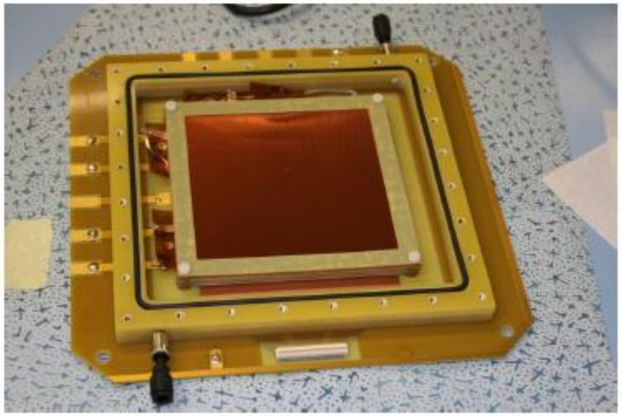


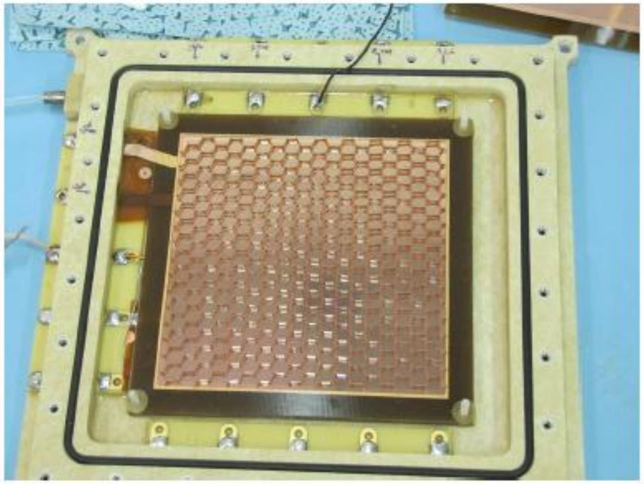
- Need good muon triggering with maximal coverage.
  - GEM+CSC results in ~20% increase in acceptance.

- **Recent achievement:** Mass production of samples with at least 1 forward muon in final state
  - H → ZZ → 4μ, H → 2μ
  - Z' → μμ, W' → μν
  - μ* → μγ
  - B_s → μμ
  - …
- Start building the physics case for GE1/1 TDR and Muon Phase-II TP

Small GEM prototypes

- 10×10 cm^2 triple-GEMs
- 1D or 2D readout configuration
- 128 of 256 channels
- Several prototypes:
  - Double-mask triple-GEM (“timing GEM”)
  - Single-mask triple-GEM
  - “Honeycomb” triple-GEM (efficiency ~70%)

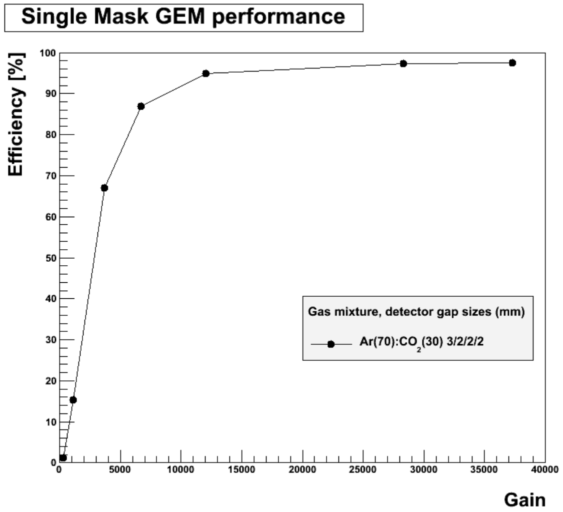




GEM project achievements

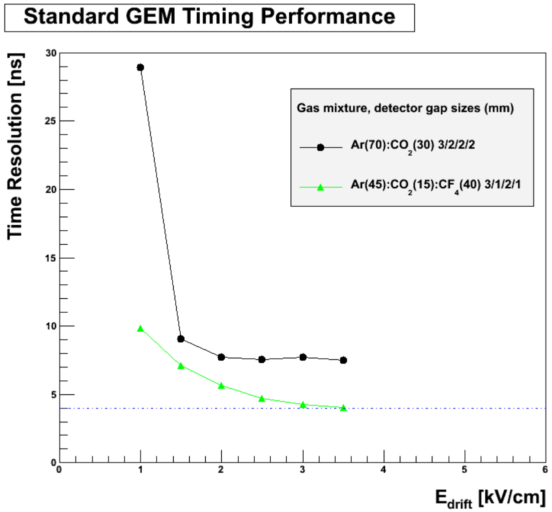
Performance

- Detector efficiencies ~98%
- Time resolution ~4ns
- Spatial resolution of about 290µm with VFAT2 (digital) and <110µm APV (analog) readout chip
- Operation of GEMs in magnetic field
- Gas mixture $Ar/CO_2/CF_4$ (45/15/40)
- Rate capability ~10^5Hz/cm^2
- Good performance in test-beams at CERN SPS and FNAL



Technology and assembly

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



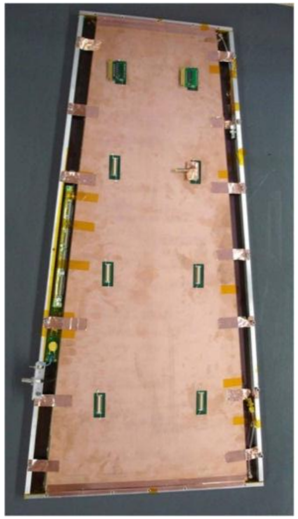
Integration

- Dummy GEMs for trial installation

Large GEM prototype evolution

GE1/1-I

2010



- 1st 1m-class type
- 2 x 4 readout sectors
- Spacers
- All glued

GE1/1-II

2011

- 1st GE1/1 type
- 3 x 8 readout sectors
- Spacers
- All glued

GE1/1-III

2012

- NS2 technology
- Outer frame still glued to drift
- Gap sizes: 3/1/2/1 mm

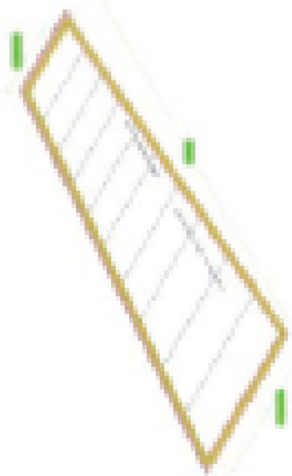
GE1/1-IV

2013

- Complete mechanical construction
- 6 types produced at several sites

GE1/1-V

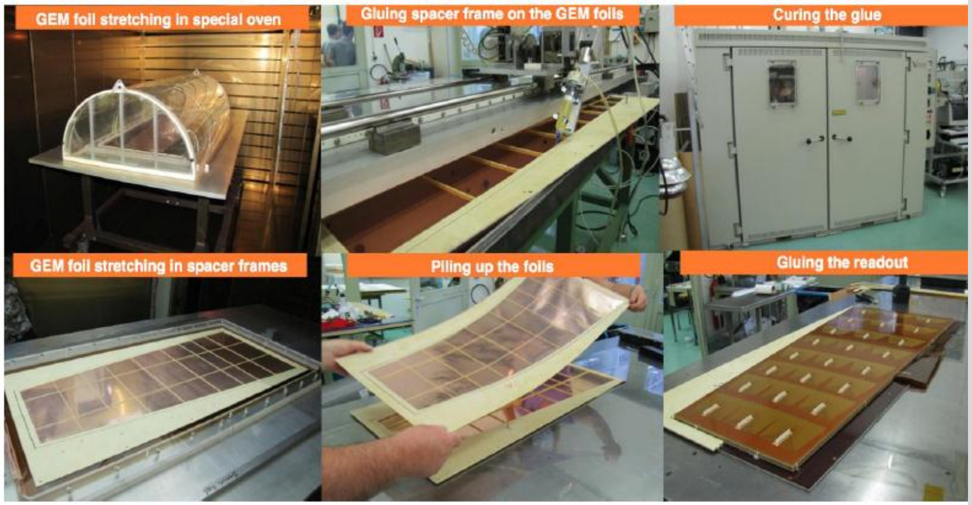
2014



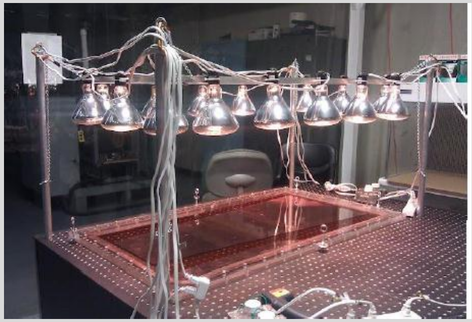
- Final design
- Optimal acceptance in eta and phi
- Short+long version

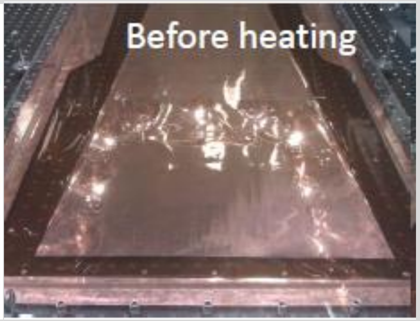
GEM foil stretching evolution

Thermal Stretching in oven (CERN)



In-situ thermal stretching (Fl. Tech)

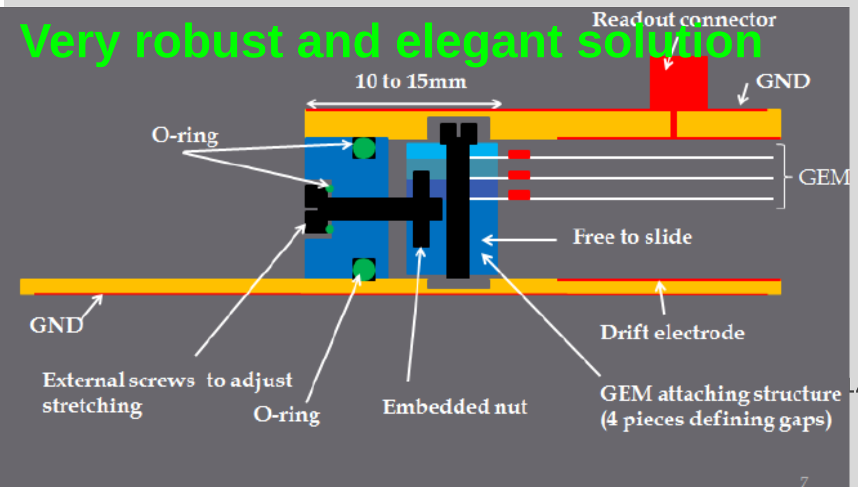




16 125W heat lamps stretch foil at 35°C

"Self-stretching" without spacers (CERN)

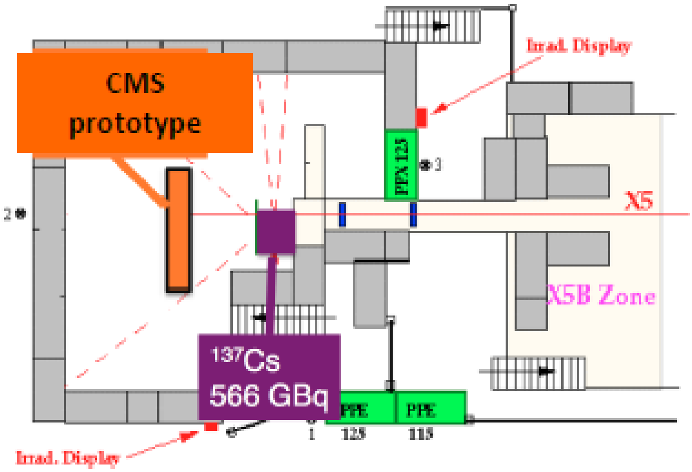
Very robust and elegant solution

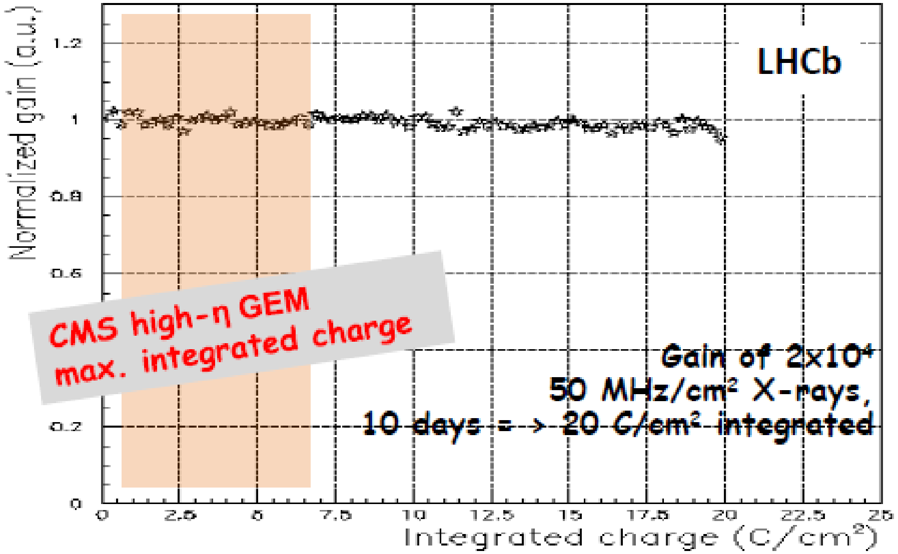


Easy to re-open detector for repair

GE1/1 aging tests

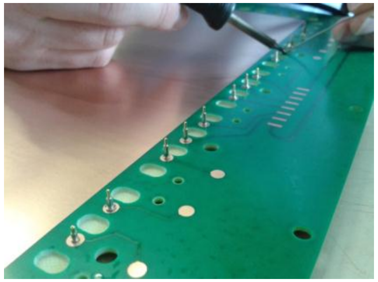
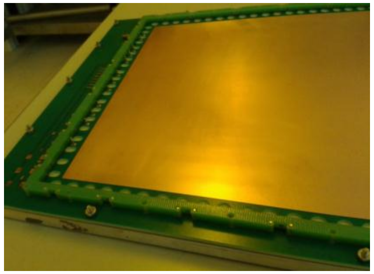
- Long lifetime for GE1/1 is expected
  - Long-term operation in LHCb, COMPASS, TOTEM
- Aging tests ongoing at CERN GIF and GIF++
- Monitoring performance with integrated charge collection
  - Ensure long-term operation in CMS
  - Understand (any) material degradation due to radiation
  - Understand ageing origin (if any) and propose solutions
- **Paper with recent results in preparation**



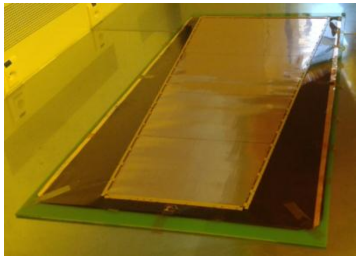
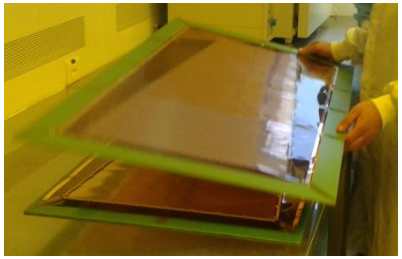
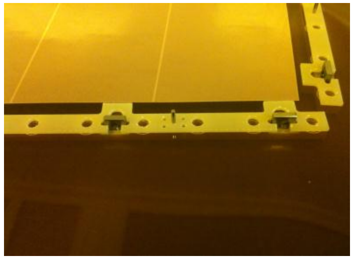


GE1/1 chamber construction

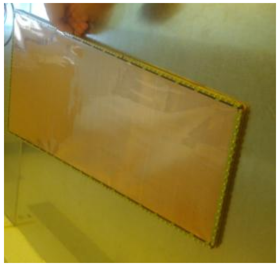
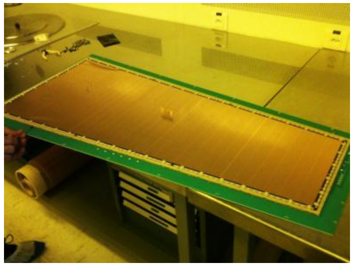
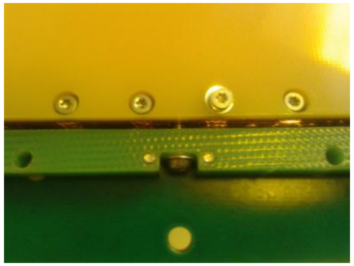
- **Step 1**: preparation of drift board
  - Equip PCB with metallic inserts and HV probes
  - Fix outer frame to PCB with guiding pins

- **Step 2**: preparation of GEM stack
  - Place 1st frame on support
  - Place GEM1 + second frame
  - Place GEM2 + 3rd frame
  - Insert stretching nuts
  - Place GEM3 + 4th frame

- **Step 3**: installation and stretching
  - Remove the guiding pins
  - Place stack on drift plane
  - Check electrical contacts & HV divider
  - Close chamber with readout PCB
  - Insert gas in- and outlets

GE1/1 chamber construction

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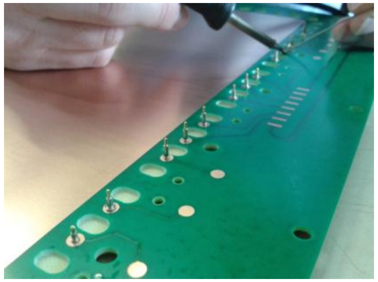

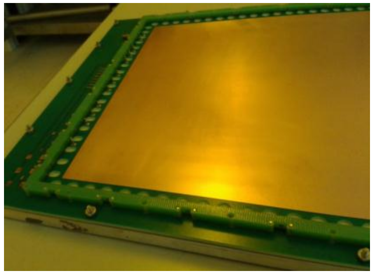

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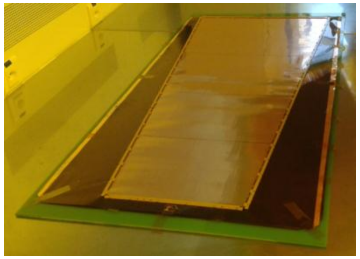
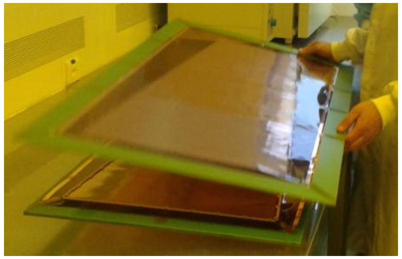
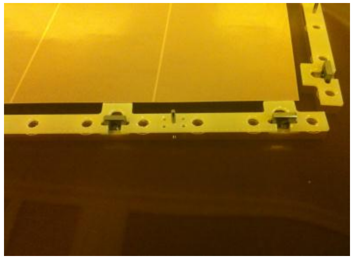
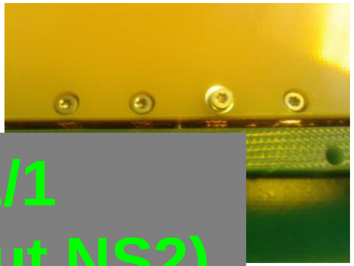
  - Insert stretching nuts
  - Place GEM3 + 4th frame







- **Step 3**: installation and stretching
  - Remove the guiding pins



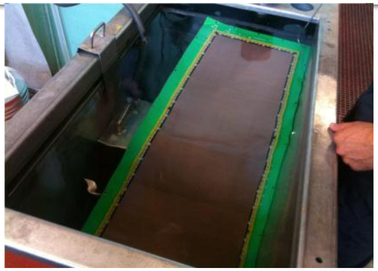
- **Only 2 hours to assemble the full-scale GE1/1**

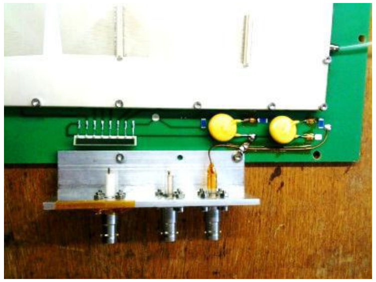
(Compared to >2 days for the triple-GEM without NS2)

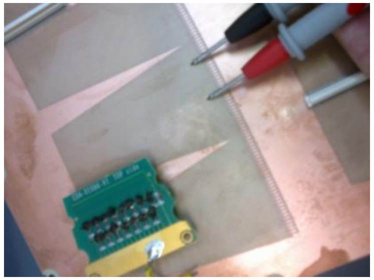
- **6 GE1/1-IV types have been built at various sites**
  - **CERN, FIT, Ugent**

Quality control

- **Step 1:** Check quality of components on receipt
  - Visual and electrical inspection of drift and readout PCB
  - Cleaning to remove dust on epoxy frames
- **Step 2:** Regularly check and clean GEM foils during assembly
- **Step 3:** Post-assembly testing
  - Test HV connections and readout strips
  - Check for gas leaks
- **Step 4**
  - Calibrate assembled chamber with MINI-X
  - Measure charge per cluster for every readout strip with APV+SRC
  - Calculate effective gas gain for each sector
- **Step 5&6**
  - Test chamber in cosmic stand to determine efficiency, Δ t and Δx
  - Install and test electronics (VFAT3+uTCA)

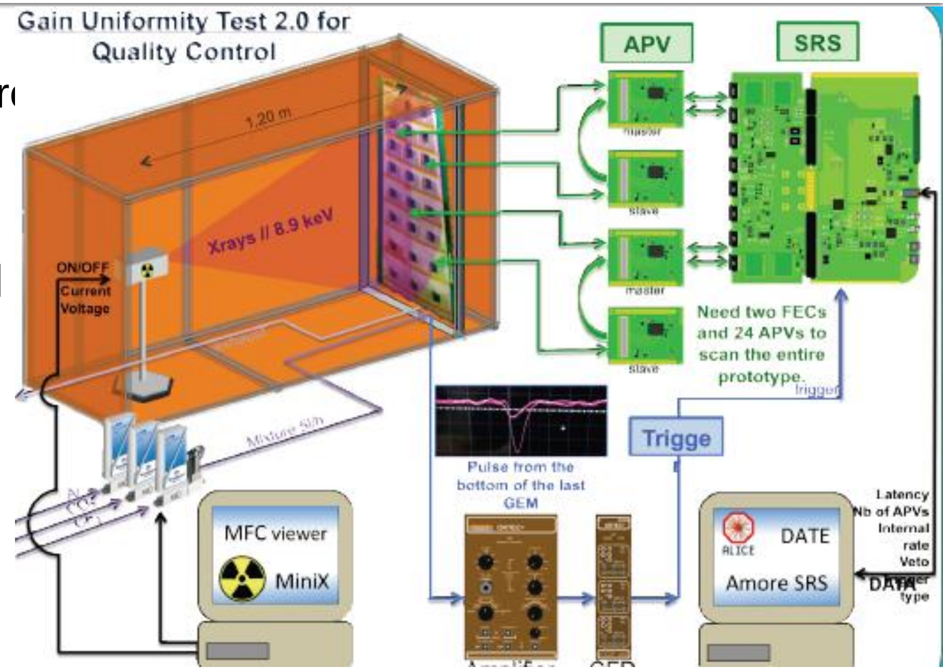




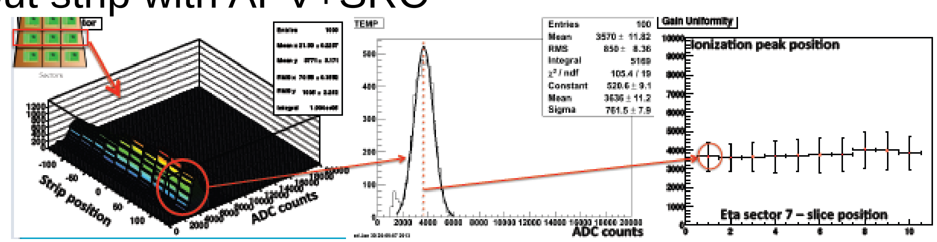


Quality control

- **Step 1:** Check quality of components
  - Visual and electrical inspection of drift and r
  - Cleaning to remove dust on epoxy frames



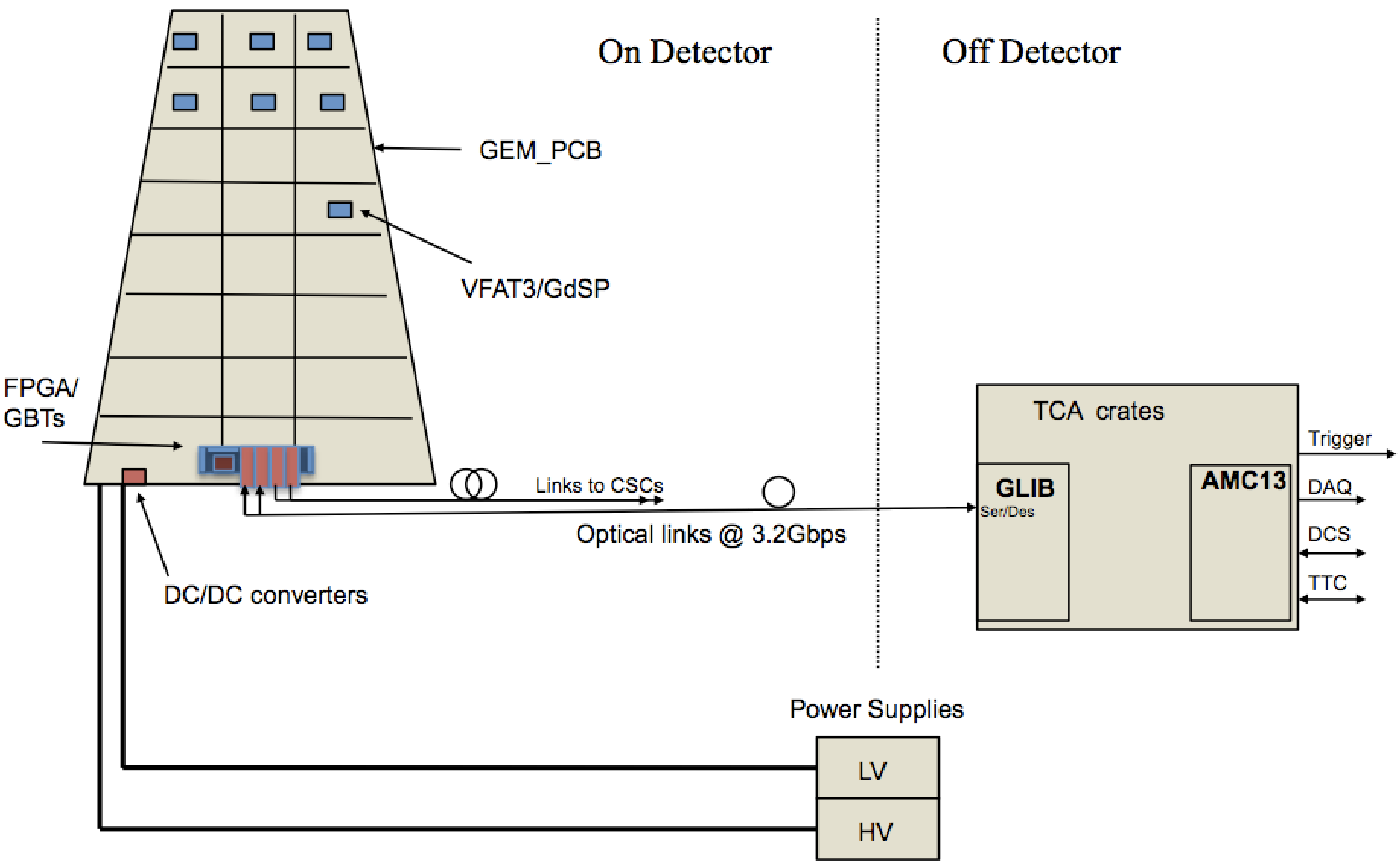
- **Step 2:** Regularly check and clean GEM
- **Step 3:** Post-assembly testing
  - Test HV connections and readout strips
  - Check for gas leaks
- **Step 4**
  - Calibrate assembled chamber with MINI-X
  - Measure charge per cluster for every readout strip with APV+SRC
  - Calculate effective gas gain for each sector



- **Step 5&6**
  - Test chamber in cosmic stand to determine efficiency, Δ t and Δx
  - Install and test electronics (VFAT3+uTCA)

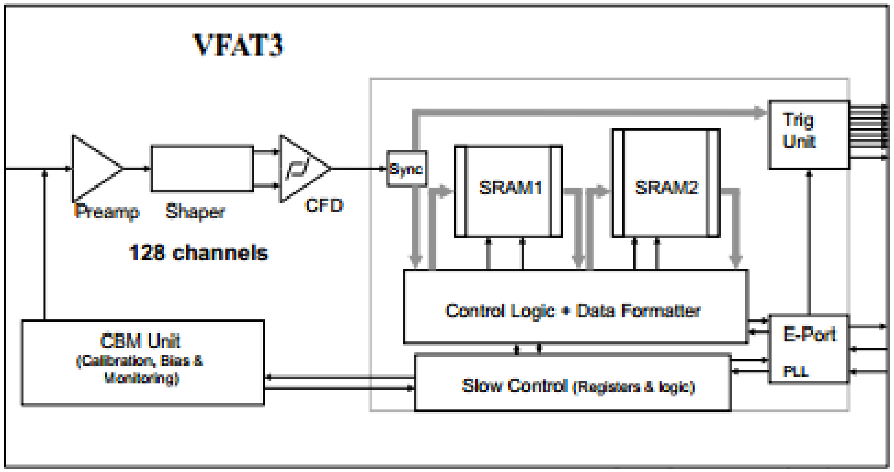
Finally: Assemble the GE1/1 superchamber

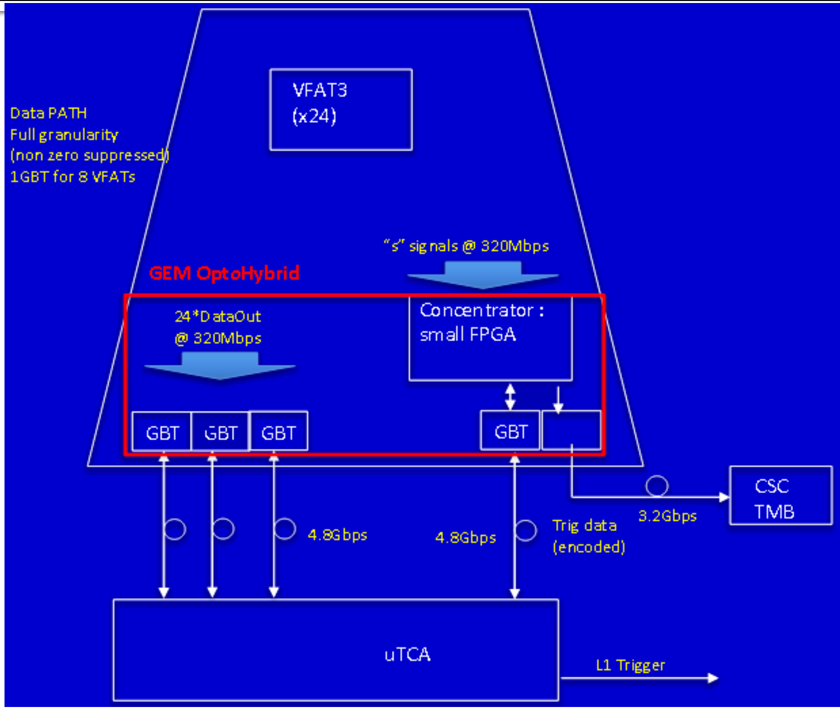
DAQ and electronics



VFAT3

- VFAT3 was chosen over GdSP for GE1/1-V electronics
- VFAT3 analog discriminator will use CFD 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

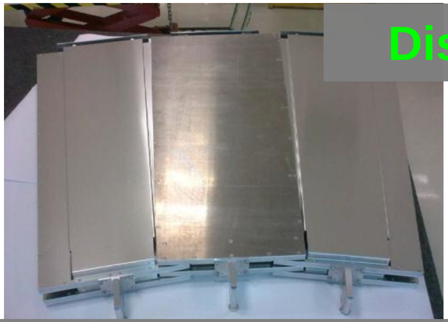




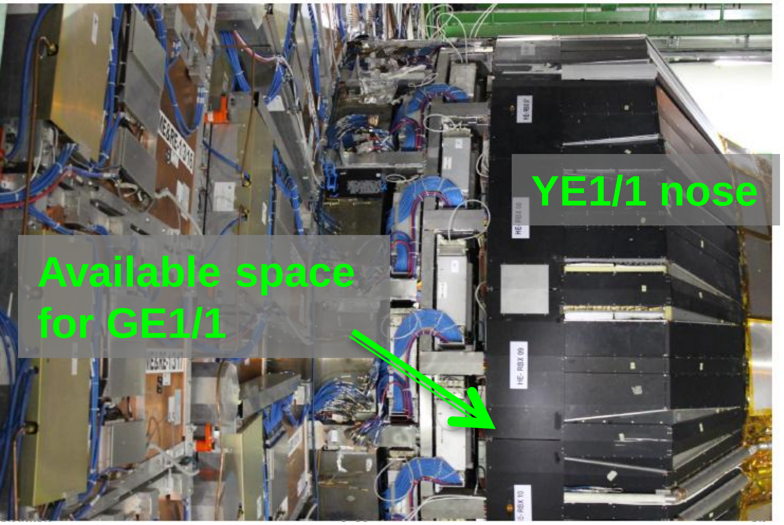
Integration into CMS

- Ongoing investigations at P5 by technical crew
  - Optimize cable and fibre routing, and layout of cooling pipes
  - Racks for electronics equipment and powering (HV/LV)
- GE1/1 super chamber dummies produced (May 2013)
  - 1st trial installation in Summer 2013
- New dummies according to updated geometry (Jan 2014)
  - 2nd trial installation in March 2014

Disassembled GE1/1 dummies



Assembled GE1/1 dummies



Dummies with short and long chambers

Trial installation Summer 2013

Pictures taken during Summer 2013

Conclusions and outlook

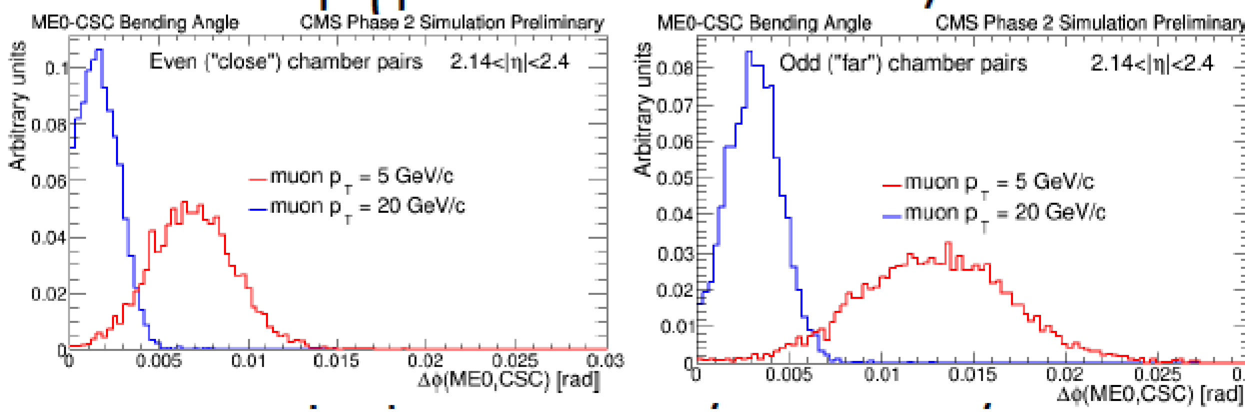
- R&D started nearly 5 years ago (2009) within the RD51 Collaboration
- Triple-GEM technology is mature and satisfies trigger and physics needs for CMS in the post-LS2 era
- Partial approval for installation of GE1/1 was obtained Summer 2013
- Full approval for installation of GE1/1 was obtained at ECFA workshop (Autumn 2013)
- A Technical Design Report for GE1/1 is in preparation (October 2014)
- Production of the finalized GE1/1-V detectors is scheduled for 2014-2015
- During the LHC Year-End Technical stop of 2016-2017, two GEM superchambers demonstrators will be installed in YE1/1

Backup slides

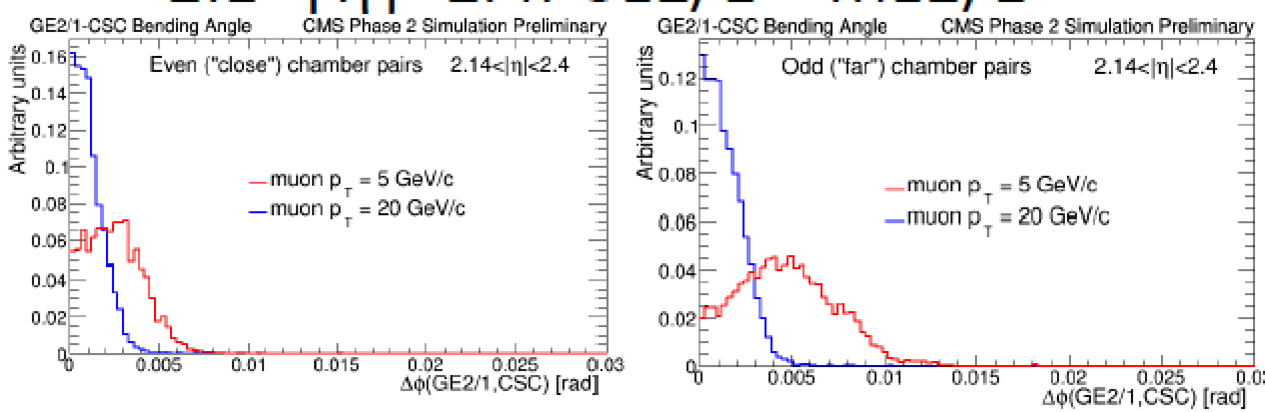
GEM-CSC bending angle

- ME0-ME1/a
- GE2/1-ME2/1

$2.1<|\eta|<2.4$: ME0 – ME1/1a

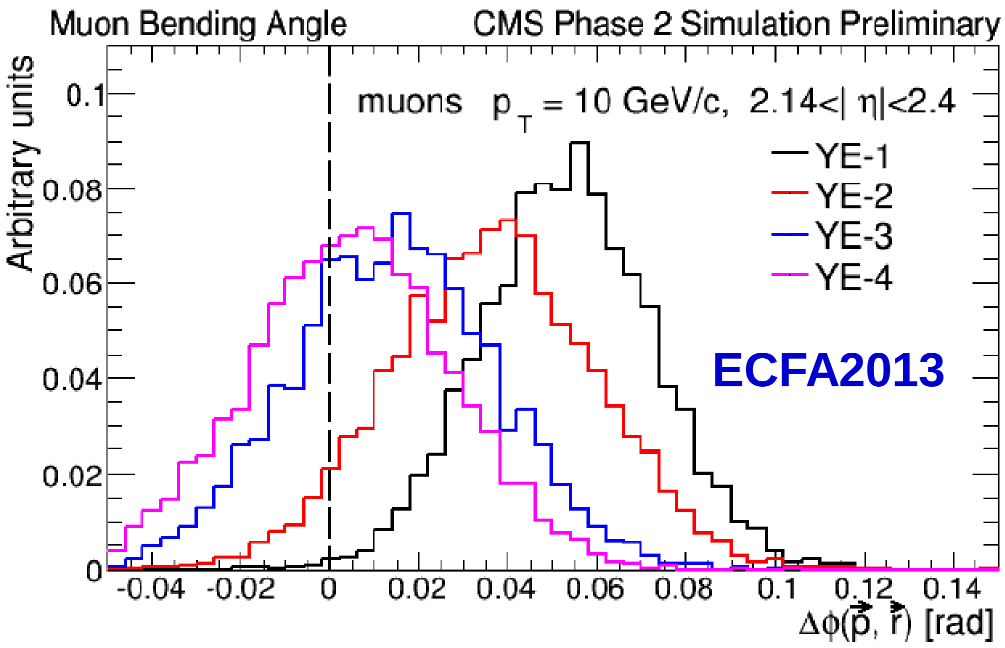


$2.1<|\eta|<2.4$: GE2/1 – ME2/1

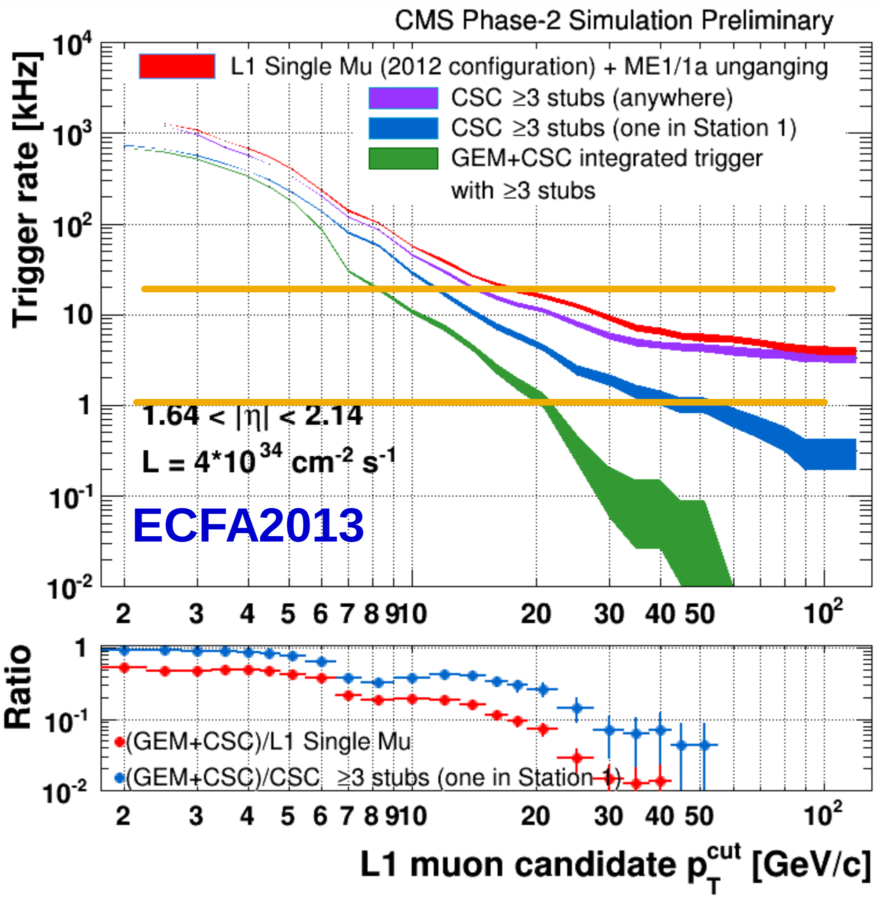


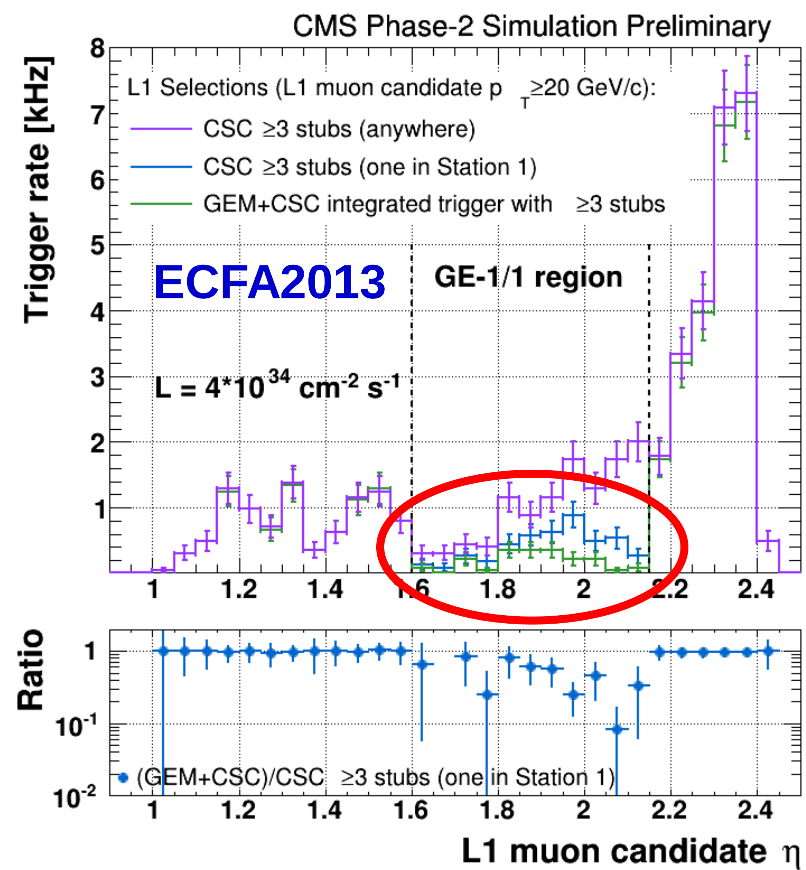
Bending angle in YE1-4

- Bending angle power of typical 10 GeV muon in endcap stations 1-4 between 2.14< eta < 2.4



Trigger rate plots for >=3 stubs





- Typical trigger rate reduction for 20GeV muon: **20kHz/cm2 to 1kHz/cm2**
- Preliminary results with not fully yet optimized trigger algorithm

Muon reconstruction with GEMs in CMS

- Realistic digitization and local reconstruction from a digital R/O are in place
- Implementation of GEMs into the seeding in ongoing (further improvements can come from this point)
- GEM recHits are successfully used in the STA muon fit, consequently GEM recHits are also involved in the GLB muon reco
- Special reconstructions: implementation of GEMs into the TeV muon special refits ongoing (important since we have seen improvements at high pT in the charge mis-ID probability and pT measurement)
- TO-DO: introduction of GEMs into the Tracker muon reco and study of the impact on the muon ID
- **Recent achievement:** Incorporated the full simulation chain for GE2/1 and ME0 in the CMS software (GE1/1 was already working)
  - Start producing signal and background samples for Muon Phase-II technical proposal
  - Start muon reconstruction efficiency studies with ME0