Enhancing the muon physics program of the CMS experiment during the high luminosity LHC with triple-foil GEM detectors in the forward region

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on behalf of the CMS Collaboration

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Outline

1 Motivation and background
   - GEM detectors background

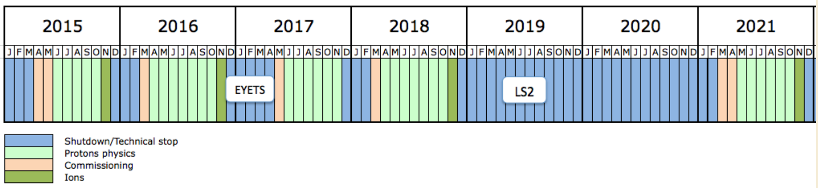
2 GEMs in CMS
   - GE1/1
      - Slice test

3 Summary

Motivation

LHC evolution

Following the upgrade of the LHC injector chain after Run 2, the LHC will begin the migration to a high-luminosity environment (instantaneous luminosity increasing from $2-5\times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)



This environment presents several challenges to the physics program of CMS

- Maintaining the low-p_T muon trigger rate
- Maintaining the performance of muon ID

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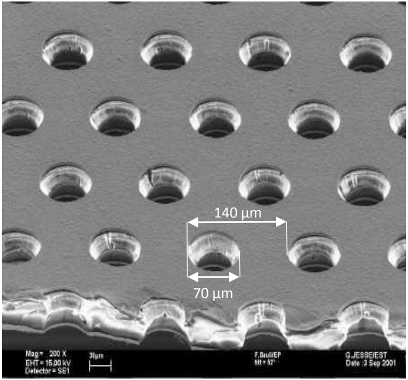
Physics impact

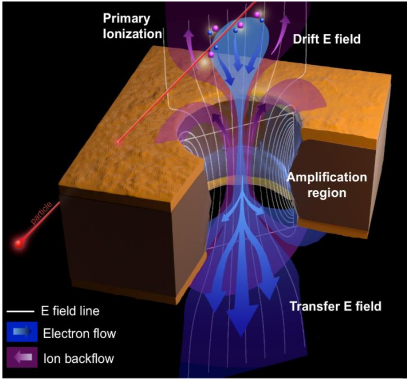
Many physics searches rely on being able to efficiently trigger on and reconstruct muons in the forward region with sufficiently low p_T

- $H \to ZZ \to \mu\mu$
- LFV, e.g., $\tau \to 3\mu$
- Long-lived particles decaying to μ's
- Compressed SUSY
- ...

GEM detectors background

Gas Electron Multiplier (GEM) detectors have a proven track record in HEP experiments and are an ideal choice for the CMS use case

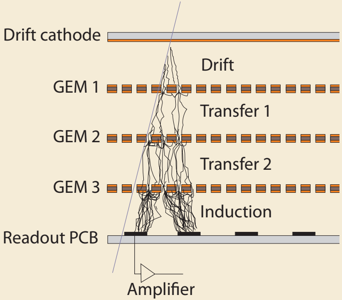




GEM detectors background

Gas Electron Multiplier (GEM) detectors have a proven track record in HEP experiments and are an ideal choice for the CMS use case

- Choice of triple-foil detectors
  - High operational gain (5×10^3 to 1×10^4) moderate voltage ($\sim$ 3500V)
  - Low discharge probability (10^{-12} to 10^{-11} per MIP)
- Small footprint
  - Fit into the available space
- Highly efficient as single chambers
- Excellent rate capability (up to $\sim 100\mathrm{MHz/cm^2}$)
- Excellent timing ($\sim$ 10*ns*) and spatial ($\sim$ 140μrad) resolution
- Robust against aging (after $3000\mathrm{fb}^{-1}$)



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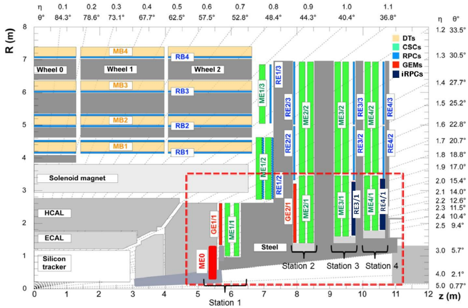
GEMs in CMS

Current detector

The CMS muon system is composed of three detector technologies used in concert: one primarily for trigger and timing (RPC), the second used for tracking as well as triggering (DT and CSC)

- DT+RPC in the barrel region ($|\eta| < 1.0$)
- CSC+RPC in the endcap region ($1.0 < |\eta| < 2.0$)
- CSC only in the forward endcap region ($2.0 < |\eta| < 2.4$)



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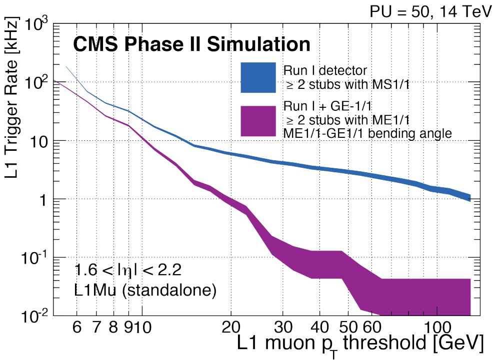

Challenges

- Lack of redundancy in the most forward region ($|\eta| > 1.6$) coupled with increased background rate and lower magnetic field
  - Potential degradation of particle ID performance
  - Increase in trigger rate for low p_T muons

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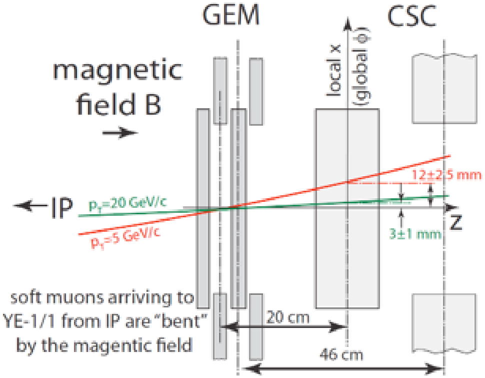

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  - Potential degradation of particle ID performance
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Goals for GEMs

- Increase the lever arm for improved high-p_T resolution in the first muon station
- Maintain acceptable trigger rate for low-p_T
- Increase redundancy

GEMs in CMS

- GE1/1, in the first muon station (coming from the IP) and closest to the beam pipe
  - 10 degree chambers, covering $1.6 < |\eta| < 2.2$
  - Approved for installation during LS2 (2019)
  - Demonstrator “slice test” installed during this past year end shutdown

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- GE2/1, in the second muon station, closest to the beam pipe
  - Quite similar to GE1/1, but in the second muon station, and covering $1.6 < |\eta| < 2.4$
  - Proposed installation during LS3 (2024)

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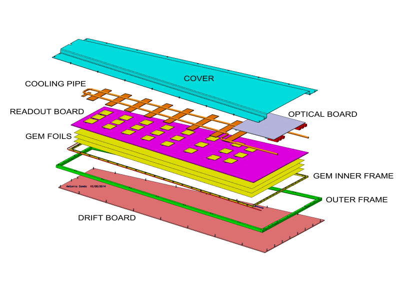
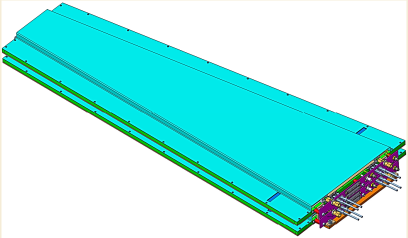
  - Quite similar to GE1/1, but in the second muon station, and covering $1.6 < |\eta| < 2.4$
  - Proposed installation during LS3 (2024)
- ME0, will be a new first muon station and closer to the beam pipe,
  - Providing coverage from $2.0 < |\eta| < 2.8$
  - Proposed design is a 6 triple-GEM sandwich
  - Proposed installation during LS3 (2024)

Chamber design

- Sandwich twin, 10° triple-foil, trapezoidal detectors together into a "GEMINI"

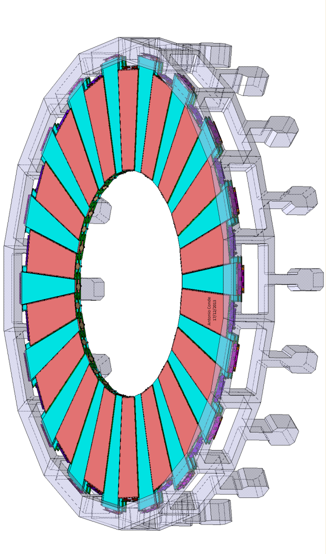




GE1/1

Chamber design

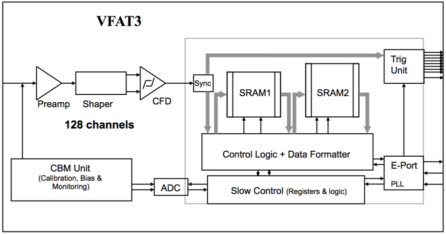
- Sandwich twin, 10° triple-foil, trapezoidal detectors together into a “GEMINI”
- Alternating “long” and “short” chambers



Readout system

- On-detector (front-end) electronics consist of:
  - 24 on-detector 128 channel digital ASICs (VFAT3)

VFAT3



- Preamp+Shaper+CFD to convert analog chamber signal to digital signal
- Trigger data transmitted synchronously with the LHC clock every 25ns
- Tracking data buffered and transmitted on receipt of L1A (possibility to zero-suppress)
- Slow controls and calibrations built-in
- Operating on a 320MHz clock (8$\times$LHC clock)

Readout system

- On-detector (front-end) electronics consist of:
  - 24 on-detector 128 channel digital ASICs (VFAT3)
  - On detector optical concentrator card (OptoHybrid V3)

OptoHybrid V3

- Virtex 6 FPGA for processing
- VTRx optical links for communication with off detector electronics
  - GBTx connects directly to VFAT3s elink
- VTTx optical links transmit trigger data

Readout system

- On-detector (front-end) electronics consist of:
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  - GEM electronics board

GEB

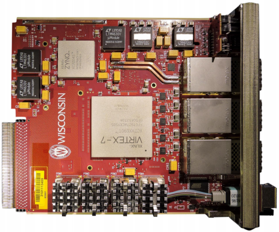
- Large (1.2m) PCB (split in two)
- Carries power to OptoHybrid and VFAT3s
- Routes signals between OptoHybrid and VFAT3s

Readout system

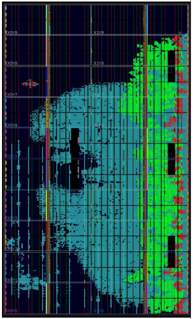
- On-detector (front-end) electronics consist of:
  - 24 on-detector 128 channel digital ASICs (VFAT3)
  - On detector optical concentrator card (OptoHybrid V3)
  - GEM electronics board
- Off-detector (back-end) electronics are µTCA based
  - AMC is a custom board built for the CMS trigger (UW CTP7)

CTP7

- Virtex 7 FPGA with Zynq SoC
- 36 Tx/Rx pairs plus additional 31 Rx+12Tx optical links (3×CXP, 1×MTP48)
- Handles event building, slow controls, fast controls (trigger/clock distribution to front-ends)
- One CTP7 can handle 12 OptoHybrids



CTP7 firmware with 36 GBT links



Green = GBT RX cores
Red = GBT TX cores (fixed latency)
The rest is mostly DAQ and Trigger

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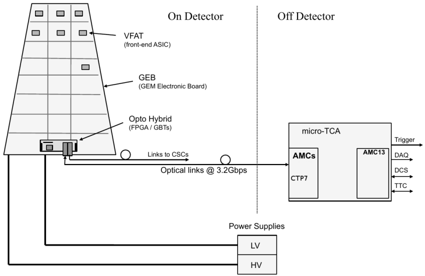
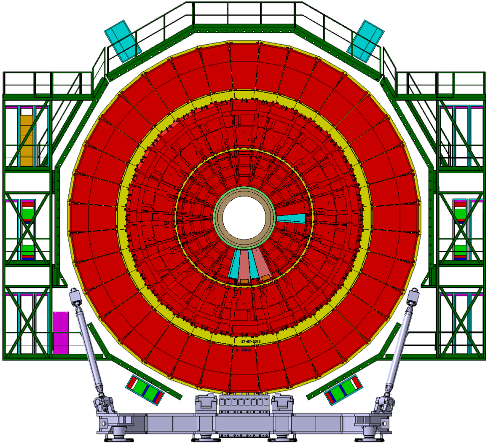
  - GEM electronics board
- Off-detector (back-end) electronics are µTCA based
  - AMC is a custom board built for the CMS trigger (UW CTP7)
  - CMS standard AMC13 to connect to central DAQ and trigger/timing control



GE1/1 slice test

In order to gain experience in installing and commissioning the system in CMS, 5 GEMINI have been installed during EYETS17

- Front-end electronics are prototype versions
    - VFAT2, OptoHybrid V2-B, GEB v2
- Back-end components are production versions
- Gaining experience with CAEN A1515 multi-channel HV board developed for GEMs



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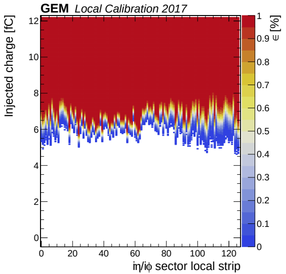
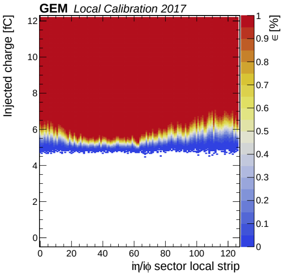
Initial results

- Calibration of the front-end chips and noise characterization
  - Using built-in calibration circuit
  - Left shows the response of one VFAT chip before applying any per-channel threshold trim adjustments
  - Right shows the response after applying per-channel adjustments





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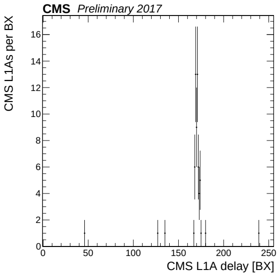
Initial results

- Calibration of the front-end chips and noise characterization
- Starting to time-in the system
    - Difference in time between the input trigger signal (CMS L1A) and the chamber trigger result (s-bit)
    - Counted in the on-chamber FPGA (OptoHybrid)
    - First time muons were seen by GE1/1 in CMS!



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Integration in CMS

- Control and safety software

Initial results

- Calibration of the front-end chips and noise characterization
- Starting to time-in the system

Progress

- DCS integration proceeding
  - FSM listens to LHC and CMS state
  - System has been operating stably

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- Back-end components are production versions
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Integration in CMS

- Control and safety software
- DAQ software

Initial results

- Calibration of the front-end chips and noise characterization
- Starting to time-in the system

Progress

- DCS integration proceeding
  - FSM listens to LHC and CMS state
  - System has been operating stably
- DAQ integration is next milestone
  - Local runs
  - “Stress” tests
  - Global runs

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Summary and Conclusions

- CMS will face challenges to maintain the quality of its physics program moving into the HL-LHC regime
- The choice of GEM detectors for the forward muon system helps to address several of these challenges
- The installation of the slice test has been successful
- Progress is being made to be integrated into the full CMS system
- The experience being gained is ensuring that the full system installation and commissioning will be smooth

Further documentation

GE1/1 TDR: `https://cds.cern.ch/record/2021453?ln=en`