Study of neutron-induced background hits in the CMS endcap muon system, and implications for the HL-LHC

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Neutron background in CMS

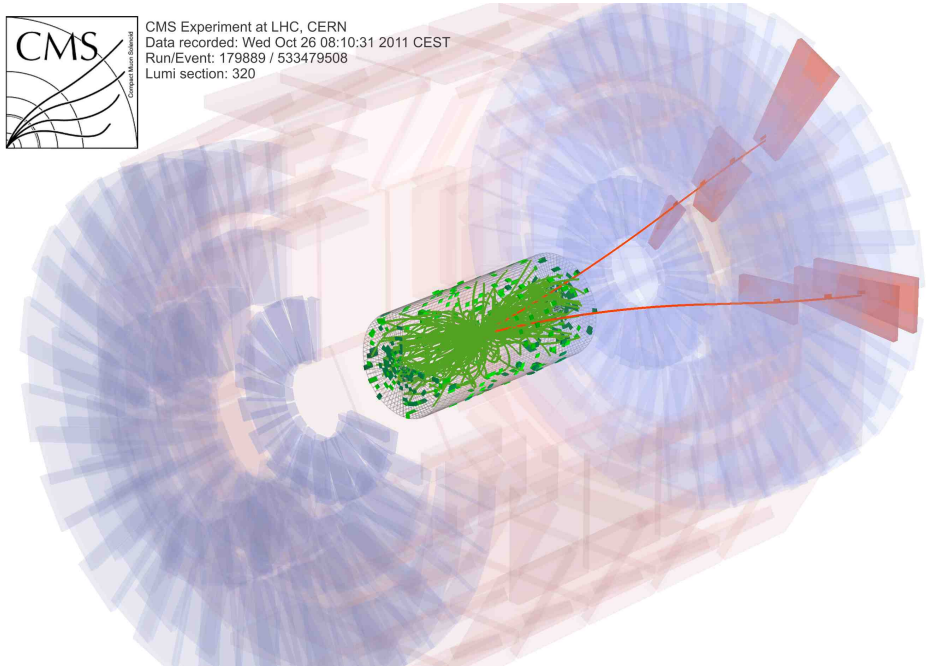
Among the many challenges to be brought by the High Luminosity upgrade to the LHC (HL-LHC) is the impact of increased hit rates in cathode strip chambers (CSCs) of the CMS endcap muon system

Both "fast" (~MeV) and thermal neutrons induce delayed hits in CMS muon detectors

- Nuclei emit gammas after neutron capture and nuclear interactions
- Gammas propagate in CSCs and mainly Compton scatter electrons which ionize chamber gas and cause background hits

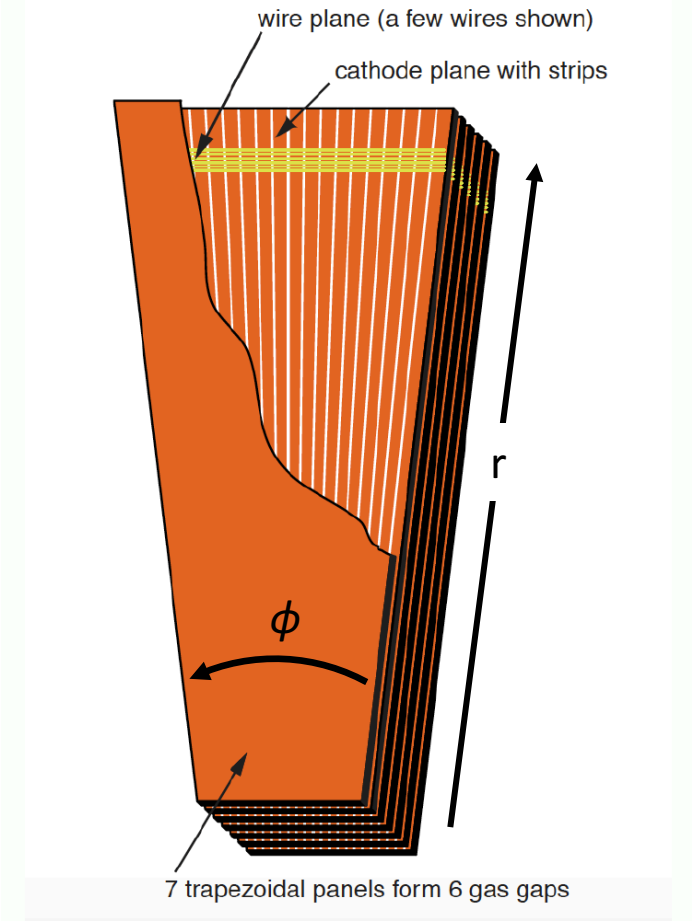
Today I will present comparisons of neutron-induced hits in data and simulation and some studies of CSC performance during a muon test beam inside a high-intensity gamma ray facility

CMS Detector Endcap Muon CSCs



Display of a candidate $B_S \rightarrow \mu^+\mu^-$ event with both of the muons passing through endcap CSCs

Cathode Strip Chamber geometry and coordinates



A muon crossing a CSC leaves a pattern of hits called a "segment"

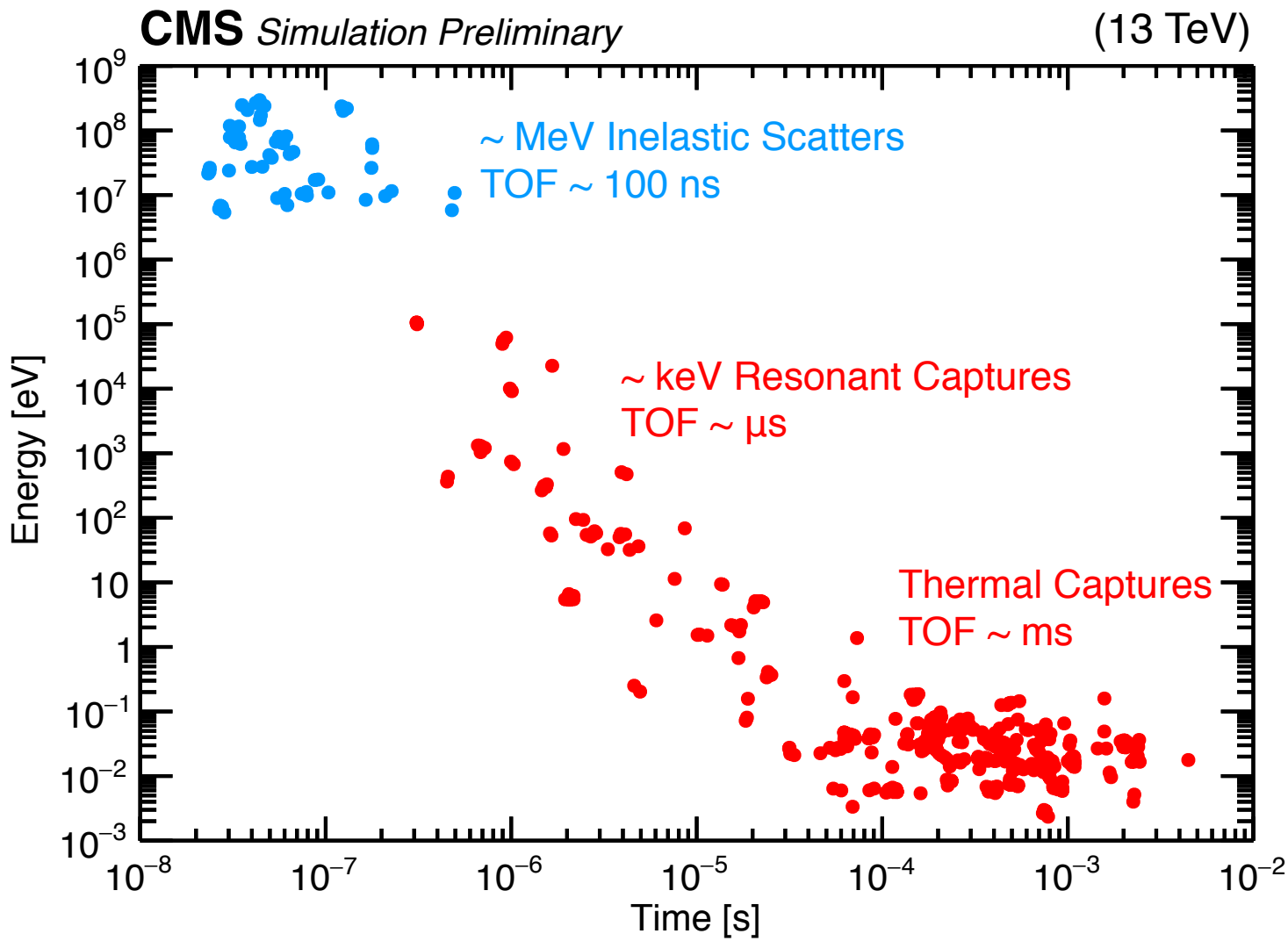
Neutron simulation

We used GEANT4 based Monte Carlo simulation of minimum-bias proton-proton (pp) collisions to help us understand the main characteristics of the neutron background

To address the long lifetime and low energy of the neutrons that we wish to study, we made two modifications to standard CMS GEANT4 simulation configurations:

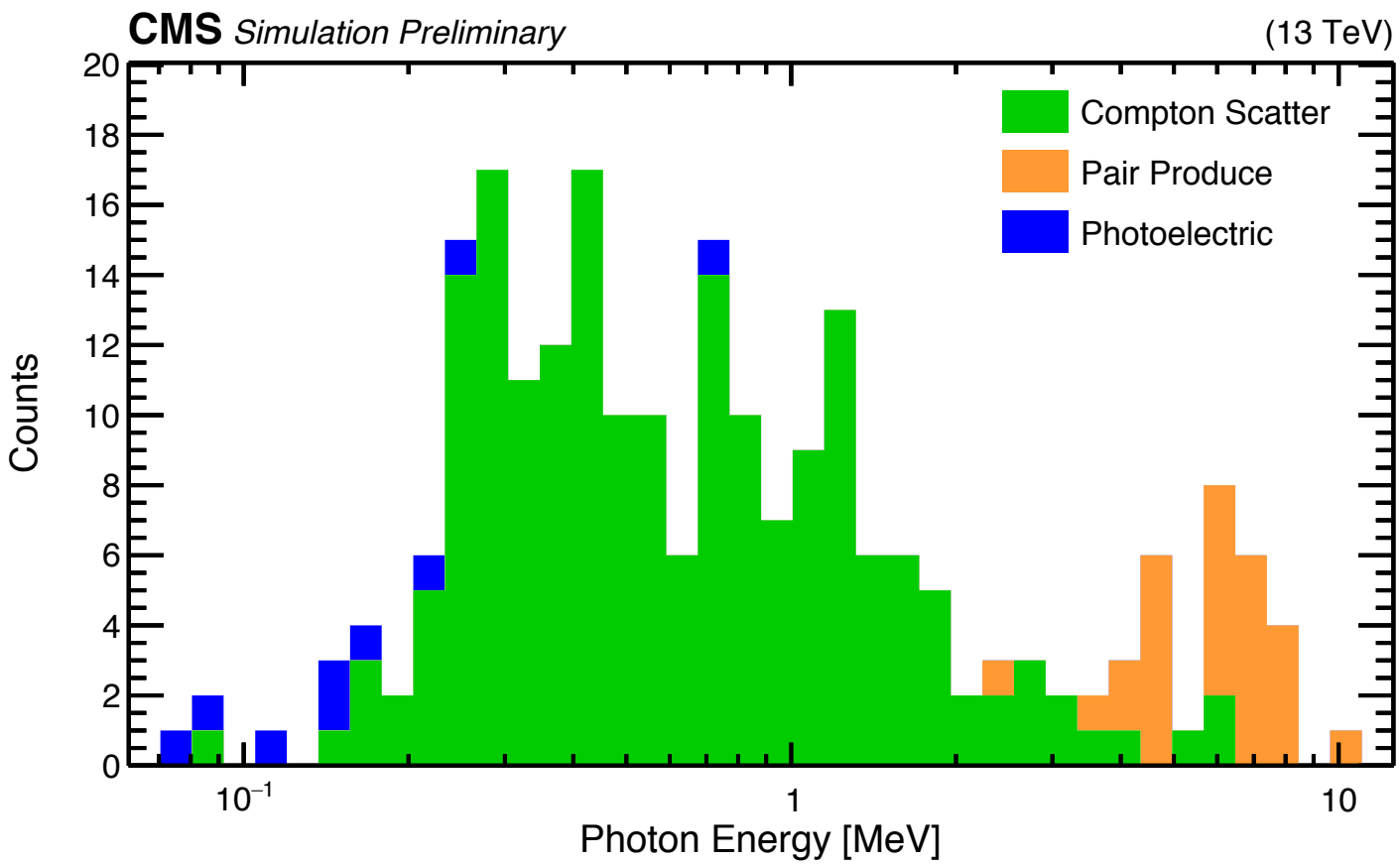
- Increased tracking time of all particles
- Removed all energy thresholds where they existed

Simulated neutron-induced hit regimes in CSCs



Photon energy regimes

Histogram of simulated photon energy emitted by nuclear de-excitations from both inelastic scattering and neutron capture which led to simulated hits, stacked by specific production or scattering process that created the electron responsible

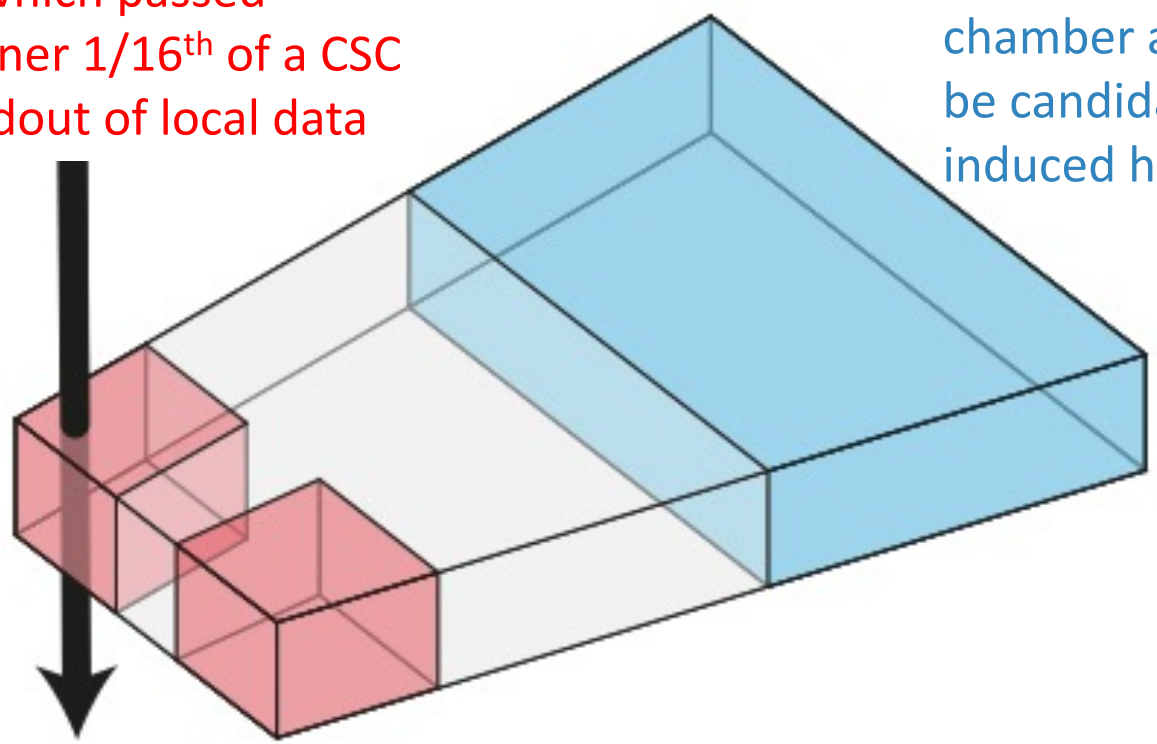


How to identify neutron-induced hits in CMS data?

To **avoid contamination from hadrons and muon showering**, we select muons from candidate $Z \rightarrow \mu\mu$ events and identify candidate neutron-induced hits by looking away from the triggering muon

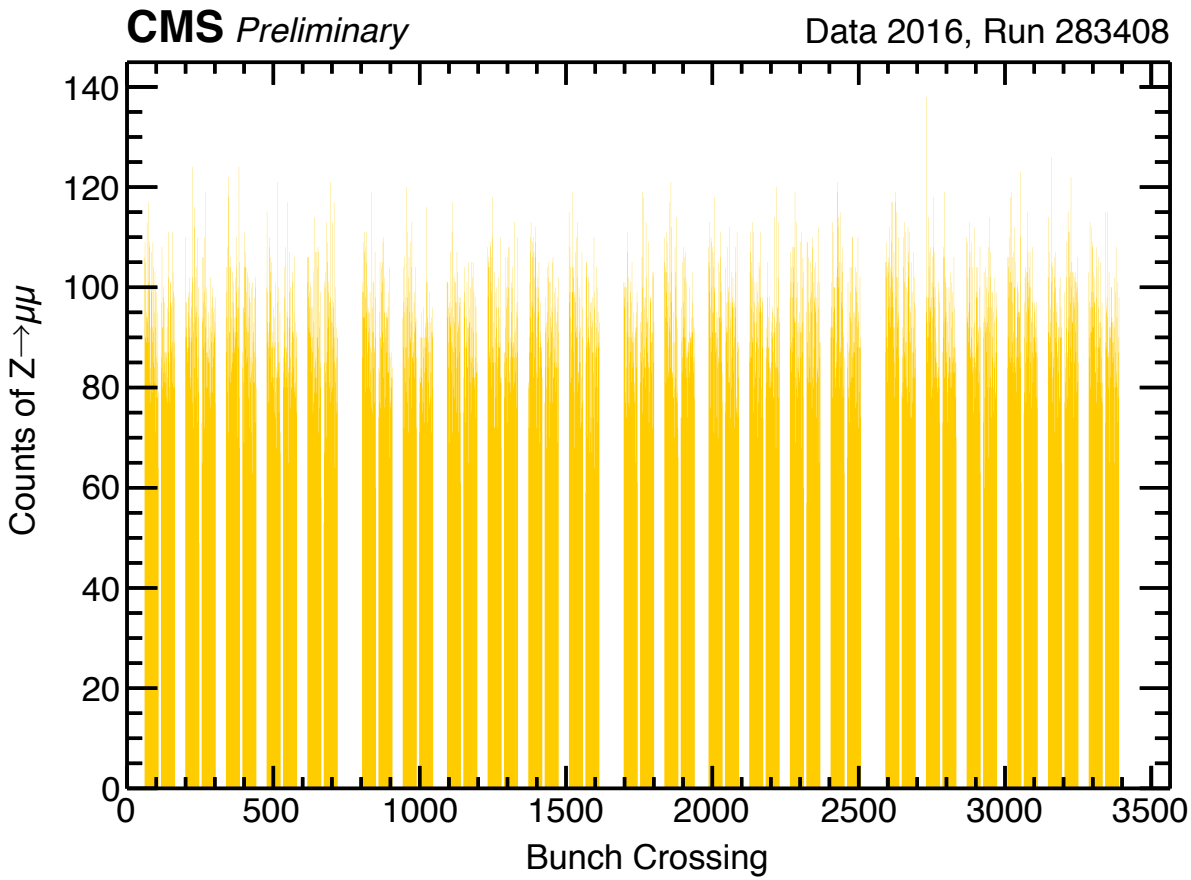
Use a muon which passed through a corner 1/16th of a CSC to trigger readout of local data

Hits which are on the opposite half of the chamber are considered to be candidate neutron-induced hits



LHC Bunch Structure

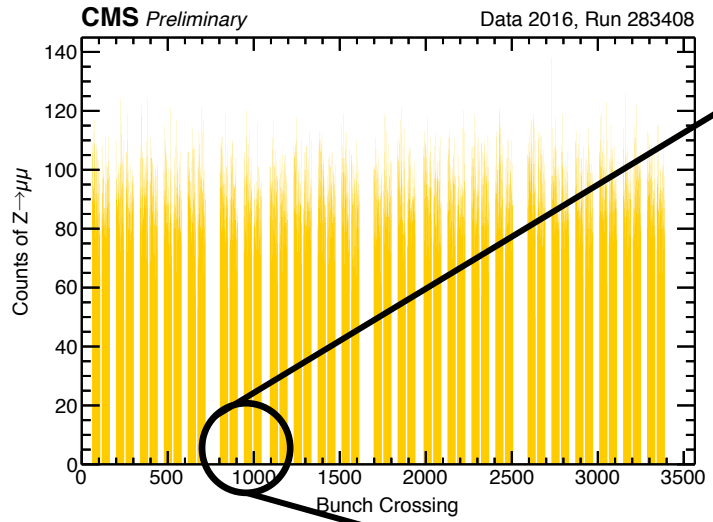
To distinguish neutrons from out-of-time pileup we consider gaps in the LHC proton bunch structure of at least 35 bunch crossings (BX) and use pp bunch trains with exactly 48 BX to **identify pp collisions occurring just after such gaps**



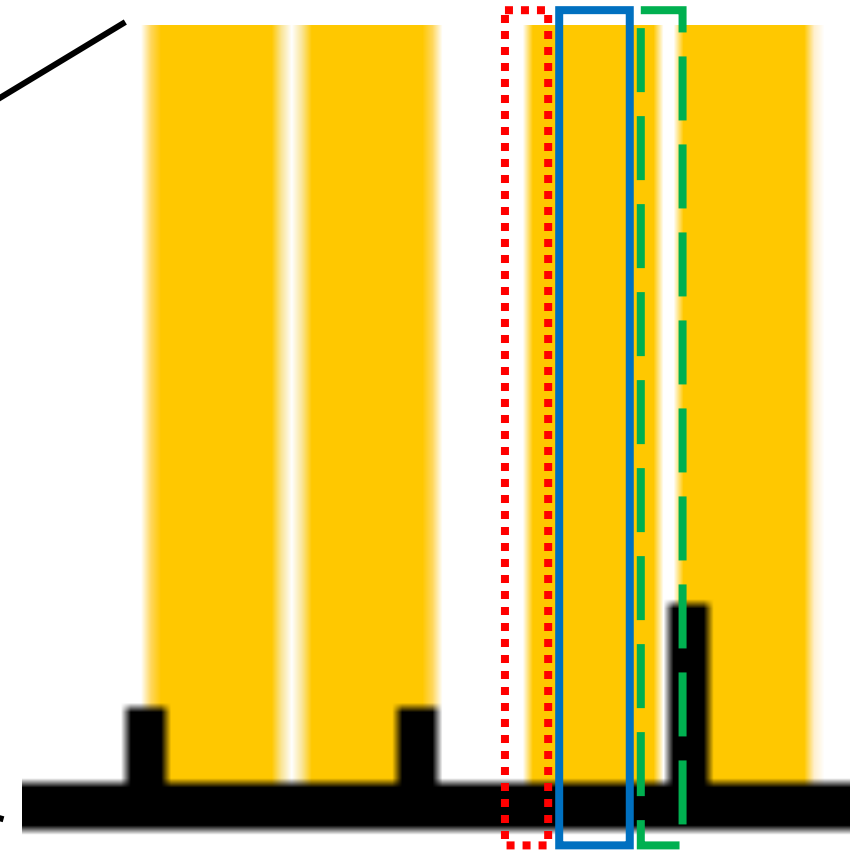
LHC Bunch Structure

Using gaps in LHC bunch structure allows us to identify

- end-of-gap hits in BX at beginning of a pp bunch train,
- hits in BX inside LHC pp bunch train, and
- beginning-of-gap hits in BX at end of a pp bunch train



Zoom in on bunch structure

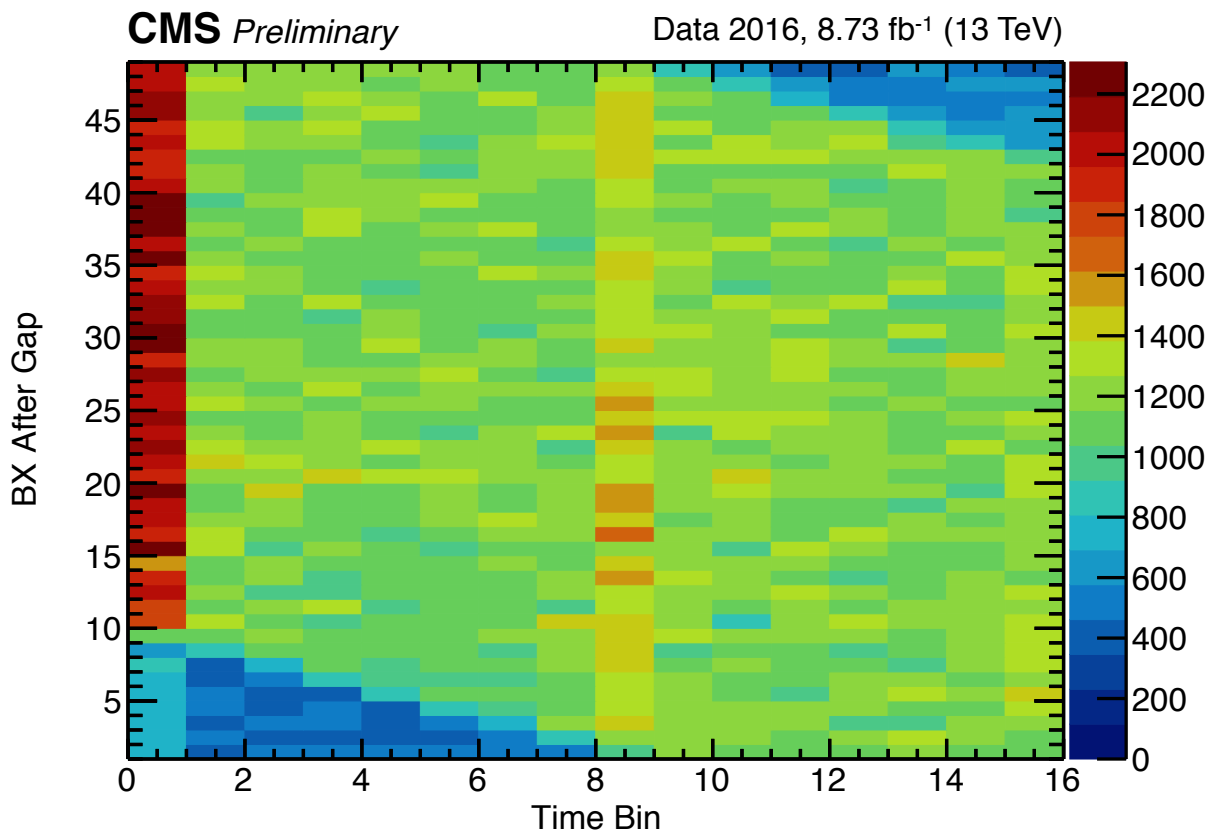


Time structure of non-segment anode wire hits

Plotted is anode wire hit occupancy of hits not associated to segments for each BX after a gap, as a function of the read out time bin

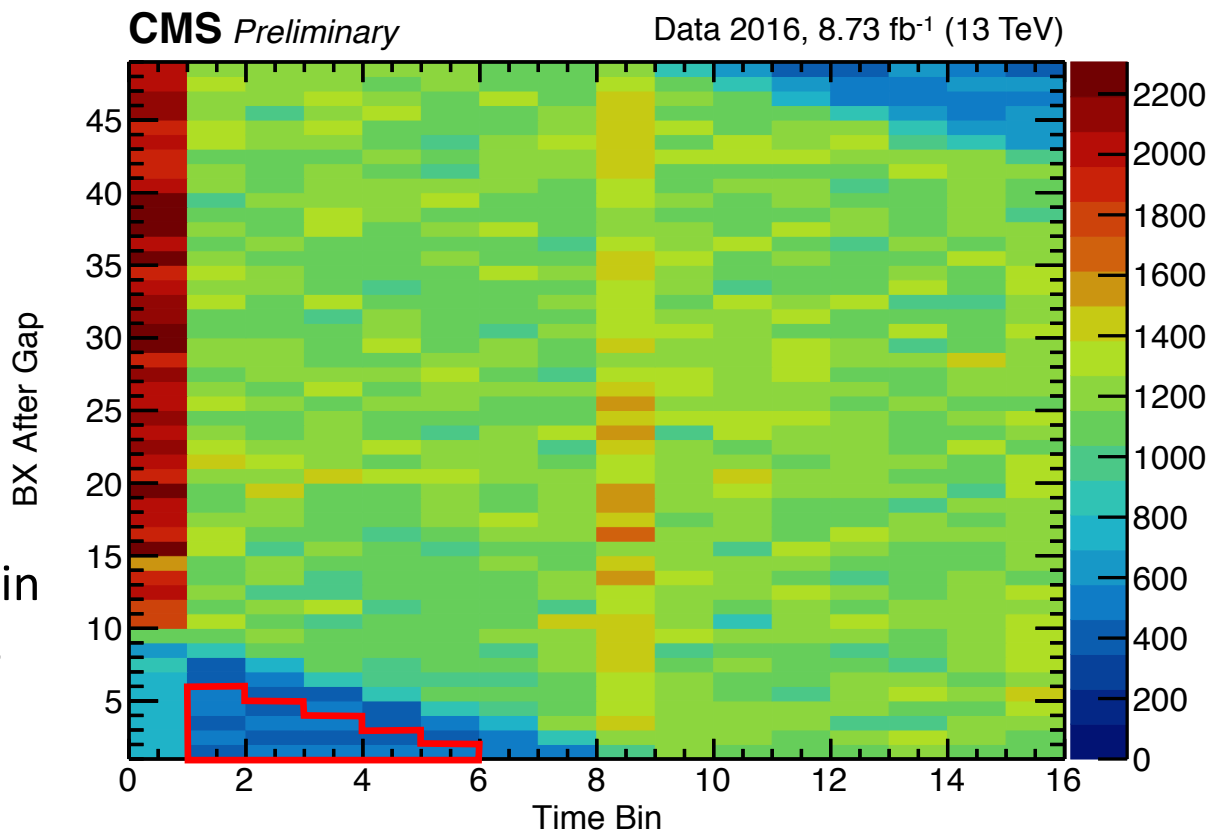
CSC anode electronics read out is 16 BX wide with hits in-time from the triggering muon centered in time bin 8

This is what allows us to examine hits in the bunch gaps



The hits in readout time bin 0 contain hits from the previous bunch crossing due anode electronics features and are therefore not considered

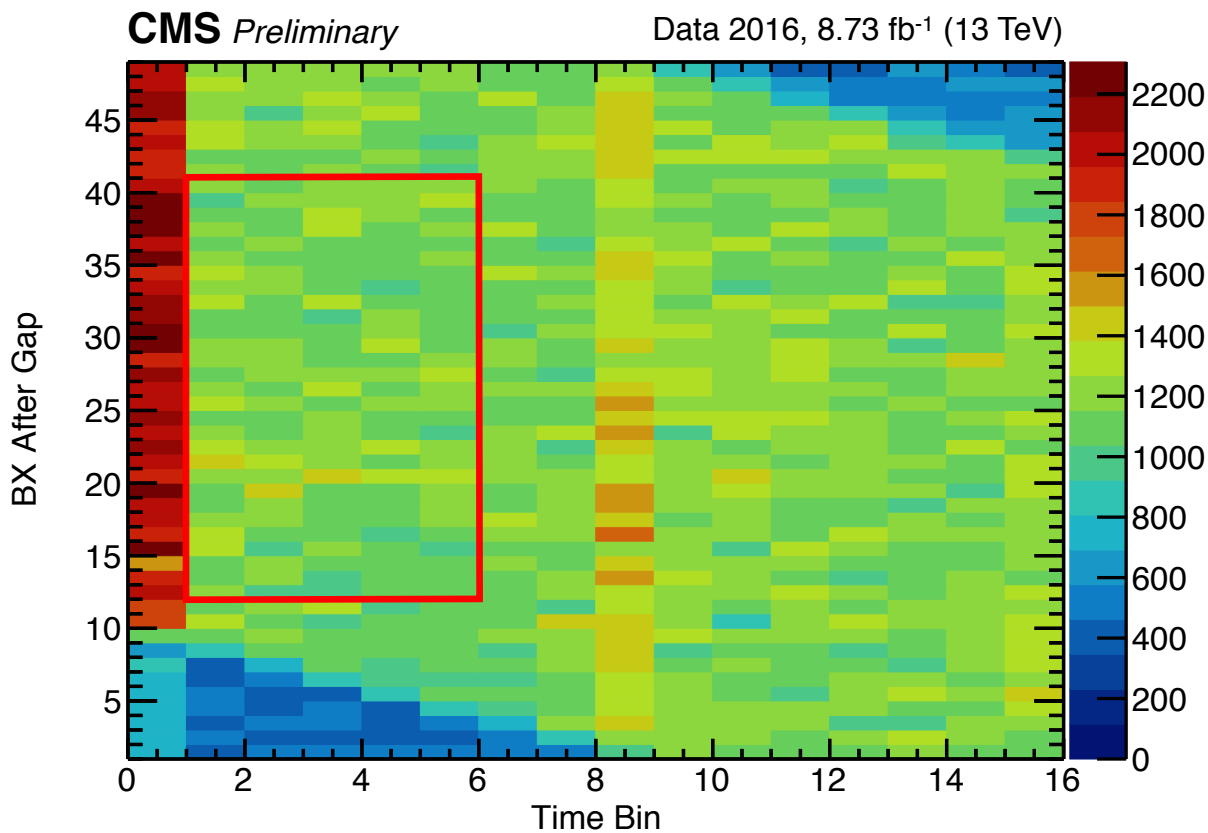
Time structure of non-segment anode wire hits



Hits in early BX in bunch train and early readout time bins occur at the **end of a LHC bunch gap** and are predominantly caused by thermal neutron captures

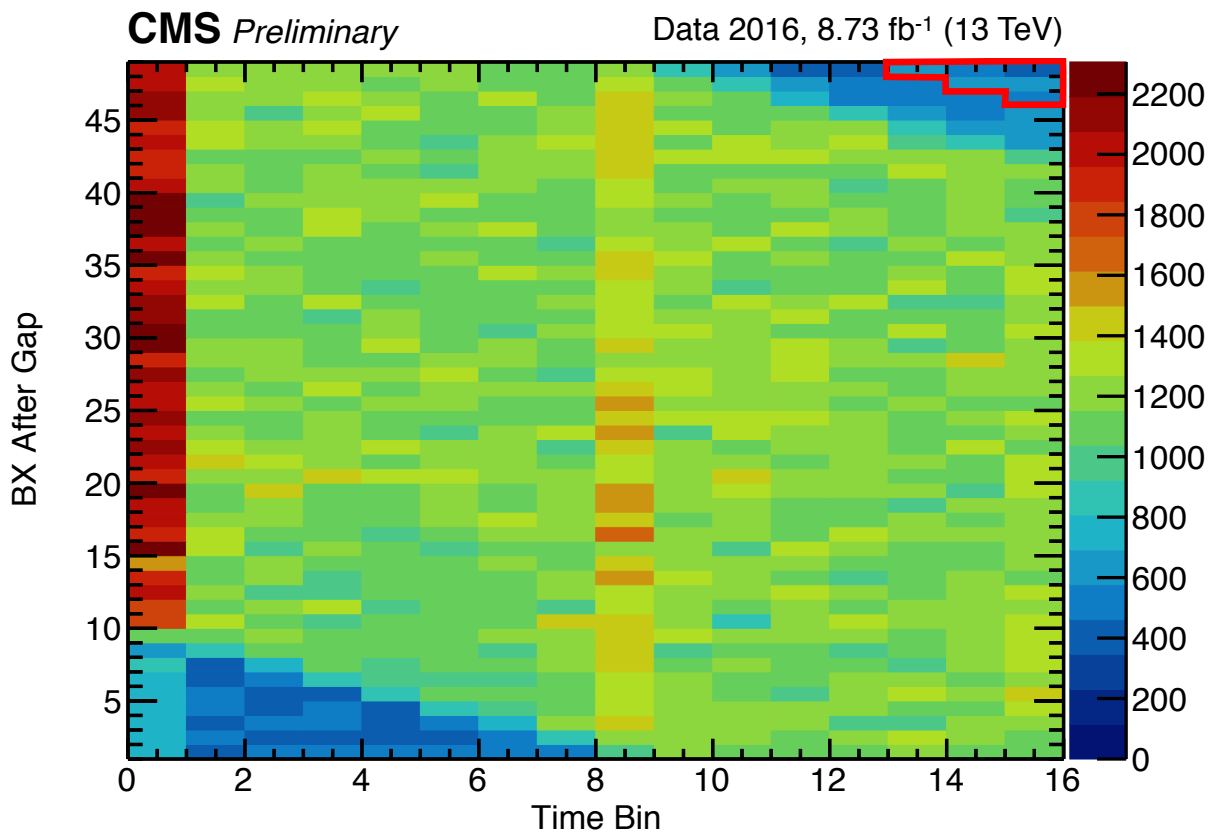
Time structure of non-segment anode wire hits

Hits that are in time with pp collisions **during LHC bunch train** are from thermal neutron captures and fast neutrons, and prompt hits from other BX



Time structure of non-segment anode wire hits

Hits in late BX in bunch train and in late readout time bins occur at the **beginning of the next LHC bunch gap** and are caused by fast neutrons as well as thermal neutron captures



Comparison of data and neutron simulations

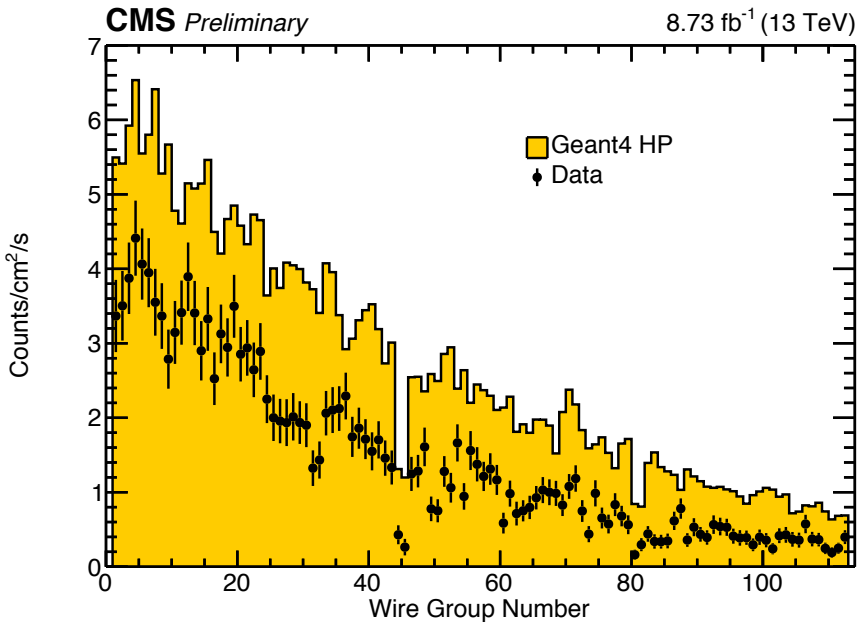
Two versions of GEANT4 neutron interaction packages are compared to a sample of candidate hits from thermal neutrons

- **HP** : "High Precision" package which parametrizes existing experimental nuclear data for neutron interaction cross sections
- **XS** : Intended for CPU optimization, XS is derived from HP by approximating detailed parametrizations in HP with averages

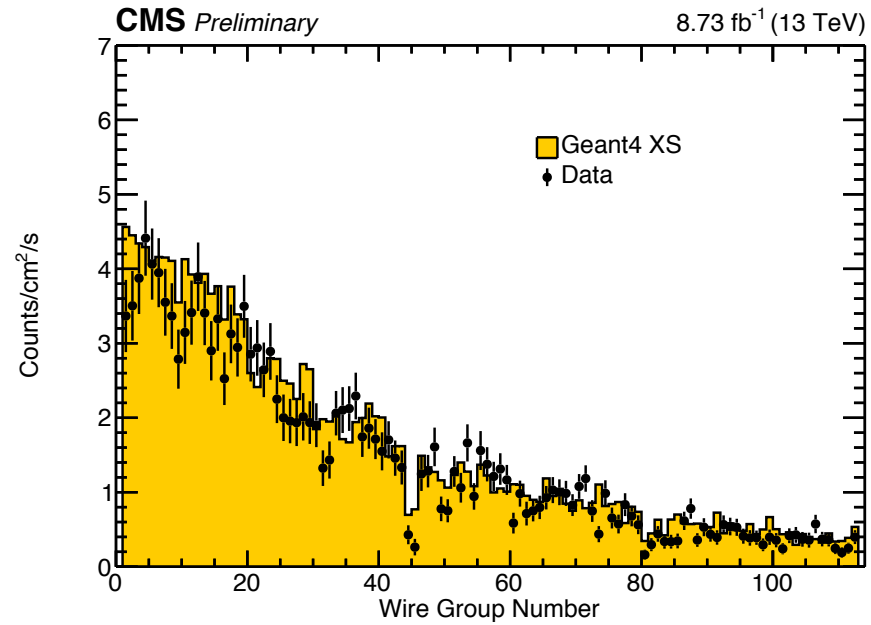
Data on each plot of the following slide are end-of-gap thermal neutron induced hits selected from lower left red triangle of above plots and are compared to thermal-neutron induced hits from simulation

Comparison of data and neutron simulations

HP Simulation



XS Simulation



Plotted are sample distributions of anode wire hits from a single CSC type per chamber area, time, and pp collision rate for CMS data and simulation

In example shown, exact data to simulation agreement is accidental

For all CSCs at various *r* and *z* positions, simulation reproduces data to within a factor of 2

How to understand CSC performance at HL-LHC now?

2 CSCs are placed in the CERN Gamma Irradiation Facility (GIF++) which features a 13.9 TBq ^{137}Cs source that emits 662 keV γ-rays with tunable attenuators

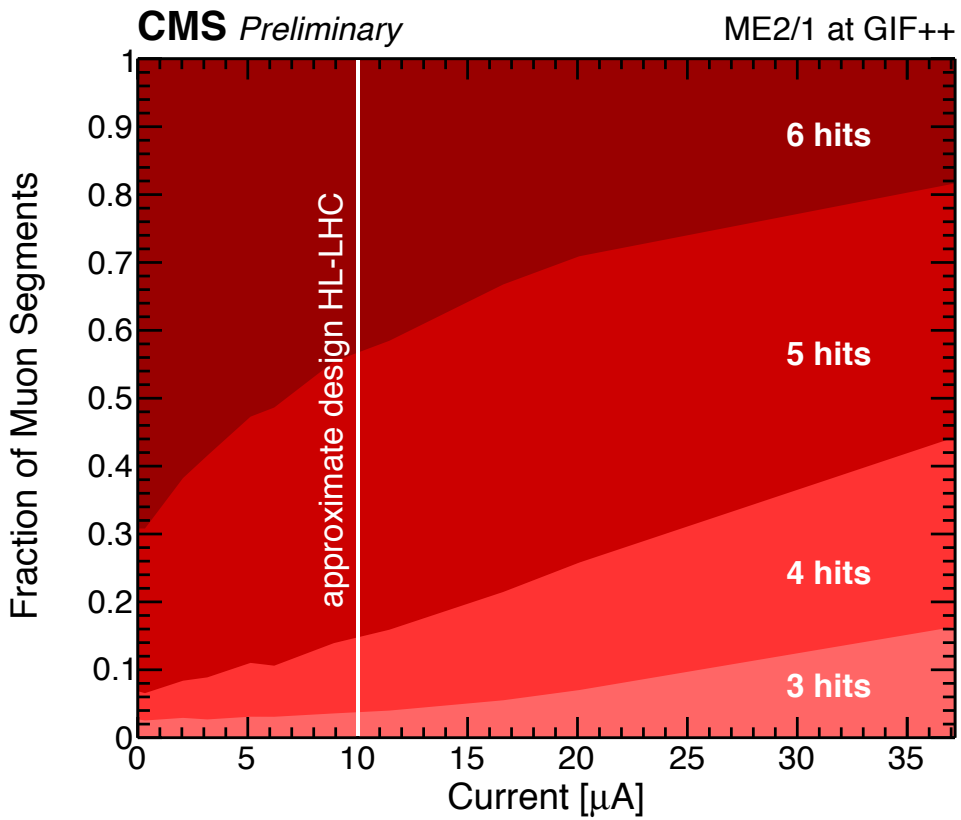
Energy of γ-rays at GIF++ is less than 662 keV so for example pair-production is not possible. We continue to study if this matters.

CSC performance studies are done in the presence of increased ionization from the γ-ray source and a fixed target beam of muons from 400 GeV protons **intended to imitate HL-LHC conditions**

See backup slide for more details.

Muon quality degrades in presence of extra hits

Plotted is fraction of offline reconstructed muon segments, categorized by the number of reconstructed hits used to form them vs. chamber anode current during a muon test beam at GIF++



Summary

Developed a method to use the LHC pp bunch structure to isolate candidate thermal neutron induced hits in data using CMS detector endcap muon CSCs

Compared a selection of thermal neutron induced hits in CMS data and GEANT4-based simulation using simulated minimum-bias pp collisions with appropriate time and energy thresholds specific to the neutron background

Found that data to simulation agreement for thermal neutron induced hits CSCs at all *r* and *z* is good to a factor of 2

Used GIF++ to study CSC local online and offline reconstruction under HL-LHC-like conditions

Backup

How to understand CSC performance at HL-LHC now?

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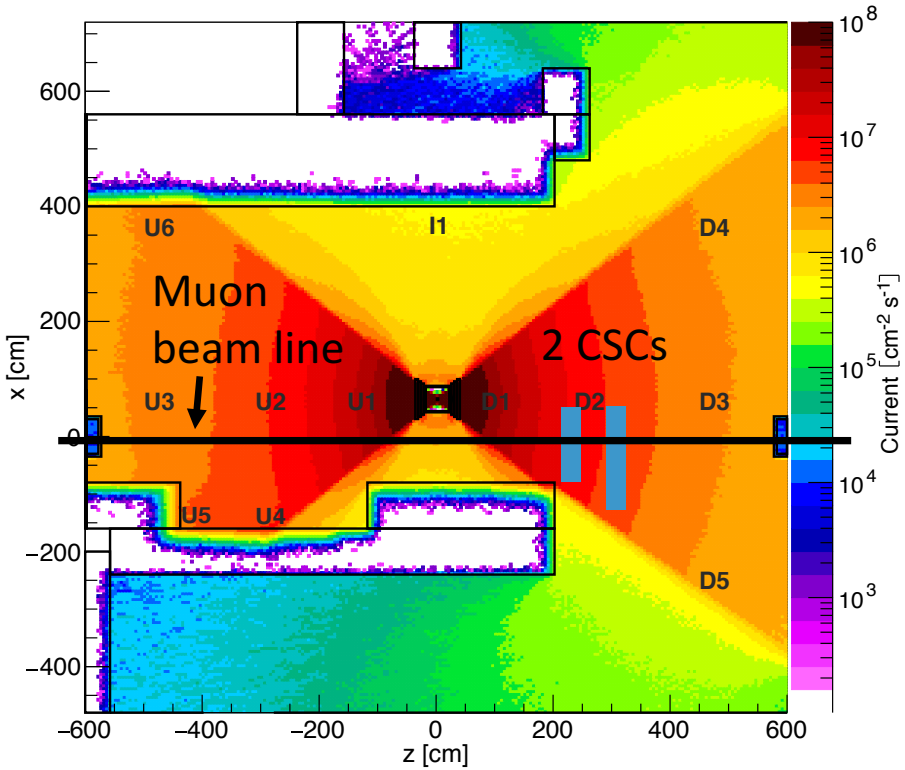
CSC performance studies are done in the presence of increased ionization from the γ-ray source and a fixed target beam of muons from 400 GeV protons **intended to imitate HL-LHC conditions**

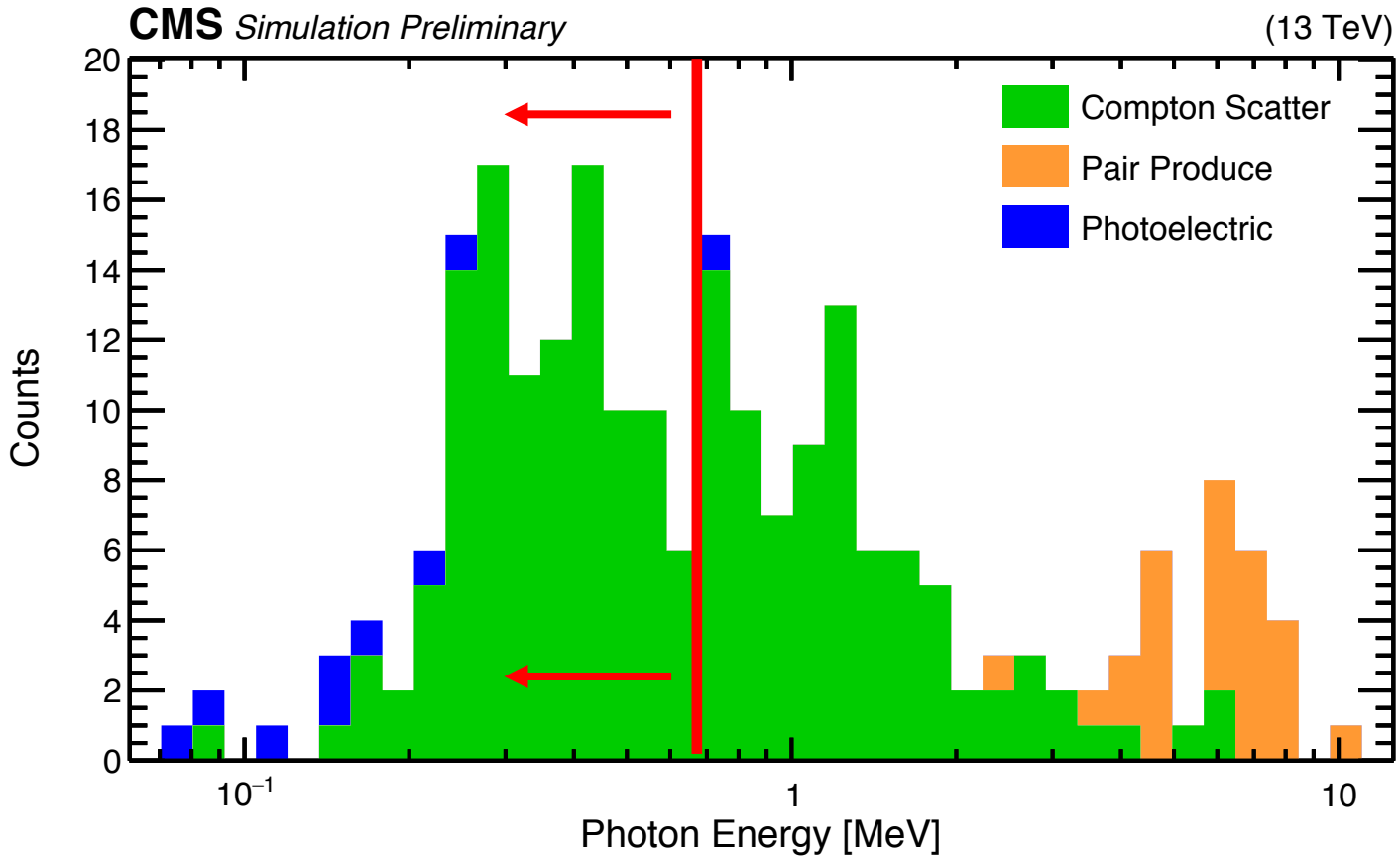


Plan view of GIF++ γ-ray flux map and approximate position of muon beam line and CSCs
Pfeiffer, et al. NIM A866 (2017) 91

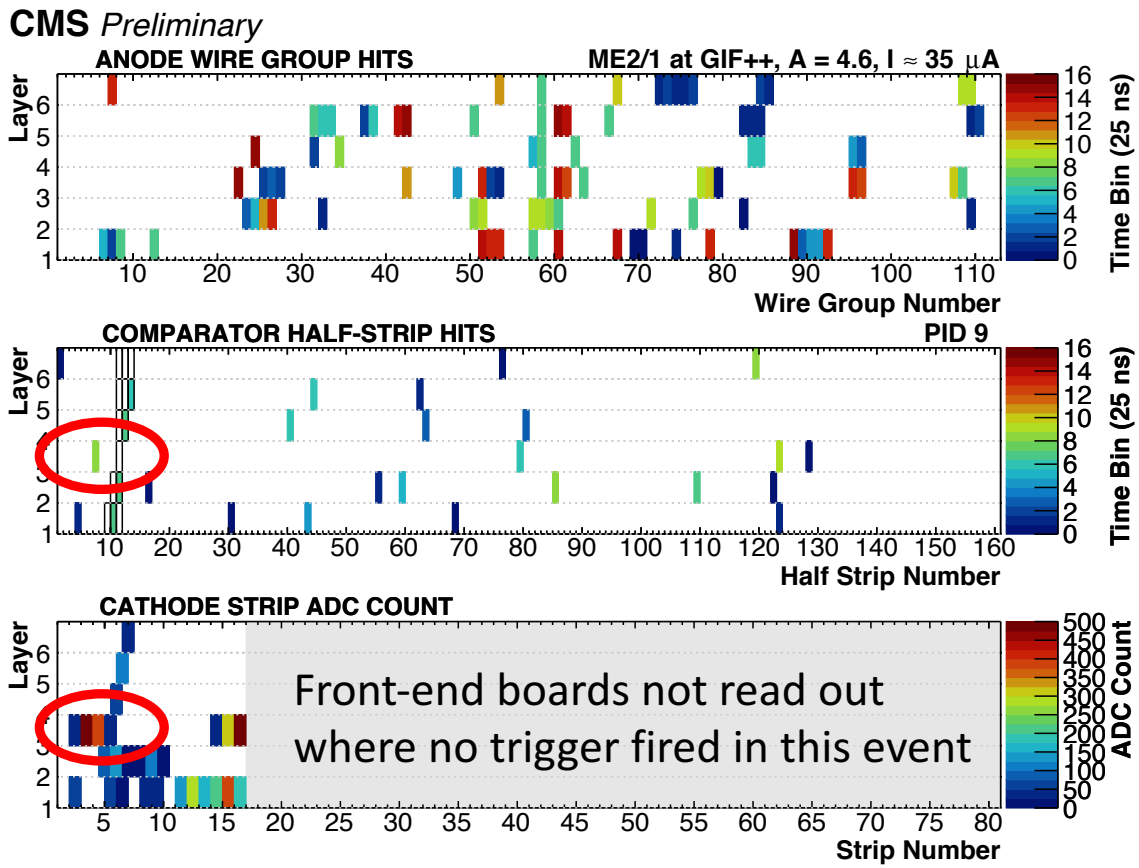
Photon energy regimes (again)

Returning to histogram of simulated photon energy from nuclear de-excitations which led to simulated hits in CMS

Energy of γ-rays at GIF++ is less than 662 keV



Example of muon hit corruption in GIF++ test beam



Top panel shows **anode wire hits** (r-axis) and their timing information

Middle panel shows **trigger cathode comparator hits** (ϕ-axis) and their timing information

Bottom panel shows **digitized cathode hits** and their ADC amplitude

Red circles illustrate an example of a **corrupted hit due to a candidate photon-induced hit**

N.B. this event was collected with the γ-ray source intensity exceeding expected HL-LHC conditions