# Commissioning and testing of real-size triple GEM prototypes for CBM-MuCh in the mCBM experiment at SIS18 facility of GSI

**Ajit Kumar**
**(On behalf of CBM-MuCh team)**

**HBNI Mumbai**
**VECC Kolkata**

**Radiation Detector and Instrumentation in Nuclear and Particle Physics (RAPID2021)**
28-10-2021

# Outline

- **CBM at FAIR**
- **Muon Chamber (MuCh) system of CBM**
- **Gas Electron Multiplier (GEM) detector prototypes**
  - **Working principle, Gain and Efficiency measurements**
- **Large area GEM detector for MuCh**
  - **Fabrication (NS-2 Technique), Test with source, Particle beams and N-N collision**
- **Commissioning and test of mMuCh-GEM modules in mCBM experiment**
  - **Design and test at VECC, Results from mCBM experiment**
- **Summary**
- **Acknowledgments**

# CBM at FAIR

**– Fixed target heavy-ion experiment**

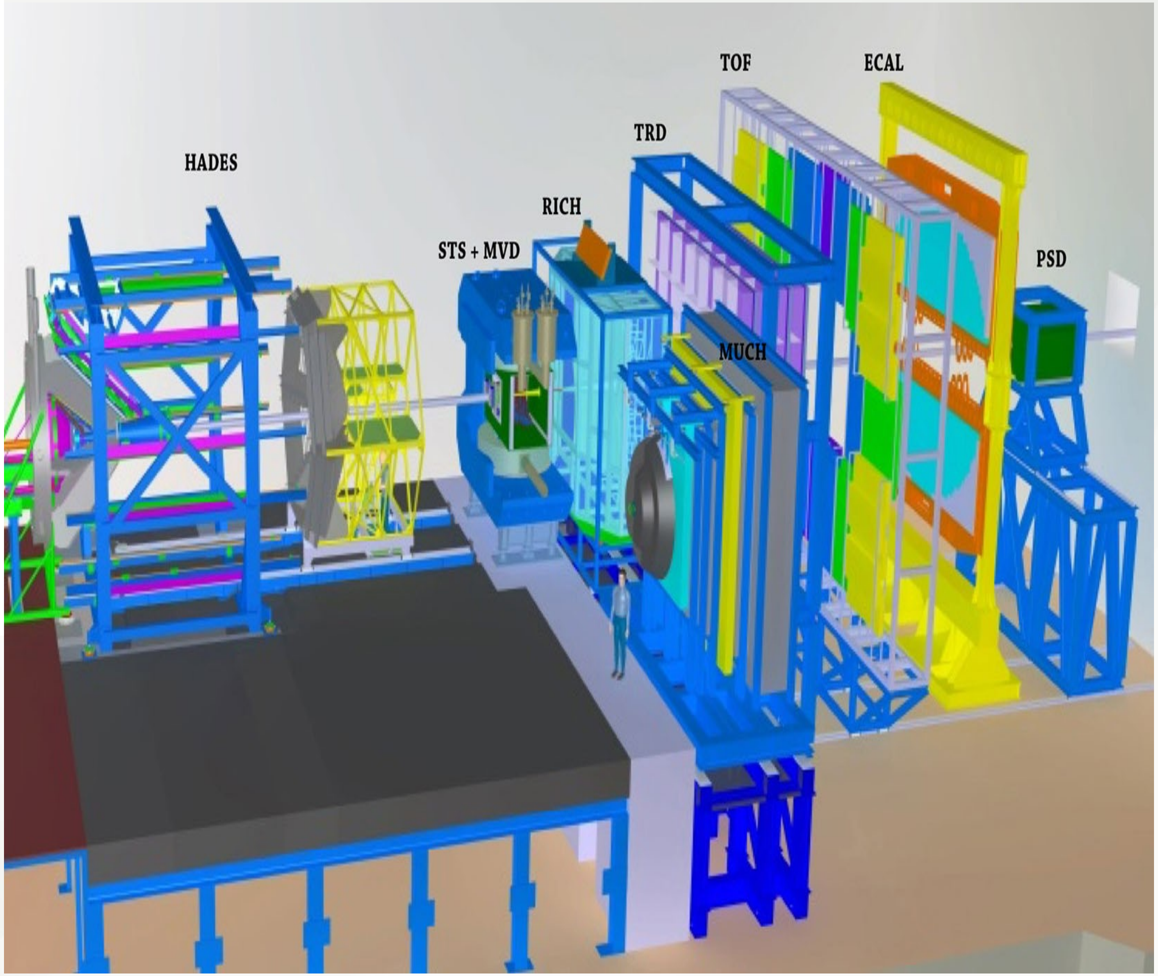
**– Designed to explore QCD phase diagram at moderate temperature and high net baryon density**

**– Measure rare diagnostic probes such as multi-strange hyperons, charmed particles and vector mesons decaying into lepton pairs with unprecedented precision and statistics**

**– Interaction rates will go up to 10 MHz**

**– Requires very fast and radiation hard detectors**

**– Several CBM detectors and data readout chain are commissioned in mCBM experiment (part of FAIR phase-0 programme)**




## Beam Energy

**@SIS100**

**Beam energy:** 2-14A GeV for heavy ions and 2-29A GeV for proton beams

**@SIS300**

**Beam energy:** 2-35A GeV for heavy ions and 2-89A GeV for proton beams

**Ref:** Eur. Phys. J. A, 53 (3): 60, 2017

# Detectors in CBM

**MVD – Micro Vertex Detector** - Secondary vertices with high precision for D meson identification

**STS – Silicon Tracking Station** - Track reconstruction and momentum determination of charged particles - with a momentum resolution ~1%

**TOF – Time-of-Flight** - Charged hadron identification

**RICH – Ring Imaging CHerenkov detector** - Measurement of electrons

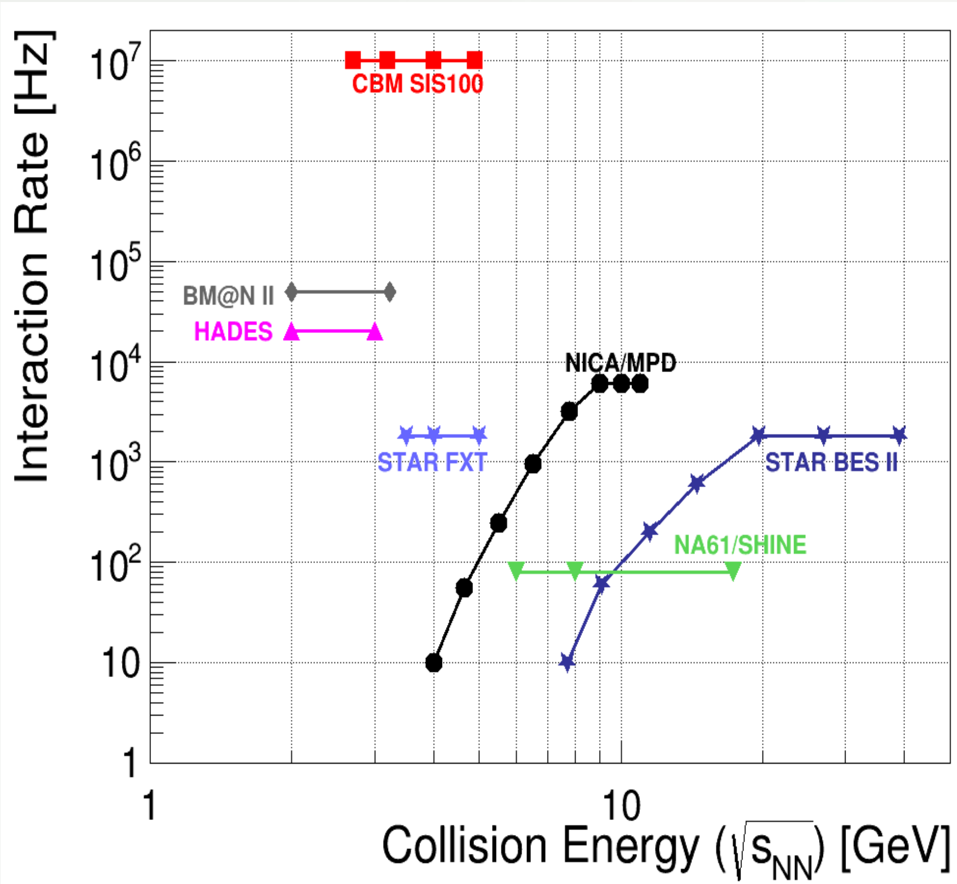
**TRD – Transition Radiation Detector** - Measurement of electrons

**MuCh – Muon Chamber** – Measurement of muons

**ECAL – Electromagnetic CALorimeter** - Photons and neutral particles

**PSD – Projectile Spectator Detector** - Determination of the collision centrality and the orientation of the reaction plane

# Experiments at Low Beam Energies




- Observables, like the flow of identified particles, multi-strange hyperons, di-leptons, and particles containing charm quarks are extremely **statistics demanding**
- The key feature of successful experiments will be rate capability in order to measure these observables with high precision
- **CERN-SPS** experiment – The detector setup is limited to reaction rates of about **80 Hz**
- **HADES** detector at SIS18 measures hadrons and electron pairs with reaction rates up to **20 kHz**
- At beam energies above 20 GeV/nucleon, the reaction rates of **STAR** are limited to about **800 Hz**
- **Nuclotron-based Ion Collider fAcility (NICA)** collider is designed to run at a maximum luminosity of L = $10^{27}$ $cm^{-2}$ $s^{-1}$ at collision energies between $\sqrt{s_{NN}}$ = 8 and 11 GeV –> Reaction rate of **6 kHz** for minimum bias Au+Au collisions
- **FAIR** will offer the opportunity to study nuclear collisions at extreme interactions rates –> Up to **10 MHz** for selected observables such as **J/ψ** and **1–5 MHz** for **multi-strange hyperons** and **di-leptons**

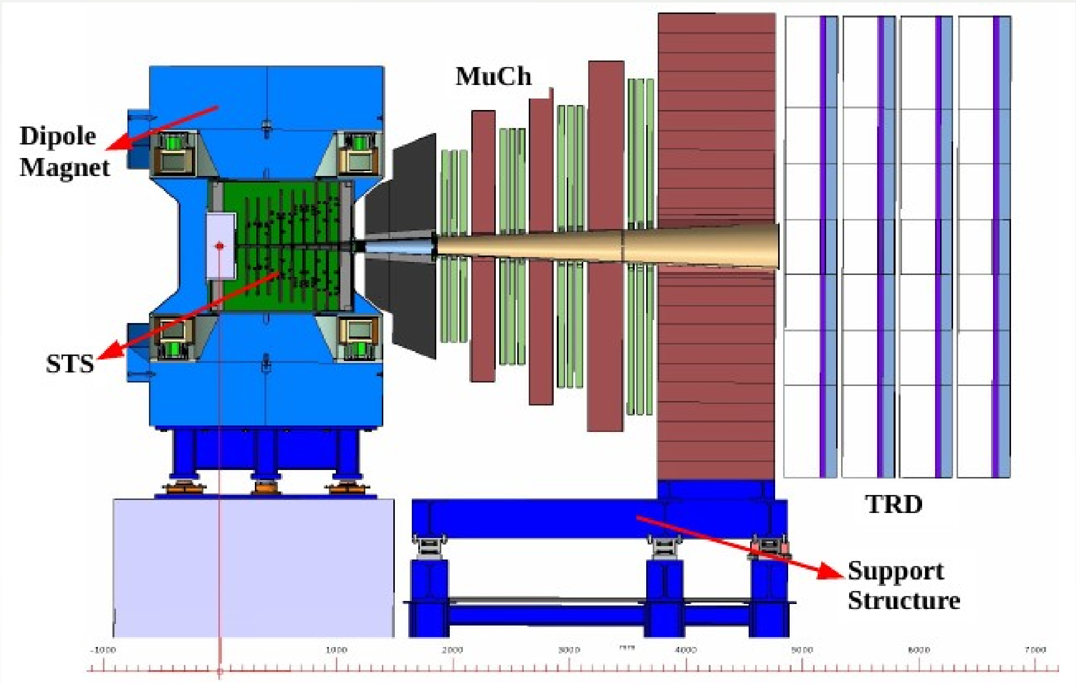
**Ref:** **Eur. Phys. J. A, 53 (3): 60, 2017**

# Muon Setup at SIS100

Aim is to measure dimuon
=> LMVM and
=> Charmonia → $\mu^+\mu^-$

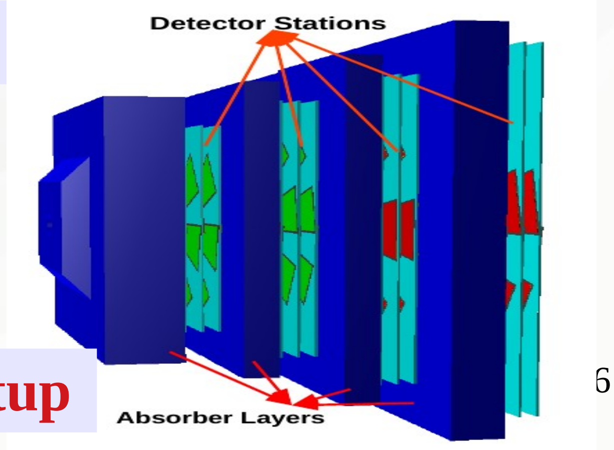
Angular coverage ~ $5^o$ to $25^o$

Segmented absorbers allow us to reconstruct low momentum muon
→ Originating from ρ, ω, φ



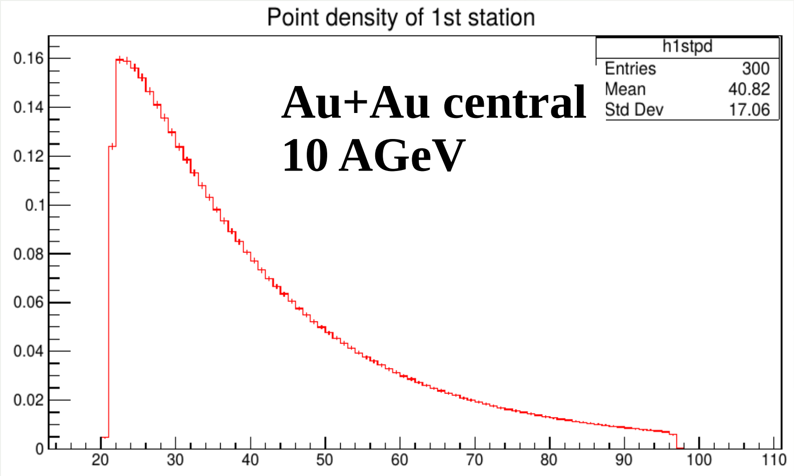

SIS100 muon setup

**Optimized Absorber Thickness:**
**60 C + 20 Fe + 20 Fe + 30 Fe**



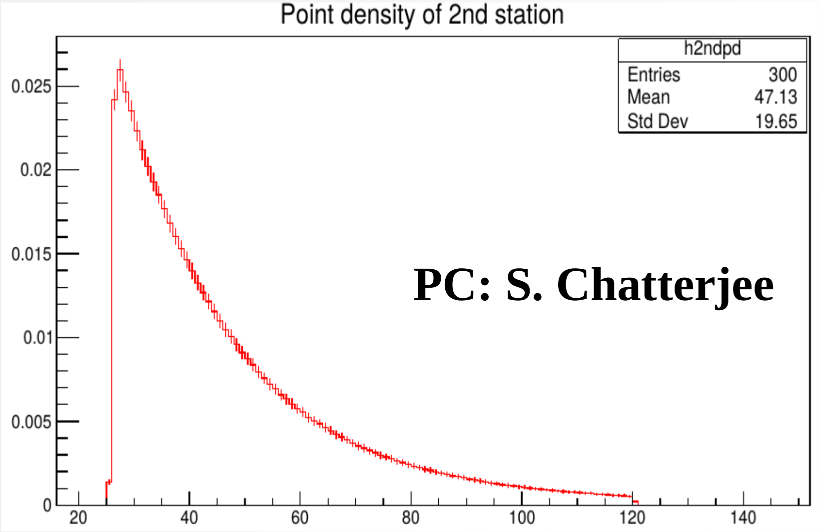

Schematic of CBM-MuCh setup

# Particle Rates on MuCh Stations




| Station No. | Rate (kHz/cm$^2$) |
|---|---|
| 1 | ~400 |
| 2 | ~65 |

**3rd and 4th station – Comparatively low particle rates**




**=> SIS100 setup => 4 station + 4 absorbers**

**=> First two stations :**

**--> GEM detector technology**

**--> High particle rate**

**=> 3rd and 4th stations :**

**--> RPC detector technology**

**--> Relatively lower rate**

# Challenges

## Design Criteria:

- High interaction rate : up to 10 MHz
- Maximum particle rate at 1st stations for Au+Au at 10A GeV minimum bias collision ~ 400 $kHz/cm^2$
- Radiation resistance
  (for Neutron ∼$10^{12}$ $n_{eq}/cm^2$ and for Gamma ∼30 krad – equivalent to 10 year operation of CBM)
- Data to be readout in a self triggered mode
  - must for all CBM detectors
  - events reconstruction will be done off-line by grouping the time-stamps of the detector hits

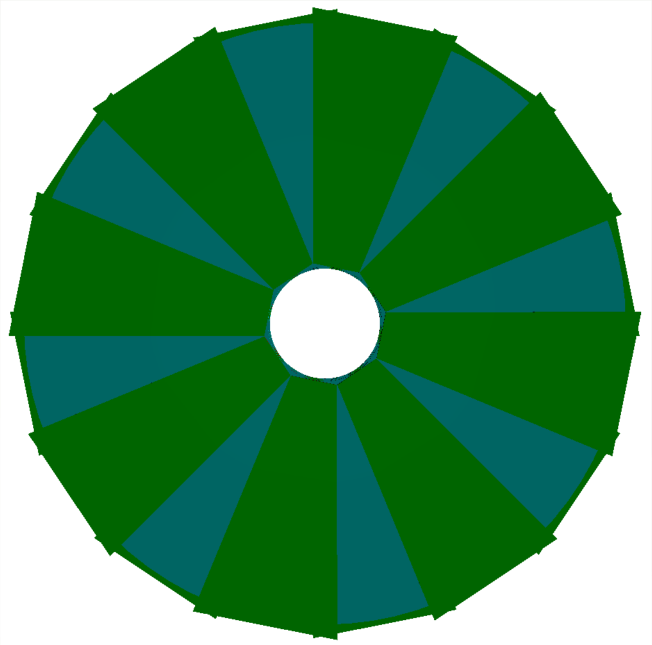
**Trapezoidal shaped triple GEM chambers will be used in the first two stations of MuCh**

# Mechanical Layout

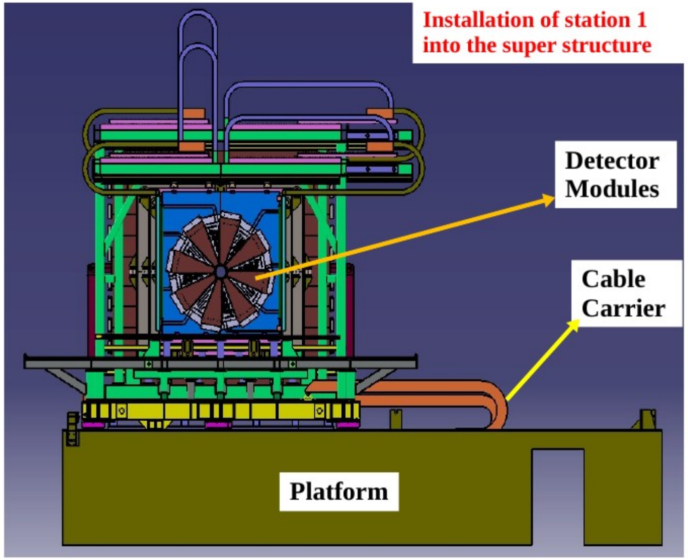
**Number of Sector for 1st station:**
16 per layer = 48 (total)
$R_{Max} - R_{Min}$ = ~ 80 cm

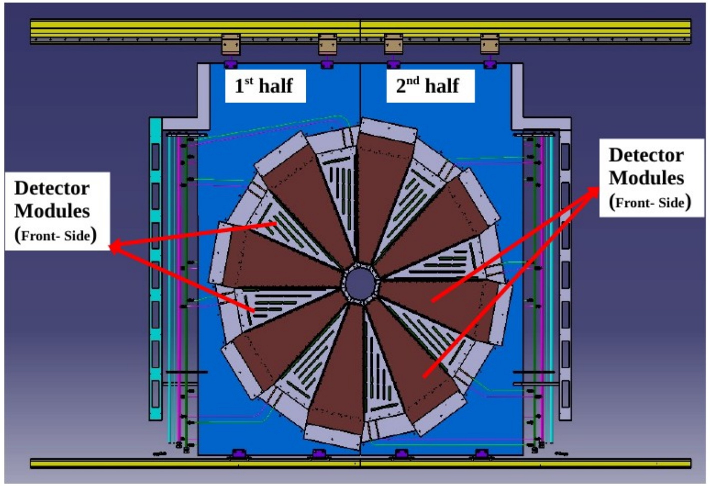
**Number of Sector for 2nd station:**
20 per layer = 60 (total)
$R_{Max} - R_{Min}$ = ~ 100 cm

**Placement of modules**



**Readout channel:**
**– 1st Station**
**~2231 per module**
**~107k**

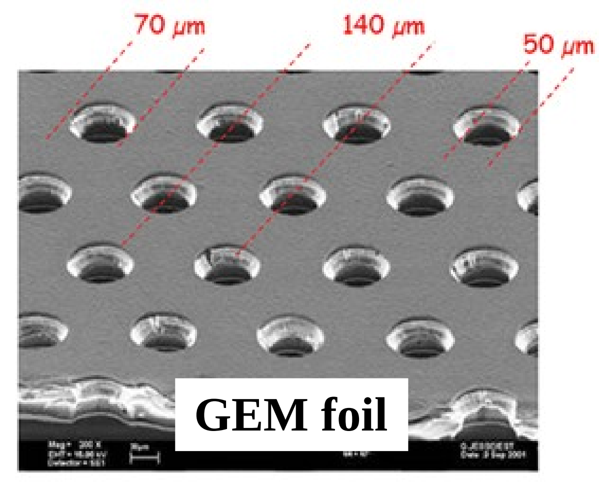


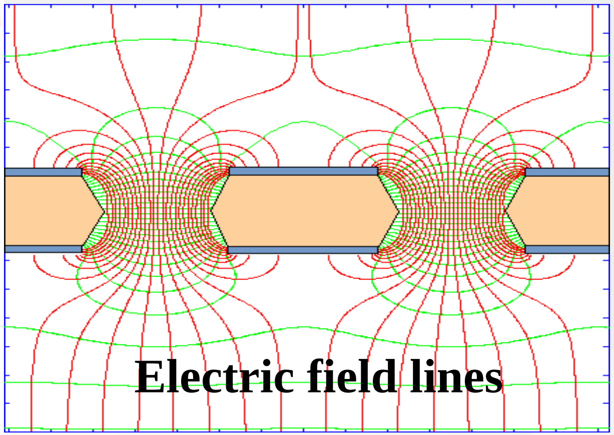
# GEM Detector

First introduced by **F. Sauli** in 1997

- The "standard" GEM foil consists of **50 µm** thin dielectric polymer (polyimide), **5 µm thick metal (copper)** layers are coated on both side of it
- Regular holes of **diameter 70 µm** with a **pitch** of **140 µm** is created using photo-lithographic technique
- Potential difference between of **500 V** (say) applied on the electrodes – High electric field **~70 kV/cm**
- When a charged particle passes through the active medium, it ionizes gas and creates **e⁻-ion pair**. These electrons then multiplied inside the holes
- The amplified electrons gives signal on the readout electrode



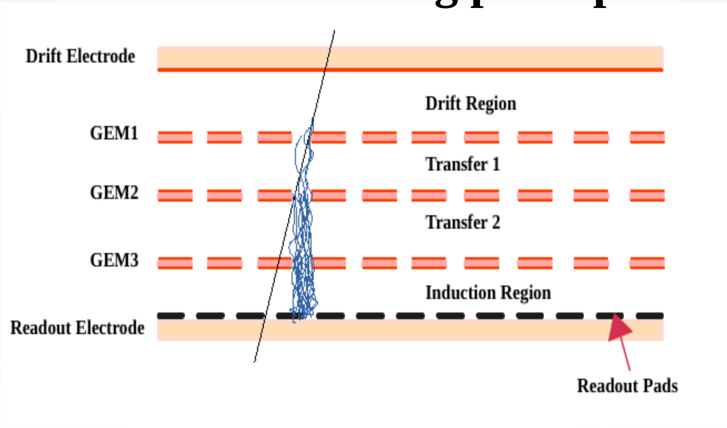
GEM foil

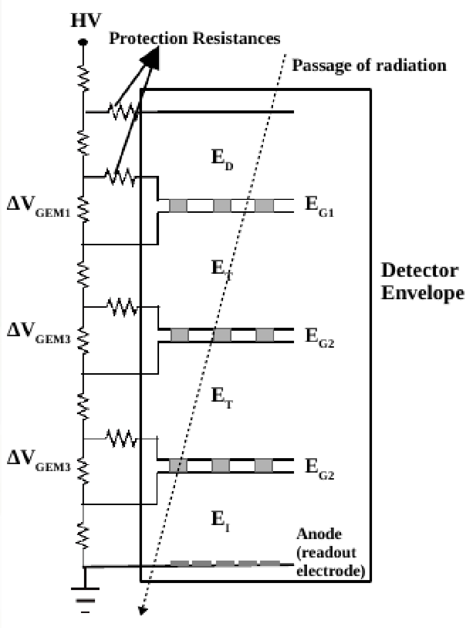

Electric field lines

## Advantage of GEM

– High rate capability
– High gas gain
– Low discharge probability
– Good spatial resolution

Working principle



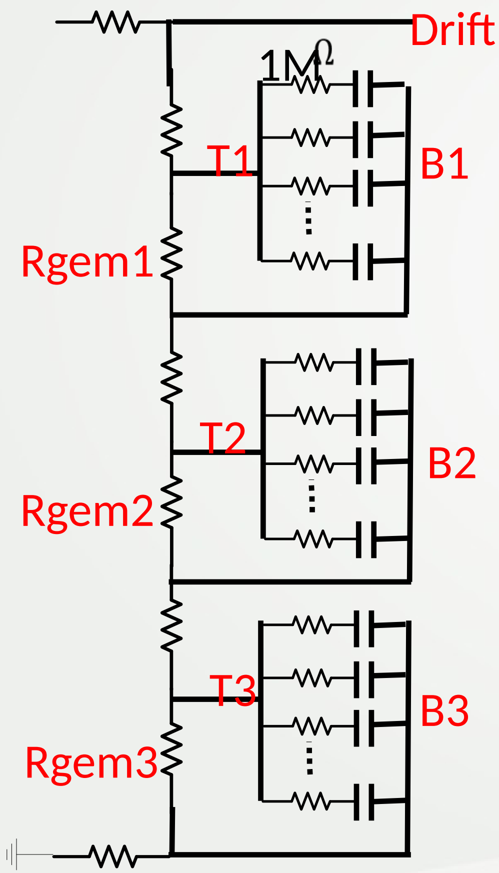



Resistive divider circuit

# Real-size GEM Detector for CBM-MuCh

# Optocoupler Based HV Design

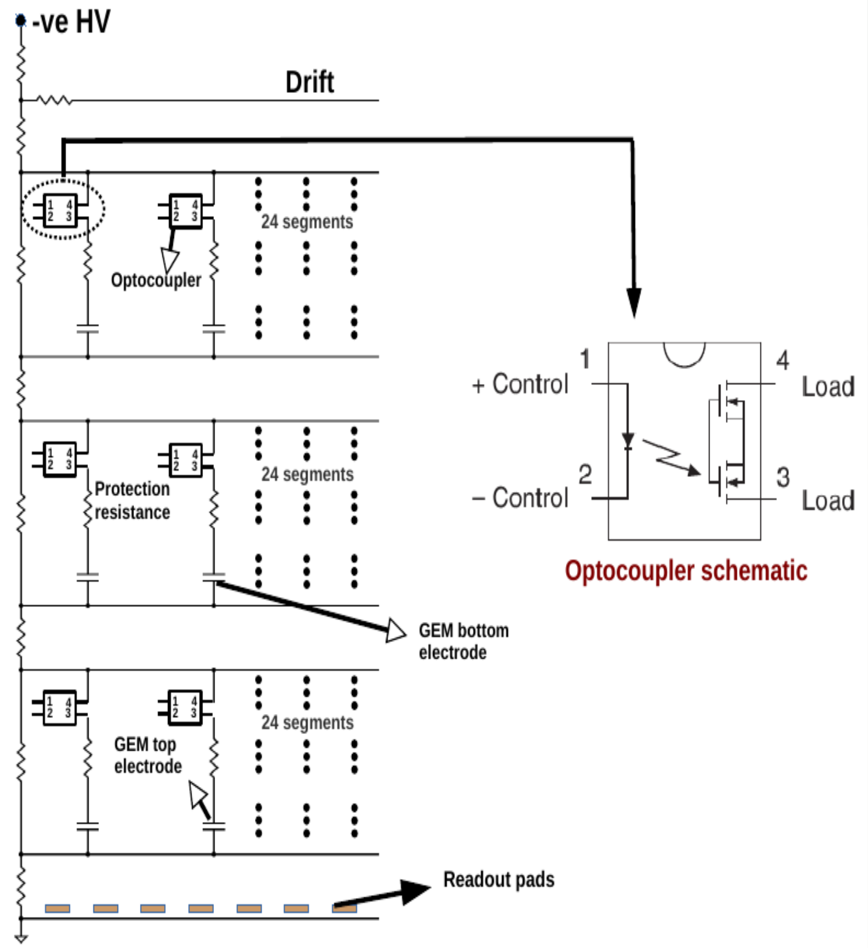
## Conventional Design




24 segments

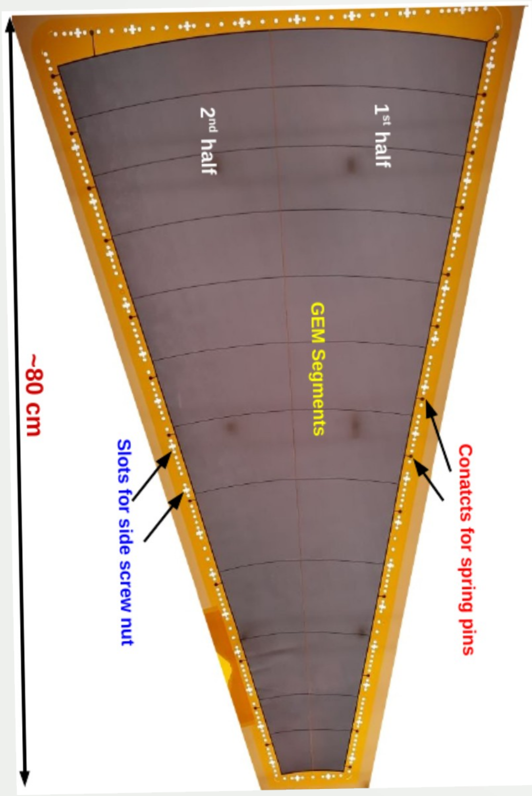
72 optocoupler switches/ module

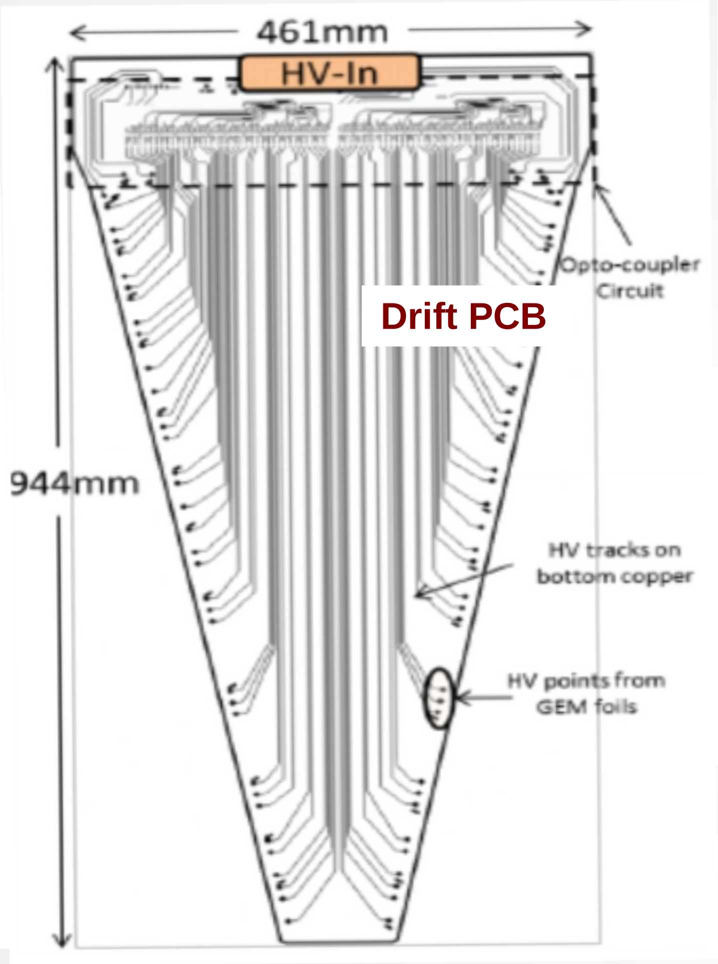
## Optocoupler Based Design



# Optocoupler Design for GEM

Schematic of HV lines for GEM foil on the drift PCB




– 24 segments on top side
– One HV connection for each segments
– Optocoupler based biasing scheme

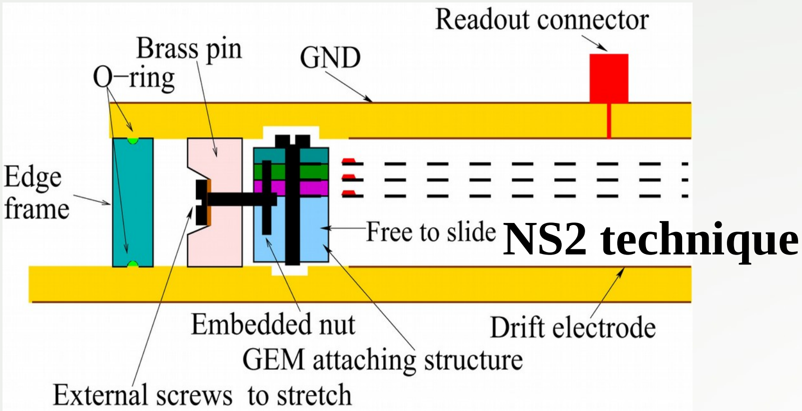
Readout PCB (first station of CBM-MuCh)
--> ~2200 pad with gradually increasing sizes
--> Total front end board needed = 18

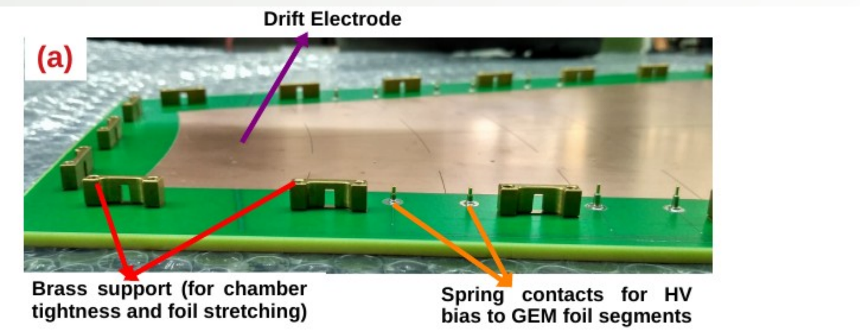
--> Active area
Dx1 = ~ 7.5 cm
Dx2 = ~ 40 cm
Dy = ~ 80 cm

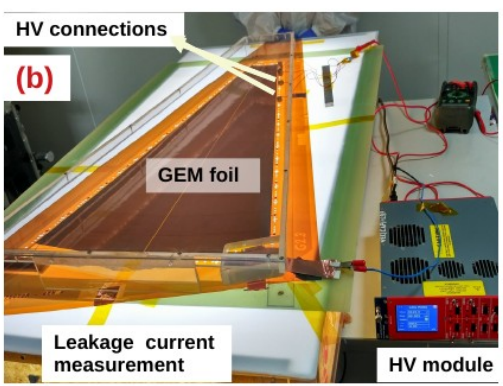


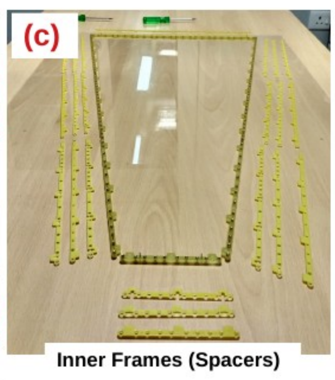
Ref: A. Kumar, et.al., Nucl. Inst. and Meth. A 958, 162905 (2020)

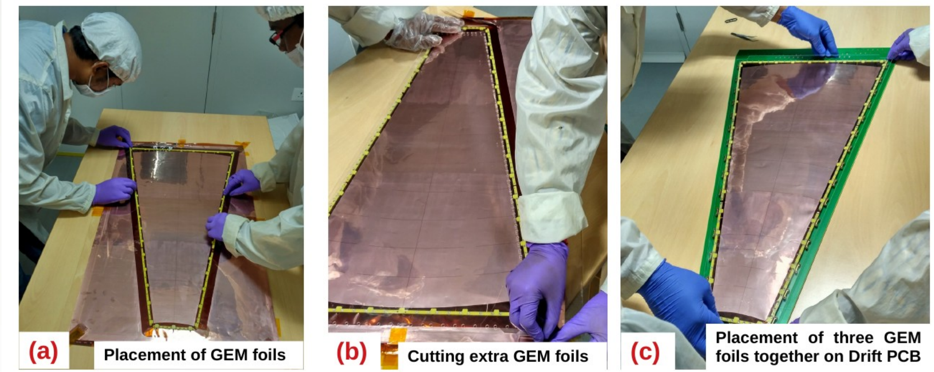
# Assembly of Real-size Chamber at VECC

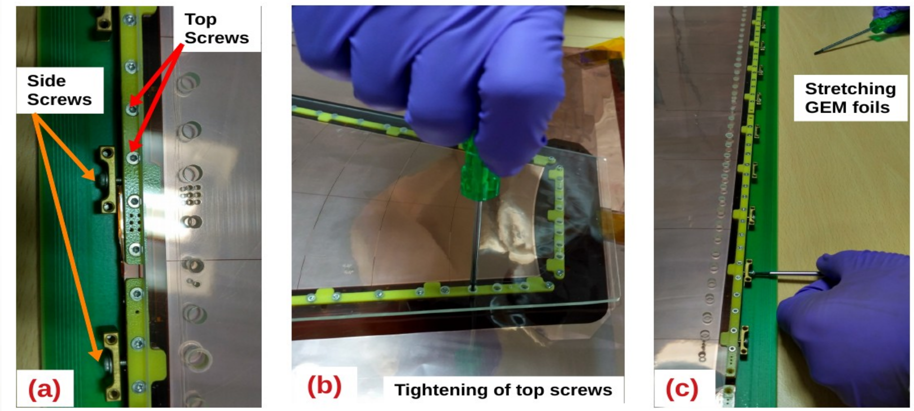


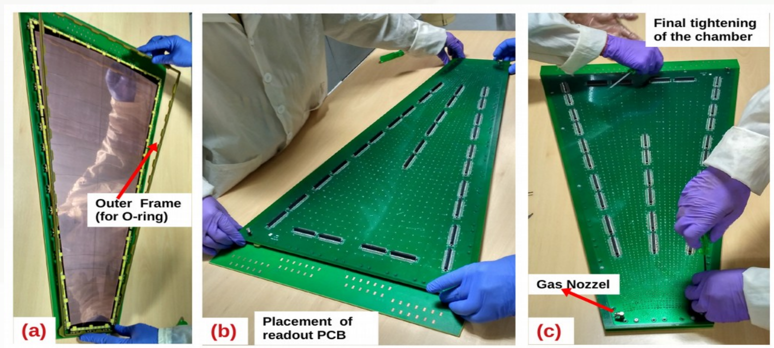



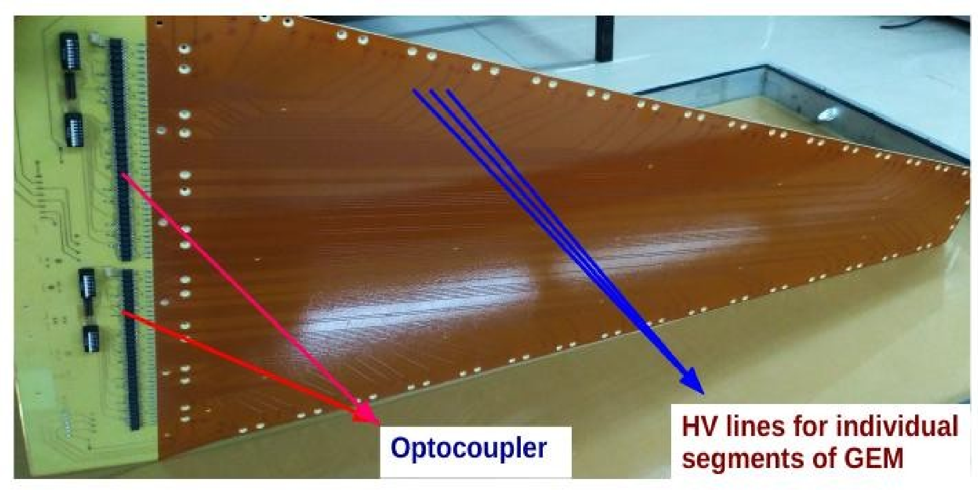



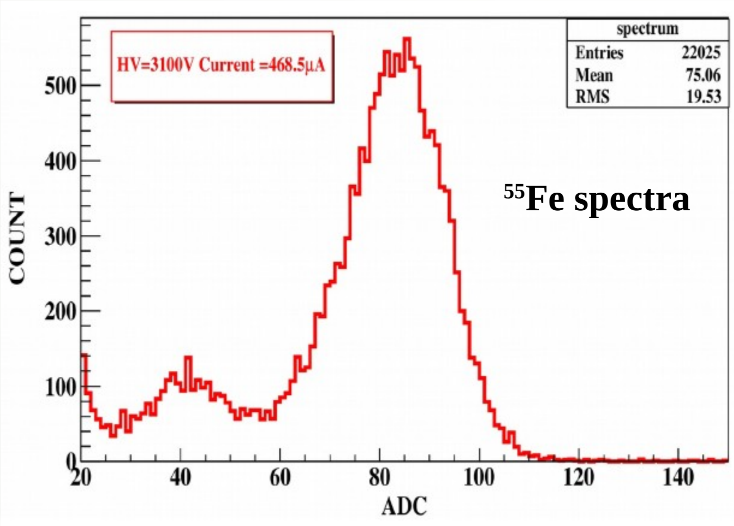



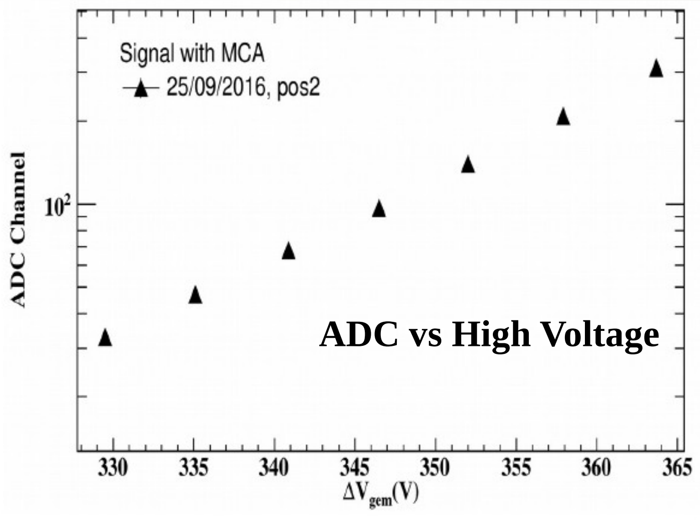



# Fabricated drift PCB and test in lab







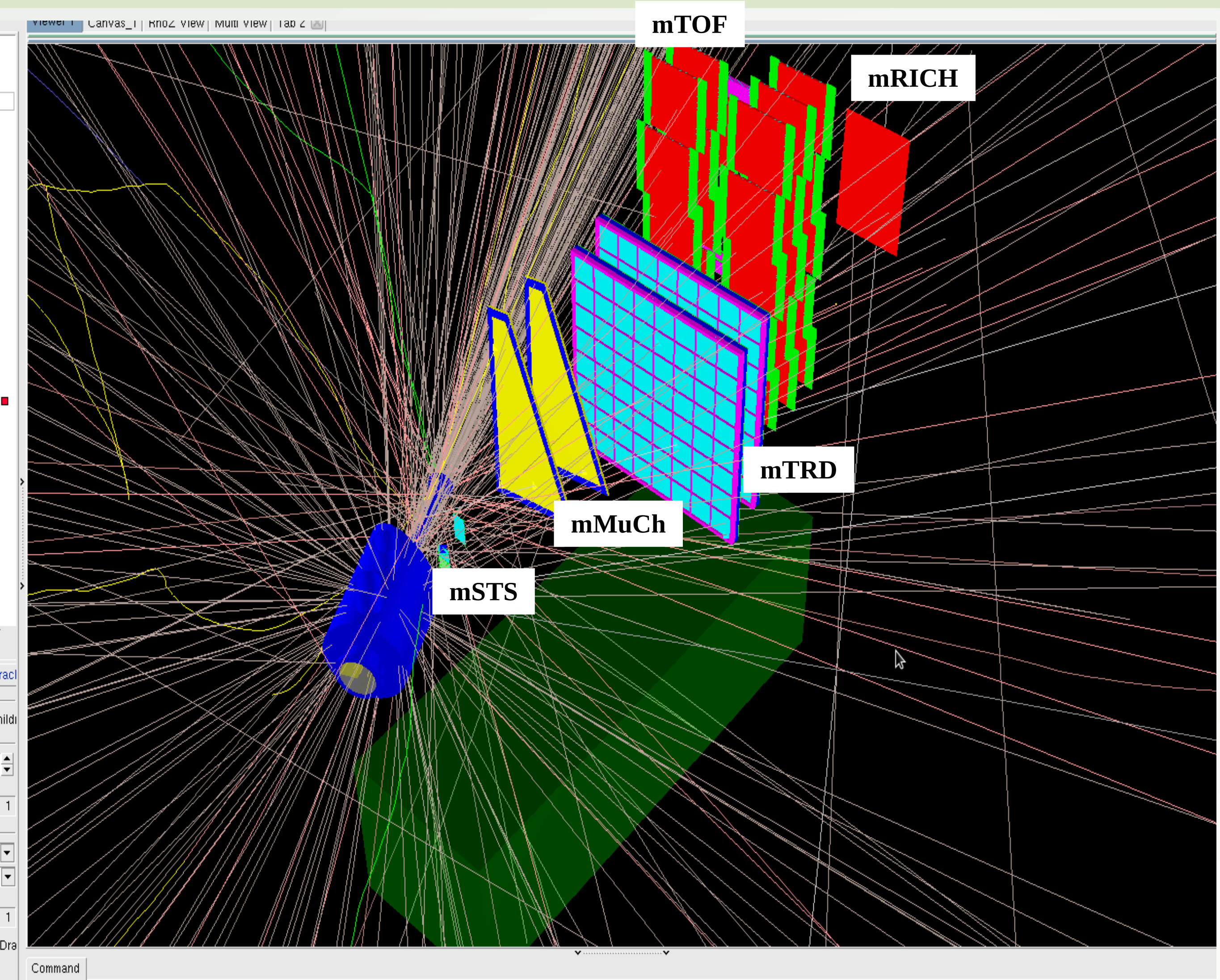
# Testing of GEM Chambers in mCBM Experiment

# Objectives

- **Test of the detectors in N-N environment with the high rate as it would be in CBM experiment**
- **Test with STS/MuCh-XYTER electronics – the version which will be used in main CBM**
- **Test with actual DAQ – free-streaming data acquisition**
- **New optocoupler based HV design**
- **Modified size – Station-1 modules**
- **Long run test of modules**

# mCBM Experiment

**mCBM experiment:** A CBM full system test-setup called mCBM@SIS18 (”mini-CBM”, shortened to mCBM) – as a part of FAIR phase-0




## Objectives:

**— Operation of the detector prototypes in a high-rate nucleus-nucleus collision environment**

**— Free-streaming data acquisition system including the data transport**

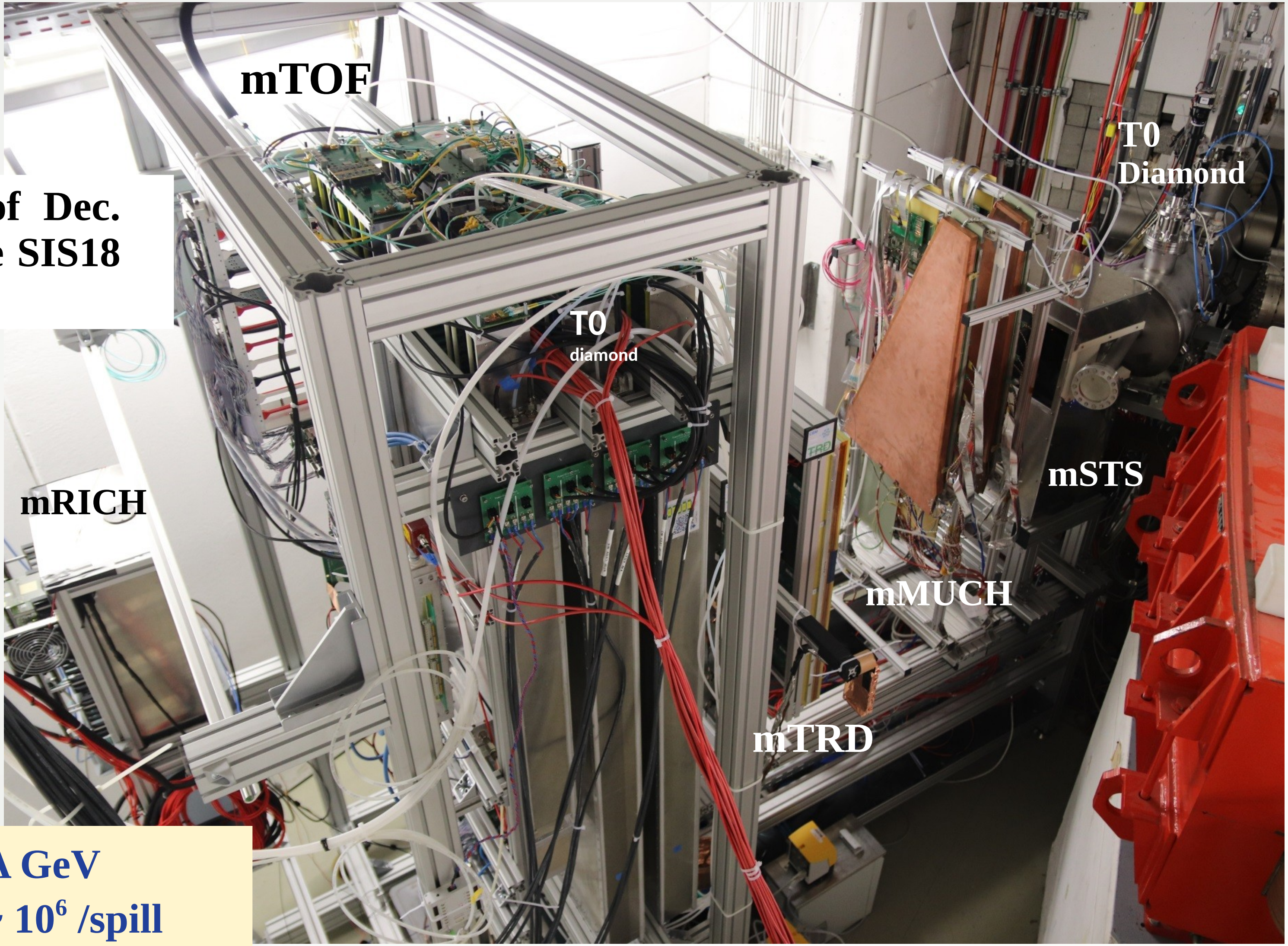
**— Online track and event reconstruction as well as event selection algorithms**

**— Offline data analysis and**

**— Detector control system**

**— $\Lambda^0$ reconstruction**

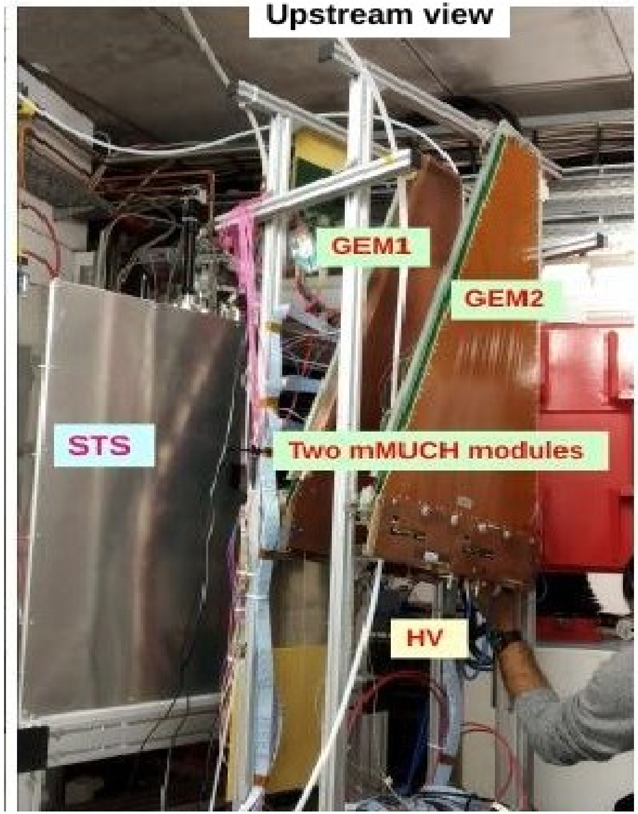
# Picture of mCBM Setup

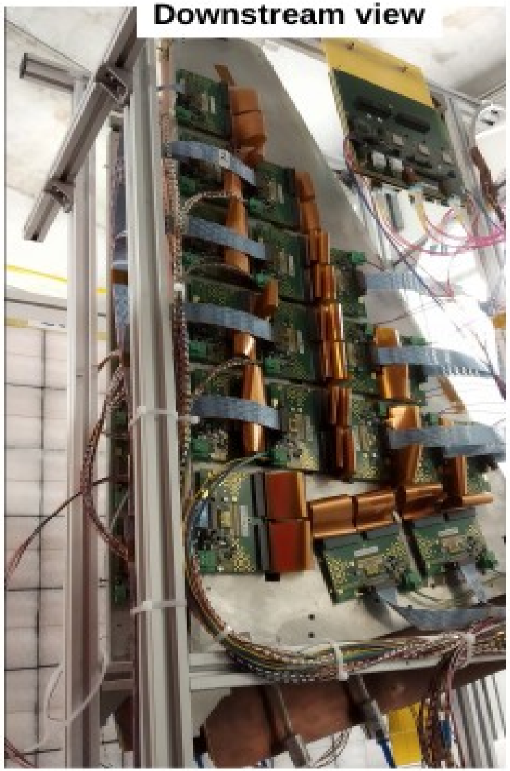



mCBM setup as of Dec. 2019, located at the SIS18 facility of GSI

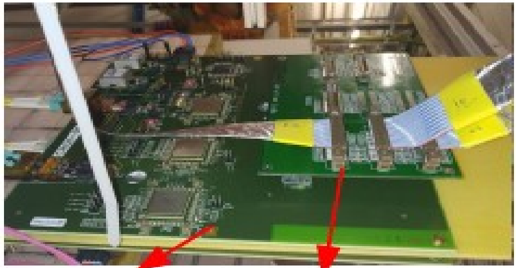
- Ar + Au @ 1.70A GeV
- Beam intensity ~ $10^6$ /spill
- Target thickness 2.5 mm

# Picture of mMuCh Setup

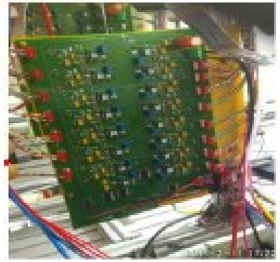


FEBs attached to the Al-cooling plate


CROB FMC


FEB


LVDB

**Z-position of MUCH**
**GEM1 : ~84 cm**
**GEM2 : ~106 cm**

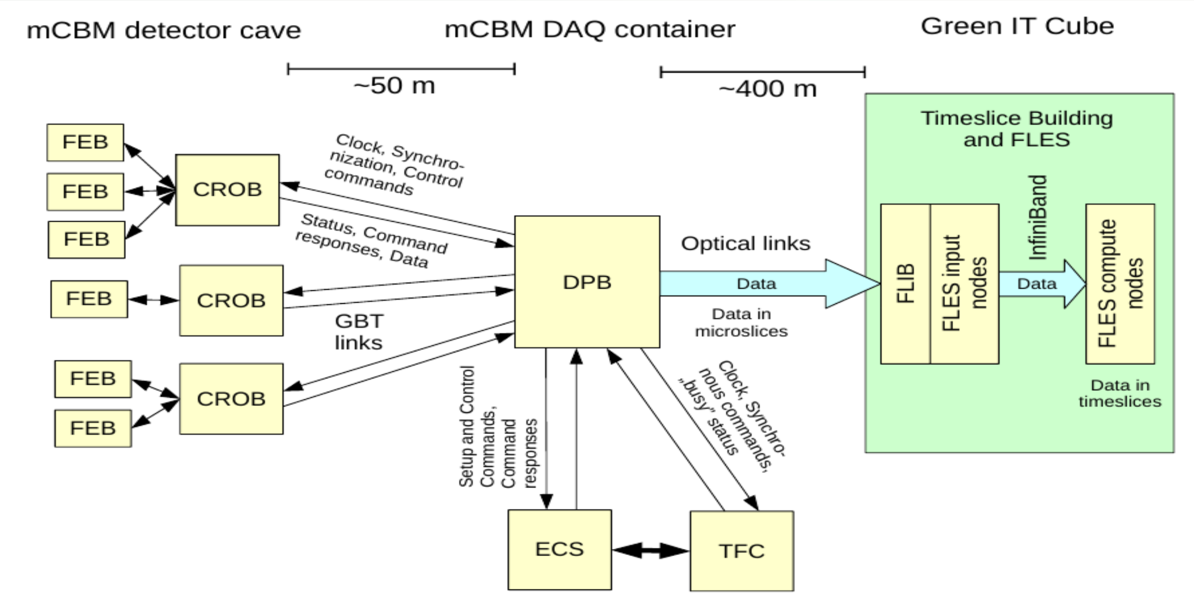
**-> Readout channels per module = ~2200**
**-> Area = ~2000 $cm^2$**

**Minimum pad size = ~4 mm**
**Maximum pad size = ~17 mm**

**GEM1 acceptance : 17 FEBs**
**GEM2 acceptance : 10 FEBs**

# mCBM DAQ

## mCBM Readout Schematic




**STS/MuCh-XYTER**

-> Self-triggered electronics

-> 128 channels + 2 test channels

-> Can handle average hit rate ~250 kHz/channel

-> Dynamic range = 100 fC

-> Provides both timing and ADC information

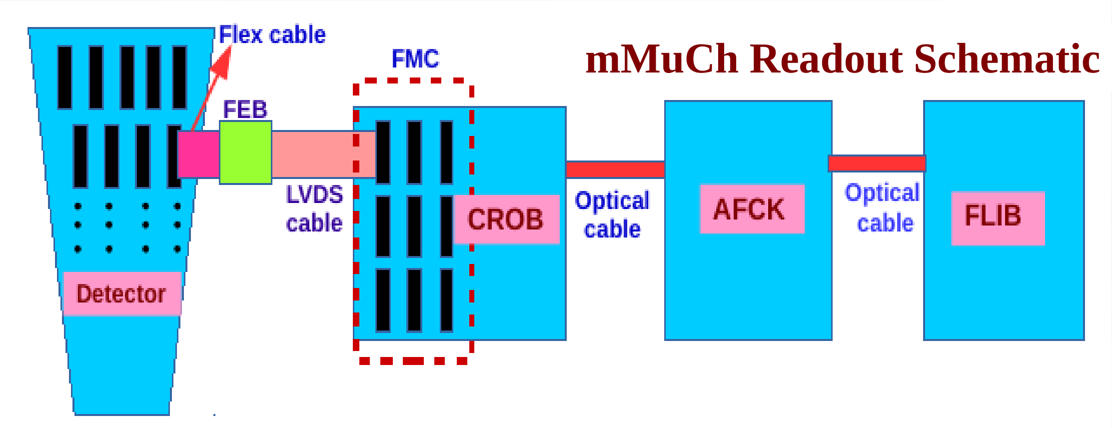
-> 5 bit flash ADC

-> Time resolution ~4-5 ns

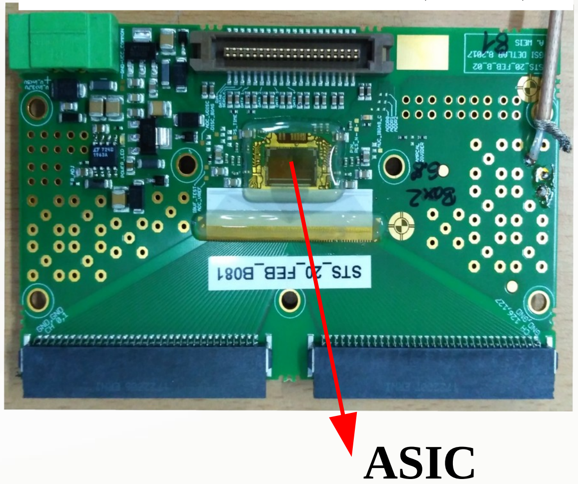
-> Heat generated = ~2-3 W / FEB

**One module require 18 FEBs**
**Heat generated for one module = 2.5 x 18 = 45 W**

## mMuCh Readout Schematic

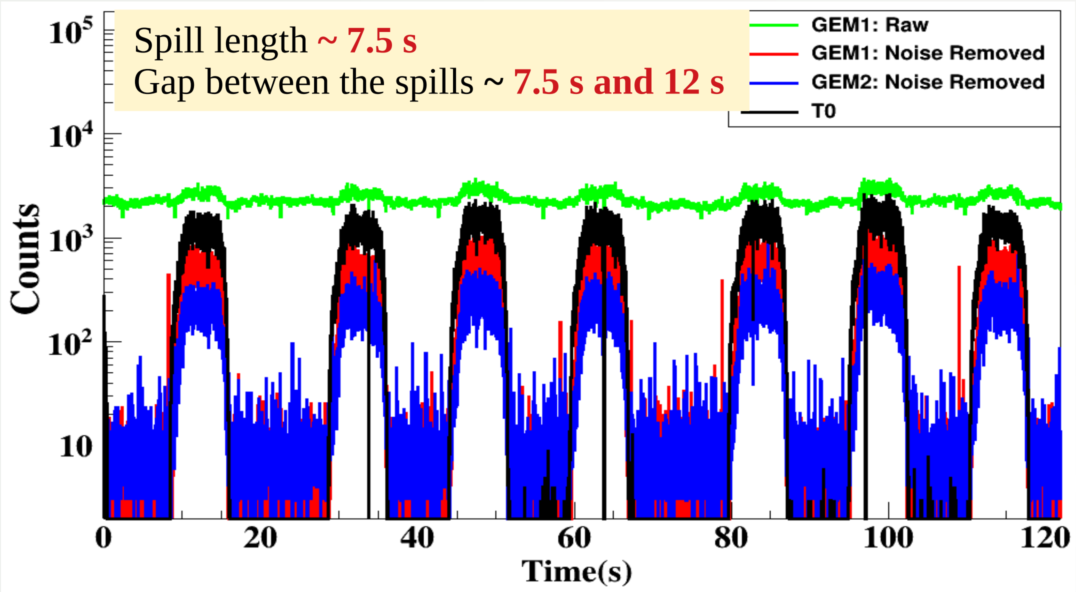


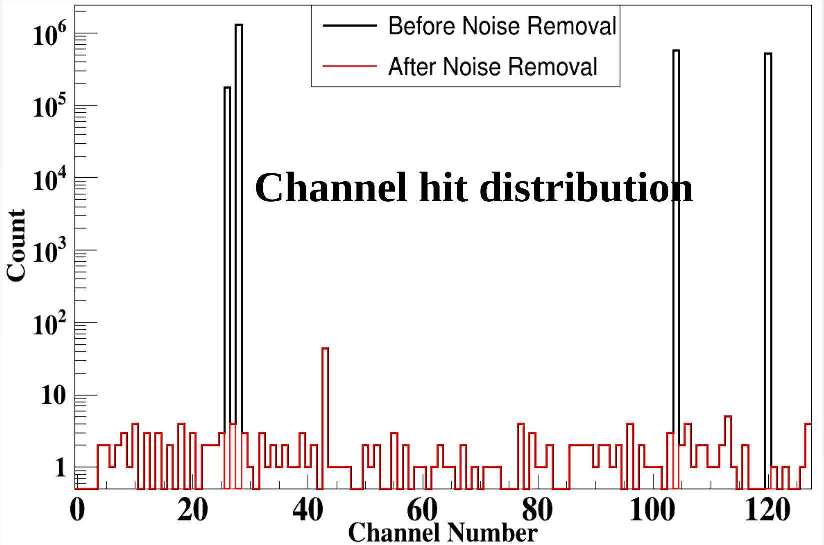

**Front-End-Board (FEB)**

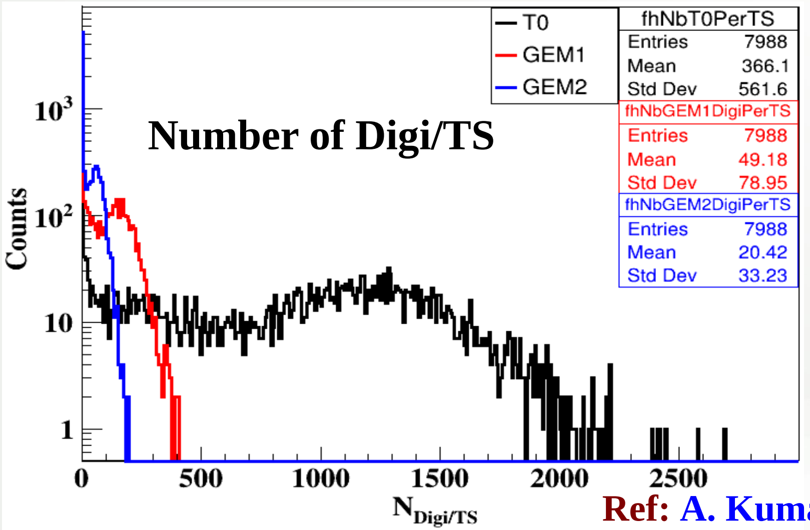


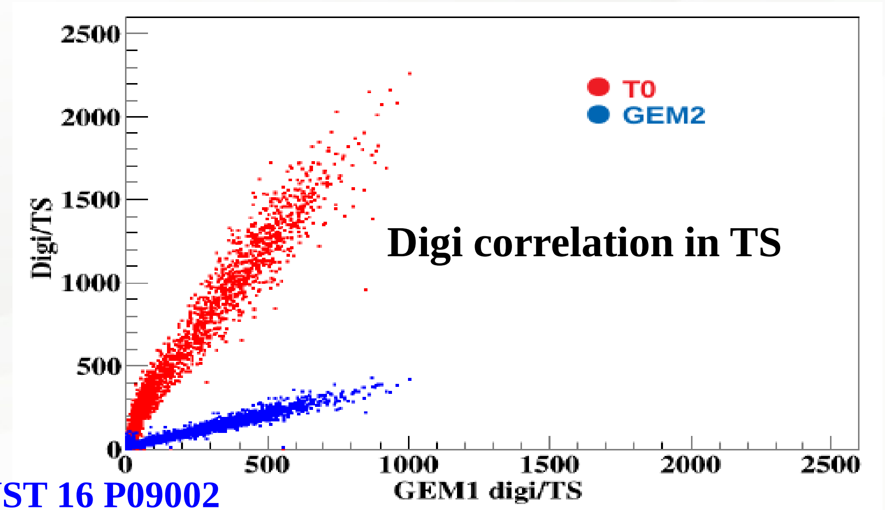
# Analysis and Results

**Ar + Au at 1.7 A GeV, Nov./Dec. 2019**



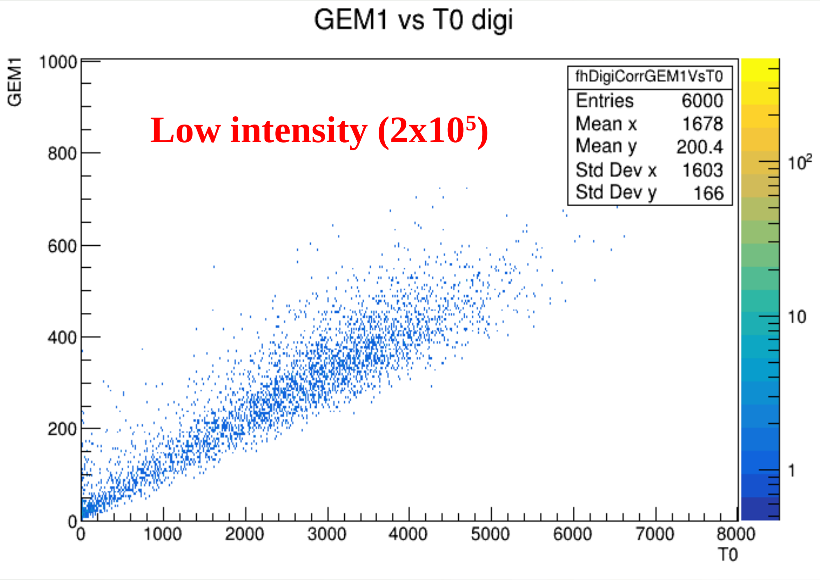



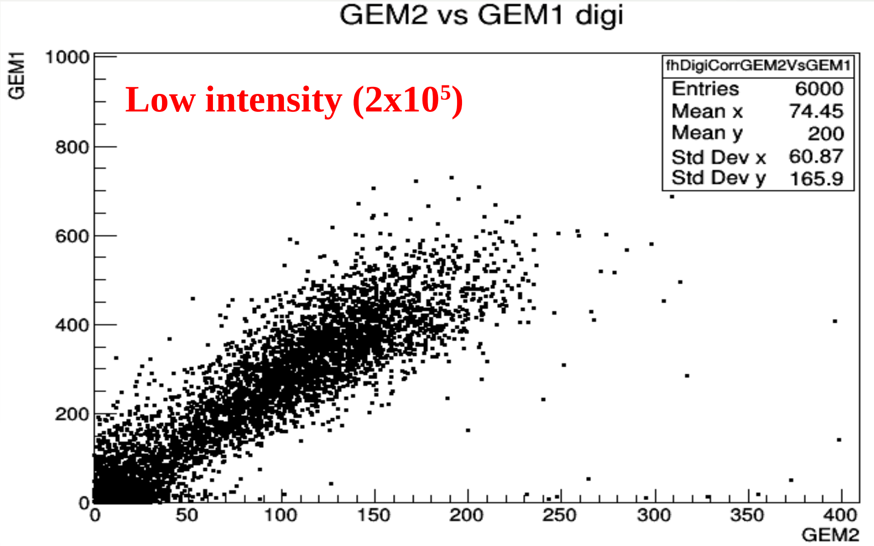



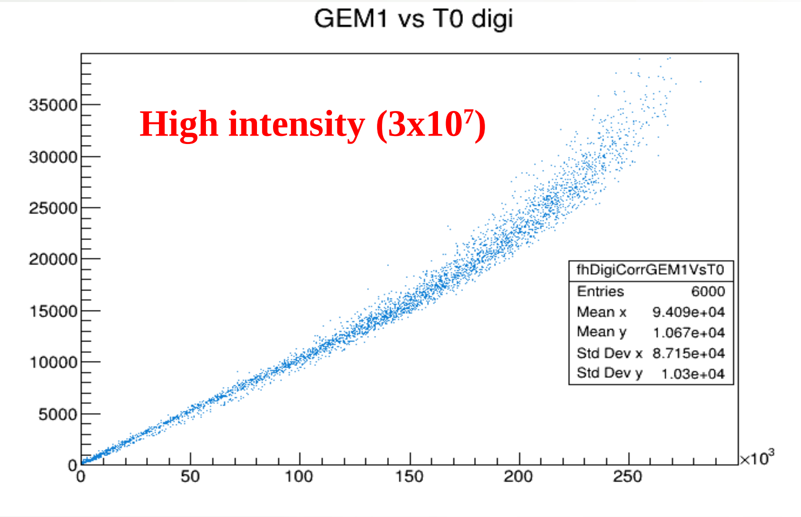



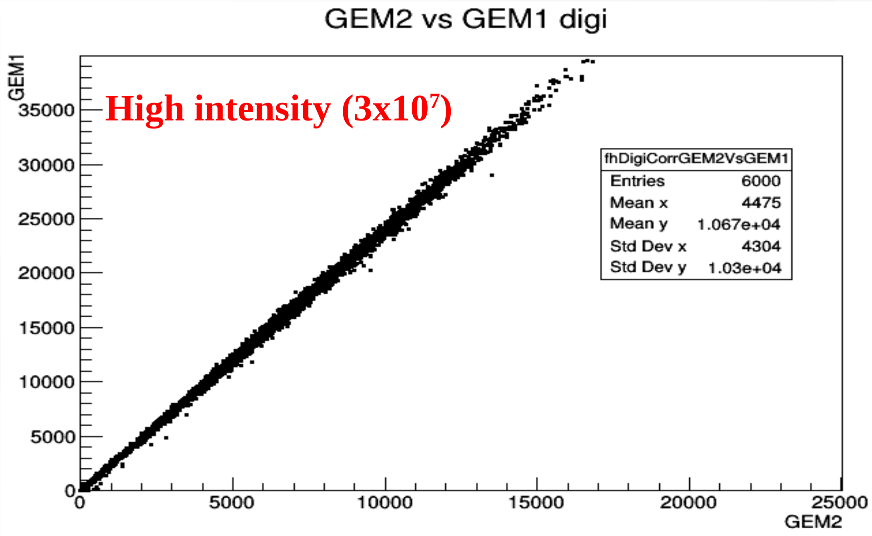

**Ref: A. Kumar et al 2021 JINST 16 P09002**

# Digi Correlation TS

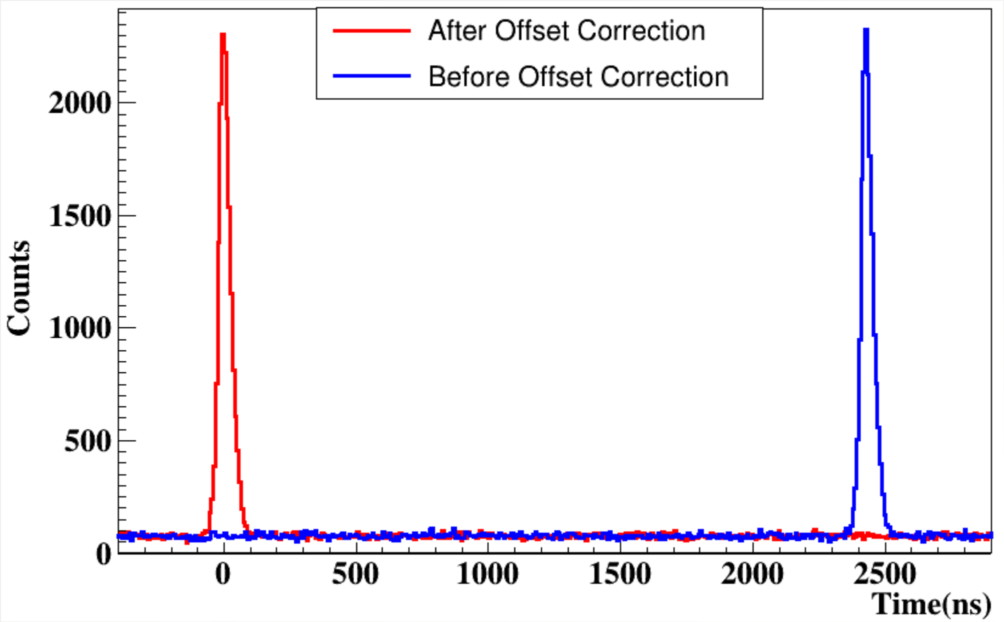


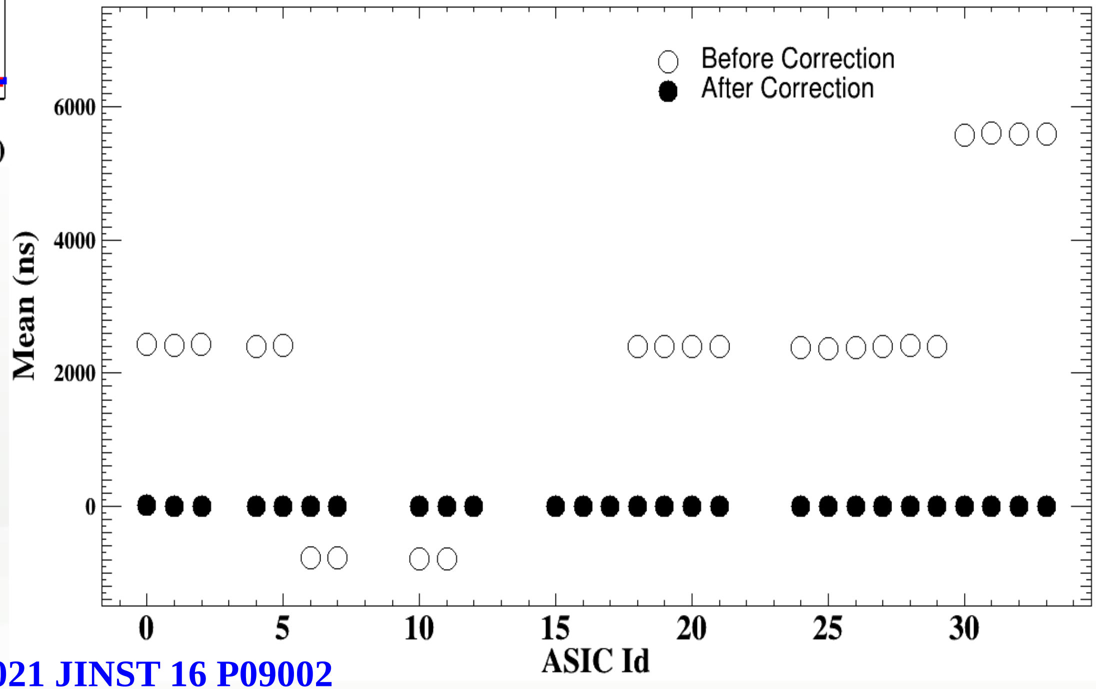



# Time-Offset and Correction




**Time correlation between one FEB of GEM1 with T0 in time-slice (TS)**
- **Before time-offset correction**
- **After time-offset correction**

**Variation of time-offset with ASIC Id**
- **ASIC Id from 0-23 – GEM1**
- **ASIC Id from 24-36 – GEM2**

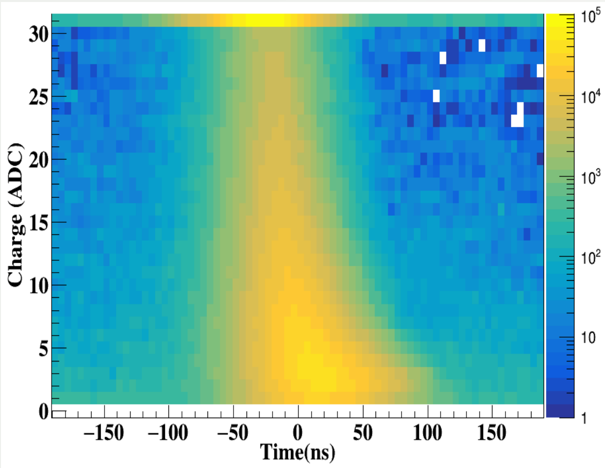


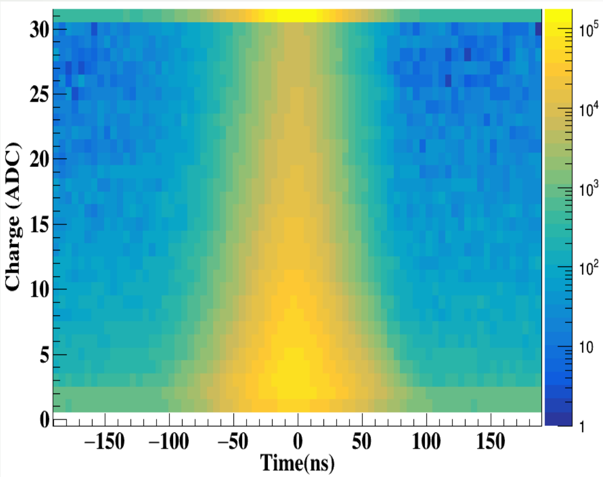

Ref: A. Kumar et al 2021 JINST 16 P09002

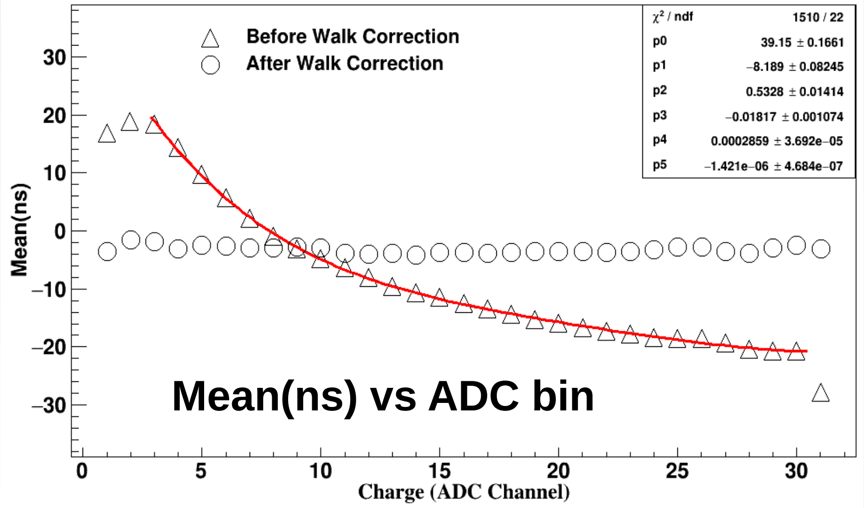
# Time-Walk Correction and Time Resolution

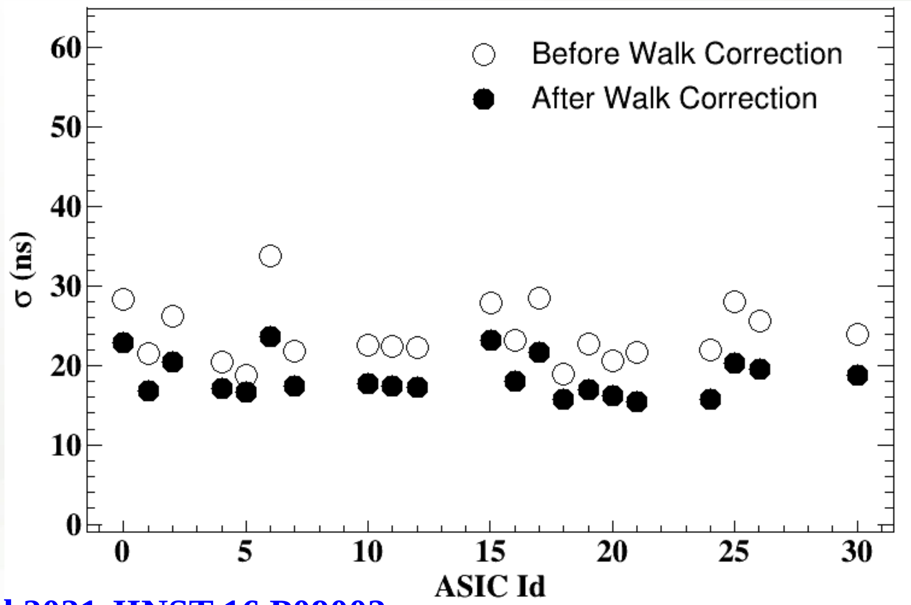
**Ar + Au at 1.7A GeV, Nov./Dec. 2019**

**ADC vs time diff**



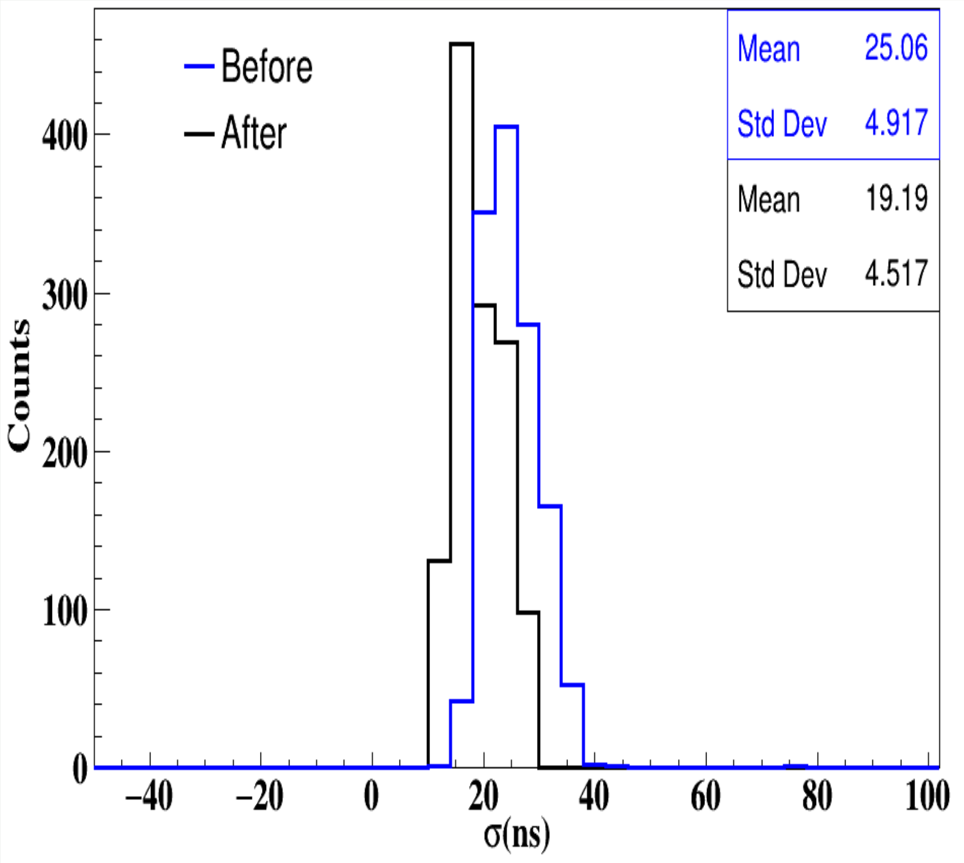



**Ref: A. Kumar et al 2021 JINST 16 P09002**

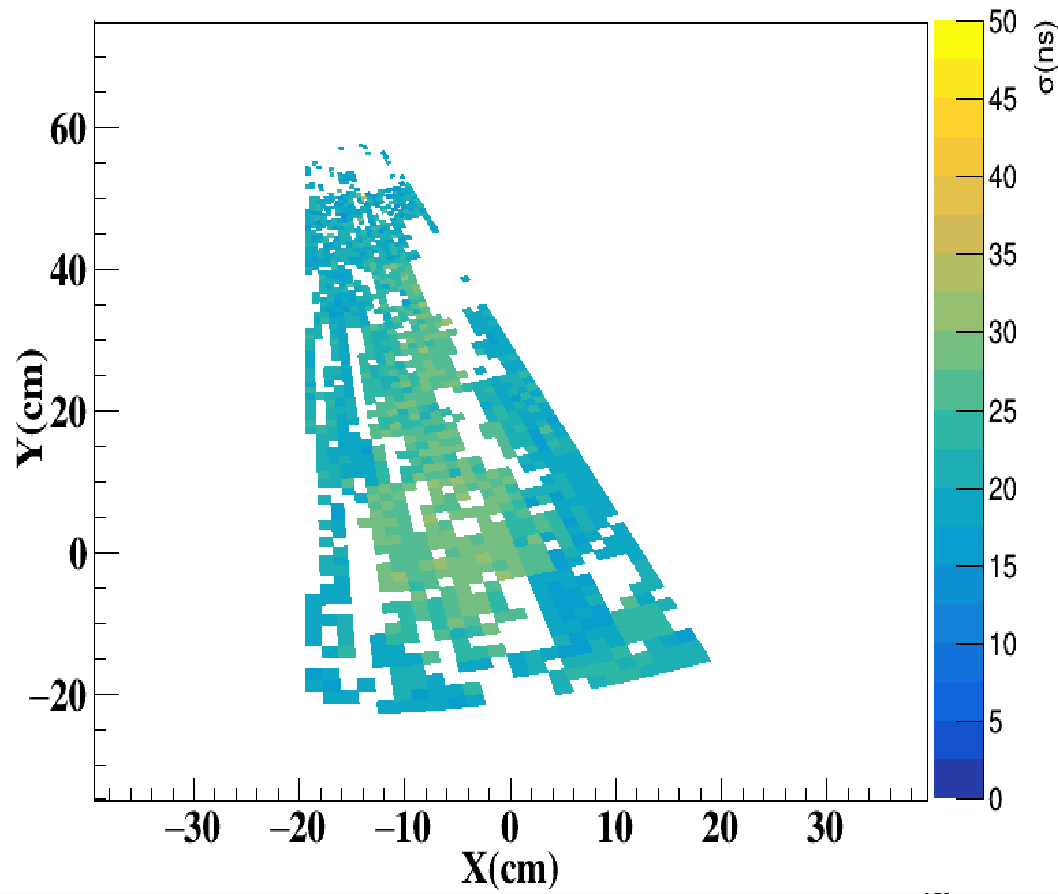
# Time Resolution Uniformity Map

Ar + Au at 1.7A GeV, Nov./Dec. 2019

**σ (ns) distribution for all channels of GEM1**




**2D map of time resolution for GEM1**



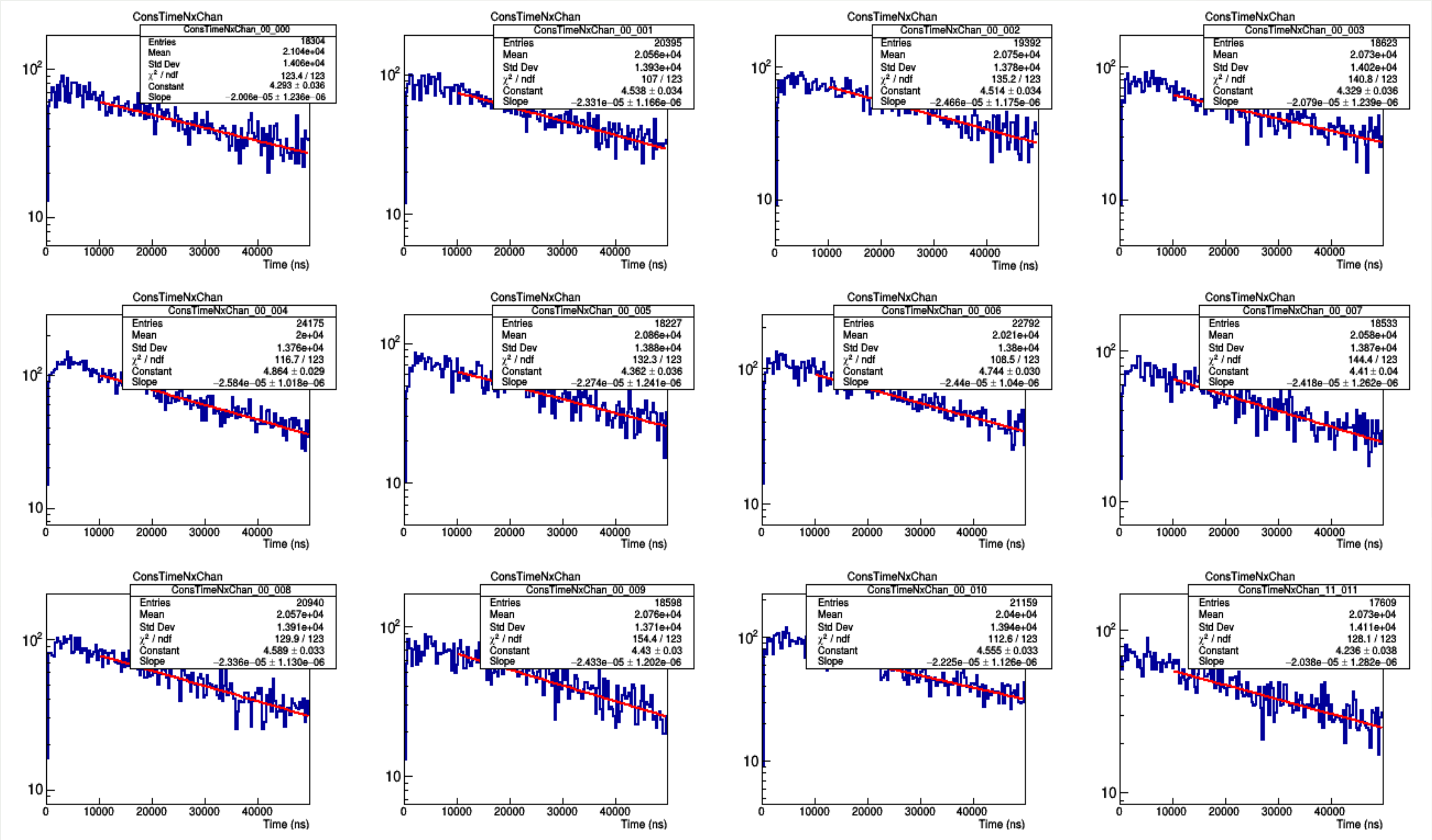



Ref: A. Kumar et al 2021 JINST 16 P09002

# Particle Rate

## Consecutive hit time distribution for each channel

**March 2019**
**Ag+Au**

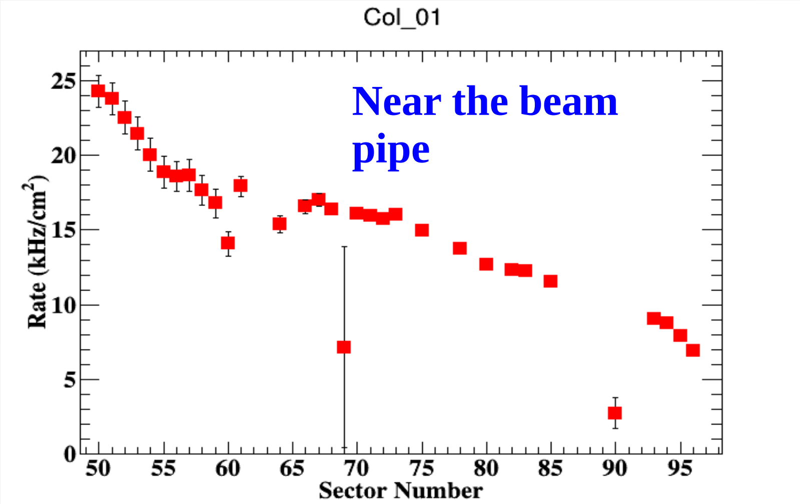


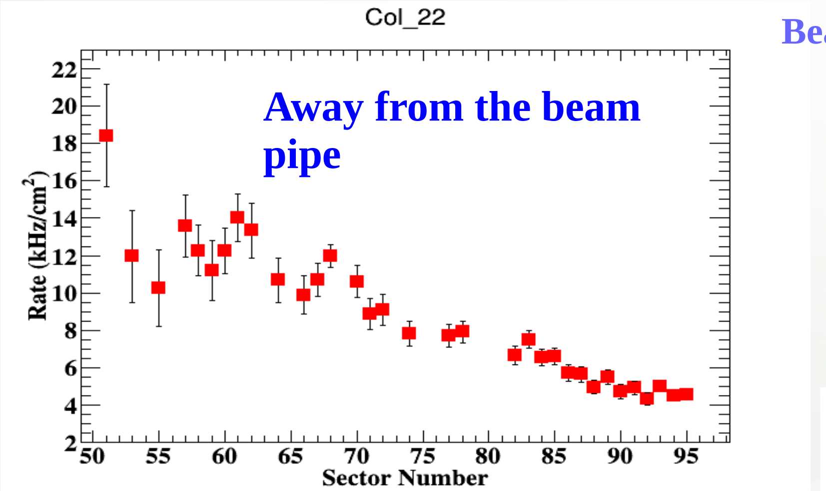

**Similar fit has been done for all other channels..**
**12 FEBs x 128 = 1536 channels**

# Rate Comparison

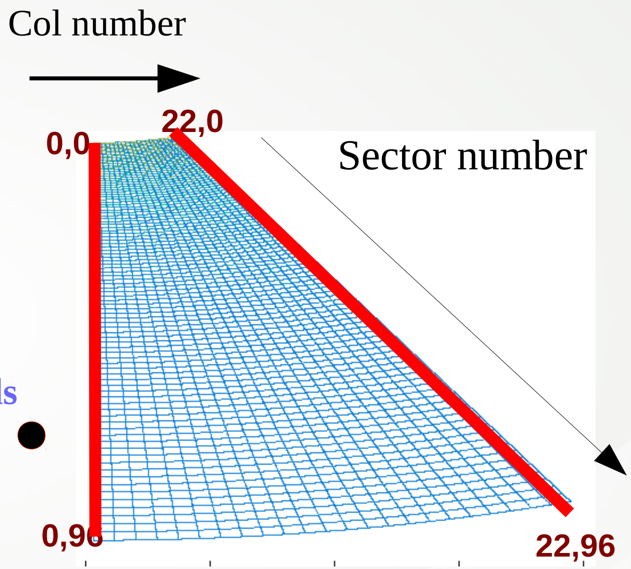
**Target thickness : 2.5 mm**
**Beam Intensity=10^7/sec**
**GEM1**

**March 2019**
**Ag+Au**




**Beam direction inwards**

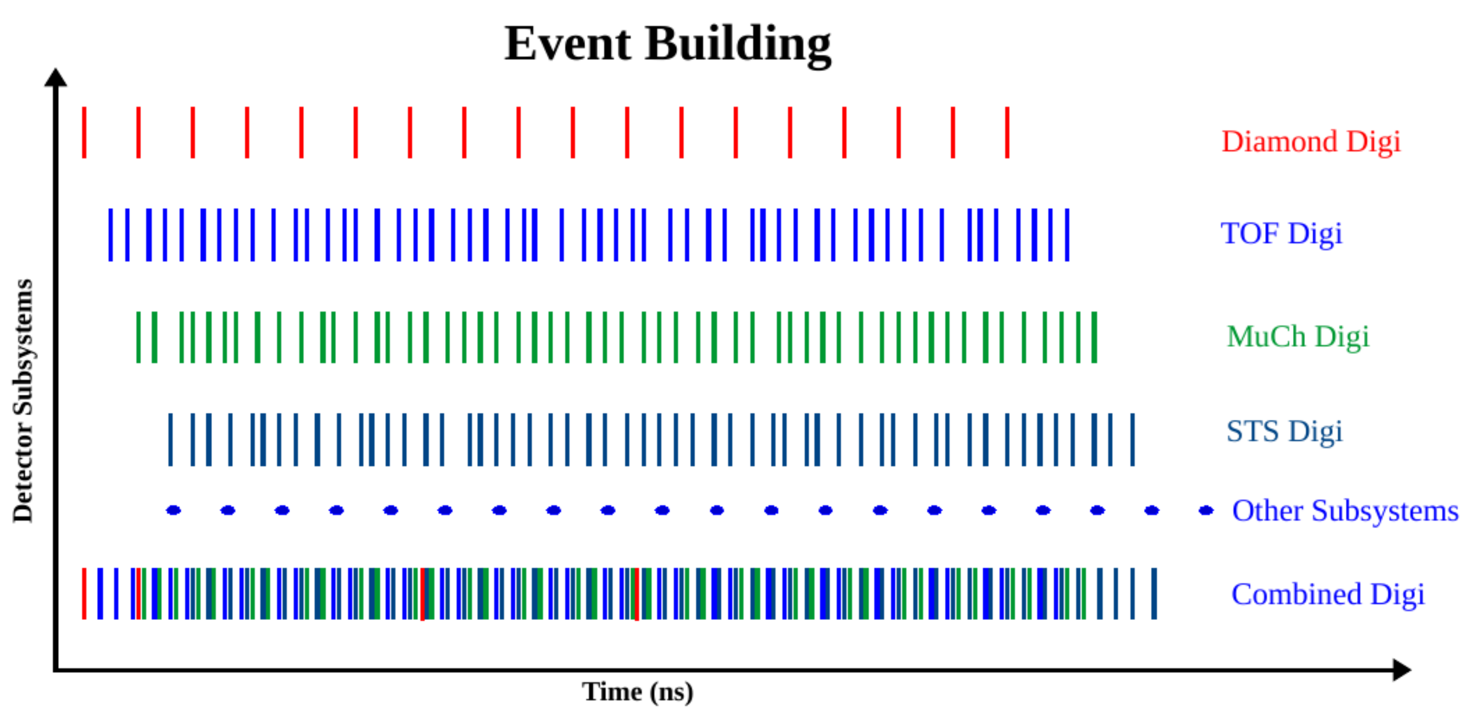



**Rate near the beam pipe is high (factor of ~1.6) compared to rate away from the beam pipe**

# Event Building in Free-Streaming Data and Analysis

# Event Building

**Algorithms :** ==> Consecutive time gap between the digis.
==> Fixed time window.

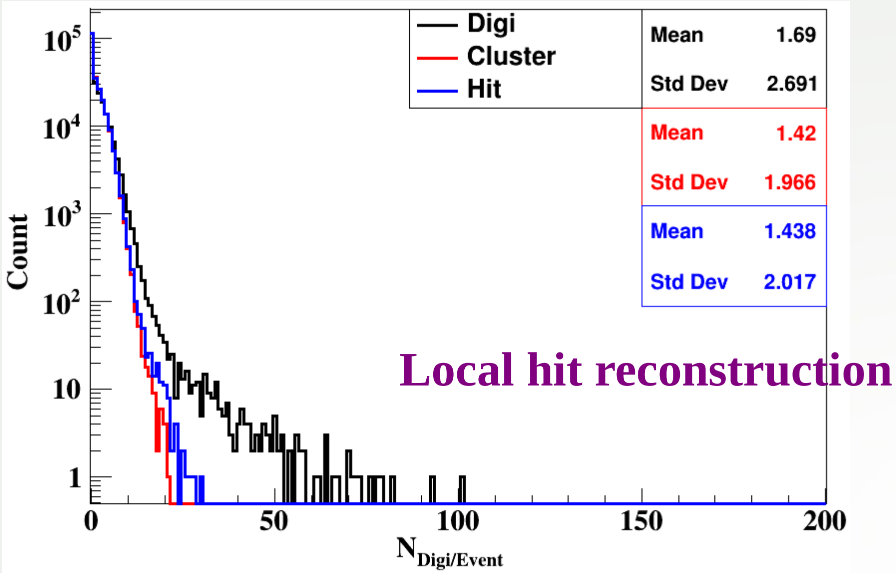


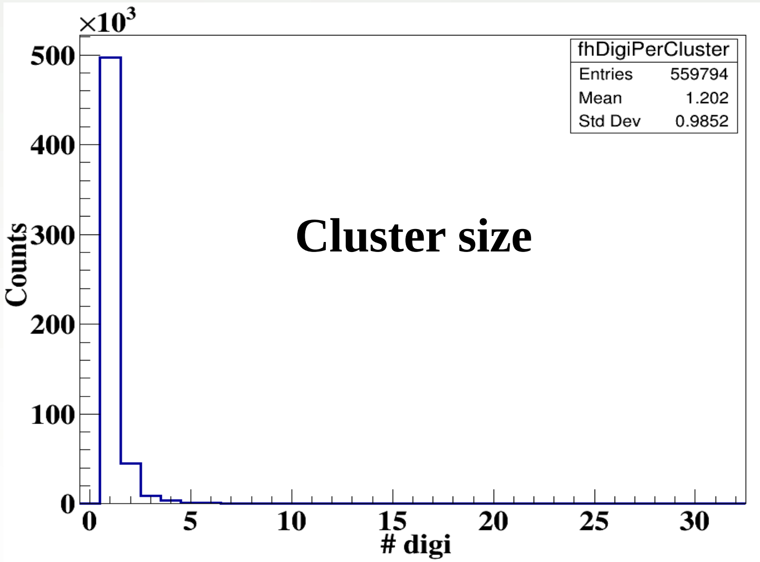

If the time gap between two consecutive Digi < 200ns (say) => Then count as one event
**With minimum TOF and T0 trigger condition**

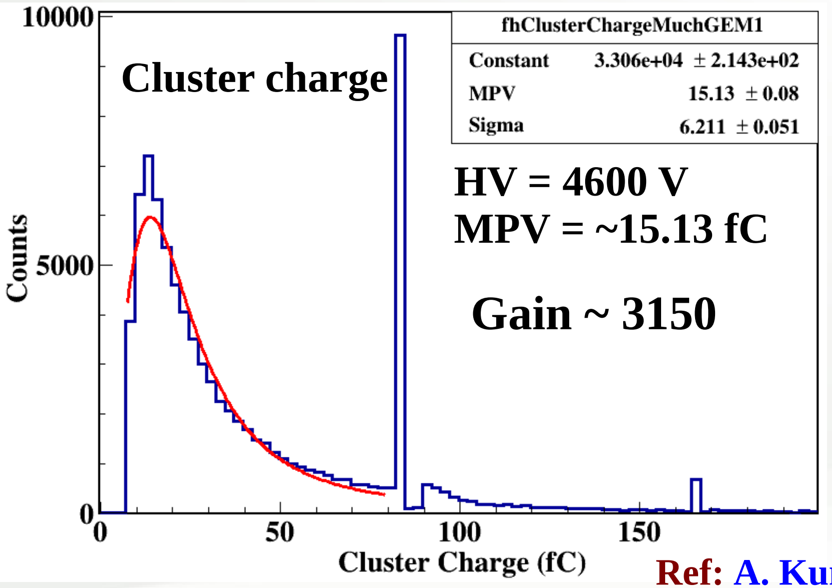
**For the current analysis** →

## Algorithm:
**Fixed time window = 200 ns**
**Minimum 6 TOF + 1 T0 Digi**

# Clustering and Hit Reconstruction



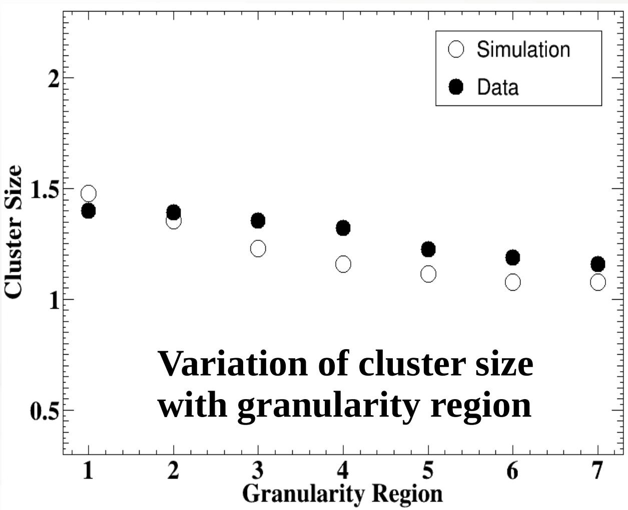
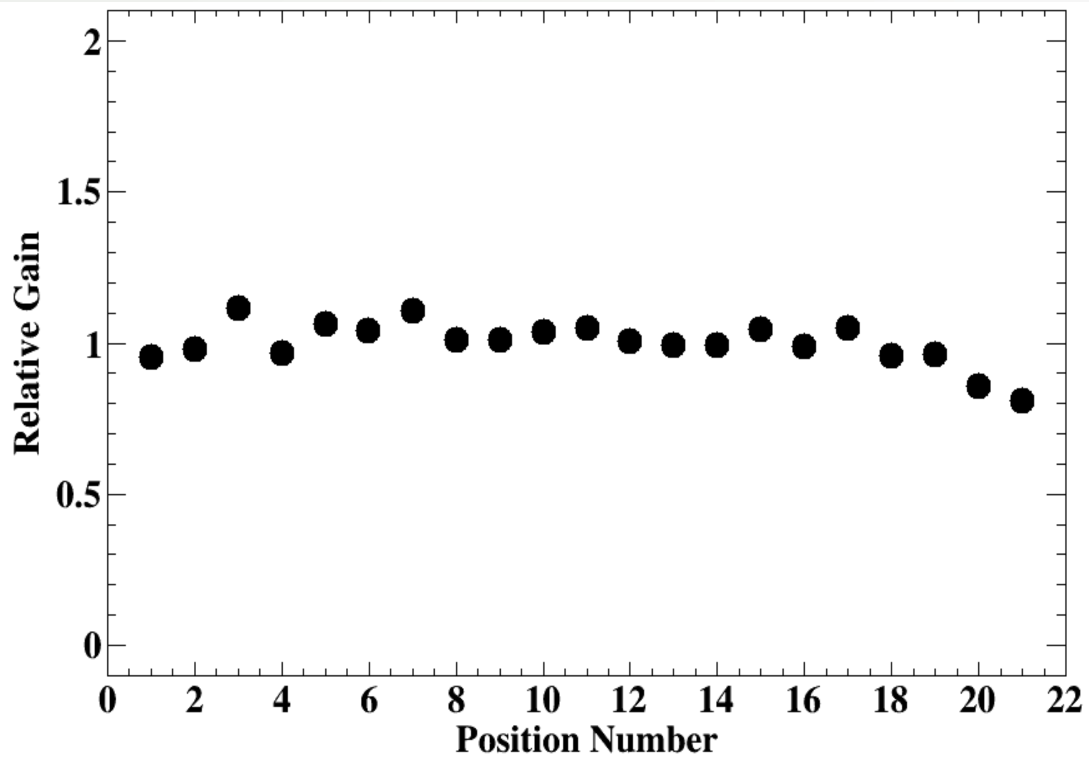



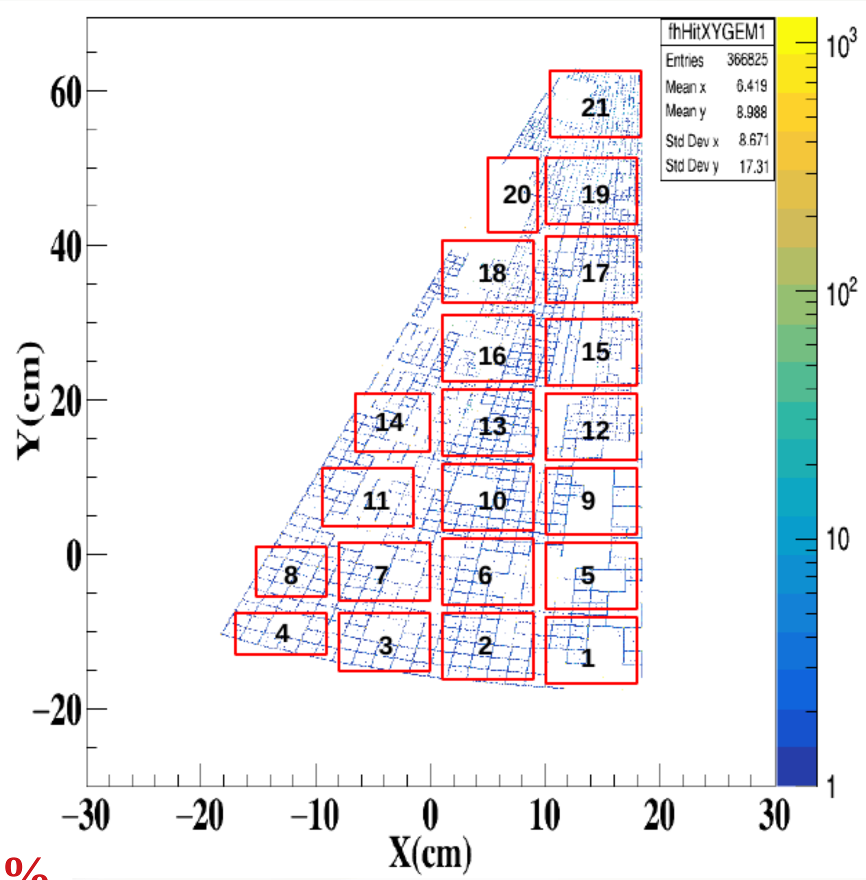

**Table for granularity region and pad size**

| Granularity Region | Pad Size (mm) |
|---|---|
| 1 | ~3.22 - ~4.55 |
| 2 | ~4.55 - ~6.22 |
| 3 | ~6.44 - ~8.49 |
| 4 | ~7.66 - ~10.09 |
| 5 | ~9.59 - ~11.40 |
| 6 | ~11.59 - ~14.02 |
| 7 | ~14.02 - ~16.97 |

Ref: A. Kumar et al 2021 JINST 16 P09002

# Gain Uniformity



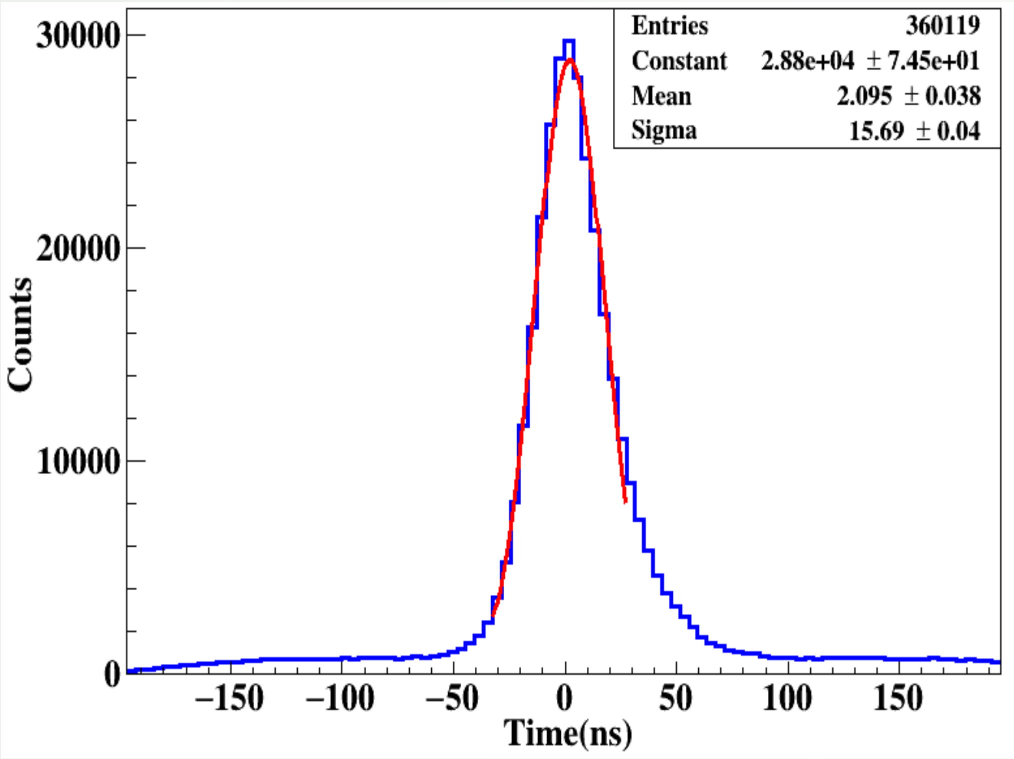

**Gain is observed to be uniform at the level of ~15%**



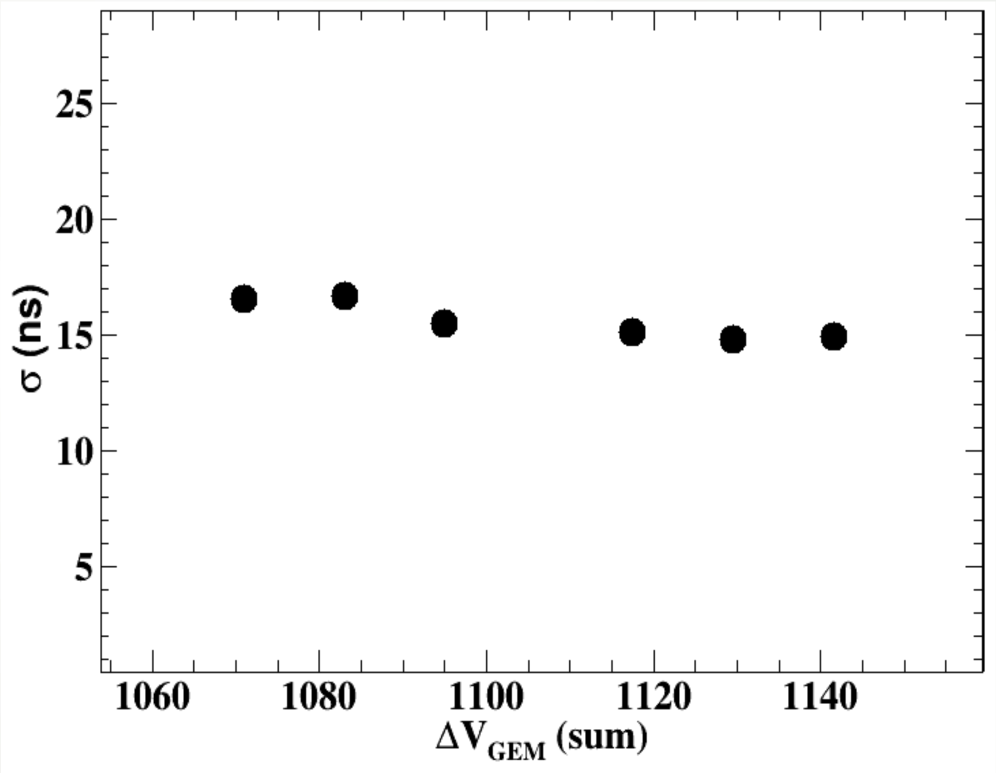
**Ref: A. Kumar et al 2021 JINST 16 P09002**

# Time Resolution

**Time difference between GEM1 hit with T0 Digi**




**Time resolution with GEM voltage**

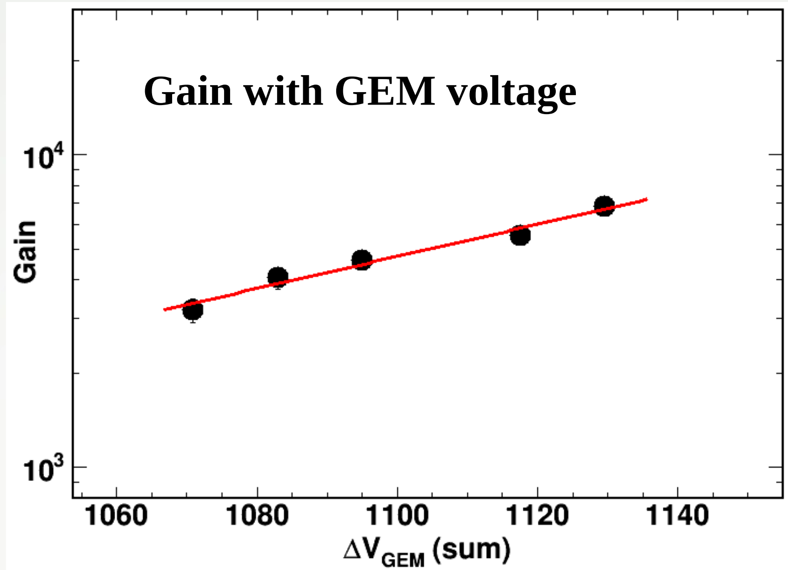


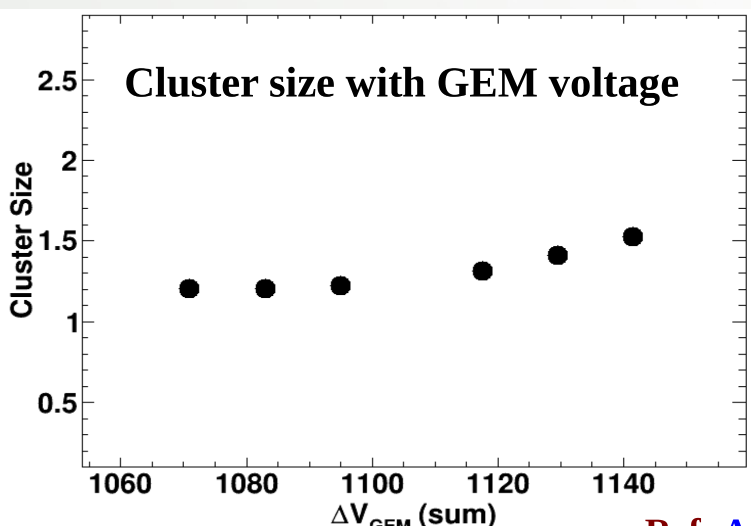


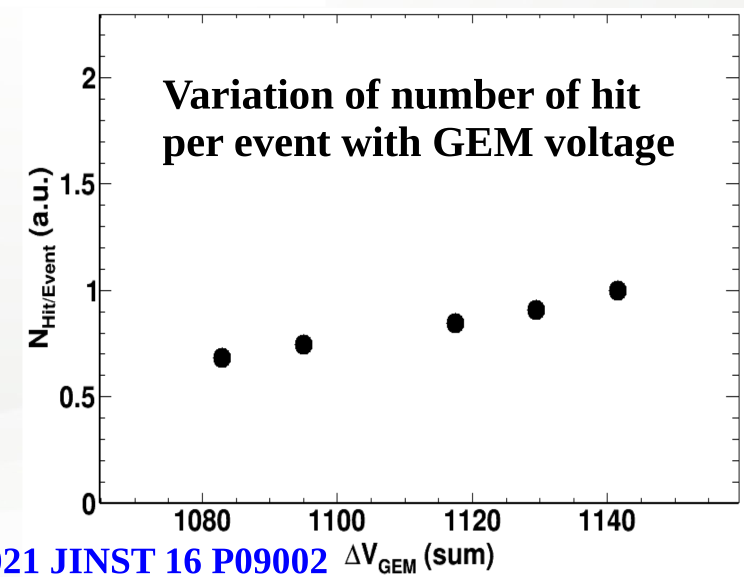

Ref: A. Kumar et al 2021 JINST 16 P09002

# Effect of GEM Voltage

**Ar + Au at 1.7A GeV, Nov./Dec. 2019**



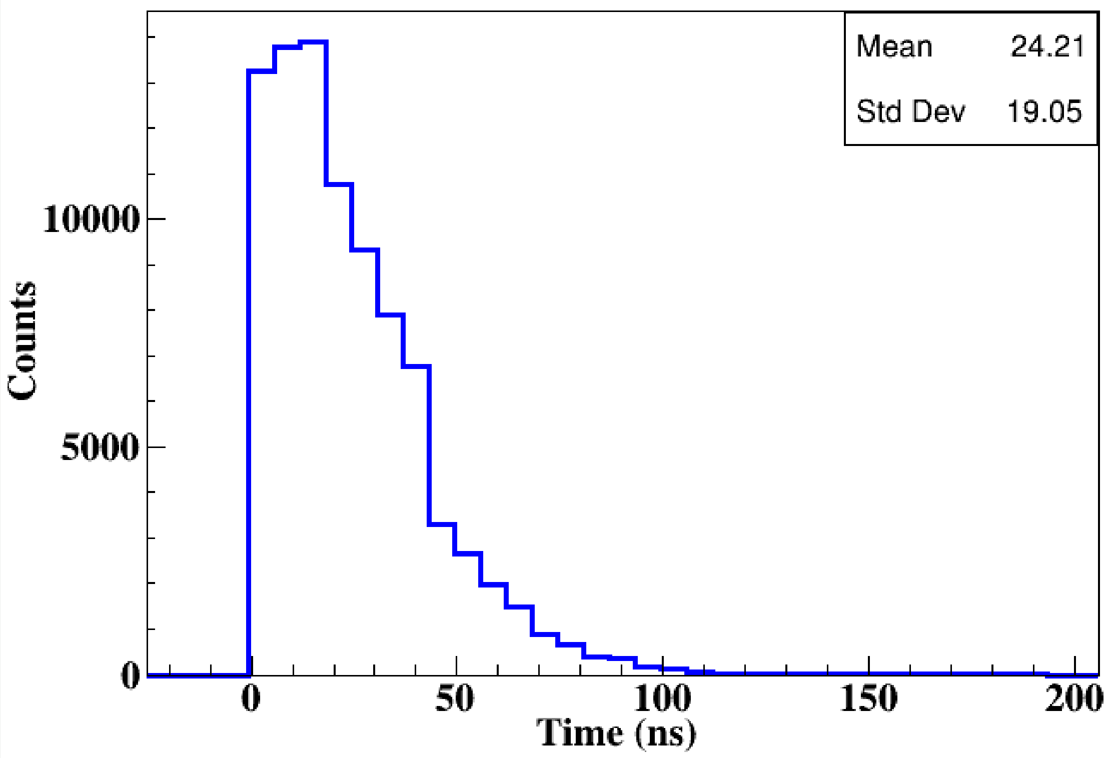




**Ref: A. Kumar et al 2021 JINST 16 P09002**

# Time Distribution of Digi in Cluster

Ar + Au at 1.7A GeV, Nov./Dec. 2019



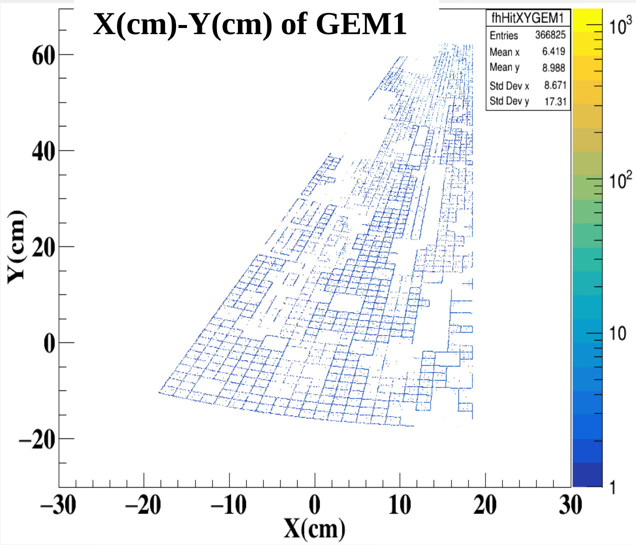

– 90% of digis are within 50 ns time separation

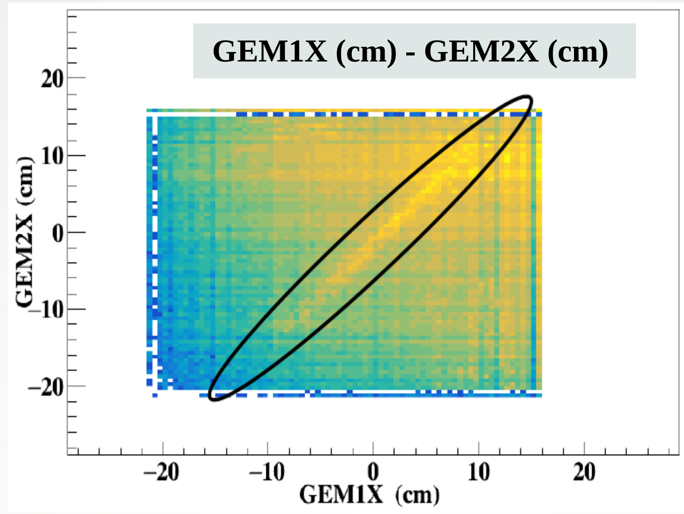
– Can be useful for 4-D tracking

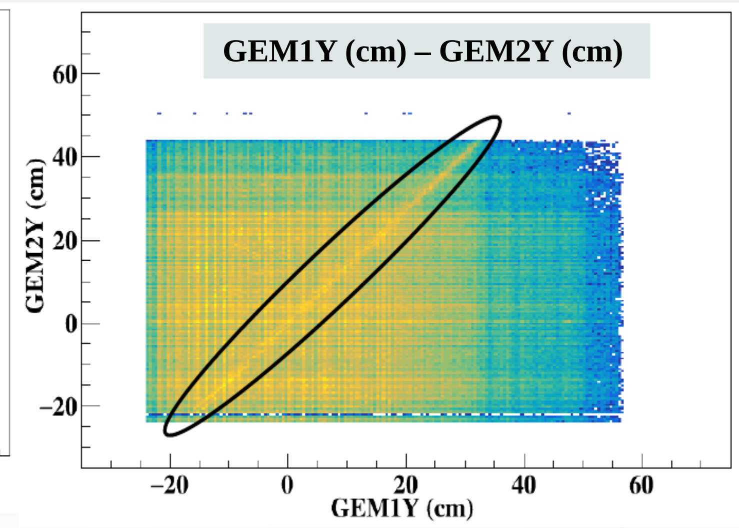


Ref: A. Kumar et al 2021 JINST 16 P09002

# Spatial Correlation




– Convey an effective event reconstruction

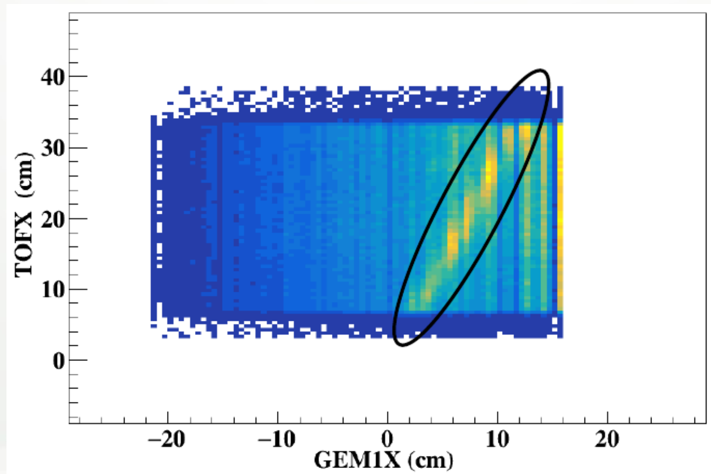
– Also demonstrate the time-synchronous behavior of two different detectors

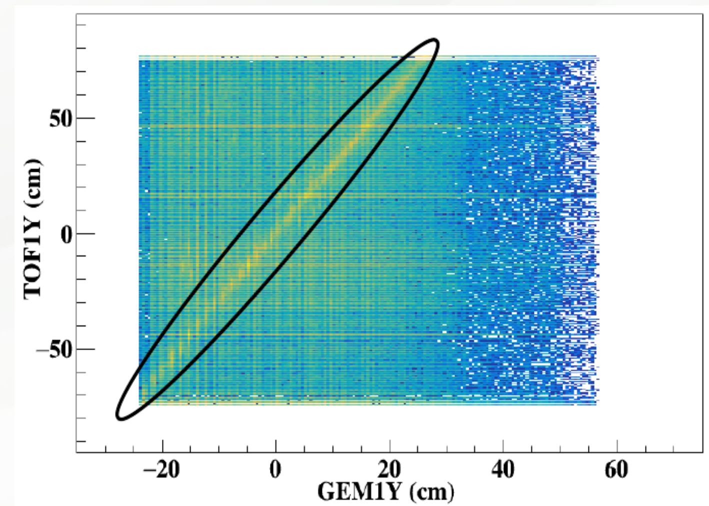
– Even two different subsystems employing entirely different detector technologies and readout electronics.

TOFX (cm) – GEM1X (cm)

TOF triple stack only

TOFY (cm) – GEM1Y (cm)



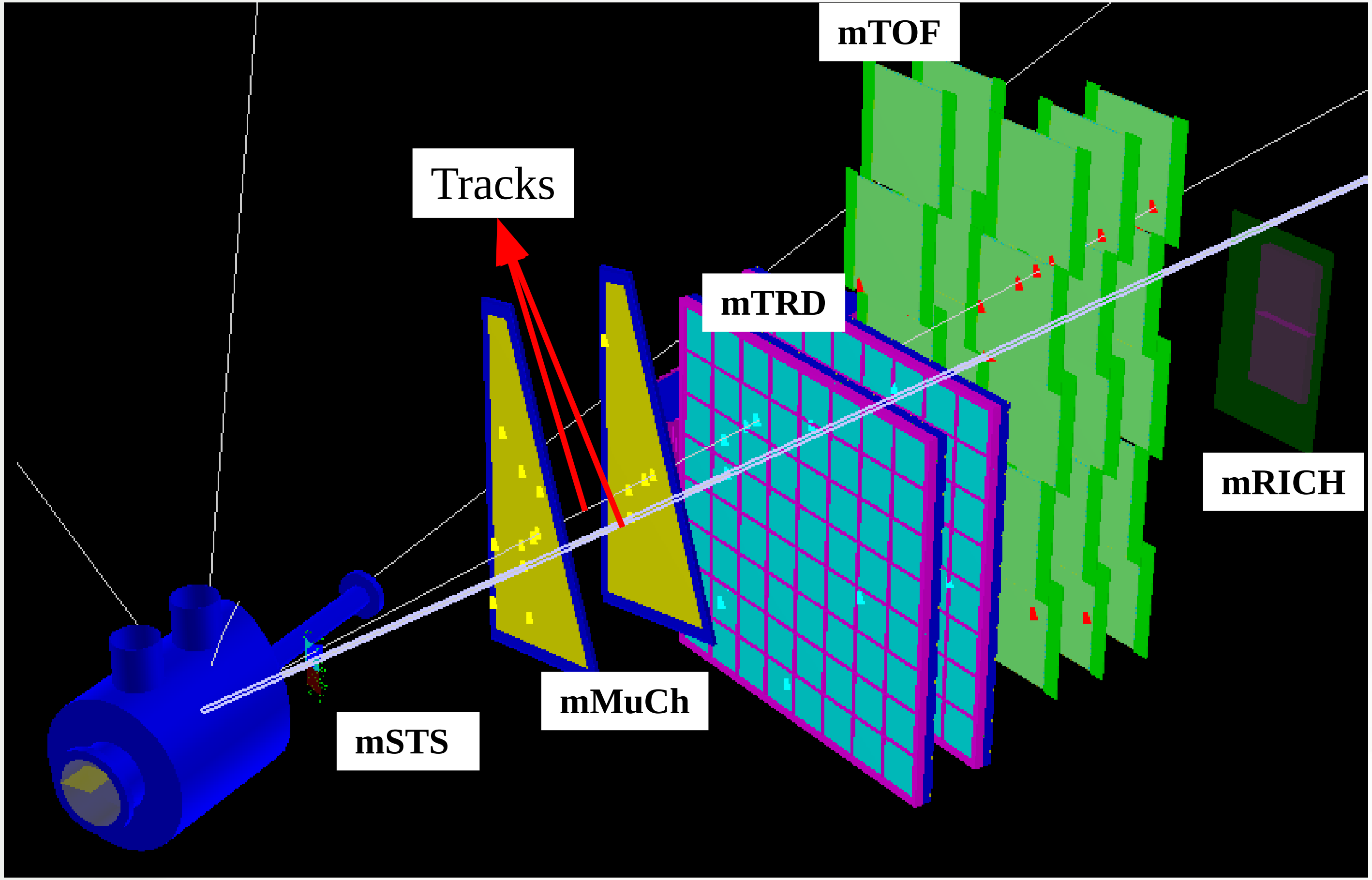




**Ref: A. Kumar et al 2021 JINST 16 P09002**

Ar + Au at 1.7 AGeV, Nov./Dec. 2019

# Track Reconstruction

- Track generated from collisions pass through the detector sub-systems
- These tracks creat hit point on each detector sub-systems
- Using these hit information – Construct a track




Parametric equation

$$x = a + b \times z$$
$$y = c + d \times z$$

a, b, c & d is calculated by minimizing the $\chi^2$ distribution

$$\chi 2 = \sum_{i=0}^{N} \frac{(x_i - a - b \times z_i)^2}{\sigma_{x_i}^2} + \frac{(y_i - c - d \times z_i)^2}{\sigma_{y_i}^2}$$

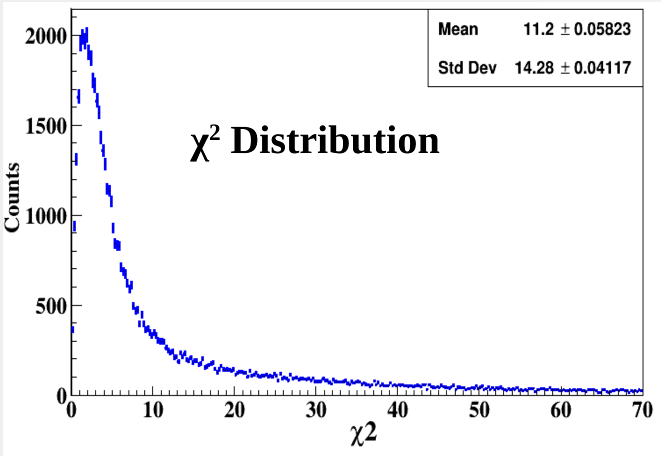
N – Number of detectors

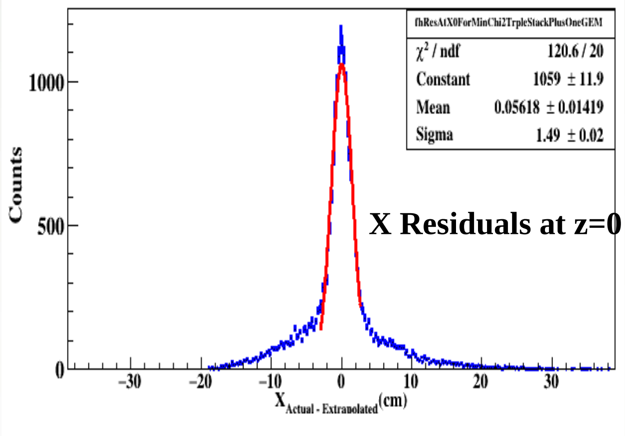
# Tracking Results

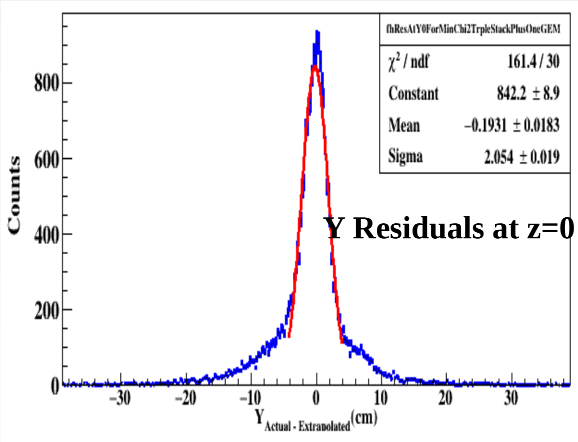
## Tracking

**Ar + Au at 1.7AGeV, Nov./Dec. 2019**

### 3 TOF plane + GEM1

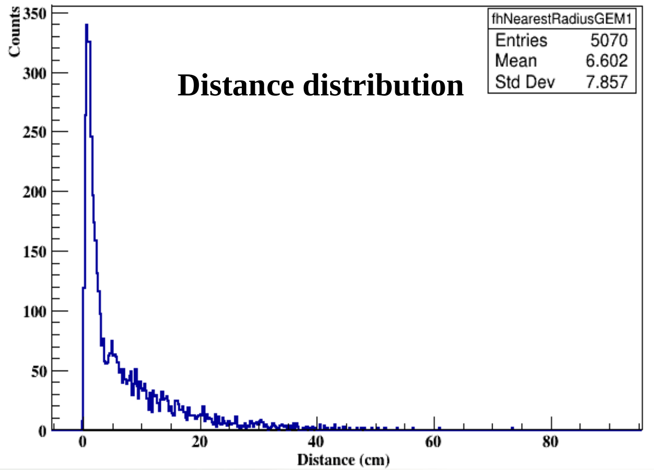


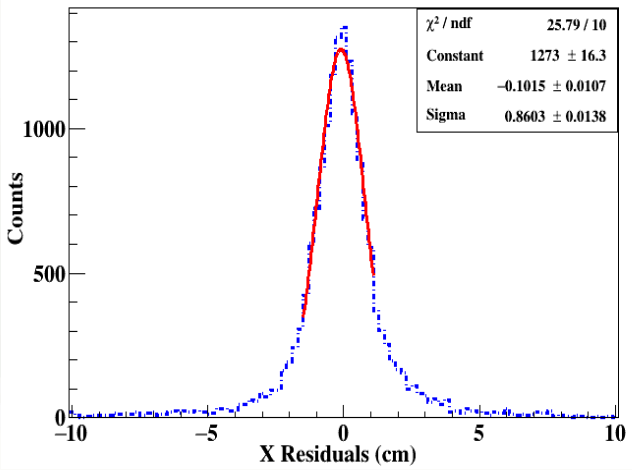




**Alignment done by translating the detector modules**

### 3 TOF plane + Vertex(z=0)

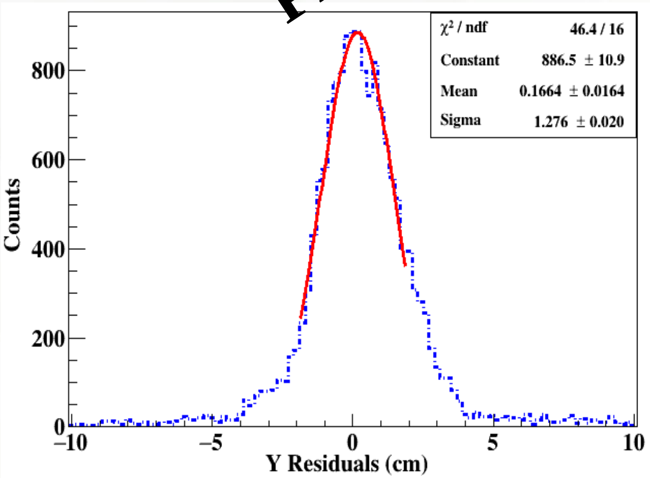



**X Residuals at GEM1 plane**
**Distance cut = 4.0 cm**




**Y Residuals at GEM1 plane**
**Distance cut = 4.0 cm**

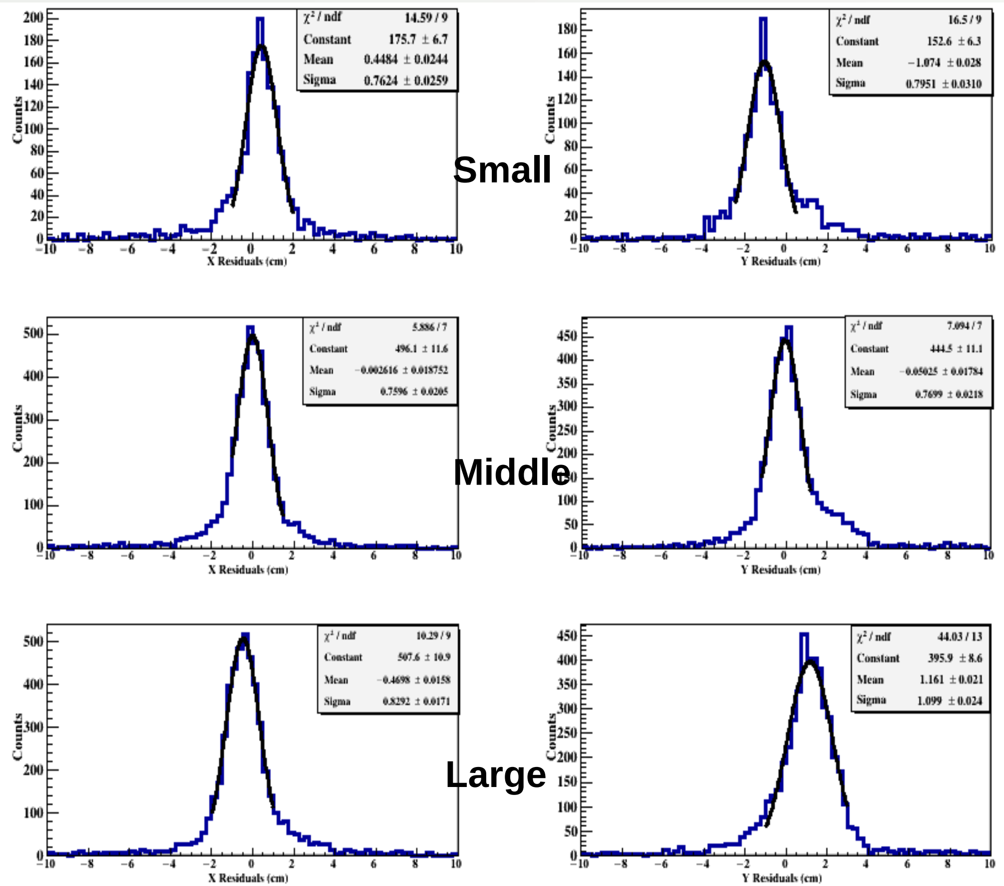
**Preliminary**



# Tracking Results and Efficiency

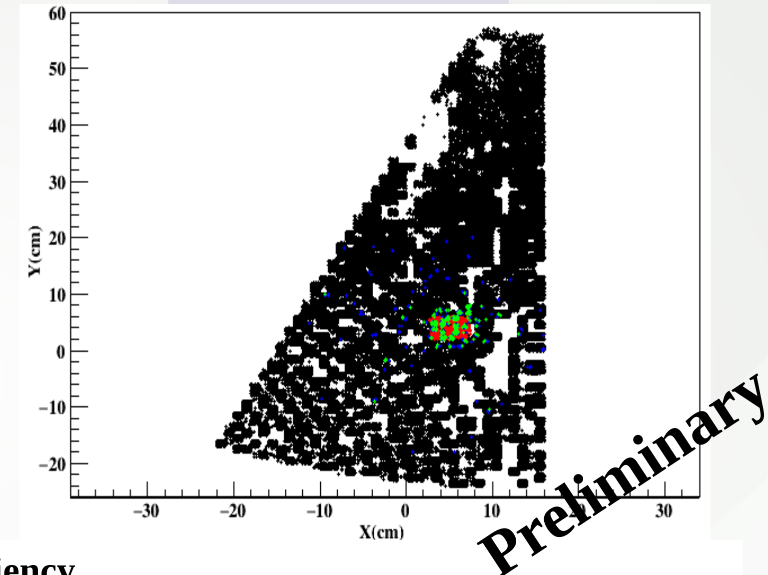
Ar + Au at 1.7A GeV, Nov./Dec. 2019

**Track residuals for varying pad size**




Small --> ~9.9 mm to ~12.9 mm
Middle --> ~13.2 mm to ~15.3 mm
Large --> ~15.5 mm to ~17.0 mm

## Efficiency




**Efficiency**
**before acceptance correction = ~74 %**
**after acceptance correction = ~83 %**

Black --> Actual X-Y Distribution
Red --> Extrapolated track X-Y distribution
Blue --> Actual X-Y for nearest hits
Green --> Actual X-Y for nearest hit with distance cut of 4 cm

# Summary

- **Assembled real-size chambers at VECC**
- **Two large size modules commissioned and its performance studied in mCBM experiment.**

- **Event reconstruction in free-streaming system performed using mCBM data**
  - **Observation of spatial correlation demonstrates first synchronous response from different sub-systems employing different detector technologies and electronics**

- **Studied voltage scan for gain, cluster size, time resolution**

- **Efficiency estimated for GEM chambers using extrapolated hit points**

- **Tracking performed. Track residuals at different granularity regions measured**

# Acknowledgments

- I would like to thank whole MuCh team of VECC
- I would like to thank GSI colleagues for the help and support
- Thanks to CPDA lab VECC for providing clean room

# Thank You For Your Kind Attention

# Backup

# Physics at CBM

**Explore QCD phase diagram at high net-baryon density**

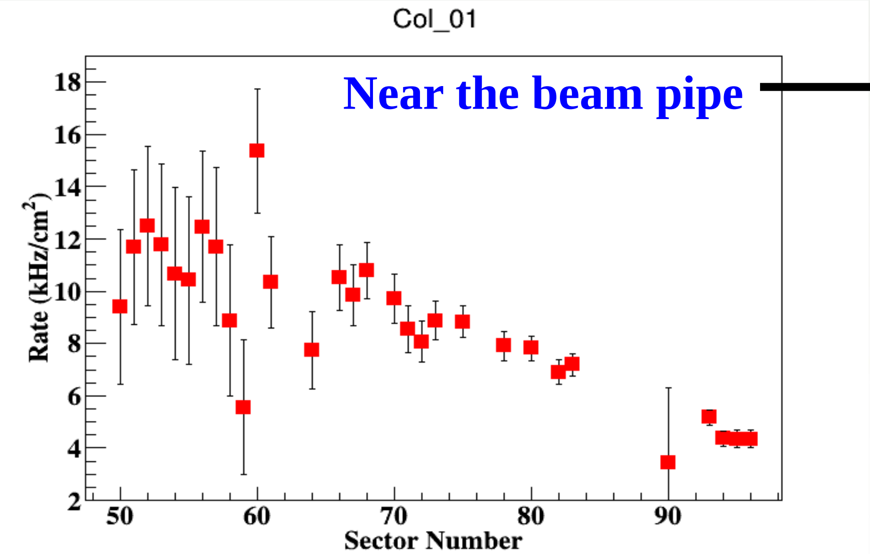
- **EOS of QCD matter at high net-baryon density**
  - Collective flow of identified particles, which is generated by the density gradient of early fireball
  - Multi-strange hyperons, produced in the dense phase of fireball via sequential collisions

- **Phase transition from hadronic matter to quark-gluon matter, region of phase co-existence**
  - Multi-strange hyperons are driven into equilibrium at phase boundary
  - 1st order phase transition – measured by invariant mass spectra of lepton pairs
  - Critical end point – event-by-event fluctuation of conserved quantities – such as S and B

- **Chiral symmetry restoration**
  - Affect the invariant-mass of di-leptons

- **Strange and multi-strange hadrons**
  - Measurement of hypernuclei – hyperon-nucleon and hyperon-hyperon interaction will be useful in understanding of hyperon-puzzle in neutron stars

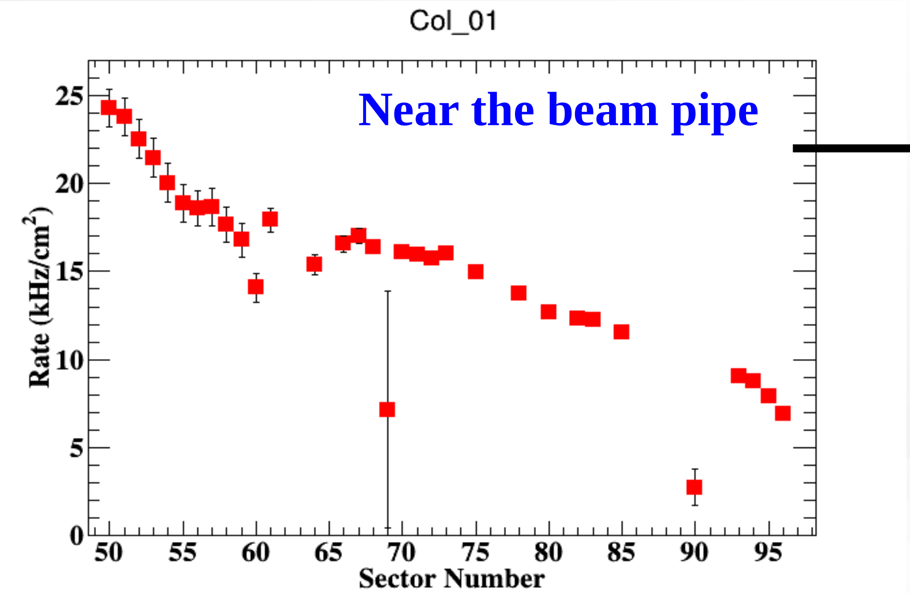
# Effect of Target Thickness on Rate




Beam Intensity=$10^7$/sec
Target thickness : 0.25 mm
GEM1

March 2019
Ag+Au

Factor of ~2 increase in the particle rate for 2.5 mm target thickness




Beam Intensity=$10^7$/sec
Target thickness : 2.5 mm
GEM1