# Application of the VMM3a/SRS for tracking systems and TPCs

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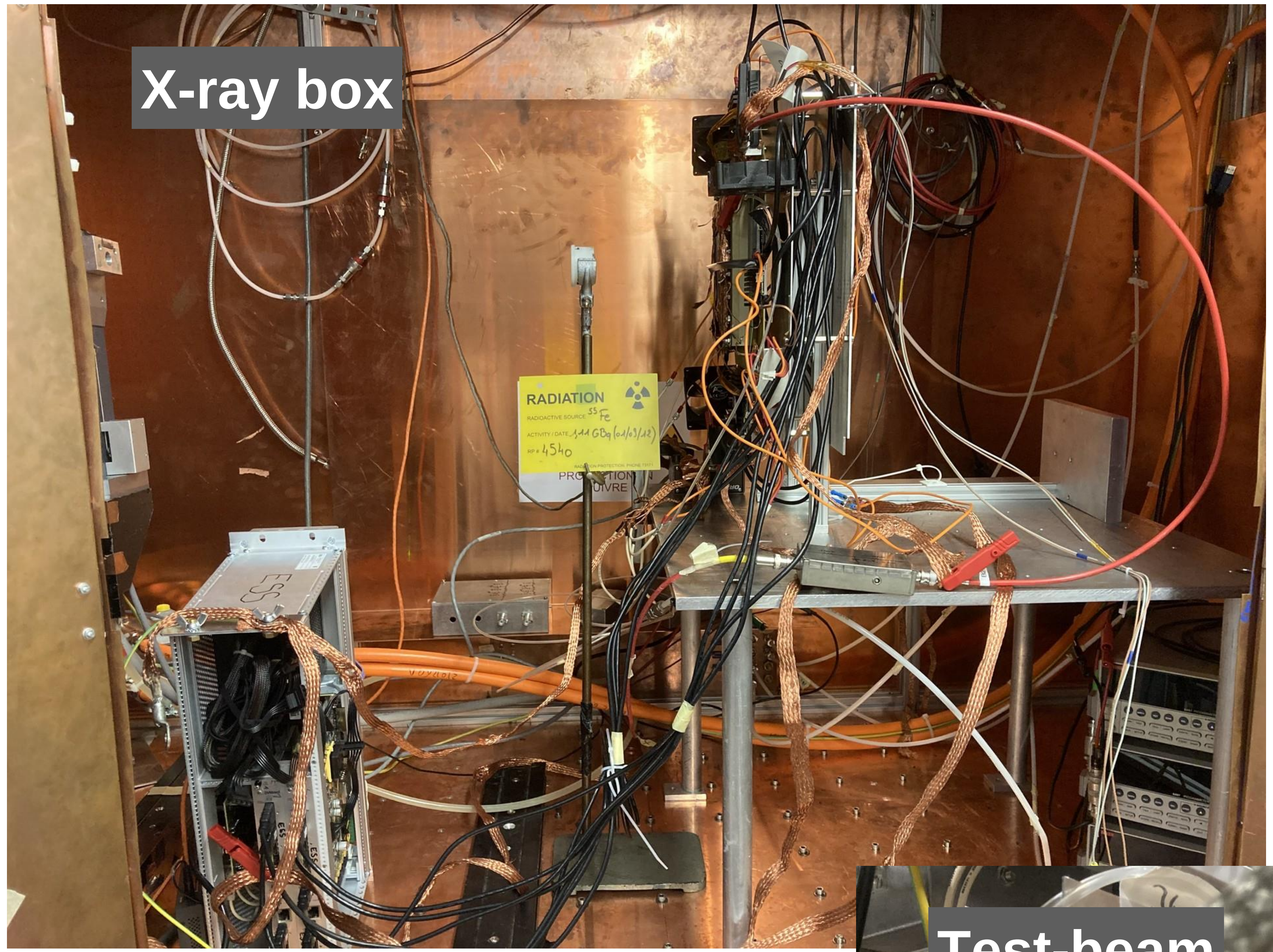
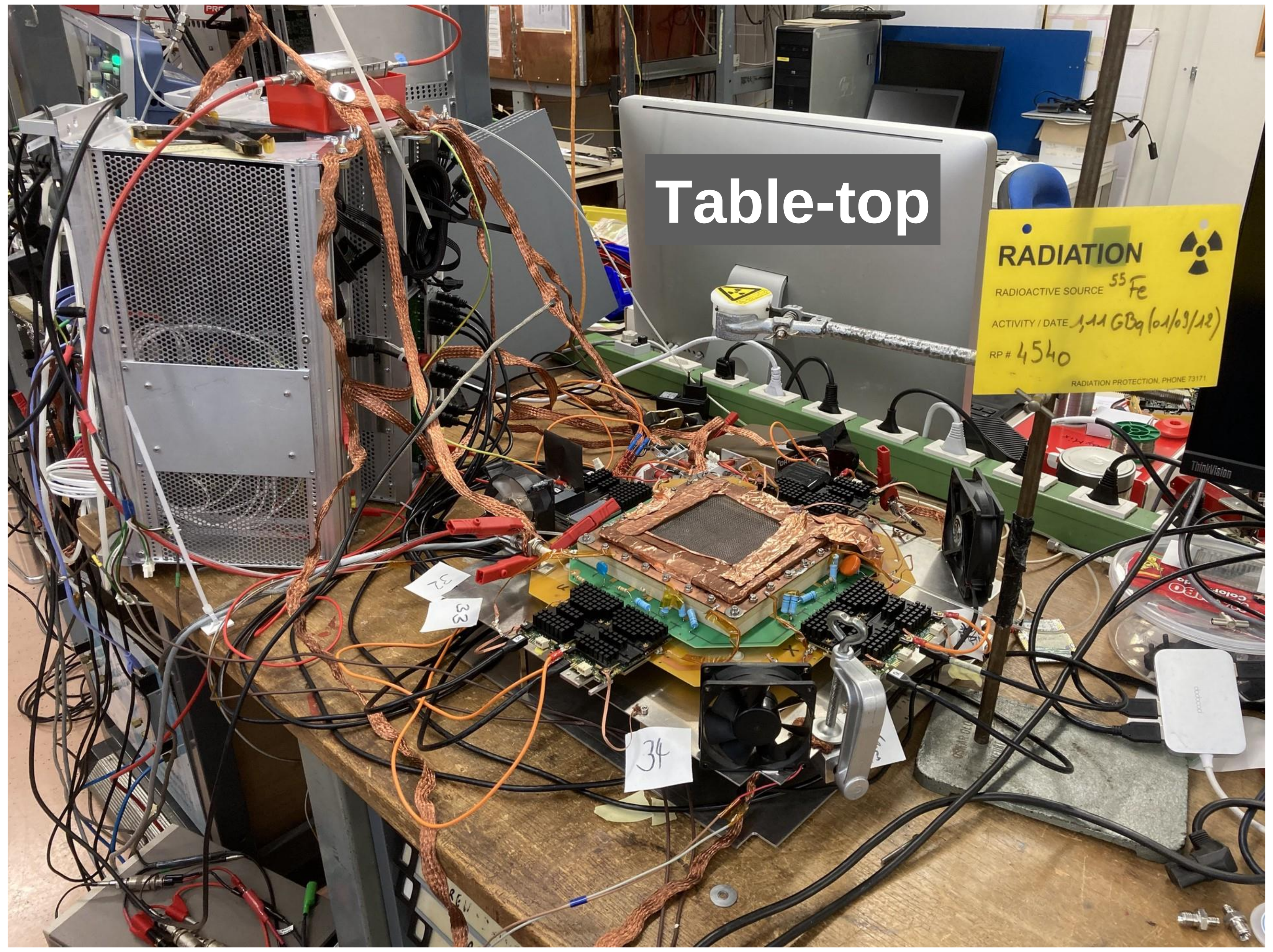
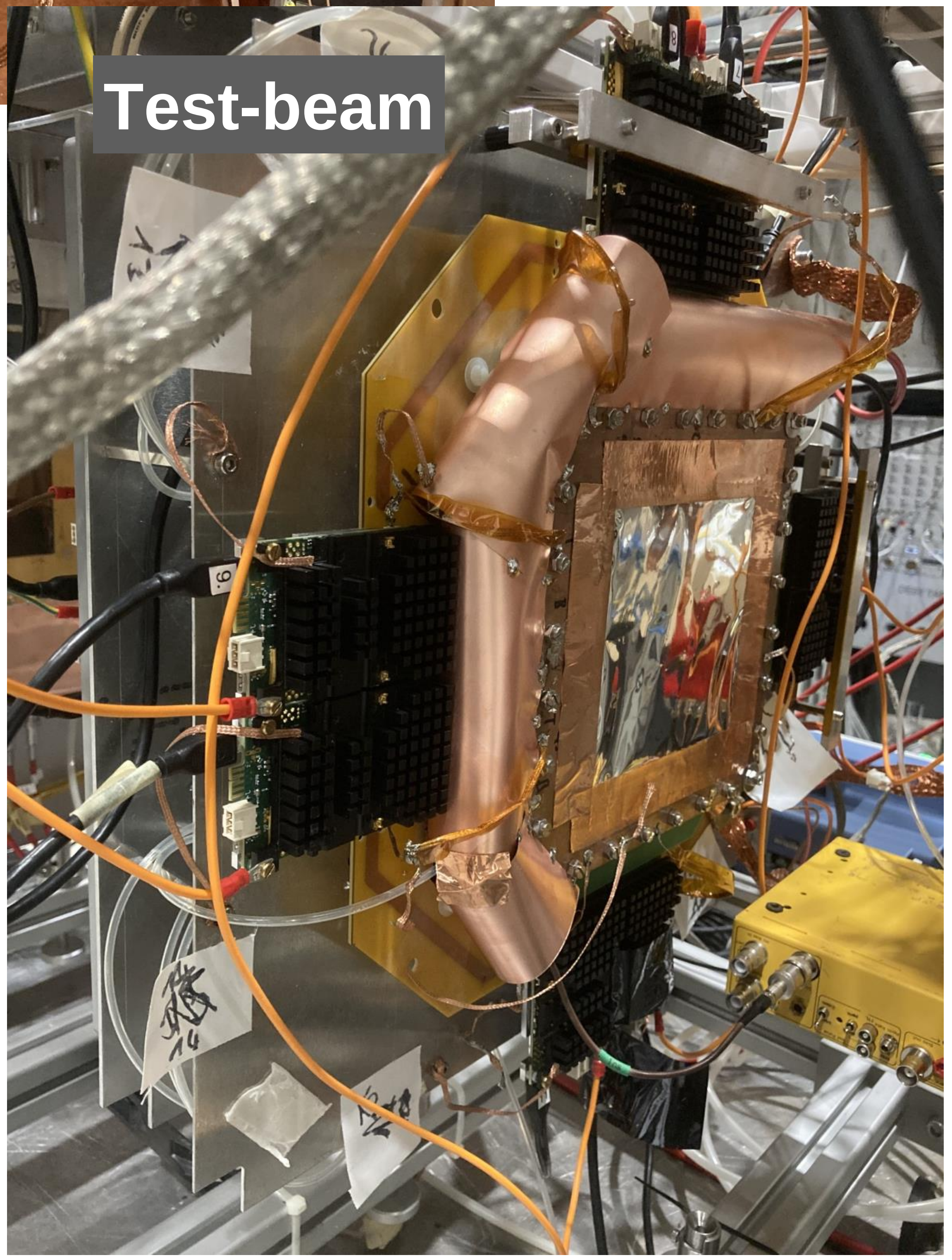
# Outline

- Introduction to the system
  - Applications
  - The VMM3a/SRS
  - The RD51/DRD1 telescope
- The new AMBER triple GEM
  - Introduction and motivation
  - Results with the VMM3a/SRS
- The Twin GEM-TPC
  - Standalone tracking station
  - Standalone tracking telescope

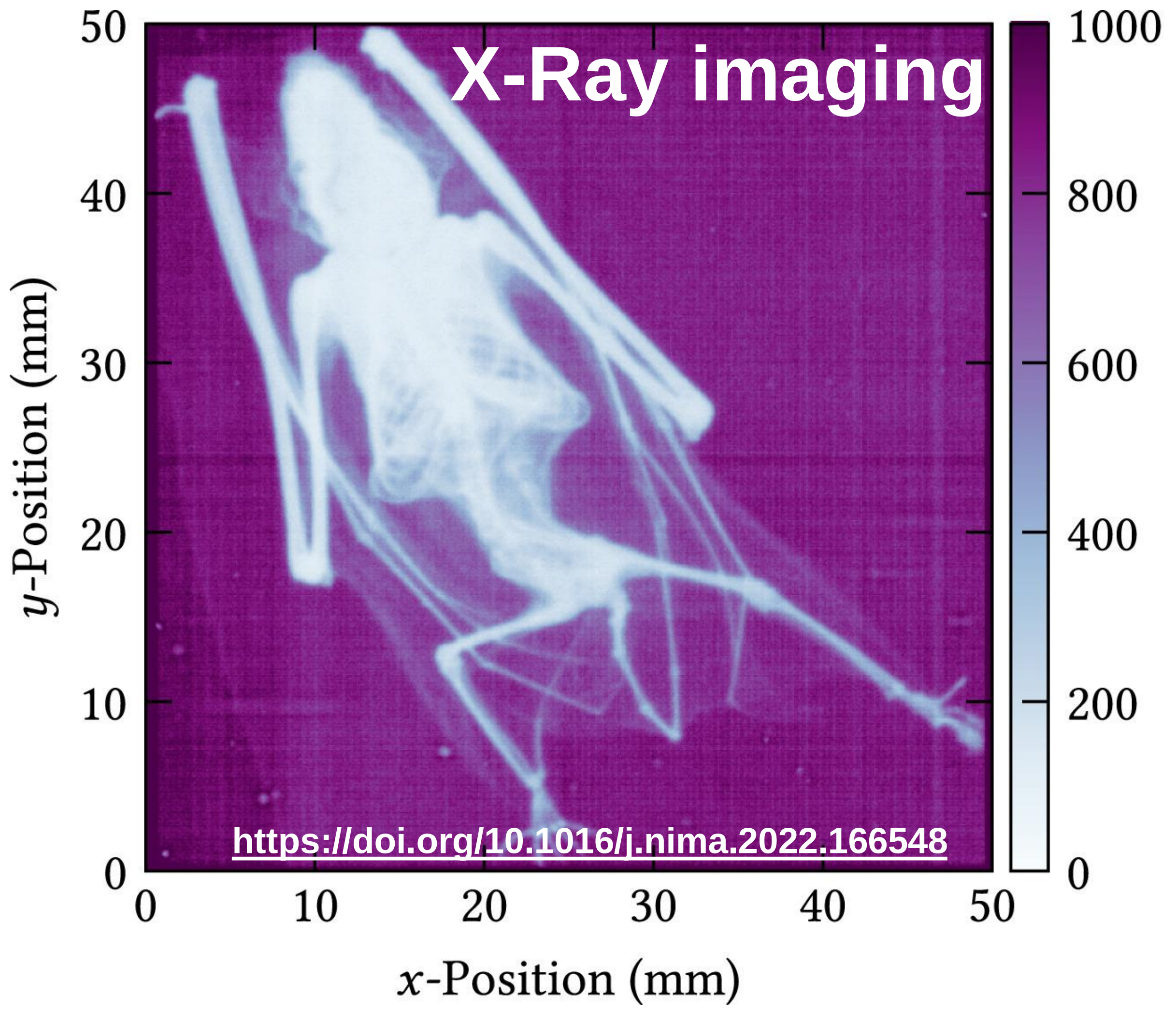


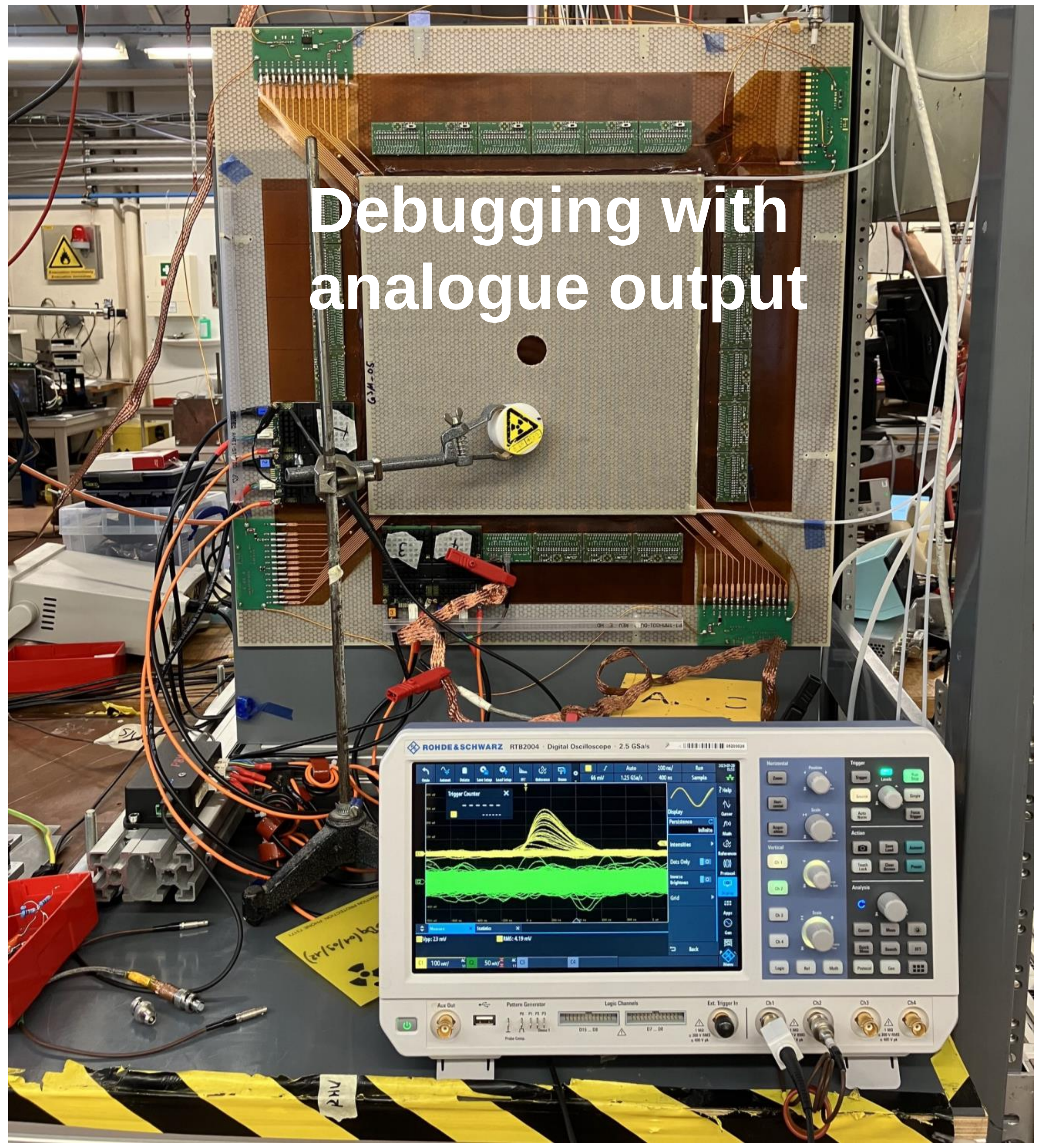



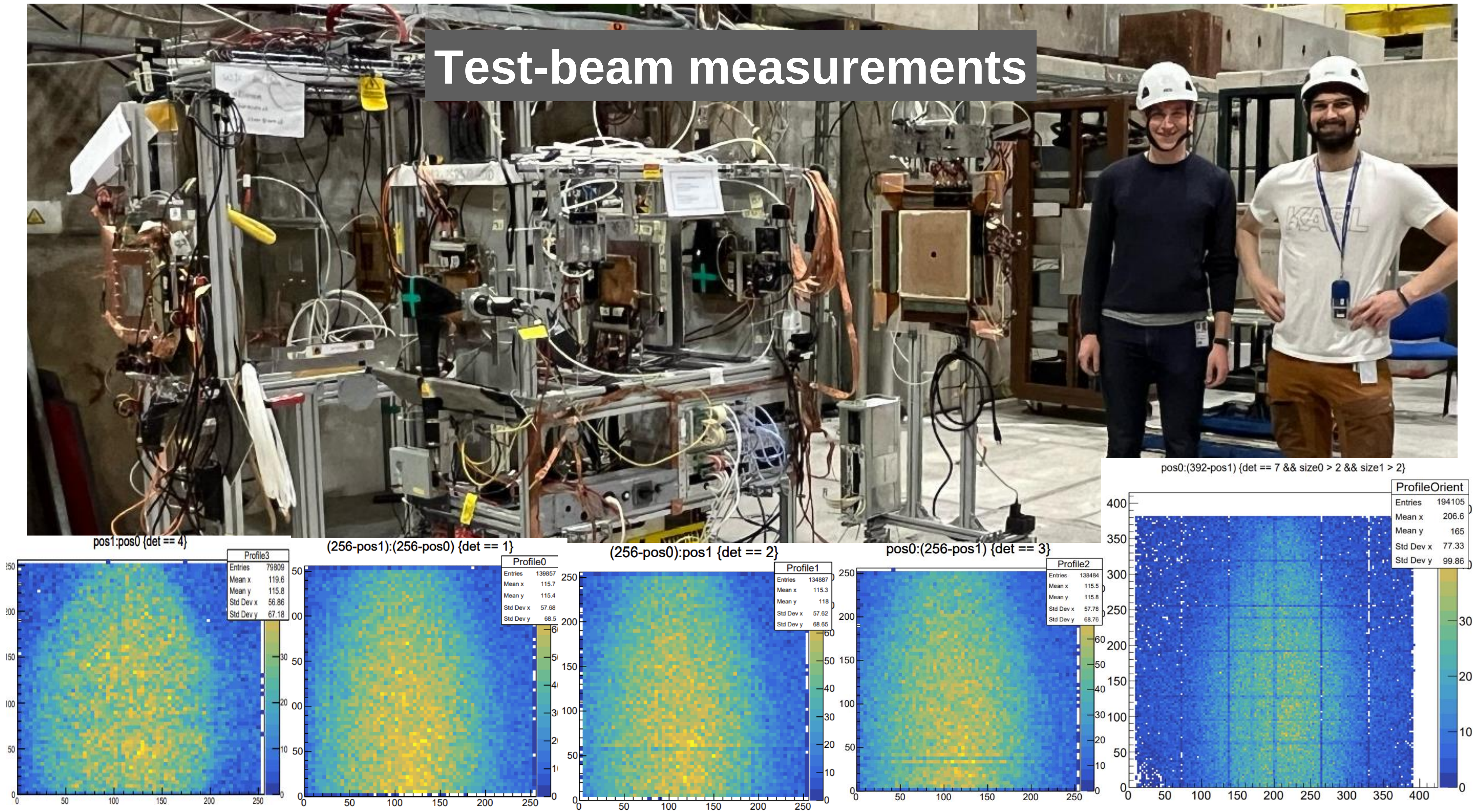



# Applications overview

- Laboratory measurements
  - General detector tests and debugging
  - **X-Ray** studies
    -> up to **2MHz interaction rate**
- Beam measurements
  - Detector characterization
    -> **Statistics of 100k per spill for Muons**
    -> High-rate studies with **up to 1 MHz Pion rate**
    -> Track time resolution below 2 ns
  - Usage in small experiments
    -> NIM-pulse injection for synchronization
    -> **Distribution of the system (20+ meter)**
    -> Triggered mode

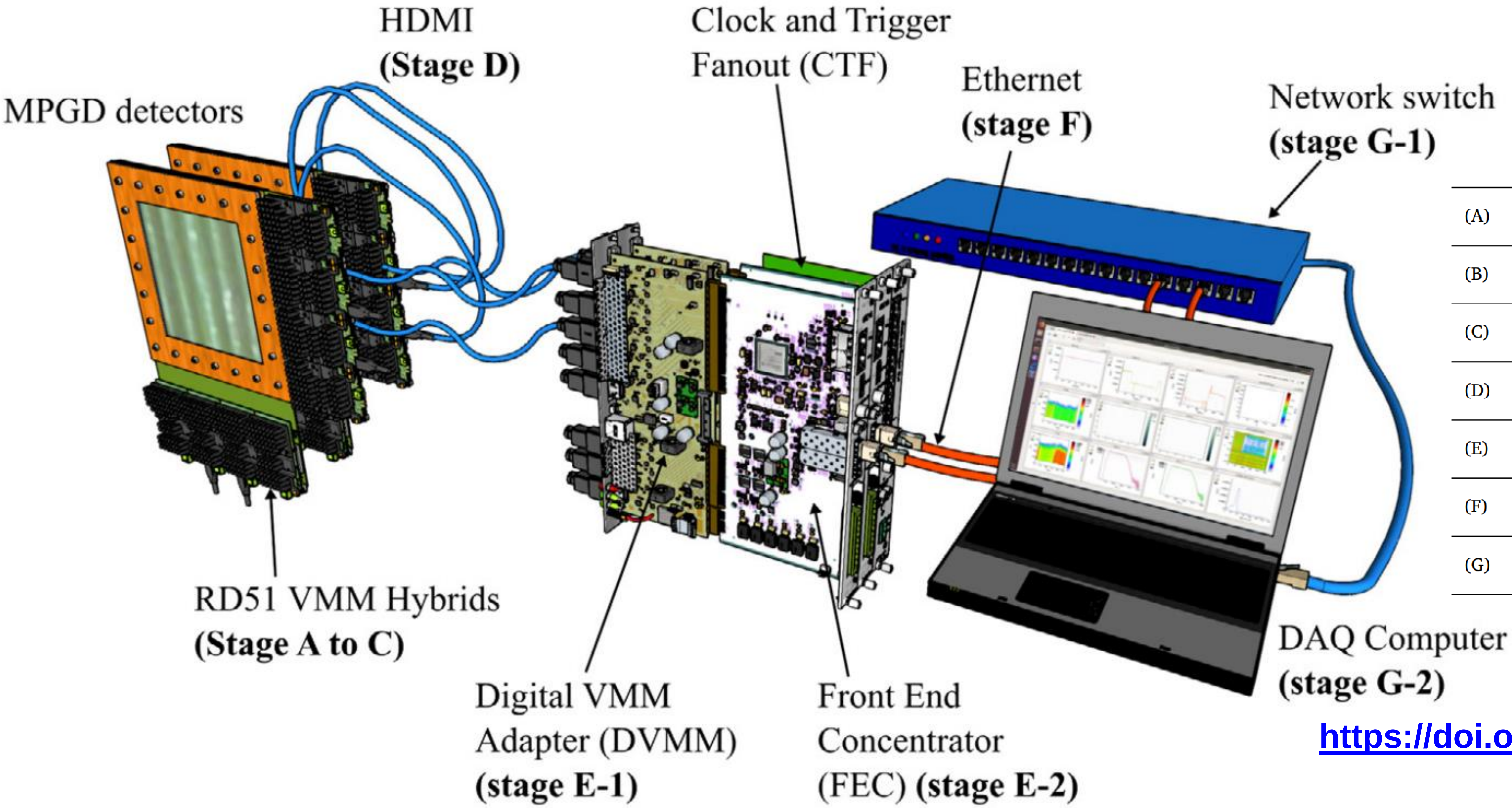


# The VMM3a/SRS

Documentation: https://vmm-srs.docs.cern.ch/



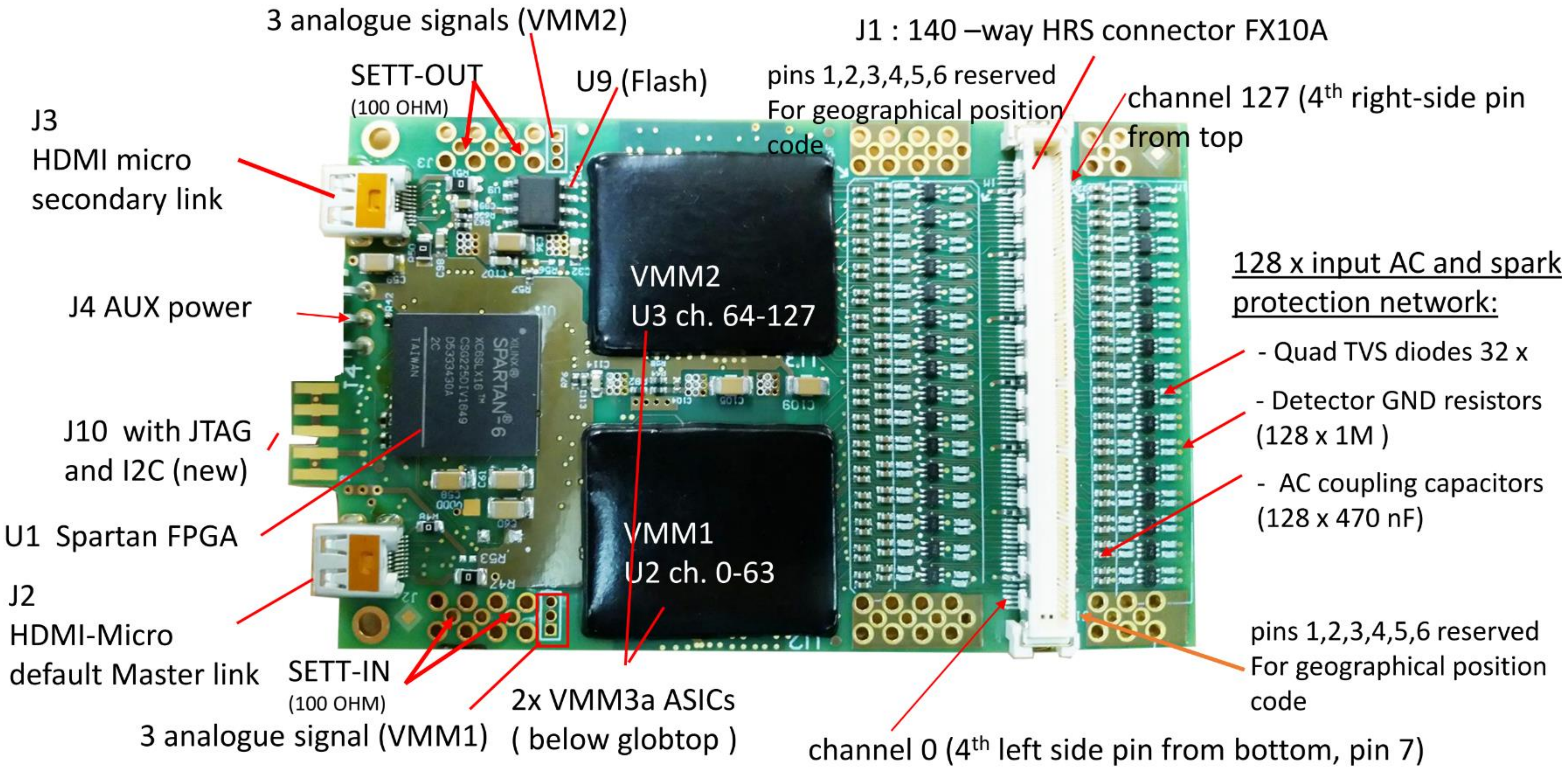

| | Readout stage<br>*Unit Quantity* | Maximum rate<br>(Mhits/s) |
|---|---|---|
| (A) | VMM3a channel<br>*Rate per channel* | 3.6 |
| (B) | VMM3a to Spartan-6<br>*Rate per VMM3a* | $8.\overline{8}$ |
| (C) | Spartan-6<br>*Rate per HDMI-SerDes* | $17.\overline{7}$ |
| (D) | HDMI<br>*Rate per Hybrid* | $17.\overline{7}$ |
| (E) | DVMM and FEC<br>*Rate per DVMM card* | $142.\overline{2}$ |
| (F) | Gigabit Ethernet<br>*Rate per FEC* | 20.8 |
| (G) | DAQ computer<br>*Rate per Switch Port* | $20.8 \times n$ |

https://doi.org/10.1016/j.nima.2022.166548

# The RD51 VMM hybrid

- The VMM3a ASIC developed by BNL for ATLAS NSW
  - 64 input channels each
  - **Self-triggered readout** (3.6 Mhits/s for individual ch.)
  - Sensitive to either pos. or neg. polarity
  - Neighbouring logic
  - Adjustable gain, **0.5 mV/fC to 16 mV/fC**
  - Adjustable peaking time, 25 ns to 200 ns
  - Input capacitance from few pF up to 1 nF
  - Cooling required, **1W/chip power consumption**
  - **Time and amplitude** of each triggered channel

- The RD51 VMM Hybrid designed for the SRS
  - Individual spark protection on each input channel
  - **Programmable analogue monitoring output**
  - Power over HDMI or external via AUX power
    (min. 1.5V (VMMs) and 2.8V (FPGA, flash))

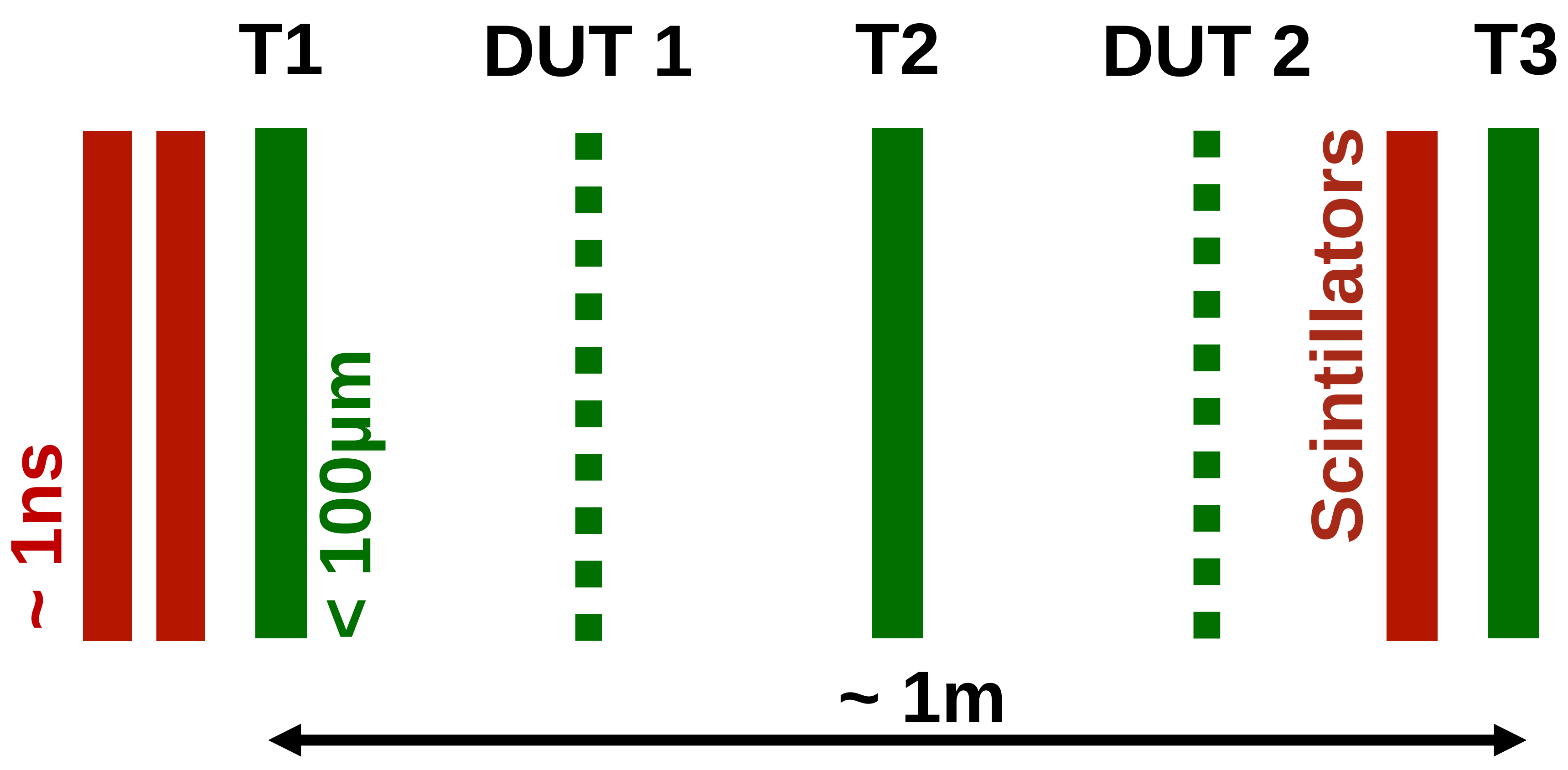


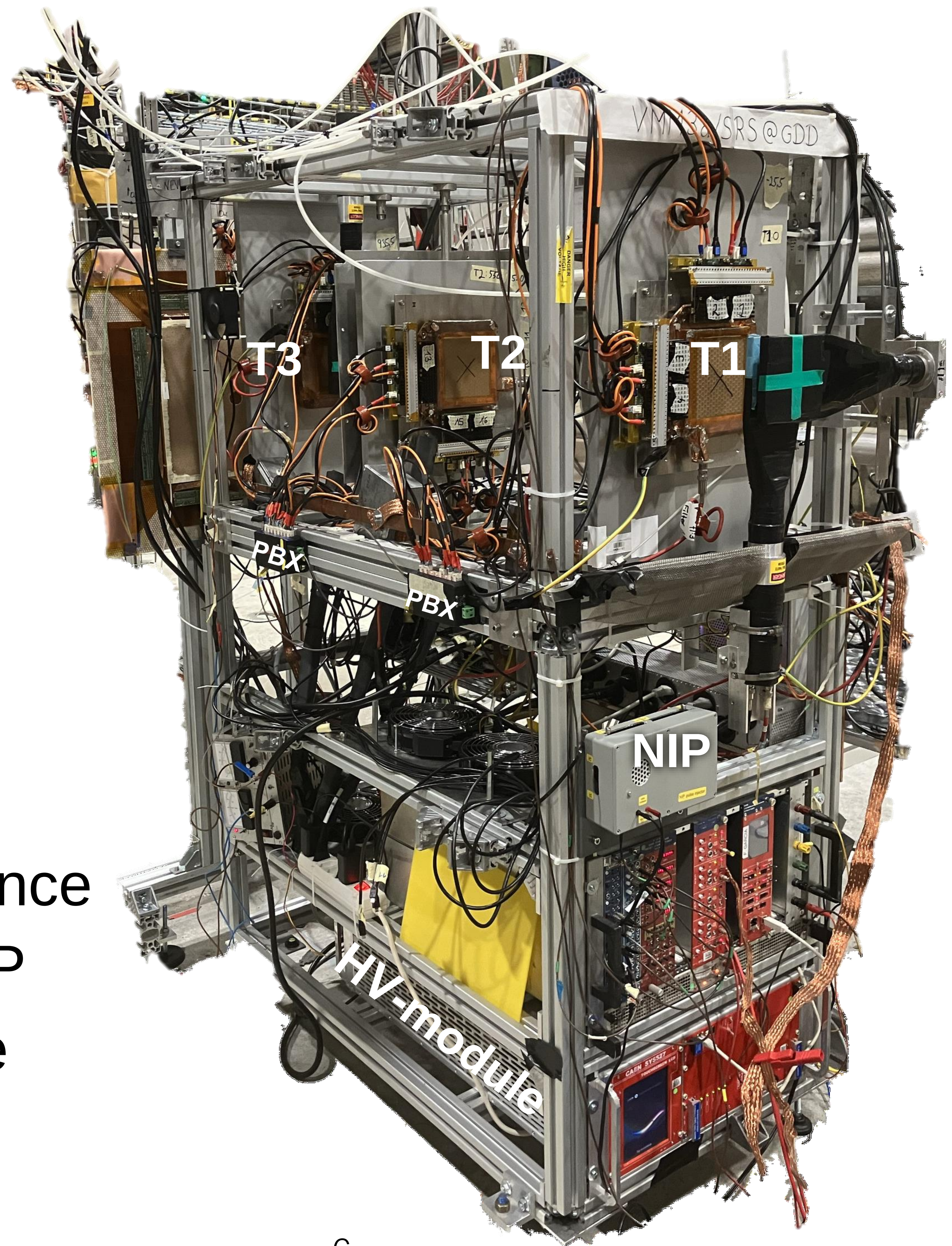

https://drive.google.com/drive/u/0/folders/1e0sFGAI4nTdauhI0-tgycQtn7mPvzLOI

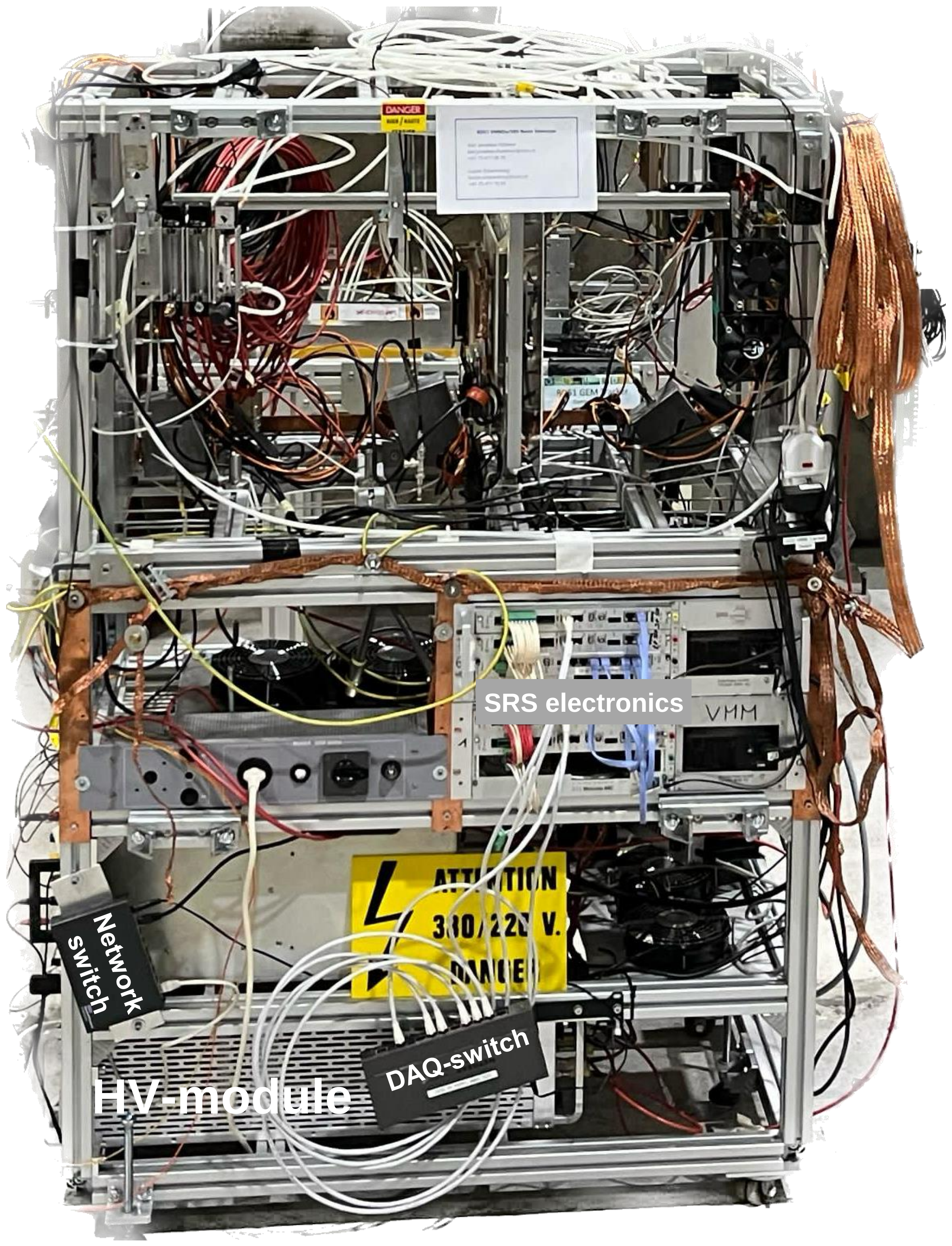
DUT = Detector/Device Under Test

# Telescope setup example

Muon/Pion beam – H4 beamline in EHN1 – DRD1 test-beam April 2024



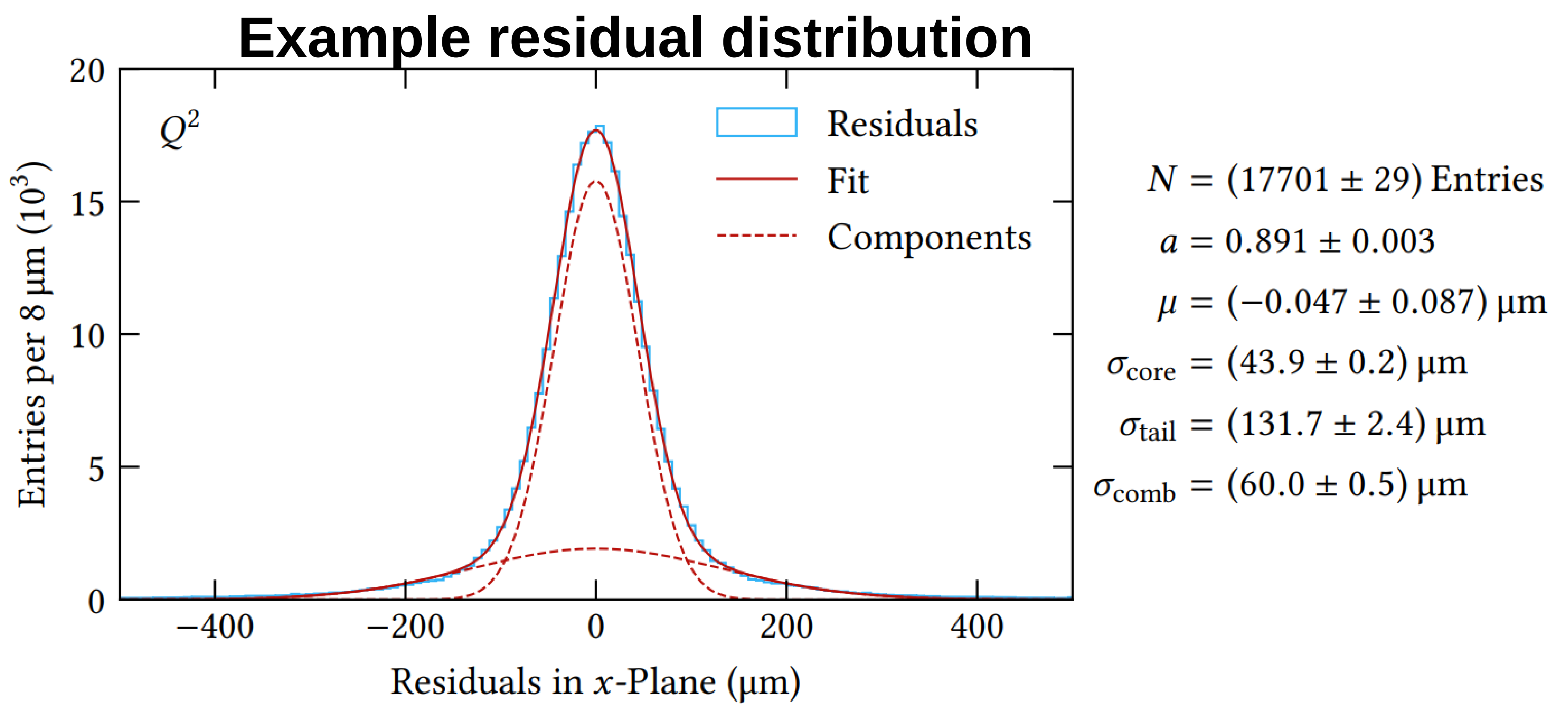



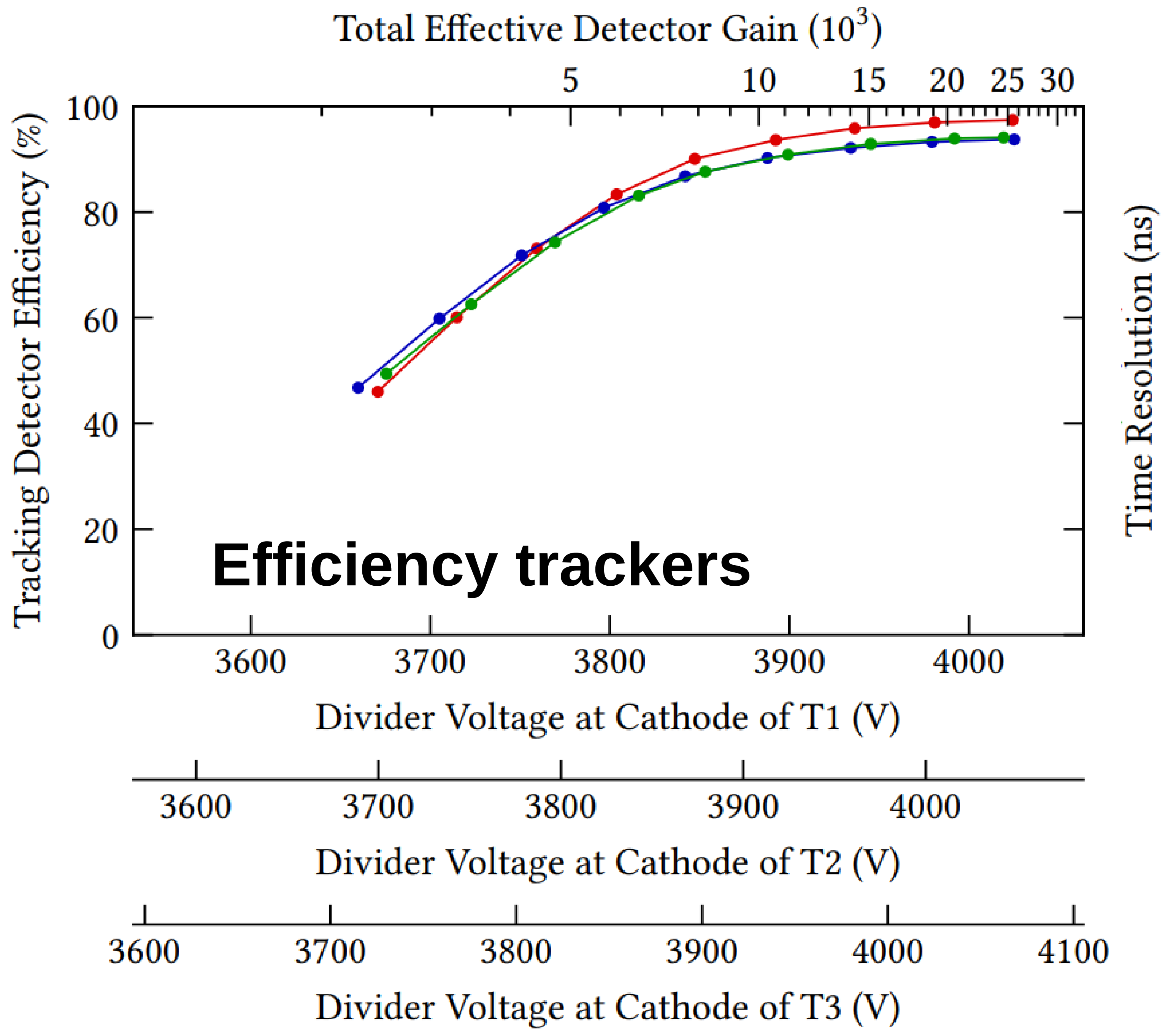

- Position reference from three trackers
  - COMPASS-like Triple-GEM
- Time reference from scintillator coincidence
- NIM-Pulse injection possible through NIP
- Space for 2-3 DUTs within the telescope

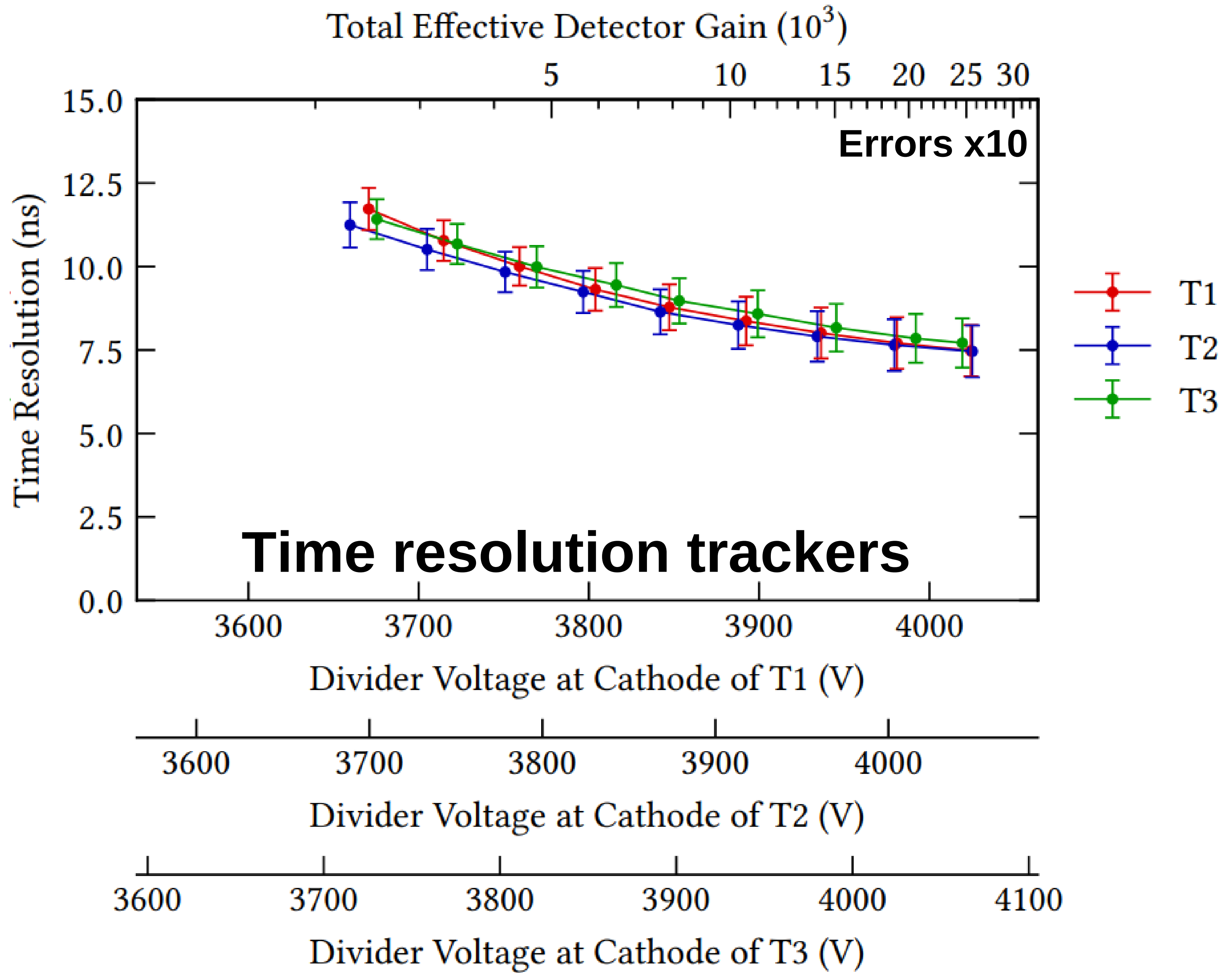
# The RD51 VMM3a/SRS telescope

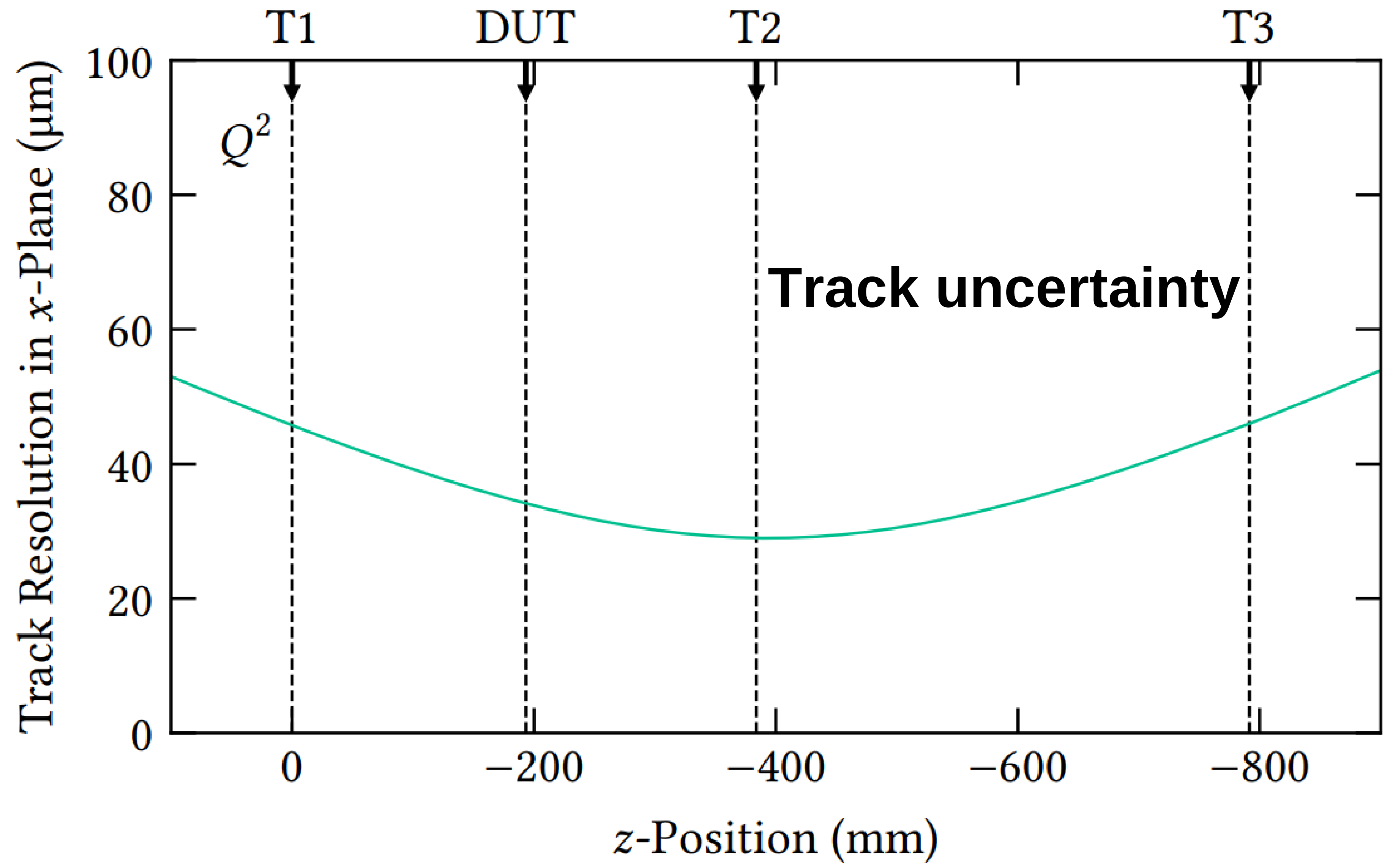
Thesis L. Scharenberg

- Coincidence of three scintillators
  - time reference in the order of 1ns
- Three triple GEM tracking detectors
  - time resolution below 10ns
  - reference track uncertainty below 100µm (depending on position in telescope)



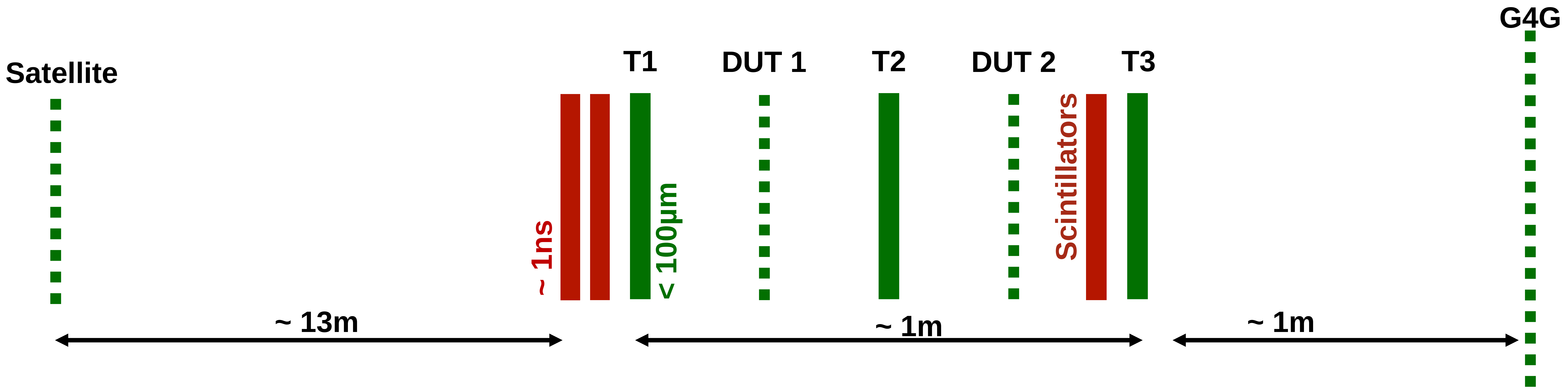



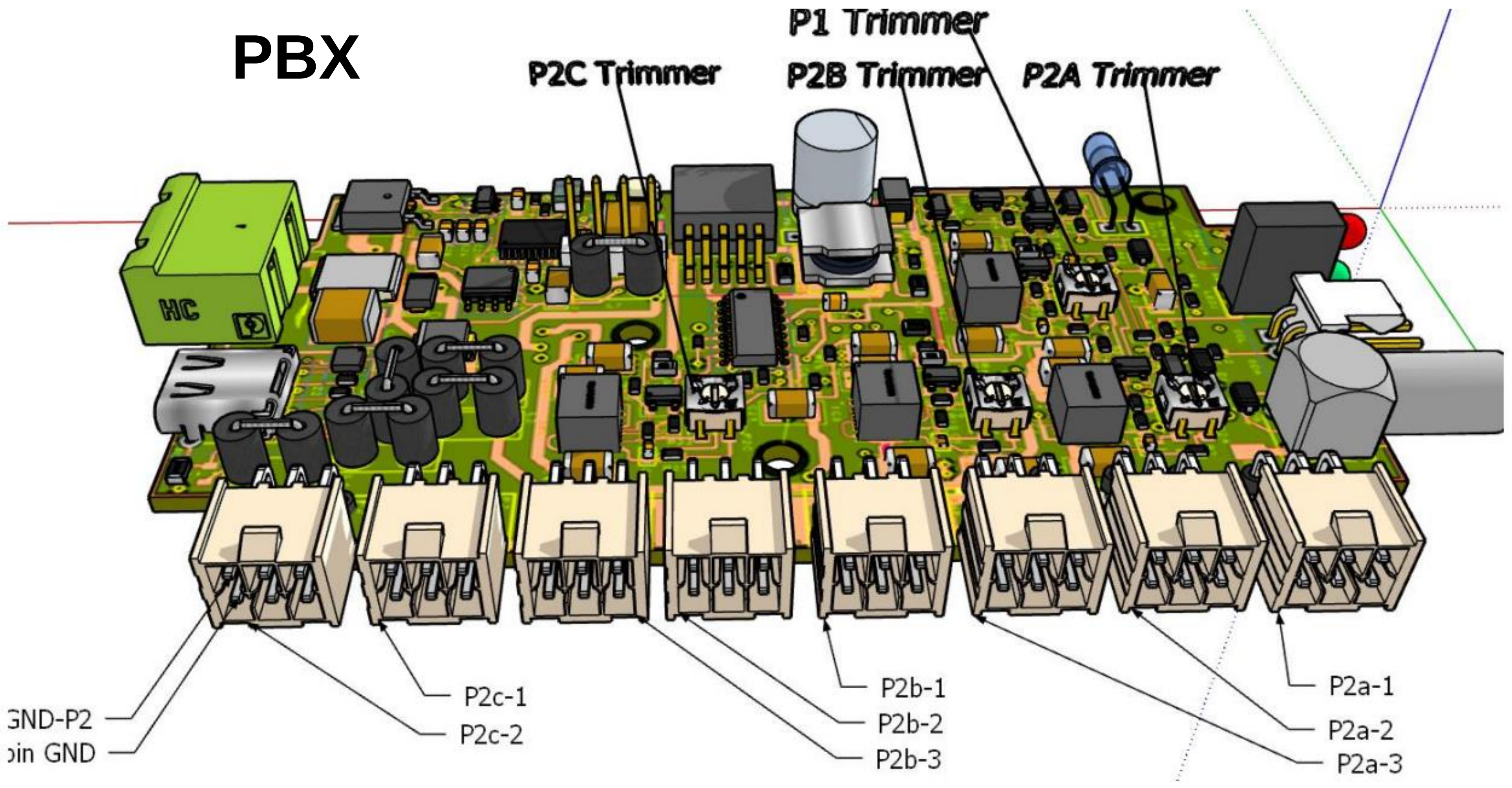
# The PBX and the distributed system

[PBX Documentation from H. Muller]




- External power enables usage of up to 30m HDMI cables (20m tested in beam – 30m tested in lab)
- The PBX was designed to supply 8 VMM-hybrids and can be powered via a 40W USB-C charger

PBX

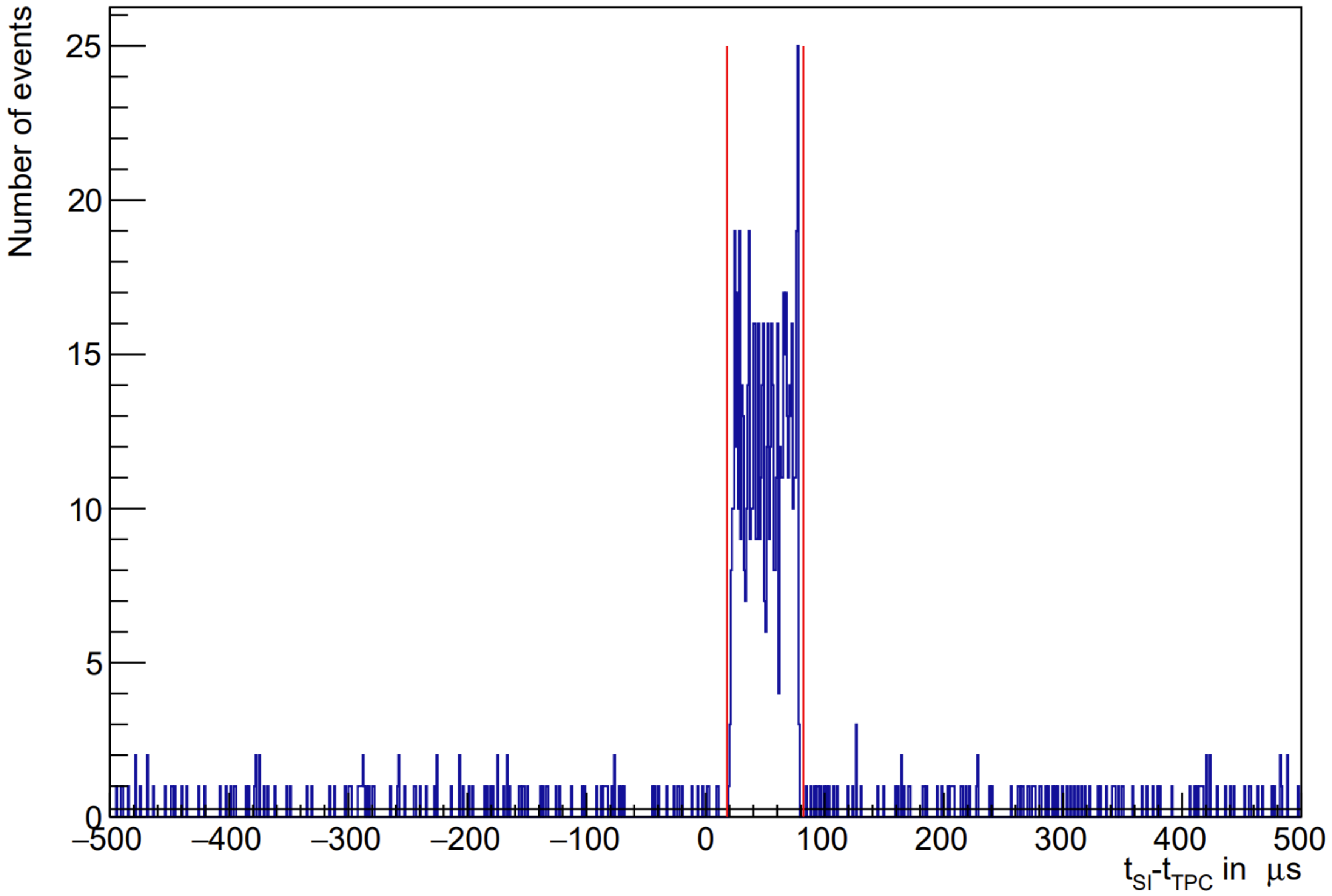


# R&D studies on the new AMBER triple GEM using the VMM3a/SRS

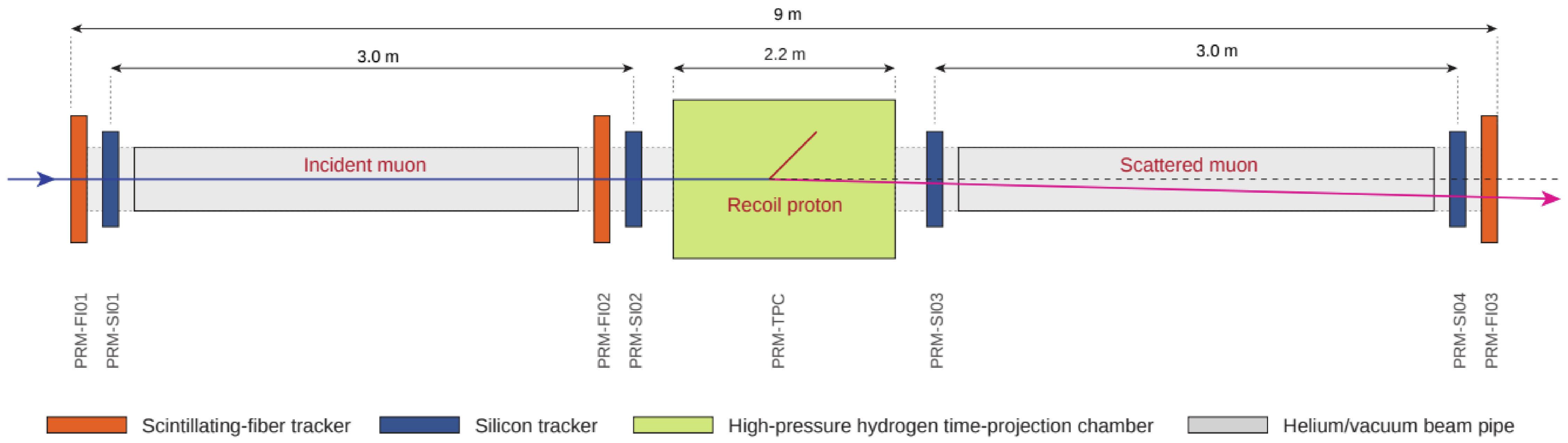
# AMBER – phase-1: PRM

https://cds.cern.ch/record/2676885/files/SPSC-P-360.pdf

- Precise measurement of the Proton radius
  - Based on Muon-Proton elastic scattering
  - Active high-pressure hydrogen target
- Recoil Proton can‘t be used as trigger
  - Trigger-less tracking system required
    -> **VMM3a as one candidate for GEM-system**




**Time difference between Trackers and TPC: 20µs – 80µs**




## General conditions for Phase-1

| Programme | Physics Goals | Beam Energy [GeV] | Beam Intensity [$s^{-1}$] | Trigger Rate [kHz] | Beam Type | Target | Hardware additions |
|---|---|---|---|---|---|---|---|
| muon-proton elastic scattering | Precision proton-radius measurement | 100 | $4 \cdot 10^6$ | 100 | $\mu^\pm$ | high-pressure H2 | active TPC, SciFi trigger, silicon tracking |
| Drell-Yan | Pion PDFs | 190 | $7 \cdot 10^7$ | 50 | $\pi^\pm$ | C/W | target modification |
| Input for Dark Matter Search | $\bar{p}$ production cross section | 20-280 | $5 \cdot 10^5$ | 25 | $p$ | LH2, LHe | liquid helium target, RICH? |

## 2022-2024 PRM SETUP

| Beam setting | TPC pressure setting | Duration | Purpose |
|---|---|---|---|
| $\mu^+$, 100 GeV | 20 bars | 92 days | $2.5 < Q^2/(10^{-3}\text{GeV}^2) < 40.0$ |
| $\mu^+$, 100 GeV | 4 bars | 67 days | $1.0 < Q^2/(10^{-3}\text{GeV}^2) < 8.0$ |
| $\mu^-$, 100 GeV | 4 bars | 67 days | control of charge dependence |
| $\mu^+$, 60 GeV | 4 bars | 34 days | control of energy dependence |

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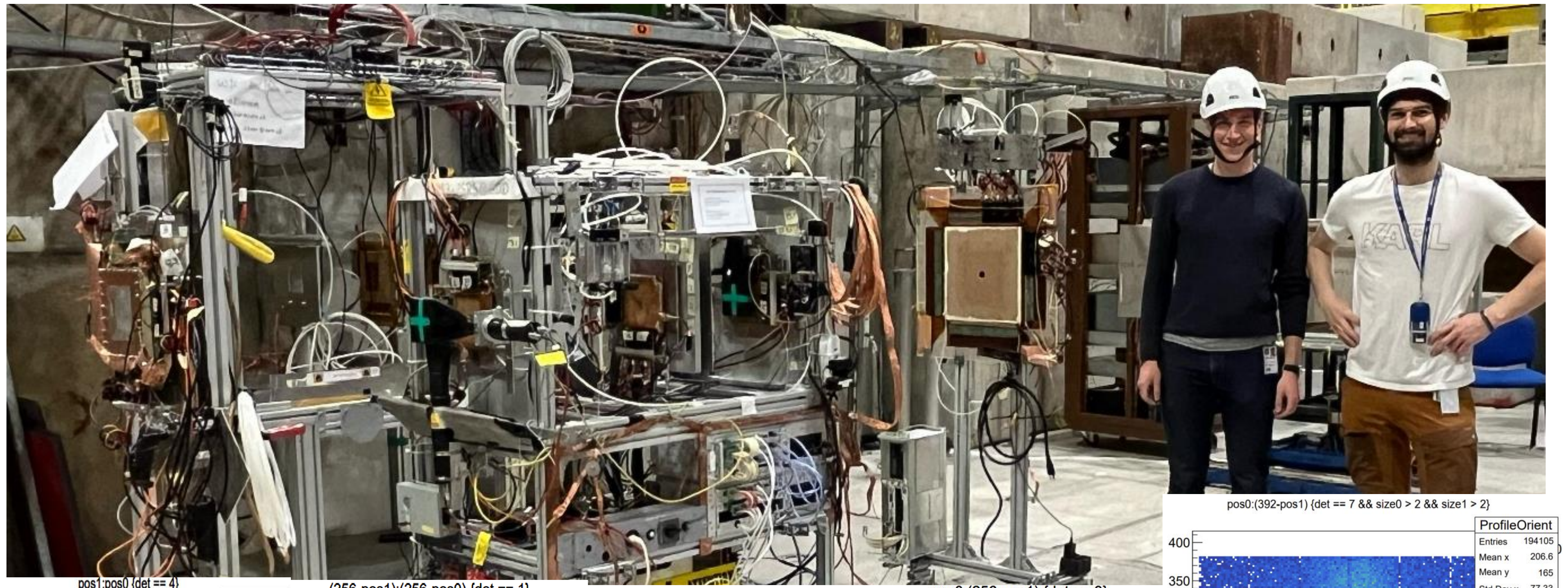
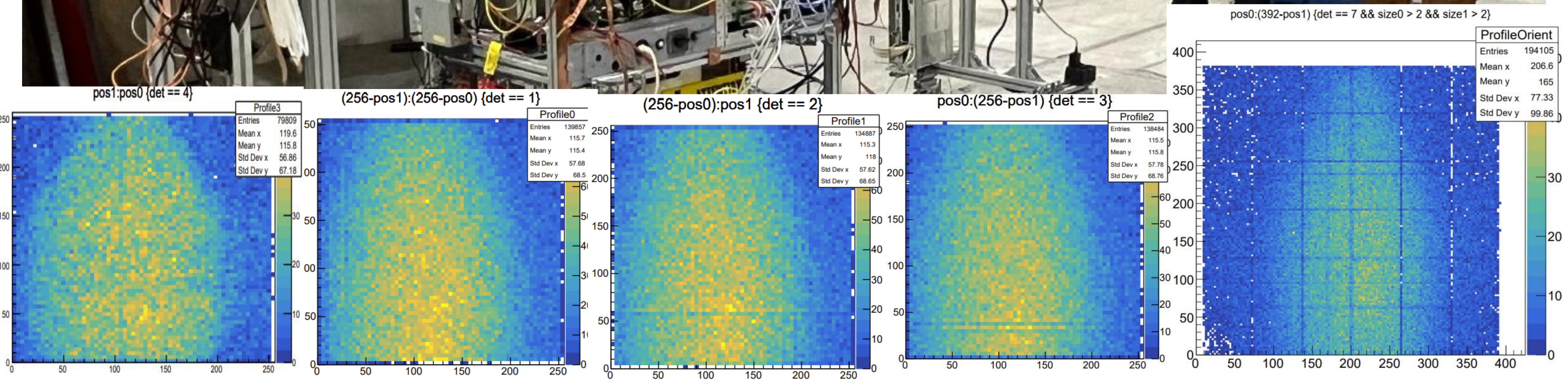
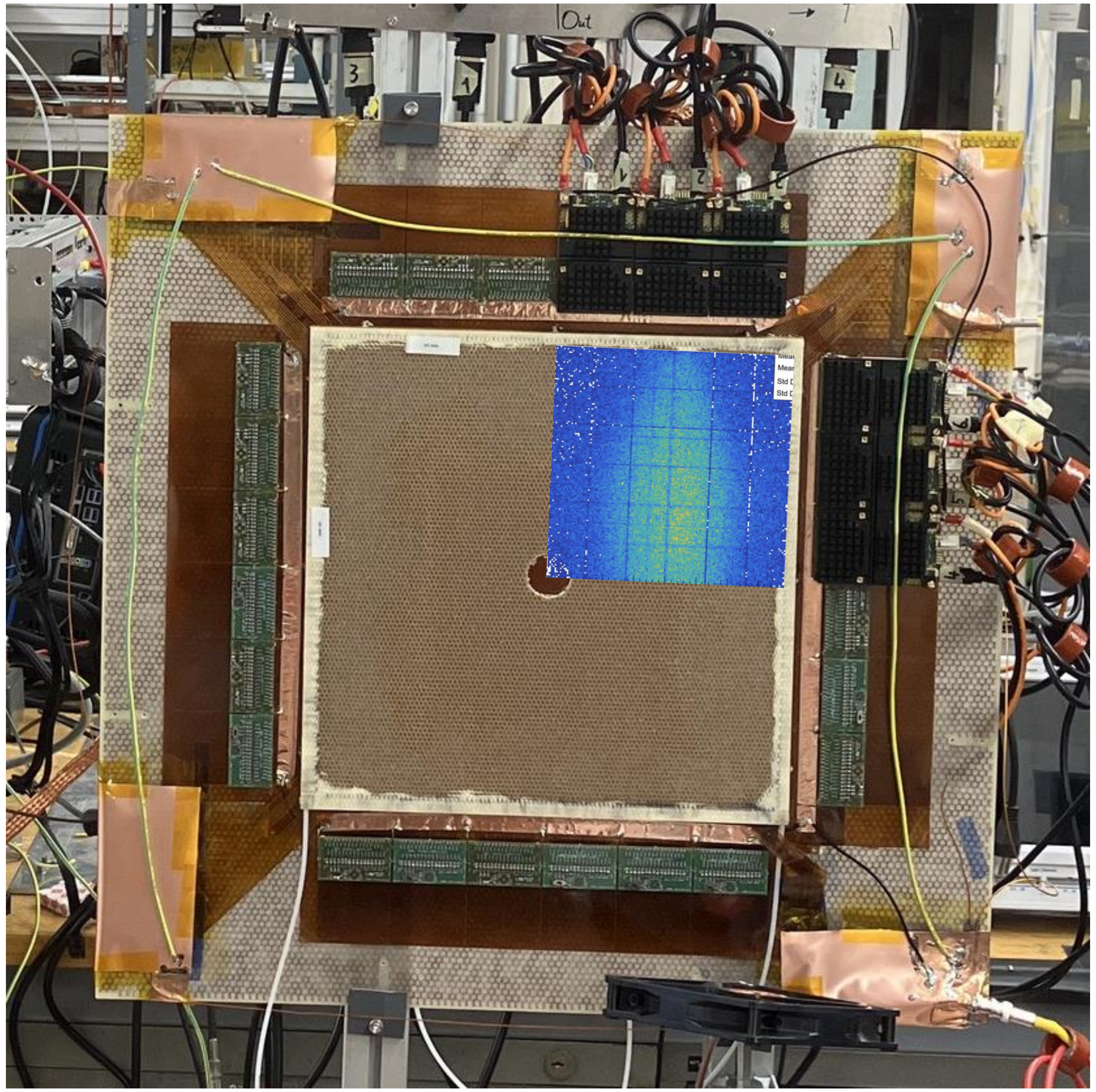
# G4G (AMBER): Triple GEM

~40kHz Muons

- Equipped with VMM3a on one quadrant
  - Prepared and optimized in the laboratory
- Successful operation after installation in beam area







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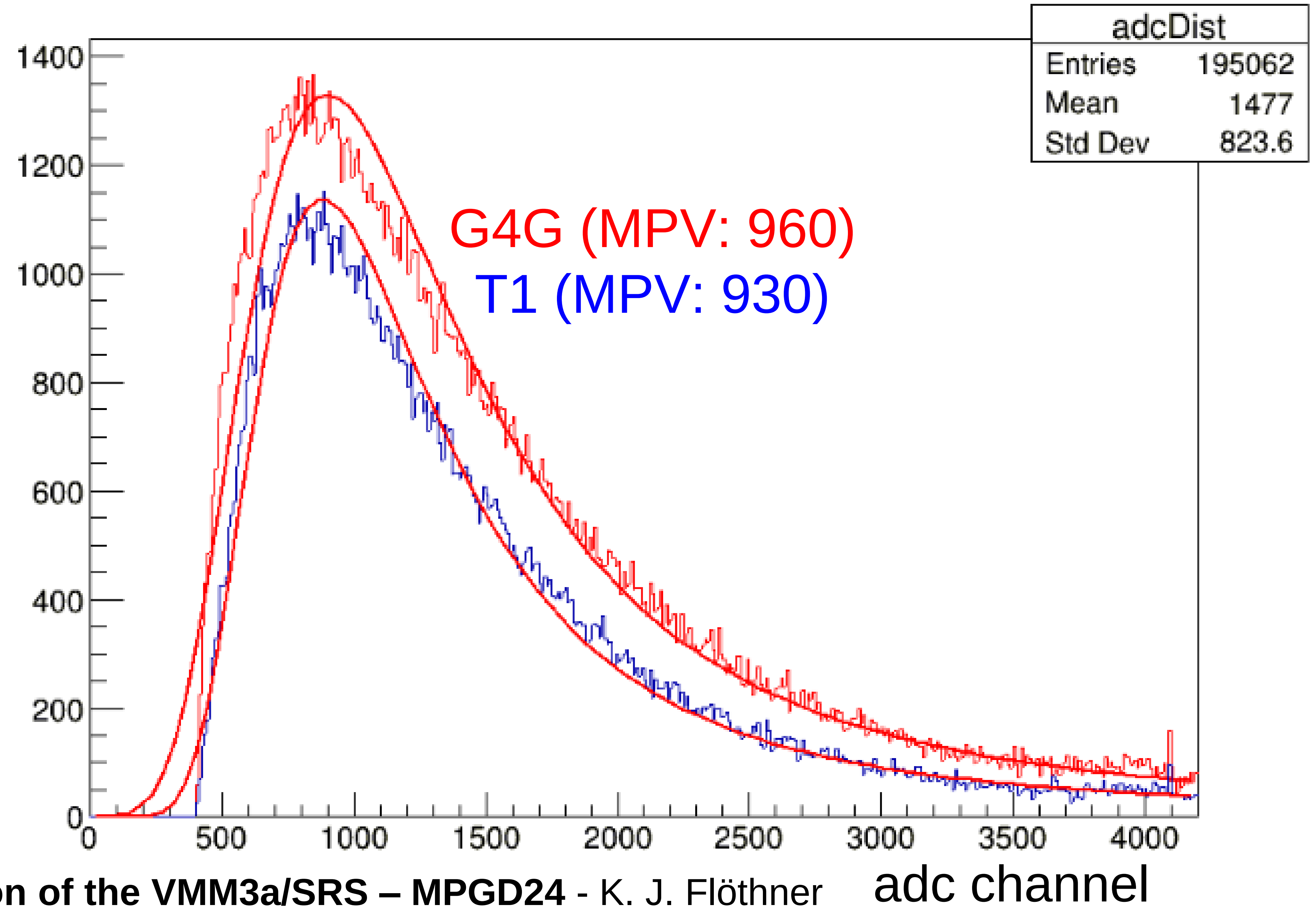
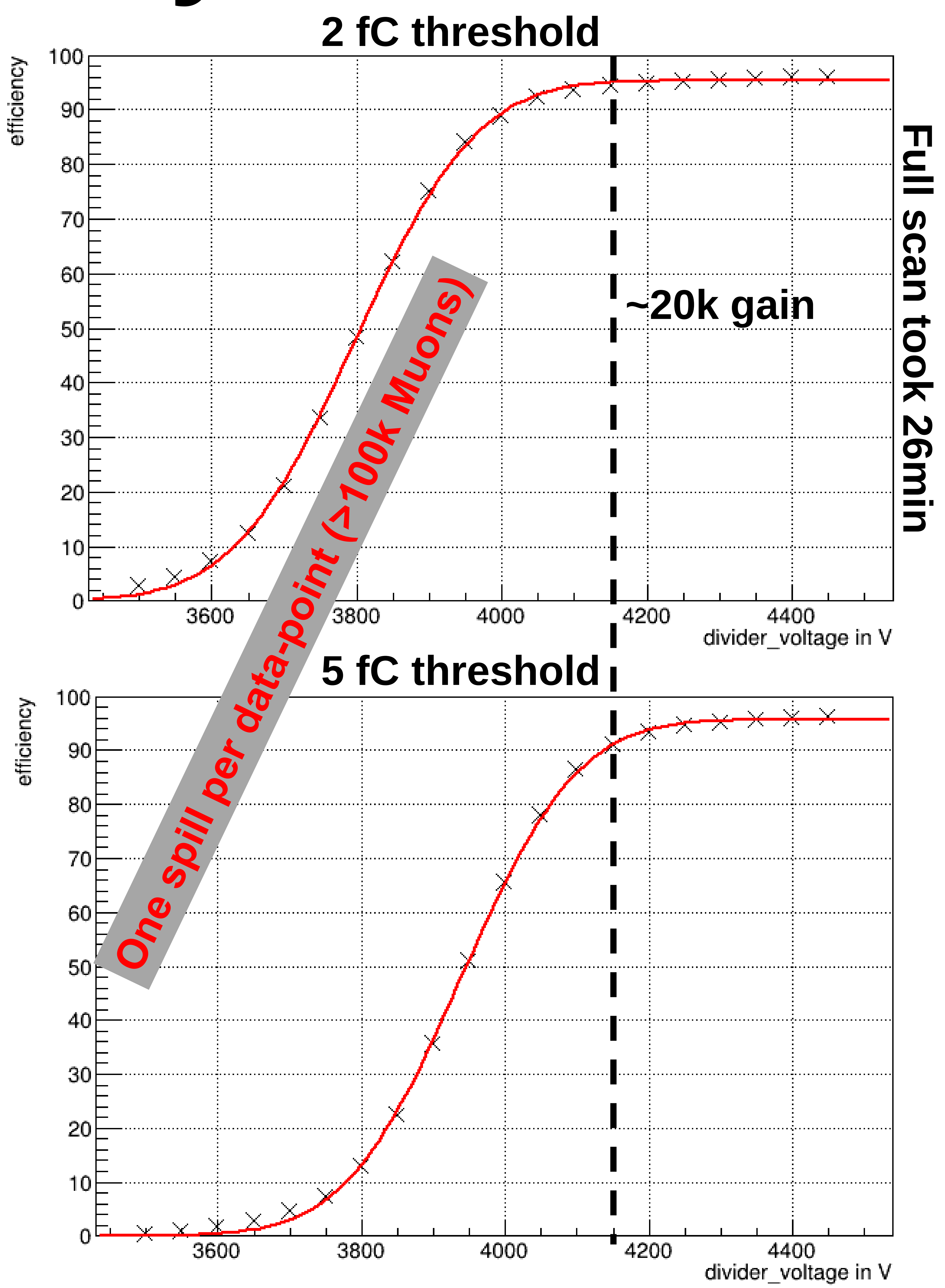
# G4G (AMBER): Efficiency

~40kHz Muons

- Efficiency scans performed for various thresholds (1.5fC to 10fC)
- Good general response and stable operation
- Further test-beam data analysis ongoing

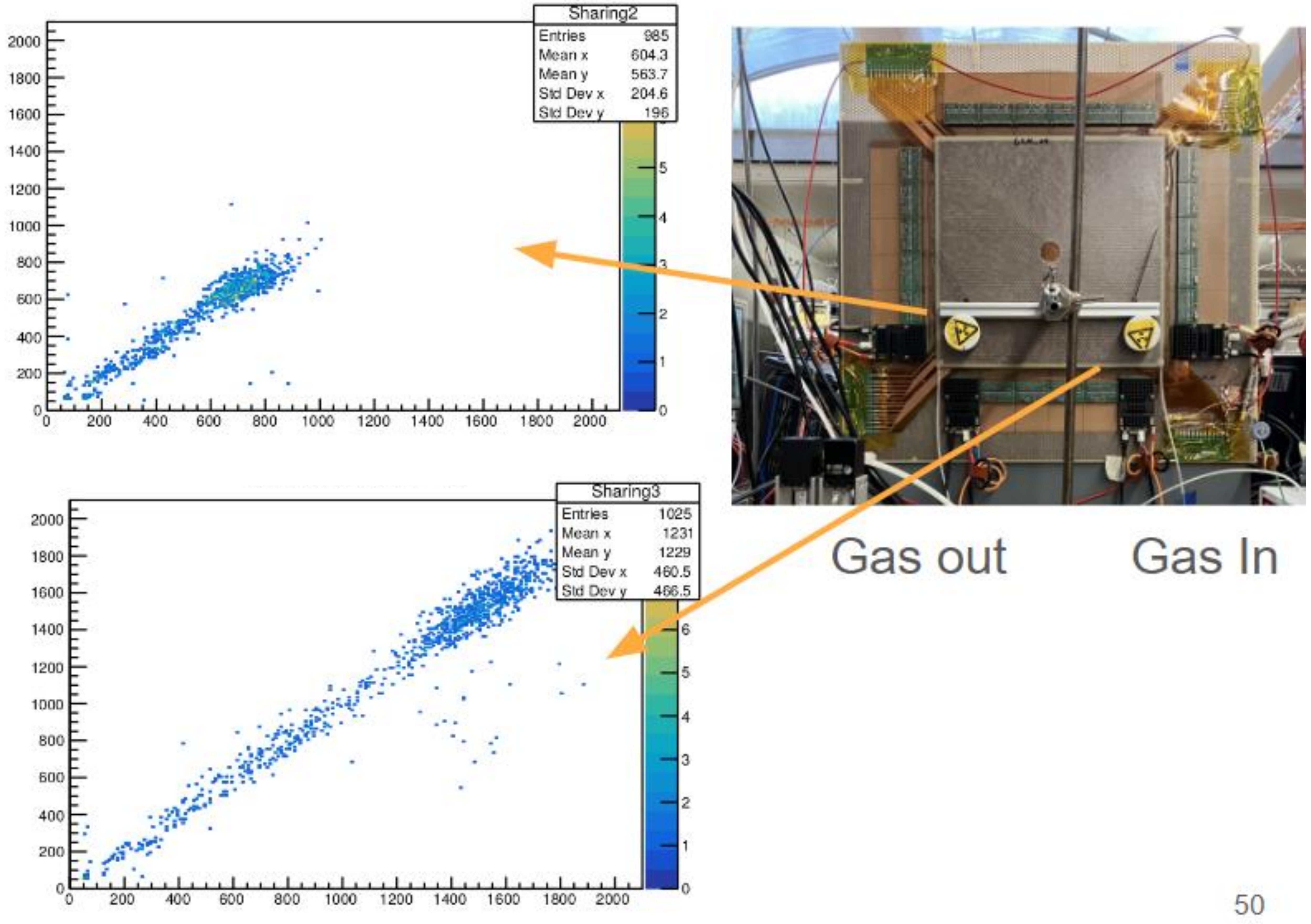


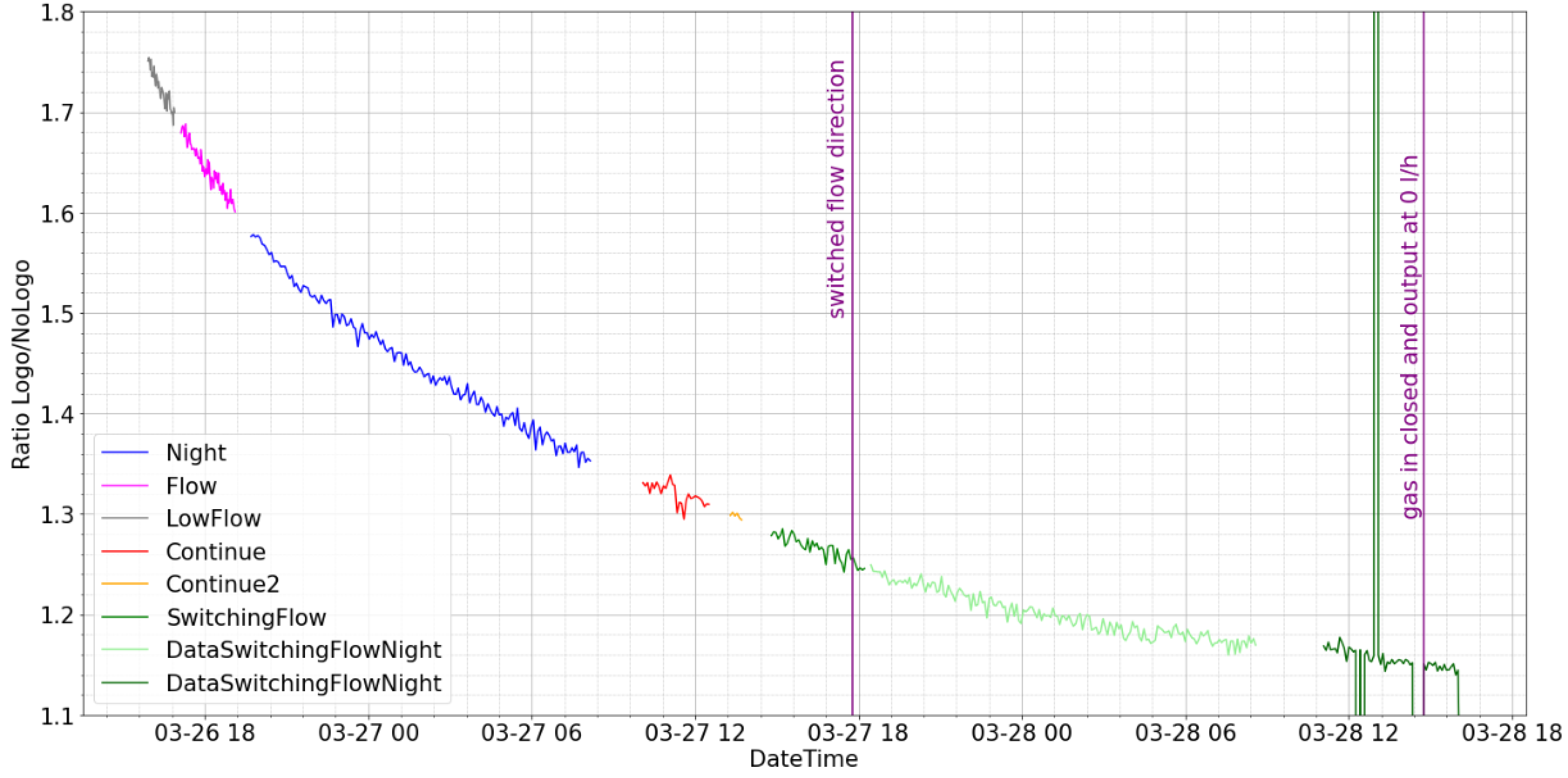



# G4G (AMBER): Gain Hotspot

~kHz $^{55}Fe$

- Higher local detector gain observed for all detectors
- Effect shows very long time constant
- VMM3a/SRS helps to investigate the problem



# R&D Studies the VMM3a as Front-End Electronics for TPCs

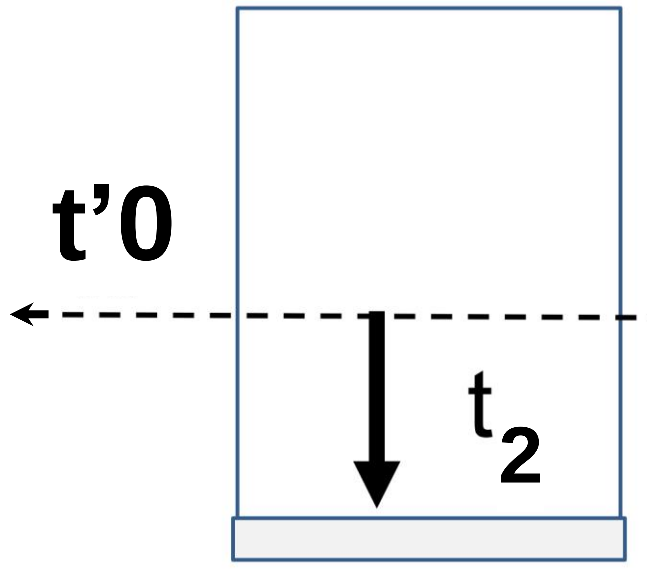
# The Twin GEM-TPC

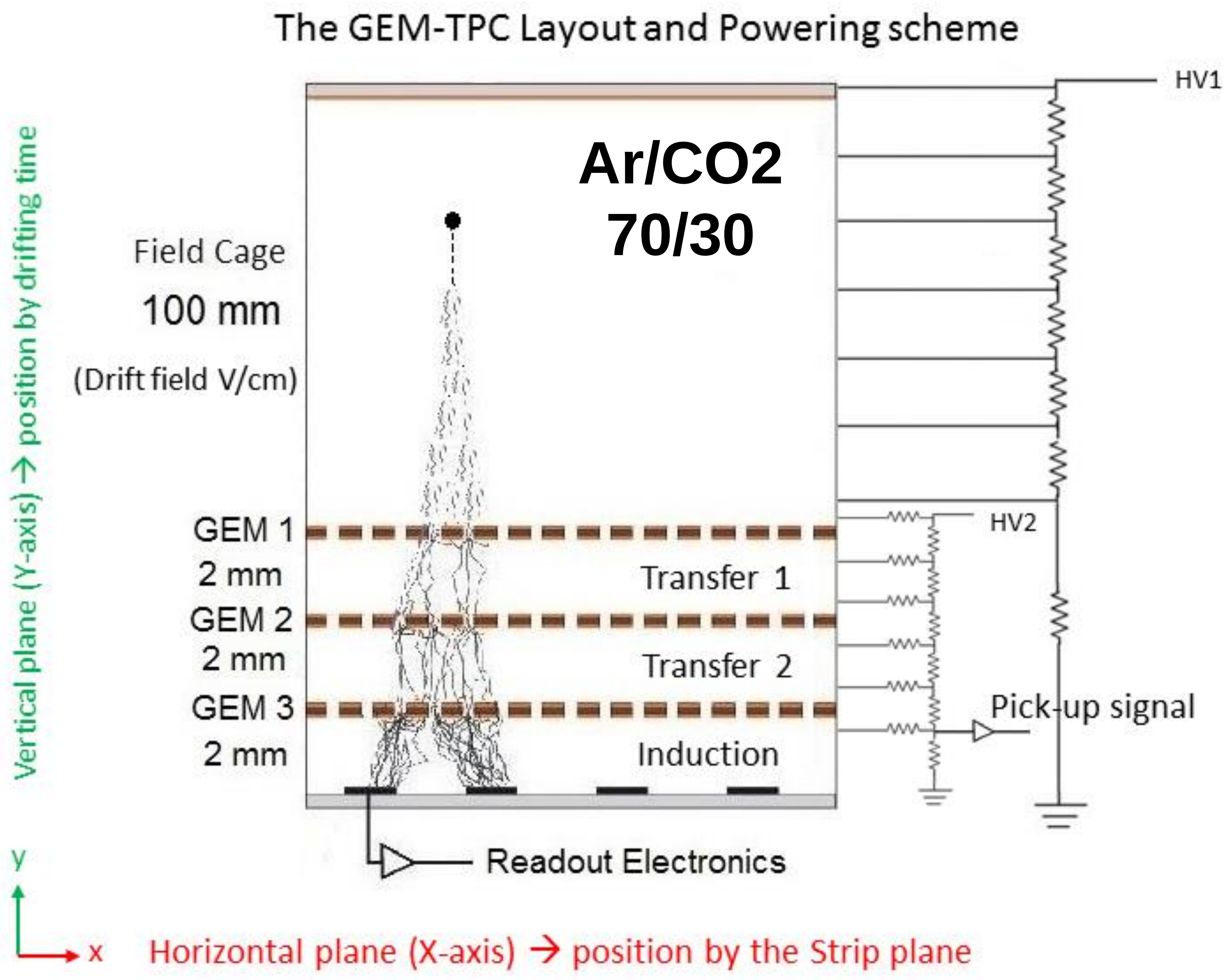
F. Garcia et al.: https://doi.org/10.1016/j.nima.2017.11.088

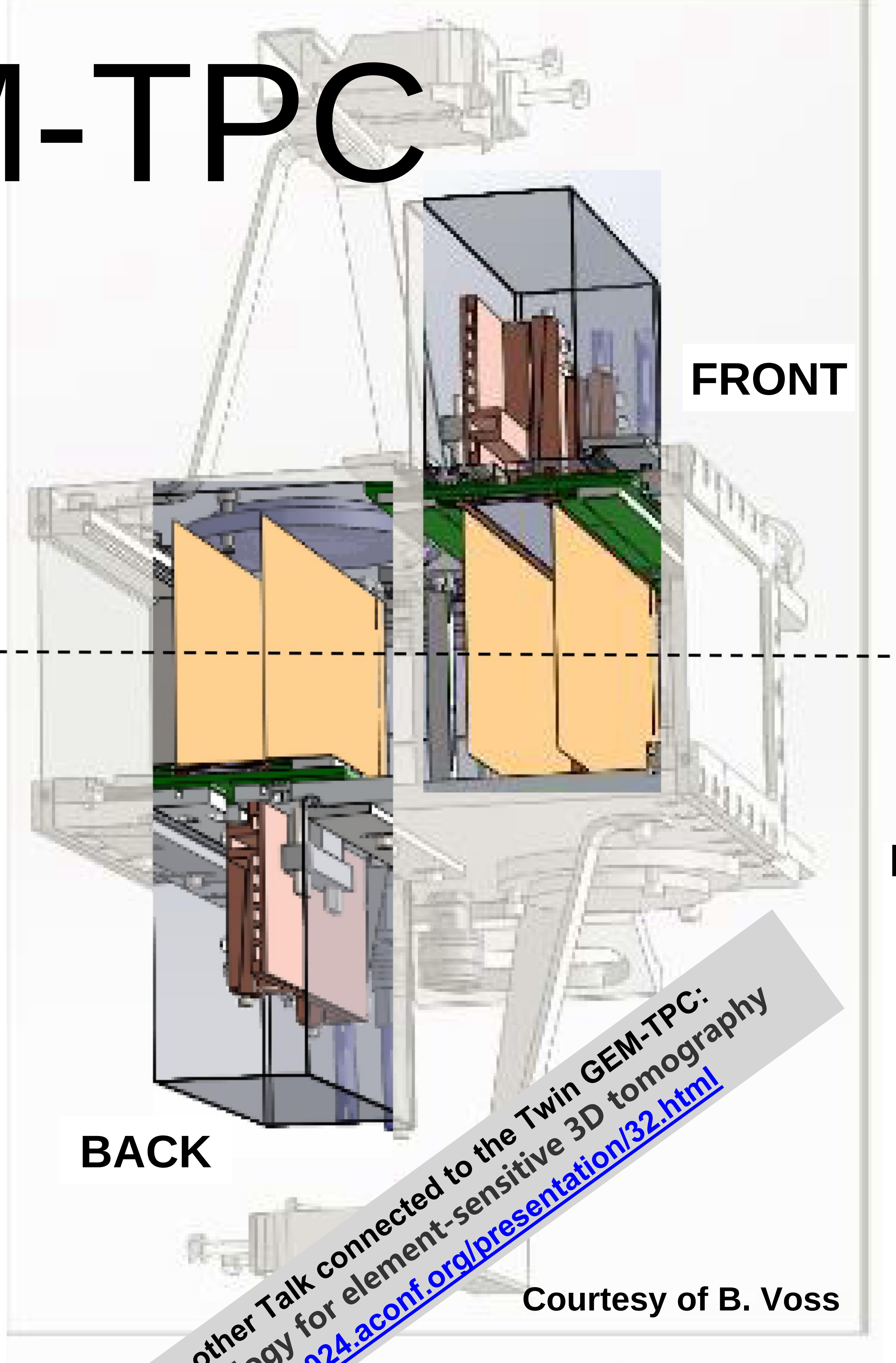
$$t'_{1,2} = t'_0 + t_{1,2}$$

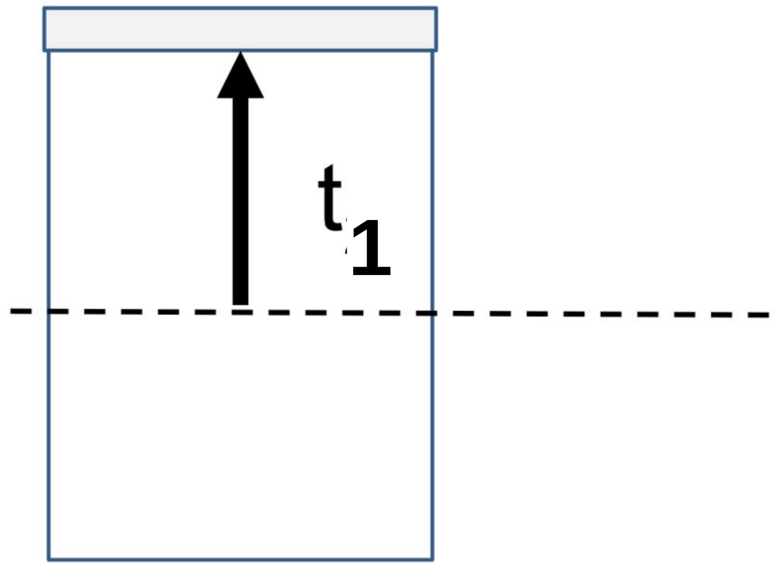
$$\text{->}\ t'_2 - t'_1 = t_2 - t_1$$

$$\text{->}\ t'_0 = \frac{t'_1 + t'_2 - t_{full}}{2}$$



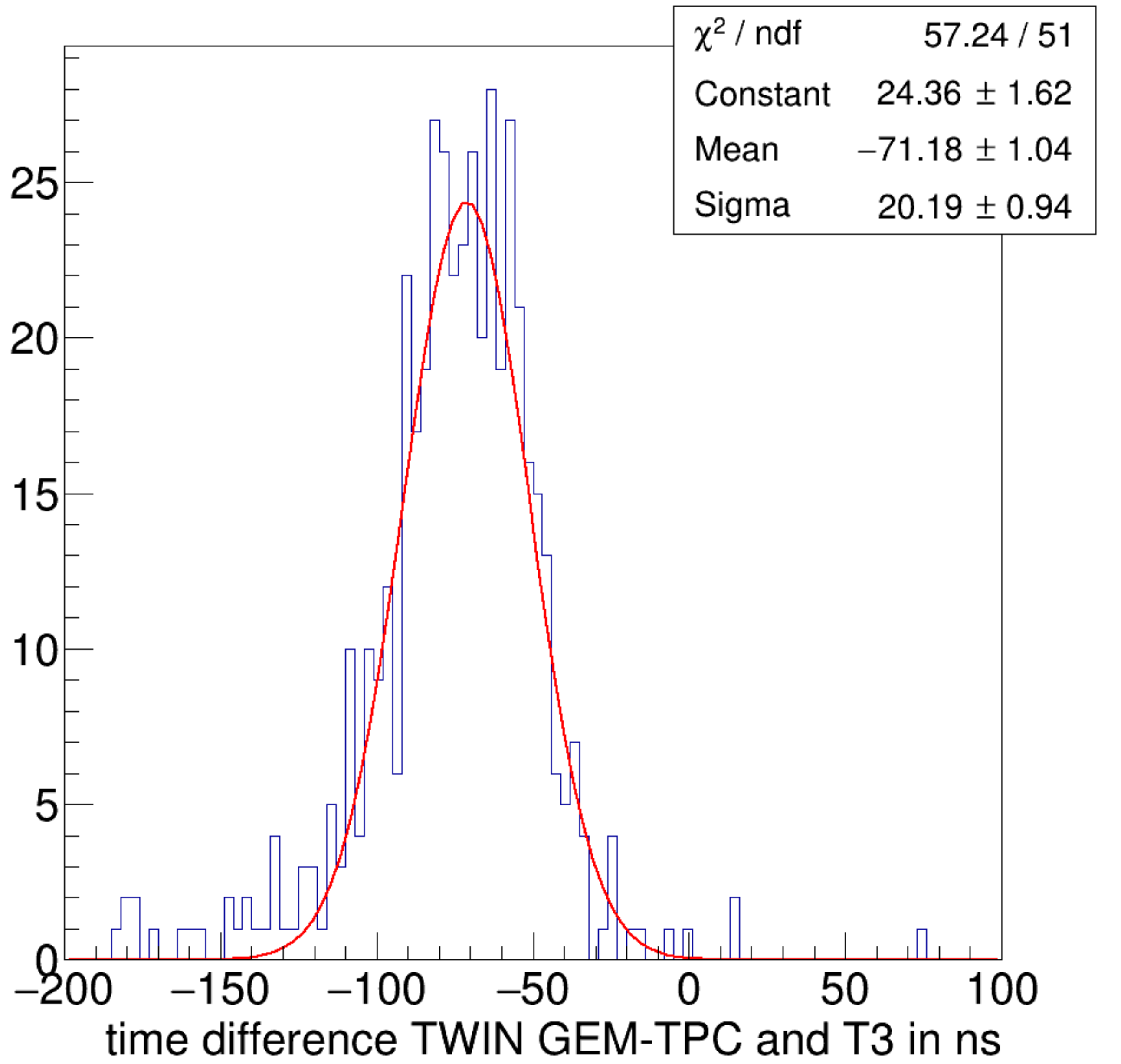




**Check the other Talk connected to the Twin GEM-TPC:**
**A novel technology for element-sensitive 3D tomography**
**https://mpgd2024.aconf.org/presentation/32.html**

## Extract t0 with known full drift time



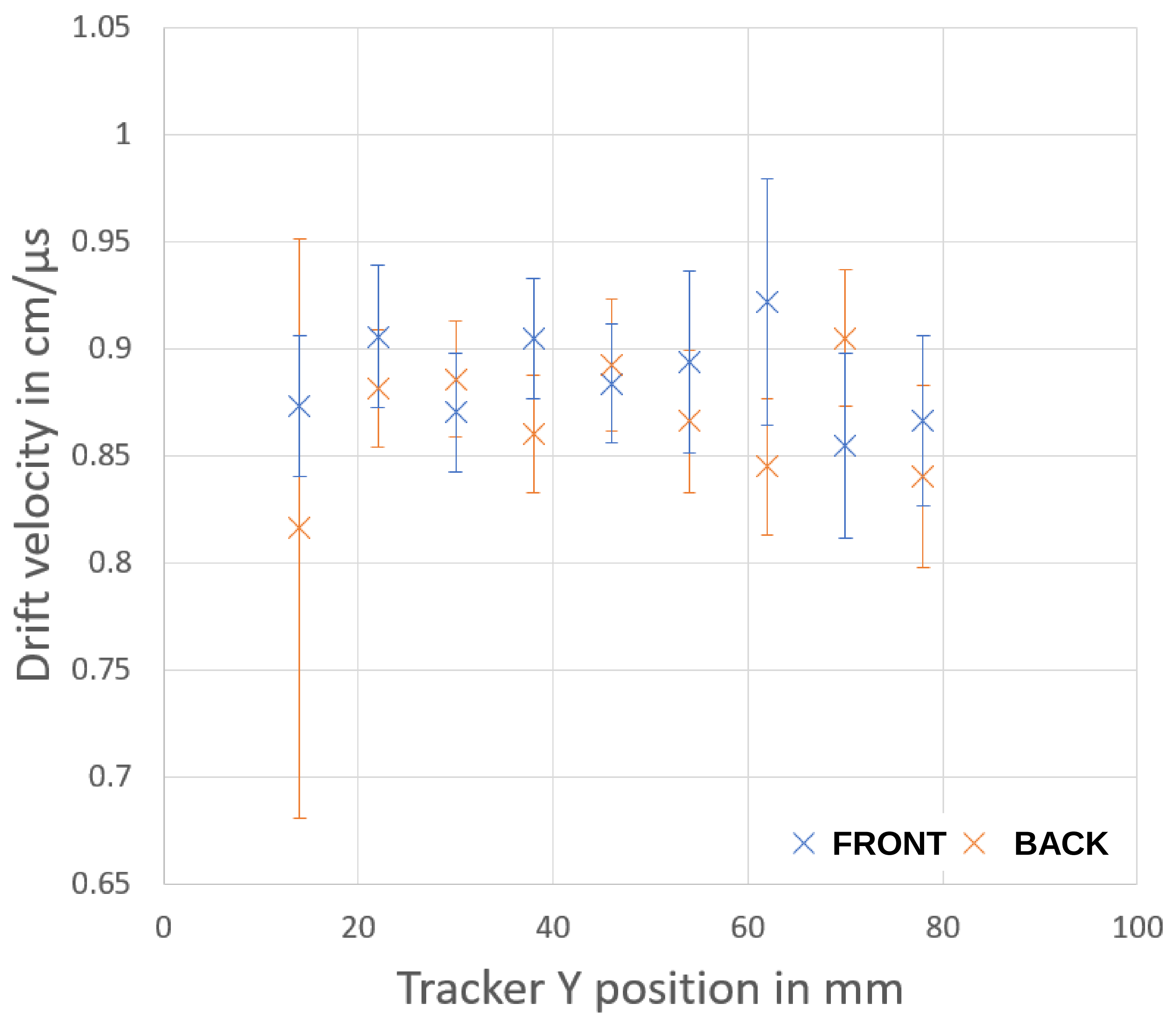
# Control measurements

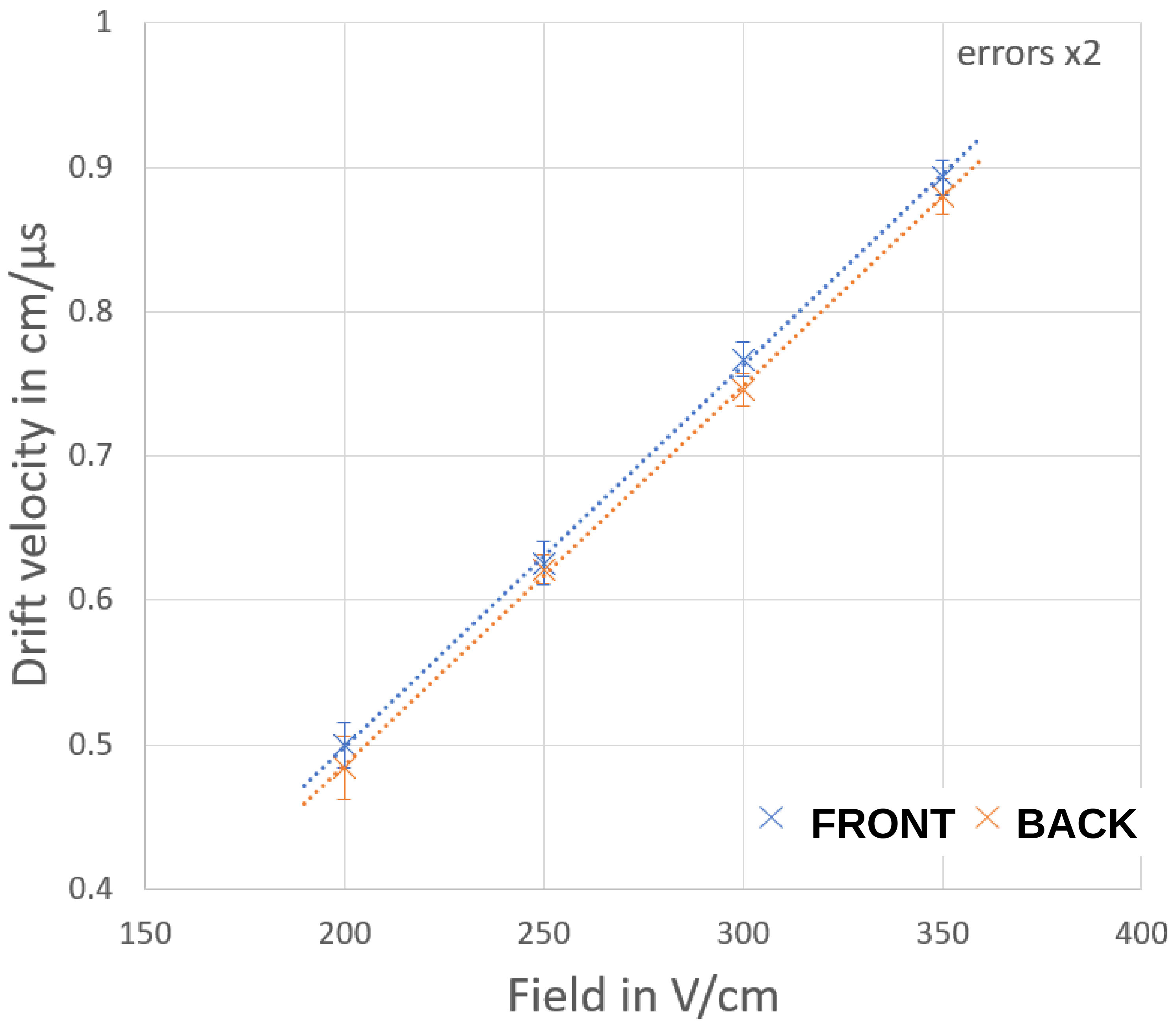
- Field scan
  - drift velocity behaves identical for both TPCs
  - difference below 2%

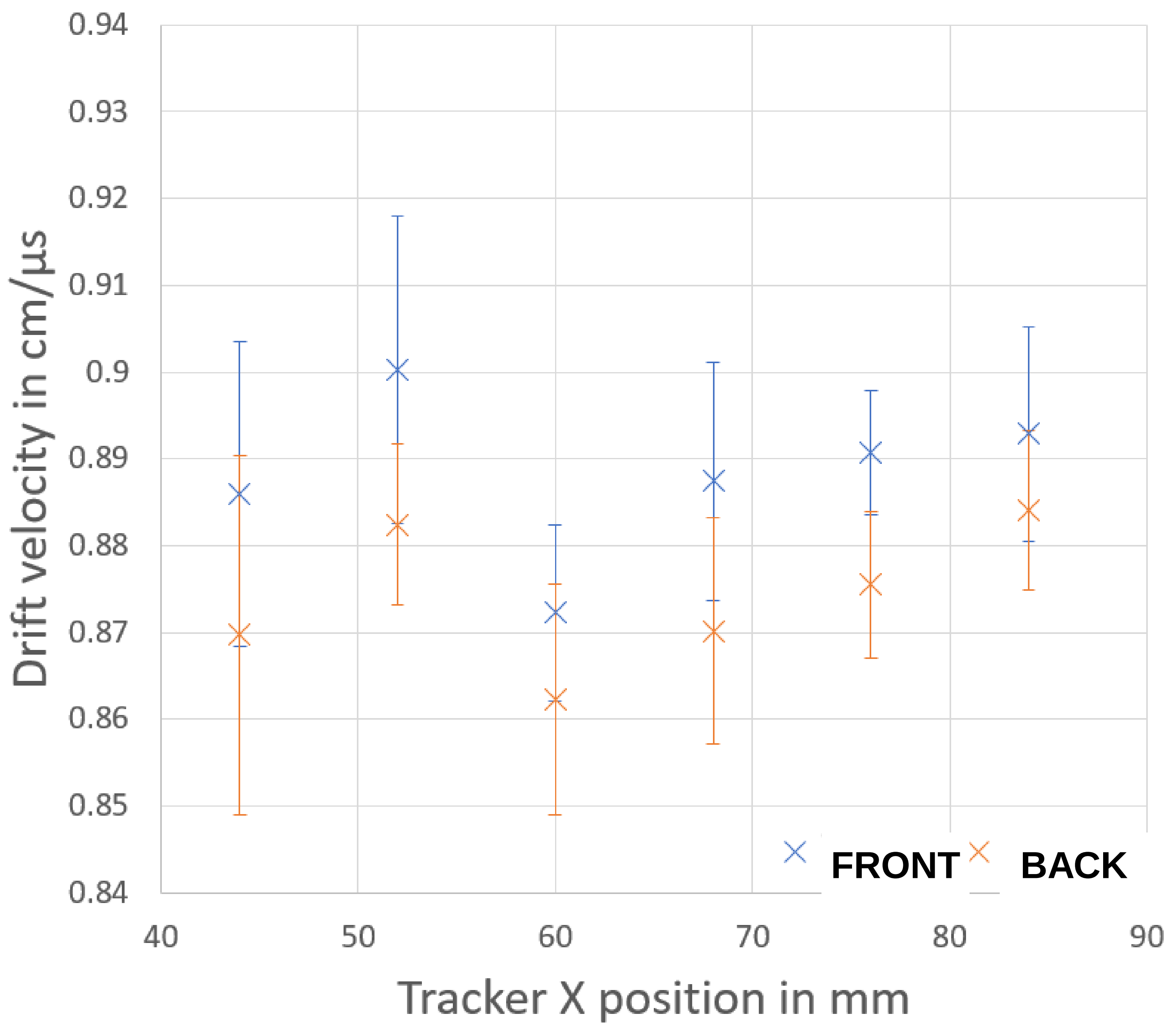
- Y position dependence
  - no significant variation
  - constant within errors

- X position dependence
  - no significant variation
  - constant within errors

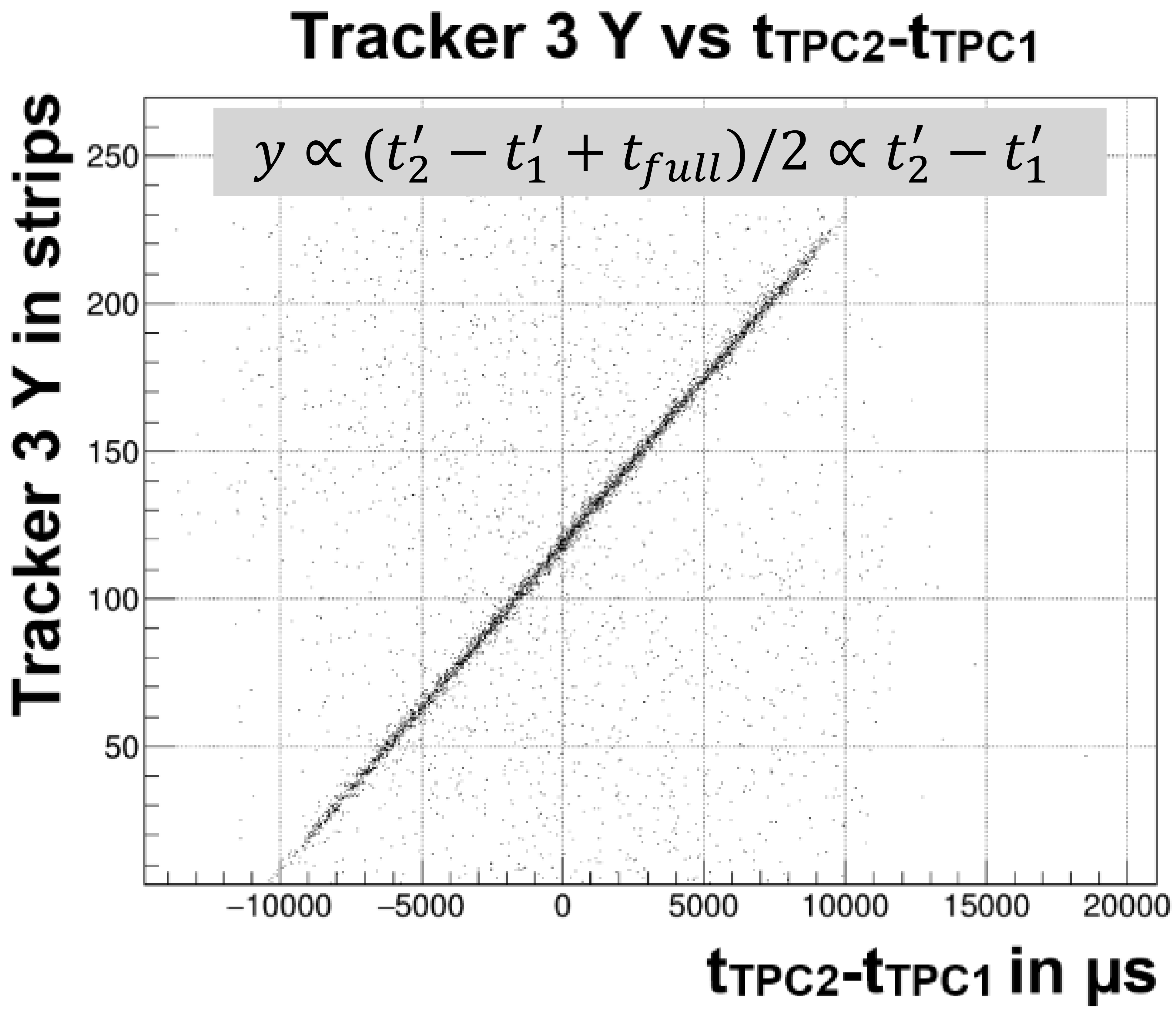
➡ Field can be assumed homogeneous and identical for both TPCs in first approximation

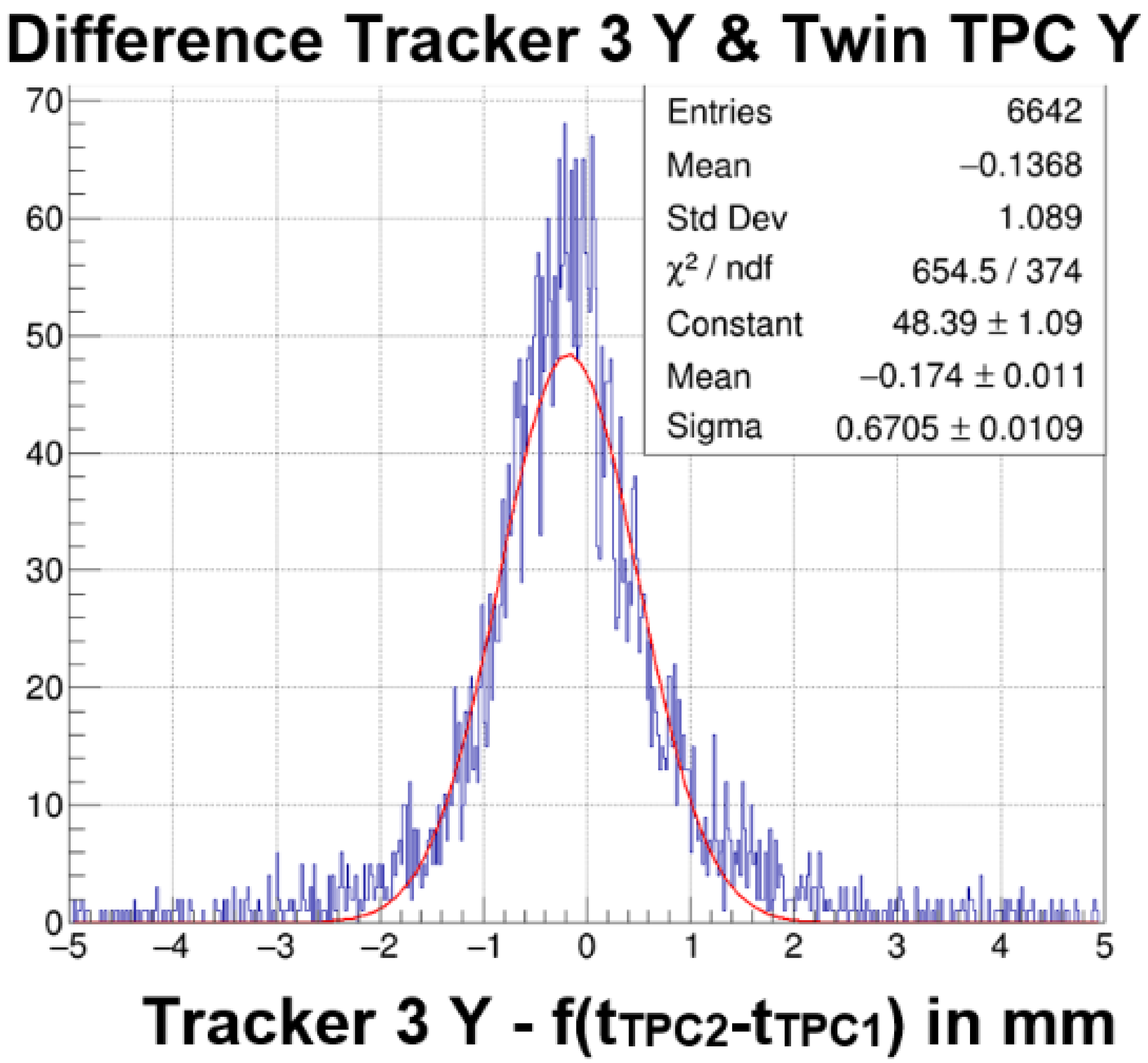


# The Twin GEM-TPC: Removing $t_0$



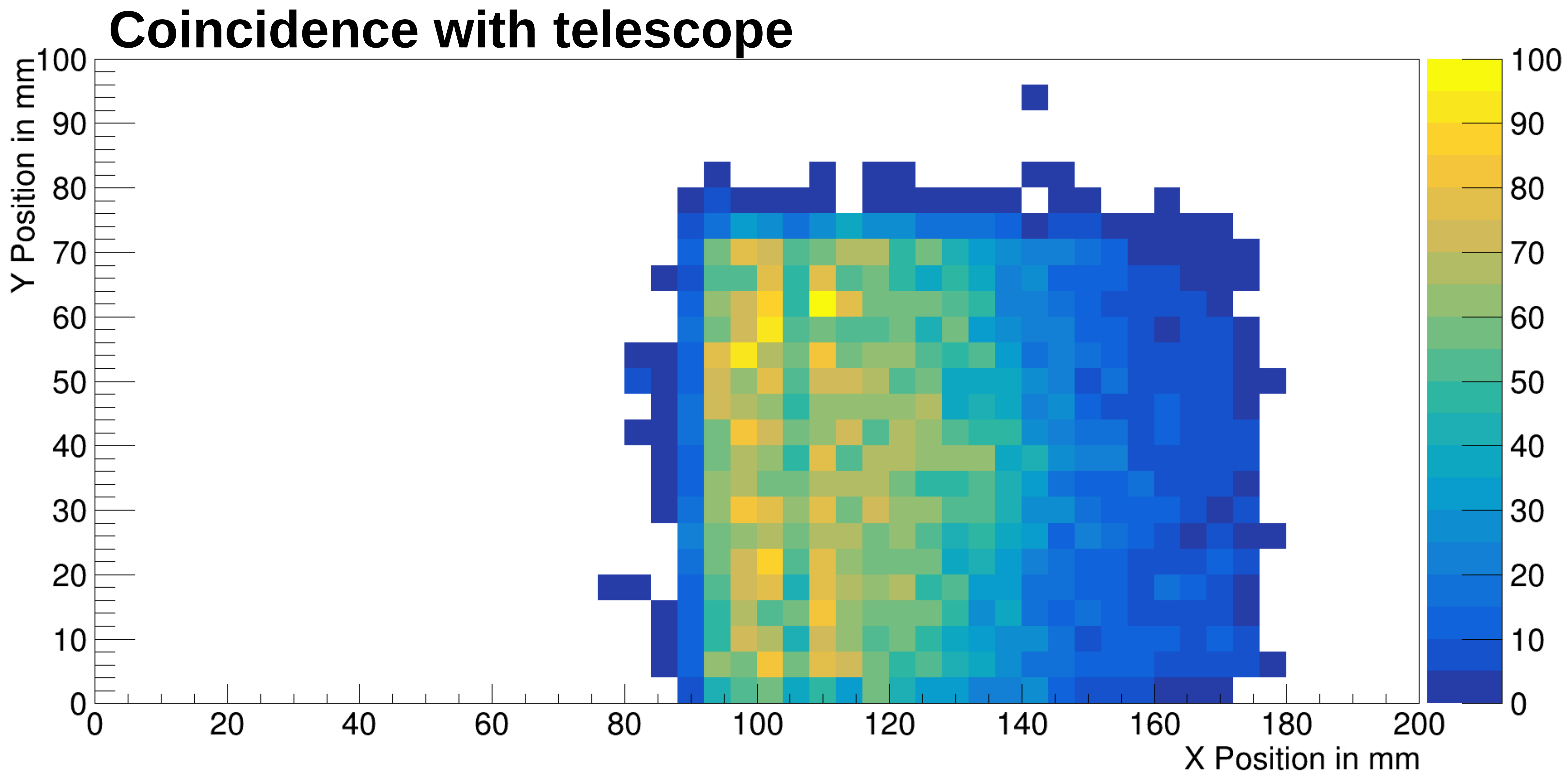

- Time differences show clear correlation with coordinate from reference tracking detector
- Position can be extracted with fit to calculate the residual

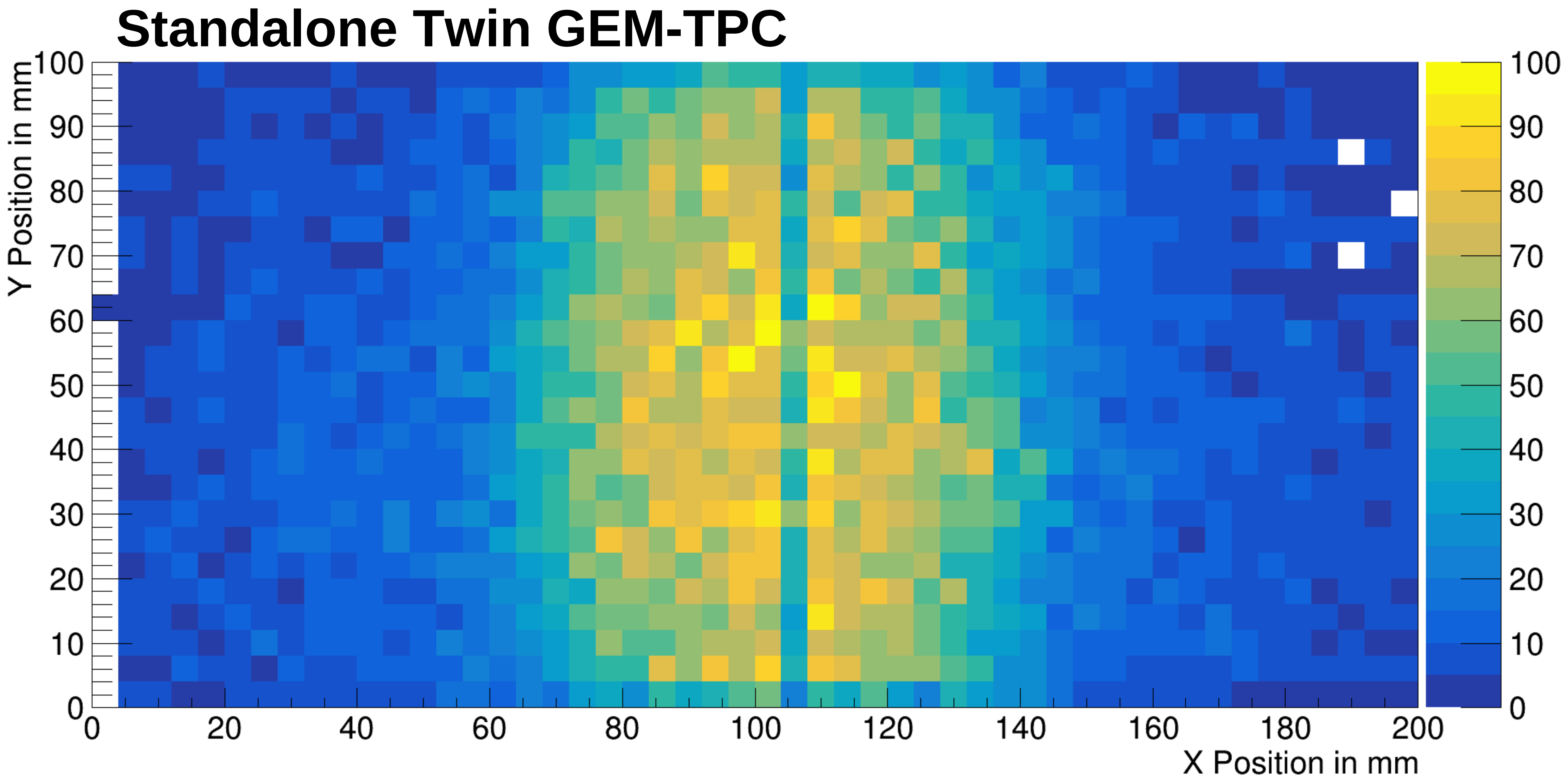
# Beam Profile

150GeV/c Muon Beam – H4 Beamline in EHN2 – RD51 test-beam

**Showcase without external information**

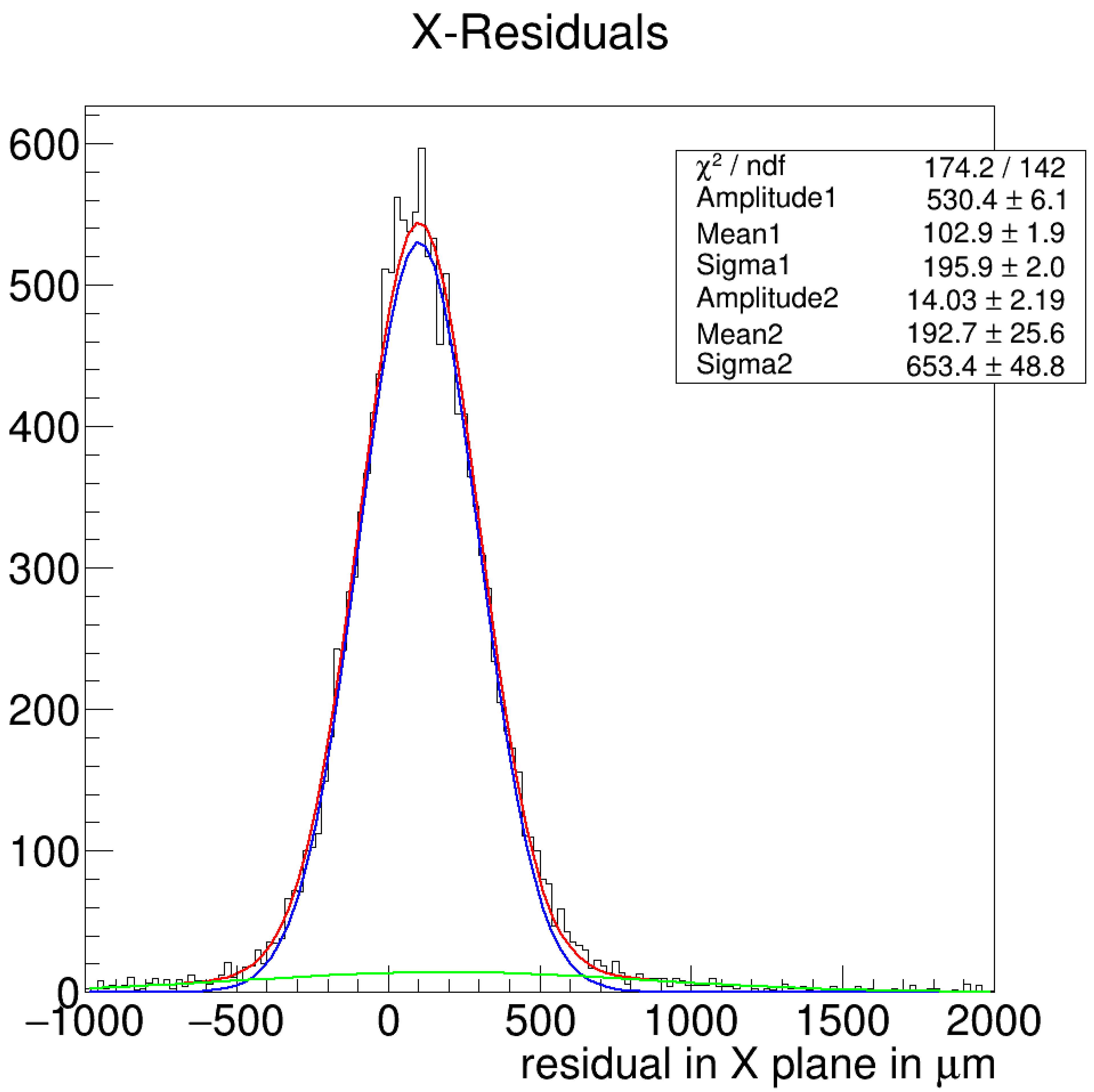
- Beam profile can be reconstructed
  - Only data from Front- and Back-TPC
  - Matching done with Front-TPC as reference (does not work well without noise-cuts)
- Cuts before matching
  - Cluster-size >2 & <10
  - Cluster adc value >800

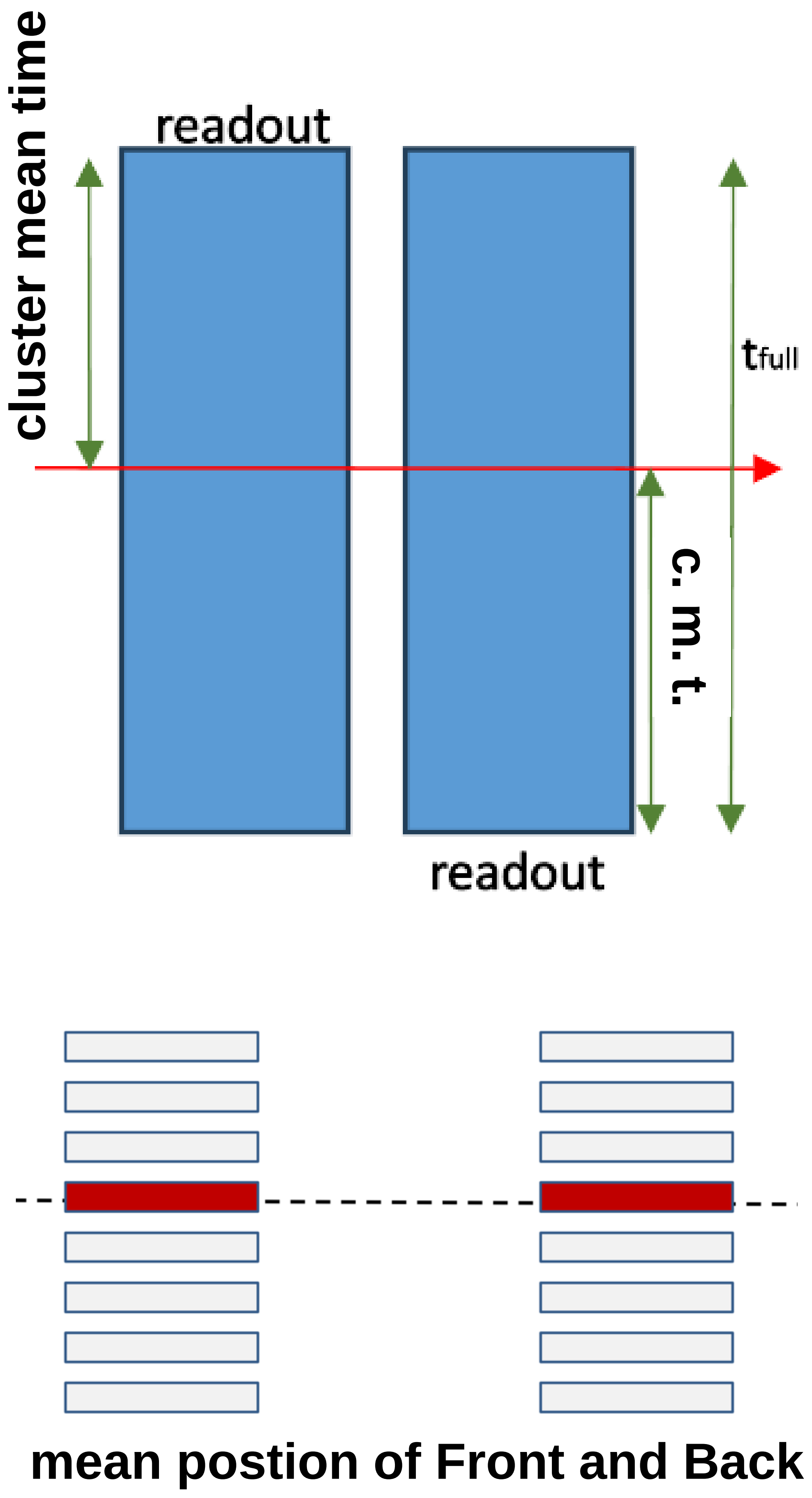


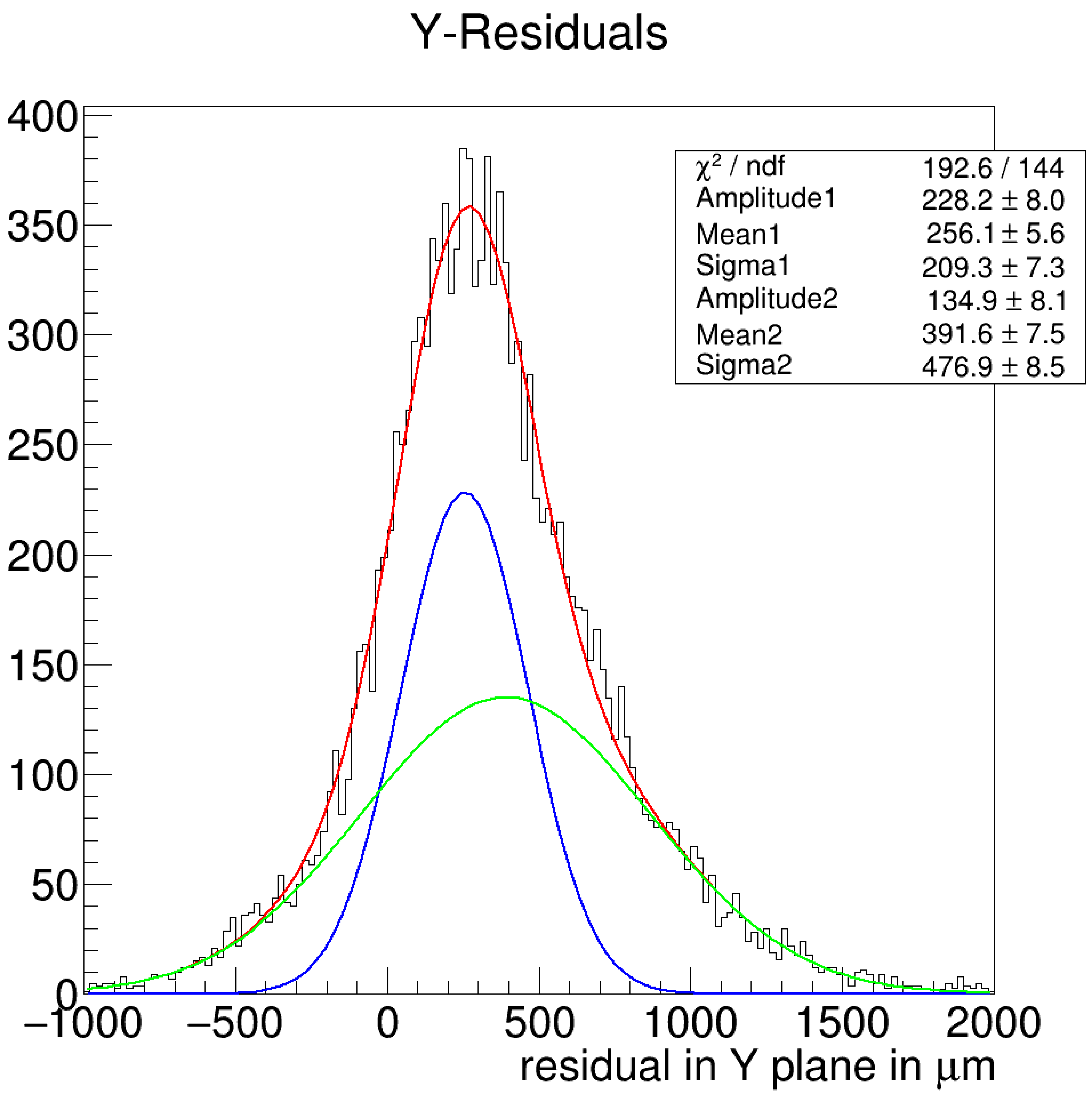



# Tracking with Mean of Clusters

150GeV/c Muon Beam – H4 Beamline in EHN2 – RD51 test-beam – H5V3 orientation



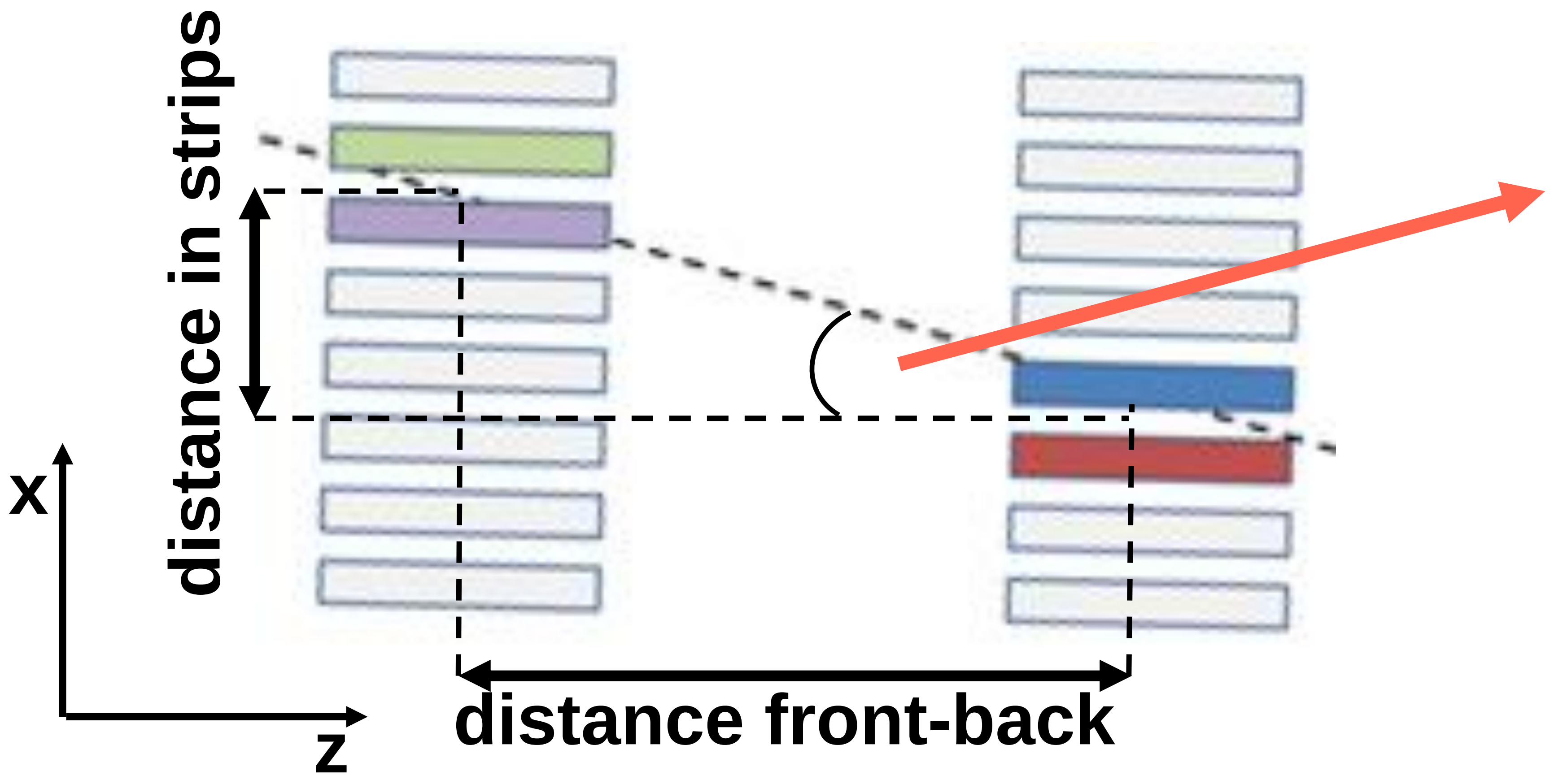



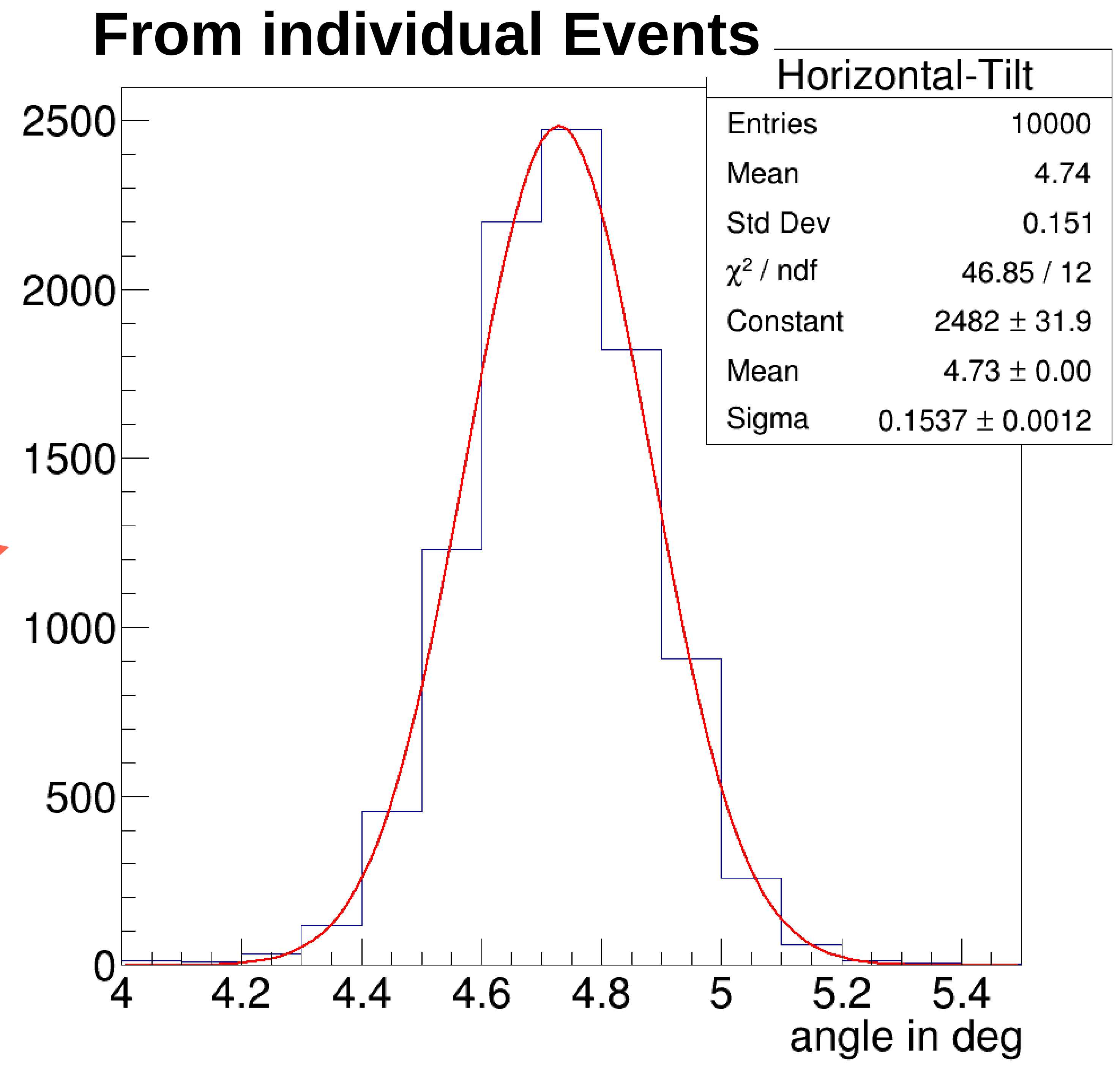

- Only gives one point per track and no information about the angle
- Could be still interesting as low material budget tracker station but does not cover full potential

# Horizontal Tilt Calculation

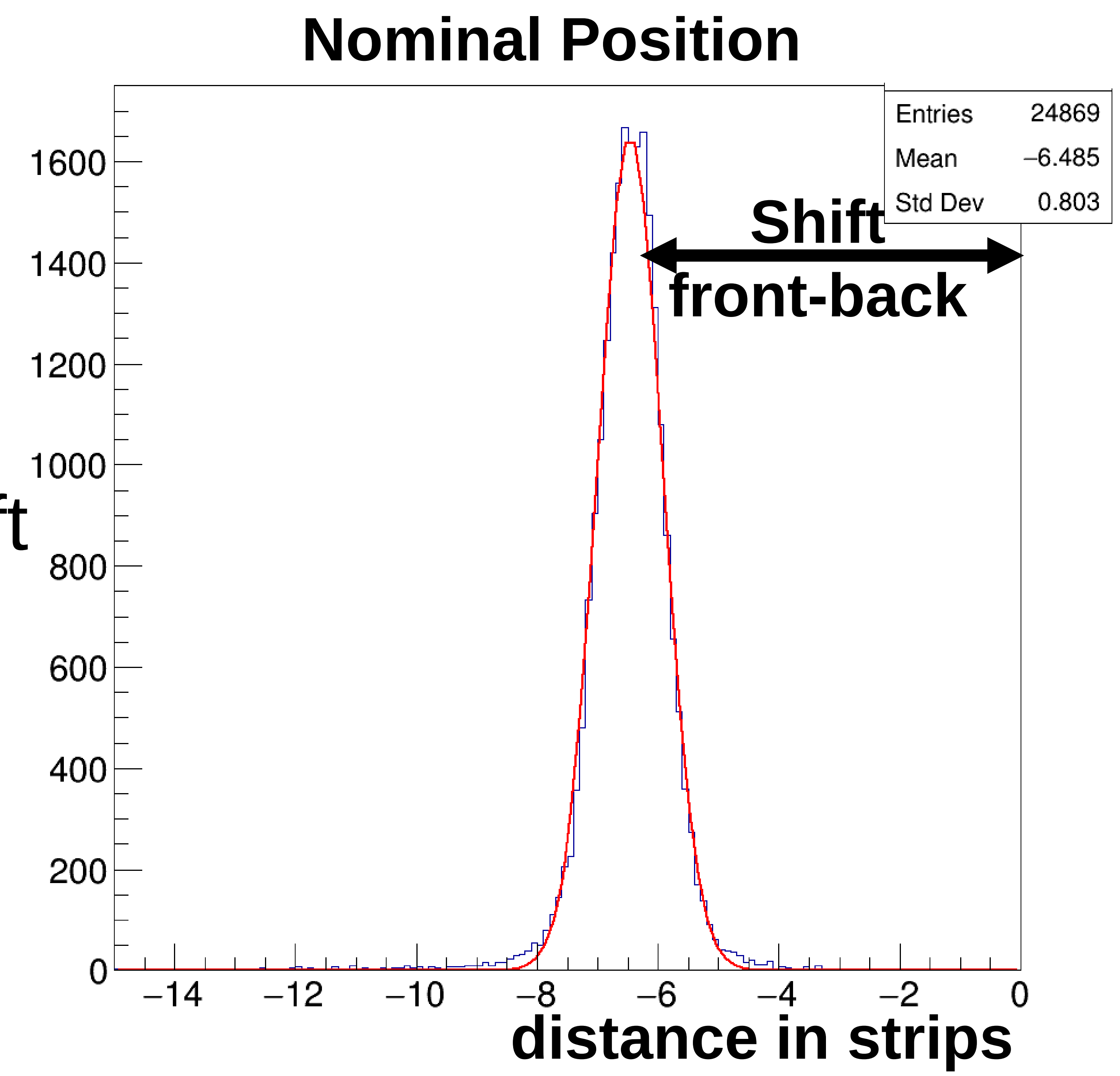
150GeV/c Muon Beam – H4 Beamline in EHN2 – RD51 test-beam – H5V3 orientation

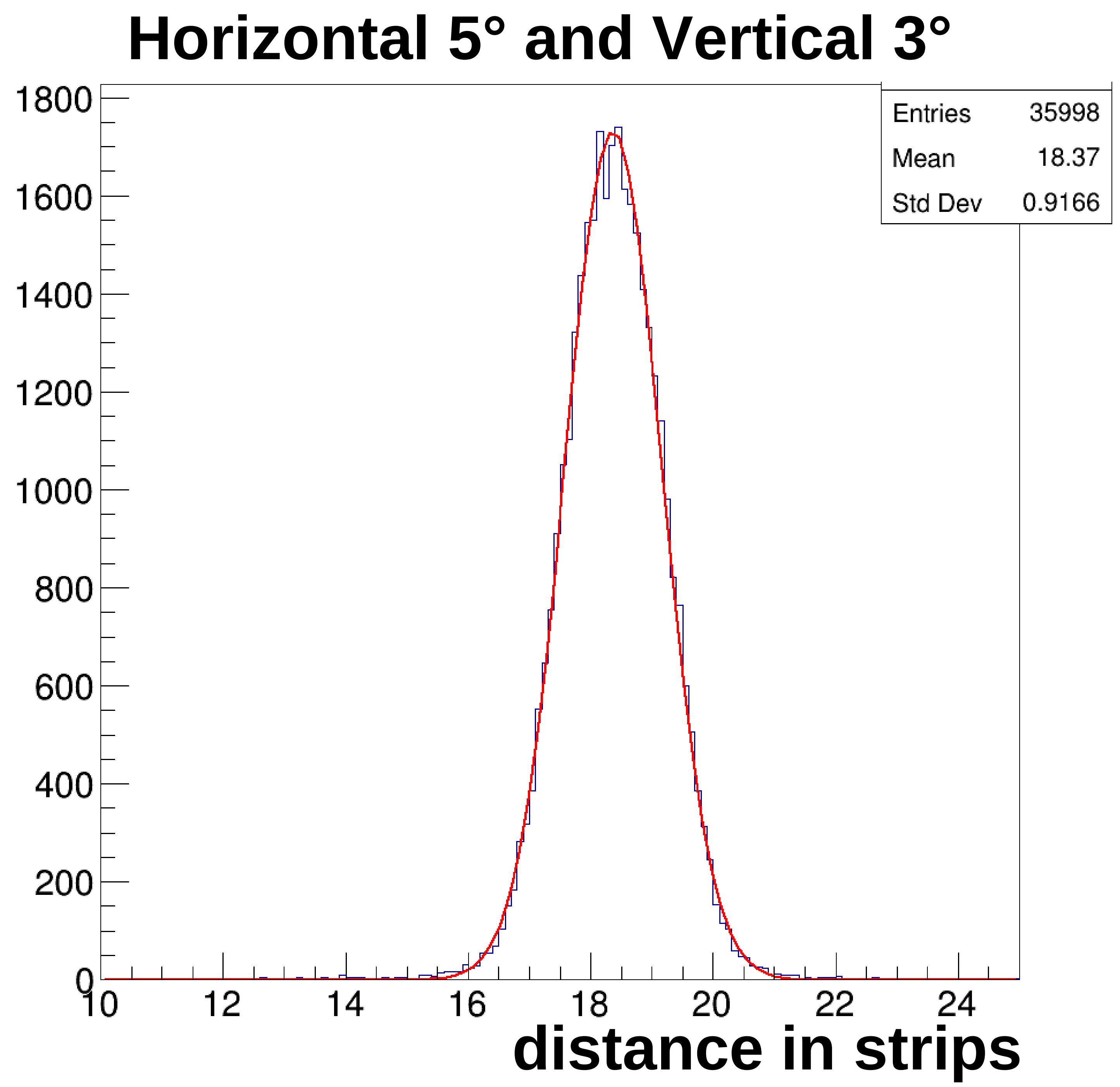
- Calculating event based
  - Calculate angle for individual events
  - Mean of distribution resembles tilt of Twin GEM-TPC setup



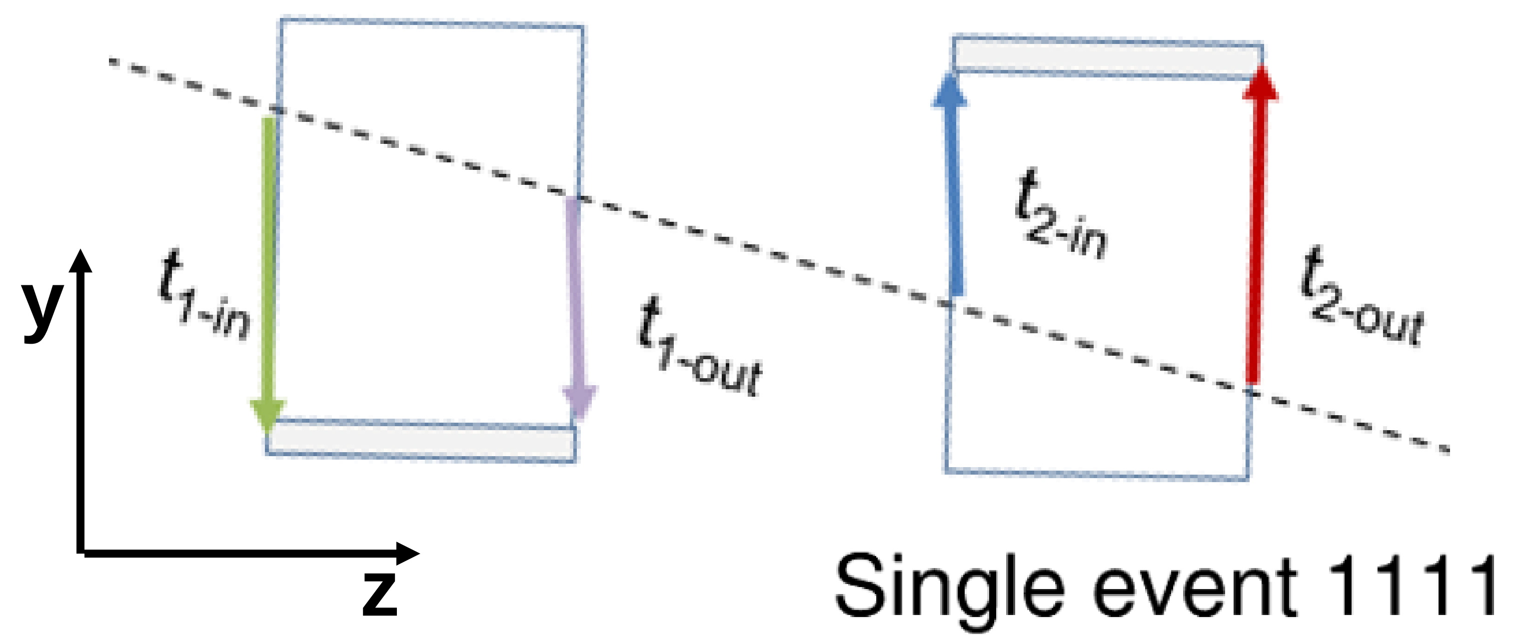

- Calculating based on average position shift
  - $x_{Front} - x_{Back}$ distribution needed for nominal and tilted orientation
  - Angle can be calculated with corrected shift
- The horizontal tilt 4.74(15)° is observed (fits with setting of 5°)

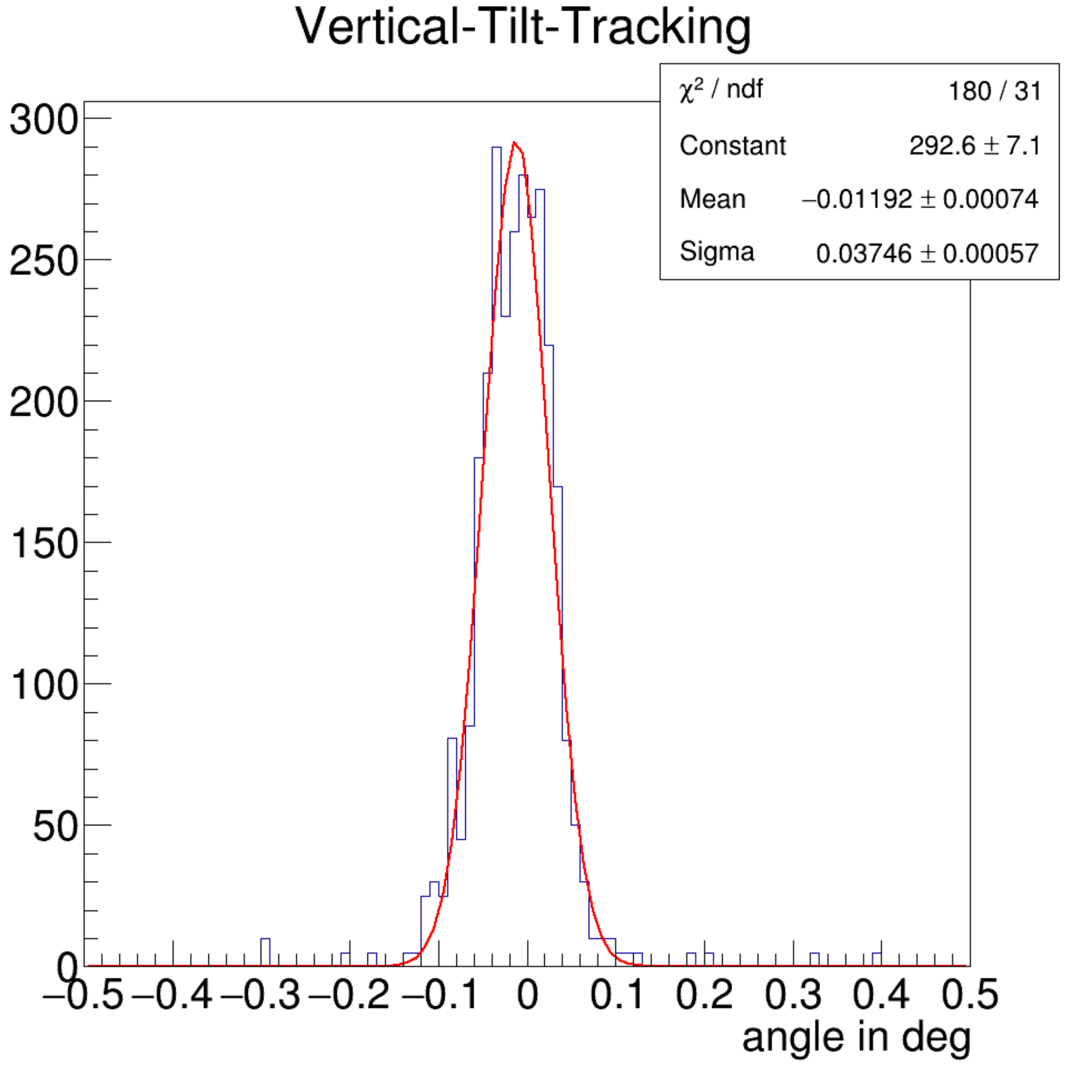


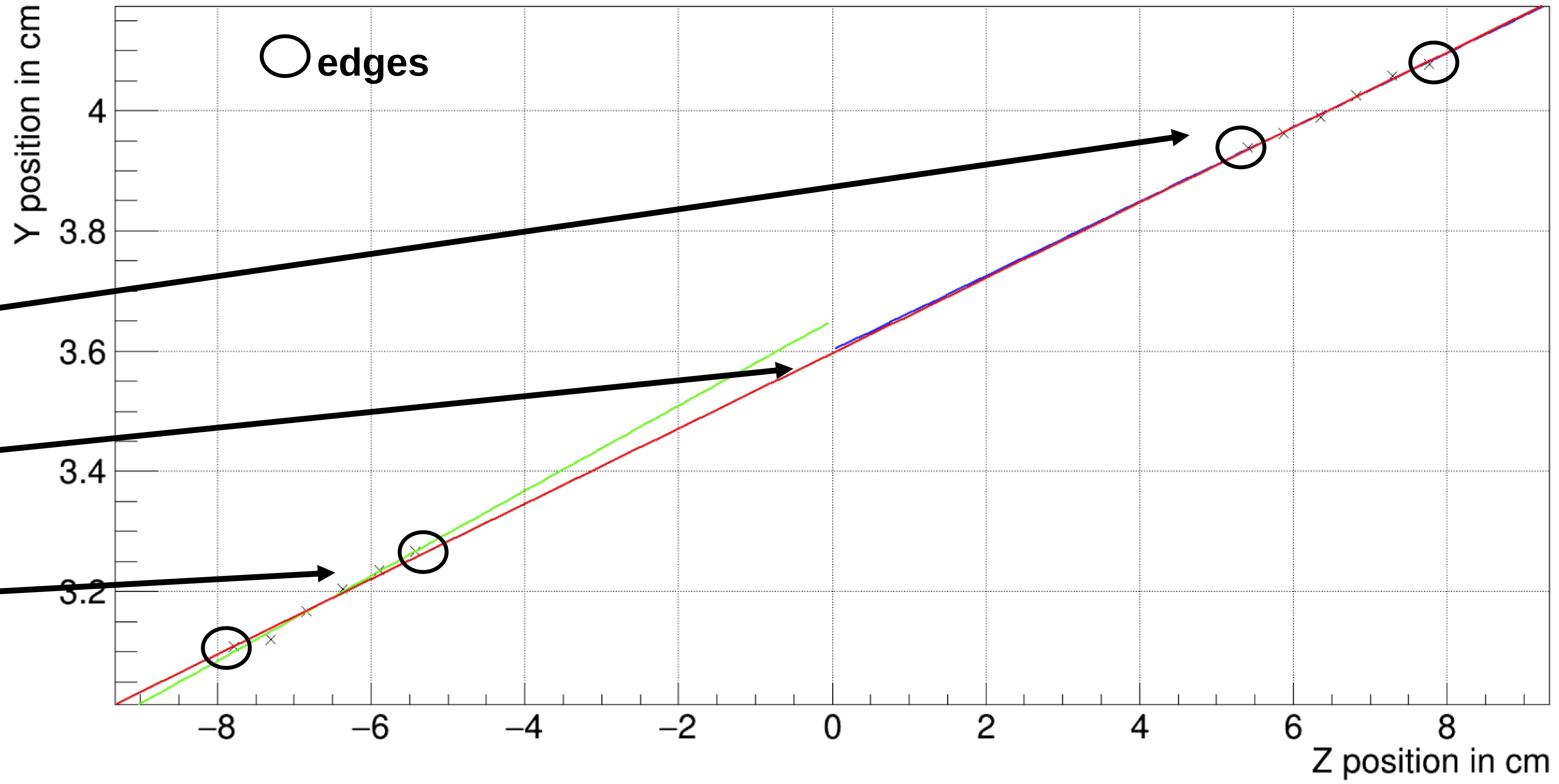
# Vertical Tilt Calculation

150GeV/c Muon Beam – H4 Beamline in EHN2 – RD51 test-beam – H5V3 orientation



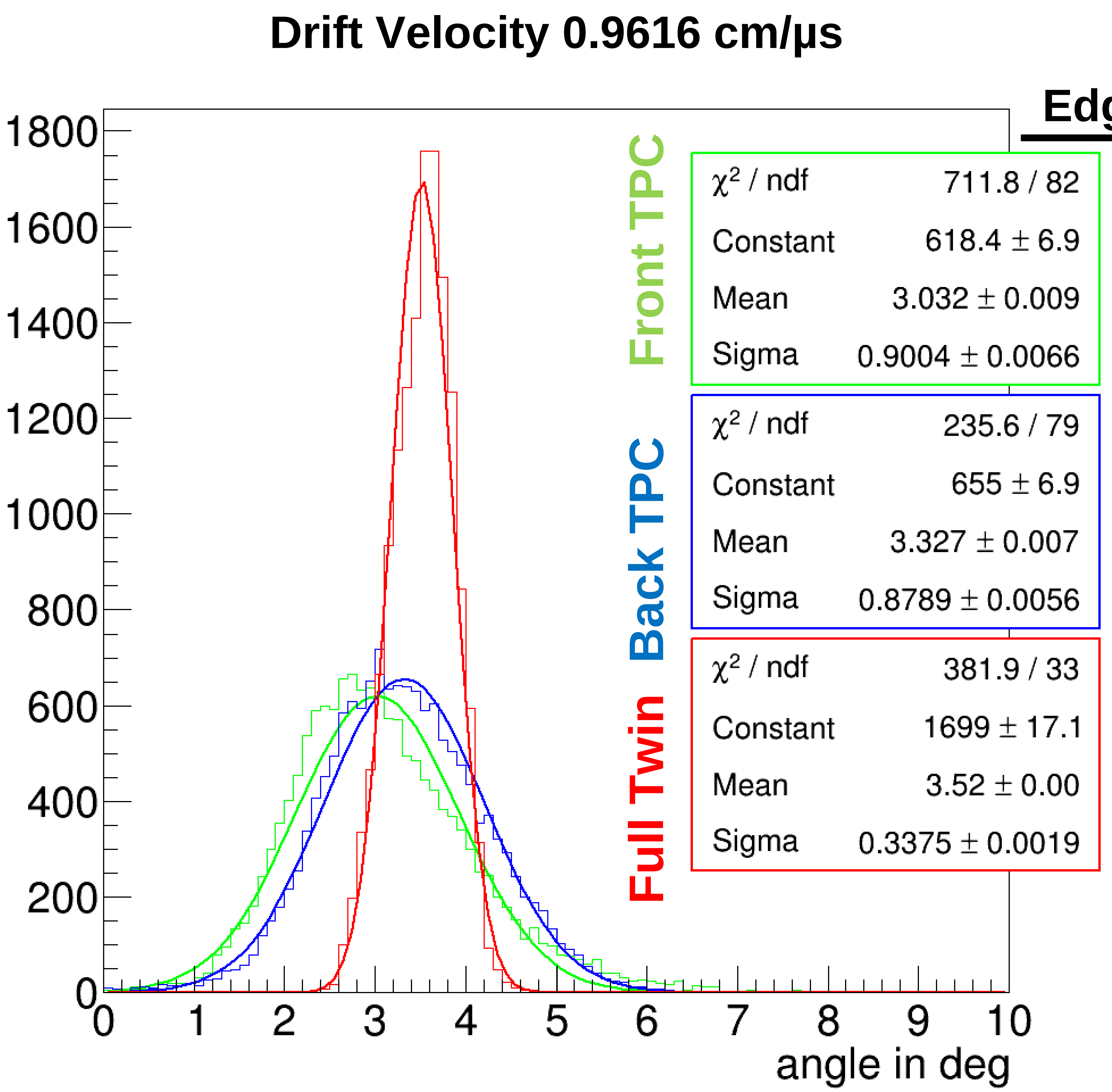




- $\frac{t_2'-t_1'+t_{full}}{2} * vdrift = y$ used to calculate y position
- Vertical tilt of telescope: -11.9(8) mdeg
- Three angles per track: (should be identical)
  - Back TPC
  - Full Twin GEM-TPC
  - Front TPC

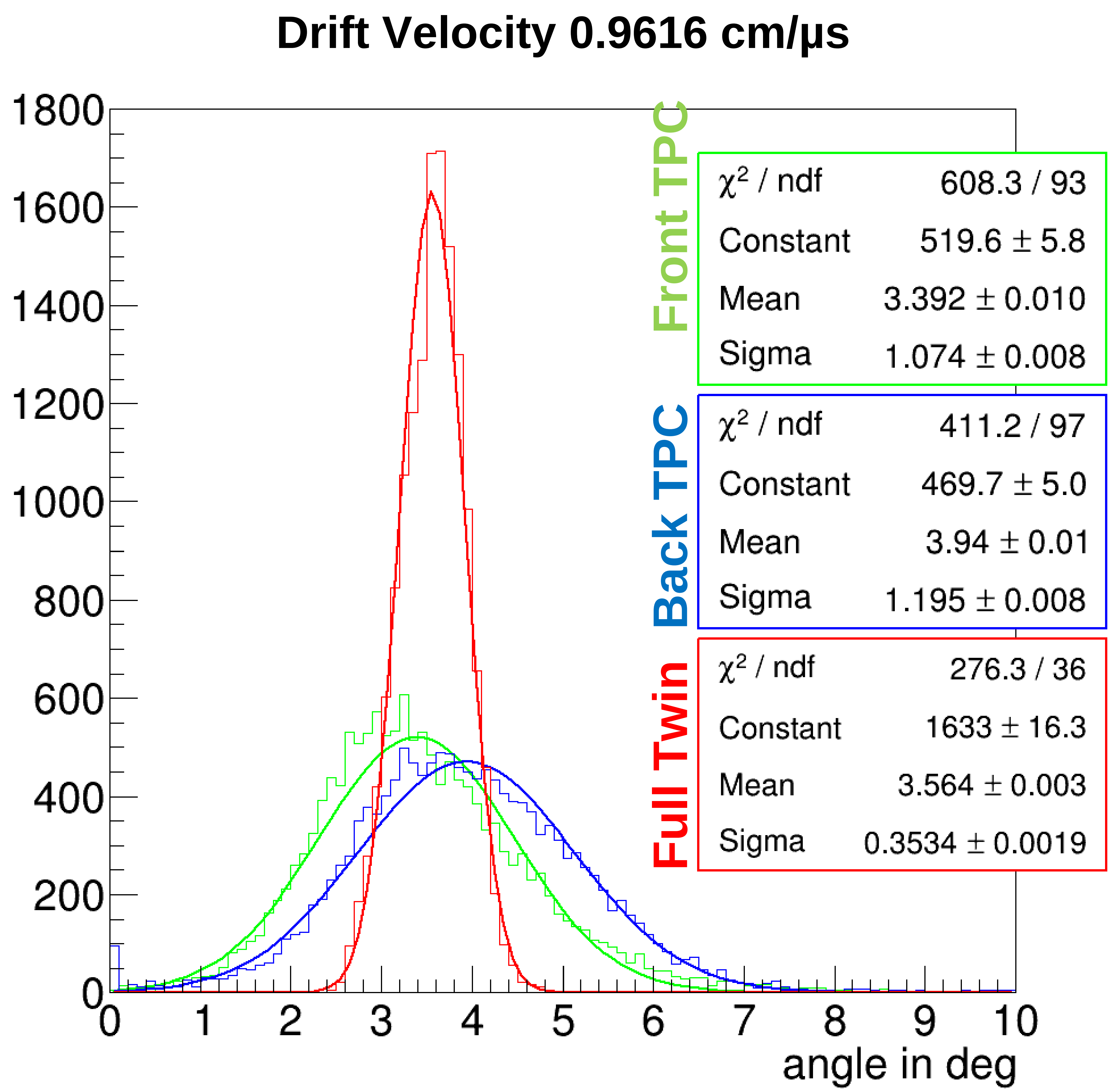


# Vertical Tilt Calculation

150GeV/c Muon Beam – H4 Beamline in EHN2 – RD51 test-beam – H5V3 orientation




Edges removed

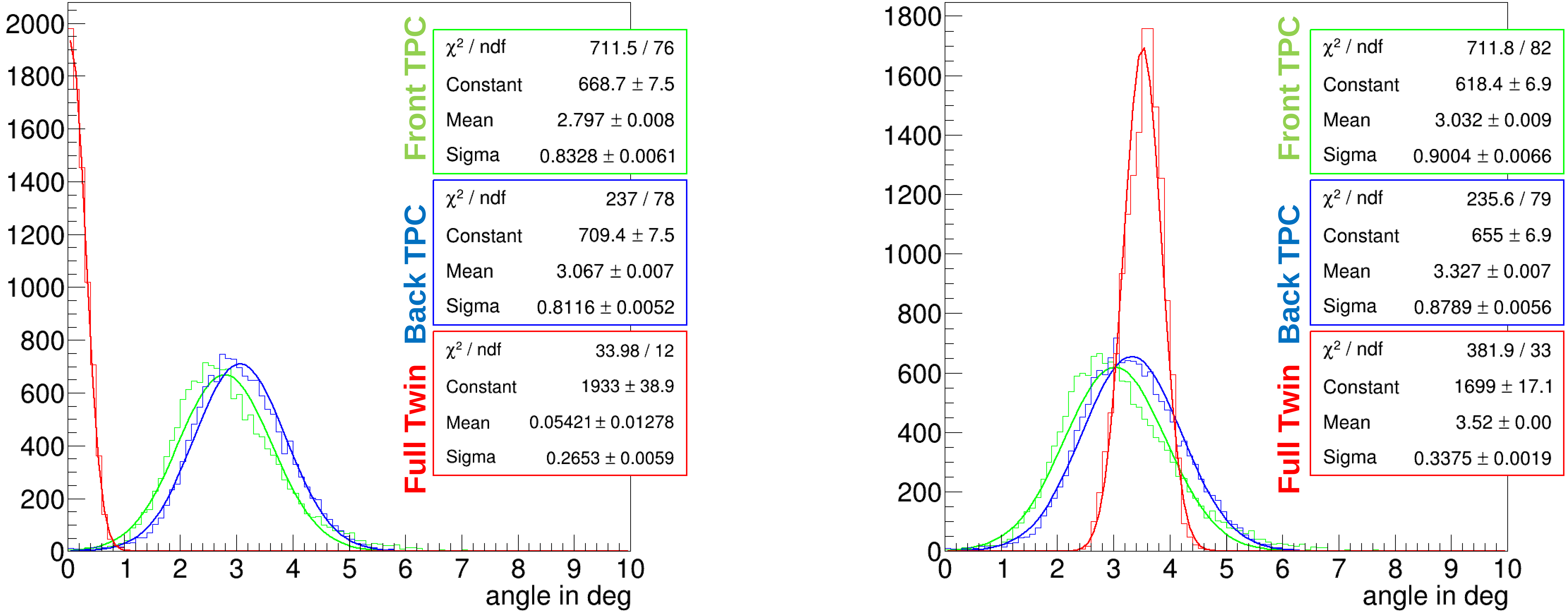



- Removing edges results in broader distributions and increased discrepancy between Front- and Back-TPC

# Vertical Tilt Calculation

150GeV/c Muon Beam – H4 Beamline in EHN2 – RD51 test-beam – H5V3 orientation

**Drift Velocity 0.8865 cm/µs** → **Adjusted drift velocity** → **Drift Velocity 0.9616 cm/µs**

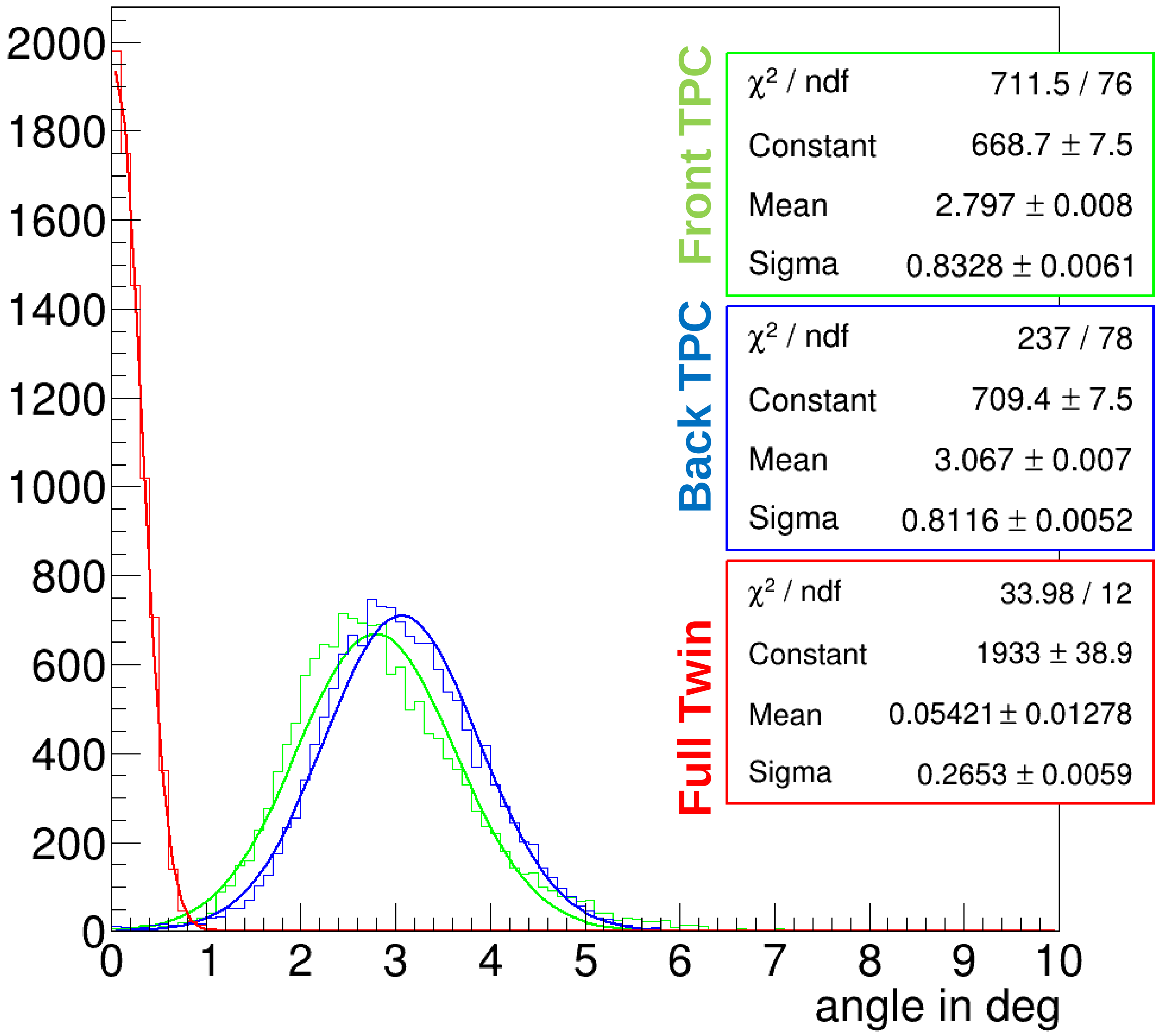



- Can correct the alignment between Front/Back but distributions are slightly wider

# Vertical Tilt Calculation

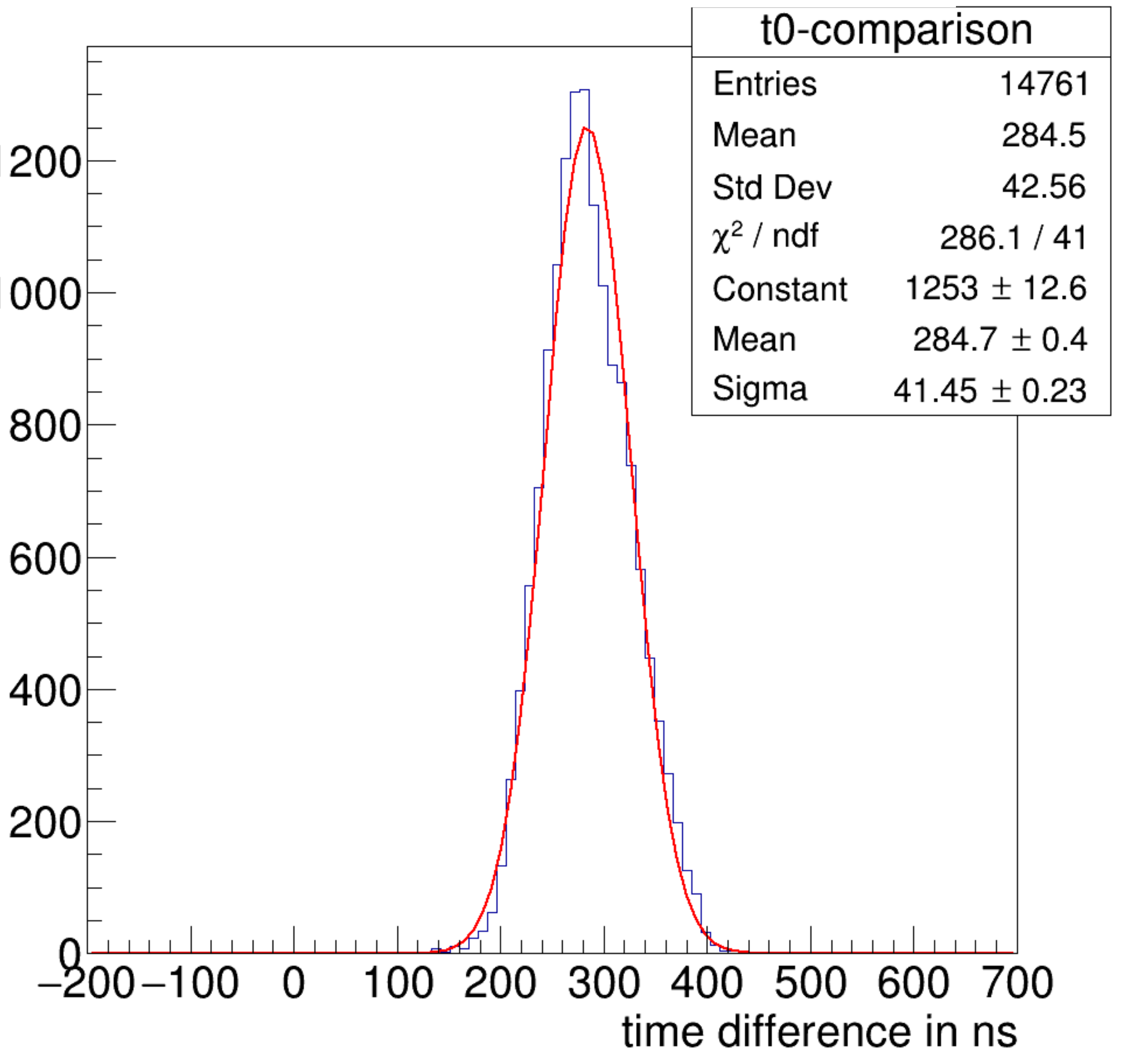
150GeV/c Muon Beam – H4 Beamline in EHN2 – RD51 test-beam – H5V3 orientation

**Drift Velocity 0.8865 cm/µs**

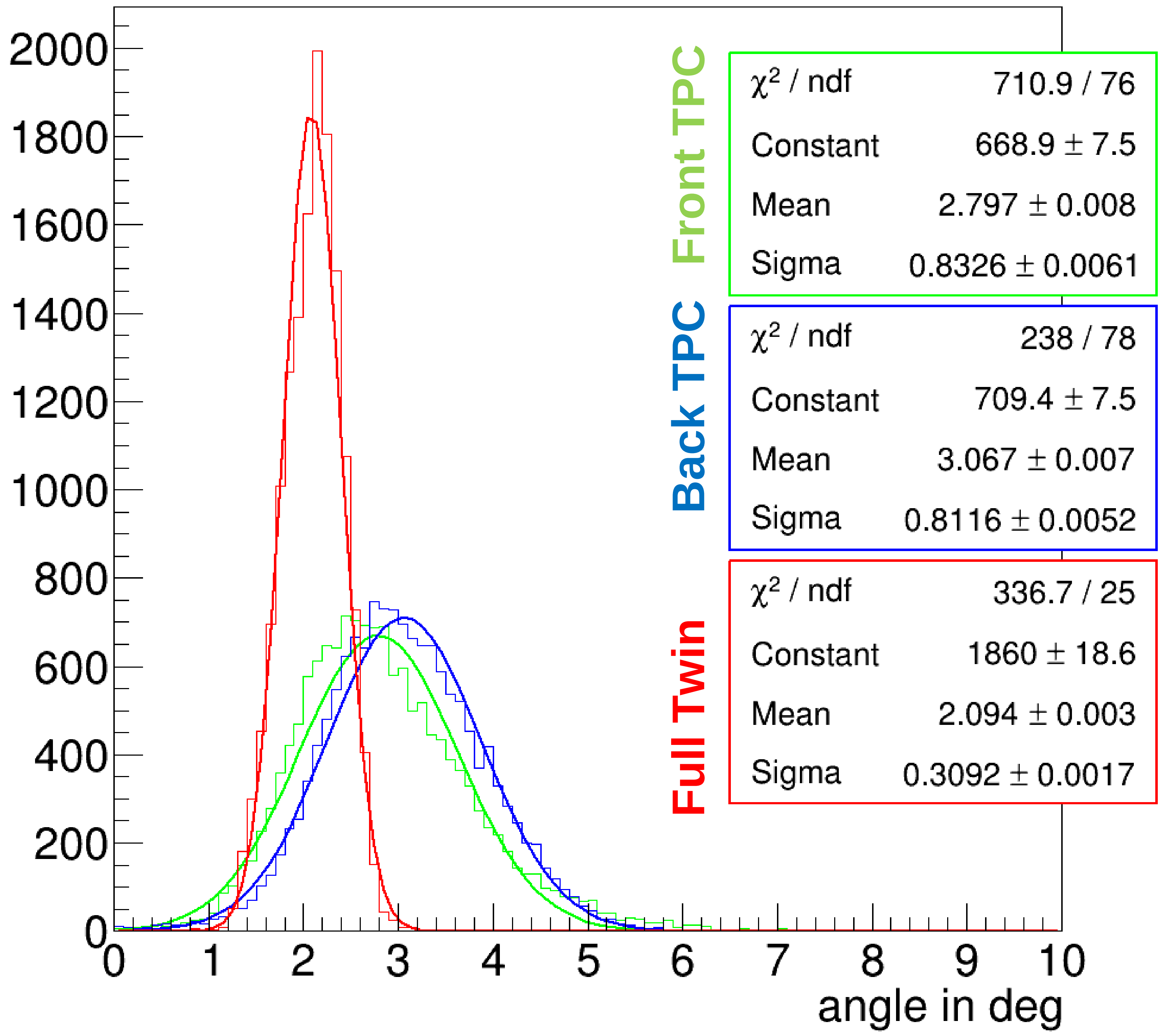



**-284.7ns t_0 Offset** →

**t_0 Offset Distribution**




**Drift Velocity 0.8865 cm/µs**

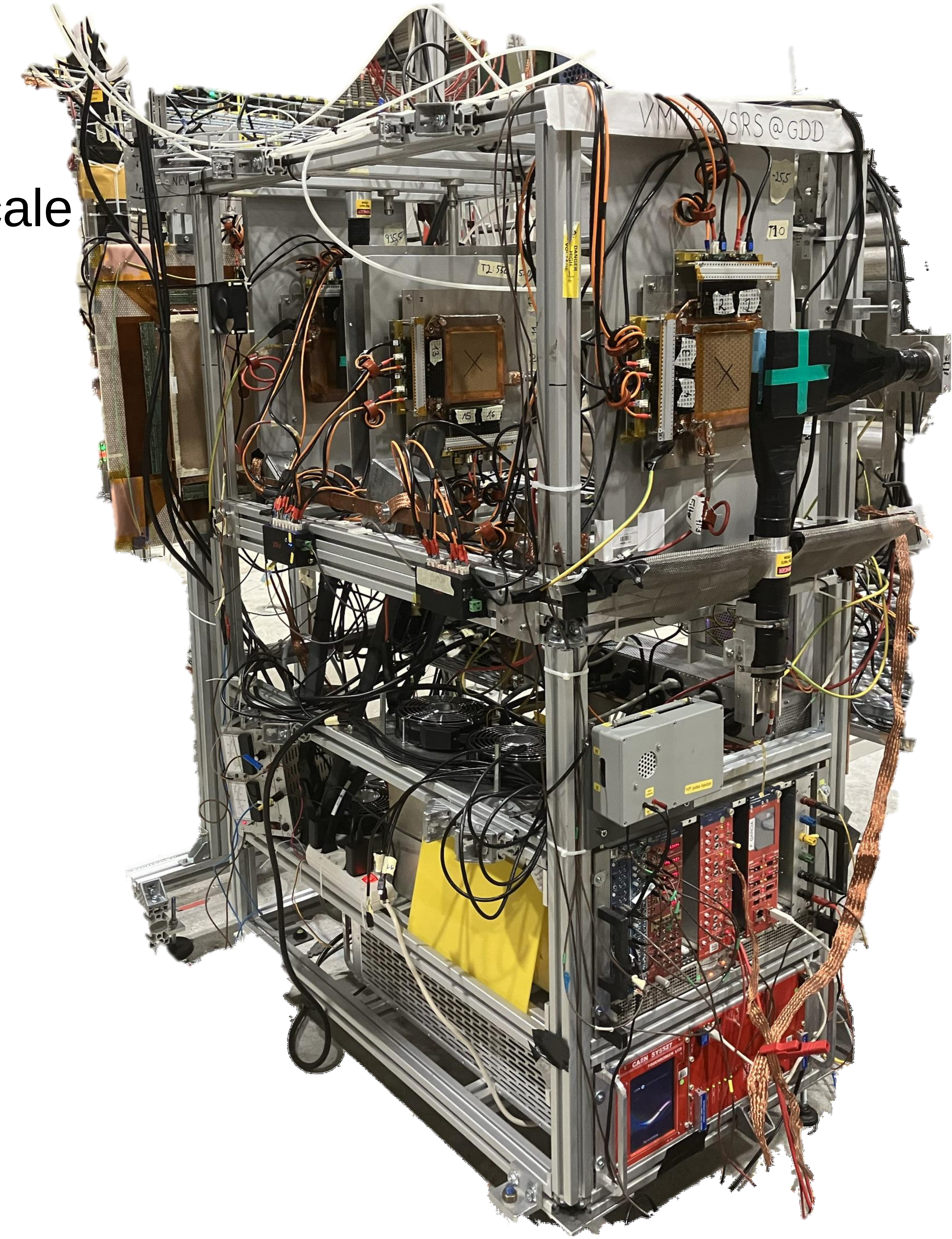



- Back/Front distributions show no change as expected
- Can correct the alignment between Front/Back

➢ The offset needs to be corrected and drift velocity adjusted for better agreement of the three slopes (Eventually different drift velocities for Back and Front)

# Summary and Outlook

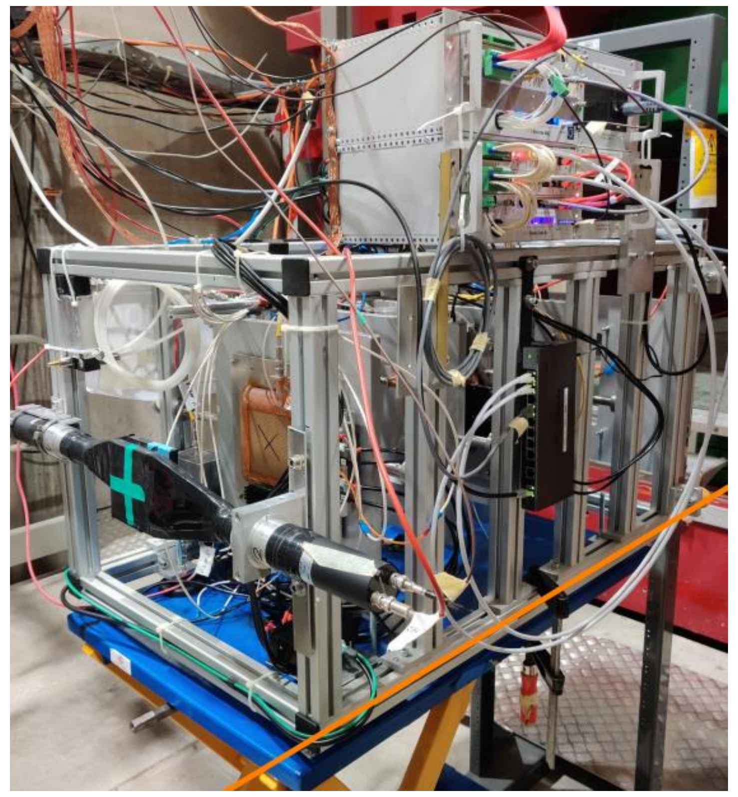
- The VMM3a/SRS is a versatile trigger-less system for full-scale prototypes and small tracking systems (up to ~20m-40m)
- The new AMBER triple GEM tracker
  - Successful operation with VMM3a/SRS
  - Performance can be optimized (improve Noise)
  - Detector nonuniformities under investigation
- The TWIN GEM-TPC in combination with the VMM3a/SRS
  - Standalone operaion without external t0 possible
  - Good detector response and resolutions of $\sigma < 200\mu m$ in x and $\sigma < 500\mu m$ in y
  - 3D tracking works but should be done with 2D readout

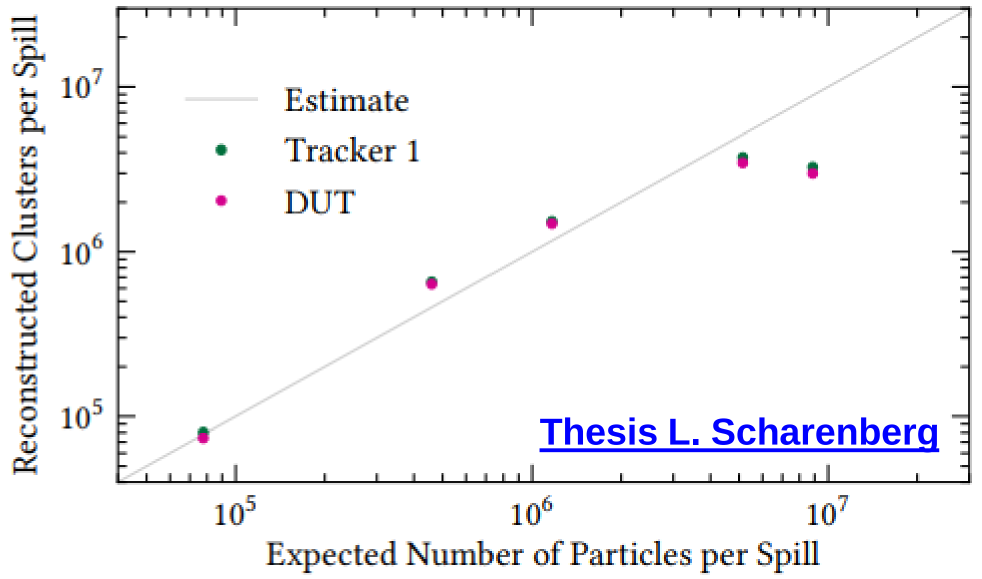


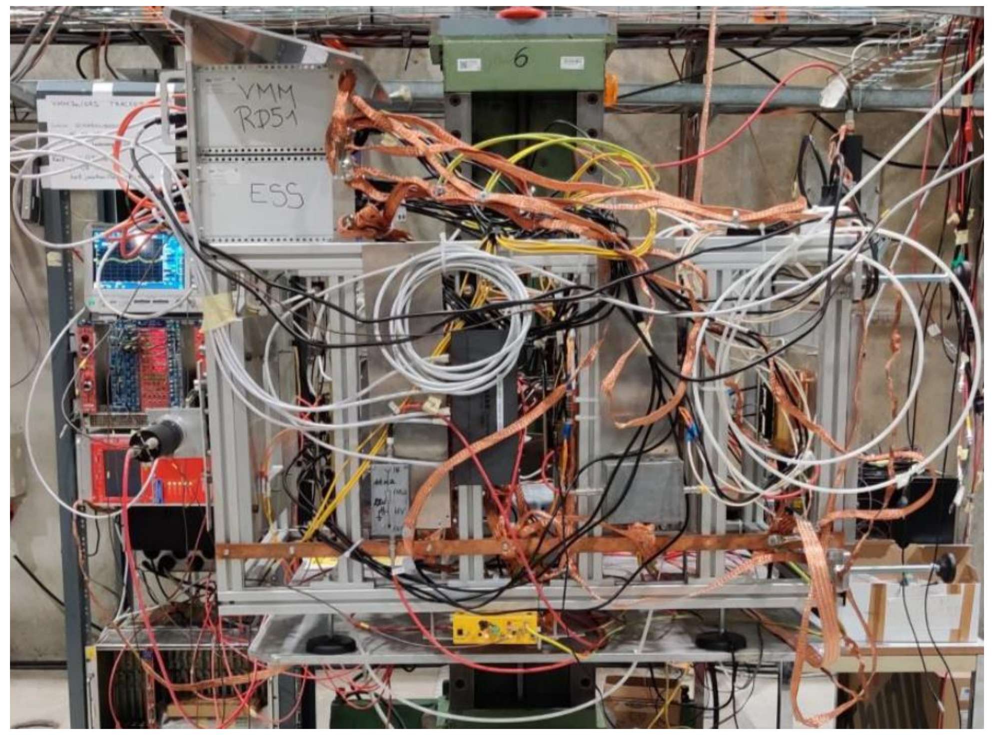
# Thanks for your attention

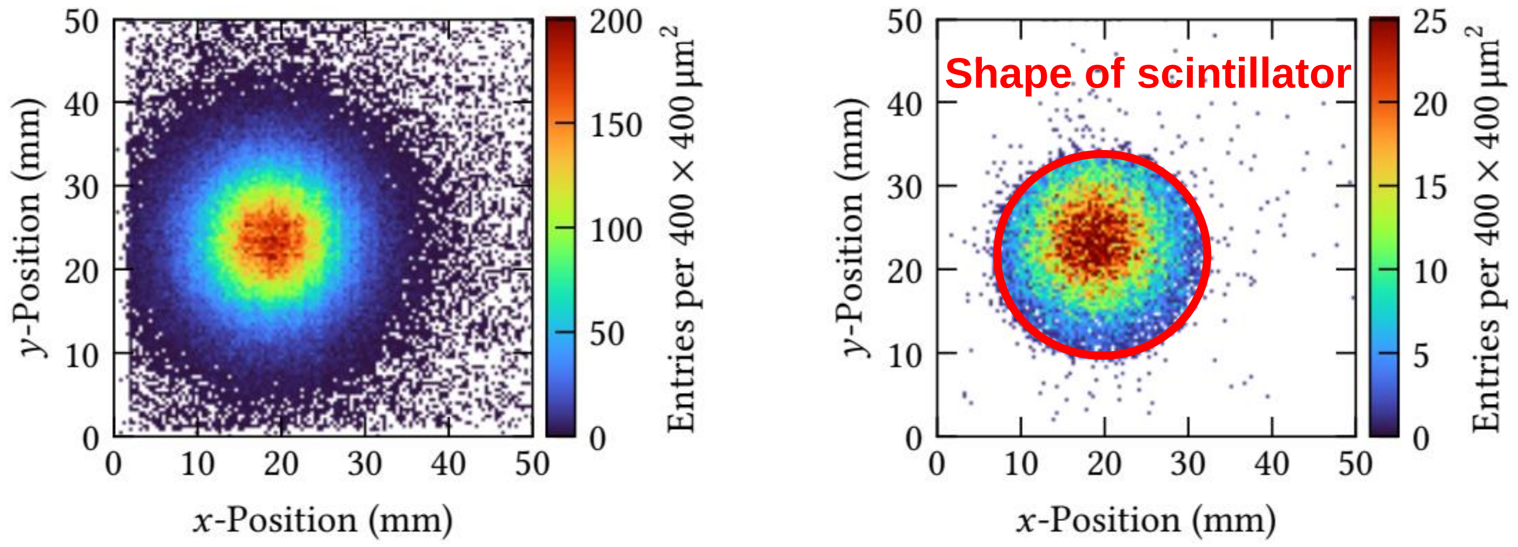
This work has been sponsored by the Wolfgang Gentner Programme of the German Federal Ministry of Education and Research (grant no. 13E18CHA).
This project has received funding from the European Union’s Horizon 2020 Research and Innovation programme under Grant Agreement No 101004761.

# Evolution of the telescope I





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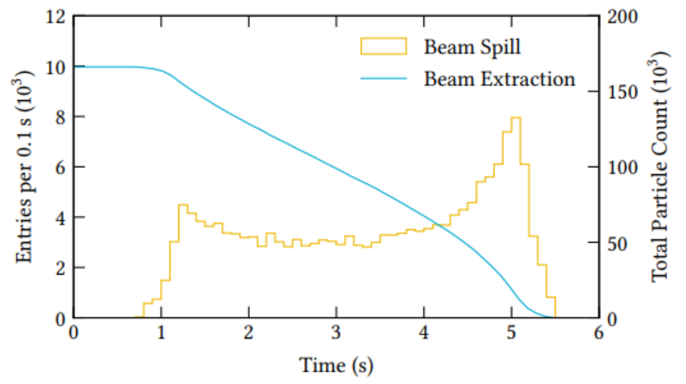
Not to scale

**First Tests**
**July 2021**

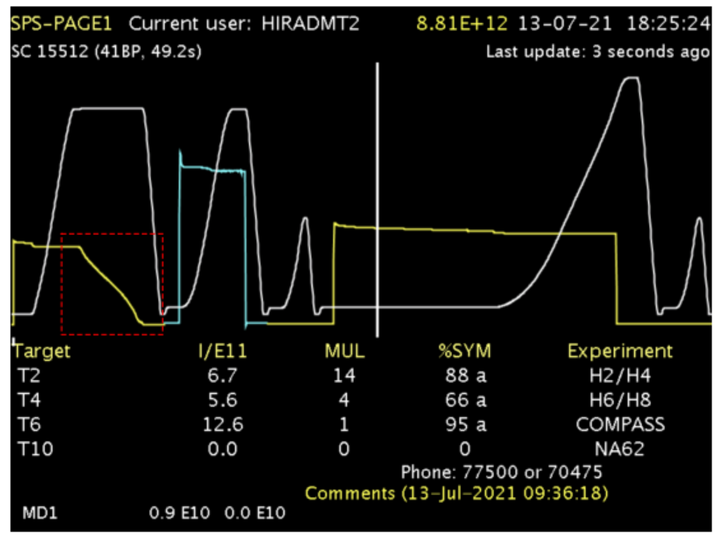
**High Rate**
**October 2021**

**Grounding, Firmware and Software improved**
**May 2022**

**Synchronisation (NIP) with other DAQs and NA61 (SHINE)**
**June 2022**




(a) – Measured SPS spill structure.




(b) – Screenshot of the SPS status monitor (SPS Page 1).

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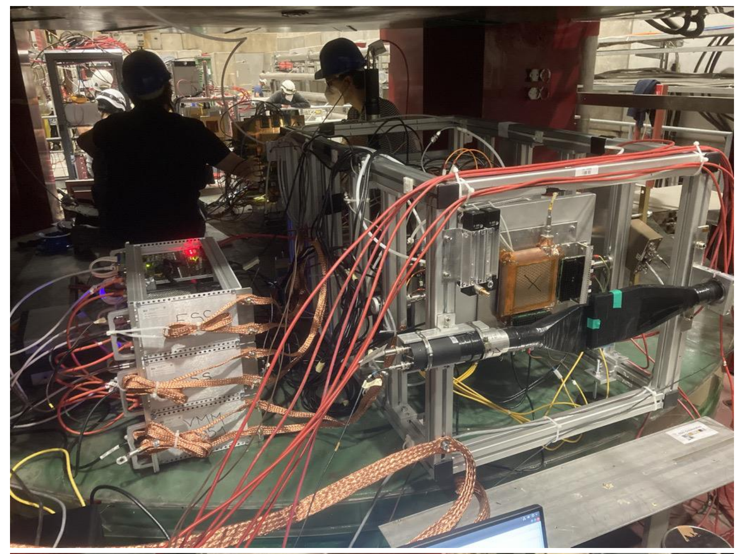

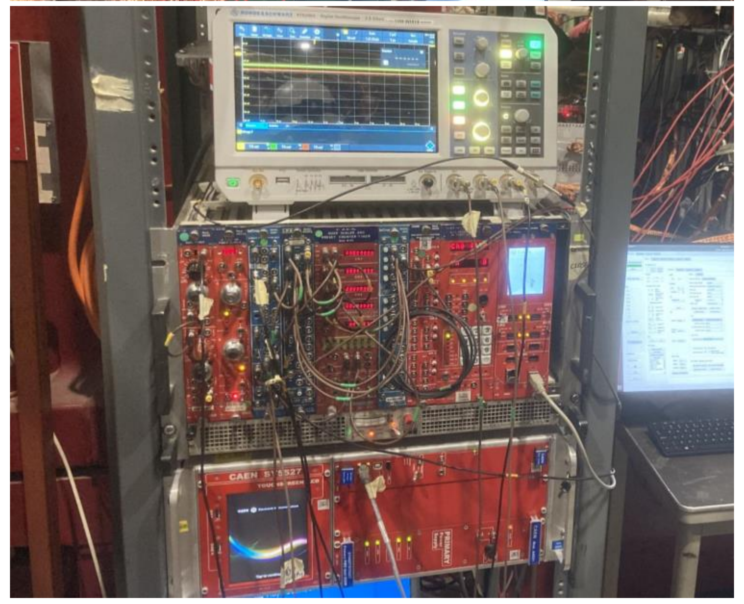

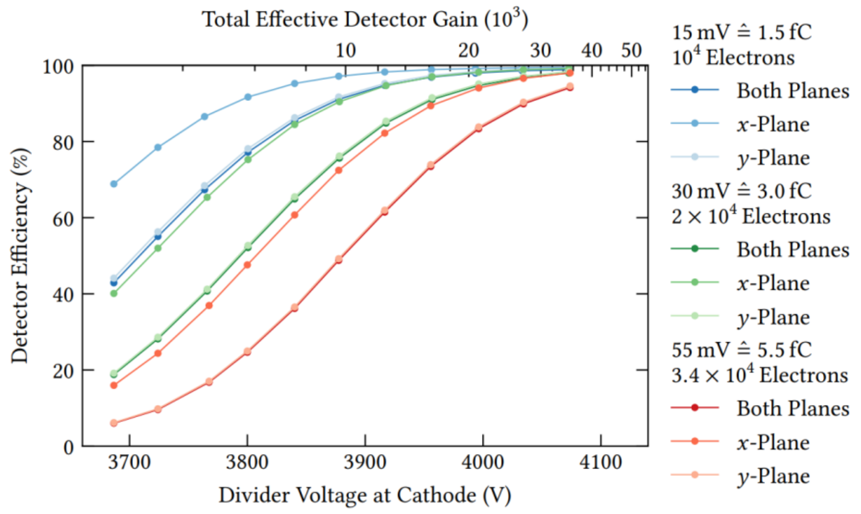


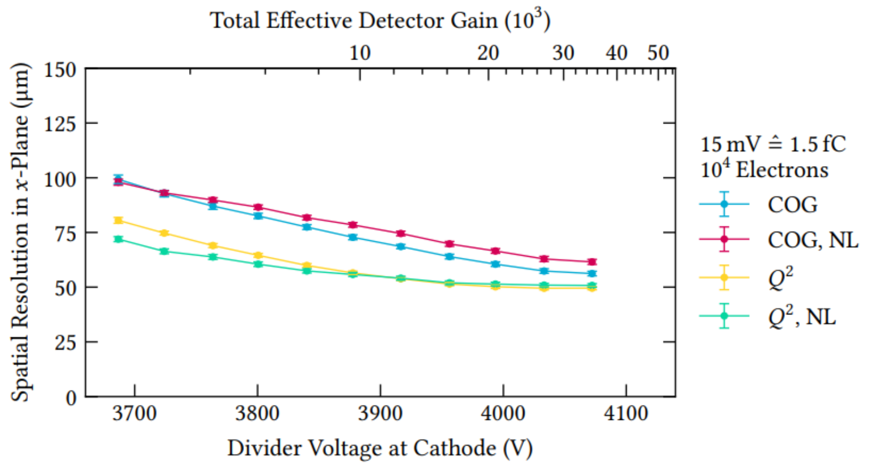


(a) – Spatial resolution in the x-plane.

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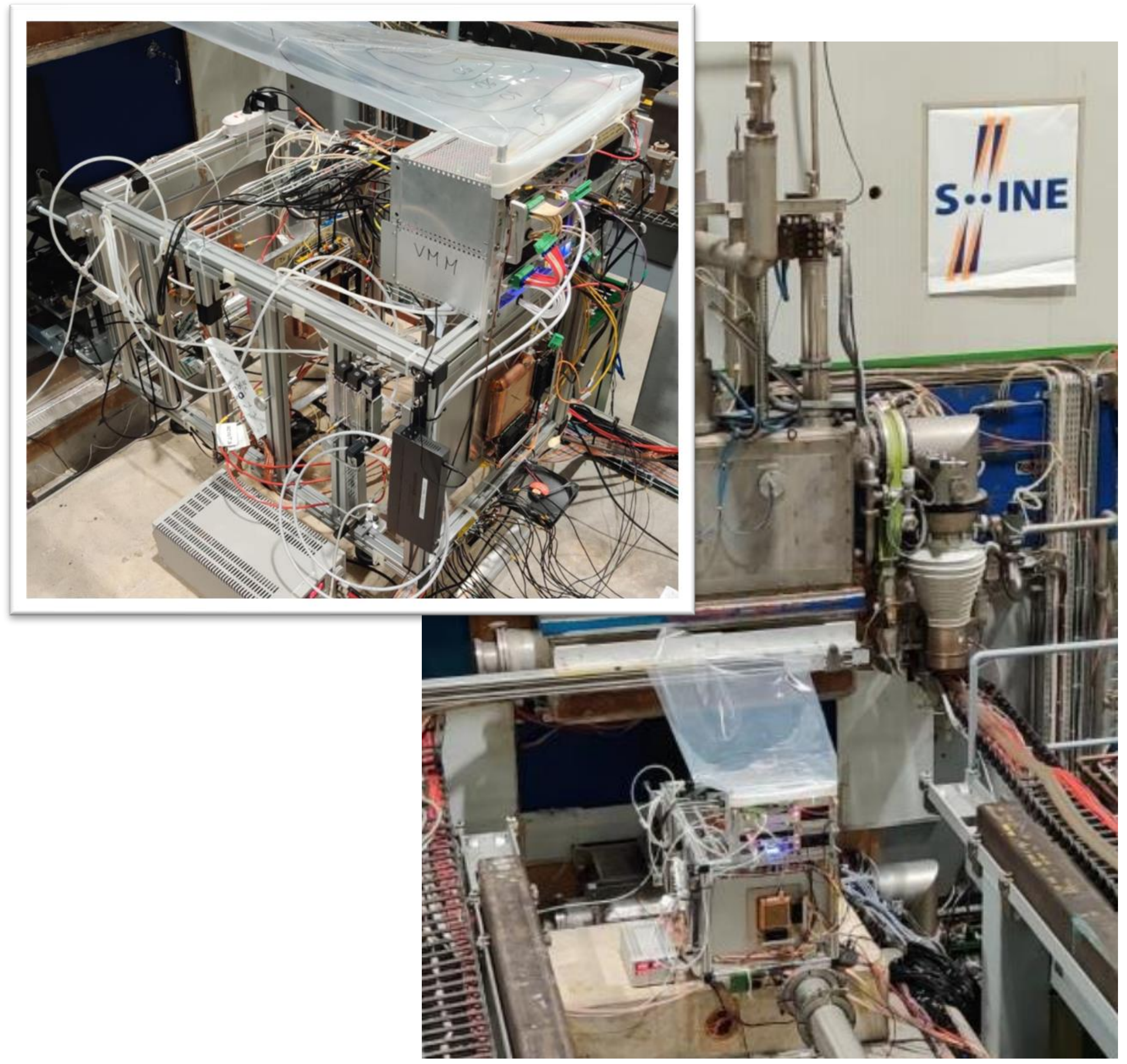
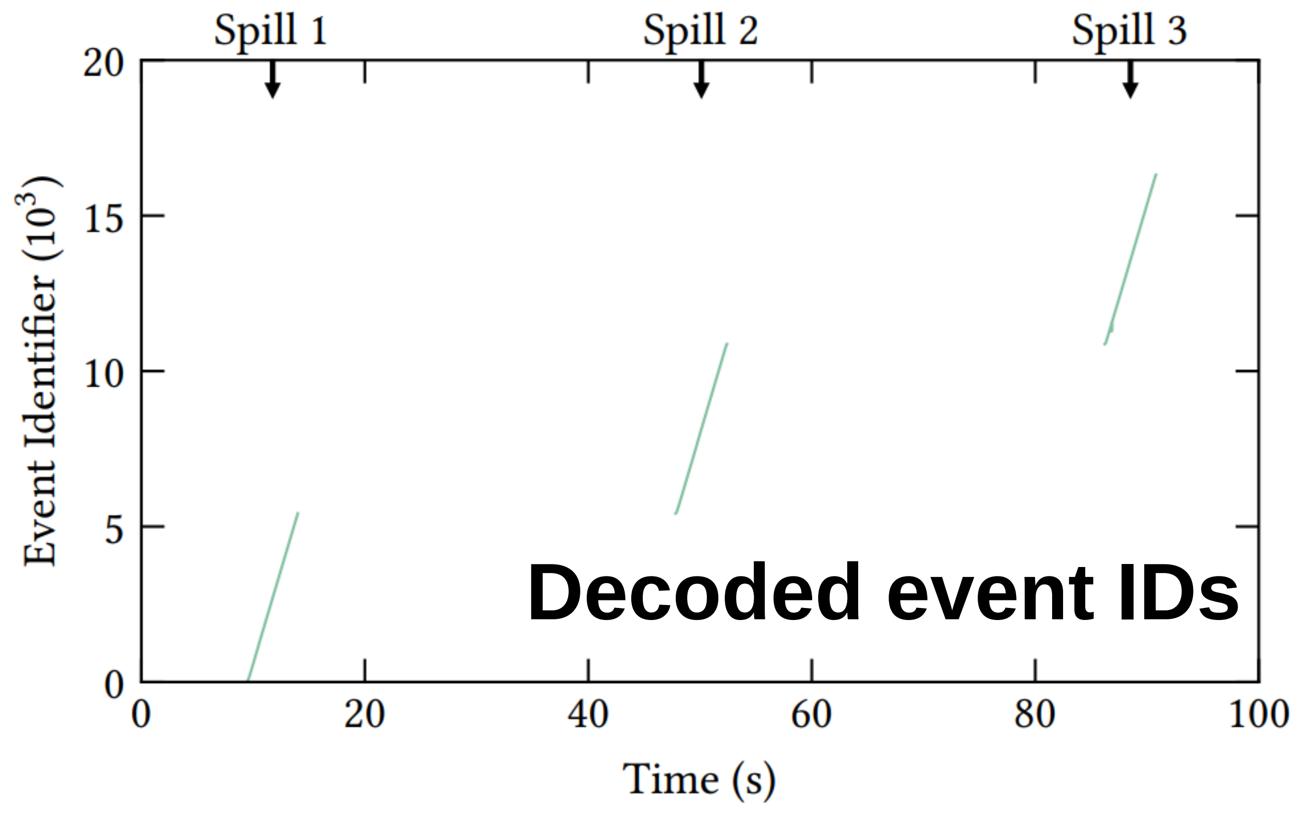


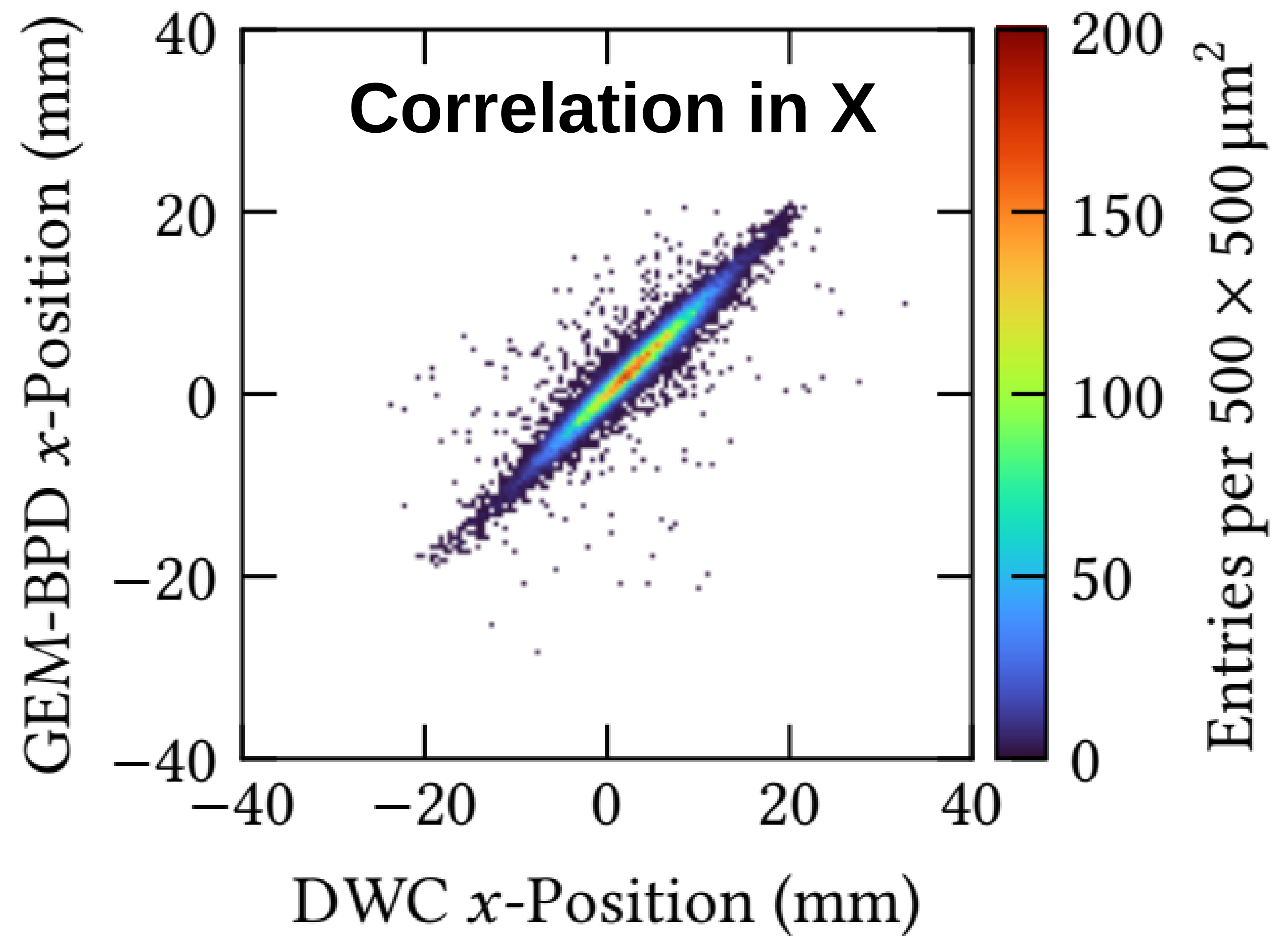
# Synchronization of DAQ systems

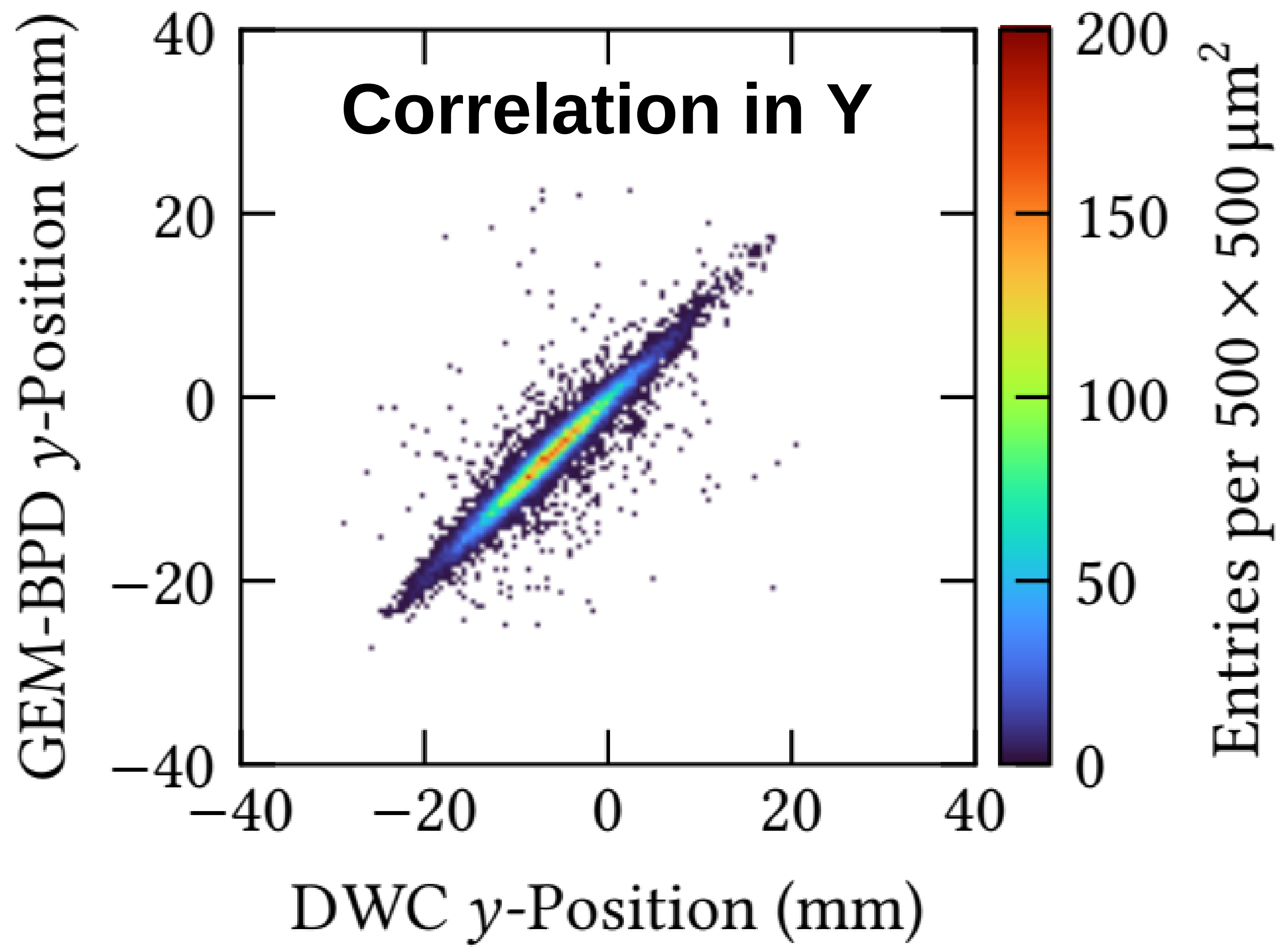
Thesis L. Scharenberg

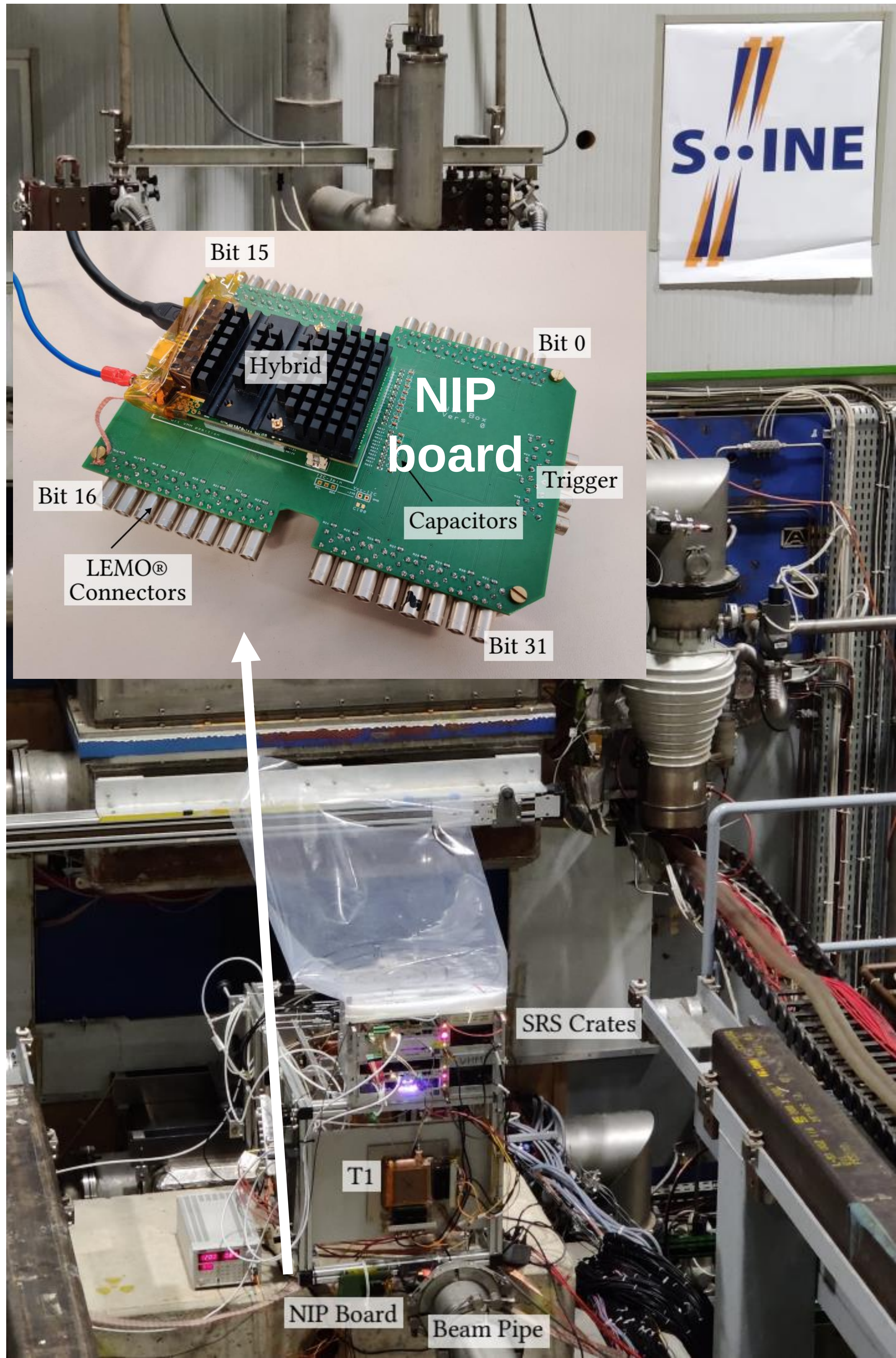
- The RD51 VMM3a telescope was used in the NA61/SHINE experiment for proton-beam tracking
  - NA61 runs with trigger and event ID
  - VMM3a/SRS runs self-triggered

- NIM Pattern Injector was designed by H. Muller
  - NA61 could send 32-bit event IDs (32 individual lines with NIM pulses)
  - knowing the mapping on the hybrid one can decode the event IDs



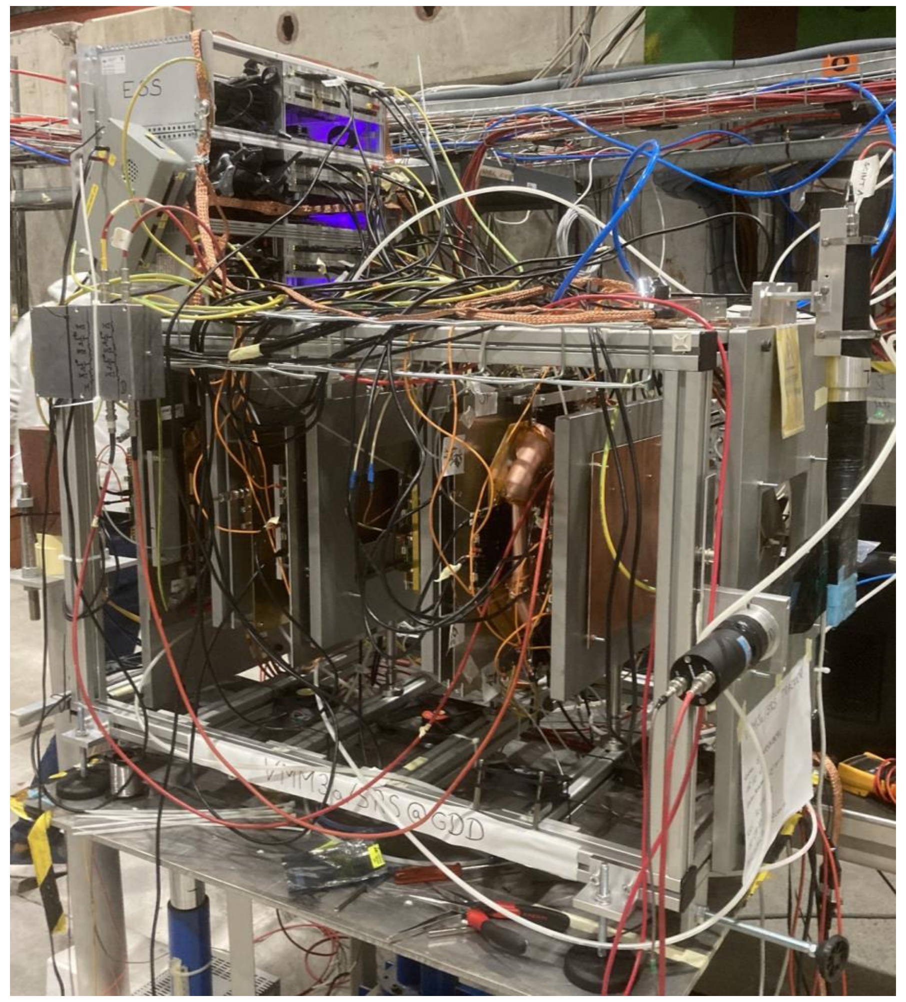



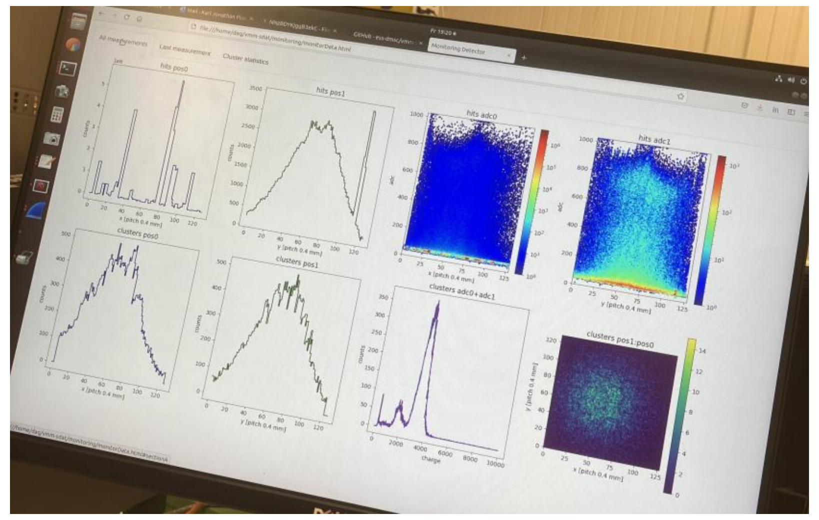



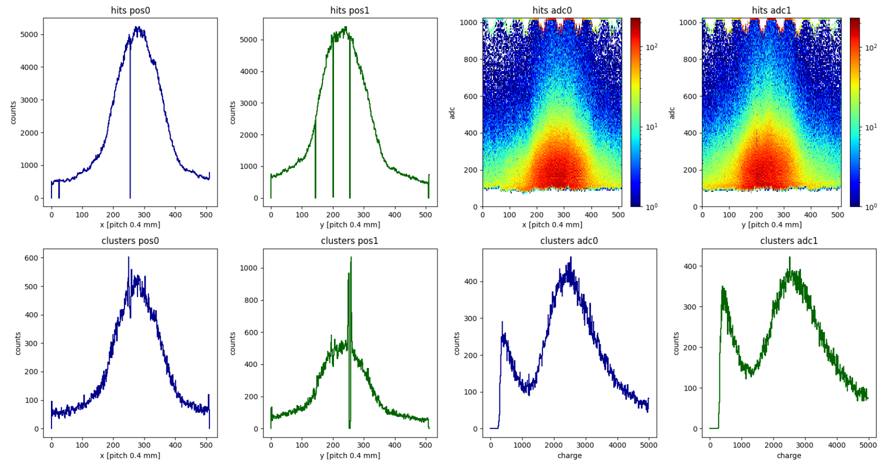



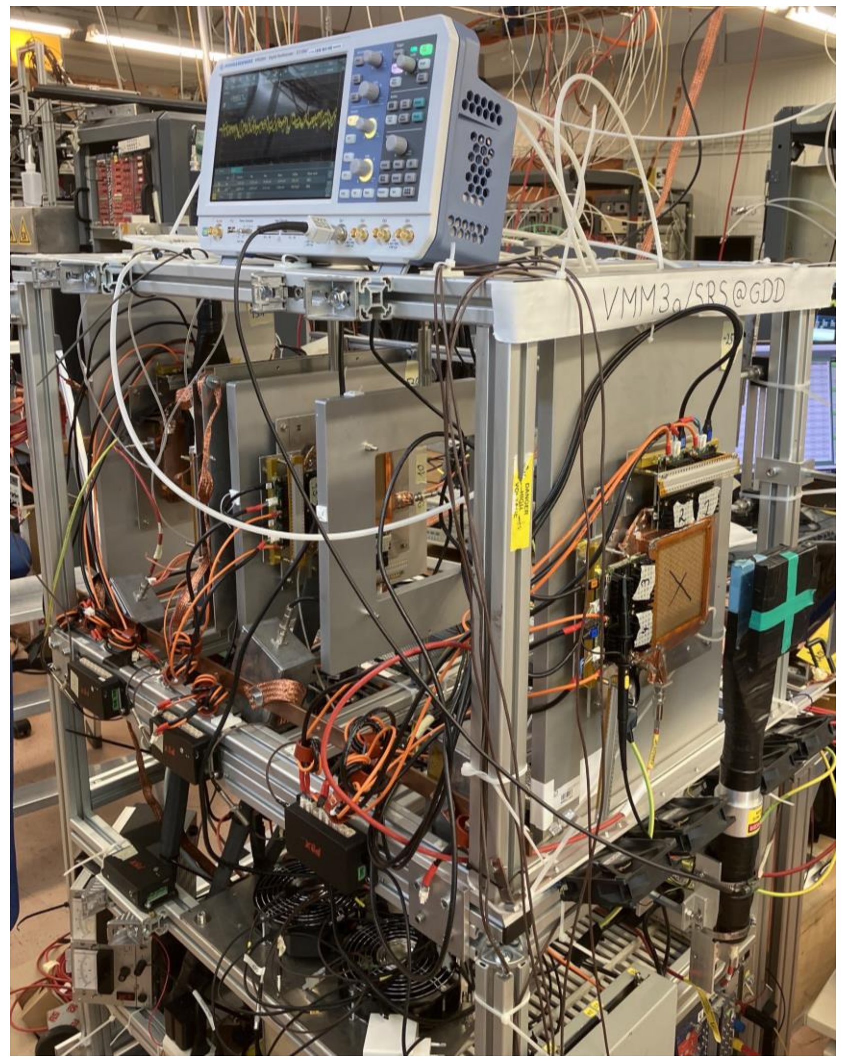

Data kindly provided by Brant Rumberger

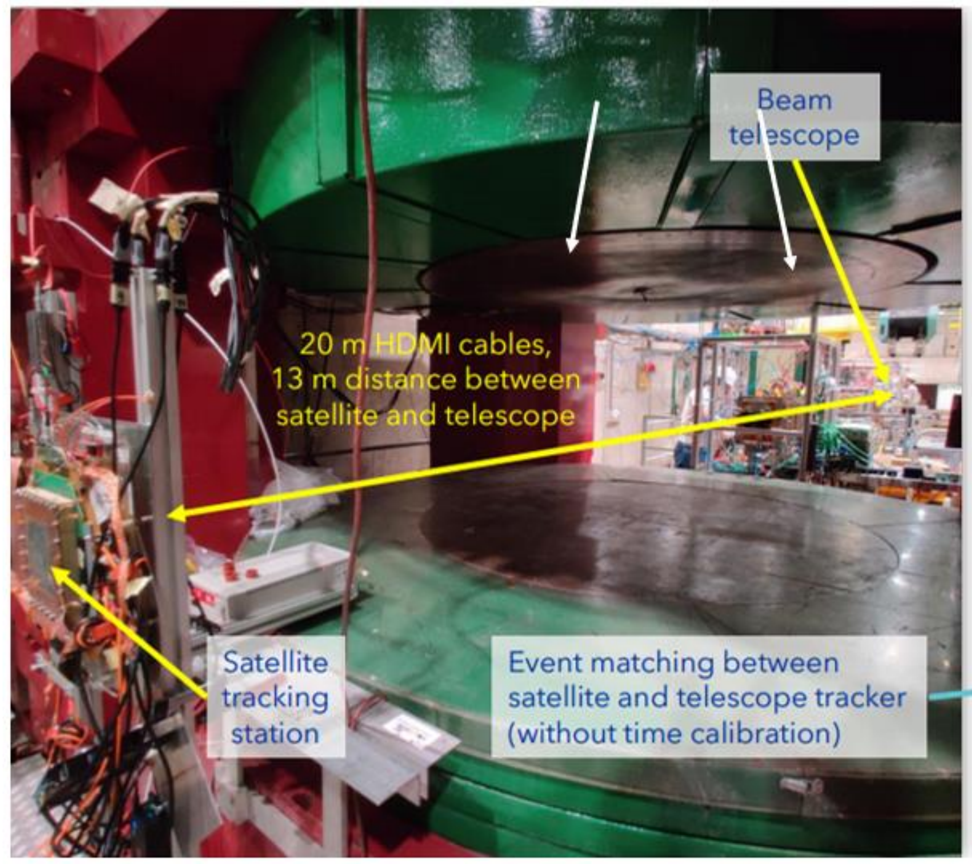
# Evolution of the telescope II

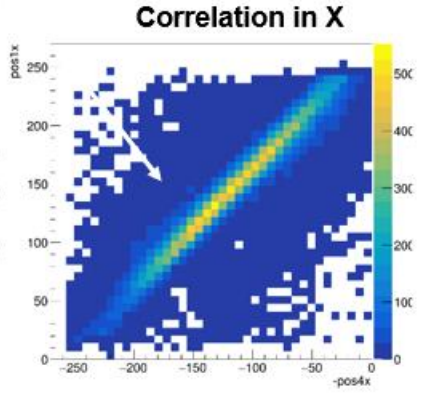


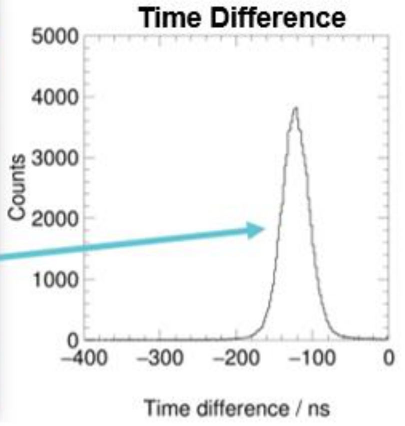






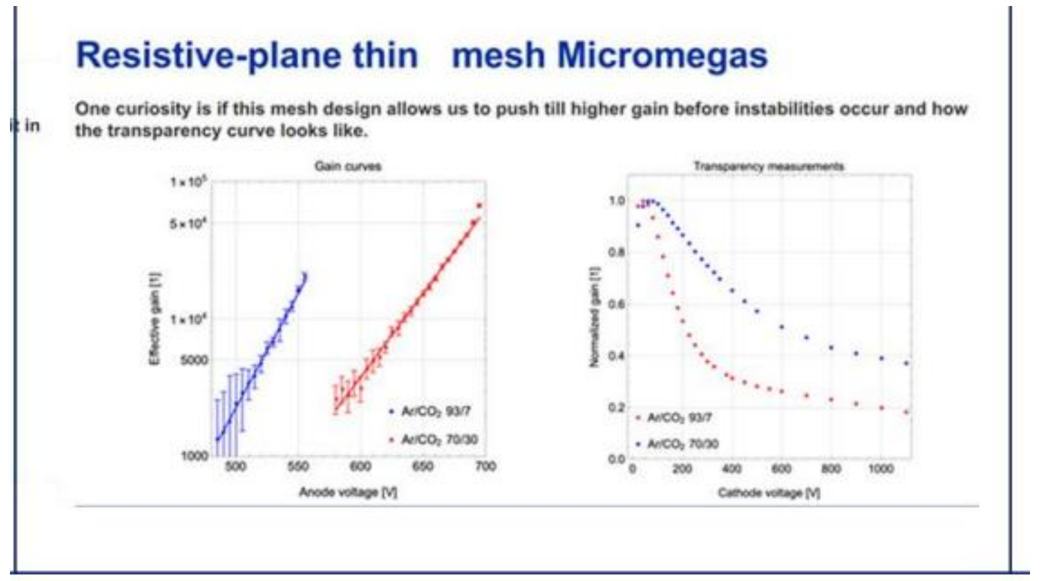

Not to scale

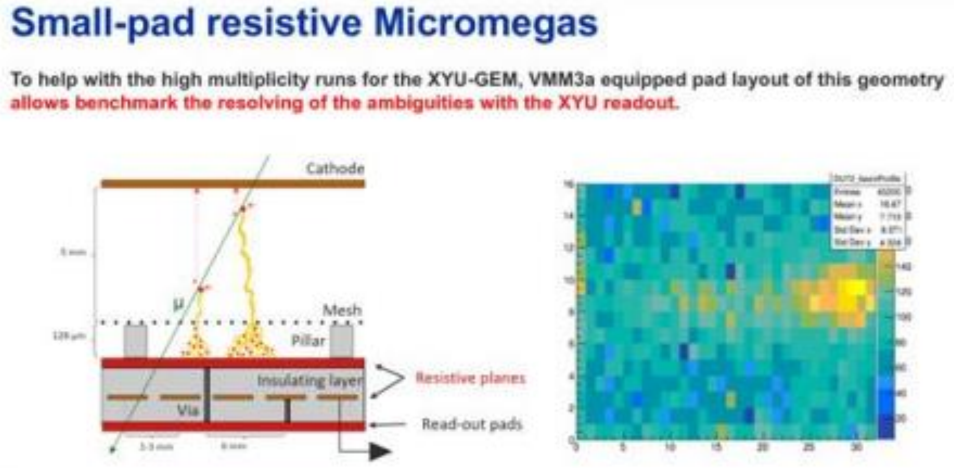
**5 DUTs incl. pad-R/O**
**October 2022**

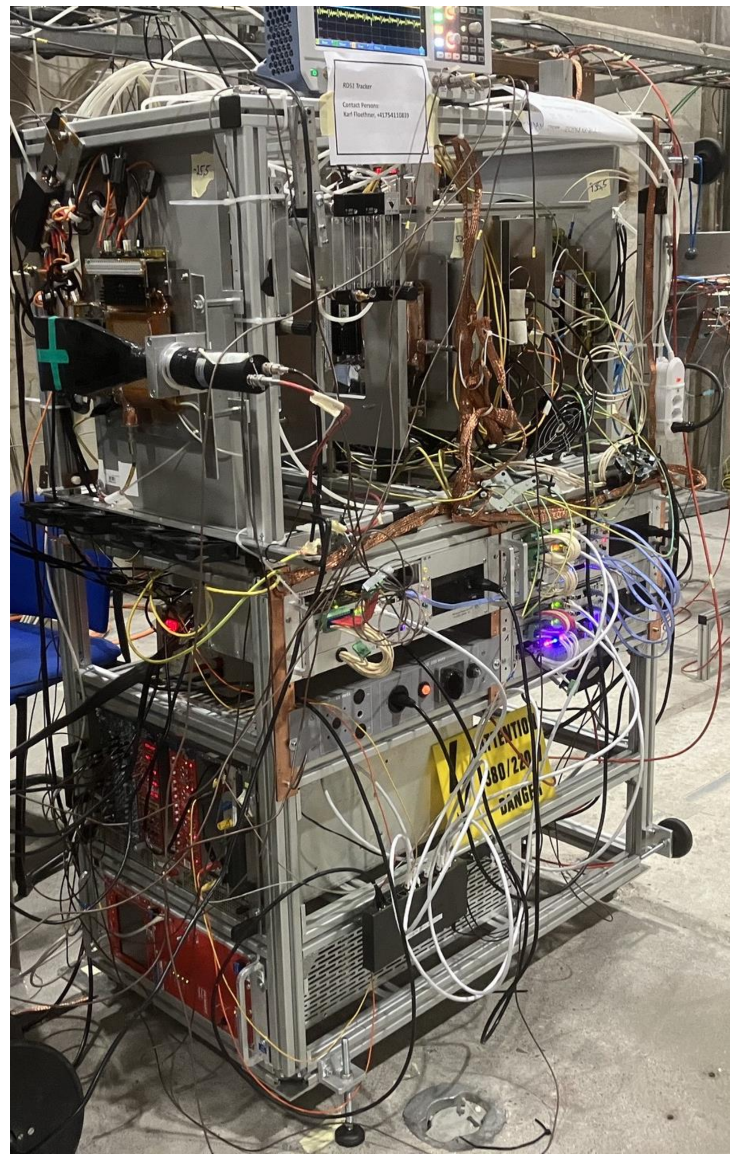
**Self contained system and optimized monitoring**
**April 2023**

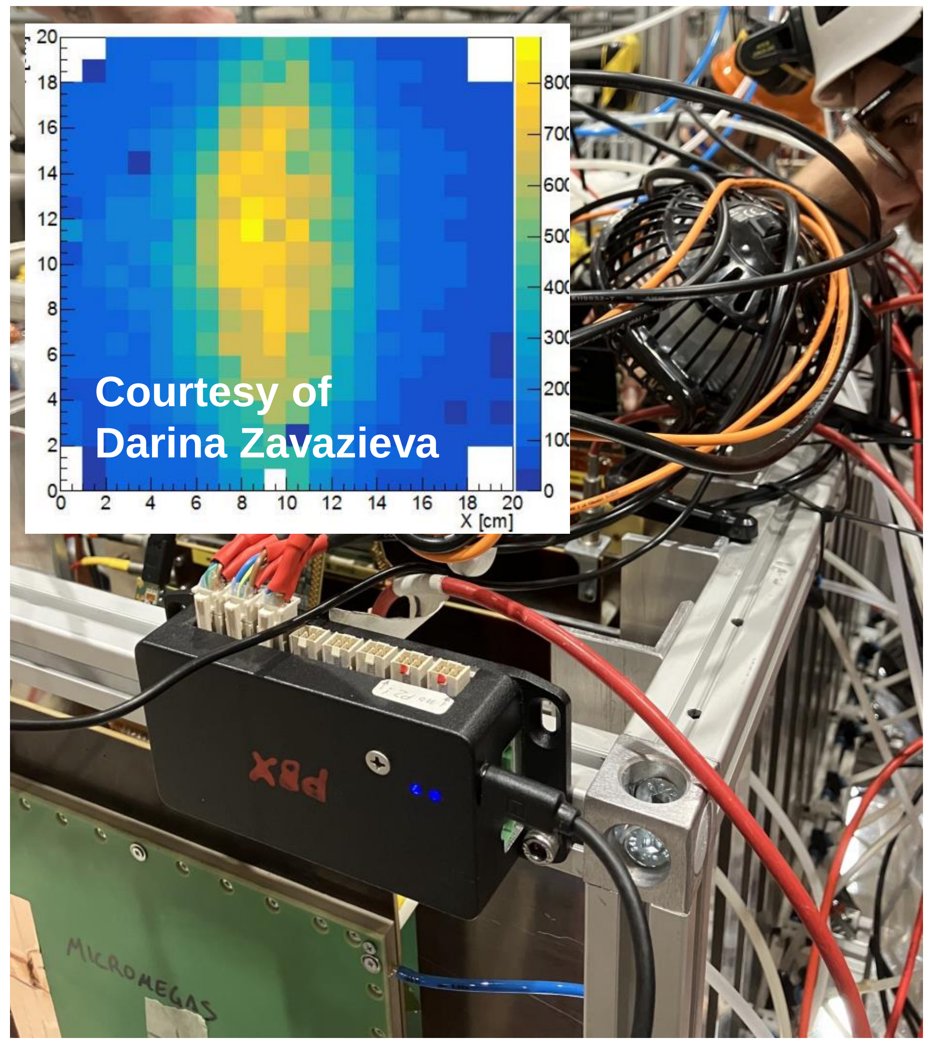
**Improved Powering (PBX)**
**July/August 2023**

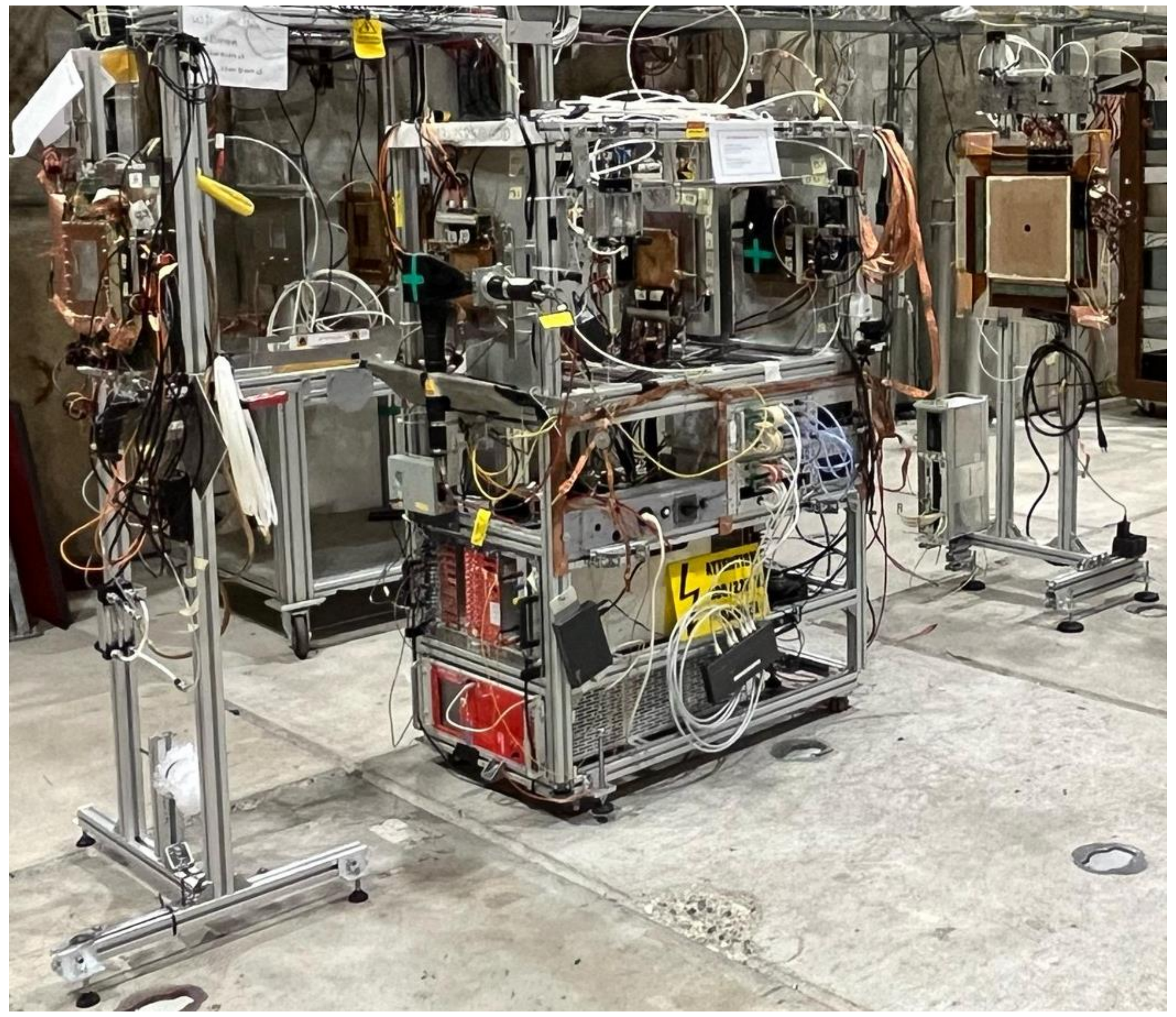
**Distributed System**
**April 2024**





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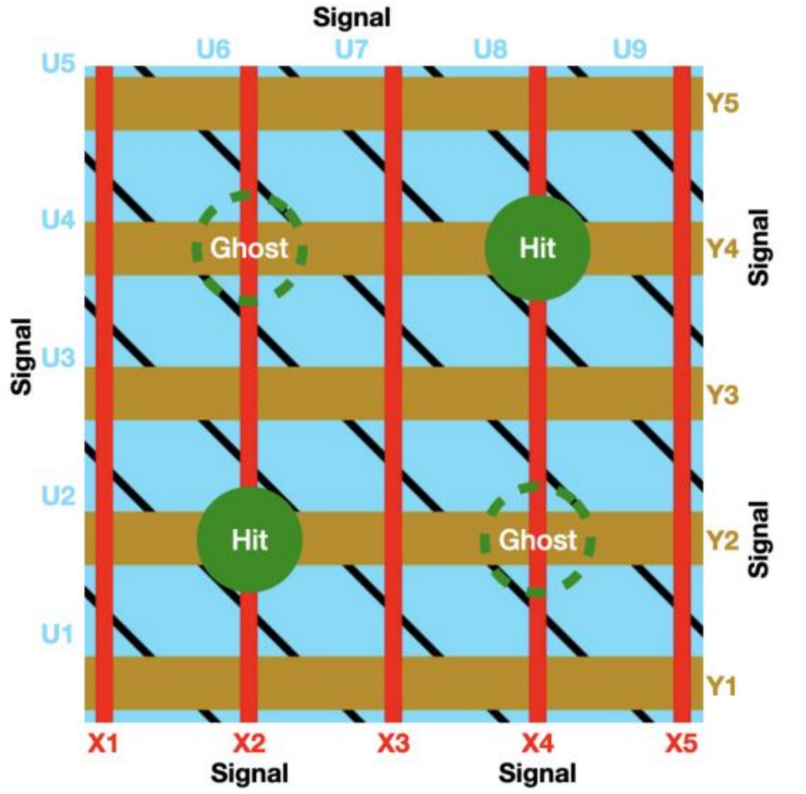
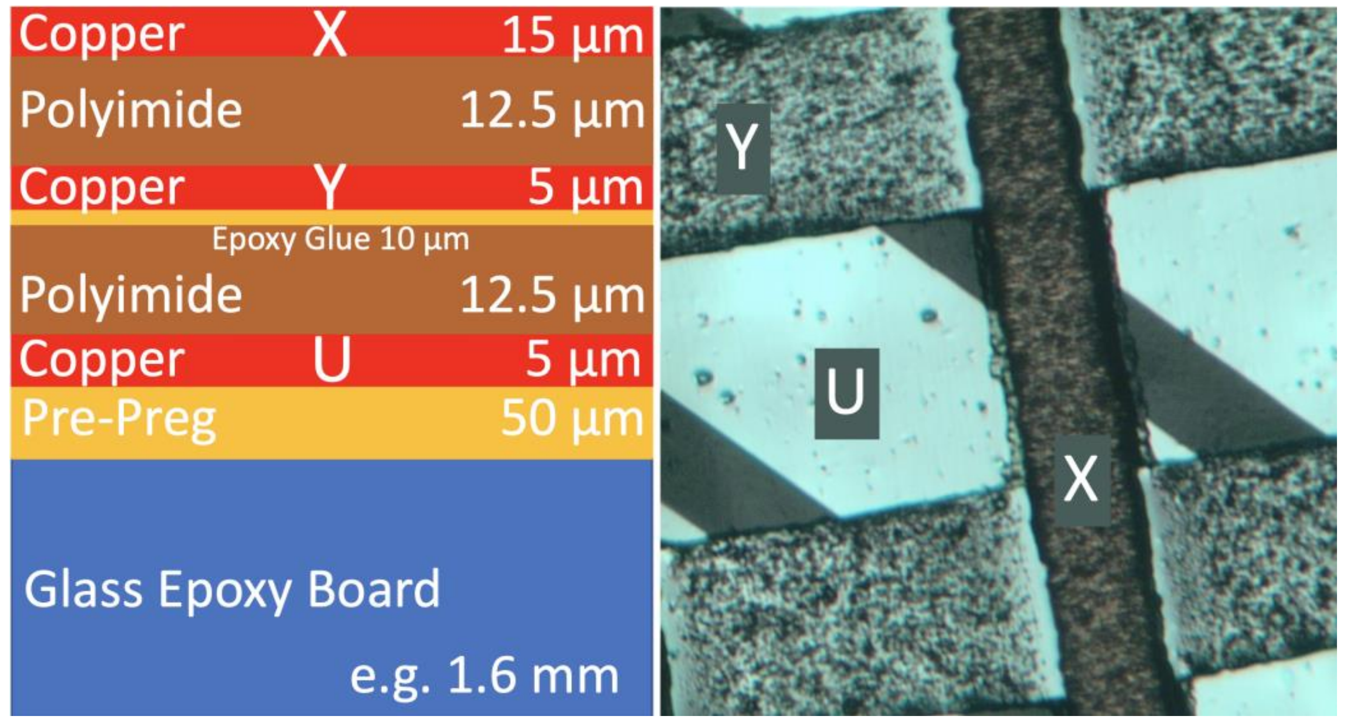
# Example DUT: XYU-GEM

**Production details (R. De Oliveira): https://indico.cern.ch/event/1110129/contributions/4720923/**



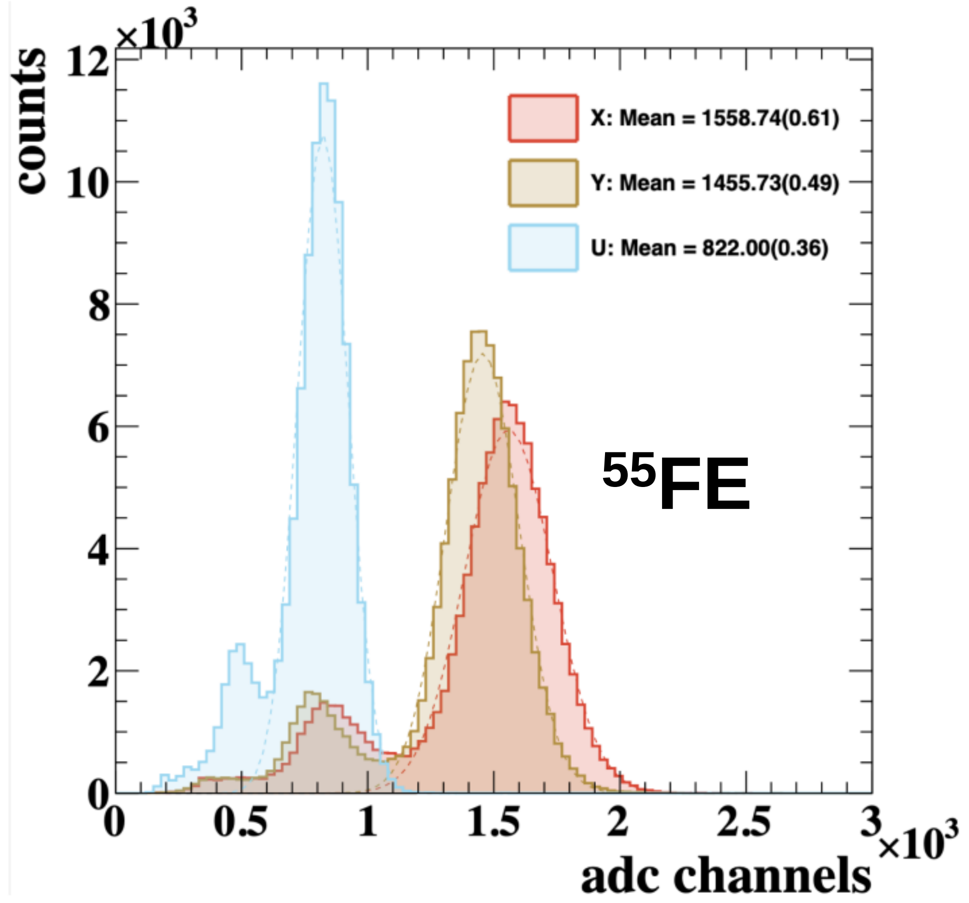



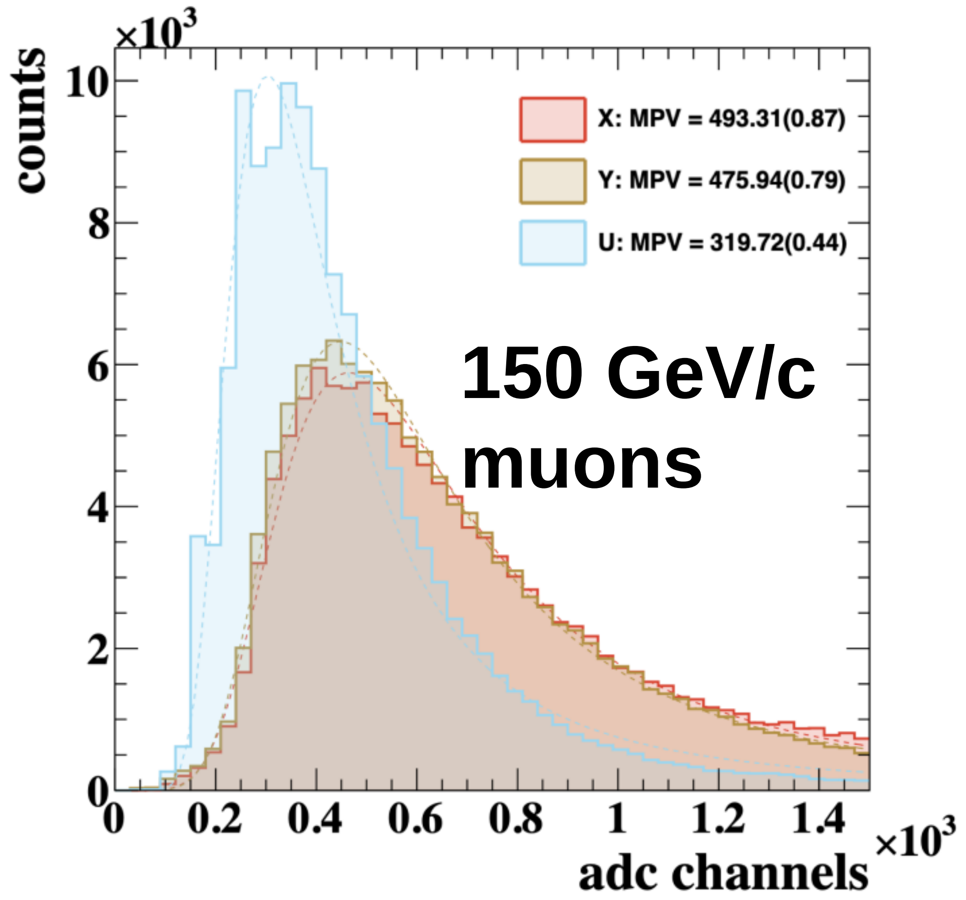

## Concept

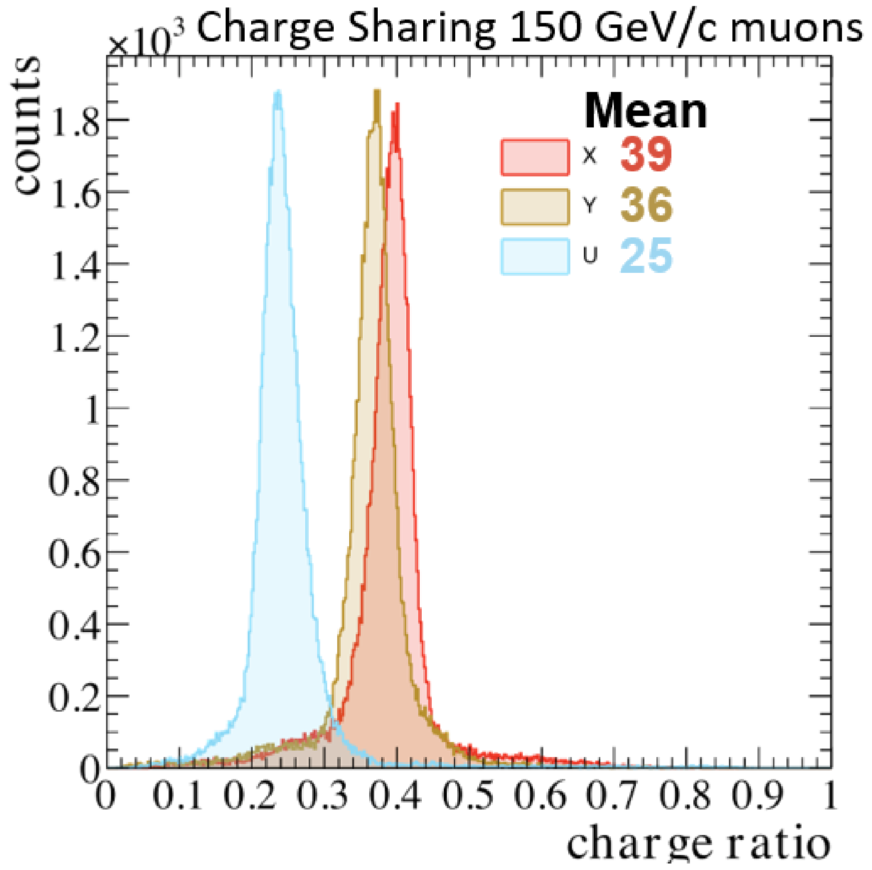
- Three projection strip readout
- No vias within the active area
- Overdetermination due to three projections -> should resolve ambiguities

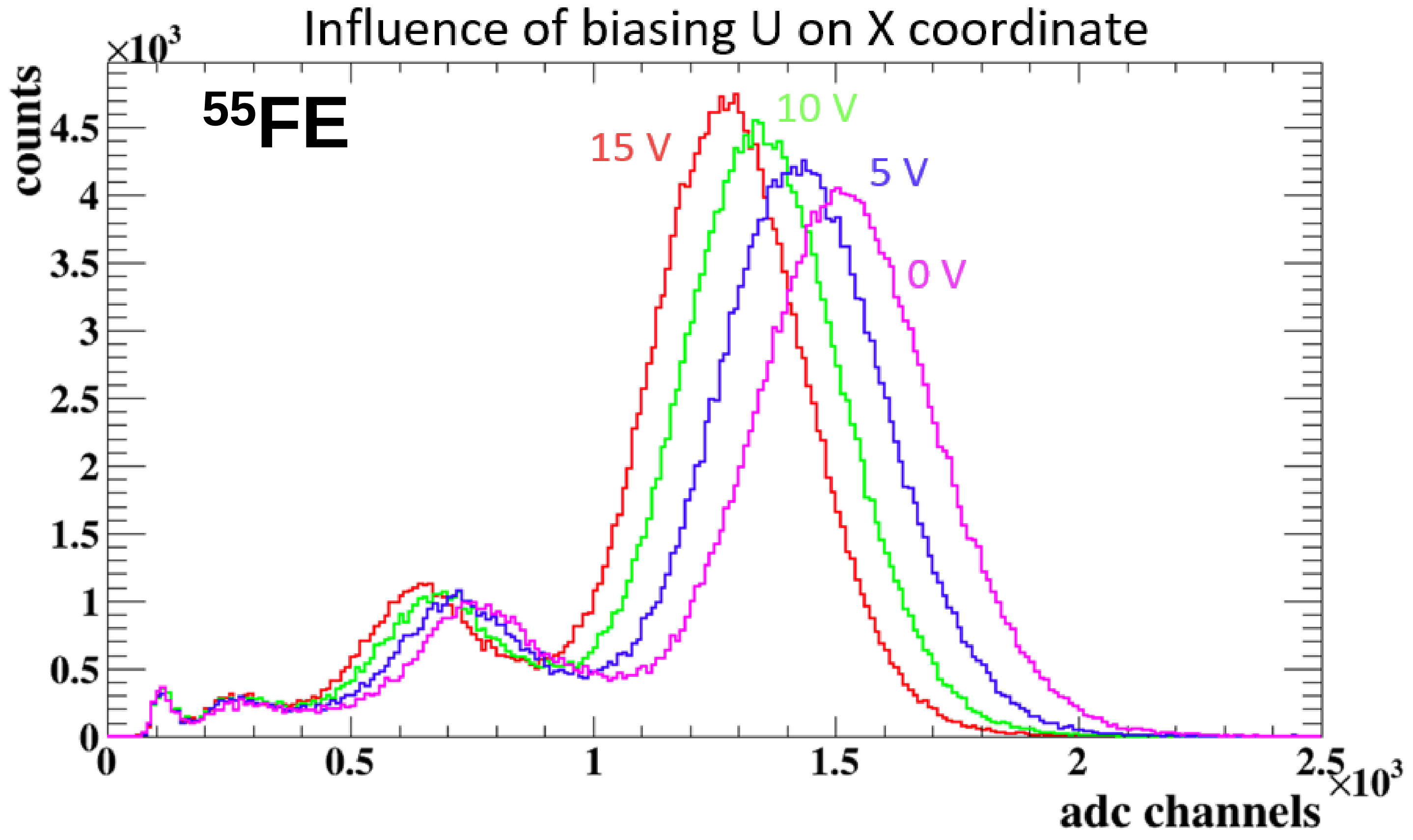
## State of the project

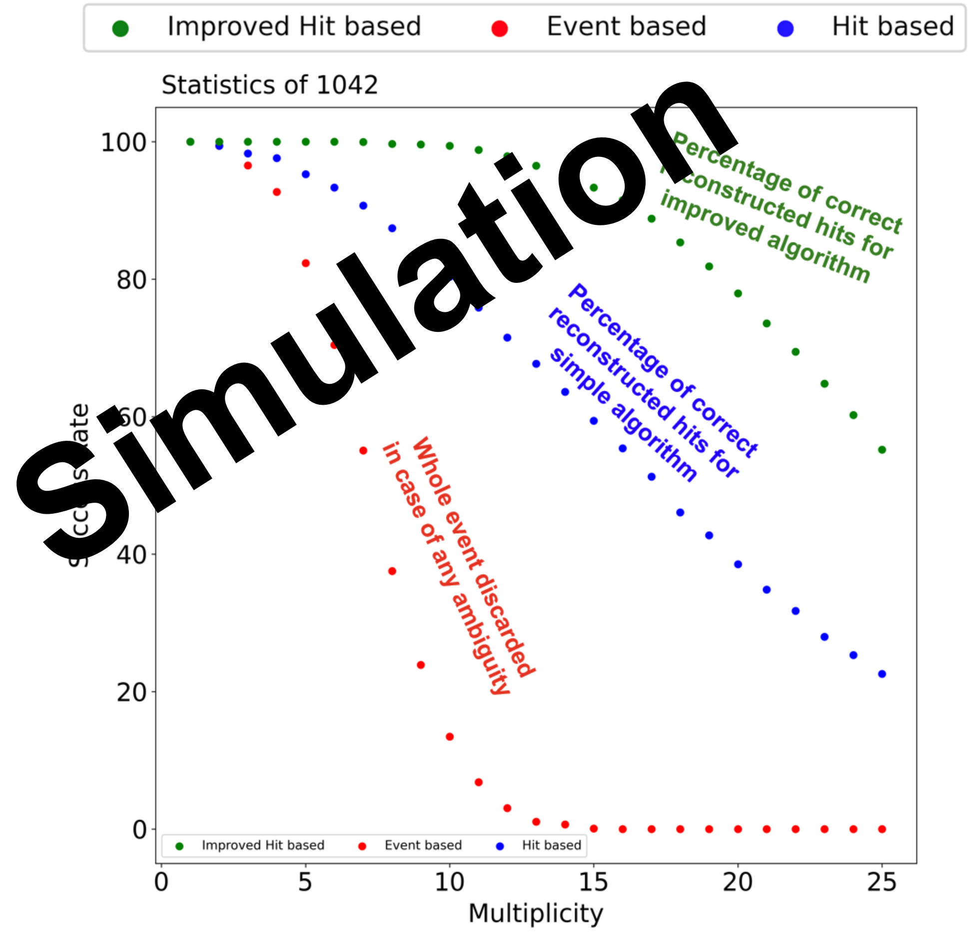
- A good response of all projections can be seen
- The sharing ratio fits with simulations (Djunes J
- The sharing can be varied with biasing strips
- First simulations done to estimate capabilities t resolve ambiguities

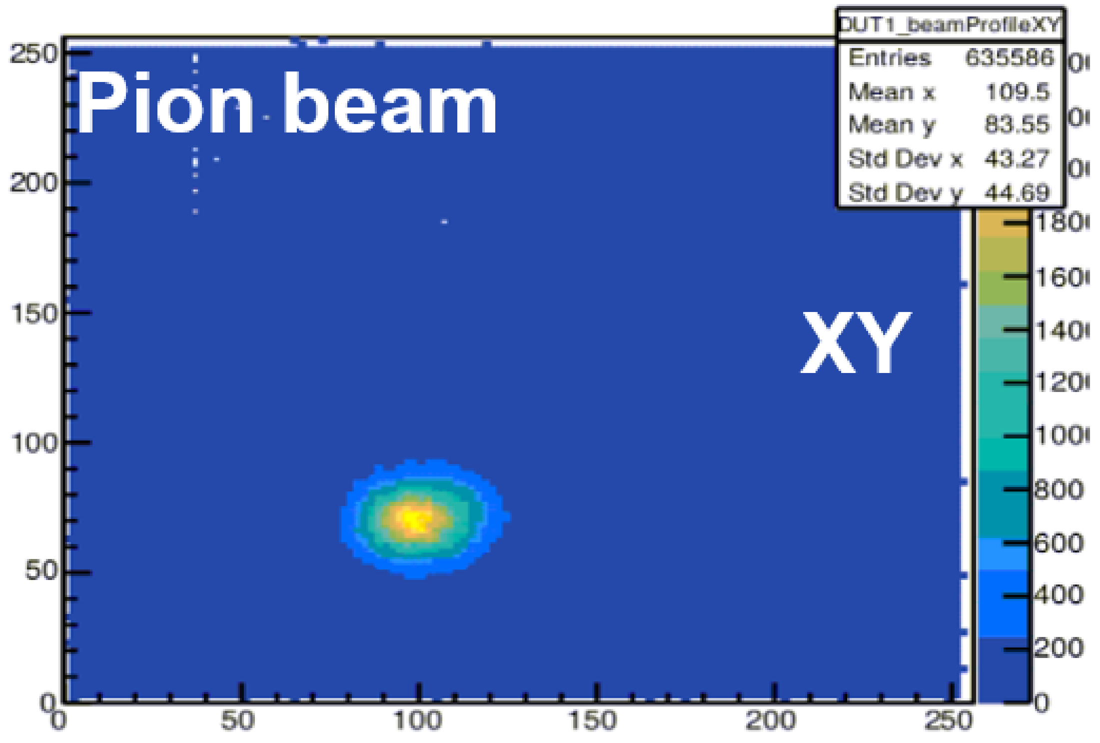


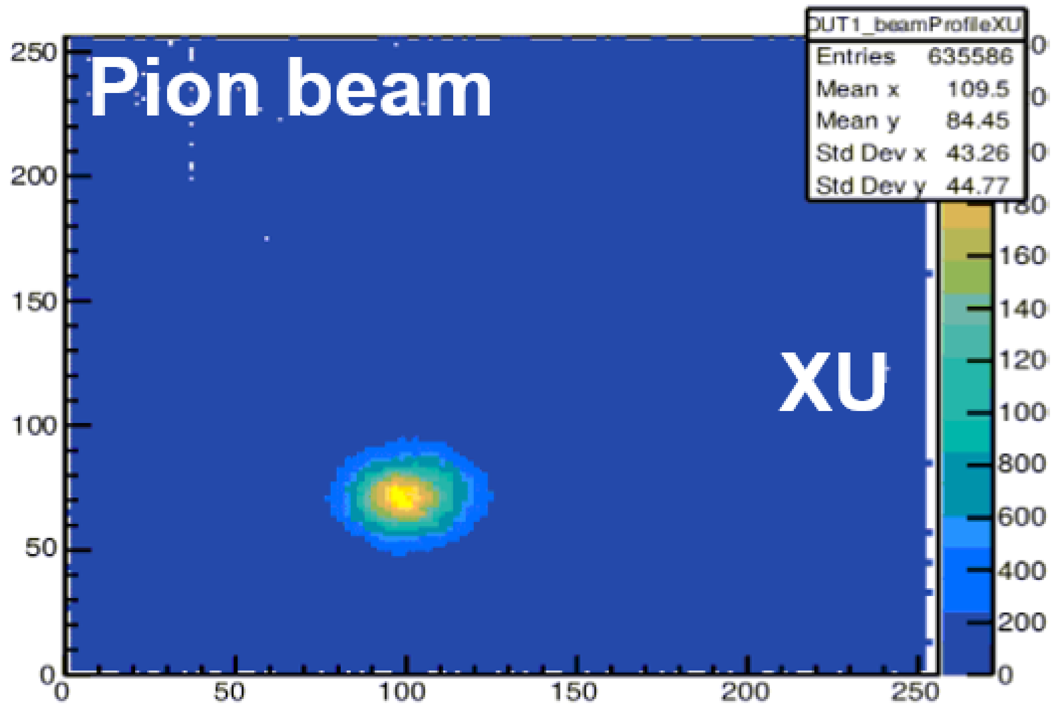



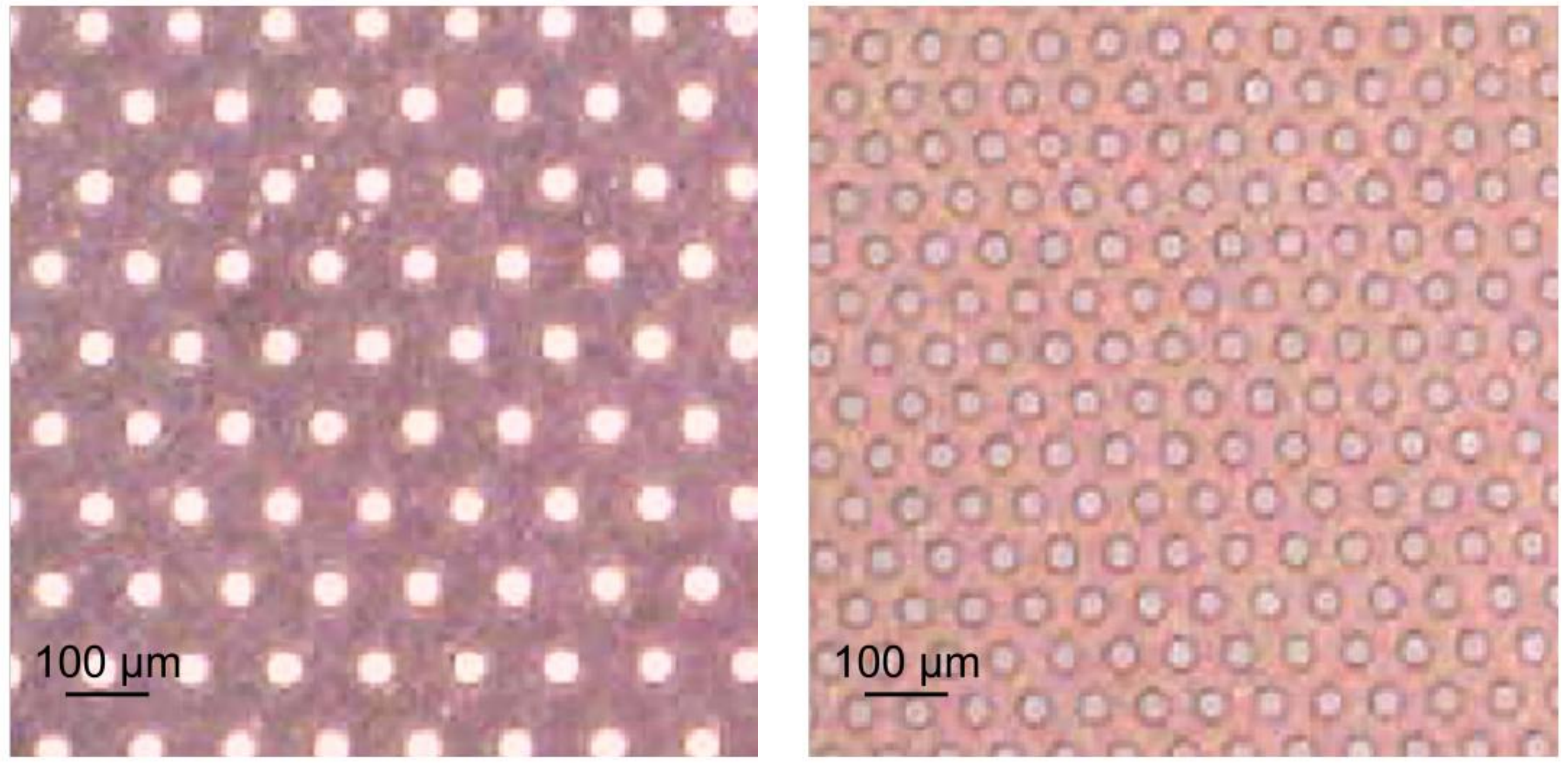



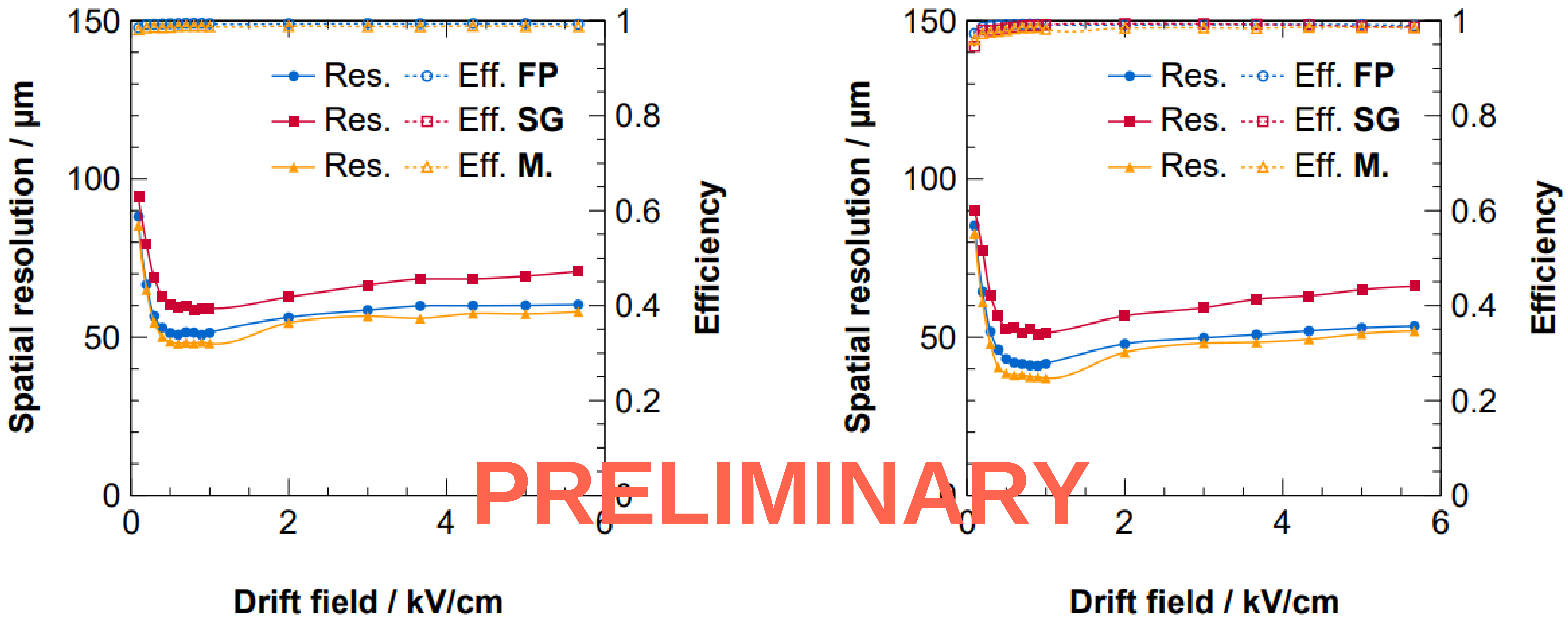



# Example DUT: Fine-Pitch GEM

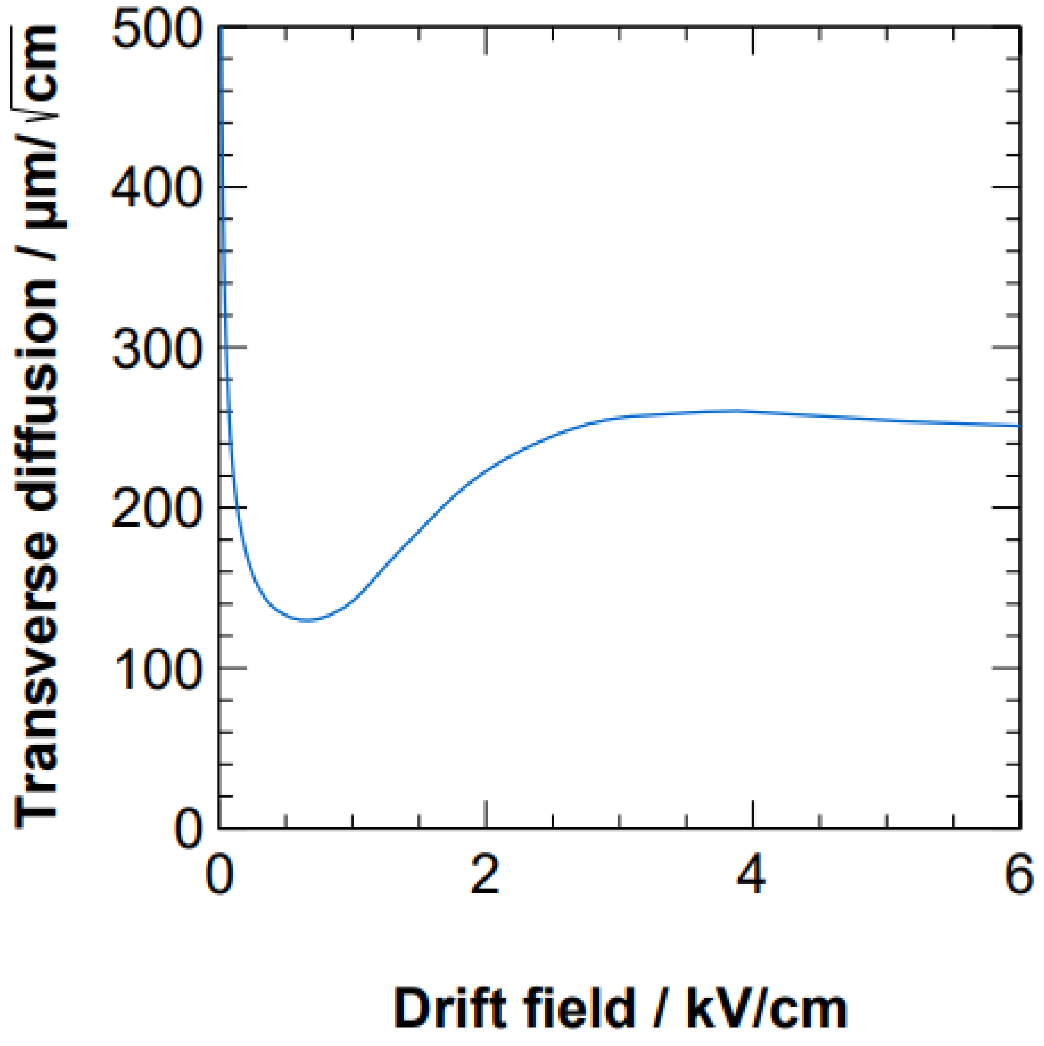
- The impact of a different pitch inbetween the GEM holes is investigated - due to better sampling we expect a better spatial resolution
- A drift field scan shows a minimum correlated to low transversal diffusion



(a) Standard GEM geometry
**140 µm pitch**
(b) Finer pitch geometry
**90 µm pitch**



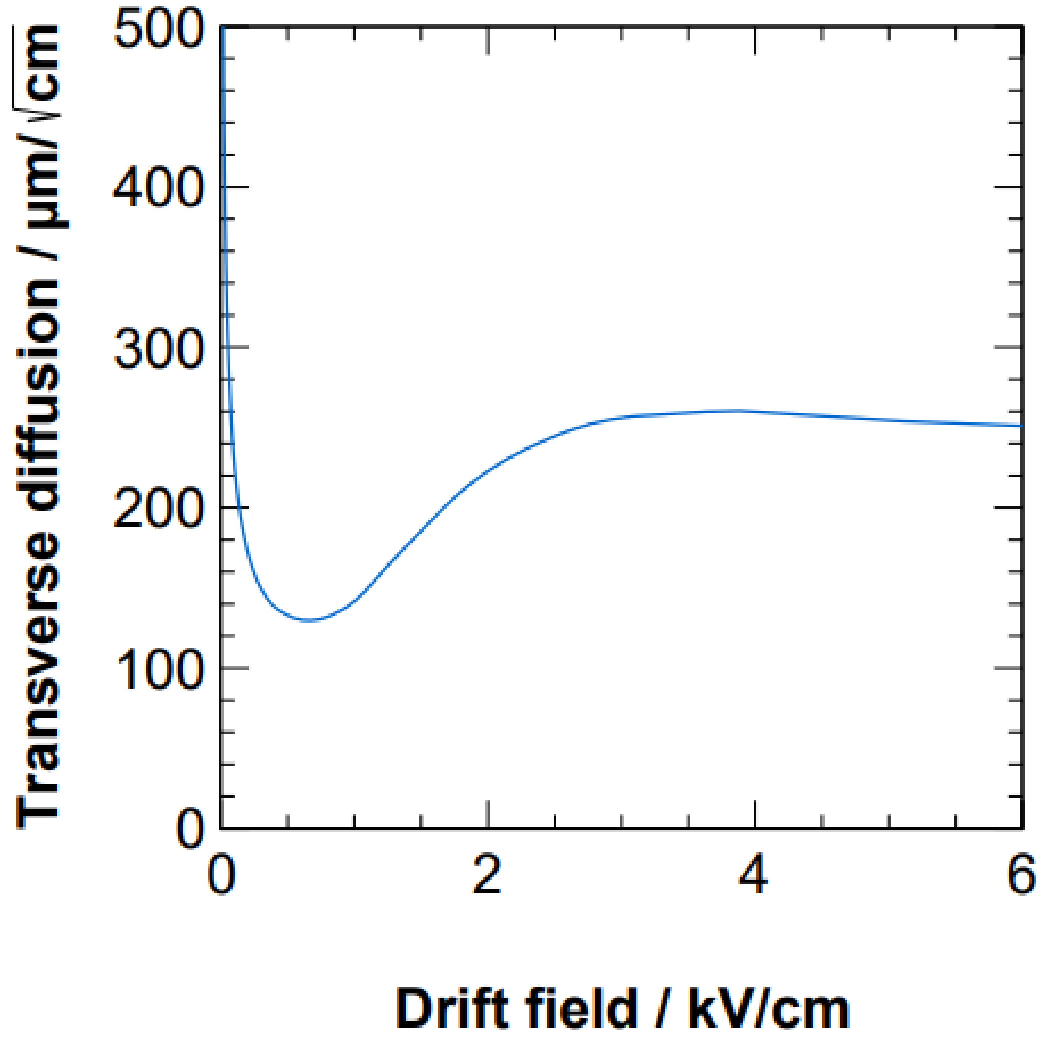
(a) Top strips
(b) Bottom strips





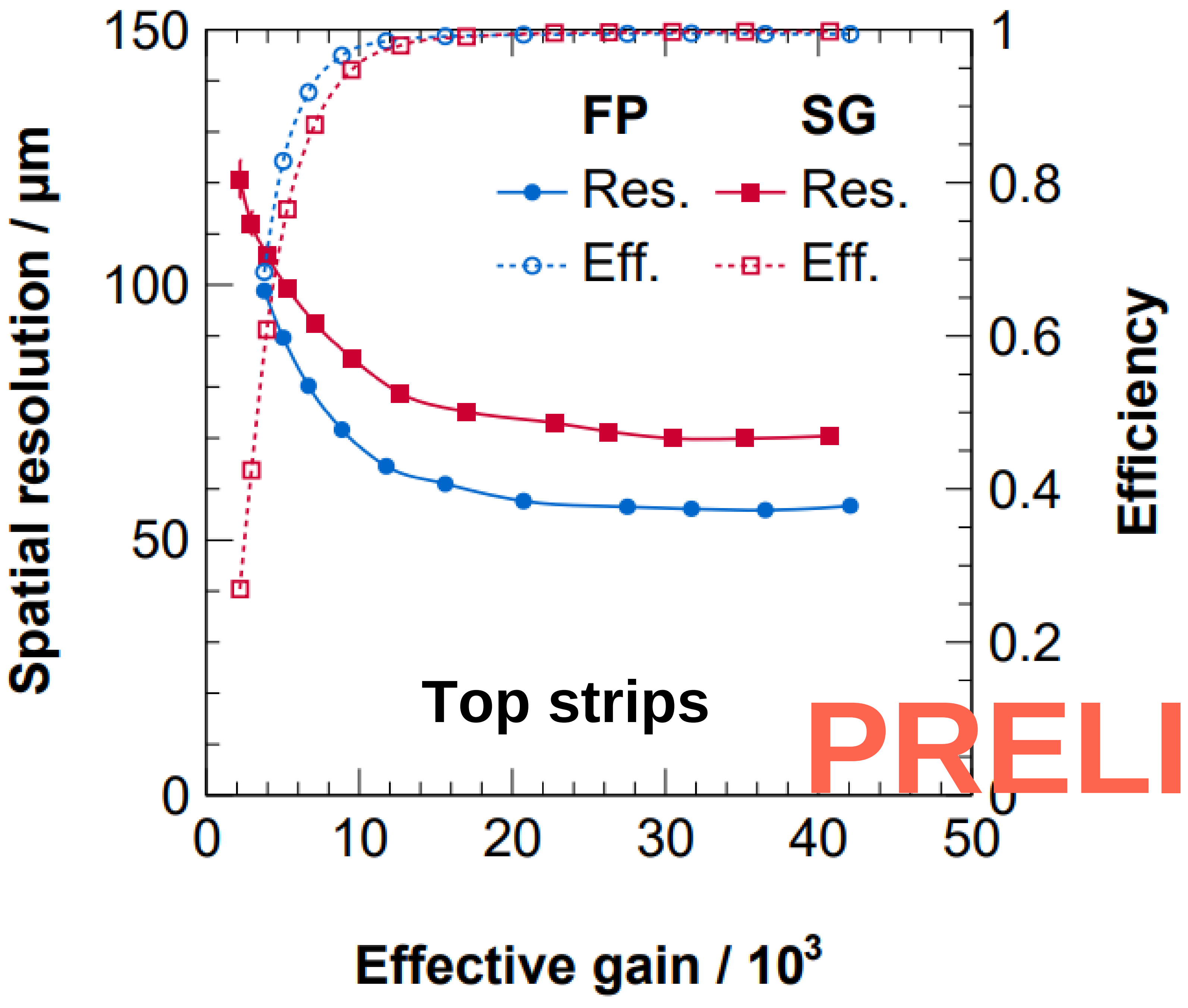

Courtesy of L. Scharenberg

# Fine-Pitch GEM: Resolution

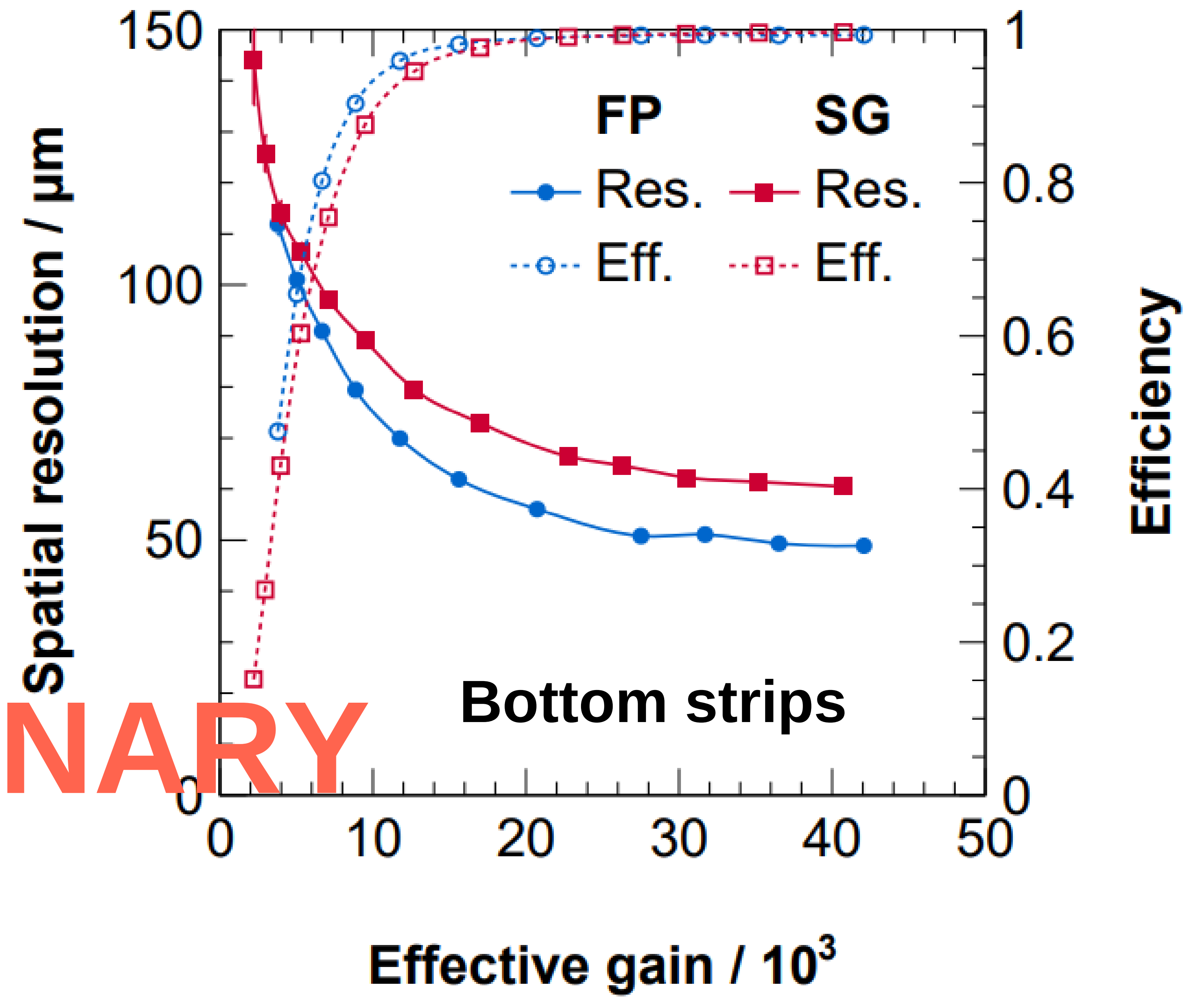


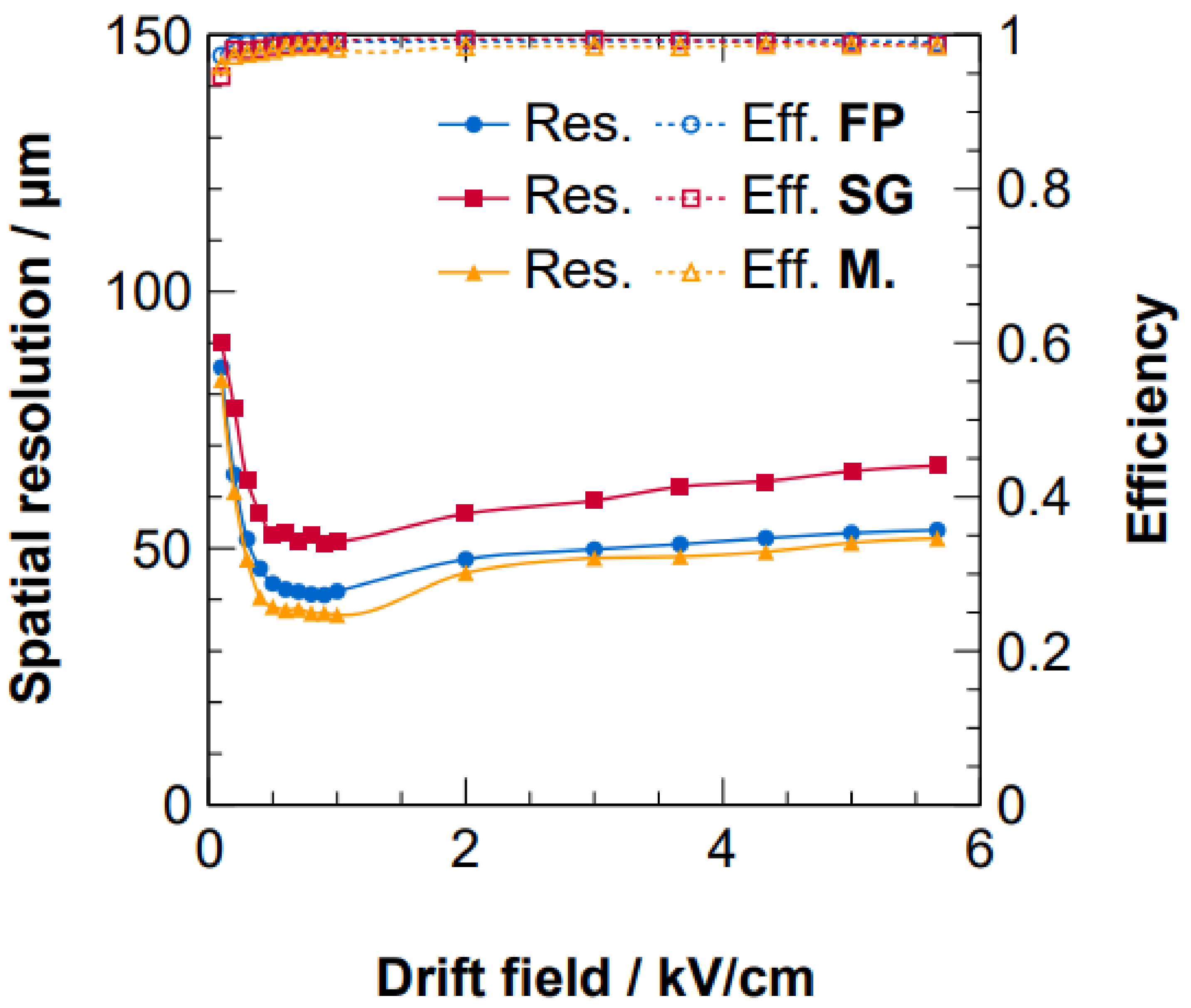

- Better sampling of the initial charge seems to improve the spatial resolution

- Transfer-fields can be adjusted to further optimize the spatial resolution
  -> Transverse diffusion seems to be a good explanation




PRELIMINARY



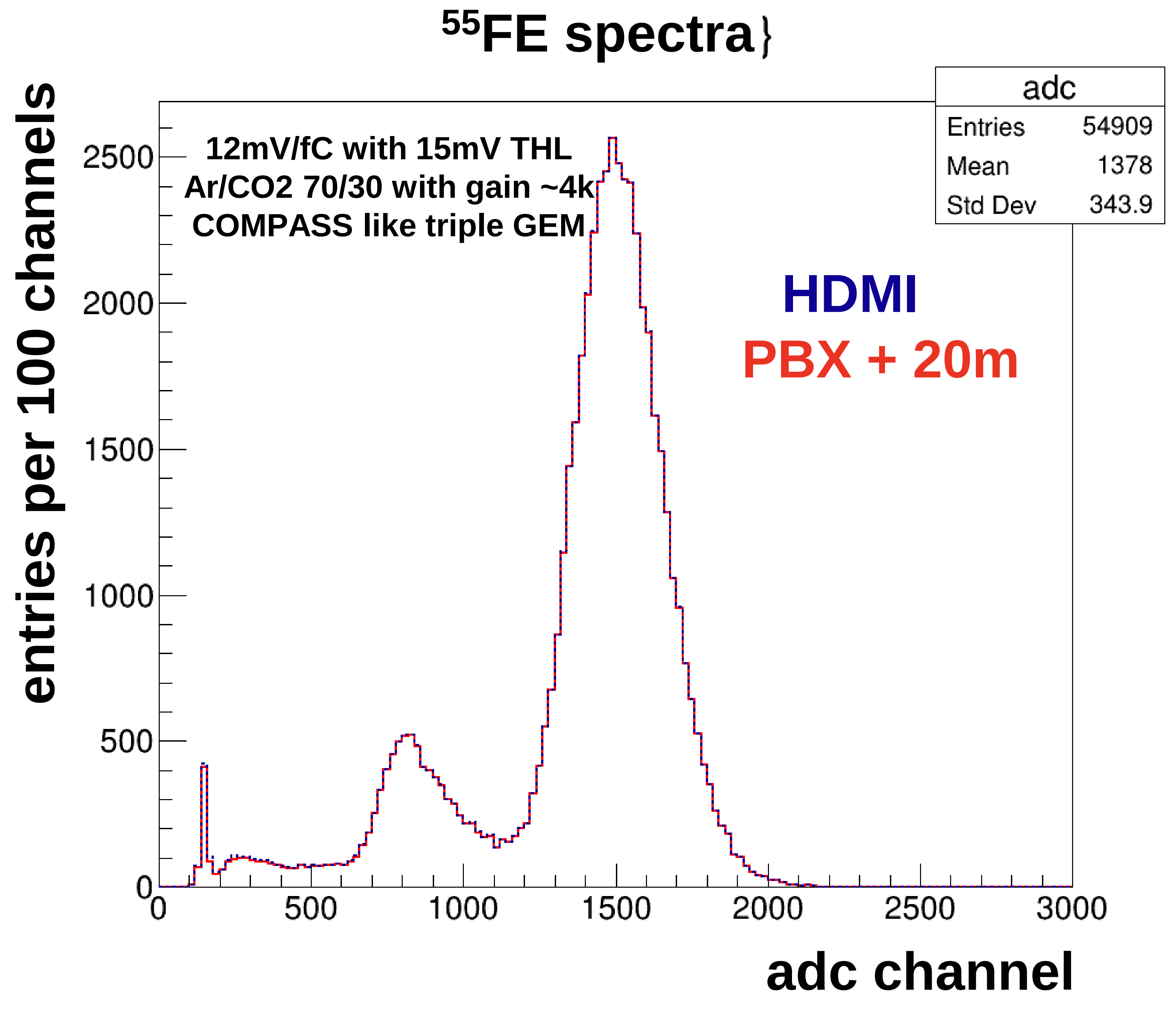



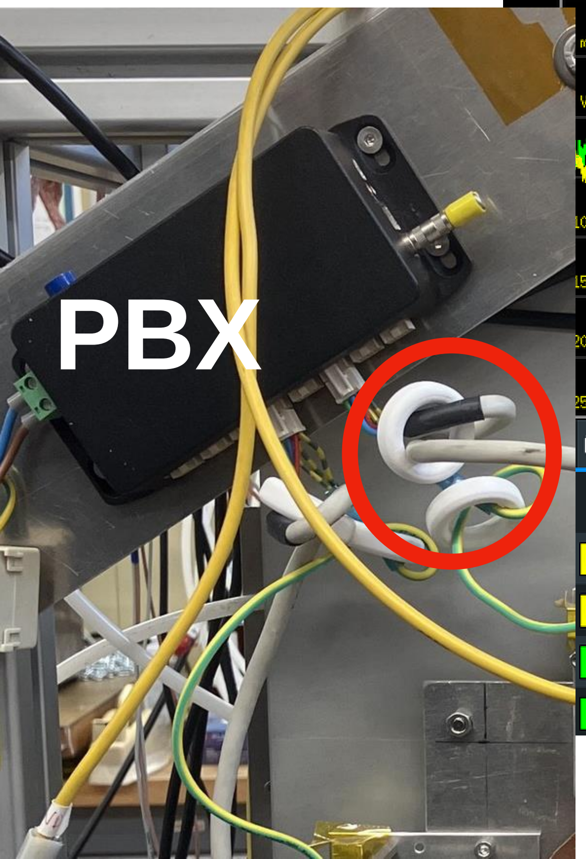
# Powering and Noise

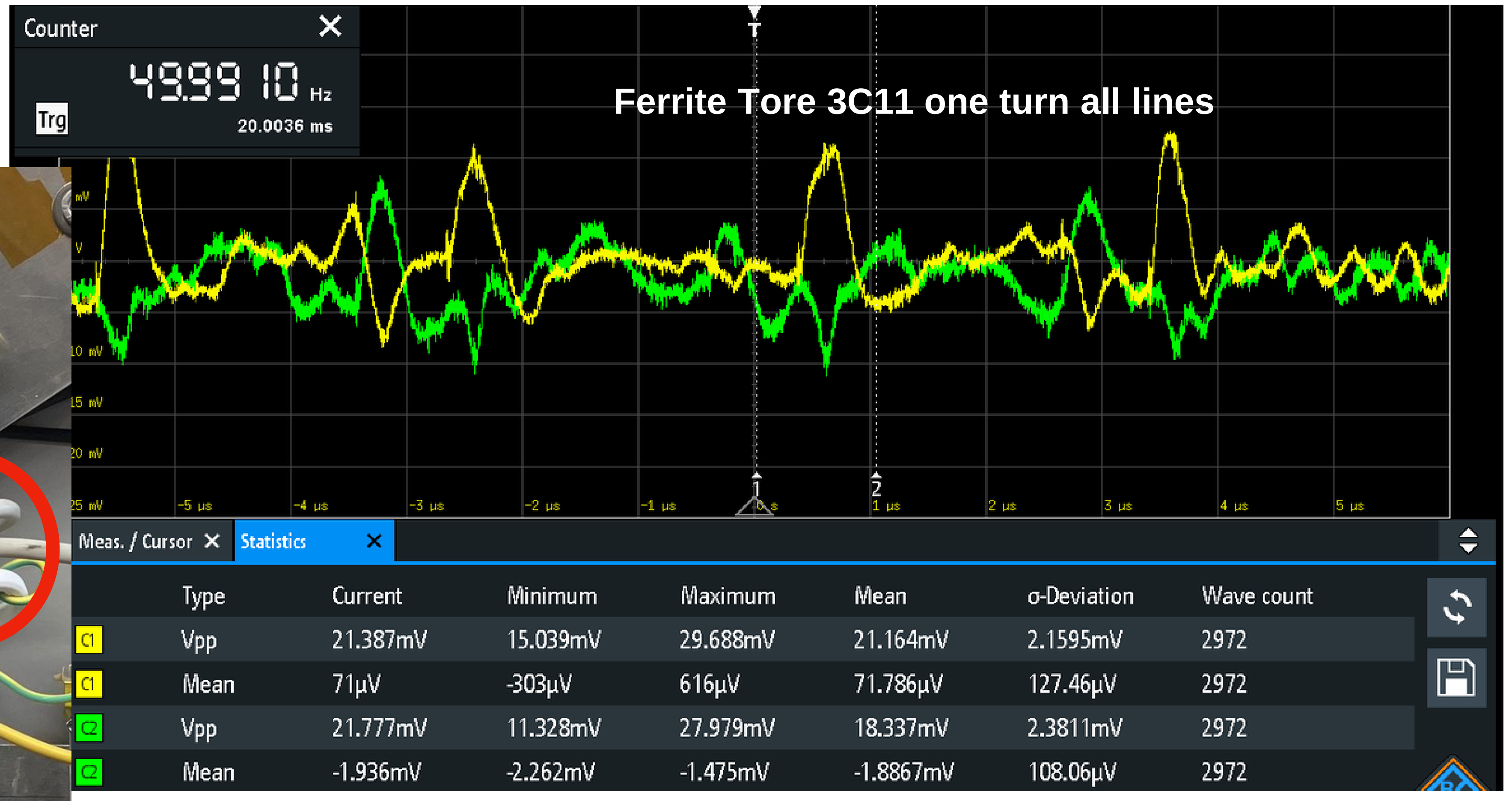
[PBX Documentation from H. Muller]

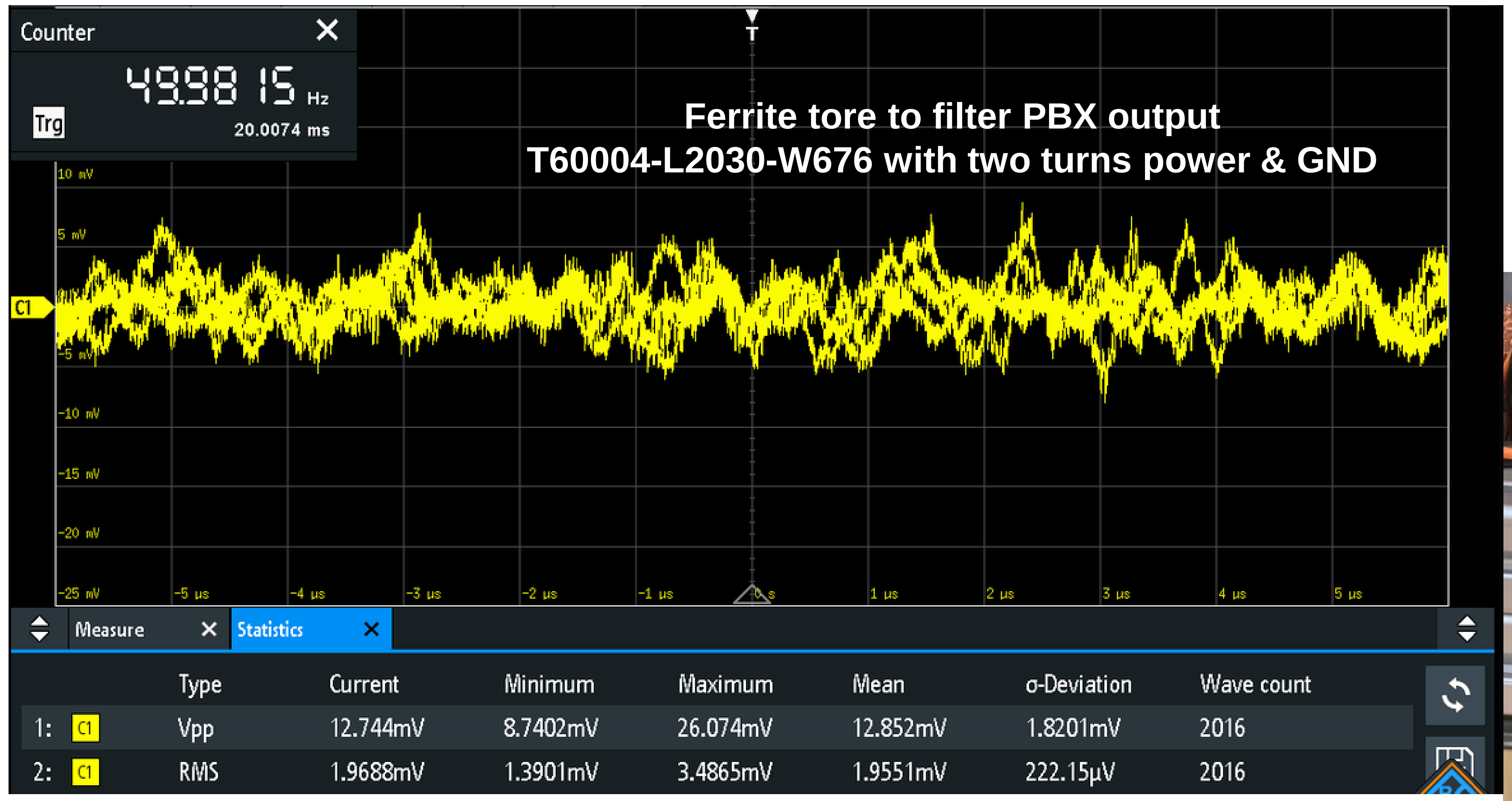
- Power over HDMI
  - unstable for many hybrids on single DVMM/FEC
  - limited in range due to voltage drop over HDMI cables
  - usually a lot of additional grounding needed for low noise

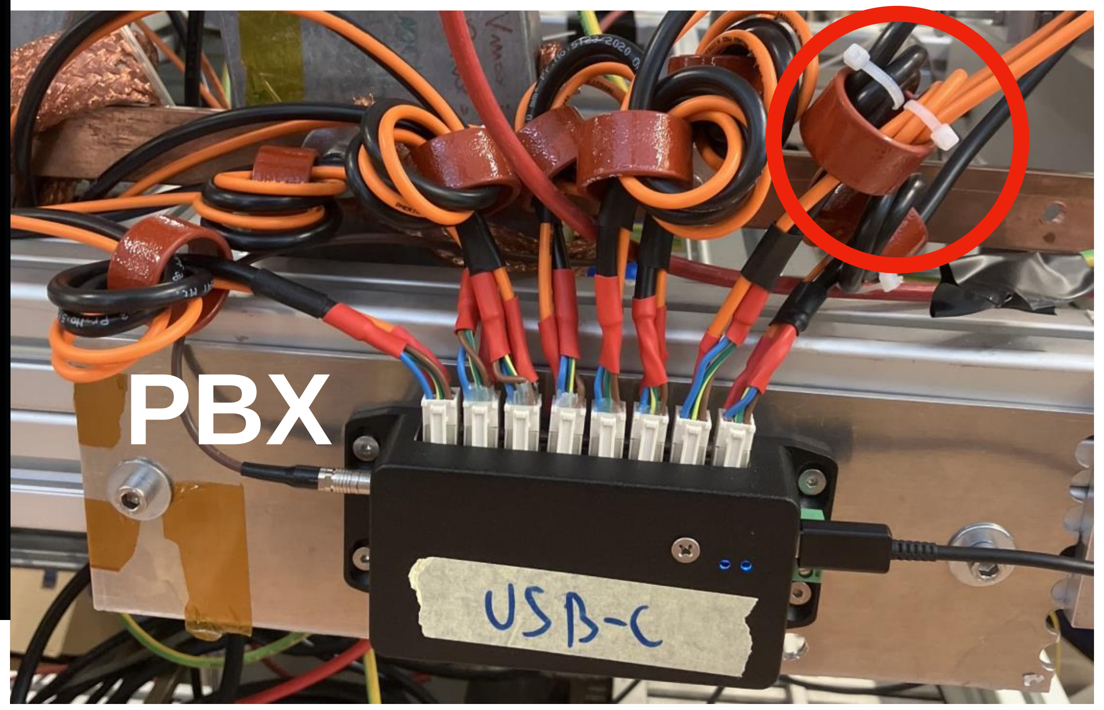
- Power over PBX (external)
  - decoupling from data and powering
  - stable operation with 8 hybrids per DVMM/FEC
  - almost no additional grounding needed
  - unfiltered power source can introduce a lot of noise
  - system can be distributed over larger areas (+20m HDMI)



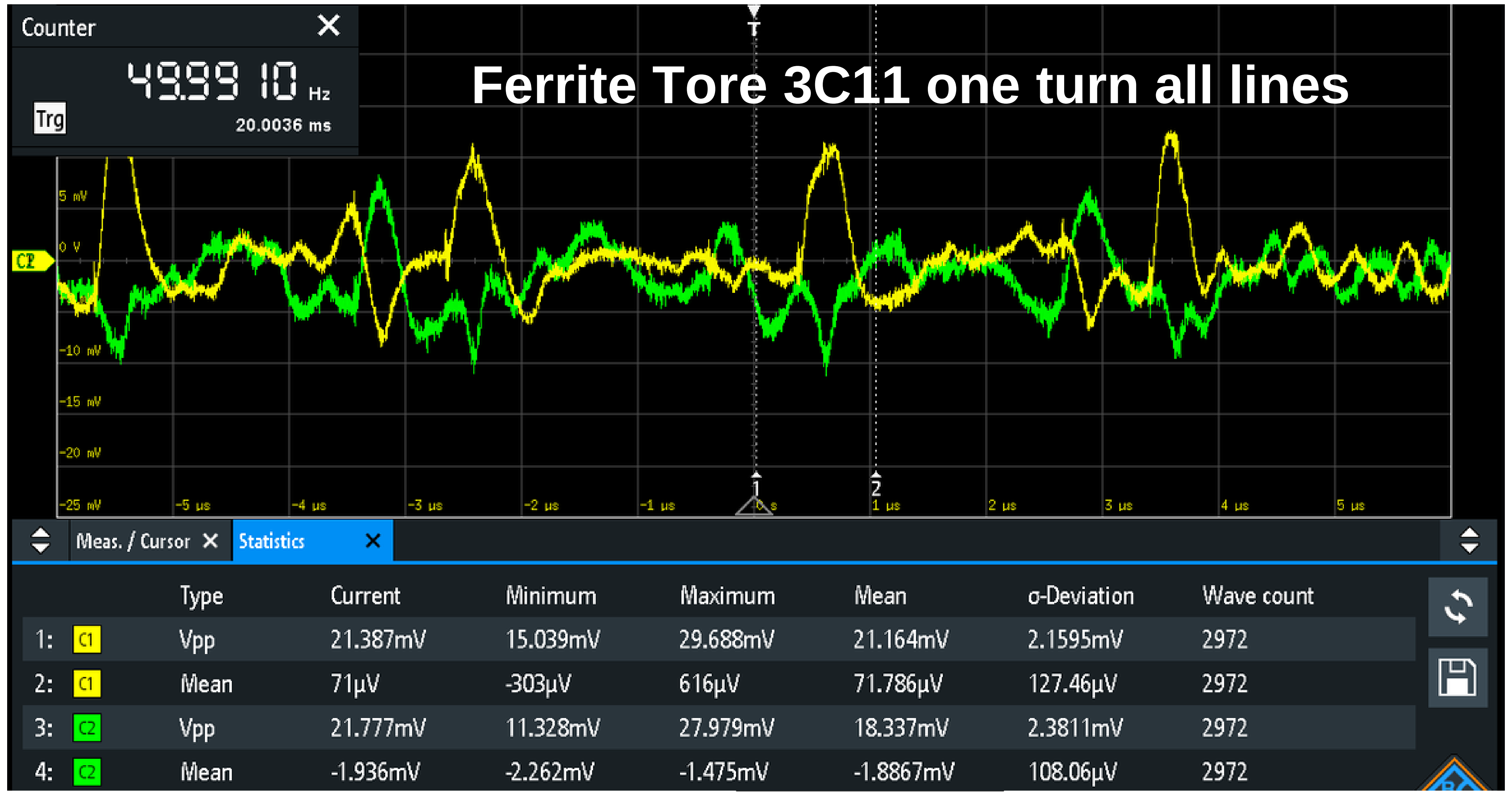
# Noise

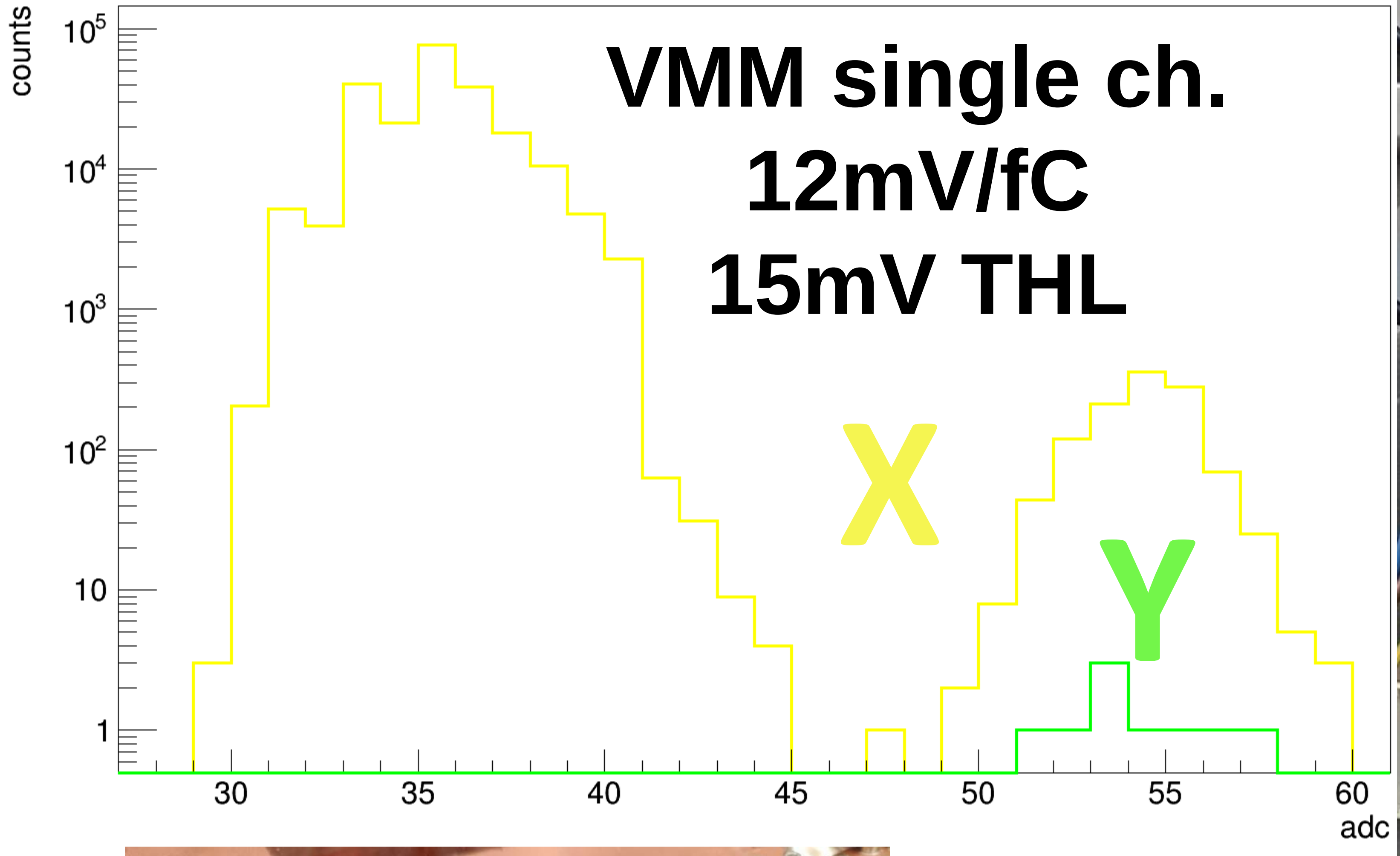
- Well controlled noise is crucial for self-triggered mode
  - bandwidth can be fully occupied by noise
  - required data storage can become a limiting factor

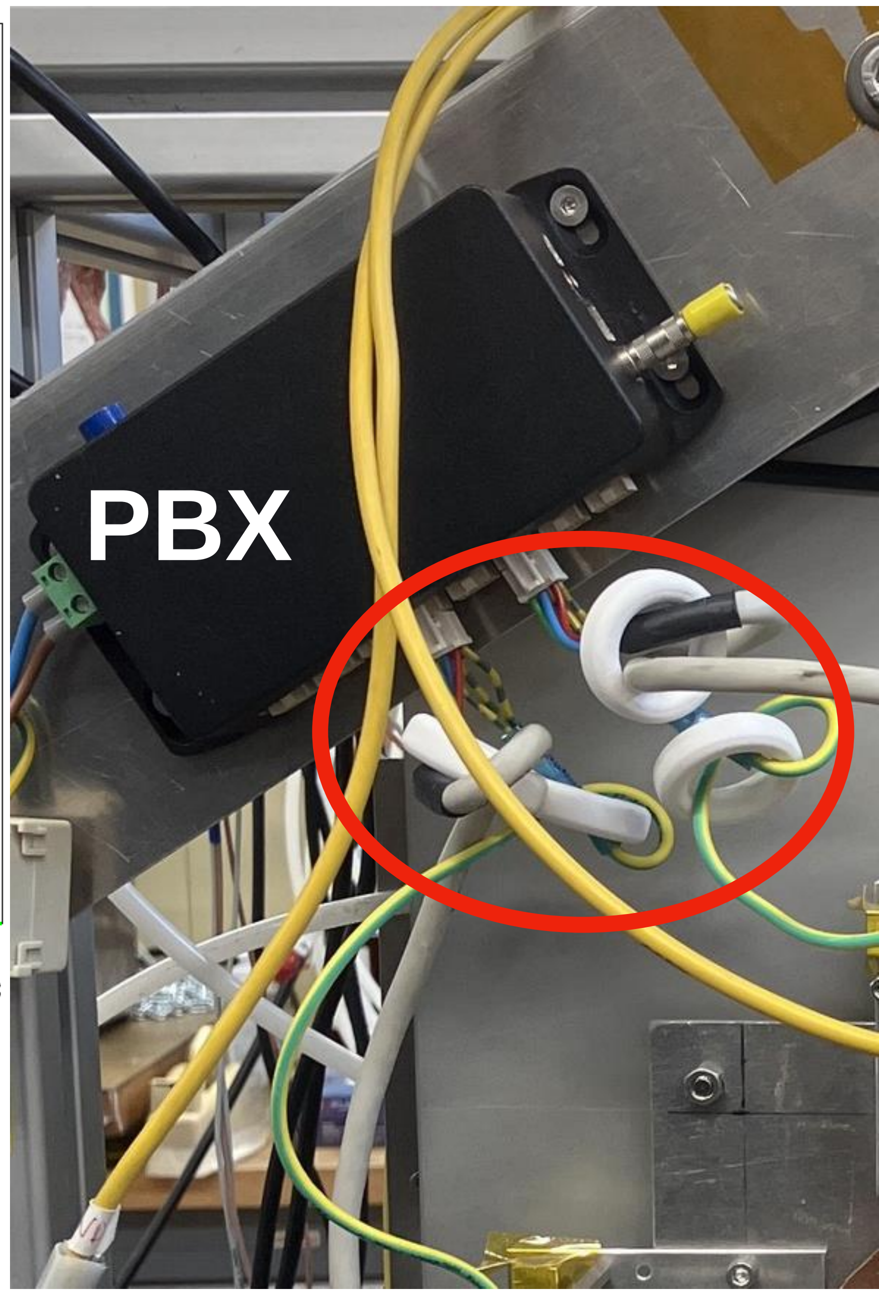
- General
  - monitoring output helps finding/fixing noise sources
  - interposer need proper GND reference
  - open connectors (e.g. HDMI) should be shielded
  - baseline shift after mounting on detector possible

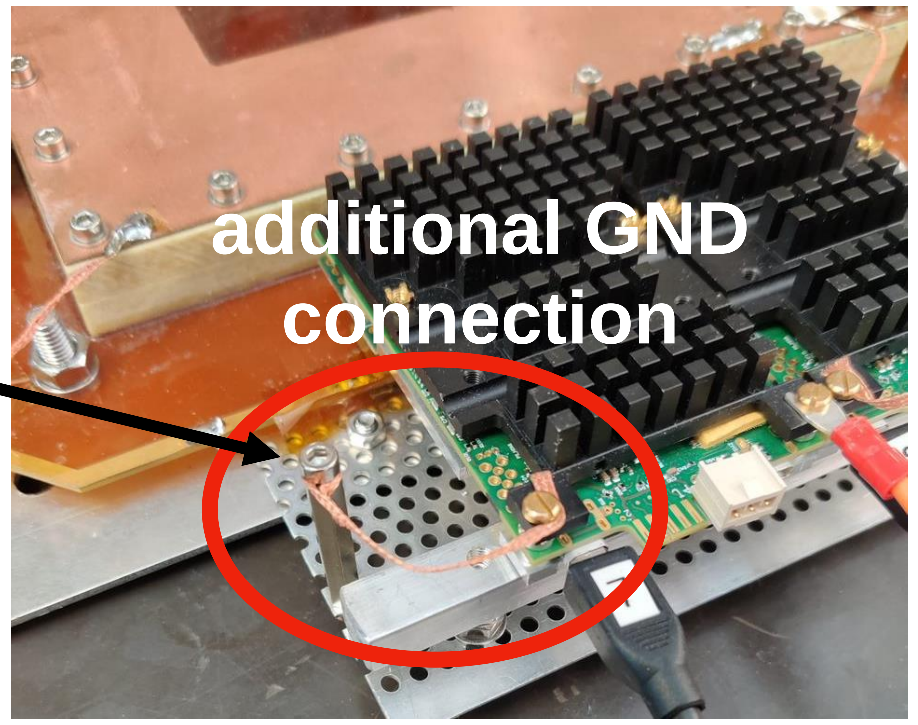
- Power over HDMI
  - GND return to SRS-crate is very important
  - additional GND connection normally helps

- External power e.g. PBX
  - stable power output needed
  - ripples need to be filtered



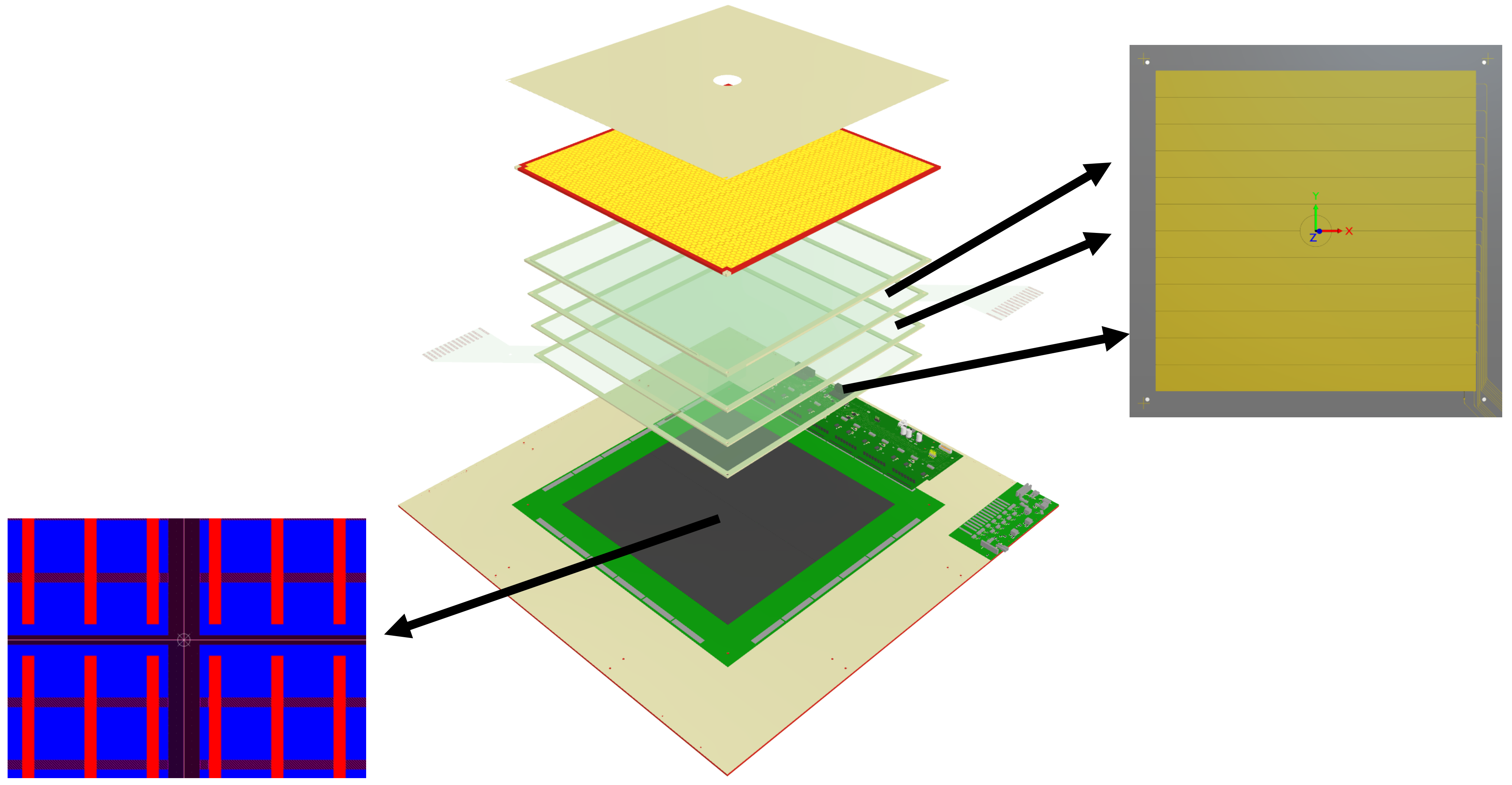



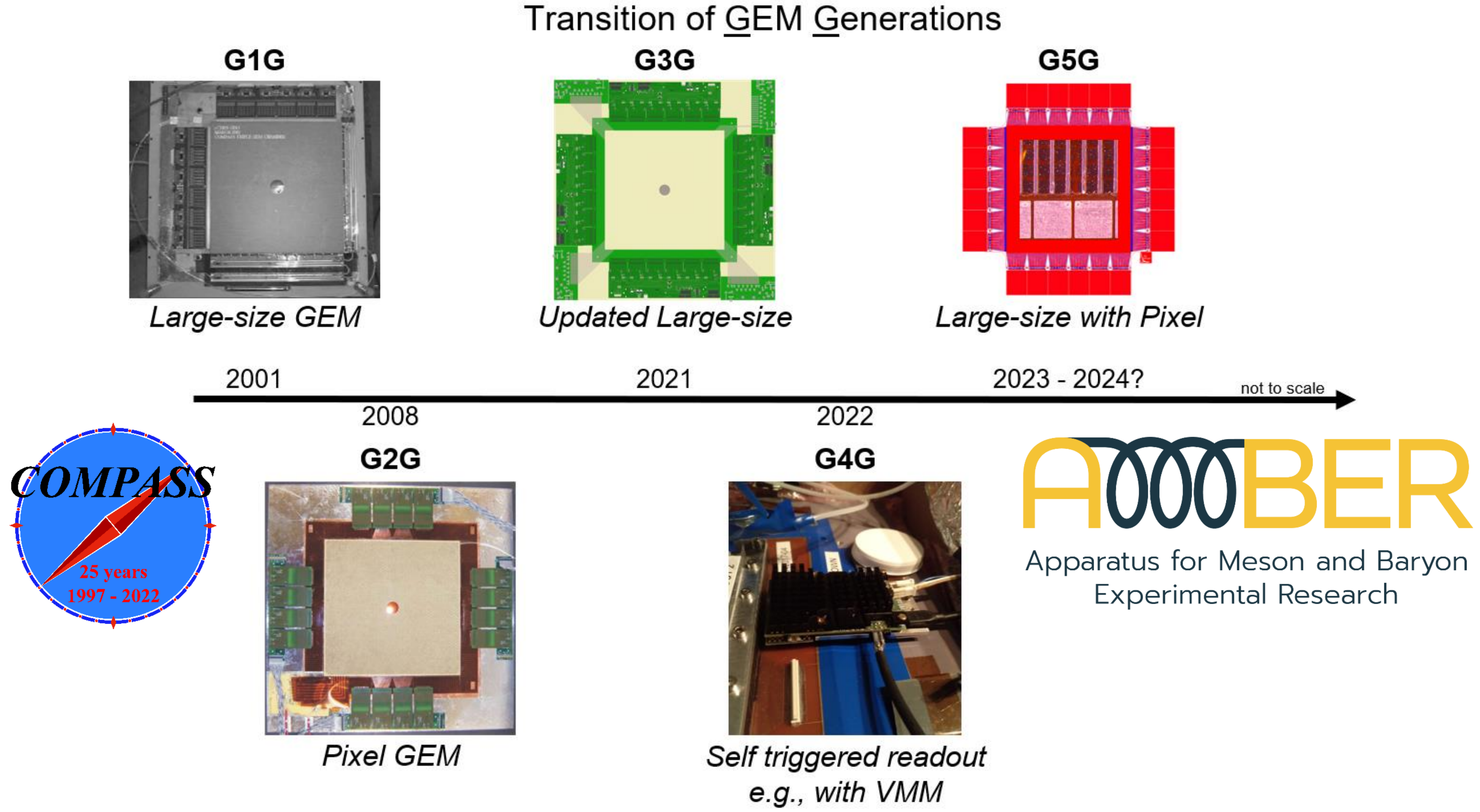



# The G4G for COMPASS/AMBER

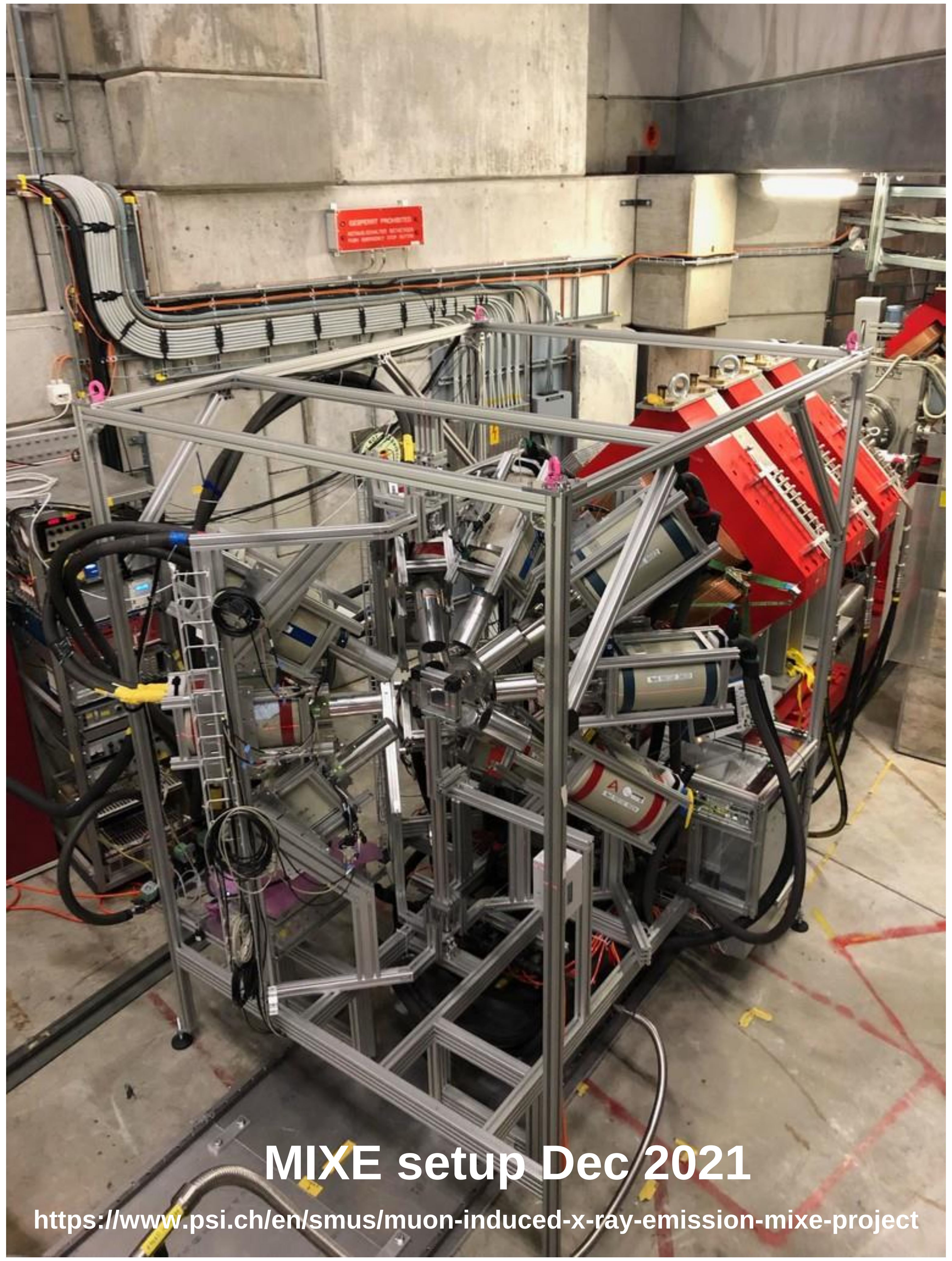
- Triple GEM tracking detector
  - 13-fold top sectored GEMs
  - Standard COMPASS configuration
    https://doi.org/10.1016/S0168-9002(02)00910-5
- 30.7 cm x 30.7 cm active area
  - XY-R/O with strips divided in center
- **Trigger-less readout**





# Very low material budget tracking

- General reduction of multiple scattering
- Fields with particular interest:
  - Inner tracking systems in HEP
  - Beam monitoring
  - Low energy beam tracking
- Specific application: MIXE experiment @ PSI
  - 45 MeV/c muon beam
  - VMM3a/SRS used



# Motivation: Phase-1 AMBER

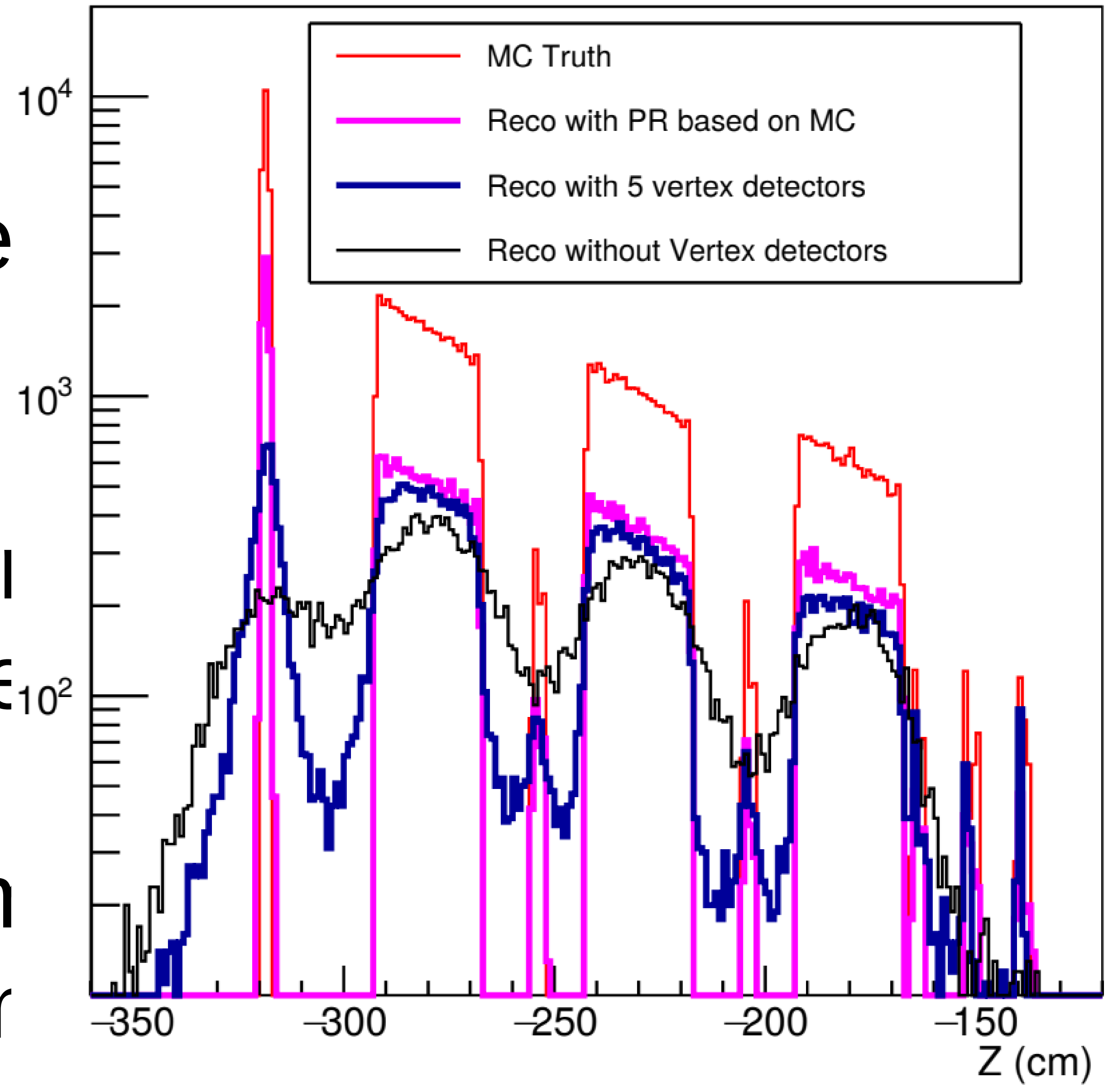
AMBER LOI: https://arxiv.org/abs/1808.00848

| Program | Physics Goals | Beam Energy [GeV] | Beam Intensity [$s^{-1}$] | Trigger Rate [kHz] | Beam Type | Target | Earliest start time, duration | Hardware additions |
|---|---|---|---|---|---|---|---|---|
| muon-proton elastic scattering | Precision proton-radius measurement | 100 | $4 \cdot 10^6$ | 100 | $\mu^\pm$ | high-pressure H2 | 2022 1 year | active TPC, SciFi trigger, silicon veto, |
| Input for Dark Matter Search | $\bar{p}$ production cross section | 20-280 | $5 \cdot 10^5$ | 25 | $p$ | LH2, LHe | 2022 1 month | liquid helium target |
| Drell-Yan | Pion PDFs | 190 | $7 \cdot 10^7$ | 25 | $\pi^\pm$ | C/W | 2022 1-2 years | |

Table 2: Requirements for future programmes at the M2 beam line after 2021. Muon beams are in blue, conventional hadron beams in green, and RF-separated hadron beams in red.

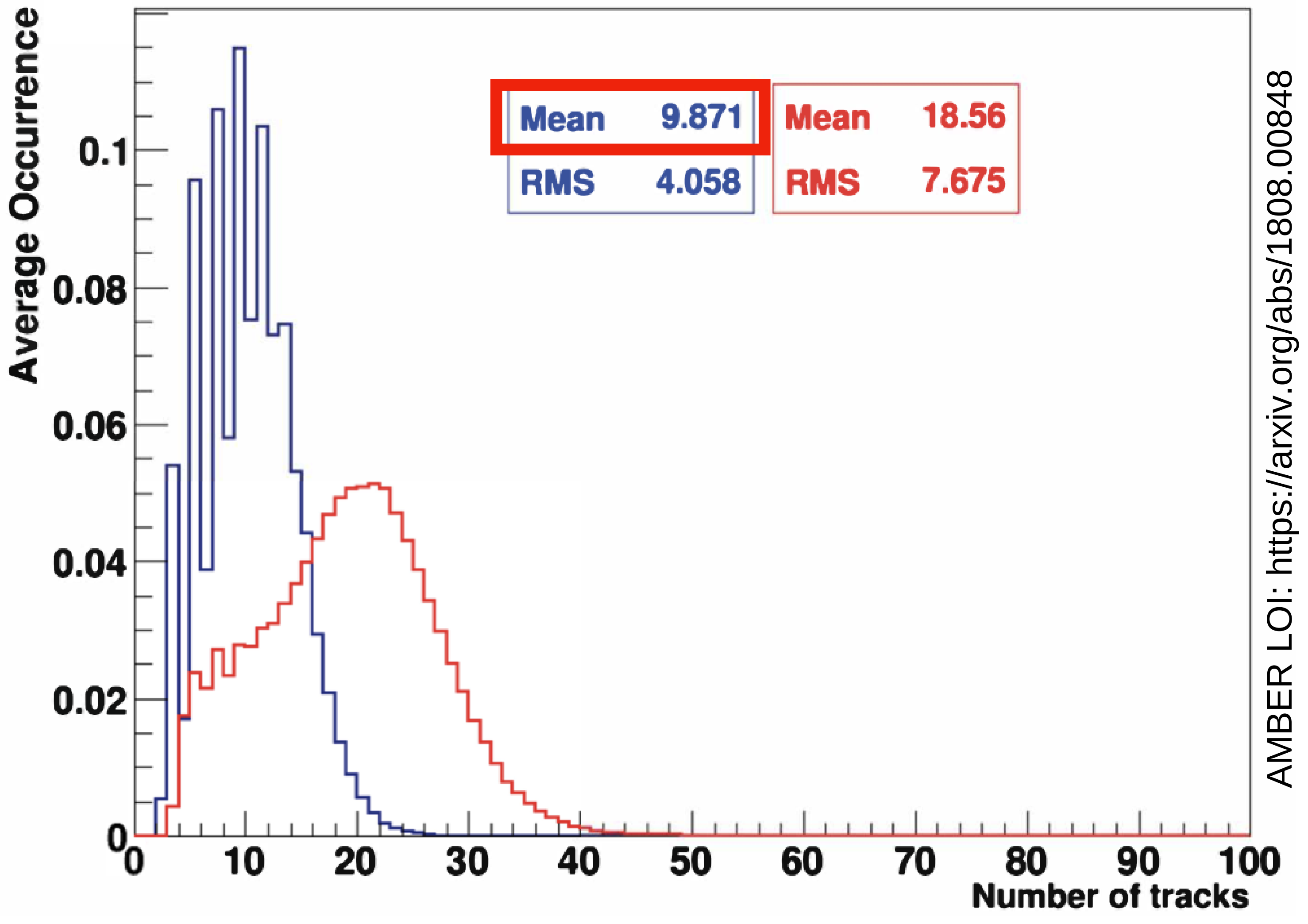
Approved Phase-1:

- Proton-radius measureme muon-proton scattering
- Measurement of antiprotoı sections for dark matter se
- Drell-Yan and charmoniun conventional hadron bean



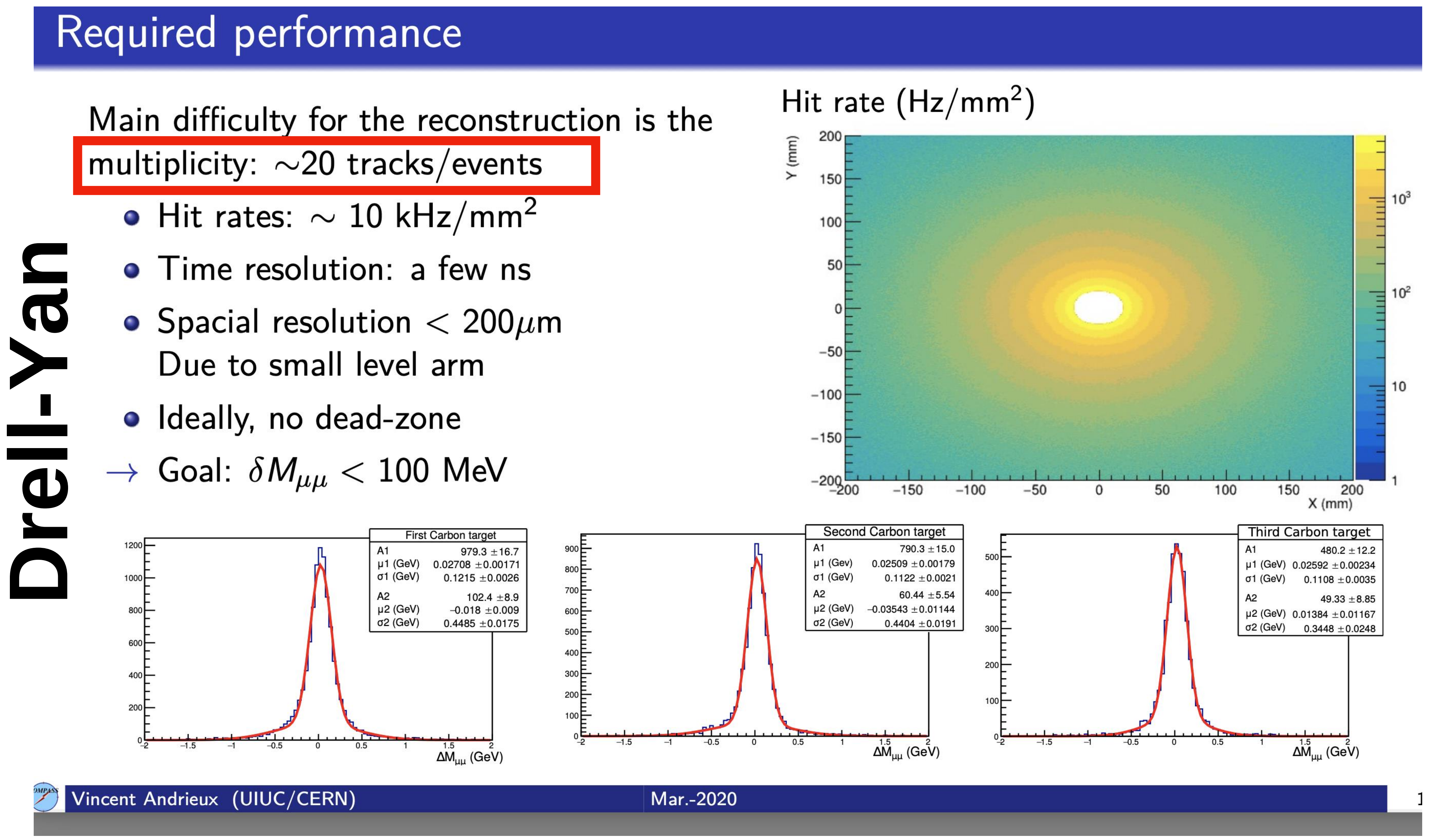

Track multiplicity in p + p interactions at 190 GeV/c: in blue the charged tracks, in red all tracks

Antiproton Production




AMBER LOI: https://arxiv.org/abs/1808.00848

Drell-Yan




https://indico.cern.ch/event/863068/contributions/3759363/attachments/1996202/3330483/Andrieux_DAQ02032020.pdf

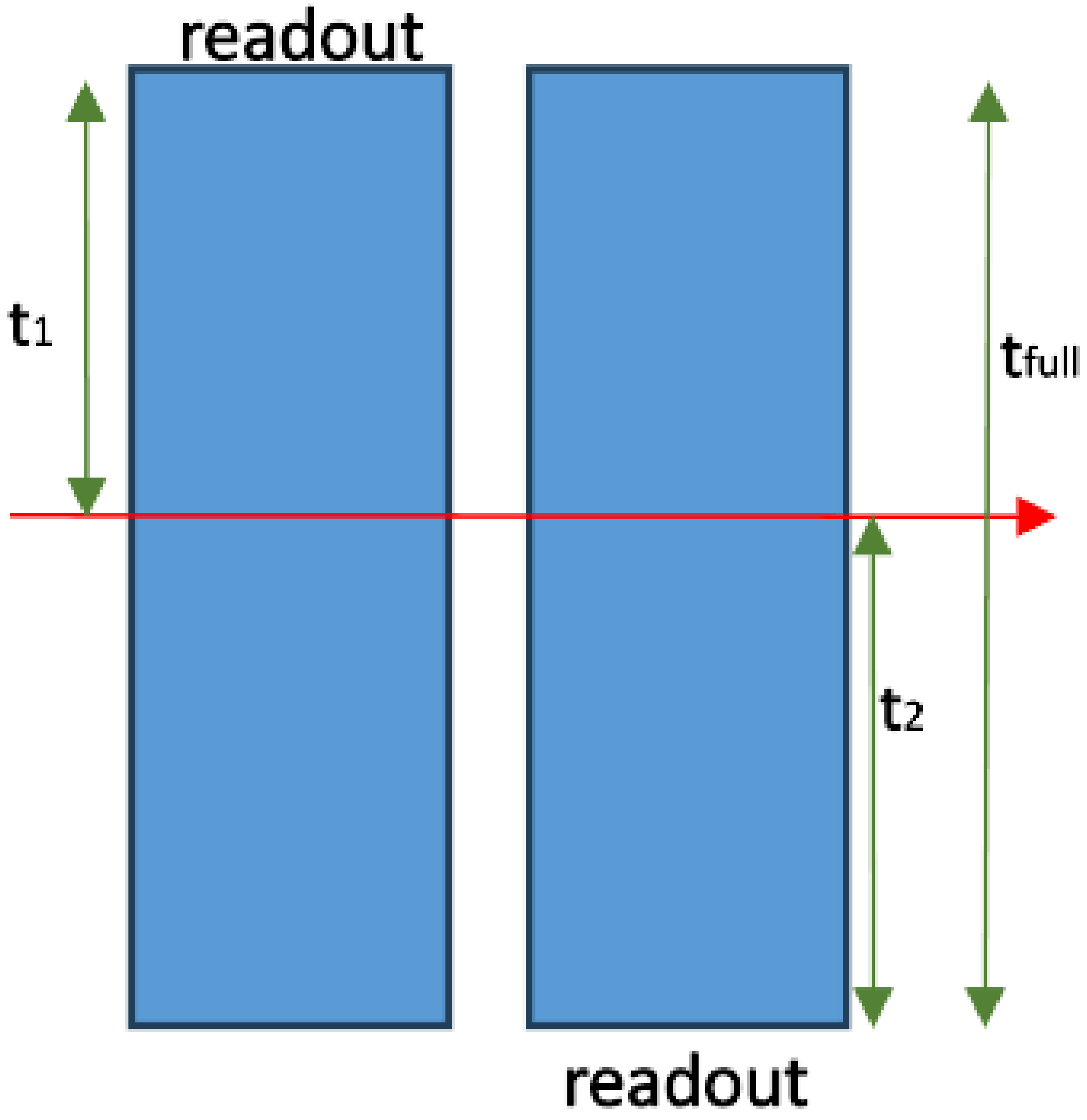
# The Twin GEM-TPC + VMM3a/SRS

Self triggered hits referring to the same absolute zero time $t_0'$

- Synchronised readouts
  -> $t_{1,2}' = t_0' + t_{1,2}$ is valid for all times

- The absolute times $t'$ can be used to get the relative times $t$
  -> Only possible if absolute times correspond to the same event
  -> $t_2' - t_1' = t_0' + t_2 - (t_0' + t_1) = t_2 - t_1$

- With access to the relative time and the full drift time $t_{full}$ it is possible to extract a time corresponding to a y-value (three examples)
  -> $\frac{t_2' - t_1' + t_{full}}{2} = 0 \; with \; t_2 = 0, t_1 = t_{full} \rightarrow y_0$
  -> $\frac{t_2' - t_1' + t_{full}}{2} = t_{full} \; with \; t_1 = 0, t_2 = t_{full} \rightarrow y_1$
  -> $\frac{t_2' - t_1' + t_{full}}{2} = 0.5 t_{full} \; with \; t_1 = t_2 \rightarrow 0.5 y_1$

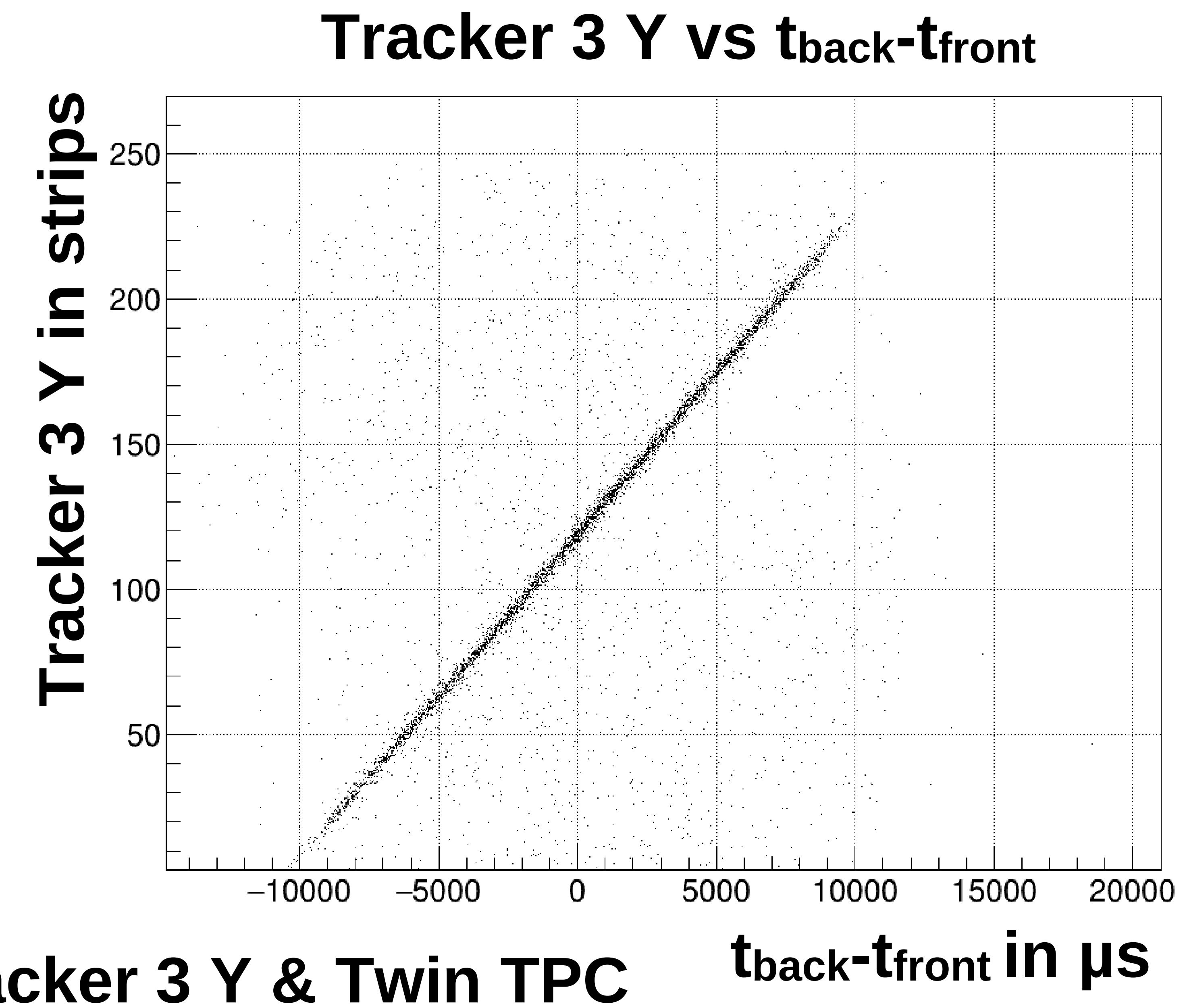


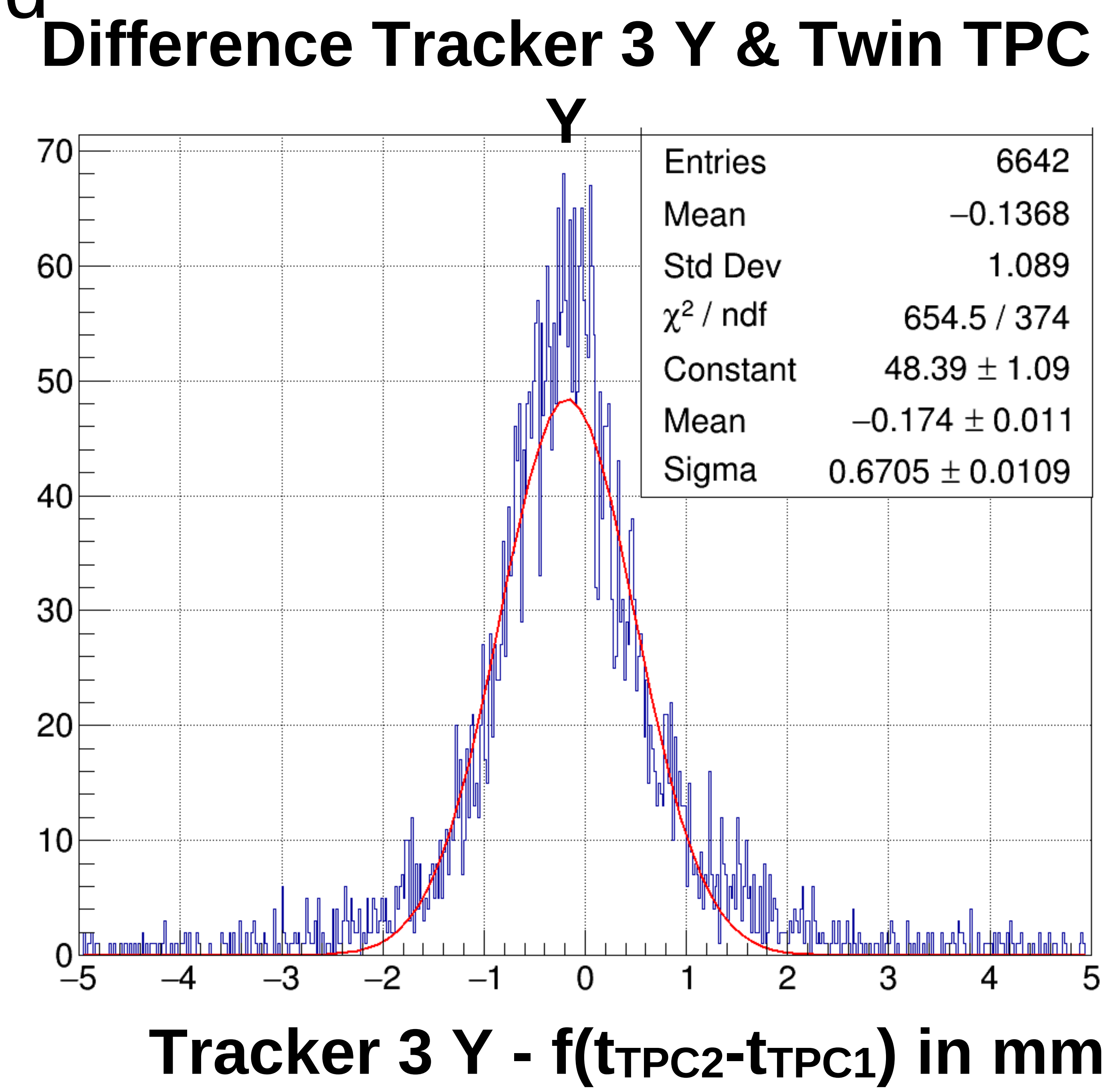
# Removing $t_0$

- A correlation can be checked just using the time difference of the TPCs
  -> $y \propto (t_2' - t_1' + t_{full})/2 \propto t_2' - t_1'$
- Linear fit gives a conversion function $f(t_{TPC2}-t_{TPC1})$
  - y position for Twin TPC can be calculated
- Difference of Tracker 3 Y and Twin GEM-TPC Y can be plotted
  - Sigma can be seen as lower limit for resolution
  (convolution of distributions not resembling only sp. res.)
  - Coordinates can be clearly correlated with a $\sigma \approx 0.67mm$

➡Correlation possible without external $t_0$

➡Twin GEM-TPC could be used as very low Material budget and stand-alone tracking station



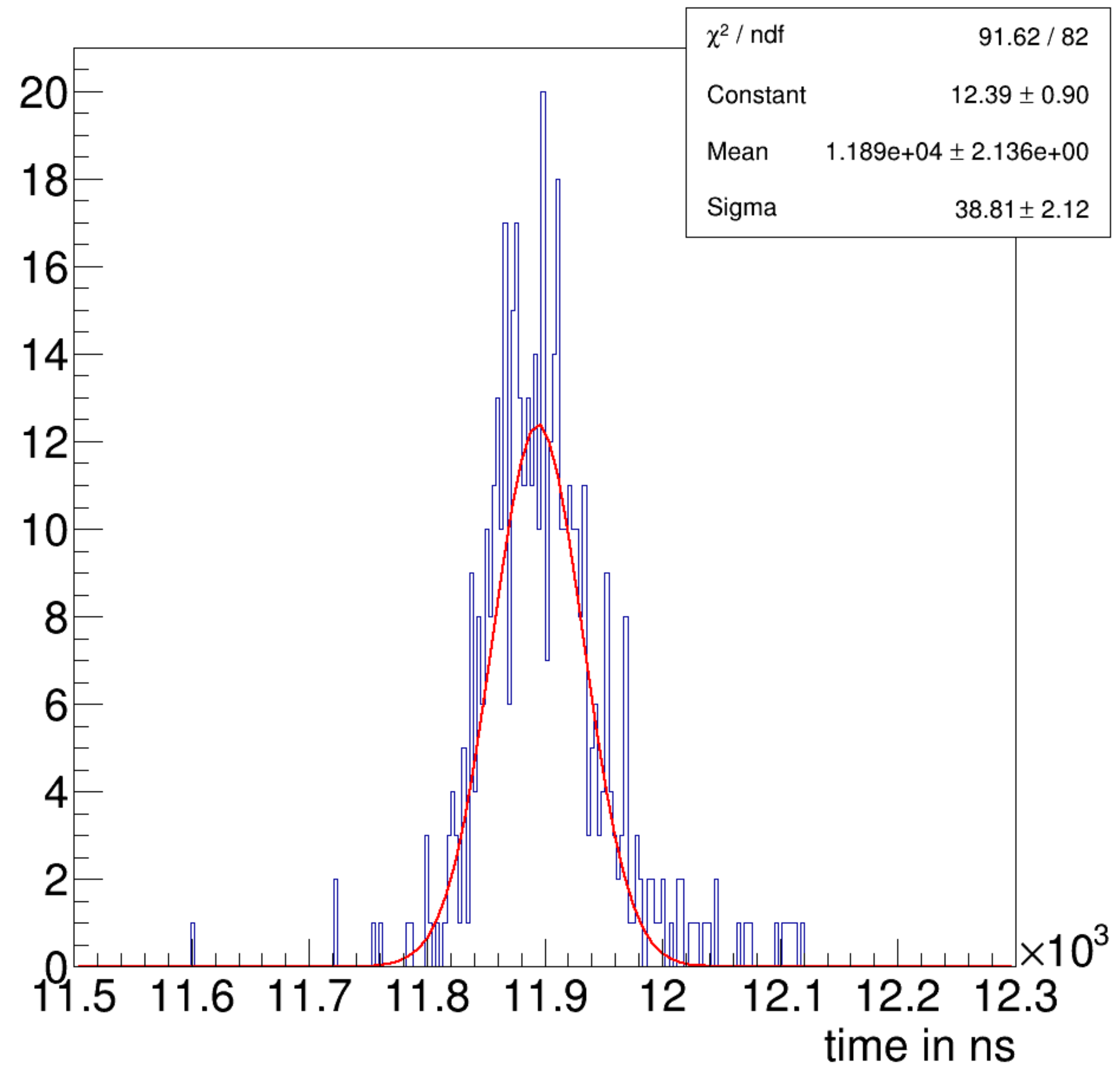
# Twin GEM-TPC: Calculate $t_{full}$ & $t_0$

- Full drift time is either known or can be checked using t0 reference
  -> $t'_{1,2} = t'_0 + t_{1,2}$
  -> $t_{full} = t_1 + t_2 = t'_1 + t'_2 - 2t'_0$

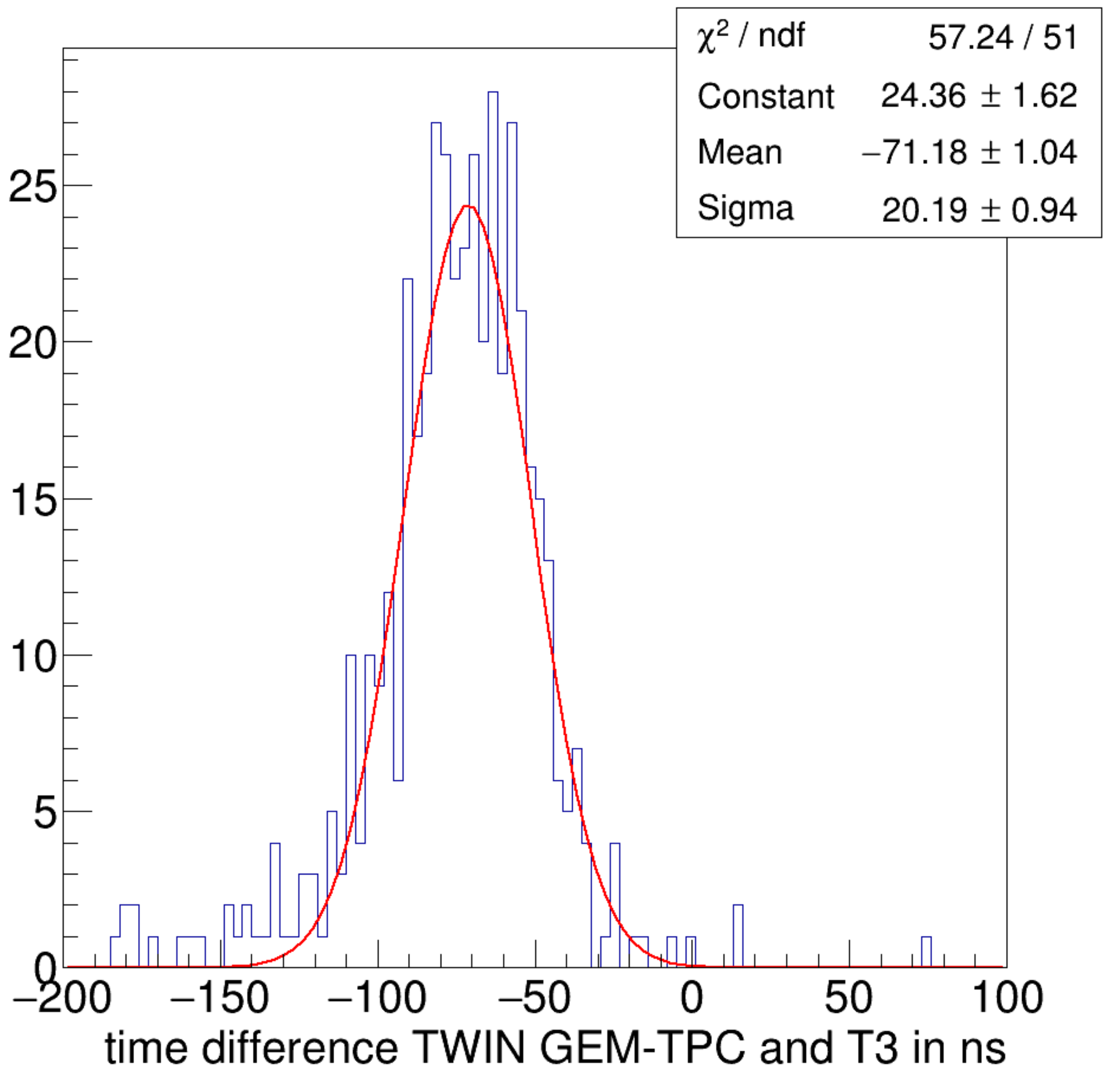
- $t_{full}$ gives distribution with clear peak at 11.85 μs

- Knowing $t_{full}$ t0 can be calculated
  -> $t'_0 = \frac{t'_1 + t'_2 - t_{full}}{2}$

**Measuring full drift time with external t0**

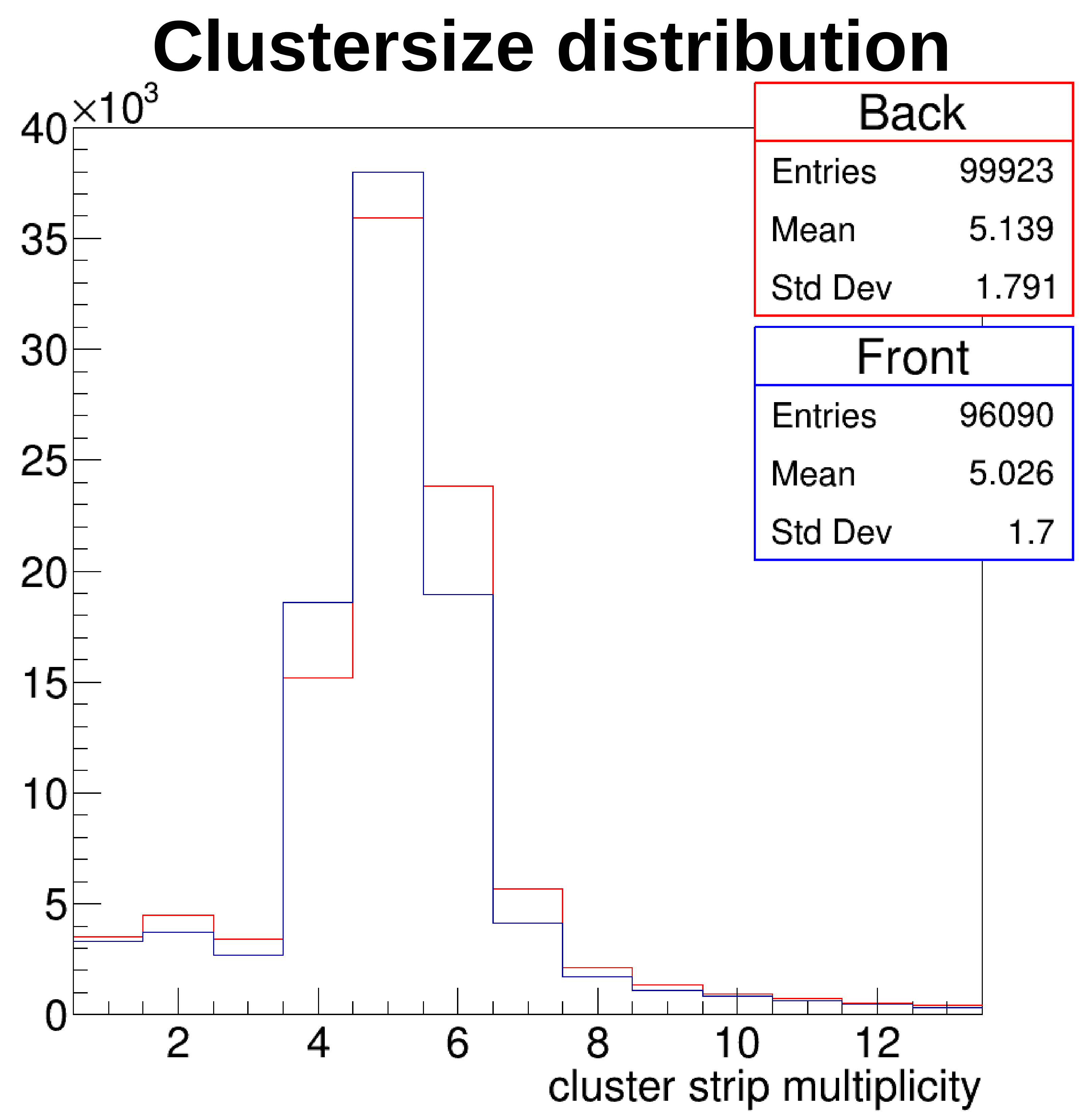


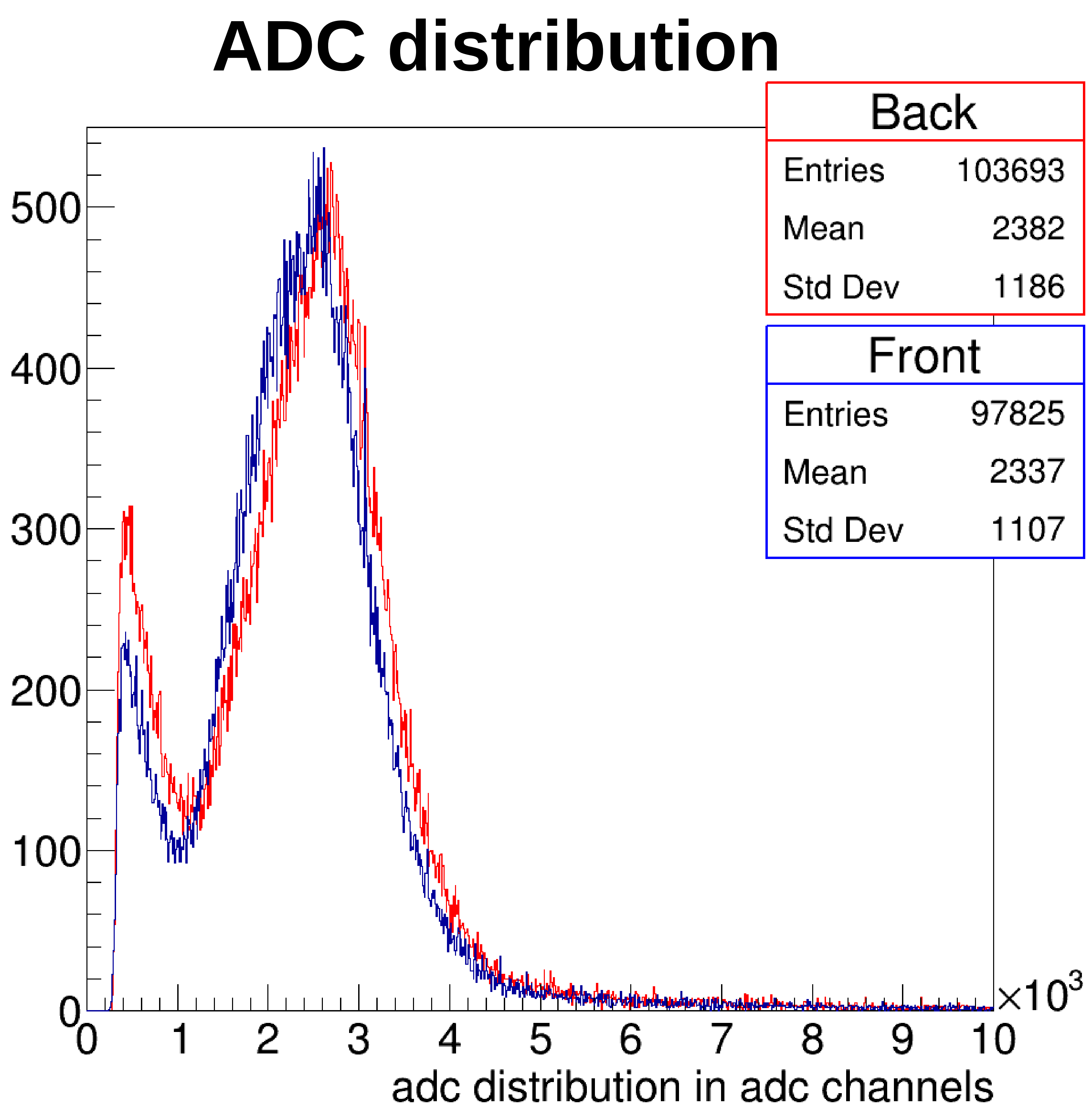

**Extract t0 with known full drift time**

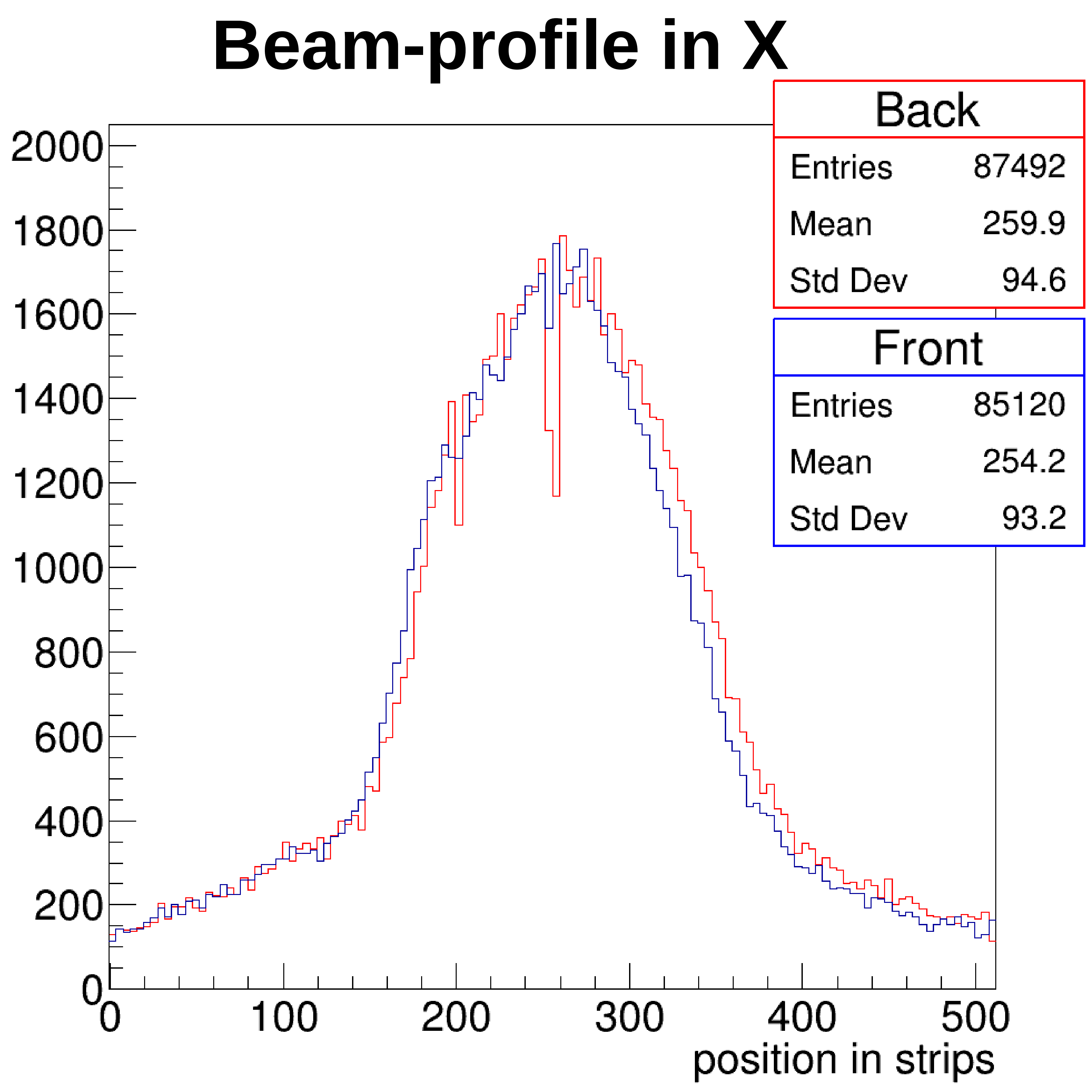


# Detector Response nominal Orientation

150GeV/c Muon Beam – H4 Beamline in EHN2 – RD51 test-beam

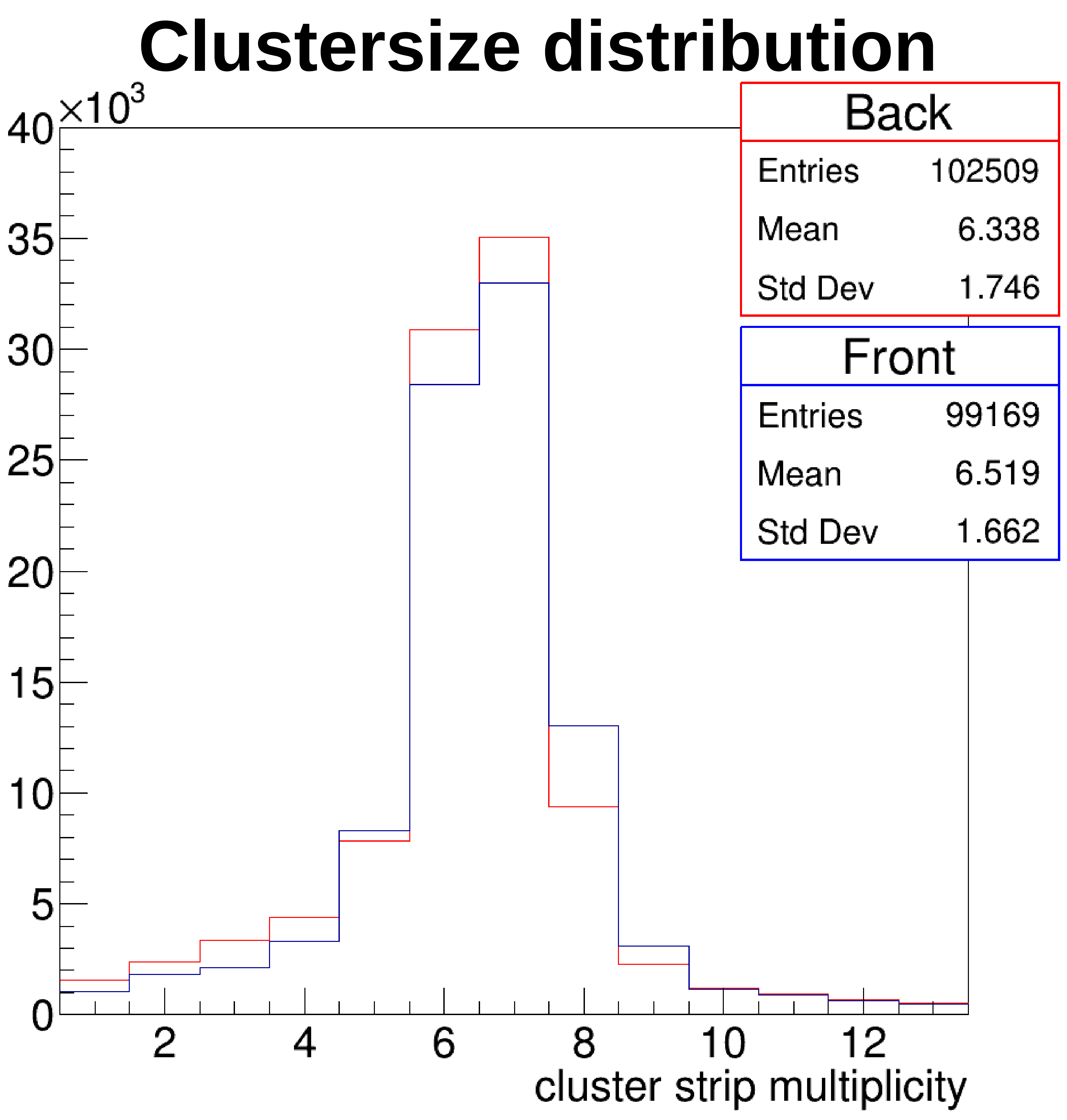


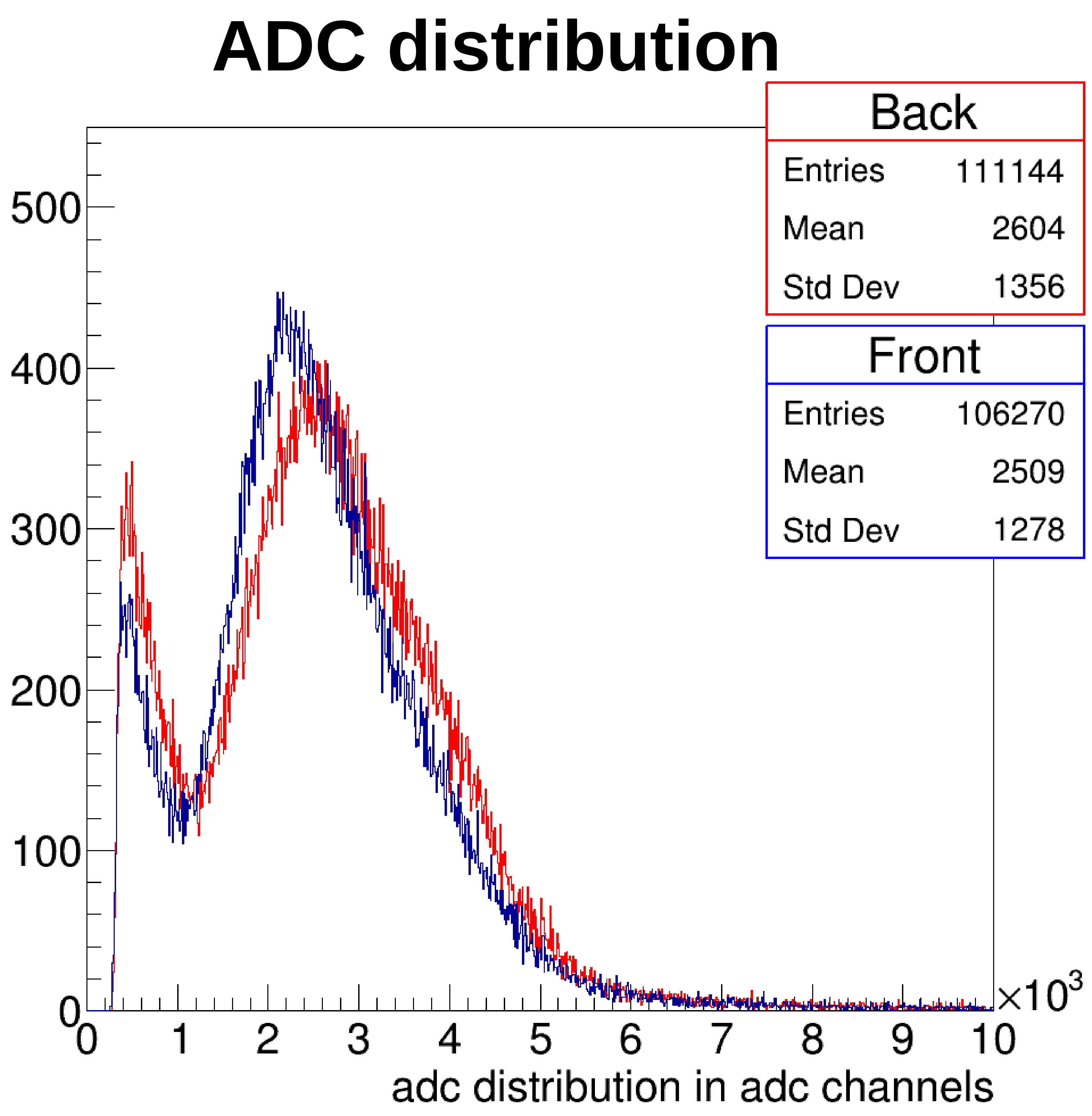



# Detector Response H5V3 Orientation

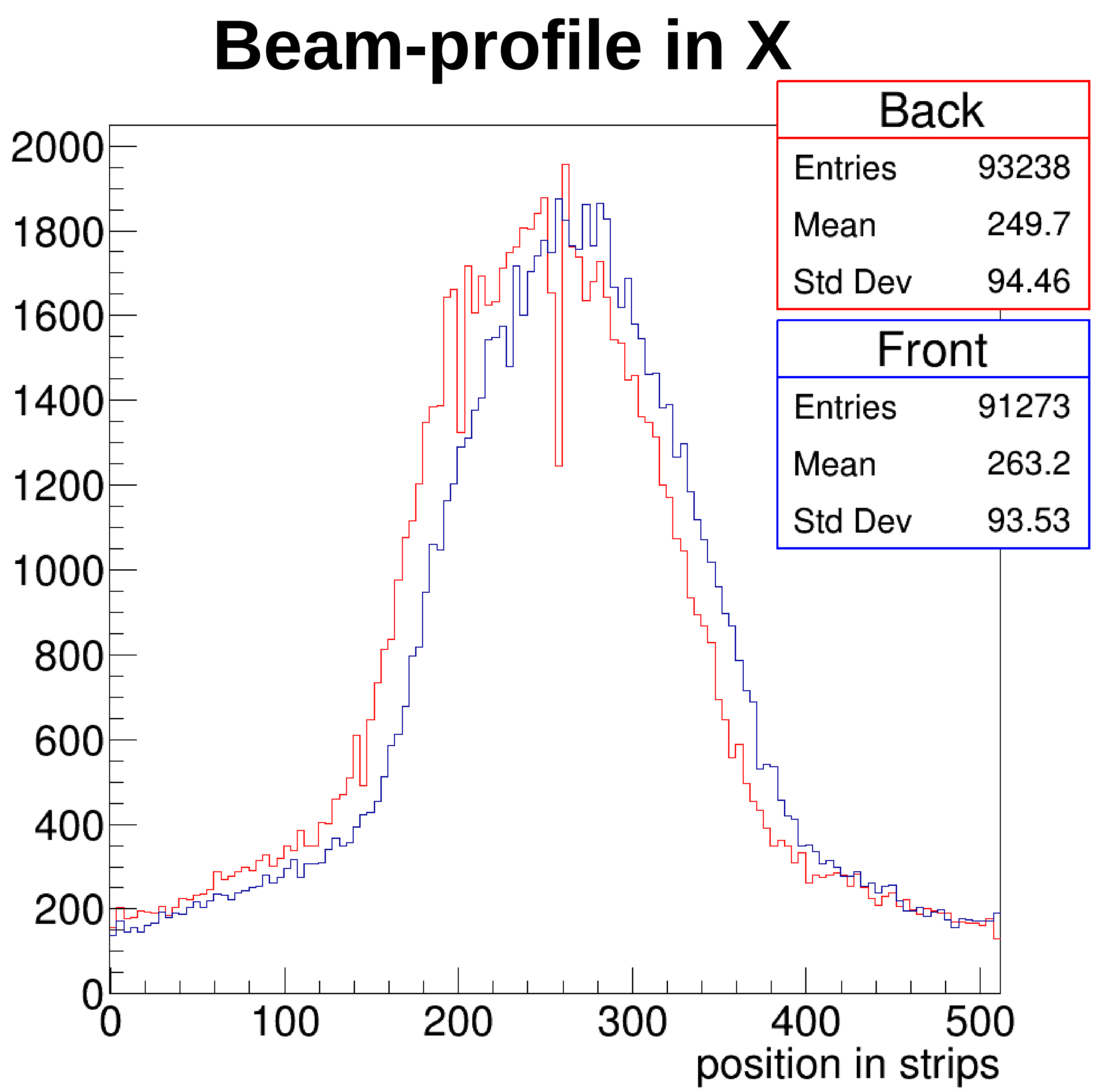
150GeV/c Muon Beam – H4 Beamline in EHN2 – RD51 test-beam




**Shift to higher strip multiplicity**

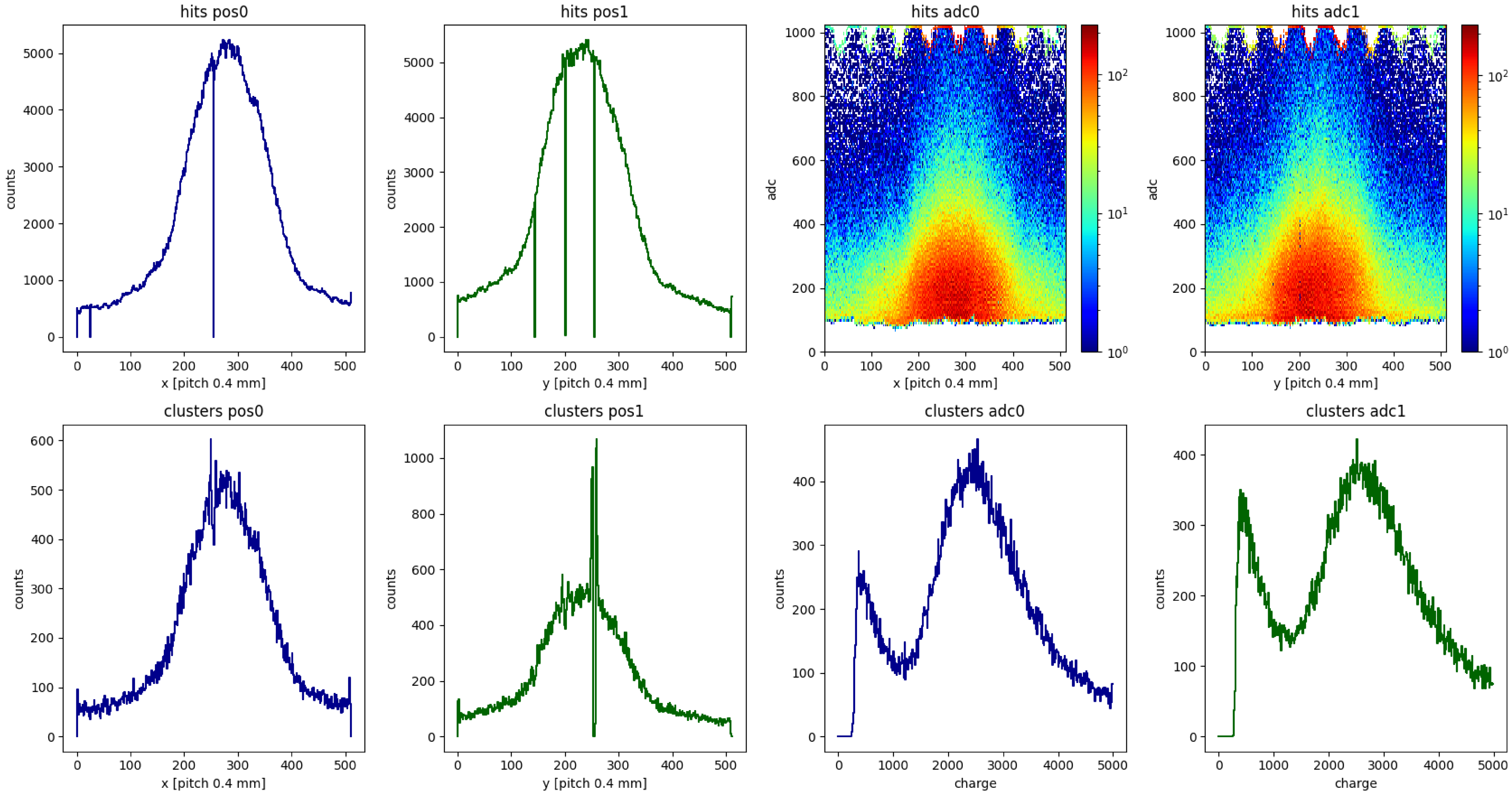



**Higher mean and broader**




**Shift in relative position between Front and Back**

# Twin TPC

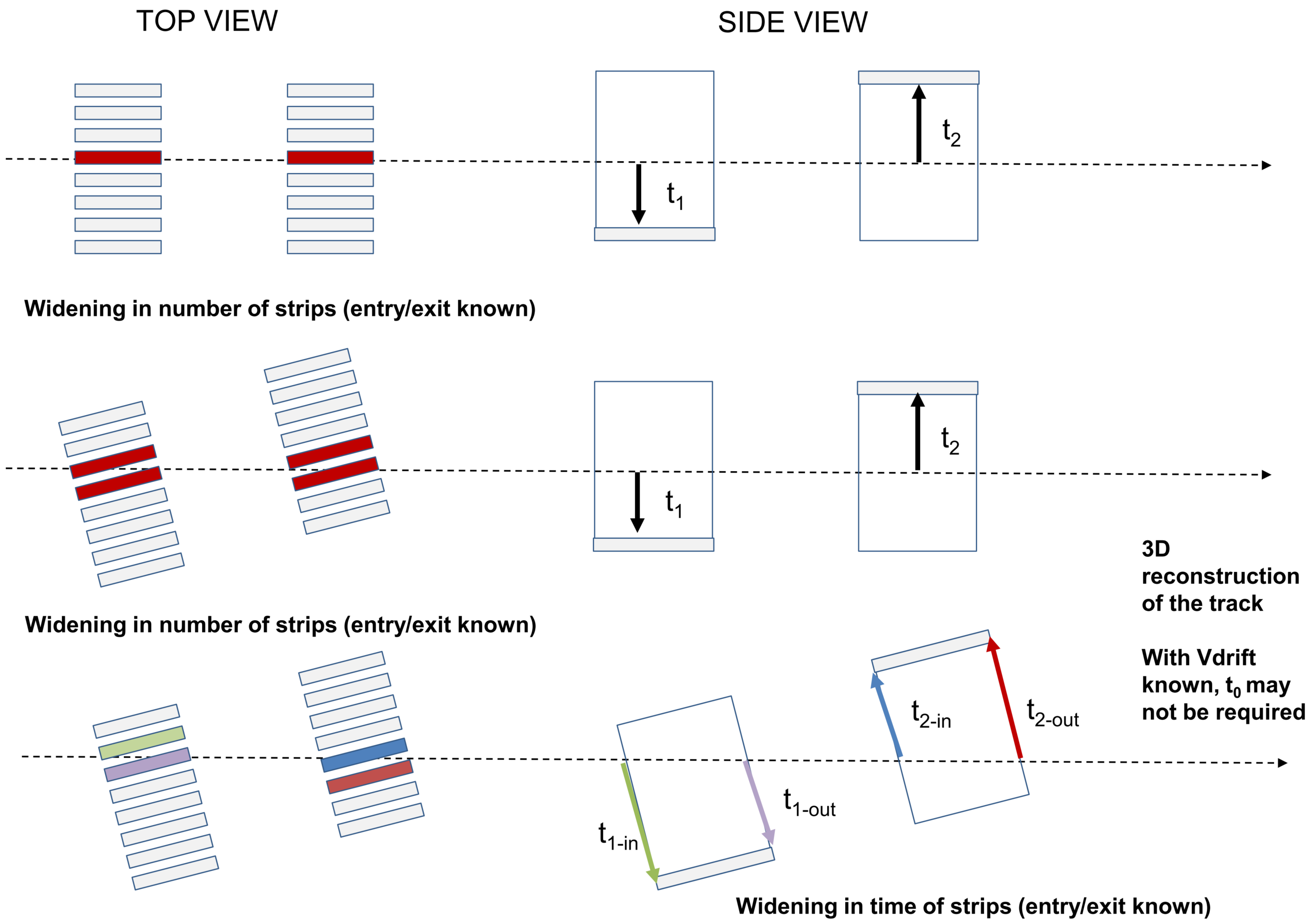

hits pos0
hits pos1
hits adc0
hits adc1
clusters pos0
clusters pos1
clusters adc0
clusters adc1
counts
adc
x [pitch 0.4 mm]
y [pitch 0.4 mm]
charge

# Tracking within TPC

**Mean Tracking applicable**

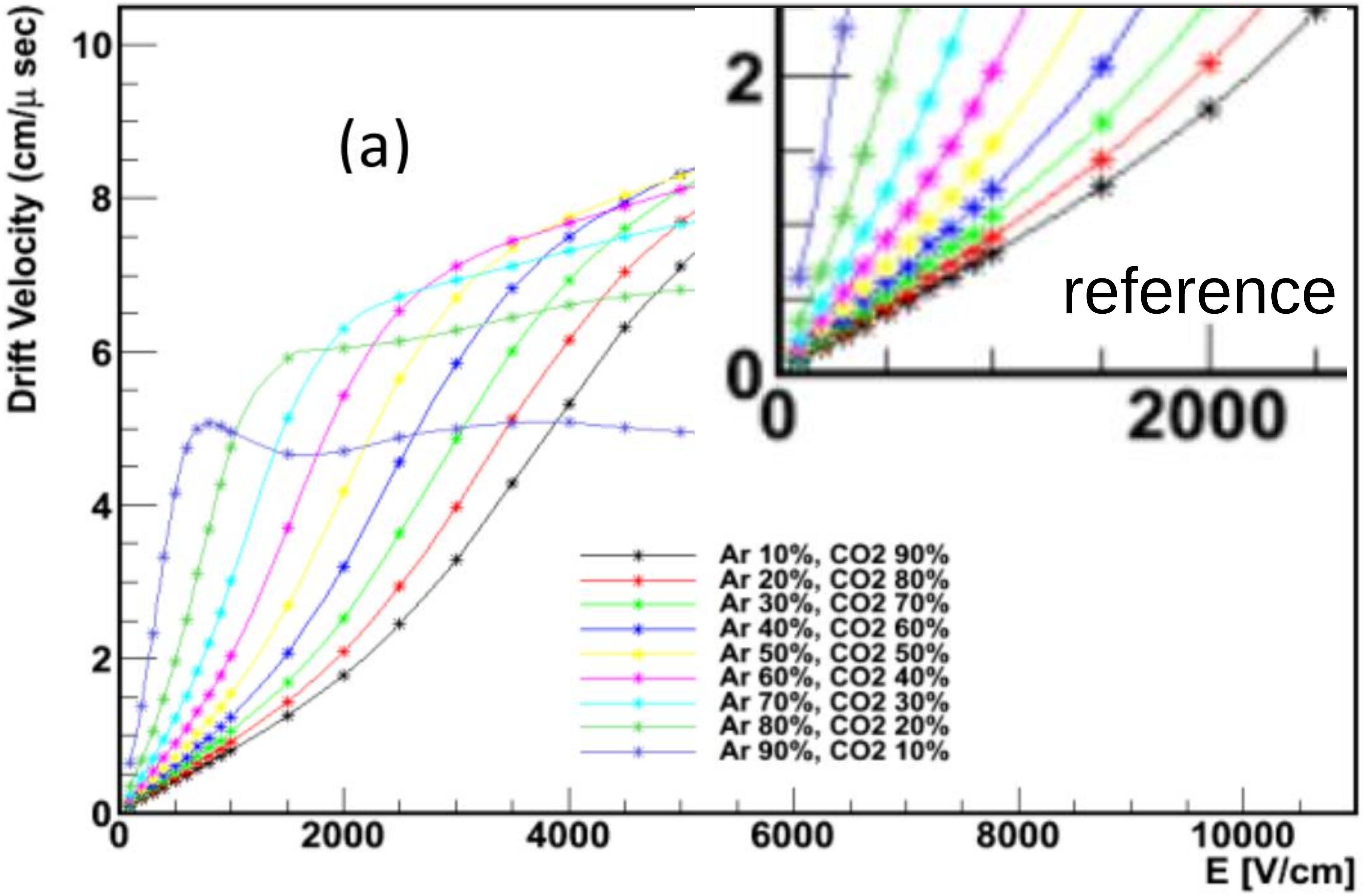
**Access to horizontal angle with dependence on strips**

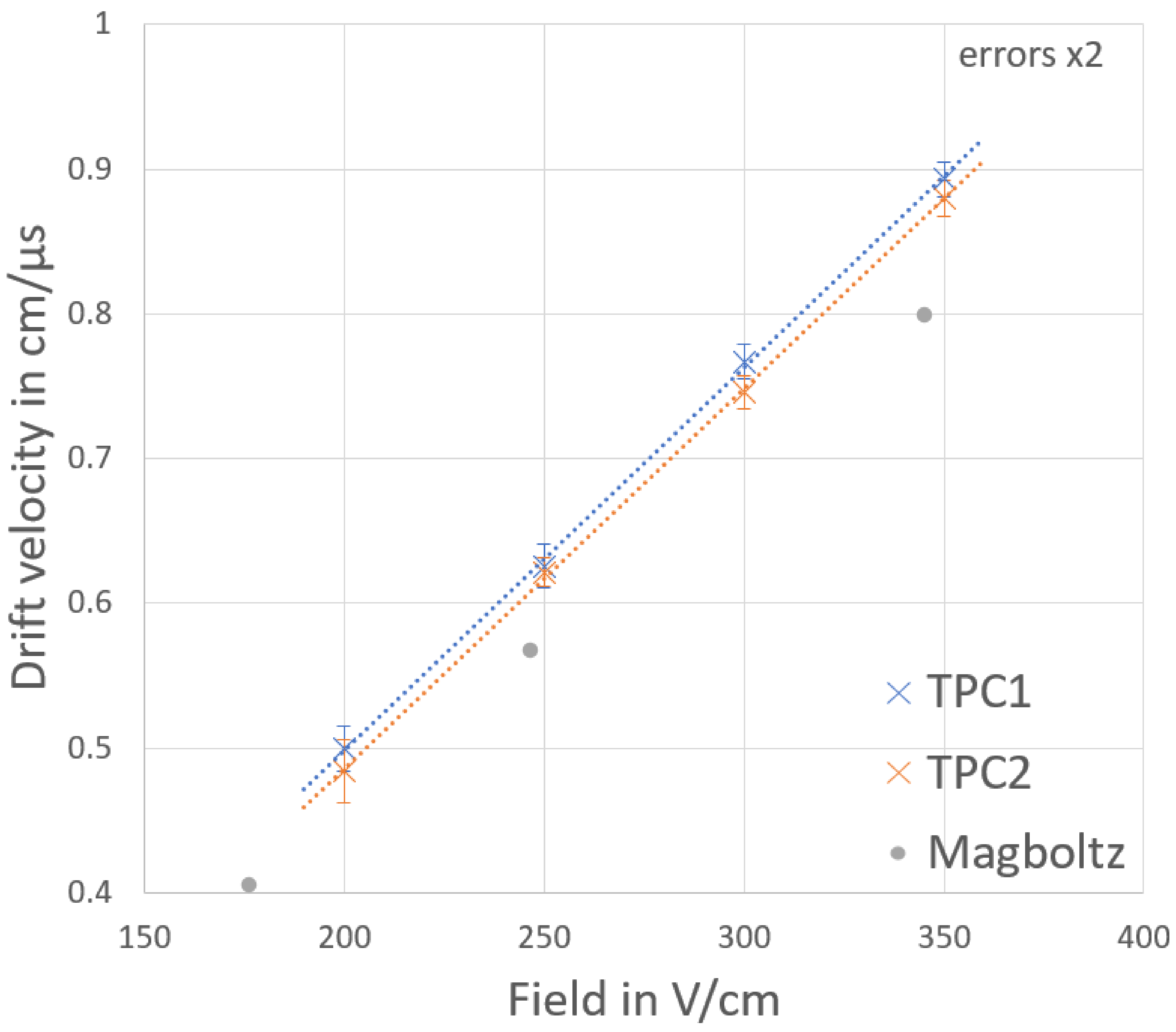
**Access to vertical angle with dependence on time**



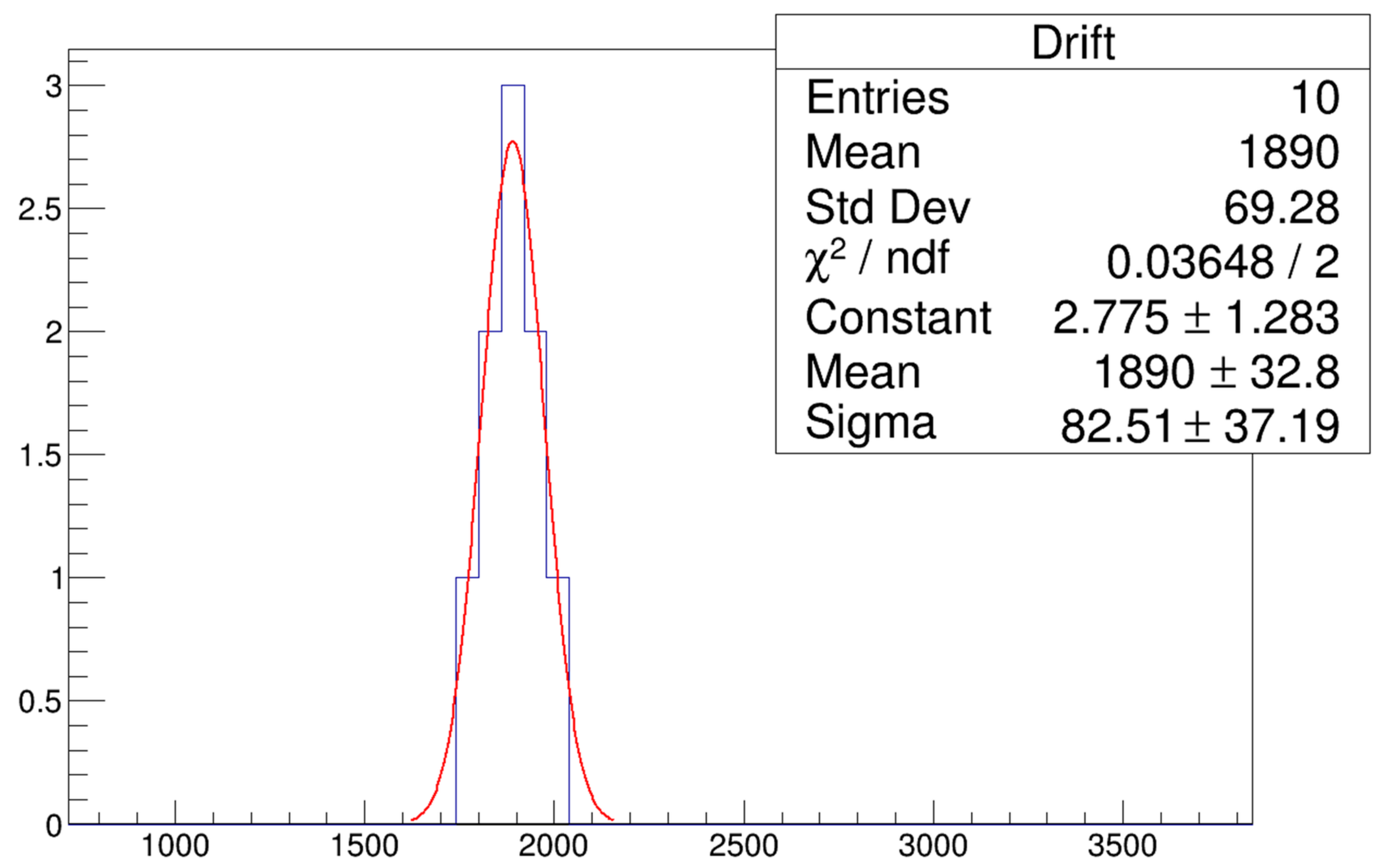
# Calculating Drift Velocity

https://arxiv.org/ftp/arxiv/papers/1110/1110.6761.pdf




Example plotted time

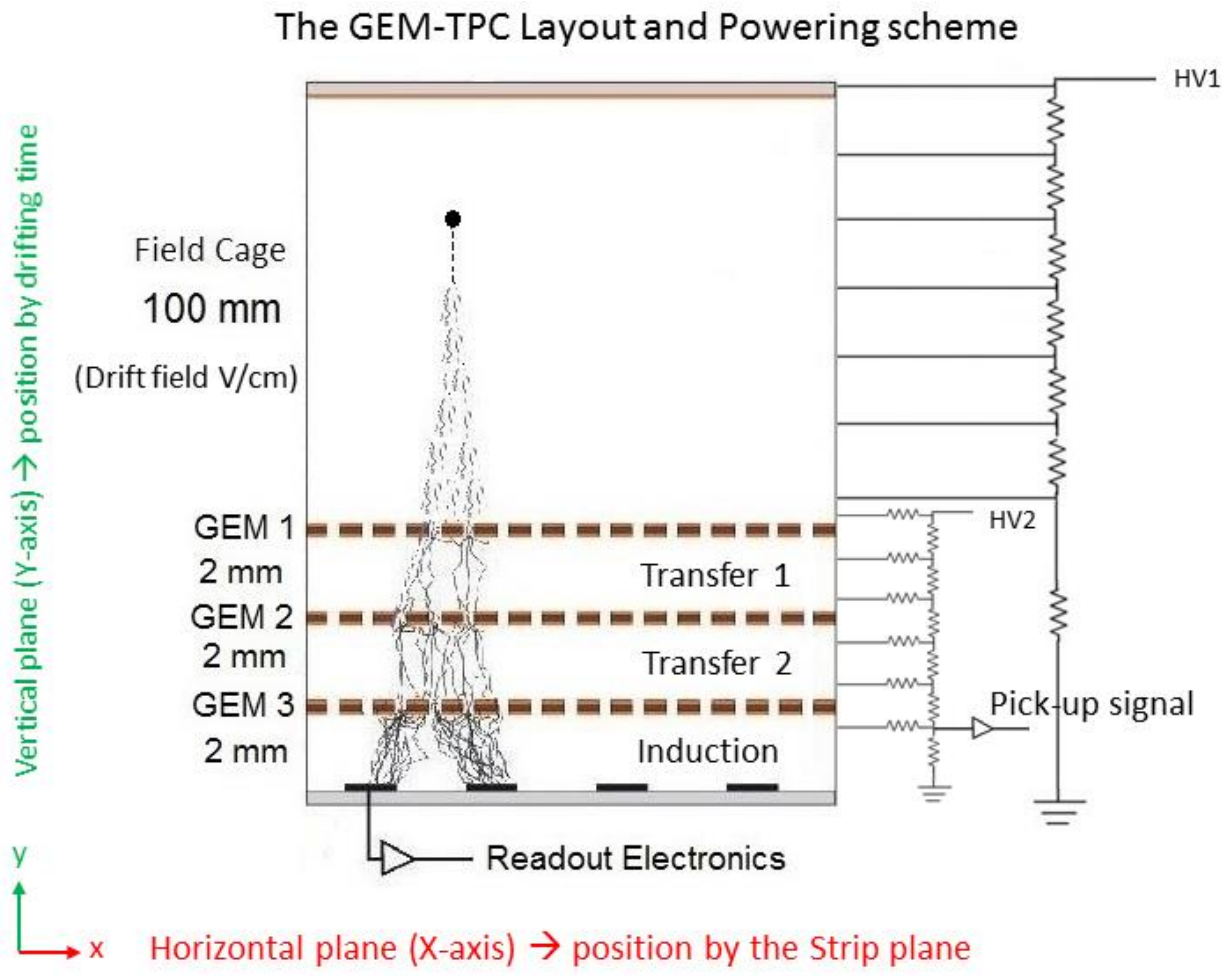



- Time calculated for different positions (cut on position in tracking detector) -> $t'_{1,2} - t'_0$ →time distribution for specific position
- Taking to different positions 2 times are obtained and the velocity can be calculated

# Twin TPC

F. Garcia et al.: https://doi.org/10.1016/j.nima.2017.11.088

- Gas type: ArCO2 (70/30)
- Flow: 5 l/h
- Two HV channels per GEM-TPC (check for the run in the logbook) --> HV1 = Cathode, Voltage is high ~6 kV, current low ~100uA. HV2= GEM stack (Triple GEM), Voltage is moderate ~3 kV, current is high ~660 uA
- Four VMM3a hybrids per GEM-TPC plus one hybrid for T0
- Bottom of GEM-TPC readout by custom made preamplifiers; one per GEM-TPC
- Total drift time: 12 μs




Courtesy of F. Garcia