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 $2 - 5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$).

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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
Motivation

LHC evolution

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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 $p_T$

- $H \rightarrow ZZ \rightarrow \mu\mu$
- LFV, e.g., $\tau \rightarrow 3\mu$
- Long-lived particles decaying to $\mu$’s
- Compressed SUSY
- ...
Gas Electron Multiplier (GEM) detectors have a proven track record in HEP experiments and are an ideal choice for the CMS use case.
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- **Choice of triple-foil detectors**
  - High operational gain ($5 \times 10^3$ to $1 \times 10^4$) moderate voltage ($\sim 3500$V)
  - 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 $\sim 100$MHz/cm$^2$)
- **Excellent timing** ($\sim 10$ns) and spatial ($\sim 140\mu$rad) resolution
- **Robust against aging** (after 3000fb$^{-1}$)
1. Motivation and background
   - GEM detectors background

2. GEMs in CMS
   - GE1/1
     - Slice test

3. Summary
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 \( (2.0 < |\eta| < 2.4) \)
GEMs in CMS

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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

![CMS Phase II Simulation](image)

PU = 50, 14 TeV

L1 trigger rate vs. L1 muon $p_T$ threshold

Run I detector
- ≥ 2 stubs with MS1/1
Run I + GE-1/1
- ≥ 2 stubs with ME1/1
ME1/1-GE1/1 bending angle
GEMs in CMS

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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-$p_T$ muons
- Increase redundancy
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
GEMs in CMS

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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)
GEMs in CMS

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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”
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×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

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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
Readout system

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- 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
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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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
Outline

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3 Summary
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.
Backup

Further documentation

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