New micropattern gas detectors for the endcap muon system of the CMS experiment at the high-luminosity LHC

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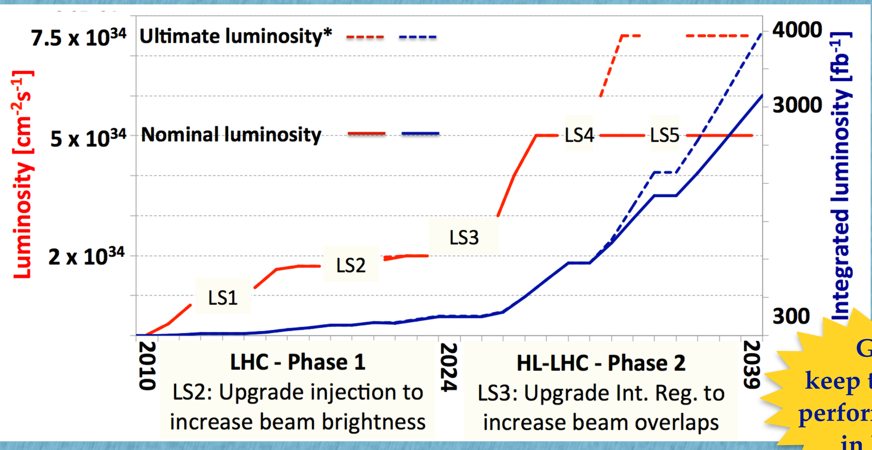
ICHEP2016: The 38th International Conference on High Energy Physics, 3-10 Aug 2016, Chicago, IL (US)

For the era of the high-luminosity LHC, new detectors are planned to enhance the performance of the endcap muon system of the CMS detector. We report on two types of these detectors that will be installed during the third long shutdown (LS3) of the LHC. In the pseudo-rapidity region $1.6 < |\eta| < 2.4$, new triple-foil large-area gas-electron multiplier (GEM) detectors will be installed in the third of five detector stations in each endcap, the first station being closest to the interaction point. These GEM detectors are in addition to ones that will have already been installed in the second station during LS2. We present a design for the third station detectors that must cover a larger geometrical area than those in the second station, while maintaining good performance for efficiency and spatial resolution. A new innermost (first) detector station will be installed in the endcaps to extend the range of muon identification up to about $|\eta| = 3.0$. We describe the geometrical constraints and particle fluxes at the first station. The detector technologies under consideration include fast-timing micropattern (FTM) structures that can tolerate large particle fluxes and provide good time resolution. FTM detectors employ multiple layers of resistive-coated kapton foils with either hole or mesh electron multiplication structures. We report on the performance of prototype FTM devices for efficiency, space and time resolution measured using X-rays, cosmic-ray muons, and extracted high-energy particle beams.

CMS Upgrade towards HL-LHC



- New tracker (4 pixel layer +3 disks), Track info at L1
- Calorimeters with higher granularity
- Enhancement of Muon endcap

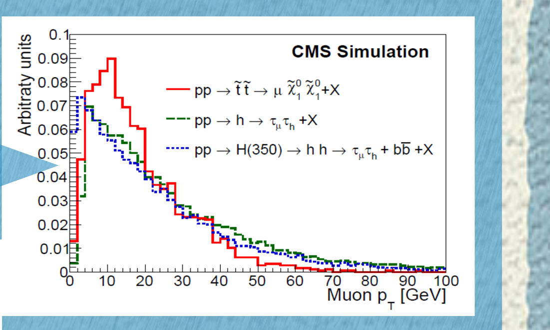
Goal: keep the same performance as in Run1

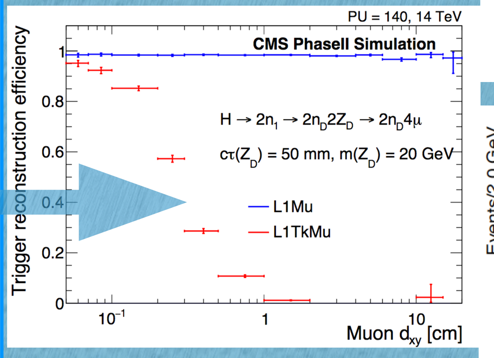
The forward region $|\eta| \geq 1.6$ is very challenging

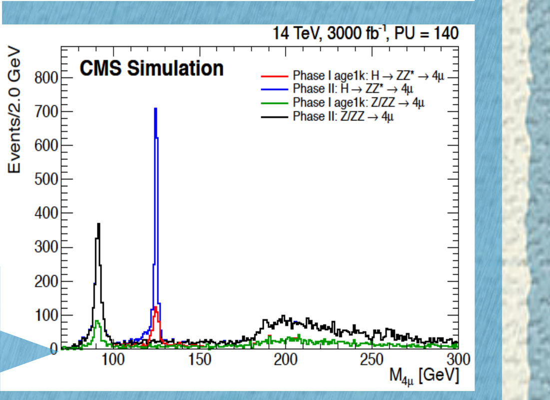
- **Redundancy**: the highest rates in the system vs fewest muon layers
- **Rate**: higher towards higher η and worse momentum resolution, already a challenge for post LS2
- **Detector longevity:** Accumulated charge ~C/cm after many years of LHC operation
- **Electronics longevity:** High occupancy/rate and latency exceeding the capabilities of the existing electronics

Physics motivation for muon upgrade

- Keeping low muon trigger thresholds has a large impact on physics that relies on triggering on a soft muon: Higgs, SUSY scenarios
- Preserving sensitivity to physics with displaced muons, from decays of long-lived new particles, relies on ultra-high purity standalone muon
- Increasing significantly the acceptance by extending the muon detector coverage to larger η values is visible



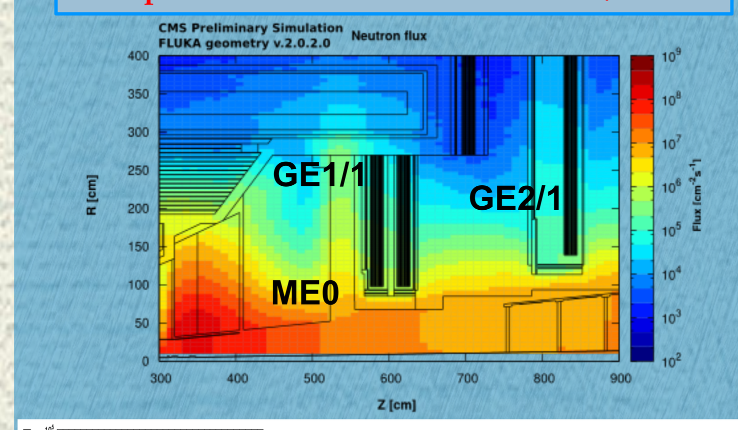


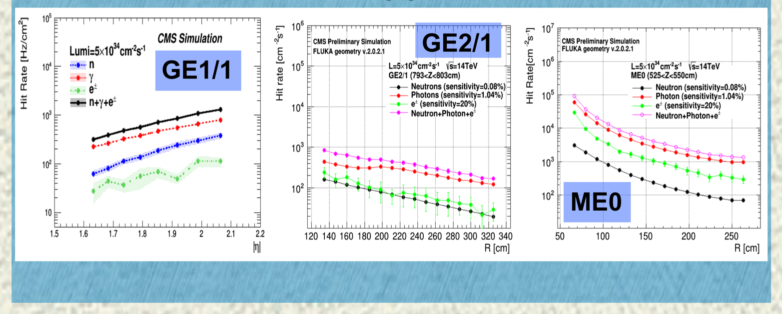


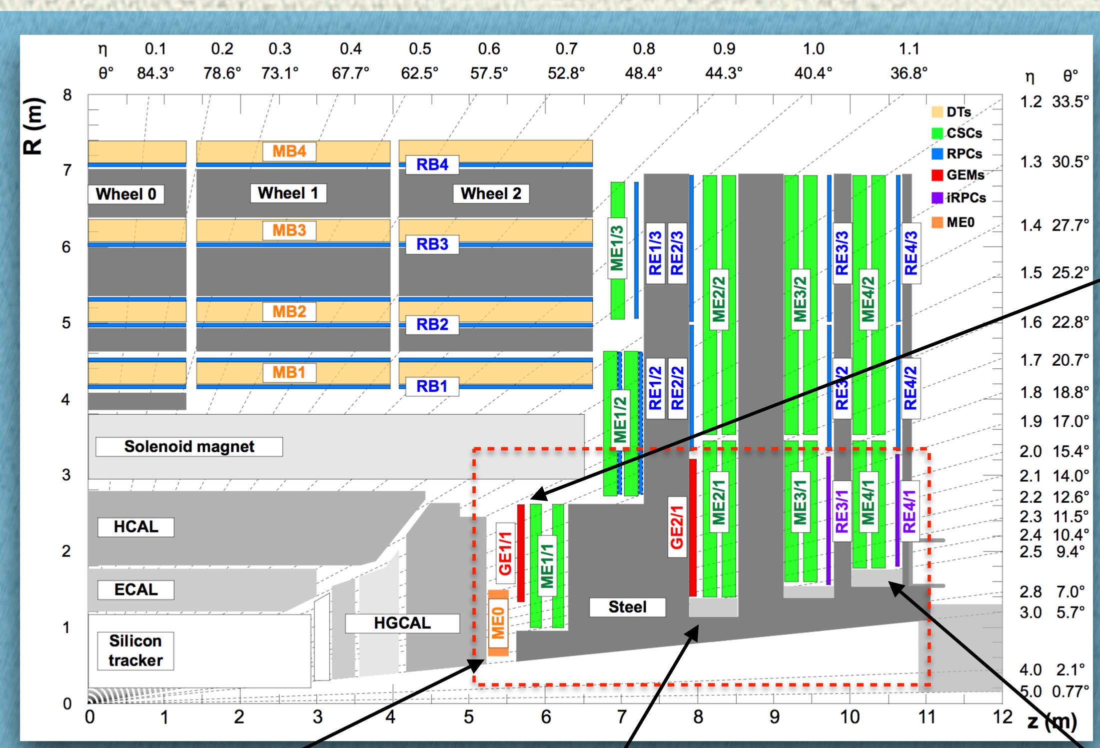
The neutron background in the forward region

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.

- very high flux: low detector sensitivity to the neutron and photons required
- Expected hit rate 250 Hz – 100's kHz/cm²







Forward muon system enhancement

GE1/1

Trigger and reconstruction

- $1.6 < |\eta| < 2.2$
- **Baseline detector for GEM project**
- 36 super-chambers (SC) per endcap, each super-chamber spans 10°
- One super-chamber is made of 2 back-to-back triple-GEM detectors
- **Installation: LS2 (2019-20)**

ME0

- **Muon trigger and reconstruction** at highest η
- each chamber spans 20°
- 6 layers of GEM-like technology

Further improvement: fast timing MPGD - fully resistive multi-layer design for background and pileup (PU) rejection

GE2/1

Trigger and reconstruction

- $1.55 < |\eta| < 2.5$
- 18 SC per endcap, each chamber covers 20°
- 2 layers of GEM-like technology

Further optimization: μ-R-Well as compact and low cost large detector

RE 3/1 – RE4/1

Trigger and reconstruction

- $1.8 < |\eta| < 2.4$
- 18 chambers per endcap, each chamber spans 20°
- 1 layer (per station) RPC-like technology

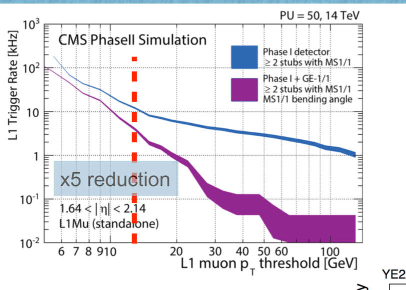
Further performance improvement: multi-gap provide high time resolution for background and pileup (PU) rejection

Forward Muon Trigger Performance

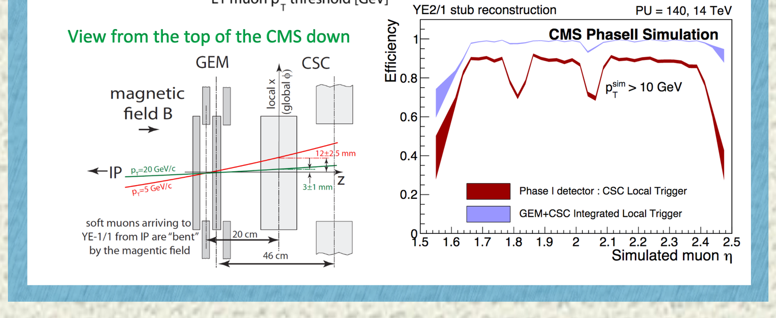
Forward trigger for $|\eta|>1.6$ relies entirely on the CSC system

Adding detector in front of CSC to measure the muon bending angle in magnetic field in the each station, keeps the rate under control and adds redundancy:

- ✓ Large improvement from GE1/1 and GE2/1 stations
- ✓ Requirement: precise $\Delta\phi$ measurement and then good spatial resolution



Maintain 15 GeV online threshold, keeping < 5 kHz rate, high efficiency



Generation I (GE1/1-I, 2010): The first 1m-class detector ever built but still with spacer ribs and only 8 sectors total

Generation II (GE1/1-II, 2011): First large detector with 24 readout sectors (3x8) and 3/1/2/1 gaps but still with spacers and all glued.

Generation III (GE1/1-III, 2012): The first sans-spacer detector, but with the outer frame still glued to the drift.

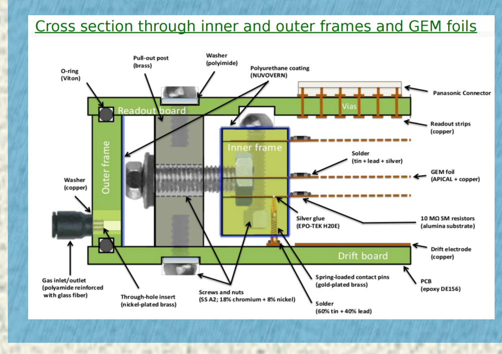
Generation IV (GE1/1-IV, 2013): First detector with complete mechanical assembly.

Generation V (GE1/1-V-S, 2014): Very close to what we will install in CMS. Features re-designed stretching apparatus that is now totally inside gas volume.

Generation VI (GE1/1-VI-L, 2015): Latest detector design. Optimized final dimensions for maximum acceptance and final η segmentation.

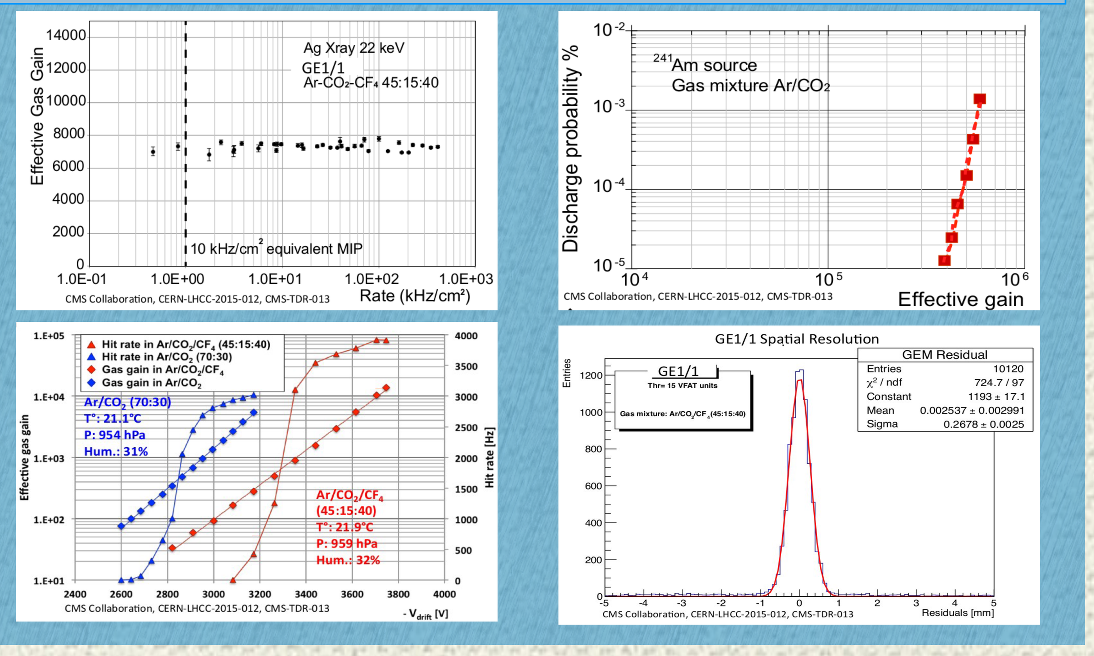
Cross section through inner and outer frames and GEM foils

- GEM foil production uses single mask technology for wet etching
  - Dramatically reduces foil production costs and allows large sizes to be manufactured
- Performance same as that of double mask
- Mechanical self-stretching technique developed
  - Construction time reduced to few hours
  - https://www.youtube.com/watch?v=Ssugh5GAVZ4&feature=youtu.be

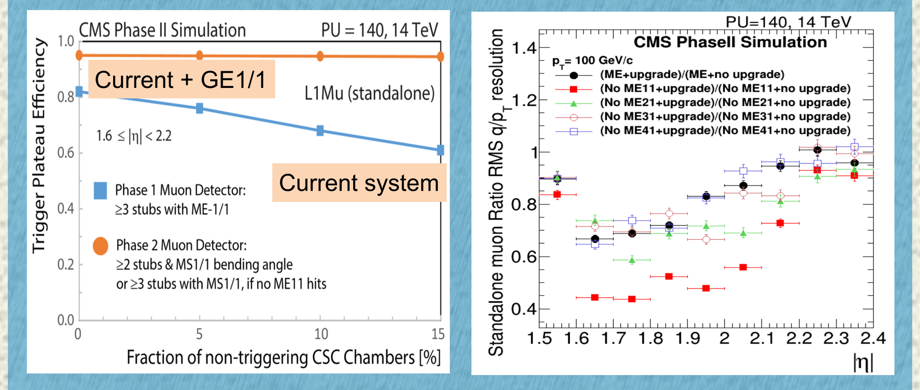


GEM Detector optimization & performance

Triple-GEM technology perfectly meets the requirements imposed by the HL-LHC



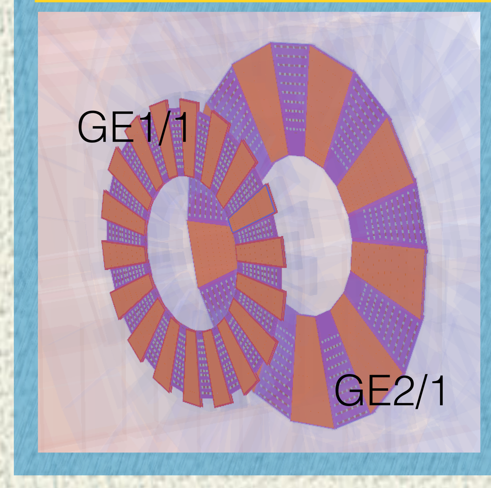
Longevity & Redundancy



Potential degradation in performance due to the aging of CSC chambers is a concernRedundancy assured by the GEM helps in:

- Reducing the deterioration of Level-1 muon trigger performance
- Reducing the large degradation in momentum resolution
- Mitigating otherwise large efficiency losses if a sizeable fraction of CSC chambers becomes partially or fully irresponsive

The GE1/1 and GE2/1 design



GE1/1 layout:

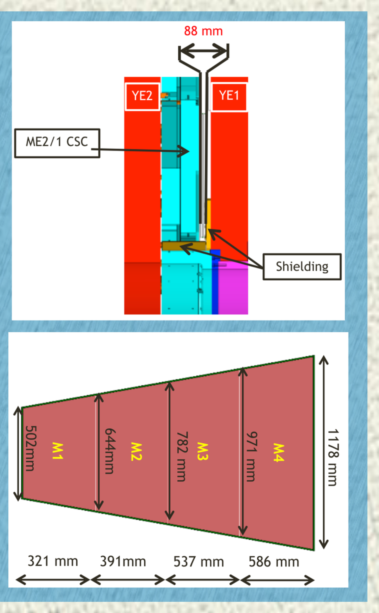
- Size: 1-1.2 × 0.22-0.45 m²
- Single–mask GEM foil × 3
- Gap configuration: 3/1/2/1 mm
- Readout sectors 3 × 8 in ϕ-η plane
- Total channel count: 3072

GE2/1 layout is similar to GE1/1, but covering much larger surface:

- Very challenging!

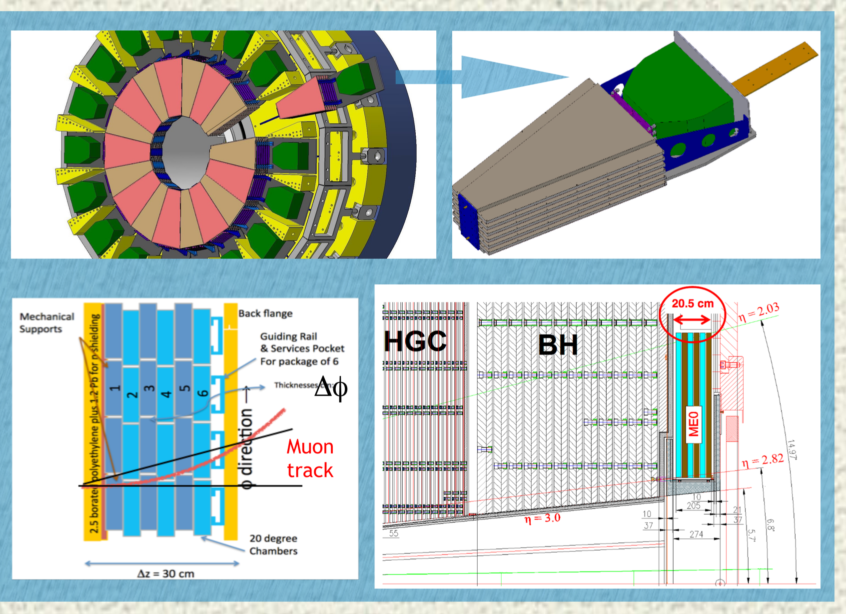
Engineering challenges:

- Very thin: only 81 mm width
- Need to splice 2-4 GEM foils together to build a chamber
- Four independent detectors to be coupled together



The ME0 design

- ME0 extends muon coverage behind the new endcap calorimeter to take advantage of the pixel tracking coverage extension
- High granularity to allows:
  - p_T assignment through $\Delta\phi$ measurement
  - to improve pile-up rejection
- Multi-layered structure allows to:
  - improve local muon reconstruction
  - discriminate muons against neutrons
  - have precision timing to reduce in-time PU
- Endcap calorimeter constrains space available

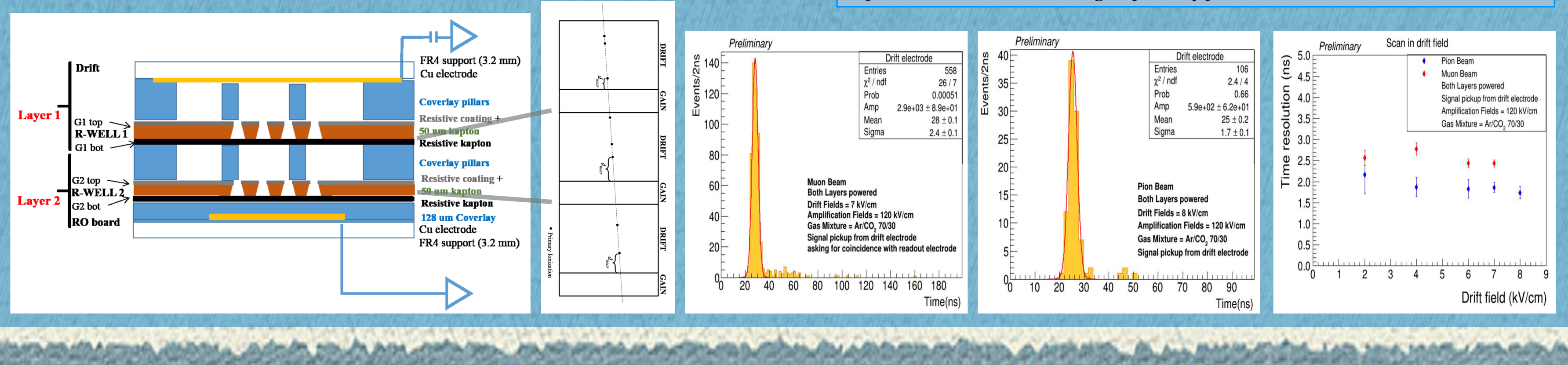


Multi-gap of drift and full resistive WELL amplification stages:

- The overall structure is spark free and transparent to the signal
  - Signals picked up by the external electrodes
- Increase in time resolution thanks to:
  - Competition of ionization processes in different drift volumes
  - Decrease of the arrival time of the nearest ionization to any multiplication volume
  - Decrease in the fluctuations

The next MPGD architecture

Test beam with muon and pion beams focusing on the time resolution measurement: time resolution ~2ns, good agreement with the expectations for a two stages prototype



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