Large-size triple GEM detectors for the CMS forward muon upgrade

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The CMS Muon System

3 technologies:
- Drift Tubes and Cathode Strip Chambers (for tracking and triggering)
- Resistive Plate Chambers (for triggering)

Goals:
- Robust, redundant and fast identification of the muons traversing the system
- Trigger capabilities and momentum measurement

Eta coverage:
- $|\eta| < 1.6$: 4 layers of CSCs and RPCs (ME4/2 and RE4 being installed during LS1)
- $|\eta| \geq 1.6$: CSCs only

New technology needed for $|\eta| > 1.6$ region of muon system
- Present CMS RPC design not suitable for high rate environment
- Sustain $O(MHz/cm^2)$ environment
- Need for good spatial resolution $O(100\mu m)$: muon tracking
- Need for good time resolution: muon triggering

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Muon Trigger Performance

Forward region trigger relies entirely on the CSC system (4 ME stations)

- Muon momentum from stub positions: \( \Delta \Phi_{xy} = \Phi(\text{ME-X}) - \Phi(\text{ME-Y}) \)
- Measurement driven by internal chambers (ME1/1, ME2/1): least scattering and strong B field
- Resolution using outer stations is quite coarse (not enough bending)

Muon trigger issues

- High background rates in forward region: trigger rate is dominated by junk muons reconstructed as high \( p_T \) muons (multiple scattering of soft muons in the iron yoke flattens the trigger rate curve)
- Muon trigger stub losses drive inefficiency
  - Dead electronics, spaces between chambers, but also algorithmic losses
  - Especially undesirable in station ME1/1, which is key for momentum resolution
Physics motivations

Muon system is critical for both bosonic and fermionic couplings:

- $H \rightarrow WW$ and $ZZ$ are key to the precision measurement of $H \rightarrow VV$ couplings. In particular:
  - $H \rightarrow ZZ \rightarrow 4\mu$:
    - 20% of signal events falls in the eta region from 1.6 to 2.1 and can benefit of the improved muon detection
    - Gain up to 40% in signal selection efficiency with extension up to $|\eta| = 4$
  - $H \rightarrow \tau\tau$ is key for measuring fermion couplings
    - $H \rightarrow ff$
      - $\mu + \tau_{\text{had}}$ is the most sensitive channel, fully relies on muon trigger
      - Fast falling muon momentum spectrum: requires an efficient muon trigger

Delphes: muon detector coverage extended from $|\eta| < 2.4$ to $|\eta| < 4.0$
**GOALS**

- **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 $|\eta| = 2.4$
- **Ensure maximum trigger efficiency** in high PU environment
- **Increase offline muon identification coverage** up to $|\eta| = 3$ (calorimeter limit)

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

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**The GEM Project**

**GEM features:**
- **Rate capability:** $10^5 \text{Hz/cm}^2$
- **Spatial/Time resolution:** $\sim 100 \mu\text{m} / \sim 4-5 \text{ ns}$
- **Efficiency:** $> 98$
- **Typical Gas gain:** $>10^4$

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LHC and detector evolution

Background (from FLUKA + GEANT4):

- Hadronic interactions lead to activation of materials and give rise to neutron backgrounds
- Long living neutrons can interact with nuclei and produce photons which further decay to electrons/positrons with some possibility to generate fake signals
- Background rates expected in each chamber normalized to $5 \times 10^{34}$ Hz/cm²
The GEM Project

GE1/1: baseline detector for GEM project

- $1.55 < |\eta| < 2.18$
- 36 staggered super chambers, super-chamber (2 layers), each chamber spans 10°
- Several prototype designs with different number of eta partitions
- **Short** and **long** super chambers for maximum coverage in pseudo-rapidity

GE2/1: station 2 upgrade

- $1.6 < |\eta| < 2.49$ - Chambers spanning 20°
- Looking into possibility of installing 2 rings of two layers of 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
- $2.0 < |\eta| < 3.0$ - 20° chambers
- Additional 6 points of measurements extending in high eta (for neutron background rejection): **R&D on-going**

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Large GEM prototype evolution

The CMS GEM collaboration has undertaken a 5-year long R&D process:

- Test of performance on small prototypes
- Development of 5 generations of large-area GEM prototypes
- Intense prototype testing on bench top and in beam tests

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.

- Small 10cm x10cm triple-GEM prototype
- From small to large area prototypes (more details in the backup slides)
GE1/1 detector layout

Main detector layout features:

- Single-mask (for etching, see backup)
- Gap sizes: 3/1/2/1 mm
- Sectors: 3 columns x (8-10) η partitions
- Strip pitch: 0.6-1.2mm (trapezoidal chambers)
- 1D readout with 384 channels

Self-stretching assembly (NS2):

- Tightening the horizontal screws tensions the GEMs & seals gas volume
- Allows re-opening of assembled detector for repairs if needed
- Assembly time reduced (2 hours)

Link to the video showing the assembly of a GE1/1 chamber:
https://twiki.cern.ch/twiki/pub/MPGD/GEMDetectorProduction/Assembly_video_compressed_into_1min.mp4

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GEM project achievements

Performance from testbeams

- Detector efficiencies: > 98% + Time resolution: ~4ns
- Spatial resolution of about 276μm with VFAT2 (digital) and < 104μm APV (analog) readout chip
- Operation of GEMs in magnetic field
- Gas mixture: Ar/CO2/CF4 (45/15/40)
- Rate capability: ~10^5 Hz/cm²
- Good performance in test-beams at CERN SPS/FNAL

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GEM project achievements

**Technology and assembly**

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

**Integration**

- Successful trial installation of dummy super chambers 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 1\textsuperscript{st} set in Summer 2013
- Trial installation of 2\textsuperscript{nd} set (short and long chambers) in March 2014

**Installation of GE1/1 foreseen during LS2**

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Impact on the trigger: bending angle

- Additional GEM detector in front of ME1/1 can measure muon bending angle in magnetic field
  - CSCs are too thin (11 cm) to see the bend with sufficient resolution (< 2 mm or better) to discriminate 5 GeV/c from 20 GeV/c muons
  - GE1/1 increase lever arm (from 20 to 46 cm)
  - Rate reduction with GEM-CSC bending angle

- GE1/1-ME1/1 bending angle provides clear separation of hard and soft muons
  - GEM-CSC bending angle power in ME0 is of the same order
  - GE2/1 has less bending angle power (weaker B field)
  - More details can be found in the poster by Raffaella Radogna: “Motivation of the CMS Muon System Upgrade with Triple-GEM detectors”

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Impact on the trigger: rate

CSC only: at least 2 CSC stations with hits + presence of a track in ME1/1:
- Muon L1 rates increase with $|\eta|$, as the momentum resolution decreases

GEM+CSC integrated local trigger (GEM hits as additional input for CSC stub generation):
- Improve the momentum resolution and reject background without much loss of efficiency
- Typical trigger rate reduction for 20GeV/c muon: 20kHz/cm² to 2kHz/cm²

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Summary & Conclusions

- CMS GEM Project started in 2009 in collaboration with RD51
- Present scope of the project includes new GE1/1, GE2/1 and ME0 stations
- Triple-GEMs provide a suitable solution for the CMS muon trigger and tracking needs in the LHC Phase-II era
- Good performance in test beams:
  - Detector efficiencies: ~98%; Time resolution: ~4ns
  - Spatial resolution of about 276μm with VFAT2 (digital)
- Design of the GE1/1 chambers for installation in CMS close to final
  - Production and test of 10 full-size GE1/1 chambers
- During LHC 2016-2017 Year-End Technical Stop two triple-GEM super chambers will be installed inside CMS, in YE1/1
- Full GE1/1 installation during LHC LS2 possible
  - 5 production sites being readied
- Preparing CMS (Muon) Phase-II Technical Proposal and GE1/1 Technical Design Report to be submitted to LHCC (late 2014)
Large-size triple GEM detectors for the CMS forward muon upgrade
Gas Electron Multipliers

- **Rate capability:** $10^5$Hz/cm$^2$
- **Spatial/Time resolution:** ~ 100 $\mu$m / ~ 4-5 ns
- **Efficiency:** > 98%
- **Gas Mixture:** Ar/CO2/CF4 (45/15/40), non flammable
- **Typical Gas gain:** >$10^4$
- **Radiation hardened**

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- **GEM foils developed using PCB manufacturing techniques**
- **Large areas:** ~ 1m x 2m with industrial processes (cost eff.)
- Each foil (perforated with holes) is 50$\mu$m kapton sheet with copper coated sides (5$\mu$m)
- **Typical hole dimensions:** Diameter = 70$\mu$m, Pitch = 140$\mu$m
GEM foil production

Single-mask technique:

- Overcomes the problems with the alignment of the masks
- Gives great control over the dimensions and size of GEM holes
- GEM are compatible with industrial production
- Price reduction for GEM foils is expected
Triple-GEM small prototype

Small 10x10 cm triple-GEM tested with 150 GeV/c μ/π beams @ CERN SPS (2010-2011)

- Standard double-mask technique
  - 128 strips with 0.8 mm pitch
- Two different gap size configurations
- Different gas mixtures
- Single-mask technique
  - 256 strips with 0.4 mm pitch

- Timing studies
- Validation of Single-Mask technique

Main results from test beams:

- Different gap size configurations had no visible effects
- ~4 ns with the Ar/CO2/CF4(45:15:40) gas mixture reached
- Best detector with a 3/1/2/1 mm gap size configuration
- Rate capability of over 10 kHz/mm²
- All single-mask performances are similar to the standard double mask triple-GEM.
GEM foil production

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Impact on the trigger: additional plots

- Comparison of the trigger rates for the Global Muon Trigger in the 2012 configuration with the CSC Track-Finder track rates for at least 3 stubs (loose) and at least 3 stubs with at least one 1 stub from ME1/b and a GEM pad (tight)

- Comparison of GEM-CSC bending angle for muons with low $p_T$ and high $p_T$ for even (close) numbered chambers

- Reduced lever arm w.r.t. the far chamber case → reduced separation power
Production sites

CERN: TIF (186)
Production, Final QC, SC assembly
Installation in CMS
Common chamber production and certification protocols, including production database, for all sites

USA
Florida Tech

Italy
Bari
LNF

India
BARC

Belgium
Gent