# Simulation of the CMS GEM system

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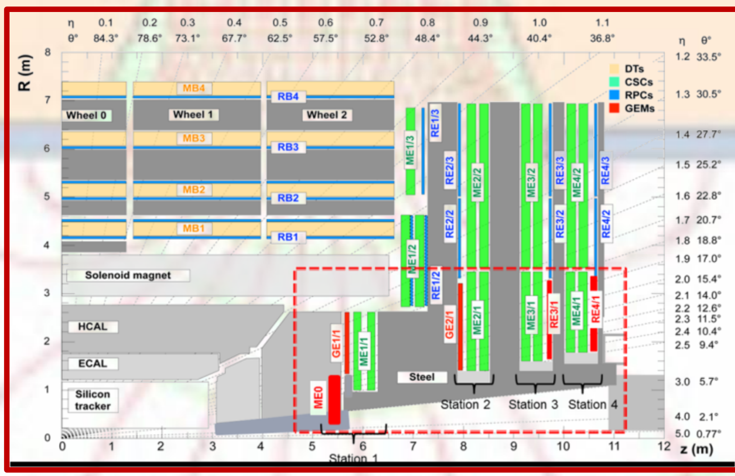
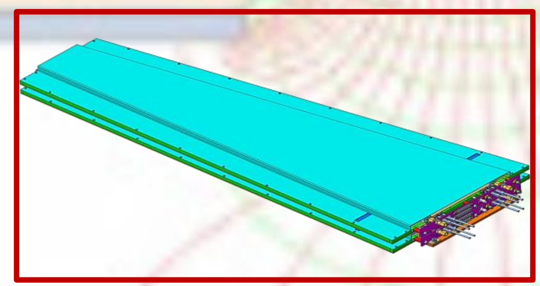
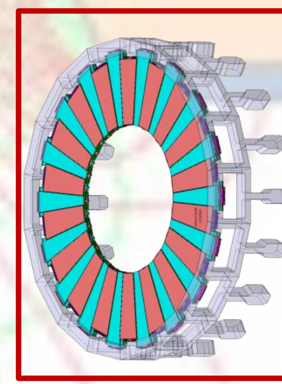
# Outline

- Introduction
- Motivation
- Simulations of the long lived backgrounds
- The Parametric Model
- Reconstruction and Detector performance
- Summary

# Introduction

- The new GE1/1 system of Gas Electron Multipliers (GEM) is going to be installed in the CMS detector in the forward region of $1.6 < |\eta| < 2.2$ after the second long LHC shutdown. 36 super-chambers are planned to be installed in order to ensure the redundancy and robustness of the muon system in high-luminosity conditions at the LHC.
- The simulation of the entire GEM system integrated in the common CMS reconstruction chain is a necessary part of the performed Monte Carlo studies.
- A dedicated parametric model based on the exhaustive standalone MC studies and experimental test beam results has been developed in order to simulate the response of the GEM system. **The model uses four main parameters – efficiency, cluster size, timing and rate parameter which include the information for the neutron induced background and intrinsic noise.**



**(Left) :** Schematic view, in the R-z plane, of one quadrant of the CMS detector, with the axis parallel to the beam (z) running horizontally and the radius (R) increasing upward. The interaction region is at the lower left corner. **(Middle):** A pair of GEM chambers form a superchamber **(Right):** Long and short chambers are combined with regards to the mechanical constraints.

# Motivation

- In the high luminosity era, introduction of the GE1/1 is going to addresses the following issues.

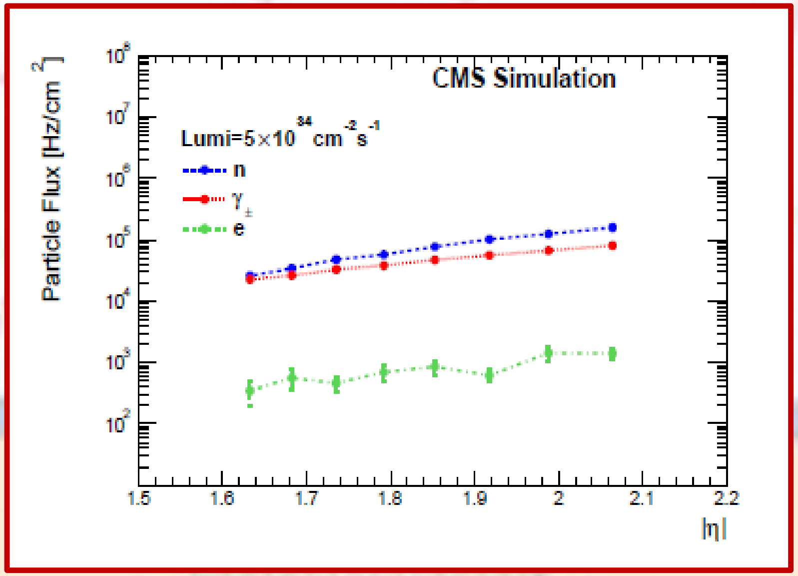
- **Maintaining a robust muon trigger:** GE1/1 allows maintaining a robust muon trigger the in the full range of current muon coverage at the higher luminosities.
- **Redundancy of muon system:** Introduction of GE1/1 strengthened the redundancy of the forward muon region by reducing any performance losses if parts or the entire CSC chambers become inoperable.
- **Impact on physics scenarios:** GE1/1 helps in maintaining the **low muon thresholds** which has an impact on some important physics channels whose sensitivity depends on the low muon trigger thresholds including some “compressed scenarios” in various flavors of SUSY, SM measurements in $h \to \tau\tau \to \mu+X$ or resonant production of Higgs boson pairs

# Simulations of the long lived background

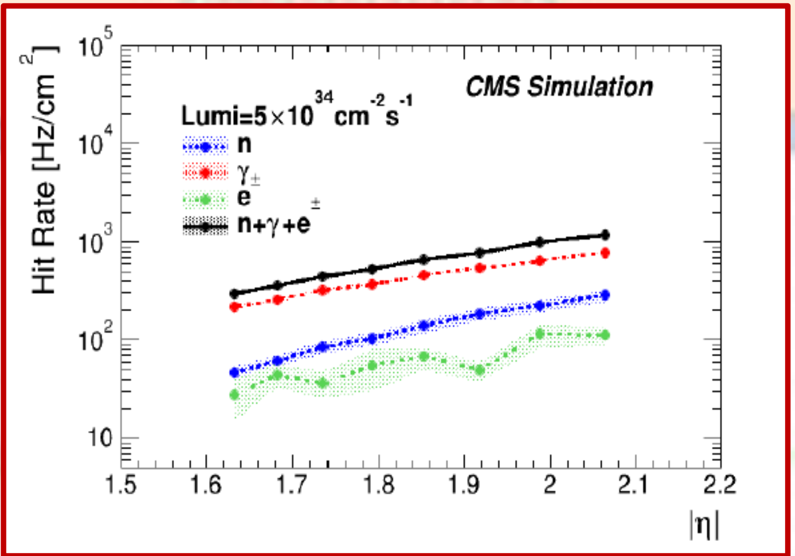
- The study of radiation environment plays an important role in selecting the detector technology and design.
- Neutrons and secondary particles (arising from neutron interaction with matter) are the dominant contributor to CMS cavern backgrounds, which determine hit rate and occupancy in the muon detectors.
- Because of a cut-off implemented in CMSSW on propagation time of particles (which reduces significantly the CPU time required to generate events), the standard CMSSW workflow does not allow simulating the long-lived backgrounds in one go with the particles originating from a p-p collisions.
- Inclusion of the long-lived background contribution in CMSSW is performed by first evaluating particle fluxes with CMSSW adaption of FLUKA package convoluted with the parameterization of the GE1/1 detector response obtained using a dedicated GEANT simulation study.

# Cont....

- Predicted flux of neutrons (blue), photons (red) and electrons (green) for GE1/1 region as a function of pseudorapidity η with a beam energy of 7 TeV normalized to an instantaneous luminosity of 5 X $10^{34}$ $cm^{-2}$ $s^{-1}$



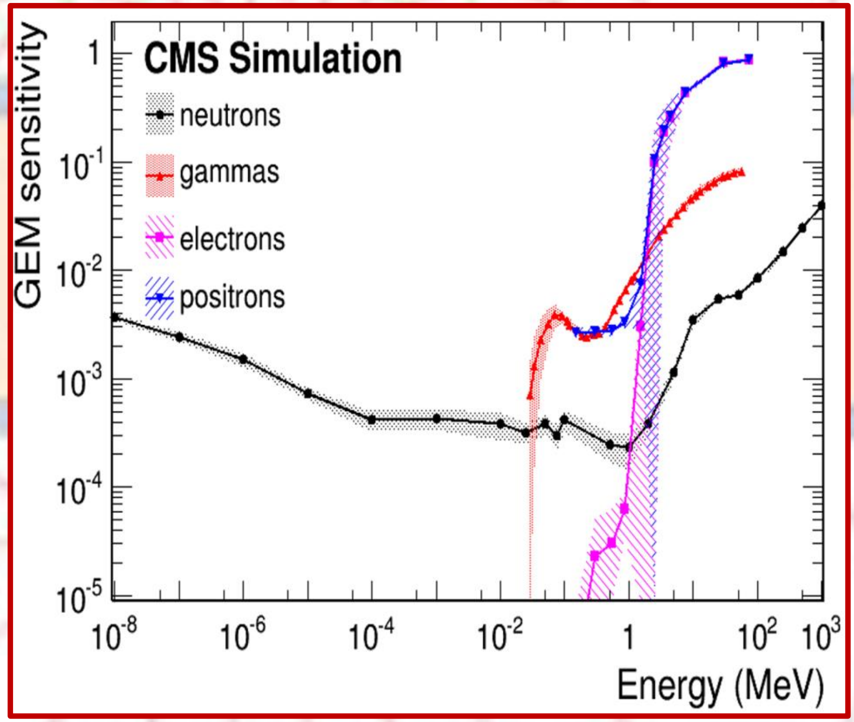

- Expected contribution to the GE1/1 per-chamber hit rate associated with backgrounds induced by long-live neutrons for an instantaneous luminosity of 5 X $10^{34}$ $cm^{-2}s^{-1}$ as a function of peudorapidity η. Each contribution is calculated as particle flux (top figure) weighed by corresponding average sensitivities (explained on next slide)




**** Photons and electrons produced from the neutron interactions in the material surrounding the enclosure that the GE1/1 chambers will be installed in***

# Cont……

- **Detector Sensitivity:** probability to generate a spurious signal in the detector for a given type of particle
- The sensitivity of the GEM chambers to neutrons, photons, electrons and positrons is evaluated using GEANT.



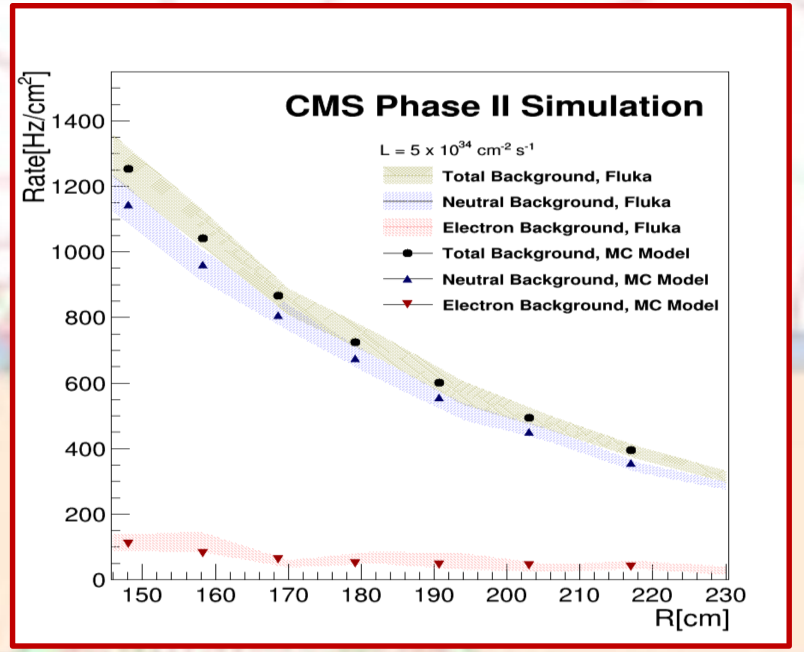

| | Averaged Sensitivity [%] |
|---|---|
| Neutrons | 0.18 ± 0.05 |
| Photons | 0.97 ± 0.04 |
| Electrons | 8 ± 3 |
| Positrons | 8 ± 3 |

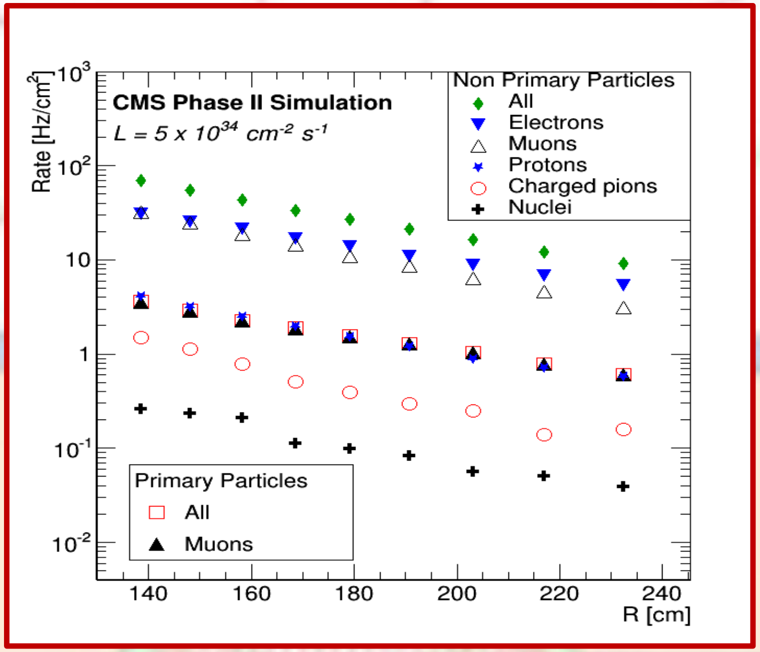
**Left plot:** Energy-dependent sensitivities as a function of the incident particle energy with bands indicating total uncertainty **Right table:** Average sensitivities with uncertainties Including both statistic and systematic uncertainty related to the different response of two layers of chambers installed in a even and odd configuration

# The Parametric Model - Background

- **Neutron-induced backgrounds:** Modelling of the long-lived backgrounds is implemented following the results of the simulation-based hit rate estimation described in previous slides. The embedding of the spurious signals due to photon, neutrons and charged particles follows the parametrized η-dependent functions described by fitting the distributions obtained from standalone simulations.
- **Backgrounds from prompt particles:** coming from secondary electrons and positrons arising from Compton scattering, secondary ionization, conversions and $e^+e^-$ pair production. Secondary muon contribution comes from nuclear interaction of hadrons in calorimeter and absorber, heavy flavor and decays in flight. Prompt backgrounds are simulated within standard CMSSW.
- **Intrinsic Noise:** Intrinsic noise rate estimated from test beam results ~0.01 $Hz/cm^2$ and hence neglected.

# Cont….




**Left:** GE1/1 Hit rate obtained due to neutron induced backgrounds with CMSSW simulation (data points) compared with FLUKA prediction used to model these backgrounds in CMSSW. (width of the band shows uncertainty) **Right:** Rates of prompt particles reaching GEM detector planes in the first endcap station as a function of the radial distance from beam pipe. As expected, contribution to the total rate due to prompt particles is substantially smaller compared to the one arising from long -lived neutrinos (on left plot).

# The Parametric Model: Efficiency and Timing

## - Efficiency:

➔ The GEMs are considered to have 98% efficiency for a registration of passing muons based on test beam results.

➔ The efficiencies for other particles are taken according to estimated sensitivities as a function of the particle energy (slide 7).

## - Timing:

➔ The timing parameter refers to the time of flight of the particle travelling with the speed of light from the interaction point of the CMS detector to the centre of a given GEM detector. The corresponding BX window is associated to a particular event taking into account the signal propagation time along the electrodes (strips) and the detector time resolution.

➔ The time resolution is simulated according to a Gaussian distribution with mean 0 and sigma 5 ns.

# The Parametric Model: Cluster size

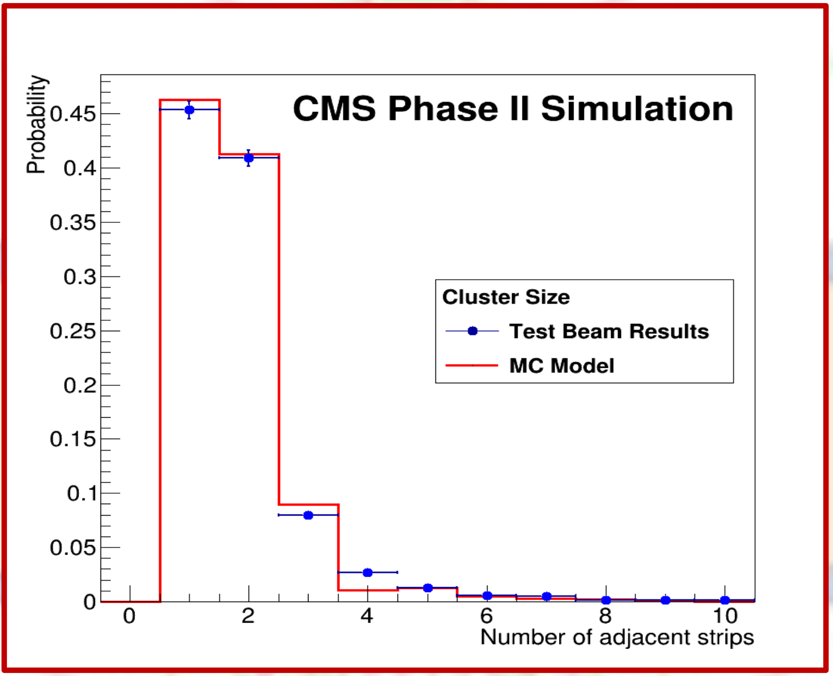
- **Cluster Size:**

- **Def.**- the number of adjacent strips fired in response of the passage of a charged particle through the detector

- Measurement of cluster size

**(a)** Cluster size measured at HV point where the GEM chamber reach the maximum efficiency using test beam data is 1.8.

**(b)** the probability of a given cluster size has been evaluated from the experimental data and used to model the number of simulated adjacent fired strips.




**Comparison of the cluster size distribution obtained with simulations (red) and with the test beam measurements (blue)**

# Reconstruction and detector performance

## Few Definitions:

**Quality:** The number of muon simHits matched to a recHit used in the fit of the track to the total number of muon simHits left by the simulated particle.

- **Purity:** The number of recHits associated to a simHit to the total number of recHits for a standalone muon.
- **Efficiency:** The number of simulated signal muon associated with a reconstructed muon over a total number of simulated signal muons.

**Fake Rate:** The number of reconstructed muons not associated to any simulated particles over the total number of reconstructed muons.

**Transverse momentum resolution:**

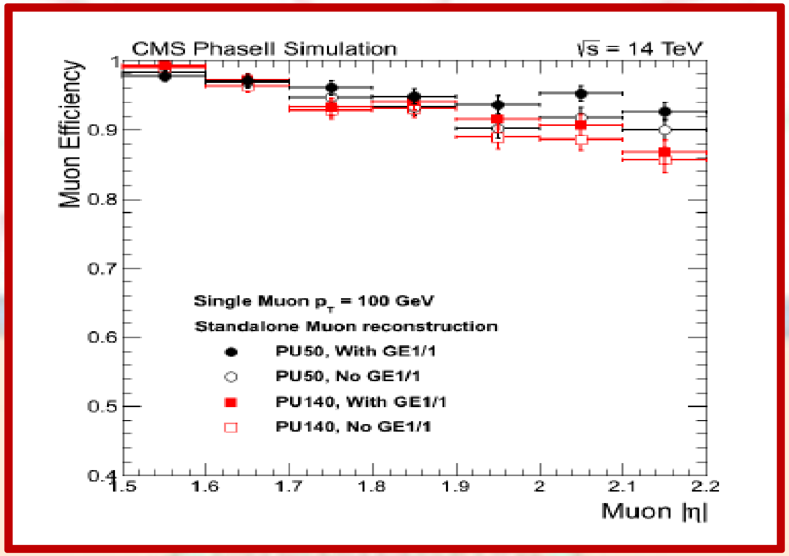
- Def. q/pt = $(q^{rec}/p_T^{rec} - q^{sim}/p_T^{sim})/(q^{sim}/p_T^{sim})$

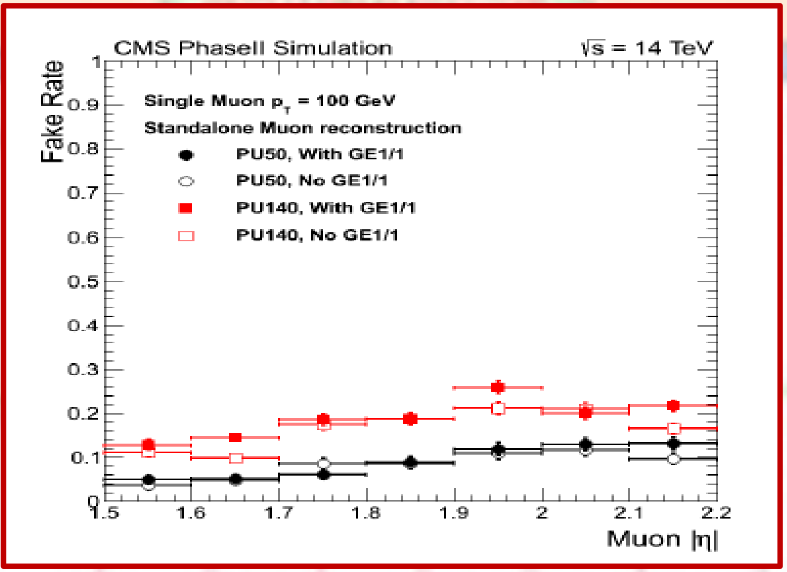
- core width or resolution = sigma parameter of the gaussian fit of the q/pt resolution

# Cont….

## STA Muon reconstruction performance

•Fixed $p_T$ muons of 100 GeV
•At least one muon station with two valid hits.
•Muons in the time window of ±12 ns to reduce the OOT.
•High quality STA muons with Q > 50% and purity > 75%
• The implementation of gem is in place, we see an improvement in the efficiency without inflating the FR.



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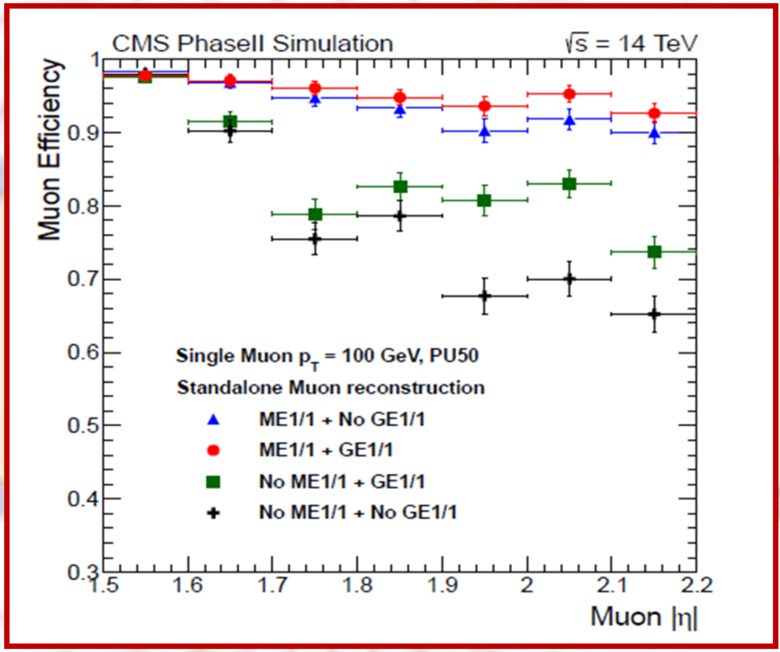
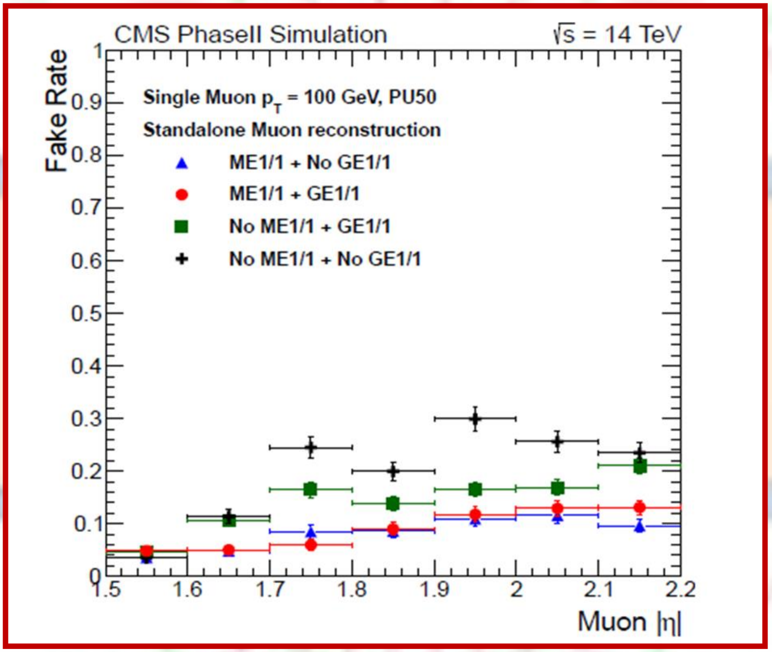
## Redundancy study: Efficiency and Fake rate PU = 50



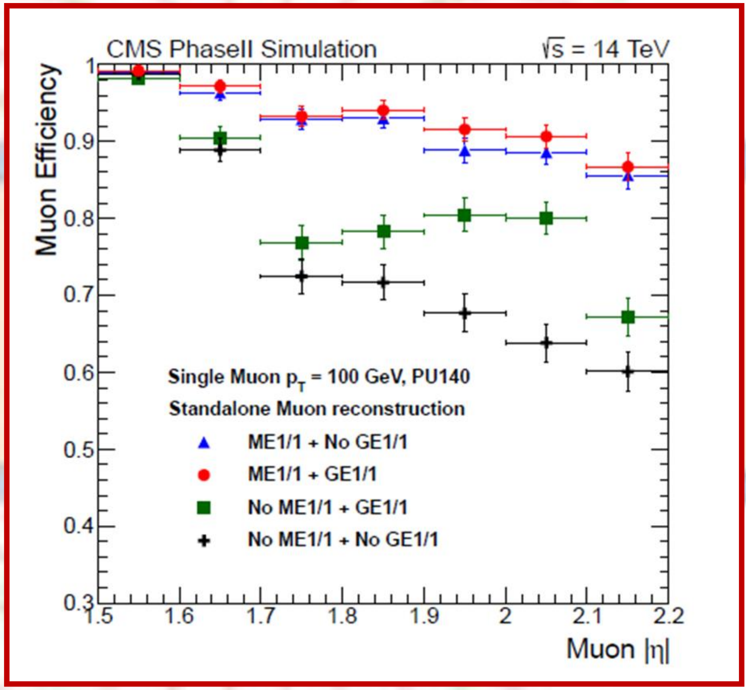



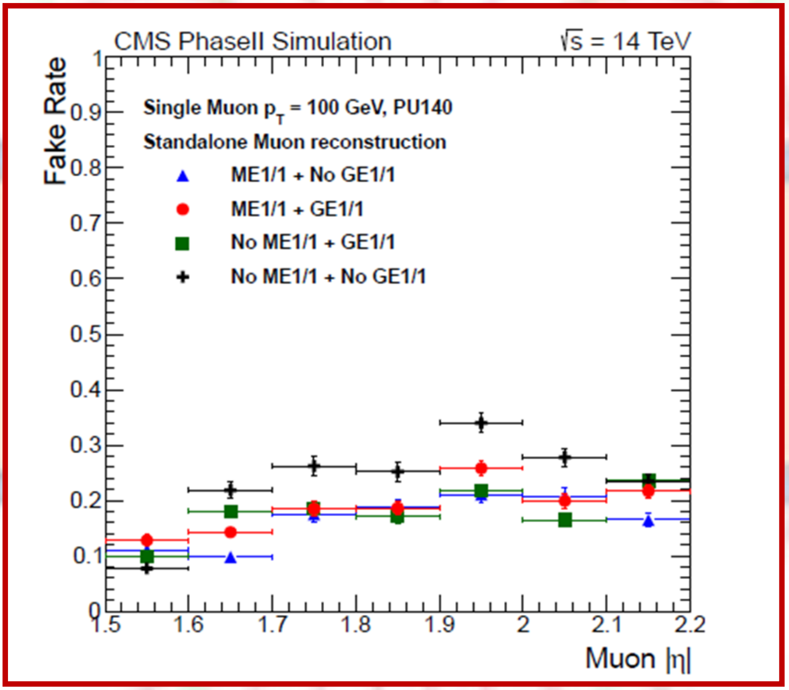

Different scenarios were considered including the case in which ME1/1 is completely broken **(black points)**

***In all the cases, GE1/1 is able to recover the efficiency in the case of ME1/1 failure, even to introduce small improvement and reducing the fake rate.***

# Cont….

## Redundancy study: Efficiency and Fake rate
## PU = 140




*In all the cases, GE1/1 is able to recover the efficiency in the case of ME1/1 failure, even to introduce small improvement and reducing the fake rate.*

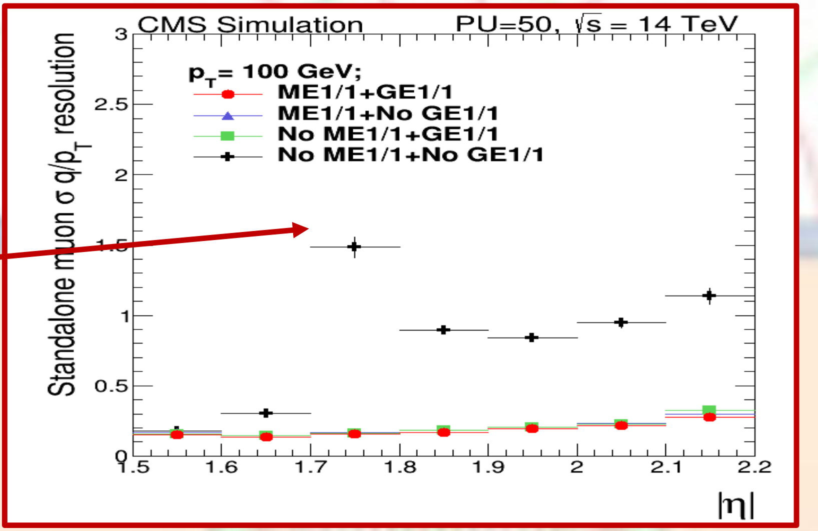
# Cont….

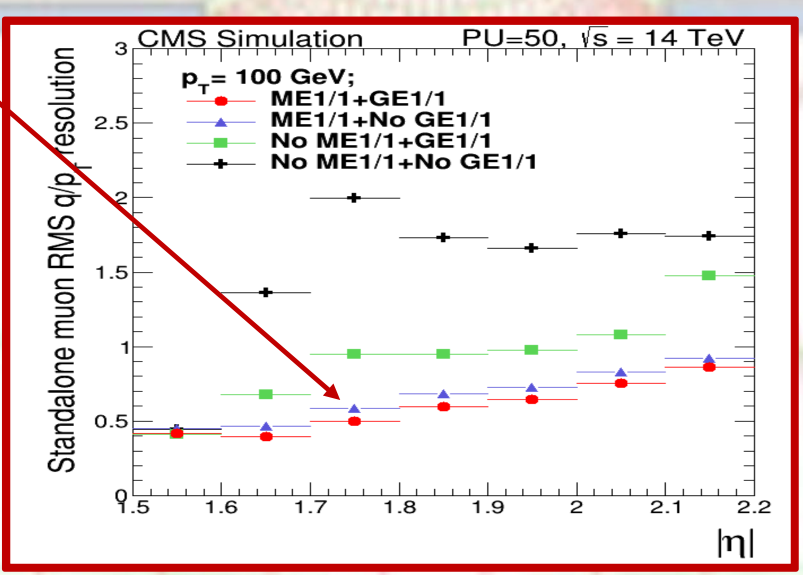
## Redundancy study: pt resolution

•GE1/1 is able to recover the STA muon performance in case of ME1/1 failure (**black points** w.r.t. **green points**)

•It is even able to introduce an improvement in the RMS (**red points** w.r.t. **blue points**)

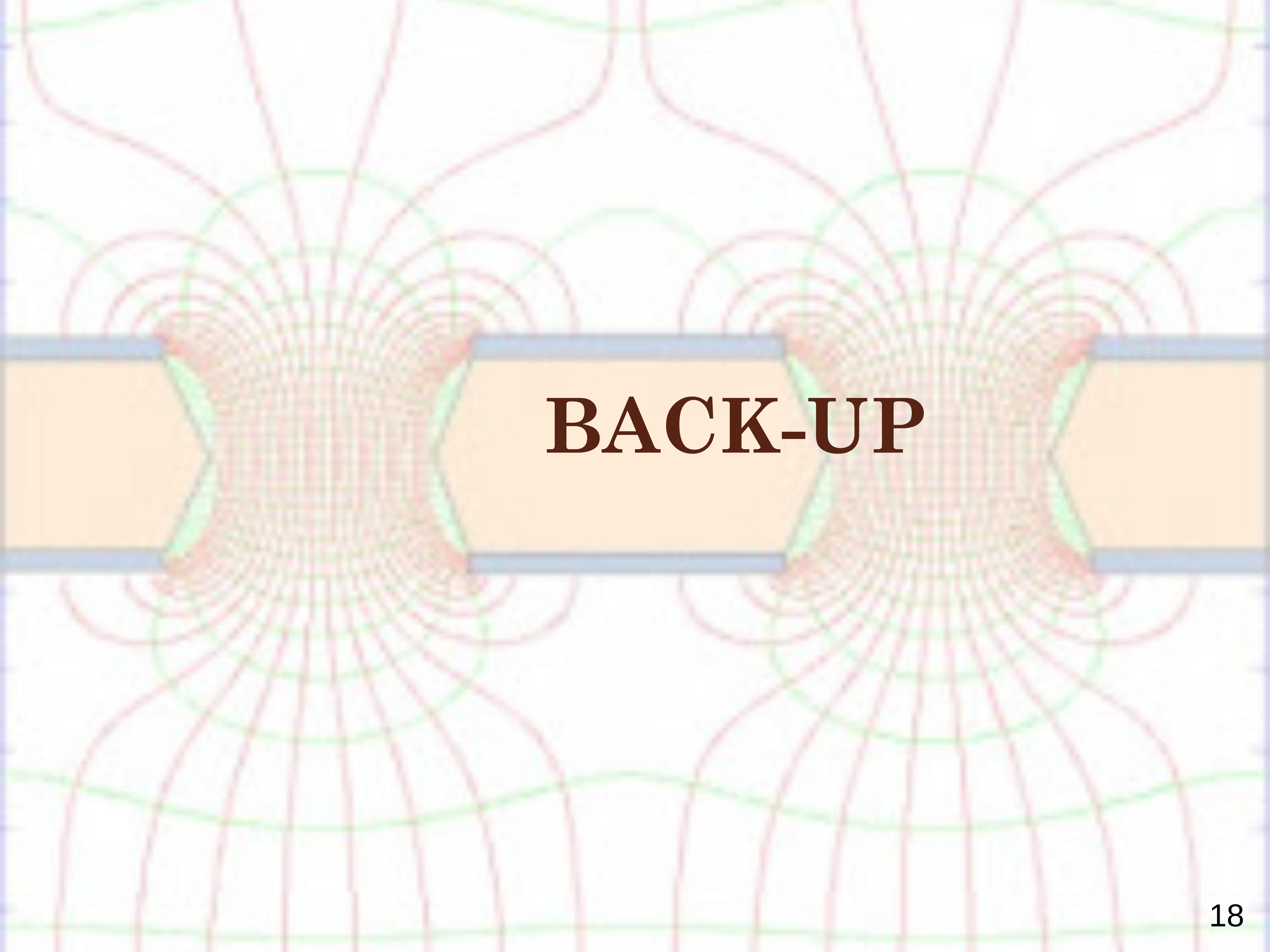
•Same results also seen in case of 2023 scenario in which ME1/1, 2/1., 3/1 and 4/1 broken at a time.



# Summary

- The GE1/1 detector has been designed in anticipation of future integration with other planned CMS upgrades at high luminosities era of LHC.
- The integration of the GE1/1 detector into full GEANT based CMSSW framework has been necessary step for the design of algorithms and performance studies related to trigger, reconstruction and identification.
- The implementation of GE1/1 digitization model with a realistic detector response and the inclusion of neutron induced backgrounds in CMSSW framework allows the evaluation of the impact of GE1/1 upgrade on the overall performance of CMS experiment
- Redundancy provided with the deployment of GE1/1 improves the quality of standalone muon reconstruction and can avert a deterioration in standalone muon momentum resolution if the performance of the ageing ME1/1 system degrades.



# BACK-UP

# SIM-RECO association Strategies

**ASSOCIATION BY CHI2**

- Association quality based on track parameters from the fit
- SimToReco association with smallest Chi2
- Probes effect from all tracking components, not only hit collection.
- It can be used also with reduced MC content

**ASSOCIATION BY HIT**

- Association tries to associate tracking recHits with simHits left by the tracking particle traversing the detector
- Association ranked on the basis of the fraction of simHits corrected associated to recHits (quality).
- It needs extended content.

- For investigating the efficiency and fake rate for high quality STA muons , AssByHits used.

- AssByHits also used to investigate muon sources.

- AssByChi2 is used for resolution measurements: reduced MC content allowed to have higher statistics. Tests with AssByHits showed that resolution is not sensible to the type of association chosen

# Classification of muon sources

**Muon Classifications:**

- Muons from a decay in flight or a light flavoured Hadron (π or K)
- Muons from a decay of heavy flavoured hadrons (b or c) or a tau lepton.
- Punch through: muons produced by a particle that is not a muon.
- Reco muon not associated to any particles.
- Duplicate events.
- Primary muons produced by decay of W, Z/ϒ* or promptly produced quarkonia states or top quark production.