Development of the straw readout electronics concept

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SPD Physics and MC meeting #31, 22.03.2023

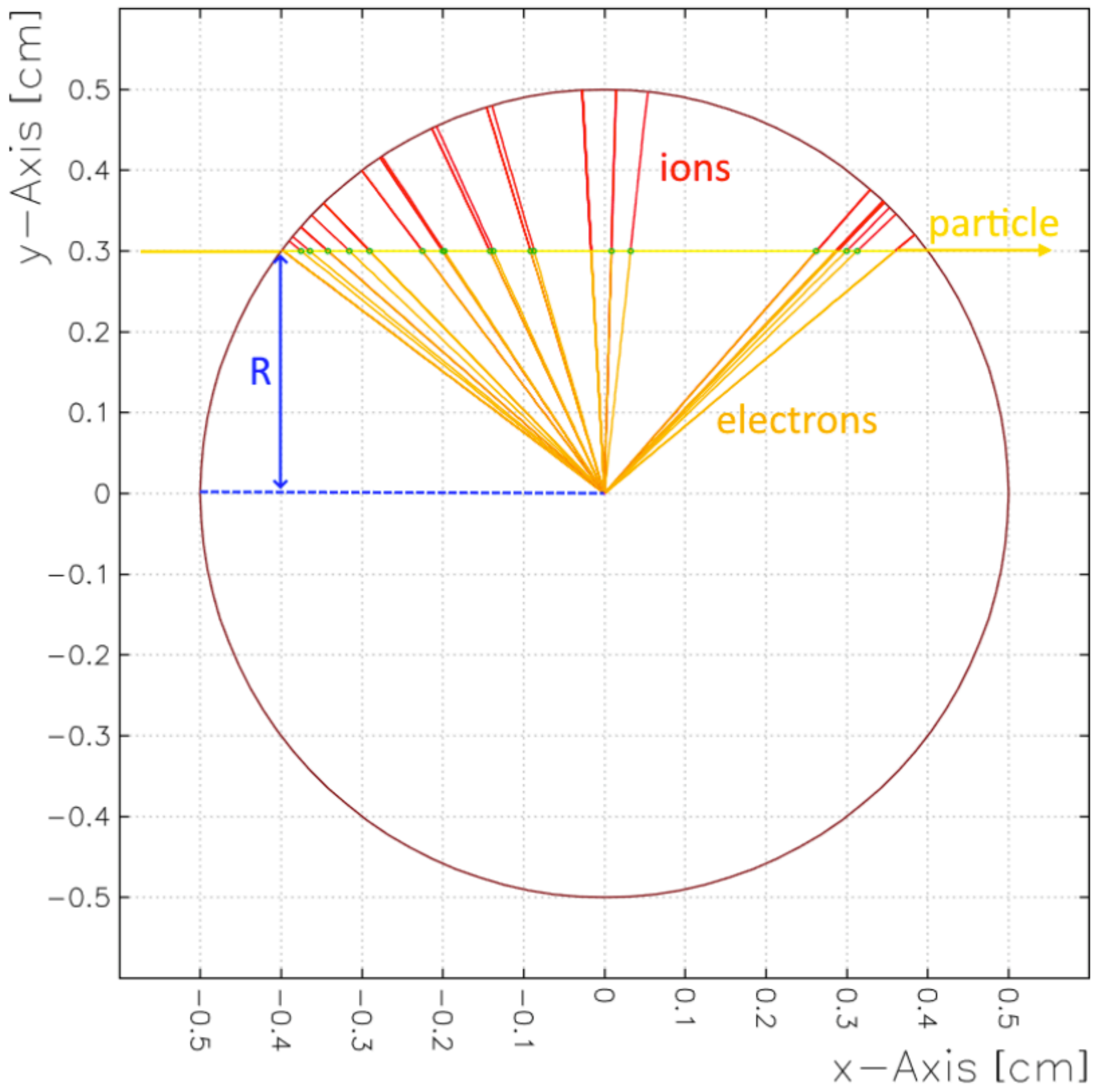
Outline

- Straw tubes
  - Main principles of operation
  - Realistic simulation
  - Readout electronics
- Testbeam measurements
- Summary

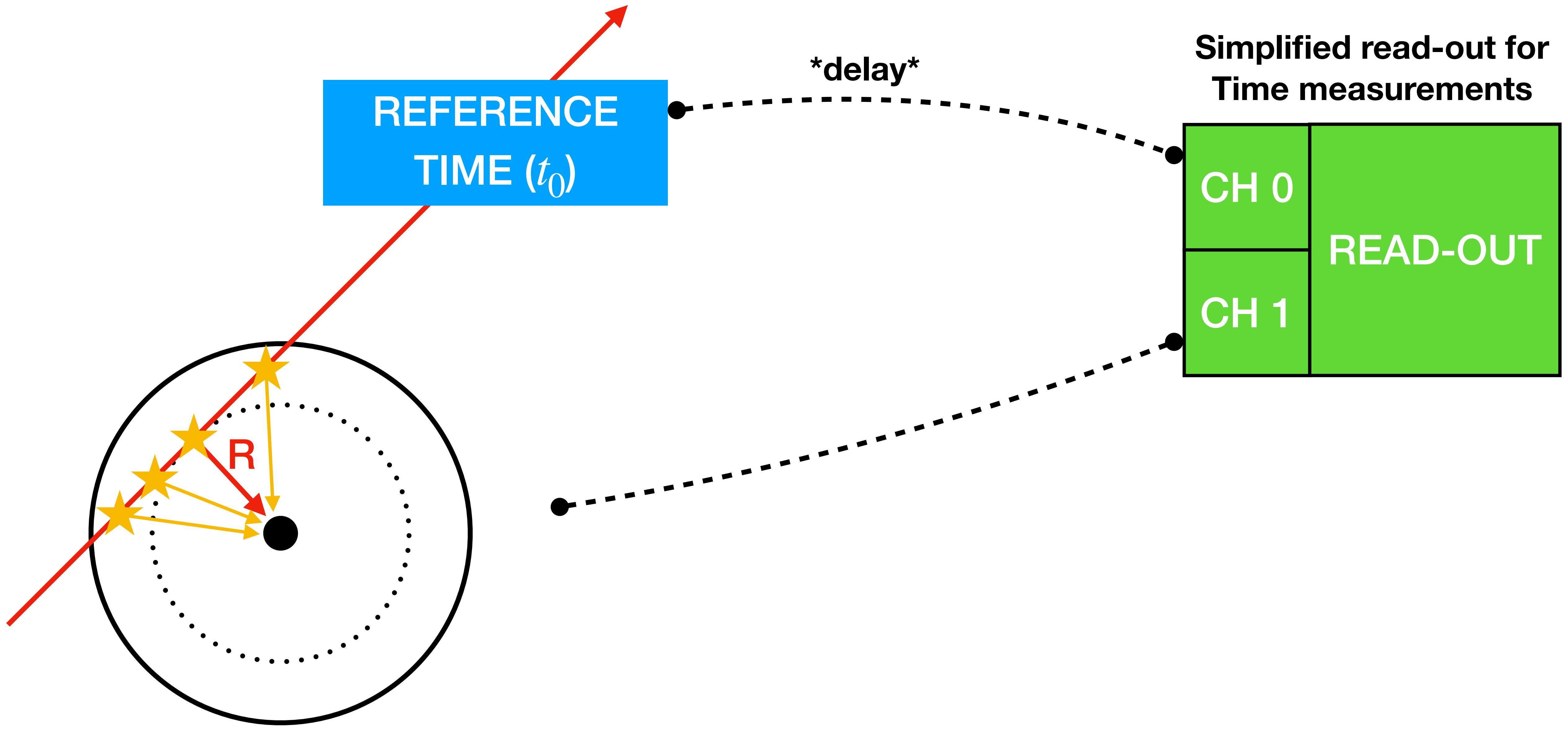
Straw Tubes

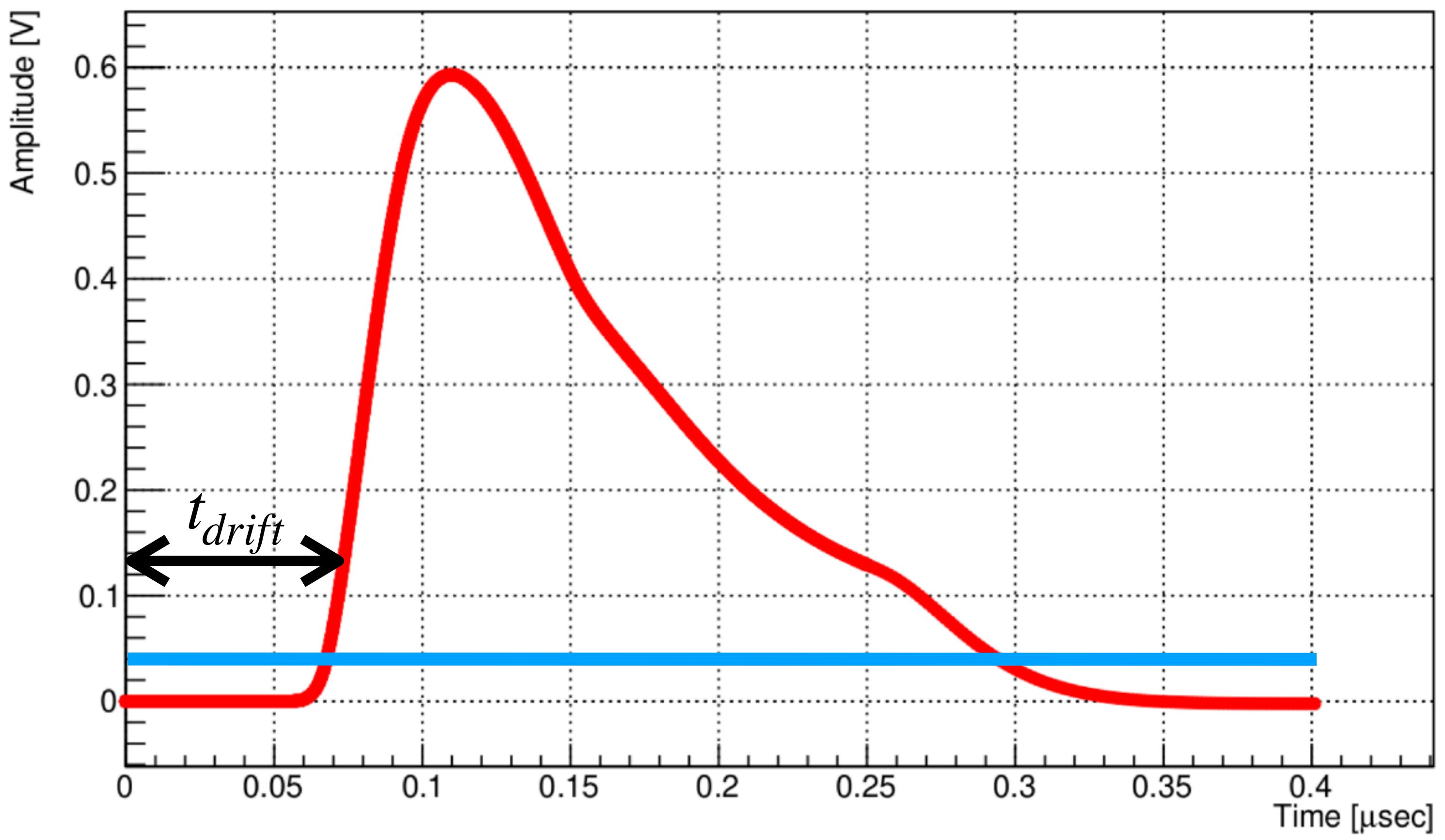
Straws are gas-filled cylindrical tubes with a conductive inner layer as cathode and an anode wire stretched along the cylinder axis.

Charged particles traversing a straw ionise the gas. The electrons drift towards the anode wire. Charge amplification occurs in the high electric field near the anode. The signal is further amplified, shaped and discriminated by read-out electronics.

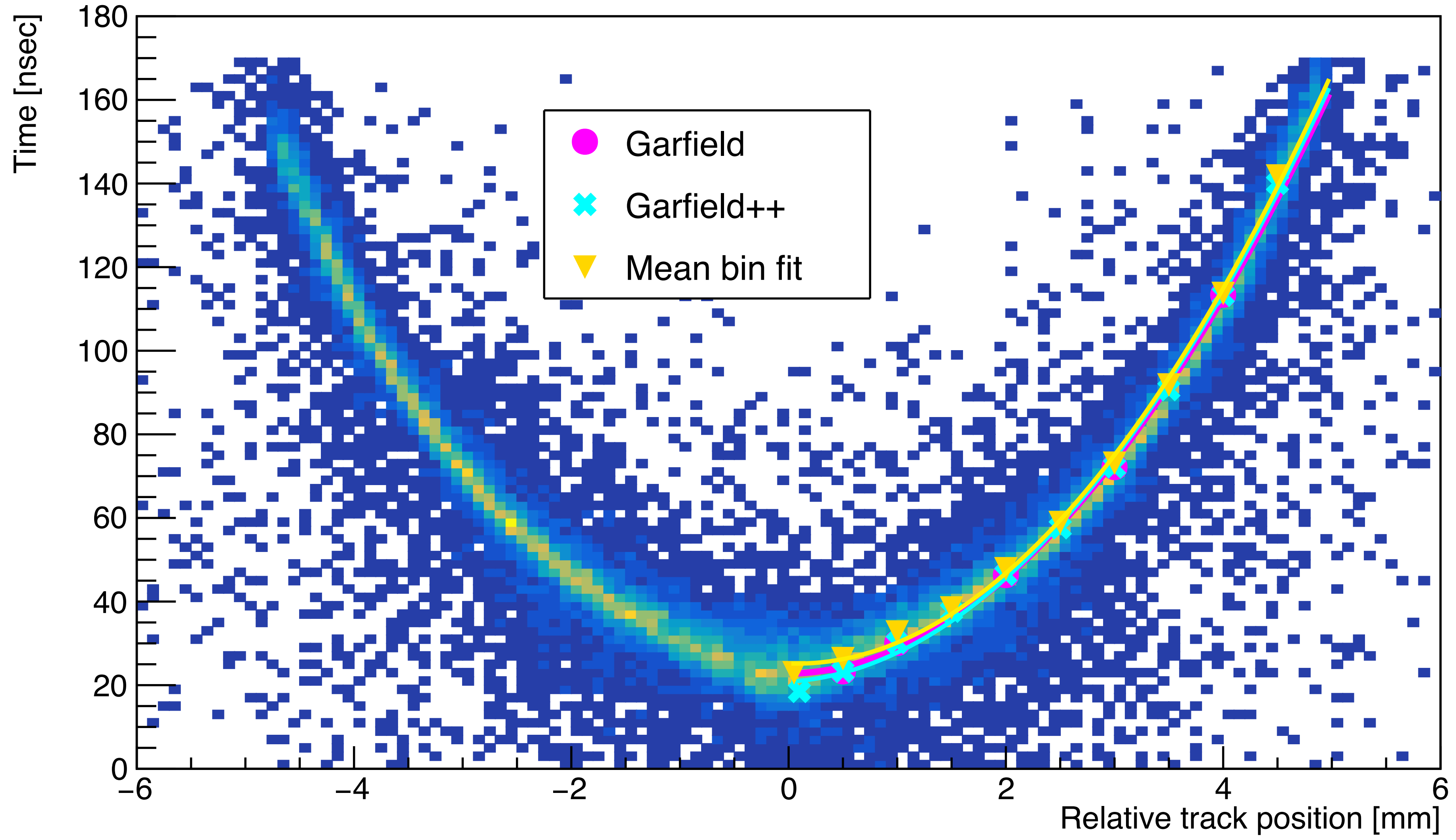


Straw Tubes





- The drift time t_{drift} is measured as the difference between time t_0 when an ionising particle crossed the straw and the time when the induced straw signal exceeds a given threshold.
- Drift time of first (or second) closest to anode electrons represents quite well the distance between the track of the ionising particle R and anode wire
- The distance between the track and anode wire is obtained from a measured or simulated $R(t_{drift})$ dependence.

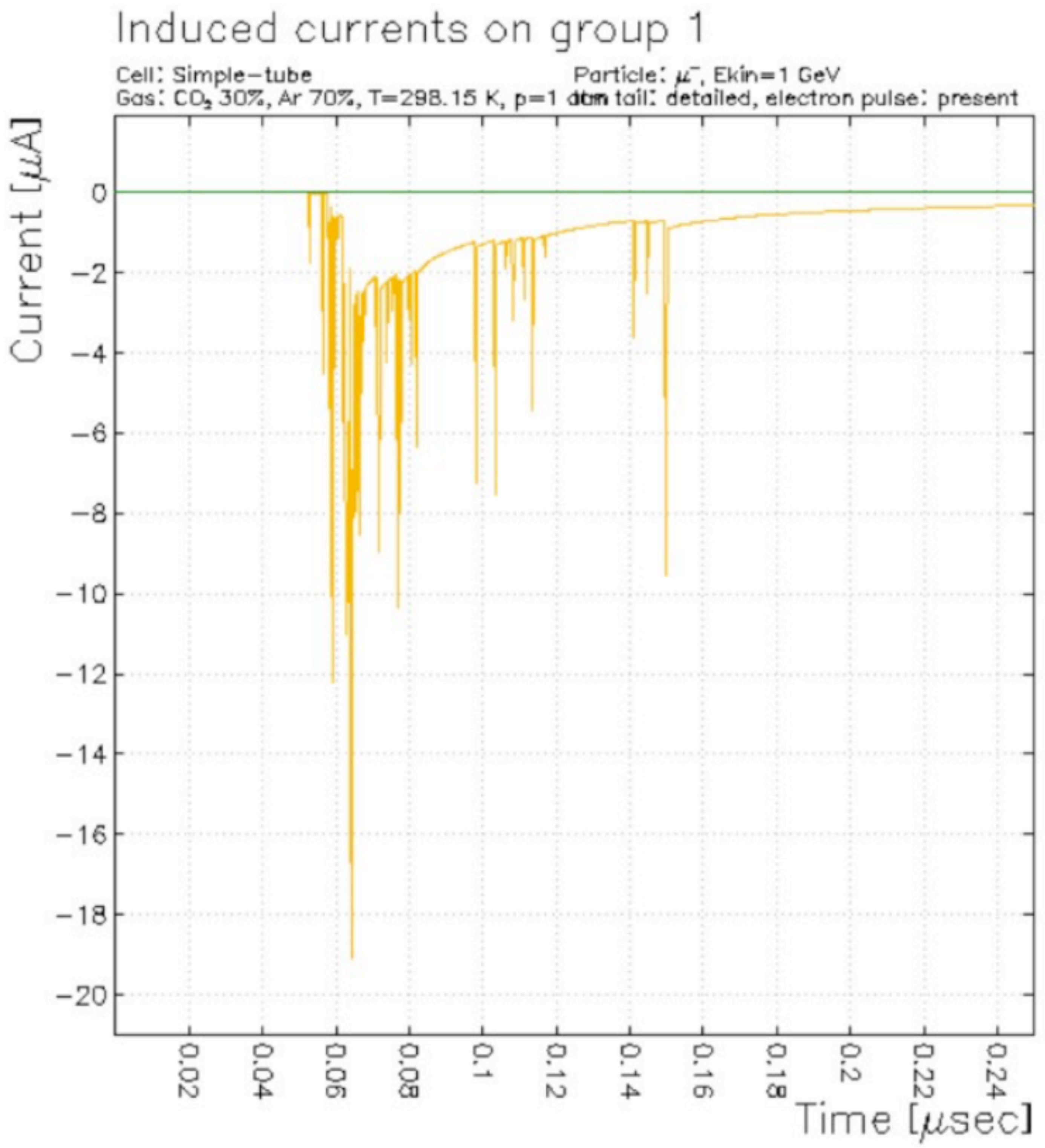


Example of the calibration $t_{drift}(R)$ dependence measured for an NA62 straw compared to *GARFIELD* simulation of the signal arrival time for first primary ionisation cluster.

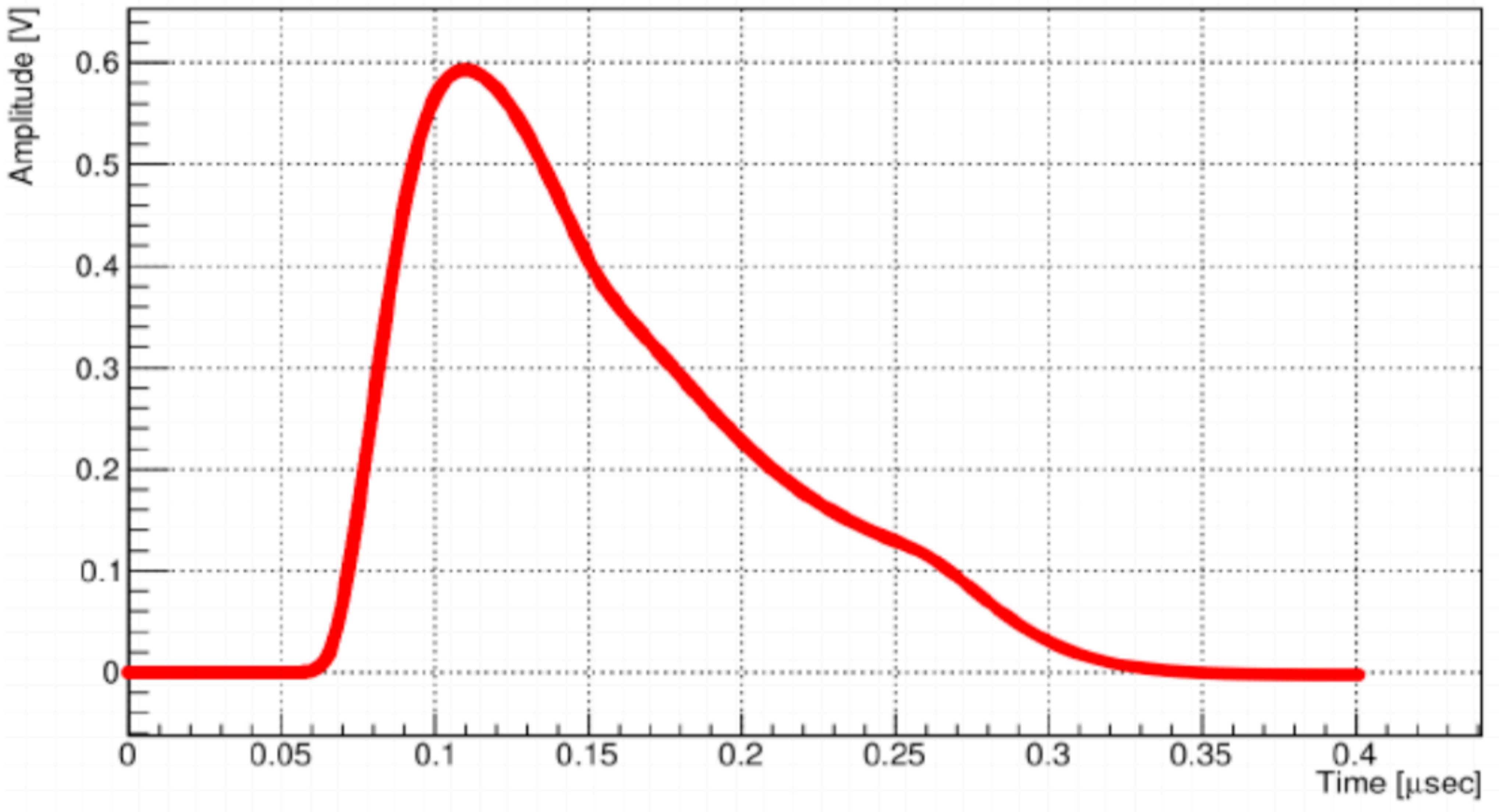
GARFIELD + LTSpice allows to predict straw response for a given readout model.

Straw signal simulation

A combination of *GARFIELD* simulation of a straw tube response interfaced to the *LTSpice* electronics simulation package allows efficient optimisation of the signal circuit path and **VMM3**(a)/**TIGER** operation mode, and supports performance studies for Straw Trackers operated in the magnetic field and with different gas mixtures.



GARFIELD simulated signal
from straw tube



LTSpice amplifier & shaper response
to the signal provided by *GARFIELD*

Straw readout: TIGER vs VMM3

Multifunctional Application Specific Integrated Circuit (ASIC)

VMM3

- widely used as readout of micro-pattern gas detectors
- was a base for the production *VMM3a* version for the ATLAS New Small Wheel readout
- flexible settings of analogue input circuitry
- time measurements (nominally 8-bit TDC)
  - time-at-threshold (T@T)
  - time-at-peak (T@P)

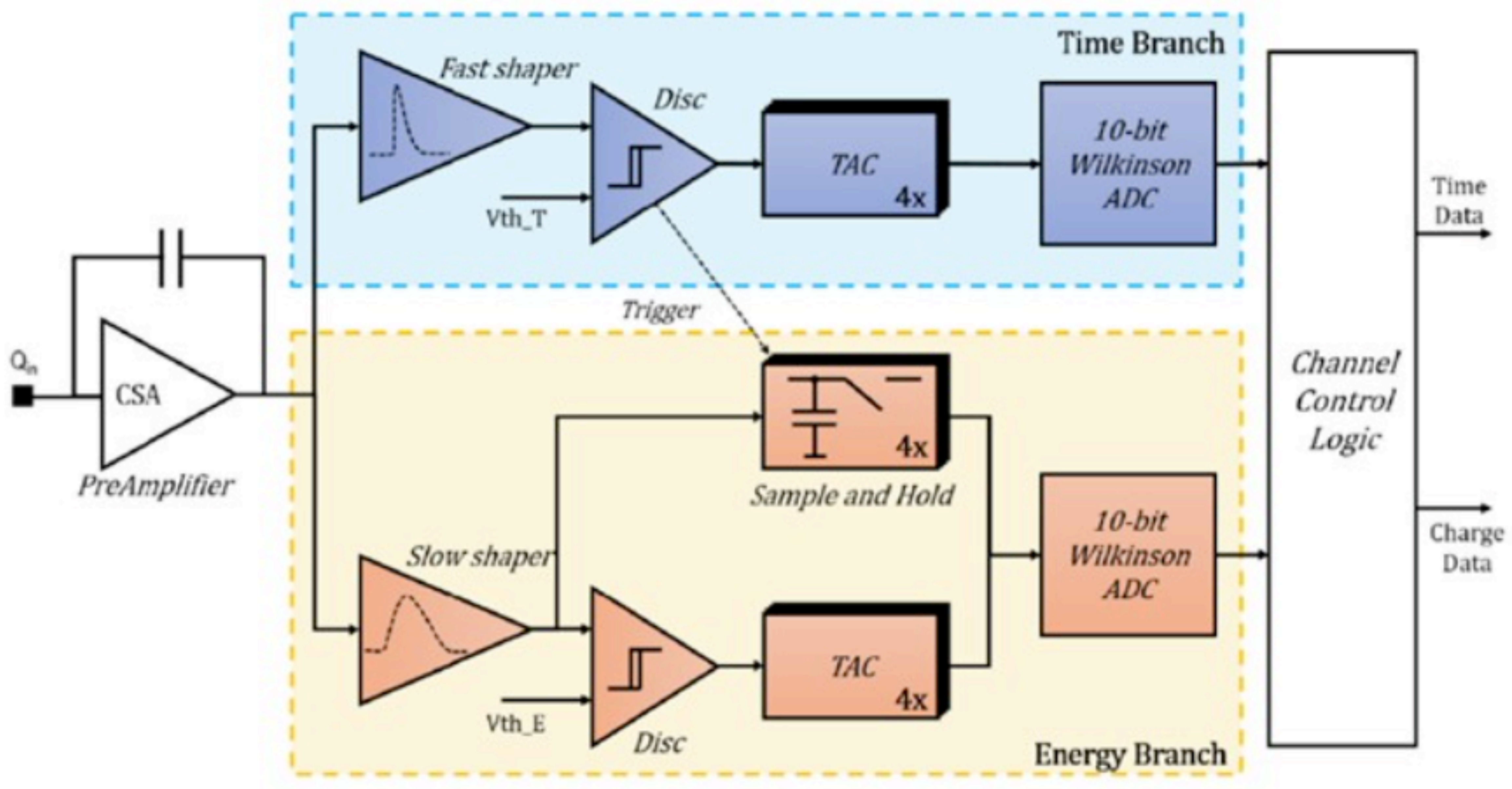
TIGER

- is used in BES-III GEM readout
- optimised architecture with two different shapers and thresholds for time and energy measurements
- precise 10-bit fine timing resolution
- charge measurement:
  - integration
  - time-over-threshold mode

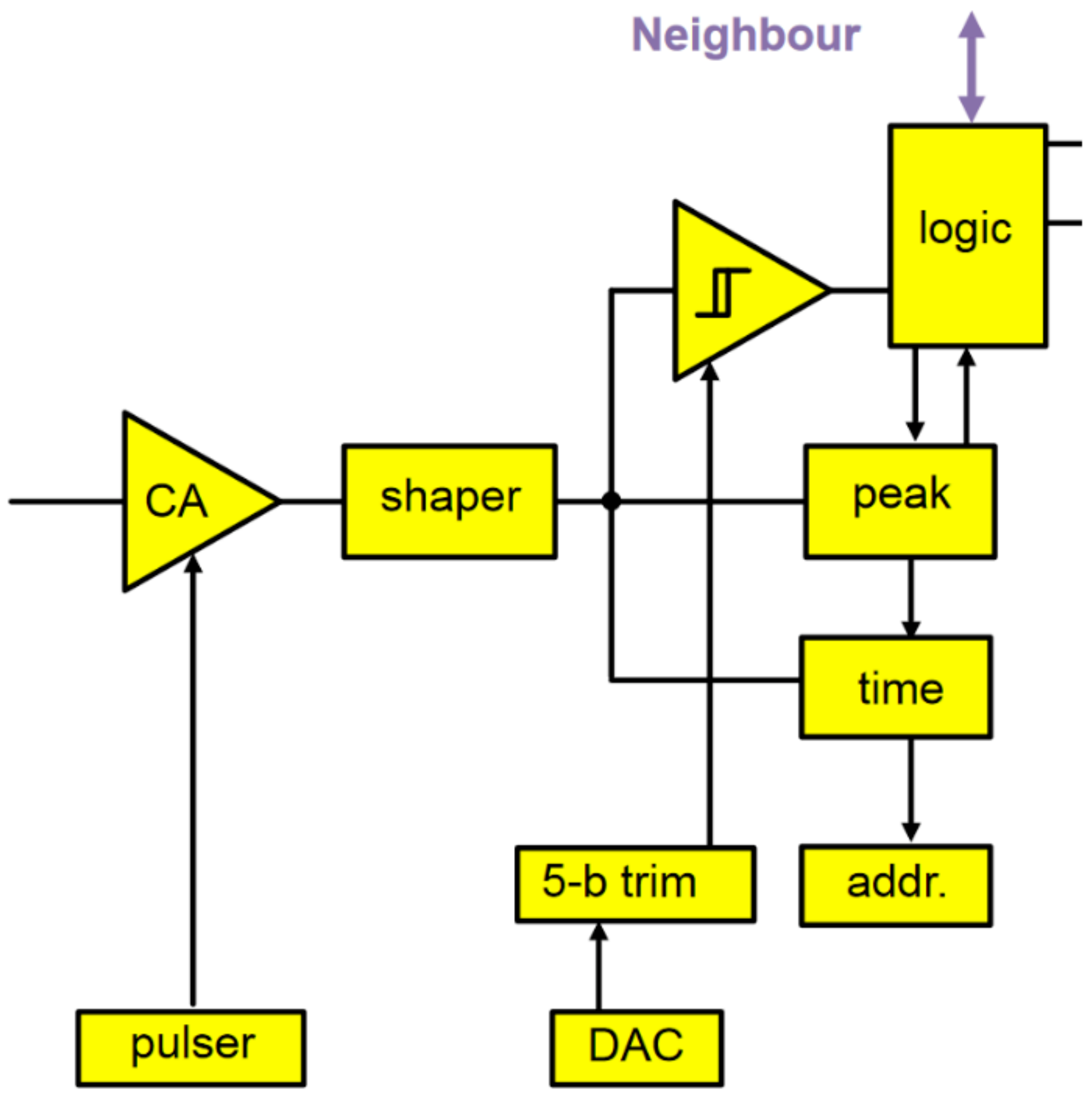
	VMM3	**TIGER**
Number of channels	64	64
Clock frequency	10...80 MHz	160...200 MHz
Input capacitance	<300 pF	<100 pF
Dynamic range	Linearity within ±2% up to 2 pC	50 fC
Gain	0.5, 1, 3, 6, 9, 12, 16 mV/fC	12 mV/fC
ENC (energy branch)	<3000	<1500
TDC binning	~1 ns	50 ps
Maximum event rate	140 kHz/ch	60 kHz/ch
Consumption	15 mW/ch	12 mW/ch

Straw readout: TIGER vs VMM3

TIGER Architecture

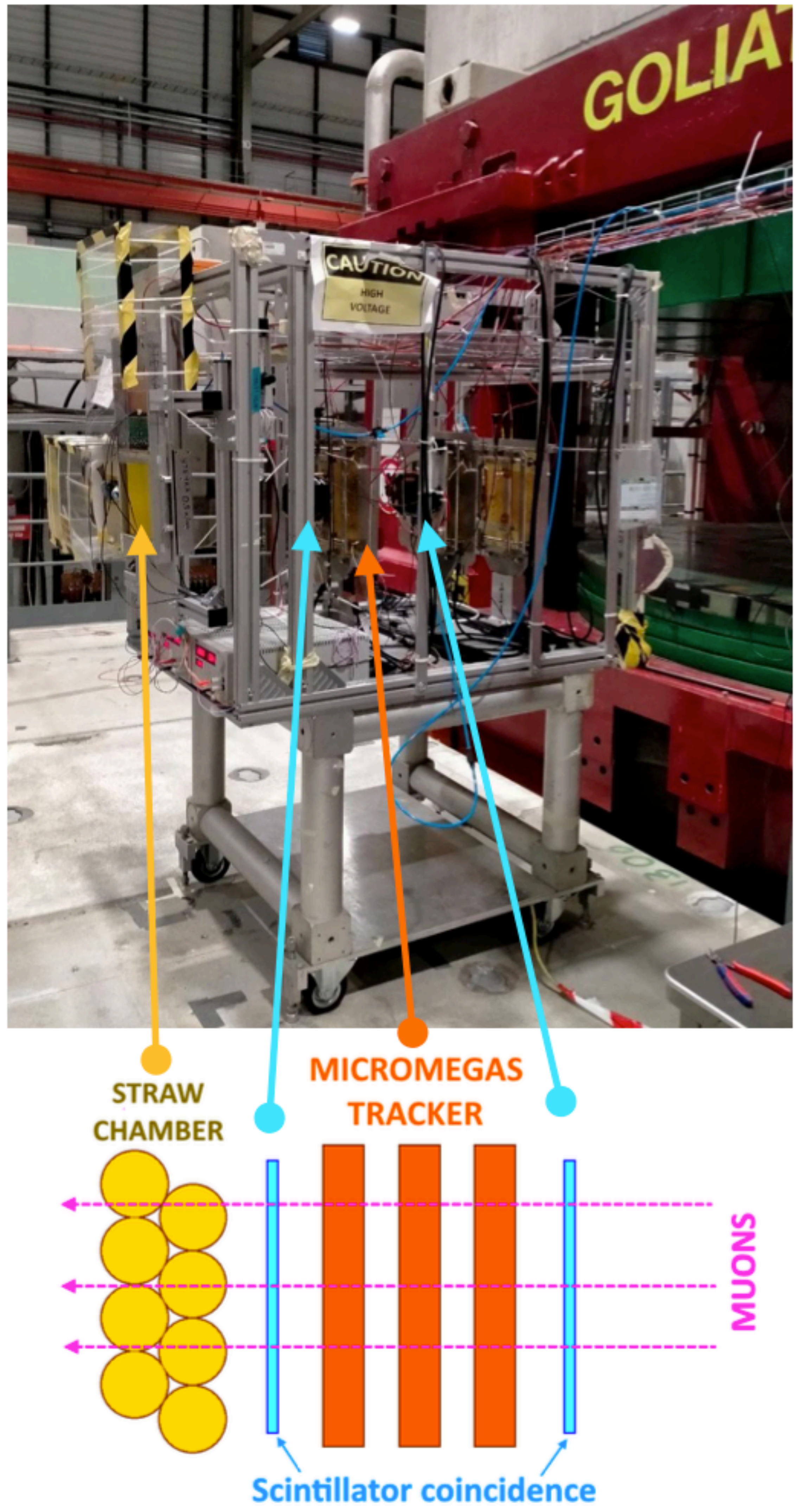


VMM3 Architecture

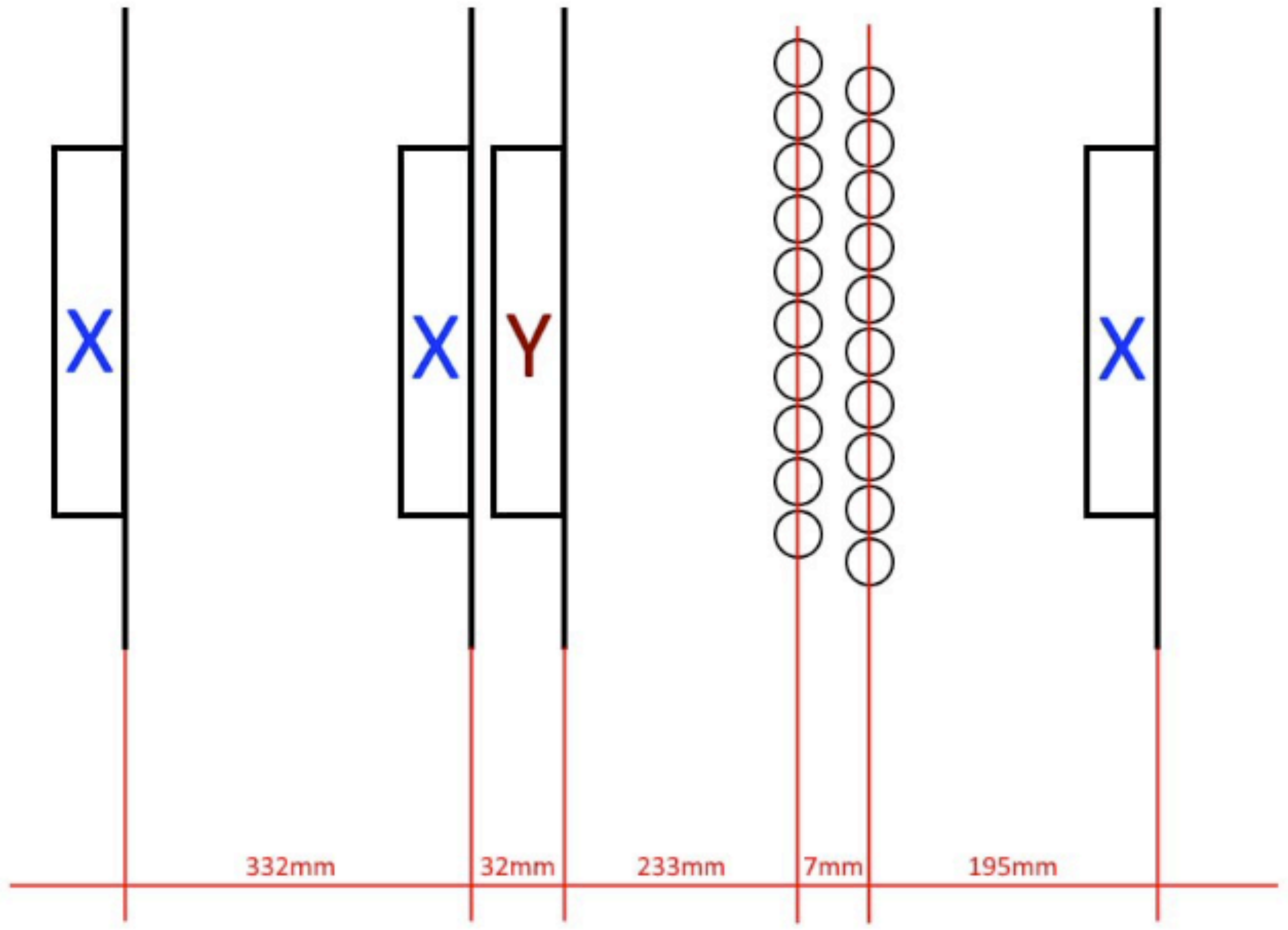


In contrast to *VMM,* the *TIGER* architecture has two different shapers for Time and Energy measurements. Two threshold levels are also possible.

Testbeam measurements



- All 3 existing readout options we study with SPS Testbeam
- For efficient data taking the following setup was developed:
  - Reference tracker: 3 GEMs or MicroMegas (3X + 1Y axis) with pitch of 250 μm
  - Reference timing: scintillator coincidence (two scintillators)
  - Straw chamber with 6mm straw



Testbeam measurements

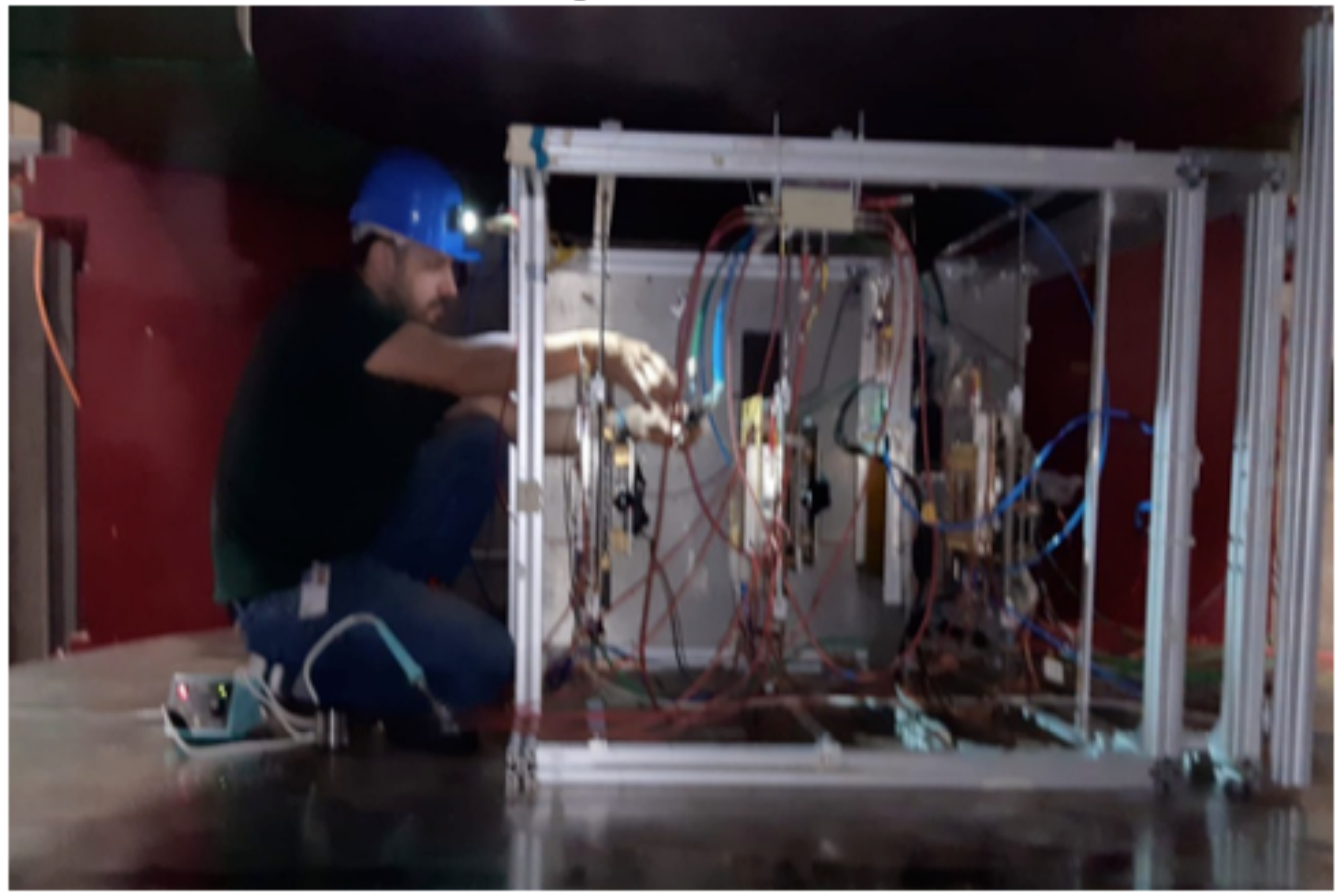
SETUP 1

- CERN, H4 (Nov 2021)
- 3 GEMs + straw station
- VMM3a readout

SETUP 2

- CERN, H4 (April–May + July 2022)
- 4 MMs w/ APV25 readout + straw station w/ VMM3 readout

SETUP 3



- CERN, H8 + H4 (Aug – Nov 2022)
- 4MMs + straw station
- TIGER readout

+ data taking in magnetic field

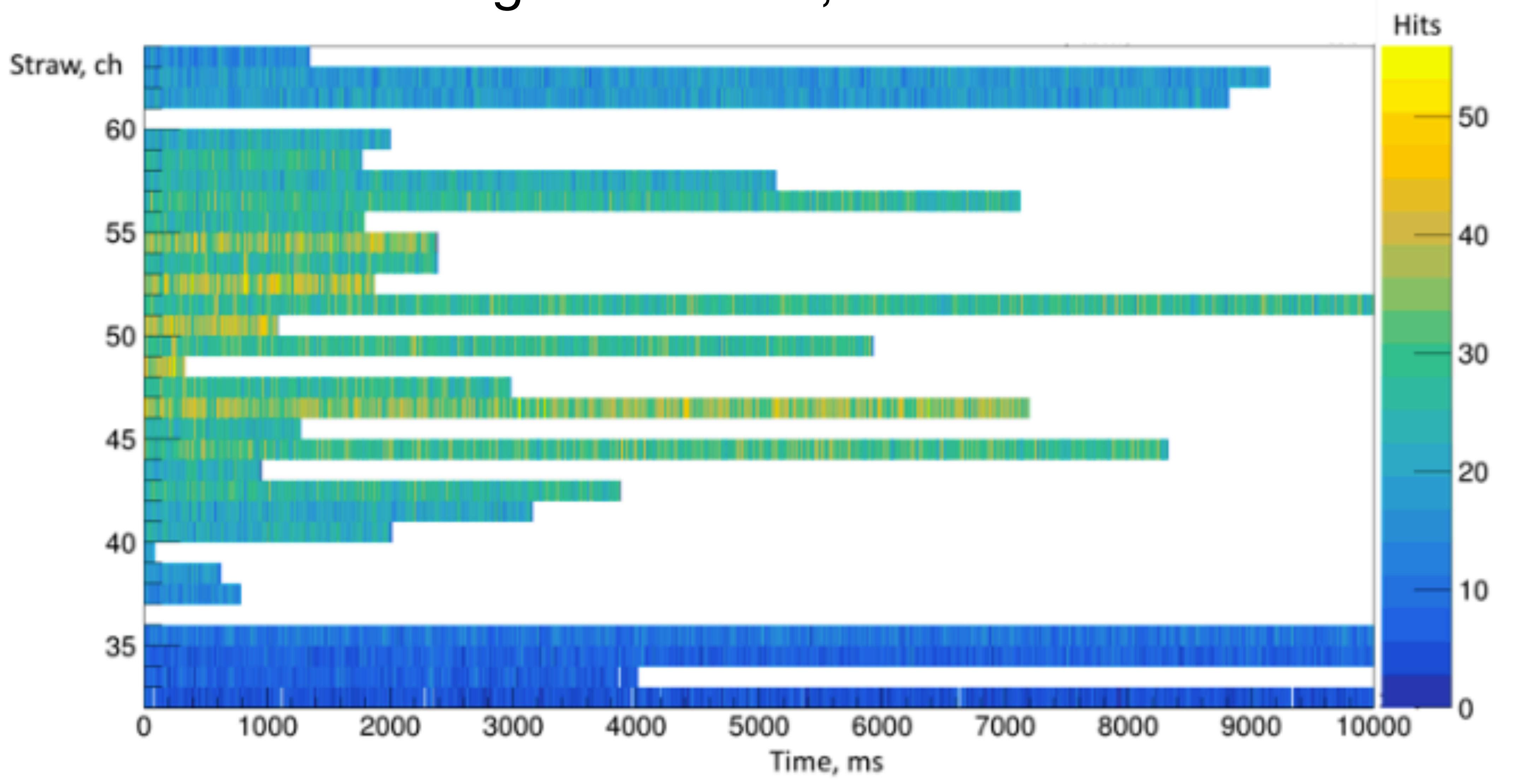
Testbeam measurements: SETUP1

VMM3a reliably operates in time-at-peak (T@P) mode only (ATLAS New Small Wheel). It was never used for time measurements in time-at-threshold (T@T) mode.

During our measurements at the Testbeam **VMM3a** "latching" in time-at-threshold (T@T) mode was observed. A possible explanation is an algorithmic problem in the cases when the time between the threshold crossing and signal peak is too short (<1 clock cycle).

Such type of "latching" makes impossible to use it with straws

Peaking time 200ns, BC = 40MHz

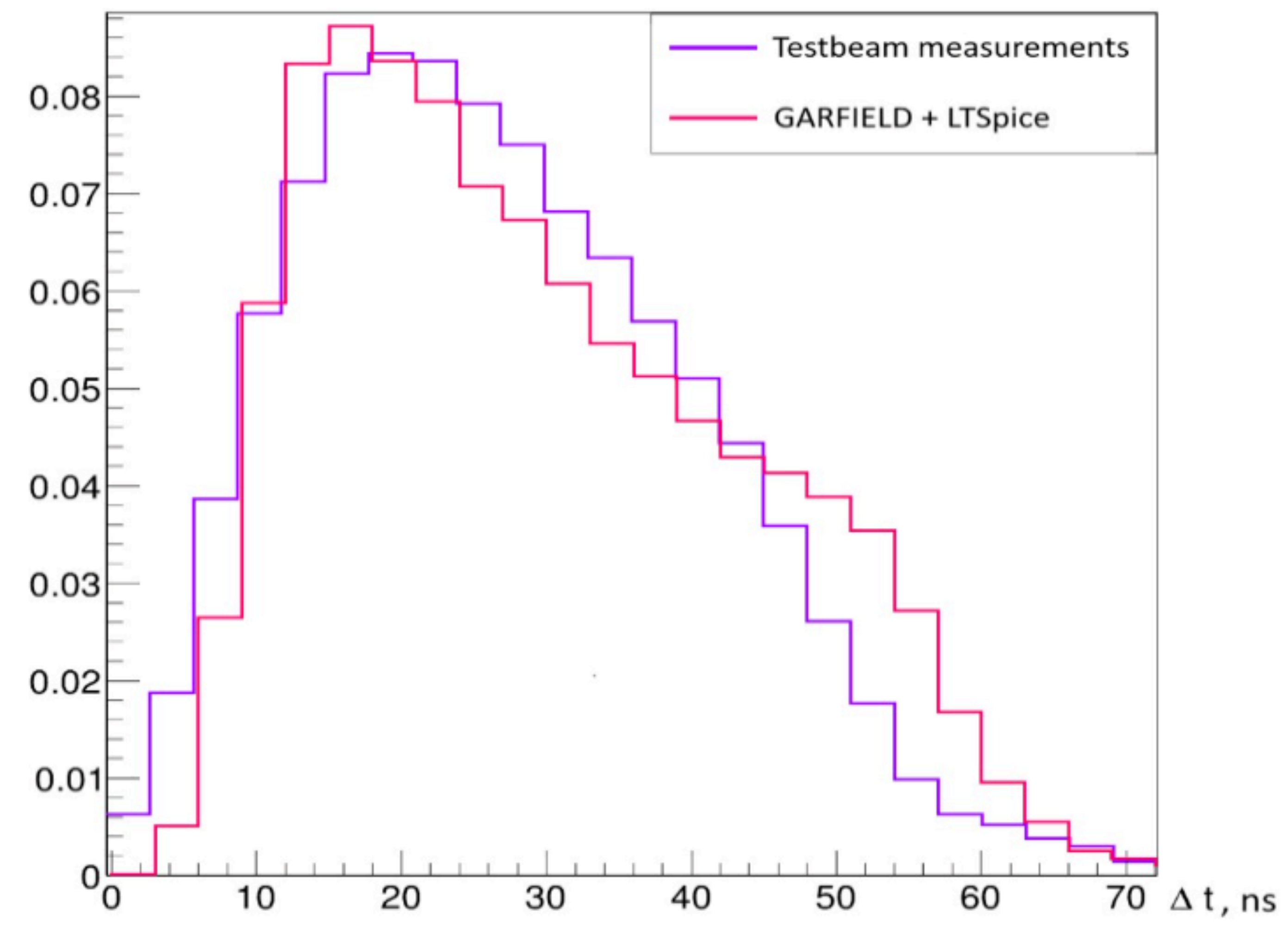


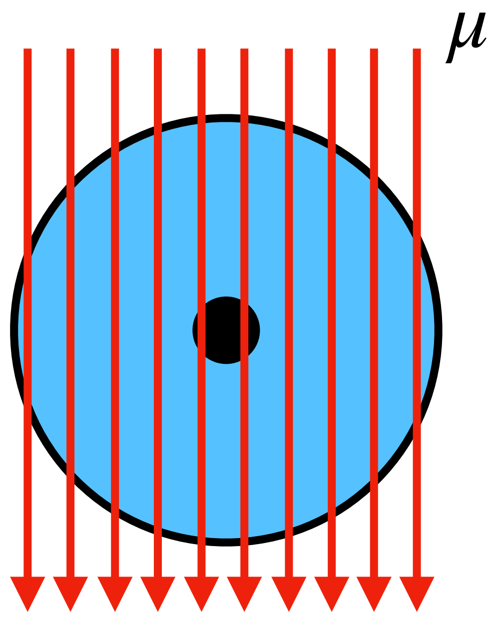
Testbeam measurements: SETUP2

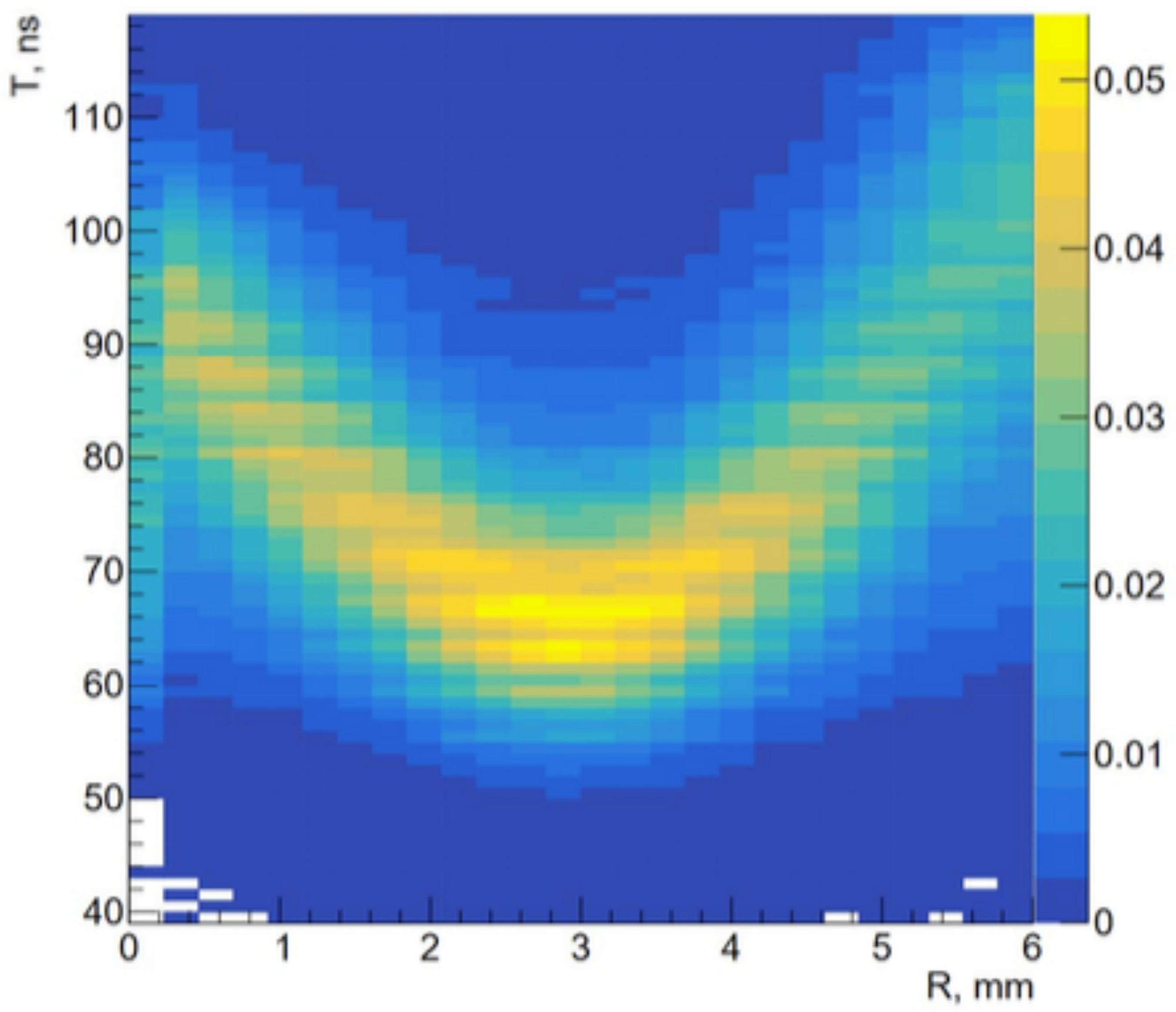
DATA ANALYSIS IS ONGOING

No such effect was found with previous revision, **VMM3**. The logic of the T@T mode slightly differs between VMM3 and VMM3a

Very preliminary data (6mm straw, D_{wire} = 30um, HV = 1650V) and comparison of drift time distribution from muon beam *data* (magenta) with the *Garfield + LTSpice* predictions (red) shows a good agreement



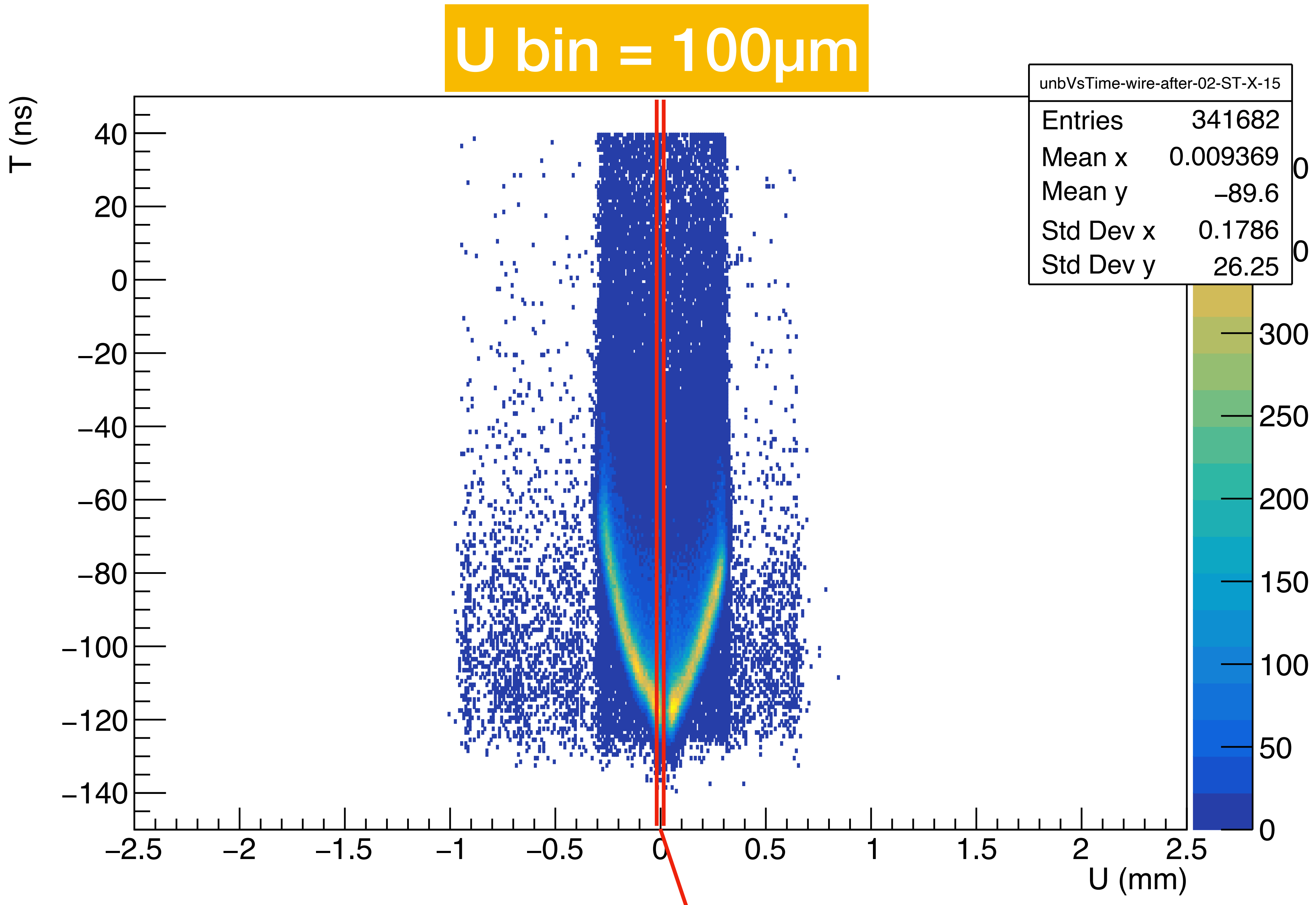


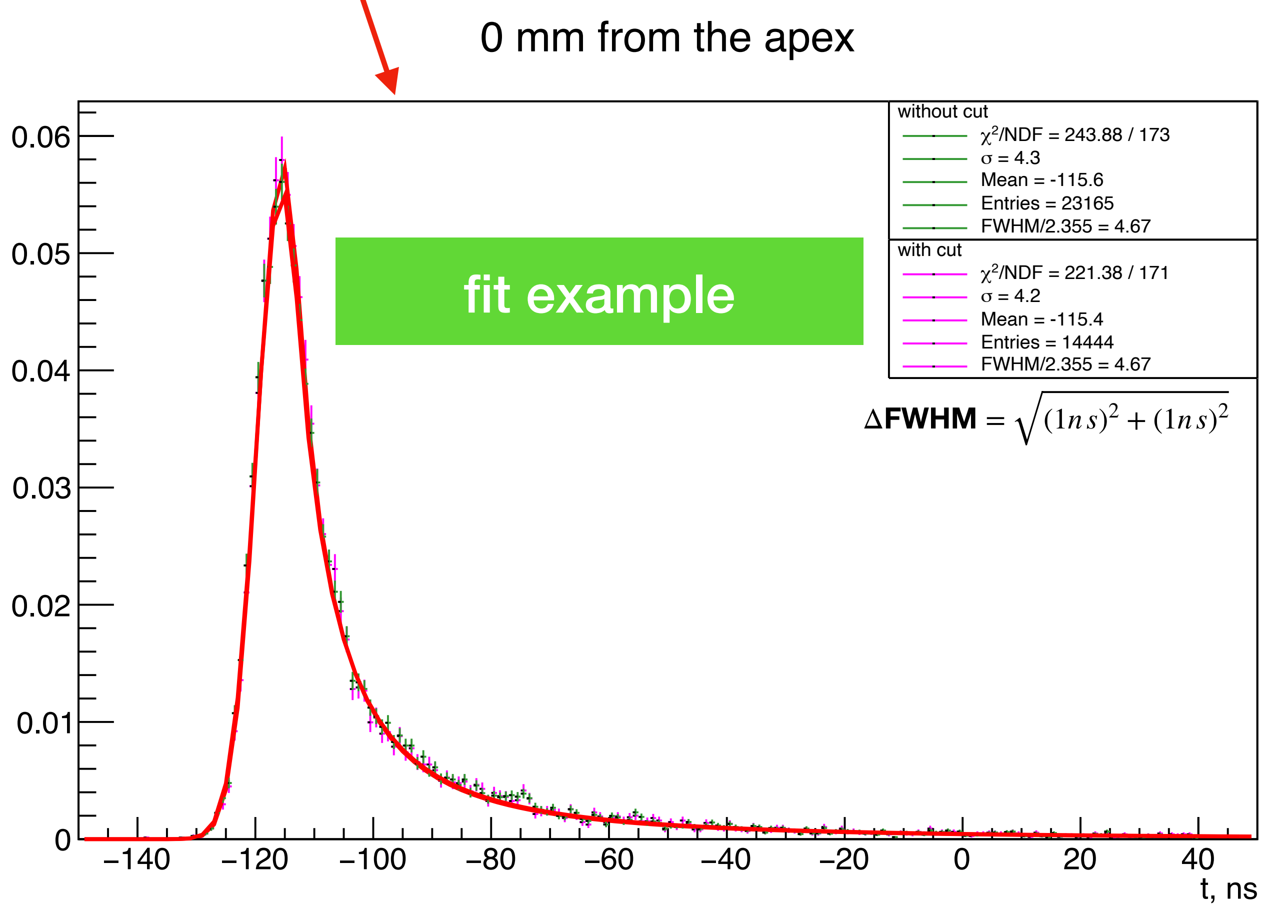


Preliminary results with the SETUP2 data

Reduced tracking information from **1 MicroMegas only** was used here

- Successful data taking with the **TIGER** readout for straws and reference tracking
- Preliminary the reference tracking is done using MicroMegas charge-weighted clusters and Least Square Method for track finding
- Extrapolated reference track coordinate *U* is used to obtain the correlation between straw signal time *T* and the track position

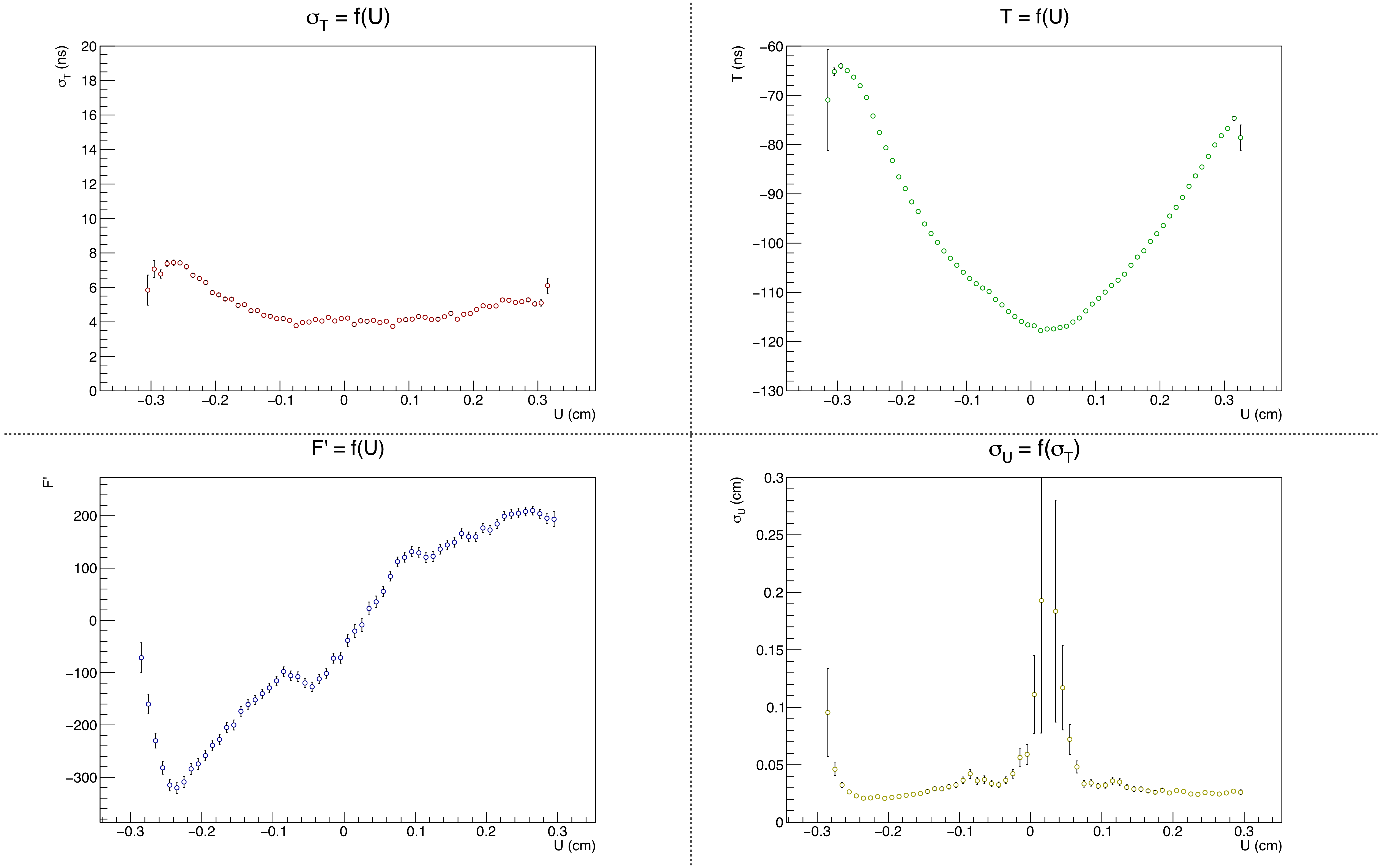




σ_T from the fit associated with Time resolution. The Idea is to obtain the **Spatial** resolution from the **Time** resolution

$$\sigma_U = \frac{\sigma_T}{|f'(U)|}$$

Coordinate resolution as a function of Time resolution



$\langle \sigma_U \rangle$ = (253 +/- 2) µm

Resolution is a weighted mean of such σ_U distributions

- The obtained σ_U still contains contribution from binning and imperfection of the reference tracking
- Work on improvement of the precision (better tracking, taking into account finite resolution of the reference tracking) is ongoing

Next steps:

- *improving the reference track reconstruction*
- *corrections for scintillator timing uncertainty*
- *data unfolding*

Summary

- A dedicated setup for Testbeam data taking has been developed
- *VMM3a* "latching" in the **T@T** mode was observed during the November 2021 Testbeam. Such type of "latching" makes impossible to use it for straw readout. The effect was discussed with developers
- During April and July Testbeams the data with *VMM3* readout was acquired
- *TIGER*-based BES-III frontend boards were adapted for reading out the MicroMegas and straw tubes
- Data with *TIGER* readout was taken during the October Testbeam for different magnetic field strength
- Very preliminary analysis of the data collected with *TIGER* readout shows reasonable results
- Data analysis is ongoing

Backup

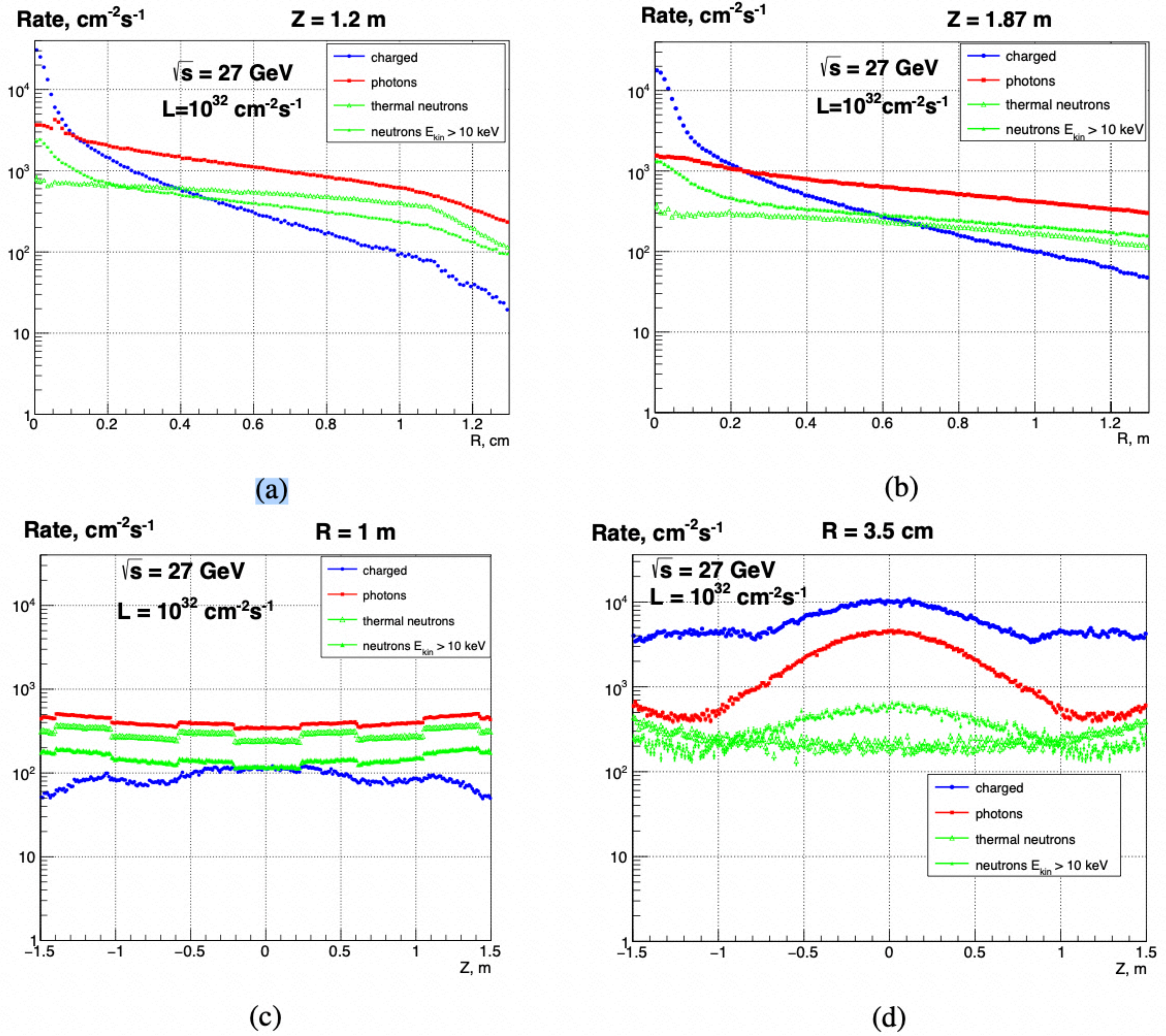
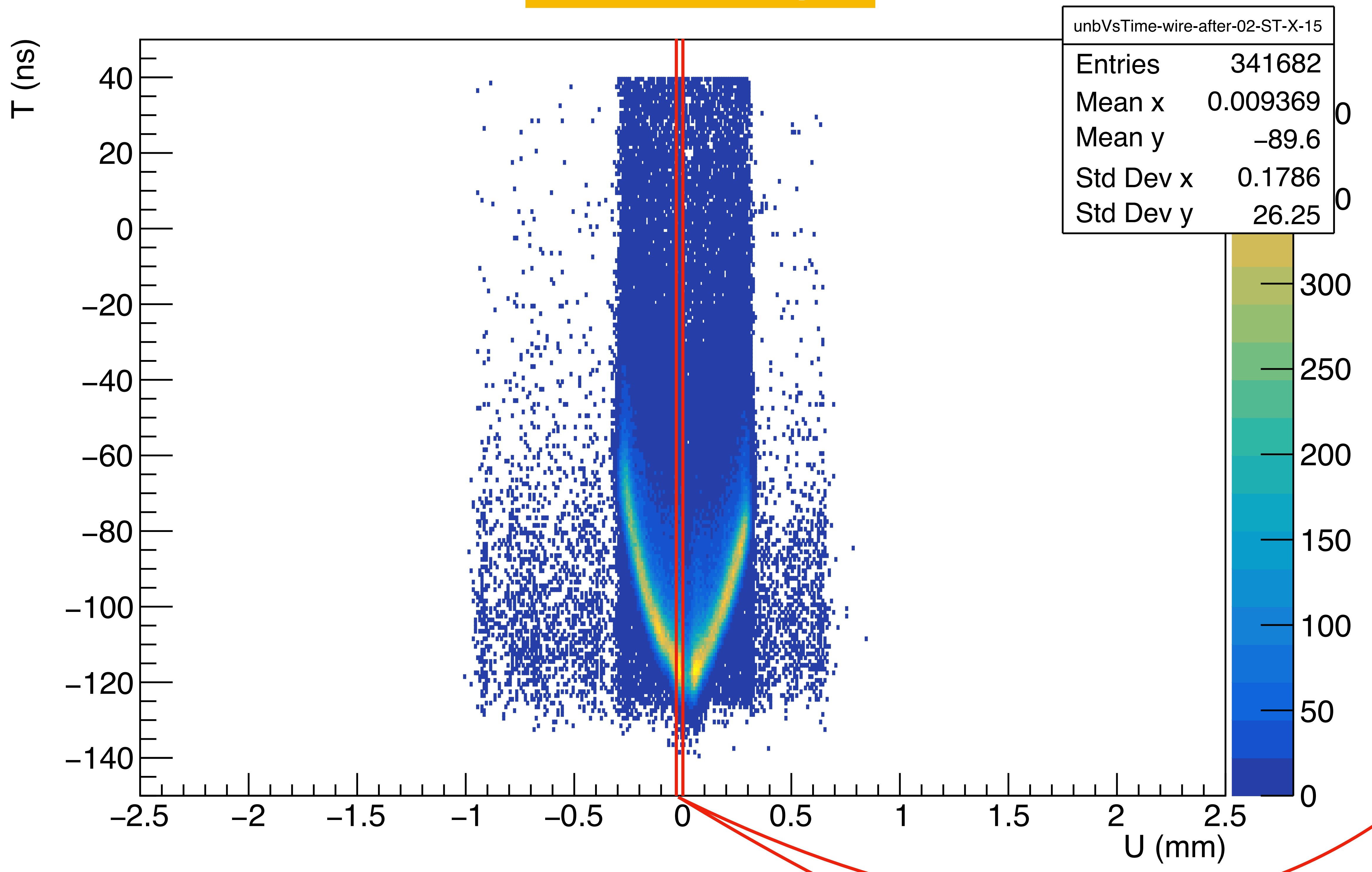


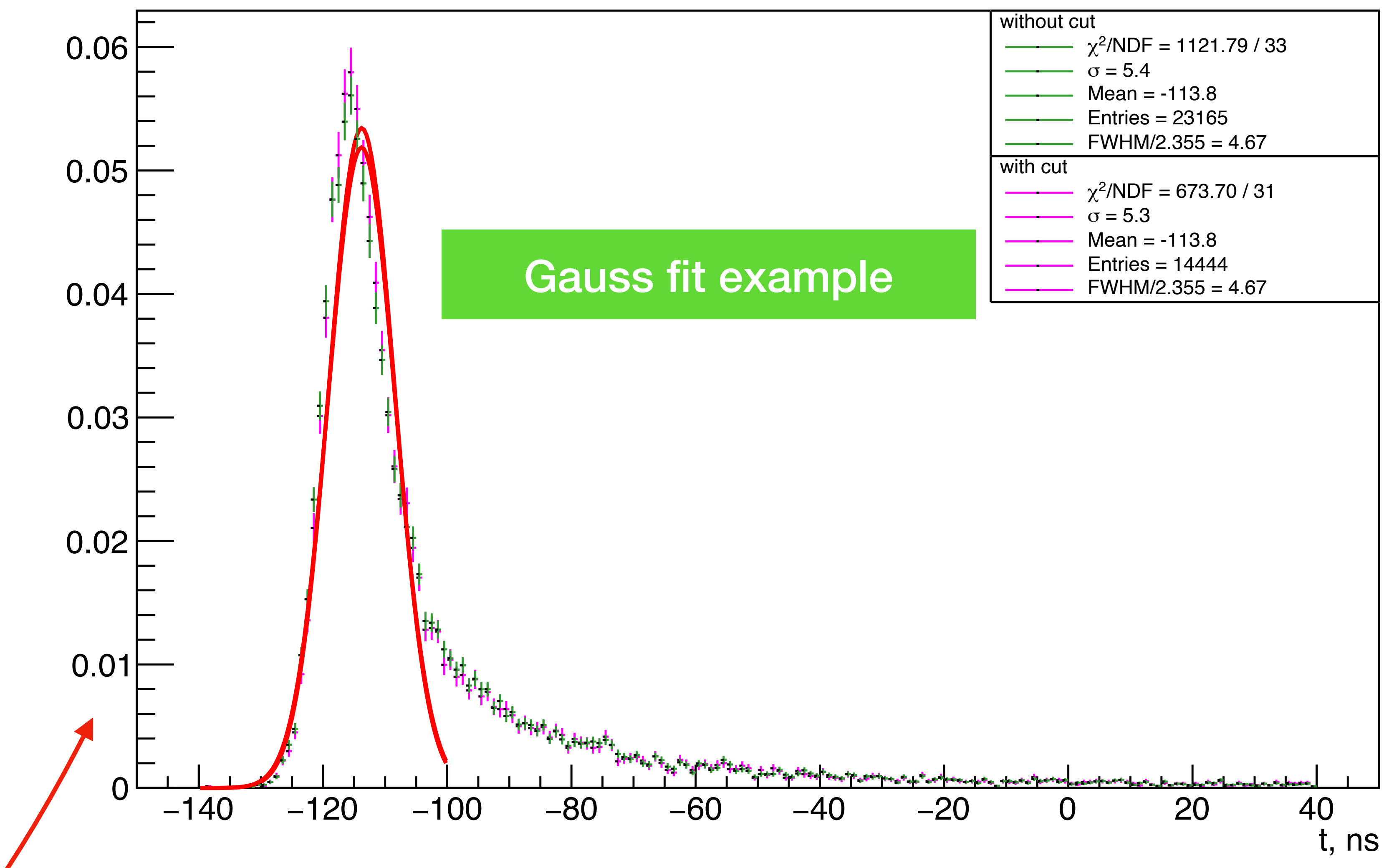
Figure 16.1: Flux of charged particles, energetic and thermal neutrons, and photons in the radial direction at (a) Z=1.2 m, (b) Z=1.87 m, and along the beam axis at (c) R=1 m and (d) R=3.5 cm.

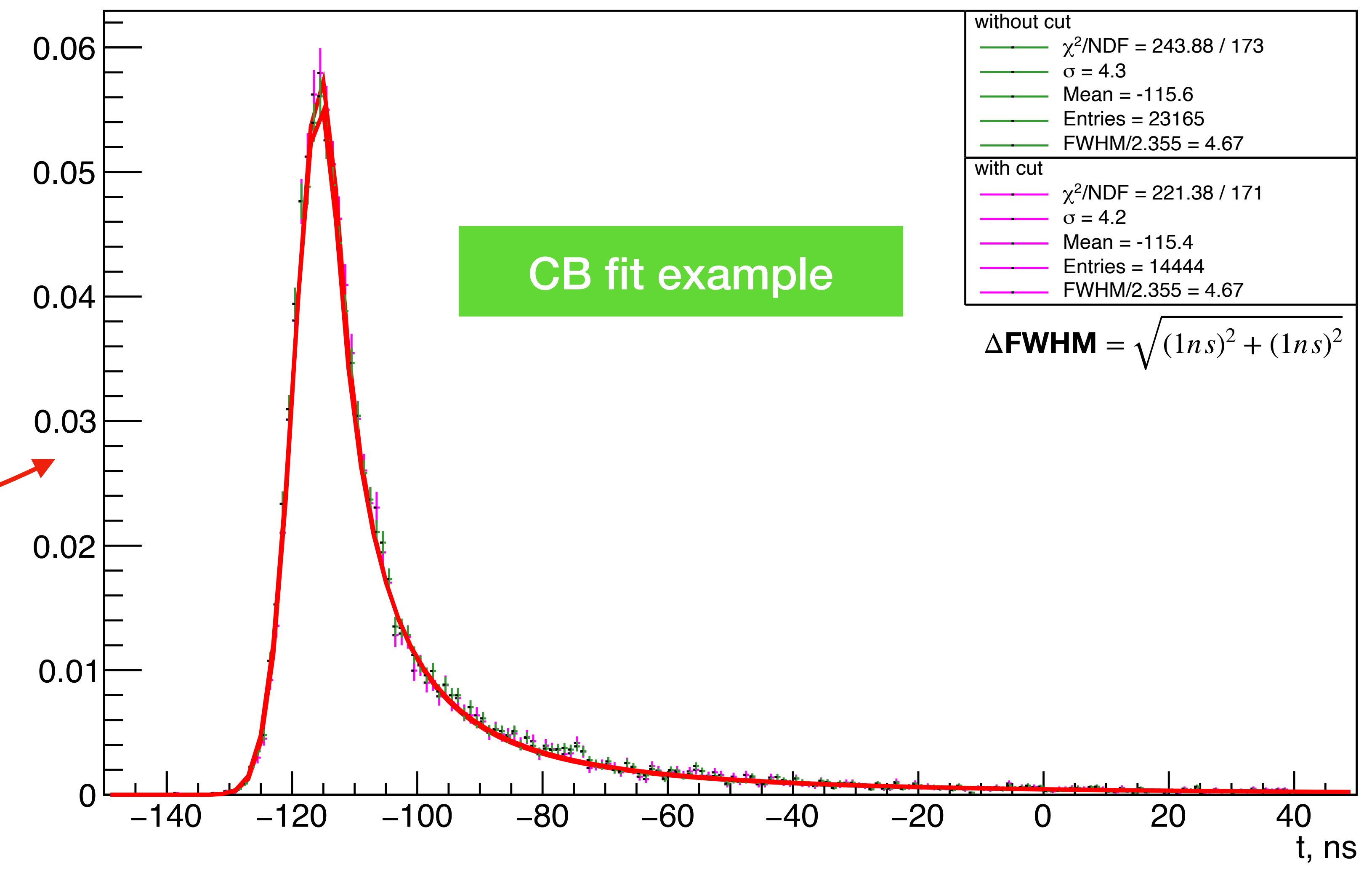
Testbeam measurements: SETUP3

U bin = 100µm



0 mm from the apex

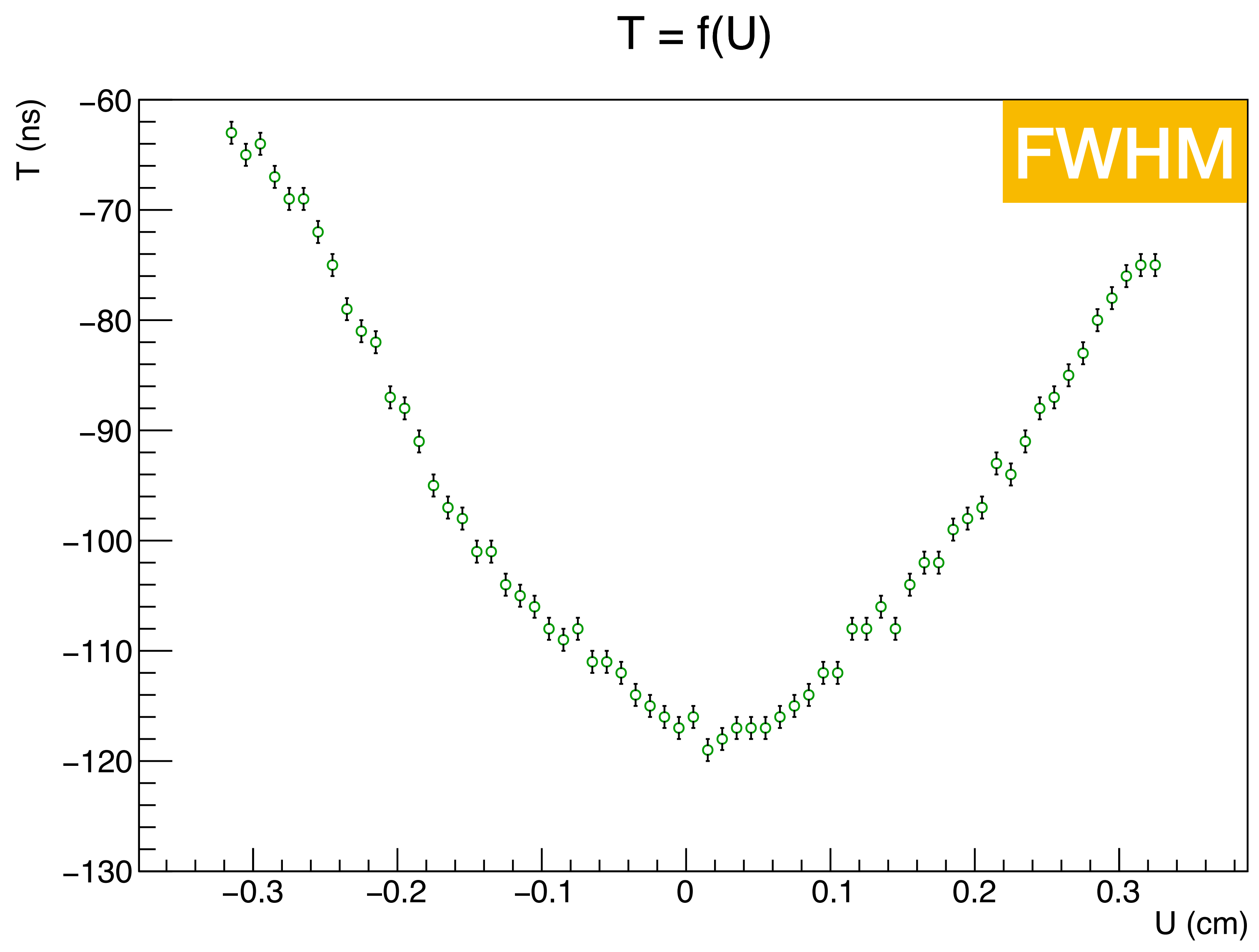


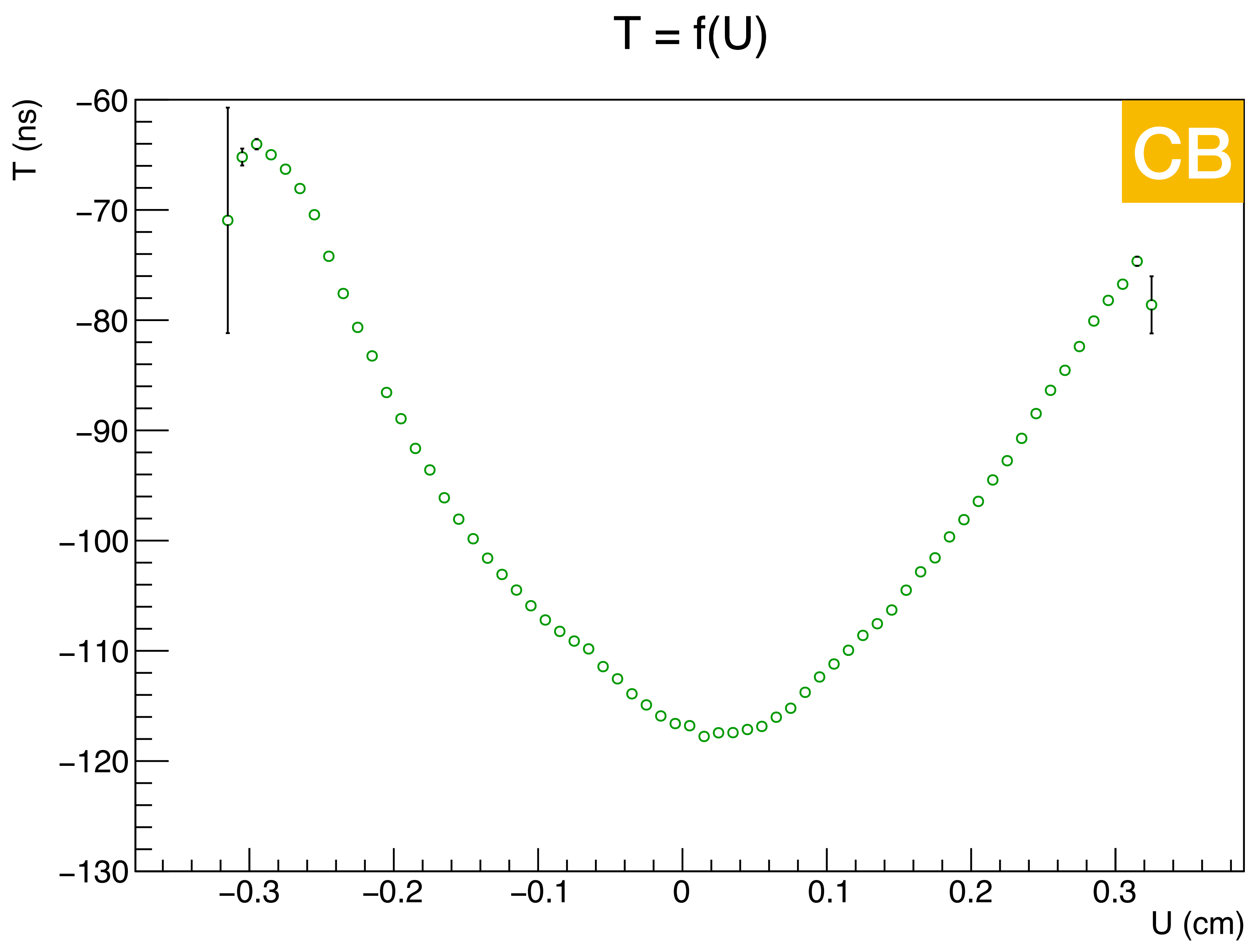


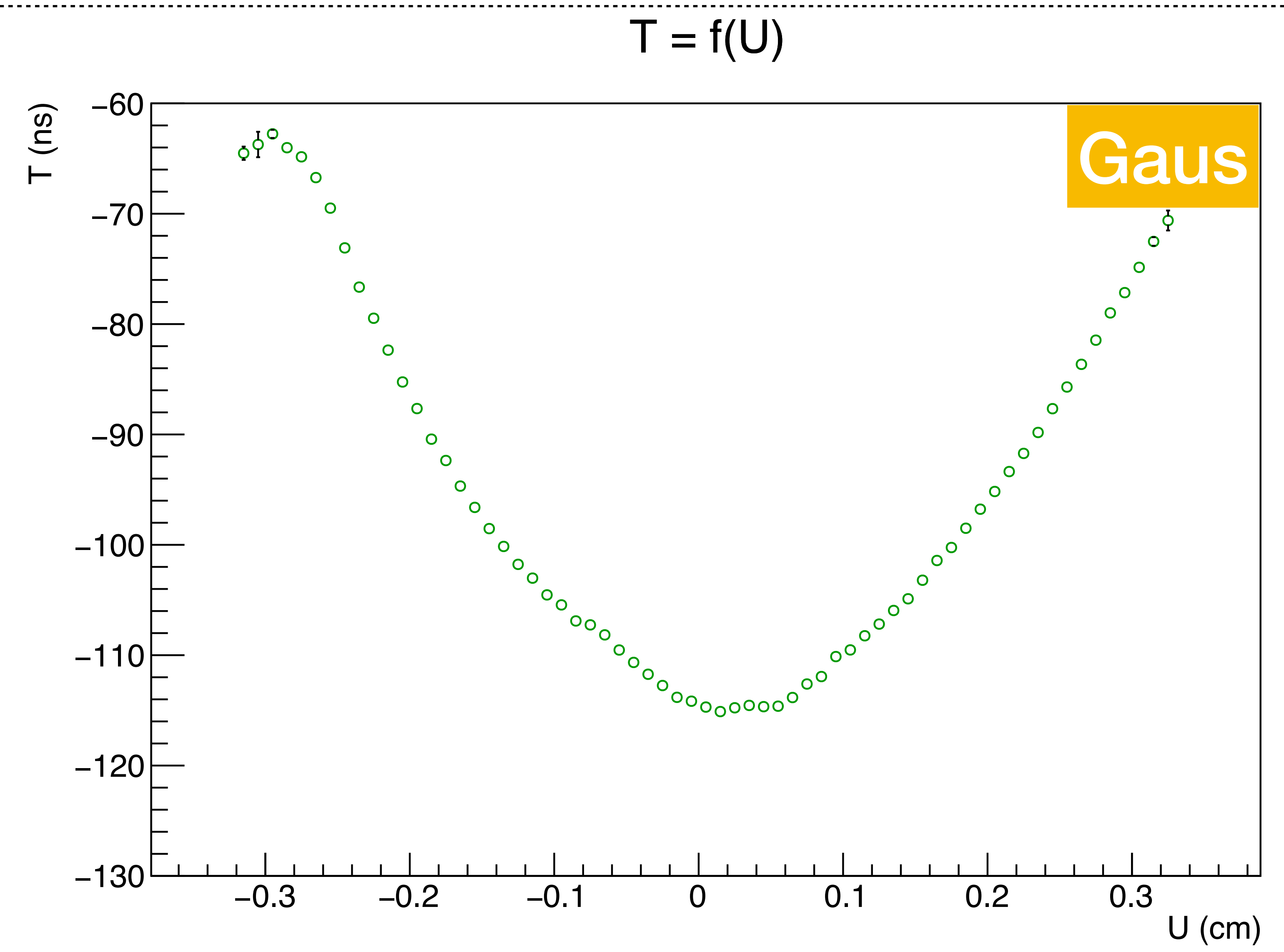
σ_T from the fit associated with Time resolution. The Idea is to obtain the **Spatial** resolution from the **Time** resolution

$$\sigma_U = \frac{\sigma_T}{|f'(U)|}$$

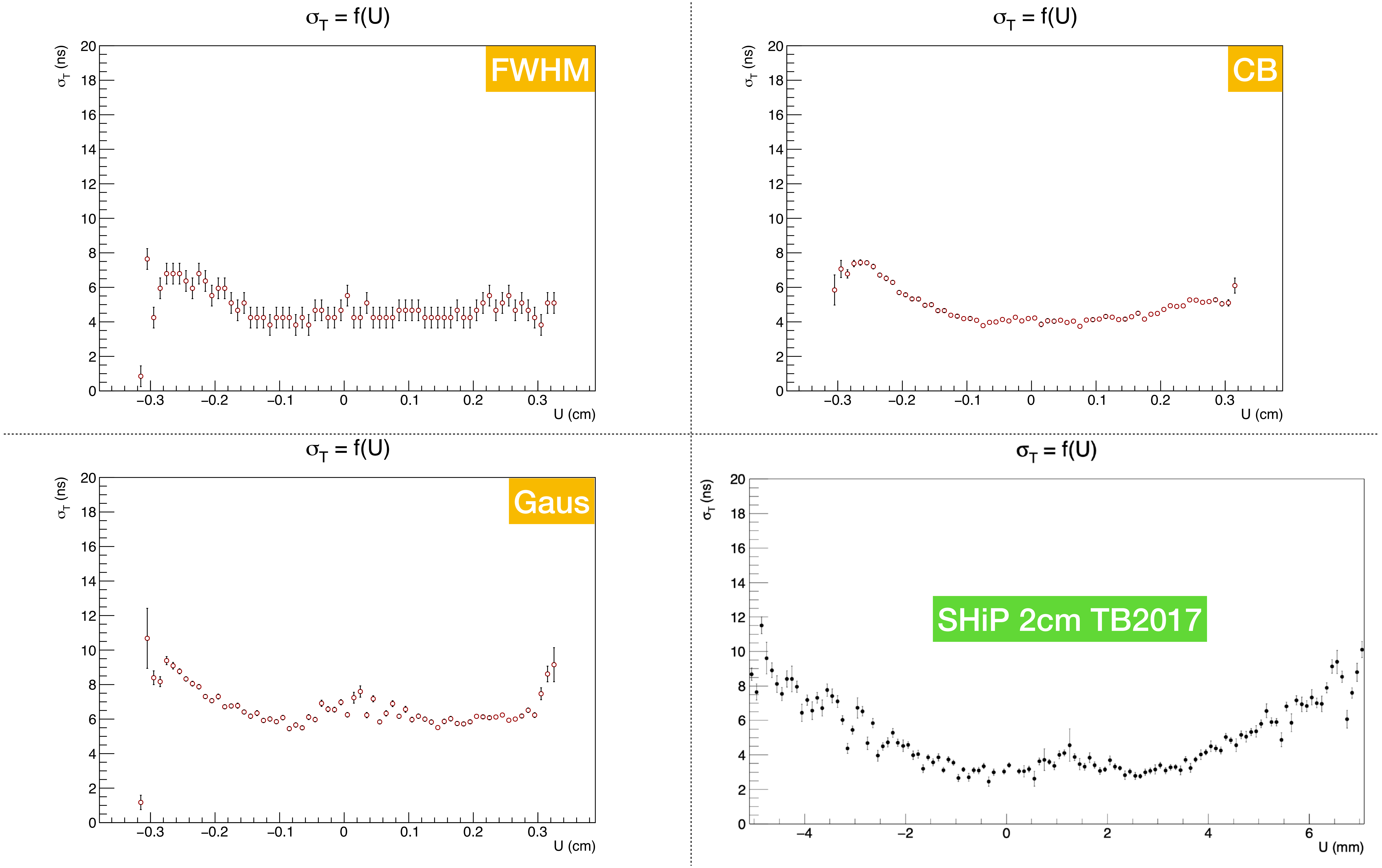
Mean T as a function of coordinate U from the fit







Sigma parameter as a function of coordinate U from the fit



Mean T as a function of coordinate U from the fit

As a result of fitting were received two distributions: $\sigma_t = F(Y)$ and $T = F(Y)$, where the σ_t error has been gotten from the fit and T error estimated as $\Delta(T) = \sigma_t/\sqrt{N}$

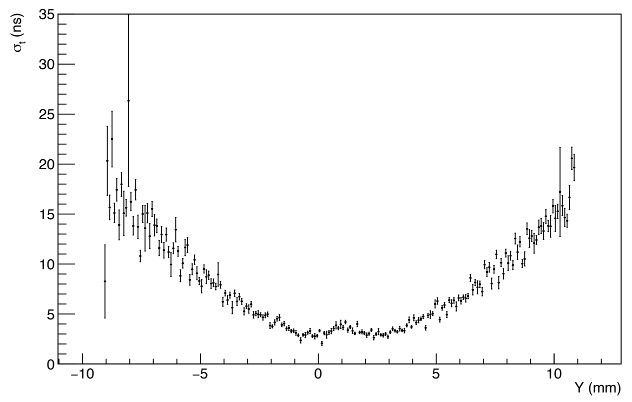


Figure 2: Sigma parameter from fit as a function of a track coordinate.

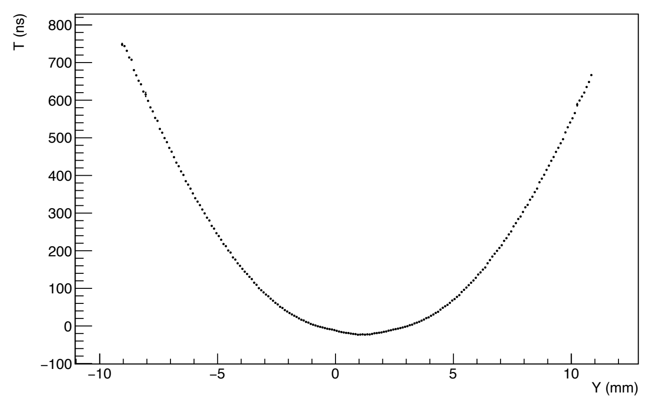


Figure 3: Fit mean value as a function of track coordinate.

1.3 Resolution estimation

For spatial resolution estimation was used the error propagation formula [1]:

$$\Delta F^2(x_1, \dots, x_n) = \sum_i \left(\frac{\partial F}{\partial x_i}\right)^2 \cdot \delta_i^2 + 2 \cdot \sum_{i \neq j} \left(\frac{\partial F}{\partial x_i}\right) \cdot \left(\frac{\partial F}{\partial x_j}\right) \cdot cov(x_i, x_j) \quad (2)$$

where F – is a function of many variables x_i, which have their own errors δ_i and $cov(x_i, x_j)$ – is the covariance between x_i and x_j. Since time (T) is a function of only one variable – the track coordinate Y: $T = F(Y)$, so based on formula 2 the coordinate resolution σ_Y can be reconstructed via measured time T which associated with the time resolution:

$$\Delta F^2(U) = \sigma_t^2 = \left(\frac{dF(Y)}{dY}\right)^2 \cdot \sigma_Y^2 \quad (3)$$

from this equation coordinate resolution can be estimated as the function of a σ_t

$$\sigma_Y = \frac{\sigma_t}{\left|\frac{dF(Y)}{dY}\right|} = \frac{\sigma_t}{|F'|} \quad (4)$$

Value of a σ_t determined for the every coordinate bin with error $\Delta\sigma_t$. Also coordinate resolution error calculated as

$$(\Delta\sigma_Y)^2 = \left[\frac{\partial\sigma_Y}{\partial\sigma_t}\right]^2 \cdot (\Delta\sigma_t)^2 + \left[\frac{\partial\sigma_Y}{\partial F'}\right]^2 \cdot (\Delta F')^2 = \left(\frac{1}{F'}\right)^2 \cdot (\Delta\sigma_t)^2 + \left(-\frac{\sigma_t}{[F']^2}\right)^2 \cdot (\Delta F')^2 \quad (5)$$

Based on numerical methods derivative of function F in coordinate bin i can be calculated in this way

$$F_i' = \frac{1}{4} \cdot \left(\frac{\delta T_1}{\delta Y_1} + \frac{\delta T_2}{\delta Y_2} + \frac{\delta T_3}{\delta Y_3} + \frac{\delta T_4}{\delta Y_4}\right) = \frac{1}{4} \cdot (g_1 + g_2 + g_3 + g_4) \quad (6)$$

where $\delta T_i = T_{i+1} - T_i$ – is a variance of straw signal time between i and $(i+1)$ coordinate bins; $\delta Y_i = Y_{i+1} - Y_i$ – is also coordinate bin size. This method gives an error:

[1] Molchanov V., Statistical methods for processing measurement results: a tutorial. – St. Petersburg: Polytechnic University Publishing House, 2008. - 100 pages. // ISBN 978-5-7422-1868-5

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$$\Delta(g_i) = \sqrt{\left(\frac{1}{\delta Y_i}\right)^2 \cdot (\Delta(\delta T_i))^2} \quad (7)$$

$$\Delta(\delta T_i) = \sqrt{(\Delta T_{i+1})^2 + (\Delta T_i)^2} \quad (8)$$

$$\Delta(\delta Y_i) = \delta Y_i \cdot \sqrt{2} \quad (9)$$

To sum up the derivative error estimated as

$$\Delta F' = \frac{1}{4} \cdot \sqrt{\sum (\Delta g_i)^2} \quad (10)$$

As a result of using formulas (4) - (10) was got the distribution of coordinate resolutions for every coordinate bin. It is rapidity increasing near the apex, but it also covered by using the weighted mean method for estimating the spatial resolution of the straw.

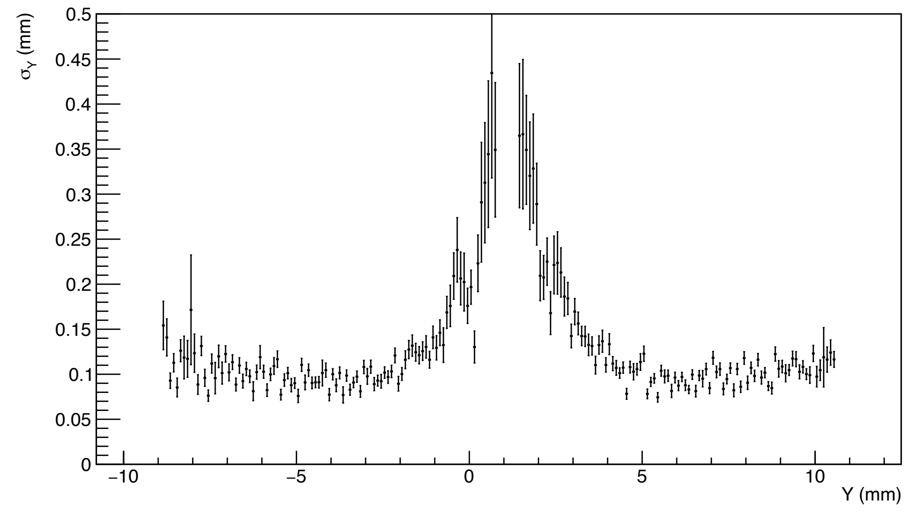

Figure 4: Distribution of coordinate resolutions for every coordinate bin

Based on this distribution the straw tube spatial resolution can be estimated as a weighted mean with error

$$\mu_{\sigma_U} = \frac{\sum \frac{\sigma_Y}{(\Delta\sigma_Y)^2}}{\sum \frac{1}{(\Delta\sigma_Y)^2}}; \quad (\Delta\mu_{\sigma_Y})^2 = \frac{1}{\sum \frac{1}{(\Delta\sigma_Y)^2}} \quad (11)$$

To check the systematic effects corresponding with the binning was made specific study. It included application of realised method for the different binning of the initial VShape. The result is also illustrated at Figure 5. It shows that the systematic error is about 13%.

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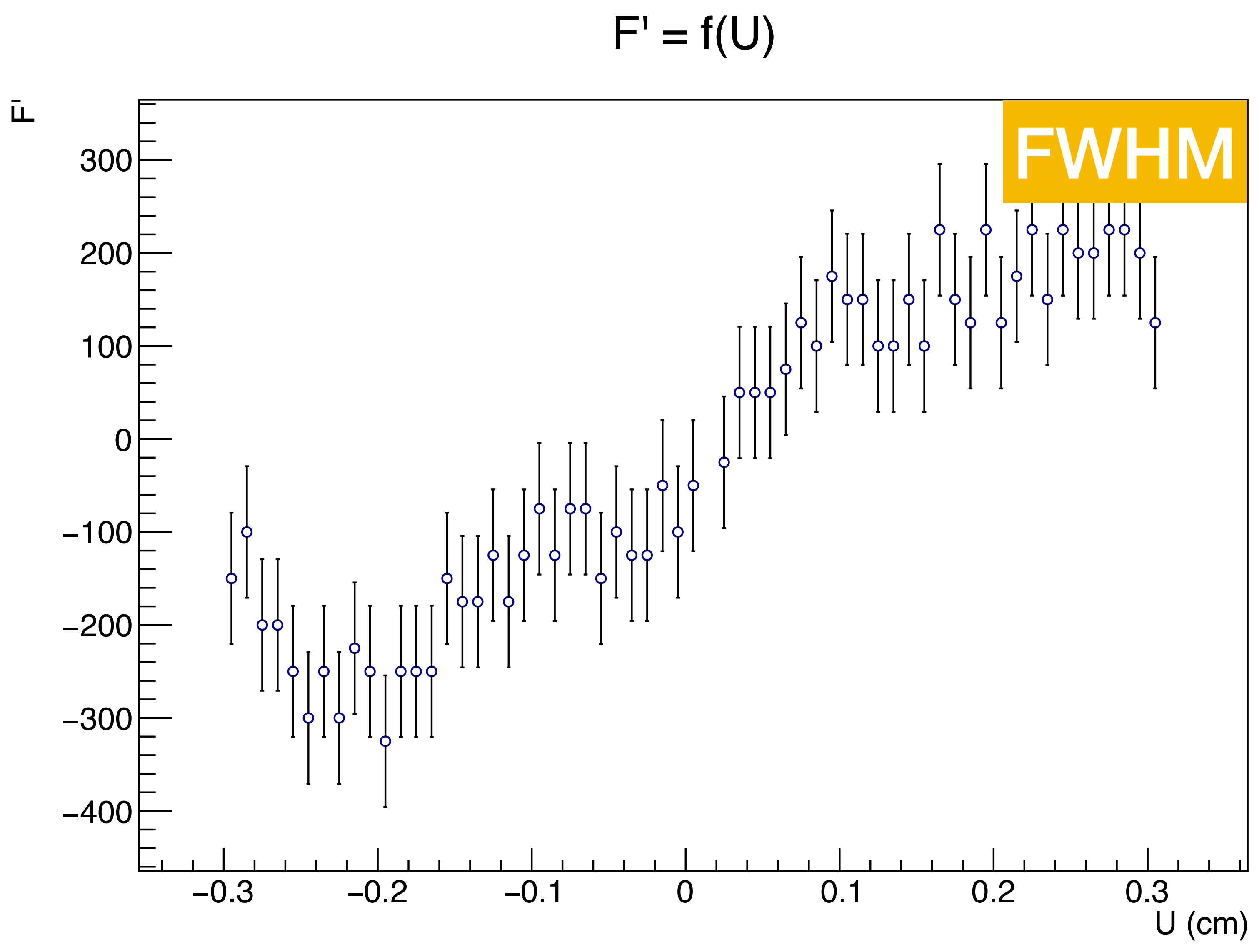
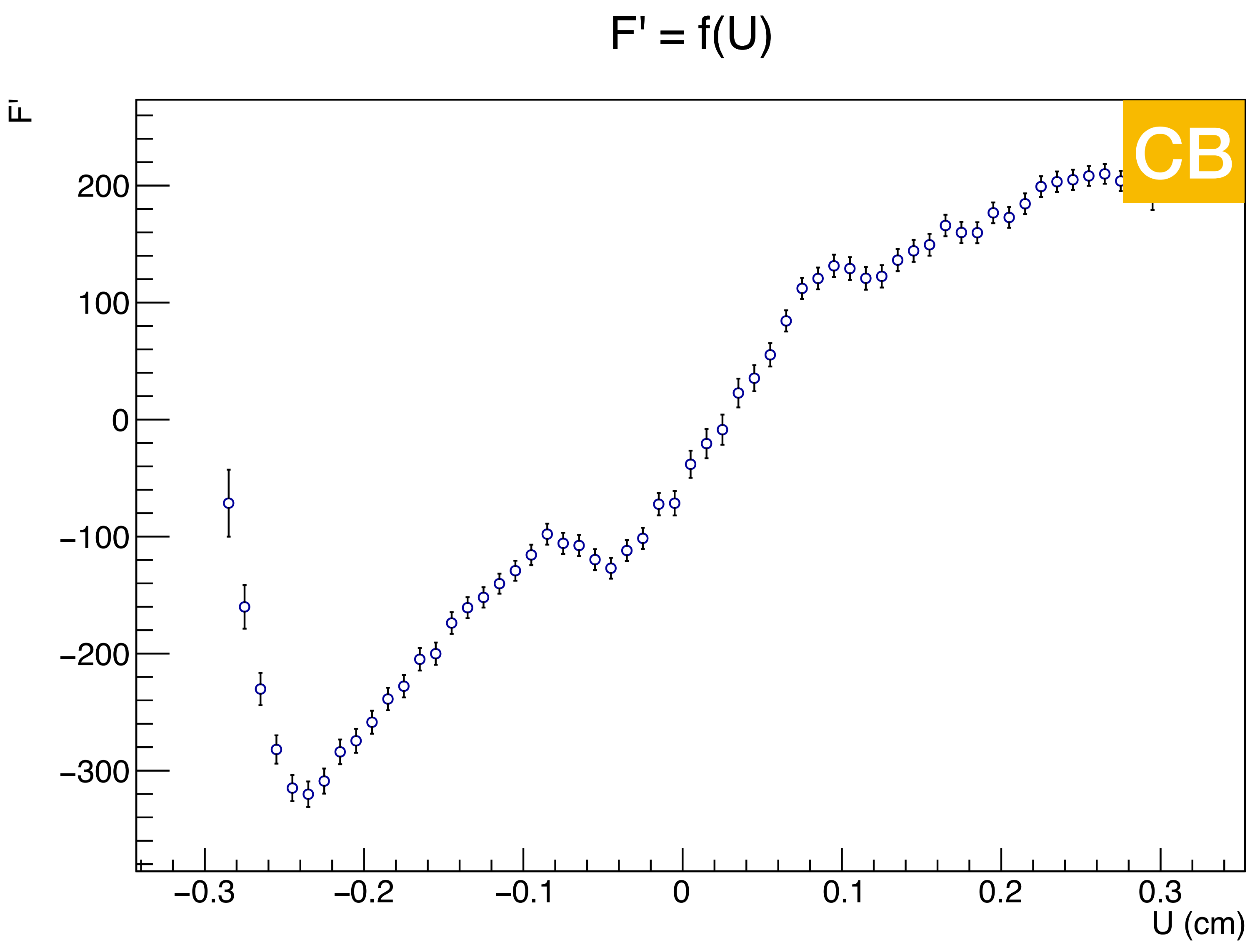
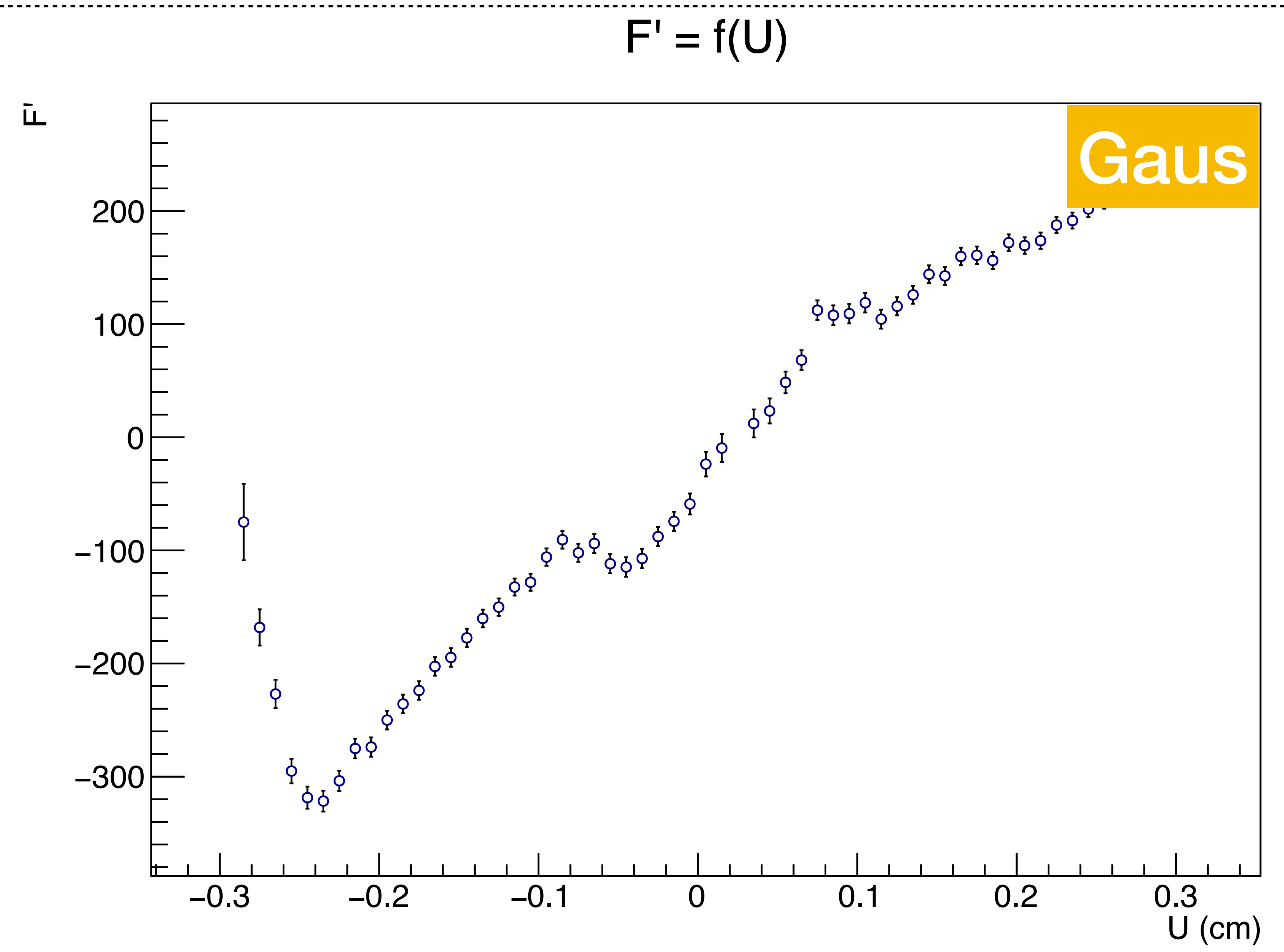
Derivative of R(T) function

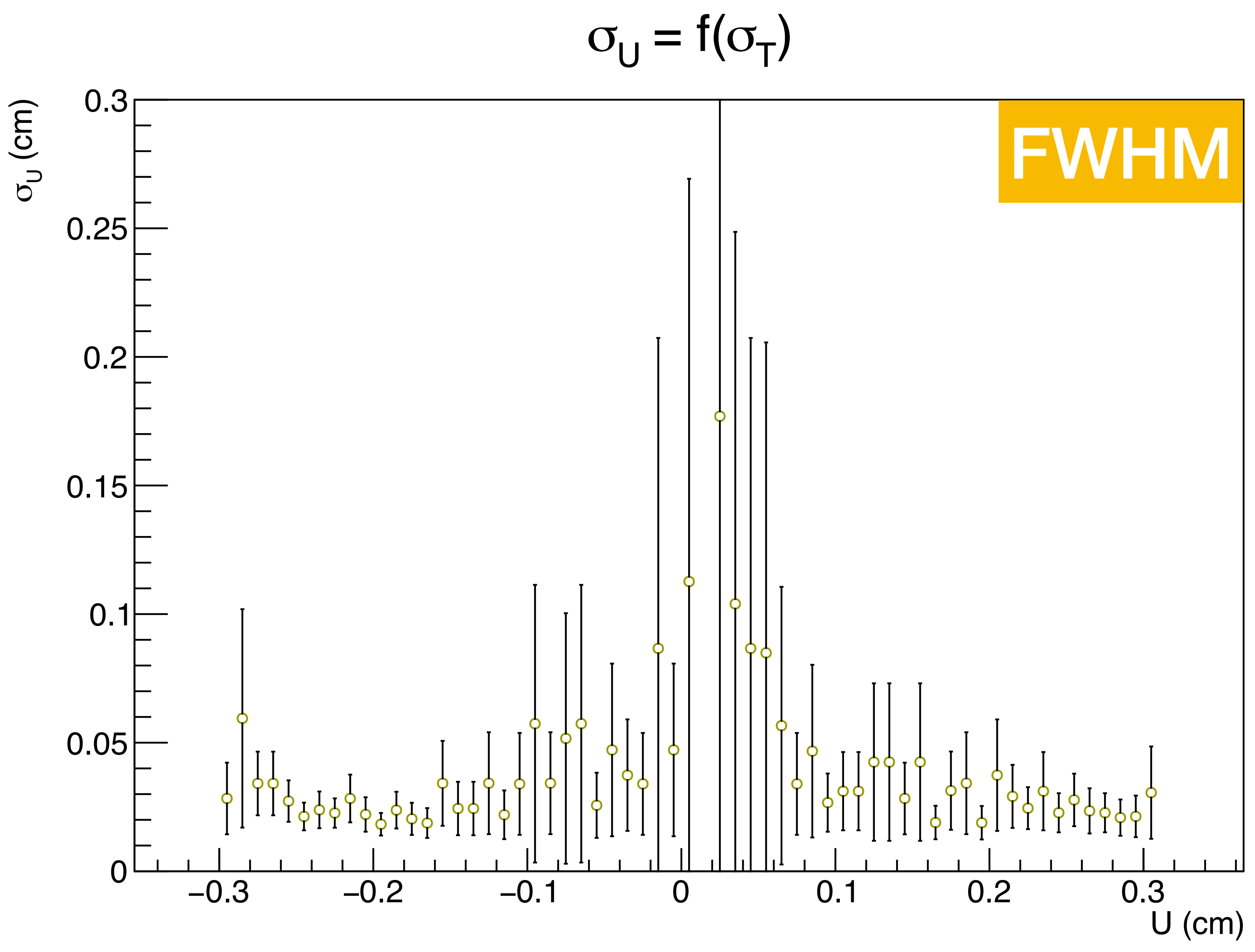


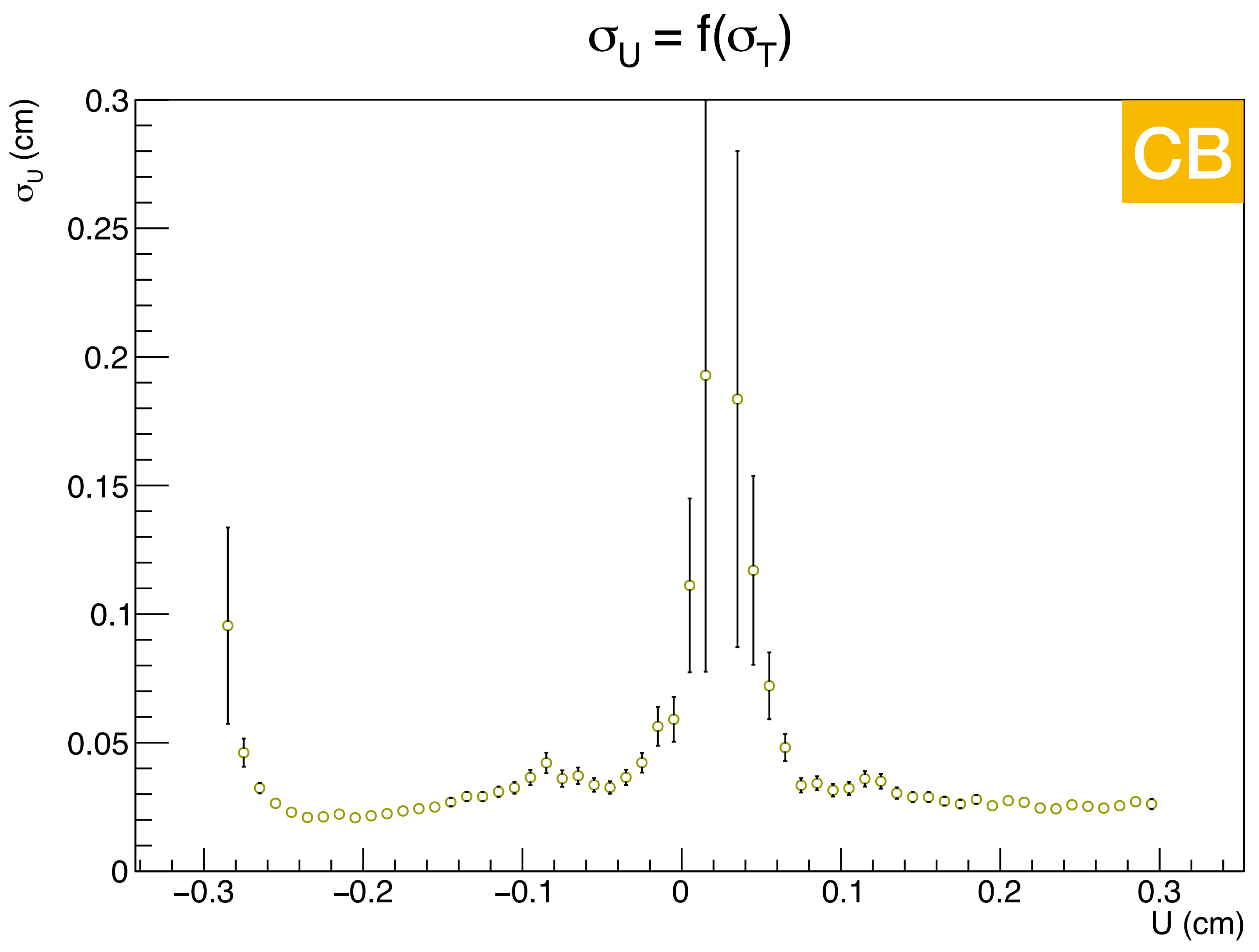


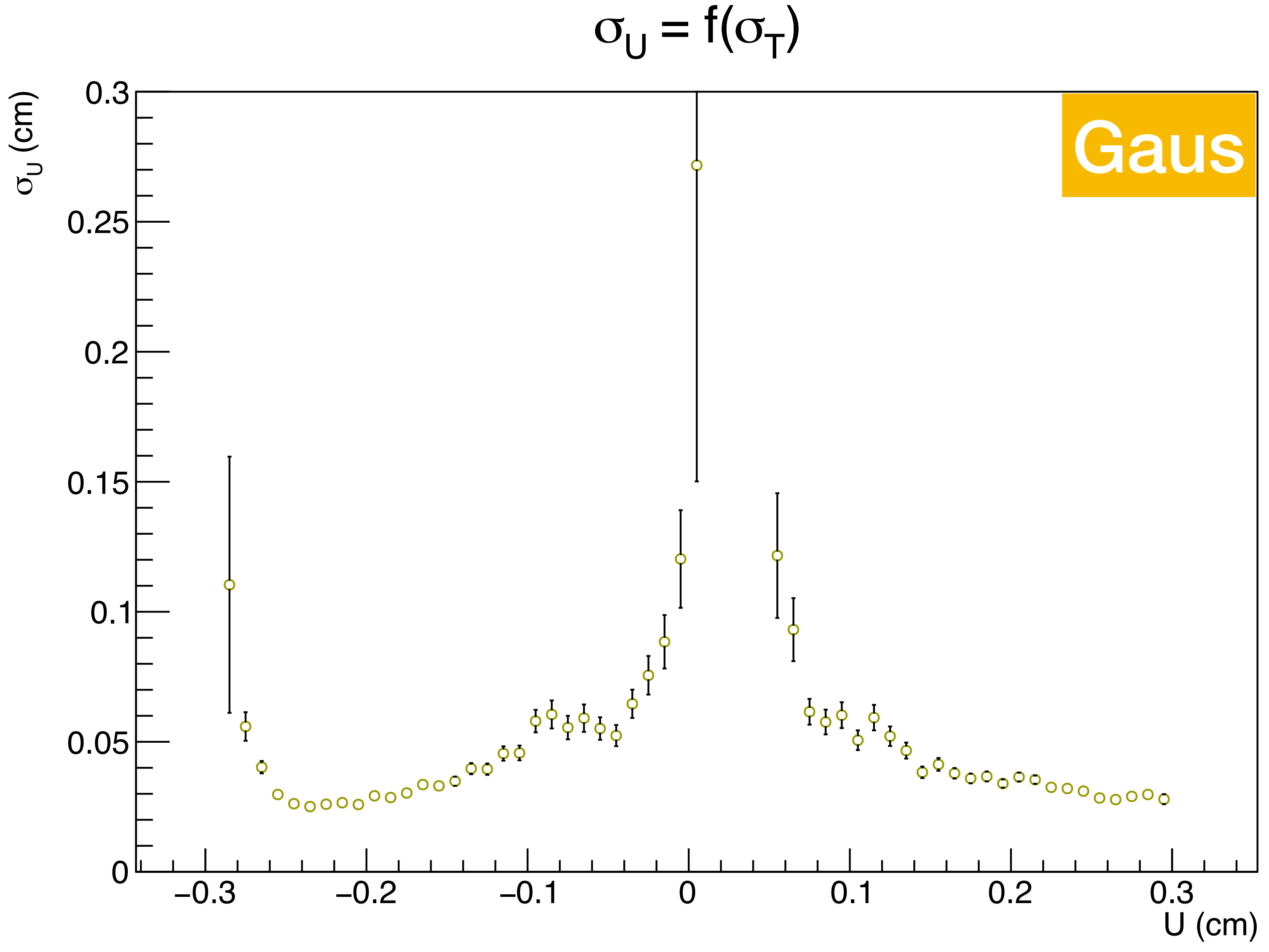


$$\sigma_U = \frac{\sigma_T}{|f'(U)|}$$

Coordinate resolution as a function of Time resolution







FWHM: (243 +/- 16) μm
CB: (253 +/- 2) μm
Gaus: (311 +/- 2) μm

Resolution is a weighted mean of such σ_U distributions