Testbeam measurements with different straw tube readouts

Andrei Zelenov[1], Vitaly Bautin[2], Sofia Bulanova[1], Temur Enik[2], Ysmaiyl Kambar[2], Ekaterina Kuznetsova[1], Victor Maleev[1], Assel Mukhamejanova[2], Sergey Nasybulin[1], Kirill Salamatin[2], Dmitry Sosnov[1]

on behalf of straw test beam team

[1]NRC «Kurchatov Institute» - PNPI
[2]JINR

SPD collaboration week, 25.04.2023

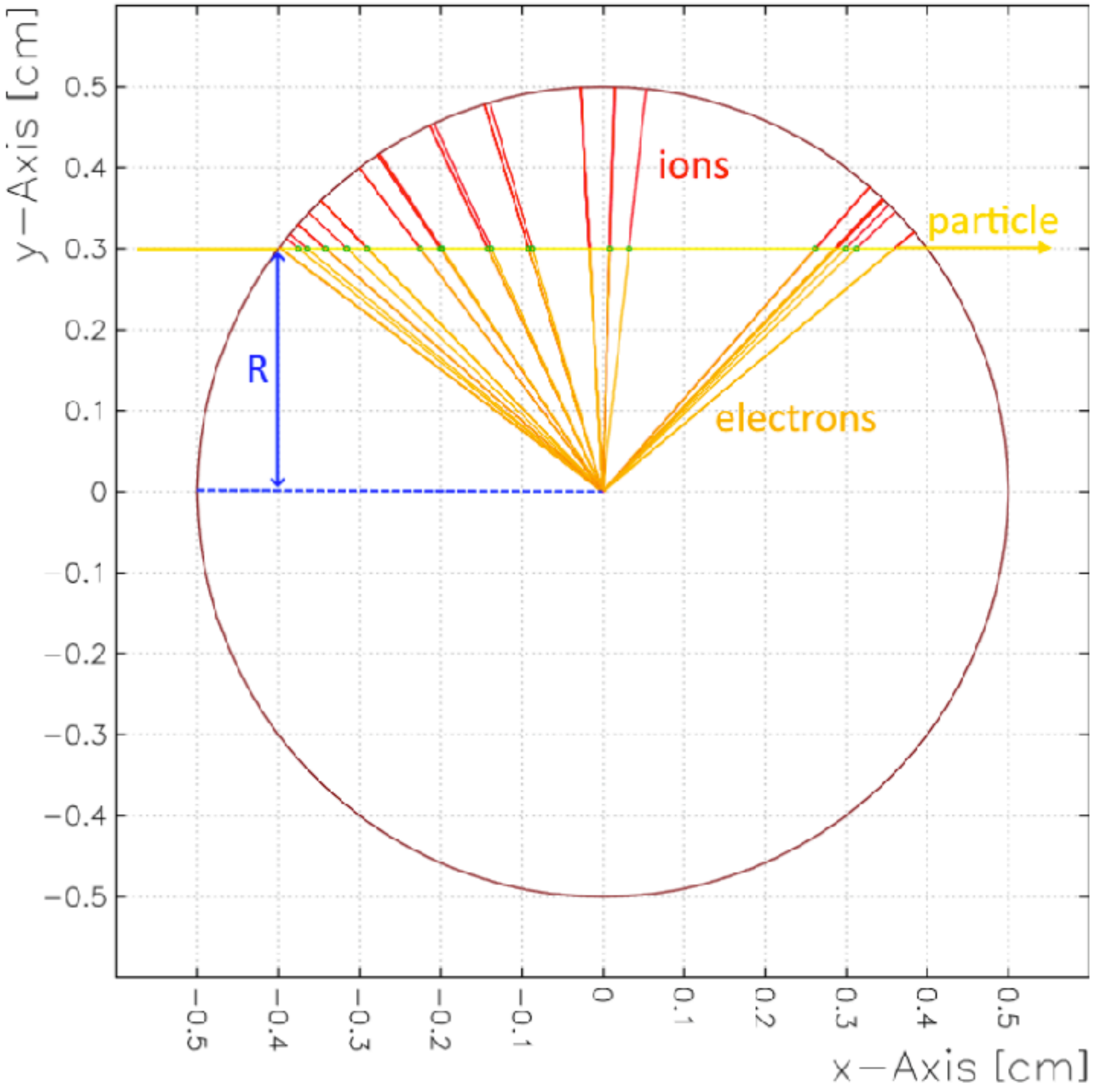
Outline

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

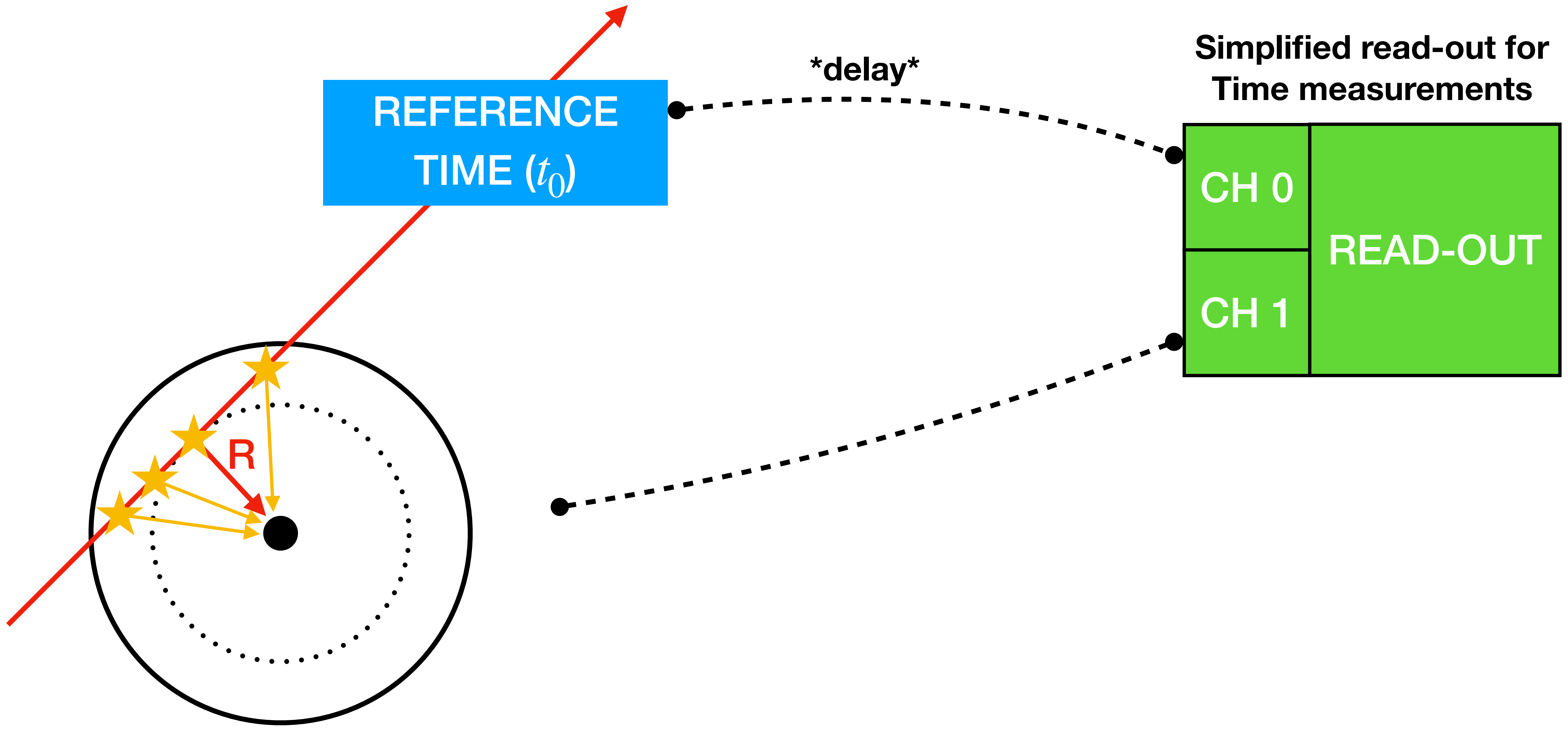
Straw Tubes

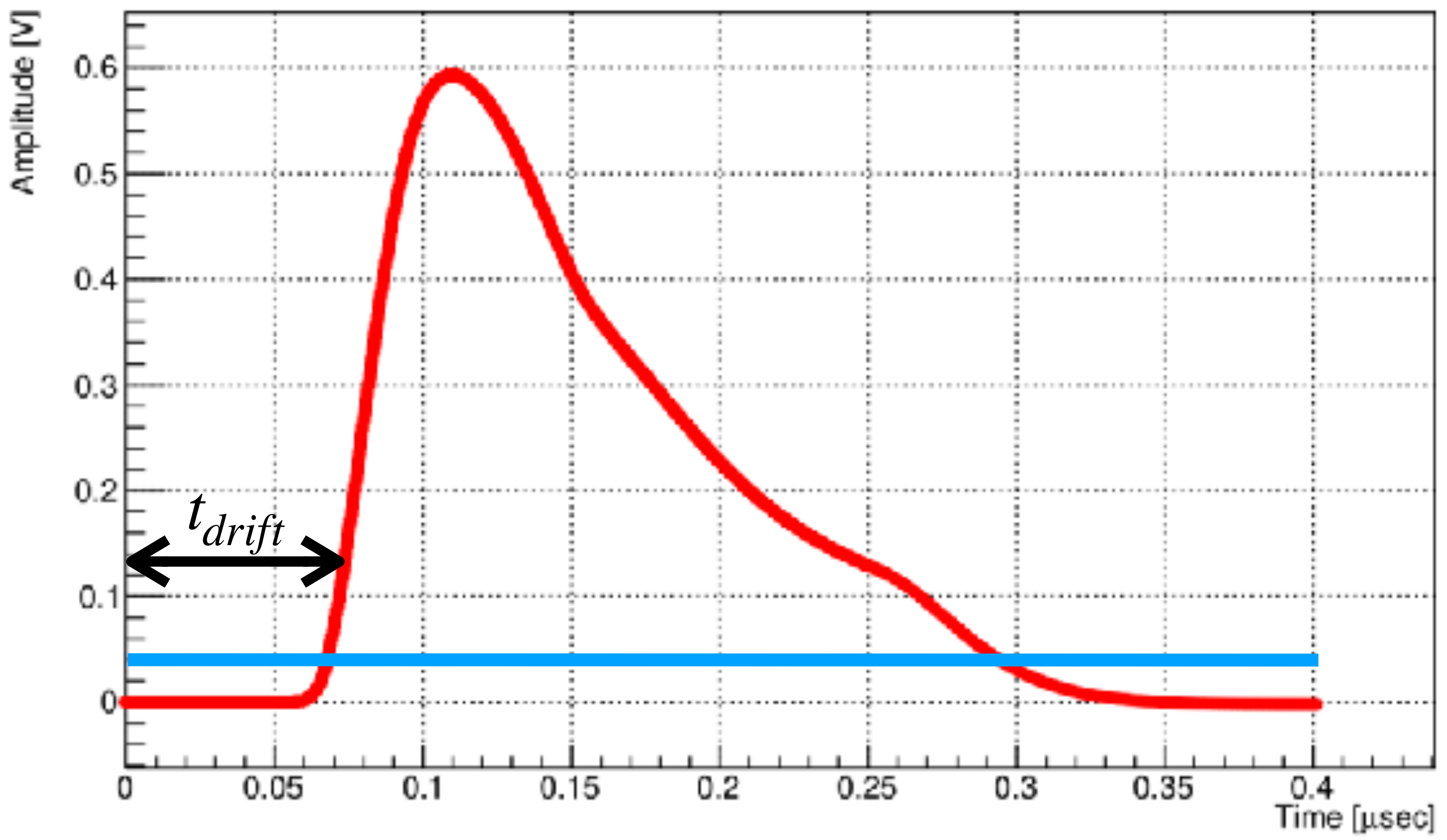
Straws are gas-filled cylindrical tubes with a conductive inner layer as cathode and an anode wire stretched along the cylinder axis.

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.

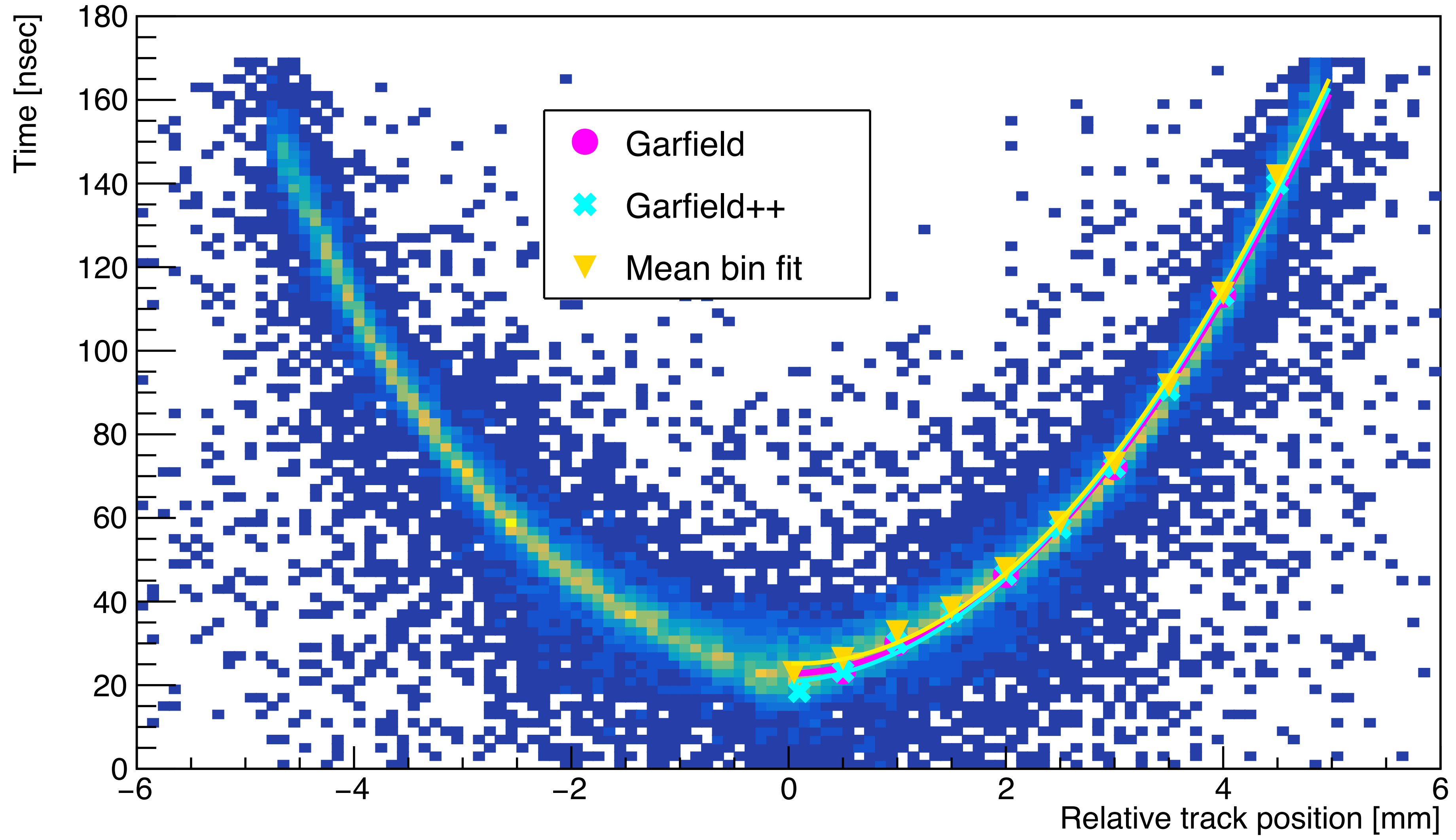


Straw Tubes





- 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.

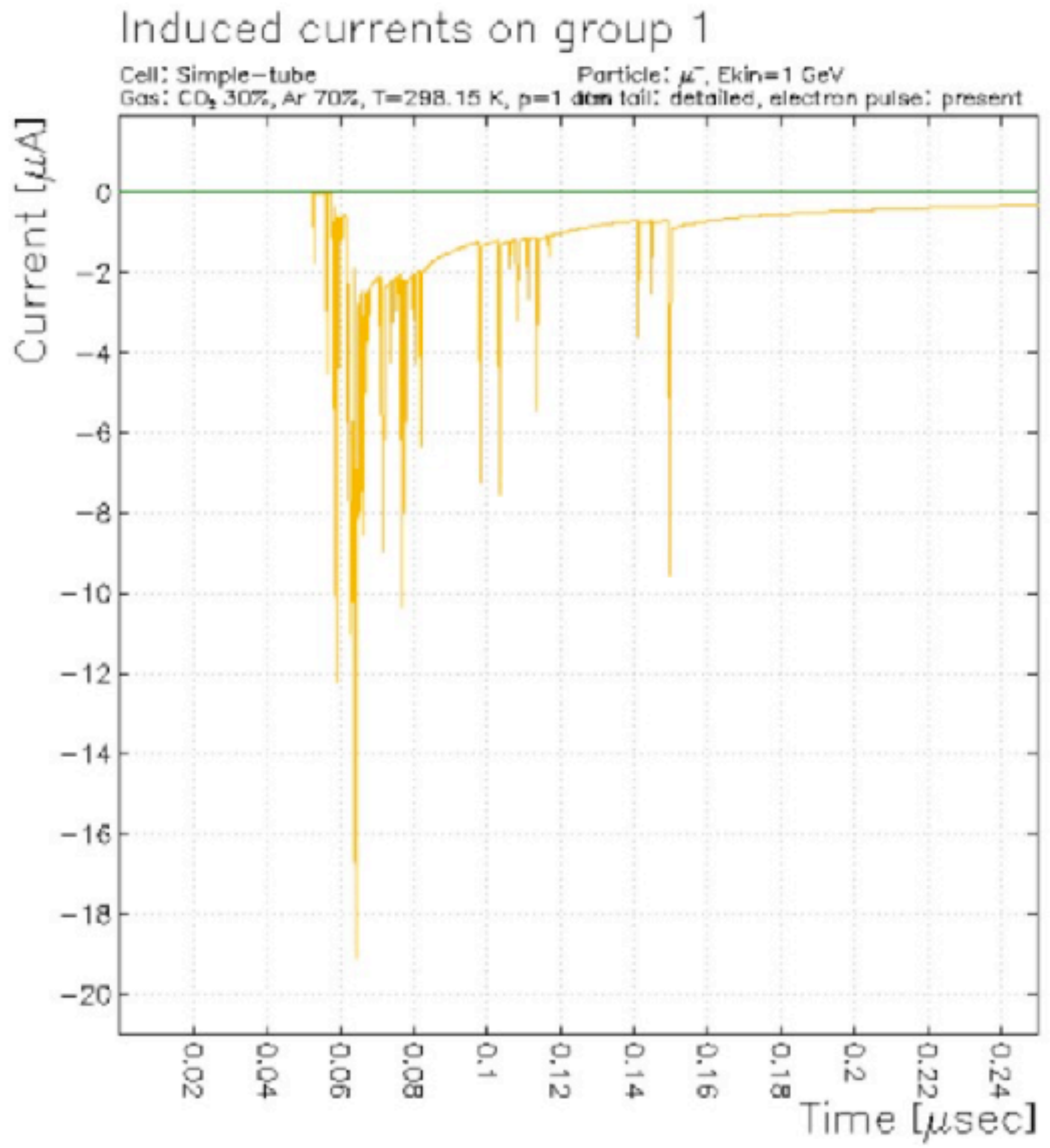


Example of the calibration $t_{drift}(R)$ dependence measured for an NA62 straw compared to *GARFIELD* simulation of the signal arrival time for first primary ionisation cluster.

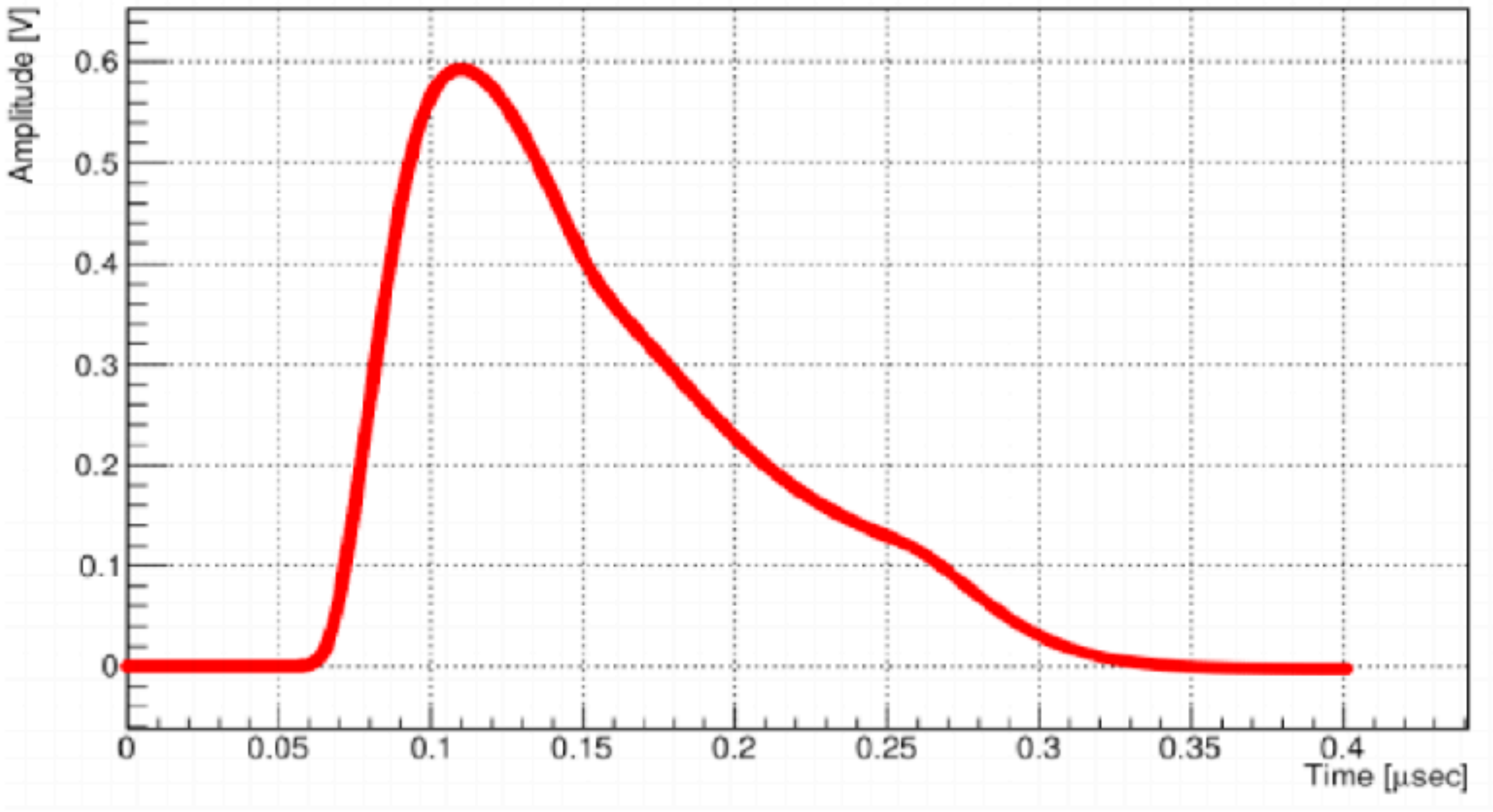
GARFIELD + LTSpice allows to predict straw response for a given readout model.

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. (see **S. Bulanova's** talk on Thursday)



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)

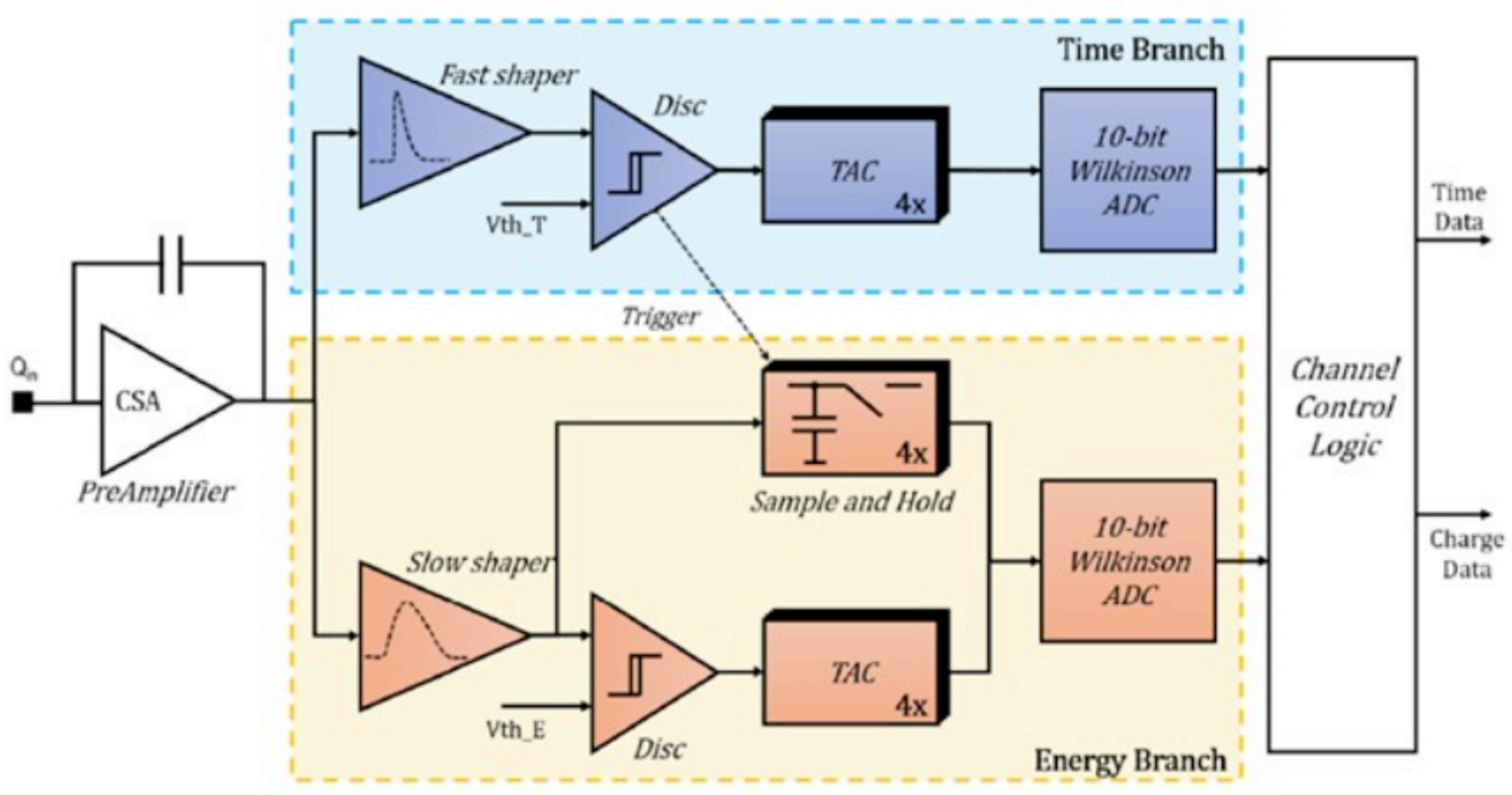
TIGER

- 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

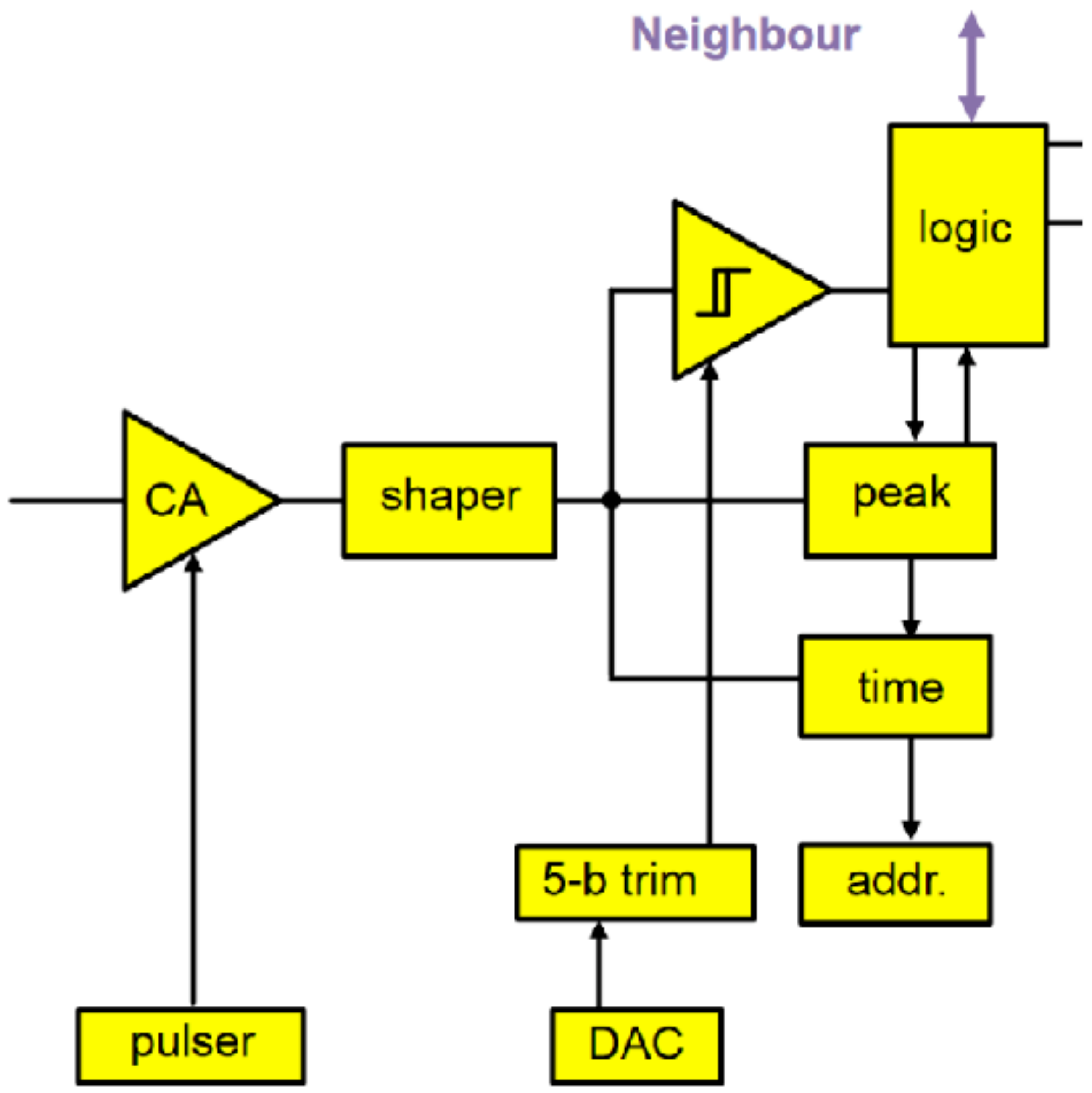
	VMM3	**TIGER**
Number of channels	64	64
Clock frequency	10...80 MHz	160...200 MHz
Input capacitance	<300 pF	<100 pF
Dynamic range	Linearity within ±2% up to 2 pC	50 fC
Gain	0.5, 1, 3, 6, 9, 12, 16 mV/fC	12 mV/fC
ENC (energy branch)	<3000	<1500
TDC binning	~1 ns	50 ps
Maximum event rate	140 kHz/ch	60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

Straw readout: TIGER vs VMM3

TIGER Architecture



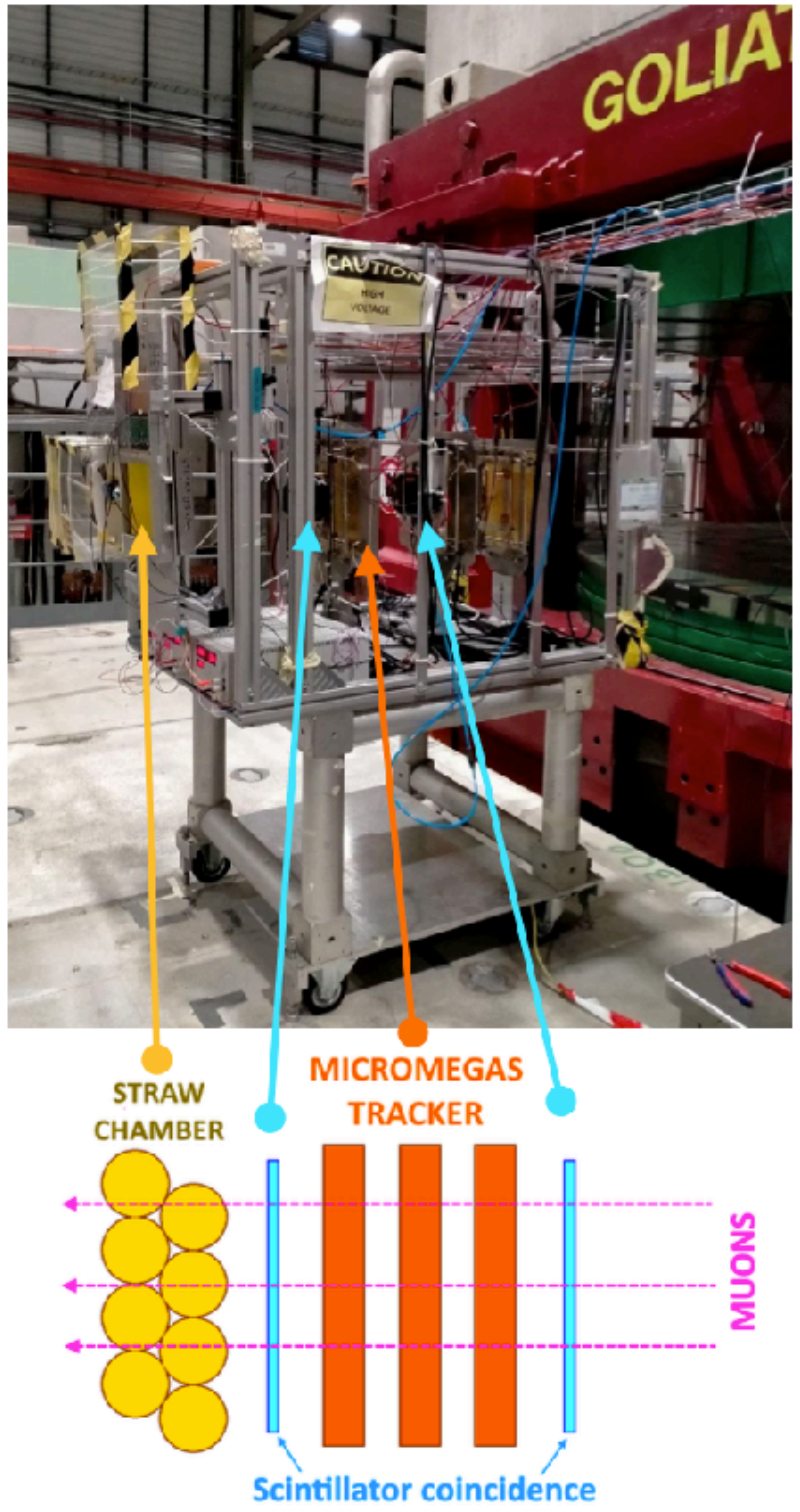
VMM3 Architecture

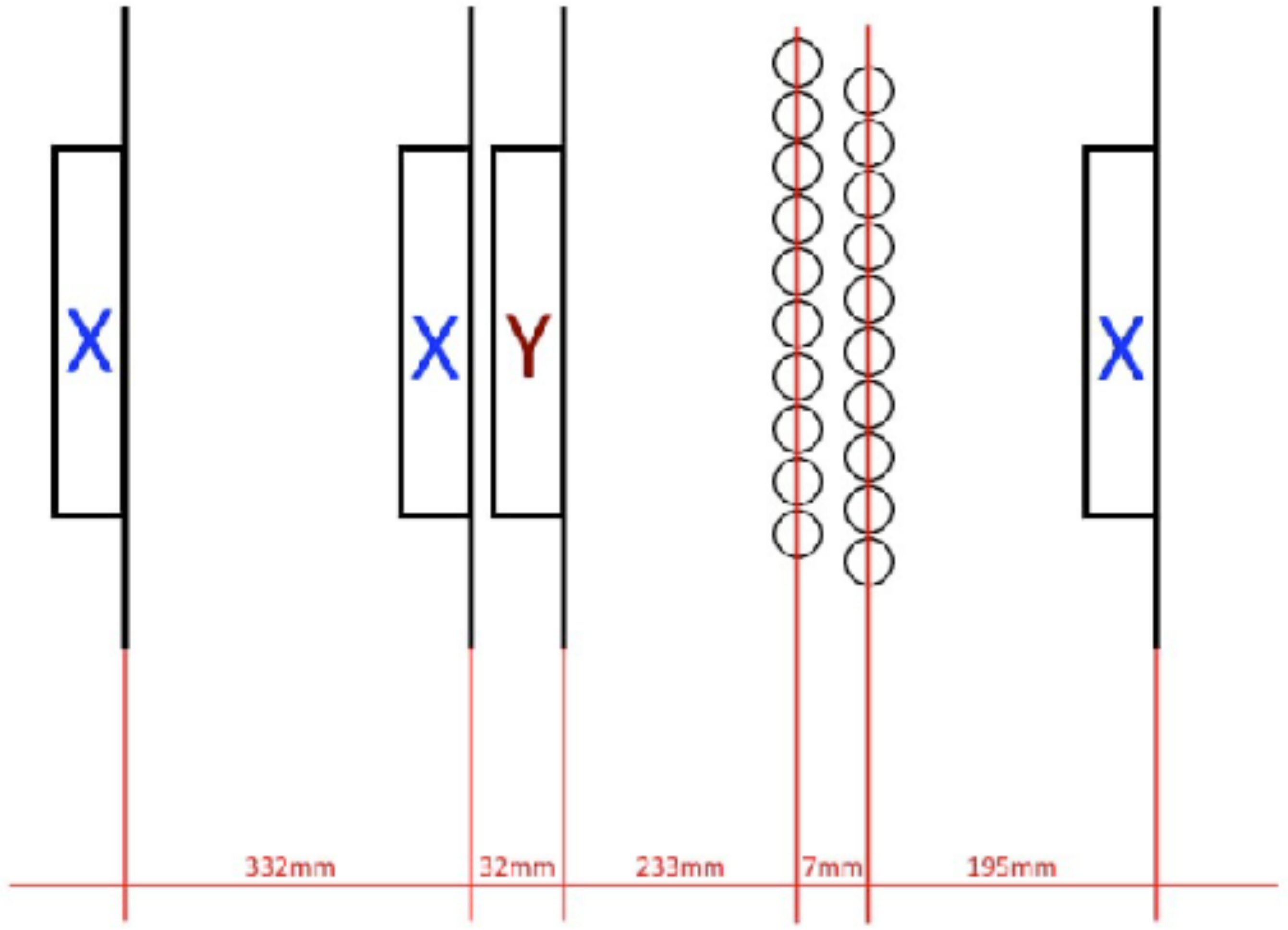


In contrast to *VMM,* the *TIGER* architecture has two different shapers for Time and Energy measurements. Two threshold levels are also possible.

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

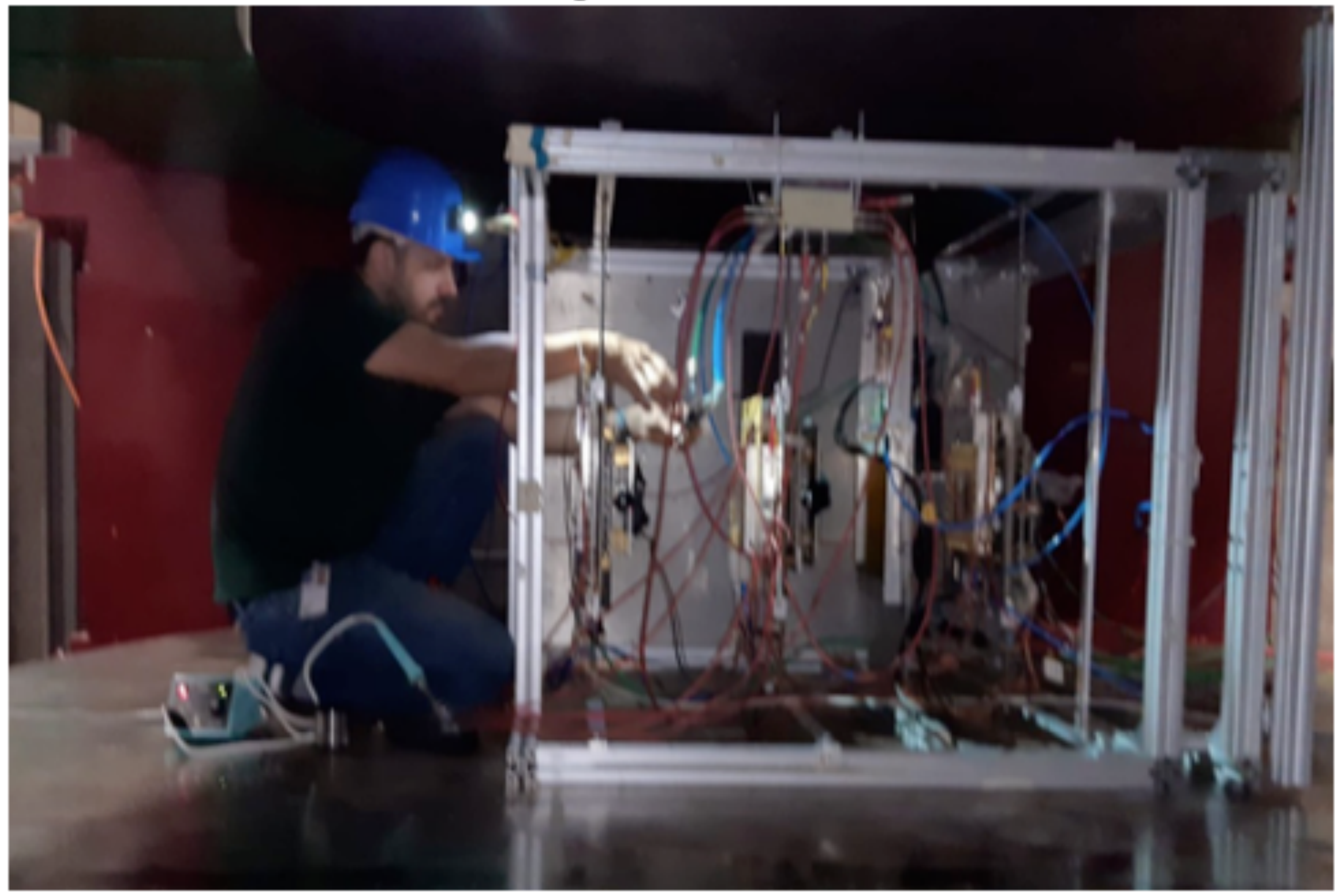
SETUP 1

- 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

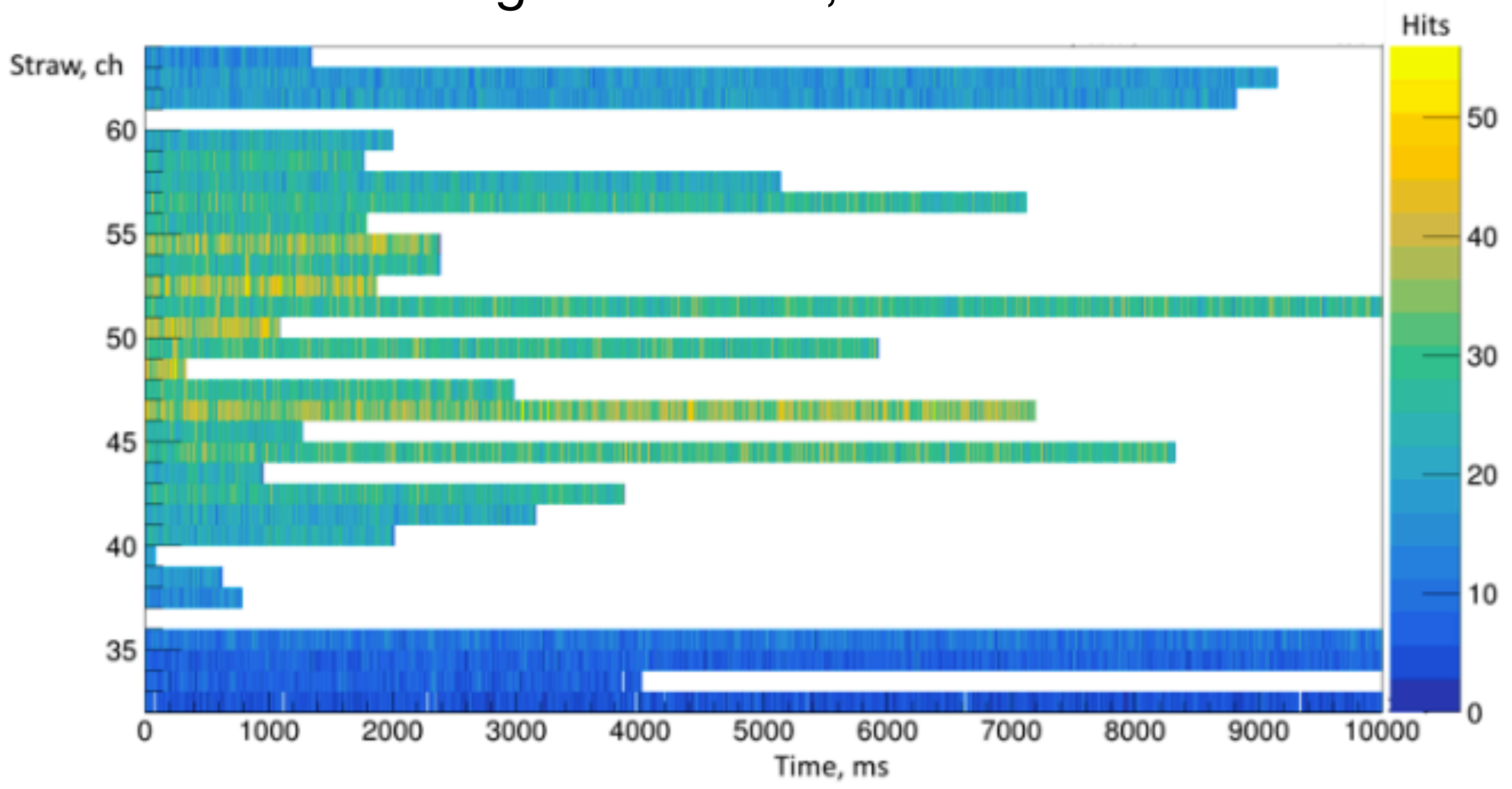
+ data taking in magnetic field

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



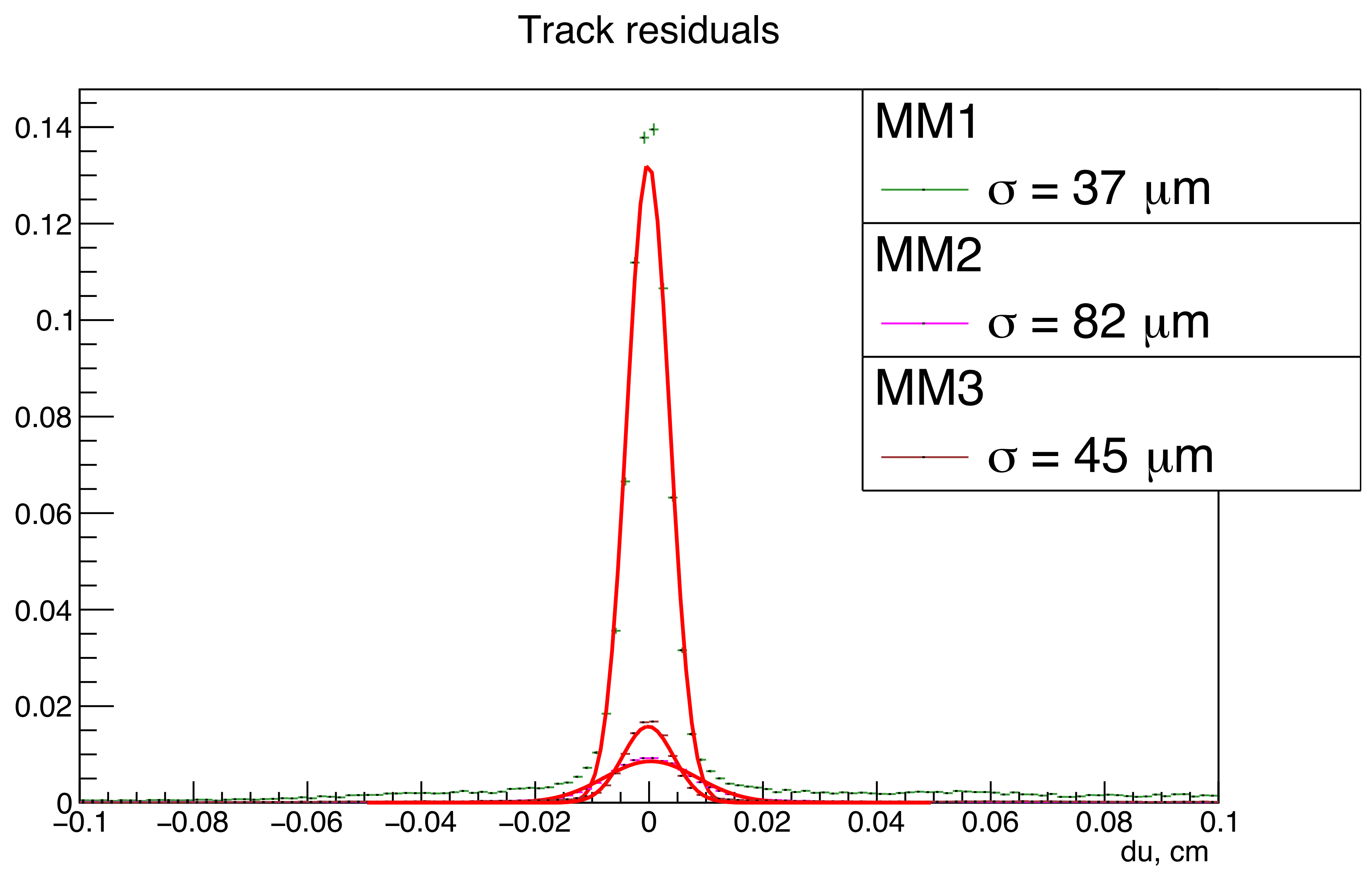
Testbeam measurements: SETUP2 (VMM3)

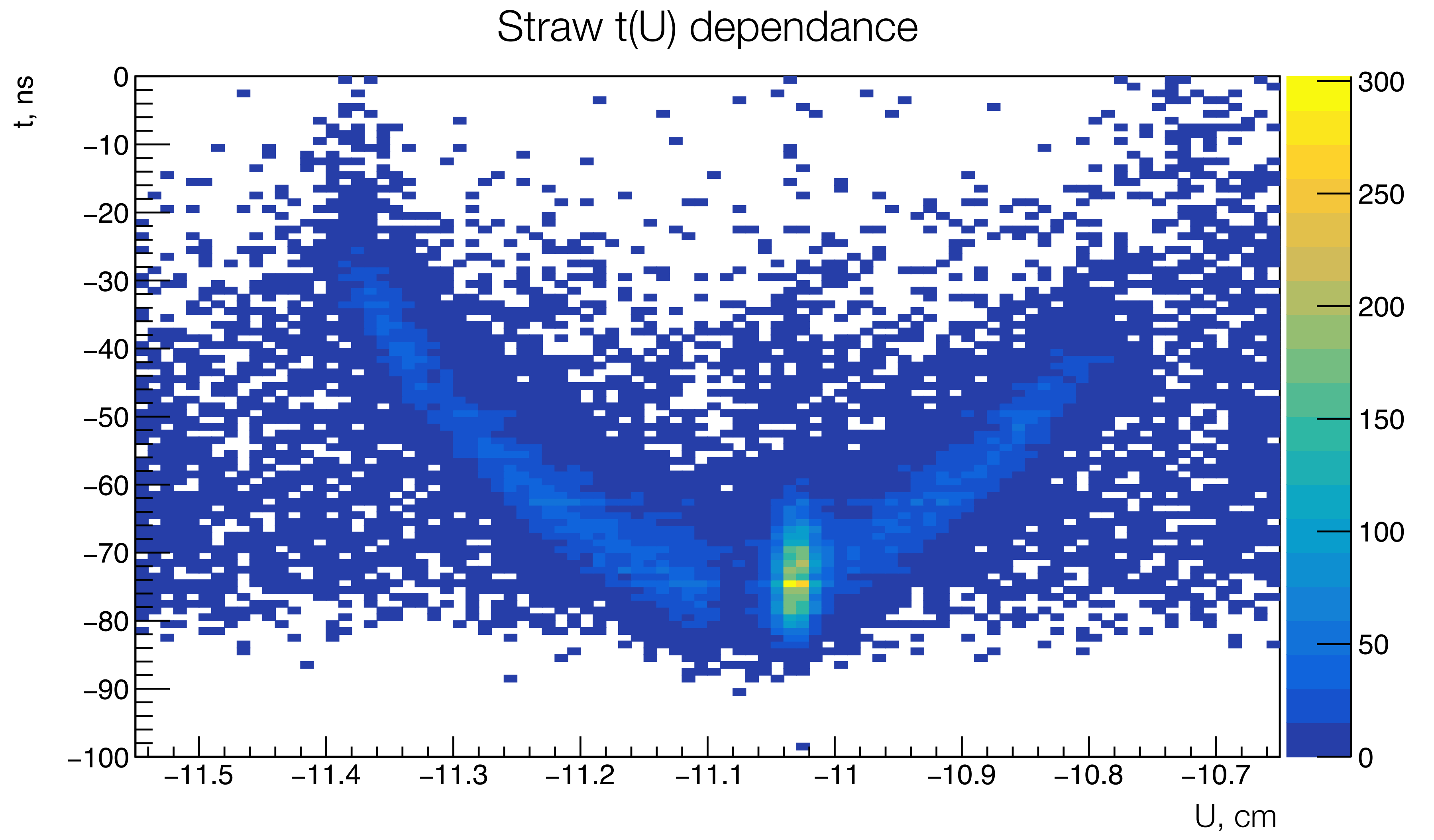
No such effect was found with previous revision, **VMM3**. The logic of the T@T mode slightly differs between VMM3 and VMM3a

- Reference tracker and straw readouts of different types were synchronised using external pulse generator and challenging merging of the tracker and straw data was performed offline

- Reconstruction of tracks in the reference MicroMegas is done using charge-weighted clusters and Least Square Method for track fitting

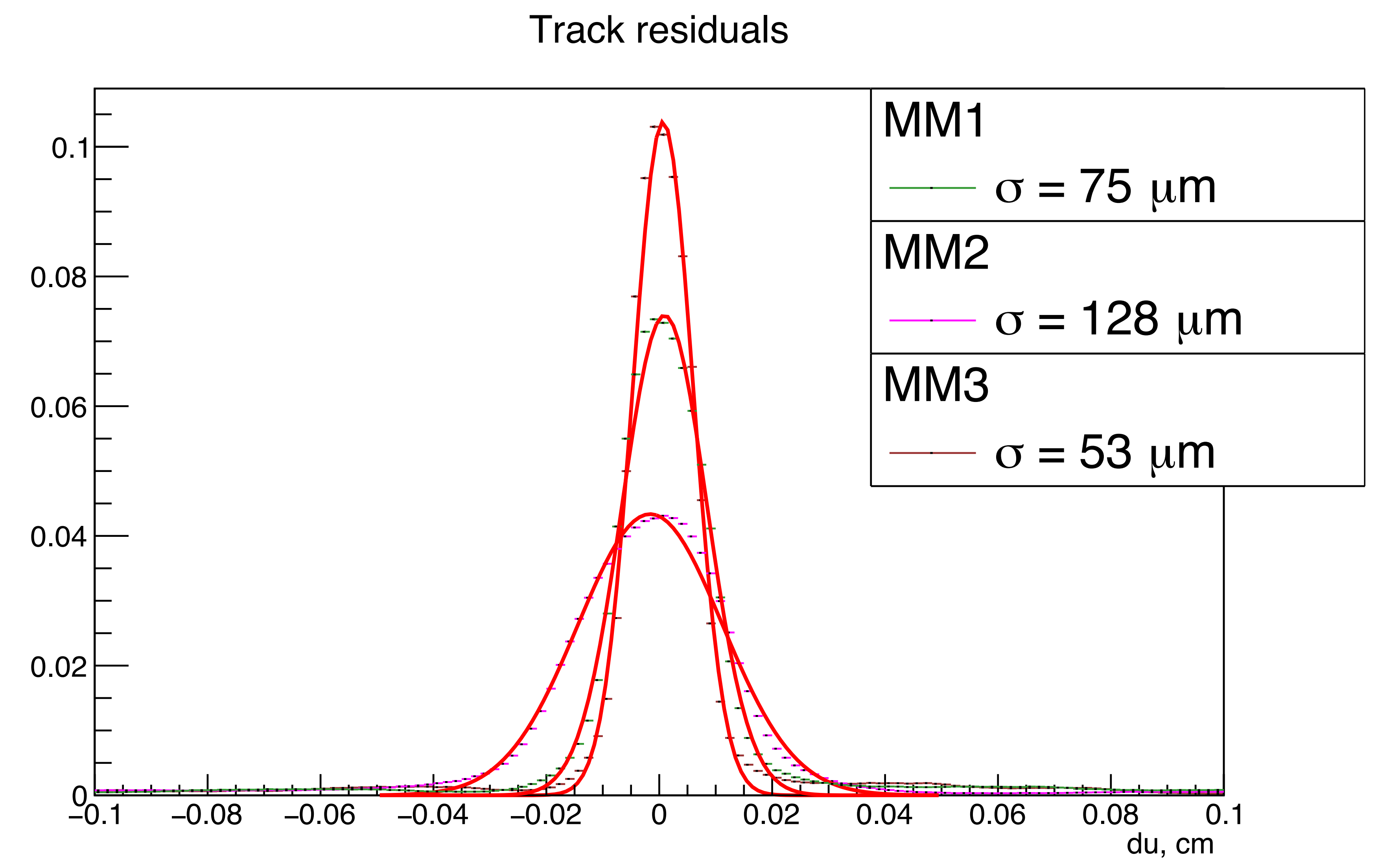
- Extrapolated reference track coordinate *U* is used to obtain the correlation between straw signal time *t* and the track position

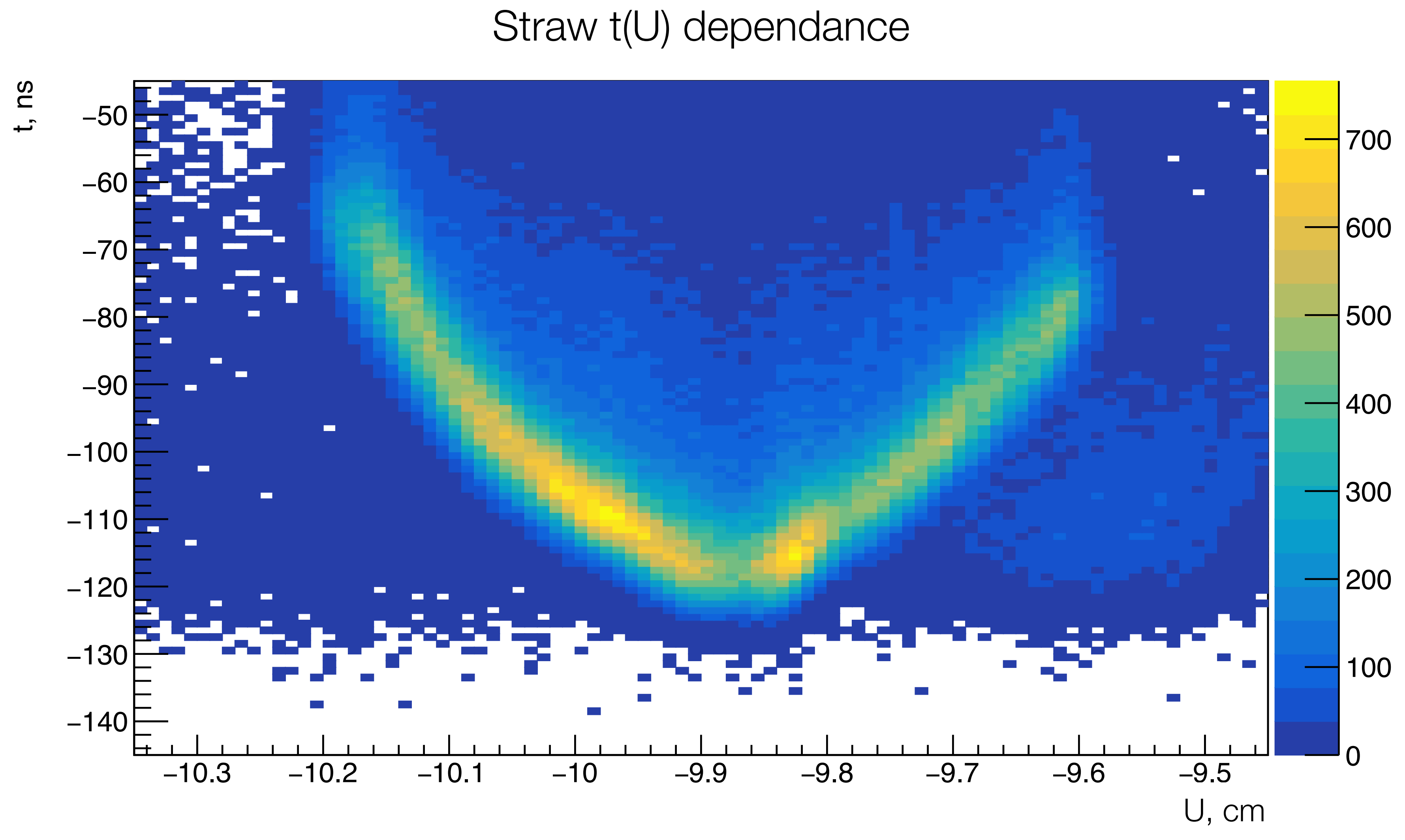




Testbeam measurements: SETUP3 (TIGER)

- At the moment the clustering in the TIGER data set is not perfect
- Work on improvement of the clustering algorithm is ongoing
- TIGER readout is adopted as the baseline for the MicroMegas readout at future TestBeam measurements

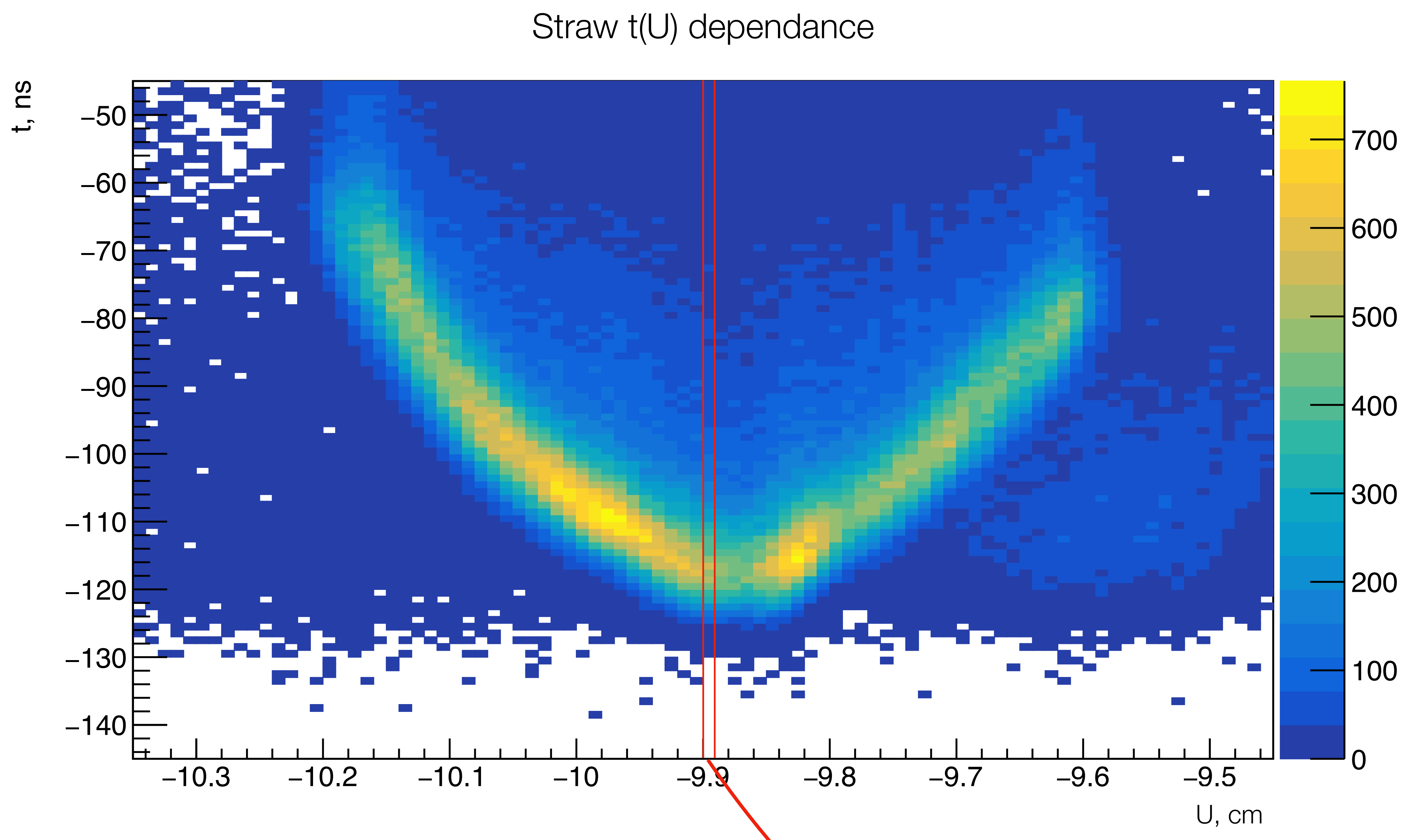




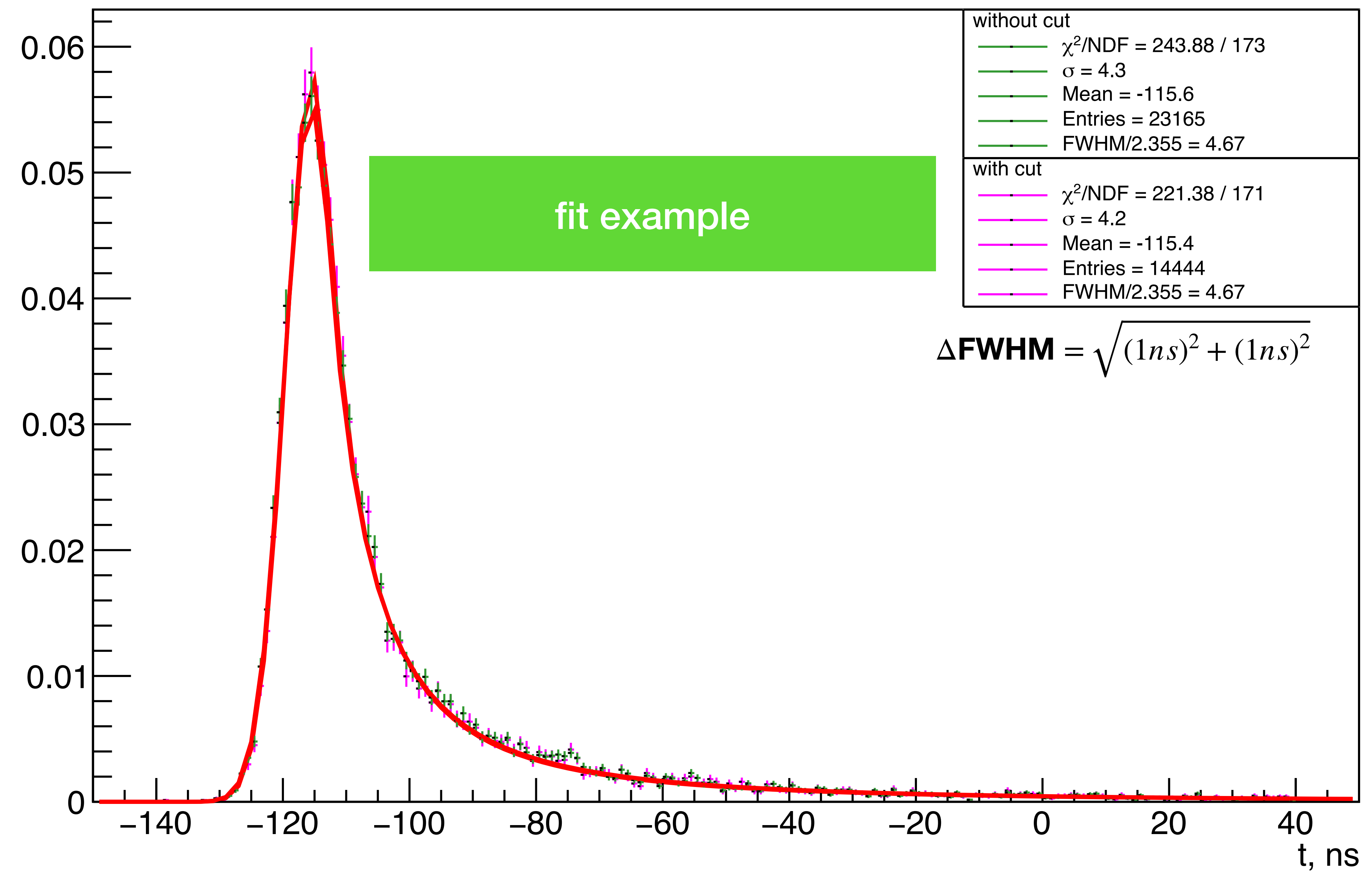
Coordinate resolution as a function of Time resolution

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

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

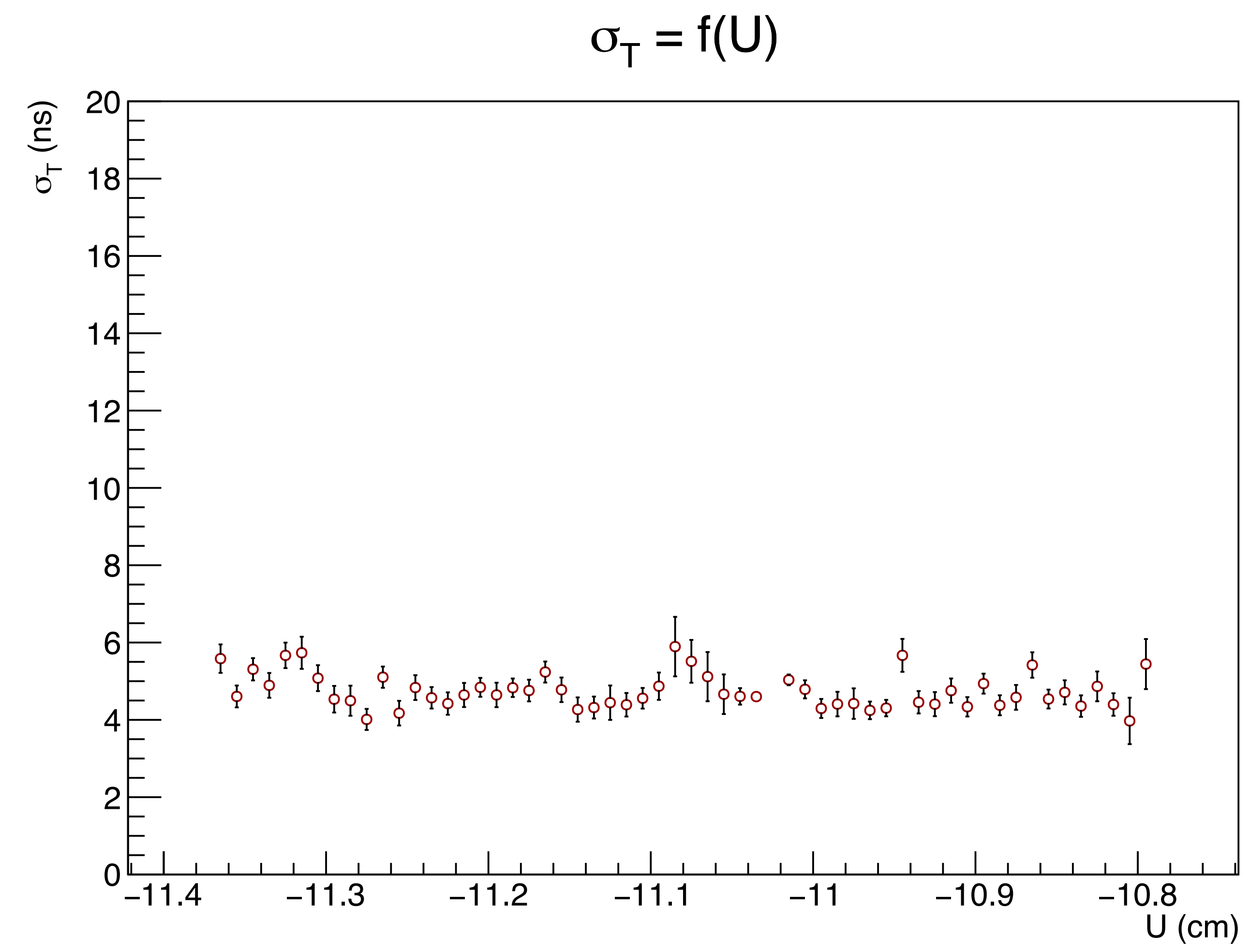


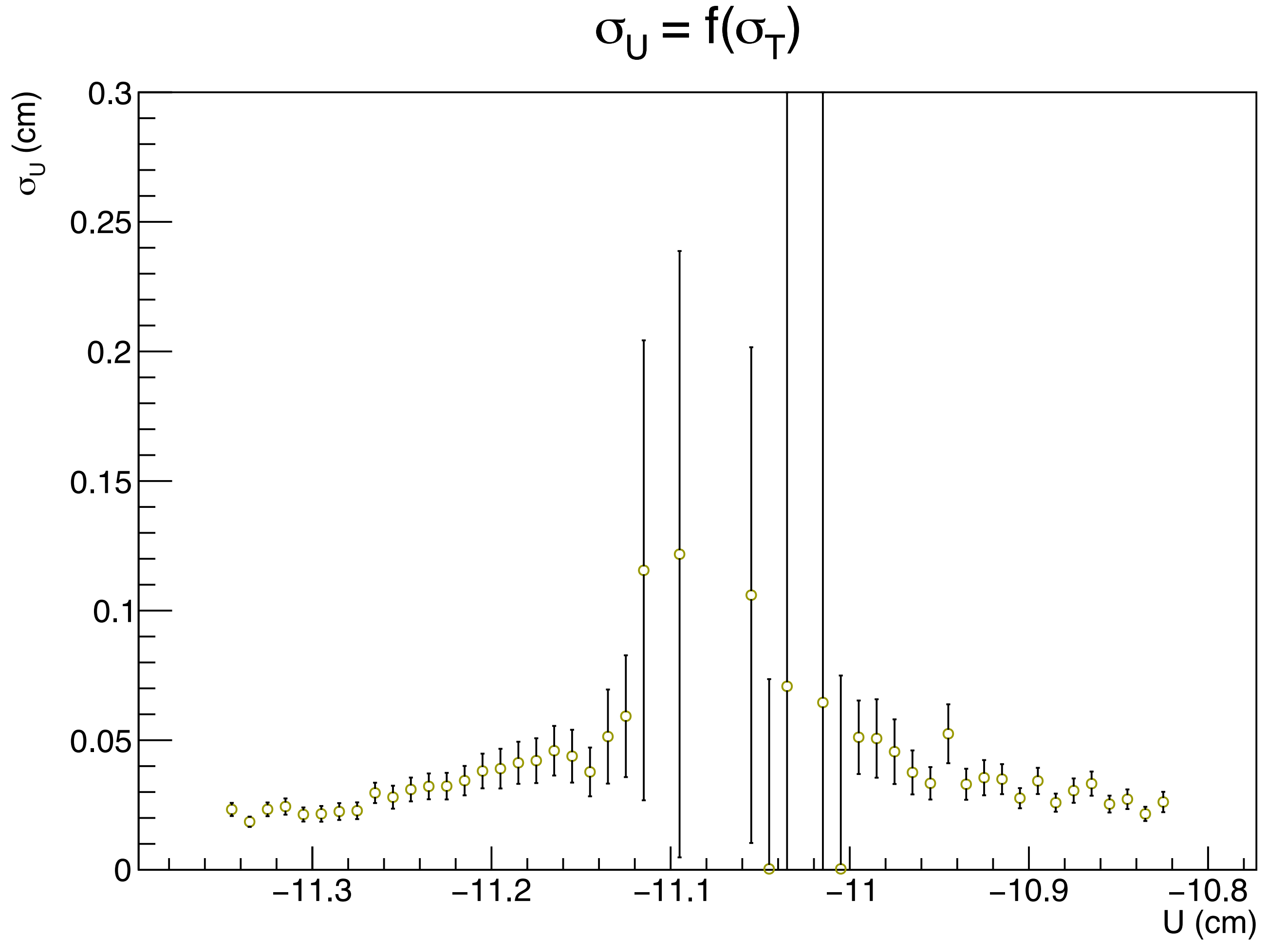
0 mm from the apex



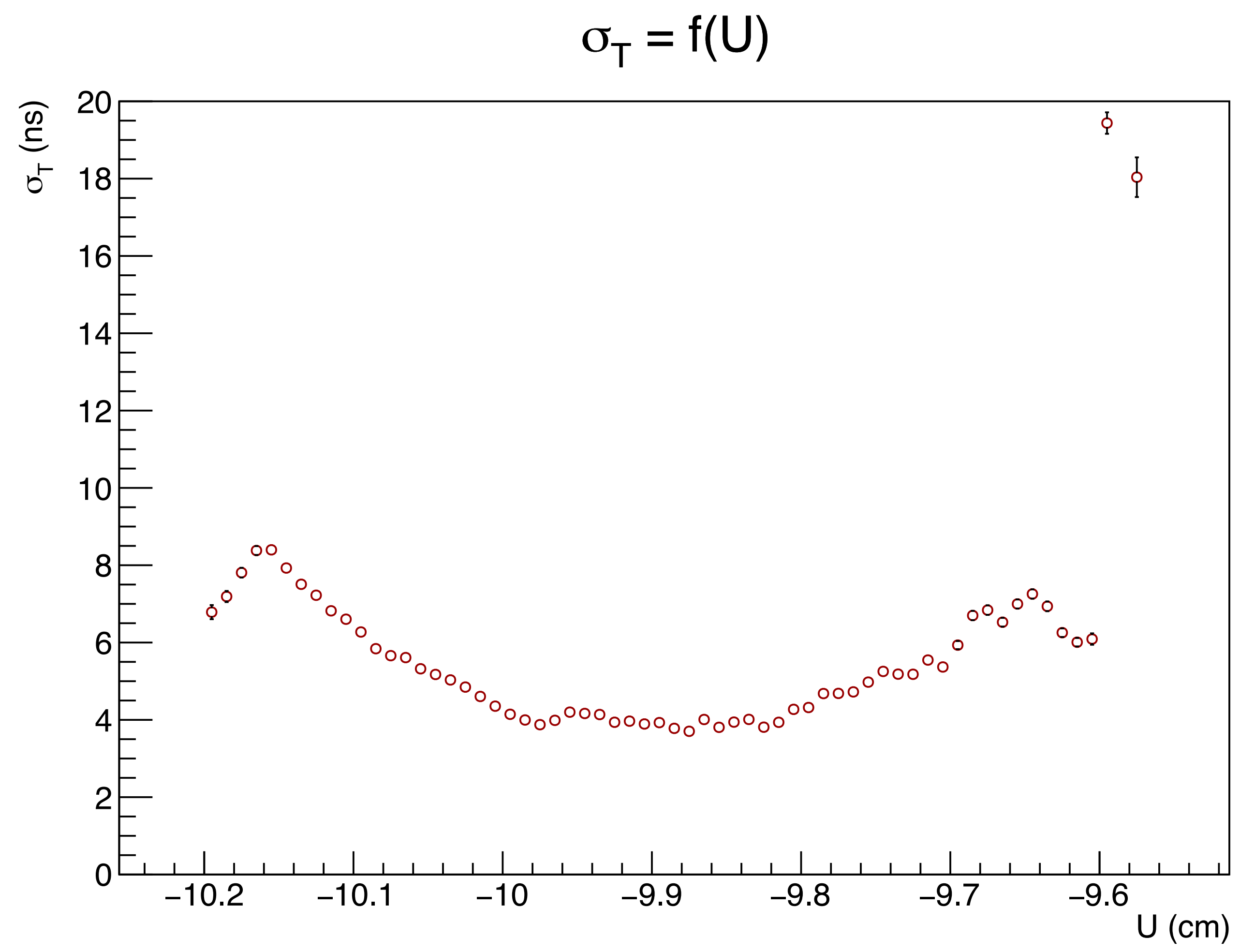
Coordinate resolution as a function of Time resolution

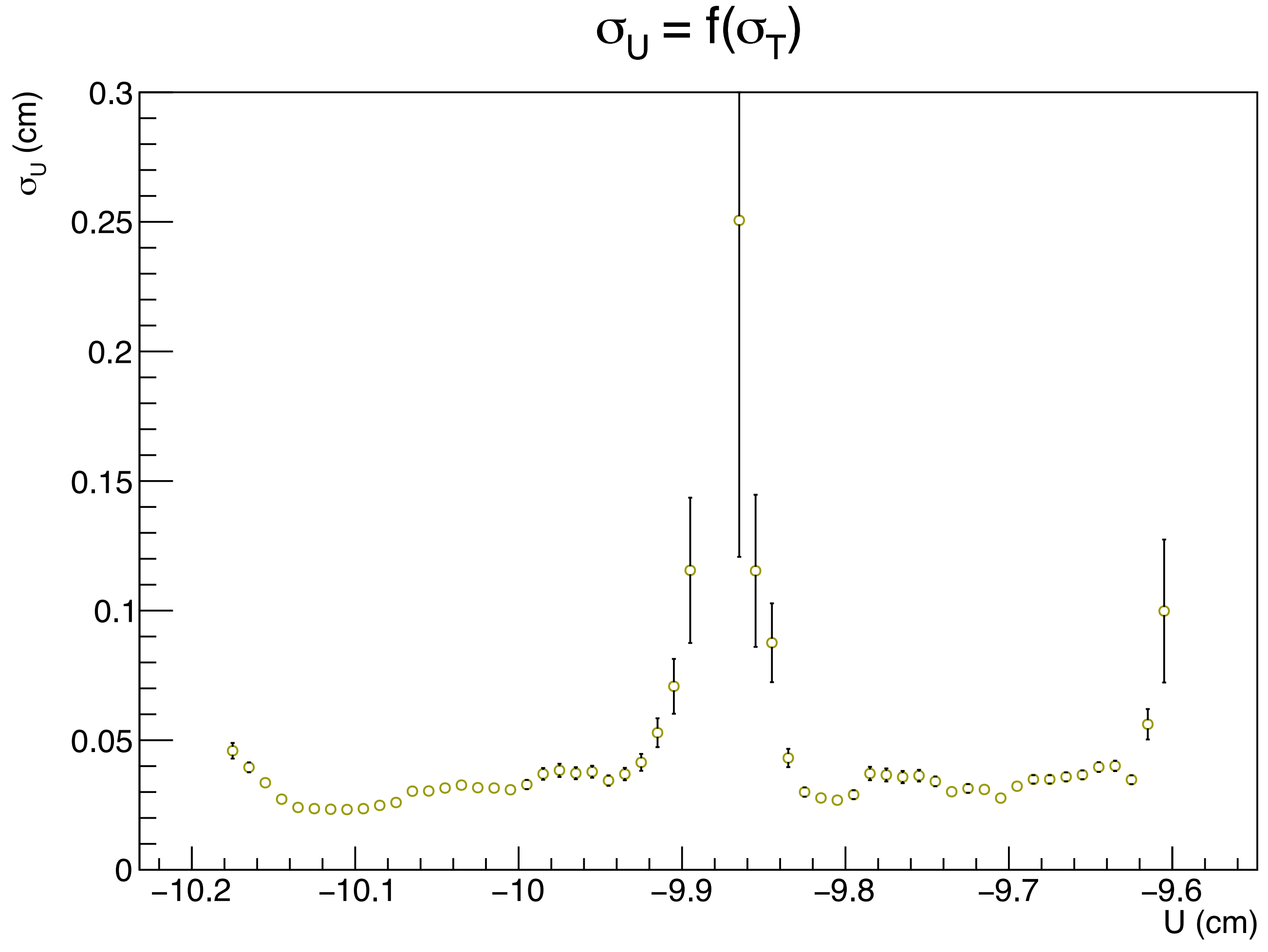
SETUP 2 (VMM)





SETUP 3 (TIGER)





$\langle \sigma_U \rangle$ = (260 +/- 2) μm

Resolution is a weighted mean of such σ_U distributions

- The obtained $\boldsymbol{\sigma_U}$ still contains contribution from the binning, imperfection of the reference tracking and finite resolution of t_0 ($\sim$1 ns)

Next steps:

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

Testbeam @ April-May 2023

- TIGER readout based Combined straw tracker prototype
- Improved operation mode for scintillators (300ps instead of 1ns in October)

Summary

- active search for the straw readout concept capable for both the time and charge measurements is ongoing
- during first Testbeams 2021-2022 three types of existing ASICs were tested
- **VMM3a** was rejected due to the latching in the time-at-threshold mode
- **VMM3** concept was found to be promising
- **TIGER** has better architecture but needs further adjustment for the straw applications
- first stage of the Testbeam data analysis shows a reasonable time resolution for the **VMM3** and **TIGER**-based readouts. Data analysis still ongoing
- more dedicated Testbeam measurements to be done in *2023* with the combined straw tracker prototype (5, 10 and 20 mm in diameter)
- based on the lab and test beam measurement results and on the gained experience, a concept of a new ASIC chip is being developed
- the work is supported with *Garfield++/LTSpice* simulation studies

Backup

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 $\Delta(T) = \sigma_t/\sqrt{N}$

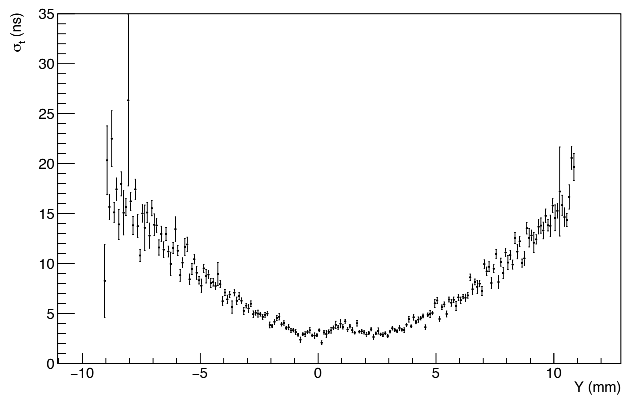


Figure 2: Sigma parameter from fit as a function of a track coordinate.

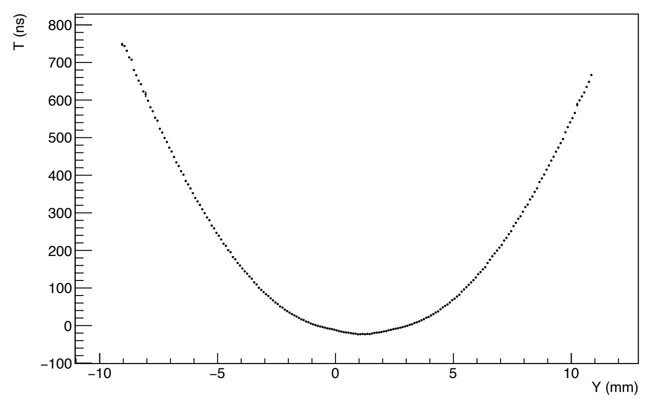


Figure 3: Fit mean value as a function of track coordinate.

1.3 Resolution estimation

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

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

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.

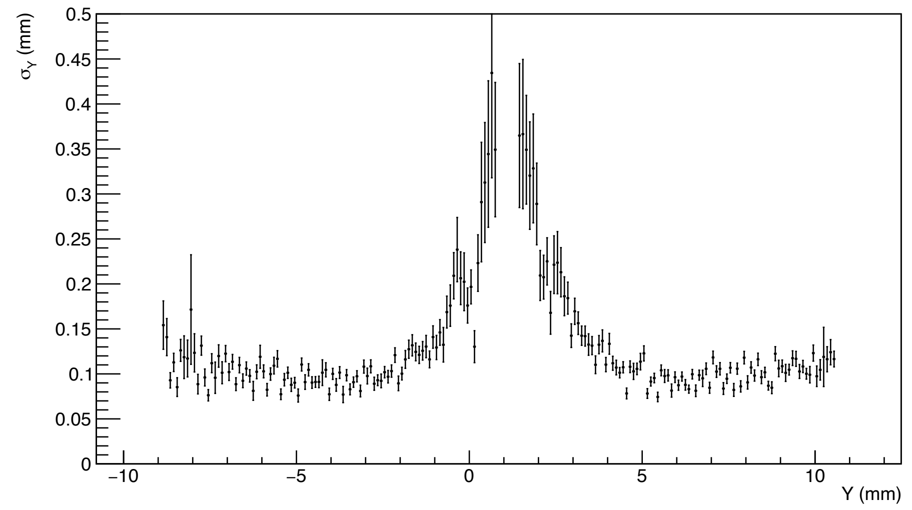

Figure 4: Distribution of coordinate resolutions for every coordinate bin

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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SHiP TB NOTE 2017